DRAFT

DEPARTMENT OF ENERGY

FISCAL YEAR 2004 BUDGET REQUEST

FIELD WORK PROPOSALS

FUSION ENERGY SCIENCES

PRINCETON UNIVERSITY

PLASMA PHYSICS LABORATORY

CONTRACT NO. DE-AC02-76CH03073

MARCH 1, 2002

Preface

The DOE Princeton Plasma Physics Laboratory has a broad plasma science program focused on scientific understanding, creative innovation, and collaboration – leading to an attractive fusion energy source.

In FY03-04 the National Spherical Torus Experiment will continue to yield important results using strongly shaped, intensely heated, very low aspect ratio plasmas. The Spherical Torus effort has great promise to contribute inexpensively to the fusion development path. It also provides a major test-bed for the understanding of toroidal plasma confinement. If theoretical predictions are correct, plasmas in NSTX should be able to access low turbulence states at extreme high beta-toroidal. The development path for the Spherical Torus is laid out in the FESAC Report on Priorities and Balance. In the period of 1999 – 2004, NSTX has and will continue to explore ST physics for pulse lengths long compared with the energy confinement time, providing important new insights in toroidal physics. During this time period we will also prepare for a staged upgrade to NSTX, able to explore operation for pulse lengths long compared with current relaxation times, as required by FESAC, at moderately higher performance.

PPPL continues to lead a major collaborative design effort for the National Compact Stellarator Experiment. New stellarator configurations have been developed utilizing both advances in stellarator theory and the insights from the last decade of advanced tokamak research. This effort has now provided an opportunity for the US program to make a contribution to the large international stellarator program, at very modest expense. The flexibility of the new NCSX design will provide an unparalleled opportunity to advance the science of toroidal plasma. Furthermore, it holds out the promise that the best features of a stellarator – low recirculating power and disruption free operation – can be combined with the best feature of the advanced tokamak – high power density – to provide a very attractive toroidal confinement system. A national collaboration is creating a revitalized U.S. Proof of Principle stellarator program, including not only a stellarator PoP experiment, but also new concept exploration experiments, theory, and reactor studies. NCSX successfully completed a Physics Validation Review in FY01. A Conceptual Design Review is planned for May 2002.

Important collaborations on the C-MOD, DIII-D, JET and JT-60U tokamaks and on LHD and MAST as well as at Universities around the nation, are benefiting both the PPPL program and the programs at each of these facilities. PPPL will continue to foster those collaborative relationships during the coming fiscal years, with special emphasis on advanced tokamak science at DIII-D and C-MOD. We are also particularly excited about near-term opportunities for the U.S. program to support and participate in experiments at the Joint European Torus, leading to a next round of DT experimentation. It would certainly be a crowning accomplishment if strong US participation facilitated the achievement of Q well above unity in JET, consistent with the FESAC goal in this area. In the longer term, U.S. participation in the KSTAR experiment will be the highlight for achieving the 2004-2009 FESAC goal of long pulse experimentation in tokamaks. These forms of international collaboration are critical to rebuild confidence in US collaboration, so that we can ultimately participate in an appropriate manner in the international effort to achieve a burning plasma, be it through ITER or, if such a device is not able to be constructed for financial reasons, through a smaller high-field copper-coil device such as FIRE.

Smaller on-site fusion experiments provide opportunities to test the most adventurous ideas, with strong theoretical and diagnostic support not available at many other institutions. These smaller experiments are also extremely effective for training students in Princeton University's Program in Plasma Physics. We are especially pleased with PPPL's new involvement with the technology side of the fusion program, through the liquid-lithium experiments on CDX-U. This provides a unique opportunity for partnership between physics and technology, and we are highly committed to its success. Our proposed broad program of plasma science and technology helps the fusion community reach out to the wider US science and technology community and to US industry. This is illustrated by the MRX research on magnetic reconnection which is of importance to both space and laboratory plasma. This highly regarded research is included in proposals to NSF.

The PPPL Theory Department will continue to provide strong intellectual leadership in the fusion community. Because of the collaborative nature of the PPPL program, this team of theorists is uniquely well positioned to compare the latest theoretical analyses with detailed data from experiments world-wide. Our collaborative partners value highly our advanced computational capabilities, so this effort is very much seen as mutually supportive. At the same time, the theoretical team itself benefits from a "critical mass" of co-located theoretical physicists, providing both a powerful brainstorming atmosphere and also quality control to assure excellence.

Internally, the laboratory continues to utilize the Science Focus Groups as its intellectual cartilage, to provide the cross-linkages that coordinate the diverse range of PPPL activities and interests. The Science Focus Groups tie together not only the diverse projects, on site and off, but also the Theory and Experimental teams themselves. These teams are also linked by the Computational Plasma Physics Group, which is providing modern computational skills in support of both experiment and theory. We look forward to two strong, and inter-related thrusts in the CPPG. On the experimental side the CPPG will continue to add critically needed new features to the TRANSP and TSC codes, and the CPPG will continue in the effort to modularize TRANSP, so that our tools can best support ongoing community thrusts such as the NTCC. Predictive capabilities in TRANSP (so called PTRANSP) will be brought on line rapidly. On the more theoretical side, the CPPG will continue to expand its thrust into modern massively parallel computing and visualization, to support the most sophisticated uses of the latest computational hardware by the theory team.

PPPL continues to support an important collaborative initiative to enhance greatly computational capability for fusion plasma science. PPPL supports vigorously the DOE initiative for advanced scientific computing. The combination of advanced 3-D modeling capabilities with highly resolved plasma diagnostic measurements should allow dramatic advances in the understanding of plasma science, and thereby accelerate the cycle of theoretical understanding and experimental innovation that is needed for fusion to succeed. The whole fusion community must work together to make this happen, or the DOE initiative will be a lost opportunity for us. The possibility that plasma science might obtain additional support from the overall DOE initiative must be pursued aggressively, both for its financial benefit and for the intellectual credit that will accrue to our field.

The budgets presented here for FY03 and FY04, including the incremental elements, will allow PPPL to function as a strong collaborative national center, supporting the full national and international fusion science program. To achieve greater recognition of the overall fusion program, the members of the fusion energy sciences community must continue to work together to present our case as both an excellent science program and also an important energy program, in a wide range of forums.

Robert J. Goldston

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FUSION ENERGY SCIENCES 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	82.5	82.1	12.0	80.6	12.9
Engineers	55.4	54.5	15.2	56.9	19.9
Administrators	18.2	15.7	.1	15.7	.1
Graduate Students	7.4	5.8	1.5	5.8	2.0
Technicians	131.9	70.9	10.5	79.9	12.4
Clerical	4.8	2.3	.2	2.5	.3
Subcontractors	7.3				
TOTAL FTEs	307.5	231.3	39.5	241.4	47.6
OPERATING COSTS $(000):					
PPPL Labor	28574.4	22606.1	3085.7	23113.2	4433.9
Subcontract Labor	769.6				
Overtime	687.2	422.7	67.2	431.4	74.6
Travel	1114.4	1247.3	156.5	1237.6	124.6
Energy	1105.7	1165.2	90.0	1187.8	101.8
Stockroom	145.1	165.0	21.7	149.7	22.5
Miscellaneous Expenses	719.8	586.1	97.6	572.8	87.5
Procurements/ICOs	8461.1	3700.3	1351.9	3420.2	2222.5
Organizational Burden	2674.9	2000.2	291.6	2039.9	435.4
Other	228.1	93.5	5.3	74.6	5.3
General + Administrative	22713.7	18186.3	2846.4	18388.5	4085.1
TOTAL OPERATING COSTS	67414.0	50172.7	8013.9	50615.7	11593.2
TOTAL OPERATING OBLIGATIONS	64633.3	50172.7	8013.9	50615.7	11593.2
EQUIPMENT COSTS $(000):					
Equipment - Direct	363.3	95.6	39.0	58.8	30.0
Equipment - G+A	90.9	34.4	14.0	21.2	10.8
Fabricated Equipment	3975.5	12073.5	5841.7	16680.1	4739.0
TOTAL EQUIPMENT COSTS	4429.7	12203.5	5894.7	16760.1	4779.8
TOTAL EQUIPMENT OBLIGATIONS	3335.0	12203.5	5894.7	16760.1	4779.8
TOTAL GPP COSTS	2616.2	1200.1	200.1	1200.1	200.1
TOTAL GPP OBLIGATIONS	1370.0	1200.1	200.1	1200.1	200.1
GRAND TOTAL COSTS	74459.8	63576.3	14108.7	68575.8	16573.1
GRAND TOTAL OBLIGATIONS	69338.2	63576.3	14108.7	68575.8	16573.1

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

FABRICATED EQ SUMMARY 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.4	4.3	.7	4.4	
Engineers	3.1	17.8	6.6	21.2	5.1
Administrators		.3		.3	
Graduate Students					
Technicians	7.7	7.9	6.5	18.1	7.8
Clerical		.3	.1	.4	
Subcontractors	.7				
TOTAL FTEs	11.9	30.6	13.9	44.4	12.9
COSTS $(000):					
PPPL Labor	1108.7	3953.4	1580.8	5395.3	1447.9
Subcontract Labor	61.8				
Overtime	68.5	1.5		3.0	3.1
Travel	38.5	102.5	55.0	163.0	27.0
Energy					
Stockroom	13.2	6.0	6.0	9.0	9.8
Miscellaneous Expenses	24.8	12.5	85.0	20.0	
Procurements/ICOs	1347.4	3225.6	1947.7	4761.5	1485.7
Organizational Burden	119.2	447.5	177.0	587.4	176.6
Other		261.0	50.0	65.0	
General + Administrative	1193.4	4063.5	1940.2	5675.9	1588.9
TOTAL COSTS	3975.5	12073.5	5841.7	16680.1	4739.0
TOTAL OBLIGATIONS	3966.4	12073.5	5841.7	16680.1	4739.0

FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY
FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1100	0	3 / 1 / 02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
NSTX	AT5505/AT5015010

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGERS:

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8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The National Spherical Torus Experiment (NSTX) is a major national fusion science facility to carry out the NSTX research, whose mission is to establish the physics principles of the Spherical Torus (ST), which is characterized by strong magnetic field curvature and high toroidal beta, and in turn enable cost-effective development of practical energy applications.

The NSTX National Team proposes to carry out during FY2002-2004 research with the goals of making progress toward a determination of the attractiveness of the ST, by assessing a full range of plasma properties for pulse lengths much greater than energy confinement times. This effort will be directed to meet a 5-Year Objective of Goal #2 recommended by the Fusion Energy Sciences Advisory Committee (FESAC) of DOE, and carried out according to the Implementation Approaches described in the Integrated Program Planning Activity. A DOE checkpoint of this objective is anticipated in 2004-2005.

The NSTX National Research Team and the NSTX Facility Operations Team proposes to install and commission during FY 2002-2004 upgrade plasma diagnostics systems to enable measurements needed to carry out the above NSTX scientific research. The activities will include support for a substantial number of diagnostics systems provided by offsite Team members.

The NSTX Facility Operations Team proposes to operate, maintain, and upgrade the NSTX device, capabilities, supporting systems, and site infrastructure during FY 2002-2004 to enable the preceding efforts. Onsite support for equipment provided by offsite Research Team members will be provided. Preparation for future upgrades, as driven by longer-term NSTX research goals, will also be carried out.

15. Signatures:

Contractor Work Proposal Manager	Contractor Work Proposal Manager

16. Human/Animal Subjects: No

OVERVIEW-PURPOSE

The scientific mission of the National Spherical Torus Experiment (NSTX) is to evaluate the physics principles of the spherical torus (ST) plasma, which is characterized by strong magnetic field curvature and high β_T, the ratio of the plasma pressure to the applied toroidal magnetic field pressure. The programmatic mission of NSTX is to determine, through the scientific investigation, the attractiveness of ST for developing practical fusion energy systems.

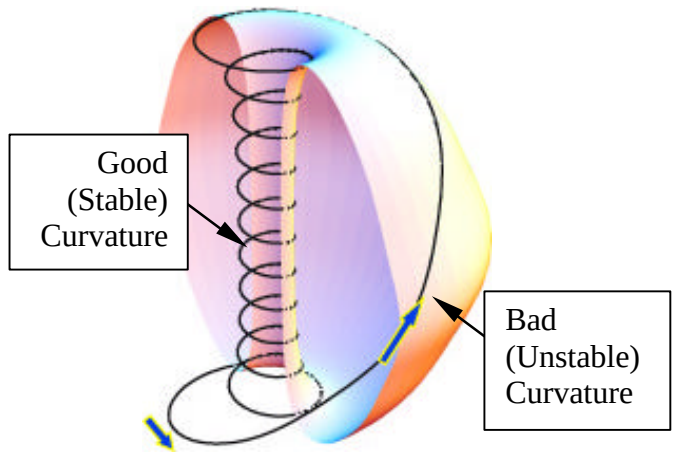

Figure 1. Magnetic field line and surface near the ST plasma edge with increased length of field line of "good (stable) curvature" over that of "bad (unstable) curvature," and a strengthened hold on high-temperature, high-pressure plasmas.

The investigation of the ST plasmas is of scientific interest because its unique magnetic field line shape, depicted in Fig. 1, theoretically can lead to the following properties of direct relevance to fusion plasmas. The NSTX plasma, as an example, is expected to have:

- Strong shaping of the plasma cross section: high vertical elongation κ ($\leq$2.5), edge safety factor q_{edge} (~10), and pitch of the field line B_p/B_T (~1) in the plasma outboard.
- Very high toroidal beta β_T ($\leq$0.4) and central local beta β_0 (~1) with an attendant high self-driven "bootstrap" current fraction f_{BS} ($\leq$0.7).
- Relatively small plasma size divided by the radius of ion gyration, ρ_{ci}, around the magnetic field, $a/\rho_{ci} = 1/\rho^*$ (~ 30-50), suggesting the possibility of moderate $1/\rho^*$ values for future energy applications.
- Large plasma flow velocities relative to the intrinsic velocity of magnetic perturbations (the so-called Alfvén velocity) in the plasma, $V_{flow}/V_{Alfvén} = M_A$ ($\leq$0.3), and flow shearing rate (~10^6 /s) due to the non-uniform flow profile.
- Large fast ion velocities (from the injected energetic beams of neutral Deuterium) relative to the Alfvén velocity, $V_{fast}/V_{Alfvén}$ (~ 4-5), i.e., the Supra-Alfvénic ions.
- Strongly refractive "over-dense" plasmas of large dielectric constant, ε (= $\omega_{pe}^2/\omega_{ce}^2$ ~ 10-100) characterizing radiofrequency wave propagation, absorption, and emission.

- Large outboard edge and Scrape-Off Layer (SOL) magnetic mirror ratios (~2 for double-null divertor and ~4 for inboard limited SOL's, and ~4 for the plasma edge region within the SOL).
- Much reduced magnitude of magnetic helicity (the product of the intertwined toroidal and poloidal magnetic fluxes) to facilitate alternative plasma startup techniques to be used.

The NSTX Science Research and Facility Operations described in this proposal, together with those proposed by other members of the NSTX National Research Team, aim to characterize and understand the plasma properties stemming from these special features to enlarge and strengthen the scientific basis of magnetic fusion energy. The ST plasma properties under investigation cover these major plasma physics topics: A. Turbulence and Transport, B. Macroscopic MHD Stability, C. Wave-Particle Interactions, D. Noninductive Startup, E. Boundary Physics, and F. Physics Integration.

The investigation of the ST plasmas is of interest to fusion program because these plasma features potentially can lead to operational properties of attractive magnetic fusion energy systems:

- Solenoid-free startup and sustainment of current $\Rightarrow$ simplified magnets and device configuration.
- Global stability at very high β_T and $\beta_0 \Rightarrow$ lowered magnet and device cost.
- Reduced turbulence and improved energy containment efficiency $\Rightarrow$ reduced unit size for sustained fusion burn.
- Strong wave-fast ion-plasma interactions $\Rightarrow$ more efficient fusion self-heating and RF heating and current drive.
- Dispersed plasma heat and particle fluxes over large wall areas $\Rightarrow$ survivable plasma facing components.

The proposed work therefore aims to establish the database needed to determine a cost-effective path of development that not only complement the other components of, but also potentially accelerate, the U.S. Fusion Energy Sciences Program. The nearer-term elements of this development path include a modest-cost pulsed Next Step ST experiment at the Performance Extension level, and a modest-fusion power (50-80 MW) steady-state Volume Neutron Source at the Energy Development level to test fusion nuclear components to high neutron fluence.

As a major component of the restructured U.S. Fusion Energy Sciences (FES) Program, the purpose of the NSTX Research and Facility proposal for FY 2002-2004 is to contribute directly to the FESAC-defined FES Goal #2: "*Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.*" The NSTX research milestones are developed to address the FESAC 5-year Objective #2.1: "*Make preliminary determination of the attractiveness of the Spherical Torus (ST), by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times.*" The strong focus of the research milestones on these FESAC recommendations is shown in Fig. 2 below.

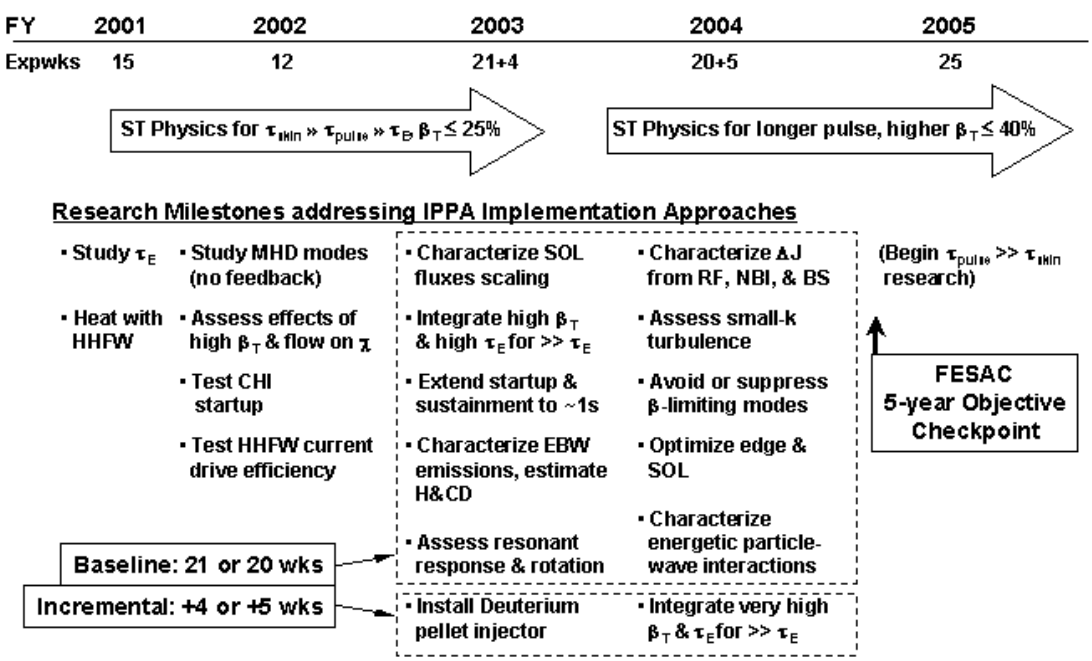

Figure 2. NSTX baseline and incremental research milestones will focus during FY 2002-2004 on meeting the FESAC 5-year Objective defined for Spherical Torus research, the checkpoint of which may be scheduled for 2004-2005.

Owing to the high scientific interest in ST plasma physics, the proposed NSTX research can make contributions to and benefit from the effort that addresses the FESAC Goal #1: "*Advance understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.*"

The NSTX research milestones, including those for FY 2001, are organized according to the Implementation Approaches developed by the OFES Integrated Program Planning Activities (IPPA (Fig. 3). A brief description of these research milestones is provided in ACCOMPLISHMENTS and FUTURE ACCOMPLISHMENTS.

NSTX Research Milestones Organized by IPPA Implementation Approaches to Achieve FESAC 5-Year Objective 2.1 on Spherical Torus

3.2.1.1. Achieve efficient heat and particle confinement (A. Transport and Turbulence)
- FY01-1 – Study τ_E
- FY02-2 – Assess effects of high beta and flow on χ
- FY04-2 – Assess long wavelength turbulence in a range of scenarios

3.2.1.2. Verify stability of large-scale MHD perturbations (B. Macroscopic MHD Stability)
- FY02-1 – Study modes without active feedback
- FY03-5 – Assess resonant plasma responses, correction field, & rotation interactions
- FY04-3 – Avoid or suppress beta-limiting modes

3.2.1.3. Heat high-beta over-dense plasmas (C. Wave-Particle Interactions)
- FY01-2 – Heat with HHFW
- FY04-5 – Characterize energetic particle-magnetosonic wave interactions

3.2.1.4. Test plasma startup with noninductive techniques (D. Noninductive Startup)
- FY02-3 – Test CHI startup
- FY02-4 – Test HHFW current drive efficiency
- FY03-3 – Extend startup & sustainment to 1 s
- FY03-4 – Characterize EBW emissions, estimate H&CD requirements
- FY04-1 – Measure J profile modifications from RF, NBI, & BS

3.2.1.5. Disperse edge heat flux at acceptable levels (E. Boundary Physics)
- FY03-1 – Study SOL fluxes
- FY04-4 – Characterize plasma edge & SOL for high β_T and τ_E

3.2.1.6. Integrate high confinement and high beta (F. Physics Integration)
- FY03-2 – Integrate high β_T and high τ_E for $>> \tau_E$
- FY04-6 (I) – Integrate very high β_T and τ_E for $>> \tau_E$

3.2.1.7. Explore spherical torus issues in directed laboratory experiments
- Pegasus, HIT-II, CDX-U – explore new ST parameter space & technologies

Figure 3. NSTX baseline research milestones for FY01-FY04 organized according to the IPPA Implementation Approaches (and the plasma science topics) to meet the FESAC 5-year Objective 2.1 on ST. The incremental research milestone FY04-6(I) is also included. Pegasus (University of Wisconsin), HIT-II (University of Washington), and CDX-U (PPPL) ST's address the final Implementation Approach 3.2.1.7.

APPROACH

A comprehensive set of approaches covering research, diagnostics, and facility operations and upgrades are developed and updated to achieve the NSTX mission and goals described above.

For research and diagnostics, a broadly based NSTX National Research Team was brought together in November 1998 to carry out the NSTX research program. DOE selected initial members of the team, which has since then been further broadened to include researchers from the following fusion research institutions: Columbia University, General Atomics, Johns Hopkins University, Lawrence Livermore National Laboratory, Lodestar, Inc., Los Alamos National Laboratory, Massachusetts Institute of Technology, New York University, Nova Photonics, Inc., Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory, Princeton Scientific Instruments, Sandia National Laboratory, University of California at Davis, University of California at Irvine, University of California at Los Angeles, University of California at San Diego, University of Washington.

The present National Research Team is also strengthened by cooperation with experts separately funded by Innovative Diagnostic, Enabling Technology, and Theory programs of OFES, for the benefit of both NSTX and these programs, and by participating scientists from European Union, Japan, and Russia. Successes in such cooperation are described in RELATIONSHIP TO OTHER PROGRAMS.

Scientists of the National Research Team and other researchers interested in NSTX research are invited to participate in an annual NSTX Research Forum, usually held in November-December of each year. The participants present and discuss the key elements of the research milestones in the current fiscal year. The results of the forum form the basis for the experimental run plan for the fiscal year. The Experimental Task (ET) forces, consisting of the National Research Team members, are formed annually to develop the Experimental Proposals (XP's) and to carry out the approved XP's, under the management of the NSTX Run Coordinator. A Team-wide operational assessment and results review are conducted in July-August to take stock of key advances of the year in preparation of the research, diagnostics, and facility plans of the subsequent fiscal year.

The NSTX Program Advisory Committee (PAC), consisting of the scientific leaders from the fusion community, meets twice annually (September, January) to advise the PPPL Director on the NSTX research program and facility operation issues. The PPPL Director provides guidance to the research program and facility operations plans in response to the PAC's recommendations.

PPPL has primary responsibility for NSTX Facility operations and upgrades in support of the research program. This activity includes all NSTX engineering operations and facility maintenance and repair, diagnostics interface support, and a number of diagnostics upgrades in addition to the diagnostics provided through collaboration research team members.

The focus of NSTX Facility operation and upgrade is the NSTX device, which is shown in Figure 4. The NSTX Facility has since the start of operation in FY2000 achieved or exceeded essentially all of the design goals (see Table 1). Recent diagnostics and device operation achievements are summarized in ACCOMPLISHMENTS. Detail of the diagnostics and facility operation and upgrade plans is provided in FUTURE ACCOMPLISHMENTS.

Table 1. NSTX Design and Achieved Parameters

Parameters	**Design**	**Achieved**
Plasma major radius (m)	0.85	0.85
Plasma minor radius (m)	0.68	0.68
Plasma cross section elongation	≤2.2	2.5
Plasma cross section triangularity	≤0.6	0.8
Plasma current (MA)	1	1.5
Toroidal field at major radius (T)	0.6	0.45
Heating and current drive		
Inductive flux (Wb)	0.6	0.6
Neutral beam injection power (MW)	5	5
High Harmonic Fast Wave power (MW)	6	6
Coaxial Helicity Injection toroidal current (MA)	0.5	0.4
Plasma pulse length (s)	≤5	0.6

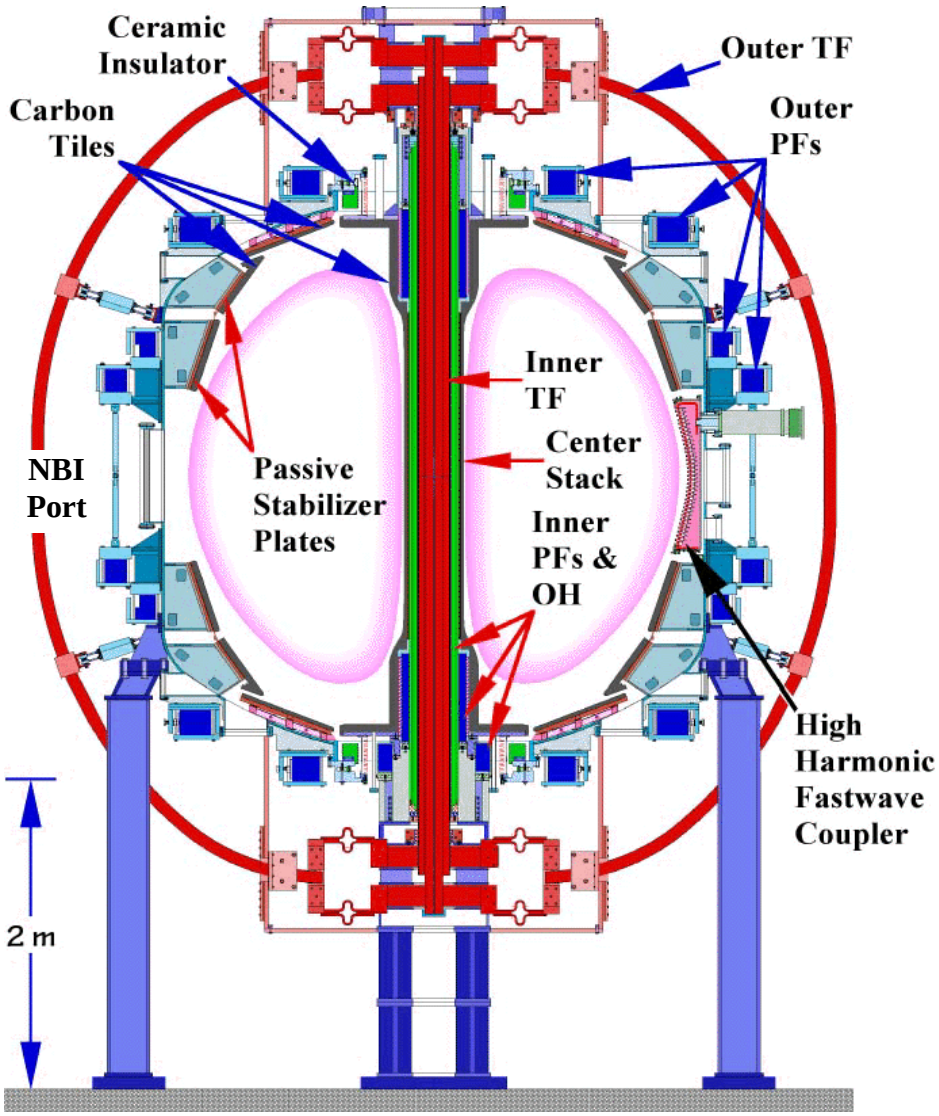

Figure 4. Layout of NSTX, characterized by magnets external to the vacuum vessel, close fitting stabilizing conducting plates, nearby HHFW coupler, large ports for NBI, ceramic insulators to enable CHI operation, and carbon tiles covering entire inboard, divertors, and the conducting plates. The fully demountable center stack assembly is a common feature of ST devices.

TECHNICAL PROGRESS (FY2001 – FY2002)

Research Accomplishments FY2001

The experiments conducted in FY2001 were organized by five Experimental Task (ET) groups, covering the main NSTX research areas of High-Harmonic Fast-Wave Heating, Coaxial Helicity Injection, Boundary Physics, Magnetohydronamic Stability and Plasma Transport. These ET groups developed NSTX Experimental Proposals (XPs) which were reviewed by the NSTX team and approved and scheduled by the project management. In all, 26 experimental proposals received run time, ranging from half a shift to several shifts of machine operation, during the FY2001 run. In addition to these experiments, 8 "Machine Proposals", which are aimed to develop operational capabilities of the NSTX device, were conducted. Machine proposals are also used to conduct some routine tasks such as boronization of the vacuum vessel and the subsequent assessment its effects on the plasma.

High-Harmonic Fast-Wave Heating

During FY2001 the high harmonic fast wave heating improved dramatically in its effectiveness and reliability for both helium and deuterium plasmas. In deuterium plasmas with $n_e(0) \sim 3 \times 10^{19}\ m^{-3}$ and HHFW power of 2.5 MW, very peaked electron temperatures profiles with a remarkably high central temperature, $T_e(0) \sim 3.7$ keV, were produced. The central ion temperature was measured by x-ray spectroscopy to be 1.5 keV. The large electron temperature gradient suggests the formation of an electron transport barrier, *i.e.* a region of reduced electron thermal diffusivity, inside a normalized minor radius $r/a \sim 0.5$. Although the HHFW power predominantly heats the electrons in NSTX conditions, absorption of these waves by the energetic ions introduced by NBI can also occur. During heating of a deuterium plasma by 3 MW of HHFW and 1.5 MW of NBI power, the neutral particle analyzer measured an energetic tail on the majority deuterium ion distribution extending to about 140 keV in energy, well above the primary NB injection energy of 80 keV. HHFW heating was also successfully applied to low current plasmas. In 0.4 MA plasmas, high values of the poloidal beta, β_P up to 0.9, were produced by HHFW power of 3.2 MW. Under these conditions, up to 40 % of the plasma current was driven by the bootstrap effect.

Coaxial Helicity Injection

Coaxial Helicity Injection (CHI) is a technique for generating significant toroidal plasma current by injecting a poloidal plasma current from electrodes inside the vacuum chamber connected to an external power supply. The technique has previously been successfully applied to small purpose-built devices. If CHI can be developed for larger devices it would be possible to dispense with the expensive central solenoid in future STs. Experiments in NSTX in FY2001 showed that CHI can indeed be applied to large ST for generating a substantial toroidal current. The experiments succeeded in producing 390 kA of toroidal plasma current without using the ohmic solenoid and using only about 28 kA of injector current. The driven toroidal currents are consistent with our understanding of current multiplication. For CHI to be successful in the ST, some of the toroidal current must be transferred by the process of magnetic reconnection onto the closed field lines needed for confining plasma. Indications were obtained that the MHD instabilities believed to accompany that reconnection were occurring in the NSTX discharges. The duration of the CHI discharges in NSTX was up to 330 ms, more than an order of magnitude longer than previously obtained by this technique. The duration was limited by the occurrence of absorber arcs, which are unwanted discharges across the secondary insulating gap between the coaxial electrodes. A new more robust CHI absorber ceramic insulator to minimize the arc problem will be implemented.

Boundary Physics

An experiment was conducted to produce the H-mode of confinement in NSTX. H-mode transitions, evidenced by a sudden decrease in the hydrogen Balmer-alpha line emission from the plasma edge, occurred in divertor discharges heated by both NBI and HHFW. The H-mode was confirmed by the subsequent rise in the radial gradient of the plasma density just inside the plasma boundary, indicating the formation of an edge transport barrier. The H-mode phases varied in duration between 0.5 and 120 ms. H-mode phases both with and without ELM instabilities were observed, with the longest ELM-free period lasting up to 65 ms.. The confinement time in the ELM-free discharges increased by a factor of 2 – 3 above the L-mode reference case, to a maximum of 120 ms.. The power threshold for the occurrence of the H-mode was measured in NBI-heated discharges to be about 2 MW in terms of total heating power and 1 MW in terms of power outflow through the last closed flux surface. This is between 16 and 33 times the predicted power threshold from the ITER international scaling. Initial experiments were conducted to determine the heat flux to the divertor target in auxiliary heated discharges by measuring

the surface temperature of the graphite tiles with the infrared camera. During 4 MW of NBI heating, heat fluxes at the outer divertor strike point, which received the majority of the power, reached 6 MWm^{-2} although the average flux was much lower. The peak flux increased with heating power, as expected, and the width of the power deposition region decreased to about 40 mm. The total divertor heat flux accounted for only about 25% of the heating power.

Magnetohydronamic Stability

Through NBI heating, NSTX plasmas reached $\beta_T = 2\mu_0 \langle p \rangle / B_{T0}^2 \sim 25\%$, defined in terms of the applied toroidal magnetic field, B_{T0}, for $B_{T0} = 0.3$ T and plasma current $I_p = 1.2$ MA. This corresponds to a Troyon-normalized beta, $\beta_N = \beta_T \cdot a \cdot B_{T0}/I_p \sim 4\ \% \cdot m \cdot T/MA$ (a is the plasma minor radius). The values of β_T and β_N were increased to their highest values by shaping the plasma cross-section to increase its triangularity to $\delta \sim 0.5$ for an elongation $\kappa \sim 1.75$. Experimentally, the β_N limit increases, then saturates with increasing peaking of the current profile (corresponding to higher values of the internal inductance parameter l_i), and decreases with increasing peaking of the pressure profile. The theoretical stability of the plasmas has been assessed using the equilibrium configuration and the profiles of pressure and current calculated by the EFIT code from experimental data. The threshold for instability of ideal low-n modes in the absence of any stabilizing effect from a conducting wall (the “no-wall limit”) agrees quantitatively with the experimental threshold for fast beta collapses. In dedicated experiments to increase the coupling to the wall and its stabilizing effect, the so-called “resistive wall mode” was observed when the ideal no-wall limit was exceeded. This is an instability which would not occur if the walls were perfectly conducting but can grow because of the interaction between the toroidally rotating plasma and the eddy currents induced in walls with finite resistivity. Analysis of the results suggests a route to increase β_N and β_T further with a broad pressure profile for example in NSTX. In addition to the ideal internal-kink instabilities mentioned above, other classes of MHD instabilities have been observed in NSTX plasmas. One of these is the neoclassical tearing mode (NTM) which occurs below the threshold for ideal instability when the perturbed bootstrap current in the vicinity of a magnetic surface having a rational value of the MHD safety-factor, q, causes an otherwise stable perturbation of the plasma current to grow. As expected theoretically, the NTM was observed in NBI-heated plasmas when the value of the poloidal-β which determines the magnitude of the bootstrap current, reached $\beta_P \sim 0.4$. The structure of the

plasma perturbations detected by the soft x-ray arrays during an NTM agreed very well with theoretical simulations of the mode growth.

High Frequency MHD Instabilities - In typical NSTX conditions, the initial velocity of the energetic ions introduced by NBI exceeds the Alfvén wave velocity in the plasma, so it was expected that various Alfvén resonant modes could be excited by the NBI. A broad spectrum of high-frequency fluctuations was indeed observed during NBI in the signals from magnetic pickup (Mirnov) coils outside the plasma. The spectrum extended in frequency from about 0.4 MHz up to 2.5 MHz, the latter being the maximum detection frequency of the coils and about 1.2 times the typical deuterium ion cyclotron frequency at the plasma boundary near the pickup coils. In detail, the spectrum consisted of a series of narrow, discrete, equally spaced peaks, either quasi continuous or showing bursts in time. The modes were also detected by a microwave reflectometer but, as yet, no quantitative measurements of their amplitudes are available. These high frequency modes have been identified as compressional Alfvén eigenmodes (CAE) excited by a Doppler-shifted resonance with the fast injected ions. Their frequency was shown to scale with the Alfvén velocity as the magnetic field and the plasma density were varied during the NBI pulse. The excitation of the CAE was shown to be very sensitive to the NBI energy. There was concern that the CAE might cause losses fast ions through scattering onto unconfined orbits, but measurements with the lost-ion detector have not revealed any anomalous losses associated with the CAE.

Plasma Transport and Confinement

One of the first tasks of the Plasma Transport group was to assess the confinement of energetic ions during NBI heating. The dependence of the heating on both the injection angle and the plasma current followed the expectations of the classical orbit model. Both the decay of the neutron rate from beam-target DD fusion reactions following brief pulses of NBI and the flux of escaping fast ions measured by the lost-ion probe also followed these expectations. No significant anomalous loss processes were apparent in MHD-quiescent plasmas. In plasma conditions typical of NSTX, the neutral beams are injected above the so-called critical energy and therefore preferentially heat the electrons. It was therefore surprising that ion temperatures significantly higher than the electron temperature were measured during NBI heating. In addition, high toroidal rotation velocities, up to 250 km/s, were measured by the CHERS diagnostic. The high ion temperatures suggest, at the least, that ion confinement is very good in NSTX plasmas.

This has been confirmed by the first analyses of the plasma transport with the TRANSP code. Ion thermal diffusivities approaching neoclassical levels have been inferred assuming a model of classical beam thermalization. In some NSTX cases, however, the standard TRANSP analysis calculates a negative power conducted through the ion channel in some regions of the plasma. This suggests that anomalous ion heating and/or energy transfer mechanisms may be operating in these unique conditions. Further experiments are planned to resolve this anomaly. It should be noted that there was generally good agreement between the total plasma energy deduced from magnetic measurements by the EFIT equilibrium analysis code and that calculated by TRANSP by integrating the measured profiles of the electron and thermal ion pressures and the profile of the fast ion pressure calculated self-consistently from the measurements. In terms of global confinement, some interesting trends are evident in the NSTX data from the FY2001 run. The NSTX data for plasmas without any H-mode transitions exceed the L-mode scaling by up to a factor 2 and even the H-mode scaling by up to a factor 1.4. Following H-mode transitions, the confinement time can transiently double in NSTX. The H-mode data have not yet been included in the confinement plot because these plasmas have not yet reached steady state. The different trends evident in the NSTX data suggest that the tokamak scalings, which were developed from tokamaks all with much higher aspect ratio, will have to be modified to account for the ST data.

Physics Analysis Accomplishments in FY2001

The year FY2001 has seen accomplishment in Physics Analysis across the full range of research areas. The related tool development is fundamental to supporting the ultimate achievement of the project's research objectives.

A major benchmarking activity was completed in the area of Macroscopic Stability involving a suite of 2D, axisymmetric ideal MHD stability codes (PEST I and II, DCON and GATO). Differences among the various codes were resolved, and all the codes eventually came into agreement in terms of calculated beta limits and mode amplitude distribution as a function of poloidal angle for a sample NSTX equilibrium. Once this was accomplished, the VALEN code, a 3D code, was also successfully benchmarked for the same equilibrium. VALEN has a detailed vessel model and a filament plasma model, and it will be critical to evaluating the need for, and then designing if necessary, an active mode control system.

Co-axial Helicity Injection (CHI) is an important means by which toroidal current can be generated non-inductively. This can preserve valuable Volt-sec from the OH transformer allowing the lengthening of the plasma pulse duration. One of the major goals in CHI research is the production of toroidal current on closed flux surfaces with subsequent diffusion to the plasma core. In order to study these dynamics, the 2D axisymmetric TSC code has been used to simulate CHI discharges, attempting to match toroidal current, poloidal flux distribution and injector current. Agreement has been found for low currents, while optimization is ongoing at the highest currents. The physics of reconnection, believed to be fundamental to flux surface closure, is being studied using a 3D resistive MHD code. This code incorporates equilibrium and stability, and has shown the importance of driving the external kink unstable to produce closed flux surfaces.

In the area of Transport and Turbulence, the use of the TRANSP code has become a staple for performing detailed local power balance calculations. Results from over 50 NSTX discharges analyzed in this fashion have pointed to questioning the validity of the classical collisional heating and coupling framework and/or the importance of considering additional heating mechanisms. The latter has been done by determining the expected turbulent spectrum of the CAE modes and possible resulting stochastic heating. The guiding center code in TRANSP was successfully modified to use radius of gyration instead of local Larmor radius to determine fast ion loss, yielding a more accurate estimate. The GS2 code was benchmarked against the FULL code at both high and low aspect ratio, and it was then used to calculate the expected spectrum of turbulence. The GS2 results indicated the importance of short wavelength ETG turbulence, consistent with the power balance calculations which indicated low levels of ion transport and high levels of electron transport. This result was further supported by experimental results and MIST modeling of impurity injection experiments.

Ray-tracing (HPRT, CURRAY) and full-wave codes (TORIC, AORSA) were used to study the absorption and associated heating and current drive from High Harmonic Fast Waves. Benchmarking the codes was started and is presently underway to understand the importance of the unique physical characteristics of the ST regime (large field gradients, non-circular geometry, and strong poloidal broadening of the launched wave spectrum), as well as identifying the high leverage physics components of the codes themselves. Of particular importance to address is the validity of the self-adjoint approach to determining current drive in the ray tracing codes as opposed to the kinetic treatment in the full wave codes. The codes have also been used to study the effects of energetic and thermal ions

on RF propagation, absorption and current drive. Finally, access to run information and data have been simplified by developing Web-based utilities. These include access to the run log, MS-SQL databases and waveform data.

Facility and Diagnostic Upgrade Accomplishments in FY 2001

FY2001 was a successful year for facility operations. All of the major facility milestones were completed including operation for 15 experimental run weeks and the coupling of 6 MW of high-harmonic fast-wave (HHFW) heating power to the plasma. There were two experimental campaign periods, the first from the beginning of the fiscal year until mid-December 2000 and the second from May to August 2001. Plasma availability increased significantly, with up to 45 plasma shots in a standard operating shift and up to 50 shots on one of 8 days with extended operation in the latter part of the campaign. Operation of NSTX with auxiliary heating by both neutral beam injection (NBI) and HHFW radio-frequency power became routine. About 740 plasma shots had neutral beam injection (NBI) heating and about 270 shots had HHFW heating totaling more than 50 kJ. Note that many of the experiments devoted primarily to HHFW heating also made use of NBI because of its beneficial effect on the startup and also to measure the ion temperature using the CHERS diagnostic. In December 2000, the toroidal field (TF) coil was tested to its full design current of 71 kA, to produce a toroidal magnetic field of 0.6 T at the nominal plasma major radius of 0.85 m. The plasma operation summary is show in Table 2. The utilization of the NSTX facility by researchers, post-doctoral researchers as well as students is also shown in Table 2.

Table 2: Facility Utilization

Facility Plasma Operations Availability

	FY 01	FY 02	FY 03	FY 04
# of run weeks	15*	12	21(4**)	20(5**)
# of hours	600*	480	840 (160**)	800 (200**)

* Actual to date, ** Incremental

Participating Research Personnel

	PPPL	non-PPPL
Researchers	45	75***
Post Doc.	3	7
Grad. Students	5	5
Undergrad. Students	3	5

*** In addition there are over 20 overseas collaborating researchers from countries including Japan, Russia, Korea, UK, Ukraine, and Canada.

Facility Highlights:

• The NBI system also successfully injected into the plasma the design goal of 5 MW of power.

• At the end of May 2001, the plasma current was successfully increased to 1.43 MA.

• The high-harmonic fast-wave heating system successfully reached its design goal of 6 MW for power delivered to the NSTX plasma.

• The plasma boronization technique was developed in which the He-TMB mixture was used to fuel normal plasma discharges and thereby replenish the boron coating in real time.

• A repair of the Ohmic Heating solenoid insulation problem was performed by removing the solenoid from the machine without breaking the high vacuum.

• The TF inner leg leak problem was fixed with an epoxy injection treatment developed for TFTR and one larger leak was fixed mechanically during the summer outage of 2001.

• Many of the internal magnetic sensors, both flux measurement loops and magnetic field measurement coils were refurbished or, in some cases, replaced with more robust designs.

Diagnostics Highlights:

• An interim charge-exchange recombination spectrometry (CHERS) system was successfully installed for measuring the ion temperature and toroidal rotation profiles at 17 spatial locations.

• The multi-point Thomson scattering (MPTS) diagnostic for the electron temperature and density profiles was upgraded by the addition of a second laser to operate at 60 measurements per second, with the possibility of syncopated operation of the lasers to provide high time resolution (< 1 ms separation of time samples) for reproducible transient phenomena, such as magnetohydrodynamic instabilities.

• A neutral particle analyzer (NPA) from ORNL was installed on NSTX viewing across the plasma midplane at a tangency radius of 0.7 m.

• The far-infrared tangential interferometer and polarimeter (FIReTIP) produced the first density data from two of its channels during the latter part of the FY2001 experimental campaign.

• A system was commissioned to determine the plasma diamagnetism by accurately measuring the magnetic flux displaced from the toroidal field coil by the plasma. The measured diamagnetic flux is used as an input to the analysis of the plasma equilibrium by the EFIT code, giving an additional constraint on the plasma energy.

• A detector for fast ions lost from the plasma after being born or scattered onto unconfined orbits was commissioned.

• During the outage to repair the center-stack coils, a set of detectors for low-frequency magnetic perturbations or “locked-mode coils” was successfully implemented on NSTX.

• Spectrometers were installed spanning the range from the visible (the VIPS-2 instrument), through the vacuum ultraviolet region (the SPRED instrument) to the extreme ultraviolet (the GRITS instrument

• A manifold was installed inside the vacuum vessel at the outboard mid-plane to inject gas into the plasma edge from a row of small jets to illuminate plasma edge turbulences.

• A camera was installed consisting of a one-dimensional array of CCD detectors viewing the filtered deuterium or carbon line emission with high time and spatial resolution from a major-radial line across the divertor.

• First measurements were made with an infrared camera of the surface temperature of tiles in the plasma contact regions of the lower divertor plates and on the center column.

FUTURE ACCOMPLISHMENTS (FY2002-FY2004)

Future Research Accomplishment

The research accomplishments anticipated for FY2002-2004 are organized by research milestones in these scientific topical areas;

A. Transport and Turbulence
B. Macroscopic MHD Stability
C. Wave-Particle Interactions
D. Noninductive Startup
E. Boundary Physics
F. Physics Integration

These areas are also organized according to the IPPA Implementation Approaches, which are directed toward meeting the FESAC 5-year Objective #2.1 on ST (see OVERVIEW-PURPOSE). For each Implementation Approach a summary of scientific objectives, and for each milestone a title, plain-English description, and the technical approaches to achieve them are provided. These milestones define the objectives of the NSTX research program proposed for FY2002-2004.

It should be noted that four of the above scientific topics (A, B, C, and E) matches the FESAC 5-year objectives #1.1 - #1.4 of Goal #1, which aims to advance fundamental understanding and enhance predictive capabilities in fusion plasma science. A remaining Objective #1.5 of Goal #1 is to advance general plasma science. Research on NSTX contributes to this objective because of the strong similarities between the space plasma, including the solar corona, and the high beta laboratory plasmas (see research milestone FY04-5 below).

A. Transport and Turbulence

IPPA 3.2.1.1. Achieve efficient heat and particle confinement

The objective of this research is to assess the efficiency of heat and particle containment as functions of externally controllable parameters of strongly heated spherical torus plasmas with high ratios of plasma to magnetic pressure (beta) and strong field line curvature. The research also aims to understand core turbulence and effect its suppression to reveal the limiting confinement (corrected neoclassical transport) mechanisms under large plasma flow and large flow gradients. However, very high beta

also increases the electromagnetic effects, which can influence the heat loss. Reduced turbulence and improved energy containment efficiency are expected to lead to reduced unit size for sustained fusion burn.

<u>Milestone FY02-2 on Transport and Turbulence:</u> *Assess the effects of very high ratio of plasma pressure to magnetic pressure and plasma flow on plasma heat containment in spherical torus.*

Theoretical calculations suggest that high plasma-to-magnetic pressure ratio (beta) can cause the magnetic field to fluctuate more with microscopic plasma turbulence than low beta, where the electrical field fluctuations are expected to be more important. Strong magnetic fluctuations may also increase plasma heat leakage via the electrons. Theory also suggests that strong shear in plasma flow can accompany the high beta and strong field line curvature unique to the spherical torus plasmas, and/or a large external momentum input (such as from the injection of energetic beams of deuterium in NSTX). A strong flow shear have been seen to reduce the larger-scale microscopic turbulence associated with heat leakage via the ions, but is less likely to modify the smaller-scale microscopic magnetic turbulence that may be associated with heat leakage via the electrons. Heat fluxes in NSTX plasmas will be inferred from plasma profile measurements and analyzed over a wide range of beta (β_T ~ 10-25%) and flow shear. Trends in the ratio of ion to electron thermal heat fluxes will be compared with predictions from theoretical calculations that account for the relatively large ion orbits and the relatively small electron orbits. External heating with varied momentum input will be used to help separate the effects of externally driven flow shear from the internal high beta driven flow shear, the magnetic field fluctuations from the electrical charge electric field fluctuations, and the electron heat leakage from the ion heat leakage. Understanding of the physics underpinning these mechanisms of heat loss will enable future investigations of plasmas with simultaneously high beta and high plasma containment efficiencies.

<u>Milestone FY04-2 on Transport and Turbulence</u>: *Assess long wavelength turbulence in the plasma core in a range of operating scenarios.*

Description – Suppression of plasma turbulence can reduce heat leakage across the magnetic field from high-temperature plasmas and is a common feature of all toroidal confinement experiments. Theory suggests that the spherical torus plasmas may naturally

yield conditions conducive to suppressing or reducing this turbulence, thereby improving the plasma's heat containment. Advanced microwave techniques will be used on NSTX to measure the turbulence properties over a wide range of conditions. These measurements will be used to test predictions from state-of-the-art theory and computation.

Technical approach – The first measurements of turbulence characteristics in a spherical torus will be carried out over a wide range of plasma flow shearing rates (up to a megahertz) and high toroidal betas (up to ~25%). To diagnose the long-wavelength turbulence driven by plasma ions, microwaves will be launched from the plasma edge. They are known to reflect off of critical layers in the plasma at a location uniquely determined by the plasma density and magnetic field. The amplitude and phase of the reflected wave will then be measured, enabling details of the high beta long-wavelength turbulence characteristics to be assessed. Diagnostics to measure the plasma density, ion temperature, electron temperature, ion flow velocity, and radial electric field will be used as input to theory codes. These codes will be used to predict turbulence characteristics and compare with the experimental measurements.

B. MHD Stability

IPPA 3.2.1.2. Verify stability of large-scale MHD perturbations

The objective of this research is to characterize the stability of large-scale magnetohydrodynamic fluid perturbations in spherical torus plasmas of high pressure and modest magnetic field with average toroidal betas up to ~25% and with self-generated, or bootstrap current fractions up to ~40%, without active control of plasma instabilities and profiles if appropriate. The research also aims to assess requirements for plasma profile and control of large-scale modes to increase beta, bootstrap current fraction and plasma pulse duration. As the sound speed approaches the Alfvén speed at very high beta, mass flow begins to alter significantly the equilibrium and stability properties of the plasma, challenging the conclusions of static equilibrium, which are well established in tokamak research. Global stability at very high β_T and β_0 is expected to lead to lowered magnet and device costs of a fusion energy system.

Milestone FY02-1 on MHD Stability: *Measure and analyze the global stability of spherical torus plasmas at high ratios of plasma pressure to magnetic pressure without applying active external control.*

Spherical torus plasmas in NSTX have been predicted to be stable against large-scale fluid-like perturbations at high ratios of average plasma-to-toroidal magnetic field pressure β_T up to 25% without active external stabilization. In theory, the global stability results directly from the increase in favorable magnetic curvature in the unique peripheral region of the spherical torus plasma, and if verified experimentally, would allow a very high efficiency of utilization of the applied magnetic field. Recently measured field errors in NSTX are being reduced and are expected to add complexity to the study. The properties of the global perturbations, including the effects of field errors, will be extensively measured, analyzed and compared with theoretical calculations. The new data and understanding will be crucial to making decisions on the need for and, if necessary, on the best techniques for active mode stabilization in NSTX. The data will also improve the reliability of projections of power density of future spherical torus devices, and will extend the existing database and understanding of global stability of toroidal fusion plasmas to very high β_T values.

Milestone FY03-5 on MHD Stability: *Assess interactions between plasma resonant field responses, correction field, and plasma rotation.*

Description: – The maximum ratio of plasma pressure to magnetic field pressure (beta) is determined by stability limits. If the limits can be increased, more efficient plasma containment will be possible. To increase these limits, studies will be performed to assess the interactions between the plasma, its rotation, the nearby conducting walls, and an externally applied “correction” magnetic field.

Technical approach – An initial set of radial correction field coils and power supplies will be designed and installed, together with in-vessel poloidal and toroidal arrays of field sensors. Neutral beam injection heating will be applied to create strongly rotating plasmas that approach the expected stability limits. A correction field will be varied to excite a resonant field response from the plasma. Magnetic sensor arrays will be used to measure this plasma response as well as the intrinsic wall-linked MHD modes of the plasma. Magnetic field and plasma responses will be measured to determine whether the "no-wall" limit can be exceeded for time scales larger than the resistive wall times in NSTX, and if so, whether this stabilization can be achieved without the need for a fast active feedback system. Detailed measurements of plasma profiles will be made to enable determination of the theoretical beta limits for comparison with the observed mode

behavior. Data will be analyzed to determine the parameters that govern the critical rotation frequencies required for plasma stabilization at high beta.

Milestone FY04-3 on MHD Stability: *Avoid or suppress beta-limiting modes in high beta NSTX plasmas*

Description – The promise of economical fusion energy systems depends on avoidance or suppression of large-scale instabilities that limit the plasma beta, the ratio of plasma pressure to magnetic field pressure. This research will focus on finding means of avoiding or suppressing instabilities that cause a sudden loss in plasma pressure, thereby extending the maximum plasma beta attainable.

Technical approach – A wide range of plasma conditions and operation scenarios will be explored and tested to reach and exceed the theoretical "no-wall" toroidal beta limit in NSTX (~25%). Additional measurements with magnetics sensors of rapid changes in the magnetic field at the plasma edge due plasma instabilities in the hot plasma core will be made. New control coils may be added to generate additional magnetic fields that may suppress beta-limiting plasma activity. These coils may be operated in a pre-programmed manner, or the coil current may be determined by feeding back on the perturbed edge magnetic field measured by the new magnetics sensors. Additional techniques will be applied to modify the plasma shape and profiles to avoid this requirement in the first place. Also, conducting surfaces near the plasma periphery are expected to stabilize certain classes of instabilities. The influence of the plasma's rotation in increasing the effectiveness of the conducting surfaces in stabilizing these modes will be studied.

C. Wave-Particle Interactions

IPPA 3.2.1.3. Heat high beta over-dense plasmas

The objective of this research is to investigate wave-particle interactions covering the frequency range of the High Harmonic Fast Wave (HHFW at 30 MHz) and the Electron Cyclotron Waves (ECW at 10-20 GHz) to heat and to drive current in plasmas of very high dielectric constant. This research also aims to assess the integration of intense heating by HHFW and the injection of neutral particle beams in creating and maintaining high-beta spherical torus plasmas. The fast beam ion speed in the ST will far exceed the Alfvén speed, likely enhancing the toroidal and compressional Alfvén Eigenmode instabilities and the associated dispersion of the energetic ions from the plasma core. The

efficient conversion between ECW and Electron Bernstein Wave (EBW) at the plasma edge allows effective access into the over-dense high-beta plasma core. The potential for EBW heating, current drive, and emission diagnostics will be explored. Strong wave-fast ion-plasma interactions are expected to introduce new opportunities for more efficient fusion self-heating and RF heating and current drive.

Milestone FY02-4 on Wave-Particle Interactions: *Test the effectiveness of using High Harmonic Fast Wave (HHFW) to drive plasma current via direct interactions with the electrons and/or fast ions to prepare for a quantitative assessment in high-temperature spherical torus plasmas.*

Maintenance of plasma current by noninductive means represents one of the most important mission elements of the NSTX Program and is of common interest to magnetic fusion energy sciences research. High power HHFW with an increased wavelength in the direction of the magnetic field and via flexible control will be launched with a fast propagation velocity along the magnetic field line. This wave is expected to maximize momentum transfer to the electrons and drive plasma current noninductively, while applying strong heating to increase plasma pressure and self-driven (bootstrap) current. Interaction of this wave with the fast ions introduced by injection of energetic deuterium will also be investigated. The efficiency of combined HHFW-driven and self-driven current drive will be estimated by comparing global measurements in modest current plasmas with theory. An understanding of the underpinning physics of HHFW and self current drive and the techniques to ensure reliable operation at high power levels will contribute to future investigation of spherical torus plasmas sustained for longer durations in NSTX.

Milestone FY03-4 Milestone on Wave-Particle Interactions: *Characterize Electron Bernstein Wave (EBW) emissions in order to estimate requirements for EBW heating and current drive.*

Description: – Maintenance of plasma current by noninductive means is important to magnetic fusion energy sciences research. Conventional rf current drive techniques have limited applicability to high beta and high density plasmas. The viability of Electron Bernstein Waves (EBW) to drive current will be explored in high beta plasmas by measuring the emission from EBW.

Technical Approach – The EBW is a promising candidate for driving current in the ST by externally launched waves. However, this will only be effective if a strong coupling can be established between electromagnetic waves launched at the edge and the EBW, which propagates only inside the plasma. Theory suggests that this coupling is highly dependent on the plasma density profile at the plasma edge. This was confirmed by experiments in the CDX-U device where localized limiters were introduced to modify the density gradient. It is proposed to install an EBW radiometer with a steerable antenna and localized limiter into NSTX to measure the EBW emission and conversion characteristics. To test theory, plasma parameters and the wave propagation angle will be varied. These results will be used to estimate the requirements for a current drive system for NSTX to supplement the CHI and HHFW schemes. In addition, this EBW radiometer will provide information on temperature changes occurring in the plasma on timescales shorter than can be resolved by the Thomson scattering diagnostic.

Milestone FY04-5 on Wave-Particle Interactions: *Characterize energetic particle-magnetosonic wave interactions.*

Description – Magnetosonic waves are important in space plasmas including the solar corona, and in high beta laboratory plasmas. The interaction of magnetosonic waves, whether externally applied or internally driven, with energetic particles will be studied on NSTX.

Technical Approach – The robust magnetosonic phenomena in high beta plasmas encompass the High Harmonic Fast Wave interactions with beam ions, and Alfvén eigenmodes driven by fast ions from Neutral Beam Injection. High frequency (up to 10s MHz) magnetic sensors and improved core reflectometers will be used to measure these oscillations and waves. The results will be compared with modern RF modeling such as those under development by the DOE Scientific Discovery through Advanced Computing (SciDAC) program. The existence of and the conditions for "channeling" supra-Alfvénic ion energy directly to thermal ions via the magnetosonic waves and oscillations in high beta plasmas will be explored in this study.

D. Noninductive Startup and Sustainment

IPPA 3.2.1.4. Test plasma startup with noninductive techniques

The objective of this research is to characterize the integration of noninductive plasma startup via magnetic reconnection such as using Coaxial Helicity Injection (CHI) with other noninductive and inductive current drive techniques. The research also aims to investigate a number of noninductive techniques to start and to increase the plasma current in spherical torus plasmas while at the same time minimizing magnetic flux and helicity injection. Noninductive startup is a requirement unique to the spherical torus, the successful development of which will enable cost-effective fusion energy applications. In preparation for the FESAC 10-year objectives for the spherical torus, plasma sustainment techniques need to be developed. Preparatory experiments for sustainment will also be described here. Solenoid-free startup and sustainment of current is expected to simplify magnets and the configuration of fusion devices.

Milestone FY02-3 on Noninductive Startup: *Test on NSTX innovative techniques for starting up plasma currents in toroidal fusion devices to prepare for a demonstration that will allow these devices to be made simpler, run longer, and cost less to construct.*

The initiation of plasma current by noninductive techniques is of crucial importance to the attractiveness of future spherical torus devices. The innovative technique of Coaxial Helicity Injection (CHI) will be utilized to initiate and noninductively maintain large plasma currents up to 400 kilo amperes. Testing will begin of strategies for controlling CHI plasmas in order to couple them to plasmas sustained by magnetic induction and heated by radio-frequency waves. Information obtained will be crucial to the preparation of a future demonstration of this technique on NSTX, including combining this and other techniques to ramp up and maintain plasma currents for longer durations. Successful noninductive-assist methods for startup will help minimize the central solenoid magnets, simplify the spherical torus concept, and lead to a major reduction in the size and cost of fusion devices.

Milestone FY03-3 on Non-Inductive Startup and Sustainment: *Measure and analyze the effectiveness of using a combination of noninductive techniques to assist in startup and sustainment of plasma pulse lengths up to 1 s.*

Description – The spherical torus concept requires the development of techniques for initiating and sustaining plasma currents. Several techniques will be studied, and their effects on the current will be measured on NSTX. The results will be compared with theoretical models to provide data needed for achieving longer pulse NSTX plasmas.

Technical approach – The first approach for generating current non-inductively is coaxial helicity injection. This creates toroidal current by injecting poloidal current into the plasma from electrodes connected to an external source in the presence of a toroidal magnetic field. The second is launching into the plasma HHFWs, which can accelerate electrons to generate the current. The third is injecting energetic neutral beams to drive current. The fourth is plasma heating to raise the plasma pressure, which generates a significant "bootstrap" current to supplement the externally driven current. Once these techniques have been established separately, they will be combined to lengthen the plasma current pulse. The 1-s goal will be a significant increase over the currently typical 0.3 s for both inductive and CHI driven plasmas. These experiments will require the development of sophisticated methods for plasma control, to provide adequate coupling of a plasma initiated by CHI to the HHFW antennas which themselves will utilize real-time feedback to maintain the appropriate spectrum of the launched waves.

Milestone FY04-1 on Noninductive Sustainment: *Measure current profile modifications from the applications of RF techniques, neutral beam injection, and the bootstrap effect.*

Description – Like tokamaks, spherical torus plasmas carry large currents that are essential for confining the plasma. Learning how to sustain these currents efficiently is a major research goal for NSTX. New measurement techniques using beams of energetic atoms and lasers will be employed to assess changes in the profile of the plasma current induced by radiofrequency waves, injected energetic neutral particles, and changes in the plasma pressure profile to determine how best to sustain large currents in spherical torus.

Technical Approach – This research will focus on measuring the plasma current profile with new diagnostics that measure the light emitted from energetic neutral atoms. The polarization of this light provides a measure of the details of the magnetic field in the plasma, which is related to the distribution of plasma current. These measurements will be performed when various techniques that may drive current in the plasma are applied, including radiofrequency waves and injection of energetic neutral atoms. Current driven

by gradients in the plasma pressure will also be tested and measured for the first time in a spherical torus. The results will be compared with theory to establish a physics basis for application in future spherical torus devices of small size and high performance.

E. Boundary Physics

IPPA 3.2.1.5 Disperse edge heat flux at acceptable levels

The objective of this research is to study the dispersion of edge heat flux over a range of externally controllable parameters and estimate the plasma facing component requirements under high heating power in the spherical torus magnetic geometry. The research also aims to determine the ability for managing intense energy and particle fluxes in the edge geometry and for increasing pulse durations significantly beyond the energy confinement time. Most elements of the physics on the edge open field lines are shared between the ST and the tokamak, while the ST introduces stronger variations of the magnetic field strength along the field lines that are closer to the magnetic mirror. The "toroidal mirror" configuration also tends to have large flux expansion in the divertor region, likely extending the physics research to new parameter regimes. Dispersed plasma heat and particle fluxes over large wall areas are expected to enable survivable plasma facing components in future fusion ST devices.

Milestone FY03-1 on Boundary Physics: *Measure and analyze the dispersion of edge heat flux and assess the impact on plasma facing component requirements under high heating power in NSTX.*

Description – Intense heat flow must be dispersed safely on the chamber walls in a high performance compact fusion device . Heat flux to the plasma facing components in high power experiments will be measured to indicate the dependence on externally controllable conditions and estimate plasma facing components required in longer pulse high heat flux experiments.

Technical Approach – The flow of heat from the hot plasma core through the cooler edge region onto the plasma facing components will be measured for plasmas heated by neutral beams, radio-frequency wave power, and resistive dissipation. While the small major radius of the scrape-off region in spherical torus is expected to concentrate the edge heat flux, the magnetic flux lines also naturally expand in the divertor region to disperse the heat flux. Edge parameters over a wide range of conditions will be measured to assess

these competing affects. Diagnostics systems include a reciprocating probe, a mid-plane tangential bolometer array, a divertor bolometer array now under development, a filtered visible camera for the divertor region, and 2D imaging infra-red cameras which can view the plasma strike points on the divertor or the center column tiles. The results will enable estimates of the required ability of plasma facing components to handle high heat flux for longer pulses.

Milestone FY04-4 on Boundary Physics: *Characterize the plasma edge and scrape-off layer under conditions of high beta and confinement.*

Description – High performance plasmas are expected to constrain the plasma edge conditions and introduce high heat fluxes that require increased control. Plasma edge conditions in NSTX will be varied to obtain the optimal dispersal of edge heat flux in conditions that have favorable performance characteristics in the core.

Technical Approach – The plasma edge efflux will be characterized under the conditions where high beta and high confinement core plasmas are obtained. Variations in parameters such as the plasma shape, density, and magnetic configuration will be performed to optimize the edge heat dispersal. The probability distribution function (PDF) of the so-called intermittent transport events recently observed in several toroidal devices will also be studied. A one-dimensional charge-coupled device (CCD) camera, fixed divertor probe arrays, a bolometer, and a infrared camera will be added to make more detailed measurements. The results will be compared with theory and computation using diffusive and turbulence models to identify plasma boundary conditions that also provide acceptable heat fluxes.

F. Physics Integration

IPPA 3.2.1.6 Integrate high confinement and high beta

The objective of this research is to test spherical torus plasmas having both high confinement and high beta for times much larger than the energy confinement times. The research also aims to determine the ability for extending the established operating regimes towards higher performance using active modification of plasma profiles and the resonant field response to external field errors. Successful outcome will enable assessments of the requirements for integrating high confinement and beta for long pulse durations with and

without active control. They will also encourage initial evaluations of the physics properties and design options for the performance extension and component-testing missions. These future efforts are defined by the FESAC 10-year objectives for the spherical torus.

Milestone FY03-2 on Physics Integration: *Explore and characterize plasmas with high beta near the "no-wall" stability limit simultaneously with high energy confinement for durations much greater than the energy confinement times.*

Description – The spherical torus is theoretically capable of containing plasma energy efficiently at high ratios of plasma pressure to applied magnetic pressure. Experiments will be conducted in NSTX to create and characterize the conditions that improve the stability and energy containment simultaneously, and the operation scenarios that maintain these conditions for timescales much greater than the energy replacement times.

Technical Approach – Large neutral beam and high harmonic fast wave (HHFW) power will be applied to modify the plasma pressure and current profiles, and approach the high beta and high confinement conditions for timescales much greater than the energy confinement times. Improved plasma control will be provided using high-speed computing that increases the input and output control parameters 10-fold and analyzes the plasma MHD equilibrium in a few ms. Increased flexibility in edge fueling and wall surface control will assist in creating and improving the plasma stability and confinement conditions simultaneously. A suite of x-ray, laser scattering, spectroscopy, visible and infrared imaging, edge probes, energetic particle, and gas injection diagnostic systems will be used to explore, measure and characterize the conditions that simultaneously increases the plasma stability and energy containment efficiency. The research may begin with conditions that separately indicated high toroidal beta (~25%) or high energy containment times, so far for relatively short durations and without active stabilization of the plasma.

Physics Analysis Tool Development in FY2002-2003

The focus of the near term (FY02-03) physics analysis needs for NSTX is guided by existing results and by those anticipated from imminent project upgrades. Addressing these needs entails the development of advanced tools, further experimental measurements, and refined analysis techniques. The tasks fall within the five primary NSTX research areas that support the FESAC objectives.

In the area of Macroscopic Stability, NSTX discharges exhibit a range of MHD phenomena that influence discharge evolution. These phenomena will be studied within a framework of ideal and non-ideal MHD using TRANSP analyses, TSC simulations and EFIT reconstructions as bases for the calculations. Once numerical solutions for the equilibria are constructed with these codes, the ideal stability of the plasma discharges will be evaluated using the PEST-I and II, DCON, GATO and the 3D VALEN codes. Non-ideal stability, including neoclassical effects, will be analyzed using M3D, NIMROD and PEST-III. An important upgrade to the suite of codes is the inclusion of near Mach unity rotation on the equilibrium and stability solutions. High rotation at significant fractions of Mach 1 is observed experimentally.

To achieve the high-beta objectives of NSTX, a stable route to high beta that necessarily requires stabilization of pressure or current-driven ideal modes (kinks, RWMs) must be developed. The electrical configuration of the passive plates will be assessed for optimal passive stabilization using the VALEN code. VALEN is a 3D code that contains a detailed vessel model and a filament plasma model. It will also be used to assess the need for and to design an active mode control system at both low frequency (i.e., error field correction) and high frequency (i.e., MHD mode control). During the past year, VALEN has been benchmarked against PEST I and II, DCON and GATO.

Co-axial helicity injection (CHI) is an important means of generating toroidal current non-inductively and thus conserving the flux of the ohmic transformer in order to produce long pulse discharges. Simulations of CHI discharges will be performed in order to develop scenarios for CHI inductive handoff. The success of CHI may also require knowledge of the fundamental physics processes that could lead to closed flux surfaces. To this end, 3D simulations based on modifications to the M3D code will be optimized.

MHD activity that may be Neoclassical Tearing Modes (NTMS), develops and limits the stored energy in NSTX when β_{pol} is in the range from 0.3 to 0.5. The characteristics of the observed modes will be assessed using the non-ideal codes mentioned above. In particular, the Glasser term, which has a small impact at conventional aspect ratio, is believed to have a larger stabilizing effect at low R/a. It will be included in the development of a tool to predict the NTM stability for a range of plasma profiles and operating conditions. Models for EBW local current drive will be developed in order to explore the potential of this approach for stabilization of the NTMs and other deleterious MHD modes

In the area of Transport and Turbulence, global confinement studies have been performed using equilibrium reconstructions obtained with the EFIT code. These recontructions are based on magnetic measurements, including the diamagnetic flux as well as some measured local profile information. Profile information is clearly essential for local transport studies, which has been carried out using the TRANSP and TSC codes. In addition, a "between-and-among-shots" TRANSP, BEAST, will be developed. This code will use equilibria from EFIT and perform a single-time slice confinement analysis of NSTX discharges. The time to completion for each time slice run is approximately 5 minutes for NB heated discharges. Further development of gyrokinetic and gyrofluid codes (GS2, GTC, FULL) will help in relating the predicted transport-inducing-turbulence to the observed transport levels of the ions and electrons inferred from experiment. Mechanisms that can possibly heat the thermal ions stochastically will be quantified and compared to experiment. These mechanisms include high frequency collective Alfvénic waves and ETG modes. Modifications to neoclassical theory to address regions of the ST plasma in which $\rho_i<L_n$ are underway.

Using observations of edge turbulence to characterize the edge stability is important for H-mode studies, wave coupling, scrape-off-layer characteristics, and CHI current penetration. The FULL, GS2 and GTC codes can be used, as well as edge specific codes such as BOUT and BAL to predict and also assess the edge turbulence as well as in the core. Predictions from BOUT and BAL will be used as a basis for experiment design.

Because of the low field of NSTX, orbit excursions of fast ions tend to be large ($\rho/a\sim1/3$), making it a challenge to estimate, in a time efficient manner, orbit losses and heating of material surfaces due to Energetic Particles. One approach, which is based on a full Lorentz orbit tracker to follow the complete particle trajectory, has severe computational

time requirements. The TRANSP code uses a faster method based on a Monte-Carlo calculation of the particle guiding center with Finite Larmor Radius corrections. However, this calculation requires refinements for some cases in NSTX since the plasmas are in the regime where the magnitude of the hot ion gyroradius can be comparable or greater than that of the characteristic scale length of the magnetic field variation. Phase space loss boundary calculations will be coupled to deposition profiles as a means of speeding up the loss calculations. The effects on the deposition profile from the non-adiabatic behavior of the fast ions will be studied analytically and numerically by using full orbit codes.

Because of the low magnetic fields of NSTX, the velocity of the neutral beam particles is greater than the Alfvén velocity. Compressional Alfvén eigenmodes can thus be excited with by the energetic ions present with neutral beam injection (NBI). Indeed, Alfvén-like modes have already been observed in NSTX discharges heated with NBI. Both the NOVA-K and PENN codes have been used in a preliminary assessment of the AE stability and the impact of these modes on fast particle confinement. Theoretical studies will continue in these areas, and will be aided greatly by experimental measurements of the modes, using fast acquisition Mirnov coils and associated energetic particle loss using the IR camera and ion loss detectors. Higher frequency modes, which have also been observed (f~1.5 MHz), will be studied within the framework of compressional Alfvén waves. The possibility that these CAE heat the thermal ions will be studied by coupling theoretical predictions to experimental results.

In the area of Wave-Particle Interactions, High Harmonic Fast Wave heating and current drive packages are essential for estimating heating profiles for transport and confinement studies, and for estimating the driven current profiles for equilibrium reconstructions and current drive accounting. Several codes are under development which utilize different physics approximations: CURRAY and HPRT are ray tracing codes based on WKB approximations, and TORIC and AORSA are full-wave kinetic codes. An important step in this development, namely the benchmarking of these codes against experimental results, is underway. Experimental and theoretical studies will continue in order to assess the effects of energetic and thermal ions on RF propagation, absorption and non-inductive current drive processes. This, along with the large field gradients and non-circular geometry of STs, and the poloidal broadening of the launched wave spectrum, will be significant effects to include in the development of the HHFW wave propagation and absorption simulation modules. Integration of some of these modules into the TRANSP,

TSC, and EFIT codes, which will enable self-consistent transport and confinement simulations of NSTX plasmas, has begun.

Finally, in the area of Boundary Physics, it is important to understand the effect of impurities on current profile evolution and resulting MHD. This was especially clear in the early experiments in which central collapses of the soft X-ray emission were associated with a build up of the central radiation. For SOL studies, it is important to benchmark models of heat and particle flux in a range of NSTX configurations, including Inner Wall limited, and Single and Double Null Diverted discharges. Codes to be used for this include B2.5/EIRENE & DEGAS2 and UEDGE/DEGAS2.

Facilities and Diagnostic Accomplishments in FY 2002

Prior to the restart of plasma operations in February 2002, a number of facility improvements were made. The high-pressure helium high temperature bake out system (350 °C) was successfully commissioned. During the FY2001 campaign, the newly installed locked mode detectors revealed significant error fields caused by a misalignment of the PF 5 coils. During the outage from August to December 2001, fixtures were fabricated and used to realign the PF 5 coils to the vacuum vessel axis. After the realignment, the n = 1 error field component was reduced by an order of magnitude. An in-board side gas injector was installed on the center stack at the midplane to aid H-mode experiments. In order to insure safe operation against possible future TF coolant leaks, a Flourinert coolant system for the TF coil was installed and commissioned. To improve the plasma control capability, the hardware for a second-generation real-time plasma control system has been installed and the software is now being implemented in collaboration with General Atomics. Plasma operations will continue through the end of May 2002. After performing post plasma calibrations, the device will be vented for the installation of the MSE and CHERS diagnostic system and modifications to some divertor plates for installing an x-ray crystal spectrometer for astrophysical studies. In parallel, with budget permitting, the center stack will be removed to install an upgrade to the ceramic insulator in the absorber for CHI operation. The next plasma campaign is scheduled to start in the last week of October 2002. The status of FY2002 Facility and Diagnostics Milestones are described below.

Facility Milestone F(02-1): Install and Operate Inboard Gas Injection System (March 2002)

This system is designed to inject deuterium or helium gas from between tiles on the centerstack near the plasma midplane to fuel the plasma during auxiliary heating. Based on both theoretical grounds and encouraging results from other devices, notably MAST, it is expected that the fueling efficiency will be higher for this gas source and that H-mode accessibility will be improved. The new high field side gas injector was commissioned and used to fuel ohmic, NBI- and RF- heated plasmas in February 2002. This milestone is now complete.

Facility Milestone F(02-2): Implement Real Time Plasma Control System Upgrade (May 2002)

The NSTX plasma control system will be upgraded by the installation of many additional channels of real-time data from magnetic diagnostics and the incorporation of real-time gas injection control. Real-time data transfer at the rates needed for plasma control has already been demonstrated. The gas injection system is now operating routinely under the control of the real-time control computer and the ability to save and restore the gas system programming has been demonstrated. The operation of the equilibrium control system with real-time analysis of the plasma configuration by an equilibrium code will be demonstrated later in the run.

Facility Milestone F(02-3): Design and Fabricate an Upgrade CHI Absorber Ceramic Insulator (September 2002)

Plasmas generated by coaxial helicity injection (CHI) in NSTX to date have frequently terminated when an arc occurred between conducting surfaces at different electrical potentials in the "absorber" region, that is near the toroidal insulating gap at the top of the vacuum vessel. Based on designs tested successfully in other devices, we are planning an upgrade to the absorber insulator and surrounding surfaces aimed to suppress the formation of arcs and to minimize their consequences should they occur. The upgrade CHI absorber has been designed and reviewed and the ceramic insulator and flange material have been ordered. The upgrade will be installed in the vacuum opening beginning in May 2002.

Facility Milestone F(02-4) "Operate NSTX Facility for 12 Experimental Run Weeks" (September 2002)

Following the NSTX Research Forum in November 2001, a program of experiments for 12 weeks of operation has been developed. This program is organized around six major topics, namely integrated scenario development, MHD physics, transport and turbulence studies, the physics of high-harmonic fast wave heating and current drive, coaxial helicity injection, and boundary physics studies. The FY2002 experimental campaign started on February 7, 2002 with good facility availability from the first week, reflecting the maturing of its capabilities and operational experience. The 12 run weeks are expected to be completed by May, 2002.

Diagnostic Milestone D(02-1) Install and Operate Fast Reciprocating Edge Probe (February 2002)

A pneumatically driven reciprocating probe drive from the University of California at San Diego has been installed on NSTX and is currently being commissioned by collaborators. This drive will be instrumented with a Langmuir probe tip and used to make measurements of plasma properties in the scrape-off layer of NSTX plasmas. The expected completion of the milestone is March 2002.

Diagnostic Milestone D(02-2): Complete Installation of High-Resolution CHERS Detection System (June 2002)

The collection optics, fiber optic transport system, analyzers and detectors for the upgraded charge-exchange recombination radiation spectrometer are being designed and fabricated to be ready for installation during the next major vacuum vessel opening. This instrument provides measurements of the ion temperature and toroidal rotation velocity at up to 51 spatial locations across the minor diameter of the plasma. The image plane of the new collection optics for CHERS, which is shared with the MSE system, is ~ 20 cm from a TF coil, and fiber optic bundles will run from the image plane around both sides of the coil. A wooden mockup of this arrangement was constructed to check clearance and assembly procedures. The CHERS fibers are being assembled into the input holder. The output holder machining is now complete for the primary view. Fabrication of the output holder for the background view is nearly complete. The expected completion date of this milestone is September 2002.

Diagnostic Milestone D(02-3): Install Divertor Bolometer Array (September 2002)

Pending the successful outcome of tests of a 4-channel prototype system, an array with up to 16 thermal bolometric detectors viewing the divertor region of NSTX will be installed for characterizing the radiation pattern in the plasma region near the divertor plates. The expected completion date of this milestone is September 2002.

Facility and Diagnostics Plan for FY2003

In FY2003, the NSTX facility will ramp up from 12 run weeks in FY2002 to 21 run weeks. The FY2003 budget will also support some preventive maintenance of the facility as well as purchase of critical spare parts to minimize unscheduled down time and improve reliability. To support the significant increase in the run time, a modest enhancement of research support both for PPPL and collaborators is proposed. The first run period of FY2003 is scheduled to start at the end of October 2002. During FY2003 the necessary hardware such as the Lithium Boron Pellet Injector, the ten-channel collisionally induced fluorescence (CIF) MSE system, the divertor bolometer, the EBW (electron Bernstein wave) antenna, the Phase-I Resonant Field Correction system, and the power supplies for the CHI absorber null-field coils will be installed.

Facility Milestone F(03-1): Install Boron/Lithium Pellet Injection System (July 2003)

The Lithium Boron Pellet Injector (LBI) will allow the injection of solid pellets or an ensemble of micro-pellets at velocities extending from very low (20 m/s) for edge experiments, to high (400m/s) for core experiments. This will permit investigating wall conditioning enhancement, bench-marking edge transport coefficients, inducing edge transport barriers, measuring q(r) profiles, enhancing charge exchange, and measuring edge rotation profiles. The injector, which is being designed to use available components as much as possible, should be simple to maintain, have high reliability and be flexible for upgrades. It will allow injection of solid pellets or micro particles of lithium, boron, or carbon, with about 6 injections per discharge, precise control of injection velocity and mass, and either horizontal or vertical injection.

Facility Milestone F(3-2): Implement Real Time Plasma Control System for HHFW (September 2003)

The real time control of the high harmonic fast wave (HHFW) antenna phasing is an essential element in the development of HHFW system for variety of applications including the plasma start-up assist and current profile control. It will be necessary to adjust the phasing of the antenna elements in response to evolving plasma conditions. A real-time plasma control system being implemented on NSTX and information from it will be used for this phase control. In addition, the plasma position could eventually be controlled by feedback to maintain good antenna loading.

Facility Milestone F(03-3) "Operate NSTX Facility for 21 Experimental Run Weeks" (September 2003)

See the run plan described above.

Facility Milestone F(03-4): Implement Phase I Resonant Field Correction Coil System (September 2003)

The recent DIII-D experimental campaign demonstrated the importance of resonant field correction in allowing plasma rotation to permit wall stabilization of beta limiting MHD instabilities. For the NSTX program, the stabilization of beta limiting MHD is an essential element of accessing the desired high-β / high-bootstrap-current regime. In order to develop a strategy for implementing the Phase I Resonant Field Correction Coil System, a Global Mode Stabilization Working Group has been formed to assess the need for a mode control system, to identify critical issues and to define system requirements.

Diagnostic Milestone D(03-1) Commission high-resolution CHERS system (March 2003)

This diagnostic will measure at up to 50 spatial locations across the plasma both the plasma ion temperature and toroidal rotation velocity by the CHERS technique, that is spectroscopy of line emission from the carbon impurity ions excited by charge-exchange reactions with deuterium atoms from the heating neutral beams. During the planned outage from May to September 2002, the combined collection optics for this diagnostic

and the Motional Stark Effect diagnostic will be installed. The collection optics for CHERS involves sightlines both crossing the neutral beams and avoiding them in order to measure the contribution of intrinsic emission from the outer region of the plasma. The external optics, consisting of the dispersive elements and detectors, will then be installed, calibrated and commissioned at the beginning of FY2003.

Diagnostic Milestone D(03-2) Commission a 10 channel Motional Stark Effect MSE diagnostic based on the collisionally induced fluorescence (CIF) from the heating neutral beams (September 2003)

This spectroscopic diagnostic shares mountings for its collection optics with the planned high-resolution CHERS diagnostic since it also views line emission collisionally excited by NBI, in this case emission from the injected deuterium itself. The collection optics will be installed during the planned outage from May to September 2002. In FY2003, the external optics, consisting of high-throughput, high-resolution filters and detectors and the data acquisition will be fabricated, installed, calibrated and commissioned.

Diagnostic Milestone D(03-3): Install a detector for the Electron Bernstein Wave (EBW) emission with a steerable antenna to measure the dependence of emission on toroidal angle (September 2003)

Electron Bernstein Waves can propagate in the over-dense plasma conditions typical of the ST and can undergo mode-conversion in the plasma edge region into a wave, which can be detected by a microwave receiver outside the plasma. In addition to carrying diagnostic information about the plasma, there is a possibility that EBW could be launched into the plasma from external sources to provide local heating and efficient current drive. We plan to install a detector for microwave radiation in the EBW range with a steerable antenna to determine the characteristics of the wave propagation and mode conversion and to assess the feasibility of EBW for heating and current drive in the ST.

Facility Plan for FY2004

In FY2004, the NSTX facility plans to operate for 20 run weeks, similar to the FY2003 level. The FY2004 budget will continue to support some preventive maintenance as well as purchase of critical spare parts to minimize down time and improve facility reliability. To support the 20 run weeks, the research support will remain at a similar level as in FY2003 for both PPPL and collaborators. The FY2004 run period is expected to start in October 2003. The new hardware to be installed during the outage will be an improved resonant field control system, a prototype microwave scattering system to measure high-k fluctuations, an imaging diagnostic for edge helium emission, and an array of absolutely calibrated x-ray detectors for Lyman-alpha emission from the divertor.

Facility Milestone F(04-1) "Operate NSTX Facility for 20 Experimental Run Weeks" (September 2004)
See the experimental run plan described above.

Facility Milestone F(04-2) "Implement Improved Resonant Field Correction coil system " (September 2004)
Base on the result of the Phase I Resonant Field Correction coil performance assessed at the end of FY2003, appropriate modifications and/or replacement coil and sensor systems will be made during the FY2004 outage.

Diagnostic Milestone D(04-1): Install a prototype microwave scattering diagnostic for high-k fluctuations. (September 2004)
A prototype scattering system for microwaves in the millimeter range will be designed, constructed and installed on NSTX. The magnetic geometry of NSTX provides a unique possibility to measure the short wavelength fluctuations, which are believed on the basis of code modeling to play a dominant role in anomalous electron transport. This prototype diagnostic will be designed to measure the radial wavenumber spectrum of fluctuations in the range 5 - 20 cm^{-1} at one radial location near the midplane.

Diagnostic Milestone D(04-2): Install CHERS system to measure poloidal plasma flow. (September 2004)
We plan to measure the poloidal plasma flow by charge exchange spectroscopy using complementary views of the plasma from above and below and crossing the heating

neutral beams. This measurement together with the toroidal CHERS and the MSE data will provide tests of neoclassical theory at low aspect ratio.

Diagnostic Milestone D(04-3): Install and commission an array of filtered absolutely calibrated x-ray detectors for Lyman-alpha emission from the divertor. (September 2004)
An array of absolutely calibrated ultra soft x-ray detectors with multi-layer interference filters to select the hydrogen Lyman-alpha line radiation will be installed to view the divertor region above the target plates. Hydrogen recombination radiation is believed to play a significant role in the energy balance and the measurements will benchmark divertor codes in the ST parameter regime.

Diagnostic Milestone D(04-4): Install and commission an imaging reflectometer for measuring long-wavelength fluctuations (December 2003)

Long-wavelength turbulent fluctuations are believed to cause anomalous ion transport in the tokamaks. However, in the ST, these fluctuations may be reduced by a combination of reduced instability drive and increased flow shearing-rate at high beta. We propose to install an imaging microwave reflectometer to measure the structure in the poloidal direction of the long-wavelength density fluctuations, i.e., those with a wavelength much larger than the ion gyroradius.

EXPLANATION of BUDGET

The NSTX research and facility funding thus far has not been sufficient to enable the first 5 years of the NSTX research program to achieve the "5-year" ST objective defined by FESAC (see OVERVIEW-PURPOSE). An incremental research milestone for FY 2004 (FY04-6) and a set of incremental diagnostics and facility activities, identified to achieve this FESAC objective, are described below.

An incremental budget (see Table 3) is proposed for this enhanced program. The incremental funding will increase during FY 2003-2004 the annual experimental plasma operations to 25 run-weeks with the required enhancements in research capabilities and facility capabilities. The 25 run weeks in FY 2003 and FY 2004 will enable the NSTX research program to achieve the "5-year" ST FESAC objective in a timely manner. This plan has received endorsement by the NSTX PAC (see PAC-12 meeting report)

Table 3
NSTX Budget Summary ($M)

Facilities (Run Weeks)	**FY02 (12)**	**FY03 (21)**	**FY03 (4)**	**FY04 (20)**	**FY04 (5)**
	Base	**Base**	**Incr.**	**Base**	**Incr.**
Facility Operation	$13.23	$15.82	$0.82	$16.28	$0.92
CHI Absorber	$0.31	$0.10			
Correction Coil Sys		$0.50		$0.25	$0.25
Pellet Injector			$0.32		$0.34
Facility Upgrades					$1.36
Facilities Total	**$13.54**	**$16.42**	**$1.14**	**$16.53**	**$2.87**

Science	**FY02**	**FY03**	**FY03**	**FY04**	**FY04**
	Base	**Base**	**Incr.**	**Base**	**Incr.**
PPPL Research	$7.04	$7.91	$0.16	$8.21	$0.16
PPPL Diagnostics	$0.79	$1.37		$0.98	$0.50
Diagnostic Interface	$0.56	$0.76	$0.10	$0.74	$0.10
Collaborations	*$4.40*	*$5.07*	*$0.27*	*$5.07*	*$0.27*
Science Total	**$12.79**	**$15.11**	**$0.53**	**$15.00**	**$1.03**

Grand Total	**$26.33**	**$31.53***	**$1.67**	**$31.53**	**$3.91**

* Note that the PPPL NSTX total budget used in this FWP is $ 0.67M less than the FY 2003 congressional budget, to provide additional support to our collaborators to carry out the baseline research during FY 2003.

Base Facility Budget - Due to the major fusion science facility utilization initiative, the base budget allows 21 run weeks in FY 2003 and 20 run weeks in FY 2004, which is a significant increase from FY 2002 with 12 run weeks budget. The main component of the facility base budget increase is the cost of additional run weeks (estimated at ~$200k/run-week, which covers extra operations, overtime, utilities cost and consumables). With the completion of the TFTR D&D work at PPPL's D-site in FY 2002, a significant portion of the responsibility of the D-site caretaking will be transferred to NSTX. This results in an increase to the NSTX facility budget in FY 2003 and FY 2004 of approximately $ 0.5 M per year.

Base Research Budget – In order to support the increased run weeks from 12 run weeks in FY 2002 to 21 run weeks in FY 2003 and 20 run weeks in FY 2004, we propose to modestly increase the research team both for PPPL and collaborations. The funding calls for about a half FTE increase in the PPPL research staff and the data analysis support personnel, and hiring of one post doctoral fellow. For the NSTX collaborations, we propose to increase by $0.27M from the FY 2002 level to support collaborator activity associated with the additional run weeks. The FY 2003 budget also includes some targeted facility and diagnostic enhancements in order to support the accelerated research program due to the increased facility utilization. We propose to enhance the collaboration budget by $0.4M from the FY 2002 level for the collaboration support of the facility and diagnostic enhancements. For FY 2003, the proposed enhancement items are as follows:

1. IR camera in support of heat load studies in the divertor. This addresses both an operational issue as well as a scientific question regarding plasma-boundary interactions. This is required to support longer pulse operation in FY 2003.
2. New dynamo-probe head to evaluate whether reconnection is taking place during CHI. This is needed to understand whether and how flux surfaces are being formed during CHI. This is required to take advantage of additional CHI run time in FY 2003.
3. Additional modeling and design of a dynamic resonant field control system as part of an effort to stabilize the resistive wall mode as well as suppress locked modes. This is required to plan for RWM studies in FY 2003 - 2004.
4. Increase support in the area of CHI Absorber, which has been limiting performance of CHI. This is required to support additional CHI run time in FY 2003.
5. Increase modeling of EBW emission. EBW is an alternative approach to tackle this difficult problem and additional modeling is required to assess its performance. The

NSTX PAC has strongly supported this activity. It is required in FY 2003 for a decision point on EBW in FY 2004.

6. Acceleration of fluctuation measurements in support of transport experiments. Initial results on NSTX indicate very good ion thermal confinement. To understand the transport mechanisms has important implications for ST research.

Explanation of Incremental Budget for FY2003;

Increase Facility Utilization – The main component of the FY 2003 incremental budget is for increased run weeks. The base funding level allows 21 run weeks in FY2003 and we propose to increase the run weeks to 25 run weeks by addition of four run weeks[Incremental Facility Milestone, IF(03-01)]. The incremental cost of additional run weeks in facility operations is ~$200k/run-week, which also covers extra operations and scientific staff, overtime, utility cost and other consumables. The increased run weeks would permit the NSTX research program to be significantly accelerated, provided that the key diagnostic and facility upgrades keep pace with the accelerated research activities. The incremental funding will also permit purchase of some key spare parts and add support staff to support off-hour activities such as diagnostic installation both by PPPL and collaborators.

Incremental Facility Milestone IF(03-2) Deuterium Pellet Injector – The FY2003 incremental budget include one significant facility capability addition of frozen pellet injector for improving the energy containment efficiency, changing the pressure profile, and controlling the edge condition and impurity flux in spherical torus plasmas characterized by large in-out asymmetries.

Explanation of Incremental Budget for FY 2004;

Incremental Milestone FY04-6 on Physics Integration: *Obtain plasmas with high beta beyond the "no-wall" stability limit and high energy containment efficiencies.*

Description – Experiments will be conducted in operating conditions in which thermal energy is efficiently contained relative to empirical extrapolations and the ratio of plasma pressure to magnetic pressure is high. These conditions will be maintained for durations much greater than the energy replacement times by suppressing the plasma amplification of external field errors to increase the achievable pressure. The results will be compared

with theoretical projections to facilitate a preliminary determination of the attractiveness of the spherical torus concept.

Technical Approach – Results and Experience of the preceding milestones that address Transport & Turbulence, MHD Stability, and Physics Integration properties of the spherical torus plasma will be utilized to achieve this milestone. These cover plasma temperature, density and current modification, plasma edge and SOL conditioning, and the plasma shaping and control systems. The tests will use pre-programmed or active suppression of the plasma resonant field amplified from the external field errors (milestone FY03-5), and the operating conditions and scenarios to avoid the beta-limiting modes without active feedback (milestone FY04-3). Several diagnostics will be utilized to measure and infer the plasma current profiles for use in stability analysis to determine progress beyond the predicted "no-wall" beta limit while maintaining high confinement. An understanding of the requirements will be obtained for achieving the plasma profiles to extend simultaneously high beta and high confinement for durations much greater than the energy confinement times. A preliminary determination of the attractiveness of the spherical torus will be made based on these results.

Increase Facility Utilization – The main thrust of the FY2004 incremental budget is for increased run weeks to 25 run weeks from 20 run weeks in the base budget [Incremental Facilty Milestone, IF(04-01)]. The incremental cost of additional run weeks in facility operations is ~$200k/run-week, which also covers extra operations and scientific staff, overtime, utility cost and other consumables. The increased run weeks would permit the NSTX research program to be significantly accelerated, provided that the key diagnostic and facility upgrades (see the incremental facility and diagnostic milestones below) to keep pace with the accelerated research activities. The incremental funding will also permit the implementation of an optimized resonant field control system [Incremental Facility Milestone, IF(04-03)] and the purchase of some key spare parts and add support staff to support off-hour activities such as diagnostic installation both by PPPL and collaborators.

Incremental Facility Milestone IF(04-1) "Facility Upgrades " (September 2004)
There are three longer term facility upgrades candidates coming up in FY2004 with decision points at the end of FY2003. They are 1.the high power EBW (electron Bernstein wave) non-inductive start-up and NTM (neoclassical tearing modes) stabilization system design and construction, 2. the second center stack design, and 3. the

power and particle handling upgrade design. The EBW system start will require an experimental demonstration on NSTX of high EBW emission coefficient (which is an inverse of the EBW coupling). In CDX-U, with suitable plasma edge density condition, near 100 % emission coefficient has been observed. The EBW coupler to be installed in FY2003 will address this issue. In parallel, the EBW ray-tracing calculations will be performed to assess the viability of externally launched EBW waves for NTM stabilization. The result on the CHI research on NSTX will provide an important input into the second center stack design. The power and particle handling system requirements will become available after the FY2003 run. In particular, the requirement for going toward higher power / longer discharge duration will be assessed to determine what kind of system is needed to satisfy the power and particle handling requirements.

Incremental Diagnostic Milestone ID(04-1): Complete fabrication and bench testing of full microwave scattering diagnostic to assess the role of short-wavelength fluctuations on electron transport.

This diagnostic would be designed to complement and expand the prototype scattering diagnostic described under the baseline diagnostic milestone D(04-1). It would provide radial resolution of the k-spectrum of fluctuations in the range k-perp = 5 - 30 cm^{-1}.

Incremental Diagnostic Milestone ID(04-2): Complete fabrication and bench testing of divertor Thomson scattering system

A multi-point, multi-pulse Thomson scattering system optimized for the conditions expected in the divertor will be designed and fabricated ready for installation on NSTX. When installed and commissioned the data from this diagnostic will be used to test and calibrate divertor modeling codes.

RELATIONSHIP TO OTHER PROGRAMS INCLUDING INTERNATIONAL COOPERATION

U.S. ST Programs:

These ST experiments address the IPPA Implementation Approach #3.2.1.7 to "*Explore spherical torus issues in directed laboratory experiments,*" covering new parameter space and technologies of interest to the ST development.

HIT-II: The HIT-II Team (Helicity Injected Tokamak-II) at University of Washington has been a key member of the NSTX Research Team, and made major contributions in the CHI startup research on NSTX. More recently, the HIT-II Team contributed directly to the design of the CHI "absorber" improvements to be implemented during the latter quarter of FY 2002 to prepare for a comprehensive test of the CHI startup physics on NSTX in FY 2003.

CDX-U: Under the funding of VLT, the CDX-U Team carried out preliminary tests on plasma-lithium surface interaction physics during the past year. The results clarified for NSTX some of the key issues on the subject for discussion with the VLT Liquid Surface Module (LSM) effort. CDX-U, VLT, and NSTX are working together to define the performance requirements and constraints of the LSM that aims to become qualified in a few years time to be considered for possible use on NSTX as an advanced particle control tool. CDX-U has also been successful in developing key new approaches for EBW emission measurements that have subsequently led to an important research milestone on NSTX (Milestone 03-4 on EBW emission and heating and current drive, see Future Accomplishments).

PEGASUS: The PEGASUS device at the University of Wisconsin aims to explore the ST plasma regime approaching the extreme low limit of R/a ~ 1.1. Plasma currents more than 100 kA and toroidal average betas more than 20% have already been obtained in PEGASUS with resistive heating alone, indicating the potential physics benefits of this regime. PEGASUS further plans to explore innovative means for rf heating (such as via conversion of Electron Cyclotron Wave to Electron Bernstein Wave) and for making a physics connection to the very low aspect ratio Spheromak plasmas.

International ST Programs:

ST experimental programs have emerged during the past 10 years in U.K., Japan, R.F., Brazil, PRC, and possibly in Italy in the near future. Substantial cooperation with the ST programs in the former three countries has made major contributions to the research on NSTX.

MAST (U.K.): The Mega-Ampere Spherical Tokamak (MAST, U.K.) started operation in late 1999, and has design features and research capabilities highly complementary to those of NSTX. At present there is no conducting shell close to the plasma edge in MAST owing to the unique merging-compression start-up scenario that reduces the requirements of the central solenoid. The combination of large vacuum chamber and internal PF coils further give MAST added flexibility in divertor configuration and edge physics studies. MAST emphasizes initial operation with NBI heating and Electron Cyclotron Heating (ECH), since the compression start-up scenario excludes the possibility of fixed outboard Fast Wave launchers. Large progress has been made on MAST in a number of topical areas, notably including the ready access to double-null H-mode plasmas sustained for the duration of NBI, and access to H-mode in inboard-limited NBI heated, and double-null Ohmically heated plasmas. (The NBI system and a Neutral Particle Analyzer on loan from ORNL and PPPL, respectively, have been instrumental in these rapid successes on MAST.) MAST made major advances on edge-divertor physics recently by showing that more than 95% of the plasma heat flux escapes to the outboard divertor plates from L-mode and ELMy H-mode ST plasmas, considerably easing the expected heat flux issues in future high-power long-pulse ST experiments. These and other results have benefited the NSTX research program. A substantial number of collaborations and exchanges on a broad number of topics are planned for FY02-04 to derive mutual benefits to the NSTX and MAST research programs.

GLOBUS-M (R.F.): This experiment at the Ioffe Institute has continued its progress toward full current operation by recently reaching ~250 kA current via solenoid induction alone. A formal collaboration to cooperate in areas of Ohmic plasmas and advanced diagnostics has been completed recently. Fusion research exchanges with researchers from Ioffe, the Kurchatov Institute in Moscow, and TRINITI in Troitsk, covering a range of topics in ST physics and diagnostics, have been completed through CY 2001.

ST Experiments in Japan: Seven fusion researchers from universities in Japan (Himeji Institute of Technology, Hiroshima University, Kyushu-Tokai University, Niigata University, Tsukuba University, Universities of Tokyo) participated in the NSTX research during the summer of 2001. Topics of cooperative research covered divertor spectroscopy, ion Doppler spectroscopy of CHI plasmas, rf heating, electron Bernstein wave, plasma operation scenarios, and 2-fluid equilibrium modeling of ST plasmas with large flows. Cooperation during 2002 on ST are expected to continue. This cooperative research activities have contributed to the success of research on NSTX as well as to enhancing the already substantial research interest in Japan in ST plasmas.

IEA Implementing Agreement on ST Research:

Progress was made recently by DOE official in obtaining agreement within the International Energy Agency (IEA) to approve a new IEA Implementing Agreement on ST Research, initially involving ST programs in U.K. and U.S., and possibly in Brazil. This agreement provides a vehicle for an effective coordination of cooperation among the already diverse world ST research programs including NSTX, and application of the best available capabilities and expertise in the world to the challenging and exciting ST research, with potential high payoff to the U.S. Fusion Energy Sciences Program.

Research Cooperation with Other DOE Programs

OFES Innovations in Magnetic Fusion Energy Diagnostic Systems: NSTX has cooperated with the this Advanced Diagnostic Program (AT 50 10 80 2) by providing access to the unique high beta high temperature plasmas and interface support for tests of innovative diagnostic techniques, which are of great interest to research on other high beta confinement concept such as the RFP, Spheromak, and FRC. The most recent examples include:

- Ground-breaking development of Motional Stark Effect (MSE) polarimetry based on laser-induced fluorescence (LIF) to enable the separation of the magnetic field and electric field effects on fast deuterium recombination spectrum, in low field high beta plasmas such as the ST.

- Innovative use of the Electron Bernstein Wave (EBW) emission from, and mode conversion at the edge of, over-dense high beta plasmas to measure fast fluctuations of the core electron temperatures and the edge density gradients.
- Innovative use of X-ray crystal spectroscopy to map in 1-D the core electron temperature fluctuations of low-field high beta plasmas.

Further, progress being made by the Advanced Diagnostics Program on fluctuation imaging using 3-D microwave reflectometry has already contributed to establishing an important research milestone (FY04-2) to assess the long-wavelength turbulence in a range of scenarios of the NSTX plasma.

OFES Enabling Technology of VLT: NSTX has substantial cooperation with the Enabling Technology program under the VLT. These include the High Harmonic Fast Wave rf technology (ORNL), the collaboration of which has led to early success in electron heating and a robust research plan on rf heating and current drive on NSTX. A cooperation of a similar nature is proposed on the Electron Bernstein Wave (EBW) technology to enable research into the unique physics features of the EBW conversion heating and current drive in high beta low field configurations such as the ST. The NSTX program has further benefited from the expert participation's of VLT researchers on the important topics of plasma facing material and particle deposition (SNL) and laser ranging measurements of the wall (ORNL). In addition, the NSTX and the ALPS/APEX programs have cooperated in developing concept exploration level tests of lithium wall-plasma interactions on CDX-U. These programs are working together to establish the scientific and technical requirements and the database needed for a possible Liquid Surface Module (LSM) in the future to enable strong control of deuterium recycling from the wall. Discussions with these programs in the near future are scheduled to develop coordinated plans to carry out these important R&D activities.

Theory Program: NSTX research has also benefited substantially from cooperation with experts in the Theory program of OFES in areas of Boundary Plasma Stability and Turbulence, Transport and RF Heating, and energetic particle driven Compressional Alfven Wave Instabilities. The new plasma regimes already evident from recent encouraging results from NSTX have introduced several new scientific opportunities of high importance to Fusion Energy Sciences Program that can benefit greatly from a fresh

look by Theory experts in the field. More recently an ad hoc ST Theory Development Panel, chaired by Professor Jim Callen of University of Wisconsin, was form by the PPPL Director. This panel participated in the September 2001 Results Review and developed expert advice on the areas of ST Theory Development having high leverage on the progress of ST research. A Panel report is available for information.

OFES DIII-D and HBT-ET Programs: In order to attain very high betas (β_T up to 40%) and high bootstrap current fractions (up to 70%) in NSTX, it is likely that the potentially unstable Resistive Wall Modes (RWM) and Neoclassical Tearing Modes (NTM) will need to be stabilized by active feedback. The experimental data and physics understanding from the on-going effort on DIII-D and HBT-ET (and other tokamaks) in FY02-04 will therefore be a strong input to macroscopic stability research on NSTX. More recently, the progress on DIII-D in identifying the important role of resonant field response from strongly rotating plasmas to an externally applied field error has contributed to the definition of the research milestone (FY03-5 on the same subject) as the first step on NSTX. Furthermore comparison between NSTX and DIII-D plasmas of equal minor radius, cross section, and applied toroidal field (~ 6 kG) at different major radii could reveal the distinguishing aspect ratio and beta effects on plasma turbulence and transport. NSTX research during FY02-04 will aim to produce data at this field to enable this comparison.

OFES Innovative Studies in Fusion Energy Sciences: NSTX has provided access and interface support for tests of X-ray crystal spectroscopy techniques to resolve large uncertainties in the spectra of ions in stellar flares, which are under study by the Chandra Observatory at the Columbia University. This cooperation supports the OFES Innovative Studies in Fusion Energy Sciences (AT 50 30 50 0) and indicates substantial beneficial synergy between fusion energy science and astrophysics research conducted within DOE.

RESEARCH MILESTONES

Milestone	Description	Baseline	Forecast	Actual
FY 2001				
FY01-1	Measure and analyze the containment properties of plasma energy and fuel within strongly heated NSTX plasmas. Good containment of energy and fuel will enable increased fusion gain in future spherical torus experiments.	Sep 01		Sep 01
FY01-2	Measure and analyze how high-power radiofrequency waves with slow propagation velocity interact with and heat high-temperature spherical torus plasmas.	Sep 01		Sep 01
FY 2002				
FY02-1	Measure and analyze the global stability of spherical torus plasmas at high ratios of plasma pressure to magnetic pressure without applying active external control.	Sep 02	Sep 02	
FY02-2	Assess the effects of very high ratio of plasma pressure to magnetic pressure and plasma flow on plasma heat loss in spherical torus.	Sep 02	Sep 02	
FY02-3	Test on NSTX innovative techniques for starting up plasma currents in toroidal fusion devices to prepare for a demonstration that will allow these devices to be made simpler, run longer, and cost less to construct.	Sep 02	Sep 02	
FY02-4	Test the effectiveness of using High Harmonic Fast Wave (HHFW) to drive plasma current via direct interactions with the electrons and/or fast ions to prepare for a quantitative assessment in high-temperature spherical torus plasmas.	Sep 02	Sep 02	

RESEARCH MILESTONES (continued)

Milestone	Description	Baseline	Forecast	Actual
FY 2003				
FY03-1	Measure and analyze the dispersion of edge heat flux and assess the impact on plasma facing component requirements under high heating power in NSTX.	Sep 03		
FY03-2	Explore and characterize plasmas with high beta near the no-wall stability limit simultaneously with high energy confinement for durations greater than the energy confinement times.	Sep 03		
FY03-3	Measure and analyze the effectiveness of using a combination of noninductive techniques to assist in startup and sustainment of plasma pulse lengths up to 1 s.	Sep 03		
FY03-4	Characterize Electron Bernstein Wave (EBW) emissions in order to estimate requirements for EBW heating and current drive.	Sep 03		
FY03-5	Assess interactions between plasma resonant field responses, correction field, and plasma rotation.	Sep 03		
FY03-6 (I)	Assess the possible benefits of pellet injection for fueling of particles in the core of high beta NSTX plasmas.	Sep 03		

RESEARCH MILESTONES (continued)

Milestone	Description	Baseline	Forecast	Actual
FY 2004				
FY04-1	Measure current profile modifications from the applications of RF techniques, neutral beam injection, and the bootstrap effect.	Sep 04		
FY04-2	Assess long wavelength turbulence in the plasma core in a range of operating scenarios.	Sep 04		
FY04-3	Avoid or suppress beta-limiting modes in high beta NSTX plasmas.	Sep 04		
FY04-4	Characterize the plasma edge and scrape-off layer under conditions of high beta and confinement.	Sep 04		
FY04-5	Characterize energetic particle-magnetosonic wave interactions.	Sep 04		
FY04-6 (I)	Obtain plasmas with high beta beyond the “no-wall” stability limit, simultaneously with high energy containment and in thermal equilibrium.	Sep 04		

FACILITY MILESTONES

Milestone	Description	Baseline	Forecast	Actual
FY 2001				
F(01-1)	Commission full feedback phase control of the power excitation of the antenna fed with six high harmonic fast wave (HHFW) sources	May 01		Jul 01
F(01-2)	Complete installation of High-Temperature Vessel Baking System	Aug 01		Nov 01
F(01-3)	Operate HHFW at 6MW of power delivered to the plasma	Sep 01		Jul 01
F(01-4)	Refurbish an additional US common Long Pulse Ion Source from TFTR for use as a spare for the NSTX NB system	Sep 01		Feb 01
F(01-5)	Operate NSTX Facility for 15 experimental run weeks	Sep 01		Aug 01
FY 2002				
F(02-1)	Install and Operate Inboard Gas Injection System	Mar 02		Feb 02
F(02-2)	Implement Real Time Plasma Control System Upgrade	May 02	May 02	
F(02-3)	Design and Fabricate an Upgrade CHI Absorber Ceramic Insulator	Sep 02	Jul 02	
F(02-4)	Operate NSTX Facility for 12 experimental run weeks	Sep 02	May 02	
FY 2003				
F(03-1)	Implement Real Time Phase Control for HHFW System	Sep 03		
F(03-2)	Operate NSTX Facility for 21 experimental run weeks	Sep 03		
F(03-3)	Implement Phase I Resonant Field Correction Coil System	Sep 03		
F(03-4)	Install Boron/Lithium Pellet Injection System.	Jul 03		

FACILITY MILESTONES (continued)

Milestone	Description	Baseline	Forecast	Actual
FY 2004				
F(04-1)	Operate NSTX Facility for 20 experimental run weeks	Sep 04		
F(04-2)	Implement Improved Resonant Field Correction coil system	Sep 04		
F(04-3)	Implement Facility Upgrade Plan based on the FY 03 Facility Upgrade decision points. The possible upgrade activities are 1. EBW Power Systems Design and Construction start, 2. Center-stack design, and/or 3. Power and Particle Control System,	Sep 04		

DIAGNOSTIC MILESTONES

Milestone	Description	Baseline	Forecast	Actual
FY 2001				
D(01-1)	Complete Installation of Locked Mode Coils.	Mar 01		Feb 01
D(01-2)	Upgrade Multi-Point Thomson Scattering (MPTS) laser system to 60 Hz and 20 spatial channels.	Sep 01		Dec 01
D(01-3)	Upgrade Collection Optics for Charge-Exchange Recombination Spectroscopy (CHERS) and Motional Stark Effect (MSE) Systems.	Sep 01	Jun 02	
D(01-4)	Install Scanning system for Neutral Particle Analyzer	Sep 01		Dec 01
D(01-5)	Install Energy & pitch angle resolving Fast Ion Loss Probe	Sep 01	Jun 02	
FY 2002				
D(02-1)	Install and Operate Fast Reciprocating Edge Probe.	Feb 02	Mar 02	
D(02-2)	Complete Installation of High-Resolution CHERS Measurement System.	Jun 02	Sep 02	
D(02-3)	Install Divertor Bolometer Array	Sep 02	Sep 02	

DIAGNOSTIC MILESTONES (continued)

Milestone	Description	Baseline	Forecast	Actual
FY 2003				
D(03-1)	Commission high-resolution CHERS system to measure the carbon ion temperature and toroidal rotation velocity at 50 radial locations.	Mar 03		
D(03-2)	Commission a 10 channel Motional Stark Effect MSE diagnostic based on the collisionally induced fluorescence (CIF) from the heating neutral beams	Sep 03		
D(03-3)	Install a detector for the EBW emission with a steerable antenna to measure the dependence of emission on toroidal angle.	Sep 03		
FY 2004				
D(04-1)	Install and commission a prototype microwave scattering diagnostic to assess the role of short-wavelength fluctuations on electron transport.	Sep 04		
D(04-2)	Install CHERS system to measure poloidal plasma flow	Sep 04		
D(04-3)	Install and commission an array of filtered absolutely calibrated x-ray detectors for Lyman-alpha emission from the divertor.	Sep 04		
D(04-4)	Install and commission an imaging reflectometer for measuring long-wavelength fluctuations	Dec 03		

INCREMENTAL MILESTONES

Milestone	Description	Baseline	Forecast	Actual
FACILITY				
FY 2003-04				
IF(03-1)	Operate NSTX Facility for 25 experimental run weeks	Sept 03		
IF(03-2)	Install Deuterium Pellet Injection System	Sep 03		
IF(04-1)	Operate NSTX Facility for 25 experimental run weeks	Sep 04		
IF(04-2)	Implement Facility Upgrade Plan based on the FY 03 Facility Upgrade decision points. The possible upgrade activities are 1. EBW Power Systems Design and Construction start, 2. Center-stack design, and/or 3. Power and Particle Control System,	Sep 04		
IF(04-3)	Implement Optimized Resonant Field Correction coil system	Sep 04		
DIAGNOSTIC				
FY 2004				
ID(04-1)	Complete fabrication and bench testing of full microwave scattering diagnostic to assess the role of short-wavelength fluctuations on electron transport.	Sep 04		
ID(04-2)	Complete fabrication and bench testing of divertor Thomson scattering system.	Sep 04		

NSTX SUMMARY		03/01/02			
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	23.7	25.3	1.0	25.3	1.0
Engineers	26.0	25.8	1.2	25.3	4.3
Administrators	3.3	3.9	.1	3.9	.1
Graduate Students	1.0	1.0		1.0	
Technicians	48.7	55.2	2.3	52.7	7.5
Clerical					
SUBCONTRACTORS	.8				
TOTAL FTEs	103.5	111.2	4.6	108.2	12.9
OPERATING COSTS $(000):					
PPPL Labor	10009.3	11513.6	334.7	11882.1	470.7
Subcontract Labor	37.1				
Overtime	276.8	389.0	37.2	395.9	44.6
Travel	174.2	183.2		186.8	
Energy	821.0	1165.2	90.0	1187.8	101.8
Stockroom	78.0	101.5	.7	99.8	.5
Miscellaneous Expenses	52.0	40.0		40.7	
Procurements/ICOs	1028.1	1383.6	235.5	1241.3	311.6
Organizational Burden	887.0	1113.7	34.8	1145.8	50.3
Other	9.8	13.4		13.7	
General + Administrative	7194.3	8980.5	343.5	9190.7	471.4
TOTAL OPERATING COSTS	20567.6	24883.7	1076.4	25384.6	1450.9
TOTAL OPERATING OBLIGATIONS	20210.0	24883.7	1076.4	25384.6	1450.9
EQUIPMENT COSTS $(000):					
Equipment - Direct	35.0	36.8			
Equipment - G+A	8.8	13.2			
Fabricated Equipment	1319.5	1526.8	323.7	1076.7	2189.4
TOTAL EQUIPMENT COSTS	1363.3	1576.8	323.7	1076.7	2189.4
TOTAL EQUIPMENT OBLIGATIONS	1635.0	1576.8	323.7	1076.7	2189.4
GRAND TOTAL COSTS	21930.9	26460.5	1400.1	26461.3	3640.3
GRAND TOTAL OBLIGATIONS	21845.0	26460.5	1400.1	26461.3	3640.3

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

NSTX SCIENCE			03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	23.7	25.3	1.0	25.3	1.0
Engineers	4.5	4.6	.1	4.4	.5
Administrators	1.2	1.2		1.2	
Graduate Students	1.0	1.0		1.0	
Technicians	5.8	5.3	.2	5.3	1.4
Clerical					
Subcontractors	.1				
TOTAL FTEs	36.3	37.4	1.3	37.2	2.9
OPERATING COSTS $(000):					
PPPL Labor	4159.6	4548.4	128.3	4690.9	134.1
Subcontract Labor	15.0				
Overtime	.8	2.5	.7	1.5	.7
Travel	161.6	170.6		174.0	
Energy					
Stockroom	9.0	16.6	.7	13.3	.5
Miscellaneous Expenses	35.4	23.4		23.8	
Procurements/ICOs	284.3	413.9	19.5	284.4	19.8
Organizational Burden	334.1	339.5	10.8	347.0	11.5
Other	7.4	11.0		11.2	
General + Administrative	2936.0	3413.3	96.2	3463.0	100.1
TOTAL OPERATING COSTS	7943.2	8939.2	256.2	9009.1	266.7
TOTAL OPERATING OBLIGATIONS	7586.0	8939.2	256.2	9009.1	266.7
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	465.1	928.7		829.3	499.2
TOTAL EQUIPMENT COSTS	465.1	928.7		829.3	499.2
TOTAL EQUIPMENT OBLIGATIONS	760.0	928.7		829.3	499.2
GRAND TOTAL COSTS	8408.3	9867.9	256.2	9838.4	765.9
GRAND TOTAL OBLIGATIONS	8346.0	9867.9	256.2	9838.4	765.9

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

NSTX OPERATIONS		03/01/02			
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists					
Engineers	21.5	21.2	1.1	20.9	3.8
Administrators	2.1	2.7	.1	2.7	.1
Graduate Students					
Technicians	42.9	49.9	2.1	47.4	6.1
Clerical					
Subcontractors	.7				
TOTAL FTEs	67.2	73.8	3.3	71.0	10.0
OPERATING COSTS $(000):					
PPPL Labor	5849.7	6965.2	206.4	7191.2	336.6
Subcontract Labor	22.1				
Overtime	276.0	386.5	36.5	394.4	43.9
Travel	12.6	12.6		12.8	
Energy	821.0	1165.2	90.0	1187.8	101.8
Stockroom	69.0	84.9		86.5	
Miscellaneous Expenses	16.6	16.6		16.9	
Procurements/ICOs	743.8	969.7	216.0	956.9	291.8
Organizational Burden	552.9	774.2	24.0	798.8	38.8
Other	2.4	2.4		2.5	
General + Administrative	4258.3	5567.2	247.3	5727.7	371.3
TOTAL OPERATING COSTS	12624.4	15944.5	820.2	16375.5	1184.2
TOTAL OPERATING OBLIGATIONS	12624.0	15944.5	820.2	16375.5	1184.2
EQUIPMENT COSTS $(000):					
Equipment - Direct	35.0	36.8			
Equipment - G+A	8.8	13.2			
Fabricated Equipment	854.4	598.1	323.7	247.4	1690.2
TOTAL EQUIPMENT COSTS	898.2	648.1	323.7	247.4	1690.2
TOTAL EQUIPMENT OBLIGATIONS	875.0	648.1	323.7	247.4	1690.2
GRAND TOTAL COSTS	13522.6	16592.6	1143.9	16622.9	2874.4
GRAND TOTAL OBLIGATIONS	13499.0	16592.6	1143.9	16622.9	2874.4

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1808	0	3/01/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
National Compact Stellarator Experiment (NCSX)	AT5015020/AT5506

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
G. H. Neilson Phone: 609-243-2726 Email: hneilson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This work covers design, fabrication, and research preparations for the National Compact Stellarator Experiment (NCSX), a proof-of-principle experimental facility being built at the Department's Princeton Plasma Physics Laboratory (PPPL). The NCSX is the key element of a national proof-of-principle program to develop the physics of compact stellarators, an innovative fusion confinement concept, in support of national Fusion Energy Sciences program goals. The project is led by PPPL, in partnership with the Oak Ridge National Laboratory (ORNL), and in collaboration with other US laboratories and universities. (This FWP covers the PPPL scope; the FWP covering ORNL scope is submitted by ORNL.) In this period, most of the work is in the design and fabrication of the NCSX major item of equipment (MIE). There is also a lower-level research preparation activity.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Purpose

The proposed work will follow the completion of NCSX conceptual design in FY-2002. The purpose of the work in FY-2003 and 2004 is to accomplish the tasks scheduled for the first two years of the NCSX Major Item of Equipment project:

- Complete design of the main stellarator core components, the vacuum vessel and modular coils, including associated manufacturing development and prototypes.
- Begin fabrication of the modular coils and vacuum vessel.
- Complete sufficient design work on NCSX ancillary systems to support system integration needs and maintain the overall schedule. These systems include power supplies, neutral beams, fueling, pumping, site utilities, diagnostics, and central instrumentation and controls.
- Complete deliverables for CD-1 (FY02), CD-2 (FY03) and CD-3 (FY04).
- Continue planning and tool adaptations as preparation for the NCSX research program.

Approach

The NCSX project is led by the Princeton Plasma Physics Laboratory (PPPL) with the Oak Ridge National Laboratory (ORNL) providing major leadership and support as a partner. Management responsibilities are clearly assigned to each partner, and PPPL has overall responsibility for the project, reporting to DOE through the PPPL Director.

The design of NCSX will be done by Laboratory (PPPL and ORNL) scientists and engineers in collaboration with US laboratories and universities. Development and manufacture of the major stellarator core components such as the coils and vacuum vessel will be done in industry, under contract to PPPL, or by a combination of industry and Laboratory efforts. The device will be assembled by Laboratory personnel. Ancillary systems will be assembled from a combination of new and existing equipment, such as the PBX-M neutral beams and D-site magnet power supplies originally used on TFTR. The facility will utilize existing PPPL infrastructure including the C-Site test cell and associated control rooms. In the final stage of the project, an integrated testing program will be carried out and a plasma ("first plasma") will be produced in the device to make it ready for experimental operations. Research preparations will be carried out by an integrated team led by PPPL and ORNL.

Further details are contained in the NCSX Project Execution Plan.

Technical Progress

FY-2001: Preconceptual design was completed following a series of major design decisions: selection of the reference plasma configuration, modular coil topology, and machine design point. A successful Physics Validation Review (PVR) confirmed the

physics design approach, including the decision to base the NCSX program on the quasi-axisymmetric stellarator concept. The PVR led to FESAC endorsement of proof-of-principle designation for the compact stellarator and DOE approval of mission need (CD-0). Conceptual design began with a set of design modifications to address PVR recommendations and improve physics capabilities: better diagnostic access, more space for in-vessel components, and improved consistency with required plasma physics properties.

FY-2002: Conceptual design of the stellarator core continued to (expected) completion. The top-level design requirements for the Major Item of Equipment (MIE) were established An updated reference coil configuration, satisfying both physics requirements and engineering criteria for buildability, was established as the basis for the design to be presented at the conceptual design review. The design, cost and schedule estimates, project plans, and status of PVR recommendations will be documented in a conceptual design report and presented at a Conceptual Design Review (CDR) in May, 2002. The report, along with the review findings and other documentation will be submitted to DOE as a basis for approval of CD-1 (start of Title I design).

Future Accomplishments

FY-2003 (MIE Project): The MIE project will start, beginning with preliminary design of the modular coils and vacuum vessel. These form the "backbone" of the machine structure and their development constitutes the project's critical path. The preliminary design phase will include small-scale manufacturing development activities in industry to optimize the design and plans for fabricating these highly shaped components. Following a preliminary design review of the central core, final design and fabrication in industry of full-scale prototype articles will begin. Design of the balance of the stellarator core components (TF and PF coils, trim coils, support structure, cryostat, PFCs), which are off the critical path and are more straightforward to build, will proceed on schedule to support the overall design during this time. Work will also be done on the design of ancillary systems to support interface decisions, including power supplies, neutral beams, fueling, pumping, site utilities, diagnostics, and central instrumentation and controls. The project will update its cost and schedule estimates to establish the performance baseline and will produce deliverables needed to support DOE approval of CD-2.

FY-2004 (MIE Project): Final design of the modular coils and vacuum vessel will continue to completion and a final design review will be conducted. Full-scale prototypes will be fabricated and tested. Contracts will be placed for production of the modular coils and vacuum vessel. Design of the balance of the stellarator core will proceed on an appropriate schedule. Work on ancillary systems will continue on a schedule to support design decisions. The project will produce deliverables needed to support DOE approval of CD-3.

FY-2003-04 (NCSX Research Preparation): While the MIE project is in progress, but operation still a few years away, the research preparation activity will focus on keeping abreast of physics developments in the broader stellarator program, taking those developments into account in the planning of the NCSX experimental program, and preparation of long-lead-time physics analysis tools for NCSX application. The effort will focus on two tasks:

1. Development of plasma control strategies for a range of operating scenarios. The NCSX team will adapt tools that are available (e.g., the free-boundary plasma optimizer) or being developed (e.g., the 3D equilibrium reconstruction code being developed by Theory) to provide the analysis capabilities and define control system requirements.

2. Development of boundary control research strategy. The plasma-facing components will be implemented in a phased manner, ultimately leading to a pumped divertor, but determining the optimum strategy requires application of analytical tools and incorporation of experimental results from foreign stellarator divertor experiments. The activity will produce analysis tools to interpret data from boundary diagnostics and determine requirements for PFC upgrades.

Relationship to Fusion Program Goals: The NCSX project supports Fusion Energy Sciences Goal 2 (innovative and reduced-cost approaches to attractive fusion systems) and Goal 1 (physics understanding leading to predictive capability) by providing a major new facility with unique physics capabilities. The NCSX is critical to the achievement of one of the key ten-year milestones within Goal 2, "Determine the attractiveness of a compact stellarator," and is designed to provide the necessary physics data for this assessment. Under the present schedule, NCSX will start operation in FY-2007 and may not provide an adequate experimental basis for assessing the attractiveness of compact stellarators until 2011 or 2012 instead of the scheduled 2009.
Incremental funding: Incremental funding of $4.0M in FY-2003 ($3.5M to PPPL, $0.5M to ORNL) is requested to speed up the NCSX MIE project. Such an increase would gain about 3 months on the schedule through FY-2004. Completing the project on a faster schedule would be expected to reduce its total cost, although the savings is difficult to quantify at this early stage.

Incremental funding of $0.4M per year ($0.3M to PPPL, $0.1M to ORNL) is requested to augment the scope of NCSX research preparation activities in FY2003-04. It will support advanced planning of the radiofrequency (rf) heating program and development of physics requirements for associated hardware upgrades. It will facilitate earlier rf heating tests on NCSX, which will be important to determine the optimum upgrade path for high-power heating.

The requested incremental funding of the NCSX MIE project and associated research preparations could, if continued in future years, produce important benefits to the Fusion Energy Sciences program:

- Schedule: Recover at least 3 months of the forecast schedule slippage in achieving the ten-year goal to determine the attractiveness of compact stellarators.
- Leadership: Maintain the strong world leadership position in compact stellarator research that the U.S. holds.

Milestone Schedule

Milestones. All pertain to the MIE project except those designated "Research prep."	**Date (Guidance)**	**Date (Incremental)**
FY-2002		
Select reference coil design for the conceptual design review	Dec., 2001	Dec., 2001
Conduct Conceptual Design Review (CDR) of NCSX	May, 2002	May, 2002
Update Review Findings Disposition Plan	July, 2002	July, 2002
FY-2003		
Award contracts for sub-scale manufacturing development activities.	Nov., 2002	Nov., 2002
Conduct preliminary design review of modular coils and vacuum vessel.	May, 2003	April, 2003
Award contracts for modular coil full-scale prototypes.	Sept., 2003	July, 2003
Award contracts for vacuum vessel full-scale prototypes.	Sept., 2003	Sept., 2003
Update boundary physics research strategy and plan. (Research Prep.)	Sept., 2003	Sept., 2003
FY-2004		
Conduct final design review of modular coils.	March, 2004	Jan., 2004
Conduct final design review of vacuum vessel.	March, 2004	March, 2004
Award contract for modular coils production articles.	June, 2004	March, 2004
Award contract for vacuum vessel production articles.	June, 2004	June, 2004
Update plasma control research strategy and plan. (Research Prep.)	Sept., 2004	Sept., 2004
Conduct final design review of TF coils.	Sept., 2004	July, 2004
Conduct final design review of PF coils.		Sept., 2004
Plan for Initial RF Studies		Sept., 2004

Explanation of Milestones

Milestone	Date (Guidance)
FY-2002	
Select reference coil design for the conceptual design review A key objective for the conceptual design review is to show that the machine as designed will be able to provide the capabilities needed for the physics program. As is often the case, physics requirements and engineering constraints are potentially in conflict, so satisfying both simultaneously is a significant step. This milestone sets a target date for the physics and engineering teams to agree on a coil geometry, leaving enough time before the review to analyze and document it.	Dec., 2001
Conduct Conceptual Design Review (CDR) of NCSX The conceptual design review is the last major step in the project planning stage and addresses several basic questions about the project. Are the project requirements defined and can they be met? Approximately how much will it cost and how long will it take to build the equipment? Are the project plans sound? Have outstanding issues from past reviews been adequately resolved? As input to the review, the project will provide documentation (a conceptual design report) and presentations addressing these issues. As output, a review panel will answer the critical review questions and make recommendations as to how the design and future plans for NCSX could be improved. The Department will use the results of the CDR as a basis for approving the start of preliminary design, Critical Decision 1.	May, 2002
Update Review Findings Disposition Plan As a follow-up to the CDR, the project is responsible for responding to all issues and recommendations raised by the review. The project's response, known as a "disposition plan" can take the form of either an immediate conclusion or decision that resolves an issue with minimal additional effort, a significant modification of the project plans to carry out work that is needed before an issue can be resolved, or something in between these extremes. This milestone provides a target date for updating the plans in response to CDR issues and incorporating them into the planning for the next phase of the project, which begins in October, 2002.	July, 2002
FY-2003	
Award contracts for sub-scale manufacturing development activities. As part of the design process, the project will test some of the manufacturing processes it plans to use by building small samples of components or assemblies and performing tests. The results will be used to guide the design and planning. This milestone provides a target date for the project to specify these so-called manufacturing development activities and chose suppliers to perform them so that the work can begin.	Nov., 2002

Conduct preliminary design review of modular coils and vacuum vessel. The first step in the NCSX project is the design of the modular coils and vacuum vessel. These are the most challenging of all the NCSX components and have the greatest impact on the design of the other components and on the overall cost and schedule. Preliminary design is the step in which the design is developed to the point where the requirements for each individual component are defined and shown to be achievable, and where the cost and schedule for fabricating the components can be estimated more accurately. A review at the end of this phase is an important part of the process. This milestone sets a target date for accomplishing these goals, which are prerequisites for the next step, final design. The Department will use the results of this review as a basis for approving start of final design, Critical Decision 2.	May, 2003
Award contracts for modular coil full-scale prototypes. Award contracts for vacuum vessel full-scale prototypes. As part of the final design process, the project will build full-scale samples of its critical components (the modular coils and the vacuum vessel) in order to prototype the entire process of manufacturing them, from beginning to end, and conduct test before producing the actual components for the machine. The results will help the project evaluate the available manufacturing processes and suppliers. This milestone provides a target date for the project to specify these prototypes and chose suppliers to build them so that the prototyping work can begin.	Sept., 2003 Sept., 2003
Update boundary physics research strategy and plan. (Research Prep.) Controlling the plasma edge conditions in NCSX is a matter of sensing the state of the edge plasma with diagnostics and designing plasma-facing structures to exhaust the heat and control the flow of particles. Long-term preparation is planned to develop the analysis tools and control system requirements. This milestone will update the research program based on progress in FY-03.	Sept., 2003
FY-2004	
Conduct final design review of modular coils. Conduct final design review of vacuum vessel. Final design is the step in which the design is developed to the point where the specifications for a component are defined to the point where it can be given to a manufacturer to build. A review at the end of this phase is an important part of the process. This milestone sets a target date for accomplishing these goals so that the fabrication can proceed. The Department will use the results of this review as a basis for approving start of fabrication activities, Critical Decision 3.	March, 2004 March, 2004

Award contract for modular coils production articles. Award contract for vacuum vessel production articles. The project will finally fabricate the actual modular coils and vacuum vessel, the so-called production articles, that will be assembled into a finished device. This milestone provides a target date for the project to specify these components and chose suppliers to build them so that the fabrication work can begin.	June, 2004 June, 2004
Update plasma control research strategy and plan. (Research Prep.) Plasma control in NCSX is a matter of sensing the state of the plasma with diagnostics and constantly adjusting the magnet currents to follow the sequence desired by the operators. Long-term preparation is planned to develop the analysis tools and control system requirements. This milestone will update the research program based on progress in FY-03 and –04.	Sept., 2004

FY03 Congressional Budget

The Congressional Budget for NCSX at PPPL is $697K higher than the Guidance Budget presented in this FWP. In the Guidance Budget, that $697K is allocated to collaborating laboratories ($617K for ORNL, $80K for LLNL), as recommended by the project. Under the Congressional Budget, significant engineering work scope on the NCSX stellarator core, for which ORNL has lead responsibility, would be assigned to PPPL instead of ORNL. Physics analysis in support of edge plasma diagnostic design would be assigned to PPPL instead of LLNL. Both ORNL and LLNL bring special expertise in their areas, which will improve the overall performance of the project.

Relationship to Other Projects

As the key element of the national stellarator proof-of-principle program, the NCSX project maintains close scientific ties with the other parts of this program, including the QPS, HSX, and CTH experiments, the theory and international collaborations program, and the reactor studies program.

As stated earlier, the NCSX project is managed by a partnership between PPPL and ORNL, working as an integrated team. The NCSX project has a close relationship with the ORNL-led QPS project which, though a separate activity, involves the same two institutions and many of the same people. This coordination has facilitated efficient development and sharing of tools as well as knowledge transfer from one project to the other, to the overall benefit of the fusion program.

1808 NCSX			03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	3.3	5.5	1.2	5.8	.5
Engineers	5.2	16.6	4.6	19.0	.1
Administrators	.1	.3		.3	
Graduate Students					
Technicians	.5	3.8	3.5	14.3	
Clerical	.4	.4	.1	.5	
Subcontractors					
TOTAL FTEs	9.5	26.6	9.4	39.9	.6
OPERATING COSTS $(000):					
PPPL Labor	1285.7	344.2	106.2	366.6	110.9
Subcontract Labor					
Overtime					
Travel	45.8	25.8	10.0	8.8	10.0
Energy					
Stockroom	.8	.9		.9	
Miscellaneous Expenses	.4	.6	5.0	.6	5.0
Procurements/ICOs	289.8	54.3	45.0	69.0	53.6
Organizational Burden	125.0	31.8	7.6	29.9	8.0
Other	12.7	5.3	5.0	.3	5.0
General + Administrative	959.8	288.5	101.2	292.8	107.5
TOTAL OPERATING COSTS	2720.0	751.4	280.0	768.9	300.0
TOTAL OPERATING OBLIGATIONS	2720.0	751.4	280.0	768.9	300.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment		8790.9	3520.1	13031.2	
TOTAL EQUIPMENT COSTS		8790.9	3520.1	13031.2	
TOTAL EQUIPMENT OBLIGATIONS		8790.9	3520.1	13031.2	
GRAND TOTAL COSTS	2720.0	9542.3	3800.1	13800.1	300.0
GRAND TOTAL OBLIGATIONS	2720.0	9542.3	3800.1	13800.1	300.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

9450 NCSX MIE		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	4.3	.7	4.3
Engineers	15.7	4.5	18.4
Administrators	.3		.3
Graduate Students			
Technicians	3.5	3.5	14.0
Clerical	.3	.1	.3
Subcontractors			
TOTAL FTEs	24.1	8.8	37.3
COSTS $(000):			
PPPL Labor	3223.8	1021.9	4546.7
Subcontract Labor			
Overtime			
Travel	75.0	50.0	80.0
Energy			
Stockroom			
Miscellaneous Expenses	12.5	25.0	15.0
Procurements/ICOs	1830.9	1073.0	3352.9
Organizational Burden	363.4	113.5	489.5
Other	261.0	50.0	50.0
General + Administrative	3024.3	1186.7	4497.1
TOTAL COSTS	8790.9	3520.1	13031.2
TOTAL OBLIGATIONS	8790.9	3520.1	13031.2

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1809	0	3/01/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
Quasi-Poloidal Stellarator Experiment	AT5015020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
G. H. Neilson Phone: 609- 243-2726 Email: hneilson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:
This work covers PPPL participation in the design, fabrication, and research preparations for the Quasi-Poloidal Stellarator (QPS) experiment, a concept-exploration-scale experiment facility being built at the Department's Oak Ridge National Laboratory (ORNL). The QPS is a new element of a national proof-of-principle program to develop the physics of compact stellarators, an innovative fusion confinement concept, in support of national Fusion Energy Sciences program goals. The QPS project is led by ORNL, with PPPL and other US laboratories and universities participating as collaborators. The QPS project has a close relationship with the PPPL-led National Compact Stellarator Experiment (NCSX) project which, though a separate activity, involves the same two institutions and many of the same people. Coordination between the two projects facilitates efficient development and sharing of tools and knowledge, to the overall benefit of the fusion program.

Signature:
15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Purpose

The purpose of PPPL's QPS work in FY-2003 is to support completion of the conceptual design. In 2004, PPPL will support tasks scheduled for the first year of the QPS Major Item of Equipment project:

- Design support and procurement, including associated manufacturing development and prototypes, for stellarator core components that have a high degree of commonality with NCSX, especially the modular coil supports.
- Physics analysis in support of the design and research preparations.

Approach

The QPS project is led by the Oak Ridge National Laboratory (ORNL). Princeton Plasma Physics Laboratory (PPPL) supports QPS as a collaborator.

Technical Progress

FY-2001-02: In support of QPS, PPPL performed physics analyses including magnetic surface quality and MHD stability. PPPL reviewed engineering concepts for the QPS device and major components such as the modular coils. PPPL supported a QPS cost assessment, based on comparisons with NCSX. PPPL supports procurement planning and drafting of specifications for the QPS components, especially the modular coils, which have manufacturing issues in common with those being addressed for NCSX.

Future Accomplishments

FY-2003 (QPS Conceptual Design): PPPL will provide requested physics and engineering support for the QPS conceptual design review in FY-2003. Physics support areas will be in compact stellarator design tasks where PPPL has expertise based on NCSX work, such as magnetic surface quality and island healing (if necessary), flexibility analysis, and stability analysis. On the engineering side, support tasks will include engineering analysis (electromagnetic, structural, and thermal) and cost estimating.

FY-2004 (QPS MIE Project): When QPS moves into Title I design in FY-2004, PPPL will also provide support in the procurement area: preparation of specifications for R&D and manufacture, coordination with NCSX procurement activities, and procurement of QPS components, especially the modular coil structures, that have a high degree of commonality with those of NCSX.

FY-2004 (QPS Research Preparation): While the MIE project is in progress, but operation still a few years away, the research preparation activity will focus on preparation of long-lead-time physics analysis tools for QPS application. PPPL will support in areas of expertise such as equilibrium and stability analysis.

Relationship to Fusion Program Goals: The QPS project supports Fusion Energy Sciences Goal 2 (innovative and reduced-cost approaches to attractive fusion systems) and Goal 1

(physics understanding leading to predictive capability) by providing unique physics capabilities. As an element of the national stellarator proof-of-principle program, it contributes to one of the key ten-year milestones within Goal 2, "Determine the attractiveness of a compact stellarator." Its role is to explore the physics of stellarators optimized for quasi-poloidal symmetry and extend the compact stellarator design space to aspect ratio less than 3.

Incremental funding: The QPS project is requesting incremental funding in FY-2003 and 2004, including incremental funds for PPPL: $60K in FY-03 and $40K in FY-04. The increment would augment PPPL support of QPS conceptual design efforts in FY-03 and research preparation activities in FY-04.

Milestone Schedule for PPPL Support of QPS

Note: PPPL milestones are tied to those of the QPS project, which are explained in more detail in the ORNL Field Work proposal.

Milestones.	**Date (Guidance)**	**Date (Incremental)**
FY-2003		
Deliver design and analysis results in support of QPS conceptual design review.	May, 2003	May, 2003
FY-2004		
Award contracts for modular coil full-scale prototypes.	Nov., 2003	Oct., 2003
Deliver design and analysis results in support of QPS preliminary design review.	March, 2004	March, 2004
Complete fabrication of modular coil full-scale prototypes.	Aug., 2004	July, 2004

Relationship to Other Projects

As an element of the national stellarator proof-of-principle program, the QPS project maintains close scientific ties with the other parts of this program, including the NCSX, HSX, and CTH experiments, the theory and international collaborations program, and the reactor studies program.

1809 QPS			03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.1	.4	.1	.2	.1
Engineers	.3	.4	.1	.9	
Administrators					
Graduate Students					
Technicians					
Clerical				.1	
Subcontractors					
TOTAL FTEs	.4	.8	.2	1.2	.1
OPERATING COSTS $(000):					
PPPL Labor	55.6	121.3	32.0	42.2	20.5
Subcontract Labor					
Overtime					
Travel		9.2			
Energy					
Stockroom					
Miscellaneous Expenses		.1		.1	
Procurements/ICOs		4.1	1.1	4.1	2.5
Organizational Burden	5.8	11.3	3.7	4.7	1.9
Other	.8	4.4			
General + Administrative	36.8	95.5	23.1	32.5	15.1
TOTAL OPERATING COSTS	99.0	245.9	59.9	83.6	40.0
TOTAL OPERATING OBLIGATIONS	99.0	245.9	59.9	83.6	40.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment				941.4	
TOTAL EQUIPMENT COSTS				941.4	
TOTAL EQUIPMENT OBLIGATIONS				941.4	
GRAND TOTAL COSTS	99.0	245.9	59.9	1025.0	40.0
GRAND TOTAL OBLIGATIONS	99.0	245.9	59.9	1025.0	40.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2104	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Next Step Option	AT6010501

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
D. M. Meade Phone: (609) 243-3301 Email: dmeade@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The purpose of the national Next Step Options (NSO) design studies is to:

- Advance the physics and engineering design of FIRE, an option for the study of burning plasmas to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.
- Support the evaluation of candidate fusion program next step options to determine their feasibility, scientific merit and estimated costs as candidates for a new DOE construction project, or for U. S. participation in an international collaboration/cost-shared project.
- Integrate these options into a coordinated multi-element program as input to program planning activities.

The NSO Plan for FY03/04 incorporates flexibility to take advantage of the possibility of a significant new initiative in Burning Plasmas, either the construction of a domestic experiment or participation in an international experiment, as called for in HR-4. The NSO study is a national activity organized by the VLT. It includes PPPL along with the other fusion laboratories and universities and a small but important industrial element. This Field Work Proposal discussion covers this national activity. However, the funding included in the PPPL budget tables covers only the PPPL tasks.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

TECHNICAL PROGRESS IN FY 2002

Since the submission of the last FWP in April 2001, the NSO activity has made significant progress. This progress has been made by a national design team that has taken advantage of the experience and strengths of the U.S. fusion infrastructure. During this period there have been two NSO/FIRE-PAC meetings, and the FIRE team has been very active in community discussions on burning plasmas. The complete NSO-PAC Reports and the Action Plan by FIRE can be found at the NSO-PAC web site (http:/fire.pppl.gov/nso_pac4). The mission for a Next Step Option Burning Plasma Experiment, to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas, has been endorsed by the NSO/FIRE-PAC. This mission led to a design concept called the Fusion Ignition Research Experiment (FIRE) that includes both burning plasma physics and advanced toroidal physics objectives. The FIRE physics objectives define the physics requirements for the initial burning plasma phase of P_α/P_{ext} = 2 as the target for the Elmy H-mode regime with conditions being sustained for ˜ 2 τ_{CR} (current redistribution times). This is essentially the same plasma performance capability as ITER-FEAT. In addition, an advanced tokamak upgrade phase is envisioned with plasma conditions pointing toward the ARIES advanced tokamak regime. The FIRE advanced tokamak regime has the plasma requirements of $P_\alpha/P_{ext} = 1, I_{bs}/I_{ext} = 1$, β_N ˜ 3.5, ˜ 100% non-inductive plasmas that are sustained for 1 – 2 τ_{CR}.

As a result of the PAC's review and recommendations, the design point for FIRE has been modified to R = 2.14 m, a = 0.595 m, B = 10 T, I_p = 7.7 MA, $P_{alpha}/P_{heat} > 0.5$ (Q = 10), with P_{fusion} ~ 150 MW for burn times ~ 20 s. The goal for the construction project cost is ~ $1B with a tokamak system cost ~ $350M. A flexible and robust engineering design has been achieved for FIRE that provides substantial margins for the magnet systems and has large access ports for remote maintenance and diagnostics. The basic FIRE design incorporates advanced tokamak features including strong shaping, very low toroidal field ripple, inside launch pellet injection, internal control coils and room for future wall stabilization systems. A design study comparing a bucked and wedged design with a wedged design for the magnet systems was completed. The bucked and wedged design offered the advantage of 50% longer pulses with lower electrical power consumption. However, the complexity of the interfaces between the TF/PF coil systems and lack of operating experience with bucked and wedged magnet systems led to the decision to retain the wedged configuration for the baseline design. Critical engineering design issues have been identified that are generic for advanced toroidal systems such as: plasma power and particle exhaust at high power density, helium ash pumping, vacuum vessel heating due neutron wall loading at ~ 3 MWm^{-2}, and low tritium inventory. A Working Group has been formed to assess the impact of plasma disruptions on thermal and electromagnetic loads and to evaluate techniques to mitigate disruptions especially vertical displacement events. A peer review of the major FIRE systems was carried out by an external group of experienced tokamak designers and engineers in June 2001. Their recommendations to focus on a single design point with a goal of Q ˜ 10 and to incorporate an additional engineering margin above the normal design allowables have been implemented. The FIRE engineering peer review team also provided an extensive list of suggestions that has served as the basis for the FY 2002 engineering work plan.

The FIRE Team also participated actively in national and international meetings including EPS 2001, the APS-DPP 2001, the ITPA meetings and has organized a special session at the spring meeting of the APS in Albuquerque. During the past year, the FIRE Team has presented > 50 talks and 10 conference papers. The FIRE web site has served as a repository for fusion program information as well as FIRE documentation.

A major recommendation from the NSO-PAC was to incorporate design guidelines that were similar to the ITER FEAT design guidelines such as the as ITER98(y,2) confinement scaling and the updated L- to H- power threshold. The ITER98(y,2) scaling analysis, presented in the FIRE paper at the IAEA Sorrento meeting (2000), indicated the importance of increasing the plasma current to 7.7 MA to access Q ˜ 10 regimes. The FIRE design basis takes advantage of the experimental result that plasmas with modest density relative to the Greenwald, density (0.6 n_{GW}), high triangularity (δ_x = 0.7), and modest density peaking $n(0)/n_{ped}$ ˜ 1.5 have 10 to 20% better confinement than the standard ITEr98(y,2) scaling. In addition, physics based models such as GLF23 have been used by Waltz and Kinsey to show that FIRE would be expected to attain Q˜ 10 conditions for pedestal temperatures of ~ 2.5 keV ---somewhat lower than required to attain Q ˜ 10 in ITER. The lowered H-mode power threshold has expanded the operating range since β_N ˜ 1.8 is now sufficient to access the Q ~ 10 regime. The 7.7 MA capability could be achieved by increasing the minor radius from 0.525 m to 0.595 m, and the major radius from 2 m to 2.14 m with B = 10T as shown in Table 1. In this case the burn duration is 20s or ˜ 1.7 skin times. The design point formerly known as FIRE* has become the new baseline for FIRE.

	R, m	a, m	$B(R_o)$, T	I_p, MA	τ_{Burn}/τ_{skin}
FIRE Old	2.0	0.525	10	6.44	1.7
FIRE New	2.14	0.595	10	7.7	1.7

Table 1. Physical Parameters for FIRE Studies

At the request of the PAC advanced tokamak scenarios (reversed shear) are being developed along with concepts for resistive wall mode stabilization. A very interesting AT mode with reversed shear has been identified by Kessel that has Q ˜ 7.5, β_N = 3.5, f_{bs} ˜ 64%. Simulations of these plasmas using fast wave current drive near the axis and lower hybrid current drive near the plasma edge are 100 % non-inductively sustained for a flat top of ˜ 30 s (> $1\tau_{CR}$). This regime would require enhanced confinement H(y,2) ˜ 1.6. The confinement in similar AT regimes has been studied with GLF23 which indicated that an internal transport barrier could be produced. This regime also requires stabilization of the n = 1 kink mode. Studies of a feedback system by Bialek and Navratil have found feasible systems for stabilizing the n = 1 kink up to β_N = 4.1. The power densities in FIRE are reactor relevant and will provide a good test of edge plasma physics understanding, and plasma facing technology. The power handling on the first wall is now the limit to full exploitation of this regime.

Simulations of disruptions using TSC and the 3-D OPERA code (Sandia) have provided improved calculations of the mechanical stresses in the divertor and vacuum vessel components that are a factor of three lower than simple estimates. These analyses are ongoing.

A preliminary cost estimate was made for the original FIRE design, with a major radius of 2.0m, 30 MW of ICRF power and 200 MW of fusion power, based on input at the subsystem level. This estimate based on U.S cost methodology indicates a cost of ~ $350M for the tokamak and a total of $1.2 B for the project built at a green field site. This estimate is being updated for the new baseline at increased major radius (2.14m), reduced ICRF power 20 MW and reduced fusion power 150 MW.

During the past year the burning plasma activities in the U.S. have gained considerable momentum. The Authorization Bill HR 4, "Securing America's Future Energy Act 2001" calls for the Secretary of Energy to *prepare a plan for U. S. construction of a Burning Plasma Experiment and submit it to Congress by July 2004. The Secretary may also develop a plan for United States participation in an international burning plasma experiment for the same purpose, whose construction is found by the Secretary to be highly likely and where United States participation is cost effective relative to the cost and scientific benefits of a domestic experiment.*

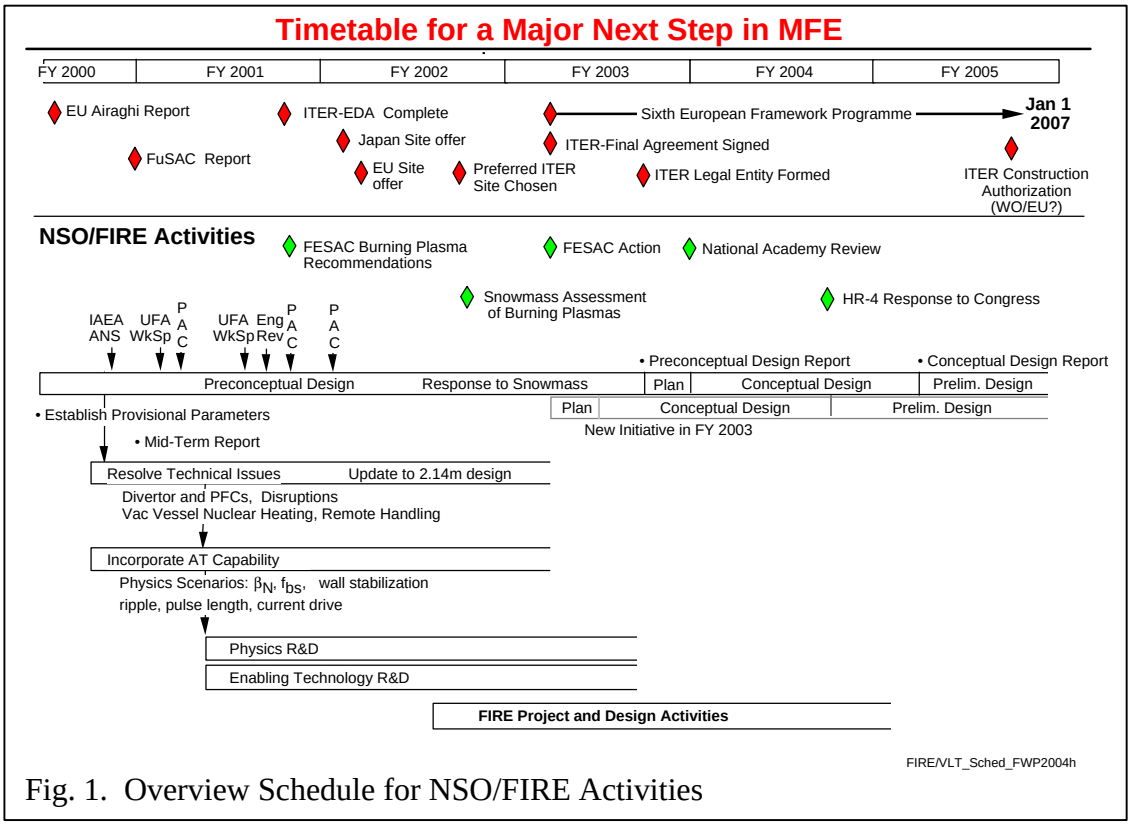

Fig. 1. Overview Schedule for NSO/FIRE Activities

The FESAC (August 2002) fully endorsed strong recommendations on burning plasmas including: *The U.S. Fusion Energy Sciences Program should establish a proactive U.S. plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs,*

the U.S. should be ready to act and take advantage of it but should not be dependent upon it.

FESAC also laid out specific plan for a community comparative assessment of three options for a next step burning plasma experiment (FIRE, ITER and IGNITOR) to be held at Snowmass in the summer of 2002. This would be followed by a high-level action panel to review the technical results from Snowmass and to recommend a preferred option for the U.S. The National Academy of Sciences will then review the Burning Plasma plan from a broader science perspective. The goal of this process is have a decision so that plans for either a domestic experiment or collaboration or an international based experiment could be submitted to Congress by July 2004 as shown in Fig. 1. The important point is that significant incremental funds will be needed for either option if we are to make the schedule laid out in HR 4.

The last part of FY 2002 will be driven by the need to respond to requests from the Snowmass Working Groups. It is anticipated that the Snowmass process will be very constructive in improving the FIRE approach to a near term affordable burning plasma experiment. The last two months of FY 2002 will focus on responding the feedback and critiques from Snowmass.

FY 2003 PLANS Baseline Flat Budget Case

This case continues the development of the FIRE Preconceptual design with the objective of addressing key technical issues so that a conceptual design could be initiated rapidly and carried out expeditiously. A prioritized work plan will be developed based on the results of the Snowmass assessment and reviewed with the NSO PAC. The main elements of the NSO/FIRE activities are shown in Fig. 1. The schedule for the NSO/FIRE activities calls for a completion of the FIRE Preconceptual Design Study by September 2003 and readiness to proceed with a Conceptual Design of FIRE at the beginning of FY 2004 as shown in Fig. 1. The ITER_EDA Extension was completed in July 2001. The milestones for ITER decisions on site proposals, Collaborative Agreement and formation of the ITER Legal Entity are also shown in Fig. 1. During this time, the U.S. program may engage the ITER partners in discussions on possible U. S. participation in the ITER-FEAT Project. Until the review and U. S. decision making process outlined above is completed, the U.S. should continue to develop a lower cost near term burning plasma experiment like FIRE. Even if Europe and Japan decide to proceed with the construction of ITER-FEAT, there will still be an important role for much lower cost experiments with missions focused on critical physics issues. If the ITER project is terminated and Japan and Europe proceed with separate national projects, the U.S. should be ready to take a leading role in a lower cost burning plasma physics experiment as recommended by SEAB (1999).

The direction of the NSO effort will be guided by the ongoing community review and DOE's decisions. PPPL will be responsive to the process could begin preparatory work on U.S. participation in ITER and IGNITOR.

Burning Plasma Initiative (Incremental Budget Case)

As shown in Tables 2 and 3, incremental funds are requested for supporting an accelerated burning plasma initiative. The goal of this initiative is to respond to the language of HR 4, namely to provide a plan for the U.S. construction of a burning plasma experiment to Congress by July 2004, be it domestic construction or participation in an international collaboration on burning plasmas. If the Secretary of Energy were to support participation in construction of an international burning plasma, then this initiative would also include activities in support of participation in an international burning plasma experiment. The requirements for the plans are specified in HR 4 and include overall design of the experiment, estimated cost and, for the U.S. experiment, potential construction sites.

Based on prior experience with conceptual designs of similar size devices such as CIT and TPX, the Conceptual Design for a U.S. based burning plasma experiment is estimated to cost ~ $15M and take ~ 15 months after initiation as shown in Fig.1. These activities would rely heavily on the past experience and the core competencies of the U.S. in carrying out burning plasma designs. These capabilities reside at the major fusion laboratories, Universities and U.S. industries. For the FIRE Conceptual design activities, the most expeditious way to proceed is to expand activities already underway and add participants as needed with experience in key areas.

The Snowmass process will uniformly assess the capabilities as well as the scientific and technological contributions of FIRE, IGNITOR, and ITER. This assessment will provide the technical basis for FESAC, the Administration and hopefully Congressional action aimed at enabling US researchers to study burning plasmas, the next frontier of fusion energy sciences. In support of this decision sequence, PPPL expects to perform work in planning for ITER management, design, research planning, and operations planning, as inputs to the decision and as preparation for subsequent project activity; this ITER activity may well be in parallel with activity on FIRE and possibly IGNITOR. If the decision process selects ITER for the US path for pursuit of burning plasmas, then PPPL, as lead laboratory for fusion, should be a major contributor to the management, science, and design of US participation in the ITER endeavor as part of a national effort. The budget tables below would have to be amended to reflect such a decision.

Budget ($M)	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004
NSO/FIRE Guidance	4.000	2.660	2.240	2.157	2.157	2.004
Snowmass 2002				1.000		
Incremental Burning Plasma Initiative					5.840	18.000
Increment						
Actual/Request	4.000	2.660	2.240	3.157	8.000	20.004

Table 2. National NSO/FIRE Budget Request

Budget ($M)	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004
NSO/FIRE Guidance	1.300	0.900	0.747	0.707	0.814	0.814
Snowmass 2002				0.299		
Incremental Burning Plasma Initiative					1.500	4.200
Increment						
Actual/Request	1.300	0.900	0.747	1.006	2.314	5.014

Table 3. PPPL NSO/FIRE Budget Request

FY 2004 PLANS Burning Plasma Initiative

The U.S. decision process laid out by FESAC (August 2002) will be culminating near the beginning of FY 2004, and our plan needs the flexibility to accelerate the conceptual design activities of a domestic burning plasma, or it needs the capability to carry out technical design and review activities to determine the role for U.S. participation in an international burning plasma experiment. The DOE project management requirements are known for a U.S. burning plasma experiment and the milestones below have been laid out to satisfy those requirements. The NSO/FIRE plan calls for a CD-0, Decision to Proceed with a conceptual design, by April 2003 that would enable the initiation of a Conceptual Design activity. This would require a Mission Need and Justification Document describing the benefits of the project, alternatives considered, rough cost and schedule estimate, which is proposed for October 2002. A Mission Validation Independent Project Review validating the mission need and funding estimate is proposed for October 2002, if incremental funding were received consistent with HR4. The goal would be to complete the Conceptual Design Activities by June 2004 to meet the HR 4 milestone.

If the U.S. joins construction activities on ITER or IGNITOR, then PPPL wishes to be a strong participant in the programs and to play scientific, engineering, and management roles.

RELATIONSHIP TO FESAC GOALS

A burning plasma experiment would make unique contributions to FESAC Goals 2, 3 and 4. The major contribution is Goal 3, to advance understanding and innovation in high-performance plasmas….). FIRE as an example of an advanced tokamak at the frontier of fusion science would also contribute to resolving scientific issues with a reduced cost development path and would drive enabling technologies for innovative solutions leading to an improved vision for fusion. A burning plasma acts as the ultimate test of the science basis by **integrating** and testing the understanding several goals simultaneously.

The most relevant Five Year FESAC Objectives for NSO/FIRE are:

3.3.3: BURNING PLASMA: 5-Year Objective: Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators. Progress will be measured by the technical readiness of next step options for a burning plasma physics experiment.

3.4.1 ENABLING PLASMA TECHNOLOGIES 5-Year Objective : Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, flow control, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems. The R&D required for a next step burning plasma experiment will drive progress in enabling plasma technologies.

3.4.2.1 ADVANCED DESIGN: Carryout engineering design work and system optimization studies for next step burning plasma devices: Identify and understand key issues that need to be addressed, resolve technical issues and be ready to move forward with participation in a next step burning plasma experiment. The ARIES work serves as a beacon to guide the general direction for FIRE.

MILESTONES

The milestones for the national NSO/FIRE activities support the overall plan shown in Fig. 1 and are summarized below. The PPPL specific milestones would be derived from these milestones in terms of physics and engineering analysis required.

Baseline Budget Milestones

Update Engineering Report for 2001	Jan 02
Update FIRE documentation for Snowmass	Jun 02
Update Preconceptual design documentation	Sep 02
Develop Prioritized Plan for FIRE in response to Snowmass	Oct 02
FESAC Decision/ITER Final Agreement	Dec 02
Technical Workshop /Review of FIRE Updates	Apr 03
Preconceptual Design Report	Sep 03
Planning for Conceptual Design of FIRE or Alternate Activity	Oct 03
Status Reviews	May 04
Activity Report	Sep 04

Accelerated Plan to meet HR4 (full incremental budget) same through Sep 02

Develop FIRE Mission Need Justification Document	Oct 02
Physics Validation review of FIRE	Nov 02
FESAC-DOE Decision/ITER Final Agreement	< Dec 02
FIRE Preconceptual Design Report	Jan 03
Begin Planning FIRE Conceptual Design Activities	Jan 03
FIRE Mission Validation Independent Project Review (Peer review of Preconceptual Design)	Mar 03
Initiate FIRE Conceptual Design Activities (CD-0)	Apr 03
FIRE Conceptual Design Report to Congress	Jun 04

Milestones and scope will be provided if the decision were made to participate in ITER, after the scope of U.S. participation in ITER is defined.

2104 NEXT STEP OPTIONS 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	1.2	1.3	1.1	1.3	1.8
Engineers	.5	.7	3.1	.7	10.0
Administrators					
Graduate Students					
Technicians		.1		.1	
Clerical			.1		.3
Subcontractors					
TOTAL FTEs	1.7	2.1	4.3	2.1	12.1
OPERATING COSTS $(000):					
PPPL Labor	320.4	379.6	650.2	389.3	1792.5
Subcontract Labor					
Overtime					
Travel	36.9	45.0	50.0	45.0	37.4
Energy					
Stockroom					
Miscellaneous Expenses	.1				
Procurements/ICOs	45.7	39.5	184.0	27.5	649.0
Organizational Burden	28.2	31.8	64.0	32.1	198.8
Other	2.5	8.0		8.0	
General + Administrative	246.5	310.0	551.5	312.1	1521.8
TOTAL OPERATING COSTS	680.3	813.9	1499.7	814.0	4199.5
TOTAL OPERATING OBLIGATIONS	707.3	813.9	1499.7	814.0	4199.5
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	680.3	813.9	1499.7	814.0	4199.5
GRAND TOTAL OBLIGATIONS	707.3	813.9	1499.7	814.0	4199.5

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2003	0	3/01/02

4. WORK PROPOSAL TITLE
ARIES – MFE and IFE

5. BUDGET AND REPORTING CODE
AT6010501 / AT6010502

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER
John A. Schmidt Phone: 609-243-2538 Email: jschmidt@pppl.gov

8. HEADQUARTERS ORGANIZATION:
Office of Science

9. OPERATIONS OFFICE:
Chicago Operations Office

10. CONTRACTOR NAME:
Princeton University
Princeton Plasma Physics Laboratory

11. DOE HQ ORGANIZATION CODE:
SC

12. DOE OPS OFFICE ORGANIZATION CODE:
CH

13. CONTRACTOR CODE:
15

14. WORK PROPOSAL DESCRIPTION:

PPPL will continue to participate in the National ARIES project to develop fusion power plant designs as a major part of an effort to develop a long-term vision for fusion. PPPL will participate in both the physics and the engineering design activities.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

To participate in the ARIES Advanced Reactor Innovation and Evaluation Studies. PPPL's activities in FY 01 and 02 included physics and engineering support for MFE reactor studies. In addition, a modest design integration effort of the final focusing region of a heavy ion fusion reactor concept was initiated. PPPL's efforts in support of ARIES in FY 03 and 04 will focus the MFE work on the start of compact stellarator design optimization studies. Such a study will advance the physics and technology of the compact stellarator concept and addresses concept attractiveness issues that are best addressed in the context of power plant studies. The IFE effort will continue to focus on engineering support of liquid chamber designs.

APPROACH

PPPL has participated in the national ARIES project since FY 1989. We have contributed to the ARIES-I, ARIES-II, PULSAR, ARIES-RS, ARIES-ST, ARIES-AT design and design integration studies for a heavy ion fusion reactor. PPPL is integrated into the ARIES team led by Farrokh Najmabadi who, in turn, reports to the Virtual Laboratory for Technology. The workscope is developed in concert with the ARIES Team and OFES. The precise workscope is defined at the beginning of the year, in response to input from OFES.

TECHNICAL PROGRESS

FY 2001: PPPL began the task of leading the design integration effort for the final focusing region of a heavy ion fusion reactor. The final focusing region consists of the focusing magnets, vacuum transition section, plasma neutralizer, and target chamber interface. A solid model of the developed configuration was developed using "Pro Engineer". The primary MFE task for FY 01 and 02 was the development of new physics modules for the ARIES systems code.

FY 2002: The IFE task for FY 02 was the development of the engineering details of the final focusing components. PPPL is collaborating with other ARIES and IFE members: L. Bromberg of MIT for the magnets; P. Efthimion of PPPL for the neutralizer; C. Jun and H. Qin of PPPL for magnet performance requirements; S. Yu of Berkeley for the target chamber interface; and other ARIES team specialists as necessary.

FUTURE ACCOMPLISHMENTS

FY 2003: The major new task for PPPL's ARIES effort in FY 03 and 04 will be in the area of Compact Stellarator Design Optimization. The initial tasks will be: development of the physics requirements and modules, development of engineering requirements and constraints, exploring attractive coil topologies. The allocation for IFE will be used for follow-up on the engineering activities associated with the final focusing region.

FY-2004: For the Compact Stellarator Studies, the development of physics requirements is an iterative process with the engineering design, particularly for the coil design. Financial constraints will limit the effort in FY 03 to the first steps in the iterative process, which will be completed in FY-04. Work will then begin on the next step – the development of attractive coil topologies. The attractiveness of a power plant design will depend on cost drivers such as overall size, complexity, and maintainability. These factors depend critically on the topology of the coils. Criteria for attractive coils (space for blanket and shield, manufacturability, maintainability) will first be developed. Stellarator designers and ARIES team experts (e.g. in materials, neutronics, costing, plant design, etc.) will collaborate in defining criteria for attractiveness. A range of coil topologies will be explored. Candidate topologies will be parameterized in numerical representations that will then be incorporated in the optimizer and tested.

The funds allocated to IFE will be used for follow-up and close-out of the engineering activities associated with the final focusing region.

MILESTONES

FY-2002:

A final report will be issued in September 2002. This report will document both the MFE and IFE activities. The MFE section will cover the initial physics basis for the stellarator magnet design. The IFE section will cover the updated heavy ion reactor final focusing configuration. There will also be a new release of the ARIES MFE systems code.

FY-2003:

A report will be issued in September 2003, which will document the progress towards establishing the physics requirements for a compact stellarator reference configuration.

FY-2004:

A report will be issued in September 2004, which will document the physics requirements resulting from this effort and describe the results of studies of coil topologies.

2003 ARIES - MFE		03/01/02	
	FY02	FY03 Baseline Incremnt	FY04 Baseline Incremnt
STAFFING(FTEs):			
Physicists	.2		.1
Engineers	.1	.3	.4
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	.3	.3	.5
OPERATING COSTS $(000):			
PPPL Labor	51.3	51.0	79.0
Subcontract Labor			
Overtime			
Travel	10.5	4.8	4.8
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs		.8	.8
Organizational Burden	4.4	5.9	8.2
Other	1.5	1.0	2.0
General + Administrative	40.3	40.5	60.3
TOTAL OPERATING COSTS	108.0	104.0	155.1
TOTAL OPERATING OBLIGATIONS	117.0	104.0	155.1
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	108.0	104.0	155.1
GRAND TOTAL OBLIGATIONS	117.0	104.0	155.1

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2105 ARIES - IFE		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	.1	.1	.1
Engineers	.1	.2	.1
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	.2	.3	.2
OPERATING COSTS $(000):			
PPPL Labor	18.9	51.6	22.8
Subcontract Labor			
Overtime			
Travel	5.0	5.5	6.0
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs			
Organizational Burden	1.8	4.9	2.0
Other	7.0	1.0	1.0
General + Administrative	16.3	40.0	20.2
TOTAL OPERATING COSTS	49.0	103.0	52.0
TOTAL OPERATING OBLIGATIONS	49.0	103.0	52.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	49.0	103.0	52.0
GRAND TOTAL OBLIGATIONS	49.0	103.0	52.0

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2103	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Socio-Economic Energy Studies	AT6010501

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER
John A. Schmidt Phone: 609-243-2538 Email: jschmidt@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The purpose of this activity is to contribute to the national Socio-Economic studies activity, which is organized as part of the Virtual Laboratory for Technology, through general coordination and specific studies. The goal of the national effort in this area is to support the development of a fusion energy vision for the twenty first century.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Approach

In addition to carrying out individual studies we will help coordinate the national Socio-Economic studies activities. Members of the Princeton University Center for Energy and Environmental Studies will be involved in this research. The work on Socio-Economic Studies is coordinated with international efforts through the Annex III workshops managed in the United States by Ron Miller.

Technical Progress

Fusion deployment scenarios have been developed and characterized and this information was used in generating the fusion report for the World Energy Council. A study has been carried out and summarized at the SOFE conference that focuses on how regional characteristics can foster the deployment of fusion power systems. Initial steps have been taken to develop a statistical framework for a power distribution system. The analysis indicates some very interesting, and to some extent counterintuitive, aspects of fusion deployment. A modest study has been carried out to assess fusions' vulnerability to terrorism in light of recent events.

Future Accomplishments

The primary task that will be pursued in FY 03 and expanded in FY 04 will be to assess how the systems nature of power distribution impacts fusion deployment. An initial assessment indicates that fusion can have important advantages relative to most renewable sources. This is particularly true when regional aspects are taken into account. Energy storage will be an important element in future distribution systems if peaking with fossil-fueled gas turbine sources are precluded because of carbon dioxide emissions. Energy storage can be integrated with a fusion power plant at a cost that is below that for most other renewable energy sources.

INCREMENTAL FUNDING
With the funding increment proposed a second avenue of study will be pursued with analysis of fusion R&D investment economics from the point of view of new economic methods that are replacing the Net Present Value and Return on Investment approaches. These new economic approaches give a more realistic and more favorable picture of long term investment in R&D.

Relationship to FESAC Goals

The Socio-Economic Studies support FESAC Goal 4.5.2. Specifically to "help shape the directions of the fusion energy sciences program by examining the technical, safety, and economic potential of specific concepts. The activities carried out in pursuit of this objective provide critical guidance to the activities being pursued for all other Goals."

Relationship to Other Projects

The PPPL activities will continue to be coordinated with the national Socio-Economic Studies activities. A particular focus will be coordinating the development of fusion deployment scenarios with PNNL. ORNL and Wisconsin. These studies are connected with similar studies, which have occurred recently in Europe and Japan, through the Annex III activity coordinated for the U.S. by Ron Miller.

Milestones

- Develop a summary report on design requirements to limit vulnerability to terrorism as it relates to fusion deployment - April 2002
- Issue a report on fusion deployment in the northeastern United States as part of a total energy portfolio. - September 2002
- Issue preliminary report on the systems aspects of fusion deployment – September 2002
- Issue preliminary report on the economics of long term investment in fusion – September 2003- Incremental
- Issue final report on the systems aspects of fusion deployment – March 2004
- Issue final report on the economics of long term investment in fusion – April 2004 - Incremental

2103 SOCIOECONOMIC STUDIE 03/01/02					
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.1	.2	.2	.2	.2
Engineers					
Administrators					
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	.1	.2	.2	.2	.2
OPERATING COSTS $(000):					
PPPL Labor	35.1	39.1	34.4	40.8	33.9
Subcontract Labor					
Overtime					
Travel	5.0	4.5		4.0	
Energy					
Stockroom					
Miscellaneous Expenses					
Procurements/ICOs	20.0	14.7		14.0	.5
Organizational Burden	2.3	2.4	2.4	2.5	2.4
Other	2.5	2.2		1.6	
General + Administrative	31.9	35.9	23.4	36.1	23.3
TOTAL OPERATING COSTS	96.8	98.8	60.2	99.0	60.1
TOTAL OPERATING OBLIGATIONS	83.8	98.8	60.2	99.0	60.1
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	96.8	98.8	60.2	99.0	60.1
GRAND TOTAL OBLIGATIONS	83.8	98.8	60.2	99.0	60.1

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2102	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Advanced Power Extraction (APEX)	AT6010401

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER
Robert Kaita Phone: 609-243-3275 Email: rkaita@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

PPPL will perform the Advanced Power Extraction (APEX) activities in the following three task areas:

1. Exploration of the options and issues for implementing a flowing liquid wall in the National Spherical Torus Experiment (NSTX).
2. Exploration of high-payoff liquid wall concepts.
3. Exploration of moving liquid metals for plasma stabilization.

This work is being conducted under the guidance provided by Professor Mohamed A. Abdou, Fusion Science and Technology, University of California, Los Angeles (UCLA).

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The Advanced Power Extraction (APEX) activities at PPPL support the national APEX effort to identify and explore novel, possibly revolutionary, concepts for Fusion Chamber Technology. They have the potential to substantially improve the performance of near term experiments and the attractiveness of future reactor designs.

APPROACH

The PPPL APEX activity is led by Robert Kaita who reports to Mohamed Abdou, leader of the national APEX program. This effort is divided into several task elements. Dr. Kaita coordinates a multi-disciplinary team of PPPL scientists, including experimentalists, theorists, and engineers in support of the following APEX areas.

Task I: Explore options and issues for implementing a flowing liquid wall in the National Spherical Torus Experiment (NSTX)

Task II. Exploration of High-Payoff Liquid Wall Concepts

Task V. Exploring Moving Liquid Metals for Plasma Stabilization

The theoretical analysis and experimental design activities supported by the PPPL APEX team are focused on the application of liquid lithium surfaces for power extraction and the control of magnetohydrodynamic (MHD) instabilities in the plasma. The liquid lithium surfaces have not only the potential for improved heat extraction but also the possibility to facilitate improved plasma performance.

TECHNICAL ACCOMPLISHMENTS

1) Experimental magnetic field components for high and low beta NSTX plasmas provided to APEX (data required for realistic modeling of liquid metal flows and heat loads on proposed liquid lithium divertor module).

2) Reports describing engineering support of operation and upgrade of UCLA toroidal liquid metal MHD experiment (MTORR).

3) Papers on stabilization of tokamak plasmas by lithium streams and analytical studies of resistive wall modes in presence of liquid walls.

4) Initiation of effort to include flowing liquid metal wall in new interactive equilibrium and stability code (ESC) at PPPL.

5) Use of Tokamak Simulation Code (TSC) to estimate eddy currents and ***jxB*** forces at vacuum vessel wall of spherical torus devices.

6) A project deliverable was a report on progress in the characterization of NSTX and CDX-U plasma operation, the identification of key issues and development of an R&D plan for implementing a liquid wall module in a major magnetic confinement device, and the refinement of concepts for magnetic propulsion and MHD mode stabilization with liquid walls. This work is described in the following papers.

   1. Modeling of Spherical Torus Plasmas for Liquid Lithium Wall Experiments
   R. Kaita, S. Jardin, B. Jones, C. Kessel, R. Majeski, J. Spaleta,
   R. Woolley, L. Zakharov, B. Nelson, and M. Ulrickson
   Proceedings of the 19th IEEE/NPSS Symposium on Fusion Engineering,
   Atlantic City, NJ (January 2002)

   2. Spherical Torus Plasma Interactions with Large-Area Liquid Lithium Surfaces in CDX-U
   R. Kaita, R. Majeski, M. Boaz, P. Efthimion, B. Jones, D. Hoffman, H. Kugel,
   J. Menard, T. Munsat, A. Post-Zwicker, V. Soukhanovskii, J. Spaleta, G. Taylor,
   J. Timberlake, R. Woolley, L. Zakharov, M. Finkenthal, D. Stutman, G. Antar,
   R. Doerner, S. Luckhardt, R. Maingi, M. Maiorano, S. Smith
   Sixth International Symposium on Fusion Nuclear Technology, San Diego, CA (April 2002)
   To be published in Fusion Engineering and Design

<u>FUTURE ACCOMPLISHMENTS</u>

Task I. Explore options and issues for implementing a flowing liquid wall in the National Spherical Torus Experiment (NSTX)

1. Continue providing NSTX plasma equilibrium data for a variety of discharge conditions as required by the Fusion Science and Technology group at UCLA and other members of the APEX effort for their design of liquid walls for NSTX.
   FY03: Input to design of liquid lithium test module that accounts for actual NSTX facility constraints and operating conditions
   FY04: Input to fabrication of liquid lithium test module (if funded) that accounts for actual NSTX facility constraints and operating conditions

2. LM experimental facility set up and initial exploratory experiments with and without magnetic field gradients and applied currents.

FY03 and FY04: Input to experimental planning and engineering support for facility operation and upgrades

3. Identification of key issues and development of an R&D plan for implementing liquid walls in NSTX

FY03: Design of NSTX liquid lithium test module with other Task I participants

FY04: Fabrication of NSTX liquid lithium test module (if funded) with other Task I participants if design is approved

Task II. Exploration of High-Payoff Liquid Wall Concepts

1. Transport and profile effects of low-recycling properties of lithium

FY03 and FY04: Reports on progress to develop a model for a spherical torus plasma in contact with a very low recycling surface, including recommendations for further experimental tests

2. Engineering properties of the liquid lithium itself

FY03 and FY04: Reports on progress in comparing methods of propulsion (e. g., electro-magnetic propulsion vs pumping), including results of tests in dedicated experimental devices

Task V. Exploring Moving Liquid Metals for Plasma Stabilization

1. Stabilizing effects of flowing lithium on MHD modes

FY03 and FY04: Reports (prepared with Task V participants) on progress in evaluating conditions under which flowing lithium will have an effect on the resistive wall mode

RELATIONSHIP TO FESAC GOALS

The APEX studies support FESAC Goals 1.5.1 and 1.5.2 on stability and transport by developing a FW that can favorably impact stability and transport. The studies will support goal 2.5.1 on ongoing ST experiments by developing a plan to implement a liquid metal first wall for NSTX. In addition the APEX studies will directly support first wall goal 4.1.3 by developing innovative first wall concepts.

MILESTONES

Report on progress in the characterization of NSTX and CDX-U plasma operation, the identification of key issues and development of an R&D plan for implementing a liquid wall module in a major magnetic confinement device, and the refinement of concepts for magnetic propulsion and MHD mode stabilization with liquid walls – September 2002

Report on design of liquid lithium test module for a large tokamak facility, support of liquid metal experiments, and predictions for flowing lithium on plasma stability – September 2003.

Report on fabrication of liquid lithium test module for a large tokamak facility, support of liquid metal experiments, and practical issues related to plasma instability control with flowing liquid walls – September 2004.

2102 APEX		03/01/02			
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.5	.3	.1	.3	.1
Engineers	.1	.2		.2	
Administrators					
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	.6	.5	.1	.5	.1
OPERATING COSTS $(000):					
PPPL Labor	80.4	72.4	16.8	73.7	16.1
Subcontract Labor					
Overtime					
Travel	10.0	7.0		6.0	1.2
Energy					
Stockroom					
Miscellaneous Expenses					
Procurements/ICOs	5.0	1.1		1.1	
Organizational Burden	6.2	5.7	1.3	5.5	1.2
Other	10.0				
General + Administrative	59.3	54.8	11.5	54.8	11.7
TOTAL OPERATING COSTS	170.9	141.0	29.6	141.1	30.2
TOTAL OPERATING OBLIGATIONS	151.9	141.0	29.6	141.1	30.2
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	170.9	141.0	29.6	141.1	30.2
GRAND TOTAL OBLIGATIONS	151.9	141.0	29.6	141.1	30.2

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Introduction to PPPL's Collaborative Off-Site Research Programs

Purpose

PPPL's Off-Site Research Program pursues the U.S. fusion program's goals of increasing scientific understanding and developing the knowledge base for attractive fusion concepts though a collaborative program of forefront research on leading facilities worldwide.

PPPL's off-site programs have evolved over recent years, from an initial emphasis on developing programmatic themes, to an intermediate stage of tool-building, to today's stage of full research participation and exploitation of PPPL-supplied tools for targeted research. PPPL's researchers and engineers have grown to play key roles in the off-site programs, and PPPL's control tools and diagnostics are central to pursuing high priority research directions.

PPPL's off-site programs now span a wide range of devices: in tokamaks, from the smaller high-field C-Mod (MIT) to the medium-scale DIII-D (GA) to the larger-scale JET (England) and JT-60U (Japan); in stellarators, from the smaller Wendelstein–AS (Germany) to the largest LHD (Japan).

PPPL's Off-Site Research focuses on key scientific questions:

- How to understand and stabilize macroscopic and energetic particle modes?
- How to understand and control plasma transport at a range of spatial scales?
- How to control plasma profiles (plasma pressure, current density, and transport) by heating and current drive?

All three questions build on and enhance PPPL's core competencies and are synergistic with PPPL's on-site theoretical and experimental programs.

PPPL's Off-Site Research Program focuses primarily on FESAC Goal 3 ("Advance understanding and innovation in high-performance plasmas…"). In addition, the program builds on the synergies available from complementary work on tokamaks and alternate toroidal concepts (stellarators) to contribute to both FESAC Goals 1 ("Advance fundamental understanding of plasma…") and 2 ("Resolve outstanding scientific issues…"). It also

contributes to Goal 4 ("Develop enabling technologies…") via the development of the tools for pursuing the Goal 3 objectives.

Approach

The process for PPPL's off-site research is, first, to work in a top-down fashion from the community's compilation of the highest priority physics issues; second, to identify the leading research opportunities on devices domestic and abroad; and, third, with the teams on the remote devices to identify areas of overlap between their high priority areas and PPPL's competencies and scientific foci. Since there is generally agreement on the primary issues, these two directions are well aligned and the PPPL and remote teams recognize and achieve mutual benefits.

The PPPL Off-Site Program involves research on a wide spectrum of leading facilities:

- DIII-D and Alcator C-Mod (optimization/understanding/innovation at medium-scale)
- JET and JT-60U (extension to larger scale/approach to burning conditions)
- KSTAR (long-pulse/steady-state)
- LHD (long-pulse/steady-state/innovative concepts)

On tokamaks, the research approach focus is on

- advanced control and diagnosis of the profiles of plasma current, plasma pressure and transport, and
- improvement of stability by feedback control of wall modes and of neoclassical tearing modes.

On alternates (stellarators), the research focus is on

- exploration and advancement of promising toroidal magnetic concepts, and
- application of diagnostic and analysis techniques to increase understanding.

There is very significant synergy between the programs due to the topical nature of the work and the focus on key scientific questions. The following table illustrates that synergy.

Scientific Questions (as per the NRC/FUSAC draft report)	**DIII-D Optimiza-tion/ under-standing/ innova-tion at medium-scale**	**C-Mod Optimiza-tion/ under-standing/ innova-tion at medium-scale**	**JET Extension to larger scale/ approach to burn-ing con-ditions**	**JT-60 Extension to larger scale/ approach to burn-ing con-ditions**	**KSTAR Long-pulse/ steady-state**	**LHD Long-pulse/ steady-state/ innova-tive con-cepts**
How to understand and stabilize macroscopic and energetic particle modes?	Feedback stabilizatio n of RWMs and NTMs by magnet-ics and ECH/CD	MSE Profile control by IC and LH heating and current drive	MSE	Energetic Particle Modes from NINB		Magnet-ics diagnos-tics
How to understand plasma transport?	ITBs and QDB (studies + EC localized heating and current drive)	Turbulence imaging + reflecto-meter + MSE + model-benchmark -ing + ITB Studies	Reflecto-metry + Escaping Ion Diag-nostic + MSE	RI-mode model-benchmark -ing	Baseline and Develop-ment Diag-nostics	
How to control plasma profiles (pressure, current density, and transport) by heating and current drive?	EC heating and current drive (launcher)	ICRF: heating and current drive (FWCD, MCCD) LHCD: current drive MSE	MSE		Lower Hybrid Launcher Design concepts	

PPPL attempts to facilitate synergies between its remote research programs both within the Off-Site Research Department and by the activities of PPPL's Science Focus Groups. These entities, which provide a forum for PPPL's researchers in each of the topical areas, actively seek out areas of complementarity among the PPPL remote programs, NSTX, and Theory; the research results

are shared and the Science Focus Groups help the project teams to identify key opportunities and to develop proposals for key experiments. The cross-cutting nature of the Science Focus Groups emphasizes the science and stimulates joint work on tools, such as data analysis codes. It also broadens the perspectives and "reach" of the researchers, permitting them to address issues in a multi-device manner.

Contributions to the FESAC Goals and 5-year Objectives

(Activities that contribute to two FESAC goals are listed, with the primary goal's listing being labeled "[PRIMARY];" the other listing, for a second goal, is labeled "[SECONDARY].")

FESAC Goal	*5 Year Objectives*	*Contributions by PPPL's Off-Site Research Program*
1. Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation	1.1 Turbulence and transport: Advance understanding of turbulent transport to the level where theoretical predictions are viewed as more reliable than empirical scaling in the best understood systems.	• On DIII-D, PPPL, working with GA researchers, will upgrade the Charge Exchange Recombination diagnostic and apply it to studies of momentum transport and flow effects, which are essential for studies of self-induced flows and shearing of turbulent eddies. [PRIMARY] • On DIII-D, PPPL supplies and utilizes flexible EC launchers to investigate control of plasma internal transport barriers. [SECONDARY] • On C-Mod, PPPL measures core fluctuations using (a) a reflectometer in order to determine the effect and changes of core fluctuations on transport and (b) a 2-D edge turbulence-visualization diagnostic. Theoretical models will be benchmarked. [PRIMARY] • On JET, measurements using the joint PPPL/UKAEA Motion Stark Effect diagnostic system, and analysis with transport simulation codes (GS2 and FULL) are used in assessing the micro-stability characteristics of the advanced tokamak plasmas. Experiments using LH will be carried out with the JET team. This work, as well as many other aspects of the JET program will be supported by analysis using the TRANSP code. [SECONDARY] • On JT-60U, modeling of the microstability and the effect of shear on improving the confinement will be significant components of the continuing program. [SECONDARY]
	1.2 Macroscopic	• On DIII-D, tightly-linked theoretical and experimental studies are increasing the

	stability: Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects.	understanding of resistive wall modes, a high-priority program on DIII-D. PPPL is a major partner (with GA and Columbia University) on these studies, which utilize specially-configured internal and external sensor coils and a combination of external and internal active toroidally-distributed coils. [PRIMARY]
	1.3 Wave-particle interactions: Develop predictive capability for plasma heating, flow and current drive, as well as energetic particle driven instabilities, in power-plant relevant regimes.	• On C-Mod, PPPL is utilizing an innovative 4-strap antenna for both heating and current drive studies using fast-wave and mode-conversion current drive. Theoretical modeling of the RF is being conducted. [SECONDARY] • On C-Mod, working with MIT, PPPL will study the control of the spatial distribution of the plasma current density using directed microwave power in the form of lower hybrid waves, and will utilize the resulting profile control to optimize the performance of the tokamak plasma. [SECONDARY] • On JET, a theoretical understanding of the stabilization of sawteeth by fast ions is being developed. [SECONDARY] • Working with the JET team and other US collaborators, understanding of the Alfven eigenmode instabilities and other instabilities driven by fast particle populations is being increased by clarification of the damping mechanisms and benchmarking of the theory. [SECONDARY] • On Japan's JT-60U, PPPL is exploring the physics effects of a significant population of energetic particles on plasma confinement and stability, utilizing the energetic particles produced by the JT-60U negative ion neutral beam. [SECONDARY]
2. Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of	2.3 Determine the performance of a large Stellarator in the areas of confinement, stability, sustainment and divertor physics through	• On Japan's Large Helical Device (LHD), PPPL is participating in research on the world's largest stellarator, diagnosing loss of fast/energetic ions and magnetic fluctuations, and analyzing the plasma equilibrium, macrostability and microstability. [PRIMARY] • On LHD, PPPL is providing support for optimizing the performance of the Negative Ion Neutral Beams. [SECONDARY]

innovative magnetic confinement configurations.	international collaboration.	
	2.4 Resolve key issues for a broad spectrum of configurations at the exploratory level.	• On DIII-D, working with GA and Columbia partners, PPPL is studying the stability effects of a nearby finite-conductivity wall and the related effects on pressure limits, and will explore the physics of feedback stabilization of these resistive wall modes. [SECONDARY]
3. Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.	3.1 Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with efficient divertor operation, pulse lengths >> energy confinement times.	• On DIII-D, working with GA, PPPL is exploring the feasibility of control of the spatial profile of the plasma current density using radio frequency waves at 110 GHz. [PRIMARY] • On DIII-D, PPPL supplies flexible EC launchers to investigate control of plasma internal transport barriers. [PRIMARY] • On C-Mod, PPPL utilizes an innovative 4-strap antenna for both heating and current drive using fast-wave and mode-conversion current drive. [PRIMARY] • On C-Mod, working with MIT, PPPL will supply lower hybrid wave launchers to study the control of the spatial distribution of the plasma current density using directed microwave power, and will utilize the resulting profile control to optimize the performance of the tokamak plasma. [PRIMARY] • On C-Mod, PPPL will continue to attempt to measure the spatial profile of the plasma current density with a Motional Stark Effect diagnostic that measures the direction of the internal magnetic field in the plasma at numerous locations. PPPL has designed, fabricated, installed and is attempting to bring the Motional Stark Effect Diagnostic into operation with the new RFX beam. [PRIMARY] • On JET, measurements using the joint PPPL/UKAEA Motion Stark Effect diagnostic system, and analysis with transport simulation codes (GS2 and FULL) are being used in assessing the stability characteristics of the advanced tokamak plasmas. This work, as well as many other aspects of the JET program will be supported by analysis using the TRANSP code. [PRIMARY]

		• On JT-60U, a program for comparing transport models for improved extrapolation for future tokamaks has been and continues to be extended through modeling a wider range of JT-60U plasmas. Modeling of the microstability and the effect of shear on improving the confinement will be significant components of the continuing program. [PRIMARY] • On JT-60U and off-line at JAERI, PPPL will continue to work with the JT-60U team to optimize the performance of the Negative Ion Neutral Beam system. [PRIMARY] • For KSTAR, PPPL is carrying out design studies, followed by full design of one or two diagnostics, assuming matching funds from KBSI. [PRIMARY]
	3.2 Develop and assess high-beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamak, for pulse lengths >> energy confinement times.	• On DIII-D, working with GA and Columbia partners, PPPL is studying the stability effects of a nearby finite-conductivity wall and the related effects on pressure limits, and is exploring the physics of feedback stabilization of these resistive wall modes. [PRIMARY] • On DIII-D, working with GA, PPPL will participate in the study of the modification and possible stabilization of neoclassical tearing modes with ECH/ECCD. [PRIMARY]
	3.3 Investigate alpha particle and advanced tokamak physics in a low-gain burning plasma experiment, through international collaboration.	• On Europe's JET and Japan's JT-60U, PPPL participates in low-ρ* experiments in the world's two largest tokamaks, assessing the effects of plasma size on the physics behavior of transport barriers and enhanced stability approaches; this permits the US to extend the results obtained on the US' medium-size tokamaks (negative- and weak-shear plasmas, and impurity-enhanced modes, among others) to larger size, to assess reactor-applicability and to facilitate the world program's study of tokamak optimization opportunities and to provide the basis for a decision on a next step large-scale tokamak experiment. [PRIMARY] • On JET, PPPL is exploring the opportunities for US participation in a low-gain deuterium-tritium

		burning plasma experiment. [PRIMARY] • On JET, a theoretical understanding of the stabilization of sawteeth by fast ions is being developed. It is being extended to provide experimental guidance for application of neutral beam and ICRF. [PRIMARY] • Working with the JET team and other US collaborators, understanding of the Alfven eigenmode instabilities and other instabilities driven by fast particle populations is being increased by clarification of the damping mechanisms and benchmarking of the theory. [PRIMARY] • On JET, PPPL participated in a study of the diagnostics required for their future D-T campaign. This will then continue into the design and fabrication of instrumentation for the campaign. An upgrade to the MSE system and a shared activity with JET in advanced reflectometry for fluctuation measurements are well underway. [PRIMARY] • On Japan's JT-60U, PPPL continues to explore the physics effects of a significant population of energetic particles on plasma confinement and stability, utilizing the energetic particles produced by the JT-60U negative ion neutral beam. [PRIMARY]

4. Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.	4.1 Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, flow control, and fueling.	• On JET, PPPL, working with ORNL, is designing, fabricating and testing a prototype ICRF antenna for JET. [PRIMARY] • On JET, technology developed in collaboration with JAERI and applicable to TFTR D&D for the in-situ measurement of tritium and for decontamination of components is being applied. [PRIMARY] • On Japan's JT-60U, PPPL will continue to work with the JT-60U team to optimize the performance of the Negative Ion Neutral Beam system. [SECONDARY] • On LHD, PPPL will continue to provide support for optimizing the performance of the Negative Ion Neutral Beams. [SECONDARY] • For KSTAR, PPPL is participating in the design of a microwave antenna for plasma breakdown studies, subject to receiving matching KBSI funds. [PRIMARY] • For KSTAR, PPPL is carrying out design studies, to be followed by full design of one or two diagnostics, subject to receiving matching KBSI funds. [SECONDARY]

Research Programs on Specific Facilities

The PPPL programs on DIII-D, C-Mod, JET, JT-60U, LHD, and other devices are described in the following detailed Field Work Proposals. In summary, the key areas of research on the individual devices include:

- On DIII-D (~11 FTEs physicists and engineers):
  - stabilization of Resistive Wall Modes by error field reduction and magnetic feedback using PPPL's poloidally and toroidally distributed sensors and the PPPL-supplied power supplies for the DIII-D external and internal coils.
  - located heating and j(r) profile modification by Electron Cyclotron Current Drive (ECCD) using PPPL's recently installed articulated launchers with both poloidal and toroidal motion compatibility, for use in study of stabilization of Neoclassical Tearing Modes by ECCD, and control of internal transport barriers by ECH/ECCD.
- On C-Mod (~7 FTEs physicists and engineers):

- control of j(0) by ICRF/FWCD using PPPL's 4MW 4-strap ICRF antenna,
- control of j(r>0) by MCCD,
- control of j(r>) by LHCD (for which PPPL is supplying the coupler and phase-shifting systems),
- measurement of j(r) using the PPPL-supplied Motional Stark Effect (MSE) system in conjunction with the Diagnostic Neutral Beam supplied by others;
- Te(r,t) heating by ICRF/MC;
- measurements of fluctuations by reflectometry, and
- measurements of edge fluctuations and 2-D imaging of edge turbulence.

- On JET (~5 FTEs physicists and engineers):
  - j(r) via MSE, reflectometer, and
  - alpha diagnostics
  - transport,
  - energetic particle effects,
  - RI-mode,
  - optimized shear, and

- On JT-60U (~1 FTE physicists and engineers):
  - reversed shear,
  - RI-mode,
  - fast-ion effects, and
  - reflectometer

- On other tokamaks (KSTAR and Tore Supra) (~1 FTE physicists and engineers):
  - diagnostic design consultation and operation

- On stellarators (LHD, W-7AS, …) (~1 FTE physicists and engineers):
  - applying PPPL's set of tokamak data analysis tools to the stellarator configuration,
  - acquiring new knowledge to enhance the U.S. program's base, and
  - exploring opportunities for these concepts to evolve into attractive, compact plasma configurations.

Engineering and Operational Support

In addition, PPPL's tokamak collaboration program provides strong engineering and operational support in both physics and engineering areas, particularly in the domestic programs.

On DIII-D, the proposed PPPL collaboration provides:

- tokamak operations support such as chief operating engineer's service and facilitating changes of the machine configuration;
- remotely-steerable actively-cooled electron cyclotron antennas to permit control of the direction of propagation and location of EC deposition; and
- power supplies for the magnetic coils that enable studies of active control of resistive wall modes.

On C-Mod, operations support and upgrades include:

- participation in the design, fabrication, and installation of a 4.6 GHz LHCD system (proposed to span FY2000-03, authorized in February 2000); and
- development and installation of edge plasma diagnostics (edge Thomson scattering and edge fluctuation measurements, and edge turbulence 2-D imaging); and
- upgrade of the microwave reflectometer diagnostic.

On KSTAR, operations support and upgrades include:

- participation in the design and fabrication of a microwave antenna, subject to receiving matching funds from KBSI

OFFSITE RESEARCH SUMMARY 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	21.7	21.3	.1	20.3	.1
Engineers	5.8	4.2	2.1	4.7	1.4
Administrators	.5	.5		.5	
Graduate Students					
Technicians	3.7	2.2	2.0	3.2	2.1
Clerical	.9	.9		.9	
Subcontractors	.4				
TOTAL FTEs	33.0	29.1	4.2	29.6	3.6
OPERATING COSTS $(000):					
PPPL Labor	3787.1	3764.4	85.2	3802.2	74.7
Subcontract Labor	1.3				
Overtime	1.5	1.5		1.5	
Travel	475.8	484.8	13.0	514.8	11.0
Energy					
Stockroom	7.1	6.0	1.0	6.0	1.0
Miscellaneous Expenses	401.3	356.1		356.1	
Procurements/ICOs	358.3	269.1	12.2	286.4	30.0
Organizational Burden	302.1	272.7	8.4	277.2	7.4
Other	5.8	5.9		5.9	
General + Administrative	2694.4	2805.5	72.4	2840.3	70.3
TOTAL OPERATING COSTS	8034.7	7966.0	192.2	8090.4	194.4
TOTAL OPERATING OBLIGATIONS	7566.0	7966.0	192.2	8090.4	194.4
EQUIPMENT COSTS $(000):					
Equipment - Direct	38.0				
Equipment - G+A	9.5				
Fabricated Equipment	2331.9	1755.8	1997.9	1630.8	1899.7
TOTAL EQUIPMENT COSTS	2379.4	1755.8	1997.9	1630.8	1899.7
TOTAL EQUIPMENT OBLIGATIONS	1425.0	1755.8	1997.9	1630.8	1899.7
GRAND TOTAL COSTS	10414.1	9721.8	2190.1	9721.2	2094.1
GRAND TOTAL OBLIGATIONS	8991.0	9721.8	2190.1	9721.2	2094.1

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1050/51/52/53	0	3/1/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Collaboration in the DIII-D Program	AT5010200 AT5502000

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Larry Johnson Phone: 858- 455-4164

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

To perform scientific research on the DIII-D tokamak at General Atomics (La Jolla, California) and to provide engineering support and technical assistance to the DIII-D team. The program calls for PPPL research participation in the DIII-D physics program as well as providing hardware for the auxiliary power and control systems, diagnostic upgrades to enhance the DIII-D research program, engineering support, and operations support.

Areas of particular emphasis include (1) detection and feedback stabilization of resistive walls modes, (2) advanced plasma control using PPPL's steerable launchers of electron cyclotron waves for localized electron heating, current drive, and stabilization of neoclassical tearing modes, and (3) control of the plasma transport profiles by a variety of means.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

PPPL proposes to conduct leading research on the DIII-D national facility in areas that are well aligned with the FESAC Goals and Near-Term Objectives for magnetic fusion energy (MFE), and to provide diagnostic, engineering and operational support to increase the productivity of the DIII-D team. Areas of major research focus include:

- active magnetic feedback control of magnetohydrodynamic (MHD) modes that are destabilized by the vacuum chamber wall resistivity;
- control of the plasma current profile and neoclassical tearing modes by localized application of microwave heating and current drive at the electron cyclotron and ion cyclotron frequencies; and
- control of the profile of plasma transport by a variety of means, including counter-injection of neutral beams, impurity injection, pellet injection, and current profile modification.

PPPL is a major participating institution in the research program of the DIII-D National Fusion Facility at General Atomics (GA). PPPL has responsibility for essential elements of the DIII-D program and makes substantial contributions toward the program mission goal: "To establish the scientific basis for the optimization of the tokamak approach to fusion energy production." These contributions include:

- participation in planning, execution, and analysis of physics experiments on DIII-D;
- theoretical analysis and modeling in support of the DIII-D program;
- applications programming support;
- engineering support for tokamak operations; and
- major equipment upgrades and additions in the areas of diagnostics, radio frequency (RF) heating and current drive, and active feedback stabilization of MHD modes.

APPROACH

The PPPL/DIII-D collaboration is an integral part of the DIII-D National Team and makes substantial contributions in most of the DIII-D research thrusts. In addition, participation in the DIII-D program is a key part of the integrated PPPL research program, focusing on concept innovation and the application of tools to increase understanding of fusion plasmas. The primary focus of the DIII-D program is advanced tokamak (AT) research, which specifically addresses FESAC Goal 3 and also coincides with PPPL's mission for optimizing the toroidal concept. For the next few years, the research program will concentrate on the optimized shear AT scenario and will attack the key problems of AT scenarios:

- current profile control,
- internal transport barrier control,
- neoclassical tearing modes,
- wall stabilization of MHD modes, and
- edge stability and optimization.

PPPL has delivered major components of enabling equipment for this research, including two steerable electron cyclotron launchers (for off-axis current drive and stabilization of neoclassical tearing modes) and diagnostics and power supplies for the feedback stabilization of Resistive

Wall Modes. In FY2002–FY2004, PPPL has responsibility for providing significant additional hardware required for carrying out the DIII-D program plan, most notably a third EC launcher, power supplies for the next generation of resistive wall mode studies, and an upgrade for the Charge Exchange Recombination diagnostic. PPPL personnel work closely with staff from GA and other collaborating institutions to achieve project goals as efficiently as possible. Six PPPL staff members are now located full-time at the GA site. Other staff members spend significant amounts of time on-site at GA but also make extensive use of physics tools and engineering design and shop resources available at PPPL.

TECHNICAL PROGRESS

The PPPL/DIII-D collaboration was extremely productive during 2001. PPPL physicists made substantial contributions to DIII-D results reported in journals and in papers presented at major conferences and also played leading roles in planning, execution, and analysis of experiments. PPPL engineering and technical staff completed important projects needed for the CY2001 and CY2002 experiments and provided valuable support for the 2001 DIII-D major shutdown activities. PPPL also continued to provide needed operations engineering and applications software support.

Stability:

- In collaboration with Columbia University and GA, PPPL continued and extended tests of active feedback stabilization of Resistive Wall Modes. Experiments in FY2001 made use of an extensive set of new sensors designed and installed by PPPL in FY2001 inside the DIII-D vacuum vessel under protective carbon tiles. The new internal sensors can measure both radial and poloidal magnetic field perturbations. With the poloidal field probes, it was possible to sense the plasma response to non-axisymmetric magnetic error fields and to use feedback techniques to actively correct field errors by minimizing the plasma response. This, in turn, allowed angular momentum input from neutral beam heating to sustain toroidal plasma rotation above the critical frequency for stabilization of the resistive wall mode at pressures approaching twice the free-boundary stability limit for more than one second.

- Significant progress was made in adapting the VACUUM code to allow theoretical modeling of active stabilization of Resistive Wall Modes. The modeling shows that a poloidal expansion of the active coil system on the outboard side of the plasma, such as GA plans to implement, will significantly increase RWM control capability and that little more would be gained by a further poloidal expansion of the system to cover the inboard side of the plasma.

- Active stabilization of m/n=3/2 neoclassical tearing modes was achieved under a variety of feedback conditions by using the fully articulated ECH/ECCD launcher, installed by PPPL in FY2000, together with GA launchers of more limited steering capability, to precisely control the beams of up to four 1 MW, 110 GHz gyrotrons. With injection in the co-current direction and within a few cm of the radial location of the magnetic island associated with the mode, the instability was completely stabilized.

RF Heating and Current Drive:

- PPPL reported further progress on development of a theoretical model to account for toroidal rotation in plasmas heated by ICRF alone, as has been observed in Alcator C-Mod.

- PPPL developed, manufactured, and delivered a new, more robust, fully articulated ECH/ECCD launcher for use in the FY2002 experimental campaign. Together with the PPPL launcher installed in FY2000, this will allow precise remote steering of four high power microwave beams.

Diagnostic Development:

- PPPL undertook responsibility for a major upgrade of the Charge Exchange Recombination diagnostic system and began procurement of the associated spectrometers and CCD cameras. Using this upgraded instrument, PPPL researchers will work with GA researchers in studies of the transport of plasma momentum and in the evolution of plasma flows.

FUTURE ACCOMPLISHMENTS

FY2002

PPPL will conduct experiments and perform theoretical modeling and simulation aimed at understanding stabilization of Resistive Wall Modes by toroidal plasma rotation and active magnetic feedback. In FY2002, PPPL will work with partners from Columbia University, General Atomics, and other institutions to investigate the limits of rotational stabilization of Resistive Wall Modes in DIII-D and will attempt to use active magnetic feedback to stabilize RWMs in plasmas with low toroidal rotation frequency, which is particularly important since it is the condition expected in larger-scale tokamak plasmas.

PPPL will participate in an extensive set of experiments using localized electron cyclotron heating and current drive for plasma profile control and neoclassical tearing mode suppression. The two ECH/ECCD launchers already provided by PPPL will support four gyrotrons for pulses of at least 2 sec duration. PPPL will provide a third steerable launcher, identical in design to the one delivered early in FY2002. The three launchers will provide precise, independent microwave beam steering for DIII-D's full complement of six gyrotron sources.

PPPL theorists will apply the upgraded VACUUM code to improved modeling of the effects of DIII-D's conducting wall on MHD mode stability.

PPPL will begin the upgrade of the DIII-D Charge Exchange Recombination diagnostic, aimed at improving its signal-to-noise ratio and temporal resolution.

A PPPL researcher will play a leading role in the preparation and presentation of the ITER design and benefits at the 2002 Snowmass Fusion Summer Study.

FY2003

Experiments in feedback stabilization of Resistive Wall Modes will be directed toward achieving sustained high beta in high-bootstrap-fraction advanced tokamak plasmas. These efforts will be augmented by using high power, localized electron cyclotron heating and current drive to actively stabilize neoclassical tearing modes and to control profiles of current density and transport properties.

GA plans to install a twelve-coil expansion of the DIII-D active coil system for control of Resistive Wall Modes. Unlike the present external six-coil system, the new coils will be situated inside the DIII-D vacuum vessel and arranged in two six-coil toroidal arrays, above and below the midplane. PPPL will procure power supplies for the new coils. Modeling predicts that the addition of twelve active coils will permit stabilization of Resistive Wall Modes at pressures approaching the ideal wall limit.

PPPL will participate in experiments on plasma transport, with particular emphasis on angular momentum transport. To facilitate these studies, PPPL will implement an upgrade of the DIII-D Charge Exchange Recombination diagnostic system.

General Atomics plans to resume operation of their ICRF systems in FY2003. PPPL will work with partners from GA and ORNL to support those plans. In particular, PPPL will provide operations support for the existing 30-60 MHz transmitter.

Experiments on study and active control of MHD instabilities would benefit from better measurement and longitudinal mode identification of non-axisymmetric internal perturbations than is possible with the present DIII-D diagnostic systems. PPPL requests incremental funds to enhance this diagnostic capability by providing a second, toroidally displaced ECE radiometer. The new radiometer, together with the present system, will constitute a Toroidal ECE Radiometer Array. This new diagnostic system would be installed and operated in cooperation with other DIII-D collaborators.

FY2004

Resistive Wall Mode stabilization experiments in FY2004 will focus on controlling the instability in high pressure plasmas, using new active coils (GA) and power supplies (PPPL) provided in FY2003 and control algorithms developed for the expanded coil system in FY2003. The new experiments will test modeling predictions that the expanded coil system should permit stabilization of the Resistive Wall Mode in plasmas with pressure approaching the ideal wall limit.

PPPL will work with partners from General Atomics and other institutions to conduct experiments aimed at assessing the feasibility of using fast steering ECH/ECCD launchers to feedback stabilize Neoclassical Tearing Modes in cases where the radial position of the magnetic island varies during the discharge. PPPL will develop and implement a rapid steering modification for one of the two second-generation ECH/ECCD launchers delivered to GA in FY2001 and FY2002. The modification will allow real-time tracking of the magnetic island

position in plasmas where the pressure varies in time. The goal is to stabilize the mode without changing the plasma position or toroidal magnetic field strength. If incremental funds are available, the second launcher will also be equipped with a fast-steering modification.

PPPL will perform engineering and hardware changes required to convert two existing ICRF transmitters for reliable operation at 115 MHz and at higher power than the present configuration allows. The conversion will include the procurement of one high power transmitter tube. The second transmitter will temporarily make use of a tube on loan from PPPL spares. If incremental funds are available, a second tube and a spare will be procured for DIII-D, and the tube on loan from PPPL will be returned.

MILESTONE SCHEDULE

	BASELINE	ACTUAL
Install in-vessel RWM sensors.	JUN 01	MAR 01
Report on experiments and modeling aimed at active control of MHD instabilities.	SEP 01	JUL 01
Deliver Remotely Steerable ECH/ECCD Launcher #2.	SEP 01	NOV 01
Report on stabilization of Resistive Wall Modes at low toroidal rotation frequency.	SEP 02	
Deliver Remotely Steerable ECH/ECCD Launcher #3.	SEP 02	
Initial assessment of Resistive Wall Mode feedback stabilization with six-pair internal active coil set.	SEP 03	
Report on initial rotation measurements in DIII-D plasmas with upgraded CER system.	SEP 03	
Procure power supplies for Resistive Wall Mode six-pair internal active coil set.	SEP 03	
Intermediate assessment of Resistive Wall Mode stabilization in high pressure plasmas with internal active coil set.	SEP 04	
Initial assessment of Neoclassical Tearing Mode feedback stabilization with a fast steering ECH/ECCD launcher.	SEP 04	
Modify two ICRF transmitters for reliable operation at 115 MHz.	SEP 04	

EXPLANATION OF MILESTONES

- Install in-vessel RWM sensors. (JUN 01 / MAR 01)

  Install and commission magnetic sensors inside the DIII-D vacuum vessel for detection and active feedback control of slowly growing magnetohydrodynamic instabilities known as Resistive Wall Modes.

  Nine diametrically opposed pairs of large-area loops will be installed on the inside wall of the DIII-D vacuum vessel, under protective carbon tiles, for detection of radial components of magnetic flux perturbations arising from Resistive Wall Modes. Two diametrically opposed pairs of magnetic probes will also be installed and used in conjunction with two existing pairs of identical probes for detection of poloidal components of the flux perturbations. Modeling calculations predict that internal sensors will allow feedback stabilization of plasmas with higher pressure than is achievable using external sensors.

- Report on experiments and modeling aimed at active control of MHD instabilities. (SEP 01 / JUL 01)

  Conduct experiments and perform theoretical modeling and simulation aimed at active control of magnetohydrodynamic instabilities that limit the performance of tokamak plasmas.

  On DIII-D, working with partners from Columbia University, General Atomics, and other institutions, PPPL will make use of new hardware and modeling capability to extend ongoing research on active control of performance-limiting magnetohydrodynamic instabilities. Magnetic sensors installed inside the DIII-D vacuum vessel and commissioned in FY01 will be used, in conjunction with existing external sensors, to detect magnetic flux perturbations arising from the slowly growing global kink instabilities known as Resistive Wall Modes. This information will be used to generate commands for applying power to external control coils so as to create magnetic fields to counteract growth of the modes. Neoclassical Tearing Modes will be controlled by applying high power microwave beams in the vicinity of the instabilities.

- Deliver Remotely Steerable ECH/ECCD Launcher #2. (SEP 01 / NOV 01)

  Design, manufacture, assemble, and deliver a remotely steerable microwave beam launcher that supports long pulse operation of two high power gyrotron sources used for electron cyclotron heating and current drive in tokamak plasmas.

  PPPL will develop a steerable launcher for assessing electron cyclotron (EC) heating and current drive for control of the plasma pressure and current profiles and for feedback control of neoclassical tearing modes. The new launcher will have actuation mechanisms sufficiently robust to withstand the large electromagnetic loads expected on the high heat capacity mirrors needed to support 10-s pulses from some of DIII-D's 1 MW, 110 GHz gyrotron microwave sources.

- Report on stabilization of Resistive Wall Modes at low toroidal rotation frequency. (SEP 02)

  PPPL will report on experiments and theoretical modeling and simulation aimed at understanding stabilization of Resistive Wall Modes by toroidal plasma rotation and active magnetic feedback.

  PPPL will work with partners from Columbia University, General Atomics, and other institutions to investigate the limits of rotational stabilization of Resistive Wall Modes in DIII-D and will attempt to use active magnetic feedback to stabilize RWMs in plasmas with low toroidal rotation frequency. The proposed new experiments are aimed at extending and quantifying recent favorable results and are directly in pursuit of FESAC Priorities and Balance Report's Objective 3.2, "Develop and assess high-beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamak, for pulse lengths » energy confinement times."

- Deliver Remotely Steerable ECH/ECCD Launcher #3. (SEP 02)

  PPPL will provide a third remotely steerable microwave beam launcher that supports long pulse operation of two high power gyrotron sources used for electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) in tokamak plasmas.

  PPPL will manufacture, assemble, and deliver a 10-s ECH/ECCD launcher to General Atomics, using the robust design developed for the second launcher delivered to GA in FY2001. The three launchers will provide precise, independent microwave beam steering for DIII-D's full complement of six gyrotron sources and will enable definitive experiments aimed at FESAC Objective 3.1, "Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with efficient divertor operation, pulse lengths » energy confinement times," and FESAC Objective 3.2,"Develop and assess high-beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamak, for pulse lengths » energy confinement times."

- Initial assessment of Resistive Wall Mode feedback stabilization with six-pair internal active coil set. (SEP 03)

  PPPL will work with partners from Columbia University, General Atomics, and other institutions to develop control algorithms and conduct initial experiments aimed at assessing the capability of a poloidally distributed, six-pair extension of the DIII-D active coil set to stabilize Resistive Wall Modes.

  Modeling predicts significant improvements in the capability for feedback stabilization of Resistive Wall Modes if the set of active coils is extended poloidally to include toroidal arrays above and below the existing six-coil midplane set. GA plans to install a twelve-coil expansion of the DIII-D active coil system inside the vacuum vessel. New control

algorithms will be developed to make use of the expanded active coil system, and initial experiments will be performed to evaluate the improved control capability.

- Report on initial rotation measurements in DIII-D plasmas with an upgraded CER system. (SEP 03)

  PPPL will report on work with partners from General Atomics and other institutions to apply the upgraded charge exchange recombination spectroscopy system to studies of the stabilizing effects of rotation in DIII-D plasmas.

  PPPL and GA are upgrading the DIII-D Charge Exchange Recombination spectroscopy system to improve its signal-to-noise ratio and temporal resolution in measurements of plasma rotation and radial electric field. This milestone will report on rotation measurements made with this new system under a variety of conditions in DIII-D plasmas. Plasma rotation has an important stabilizing effect both on large-scale modes (MHD modes) and on fine-scale modes (microturbulence) in tokamak plasma. The proposed experiments are directly in pursuit of FESAC Priorities and Balance Report's Objective 1.1, "Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems," and Objective 1.2, "Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects."

- Procure power supplies for Resistive Wall Mode six-pair internal active coil set. (SEP 03)

  PPPL will provide feedback power supplies required for support of GA-supplied poloidal expansion of active coil system used for feedback stabilization of Resistive Wall Modes in DIII–D.

  GA plans to install a twelve-coil expansion of the DIII-D active coil system for control of Resistive Wall Modes. PPPL has responsibility for procuring power supplies for the new coils. The addition of twelve active coils will enable a nearly definitive determination of the feasibility of feedback stabilization of Resistive Wall Modes.

- Intermediate assessment of Resistive Wall Mode stabilization in high pressure plasmas with internal active coil set. (SEP 04)

  PPPL will report on work with partners from Columbia University, General Atomics, and other institutions to conduct experiments and perform theoretical modeling and simulation aimed at assessing the ultimate capability of a toroidally and poloidally distributed set of active coils to stabilize the Resistive Wall Mode in high pressure plasmas.

  Experiments in FY2004 will make use of new active coils (GA) and power supplies (PPPL) provided in FY2003 and will use control algorithms developed for the expanded coil system in FY2003, The new experiments will test modeling predictions that the expanded coil system should permit stabilization of the Resistive Wall Mode in plasmas with pressure approaching the ideal wall limit.

- Initial assessment of Neoclassical Tearing Mode feedback stabilization with a fast steering ECH/ECCD launcher. (SEP 04)

  PPPL will work with partners from General Atomics and other institutions to conduct experiments aimed at assessing the feasibility of using a fast steering ECH/ECCD launcher to feedback stabilize Neoclassical Tearing Modes in cases where the radial position of the magnetic island varies during the discharge.

  PPPL will develop a rapid steering modification for ECH/ECCD launchers #2 and #3 and implement that modification on launcher #2. The modification will allow real-time tracking of the magnetic island position in plasmas where the pressure varies in time. The goal is to stabilize the mode without changing the plasma position or toroidal magnetic field strength.

- Modify two ICRF transmitters for reliable operation at 115 MHz. (SEP 04)

  PPPL will perform engineering and hardware changes that are required to convert two existing ICRF transmitters for reliable operation at higher frequencies and higher power.

  The converted transmitters will use higher power output tubes. In addition to improving the reliability of the sources, this will increase the power output of each transmitter from 1.5 MW to 2.5 MW at frequencies up to 80 MHz and will provide ~1.7 MW per source at 115 MHz. Initial operation of the upgraded system will make use of one new tube and one on loan from PPPL.

MILESTONE SCHEDULE FOR ADDITIONAL SCOPE IN INCREMENTAL BUDGET

	BASELINE	ACTUAL
Install second ECE radiometer for MHD analysis.	SEP 03	
Procure two high power output tubes for 115 MHz ICRF systems.	SEP 04	
Modify ECH/ECCD launcher #3 for fast steering operation.	SEP 04	

EXPLANATION OF MILESTONES FOR ADDITIONAL SCOPE IN INCREMENTAL BUDGET

- Install second ECE radiometer for MHD analysis. (SEP 03)

  Procure and install a second, toroidally displaced ECE radiometer to increase diagnostic capability for measurement and longitudinal mode identification of non-axisymmetric

magnetohydrodynamic perturbations.

Experiments on study and active control of MHD instabilities would benefit from better measurement and longitudinal mode identification of non-axisymmetric internal perturbations than is possible with the present DIII-D diagnostic systems. PPPL proposes to enhance this diagnostic capability by providing a second, toroidally displaced ECE radiometer which, together with the present system, will constitute a Toroidal ECE Radiometer Array. This new diagnostic system would be installed and operated in cooperation with other DIII-D collaborators.

- Procure two high power output tubes for 115 MHz ICRF systems. (SEP 04)

  PPPL will procure two high power tubes for the ICRF transmitters to be converted for reliable operation at 115 MHz by PPPL under the baseline budget. One tube will replace a tube on loan from PPPL, and the second tube will be a spare for the two transmitters.

- Modify ECH/ECCD launcher #3 for fast steering operation. (SEP 04)

  PPPL will equip ECH/ECCD launcher #3 with a fast-steering modification to allow real-time tracking of the NTM magnetic island position in plasmas where the pressure varies in time. The modification will be identical to that to be developed for launcher #2 under the FY2004 Baseline Budget. The goal is to stabilize the mode without changing the plasma position or toroidal magnetic field strength.

RELATIONSHIP TO OTHER PROJECTS

PPPL will participate in the DIII-D Program as a major collaborator in research and operations. General Atomics is the organization primarily responsible for the operations of DIII-D and the coordination of the research program. The DIII-D team consists of numerous institutions, including national laboratories (PPPL, LLNL, ORNL, SNL), international laboratories, industry collaborators, and universities.

The DIII-D program on feedback stabilization of MHD modes includes especially strong participation by PPPL and Columbia University.

DIII-D SUMMARY 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	6.9	8.0		8.0	
Engineers	3.0	1.9	.2	2.4	.1
Administrators	.2	.2		.2	
Graduate Students					
Technicians	1.9	.4	.2	1.6	.1
Clerical	.4	.4		.4	
Subcontractors	.1				
TOTAL FTEs	12.5	10.9	.4	12.6	.2
OPERATING COSTS $(000):					
PPPL Labor	1389.1	1473.9		1564.5	
Subcontract Labor					
Overtime	.2	.2		.2	
Travel	184.2	209.6		244.6	
Energy					
Stockroom	1.4	1.3		1.3	
Miscellaneous Expenses	306.4	259.3		259.3	
Procurements/ICOs	107.8	109.6		103.4	
Organizational Burden	112.1	108.5		115.8	
Other	2.4	2.4		2.4	
General + Administrative	910.5	1034.0		1104.3	
TOTAL OPERATING COSTS	3014.1	3198.8		3395.8	
TOTAL OPERATING OBLIGATIONS	3276.0	3198.8		3395.8	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	1012.7	817.6	404.0	620.2	431.0
TOTAL EQUIPMENT COSTS	1012.7	817.6	404.0	620.2	431.0
TOTAL EQUIPMENT OBLIGATIONS	520.0	817.6	404.0	620.2	431.0
GRAND TOTAL COSTS	4026.8	4016.4	404.0	4016.0	431.0
GRAND TOTAL OBLIGATIONS	3796.0	4016.4	404.0	4016.0	431.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

DIII-D SCIENCE		03/01/02		
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists	6.7	7.8		7.8
Engineers	1.2	.7	.2	.5
Administrators	.2	.2		.2
Graduate Students				
Technicians	.2	.2	.2	.2
Clerical	.3	.3		.3
Subcontractors				
TOTAL FTEs	8.6	9.2	.4	9.0
OPERATING COSTS $(000):				
PPPL Labor	1148.9	1227.4		1282.9
Subcontract Labor				
Overtime	.1	.1		.1
Travel	163.2	173.6		173.6
Energy				
Stockroom	.2	.1		.1
Miscellaneous Expenses	234.8	182.6		182.6
Procurements/ICOs	71.7	48.1		45.2
Organizational Burden	92.4	85.1		89.0
Other	1.4	1.4		1.4
General + Administrative	746.9	842.6		870.3
TOTAL OPERATING COSTS	2459.6	2561.0		2645.2
TOTAL OPERATING OBLIGATIONS	2009.0	2561.0		2645.2
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment	401.6	817.6	404.0	
TOTAL EQUIPMENT COSTS	401.6	817.6	404.0	
TOTAL EQUIPMENT OBLIGATIONS	380.0	817.6	404.0	
GRAND TOTAL COSTS	2861.2	3378.6	404.0	2645.2
GRAND TOTAL OBLIGATIONS	2389.0	3378.6	404.0	2645.2

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

DIII-D OPERATIONS		03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.2	.2		.2	
Engineers	1.8	1.2		1.9	.1
Administrators					
Graduate Students					
Technicians	1.7	.2		1.4	.1
Clerical	.1	.1		.1	
Subcontractors	.1				
TOTAL FTEs	3.9	1.7		3.6	.2
OPERATING COSTS $(000):					
PPPL Labor	240.2	246.5		281.6	
Subcontract Labor					
Overtime	.1	.1		.1	
Travel	21.0	36.0		71.0	
Energy					
Stockroom	1.2	1.2		1.2	
Miscellaneous Expenses	71.6	76.7		76.7	
Procurements/ICOs	36.1	61.5		58.2	
Organizational Burden	19.7	23.4		26.8	
Other	1.0	1.0		1.0	
General + Administrative	163.6	191.4		234.0	
TOTAL OPERATING COSTS	554.5	637.8		750.6	
TOTAL OPERATING OBLIGATIONS	1267.0	637.8		750.6	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	611.1			620.2	431.0
TOTAL EQUIPMENT COSTS	611.1			620.2	431.0
TOTAL EQUIPMENT OBLIGATIONS	140.0			620.2	431.0
GRAND TOTAL COSTS	1165.6	637.8		1370.8	431.0
GRAND TOTAL OBLIGATIONS	1407.0	637.8		1370.8	431.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1060/61/62	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Collaboration in the Alcator C-Mod Program	AT-50-10-30-0 AT-55-03-00-0

6. WORK PROPOSAL TASK TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
G. Schilling (609-243-3195 PPPL, 617-253-8680 MIT)

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

(1) Perform scientific research as part of the Alcator C-Mod team, addressing key physics issues in toroidal research including control and measurement of the plasma current profile, ICRF heating, lower hybrid current drive, and plasma transport and stability enabled by doubling the auxiliary heating power, and general transport and stability studies including advanced diagnostics of turbulence; and

(2) Provide engineering/technical assistance to the MIT team, especially in the area of RF technology, target at improving system performance and enabling increased run-time.

The program calls for participation in the C-Mod physics research program as well as PPPL providing hardware for heating/current drive systems and diagnostic upgrades to enhance the C-Mod research program.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The purpose of the PPPL C-Mod collaboration is to conduct and enable forefront scientific research on the Alcator C-Mod tokamak and to perform engineering/technical support for the C-Mod team.

Research aims include:

- the experimental study of basic ICRF plasma-wave interaction processes and their comparison with theory in order to gain predictive capability for heating and current drive in reactor-grade experiments;
- creation and understanding of internal transport barriers, off-axis current drive for PEP/ITB mode studies, and low frequency ($\omega<\Omega_{ci}$) current drive for reactor application via ICRF heating and mode conversion current drive;
- core confinement, and H-mode behavior including pedestal characteristics and fluctuations; and
- research on the effectiveness of off-axis current drive via Lower Hybrid current drive and its effect on plasma performance (including design and fabrication of the launcher and participation in the associated research).

Hardware upgrades include both plasma control and diagnostic components:

- ICRF antennas for plasma heating and current drive;
- LHCD launchers and coupling hardware for control of the plasma current profile;
- current profile diagnostics to increase understanding of current drive and plasma behavior (in conjunction with a C-Mod-proposed diagnostic neutral beam);
- edge diagnostics (edge fluctuation measurements at the plasma periphery and 2-D imaging of edge turbulence) to increase understanding of turbulence and transport; and
- core diagnostics (extension of the reflectometer upgrade to allow fluctuation measurements of the plasma core) to increase understanding of the plasma core.

Engineering and technical support for RF power systems include:

- engineering assistance in tuning and maintaining the ICRF transmitters,
- technical assistance in modifying the new 4-strap ICRF antenna following its initial operation in FY2000 and FY2001, and
- engineering participation in the design, fabrication, and installation of the Lower Hybrid current drive system as part of the Lower Hybrid project.

In all these areas PPPL provides assistance in areas where PPPL has competence and capabilities needed by the C-Mod program while enhancing research opportunities for PPPL scientists. PPPL works as a strong team-player.

APPROACH

Members of the PPPL research staff are participating in experiments on C-Mod at MIT. These scientists are supported by core teams at the laboratory for theoretical support, data analysis and modeling and, through the PPPL science focus groups, coordination with other PPPL research endeavors. In addition, PPPL provides a team of engineers and technicians for the design and construction of upgrades.

In the area of plasma heating and current drive in the Ion Cyclotron Range of Frequencies (ICRF) our approach is twofold:

- Increase the understanding of the physics of ICRF heating and current drive at high power.
- Use the increased heating power and current drive capability to expand the C-Mod physics operating regime and enable understanding of a wider range of plasmas, especially relevant to the high-field approach to burning plasmas.

Additional experimental capability has been achieved through the addition of a new 4-strap ICRF antenna, connected to the two 2 MW tunable transmitters delivered by PPPL to C-Mod in 1997. This addition doubled the total ICRF heating source power from 4 MW to 8 MW, as well as providing new frequency capability and an improved directed wave launch for current drive, which was not previously available. The ability to launch directed waves for current drive is a unique contribution to the C-Mod project.

Existing C-Mod ICRF diagnostics will be used to assist in these studies. These include phase contrast imaging to measure density fluctuations, RF probes, microwave reflectometry to measure edge and pedestal density profiles, and passive charge exchange to measure ion distribution functions and H/(H+D) ratios.

The heating and current drive upgrade also allows an extension of the C-Mod operating parameters. Doubling the available auxiliary heating power allows us to:

- heat the core of internal transport barrier confinement modes,
- exceed the H-mode threshold at 5.4 Tesla by a factor of 2 – 3,
- push past the H-mode threshold at 8 Tesla,
- investigate the EDA mode at lower q-values,
- explore high power divertor operation, and
- achieve higher β_N up to 2 at 5.4 Tesla with multiple frequency operation.

Improving the directed wave launch allows us to drive plasma current by FWCD (core) and MCCD (off-axis):

- explore further plasma rotation with directed waves without external momentum input,
- explore flow shear suppression of turbulence through off-axis mode conversion current drive,
- attempt to form an internal transport barrier through flow shear generation,
- develop the capabilities to control the radial electric field through toroidal rotation, and
- extend the pellet enhanced performance mode.

Modification of the current profile, whether by FWCD, MCCD or LHCD, requires a measurement of the resulting current profile for analysis. This will be achieved through the motional Stark effect (MSE) diagnostic. The optical system, electronics, and software have been supplied by PPPL; the diagnostic neutral beam (DNB) generating the signal is supplied by the University of Texas and MIT.

The study of plasma edge physics is being aided through the upgrading of the C-Mod reflectometer for edge density and fluctuation measurements farther up the edge pedestal and the addition of a new fast camera to obtain 2-D imaging of edge turbulence.

A considerable further expansion of the C-Mod operating space into the advanced tokamak regime will be achieved through the addition of lower hybrid current drive (LHCD) off-axis.

This will provide information for the extension of the already successful tokamak concept toward an attractive reactor. This will allow us to:

- achieve quasi-steady state operation at the β limit ($\beta_N \sim 3 - 3.5$),
- increase the β limit due to plasma current profile modification,
- achieve non-inductive current drive with high bootstrap fraction and current profile control,
- heat with 4 – 8 MW of ICRF power, and
- drive current with ~ 3 MW of lower hybrid power with an efficiency of ~ 0.1 (10^{20}A/W/m^2).

The proposed lower hybrid system will be the 4 MW 4.6 GHz system originally used on Alcator C. The project plans to initially install the 2 MW used at PPPL on PBX-M and then the remaining 2 MW now in storage at MIT. PPPL will design and build a suitable waveguide coupler, procure new high power phase shifters/splitters, and assist in performing integrated commissioning and testing of the entire system. MIT will provide a suitable location for the equipment, the high voltage power system and controls, water and energy supply, and the installation labor.

CONTRIBUTIONS TO THE FESAC 5-YEAR GOALS

The table in the Off-Site Research Overview lists the PPPL/C-Mod activities that contribute to the FESAC goals and IPPA 5-year objectives.

TECHNICAL PROGRESS

- Following predictions of the effect of off-axis ICRF heating on plasma toroidal rotation by PPPL theorists, experiments were performed in FY 2000; results did not support the theoretical predictions, but instead led to the discovery of a new internal transport barrier near the resonance location, in addition to the H-mode edge barrier, resulting in highly peaked discharges. Experiments were extended in FY 2001 to include placement of the off-axis ICRF resonance both on the high-field side or the low-field side; both configurations resulted in the formation of the internal barrier. On-axis heating with a second ICRF frequency was also performed, resulting in a central ion temperature increase. This discharge configuration may turn out to be an extremely attractive candidate for the planned Advanced Tokamak investigations.

- Operation and optimization of a 4-strap ICRF antenna to allow a doubling of the ICRF heating power and a directed wave-launch for current drive was begun in December of 1998. Upon startup in the Spring of 1999, repeated ICRF transmitter failures necessitated a major transmitter rebuild. Antenna conditioning started in September 1999, and initial high power operation was performed and assessed by November 1999. Antenna modifications were performed in January 2000, and operation was resumed with the C-Mod startup in April 2000. The initially high levels of antenna arcing and metallic impurity generation were reduced, but the heating efficiency was found to be low when operated with all four current straps excited. Further antenna modifications were performed in July 2000, and the heating efficiency came up to the level of the original C-

Mod antennas. Total ICRF power launched into the plasma from all three antennas came up to 5 MW.

RF-plasma edge interactions as well as arcing in the strip lines feeding the antenna current straps limited reliable operation to about 2.5 MW from the 4-strap antenna, rather than the 4 MW design value, and a third set of modifications was performed in early 2001. A boron nitride insulating septum was placed at the center of the Faraday shields, extended vertically to interrupt the electric fields developed along the magnetic field lines by sheath rectification. The strip lines feeding the current straps were reoriented by 90°, now aligning the RF electric field perpendicular to the magnetic field, rather than the previous parallel alignment. High voltage clearances were also improved in several locations, but one remaining clearance is being improved in early 2002. In FY 2001 the 4-strap antenna reached power levels into the plasma up to 3 MW, with 25 kV RF voltage holdoff.

- Design of an MSE system to be used in conjunction with the University of Texas-supplied DNB was begun in FY1997 and installation of the in-vessel components was performed in December of 1998. External optics and data acquisition hardware were installed throughout 1999, and initial measurements were attempted with the start of operation of the diagnostic neutral beam system being prepared by the team from the University of Texas. Signal levels far below those expected were observed. Inspection of the MSE optical components in early 2001 revealed lens and mirror damage from disruption mechanical shocks, exacerbated by mounts that had loosened. Components were replaced, and mounts were repaired and improved. Further measurements in Summer 2001 again revealed extremely low signal levels. Joint work showed that these low signals result mainly from an abnormally low diagnostic beam full-energy component, although some new optical component damage was seen.

- The initial improvements to the C-Mod reflectometer allowed plasma fluctuations to be detected at the plasma edge. Further upgrades are in progress that will enable the fluctuation measurements to be extended farther up the edge density pedestal. At lower edge densities it may be possible to measure to the internal transport barrier generated by off-axis ICRF heating.

- Initial experiments to attempt 2-D visualization of turbulence in the edge plasma by photographing a small gas puff with a tangentially-viewing fast camera borrowed from LANL were performed in the Summer of 1999. These images were successful, and a dedicated optical system with its own fast camera was installed into C-Mod in July 2000. These fast snapshots of edge light show discrete bright “blobs” of varying size and shape, and their behavior is being studied and correlated with edge probe measurements under different plasma edge conditions. Initial images using a fast exposure (4 μs)/fast repetition rate (250,000 frames per second) camera loaned by Princeton Scientific Instruments have produced the first “movies” of edge turbulence. The measurements are compared to both non-local and edge turbulence models.

- Studies of plasma transport included the comparison of C-Mod discharge characteristics with various transport models. Predictions of the linear ITG/TEM microturbulence were found to be inconsistent with the measured ion temperature gradient scale length of typical H-mode plasmas. This work has been extended to include nonlinear calculations,

which are giving closer agreement with measurements. The gyrokinetic modeling has also been used to study the effect of microinstabilities on transport in the Internal Transport Barrier discharges.

- Basic ICRF modeling has compared the results of the full-wave code TORIC with those obtained from the 1-D integral wave code METS. In a comparison of results in the mode conversion regime, power partitioning between the ion species converges as the poloidal number resolution is increased in TORIC. Good agreement is obtained in the minority ion heating regime. Numerical analysis of the ICRF physics experiments has focused on the coupling of the PPPL TRANSP transport analysis code to the TORIC ICRF module. This enables transport analysis of the Internal Transport Barrier discharge to be carried out.

- The Lower Hybrid project was authorized in February 2000, the launcher design was started, and a successful Conceptual Design Review was held at PPPL in August 2000. PPPL was assigned the task of providing the high-power phase shifters/splitters as well as the launcher. A successful Final Design Review was held in July 2001, and fabrication started in October 2001.

FUTURE ACCOMPLISHMENTS

FY2002

- The 4-strap antenna's remaining voltage (and power) limitation is being addressed by modeling and redesigning the antenna current strap crossover, the site of remaining arcing. The sensitivity and response time of fault protection circuits are also being increased. The antenna's performance at higher power levels and in current drive phasing configuration will be checked out.
- The upgraded ICRF system and improvements in codes will continue to be used for basic ICRF physics investigations, to attempt current profile control, to study transport barriers, and to extend the C-Mod plasma parameter space. Antenna behavior will be explored over the full range of plasma parameters and power and phase levels in order to validate the modifications. The initial physics emphasis will be on high power heating in general, and central heating of the internal transport barrier mode in particular.

- Mounts for the optical components of the MSE diagnostic are being improved to reduce damage from disruption mechanical shocks. C-Mod has obtained the loan of a new diagnostic neutral beam from the RFX experiment at the University of Padua. This beam has lower divergence and a considerably higher full-energy atom component, and is expected to give considerably higher MSE signal levels. Measurements of actual signals will be performed under all possible plasma and beam conditions in order to validate the usefulness of this diagnostic with the new beam.

- The C-Mod reflectometer will be upgraded a second time to provide the capability to measure fluctuations in the plasma core as well as higher up the pedestal at the edge. A design for a multichannel higher frequency upgrade has been prepared, but its implementation will be postponed and the funds dedicated to the preparation of reliable

current profile diagnostics due to the higher priority of the current profile control/measurement program.

- A fast camera with fast framing rate will be installed to allow the edge turbulence imaging diagnostic to capture movies rather than snapshots of the turbulent structures and display their growth and motion. This camera will have the same repetition rate of the Princeton Scientific Instruments camera on loan, but will have a higher total frame capability. A second fast exposure/slow repetition rate camera will be installed to allow sequential "still" images to be captured with short time separation, or simultaneously at two different wavelengths, which would separate the effect of local density fluctuations from local temperature fluctuations.

- Comparison of EDA H-Mode C-Mod discharges with transport models will be extended to include further nonlinear turbulence simulations using the gyrokinetic stability code GS2. The gyrokinetic modeling of the Internal Transport Barrier discharges will be used to compare their behavior with that of other high neutron cases. The analysis will then be extended to reversed shear experiments.

- The ICRF modeling will be extended to include recent improvements in the TORIC code in order to obtain a closer agreement with C-Mod experiments and improve the code's predictive ability. The 1-D integral wave code METS will be parallelized for use on computer clusters. The resulting performance improvement will allow extension of this code to the Lower Hybrid frequency domain and will permit the numerical investigation of Lower Hybrid wave propagation and absorption in C-Mod.

- PPPL will continue to utilize the provided array of plasma control and diagnostic tools to study plasma confinement and stability.

- Launcher fabrication will continue for the Lower Hybrid project.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.

<u>FY2003</u>

Physics studies will continue on C-Mod making maximum use of the upgraded ICRF system and the new or upgraded diagnostics. The possible extension of run time from the present ~8 weeks per year to ~21 weeks will greatly increase the number of experiments that can be carried out but will put increased operational demand on PPPL's team.

- Studies of the Internal Transport Barrier mode will be extended to higher levels of heating power, and its suitability as a target plasma for the Advanced Tokamak LHCD experiments will continue to be investigated.

- Studies of plasma heating in general will be extended to higher power levels and under a greater variety of plasma conditions. The resumption of C-Mod operation at 8 Tesla toroidal field in 2002 will allow additional ICRF heating scenarios to be included in FY2003. These studies will investigate both the basic plasma-wave interactions in an

extended plasma parameter space as well as allowing the study of confined plasma behavior at the extended parameters.

- The physics of mode conversion of a launched fast wave into an ion Bernstein wave and the associated poloidal flow drive will be studied. If sufficient run time becomes available, this might be extended to include an attempt to suppress plasma turbulence through flow shear, or even to attempt to form an internal transport barrier through flow shear.

- The 2-D turbulence imaging diagnostic will be improved by modifying the gas nozzle design to produce a more uniform gas source, resulting in a more uniform illuminating medium for the turbulence images. The number of edge-viewing transient digitizer sightlines will be increased.

- Both transport and ICRF modeling will continue strongly in order to assist a deeper understanding of C-Mod's plasma behavior and the understanding of plasma-wave interactions at extended plasma parameters. The transport modeling will obtain experimental data from the core and edge reflectometer fluctuation measurements, while the 2-dimensional edge turbulence imaging diagnostic will reveal enhanced edge information. The ICRF modeling will receive additional experimental input from the current profile measurements as well as the full set of C-Mod plasma diagnostics.

- The first Lower Hybrid launcher will be delivered to MIT and installed on C-Mod. Hookup and interfacing to the C-Mod-supplied power and control system will be performed. The launcher's coupling efficiency and power handling capability will then be investigated.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs.

<u>FY2004</u>

Continue the basic plasma heating and current drive studies at high ICRF power levels and initial Lower Hybrid power, and start to place greater emphasis on the study of those processes relevant to the generation of Advanced Tokamak discharge scenarios.

- Continue physics studies on C-Mod with the ICRF heating and current drive system, using the full set of C-Mod diagnostics and plasma controls. Investigate the physics of particle-wave interactions and plasma heating processes at high power levels, and investigate the behavior of plasmas subjected to high power heating.

- Continue to extend and improve C-Mod-relevant transport and ICRF modeling capability. Compare the advances in modeling with C-Mod experiments on an ongoing basis.

- Continue to evaluate and optimize the coupling efficiency and power handling capability of the first Lower Hybrid launcher.

- Assess and optimize current drive in the plasma with the first Lower Hybrid launcher.

- Investigate the physics of coupling Lower Hybrid waves to high density plasmas.

- Begin fabrication of second Lower Hybrid launcher in order to reduce power flux inside the waveguide for greater reliability at long pulse lengths and to increase the total LHCD power from 3 MW to 4 MW. Complete fabrication of the second launcher, if funded in FY2003I.

- PPPL RF engineers and technical staff will continue to assist MIT with ICRF transmitter operation, retuning, and repairs. PPPL staff will also assist with the Lower Hybrid launcher operation.

FUTURE ACCOMPLISHMENTS - INCREMENTAL

FY2003I

Incremental funding could be used to pull forward the start of fabrication of a second LHCD launcher, if approved, or to start the fabrication of a second 4-strap ICRF antenna.

- Begin fabrication of second LHCD launcher, if funded.

  Or

- Begin fabrication of second 4-strap ICRF antenna, if funded.

- Retrofit the existing 4-strap ICRF antenna with molybdenum Faraday shields for 5 second pulse length, if funded.

FY2004I

Incremental funding would be used to complete the fabrication of the second 4-strap ICRF antenna, if funded in FY003I. The incremental funding could also be applied to begin fabrication of tunable cavities for the C-Mod ICRF transmitters #1 and #2.

- Complete fabrication of the second 4-strap ICRF antenna, if funded.

  Or

- Begin fabrication of tunable cavities for ICRF transmitters #1 and #2.

PLAIN–ENGLISH RESEARCH ACCOMPLISHMENTS FOR FY2002-2004

Working closely with its collaboration partner MIT, PPPL researchers will utilize an innovative 4-strap antenna for both heating and current drive using fast-wave and mode-conversion current drive. Modeling of both plasma transport processes and the interaction of radiofrequency waves with the plasma will be used to help in understanding the physics involved in these studies.

Working with MIT and the University of Texas, PPPL researchers will attempt to measure the spatial profile of the plasma current density with a Motional Stark Effect (MSE) diagnostic that measures the direction of the internal magnetic field in the plasma at numerous locations, permitting derivation of the plasma current density profile. PPPL has designed, fabricated, and installed the diagnostic. PPPL will perform research using the MSE diagnostic, but the MSE system's performance will be dependent on the performance of the DNB, supplied by MIT and the University of Texas.

PPPL and MIT researchers will measure plasma edge fluctuations using a reflectometer in order to determine the effect and changes of fluctuations on transport. Researchers will capture images of turbulence at the plasma edge, determine the behavior of this turbulence under different plasma conditions, and correlate the effect of edge turbulence with plasma transport.

Working with MIT, PPPL researchers will prepare equipment to study the control of the spatial distribution of the plasma current density using directed microwave power in the form of Lower Hybrid waves, and will utilize the resulting profile control to optimize the performance of the tokamak plasma.

RELATIONSHIP TO OTHER PROJECTS

PPPL participates in the C-Mod program as a major collaborator. The MIT Plasma Science and Fusion Center has primary responsibility for the operation of the Alcator C-Mod facility and the structuring of its research program. The University of Texas has responsibility for operating the diagnostic neutral beam and charge-exchange diagnostics.

EXPLANATION OF MILESTONES

- Extend the study of plasma heating by radio waves to higher power and attempt to drive an electric current in the plasma with radio waves. (JUN 01/AUG 01)

  Total ICRF power launched from all the ICRF antennas into C-Mod plasmas will be extended beyond the present ~5MW level, with the 4-strap antenna power extended beyond 2.5 MW. The new ICRF antenna will also be operated in a current drive phasing mode in an attempt to drive a current either through fast wave or mode conversion current drive.

- Complete design of Lower Hybrid coupler for control of the plasma current profile on C-Mod. (JUN 01/JUL 01)

  The design of the coupler which will be used to launch the lower hybrid wave into the C-Mod plasma will be completed and a successful Final Design Review will be held.

- Extend studies of plasma transport using new diagnostics and transport analysis using nonlinear turbulence simulations. (SEP 01/SEP01)

  The new reflectometer diagnostic upgrade for edge and core turbulence measurements and the new two-dimensional edge turbulence imaging diagnostic will be used to

provide experimental data on the effect of turbulence on transport in C-Mod discharges. The experimental results will be compared to new nonlinear turbulence simulations.

- Assess performance of the 4-strap ICRF antenna and prepare any further needed modification. (OCT 01/OCT 01)

  The performance of the new ICRF antenna following the latest (1-3/2001) modifications will be assessed in terms of higher power operation into a variety of plasmas. This assessment may result in a need for further antenna modifications, and these must be prepared in time for the resumption of C-Mod plasma operation in 2002.

- Complete fabrication of the forward Lower Hybrid system components. (MAY 02)

  Those parts of the Lower Hybrid launcher adjacent to the plasma will be completed. These include the launcher grill and ceramic vacuum windows.

- Assess the performance of the modified 4-strap ICRF antenna at higher power levels with both heating and current drive phasing. (SEP 02)

  The modified 4-strap ICRF antenna will have its power raised to the transmitter output limits, until repeated antenna arcing occurs, or until antenna-plasma interactions limit the power handling capability, all in heating phasing. The antenna behavior will also be tested in current drive phasing.

- Extend and report on the study of plasma heating by radio waves at high power. (SEP 02)

  Study the response of a variety of plasmas to total ICRF heating power above 5 MW. This work would include on-axis heating of Internal Transport Barrier discharges.

- Report on the effects of edge turbulence on plasma transport using the upgraded reflectometer and 2-D turbulent imaging diagnostics. (SEP 02)

  The upgraded reflectometer and 2-D turbulence imaging diagnostics will be used to measure edge turbulence under a variety of plasma conditions. The experimental turbulence levels will be compared with simulations obtained from turbulence-based transport models using experimental C-Mod discharge parameters.

- Assess the performance of MSE with the RFX diagnostic beam. (SEP 02)

  The new diagnostic neutral beam on loan to MIT from the University of Padua's RFX experiment must be returned to them in two years. The adequacy of the beam parameters, beam energy and current will be assessed from the point of providing sufficient signal to the Motional Stark Effect diagnostic to allow magnetic pitch angle measurements to be made with sufficient accuracy for plasma current distributions to be deduced.

- All PPPL-supplied Lower Hybrid hardware delivered to C-Mod ready for installation. (MAR 03)

All hardware fabricated and procured by PPPL for the Lower Hybrid project, including the first launcher and high-power phase shifters/splitters, will be delivered to MIT prior to the planned FY2003 machine opening (4/2003).

- Lower Hybrid launcher system (PPPL supplied) ready for operation. (SEP 03)

  Perform pre-operational testing of the first Lower Hybrid launcher. If successful together with the MIT-supplied power system, begin to launch Lower Hybrid waves into plasma at low power for launcher conditioning and coupling efficiency assessment.

- Continue to extend the study of plasma heating by radio waves at high power. (SEP 03)

  Use the high levels of ICRF power (~6 MW) for plasma heating experiments. Also study the basic wave-particle interactions relevant to ICRF heating, such as mode converted ion Bernstein wave flow drive, and perform a D(H)/D(^{3}He) minority ion heating comparison.

- Extend the study of plasma heating by radio waves for Burning Plasma and Advanced Tokamak studies. (SEP 04)

  Continue to use the high levels of ICRF power for plasma heating experiments in a variety of discharges. The emphasis will now shift over to those experiments aimed toward the Burning Plasma and Advanced Tokamak studies.

- Evaluate performance of the Lower Hybrid launcher in plasma. (SEP 04)

  Operate the first Lower Hybrid launcher in plasma. Start with heating phasing and evaluate coupling efficiency and power handling capability. As power increases, study physics of coupling Lower Hybrid waves at high density.

- Attempt to drive current in plasma with Lower Hybrid launcher. (SEP 04)

  Adjust phasing of launcher to current drive settings. Study wave coupling and optimize in order to drive an electric current in the plasma and report on the results.

<u>EXPLANATION OF MILESTONES – INCREMENTAL</u>

- Begin fabrication of second Lower Hybrid launcher. (OCT 02)

  Complete design of second launcher. Procure and/or fabricate those components deemed to be low-risk.

  Or

- Begin fabrication of second 4-strap ICRF antenna. (OCT 02)

Complete design of second 4-strap ICRF antenna based on operating experience with the modified first 4-strap antenna. Initiate procurement and fabrication of antenna components.

- Fabricate Molybdenum Faraday shields for 4-strap ICRF antenna. (SEP 03)

  Retrofit the existing 4-strap ICRF antenna with molybdenum Faraday shields for 5 second pulse length capability.

- Complete fabrication of second 4-strap ICRF antenna. (SEP 04)

  Complete fabrication of antenna elements. Assemble in clean room for mechanical checkout. Install in C-Mod at next available machine opening.

  Or

- Begin fabrication of tunable cavities for ICRF transmitters #1 and #2. (OCT 03)

  Design tunable cavities based on existing units. Initiate procurement and fabrication of cavity components.

MILESTONE SCHEDULE

	Baseline	Actual
Extend the study of plasma heating by radio waves to higher power and attempt to drive an electric current in the plasma with radio waves (Insufficient run time available for current drive attempt)	JUN 01	AUG 01
Complete design of Lower Hybrid coupler for control of the plasma current profile on C-Mod	JUN 01	JUL 01
Extend studies of plasma transport using new diagnostics and transport analysis using nonlinear turbulence simulations	SEP 01	SEP 01
Continue to provide RF operations support	SEP 01	SEP 01
Assess performance of the 4-strap ICRF antenna and prepare any further needed modification	OCT 01	OCT 01
Complete fabrication of the forward Lower Hybrid system components	MAY 02	
Assess the performance of the modified 4-strap antenna at higher power levels with both heating phasing and current drive phasing	SEP 02	

Extend and report on the study of plasma heating by radio waves at high power	SEP 02
Report on the effect of edge turbulence on plasma transport using the upgraded reflectometer and 2-D turbulence imaging system	SEP 02
Assess performance of MSE with RFX diagnostic beam	SEP 02
All PPPL-supplied Lower Hybrid hardware delivered to C-Mod ready for installation	MAR 03
Lower Hybrid launcher system (PPPL supplied) ready for operation	SEP 03
Continue to extend the study of plasma heating by radio waves at high power	SEP 03
Extend the study of plasma heating by radio waves at high power for Burning Plasma and Advance Tokamak studies	SEP 04
Evaluate performance of the Lower Hybrid launcher in plasma	SEP 04
Attempt to drive current in plasma with Lower Hybrid Launcher	SEP 04

MILESTONE SCHEDULE - INCREMENTAL

Begin fabrication of second Lower Hybrid launcher	OCT 02
Or	
Begin fabrication of second 4-strap ICRF antenna	OCT 02
Fabricate Molybdenum Faraday shields for 4-strap ICRF Antenna	SEP 03
Complete fabrication of second 4-strap ICRF antenna	SEP 04
Or	
Begin fabrication of tunable cavities for ICRF transmitters #1 and #2	OCT 03

IMPACT OF CONGRESSIONAL BUDGET REQUEST

The FWP budget request submitted last year to complete the PPPL portion of the Lower Hybrid launcher project by March 2003 was $600K in FY03. The FY03 Congressional Budget number for PPPL LH C-Mod is only $500K, which is insufficient to complete the project on schedule. Subsequent to receiving the Congressional Budget numbers, discussions were held and agreement was reached that DoE will provide PPPL with the $100K of additional funding in FY03 to maintain the original schedule. This will be accomplished by reprogramming the necessary funds from MIT to PPPL.

ALCATOR C-MOD SUMMARY 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	5.2	5.2		5.2	
Engineers	1.8	1.3	.5	1.4	.5
Administrators	.1	.1		.1	
Graduate Students					
Technicians	1.4	1.3	.8	1.1	1.7
Clerical	.2	.2		.2	
Subcontractors					
TOTAL FTEs	8.7	8.1	1.3	8.0	2.2
OPERATING COSTS $(000):					
PPPL Labor	903.1	944.4		986.9	
Subcontract Labor					
Overtime	1.1	1.1		1.1	
Travel	124.2	137.8		132.8	
Energy					
Stockroom	4.8	3.8		3.8	
Miscellaneous Expenses	47.7	47.6		47.6	
Procurements/ICOs	166.9	79.4		111.6	
Organizational Burden	71.4	67.9		70.9	
Other	1.5	1.5		1.5	
General + Administrative	711.4	760.5		796.0	
TOTAL OPERATING COSTS	2032.1	2044.0		2152.2	
TOTAL OPERATING OBLIGATIONS	1666.0	2044.0		2152.2	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	903.7	708.1	630.6	600.0	552.0
TOTAL EQUIPMENT COSTS	903.7	708.1	630.6	600.0	552.0
TOTAL EQUIPMENT OBLIGATIONS	655.0	708.1	630.6	600.0	552.0
GRAND TOTAL COSTS	2935.8	2752.1	630.6	2752.2	552.0
GRAND TOTAL OBLIGATIONS	2321.0	2752.1	630.6	2752.2	552.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

ALCATOR C-MOD SCIENCE 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	5.1	5.1		5.1	
Engineers	.9	.7		.6	
Administrators	.1	.1		.1	
Graduate Students					
Technicians	.6	.4		.3	
Clerical	.2	.2		.2	
Subcontractors					
TOTAL FTEs	6.9	6.5		6.3	
OPERATING COSTS $(000):					
PPPL Labor	831.7	869.3		908.4	
Subcontract Labor					
Overtime	.1	.1		.1	
Travel	116.4	115.0		115.0	
Energy					
Stockroom	3.0	2.0		2.0	
Miscellaneous Expenses	47.2	47.2		47.2	
Procurements/ICOs	98.9	48.0		78.6	
Organizational Burden	65.4	61.7		64.5	
Other	1.0	1.0		1.0	
General + Administrative	635.7	678.6		714.6	
TOTAL OPERATING COSTS	1799.4	1822.9		1931.4	
TOTAL OPERATING OBLIGATIONS	1517.0	1822.9		1931.4	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	399.6	108.1			
TOTAL EQUIPMENT COSTS	399.6	108.1			
TOTAL EQUIPMENT OBLIGATIONS	160.0	108.1			
GRAND TOTAL COSTS	2199.0	1931.0		1931.4	
GRAND TOTAL OBLIGATIONS	1677.0	1931.0		1931.4	

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

ALCATOR C-MOD OPERATIONS 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.1	.1		.1	
Engineers	.9	.6	.5	.8	.5
Administrators					
Graduate Students					
Technicians	.8	.9	.8	.8	1.7
Clerical					
Subcontractors					
TOTAL FTEs	1.8	1.6	1.3	1.7	2.2
OPERATING COSTS $(000):					
PPPL Labor	71.4	75.1		78.5	
Subcontract Labor					
Overtime	1.0	1.0		1.0	
Travel	7.8	22.8		17.8	
Energy					
Stockroom	1.8	1.8		1.8	
Miscellaneous Expenses	.5	.4		.4	
Procurements/ICOs	68.0	31.4		33.0	
Organizational Burden	6.0	6.2		6.4	
Other	.5	.5		.5	
General + Administrative	75.7	81.9		81.4	
TOTAL OPERATING COSTS	232.7	221.1		220.8	
TOTAL OPERATING OBLIGATIONS	149.0	221.1		220.8	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	504.1	600.0	630.6	600.0	552.0
TOTAL EQUIPMENT COSTS	504.1	600.0	630.6	600.0	552.0
TOTAL EQUIPMENT OBLIGATIONS	495.0	600.0	630.6	600.0	552.0
GRAND TOTAL COSTS	736.8	821.1	630.6	820.8	552.0
GRAND TOTAL OBLIGATIONS	644.0	821.1	630.6	820.8	552.0

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

9455 CMOD LOWER HYBRID 03/01/02					
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists					
Engineers	.7	.3	.5	.5	.5
Administrators					
Graduate Students					
Technicians	.7	.8	.8	.7	1.7
Clerical					
Subcontractors					
TOTAL FTEs	1.4	1.1	1.3	1.2	2.2
COSTS $(000):					
PPPL Labor	153.8	122.4	142.2	138.9	230.1
Subcontract Labor					
Overtime					
Travel	1.0	2.0			5.0
Energy					
Stockroom	1.0	2.0	4.0	2.0	2.0
Miscellaneous Expenses			60.0		
Procurements/ICOs	180.4	272.8	195.0	250.8	92.3
Organizational Burden	18.5	14.0	18.0	17.8	24.1
Other					
General + Administrative	149.4	186.8	211.4	190.5	198.5
TOTAL COSTS	504.1	600.0	630.6	600.0	552.0
TOTAL OBLIGATIONS	495.0	600.0	630.6	600.0	552.0

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1020/21/22	0	3/1/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
International Collaboration	AT5010701

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Raffi Nazikian Phone: 609-243-3504

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

To perform scientific research on International facilities which provide unique opportunities for advancing the US fusion science goals. The program calls for PPPL participation in the largest existing fusion devices in the world (the JET tokamak in Europe and the LHD stellarator in Japan) and other facilities, which allow science to be pursued in regimes inaccessible to the facilities in our domestic program.

Areas of particular emphasis include joint experimental/theoretical studies of: (1) fluctuation studies and transport in advanced confinement regimes on JET, (2) MHD stability and operational limits in advanced confinement regimes on JET (3) energetic particle and alpha particle simulation experiments on JET, and (4) MHD operational limits and confinement in the W7-AS and LHD stellarators.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

PPPL proposes to conduct integrated research on international facilities with research emphases that are well aligned with PPPL's core competencies in theory, modeling and experiment and that are focused towards meeting the FESAC fusion energy science goals. The collaborations in the various focus areas are organized into project teams of experimentalists, theorists and modelers in order to maximize the productivity of the research conducted on off-site facilities. The major areas of research focus are aimed at addressing key fusion energy science goals as outlined by FESAC in the Integrated Physics Planning Activity document:

Areas of major research focus include:

- Fluctuations, ITB formation and thermal energy transport in advanced confinement regimes on JET

[FESAC Goal 1.1 *Turbulence and Transport:* Advance scientific understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems.
FESAC Goal 3.3 *Burning Plasma:* Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators.]

- MHD stability of the current-hole regime in JET and operational limits in advanced confinement regimes with large off-axis current drive.

[FESAC goal 3.1*Profile Control:* Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with efficient divertor operation, pulse lengths much greater than energy confinement times.
FESAC Goal 1.2 *Macroscopic Stability:* Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects.]

- Energetic particle effects on ideal MHD modes, Alfvén frequency modes driven by energetic particles in advanced confinement regimes, and transport of energetic particles on JET,

[FESAC Goal 3.3 *Burning Plasma:* Develop and assess burning plasma scenarios and potential next step burning plasma options utilizing domestic resources and working in concert with international collaborators.
FESAC Goal 1.3 *Wave Particle Interactions:* Develop predictive capability for plasma heating, flow, and current drive, as well as energetic particle driven instabilities, in a variety of magnetic confinement configurations and especially for reactor-relevant regimes.]

- MHD operational limits in current carrying 3-D configurations, including equilibrium island formation and control, and thermal/energetic particle transport in the W7-AS and Large Helical Device (LHD).

[FESAC Goal 2 .3 *Stellarator:* Determine the performance of a large stellarator in the areas of confinement, stability, sustainment and divertor physics through international collaboration.]

These activities are enabled by the provision of diagnostics to perform essential measurements, by off-site personnel to provide operational support enabling joint experimental proposals to be conducted on the international facility, and by modeling support and code maintenance essential for the interpretation of experimental data.

By participation in international facilities, PPPL is also making significant contributions to the research goals of the international fusion energy science programs. PPPL provides approximately 10% of all physics operator support on the JET facility, and is also contributing in the area of

TRANSP code development, code maintenance and TRANSP modeling support of other JET experiments. These activities provide an essential service to the JET team and allow PPPL to maximize its effectiveness as a collaborating institution in order to remain a strong partner on the worlds largest tokamak program.

APPROACH

PPPL's approach to international collaboration is based on teams of researchers spanning experiment, theory and modeling, enabling a focused, integrated effort on key issues contributing to both the US and international program goals. Experimental participation consists of operator support, joint development of experimental proposals, on-site participation in experiments and the development of key diagnostics and their operation on the facility. The modeling effort in support of experiment involves development and maintenance of key codes and their modules such as TRANSP, which has become a very valuable community-wide resource. Theory analysis is usually performed based on the output of interpretive codes such as TRANSP. The application of advanced physics simulation tools such as the M3D code, the FULL linear stability and GTC microturbulence codes involve strong theory participation. The application of these US based codes to experiments on international facilities provides unique opportunities for advancing fundamental theory and predictive simulation capability in the US.

Participation in state-of-the-art measurements on these facilities provides US researchers with a unique opportunity to increase understanding and address measurement challenges in large fusion facilities relevant to burning plasmas. Perhaps the greatest problem for the international collaboration program relative to our domestic collaborations is the inadequacy of resources for developing diagnostic tools, which can further contribute to our science goals and add unique physics capability at our host institutions. This issue is addressed later in the discussion of our request for incremental funding to support enabling technologies and basic science on our international projects.

In the JET collaboration PPPL is actively engaged in the installation of microwave hardware for fluctuation measurements in Optimized Shear plasmas. In parallel, the role of flow shear in ITBs is being analysed using TRANSP and theory-based codes. Improved predictive transport simulation codes are being developed, in part using international collaboration funds, to analyze JET profiles and predict core pressure profiles and ITB-formation-conditions in a burning plasma. For MHD studies, PPPL has installed and operated an MSE diagnostic for q-profile measurements, which has identified the phenomenon of the plasma current-hole. State of the art theory codes such as M3D and PEST3 are being employed to analyze the current-hole phenomenon. Alfvén eigenmodes are a focus of PPPL research on JET and plans are being made for the addition of new diagnostics on JET to advance these studies. Operator support is provided by the long-term presence of a full time researcher. Modeling support is provided by a research staff member working full-time on the collaboration. Other staff members spend significant amounts of time on-site at JET, particularly during the experimental campaigns, and perform much of their analysis at PPPL where they engage other PPPL researchers and analysis tools as the need arises.

In the JT-60U collaboration, PPPL continues its long-standing investigation of energetic particle physics phenomena using the negative ion based neutral beams and the analysis of plasma turbulence using core reflectometry and equilibrium profile analysis. The JT-60U collaboration on energetic particles and transport provides an ideal point of comparison with JET studies. The combined experience on both JET and JT-60U is more effective than the two taken independently. For example, on JET the stability of Alfvén eigenmodes is addressed for deeply trapped RF minority ions, which is complimentary to the study of passing particle driven beam instabilities on JT-60U. The discovery of current holes in both JET and JT-60U confirms the robustness and universality of this plasma regime, indicating that it is not simply a phenomenon specific to particular parameters in a single device. The investigation of the formation of the ITB in reverse magnetic shear discharges on both JET and JT-60U using different heating/fueling methods allows valuable physics insights to be formed from the application of common analysis tools.

The KSTAR collaboration is principally focused on the joint development of the technology required for long pulse operation. In this regard, PPPL is actively engaged in the design of diagnostics and diagnostic access required for a steady state feedback controlled plasma, as well as essential control tools such as an articulated ECH launcher and real time control of lower hybrid phasing.

The stellarator collaboration in the area of energetic particle phenomena is well established on LHD and involves the active participation of experimentalists, installation of PPPL hardware and theoretical studies of Alfvén modes in 3-D configurations. The theoretical study of microturbulence has been established for some time on LHD and new modeling effort is being applied in the area of neoclassical transport. A significant interaction exists in the theory of equilibria with 3-D islands and these efforts will be enhanced with closer experimental work on W7-AS and LHD.

TECHNICAL ACCOMPLISHMENTS

PPPL's international collaborations were highly productive during 2001. PPPL researchers made major contributions to JET and JT-60U results reported in journals and in papers presented at major conferences and also played leading roles in planning, execution, and analysis of JET and JT-60U experiments. PPPL engineering and technical staff undertook important projects needed for the JET-EP program. Valuable physics operator support was provided to JET in 2001. PPPL also continued to provide needed modeling analysis and applications software support, particularly for transport and energetic particle physics studies.

Turbulence and Transport

The design of a new reflectometer system for the analysis of turbulent fluctuations in the internal transport barrier on JET was completed and a contract was signed for its manufacture in FY01. The hardware was delivered to PPPL in 2001 and is currently undergoing tests before installation on JET.

A new full-wave reflectometer simulation code was developed at PPPL for arbitrary 2-D geometry and was applied to correlation data obtained on the JT-60U tokamak. The analysis demonstrated the robustness of refectometry for turbulence measurements in fusion plasmas. These results were presented at the APS-DPP meeting and the code capabilities were reported in papers submitted for publication in 2001. Analysis has also been completed for the turbulence correlation length in the ITB of JT-60U and results are being prepared for publication.

The role of the radial electric field and importance of ExB flow shear in enhanced confinement regimes was investigated on both JET and JT-60U. Analysis of the dependence of the linear growth rate of drift waves with the confinement of the ITB in JT-60U was performed and the results published. The analysis indicates that the region of greatest instability moves radially outward as the ITB strengthens, particularly with the inclusion of ExB shear. The relative role of Shafranov shift and ExB shear on ITB sustainment will be investigated in JET in 2002.

The FULL code was also extended to the LHD and detailed analysis of the role of 3-D shaping on microstability was addressed and published for several LHD configurations. Neoclassical transport analysis was initiated on both LHD and W7-AS in 2001. A key issue to explore in the future is the role of collisional single particle loss in explaining the degradation of performance with plasma major radius observed on the LHD.

Equilibrium and stability

On JET, detailed MSE analysis had begun in FY01, immediately leading to the discovery of the current-hole in lower hybrid current drive experiments. These observations and subsequent analysis led to a Physical Review Letter in which the phenomenon of the current-hole was reported, but with no explanation of the physical mechanism for its existence. The reactor relevance of the current-hole, its sustainment, and formation condition are currently under active investigation.

In stellarators, new magnetic probes using thick film technology were completed and installed on LHD. This novel approach to magnetic measurements in stellarators promises to be very valuable for future efforts at equilibrium reconstruction in 3-D systems. Sixty-four of these coils were installed on LHD and a paper was published in Review of Scientific Instruments in 2001 on the initial results from the detectors for magnetc fluctuation measurements.

Energetic Particle Physics

Application of the non-perturbative HINST code to JT-60U data on Alfvén modes observed in NNBI experiments was reported in the IAEA technical committee meeting on energetic particles in 2001. This work confirms that the low frequency chirping modes observed in these experiments are EPMs. Participation in these experiments led to the observation of strong (~10%) fast ion loss per mode burst in a regime of fast ion beta and alpha Mach number comparable to a reactor. Extrapolation of such results to JET and burning plasma regimes will be performed in 2002.

On JET, a model was developed for the rapid loss of RF tail ions induced by infernal modes in weak shear plasmas. The nonlinear analysis indicates that the complete loss of central alpha particle loss can occur in a burning plasma for sufficiently large mode amplitude in weak

magnetic shear. The work highlights the potential for a burning plasma experiment to address the interaction of alpha particles with ideal unstable modes in AT regimes.

Analysis of sawtooth stability also continued in 2001 and results were reported in the literature. An important issue addressed in these studies is the role of tangentially injected neutral beam ions in JET in the observed enhancement of sawteeth stability even in the absence of stabilizing pressure gradients. The analysis indicates that the trapped particle fraction of the beam ions is sufficient to account for the anomaly, validating the current model of sawtooth stabilization used to extrapolate to reactor parameters.

RF physics, Heating and Current Drive

The development of an ITER-relevant ICRF antenna is an important activity for the JET program. PPPL began a collaboration activity with ORNL and EFDA in 2001 aimed at developing a prototype ICRF antenna for the JET-EP, which is designed to improve coupling of the RF waves into the plasma during ELM activity. The construction of the antenna is expected in 2002. The optimization of lower hybrid coupling efficiency into JET optimized shear plasmas is an important activity for future investigation, as is the optimization of fast wave current drive using existing ICRF antennas.

In 2002 significant progress was made in RF-induced rotation experiments in JET. TRANSP analysis of the expected ICRH-induced rotation was performed and compared to diagnostic measurements of the plasma rotation without neutral beam injection. The results suggest that the expected level of rotation is within the experimental uncertainty of the measurement. Quite surprisingly, the rotation measurements reveal a large degree of edge toroidal rotation quite inconsistent with the location expected from ICRF heating. Further analysis is planned to identify the source of this edge rotation.

Boundary Physics

The role of the divertor to screen out impurities in L-mode plasmas was investigated in JET through dedicated experiments and detailed DIVIMP edge transport modeling. The US led an experimental proposal aimed at measuring impurity transport from methane released through a gas valve near the outer mid-plane of the plasma. The analysis indicates that the divertor is considerably more effective in screening impurities than the L-mode limiter plasma; however, this advantage may be reduced due to higher potential impurity release due to higher power density in the divertor. The work was reported in an EPS paper of 2001.

Technology for KSTAR

In FY01 significant progress was made in the design of the diagnostic cassette on KSTAR and on the development of a concept for lower hybrid wave absorption needed for long pulse operation. In FY 02 the completion of the engineering design of two key diagnostic port cassettes were completed, including the conceptual design of the CRX and MSE diagnostics to go into these ports, with a design review in KBSI in January of 2002. This work is being undertaken with matching funds from KBSI, which will be the model for joint design work in the future.

FUTURE ACCOMPLISHMENTS

PPPL will conduct experiments and perform theoretical modeling and simulations aimed at understanding equilibrium, stability, alpha physics, transport and RF heating/CD in advanced tokamak regimes and stellarator configurations. For advanced tokamak physics PPPL will work closely with JET to resolve critical issues for extrapolation to burning plasma scenarios and steady state reactor regimes. For stellarators, PPPL will work closely with the W7-AS group to assess the stability and equilibrium of current carrying plasmas, and will work closely with LHD to develop a strong program aimed at understanding equilibrium island and transport physics for extrapolation to parameters relevant to a future stellarator burning plasma experiment. Main points for future accomplishments are listed below.

FY2002 BASE

Advanced Tokamak

A. Operate the upgraded MSE diagnostic for time dependent measurements of the evolution of the current-hole in JET. Assess the presence of n=0 instabilities predicted by nonlinear simulation analysis. Analyse the effect of off-axis n=1 modes on the redistribution of core current in JET experiments.

B. Perform pre-conceptual design of fast ion scintillator detectors for JET-EP. Apply NOVA-K, HINST and NOVA-2 analysis to weak shear and reverse shear plasmas on JET and assess regimes most unstable to Alfvén frequency modes. Simulate the conditions needed for multimode resonance overlap in JET by a combination of NOVA-K and ORBIT code analysis, as an input to he design of an experimental proposal.

C. Install the correlation reflectometer for ITB fluctuation analysis on JET. Assess linear stability of ITB plasmas on JET using FULL and GS2 codes and compare the predictions to reflectometer measurements of fluctuations in the ITB.

D. Complete fabrication of the HPP antenna for JET.

E. Participate in LH experiments and assess status of Lower Hybrid phasing on JET.

F. Install new pellet spectrometer on JET to analyze pellet ablation on high and low field side pellet injection.

G. Perform conceptual study of lost alpha detector, including testing of the heat resilience of the scintillator material and the neutron sensitivity of the proposed quartz fiber bundle.

H. Complete analysis and publish results of the reflectometer measurements in the ITB of JT-60U.

I. Perform microstability analysis of ITB plasmas with FULL code and GS2 code aimed at resolving the conditions required for formation and sustainment of ITBs in JT-60U.

J. Analyze NNBI driven instabilities in JT-60Uusing HINST and NOVA-K analysis. Resolve the physics of the fast chirping modes in JT-60U associated with reverse shear operation.

K. Initiate study of edge instabilities and the dependence of growth rate on the proximity of the plasma to the vacuum vessel wall. This analysis is well aligned with PPPL research interests in RWM studies on DIII-D and JET.

Technology

A. Complete the engineering design of diagnostic cassettes Bay J and Bay M on KSTAR, with joint funding from KBSI.

B. Continue analysis of tritiated tiles on JET, and model the distribution and retention of Tritium.

Stellarator

A. Develop joint experiments with the W7-AS team aimed at exploring operational beta limits in current-carrying configurations. Assess the robustness to disruption as a function of external to internal rotational transform. Measure mode activity and identify major characteristics of MHD modes.

B. Explore the technical requirements for integrators on the thick-film Takahashi probes for application to equilibrium reconstruction on LHD.

C. Participate in energetic particle transport studies on LHD using scintillator detectors and Neutral Particle Analyzers designed by PPPL.

D. Calculate linear growth rates using the FULL code and neoclassical transport coefficients for a range of LHD plasmas with different major radii. Assess the relation between these calculations and the performance of these plasmas versus major radius and collisionality.

E. Assess equilibrium island structure at finite beta on W7-AS by participation in joint experiments and application of the PIES code to well documented configurations.

F. Assess the relation between calculated neoclassical transport rates and plasma performance as a function of collisionality and major radius in LHD.

FY2003 BASE

Advanced Tokamak

A. Apply PEST3 analysis to current-hole experiments and identify n=0 and n=1 modes associated with the presence and possible relaxation of the current-hole. Compare to nonlinear simulations using M3D. Apply TSC simulations to assess the formation condition and sustainment of current-holes at reactor-scales. Present results on current-hole experiments at the IAEA in 2002.

B. Complete a conceptual design of fast ion scintillator detectors for installation on JET. Participate in joint experiments on JET to excite multiple high-n modes in weak magnetic shear plasmas. Assess the criterion for resonance overlap and fast ion loss in JET by comparing ORBIT analysis with experimental measurements of magnetic fluctuations and fast ion losses observed on NPA detectors.

C. Simulate turbulence in the ITB using the GTC code and compare to reflectometer measurements. Investigate the behavior of the radial correlation length of turbulence during ITB formation in JET and compare with non-linear simulation.

D. Complete high power test of the JET-EP HPP ICRF antenna.

E. Collaborate with JET to optimize LH coupling and phasing for current drive at high power. Participate in fast wave current drive experiments on JET.

F. Perform microstability analysis of ITB plasmas in JT-60U using the GTC nonlinear simulation code and compare with reflectometer measurements of the correlation length. At this point, the GTC code should have nonadiabatic electrons necessary for the description of turbulence in the ITB.

G. Analyse NNBI driven instabilities in JT-60 using the global non-perturbative NOVA-2 code.

H. Continue investigation of MHD edge instabilities and the dependence of growth rate on the proximity of the plasma to the vacuum vessel wall. This analysis is well aligned with PPPL research interests in RWM studies on DIII-D and JET.

Technology

A. Complete the design of two more diagnostic cassettes with matching funds from KBSI.

B. Initiate design of a microwave antenna for plasma breakdown studies with joint funding from KBSI.

C. Continue analysis of tritiated tiles on JET, and model the distribution and retention of Tritium.

Stellarator

A. Conduct theoretical investigations into the linear MHD stability of modes observed in current carrying W7-AS plasmas. Participate in experiments on LHD using the thick-film Takahashi probes to assess linear stability of high beta LHD plasmas.

B. Assess energetic particle-driven modes in LHD by participation in joint experiments. Measure beam ion loss using scintillator probes and NPAs. Model energetic particle driven modes in LHD using the HINST code upgraded for 3-D geometry.

C. Collaborate in existing fluctuation measurements on LHD by contributing simulation capability for the interpretation of reflectometer measurements in 3-D geometry. Analyze the radial profile of fluctuations against linear stability analysis in LHD.

D. Investigate equilibrium island healing with neoclassical current in LHD through participation in joint experiments and application of the PIES code.

FY2003 INCREMENTAL

Advanced Tokamak

A. Complete design of fast ion scintillator detectors for installation on JET and begin fabrication and procurement of fast ion detector components.

B. Complete new microwave interface design for JET high field experiments expected in the EP program.

Technology

A. Complete conceptual design of a LH coupler KSTAR. The successful design of a lower hybrid system on KSTAR will require effective control of the reflected power. No solution yet exists for a steady state absorber. The proposed work includes development of a steady state absorber aimed at providing a technology solution in time for the engineering design phase of the KSTAR LH system.

Stellarator

A. Complete design and start construction of integrators for Takahashi probes on LHD.

FY2004 BASE

Advanced Tokamak

A. Identify MHD modes associated with the relaxation of the ITB and plasma current (observed with the MSE diagnostic) in high performance plasmas on JET and model

MHD activity using PEST2 and M3D. Identify performance-limiting modes in ITB plasmas and extrapolate to AT regimes in a burning plasma.

B. Complete design of a fast ion scintillator detector on JET for the start of the EP program in FY05.

C. Model fast wave and lower hybrid current drive efficiency in JET with 1-D and 2-D full wave codes and compare with experimental results obtained from MSE. Assess reactor relevance of the two methods for current drive.

D. Present analysis of fast ion loss (NPA detectors) and multi-mode Alfvén wave excitation in the JET tokamak. This work will be initiated in experiments planned in FY03 and the analysis of fast ion and magnetics data will be completed in FY04.

Technology

A. Complete engineering design of two more diagnostic cassettes for KSTAR.

B. Complete design of a microwave antenna for plasma breakdown studies with joint funding from KBSI.

C. Continue analysis of tritiated tiles on JET, and model the distribution and retention of Tritium.

Stellarator

A. Perform nonlinear simulations of plasma instabilities and assess their potential to limit plasma performance in current-carrying plasmas explored on W7-AS. Participate in a theoretical and experimental investigation of MHD limiting mechanisms in LHD.

B. Model beam and RF ion loss in LHD using measured or inferred MHD mode structure and ORBIT code analysis of fast ion interaction with the mode(s) in 3-D geometry.

C. Apply GTC nonlinear gyrokinetic simulations combined with diagnostic simulation codes to LHD plasmas and compare simulated measurements with actual diagnostic measurements. Assess the role of turbulence in confinement degradation on LHD.

FY2004 INCREMENTAL

Advanced Tokamak

A. Complete fabrication of a fast ion scintillator detector on JET and install the detector for the start of the EP program in FY05.

B. Complete fabrication and install a new reflectometer interface for high field studies of the ITB in JET-EP.

Technology

A. Complete the design of a LH coupler KSTAR. The successful design of a lower hybrid system on KSTAR will require effective control of the reflected power. This work will be supported with joint funding from KBSI.

Stellarator

A. Complete construction of integrators for Takahashi probes and install on LHD. Collaborate with ORNL and GA in the equilibrium reconstruction of LHD plasmas using the integrated signal from Takahashi probes and the 3-D version of EFIT currently under development.

MILESTONE SCHEDULE- BASE BUDGETS

	BASELINE	ACTUAL
The use of methane screening experiments on JET to evaluate the performance of the gas box divertor and to infer the level of intrinsic impurities.	JUL 01	JUN 01
Evaluate the effects of the radial electric field on MSE measurements on JET	JUL 01	JUN 01
Report on the current-hole evolution and stability of JET discharges using MSE measurements and nonlinear MHD simulation.	SEP 02	
Install core reflectometer diagnostic for turbulence measurements in JET. Participate in ITB experiments and report on the analysis of JET discharges using GS2 and the FULL code.	SEP 02	
Report on MHD analysis of current carrying configurations on W7-AS.	SEP 03	
Report on reflectometer measurements and modeling of fluctuations in ITB plasmas on JET.	SEP 03	
Report on study of the condition for resonance overlap of Alfvén eigenmodes in JET ICRH experiments in weak and reverse magnetic shear plasmas at high toroidal field.	SEP 04	

MILESTONE SCHEDULE- INCREMENTAL BUDGETS

	BASELINE	ACTUAL
Complete fabrication and installation of new microwave interface on JET, if sufficient incremental funding is provided to support this work.	SEP 04	
Complete fabrication and installation of fast ion detectors on JET, if sufficient incremental funding is provided to support this work.	SEP 04	

EXPLANATION OF MILESTONES- BASE

- The use of methane screening experiments on JET to evaluate the performance of the gas box divertor and to infer the level of intrinsic impurities. (JUL 01 / JUN 01)

Methane gas puffs at the outer midplane of JET discharges were used to infer the impurity screening effect of the divertor relative to limiter L-mode discharges. Results were reported at the EPS meeting in 2001.

- Evaluate the effects of the radial electric field on MSE measurements on JET. (JUL 01 / JUN 01)

Calculations of the effect of the radial electric field on MSE measurements has been performed and shown to be negligible compared to the effect of the magnetic pitch angle. The discovery of current-holes in the core of LHCD plasmas on JET was reported in PRL in 2001.

- Report on the current-hole evolution and stability of JET discharges using MSE measurements and nonlinear MHD simulation. (SEP 02)

Current-hole discharges represent a new state of self organization in fusion plasmas which may have profound implications for plasma start up and non-inductive current evolution in a burning plasma. Dedicated plasma jog experiments are expected in FY02 on JET to resolve the structure of the current hole. Comparison of MSE measurements, MHD activity and 3-D simulation of current-hole dynamics using the M3D code will be reported.

- Participate in ITB experiments on JET using the newly-installed PPPL core reflectometer diagnostic for turbulence measurements on JET. Report on the analysis of JET discharges using GS2 and the FULL code and on the findings relevant to size-scaling of the ITB and related turbulence characteristics. (SEP 02)

Assessing the scale length and fluctuation level at small ρ^* on JET will provide important

informantion on the physics and scaling of transport in ITBs for extrapolation to burning plasma regimes. A 110 GHz correlation reflectometer system is designed and fabricated in the US for installation on JET just prior to the start of the C5 campaign in the spring. The reflectometer will allow for the radial correlation length and fluctuation level of the density in the ITB to be evaluated. In parallel, microstability analysis of ITB plasmas comparing GS2 and FULL codes will be performed. The importance of the ExB shearing rate in the formation and sustainment of the ITB will be reported.

- Report on MHD analysis of current carrying configurations on W7-AS. (SEP 03)

Joint experiments and analysis of the MHD stability of current carrying 3-D configurations begin as interactions with the W7-AS team in FY02. The analysis of experiments using the stellarator optimizer code should be performed as well as the linear low-n stability of these discharges.

- Report on reflectometer measurements of fluctuations in ITB plasmas on JET. (SEP 03)

The core correlation reflectometer will be installed on JET in FY02. By FY03 the analysis of the first data from the system taken in ITB plasmas should be reported and compared with linear stability analysis of the same discharges.

- Report on study of the condition for resonance overlap of Alfvén eigenmodes in JET ICRH experiments in weak and reverse magnetic shear plasmas at high toroidal field. (SEP 04)

The project initiated in experiments planned for FY03 will be completed and the data analysed in FY04 for presentation. These experiments aim to assess the criterion for resonance overlap and avalanche loss of fast ions at small ρ^* for extrapolation to next step burning plasma experiments.

EXPLANATION OF MILESTONES- INCREMENTAL

- Complete fabrication and installation of new microwave interface on JET. (SEP 04)

For the JET-EP, a toroidal field of 4 T and plasma current of 2.5 MA at high triangularity will be achieved. For the reflectometer to continue to measure core fluctuations the frequency range will necessarily need to increase. This calls for a new microwave interface on the machine and, in later years, the addition of extra high frequency microwave channels. Microwave reflectometry is an essential element of the JET collaboration and needs to be supported with additional funds for JET-EP.

- Complete fabrication and installation of fast ion detectors on JET. (SEP 04)

The project initiated in FY03 will be completed and installed on JET for fast ion physics experiments in FY05 upon restart of JET. The measurement of the pitch angle and energy of RF ions in JET will provide essential information on the mechanism for fast ion transport. The engineering design of the detectors needs to be initiated in FY03 to meet the installation deadline during the FY04 opening on JET.

RELATIONSHIP TO OTHER PROJECTS

International collaboration on advanced tokamak physics is integrally tied to the physics program on DIII-D in the area of core transport and to the rf physics program on C-mod in the area of lower hybrid and fast wave current drive. The success of us off-site collaborations depends significantly on the integration of activities relevant to the two major us facilities with the international programs.

INTERNATIONAL COLLAB	03/01/02				
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	9.6	8.1	.1	7.1	.1
Engineers	1.0	1.0	1.4	.9	.8
Administrators	.2	.2		.2	
Graduate Students					
Technicians	.4	.5	1.0	.5	.3
Clerical	.3	.3		.3	
Subcontractors	.3				
TOTAL FTEs	11.8	10.1	2.5	9.0	1.2
OPERATING COSTS $(000):					
PPPL Labor	1494.9	1346.1	85.2	1250.8	74.7
Subcontract Labor	1.3				
Overtime	.2	.2		.2	
Travel	167.4	137.4	13.0	137.4	11.0
Energy					
Stockroom	.9	.9	1.0	.9	1.0
Miscellaneous Expenses	47.2	49.2		49.2	
Procurements/ICOs	83.6	80.1	12.2	71.4	30.0
Organizational Burden	118.6	96.3	8.4	90.5	7.4
Other	1.9	2.0		2.0	
General + Administrative	1072.5	1011.0	72.4	940.0	70.3
TOTAL OPERATING COSTS	2988.5	2723.2	192.2	2542.4	194.4
TOTAL OPERATING OBLIGATIONS	2624.0	2723.2	192.2	2542.4	194.4
EQUIPMENT COSTS $(000):					
Equipment - Direct	38.0				
Equipment - G+A	9.5				
Fabricated Equipment	415.5	230.1	963.3	410.6	916.7
TOTAL EQUIPMENT COSTS	463.0	230.1	963.3	410.6	916.7
TOTAL EQUIPMENT OBLIGATIONS	250.0	230.1	963.3	410.6	916.7
GRAND TOTAL COSTS	3451.5	2953.3	1155.5	2953.0	1111.1
GRAND TOTAL OBLIGATIONS	2874.0	2953.3	1155.5	2953.0	1111.1

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3104 & 3107	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Tokamak and Alternate Theory	AT502010/AT502020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
William M. Tang Phone: 609-243-2612 Email: wtang@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Predicting the properties of an energy-producing fusion plasma is recognized as a formidable scientific challenge which depends on the integration of many complex physics phenomena that cannot be deduced from empirical scaling and extrapolation alone. Increasingly powerful computational resources have stimulated progress, and the PPPL Theory Department continues to be at the forefront in demonstrating how such capabilities advance scientific knowledge and impact innovation and discovery. In doing so, it has continued in its lead role of helping the fusion energy sciences program make progress toward attaining the scientific understanding needed to establish magnetic confinement as an attractive, technically feasible reactor option. This involves innovative development of improved calculation capabilities and the application of state-of-the-art theoretical and computational tools to the interpretation of experimental results. The research areas addressed by this Department impact plasma science issues of importance to the major magnetic confinement experiments and to the design and operation of proposed future devices. A favorable overall assessment of PPPL's Theory Program has been provided by an official OFES review, and the response to the associated PPPL Theory Five-Year Planning Document was positive. Key areas of research include: (1) classical as well as turbulence-driven transport in the presence of sheared magnetic topology and plasma flow; (2) dynamical interplay between small-scale dissipation mechanisms and the evolution of large-scale MHD systems; (3) wave-particle interactions featuring energetic particle dynamics and their influence on alpha-particle physics in present-day experiments and future ignited plasmas; and (4) plasma boundary physics with emphasis on a realistic depiction of the transport of neutrals which is needed to realistically assess the properties of advanced divertor configurations.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The Theory Department at PPPL continues to help provide the scientific foundations for establishing magnetic confinement as an attractive, technically feasible renewable energy source. It does so (1) by generating the physics knowledge required for realistic extrapolation of present experimental results; (2) by suggesting new ideas and approaches to stimulate experimental campaigns leading to improved performance; (3) by developing improved theoretical analysis capabilities and associated computational tools that are fundamentally sound as well as efficient; (4) by contributing to the innovative design of new experimental devices; and (5) by providing a stimulating research environment which enables attracting, training, and assimilating the young talent essential for future progress.

APPROACH

The key contributions from the areas highlighted in the following section are reminders of the lead role theory can play in the fusion program and serve to underscore the fact that many of the advances in the field have resulted from an improved understanding of the basic mechanisms involved in toroidal confinement. The continuing improvements in operating regimes in magnetically-confined plasmas and in diagnostic techniques should enable even more realistic comparisons of experimental results with theoretical models. As more reliable physics-based models emerge, it is expected that the pace of technical advances will be accelerated by more efficient harvesting of key results from experimental facilities and from identification of attractive new approaches and the associated designs for new facilities. The endorsements and requests from the national and international plasma science community for enhanced collaborations in both tokamak and alternate concept research areas have been stimulated not only by the group's record for generating key seminal concepts but also by its development and maintenance of the most comprehensive set of toroidal design and analysis codes. Development and improvement of theoretical and computational methods to advance fundamental understanding and innovation constitute the primary workscope for the contractor numbers 3104 and 3107. The latter (contractor no. 3107) is distinguished by the special relevance of the research results for alternate concept magnetic confinement areas including advanced stellarators and spherical tori.

Work in support of direct applications of theoretical studies to NSTX and to national and international experimental facilities are funded by those specific projects (i.e., the NSTX project and PPPL Off-Site Research). While the development of the theoretical and computational tools for stellarator design and analysis is supported by theory funding (contractor no, 3107), the application of these tools to specific design efforts for the National Compact Stellarator Experiment (NCSX) is funded by that program. In addition, Theory personnel (e.g., W. Tang, S. Jardin, Z. Lin, W. Park, and others), who have provided leadership and key research contributions to the Plasma Science Advanced Computing Institute (PSACI) and to DOE’s Scientific Discovery through Advanced Computing (SciDAC) Program, have and will continue to be supported in part by the Advanced Scientific Computing funding provided under contractor no. 3130.

TECHNICAL PROGRESS

Examples of significant progress in the fusion program enabled by scientific results from the PPPL Theory Department include:

1. MHD STUDIES

(i) The multilevel physics MPP plasma simulation code M3D has been used to study tokamaks and STs. M3D uses unstructured meshes and now has several physics levels, including resistive MHD, two fluids, a hybrid gyrokinetic-particle/fluid model. Early in the year, simulations have been performed of the internal reconnection event (IRE) in NSTX with the measured central q value near unity. However, the experiment often shows a long saturated m=1 phase, which usual MHD simulation cannot reproduce. Later in the year it was demonstrated that strong sheared rotation and by energetic particles may stabilize the mode.

(ii) Recent experiments in JET and JT-60 with a fast current ramp-up and external current drive exhibit a central region with virtually zero current density. Simulation of these current hole discharges indicate that the current clamping is due to sawtooth like crashes, but with n=0, where n is the toroidal mode number, rather than n=1. The crash free energy comes from two sources, (i) the 2D state having no regular equilibrium gives rise to a singular current sheet with finite jump of magnetic field strength (related to the Shafranov shift), and (ii) a free energy analogous to the usual n=1 internal kink.

(iii) The M3D code has been applied to ideal, resistive, two fluid, and hybrid simulations of compact quasi axisymmetric stellarators. For beta values above the ideal MHD threshold, low mode number ballooning-like modes appear. For unphysically large values of the resistivity (low Lundquist number cases), resistive modes with tearing mode scaling can occur well below the ideal limit. As the resistivity is decreased, a transition to resistive ballooning scaling will occur and the mode can be stabilized by the resistive interchange term (Glasser effect in tokamaks). Even if they should persist in some cases, it is expected that they could be suppressed by diamagnetic drift stabilization and neoclassical dynamics in a two fluid model Also, these modes could very well saturate with small magnetic islands. These questions are currently being studied. Hybrid simulations with energetic particles have also shown that global shear Alfven TAE-like modes can be destabilized in some stellarators.

(iv) The VACUUM code, which was initially created to provide the outer boundary conditions and diagnostics to the PEST and NOVA Fourier codes, has been substantially modified to be interfaced to a variety of other stability codes, including DCON, the finite element GATO code, as well as the nonlinear NIMROD and M3D codes. It now also includes the ability to model the feedback stabilization of external MHD modes in toakamaks so that the effects of a thin resistive shell and the feedback circuitry together with the associated sensor loops and feedback coils are incorporated.

2. TURBULENT TRANSPORT SIMULATIONS & ANALYSIS

(i) Gyrokinetic Particle-In-Cell Simulations: Massively parallelized large scale full torus gyrokinetic particle simulations show that transport scaling changes from Bohm to gyroBohm gradually as minor radius exceeds around 400 ρ_i. GyroBohm-like transport persists for minor radius up to 1000 ρ_i [Z. Lin et al., to be submitted to Phys. Rev. Lett, 2002; T.S. Hahm, invited talk, APS-DPP, 2001]. Progress towards gyrokinetic particle simulations with more accurate kinetic electron dynamics in finite-\beta plasmas has been made via the split-weight scheme [W. Lee et al., Phys. Plasmas 8, 4435 (October 2001)] and the fluid-kinetic hybrid scheme [Z. Lin et al., Phys. Plasmas 8, 1447 (May 2001)].

(ii) Continuum Gyrokinetic/Gyrofluid Simulations: Detailed comparisons between nonlinear gyrofluid simulations and the fluctuation characteristics measured by Beam Emission Spectroscopy on DIII-D have been made in collaboration with Institute for Fusion Studies [D. Ross et al., Phys Plasmas 9, 177 (January 2002)]. An algebraic formula for the threshold of the electron temperature gradient instability has been derived from the numerical solutions of the linear gyrokinetic equations in collaboration with IPP Garching Germany [F. Jenko et al., Phys. Plasmas 8, 4096 (September 2001)].

3. KINETIC MICROSTABILITY ANALYSIS:

Linear stability calculation based on the extended version of the FULL code with an ExB rotation model confirms the role of ExB shear in reducing the radial extent of linearly unstable zone in box-type internal transport barrier in JT-60U [G. Rewoldt et al., to appear in Nuclear Fusion (2002)].

4. BASIC TURBULENCE:

(i) A review paper covering the conceptual foundations of turbulence theory has been accepted for publication [J.A. Krommes, Review Paper: Phys. Report in press (2002)].

(ii) An imperfect cancellation between the Reynolds' stress and Maxwell's stress in 3D reduced MHD due to seed zonal flows and dissipation has been analytically demonstrated in collaboration with University of California at San Diego [Eun-jin Kim et al., Phys. Plasmas 8, 3576 (September 2001)].

5. STELLARATOR PHYSICS

(i) PPPL theory efforts have made important progress in fundamental theoretical issues related to the analysis of profiles in stellarator experiments and to global optimization of stellarator designs. The associated applications in the NCSX workscope have played a major role in the successful NCSX Physics Validation Review (PVR).

(ii) New methods have been developed, using the PIES code, to modify coil designs to produce good flux surfaces. A series of PIES calculations verified that the flux surfaces were robustly preserved for a range of equilibria. Theoretical flexibility studies for the

PVR demonstrated a previously unanticipated level of flexibility of proposed coil sets to produce a range of configurations with good stability and transport properties.

(iii) An improved "dynamical healing" code for modifying coil designs has been built around the PIES code. The new code is capable of preserving the flux surfaces for the more challenging coil designs that have now emerged. Flexibility studies since the PVR have demonstrated that coil sets with fewer modular coils can access the same corners of flexibility space delineated in the PVR studies.

(iv) A differential evolution algorithm has been implemented for global optimization studies, and initial studies with this tool are promising. In tandem with this work, studies of the topography of stellarator design space are being pursued. Initial work shows that contour plots of the target function on hyperplanes in the design space have a complicated structure, with attractive configurations lying in basins separated by ridges of instability.

6. SPHERICAL TORUS PHYSICS

PPPL theory efforts have assisted the NSTX experimental team in both theory and modeling.

(i) In the area of MHD, beta limits have been identified with pressure-driven dominantly internal modes. Profile modification, mainly broadening of the pressure profile, has been identified as a means of improving performance. The resistive code, PEST-III, has been used to evaluate Δ', a key parameter in the modified Rutherford equation which describes the evolution of island driven by neo-classical tearing modes. Co-axial helicity injection has been modeled successfully with the TSC code. All but one magnetic sensor in this simulation are in agreement with experimental measurements up to plasma currents reaching 250kA. External kink instabilities driven by current pedestals near the plasma edge have been successfully modeled with the PEST code.

(ii) In the area of turbulence and transport modeling, there have been extensive parametric studies with GS2 in the linear regime to determine the role of different plasma parameters on micro-instabilities. These results have suggested that unstable ETG modes might account for the dominant electron transport observed. Several experiments to test the parametric dependence have accordingly been suggested.

(iii) In the energetic particle physics area, Compressional Alfven Eigenmodes, CAEs, have been successfully identified in the experiment and detailed modeling is underway. The possibility of CAE's contributing to stochastic ion heating has been shown to have relevance to the experiment. Stochastic diffusion is studied to address (a) Goldston-White-Boozer diffusion in a rippled field; (b) cyclotron-resonance-induced diffusion caused by the ripple; (c) effects of non-conservation of the magnetic moment in an axisymmetric field. It is found that the stochastic diffusion in spherical tori with a weak magnetic field has a number of peculiarities in comparison with conventional tokamaks; in particular, it is characterized by an increased role of mechanisms associated with non-conservation of the particle magnetic moment. It is concluded that in current experiments on NSTX the stochastic diffusion does not have a considerable influence on the

confinement of energetic ions. It is shown that the confinement of trapped energetic ions in spherical tokamaks during MHD events, such as sawtooth oscillations and internal reconnection events (IRE), essentially depends on beta. Namely, when beta is high, the energetic ions are expelled from the plasma core, whereas they are only weakly influenced by the MHD activity at relatively low beta. These differences are associated with the different character of the particle precessional motion in low- and high-beta plasmas.

(iv) Development of the HYM Code for NSTX Geometry -- A new nonlinear 3D hybrid-MHD simulation code, HYM, has been modified for ST geometry from the FRC hybrid code. The benchmark with the M3D code on nonlinear MHD simulations of sawtooth oscillations in NSTX has been performed. The analytic form of the anisotropic fast ion distribution function has been used in delta-f simulations and a Grad-Shafranov solver has been modified for the general case of the two component plasmas, MHD background plasma and energetic ions with large Larmor radius and anisotropic pressure. Self-consistent NSTX equilibria including the fast ion current have been obtained. It is shown that contribution of beam ions with E=80keV, and density of ~3% is comparable to that of background plasma, and equilibrium profiles are significantly modified on the low-field side. The effects of fast ion finite Larmor radius effects on fast ion profiles are investigated.

7. ENERGETIC PARTICLE PHYSICS

(i) NNBI Energetic Particle Driven TAEs in JT-60U -- the excitation of Alfvén modes in NNBI experiments in JT-60U have provided a new regime for studying the behavior of energetic particle driven modes in reactor relevant regimes. Experiments have been performed in regimes relevant to ITER in terms of V_{beam}/V_A and volume averaged fast ion pressure. Strongly chirped modes, called Fast Frequency Sweeping (FS) modes and Abrupt Large-Amplitude Events (ALEs) were observed. Stability of the RTAEs has been studied by using the high-n kinetic, non-perturbative code, HINST. Based on these theoretical studies of the excitation of TAE type modes, three physical mechanisms were identified: First is the slowly evolving q profile, which leads to the radial shift of the mode location and its subsequent change in the frequency. The second one is the change in the fast particle pressure profile as a result of increased plasma density and broadening of the beam deposition profile. The position of the strongest fast particle pressure gradient is shifted radially and, thus, it leads to the slow movement of resonant TAE modes (RTAEs) in radial direction and slow frequency chirping within 100-200 msec. The third mechanism is due to the change of fast particle distribution function in phase space during a very short time of 3 - 5 msec.

(ii) Energetic Particle Effects on Alfvén Modes in DIII-D -- During neutral beam injection in DIII-D experiments, in addition to TAEs with frequencies of about 0.8 of theoretically computed TAE frequency, modes with frequencies about 0.2 – 0.4 of TAE frequencies are often observed and are called BAEs. The analysis of an unstable DIII-D discharge with a high-n stability code HINST shows that the experimentally observed "TAE" and "BAE" modes can be explained as the resonant branches of the TAE and kinetic ballooning mode (KBM), respectively.

(iii) Neutral Beam Stabilization of Sawtooth Oscillations in JET -- Recent experiments in JET have provided evidence of sawtooth stabilization by fast ions arising from deuterium NBI. A theoretical model for the interpretation of the observed sawtooth period behavior is investigated and predictions are compared with experimental results, using a sawtooth period model developed to predict the sawtooth period in ITER. The beam ion contribution to the internal kink potential energy valid in the limit of isotropic fast particles has been studied and the results compare well with detailed calculations performed with a hybrid kinetic/MHD code, NOVA-K, using fast particle distribution functions computed from the TRANSP code. The beam ion term is found to be sufficiently stabilizing to produce sawtooth periods in agreement with the experimental results. Sawtooth periods computed without taking this contribution are much shorter than the measured periods. The model indicates that sawteeth are triggered in these JET discharges by the excitation of the internal kink in the semi-collisional ion kinetic regime.

8. BOUNDARY PHYSICS

The DEGAS 2 Monte Carlo neutral code was used to generate radial emission profiles of the D_α line for a series of experiments using visible imaging of gas puffs to characterize edge plasma turbulence in NSTX and ALCATOR C-Mod. This simulation data was essential in the comparison of the experimental data with that from edge plasma turbulence codes.

FUTURE ACCOMPLISHMENTS - FY2003/04

The preceding section has provided examples of how the PPPL Theory Department has continued not only to carry out the essential longer-range research providing the basic understanding to develop new analysis techniques and tools but also to apply state-of-the-art theoretical codes to the interpretation and design of key experiments. Theory support for the alternate confinement workscope (contractor no. 3107) has been highly productive and well appreciated by projects such as NCSX. Together with active demands for enhanced national and international collaborations, this area provides attractive opportunities for greater investments in PPPL theoretical resources. In addition to individual initiatives, collaborative work is strongly encouraged and effectively conducted through internal theory working groups as well as via the Science Focus Groups composed of staff members from both the Theory and Experimental Departments at PPPL. The main topical areas include: MHD, Transport, Energetic-Particle Physics, Waves and Auxiliary Heating, and Plasma Boundary Physics. Expected future accomplishments include:

1. MHD WORKSCOPE

FY 2003:

(i) Interpretation and Explanation of Current Hole Experiments -- Recently there has developed considerable interest in tokamak discharges with zero or near-zero current density in the center. Discharges of this type have been observed in JET and in JT-60,

and are also thought to have occurred in earlier experiments in DIII-D and possibly in TFTR. Some of the theoretical and practical questions are: (1) Why does the current approach zero, but not go negative in these experiments? (2) Over what regime are these profiles stable to ideal MHD, resistive MHD, and extended-MHD models? (3) Are there reactor implications for this class of discharges. To address these questions, theoretical studies will target the physics of axisymmetric reconnection events, other MHD stability issues, and double tearing modes in annular current discharges.

(ii) MHD Studies with Shear Rotation -- NSTX and several other experiments can have large plasma rotations that can have a substantial effect on both the equilibrium and stability properties of the plasma. The nonlinear 3D MHD code, M3D, is being used to compute the effects of the toroidal and poloidal rotation on the equilibrium density and pressure profiles, and on plasma stability. A comprehensive study would include a comparison of the equilibrium effects of rotation with experiment, and a systematic study of the effects of sheared rotation on plasma stability.

(iii) Initial Value Computations of Three-Dimensional Configurations -- Most of the initial-value MHD simulations performed to date have been of axisymmetric configurations such as tokamaks, spherical tokamaks, and reversed field pinches. These codes will be used to examine fully three-dimensional configurations such as current-carrying stellarators. These will allow us to address ideal and resistive MHD stability, both linear and nonlinear, and also to begin understanding the theoretical implication of the resistive interchange criteria D_R being unstable, as it is in many contemporary stellarator designs. The comparison of the results of this code with those of the 3D equilibrium code PIES should help greatly in the interpretation of the results of these two major codes. Also, since the initial value code M3D has an option to include kinetic particles, the application of this code to stellarators will enable an initial study of energetic particle modes in stellarators.

(iv) Nonlinear behavior of Energetic Particle Modes -- Completion of the project to incorporate a high-energy particle component in the M3D code will represent a unique capability for studying the nonlinear development of energetic particle modes in shaped geometry of arbitrary aspect ration. It is thus applicable to interpret results from NSTX and present day tokamak experiments, and is also a unique tool for assessing the effects of energetic particle modes in a burning plasma.

(v) Current Limits in Tokamaks and the Spherical Torus -- The spherical torus provides an opportunity to identify the mechanism that causes external kink instabilities in tokamaks and thus sets the current limits. In a standard aspect ratio tokamak, the q-profile and current density profile are very closely linked together, and it is impossible to change one of them without changing the other. The spherical torus has a very different relation between the q-profile and the current density profile, and this allows us to study the two independently. A series of carefully designed experiments on NSTX, supported by similar experiments on tokamaks, will allow us to clarify the separate roles of the q-profile and current density profile in driving instability. This understanding may help us to understand the rich behavior of edge localized modes (ELMs) in tokamaks and spherical tori.

(vi) Analysis and design of the Resistive Wall Mode Experiment -- In a recent series of experiments on the DIII-D tokamak, high-β tokamaks have been observed to be stabilized by a combination of plasma rotation, a nearby conducting wall, and active feedback coils. We have developed a unique tool for analyzing these experiments using an eigenmodes approach, and incorporating feedback at a fundamental level so that it's effect on the plasma eigenfunction can be calculated self-consistently.

FY 2004:
In FY 2004, most of the FY 2003 MHD projects will be continued and extended in different ways. Some of the FY 2004 goals we have identified are as follows:

- Complete a study of the effect of sheared rotation on plasma stability in NSTX
- Combine the 2 fluid equations with the energetic particles in M3D and apply this to energetic particle modes in burning plasmas
- Apply the M3D code to the sawtooth instability in burning tokamaks and use this to obtain a scaling for the period, crash time, and for when the sawtooth will interact with other modes
- Determine the feasibility of modeling the neoclassical tearing modes in nest-step tokamaks with an initial value code
- Model the CHI experiments in NSTX with a M3D model including open field lines, and clarify the mechanism for field line formation.
- Incorporate plasma rotation in the RWM eigenmode code.

2. TURBULENT TRANSPORT SIMULATIONS & ANALYSIS

(A) GYROKINETIC PARTICLE-IN-CELL SIMULATIONS:

(i) Electrostatic gyrokinetic simulations in large system size will address the role of zonal flows, nonlocal transport, and heat flux probability distribution function (PDF) in transport scaling with respect to ρ_i. The validity regime of mixing length estimates will be critically examined.

(ii) Electrostatic simulations using GTC code with trapped electrons are being benchmarked against FULL code in the linear regime, and nonlinear simulations addressing electron thermal and particle transport will be initiated.

(iii) More accurate electron dynamics will be included in the GTC by using the hybrid split-weight scheme, which has shown promising features in 1-d model problems.

(iv) Comprehensive diagnostics and visualization for turbulence characteristics and spectral transfer are being developed for advances toward detailed and fundamental understanding of nonlinear saturation mechanisms of turbulence with zonal flows, and for more detailed comparisons with experiments. These include developing simulation diagnostics packages, which model experimental measurements (as part of SCIDAC).

(v) Generation and damping of zonal flows in stellarators will be studied both analytically and computationally using the GTC code. The effects due to the lack of a symmetry direction will be elucidated.

(B) CONTINUUM GYROKINETIC/GYROFLUID SIMULATIONS:

(i) The gyrofluid approach and subgrid method will be explored to reduce the required phase space resolution needed for for the gyrokinetic continuum simulations.

(ii) The possible relevance of radially elongated streamers generated by Electron Temperature Gradient (ETG) turbulence will be studied via the gyrokinetic continuum code in collaboration with U. Maryland and IPP-Garching.

(iii) Interaction of ITG and ETG scale turbulence will be studied via the gyrokinetic/gyrofluid continuum code in collaboration with U. Maryland and IPP-Garching..

3. STELLARATOR PHYSICS:

(i) Near term work will focus on critical issues for the Conceptual Design Review (CDR) for the National Compact Stellarator Experiment (NCSX). The new coil healing code will be applied to modify the coil design to produce good free boundary equilibrium flux surfaces. (May ’02) Extensive PIES runs will determine the robustness of the flux surfaces for different pressure and current profiles, including a set of equilibria providing a startup scenario. The effect of field errors will be checked. Also, an extensive set of calculations will assess the flexibility of the reference coils to produce a range of configurations with good stability and transport properties.

(ii) The experience gained in the course of the NCSX design work has helped to sharpen the recognition of critical needs for further tool development and for improvements in the understanding of fundamental physics issues. Following the NCSX CDR, the theory group will turn increasingly to the development of computational tools and fundamental stellarator theory, and will test the tools and theory against existing stellarator experiments.

(iii) Studies will continue after the CDR to provide a definitive determination of the theory and practicalities for the determination of experimental current and pressure profiles from information about the shape of the flux surfaces.

(iv) Comparisons of PIES calculations with analytic models (e.g., Hegna et al) are expected to lead to a clarification of the role of resistive interchange driving term in stellarator equilibrium island formation. Code development work on the PIES code will enhance the free-boundary capability to facilitate edge modeling and comparison with experiment. This will provide a capability to move the reference surface further from plasma. Algorithm improvements for the PIES code will also focus on speeding up the

code. Subroutines representing bottlenecks will be sped up, the under-relaxation scheme will be improved, and the grid for calculating the current will be modified to smooth and accelerate convergence. This will be followed by the incorporation of neoclassical effects in PIES and by the application of the modified code to studies of neoclassical tearing modes in stellarators and tokamaks.

(v) Work on global optimization will continue, and will lead to an assessment of the feasibility of global optimization for stellarator design and to a fuller understanding of the topography of stellarator design space.

4. ENERGETIC PARTICLE PHYSICS -- Progress in the area of energetic particles research will be enabled by:

(i) Stability analysis of low frequency energetic particle driven MHD instabilities such as TAE, sawtooth stabilization and fishbones in JT-60U, JET, NSTX and burning plasma devices using analytical theories, NOVA-K and HINST codes.

(ii) Modification of the non-perturbative NOVA-2 code to include passing fast particle physics. This will allow us to perform non-perturbative analysis of kinetic effects on MHD type modes as well as RTAEs that exist only in the presence of fast ions.

(iii) Study of the stability of kinetic ballooning modes due to effects of fast ions as well as thermal ion gyroradii and trapped electron dynamics in NSTX using analytical theory and the HINST code with numerical equilibria.

(iv) Study of sub-ion cyclotron instabilities (CAEs) observed in NSTX and study background ion stochastic heating by CAEs. Based on a toroidal plasma equilibrium code that includes large fast ion orbit physic, we will perform hybrid-MHD simulations of CAE instability in NSTX using the HYM code. Also, we will improve low density/vacuum treatment, using same grid (cylindrical) for both fields and particles, which allows for more computing efficiency, and convert the HYM code to massively parallel computers.

(v) Employment of the massively parallel computer version of the M3D-K to study nonlinear behavior of fast particle driven modes such as TAEs and fishbones in advanced tokamaks and STs.

(vi) Collaboration on the extension of the HINST code for helical devices (LHD and NCSX) for studying high-n kinetic ballooning modes and TAE type modes with the Japan NIFS group

(vii) Investigation of ICRF induced plasma rotation in JET.

5. BOUNDARY PHYSICS:
(i) The DEGAS 2 code will continue to be maintained and developed. There will be substantial improvements to the user interface. Sputtering sources will be added. We will begin work on coupling this with B2.5.

(ii) The C-Mod modeling work on simulating the divertor baffling experiments will be completed. We will also support the edge turbulence visualization experiments on NSTX and model the lithium experiments in CDX-U. This latter work will involve the accumulation of relevant data in DEGAS 2.

6. SPHERICAL TORUS PHYSICS:

Near term work will focus on: Analysis of beta-limiting MHD in NSTX; modeling of co-axial helicity injection with the TSC code, role of shear flow on equilibrium and stability; improved access of modeling tools for experimentalists; study of neo-classical tearing mode island evolution; improve the understanding of neo-classical ion and electron thermal transport; use visualization tools to compare theory and experiment; non-linear applications with the GS2 code; complete interface of GTC with realistic ST geometry; application to high beta equilibrium; assess role of circulating particles on CAE and TAE modes; examine fast particle transport due to stochastic interactions; application of UEDGE to compare theory and experiment.

RELATIONSHIP TO OTHER PROJECTS

The PPPL Theory Department has helped provide the physics basis for many of the experimental initiatives pursued at PPPL and elsewhere in the fusion energy science program. Close collaborations between individual theorists (some of whom are directly funded by the experimental projects) and the various experimental programs both locally (e.g., NSTX) and externally (e.g., DIII-D, C-Mod, JET, JT-60U, LHD, etc.) have been clearly evident in significant refereed journal publications, IAEA and APS oral presentations, and completed as well as planned experimental proposals. Collaborations with alternate confinement concept programs (e.g., LHD at NIFS; advanced stellarator concepts exploration with Max-Planck, Lausanne, Columbia University, NYU, etc.; spherical torus studies with START; MAST, etc.), have been quite productive and are expected to be enhanced in the future. Such external collaborations have helped to establish PPPL theory as a national and international resource.

1. NSTX: State-of-the-art theoretical research capabilities are well coupled to the NSTX project and will continue to play an important role. This has been addressed in the preceding sections.

2. PSACI: The PPPL Theory Department has continued to lead the national participation of the Fusion Energy Sciences in the DOE Office of Science (SC) initiatives for advanced scientific computing such as the Scientific Discovery through Advanced Computing (SciDAC) Program. Within the OFES, PPPL has led the establishment of the Plasma Science Advanced Computing Institute (PSACI), which is well appreciated by the leadership at DOE SC. Helping to develop such programs, which complement the overall DOE SC efforts in this key area, is clearly of great importance to FES not only for the exciting opportunities afforded by access to powerful new computational resources but also for the scientific recognition that comes with being acknowledged as a valued contributor to such programs. These activities are complementary to those described in

PPPL's Advanced Scientific Computing (contractor no. 3130) and various SciDAC workscopes.

3. EXTERNAL COLLABORATIONS:

Productive collaborations between PPPL Theory Department and prominent national and international institutions such as General Atomics, JAERI, JET, Institute for Fusion Studies, etc. as well as individual scientists from university programs at MIT, UCSD, etc., have continued to be productive in the past year. Some examples include:

(i) A review paper on transport barrier physics based on collaboration with TFTR, DIII-D, and JT-60U has been finished [T.S. Hahm, to appear in Plasma Phys Control. Fusion (2002)]

(ii) NSTX is a national collaborative project and the theory group actively collaborates with scientists at other institutions by sharing codes and working together on the experiment. In many cases collaborators from other institutions have adopted codes developed here for analysis of the experiment. The reverse is also true.

(iii) The energetic particle physics group has been very active in collaboration with major fusion research groups in the world (JT-60U, JET, LHD, DIII-D). Numerous publications and co-authorship on journal publications as well as IAEA papers have resulted from these collaborations, indicating a clear acknowledgment of PPPL's well-appreciated involvement from the host institutions.

(iv) Two members of the theory group shared in the ORNL Scientific Research by a Team Award for their contributions to the design of the QPS stellarator. The theory stellarator group has also contributed to the design of the CTH device at Auburn, and to the design of a nonneutral confinement device being proposed by Pedersen at Columbia.

(v) Role of self-generated zonal flows, Shafranov shift, and trapped electron precession shear in internal transport barrier formation will be studied in collaboration with JET and JT-60U teams, and in the context of ITPA activity.

(vi) Collaboration with JET and JT-60U are expected to continue involving modeling of the observed MHD phenomena with particular emphasis on issues relating to external kinks and RWM stabilization, interactions of energetic particles with MHD modes as they relate to sawteeth, fishbones and TAE like instabilities.

5. STELLARATOR PROJECT:

The theory department has played and will continue to have a key role in the NCSX Project. This has been described in the preceding sections.

6. NON-FUSION RESEARCH:

In order to enhance the creative environment by diversification of research activities, the PPPL Theory Department has maintained a modest but very productive effort in non-fusion (i.e., non-MFE and often non-DOE supported) areas such as space physics, laser-plasma interactions, and industrial applications of advanced particle simulation methods. Non-fusion initiatives include space plasma physics studies of the influence of energetic particles in the magnetosphere, hybrid code development of capabilities to simulate laser-plasma interactions of interest to the National Ignition Facility at LLNL, the analysis of collective plasma effects limiting performance of accelerators and heavy-ion-beam fusion prospects, and the application of advanced particle simulation methods to aid the development of plasma display panels for industry.

7. EDUCATION:

The PPPL Theory Department continues to have a vital role in producing first-rate young scientists for the plasma sciences program. Education of graduate students and the training of postdoctoral students are key to providing the young talent needed to ensure the future health of the Plasma Sciences. The Theory Department prominently supports the DOE mission in the area of education. It has actively participated in valuable undergraduate training programs such as the National Undergraduate Fellowship (NUF) Program centered at PPPL. Moreover, PPPL theory is the primary contributor to the internationally acknowledged premier graduate program in plasma physics. Activities involve the full spectrum of academic duties including teaching courses, admissions and qualifying exam responsibilities, providing guidance to second year students in theory projects, and advising Ph.D. thesis students. In addition to those serving on the teaching faculty, many members of the group have provided invaluable support to the program by serving as thesis research advisors. This has been a mutually beneficial relationship in that the high quality students in the graduate program here have been a valuable and stimulating source of youthful energy, enthusiasm, and creativity for the Theory Department.

COMPUTATIONAL RESOURCES

In order to help maximize scientific productivity by effectively taking advantage of the exciting advances in computational technology, it will be necessary for OFES to invest in appropriate distributed (local) resources to complement NERSC. Computational support personnel are also much needed to help link scientists with these powerful tools.

Workstation/servers: Since many of the "workhorse" applications codes are not readily compatible with the MPP (massively parallel processing) architecture of the T3E and SP at NERSC, continuing substantial upgrades of more flexible local computational resources will be a very cost effective solution to meet these needs. As of January 2002, the principal computational horsepower at PPPL is embodied in 9 dual-processor ALPHA workstations (“loki” cluster) and 34 dual-processor Intel workstations (“petrel” cluster). Both clusters use the Linux operating system. These machines are heavily used for a variety of tasks: TRANSP runs, ray tracing, stellarator design and optimization, data analysis, reflectometry simulation, particle simulation, etc. They are enormously successful, to the point that they are saturated much of the time. In order to satisfy the

evident unmet needs for local CPU cycles, $150K is budgeted in FY02 under the Laboratory Support Equipment task (contractor number 1075) to increase the size of the petrel cluster – the most cost effective method of obtaining additional cycles (at a cost of approximately $2,000 / processor). Theory's contribution to the $150K purchase (through a financial plan transfer) was $50K, which will add 12.5 machines to the Theory batch. A budget on the order of $200K is needed on a continuing basis to meet the constantly increasing requirements for CPU cycles. Theory will likely contribute about 25% to this total maintenance cost. Myrinet 2000 connectivity hardware with 2Gb/sec bandwidth is installed on a subset (8) of the petrel cluster to enable parallel computation at high bandwidth.

Disks & Software: The cluster archival storage facility (robotic data silo) was upgraded in FY01 with the replacement of several drives with new generation devices. These enable use of higher density tape. Current UNIX cluster disk capacity exceeds 1 Terabyte. Based on trends, usage is expected to increase by several hundred GB each year, requiring further expansion of cluster disk capacity. $20K is allocated in the FY02 budget under the Laboratory's Computer Maintenance and Operations indirect funded task for purchase of a second 1TB central file server. Funds for additional capacity are required at the level of $20K/yr, in order to provide approximately 1 additional Terabyte/year at current prices. Additional software packages and upgrades to new versions are clearly needed and will be purchased. These software costs are included at last year's level.

Communications & Desktop/Home Workstations: At the desktop, scientists generally use a midrange PC with a relatively high-end graphics card and OpenGL 3d software support to facilitate visual analysis of datasets. Approximately $30K/year is budgeted in the Research Administration Organization Burden account to support continuing upgrades of desktop equipment for the Laboratory's Theory staff. This will allow renewal of desktop and home workstations on a 3-year cycle, consistent with the rate of obsolescence and with laboratory goals. Connectivity to home workstations via a reasonably fast data communications connection is essential. Either cable modem, ISDN or DSL service is provided to researchers as necessary. Approximately $20K is required to support this connectivity, as well as funds of $10K for several more workstations for this purpose.

MILESTONES:

FY2002

Produce results from nonlinear gyrokinetic full torus (GTC) simulations using the full power of the NERSC IBM-SP to advance understanding of transport scaling trends (Bohm vs. Gyro-bohm) in large toroidal plasmas.

Develop the capability for simulating simple 3D geometrics in DEGAS2 (e.g., finite length cylinder or tokamak with a toroidally discrete feature)

Implement new "dynamical healing" scheme in PIES code to develop "healed coils" for the NCSX design which produce good equilibrium flux surfaces while preserving desired stability, transport, and engineering properties of the configuration.

Produce results from high-resolution nonlinear MHD simulations (M3D) of internal reconnection events in the National Spherical Torus Experiment.

The eigenmode structure and spectrum of compressional Alfven waves in ST plasmas will be calculated using NOVA and compared with analytic estimates.

FY2003Design and analyze a series of experiments on NSTX to clarify the role of the q-profile and current density profile in driving the external kink mode unstable. Relate this to standard tokamaks and to ELMs as possible.
Apply the TSC code to model CHI and develop scenarios for enhancing the induced current.

Apply eigenmode analysis to the DIII-D Resistive Wall Mode (RWM) feedback experiments and compare simulation and experimental results.

Produce global gyrokinetic simulation results from the GTC code to clarify the physics associated with the radial electric field in the neoclassical limit, anomalous ion thermal diffusivity, and the Bootstrap current for spherical toruses and stellarators.

FY2004

Obtain results from PIES code studies of neoclassical tearing modes in stellarators and tokamaks.

Implement kinetic electromagnetic effects and rotation profiles and obtain results from more comprehensive nonlinear gyrokinetic studies of turbulent transport losses in toroidal systems.

Obtain new physics insights on internal reconnection events in toroidal systems from applications of the nonlinear M3D code.

<u>INCREMENTAL FUNDING AREAS</u>:

1. ST THEORY WITH APPLICATIONS TO NSTX

Lead Investigator: J. Manickam
It is proposed that incremental funding be provided to support the National Spherical Torus (NSTX) workscope now organized under the leadership of J. Manickam. This coordination of ST theory activities at PPPL along with good external connections has been strongly endorsed by national ST theory panel chaired by J. Callen. As the NSTX project moves forward with more dedicated operation time in the coming year, present theoretical challenges as well as new ones will need to be addressed in order to help harvest the new physics. For example, the understanding of ion and electron thermal transport, particularly the apparent dominance of electron transport relative to the ions is a major challenge to theory and modeling for NSTX. The high beta requires inclusion of electromagnetic effects, the enhanced scale length of ion Larmor radius relative to the

device requires full orbit physics and the reduced aspect-ratio requires correct treatment of the geometry. Extensive code modifications and improvements are underway to address these needs. On the other hand, even with the present staffing level in theory, the applications of the codes to the Spherical Torus at various stages of development suffers from lack of manpower. It is therefore critically important to add one FTE of support in FY '03 to be able to ensure maintaining sufficient theoretical expertise to deal with this very important expanding workscope.

2. Stellarator PIES Code Parallelization and Modernization
Lead Investigators: A. Reiman

It is proposed that incremental funding be provided to support the stellarator theory workscope now organized under the leadership of Allan Reiman. As the NCSX project moves forward to its next phase, it is critically important for PPPL theory to add one FTE of support in FY '03 to be able to ensure maintaining sufficient theoretical expertise to provide the key theoretical and modeling support needed. If additional funds beyond an FTE were made available, a vital area for support would be to add computational specialist to aid in parallelizing and modernizing the PIES stellarator code. The PIES code solves the three-dimensional equilibrium equations using a general representation for the magnetic field, so that it is capable of handling magnetic islands and stochastic regions. It is the only code of this type capable of solving for free-boundary equilibria. The code has been used to design the coils for the National Compact Stellarator Experiment (NCSX), and has been used extensively to evaluate flux surfaces in NCSX equilibria. It will be a crucial tool for the analysis of data from the NCSX.

The routine use of the PIES code has been limited by its speed. A typical free-boundary calculation takes several days on a DEC Alpha workstation. This slowness has also made it impractical to do full torus calculations for stellarators, in which the periodicity is broken by a tearing mode or external perturbation. We propose to speed up the PIES code by parallelizing it. There are several bottlenecks in the code where a large number of calculations could be done in parallel.The PIES code was written well over a decade ago. It has recently been converted from the RATFOR language to Fortran 90. Further modernization of the code structure will likely be desirable prior to parallelization. Upgrading and speeding of some of the individual components will also be desirable, and some of this work is included in the base plan. A faster PIES code would be used more routinely worldwide for the analysis of stellarator experimental data. The additional funding would target conversion of the PIES code to a tool that could be routinely used worldwide in the interpretation of data from stellarator experiments. The PIES code solves the three-dimensional equilibrium equations using a general representation for the magnetic field, so that it is capable of handling magnetic islands and stochastic regions. It is the only code of this type capable of solving for free-boundary equilibria. To upgrade the code, preconditioning would be used to enhance the speed of the algorithm, and a quasi-Newton version of the algorithm would be developed. The code would be adapted to massively parallel computers. The resulting increase in speed would allow routine application of the code to calculate free-boundary equilibria obtained during the operation of stellarator experiments, facilitating comparison with experimental data. The increase in speed would also allow adequately resolved full torus calculations for the ten-

period LHD device, which are presently outside the capability of existing codes, allowing computational studies of the important but puzzling results obtained on that machine for n=1 islands that break the periodicity of the stellarator.

IMPACT OF CONGRESSIONAL BUDGET REQUEST:

The Theory Department is manpower sensitive and already has a serious budget problem even with the flat budget projections assumed here, which does not enable the existing level of research to be continued. At the Congressional budget level for Theory, a significant decrease in the staff currently assigned to the Theory effort would result. The impact would be a major reduction in the ability to sustain the strong theory and modeling workscopes, which are generally regarded to be of critical importance to the national FES program. The incremental budget is being requested here to enable support for the existing theory research staff.

TOKAMAK THEORY		03/01/02		
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists	7.6	6.7	1.3	6.5 1.5
Engineers	.4	.3		.3
Administrators				
Graduate Students	1.5	1.0		1.0
Technicians	1.3	.7		.7
Clerical				
Subcontractors				
TOTAL FTEs	10.8	8.7	1.3	8.5 1.5
OPERATING COSTS $(000):				
PPPL Labor	1223.6	1038.5	183.5	1052.7 221.2
Subcontract Labor				
Overtime				
Travel	60.0	120.0	10.9	120.0 7.7
Energy				
Stockroom	1.0	5.0		5.0
Miscellaneous Expenses	51.3	59.8		53.0
Procurements/ICOs	87.0	96.2	8.2	98.6 .1
Organizational Burden	93.6	71.6	12.8	72.5 15.5
Other		39.8		29.6
General + Administrative	844.9	887.1	134.6	886.6 155.2
TOTAL OPERATING COSTS	2361.4	2318.0	350.0	2318.0 399.7
TOTAL OPERATING OBLIGATIONS	2229.0	2318.0	350.0	2318.0 399.7
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	2361.4	2318.0	350.0	2318.0 399.7
GRAND TOTAL OBLIGATIONS	2229.0	2318.0	350.0	2318.0 399.7

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

3107 ALTERNATE THEORY 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	6.6	5.8	3.1	5.6	3.2
Engineers	.2	.2		.2	
Administrators					
Graduate Students					
Technicians		.2		.2	
Clerical					
Subcontractors					
TOTAL FTEs	6.8	6.2	3.1	6.0	3.2
OPERATING COSTS $(000):					
PPPL Labor	836.1	733.5	392.8	736.9	425.9
Subcontract Labor					
Overtime					
Travel	7.0	73.3		69.7	
Energy					
Stockroom					
Miscellaneous Expenses	2.3	18.2	7.8	20.1	3.0
Procurements/ICOs	15.7	72.8	.1	70.4	
Organizational Burden	67.9	53.1	27.5	53.3	29.8
Other		6.4		6.4	
General + Administrative	557.9	592.7	271.8	593.2	291.3
TOTAL OPERATING COSTS	1486.9	1550.0	700.0	1550.0	750.0
TOTAL OPERATING OBLIGATIONS	1519.9	1550.0	700.0	1550.0	750.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	1486.9	1550.0	700.0	1550.0	750.0
GRAND TOTAL OBLIGATIONS	1519.9	1550.0	700.0	1550.0	750.0

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1812	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Field Reversed Configuration (FRC) Theory	AT5015020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Ronald C. Davidson Phone: 609-243-3552 Email: rdavidson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University	13. CONTRACTOR CODE:

14. WORK PROPOSAL DESCRIPTION:

In order to assess the potential of Field Reversed Configurations (FRCs) as an innovative confinement concept for fusion, it remains important to develop an improved understanding of FRC macroscopic stability properties both in low-s (kinetic) and high-s (MHD-like) regimes. The purpose of the proposed research is to carry out a detailed theoretical study of stability properties of FRCs using a newly developed 3D nonlinear hybrid and MHD simulation code (HYM). The proposed theoretical studies include detailed investigations of: (a) the effects of non-Maxwellian ion distribution on stability properties of prolate and oblate FRCs, (b) the effects of energetic beam ions, (c) the effects of additional electron physics (e.g., finite electron pressure and the trapped electron curvature drifts) on FRC stability, (d) a detailed comparison between simulations and experimentally observed FRC operating space, and (e) the effects of different equilibrium profiles and different boundary conditions.

The key technical milestones proposed for FY2003 and FY2004 are the following:
(a) Investigate the possibility of stabilizing medium-to-large *s* FRCs for non-Maxwellian ion distribution functions, including the effects of energetic beam ions.
(b) Determine the effects of finite electron pressure on the MHD and kinetic stability properties of FRCs.
(c) Characterize the stabilization and sustainment of FRCs by injection of energetic ion beams. Begin preliminary experimental design.
(d) Incorporate additional electron physics (e.g., trapped electron effects) into the numerical model, and determine the effects on FRC stability.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Field Reversed Configuration (FRC) Theory

A. Purpose and Goals

The Field-Reversed Configuration (FRC) is an innovative confinement approach that offers a unique fusion reactor potential because of its compact and simple geometry, translation properties, and high plasma beta. These attractive features have motivated extensive experimental and theoretical research on FRCs. One of the most important issues is FRC stability with respect to low-n (toroidal mode number) MHD modes. There is a clear discrepancy between the predictions of standard MHD theory that many modes should be unstable on the MHD time scale, and the observed macroscopic resilience of FRCs in experiments. Most of the theoretical work, therefore, has focused on investigating a variety of non-ideal MHD effects, including plasma flow and kinetic effects on FRC stability properties, particularly with respect to the $n = 1$ tilt mode. Although considerable progress has been made, a complete understanding of the observed FRC stability properties is still lacking. In order to assess the potential of FRCs as an innovative confinement concept for fusion, it remains important to develop an improved understanding of FRC macroscopic stability properties both in low-$\bar{s}$ (kinetic) and high-$\bar{s}$ (MHD-like) regimes. The purpose of the proposed research is to carry out a detailed theoretical study of stability properties of FRCs using a newly developed 3D nonlinear hybrid and MHD simulation code (HYM). The proposed theoretical studies include detailed investigations of: (a) the effects of non-Maxwellian ion distribution on stability properties of prolate and oblate FRCs, (b) the effects of energetic beam ions, (c) the effects of additional electron physics (e.g., finite electron pressure and the trapped electron curvature drifts) on FRC stability, (d) a detailed comparison between simulations and experimentally observed FRC operating space, and (e) the effects of different equilibrium profiles and different boundary conditions.

B. 2000-2001 Publications

"Numerical Study of Tilt Instability of Prolate Field-Reversed Configurations", E. V. Belova, S. C. Jardin, H. Ji, M. Yamada, R. Kulsrud, Phys. Plasmas **7**, 4996 (2000).

"Global Stability of the Field Reversed Configuration", E. V. Belova, S. C. Jardin, H. Ji, R. M. Kulsrud, W. Park, M. Yamada, Plasma Physics and Controlled Nuclear Fusion Research, Proceedings of the 18th Int. Conf. Sorrento (2000) (International Atomic Energy Agency, Vienna, 2000).

"Numerical Study of Global Stability of Oblate Field-Reversed Configurations", E. V. Belova, S. C. Jardin, H. Ji, M. Yamada, R. Kulsrud, Phys. Plasmas **8**, 1267 (2001).

"Kinetic effects on FRC stability", E. V. Belova, Proccedings of US-Japan Workshop on Physics of Innovative High Beta Concepts, Osaka Japan, February 2001.

"Nonlinear gyroviscous force in a collisionless plasma", E. V. Belova, Phys. Plasmas **8**, 3936 (2001).

C. Approach and Technical Progress

We have developed a nonlinear 3-D simulation code (HYM) to study the macroscopic stability of FRCs. The description of the numerical model and the results of extensive and systematic studies of stability properties for both prolate and oblate FRC configurations are presented in detail in the 2000-2001 publications. In HYM, three different physical models have been implemented: (a) a 3-D nonlinear resistive MHD model, (b) a 3-D nonlinear hybrid scheme with all particle ions and fluid electrons, and (c) a 3-D nonlinear hybrid MHD/particle model where a fluid description is used to represent the thermal background plasma and a kinetic (particle) description is used for the low-density energetic beam ions. In contrast to previous work, a fully kinetic particle description has been used to describe the ions, and the nonlinear delta-f method has been implemented to reduce numerical noise and computational requirements in the particle simulations. The ability to choose between different physical models allows the study of a variety of stabilizing effects for a wide range of FRC parameters: $E = 0.5 - 10$ and $\bar{s} > 0.8$, where E is the separatrix elongation, and $\bar{s}$ is a kinetic parameter which measures the number of thermal ion gyro-radii in the configuration.

Thus, global stability of the oblate ($E < 1$) FRC has been investigated numerically using both MHD and hybrid simulations. It has been shown that all $n = 1$ modes (the tilt, the radial shift and the interchange modes) can be stabilized in the oblate FRC in the small Larmor radius (MHD) limit if a close-fitting conducting shell is present. The stability to $n > 1$ interchange modes can be achieved for a favorable pressure profile and a finite separatrix beta. However, the low n ($n > 1$) co-interchange modes remain unstable even in the highly kinetic (small $\bar{s}$) regime when the ion distribution function is taken to be Maxwellian.

The stability properties of prolate ($E > 1$) configurations have been examined as well. We have performed hybrid simulations of the $n = 1$ tilt mode in prolate FRCs with $E = 2-8$ and $\bar{s} = 1 - 8$ to study how the kinetic effects associated with large thermal ion orbits can modify MHD predictions. Our simulations show that there is a significant reduction in the tilt mode growth rate due to finite Larmor radius effects, but no absolute linear stability has been found. However, at low $\bar{s}$, typical of much of the experimental work to date, we find that the nonlinear evolution of the tilt mode is different from that of the MHD model, and the nonlinear saturation of the tilt instability becomes possible. In order to understand how this saturation occurs we have investigated the linear instability mechanism. A linear analysis of the tilt instability has shown that the resonant particles contribute significantly to the instability drive and can be responsible for a finite linear growth rate in the large gyroradius regime. A generalized resonance condition has been found, and it has been demonstrated that multiple resonances are possible in racetrack configurations. The nonlinear stabilization of a linearly unstable tilt mode explains the observation in the low $\bar{s}$ ($\bar{s} \lesssim 2$) experiments of initial $n = 1$ tilt motion that does not result in total loss of confinement. However, the reported FRC stability for larger values of $\bar{s}$ ($\bar{s} \gtrsim 4$) has not been explained and requires further investigation.

D. Future Accomplishments (FY2003-FY2004)

The proposed theoretical program will focus on two major issues: providing an improved understanding of FRC stability properties in the experimentally relevant kinetic regime, and determining whether and under what conditions this stability can be extended to the large $\bar{s}$, reactor relevant regime. Investigations of the mechanism providing low-$\bar{s}$ stability are of considerable scientific interest, and are directly relevant to the MTF (Magnetized Target Fusion) program. Achieving better agreement between the theoretical results and the existing experimental data is also essential for a validation of the theoretical models. The fusion reactor potential of the FRC, on the other hand, is enhanced significantly if the FRC macroscopic stability is demonstrated for the large $\bar{s}$ ($\bar{s} \sim 10 - 20$).

The proposed studies will include the following tasks.

(a) Determine the effects of the ion distribution function on stability properties of prolate and oblate FRCs. This includes the numerical study of the tilt mode in prolate FRCs in the kinetic regime including sheared rotation, and numerical simulations of oblate FRCs with a strongly anisotropic ion distribution function in order to establish the kinetic stabilization of low n ($n > 1$) co-interchange modes.

(b) Perform numerical simulations of the FRC including energetic beam ions, and determine the condition (the fraction of the beam current) necessary for stability of the hybrid beam/thermal plasma system.

(c) Determine FRC stability properties using an improved physical model and realistic boundary conditions. In particular, the effects of the finite electron pressure and trapped electron effects on FRC stability will be studied.

(d) Improvement of the numerical model, in particular, implementation of an improved numerical treatment of the low density/vacuum region, and modifications of the existing nonlinear delta-f particle simulation method in order to accurately follow the dynamics of the unstable global modes from the linear growth phase to the large-amplitude, strongly nonlinear phase.

The proposed funding level for these tasks activities corresponds to the guidance funding level of $195 K in each of the fiscal years FY 2003 and FY 2004.

E. Milestones for FY 2003 and FY 2004

1. Investigate the possibility of stabilizing medium-to-large $\bar{s}$ FRCs for non-Maxwellian ion distribution functions, including the effects of energetic beam ions (April, 2003).

2. Determine the effects of finite electron pressure on the MHD and kinetic stability properties of FRCs (September, 2003).

3. Characterize the stabilization and sustainment of FRCs by injection of energetic ion beams. Begin preliminary experimental design(March, 2004).

4. Incorporate additional electron physics (e.g., trapped electron effects) into the numerical model, and determine the effects on FRC stability (September, 2004).

1812 FRC THEORY		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	.7	.6	.6
Engineers			
Administrators			
Graduate Students	.5		
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	1.2	.6	.6
OPERATING COSTS $(000):			
PPPL Labor	81.6	64.2	67.0
Subcontract Labor			
Overtime			
Travel	2.0	2.5	2.5
Energy			
Stockroom			
Miscellaneous Expenses	.2		
Procurements/ICOs	50.4	57.3	53.7
Organizational Burden	5.6	4.7	4.9
Other			
General + Administrative	66.2	66.4	67.0
TOTAL OPERATING COSTS	206.0	195.1	195.1
TOTAL OPERATING OBLIGATIONS	178.0	195.1	195.1
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	206.0	195.1	195.1
GRAND TOTAL OBLIGATIONS	178.0	195.1	195.1

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3130	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Advanced Scientific Computing	AT5020400

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER
William M. Tang Phone: 609-243-2612 Email: wtang@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The PPPL Advanced Scientific Computing activity has continued to provide leadership and contribute technical progress towards the effective application of modern computational techniques and high-performance computers to address outstanding issues facing fusion energy research. The present work scope also responds to the charge from the Office of Fusion Energy Sciences to continue to lead the Plasmas Science Advanced Computing Institute (PSACI) and associated coordinating activities relevant to the Fusion SciDAC activities. Technical progress, which has entailed close collaborations between the Theory Department and the Computational Plasma Physics Group (CPPG) staff, includes continuing to develop new physics capabilities and to convert and optimize PPPL codes to effectively utilize massively parallel computers. The associated activities have involved the introduction of new algorithms and computational techniques and also the application of modern visualization tools.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

A key challenge facing the Fusion Energy Sciences research program is to make timely progress on solving highly complex physics problems requiring the effective application of modern computational resources. In doing so, it is now and will continue to partner in new advanced computing programs within the DOE Office of Science, such as SciDAC (Scientific Discovery through Advanced Computing. The Plasma Science Advanced Computing Institute (PSACI) continues to steer the OFES thrust advanced scientific computing with the objective to accelerate research advances and to improve the general perception of its scientific stature. In addition to securing funding resources, this will require improvements within the FES community in employing crosscutting computer science and applied mathematical methods to help drive research progress. Because of the broad scope of the PSACI and the eventual need for possible interagency and interdisciplinary coordination, it is managed as a project. PPPL continues in its role designated by OFES to serve as the lead institution in managing these PSACI activities in the interest of the overall Fusion Program. In the coming year, the Advanced Scientific Computing program at PPPL will continue to participate in the research work scope as well as provide leadership for the PSACI. The PSACI, which is now designated as a virtual "institute," is charged with coordination of an increased number of individual projects within the FES SciDAC portfolio.

PURPOSE

The PPPL Advanced Scientific Computing activity is directly funded by contractor number 3130 and also with resources awarded from national peer-reviewed competitive proposals within the DOE Office of Science SciDAC Program. Within PPPL, computational physicists in the Theory Department and computer science professionals in the Computational Plasma Physics Group (CPPG) actively contribute to this work scope. The general goal of this key research area is to successfully apply modern computational techniques and high-performance computers to the solution of outstanding problems in fusion energy and plasma science research. The advanced computational plasma physics activities at PPPL have the following thrusts:

1. To significantly enhance the physics capabilities and modernize the computational architecture of the most scientifically advanced plasma physics simulation and design codes for optimal utilization of massively parallel computers.

2. To work with plasma science community to plan a highly productive, cost-effective growing program and to lead the successful implementation of this plan. The PSACI now has a major lead role for coordinating and planning the Plasma Science component of the Office of Science SciDAC Program.

BACKGROUND

The scientific community's recognition of the importance of a strong U.S. computational effort in fusion energy research is evident in reports such as the DOE/NSF Workshop on Advanced Scientific Computing held at the National Academy of Sciences (July, 1998) and also by it's inclusion in the DOE Office of Science SciDAC Program. Building upon a prominent history of advanced computation, which can be traced back to the establishment of the predecessor to the National Energy Research Scientific Computing Center (NERSC) nearly 25 years ago, the U.S. fusion community has been rewarded by impressive advances in the modeling of plasma confinement and the interactions of plasma with its surroundings. This has led to major progress in the simulation of key processes such as turbulence-driven energy transport. Nevertheless, the majority of the fusion codes developed over the past 20 years were developed and optimized for vector-processor architecture along with the associated programming methods and graphical packages prevalent during that period. Since computer vendors in the U.S. have now phased out for the most part the high-end vector processors in favor of the massively parallel processor architectures, it is clear that (i) modern object-oriented programming paradigms should be utilized in managing the complexity of modern large code packages; and (ii) modern visualization capabilities have superceded the computer graphics of the past. The PPPL work scope in this area is directed at performing the essential tasks needed for taking advantage of modern computational techniques and high-performance computing. As part of the PSACI/SciDAC, these efforts will also be coordinated with similar activities taking place in the fusion energy sciences community leading to both direct and indirect benefits via collaborations and code-sharing activities.

Last year the multi-institutional PSACI management team centered at PPPL together with it's distinguished Program Advisory Committee was charged with the task of coordinating and steering the new portfolio of Fusion Energy Science applications within the SciDAC portfolio.

MANAGEMENT AND INFRASTRUCTURE PROGRESS

Building upon the progress over the past year, the OFES has requested that PPPL continue to lead the PSACI which is now designated a virtual "institute" coordinating the computational projects within the FES SciDAC portfolio. This institute is also expected to maintain effective linkages with the overall DOE Office of Science SciDAC Program. For example, at the first SciDAC PI Meeting this past year, PSACI director, W. Tang, provided an effective overview presentation of the FES area, and PSACI deputy director, V. Chan, presented the summary of goals and associated CSET linkages for the FES portfolio of applications. A clearer definition of the Fusion SciDAC roles and responsibilities of OFES, PSACI, and the Principal Investigators in each project area was provided by OFES and further discussed and clarified at the PSACI Program Advisory Committee (PAC) Meeting held at PPPL on August 3-4, '01. The PSACI areas include:

- Provide analyses and plans on how best to ensure timely progress toward scientific goals and deliverables targeted by the Fusion SciDAC centers
- Convene PSACI meeting with PI's from existing Fusion SciDAC centers for annual progress assessments and to recommend priorities for future work
- Provide advice to prospective PI's on SciDAC goals and technical objectives
- Promote good communication and cross-fertilization/sharing of ideas among the fusion SciDAC centers
- Facilitate communication and promote collaborations between the Fusion centers and the other SciDAC activities, especially in the Computer Science and Enabling Technology (CSET) community
- Assist with reporting to higher levels of DOE, OMB, and Congress regarding Fusion SciDAC progress

In order to provide the needed local infrastructure needed both to support the Princeton research efforts and to lead the national Plasma Science Advanced Computing effort, PPPL has and will continue to invest and utilize the dedicated OFES funding in this area (CC-3130) to develop cutting-edge computational physics capabilities produced by multi-disciplinary professionals who combine expertise in theoretical plasma physics, computational physics,

computer science, and software engineering. Complementing the traditional strengths of PPPL in theoretical and computational physics, expertise in parallel programming, high-end visualization, object-oriented programming as applied to physics research codes has been assembled.

TECHNICAL PROGRESS:

In addition to the leadership activities described in the preceding section, this work scope at PPPL has addressed the scientific challenges associated with the research, development, and deployment of mathematical models, and computational methods to improve scientific codes with emphasis on taking advantage of the capabilities of modern supercomputing resources. Examples of progress include:

Software Advances for the M3DP code:

Advances were made in parallel scaling efficiency and better understanding was obtained of bottlenecks in performance. Significant progress was made on the implementation of more realistic boundary conditions based on a surrounding vacuum region with a Green's function technique. The two-fluid capability in M3D was operative, and the capability for particle ions in order to enable the hybrid feature was put in place. Benchmarking with NIMROD was continued. Impressive advanced visualization of new phenomena was demonstrated via the movie of the dynamical evolution of the internal reconnection event on NSTX recently computed by M3D.

Software Advances for the 3D Gyrokinetics Code, GTC:

The further development of the global particle-in-cell 3D Gyrokinetic Code, GTC, has continued to exhibit impressive progress. This past August '01, it successfully demonstrated effective utilization of the full power of the newly-configured 5 TF IBM-SP supercomputer at NERSC. This was enabled not only by efficient massive parallelization of this state-of-the-art code but also by algorithms utilizing the proper field-line coordinates for 3D toroidal geometry. In addition, PPPL computational scientists were able to successfully combine the use of OpenMP to communicate within a single SMP node and to use MPI for cross-node communication. The coupling of the neoclassical version of this code to actual non-axisymmetric MHD equilibrium

codes has enabled the unique capability to simulate transport dynamics in non-axisymmetric 3D systems such as stellarators. Computational support for the further development of the GTC is clearly mandated by the fact that it has continued to receive the highest endorsements both as a featured advanced scientific computing code in the Fusion SciDAC portfolio and also as a heavily-requested new tool for application to transport studies in magnetically confined plasmas.

Advances in Modern Visualization Capabilities:

PPPL's High Resolution Display Wall, which resulted from productive collaborations between PPPL (W. Tang) and the Computer Science (CS) Department at Princeton University (Prof. Kai Li) has proven to be a modern visualization resource which has been heavily utilized for both scientific presentations and discussions. Led by S. Klasky of the Computational Plasma Physics Group at PPPL with support from both CS and of PPPL's Engineering Department, this new Display Wall was completed by the end of May, 2000 and has been significantly upgraded both in size and in alignment capabilities.

FUTURE ACCOMPLISHMENTS

In addition to the community leadership and associated coordination goals associated with the PSACI/SciDAC, the PPPL Advanced Scientific Computing Program for FY02 and FY03 will be targeting key technical accomplishments. Many of the activities listed in the preceding section will continue in this period and beyond along with some important new ones. It should also be kept in mind that as technical advances and research opportunities develop, changes in priorities may also be necessary.

Modernization, and Parallelization of State-of-Art Codes:

The state-of-the-art advanced scientific simulation codes developed at PPPL can continue to be expected to provide enhanced benefits both locally and externally if provided the resources to (i) continue to improve architecture for efficient implementation on high-end MPP computers; (ii) further enhance visualization capabilities; and (iii) improve user interfaces. The technical progress on improving state-of-art codes such as M3D and GTC described in the preceding section will be continued in FY'03 and '04. For example, the GTC capabilities for simulating both neoclassical and anomalous transport in general geometry will be further enhanced in FY'03 and

’04 by implementation of an improved split-weight hybrid methods to deal with non-adiabatic electron as well as electromagnetic dynamics and by the development of higher-dimensionality domain decomposition algorithms to enable effective usage of the full power of MPP supercomputers. Spin-offs of delta-f methods originally introduced for MFE gyrokinetic applications have now been implemented in simulations of particle beams of interest to IFE. The delta-f approach (where only the deviation of the distribution function from a Maxwellian is treated with high-resolution) has enabled simulation of a new two-stream instability, which is deemed very relevant to the Spallation Neutron Source experiment. Further contribution to progress for IFE simulations is expected in FY’03 and ’04. Another major code PIES (a unique 3D MHD equilibrium code that does not assume the existence of good magnetic surfaces for analyzing flux surfaces in non-axisymmetric 3D systems) could be restructured to enable efficient usage of the new generation of MPP machines. More specific plans for the two major areas of development, 3D MHD and 3D Global Gyrokinetic PIC Codes are described in the following.

Milestones:

FY 2002:

Develop a parallel version of the M3D/Hybrid code where the energetic particles are being advanced on the M3D unstructured grid.

Implement, benchmark, and apply complete trapped-electron dynamics capability in the global gyrokinetic simulation code (GTC) utilizing the split-weight hybrid method.

Produce on-line documentation for the GTC code and initiate second level of domain decomposition (poloidal plane).

FY 2003:

M3DP Code Development and Visualization:

Incorporate the options for field line tracing, particle pushing on an unstructured mesh, and field line coordinates in the standard code version

Implement parallel data transfer and customized collaborative visualization, and refine the system for code documentation and validation

Developmental plans are aimed at incorporating new physics capabilities into the code, making it more efficient, and making it easier to use, and easier to interface with other codes from other communities.

GTC Code Development and Visualization:

Convert GTC code from 1D (toroidal plane) to 2D (annular region) domain decomposition and extend scalability improvements to higher radial resolution and more particles.

Conversion from IDL based to AVS based visualization

Developmental plans are aimed at effectively implementing two-dimensional domain decomposition. This will enhance the number of processors that can be used efficiently which would better enable taking advantage of the next generation of machines. Also, the present graphics package, while convenient for many applications, needs to be converted to the more powerful AVS system to take advantage of many recent advantages in visualization and to allow development of volume rendering capabilities needed to deal with the terabyte scale data sets generated in the most recent GTC simulations using the full power of NERSC's IBM-SP.

FY 2004:

In FY 2004, the work described above will be continued and further extended. Associated milestones include:

Implement more general domain decomposition, quadratic bilinear elements, higher order elements, and 1D and 2D grid packing in M3DP.

Implement a high efficiency interface between M3DP and MDS+ for storage and visualization.

Develop more powerful data analysis and visualization capabilities for GTC via utilizing parallel data streaming, parallel visualization rendering, collaborative visualization, and feature extraction to deal with the terabyte scale data sets generated by these advanced simulations.

3130 ADV SCI COMPUTING 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	2.8	2.7		2.7	
Engineers	2.9	2.3		2.1	
Administrators					
Graduate Students					
Technicians	.1	.1		.1	
Clerical					
Subcontractors					
TOTAL FTEs	5.8	5.1		4.9	
OPERATING COSTS $(000):					
PPPL Labor	696.2	617.6		619.8	
Subcontract Labor					
Overtime					
Travel	17.0	18.0		18.0	
Energy					
Stockroom					
Miscellaneous Expenses	9.1	8.8		6.4	
Procurements/ICOs	98.6	124.6		124.7	
Organizational Burden	57.4	44.6		44.8	
Other					
General + Administrative	501.1	486.4		486.3	
TOTAL OPERATING COSTS	1379.4	1300.0		1300.0	
TOTAL OPERATING OBLIGATIONS	1260.4	1300.0		1300.0	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	1379.4	1300.0		1300.0	
GRAND TOTAL OBLIGATIONS	1260.4	1300.0		1300.0	

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3120	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Computational Physics	AT5020100

6. WORK PROPOSAL TERM: Begin: 10/1/02 End: 9/30/04

7. CONTRACTOR WORK PROPOSAL MANAGER:
Stephen C. Jardin/ D.McCune Phone: 609-243-2635 Email: sjardin@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The PPPL computational physics activity is focused on the application of modern computational techniques, advanced visualization, and high-performance computers to outstanding problems in controlled fusion and plasma physics. This work scope includes the unification and modernization of the PPPL production physics codes to make them more accessible to the research staff, the conversion and optimization of several of the major codes to utilize massively parallel computers, the introduction of new algorithms and computational techniques into plasma physics codes, and the application of modern visualization tools to plasma physics applications.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The PPPL computational physics activity consists of both computational physicists and computer science professionals. The focus of the workscope is the application of modern computational techniques and high-performance computers to outstanding problems in controlled fusion and plasma physics. The computational plasma physics activities have the following thrusts:

1. To streamline, modernize, unify and extend existing production physics codes to improve performance, usability, accessibility to the wider fusion science community, and applicability to a wider range of research problems.

2. To develop new methods and standards for on-line and between-shot experimental data analysis, which could be utilized by NSTX, DIII-D, C-Mod, and other tokamaks located overseas, and ultimately to extend these methods to stellarators and/or other alternate concept magnetic confinement devices.

3. To convert the major plasma physics simulation and design codes to utilize massively parallel computers, and in so doing to optimize the algorithms and computational techniques, in a way that is compatible with the complementary goals of extending their physics and improving their user interface and visualization capabilities.

BACKGROUND

The fusion program has long been a leader in the cutting-edge application of computers and computational physics techniques to contemporary problems in science, and there is now no doubt but that modern high-performance computing is an essential element in the fusion science program. The majority of the fusion codes developed in the last 20 years were optimized to the vector-processor architecture that was prevalent during that period, and have been developed in the programming style and utilize the graphical packages offered in 1980s and 1990s. U. S. computer vendors have now all but phased out the high-end vector processors in favor of the massively parallel processor architectures. It is also clear that modern object-oriented programming paradigms offer real advantages in managing the complexity of modern large code packages, and that modern visualization packages have much to offer compared to the older computer graphics. The work proposal presented here is aimed at continuing the work that is necessary and essential for PPPL and the fusion community as a whole to take full advantage of the modern computer techniques and high-performance computing.

APPROACH

PPPL has developed a cutting-edge computational physics capability consisting of multi-disciplinary professionals who combine expertise in theoretical plasma physics, computational physics, computer science, and software engineering. Besides the traditional strengths of PPPL in theoretical and computational physics, we now have assembled expertise in parallel programming, high-end visualization, object oriented programming, graphical user interface (GUI) development, UNIX systems knowledge, and documentation and user support, as applied to physics research codes. We have established a group for computational plasma physics at PPPL.

TECHNICAL PROGRESS

We list here progress during the last year on some of the major computational plasma physics projects that fall under this workscope.

Standardized unified interfaces to MHD equilibrium:
We have developed two high-leverage interface tools that allow plasma transport and stability codes to extract information from the many different plasma equilibrium codes. XPLASMA provides a common equilibrium representation for transport codes, and I2MEX provides a standard equilibrium representation for stability codes to obtain metric information from a variety of equilibrium sources. These routines are fully coupled to MDSplus and can thus extract EFIT or TRANSP database equilibrium across the network. The I2MEX has now been interfaced with PEST-I, II, and –III.

Visualization Wall Development and Applications
We have assisted several groups in using the visualization wall and the associated 24-processor computer cluster PARED. AVS Express is now available on the wall for routine high-resolution visualization of 3D data. We have produced several high-impact movies for visualization of M3DP, GTC, and reflectromety data. We have evaluated several advanced visualization packages, including Amira and several parallel visualization software systems. As a result, we have implemented the Wire-GL software from the Stanford University Computer Graphics Lab to allow a parallel implementation of the Visualization software package OPEN-DX on the wall.

FUTURE ACCOMPLISHMENTS

We list here some of the major projects that have been identified for FY03/04. We also provide general computational support on UNIX, Makefiles, portability, web documentation, etc. It must also be kept in mind that other projects will develop and change priorities during the year in response to new research results and opportunities as they develop.

Visualization Applications, Support and Development
We will continue to work with the different application groups at PPPL and elsewhere to improve the use and value of the visualization wall and of the AVS visualization software. We will pioneer new techniques for visualizing such things as complex motions of tracer particles, 3D processes leading to magnetic reconnection, wave-particle trapping, intermittence, and long-lived coherent vortices. We will work with the AVS developers to obtain a parallel version of AVS for use on the wall. We will also continue to evaluate new visualization software, and will co-host a follow-on Visualization Display Environment (VDE) workshop.

Modernization, and Parallelization of the Leading Edge Codes
PPPL has several other leading-edge 3D codes that will benefit from enhanced support, restructuring to allow efficient implementation on the high-end parallel computers, improved visualization capabilities, and improved user interfaces.

Transport Code development, Speedup, and Modernization
We will continue our activities to modernize and unify the TRANSP and TSC codes. The Neutral Beam package from TRANSP is being extracted, modularized, and made parallel, and a newly formulated collision operator will be implemented (supplemental funding was provided by Lawrence Berkeley National Laboratory through the Office of Advanced Scientific Computing Research). The TRDAT package for accessing experimental data will also be extracted and made available for TSC and other codes. The TSC graphics package will be updated.

MILESTONE SCHEDULE

FY 2002
- Implement the I2MEX interfaces in PEST-I, -II and other theory codes.
- Demonstrate new applications of parallel visual display wall to GTC, M3DP, and Adaptive Mesh Refinement MHD
- Develop the predictive capability of TRANSP to include nonlinear transport modules GLF23 and MMM and a comprehensive radiation package

FY 2003
- Demonstrate parallelization of stand-alone Monte Carlo Neutral Beam Package
- Unification and modernization of TSC and TRANSP graphics
- Implement advanced visualization on display wall with parallel rendering

FY 2004
- Continue conversion of TRANSP to parallel computation

RELATIONSHIP TO OTHER PROJECTS

PPPL is a member of the National Transport Code Consortium and the activities described here are done in coordination with them, especially the Fusion Codes and Modules Library. This activity also supplies the massively parallel programming and visualization expertise needed by several SciDAC projects, the Theory Department, and the NSTX and NCSX programs.

3120 COMPUTATIONAL PHYSIC 03/01/02			
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists			
Engineers	1.5	1.3	1.3
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	1.5	1.3	1.3
OPERATING COSTS $(000):			
PPPL Labor	172.1	159.6	166.8
Subcontract Labor			
Overtime			
Travel	13.0	18.0	18.0
Energy			
Stockroom			
Miscellaneous Expenses	5.0	15.5	13.0
Procurements/ICOs	12.5	19.5	13.1
Organizational Burden	14.9	12.7	13.2
Other	1.8		
General + Administrative	129.7	138.8	140.0
TOTAL OPERATING COSTS	349.0	364.1	364.1
TOTAL OPERATING OBLIGATIONS	355.0	364.1	364.1
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	349.0	364.1	364.1
GRAND TOTAL OBLIGATIONS	355.0	364.1	364.1

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3132	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Numerical Computation of Wave-Plasma Interactions in Multi-dimensional Systems	AT5020400

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Cynthia K. Phillips Phone: 609-243-2836 Email: ckphillips@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Massively parallel processor systems will be utilized to extend numerical models for the dielectric response of the plasma to include non-Maxwellian particle distribution functions and non-local effects arising from parallel gradients in the equilibrium magnetic field. The generalized models will be used to evaluate the potential for lower hybrid current profile control on C-Mod, including effects of wave-driven nonthermal electrons and full wave interference effects on the spectral gap problem, and to evaluate high harmonic fast wave heating and current drive characteristics, with and without combined neutral beam injection, in the NSTX device. A close interaction with the experimental programs on both C-Mod and NSTX will be essential in the development of quantitatively accurate predictive simulation codes.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The complex physics of wave-plasma interactions are encapsulated in the dielectric response of the plasma, obtained by combining the vacuum displacement current with the wave-driven plasma currents. In general, plasmas that occur in nature or in the laboratory are spatially inhomogeneous, and, if magnetized, are also anisotropic. The dielectric response function can be quite complex and has yet to be included in its full generality in the simulations of wave fields in plasmas. Most wave field simulation codes developed to date utilize dielectric response functions that are based on the assumption of linear wave perturbations, local plasma uniformity, thermal equilibrium particle distributions, and straight-line equilibrium magnetic fields. These models ignore key physical characteristics of fusion relevant plasmas including non-thermal velocity-space distribution functions and effects related to inhomogeneities in the equilibrium configuration. Non-Maxwellian distribution functions or inclusion of local equilibrium magnetic field gradients result in the replacement of the well-known (and computationally efficient) plasma dispersion function by more complex functions involving (in general) velocity space integrals. Massively parallel processor systems will be utilized to extend numerical models for the dielectric response of the plasma to include non-Maxwellian particle distribution functions. Further related research to extend the dielectric response functions to incorporate non-local effects arising from parallel gradients in the equilibrium magnetic field will be described below in the section, Related Work. The generalized models to be developed under this proposal will be used to evaluate the potential for lower hybrid current profile control on C-Mod, including effects of wave-driven non-thermal electrons and full wave interference effects on the spectral gap problem, and to evaluate high harmonic fast wave heating and current drive characteristics, with and without combined neutral beam injection, in the NSTX device. A close interaction with the experimental programs on both C-Mod and NSTX will be essential in the development of quantitatively accurate predictive simulation codes.

BACKGROUND

This project was funded in FY2001 as part of a competitive solicitation in conjunction with the DOE SciDAC program. The Principal Investigator for this collaborative research project is Dr. Donald B. Batchelor of ORNL. It is a collaborative project involving personnel from ORNL, PSFC-MIT, Lodestar Research Corporation, and CompX Corporation as well as PPPL. Research efforts focusing on nonlocal effects in the plasma dielectric response function are to be completed via a subcontract from PPPL to Mission Research Corporation. This related work, which is described below, requires additional funding, as specified in the original proposal submitted to OFES.

APPROACH

The project web site can be viewed at http://www.ornl.gov/fed/scidacrf/. At Princeton, the major focus is on the development and application of electromagnetic field solvers which self-consistently include effects of non-Maxwellian particle distributions. Effects of non-local equilibrium gradients on both wave propagation and absorption processes

are to be completed via a subcontract to Mission Research Corporation, with additional funding to cover that research.

TECHNICAL PROGRESS

The METS 1D kinetic wave solver which is valid for all ratios of the particle Larmor radii to the perpendicular wavelength of the excited wave fields has been generalized to take advantage of massively parallel processor systems. As a result, the code runs more rapidly and is now capable of treating very short wavelength modes into the lower hybrid frequency range. Modifications needed to include non-Maxwellian velocity distribution functions in the plasma conductivity operator are currently in progress. Under a subcontract in FY01 and FY02 to MRC, computation of the plasma dielectric operator, which incorporates effects of quasi-local equilibrium gradients, has been significantly improved, rendering it feasible to include these effects in more simulations.

FUTURE ACCOMPLISHMENTS

In the remainder of FY2002, the implementation of enhanced dielectric tensor elements in 1D, assuming a general velocity space distribution function, in the METS 1D all orders kinetic wave solver will be completed. The efficacy of various representations for the non-Maxwellian distributions – for example, as a weighted sum over known analytic functions – will be evaluated. The extended METS code will then be utilized to assess effects of various model non-Maxwellian distributions on wave absorption and mode conversion in 1D. In particular, changes in the wave propagation and absorption in plasmas with energetic beam distributions or with ICRF-driven tail distributions present will be evaluated in the1D limit.

The specific improvements and physics applications planned for FY2003 and FY2004 are listed below in the next section. Additional work scope to be completed under a subcontract to Mission Research Corporation with separate funding is described below in the section “Related Work”.

MILESTONE SCHEDULE AND EXPLANATION

FY 2002

- Include the effects of non-Maxwellian particle distribution functions, such as arise from neutral beam injection, fusion products, or rf-driven fast particle generation, in dielectric response functions used in the ICRF and lower hybrid modeling packages – September 2002

FY 2003

- Develop a module for the local dielectric tensor elements in 2D, assuming a general velocity space distribution function.

- Evaluate wave propagation and absorption processes in 2D for plasmas heated with high harmonic fast waves (HHFW) combined with neutral beam injection (NBI) in spherical tokamaks, using model velocity distributions obtained from stand-alone Fokker-Planck codes.

FY 2004

- Complete implementation of FLR-version of dielectric tensor elements with arbitrary velocity distributions, specialized for lower hybrid regime, in TORIC.

- Evaluate wave propagation and absorption in plasmas with ion cyclotron range of frequency (ICRF) heating combined with NBI in conventional tokamaks in 2D, using model velocity distributions obtained from stand-alone Fokker-Planck codes.

Impact of the Congressional Budget

The funding provided for this research in the Congressional Budget for FY 2003 is approximately 42% lower than the funding requested in the original RF SciDAC proposal. In FY2004, assuming flat funding, the funding shortfall is approximately 17%. As a result, most of the research centered on non-local modifications of wave absorption and propagation in 2D equilibria that is described below in the section, Related Work, will not be completed unless the funding is restored. Furthermore, development of integrated wave and Fokker-Planck solvers for self-consistent studies of the effects of non-Maxwellian particles, such as fusion alphas or neutral beam injected ions, on wave absorption processes will be delayed and probably not completed within the three year life of this project.

RELATED WORK

As indicated above, this research program is part of a collaborative effort between ORNL, PPPL, PSFC-MIT, Lodestar Research Corporation, and CompX Corporation. In addition to the work scope discussed above, specific additional research thrusts were identified which would be completed by Mission Research Corporation, under a subcontract to PPPL, paid for with additional funds from OFES beyond those currently provided in the budget for FY 2003 and FY 2004 accompanying this proposal. The MRC research will focus on the generalization of the plasma dielectric function operators to include effects of both 2D and 3D non-local equilibrium gradients. The funding level required for this subcontract is approximately $77K in FY 2003, and is approximately $53K in FY 2004, including direct and indirect costs.

In FY 2001 and FY 2002, MRC has completed upgrades to the plasma dielectric response function operator which includes effects of quasi-local equilibrium gradients, resulting in a substantial speedup in the computational time required for a simulation. MRC has also identified potentially efficient formulations for a non-local quasi-linear RF operator and has begun work to extend these operators to include effects of non-Maxwellian particle distribution functions. In the remainder of FY2002, the computationally improved parallel gradient plasma dielectric response operator will be installed in the parallelized METS 1D code. The resulting simulation package will be

used to evaluate the effects of strong local shear in the equilibrium magnetic field on wave propagation and absorption. For example, the effects of parallel magnetic field gradients on the ion absorption expected near the cyclotron harmonics in HHFW heating scenarios in the NSTX device will be evaluated.

The specific improvements and physics applications to be completed by Mission Research Corporation for FY2003 and FY2004 are listed in the milestones given below:

FY 2003:

- Complete inclusion of 2D non-local effects in AORSA-2D, in collaboration with ORNL

FY 2004:

- Extend the formulation of the generalized dielectric tensor to self-consistently include both non-local effects and non-Maxwellian particle velocity distribution functions.

- Evaluate differences in mode conversion and heating arising from 2D equilibrium magnetic field gradients, in collaboration with ORNL.

3132 SCIDAC WAVE PLASMAS 03/01/02			
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	1.0	1.0	.9
Engineers	.4	.2	
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	1.4	1.2	.9
OPERATING COSTS $(000):			
PPPL Labor	150.7	125.2	95.9
Subcontract Labor			
Overtime			
Travel	5.0	8.8	5.3
Energy			
Stockroom			
Miscellaneous Expenses	3.2		
Procurements/ICOs	45.0	3.1	3.1
Organizational Burden	13.4	9.1	7.1
Other			
General + Administrative	114.7	92.8	70.6
TOTAL OPERATING COSTS	332.0	239.0	182.0
TOTAL OPERATING OBLIGATIONS	203.0	239.0	182.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	332.0	239.0	182.0
GRAND TOTAL OBLIGATIONS	203.0	239.0	182.0

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3142	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
SciDAC: Global Simulation of Microturbulence	AT5020400

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
W. W. Lee Phone: 609-243-2647 Email: wwlee@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This research aims at the improvement of our Gyrokinetic Toroidal Code (GTC) for microturbulence research in toroidal plasmas. It is a part of the SciDAC Plasma Turbulence Project (W. M. Nevins, LLNL, PI) and is also funded in part by the Office of Advanced Scientific Computing Research (OASCR).

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

This workscope is intended to develop a global gyrokinetic particle code in general geometry for turbulence and transport studies in tokamaks and stellarators. The code utilizes modern day parallel supercomputers and visualization techniques.

BACKGROUND

PPPL has been the leader of gyrokinetic particle simulation and microturbulence studies in the community. Our GTC code is the state of the art global simulation code, which is capable to handle truly three-dimensional physics.

APPROACH

Our plan is to develop the multi-dimensional domain decomposition capability utilizing MPI and OpenMP as well as Parallel I/O for the GTC code, effectively linking with general geometry input and the AVS output. In addition, we will develop efficient multigrid algorithms for solving field equations and methods to incorporate electron dynamics as well as electromagnetic effects.

TECHNICAL PROGRESS

The following topics include areas of current technical progress and targets for technical accomplishments during FY 2002.

- 2D domain decomposition with ghost cells.
- Multigrid method for solving field equation in unstructured mesh.
- Development of split weight hybrid and kinetic schemes for electron and shear Alfven effects.
- Scaling trends in reactor size tokamaks.

MILESTONE SCHEDULE

FY 2003:

- Simulate trapped electron modes in global geometry.
- Investigate finite-beta modified ITG modes in global geometry.
- Zonal flow physics will be analyzed including non-adiabatic electrons and shear-Alfven physics.

FY 2004:

- Simulate Alfvenic ITG modes in global geometry.
- Transport issues (e.g., scaling, zonal flow physics, microtearing dynamics) will be addressed with the new physics models.

Realtionship to Other Projects

Activities in this workscope are complementary to those in the theory and other advanced scientific computing cost centers. Closer applications collaborations are also being developed with the NSTX and NCSX projects at PPPL.

3142 MICROTURBULENCE SIM 03/01/02				
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.7				
Engineers		.3		.3	
Administrators					
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	.7	.3		.3	
OPERATING COSTS $(000):					
PPPL Labor	90.5	39.7		41.5	
Subcontract Labor					
Overtime					
Travel		5.8		3.9	
Energy					
Stockroom					
Miscellaneous Expenses	1.0				
Procurements/ICOs					
Organizational Burden	7.2	2.8		2.9	
Other	.1				
General + Administrative	59.2	30.7		30.7	
TOTAL OPERATING COSTS	158.0	79.0		79.0	
TOTAL OPERATING OBLIGATIONS	129.0	79.0		79.0	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	158.0	79.0		79.0	
GRAND TOTAL OBLIGATIONS	129.0	79.0		79.0	

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3141	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Center for Extended Magnetohydrodynamic Modeling (CEMM) Code Development	AT5020400

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Stephen C. Jardin Phone: 609-243-2635 Email: sjardin@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This is the PPPL portion of the national Extended MHD Project funded by the Office of Fusion Energy Sciences through the SciDAC Program. PPPL is coordinating the entire CEMM workscope, and is particularly involved in development and application of the extended MHD code M3D.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The objective of the Center for Extended Magnetohydrodynamic Modeling project is to develop and deploy predictive computational models for the study of low, frequency, long wavelength fluid-like dynamics in the diverse geometries of modern magnetic fusion devices. This application has high programmatic relevance because MHD instabilities are responsible for disruptions and reconnections, which set limits for maximum current and pressure sustained by a magnetic confinement device. To enhance the predictive capability of the codes, significant improvement in the plasma models is needed, specifically in the direction of hybrid and particle-fluid models. Successful implementation will benefit from close collaboration with the computer science community.

BACKGROUND

This project was funded in FY2001 as part of a competitive competition in conjunction with the DOE SciDAC program.

APPROACH

The project web site can be viewed as w3.pppl.gov/CEMM. At Princeton, our major focus is on further development and application of the massively parallel 3D MHD code M3D.

FUTURE ACCOMPLISHMENTS

The emphasis at PPPL will be to extend and apply the M3D code. The specific improvements planned are:

- Implement field line tracing
- Parallel particle pushing on an unstructured mesh
- Implement field-line following coordinates
- Improve efficiency of elliptic solvers
- Refine system for code documentation and validation
- More general domain decomposition
- Quadratic bilinear elements
- Higher order elements
- 1D and 2D grid packing

MILESTONE SCHEDULE

FY 2003
Install parallel data transfer and customized collaborative visualization.

FY2004
Accommodate higher order elements, and 1D and 2D grid packing.

3141 CEMM		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	.9	.3	.2
Engineers		.3	.3
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	.9	.6	.5
OPERATING COSTS $(000):			
PPPL Labor	76.9	50.7	50.2
Subcontract Labor			
Overtime			
Travel			
Energy			
Stockroom			
Miscellaneous Expenses	1.8	.2	.7
Procurements/ICOs		.1	.1
Organizational Burden	6.2	3.5	3.5
Other	.2		
General + Administrative	50.9	34.5	34.5
TOTAL OPERATING COSTS	136.0	89.0	89.0
TOTAL OPERATING OBLIGATIONS	89.0	89.0	89.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	136.0	89.0	89.0
GRAND TOTAL OBLIGATIONS	89.0	89.0	89.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3115	0	03/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Transport Task Force	AT5020100

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER
Edmund J. Synakowski Phone: 609-243-2748 Email: esynakowski@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Coordinate and support annual meeting dedicated to Transport Task Force issues, support small working groups, and support break-out meetings at appropriate gatherings such as the APS/DPP annual meeting.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

3115 TRANSPORT TASK FORCE 03/01/02				
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists				
Engineers				
Administrators				
Graduate Students				
Technicians				
Clerical				
Subcontractors				
TOTAL FTEs				
OPERATING COSTS $(000):				
PPPL Labor				
Subcontract Labor				
Overtime				
Travel		2.2		2.2
Energy				
Stockroom				
Miscellaneous Expenses	17.0	10.0		10.0
Procurements/ICOs		.1		.1
Organizational Burden				
Other				
General + Administrative	10.2	7.7		7.7
TOTAL OPERATING COSTS	27.2	20.0		20.0
TOTAL OPERATING OBLIGATIONS	20.2	20.0		20.0
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	27.2	20.0		20.0
GRAND TOTAL OBLIGATIONS	20.2	20.0		20.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3110	0	3/1/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
National Transport Code Collaboration	AT5020400

6. WORK PROPOSAL TERM: Begin: 10/1/02 End: 9/30/04

7. CONTRACTOR WORK PROPOSAL MANAGER
Stephen C. Jardin /D.McCune Phone: 609-243-2635 Email: sjardin@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This work covers the PPPL contribution to the National Transport Code Collaboration (NTCC). The primary PPPL program activity in FY 2000 and FY 2001, the last years this task was funded, has been to maintain and contribute to the modules library.

PPPL proposes to make a predictive version of the PPPL TRANSP code, P-TRANSP, available to the community, if incremental funding is provided. This would leverage the ongoing SciDAC Fusion Collaboratory work enabling Globus/GRID access to TRANSP for experimental data analysis run as a service run on PPPL computers. This service would be extended to the theory/modeling community for predictive TRANSP runs. The service would be closely supported by the PPPL Computational Plasma Physics Group

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

Modules Library.

We recognize that there are likely to be many transport codes in our community for the foreseeable future. The user should be free to choose the one best suited for his/her needs. These codes should be able to share their best physics packages as modules via the modules library. The modules will thus benefit all codes, and all code users. Also, as individual codes become dormant, and as key code developers retire or leave our field, there is a need to preserve the key modules so that this capability is not lost.

P-TRANSP.

Predictive TRANSP (P-TRANSP) would be maintained and supported as a service to the plasma physics research community—accessible from Fusion Collaboratory client software without requiring local download, installation or maintenance of this 1,000,000 line code. TRANSP currently combines code components from the Modules Library to form a comprehensive modeling capability for tokamak and spherical torus experimental data analysis; this is being augmented to provide a comprehensive predictive modeling capability as well. The entire operation—code development and maintenance, user support, and trouble-shooting, would be provided to the national fusion community as a PPPL service supported by expert PPPL staff.

BACKGROUND

Modules Library.

We have worked with others in the NTCC Modules Library Committee to set-up the fusion modules library in such a way as to provide convenient, documented access to widely used MFE code modules conforming to good programming standards. The library has now been operational for several years. It can be viewed on *http://w3.pppl.gov/NTCC*. This web site also has download and submit capabilities available.

P-TRANSP.

The NTCC originally planned to provide an independently developed comprehensive predictive modeling code, but this plan has been shelved due to the high cost of building a new code. The TRANSP code, which is heavily used by the major tokamak experimental programs for data analysis applications, as well as NSTX, has long had a predictive capability, mainly used by experimentalists to plan research on existing devices, rather than to do predictive modeling for future devices. The extensions needed to enable TRANSP to operate as a full featured prescribed boundary predictive modeling code, applicable to future experiments, are relatively straightforward and inexpensive. The larger issue has always been one of a long-term commitment of an experimental group to support the *use* of TRANSP for this purpose.

Historically there has also always been the practical difficulty of installing and supporting such a large code at remote sites—especially university sites with minimal Unix systems support—but these problems are now being solved by the SciDAC Fusion Collaboratory, which will allow P-TRANSP to run as a service at PPPL, not requiring local installation

other than minimal client software: MDSplus, Globus client, and some NTCC Modules Library tools.

APPROACH

Modules Library.

A library of code modules has been developed under the auspices of the National Transport Code Collaboration (NTCC). Code modules are software packages which implement numerical physics models, or perform necessary ancillary functions such as i/o or graphics, or provide tools for dealing with common issues in scientific programming such as portability of Fortran codes. Code modules are submitted by researchers in the plasma physics community, and then reviewed for adherence to programming and documentation standards. All code modules come with source code and clear instructions for compilation of binaries on a variety of target architectures. The goal of the project is to develop a resource of value to builders of transport codes.

P-TRANSP.

Modules important to predictive modeling, such as the GLF23 and MMM95 packages which give "critical gradient" models (and other physics features) for thermal diffusivity, will be integrated into TRANSP. TRANSP grids and solvers will be updated as required to accommodate these packages (no fundamental difficulty expected here). Client software will be developed (or existing software enhanced) to aid the setup of predictive modeling scenarios, e.g. specification of plasma boundary, auxiliary heating and current drive, boundary conditions, etc. Because the SciDAC Collaboratory mechanism allows the actual P-TRANSP jobs to run on PPPL systems carefully tuned for this purpose, any difficult situation arising at runtime will be solvable at PPPL by PPPL expert staff without a requirement for travel or the purchase of expensive licensed software such as might be needed for debugging at a remote site.

TECHNICAL PROGRESS

Modules Library.

We have overseen the insertion of several new modules into the modules library and assisted users of this library. Utilizing uncosted funds from FY 2001, we have begun the conversion of the TRANSP MC Neutral Beam package to module form (with Lehigh University) and expect that to be completed by the end of FY02. We have also begun the conversion of the TRANSP ICRF Spruce and TORIC codes to module form.

P-TRANSP.

Versions of GLF23 and MMM95 have been installed into P-TRANSP, along with an enhanced solver, and these are being tested, with careful benchmarking against the PPPL TSC free boundary predictive transport code. A multi-impurity multi-charge-state predictive radiative loss model has been added to the code. As the TRANSP fast ion package modules are fully separated from the main TRANSP framework, the spatial resolution of the code will be increased (expected to be completed by early in the next FY).

FUTURE ACCOMPLISHMENTS

If incremental funding is approved for P-TRANSP, then P-TRANSP development will continue, and the code will be deployed as a Fusion Collaboratory service.

MILESTONE SCHEDULE

FY 2003

- Benchmark P-TRANSP against BALDUR and other existing predictive codes as requested.
- Increase P-TRANSP radial resolution; carry out other prediction-motivated TRANSP enhancements as requested.

FY 2004

- Add density prediction capability including pellet injection.

RELATIONSHIP TO OTHER PROJECTS

PPPL is a member of the National Transport Code Consortium and the activities described herein are done in coordination with them. This work supports all the research areas in the fusion program.

3110 NATL TRANSPORT CODE	03/01/02			
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists				
Engineers	.4		.9	.9
Administrators				
Graduate Students				
Technicians				
Clerical				
Subcontractors				
TOTAL FTEs	.4		.9	.9
OPERATING COSTS $(000):				
PPPL Labor	45.1		102.1	106.7
Subcontract Labor				
Overtime				
Travel			9.0	5.0
Energy				
Stockroom				
Miscellaneous Expenses				
Procurements/ICOs			4.7	3.6
Organizational Burden	4.2		7.1	7.5
Other				
General + Administrative	29.6		76.8	77.0
TOTAL OPERATING COSTS	78.9		199.7	199.8
TOTAL OPERATING OBLIGATIONS	-.0		199.7	199.8
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	78.9		199.7	199.8
GRAND TOTAL OBLIGATIONS	-.0		199.7	199.8

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1313	0	3/01/02

4. WORK PROPOSAL TITLE:
Offsite University Research Support

5. BUDGET AND REPORTING CODE
AT5015020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Stewart Zweben Phone: 609- 243-3243 Email: szweben@pppl.gov

8. HEADQUARTERS ORGANIZATION:
Office of Science

11. DOE HQ ORGANIZATION CODE:
SC

9. OPERATIONS OFFICE:
Chicago Operations Office

12. DOE OPS OFFICE ORGANIZATION CODE:
CH

10. CONTRACTOR NAME:
Princeton University
Princeton Plasma Physics Laboratory

13. CONTRACTOR CODE:
15

14. WORK PROPOSAL DESCRIPTION:

This program applies PPPL's expertise in plasma science and technology to support a broad range of US University research programs in fusion energy and plasma science. The main purpose is to help these University groups succeed with their programs. At the same time, new ideas and results from these Universities are also brought back to PPPL, which benefits our programs.

Signature:
15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Approach:

The basic approach is to offer "scientific outreach" to a broad range of University fusion and plasma science programs, with preferential support for smaller Universities and small groups which could most benefit from PPPL's help. All OFES efforts, including innovative concepts in MFE and IFE, can be supported through this program. In addition, some support will be given to basic and applied plasma science groups which are not presently funded by OFES, in order to help increase communication with other science programs (such as those funded by NSF and NASA).

Specifically, this program will provide funding for PPPL scientists and engineers to assist and collaborate with Universities in such areas as: experimental design, diagnostics, data acquisition and analysis, plasma heating systems, engineering, and theory. It is expected that each of these University support projects will have a timescale of about 3 years for completion of its initial scope.

Technical Progress FY '01-'02 (Highlights):

About 25 University research projects were supported through this program in FY '01-'02, including many new projects started in these years. Highlights of the technical progress for a few of these projects are below. The principal University contact people are shown in parenthesis.

Auburn (Knowlton): PPPL provided engineering support in developing the design of the CTH device. A design concept for the stellarator core, including the vacuum vessel, helical coils, and support structure was developed. Structural analysis of the vacuum vessel and helical coil was performed. Drawings and 3D models were generated to provide a basis for the procurement of the vacuum vessel and helical coils.

Augsburg University (Engebretson): PPPL provided Prof. Engebretson with theoretical calculations relevant to ion cyclotron wave propagation in the magnetosphere/ionosphere, which can be used to interpret his satellite/ground wave studies. Prof. Engebretson has also suggested a number of interesting topics of interest to his current research, which we are currently exploring.

Berkeley (Wurtele): PPPL installed the XOOPIC code (developed by UCB for the problems of relevance to inertial confinement fusion) on the puffin cluster at PPPL to benchmark the results against a PPPL fluid code. A new area of research was initiated relating to modeling plasma using a thin-wire metamaterial. Potential applications include novel accelerating structures and "perfect" microwave lenses.

Columbia (Pedersen): PPPL provided engineering support in developing a design concept for the Columbia non-neutral torus experiment. Plasma configurations generated by using simple, planar coil systems were investigated. The proposed concept features two interlocked, circular coils and two pairs of circular PF coils. A Pro/Engineer model of the stellarator core was generated.

Maryland (Hassam/Ellis): PPPL provided extensive engineering analysis and coil design support for the MCX experiment being built at Maryland, and also provided advice and assistance on wall conditioning and vacuum systems for their experiment.

Prairie View A&M (Huang): PPPL engineers and technicians helped Prairie View to evaluate the assembly of their rotamak and determine what equipment they needed. PPPL loaned them excess vacuum related items including a turbo and forepump and some oscilloscopes, and a PPPL RF expert suggested ways to improve their RF systems.

Future Accomplishments (FY '02-'03):

The plan for this program in FY '03 and FY '04 is to continue to support a broad range of about 25 University research programs, with preferential support for "scientific outreach" to smaller University groups. Since many new projects were started in FY '01-'02, the emphasis in FY '03 and '04 will be to continue and complete these projects wherever possible. The University support list for FY '02 is given below, with the University contact person.

University Name	University Contact	Topic of PPPL Support
1) Alaska	Otto	MHD in magnetopause
2) Auburn	Knowlton	Engineering for CTH
3) Auburn	Lin	Parallel simulation
4) Augsburg	Engebretson	Waves in magnetosphere
5) Berkeley	Shvets/Kaganovich	Particle-in-cell code
6) Chicago	Rosner	Magnetic reconnection
7) Columbia	Mauel/Navratil	HBT-EP diagnostic
8) Columbia	Sen	Linear Machine
9) Columbia	Boozer	Stellarator coil calculations
10) Columbia	Pederson	Non-neutral stellarator design
11) Houston	Economou	Ion-ion plasmas
12) Illinois	Ruzic	Helicon plasmas and liquid metals
13) Johns Hopkins	Wing	Space physics
14) Lehigh	Kritz/Bateman	Transport simulations
15) Maryland	Hassam/Ellis	Support for MCX
16) Maryland	Drake	Magnetic reconnection
17) Michigan	Keidar	Plasma thrusters
18) MIT/Columbia	Kesner/Mauel	LDX diagnostics
19) NJIT	Wang/Gary	Solar magnetism
20) Prairie View	Huang	Rotamak experiment

21) Swarthmore	Brown	Magnetic reconnection
22) UCLA	Taylor	ET tokamak
23) UCLA	Abdou	Liquid metal MHD
24) UCLA	Morely	MTOR engineering
25) UCLA	Stenzel	Electron MHD physics
26) UCSD	Antar	Liquid gallium physics
27) UCSD	Tynan	Turbulence analysis
28) Wisconsin	Prager	MST experiments

Milestones Schedule and Explanation of Milestones:

FY 2002:
12/01 - Define list of Universities which will be supported in FY '02
5/02 - Add additional University programs or increase support for some programs if budget is available

FY 2003:
12/02 - Define list of Universities which will be supported in FY '03
5/03 - Add additional University programs or increase support for some programs if budget is available

FY 2004:
12/03 - Define list of Universities which will be supported in FY '04
5/04 - Add additional University programs or increase support for some programs if budget is available

Incremental Requests:

$100K/year for FY 2003 and FY 2004 to increase specific programs as indicated below.

Since many new University support projects were added in FY '01-02, the incremental requests for FY '03 and '04 will concentrate on increasing the level of support for those existing projects that could not be adequately supported from the baseline budget. An additional $100K is requested to significantly increase the level of support for about three of the University groups already within the list of Universities supported in FY '01. Good candidates for such increased support are:

Prairie View A&M – technical support for construction of rotamak
Columbia - construction assistance for non-neutral stellarator
Maryland – construction assistance and diagnostic support for MCX

For FY 2004 additional support may be provided to different projects than those noted above from the list of FY '02 baseline support projects.

$200K/year for FY 2003 and FY 2004 to support the ET program at UCLA.

The ET program at UCLA is well underway and is operating with relatively long pulses with startup plasma parameters as expected for the initial phase of operations. The emphasis now is on pushing the plasma beta to higher values in order to study the parameters of the ET regime with a strong magnetic well. As part of this effort to put more power into the plasma, ORNL is proposing providing an ITER-like antenna, which can be used for HHFW heating. This antenna can be powered to start with the 80 MHz source already installed at UCLA up to the 1 MW level and ultimately with a new 2 MW source, if warranted by these explorations. PPPL can add substantially to this HHFW effort in FY03 by helping to bring up the 80 MHz system to routine 1 MW operation. As additional support of the innovative concept study on ET, PPPL would investigate adding Thomson scattering receivers to the UCLA Thomson scattering system to increase the number of radial points for the critical temperature and density profiles. PPPL would also explore other diagnostic techniques, which could help measure the critical parameters which define the ET performance - such as flow and flow shear accompanying the strong radial electric fields, magnetic well, etc.

PPPL can also provide a separate power supply for the 80 MHz system in FY04 so that the second harmonic and HHFW systems can be run simultaneously to obtain maximum beta with up to 3 MW total RF power. This second power supply would then serve as the first component of a new 2 MW source which can be added with ~ $1.5 M as part of the ET renewal proposal if the results in FY03-04 show promise that the ET regime is supportable as a POP experiment for the electric toroidal confinement concept.

1313 OFFSITE UNIV SUPPORT 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	1.8	2.0	.6	2.0	.6
Engineers	.4	.3	.1	.3	.1
Administrators					
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	2.2	2.3	.7	2.3	.7
OPERATING COSTS $(000):					
PPPL Labor	338.1	361.9	98.0	378.3	102.4
Subcontract Labor					
Overtime					
Travel	36.2	46.8	10.0	41.2	8.0
Energy					
Stockroom	1.1	1.1		1.1	
Miscellaneous Expenses	13.5	17.6		7.3	
Procurements/ICOs	27.7	48.5	80.4	45.6	77.9
Organizational Burden	48.7	48.1	8.6	50.2	8.2
Other		.5	.1	.4	.2
General + Administrative	279.0	323.5	102.9	323.9	103.3
TOTAL OPERATING COSTS	744.3	848.0	300.0	848.0	300.0
TOTAL OPERATING OBLIGATIONS	750.0	848.0	300.0	848.0	300.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	744.3	848.0	300.0	848.0	300.0
GRAND TOTAL OBLIGATIONS	750.0	848.0	300.0	848.0	300.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2130	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Current Drive Experiment-U	AT6010301

6. WORK PROPOSAL TERM: Begin: 10/1/02 End: 9/30/04

7. CONTRACTOR WORK PROPOSAL MANAGER:
Richard P. Majeski Phone: 609-243-3112 Email: rmajeski@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The research on the Current Drive Experiment-Upgrade (CDX-U) spherical torus (ST) is funded under the fusion technology program as part of the Advanced Liquid Plasma facing Surfaces (ALPS) liquid metal divertor program. This program is related to the liquid walls effort of the Advanced Power Extraction (APEX) program.

The overall CDX-U program goal is to investigate the interaction of an ST plasma with liquid lithium limbers, and large area lithium divertor targets. The effects – potentially both beneficial and deleterious – of operating with lithium walls are being quantified for the first time in CDX-U, thus reducing the uncertainties in planning for liquid lithium walls in a large, ST, advanced tokamak, or other reactor design.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

In FY02, the following activities related to lithium will be completed.

1. Replacement of the present toroidal liquid lithium limiter tray with a new tray.
2. Deployment of a system to fill the tray with liquid, rather than solid lithium. This system is under development by the UCSD PISCES group.
3. Implementation of improved discharge cleaning techniques for the lithium tray fill.
4. Begin installation of gas puff systems, which fuel inside the last closed flux surface.
5. Determination of recycling on the resultant larger area, clean liquid lithium surface.
6. Completion of the upgraded chopper-based ohmic system power supply.

This work will lead to the following activities in FY03 and FY04.

1. Further implementation of core fueling techniques in FY03.
2. Design and construction of a recirculating liquid lithium limiter in FY03.
3. Begin experiments with the recirculating limiter in FY04.
4. Design for diverted operation. Divertor implementation will be delayed until FY05 under the present budget.

This effort will build on the experience gained from all the elements of the Advanced Liquid Plasma-facing Surface (ALPS) program. The work will be carried out in conjunction with experimental and theoretical collaborations with the plasma-materials interaction community.

PURPOSES AND GOALS

The concept of a lithium first wall for a fusion reactor may lead to a significant advance in reactor design. A flowing liquid lithium first wall or divertor target could virtually eliminate the concerns with erosion, tritium retention, and cooling associated with solid walls. A fast flowing liquid lithium wall in close proximity to the last closed flux surface may significantly increase the operational beta limit and core confinement of a tokamak plasma [L Zakharov, Bull. Am. Phys. Soc. **44** 1999) 313]. Finally, the beneficial effect of lithium wall coatings on confinement was noted during the TFTR D-T experiments [D K Mansfield et al., Phys. Plasmas 3 (1996) 1892].

The CDX-U program in large-area liquid lithium plasma-facing components (PFCs) is the only experimental program of its kind in the world. Experiments utilizing a large-area liquid lithium toroidal tray limiter began in CDX-U during FY01. The primary goal of the FY01 experiments was a first assessment of the compatibility of a toroidal liquid lithium limiter with tokamak operations; this compatibility has now been demonstrated. The remaining technology program objectives for the CDX-U liquid lithium PFC program are:

1. Determination of the irreducible minimum recycling of hydrogenic plasmas on a clean liquid lithium surface.
2. Quantify the plasma performance enhancement provided by an enlarged, clean liquid lithium surface.
3. Investigate flowing liquid lithium limiter and divertor target systems.
4. Investigate the effect of high localized heat flux (5 - 10 MW/m^2) on the lithium in the tray limiter and divertor targets.
5. Investigate motion of the liquid lithium produced by J x B forces due to plasma motion or disruptions during divertor operation.

The CDX-U experiments will continue to involve many collaborators from the ALPS/APEX community. The major collaboration during FY02 will be the new liquid lithium filling system for the replacement tray, which is under development by the UCSD PISCES group. There is also participation by the Oak Ridge National Laboratory (ORNL) in modeling, diagnostics, and fueling, and Sandia National Laboratory (SNL) in wall coupon analysis, diagnostics, and experimental participation. Lawrence Livermore National Laboratory (LLNL) is performing modeling of the edge plasma and fueling. The spectroscopy group at the Johns Hopkins University remains a major collaborator on CDX-U. The design of the flowing lithium limiter/divertor target system will involve the liquid walls group at UCLA. Coordination with ALPS occurs through the Argonne National Laboratory (ANL), and the connection with the APEX effort is through the University of California at Los Angeles (UCLA). These collaborations will continue through FY03-04.

APPROACH

FY03: CDX-U began investigations in FY01-02 using an axisymmetric, lithium filled shallow trough or tray as a primary limiter of the tokamak discharge. These experiments have yielded data, which indicate that plasma recycling is very low on liquid lithium. Lowered recycling in combination with an associated reduction in discharge impurities was also shown to be strongly correlated with significant improvements in the CDX-U discharge reproducibility and performance when liquid lithium PFCs are used. However, the lithium filling the tray at present is not uniformly distributed, nor is it free of surface coatings. Much of the effort in FY02 will focus on providing a cleaner, more uniform liquid lithium surface as a PFC, in the expectation that further reductions in recycling and improvements in performance will result. In the first half of FY03 experiments with a

second-generation static-fill toroidal tray will continue while an internally recirculating (flowing) lithium limiter is designed.

In FY03:

1. Research into cleaning techniques which produce a better conditioned lithium surface will be continued.
2. Gas puffing systems which fuel the plasma inside the last closed flux surface will be designed and tested.
3. Internally recirculating lithium limiter systems will be evaluated.

FY04: The primary CDX-U missions for FY04 will be to introduce operation with a recirculating lithium limiter. The recirculating lithium limiter will provide a demonstration of MHD drive technology in a working tokamak, a test of the behavior of flowing lithium in the presence of time-varying vacuum and plasma fields, and a physics investigation into plasma edge behavior with a freshly formed lithium surface.

Also during FY04, poloidal field systems for producing a diverted discharge will be designed and constructed.

TECHNICAL ACCOMPLISHMENTS

The highlight of FY01-02 was the installation and first operation of the toroidal liquid lithium tray limiter. Several problems were encountered during commissioning of the new limiter, including difficulties in obtaining a uniform fill, in discharge cleaning surface coatings, and in mobilization of lithium particulate due to unipolar arcing in the tokamak edge as the lithium surface is “conditioned”. Despite these problems:

1. Discharges initiated with liquid lithium as a primary PFC show remarkable consistency in terms of high maximum plasma current, compared to discharges initiated with either the bare stainless tray or the solid (room temperature) lithium-filled tray.
2. Discharges, which utilized liquid lithium in the tray, showed a lower level of oxygen impurities in the discharge than comparable discharges with solid lithium in the tray. Discharges with solid lithium in the tray showed lower oxygen levels than discharges initiated using the bare stainless steel tray as a limiter.

3. No evidence whatever of poloidal field or plasma induced motion of the bulk liquid lithium was obtained. Unipolar arcing to the tray surface during tokamak discharges did however mobilize fine particles of lithium to coat the lower vacuum vessel heat shield.

Extensive experience has also been gained on the use of large-area liquid lithium surfaces as plasma-facing components. As a result of this experience and advice from the remainder of the ALPS/APEX community, the CDX-U program has been rearranged. There is now increased emphasis on cleanliness of the lithium surface and early implementation of a large-area flowing lithium system. Divertor operation has been accordingly delayed.

PUBLICATIONS AND STUDENT TRAINING

Since the last field work proposal, there have been nine publications and journal submissions from the CDX-U group (five journal articles, including a Physical Review Letter, three papers in conference proceedings, and one PPPL report). Presentations were made at the American Physical Society Division of Plasma Physics meeting, the Symposium on Fusion Engineering, and the Innovative Confinement Concepts meeting. Two Ph. D. theses based on work on CDX-U were defended, one by a Princeton University student and one by a student from Johns Hopkins University. A third Ph.D. defense (Princeton University) is expected in Spring 2002, while a fourth student is working on his dissertation research. CDX-U also hosted students from the National Undergraduate Fellowship program, and is currently hosting two Drexel University co-op students.

EXPECTED PROGESS IN FY03-04

The program in FY03-04 will be to extend the work with liquid lithium plasma-facing components to cleaner lithium surfaces, which uniformly fill the 2000 cm^2 tray limiter. Following the work with static lithium limiters, a flowing lithium limiter which uses internally recirculated liquid lithium will be implemented and investigated. Following the implementation of the recirculating limiter, diverted operation will be investigated.

FY03-04 TASKS

This schedule assumes a budget of $708k for each of FY03 and 04, in accordance with the guidance received. If the budget is restored to the requested level of $800k for FY03 and FY04, then the recirculating liquid lithium limiter will be installed in FY03 rather than FY04. This will permit an assessment of the compatibility of flowing liquid lithium surfaces with tokamak operation prior to proceeding with an assessment of a liquid lithium system on NSTX. This would be an important experimental input to the assessment. Furthermore, this funding level will permit divertor operation to commence in FY04 rather than FY05.

The tasks to be undertaken in FY03 at the current guidance level are therefore:

1. Continued tests of DC, AC, and RF glow discharge cleaning techniques to ensure surface cleanliness of the liquid lithium during tokamak operations.
2. Fueling of the plasma will be accomplished within the last closed flux surface, on either the high field or low field side (or both).
3. A flowing liquid lithium limiter system will be designed and constructed.

Tasks for FY04:

1. The flowing liquid lithium limiter system will be installed and operated as a plasma limiter.
2. Divertor systems will be prepared for operation in FY05.

MILESTONE SCHEDULE FOR FY02	Date complete
Complete initial investigation of recycling in core-fueled discharges	June 2002
Install replacement lithium tray in CDX-U	April 2002
Commence long pulse operation	September 2002

MILESTONE SCHEDULE FOR FY03-04

Activity	Date complete
Complete investigation of recycling and impurity production on clean, well conditioned liquid lithium surfaces	June 2003
Complete construction of internally recirculating liquid lithium limiter	September 2003
Install recirculating limiter	December 2003
Modify poloidal field systems for diverted operation	August 2004
Complete limited plasma experiments with the recirculating lithium limiter	September 2004

2130 CDXU		03/01/02		
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists	.9	.7		.7
Engineers	.5	.1		.1
Administrators				
Graduate Students	.5	.5		.5
Technicians	1.1	1.1		1.1
Clerical				
Subcontractors				
TOTAL FTEs	3.0	2.4		2.4
OPERATING COSTS $(000):				
PPPL Labor	269.1	218.5		228.3
Subcontract Labor				
Overtime	23.5	30.2		32.0
Travel	8.0	14.0		14.0
Energy				
Stockroom	5.0	18.8		15.0
Miscellaneous Expenses	7.1	6.5		6.0
Procurements/ICOs	148.1	130.1		118.6
Organizational Burden	47.1	36.3		37.9
Other		2.0		2.1
General + Administrative	258.3	251.6		254.1
TOTAL OPERATING COSTS	766.2	708.0		708.0
TOTAL OPERATING OBLIGATIONS	749.2	708.0		708.0
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	766.2	708.0		708.0
GRAND TOTAL OBLIGATIONS	749.2	708.0		708.0

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FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
4501	0	2/11/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Heavy Ion Fusion	AT 50 15 03 3 / AT 60 10 50 2

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Ronald C. Davidson Phone: 609-243-3552 Email: rdavidson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

The long-term objective of the U.S. heavy ion fusion program is to provide a comprehensive scientific knowledge base and the enabling technologies required for inertial fusion energy driven by high-brightness heavy ion beams.

The research described in this field work proposal for FY 2003-2004 will be carried out in close collaboration with the inertial fusion energy community through PPPL's integrated participation in the Heavy Ion Fusion Virtual National Laboratory.

Under the auspices of the proposed research, we will carry out a vigorous theoretical and computational program to investigate the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of heavy ion beams, and beam-plasma interactions in the target chamber. Particular emphasis will be placed on the following task areas:

(a) Develop improved kinetic models to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems; (b) Investigate collective instabilities in intense heavy ion beams, and identify optimum beam distributions and parameter regimes for stable beam propagation; (c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream and filamentation instabilities; (d) Develop robust numerical models of beam compression dynamics and nonlinear beam dynamics in the final focus system; (e) Develop self-consistent theoretical models of charge and current neutralization, benchmarked against simulation and experimental results; (f) Explore collective mechanisms for halo formation, and identify operating regimes that minimize the production of halo particles; and (g) Apply the 2D and 3D nonlinear delta-f simulation method to augment and validate the analytical studies, with particular emphasis on collective instabilities, halo formation and control, and emittance growth. Explore the influence of three-dimensional effects on stability behavior including beam-plasma interactions in the target chamber and ion-electron two-stream processes in the transport lines.

It is also proposed to carry out a vigorous program that makes use of PPPL's considerable experimental and engineering design capabilities to investigate several critical problems related to beam propagation and beam-plasma interactions in the target chamber. The proposed research will include:

(h) Development and application of rf techniques for formation of preionized plasma in the Neutralized Transport Experiment. Experimental investigations of beam-plasma interactions; (h) Measurements of multielectron loss events for intense ion beam propagation through background gas, including detailed comparison with theoretical models; (i) Design, fabrication and testing of high-gradient induction test modules; and (j) Vacuum pumping analysis for final focus interface with the target chamber.

14. Signature

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Contractor Work Proposal Manager

15. Human/Animal Subjects: No

Heavy Ion Fusion

A. Purpose and Goals

The long-term objective of the U.S. heavy ion fusion program is to provide a comprehensive scientific knowledge base and the enabling technologies required for inertial fusion energy driven by high-brightness heavy ion beams.

A fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-brightness (high-current and low-emittance) heavy ion beams is essential to the identification of optimal operating regimes in which emittance growth and beam losses are minimized in periodic focusing accelerators and transport systems for heavy ion fusion. A major objective of the proposed research is to develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense nonneutral beams propagating in periodic focusing accelerators and transport systems, and to identify and mitigate the effects of collective beam-plasma interactions in the target chamber. A second major objective of the proposed research, building on PPPL's considerable experimental capability, is to investigate the effects of multielectron loss events, develop techniques for preionized plasma formation, and study collective beam-plasma interactions in the target chamber. A third major objective of the proposed research, building on PPPL's engineering design capabilities, includes investigations of pulse compression, nonlinear beam optics, and the development of engineering design concepts and test facilities for next-generation experimental facilities.

The proposed research will be carried out in close collaboration with the heavy ion fusion community, particularly through PPPL's integrated participation in the Heavy Ion Fusion Virtual National Laboratory.

Under the auspices of the proposed research, we will carry out a vigorous theoretical and computational program to investigate the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of heavy ion beams. Particular emphasis will be placed on the following task areas relevant to heavy ion fusion:

(a) Develop improved kinetic models based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems.

(b) Investigate collective instabilities in intense heavy ion beams, and identify optimum beam distributions and parameter regimes for stable beam propagation.

(c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream and filamentation instabilities.

(d) Develop robust numerical model of beam compression dynamics and nonlinear beam dynamics in final focus system.

(e) Develop self-consistent theoretical models of charge and current neutralization for intense beam propagation in the target chamber, benchmarked against simulation and experimental results.

(f) Explore mechanisms for halo formation through detailed comparisons between theory, simulation, and experiment. Identify operating regimes that minimize the production of halo particles.

(g) Apply the 2D and 3D nonlinear δf-simulation schemes to augment and validate the analytical studies in (a)–(f) above, with particular emphasis on collective instabilities, halo

formation and control, and emittance growth. Explore the influence of three-dimensional effects on stability behavior, including beam-plasma interactions in the target chamber, and two-stream instabilities in the beam transport lines.

Under the auspices of the proposed research, we will also carry out a vigorous experimental program that makes use of PPPL's considerable experimental capabilities and off-site research facilities, including the Neutralized Transport Experiment (NTX), to investigate several critical problems related to beam propagation and beam-plasma interactions in the target chamber. These activities include:

(h) Development and application of rf techniques for formation of preionized plasma in the NTX experiment. Experimental investigations of beam-plasma interactions.

(i) Measurement of multielectron loss events for intense ion beam propagation through background gas. Detailed calculations of cross-sections, including benchmarking against experiment.

(j) Feasibility study of developing a heavy ion neutral beam driver based on the acceleration of negative ions.

In FY 2003 and 2004, PPPL proposes increased efforts in areas (b)–(i) above, and also proposes an increased effort in PPPL's engineering design activities initiated in FY 2001 and FY 2002 under the auspices of ARIES support. These activities include:

(k) Configuration and engineering design studies of final focus magnet system.

(l) Vacuum pumping analysis for final focus interface with the target chamber.

Also proposed for increased PPPL engineering effort in FY 2003 and FY 2004 are:

(m) Design, fabrication and testing of advanced, short-pulse high-gradient induction test modules for next-generaton heavy ion fusion experiments.

(n) Design and fabrication of scaled drift compression line for upgrade of the Neutralized Transport Experiment (NTX).

As noted earlier, this research will be carried out through PPPL's integrated participation in the Heavy Ion Fusion Virtual National Laboratory.

B. Approach

It is critical to develop an improved theoretical and experimental understanding of the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of high-brightness (high-current *and* low emittance) ion beams in heavy ion fusion research, as well as beam-plasma interactions in the target chamber. Development of an improved understanding will play an important role in identifying optimal operating regimes in which emittance growth and beam losses are minimized in the acceleration and beam transport regions, and the effects of beam-plasma interactions are mitigated in the target chamber.

PPPL has developed a strong theoretical capability in analytical and numerical studies of the equilibrium, stability and transport properties of intense heavy ion beams propagating in periodic focusing transport systems using a kinetic treatment based on the nonlinear Vlasov-Maxwell equations. Under the auspices of the proposed research, we will carry out a vigorous theoretical and computational program to investigate the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of heavy ion beams, and beam-plasma interactions in the target chamber. During FY 2003–FY 2004, particular emphasis will be placed on the following task areas relevant to heavy ion fusion:

(a) Develop improved kinetic models based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems.

(b) Investigate collective instabilities in intense heavy ion beams, and identify optimum beam distributions and parameter regimes for stable beam propagation.

(c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream and filamentation instabilities.

(d) Develop robust numerical model of beam compression dynamics and nonlinear beam dynamics in final focus system.

(e) Develop self-consistent theoretical models of charge and current neutralization for intense beam propagation, benchmarked against simulation and experimental results.

(f) Explore mechanisms for halo formation through detailed comparisons between theory, simulation, and experiment. Identify operating regimes that minimize the production of halo particles.

(g) Apply the 2D and 3D nonlinear δf-simulation schemes to augment and validate the analytical studies in (a)–(f) above, with particular emphasis on collective instabilities, halo formation and control, and emittance growth. Explore the influence of three-dimensional effects on stability behavior, including beam-plasma interactions in the target chamber, and two-stream instabilities in beam transport lines.

Under the auspices of the Heavy Ion Fusion Virtual National Laboratory we have also initiated a vigorous experimental program that makes use of PPPL's considerable experimental and engineering design capabilities to investigate several critical problems related to beam propagation and beam-plasma interactions in the target chamber. During FY 2003 – FY 2004, the proposed research activities will include:

(h) Development and application of rf techniques for formation of preionized plasma in the Neutralized Transport Experiment (NTX). Experimental investigations of beam-plasma interactions.

(i) Measurement of multielectron loss events for intense ion beam propagation through background gas. Detailed calculations of ionization cross-sections, including benchmarking against experiments.

(j) Feasibility study of developing a heavy ion neutral beam driver based on the acceleration of negative ions.

(k) Configuration and engineering design studies of final focus magnet system.

(l) Vacuum pumping analysis for final focus interface with the target chamber.

(m) Design, fabrication and testing of advanced, short-pulse high-gradient induction test modules for next-generaton heavy ion fusion experiments.

(n) Design and fabrication of scaled drift compression line for upgrade of the Neutralized Transport Experiment (NTX).

As noted earlier, this research will be carried out through PPPL's integrated participation in the Heavy Ion Fusion Virtual National Laboratory, including the use of facilities at LBNL for the experimental investigations in Task area (h) above.

C. Technical Progress

Under the auspices of the present contract, we have conducted vigorous theoretical and numerical investigations of a wide range of beam dynamics problems related to heavy ion

fusion, and have also initiated an experimental program that investigates a variety of critical problem areas related to beam propagation and beam-plasma interaction in the target chamber. Through PPPL's integrated participation in the heavy ion fusion Virtual National Laboratory, we have also established collaborative ties with the heavy ion beam researchers at Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory.

The investigations carried out under the auspices of the present contract have included, for example: (a) development and application of a kinetic formalism based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense ion beams propagating through a periodic focusing lattice; (b) development of a self-consistent theoretical model describing nonlinear charge and current neutralization of an intense ion beam pulse in a pre-formed plasma; (c) kinetic investigations of collective two-stream interactions based on the Vlasov-Maxwell equations; (d) investigations of chaotic particle dynamics and phase-space structure for intense beam propagation in a periodic focusing lattice, including the implications for halo formation; (e) evaluation of ionization cross-sections in energetic ion-atom collisions and application to multielectron loss events; (f) development and application of 3D multispecies nonlinear perturbative particle simulation code for investigation of collective processes, including two-stream instabilities and anisotropy-driven instabilities, in intense charged particle beams; (g) development and application of a macroscopic warm-fluid model to describe intense beam propagation and stability properties; (h) fabrication and testing of an rf source in the 10^{-4} Torr range for preionized plasma formation for beam-plasma interaction experiments planned at LBNL; and (i) experiments using the Texas A& M cyclotron that demonstrate the multiple electron stripping of 3.4 MeV/μ Kr^{7+} and Xe^{11+} ions in nitrogen gas.

There have been thirty-nine publications and conference proceedings papers supported under the auspices of the present contract during 2000–2001.

The following is a brief summary of selected recent research accomplishments.

(a) Kinetic Description of Electron-Ion Two-Stream Instability in Intense Heavy Ion Beams

In recent calculations we have made use of the Vlasov-Maxwell equations to develop a fully kinetic description of the electrostatic, electron-ion two-stream instability driven by the directed axial motion of a high-intensity ion beam propagating through a stationary population of (unwanted) background electrons in the accelerator/transport systems. The ion beam is treated as continuous in the z-direction, and the applied transverse focusing force on the beam ions is proportional to the transverse displacement from the beam axis in the smooth-focusing approximation. The electrons are electrostatically confined in the transverse direction by the space-charge potential produced by the excess ion charge, and the analysis retains- the effects of a perfectly conducting cylindrical wall located at radius r. The kinetic stability analysis is carried out for arbitrary beam intensity and arbitrary fractional charge neutralization f, consistent with transverse confinement of the beam particles. For the case of overlapping step-function ion and electron density profiles, corresponding to Kapchinskij-Vladimirskij (KV) electron and ion distributions in the transverse direction, detailed stability properties are calculated including parallel kinetic effects over a wide range of system parameters for dipole perturbations with azimuthal mode number $m = 1$, and for axisymmetric perturbations with $\partial/\partial\theta = 0$. The instability growth rate is found to increase with increasing beam intensity, increasing fractional charge neutralization, and decreasing

proximity of the conducting wall. For space-charge-dominated beams, it is shown that Landau damping associated with a modest axial momentum spread of the beam ions and background electrons has a strong stabilizing influence on the two-stream instability.

(b) 3D Multispecies Nonlinear Perturbative Particle Simulations of Intense Charged Particle Beams

A three-dimensional nonlinear perturbative (δf) particle simulation scheme has been developed for studying the stability and transport properties of intense charged particle beams for heavy ion fusion applications. As a numerical method to solve the nonlinear Vlasov-Maxwell equation system, the scheme splits the distribution function into equilibrium and perturbed parts. The perturbed distribution function is represented as a weighted summation over discrete particles, where the particle orbits are advanced by equations of motion in the focusing field and self-consistent fields, and the particle weights w_j are advanced by the coupling between the perturbed fields and the zero-order distribution function f_j^0. The nonlinear δf scheme exhibits minimal noise and accuracy problems in comparison with standard particle-in-cell simulation. This simulation scheme has been implemented in the Beam Equilibrium Stability and Transport (BEST) code. This code provides an effective numerical tool to investigate collective instabilities, periodically-focused beam propagation in alternating-gradient focusing fields, halo formation, and many other important nonlinear processes in intense beam propagation. In the absence of background electrons, the BEST code has been used to demonstrate quiescent (stable) beam propagation over thousands of equivalent lattice periods. In the presence of background electrons, however, a strong two-stream instability is observed, leading to a dipole ($m = 1$) transverse displacement of the beam ions and background electrons. The BEST code has also been applied to investigations of anisotropy-driven instabilities in intense charged particle beams. The BEST code will be an important tool in the theoretical studies proposed in Section D. Finally, the nonlinear δf-simulation scheme has also been applied to the case of a periodic-focusing solenoidal field configuration, and quiescent, matched-beam propagation of a thermal equilibrium beam has been demonstrated at high beam intensities over large distances.

(c) Production of Halo Particles by Excitation of Collective Modes in High-Intensity Beams

Under the auspices of the present contract, we have examined analytically and numerically the effects of self-consistent collective oscillations excited in a high-intensity charged particle beam on the motion of a test particle in the beam core. Even under ideal conditions, assuming a constant transverse focusing force (smooth focusing approximation), and perturbations about a uniform-density, constant radius beam, it is found that collective mode excitations, in combination with the applied focusing force and the equilibrium test fields, can eject particles from the beam core to large radii. The infinite set of linearized eigenmodes of a waterbag equilibrium beam have been determined using the smooth-focusing approximation and assuming axisymmetric perturbations. These eigenmodes, in combination with the nonlinear equilibrium charge-density and applied fields, cause areas of phase-space to break into islands and, in the case of sufficiently large-amplitude perturbations and intense beams, to become stochastic. Nonlinear shifts in the transverse oscillation frequency are determined analytically. Using this frequency shift and the eigenmode frequencies, the lo-

cation of resonant islands as a function of particle orbit amplitude, beam intensity, and mode number is predicted analytically and confirmed numerically. The dependence of island width on perturbative mode amplitude and beam intensity is explored numerically. Using the Poincaré technique, the particle phase space in the beam core and the beam halo region is investigated by numerically integrating the test particle equations over long periods.

(d) Ion Beam Charge and Current Neutralization by Background Plasma

The propagation of a high-current finite-length ion charge bunch through a background plasma is of interest for many applications, including heavy ion fusion. Under the auspices of the present contract, charge and current neutralization has been studied both analytically and numerically during ion beam entry, propagation, and exit from the plasma. A suite of codes has been developed for calculating the degree of charge and current neutralization of the ion beam pulse by the background plasma. The code suite consists of two different codes: a fully electromagnetic, relativistic particle-in-cell (PIC) code, and a relativistic Darwin model for long charge bunches. As a result of a number of simplifications, the second code is hundreds of times faster than the first one and can be used for most cases of practical interest, while the first code provides important benchmarking for the second. The analytical theory has been derived using the assumption of long charge bunches and conservation of generalized vorticity. The analytical results agree well with the results of numerical simulations for ion beam charge and current neutralization. The numerical simulations also show complex phenomena, including collective wave excitations, during beam entry into the plasma.

(e) RF Plasma Source for Heavy Ion Beam Charge Neutralization

Highly ionized plasmas are being considered as a medium for charge neutralizing heavy ion beams in order to focus beyond the space-charge limit. Calculations suggest that plasma with density of $1-100$ times the ion beam density and length $\sim 0.1-2$ m would be suitable for achieving a high degree of charge neutralization. An electron cyclotron resonance (ECR) source has been built at PPPL to support the Neutralized Transport Experiment (NTX) at LBNL to study ion beam neutralization with plasma. The ECR source operates at 13.6 MHz with solenoidal magnetic fields of $5-20$ gauss. The goal is to operate the source at pressures $\sim 10^{-6}$ Torr at full ionization. The initial operation of the source has been demonstrated at pressures of $10^{-4} - 10^{-1}$ Torr. Electron densities in the range of $10^{8} - 10^{11}\mathrm{cm}^{-3}$ have been achieved. Low-pressure operation is important to reduce ion beam ionization. A cusp magnetic field is being considered to improve ionization and reduce the confining field on the beam axis.

(f) Experimental Measurements of Multiple Electron Stripping of 3.4 MeV/μ Kr^{7+} and Xe^{11+} in Nitrogen

Use of heavy ion beams with ~ 10 MeV/μ, mass numbers in the range 130-200, and average charge state of 1^{+} has been proposed as a driver for heavy ion fusion. Stripping of the ion beam by background gas results in an increase in the space-charge density of the beam, which may make focusing the intense ion beam onto small targets more complex. Knowledge of the electron-loss cross-sections is essential to understand and address this important tech-

nical issue. Currently, there are no 10 MeV/μ, charge-state one, heavy ion beams available, and the theories that calculate electron-loss cross-sections can be experimentally tested only by using available beams of somewhat lower energy and higher initial charge state. The charge state distribution of ions produced in single collisions of 3.4 MeV/μ Kr^{7+} and 3.4 MeV/μ Xe^{11+} in nitrogen have been measured at the Texas A& M Cyclotron Institute using a windowless gas cell. The charge states of the outgoing ions are determined by magnetic analysis using a position-sensitive microchannel-plate detector. The cross-sections for single and multiple electron loss are determined, and the results indicate that substantial multiple-electron loss occurs. The relative cross-section for loss of $n+1$ electrons is 0.3 to 0.7 times that for n electron loss. The average number of electrons removed per single collision (sum of the electron-weighted cross-sections normalized to the total cross-section) is 1.86 for Kr and 1.97 for Xe.

(g) Longitudinal Drift Compression and Pulse Shaping for High-Intensity Ion Beams

High beam current can be achieved by longitudinally compressing bunched beams. The objective of drift compression is to compress a long beam bunch by imposing an initial longitudinal velocity distribution over the length of the beam in the beam frame. Under the auspices of the present contract, the longitudinal dynamics of drift compression and pulse shaping for high intensity particle beams has been studied using a one-dimensional warm-fluid model. Two self-similar drift compression solutions admitted by the one-dimensional warm-fluid equations have been derived, and the pulse shaping problem has also been solved such that an arbitrary input pulse shape can be shaped into those required by the self-similar drift compression solutions.

D. Future Accomplishments (FY 2003 – FY 2004)

D.1 Theory and Computations

Understanding the collective processes and nonlinear dynamics of an intense ion beam propagating in an alternating-gradient focusing lattice is a critical scientific problem in heavy ion fusion, which relies on high-brightness and high-current heavy ion beams to deliver high power to the target. In this section, we summarized in more detail the proposed research outlined in the Task Description Summary at the beginning of this proposal. Extensive use will be made of the analytical and numerical techniques summarized in Section C of this proposal and developed under the auspices of the present contract.

(a) Kinetic Description of Nonlinear Beam Dynamics and Stability Properties

As summarized in Section C of this proposal, we have made considerable analytical and numerical progress in developing a kinetic model based on the nonlinear Vlasov-Maxwell equations to describe intense nonneutral beam propagation through a periodic-focusing field configuration. The advantage of such a kinetic approach, of course, is that it provides a robust framework for investigating nonlinear beam dynamics and collective processes that depend on the detailed properties of the distribution function $f_b(\mathbf{x}, \mathbf{p}, t)$ in the phase space $(\mathbf{x}, \mathbf{p})$. While considerable analytical progress has been made, e.g., in developing Hamiltonian

averaging techniques for periodic focusing field configurations, in developing a nonlinear stability theorem, and in describing collective two-stream interactions, much remains to be done in order to fully exploit and further improve the kinetic model.

Under the auspices of the proposed research, we will carry out the following kinetic studies of collective processes in intense heavy ion beams in order to better identify the class of beam distributions and operating regimes required for stable beam propagation:

(a) Investigate the class of electrostatic and electromagnetic beam-plasma instabilities that can result from intense beam propagation through background plasma in the target chamber, and identify operating regimes that optimize beam quality and spot size.

(b) Extend the kinetic model based on the nonlinear Vlasov-Maxwell equations to incorporate three-dimensional effects associated with the coupling between the longitudinal and transverse particle motions.

(c) Determine the influence longitudinal kinetic effects (e.g., Landau damping by the beam ions) on collective processes such as two-stream interactions in the target chamber.

(d) Develop robust formulation of Darwin model for incorporation of electromagnetic effects in the nonlinear δf simulation method.

(e) Through comparison with simulation, determine the range of the Hamiltonian averaging techniques developed under the auspices of the present contract.

In these studies, smooth-beam and/or periodic-focusing models for the background lattice will be used as appropriate, and the BEST nonlinear δf simulation capability will be fully exploited wherever possible to validate analytical models.

(b) Application of 2D and 3D δf Simulation Methods to Investigate Nonlinear Beam Dynamics and Stability Properties

As summarized in Section C, a three-dimensional nonlinear perturbative (δf) particle simulation scheme has been developed for studying the stability and transport properties of intense charged particle beams for heavy ion fusion applications. As a numerical method to solve the nonlinear Vlasov-Maxwell equation system, the scheme splits the distribution function into equilibrium and perturbed parts. The perturbed distribution function is represented as a weighted summation over discrete particles, where the particle orbits are advanced by equations of motion in the focusing field and self-consistent fields, and the particle weights are advanced by the coupling between the perturbed fields and the zero-order distribution function. The nonlinear δf scheme exhibits minimal noise and accuracy problems in comparison with standard particle-in-cell simulations. This simulation scheme is implemented in the Beam Equilibrium Stability and Transport (BEST) code. This code provides an effective numerical tool to investigate collective instabilities, periodically-focused beam propagation in alternating-gradient focusing fields, halo formation, and many other important nonlinear processes in intense beam propagation. In the absence of background electrons, the BEST code has been used to demonstrate quiescent (stable) beam propagation over thousands of equivalent lattice periods. In the presence of background electrons, however, a strong two-stream instability is observed in circumstances where the axial momentum spread of the beam ions is sufficiently small. The nonlinear δf-simulation scheme has also been applied to the case of a periodic-focusing solenoidal field, and quiescent, matched-beam propagation of a thermal equilibrium beam has been demonstrated at high intensities over large distances.

Under the auspices of the proposed research, we will continue development and application of the 2D and 3D nonlinear δf-schemes to augment and validate the analytical studies

of intense beam propagation. Particular emphasis will be placed on: (a) determination of collective stability properties for various choices of input distribution function f_b^0, and identification of optimal parameter regimes for stable beam propagation; (b) examination of mechanisms for emittance growth and halo formation and control; and (c) application of 3D nonlinear δf simulation scheme to explore electrostatic two-stream instabilities that can result from intense beam propagation through background plasma in the beam transport lines, or in the target chamber. Either smooth-focusing or periodic-focusing models for the background lattice will be used, as appropriate.

(c) Collective Processes Driven by Temperature Anisotropy in Intense Charged Particle Beams

While considerable progress has been made in analytical investigations based on the Vlasov-Maxwell equations, such kinetic analyses are often complex, even under idealized assumptions. It is therefore important to develop and test the robustness of alternative theoretical models, such as macroscopic models based on the fluid-Maxwell equations, for investigating beam equilibrium and stability properties. Such macroscopic fluid descriptions have met with recent success in describing the propagation of space-charge-dominated (low-emittance) beams in periodic-focusing transport systems, and in describing high-frequency collective oscillations in high-intensity beams. Under the auspices of the present contract, we have completed studies using a macroscopic warm-fluid model in the smooth-focusing approximation to investigate the linear stability properties of an intense charged particle beam, allowing for equilibrium pressure anisotropy. In beams with strongly anisotropic distributions ($T_{\|b}/T_{\perp b} \ll 1$) a collective instability may develop if there is sufficient coupling between the transverse and longitudinal degrees of freedom. Such anisotropies develop naturally in accelerators and may lead to a deterioration of beam quality. Both kinetic and fluid descriptions predict instability. Under the auspices of the present contract, the 3D nonlinear perturbative particle simulation code BEST has also been used to initiate studies of the stability properties of intense nonneutral charged particle beams with strong temperature anisotropy. The most unstable modes have been identified and their eigenfrequencies and radial mode structure have been determined for axisymmetric perturbations. Preliminary simulation results show that moderately intense beams with $s_b = \omega_{pb}^2/2\gamma_b^2\omega_{\beta\perp}^2 \gtrsim 0.5$ are linearly unstable to short wavelength perturbations with $k_z^2 r_b^2 \gtrsim 1$, provided the ratio of longitudinal to transverse temperatures is smaller than some threshold value. In the nonlinear saturation stage, the total distribution function is still far from equipartitioned, and free energy is available to drive an instability of the hydrodynamic type. Under the auspices of the proposed research, we will carry out a systematic analysis of this instability using the 3D nonlinear δf simulation code BEST to determine the instability's dependence on beam intensity, its nonlinear saturation properties, and the effects of the instability on beam emittance.

(d) Longitudinal Drift Compression and Pulse Shaping for High-Intensity Ion Beams

High beam current can be achieved by longitudinally compressing bunched beams. For example, in the currently envisioned configurations for heavy ion fusion, it is necessary to longitudinally compress the beam bunches by a large factor after the acceleration phase and

before the beam particles are focused onto the fusion target. In order to obtain enough fusion energy gain, the peak current for each beam is required to be order 10^3 A, and the bunch length as short as 0.5 m. However, to deliver the beam particles at the required energy, it is both expensive and technically difficult to accelerate short bunches at high current. First of all, because of the finite rise time of the accelerating waveform, it is much easier to accelerate and transport beam bunches longer than 10 m. Second, short bunches have higher current (density) and therefore stronger space-charge effects which can increase the beam emittance and induce halo particles. The objective of drift compression is to compress a long beam bunch by imposing an initial longitudinal velocity distribution over the length of the beam in the beam frame. As a result, the beam length is reduced as the beam drifts downstream, until the space-charge force in the longitudinal direction becomes strong enough to remove the initial velocity distribution. Different longitudinal compression schemes have been studied in particle simulations and in numerical solutions of a cold-fluid model. There are also variations in the assumed axial line density profile of the bunched beam. In Haber's study, for example, the line density is uniform in the middle of the pulse but falls off at the ends, whereas in the study of Bisognano, et al., the line density is parabolic. The quality of drift compression is determined by two factors. A good drift compression scheme should, first of all, work for any reasonable beam pulse shape generated by accelerators, and second, the velocity distribution initially imposed for the purpose of compression should be minimized when the compression is finished. Because the beam length is much shorter after the compression, it is difficult to apply an external field to eliminate the residual longitudinal velocity distribution over the beam length. In desirable drift compression schemes, the space-charge force and the emittance in the longitudinal direction are utilized to minimize the residual longitudinal velocity distribution.

As discussed in Section C, under the auspices of the present contract we have initiated studies of the longitudinal drift compression and pulse shaping of high intensity ion beams using a one-dimensional warm-fluid model. Two self-similar drift compression solutions have been derived. The first solution is characterized by a flat-top density profile, a linear velocity profile (i.e., a linear velocity tilt), and a parabolic pressure profile, which is referred to as the linear self-similar drift compression solution. The second solution is characterized by a parabolic density profile, a linear velocity profile, and a double-parabolic pressure profile, which is referred to as the parabolic self-similar drift compression solution. For the parabolic self-similar drift compression solution, the residual longitudinal velocity distribution can be eliminated by the space-charge force and emittance. It has also been shown how to shape an arbitrary pulse shape into a parabolic form so that it can be subsequently self-similarly compressed after a linear velocity tilt is applied. More generally, we have obtained approximate solutions to the pulse shaping problem. That is, we calculate the initial velocity distribution such that a given initial pulse shape gradually evolves into the desired final pulse shape after a certain length of time. Under the auspices of the proposed research, we will continue these studies with particular emphasis on optimizing drift compression and pulse shaping scenarios for upgrades of the Neutralized Transport Experiment (NTX), for the Integrated Beam Experiment (IBX), and for reactor-scale heavy ion fusion configurations. We will also develop design concepts for the final focus magnet configurations that optimize beam properties on entrance to the target chamber.

(e) Nonlinear Charge and Current Neutralization of an Ion Beam Pulse in Preformed Plasma

As discussed in Section C, under the auspices of the present contract we have investigated theoretically the propagation of a high-current finite-length ion beam in a cold preformed plasma. The outcome of the calculation is the quantitative prediction of the degree of charge and current neutralization of the ion beam pulse by the background plasma. The electric and magnetic fields generated by the ion beam are studied analytically for the nonlinear case where the plasma density is comparable in size with the beam density. Particle-in-cell simulations and fluid calculations of current and charge neutralization have been performed for parameters relevant to heavy ion fusion assuming long, dense beams with length $\ell_b \gg V_b/\omega_b$, where V_b is the beam velocity, and ω_b is the electron plasma frequency evaluated with the ion beam density. An important conclusion is that for long, nonrelativistic ion beams, charge neutralization is, for all practical purposes, complete even for very tenuous background plasma. As a result, the self-magnetic force dominates the self-electric force and the beam ions are always pinched during beam propagation in a background plasma. Under the auspices of the proposed research, we will continue these analytical and simulation studies with particular emphasis on developing improved theoretical models with predictive capability for determining the degree of charge and current neutralization over a wide range of system parameters, including transient beam-pulse conditions. These studies will include detailed comparison with LSP simulations and other simulation codes, as well as available experimental results. Emphasis will also be placed on developing optimum operating scenarios for charge and current neutralization in the Neutralized Transport Experiment (NTX) and the Integrated Beam Experiment (IBX).

(f) 3D LSP Simulation Studies of Intense Beam Transport in the Target Chamber

A critical problem in heavy ion fusion is the determination of optimal operating conditions for quiescent beam transport through background gas and plasma in the target chamber, and assurance of good convergence properties and small focal spot size at the fuel pellet. Technical and administrative responsibility for oversight of the Mission Research Corporation (MRC) subcontracted modeling effort using the advanced LSP and IPROP simulation codes have been transferred from Lawrence Berkeley National Laboratory to the Princeton Plasma Physics Laboratory. The technical scope of the research for this subcontract to MRC will include: (a) investigations of neutralized ballistic transport of heavy ion beams using the 3D LSP simulation code, including modeling of beam ion stripping, ionization of the ambient gas by beam ions and target photons, beam-plasma interactions, and the effects of multiple beams and target charging; (b) simulations of beam-neutralization experiments in collaboration with LBNL and PPPL personnel, including the optimization of ion beam spot size with regard to ambient plasma conditions; (c) simulations for the ARIES heavy ion fusion study for relevant chamber transport conditions; (d) simulation studies of the Neutralized Transport Experiment (NTX), including modeling of beam propagation and plasma creation, assistance in the optimization of ion beam spot size, and comparison of simulation results with experimental data; and (e) implementation of improvements in the LSP and IPROP codes, as necessary, to investigate the chamber transport modes.

The budget request for the theory and computations Task Activities (a)–(e) is \$700 K in FY 2003 and \$700 K in FY 2004. Of this, the "guidance" level for both fiscal years is \$600

K, and $100 K in the "incremental" request to be added to this amount.

The budget request for the theory and computations Task Activity (f) is $240 K in FY 2003 and $240 K in FY 2004. Of this, the 'guidance' level for both fiscal years is $168 K, and $72 K is the "incremental" request to be added to this amount.

The milestones for Task Activities (a)–(e) are summarized in Section E.1 of this proposal.

D.2 Experimental Activities and Feasibility Studies

Under the auspices of the proposed research, we will also carry out a vigorous experimental program that makes use of PPPL's considerable experimental capabilities and off-site research facilities, such as the Neutralized Transport Experiment (NTX) at LBNL and the Texas A& M cyclotron, to investigate several critical problems related to beam propagation and beam-plasma interaction in the target chamber. These activities include: (i) development and application of rf techniques for formation of preionized plasma in the target chamber, and experimental investigations of beam-plasma interactions; (ii) measurement of multielectron loss events for intense ion beam propagation through background gas; and (iii) feasibility study of developing a heavy ion neutral beam driver based on the acceleration of negative ions.

(g) Development and Application of RF Techniques for Formation of Preionized Plasma

For heavy ion beam propagation in the target chamber, there are several advantages (e.g., controlling the rate and degree of charge neutralization) to injecting the ion beam into a preionized plasma, with a considerable degree of control over the background plasma density. In the parameter range of interest, injected beam densities would be in the $10^{10} - 10^{11}\mathrm{cm}^{-3}$ range, and the background gas pressure in the target chamber before ionization would be in the 10-1000 milliTorr range. Under the auspices of this proposal, we will develop and apply techniques for forming preionized plasma in the target chamber over dimensions of several meters. Scaled experimental tests will be carried out in collaboration with scientists at LBNL using the Neutralized Transport Experiment facility.

Uniform plasmas of large dimension are not readily created. Plasmas made with electrodes are naturally nonuniform in the vicinity of the electrodes. Alternatively, plasmas made with electromagnetic waves are naturally heterogeneous and difficult to make into large plasma volumes due to short skin depths (typically less than 1 cm). This problem has been studied in the development of plasma processing techniques for the manufacturing of semiconductor devices. A classic plasma "whistler" wave has been used to produce *highly uniform and large dimensional plasmas*. The electron whistler wave ($k||B$) is an ideal wave for this purpose because it has no cutoffs or resonances for any density, and its wavelength is very short, which provides good damping and high spatial uniformity. Furthermore, it has been shown at pressures in excess of 1 milliTorr that the skin depth of the wave can be greatly extended with the addition of a modest magnetic field on the order of 10s of gauss. This allows for very long plasma channels to be produced at modest magnetic fields. Therefore, for a heavy ion fusion scenario in which preionized plasma is formed in the target chamber, rf waves (1-100 MHz) with a 10-20 gauss field can be used to produce the required plasma with a length in excess of several meters.

At the background gas pressures and electron densities envisioned in near-term experiments, the plasma is collisionless and therefore the required wave damping mechanism needs to be collisionless. Cyclotron damping appears to be the most favorable means of producing the plasma. It is likely that the plasma density created at breakdown may be significantly higher than desired. Therefore, pulsing the plasma and neutralizing the ion beam in the plasma afterglow are probably necessary. There also exist other plasma waves that can be considered, including Helicons and X-mode cyclotron damping. The experimental configuration is an important consideration in the wave choices. Helicon sources have recently been developed into a process plasma source for etching. The rf power is coupled to bounded whistler waves. Damping mechanisms are collisional and Landau damping. The antenna is either helical or a set of cylindrical straps around a cylindrical dielectric (k_{11} is determined by the antenna). The helicon dispersion relation strongly couples the axial magnetic field, the density, and the wave frequency. For the whistler wave, the damping can be either collisional, Landau or cyclotron damping. The damping depends on plasma parameters such as temperature, density, collisionality, and the proximity of the wave frequency to the cyclotron frequency.

Under the auspices of the proposed research, charge neutralization experiments will be conducted on the Neutralized Transport Experiment at LBNL. RF preionization techniques that produce both localized and large-volume collisionless plasmas and can be integrated into the NTX experiment are being developed in laboratory tests. The proposed research will extend and modify schemes presently used in semiconductor plasma devices.

As discussed in Section C, under the auspices of the present contract an electron cyclotron resonance (ECR) source has been built at PPPL to support the Neutralized Transport Experiment to study ion beam neutralization with plasma. The ECR source operates at 13.6 MHz with solenoidal magnetic fields of $5-20$ gauss. The goal is to operate the source at pressures $\sim 10^{-6}$ Torr at full ionization. The initial operation of the plasma source has been demonstrated at pressures of $10^{-4} - 10^{-1}$ Torr. Electron densities in the range of $10^{8} - 10^{11}\mathrm{cm}^{-3}$ have been achieved. Low-pressure operation is important to reduce ion beam ionization. A cusp magnetic field is being installed to improve ionization and reduce the magnetic field on the beam axis. The plasma density will be measured to assure that the necessary conditions are obtained. In early FY 2003, the plasma source apparatus will be moved to LBNL to integrate the plasma formation scheme with the ion beam experiments on NTX. During FY 2003 and FY 2004, PPPL will participate in the charge neutralization experiments carried out with this apparatus on NTX. These experiments will provide an important test of the preionized plasma formation techniques, and will also examine fundamental properties of collective beam-plasma interactions.

The budget request for this task activity is \$300 K in FY 2003, and \$300 K in FY 2004. Of this, the "guidance" level for both fiscal years is \$225 K, and \$75 K is the "incremental" request to be added to this amount.

The milestones for Task Activity (g) are summarized in Section E.2 of this proposal.

(h) Measurement of Multielectron Loss Events for Intense Ion Beam Propagation Through Background Gas

The main approaches presently envisioned for heavy ion fusion calculate the charge state of the beam traversing the target chamber under the assumption that one electron at a time will be removed per collision. This will not likely be the case. In an earlier experimental

study, we made measurements of the charge state distribution produced by light ions (lithium to silicon) at energies of up to 7 MeV [Rev. Sci. Instr. **53**, 281 (1982)]. It was found that, even at the lowest line densities for which any single-electron loss events were observed, there were also multielectron losses for beams heavier than lithium, and that these could contribute more to the charge state of the beam than the single-electron loss events. This process occurs because inner-shell electrons are knocked out, resulting in ejection of further electrons.

As discussed in Section C, under the auspices of the present contract the charge state distribution of ions produced in single collisions of 3.4 MeV/μ Kr^{7+} and 3.4 MeV/μ Xe^{11+} in nitrogen gas have been measured in experiments at the Texas A& M Cyclotron Institute using a windowless gas cell. The charge states of the outgoing ions are determined by magnetic analysis using a position-sensitive microchannel-plate detector. The cross-sections for single and multiple electron loss are determined, and the results indicate that substantial multiple-electron loss occurs. The relative cross-section for loss of $n+1$ electrons is 0.3 to 0.7 times that for n electron loss. The average number of electrons removed per single collision (sum of the electron-weighted cross-sections normalized to the total cross-section) is 1.86 for Kr and 1.97 for Xe.

Based on these experiments, it is planned to carry out further detailed experimental studies of multielectron loss events using the Texas A& M cyclotron during FY 2002 and FY 2003, including detailed comparisons with theory in order to benchmark and validate the most robust theoretical models. During FY 2003 and FY 2004 it is proposed to plan and conduct similar experiments using a low-charge-state beam (preferably +1) of a heavier element more appropriate to heavy ion fusion, at energies as high as practical. Since this is an atomic physics experiments, only a small (picoampere level) current is required, but even this is not immediately available on existing facilities. It appears that the most promising facility for such an experiment would be at GSI-Darmstadt using the upgrade of the Wideroe injector. This is expected to allow acceleration of ions with a charge-to-mass ratio of 1/60 to 1-1.5 MeV/amu. Although this is much less than heavy ion fusion energies, it should, coupled with our earlier data, give a better basis for estimating the impact of multi-electron loss events upon fusion-relevant heavy ion beams. A higher average charge state would require more complete space-charge neutralization in order to control the spot size.

The research in FY 2003 will involve detailed planning of the experiment on the GSI (or alternate) facility. Components for a beamline would be fabricated or purchased only if there is not a suitably equipped beamline already installed on the GSI-Darmstadt injector. Required in the experiments are a target gas cell, an analyzing deflector, and a position sensitive detector to record the emerging charge-state distribution. To carry out this research a collaborative arrangement with GSI-Darmstadt or another Laboratory will be established. The research in FY 2004 will focus primarily on conducting and finishing the experiments, and interpreting and publishing the data.

The budget request for Task Activity (h) is $230 K in FY 2003, and $230 K in FY 2004. Of this, the "guidance" level is $100 K for FY 2003 and $100 K for FY 2004. Funding at the "guidance" level will result in a significant delay in gas cell preparation and execution of the multielectron loss experiments on the GSI (or alternate) facility.

The milestones for Task Activity (h) are summarized in Section E.2 of this proposal.

D.3 Engineering Design and Technology Development

(i) Final Focus Design Studies and Nonlinear Beam Optics

Under the auspices of the proposed contract, we will make use of PPPL's considerable engineering design capability to develop optimized design options for the final focus magnet systems in reactor-scale and next-generation facilities in heavy ion fusion. The final focusing system is the last stage of the heavy ion beam transport system, and it performs the important task of directing the beam ions onto the millimeter-scale fusion pellet. The proposed design studies will focus on the following key technical issues: (a) magnetic configuration optimization studies to minimize the effects of chromatic and geometric lens aberrations, (b) nonlinear beam optics studies to determine the effects of fringing fields, momentum spread, and degree of space-charge neutralization; (c) optimization of the geometry of the final focus system to minimize the contamination of beam transport lines by fusion neutrons from the target; (d) development of a compact final focus system design that is compatible with the reactor vessel configuration; and (e) development of a differential pumping system design for a multiple beamline configuration. In addition to PPPL's existing engineering design tools, the proposed research will make use of established nonlinear beam transport and optics codes, modified as appropriate, in the design optimization of the final focus system.

Engineering design activities has been initiated during FY 2001 and FY 2002 under the auspices of ARIES support for heavy ion fusion, with $70 K support provided for ARIES activities in FY 2002. While the ARIES guidance is zero funding for heavy ion fusion reactor studies in FY2003 and FY2004, we believe that a continued strong effort in this area over the next two years is essential in order to complete the configuration studies for an optimum reactor configuration. Therefore, incremental funding of $200 K is requested for this activity in both FY2003 and FY2004.

The milestones for Task Activity (i) are summarized in Section E.3.1 of this proposal.

(j) Neutralized Transport Experiment (NTX) Upgrade and Integrated Beam Experiment (IBX) Design, Fabrication and Test Activities

Two key future experimental facilities in the national heavy ion fusion program are planned to be an upgrade of the Neutralized Transport Experiment (NTX) including drift-compression capabilities, to be sited at PPPL, and the Integrated Beam Experiment (IBX) to integrate beam production, acceleration, transport, compression and beam focusing at the proof-of-principle level. The Princeton Plasma Physics Laboratory, through its participation in the Heavy Ion Fusion Virtual National Laboratory, will be actively involved in the design, construction and operation of these facilities.

During FY 2003 and FY 2004, the principal PPPL engineering activities proposed in support of NTX Upgrade and IBX include the following:

(a) Design, fabrication and testing of prototype, advanced, short-pulse, high-gradient induction test modules and test stand for next-generation heavy ion fusion experiments.

(b) Preliminary design for IBX non-intercepting beam diagnostics and data acquisition and control systems.

(c) Design, fabrication and testing of drift compression line for NTX Upgrade; design drift compression line for IBX.

(d) PPPL participation in preparation for IBX Conceptual Design Review, including development of cores, insulators, and pulsed-power components of IBX acceleration modules; data acquisition and control systems; and non-intercepting beam diagnostics.

The incremental budget request for Task Activity (j) is $800 K in FY 2003, and $1.5 M in FY 2004, and the milestones are summarized in Section E.3.2 of this proposal.

E. Milestones for FY 2003 and FY 2004

E.1. Theory and Computations

E.1.1 Milestones at Guidance Funding Level

1. Complete initial assessment of beam-plasma instabilities in the target chamber. Identify operating regimes for optimum beam propagation and focal spot size (March, 2003).
2. Complete assessment of the effects of two-stream collective interactions on beam quality in the acceleration and beam transport regions (September, 2003).
3. Develop and apply robust model describing pulse shaping and compression dynamics for Integrated Beam Experiment (IBX) and Neutralized Transport Experiment (NTX) Upgrade options (December, 2003).
4. Extend self-consistent analytical and numerical models for beam charge and current neutralization to incorporate finite electron temperature and ionization effects (February, 2004).
5. Complete assessment of optimum beam and chamber conditions for quiescent beam propagation to small focal spot size (September, 2004).

E.1.2 Additional Milestones at Incremental Funding Level

6. Modify BEST simulation code to incorporate effects of secondary electron emission in studies of electron-ion two-stream instabilities (March, 2004).

E.2. Experimental Activities and Feasibility Studies

E.2.1 Milestones at Guidance Funding Level

1. Complete initial suite of plasma neutralization experiments on the Neutralized Transport Experiment (NTX) (September, 2003).
2. Complete suite of multielectron loss experiments using the Texas A&M cyclotron for a range of projectile ions and target atoms (e.g., N, He, Ar) to finalize benchmarking and identification of the most robust ionization models (September, 2003).
3. Complete component fabrication for multielectron loss experiments on GSI-scale facility, including gas cell and deflector preparation (December, 2003).
4. Complete suite of plasma neutralization experiments on the Neutralized Transport Experiment (NTX), including mock-up of photo-ionization effects (September, 2004).

E.2.2 Additional Milestones at Incremental Funding Level

5. Identify optimum source operating conditions for most effective charge neutralization in the Neutralized Transport Experiment (NTX) (September, 2004).

6. Complete initial suite of multielectron loss experiments and data interpretation on GSI-scale facility (September, 2004).

E.3. Engineering Design and Technology

E.3.1 Reactor Studies Milestones at Incremental Funding Level

1. Prepare design description and technical specifications for final focus interface concept (September, 2003).

2. Complete optimization and configuration studies for vacuum pumping interface and beam compression dynamics for final focus magnet system (September, 2004).

E.3.2 Engineering Milestones at Incremental Funding Level

3. Develop design concepts for IBX non-intercepting beam diagnostics and data acquisition and control systems (September, 2003).

4. Complete design and fabrication, and begin performance testing of prototype, advanced, short-pulse, high-gradient test modules and test stand for next-generation heavy ion fusion experiments (April, 2004).

5. Finalize design concepts for IBX drift compression line, non-intercepting beam diagnostics, and data acquisition and control systems (July, 2004).

6. Design and fabrication of components for scaled drift compression line for the Neutralized Transport Experiment (NTX) Upgrade experiment (September, 2004).

45XX HEAVY ION FUSION			03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	4.1	2.9	1.3	2.7	1.3
Engineers			2.5		2.5
Administrators					
Graduate Students					
Technicians	1.1	.4	.2	.4	.2
Clerical					
Subcontractors					
TOTAL FTEs	5.2	3.3	4.0	3.1	4.0
OPERATING COSTS $(000):					
PPPL Labor	562.4	418.7	504.5	413.5	383.5
Subcontract Labor					
Overtime					
Travel	41.0	26.6	16.1	33.0	3.8
Energy					
Stockroom	14.5	4.0		4.0	
Miscellaneous Expenses	26.7	10.8	4.6	18.6	2.7
Procurements/ICOs	393.8	179.3	306.5	167.6	527.7
Organizational Burden	85.7	56.2	62.0	57.0	43.9
Other		2.5	.2	2.5	.1
General + Administrative	534.0	394.9	483.0	396.8	465.3
TOTAL OPERATING COSTS	1658.1	1093.0	1376.9	1093.0	1427.0
TOTAL OPERATING OBLIGATIONS	1149.1	1093.0	1376.9	1093.0	1427.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					649.9
TOTAL EQUIPMENT COSTS					649.9
TOTAL EQUIPMENT OBLIGATIONS					649.9
GRAND TOTAL COSTS	1658.1	1093.0	1376.9	1093.0	2076.9
GRAND TOTAL OBLIGATIONS	1149.1	1093.0	1376.9	1093.0	2076.9

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1030	0	3/1/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Magnetic Reconnection Experiment	AT5030500

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Masaaki Yamada Phone: 609-243-2566 Email: myamada@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The objective of the MRX (Magnetic Reconnection Experiment) program is to investigate the fundamental physics of magnetic reconnection and the associated plasma physics phenomena in a well-controlled laboratory setting. A primary goal of the present program is to comprehensively analyze the most characteristic form of plasma-magnetic field interaction, magnetic reconnection. The study will be carried out from both local and global points of view by investigating the coupling between micro-scale reconnection layers on one hand and global forcing and the MHD equilibrium changes on the other. A fully three dimensional magnetic reconnection experiment is possible. The results will have an important impact on theories of reconnection in solar flares, the magnetosphere, astrophysical plasmas and laboratory fusion plasmas. Joint support has been provided from DOE, NASA, and NSF because of the relevancy of this research subject to many fields.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Purpose

The primary purpose of MRX is the comprehensive analysis of magnetic reconnection physics, which is crucial for understanding self-organization phenomena of fusion plasmas as well as solar and magnetospheric plasmas. The analysis focuses on the coupling between local micro-scale features of the reconnection layer and global properties such as external driving force, MHD flows, and the evolution of plasma equilibrium.

In particular, MRX has the following research goals:

- Experimentally test 2D and 3D theoretical models of reconnection layer
- Investigate the role of non-MHD physics in the reconnection layer
- Study global MHD issues including evolution of magnetic helicity
- Determine the circumstances under which 3-D effects dominate
- Identify the mechanisms by which magnetic energy is converted to plasma kinetic and thermal energy
- Explore the fruitful utilization of reconnection to fusion concepts, such as application to self organized plasmas, FRC, Spheromak, and RFP.

These studies will contribute to the advancement of plasma physics and fusion energy research and directly impact the physics understanding of reconnection in fusion plasmas, the solar atmosphere, the earth's magnetosphere and related astrophysical phenomena.

Approach

Two toroidal plasmas with variable toroidal and poloidal fields are formed using inductive electric fields generated from two sets of coil windings in two flux cores. Magnetic reconnection is produced in a controlled manner by externally programmed coil currents. MRX is designed to achieve a variety of merging geometries and magnetic field topologies. The reconnection layer has been identified both by magnetic probes and by LIF (laser induced fluorescence) imaging. A Lundquist number of $S \approx 1000$ has been obtained and $S \approx 10^4$ is eventually expected with some upgrades on the system and the plasma size ranges 20-60 ion gyro radii in extent.

A set of carefully chosen diagnostics provides insight into the physics of magnetic reconnection and allows detailed space and time analysis of MRX plasmas. These

include Langmuir probes (electron density and temperature), Mach probes, spectroscopy (ion temperature and flows), arrays of magnetic probes (spatial profiles of local magnetic field vector) and newly installed LIF diagnostic system. The main objective of the LIF diagnostics is to obtain time and space resolved measurement of plasma density, ion temperature and flow velocity without perturbing the reconnection region.

Magnetic reconnection can also be used to explore the formation of compact toroid plasmas such as FRC, spheromak, and RFP by plasma merging. The compact toroid plasmas are formed by merging two spheromaks with the same or opposite polarity helicities. The two spheromaks are created inductively at both ends of the MRX vacuum vessel by properly programming currents inside the flux cores.

Summary of Progress in FY 2001/2002

The MRX laboratory experiment has been intensively studied in both the collisional and the less-collisional regimes with a large Lundquist number $S = LV_A/\eta \sim$ 200-1000 with magnetized plasmas ($L/\rho_i > 10$). The magnetic profile of the neutral sheet was precisely measured by magnetic probes with a spatial resolution of 1/4-1/2 of the ion gyro-radius, and B(x) data fit excellently to the Harris profile, $B(x) \sim \tanh(x/\delta)$, suggesting a stable axisymmetric neutral sheet being formed. The sheet thickness δ is found to be equal to 1/3 of the ion skin depth, which is in very good agreement with the Harris theory and with numerical simulations as well as recent space observations. The relationships of the MRX data to the recent space observations and numerical simulations have been discussed extensively in various meetings and conferences.

The advantage of MRX experiment is that it can cover a wide operational regime of collisionality. In the highly collisional regime, the classical transverse Spitzer resistivity was verified. In the less collisional regime where the mean-free-path is longer than the current sheet thickness, enhanced resistivity over the classical value by the order of 10 has been detected and its correlation with the detected fluctuation amplitude has been investigated. A transition regime from the collisional to the collisionless regime has also been studied.

<u>Verification of the Transverse Spitzer resistivity</u>

The magnetic reconnection rate was measured accurately in the neutral sheet of highly collisional plasmas, where the mean free paths of electrons were much shorter than the sheet width. The Spitzer's transverse resistivity has been recently verified in these plasmas with accurate measurement of the electron temperature. In a typical neutral sheet

where plasma is reconnecting without a guide field (null helicity), the transverse resistivity directly determines the reconnection rate of merging plasmas. A remarkable agreement was found between the measured resistivity and the classical values derived by L. Spitzer. In his calculation the transverse resistivity for electrons should be two times the parallel resistivity. The measured values have verified this theoretical number within 30% uncertainty, and its value changes as $(T_e)^{-3/2}$ as expected. This is the most accurate measurement of the transverse Spitzer resistivity to date. This result is not only the most accurate measurement of the transverse Spitzer resistivity to date but also it is the most direct verification of the classical Sweet-Parker theory.

Progress in measuring micro-turbulence in the neutral sheet

In searching for physical mechanisms responsible for the observed fast reconnection or "anomalous resistivity" in MRX, electrostatic and electromagnetic fluctuations were detected in the reconnection region. The high-frequency electrostatic fluctuations have been just recently identified as lower hybrid drift waves (LHDW). The measured frequency spectra are in the frequency range between the ion cyclotron and lower hybrid frequencies, qualitatively consistent with our theoretical model. The propagation characteristics have been measured. The correlation of the fluctuation amplitudes with the observed resistivity enhancement has been investigated and it is now concluded that this electrostatic LHDW does not solely determine the reconnection rate. In the end of this fiscal year, a thorough investigation of the observed electromagnetic fluctuations will be initiated.

Refurbishment of the MRX system

To improve the vacuum integrity and high voltage runs, the MRX facility has been refurbished. For this goal, the higher voltage discharges will be made with more diagnostic capabilities. The recently developed diagnostics (such as micro-probes, LIF, and IDSP etc.) will be fully utilized in the next experimental campaign.

Expected Progress in FY 2003

Installation of less invasive diagnostics

A new LIF diagnostic is being developed on MRX. The electron density profile of the neutral sheath has been monitored by LIF and its validity was tested. With a newly built Ion Dynamics Spectroscopy Probe (IDSP) for local ion temperature measurement, we will investigate mechanisms by which magnetic energy is transferred to ion kinetic energy during magnetic reconnection. The enhanced ion heating will be carefully

examined by the IDSP at the neutral sheet and its relationship with the observed high frequency fluctuation will be investigated.

Search for new physics in the less collisional regime

In this fiscal year we will carry out a study of the less-collisional magnetic reconnection. Our experiments will be focused on the regime of long collisional mean free path ($\lambda_{mfp} > L$). The newly installed diagnostics (such as micro-probes, LIF, and IDSP etc.) will be utilized in this experimental campaign. In particular, we will investigate intensively the role of Hall effects on the existence of the quadrupole out-of-reconnection-plane fields predicted by the recent 2-D numerical simulations. The plasma parameters of the inside and the surrounding region of the neutral sheet will be monitored simultaneously. We will also investigate additional non-MHD physics issues such as excitation of whistler waves.

Study of electromagnetic wave turbulence in the reconnection region

To date, the effects of electrostatic turbulence on magnetic reconnection have been intensively studied in MRX. In this fiscal year, we will investigate electromagnetic waves in the reconnection region and how the reconnection rate quantitatively depends on the fluctuation amplitudes of the broad reconnecting region.

Controlled 3-D reconnection experiments

As part of the base program, a new set of experiments will be performed in which 3D effects are introduced by perturbing the 2D reconnection layers in the third direction. An asymmetric perturbation can be imposed either locally or globally. Locally, a pair of “pinch” coils located on both sides of the current sheet can pinch a 2D current sheet only at one point along the neutral line. We will investigate under what circumstances reconnection is a steady or bursty process. We also plan to determine how patchy and fully three-dimensional reconnection proceeds when plasmas contact at a point instead of along a line, and to document magnetic helicity evolution during many modes of magnetic topology change. A local plasma flow pattern will be measured utilizing optical diagnostics and the IDSP probe system. The resulting change in reconnection rate, plasma resistivity, and the dynamical response of the global 3-D plasma configuration will be examined.

Expected Progress in FY 2004

Our study of three-dimensional magnetic reconnection will be extended to hotter plasma regimes with reduced collisionality. We plan to measure the spatial extent and shape of the reconnection region in two-dimensional and three-dimensional views, and evaluate Taylor's helicity conservation during magnetic reconnection.

Global reconnection

The quantity that describes global magnetic characteristics and is expected to change through local reconnection of field lines is magnetic helicity. The effect of magnetic reconnection on the time evolution of magnetic helicity is of great interest in solar and laboratory plasma physics especially with respect to whether helicity is conserved relative to magnetic energy. The relative ratio of the change in helicity to the change in magnetic energy bears important physics for the fundamental theories for plasma relaxation. Two experiments are proposed in MRX to study the time evolution of magnetic helicity and magnetic energy during reconnection. The first experiment focuses on inventory of magnetic helicity in the reconnection region, where field lines lose their identities and a global topology change begins. The second experiment will be focused on simulating variety of solar flare evolution and start at the end of this period.

Merging experiments

In this fiscal year, an investigation of global 3-D magnetic reconnection will start by use of the merging toroidal plasmas in the well-established MHD regime. Merging of co- and counter-helicity spheromaks produced by inductive discharges utilizing flux cores will generate compact toroid plasmas. Measuring both magnetic and flow profiles before and after merging will enable the study of the time evolution of magnetic helicity, magnetic energy, kinetic helicity, and even cross helicity. In particular, we will investigate systematically the validity of the Taylor principle with large kinetic parameters ($s^* > 10$; $s^* = R_S/\rho_i$). With the incremental budget, we will utilize the upgraded facility to carry out this experiment in hot plasmas with the LIF diagnostics to attain time and space resolved measurements of ion temperature and flow velocity without perturbing the reconnection region.

Milestones

Initiate a study of global reconnection issues	May 2002
Study the helicity conservation principle during reconnection	Sept. 2002
Complete runs for studying electromagnetic LHDW	Dec. 2002
Complete assessment of 3-D effects in the reconnection layer	Sept. 2003
Assess the status of the local physics in the reconnection layer	Sept. 2003
Assessment of Hall effects in MRX reconnection	June 2004
Complete runs for studying the helicity conservation principle	Sept. 2004
Assess the status of the global physics in the reconnection layer	Sept. 2004

Incremental Requests for FY 2003/2004

Two Physics Frontier Center proposals have been recently submitted to DOE through NSF by invitation: (1) 'Interdisciplinary Center for Magnetic Reconnection' and (2) 'Interdisciplinary Center for Magnetic Self-organization in Laboratory and Astrophysical Plasmas.' The two full proposal texts will be separately submitted to DOE-OFES, together with proposed incremental budgets for MRX, respectively. In the Field Work Proposal for Contractor Number 3501, NSF Collaborations, a brief description of the NSF Center Proposals and the role of MRX is provided, including funding requirements from OFES. If neither of the two Center proposals are endorsed by NSF, incremental funding is requested to support many of the experiments on MRX in those proposals. The MRX laboratory experiment has been successfully carried out in past several years covering both collisional and the less-collisional regimes with a modest Lundquist number of S = 300-1000 with magnetized plasmas. Since 1995, more than 30,000 research grade discharges have been reliably fired. In order to expand the operation regime of MRX to make our data more relevant to the space physics issues, it is crucial to upgrade the facility to cover a fully collision-free regime with larger Lundquist number of ~ 10^4 and to facilitate a variety of merging geometries and magnetic field topologies. In this request, the essential elements of our comprehensive upgrade plans are described.

Expected progress in 2003/2004

MRX facility upgrade in FY 2003/2004 (included in UMD center proposal)

A significant upgrade of the MRX facility is required to address the science issues for collision-free reconnection of greatest interest in space, astrophysical and laboratory applications. The installation of a 1 MJ capacitor bank will double the peak magnetic field strength raising the peak electron temperature to 40-50 eV, increasing the Lundquist number to 10^4 compared with 300-800 in the present experiment. The increased temperature will allow the experiment to more deeply access the collisionless regime. The upgrade will increase the size of the vacuum vessel so the separation between the two flux cores can be increased to 1.5 m. This will allow us to study the effects of plasma boundary and to reduce the down-stream plasma pressure, which might have been limiting the outflow speed. The increased outflow velocities could also generate the slow shocks, which are seen in some MHD and kinetic simulations to develop. In this high temperature plasma, the existence of the self-induced out-of-plane magnetic field, which is a signature of dispersive wave, will be experimentally investigated.

Development of comprehensive diagnostics system in FY 2004 (in UMD center proposal)
(part of the diagnostic upgrades also in UW center proposal)

In order to measure the local ion temperature and plasma flow non-invasively, a new method based on Laser Induced Fluorescence (LIF) is planned. We plan to employ this diagnostic technique to measure local ion acceleration and heating in the reconnection layer and the slow shocks bounding the outflow region. Changes in electron temperature and changes in the non-thermal electron distribution, associated with reconnection, will be monitored by Thompson scattering.

Investigation of a shock in reconnection region in FY2004 (in UMD center goals)

The measurement of the structure of slow shocks in a laboratory reconnection setting has not previously been successfully achieved. This is one of the most important goals of the experimental efforts for the UMD Center research. The upgrade of the MRX experiment should sufficiently raise the outflow velocity to force the formation of slow shocks to drive these large velocities. If the slow shocks are seen to develop, the jump conditions across the shock will be tested and compared with the Rankine-Hugoniot conditions. We emphasize that the exploration of ion heating topic will be closely coordinated with the fluctuation measurements since naturally, the enhanced wave-particle interactions not only enhance resistivity but also heat ions.

Global merging experiments in collision-free plasmas in FY2004 (in UMD and UW center proposals)

The physics of global reconnection will be studied in the controlled merging of two plasma toroids with high electron temperature (T_e > 30 eV) in MRX. The first set of experiments will yield the time evolution of flux, magnetic helicity and magnetic energy during the reconnection process. Magnetic helicity in each initial torus can be varied systematically from co-helicity (same sign of helicity in the two toruses) to counter-helicity (opposite sign of helicity in the two toruses). Conversion from toroidal flux to poloidal flux or vice versa is expected to occur during the merging process as the plasma relaxes. Non-axisymmetric modes are likely to occur, accompanied by reconnection at multiple locations. The radial location of the dominant reconnection sites will be measured to compare with the simulations. In the case of counter-helicity merging, substantial amount of toroidal flux is expected to be annihilated to heat ions, which may in turn affect the reconnection process. In addition, kinetic helicity and even cross-helicity may play a role in determining the final global relaxed state. The main diagnostic tools will be 2D and 3D magnetic probe arrays, LIF, spectroscopy, fast CCD camera, and energetic ion detectors.

Milestones for PPPL incremental budget

Complete design activities for MRX upgrade for global merging experiments	Nov. 2002
Complete assessment of present MRX Resistive regime with T_e < 15 eV and S < 1000	Mar. 2003
Complete the upgrade of MRX, consisting of the installation of a new MJ capacitor bank and a large vacuum vessel	Dec. 2003
Install new MRX diagnostics	Feb. 2004
Complete search for a shock structure	June 2004
Complete preliminary characterization of collisionless Reconnection regime with T_e > 15 eV and S > 1000;	July. 2004
Complete initial assessment of Hall effects in the sheet	Sept. 2004

Recent publications

1.‘ Experimental study of ion heating and acceleration during magnetic reconnection’ S. Hsu et al., Phys. Plasmas **v.8,** 1916 (2001).

2. ‘Review of recent studies of magnetic reconnection region in controlled laboratory experiments" by M.Yamada, Earth, Planetary and Space Science, **53**, 509(2001).

3. ‘Study of local reconnection physics in a laboratory plasma" by H.Ji, T. Carter, S. Hsu and M. Yamada, Earth, Planetary and Space Science, **53**, 539(2001).

4. ‘Measurement of Lower-Hybrid Drift Turbulence in a Reconnecting Current Sheet’ T. A. Carter, H. Ji, F. Trintchouk, M. Yamada, and R. M. Kulsrud Phys. Rev. Letts. **88,** 15001, (2002).

5. ‘Measurement of the transverse Spitzer resistivity during collisional magnetic reconnection’.
F. Trintchouk, M. Yamada, H. Ji, R. M. Kulsrud and T. A. Carter, Submitted to Phys. Rev. Letts. (2002).

In addition several invited talks were given to APS meetings and international meetings on the above subjects.

1030 MRX			03/01/02		
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.7	.9	.3	.9	.3
Engineers			.3		.4
Administrators					
Graduate Students	1.1	1.0		1.0	
Technicians	1.1	.7	.9	.7	.9
Clerical					
Subcontractors					
TOTAL FTEs	2.9	2.6	1.5	2.6	1.6
OPERATING COSTS $(000):					
PPPL Labor	240.0	233.6	150.9	244.0	171.0
Subcontract Labor					
Overtime					
Travel	14.0	9.0	12.0	5.0	13.0
Energy					
Stockroom	2.5	22.1		13.3	
Miscellaneous Expenses	.8	8.0	73.6	8.0	70.3
Procurements/ICOs	116.7	74.4	100.0	74.0	85.0
Organizational Burden	34.6	29.3	14.9	30.6	17.0
Other					
General + Administrative	207.5	214.6	195.6	216.1	202.9
TOTAL OPERATING COSTS	616.1	591.0	547.0	591.0	559.2
TOTAL OPERATING OBLIGATIONS	575.1	591.0	547.0	591.0	559.2
EQUIPMENT COSTS $(000):					
Equipment - Direct			39.0		30.0
Equipment - G+A			14.0		10.8
Fabricated Equipment					
TOTAL EQUIPMENT COSTS			53.0		40.8
TOTAL EQUIPMENT OBLIGATIONS			53.0		40.8
GRAND TOTAL COSTS	616.1	591.0	600.0	591.0	600.0
GRAND TOTAL OBLIGATIONS	575.1	591.0	600.0	591.0	600.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
2110	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Development of the Magnetic Nozzle Technique to Promote Rapid Plasma Recombination	AT5030500

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Samuel A. Cohen Phone: 609-243-3185 Email: scohen@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

In the magnetic-nozzle research program, we perform experimental studies of plasma acceleration, cooling, and recombination in the expansion zone of a nozzle whose shape is set by a magnetic field. The experiments are aimed at forming a supersonic neutral jet from low-temperature, moderate-density, magnetized helium, argon, and xenon plasmas. Novel applications of such jets are possible in the fields of magnetic fusion power, space propulsion, materials processing, and lasing systems. Emphasis will be placed on understanding the basic science of the operative processes. Research activities include;

a) Experimental and theoretical analysis of spectral signatures of recombination.

b) Determination of the electric field along the plasma flow, including a search for double layer (DL) structures in the nozzle threat.

c) Refined measurement of the ion and neutral particle temperatures, densities, and flow velocities in the breech and expansion regions.

d) Measurement of the electron temperature by probes and studies of the continuum-emission.

e) Observation of spectrally and spatially resolved photon emission from the plasma, to provide the atomic-state (bound-electron) distribution functions of the atoms and ions.

The work will be performed in close consultation with research teams at Los Alamos National Laboratory, NASA's Johnson Spaceflight Center, Princeton University, and West Virginia University. This research program provides excellent education and training opportunities to graduate and undergraduate students.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

A. Purpose, goals, and applications

The purpose of MNX is to develop techniques that promote rapid volumetric recombination of plasma expanding along magnetic field lines.

The phase transition of a magnetized plasma stream into a supersonic jet of neutral gas is of fundamental interest, probing normal modes and irreversible processes of the system. One basic physics parameter controlling the transition is the polytropic coefficient, γ (the ratio of specific heats), which is determined by the plasma's degrees-of-freedom. The lower the value of γ, i.e., the closer to 1, the more degrees-of-freedom the plasma possesses and the more difficult to cool the plasma and to promote recombination. Magnetized plasmas are expected to possess fewer degrees-of-freedom than unmagnetized plasmas, hence are expected to recombine more readily. Other parameters, which strongly affect the recombination rate, are the electron temperature and density and the so-called re-heat energy, ΔE_{rh}, given to the free electron in the three-body recombination process.

The proposed research is to perform experimental and theoretical studies of plasma acceleration, cooling, and recombination in the expansion zone of a nozzle whose shape is formed by a constriction in magnetic field. In these experiments, the plasma flow will be predominantly along the magnetic field. The first research activity is to explore conditions in the magnetic-nozzle geometry under which a supersonic neutral jet is expected to be formed from a low-temperature, moderate-density, magnetized plasma.

Novel applications of supersonic neutral jets are possible in the fields of fusion power, space propulsion, materials processing, and lasing systems. The research program will investigate whether expansion cooling can promote rapid plasma recombination in the parameter range appropriate for these applications.

In magnetic fusion research, the power-exhaust role is usually assigned to the divertor component. In tokamaks, detached divertor plasmas have evolved into the method-of-choice to distribute the heat load. The experiments we are pursuing are related to detached plasmas, with the novel change that detachment, i.e., plasma recombination, would be promoted by plasma expansion rather than collisional cooling. The configuration we are examining could be implemented on the major axis of spheromak or FRC devices, or as a bundle divertor on a spherical torus or stellarator.

The efficient generation of a collimated intense supersonic neutral jet with low electron temperature and low plasma density allows specialized use in two of the application areas named: the directionality allows development of thrust for space propulsion and of anisotropic material deposition or erosion for materials processing. Applicability to lasing systems will depend on whether expansion cooling can be sufficiently rapid to produce a specific population inversion. A population inversion has nearly been attained in collisionally cooled plasmas previously generated in our facility.

B. Approach

Experiments are a continuation of inert-gas-plasma studies performed in the magnetized (to 3.5 kG) linear plasma device named MNX, the Magnetic Nozzle Experiment. Inert gases have fewer degrees-of-freedom (no rotational and vibrational modes) than molecular gases, hence higher values of γ. The choice of helium as a working gas is directly relevant to advanced-fuel fusion scenarios, such as D-^{3}He.

Higher atomic-mass inert gases are frequently favored for space-propulsion applications, hence are included in the research plan.

Steady-state He, Ar and Xe plasmas are now formed in MNX by helicon wave absorption. The Ar and Xe plasmas generated in MNX have a maximum density of 10^{14} cm^{-3} and an electron temperature near 5 eV. For these inert-gas plasmas to recombine, the electron temperature must drop to below ~ 0.1 eV. (At the same density, less cooling is required for He because of its higher ionization potential.) The magnetic nozzle geometry has been upgraded to produce a magnetic expansion value up to $R_M \equiv B_{nozzle}/B_{target} = 240$ in steady state, at a distance of 0.21 m from the nozzle. These expansion values and inert-gas plasma parameters are promising for cooling and recombination studies.

In our earlier experiments, where ion-neutral and electron-ion collisions were important, double layers (DLs) and steep electron-temperature steps (STSs) were observed. The experimental program will test whether a DL and a STS will occur in plasmas where electron-electron collisions, magnetic expansion, and Poisson's equation dominate. The temperature drop to below 0.1 eV is expected to occur in two sequential stages, by the formation of a DL/STS in the nozzle throat, and by cooling in the magnetic-field expansion zone.

The diagnostics must be able to detect a DL and a STS in the nozzle throat and to measure the charged and neutral particle concentrations, temperatures, and velocities in the expansion region. The diagnostics to detect and quantify the DL and STS phenomena are scanning Langmuir probes. Spectrally resolved emissivity measurements will yield the atomic-state distribution functions of the atoms and ions as well as, in some cases, the electron temperature.

An iCCD camera/spectrometer system will be used for emission spectroscopy. Doppler broadening and Doppler shift measurements are possible with the iCCD/spectrometer, yielding time- and line-integral ion temperature and flow measurements. Additionally, there are two institutional collaborations on MNX. First, Dr. F. Levinton, (Nova Photonics, Inc.), is using MNX for NSTX's Motional Stark Effect (MSE) diagnostic development. NPI's state-of-the-art MSE laser-induced-fluorescence (LIF) system with diagnostic neutral beam (DNB) can provide Ar-ion temperature and flow velocity measurements in MNX with better spatial and time resolution than emission spectroscopy. Secondly, Prof E. Scime (WVU) is developing a LIF diagnostic for both Ar ions and He neutrals and ions in MNX. He used his Ar-ion LIF diagnostic on MNX in the summer of 2001.

Numerical models of the expanding plasma will be developed to compare with the acceleration, cooling, and recombination processes that have occurred.

C. Selected accomplishments (FY2002)

(i) Operation of a steady-state helicon plasma source with helium

In FY2001, using an m=0 helicon antenna, we achieved steady-state He plasmas of density 10^{13} cm^{-3} at an absorbed power of 1 kW at fields as high as 4 kG. This extended the operating range for moderate density helium plasmas to magnetic fields 5 times higher than previously achieved.

(ii) Improvements to the first magnetic-nozzle coil system

In FY2001, we implemented the method (discovered in FY2000) to increase the steady-state expansion ratio, R_M, to 240 and to steepen the axial gradient scale length by a factor of 5.

(iii) Spectral studies of argon and helium plasmas

Recombination radiation from helium plasmas, measured in the main region in FY2000, was analyzed by Prof. V. Sevastyanenko, formerly of the Belorussian State Polytechnic Academy. The model used was a 9-temperature non-LTE quasi-Boltzmann approach.

iv) LIF studies of Ar* II temperature

Dr. R. Boivin (WVU) came to PPPL for two research stays, each ~ 3 weeks in length. He used the WVU LIF system to measure the Ar^{*+} transverse temperature. Values between 0.1 and 0.4 eV were found over a wide range of pressures and powers.

v) Particle orbit model

Dr. A. Glasser (LANL) modified his Hamiltonian orbit-following code (RMF2.00) to allow studies of ion and electron trajectories in both Helmholtz and solenoidal configurations, as produced in MNX.

vi) Diagnostics

A scanning Langmuir probe was built. Rapid radial profiles of He plasmas were made quantifying peaked versus hollow modes of plasma operation.

(vii) Education/student research activities

Graduate student Tom Kornak continued magnetic field calculations that showed how to improve R_M. Graduate student K. Stokke analyzed a filter-based Doppler diagnostic and participated in experimental operations and probe measurements. Undergraduates R. Gondahlekar and J. Sapan worked on MNX during the summer, designing and building in data acquisition systems and RF electronics. Mr. Sapan will continue on the project during the Spring semester. Mr. N. Siefert, a Princeton senior in Mechanical and Aerospace Engineering, is pursuing his Certificate in Robotics, by automating MNX controls and diagnostics.

D. Goals for the remainder of FY2002 and for FY2003 and FY2004

We will further investigate methods to generate higher density helium plasmas, to 5×10^{13} cm^{-3}. This will be accompanied by iCCD/spectroscopic studies of recombination radiation with a magnetic expansion up to 240. In FY2002 we will perform studies of He^+ acceleration with $R_M = 240$ using the iCCD. LIF will be used for $Ar^{+}*$ acceleration studies. The FY2003 phase is a continuation of the MNX program, necessary to meet the original milestones that were delayed because funding was below the proposed level. Here we shall perform studies of plasma cooling and recombination and ion acceleration with R_M increased to 2500. We shall also use the WVU LIF system for He^+ studies. Research in FY2004 will be further studies of He plasmas, energy balance studies with several inert gases, and the implementation of a triple-probe

technique (pioneered by M. Meier, R. Bengston, and G. Hallock at University of Texas, Austin) to measure γ.

(i) Technique and equipment modifications and improvements

Methods to make higher density helium plasmas will be explored. We have tested use of gas mixtures, e.g., helium/neon or helium/argon, of progressively larger helium concentrations. These were not successful because of the low electron temperatures produced. Subsequently we were successful with a combination of techniques: operation with an m = 0 antenna; more uniform B; lower axial field; and higher helium pressure. We shall continue to explore these methods at higher, possibly modulated, power.

(ii) Diagnostic improvements

RF-compensation will be added to the single Langmuir probe, to provide axial and radial electric field, density, T_e, and EEDF (electron energy distribution function) measurements in the main vessel and expansion region. A triple probe will be constructed for better time resolution of T_e and γ measurements.

Magnetic coils will be built for the purposes of measuring diamagnetism, helicon fields, and fluctuations.

The WVU LIF system will be re-installed with an axial view line. Measurements of ion temperature and flow will be made, first for Ar^+ and Ar^0. WVU will continue its development of a diode laser system for He^0 and He^+.

(iii) Plan for experimental work

Magnetic nozzle experiments will continue in the regime $B/\nabla B > \lambda_{ee}$, (where λ_{ee} is the electron-electron mean-free-path), with $\mathcal{R}_M < 30$ and gradient $\nabla B < 2$ T/m. This relatively weak nozzle is predicted to generate a Mach number up to 3 and up to a ten-fold increase in recombination rate. We will make first estimates of γ and first measurements of the axial plasma potential in the weak nozzle geometry. Increased density (FY2002) and the modified nozzle coil system ($R_M = 240$) will allow investigations of the regime $B/\nabla B < \lambda_{ee}$. Mach numbers as high as 10 are predicted.

Experimental investigations of spectral signatures of recombination (continuum emission and emission from highly excited levels) in Ar, Ne and He plasmas will be made in the nozzle expansion region for both collisionality regimes. Probes will measure the electric field in the expansion region. A search for double layer (DL) structures in the nozzle throat is part of this activity.

We will make systematic measurements of the ion and neutral particle temperatures, densities, and flow velocities in the breech and expansion regions. We have made first measurements by both emission spectroscopy and LIF.

Using emission from helium plasmas, we will measure the free-electron temperature in the expansion region by continuum emission studies.

Using emission spectroscopy, observations of spectrally and spatially resolved photon emission from the plasma will provide the atomic-state (bound-electron) distribution functions of the atoms and ions.

Time- and spatially resolved measurements of plasma parameters will be made with the WVU LIF system. Many candidate neutral helium lines lie in a suitable wavelength range: from 587.5 nm 2^3P-3^3D to 728.1 nm 2^1P-3^1S. Singlet and triplet

excited states are populated by the recombination cascade. The experiment will test which scheme produces the best signal.

A triple probe technique, (see M. Meier, et al. Phys Rev. Lett. 87, (2001) 85003), will be used to measure γ.

The program would then continue with the strongest magnetic nozzle practical in MNX, $R_M \cong 2500$. During this period, the efficiency of the nozzle in converting input power into exhaust power will be documented. There are two reasons for this. The first is the obvious, to quantify the efficiency of the "rocket engine." The second is to help understand the reheat process. Recent theoretical work (see F. Robicheaux and D. Hanson, Phys. Rev. Lett. 88, (2002) 55002), predicts that more reheat energy results in greater expansion velocities. Data acquisition and analysis and assessment of the experimental results will continue into FY2004.

(iv) Plan for theoretical work

The theory for plasma expansion from this nozzle is complex because of the mixed collisionality, boundary conditions, and non-adiabatic character of the system. The collisionality is different for the ions and electrons and also changes with distance. The downstream boundary condition will depend on whether the plasma recombines. The non-adiabatic nature arises from irreversible energy transfer between the two species.

To address this complex problem we plan two approaches. The first is to modify the RMF code (A. Glasser, LANL) to study ion orbits in the specific full 3D magnetic field of MNX. Departures from axial symmetry could result in ions becoming detached from the magnetic field lines without recombination. We will collaborate with Drs. A.V. Ilin and F. Chang-Diaz (NASA) who work on a related research program.

The second approach is to modify a 1-dimensional hybrid code (fluid electron/discrete ions and neutrals) to be 2-dimensional. The electric field along and across B will be self-consistent. Charge-exchange, Coulomb, and recombining collisions will be included. Solutions will be sought as functions of initial conditions, i.e., without fixing the downstream boundary. Comparison of the radial density profile with the model of I. Kaganovich (PPPL) will be made.

E. Schedule/Milestones

<u>FY2002</u>	
June	Operate WVU LIF system, studying Ar^+ flow.
Aug	Perform studies of He^+ velocity using iCCD.
<u>FY2003</u>	
Oct	Increase R_M to 2500.
Dec	Perform iCCD studies of recombination to $R_M = 2400$.
July	Operate WVU LIF system, studying He^+ flow.
<u>FY2004</u>	
Feb	Implement triple probe method for γ determination.
July	Perform energy balance measurements with He, Ne, Ar, Kr.

2110 MAGNETIC NOZZLE		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	.1	.3	.3
Engineers	.1		
Administrators			
Graduate Students	.8	.8	.8
Technicians	.2	.1	.1
Clerical			
Subcontractors			
TOTAL FTEs	1.2	1.2	1.2
OPERATING COSTS $(000):			
PPPL Labor	63.0	75.5	78.9
Subcontract Labor			
Overtime			
Travel	3.0	3.9	3.9
Energy			
Stockroom	2.5		
Miscellaneous Expenses	1.6	8.1	4.4
Procurements/ICOs	39.0	27.6	27.6
Organizational Burden	8.1	9.5	9.9
Other			
General + Administrative	55.8	72.4	72.3
TOTAL OPERATING COSTS	173.0	197.0	197.0
TOTAL OPERATING OBLIGATIONS	188.0	197.0	197.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	173.0	197.0	197.0
GRAND TOTAL OBLIGATIONS	188.0	197.0	197.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1815	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
FRC Plasma Heating by Rotating Magnetic Fields (RMFs) that Maintain Closed Flux Surfaces	AT5015020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Samuel A. Cohen Phone: (609) 243-3185 Email: scohen@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This research program explores a solution to a long-standing fundamental problem in FRC physics, how to apply rotating magnetic fields (RMFs) so that the FRC's closed field-line structure is maintained. RMFs, because of their ability to drive current, are considered desirable in FRCs in that they could make the FRC into a steady-state device. Decades ago, though, theoretical work showed that even-parity RMFs destroyed field closure. But our recent theoretical work proved that odd-parity fields would preserve closure. Moreover, in the last year, rotating small-amplitude odd-parity magnetic fields were predicted to heat electrons and ions to fusion-relevant energies. Having one system, the RMF, perform several functions - drive current and heat ions and electrons while maintaining the good confinement properties of closed field lines - provides a distinct technological advantage and strongly motivates this research.

The experimental program is to study FRC formation, plasma confinement, electron heating, and ion heating with up to 100 kW of odd-parity RMF power applied to a 2-cm radius, 30-cm long helium plasma column. With the attainment of a closed magnetic field structure, operation at the proposed power/unit volume would yield an electron temperature above 100 eV at $n_e = 5 \times 10^{12}$ cm^{-3}.

These results will have relevance to the design of a compact fusion reactor.

To improve understanding of the processes responsible for heating and confinement, the research will be performed in collaboration with scientists at the Los Alamos National Laboratory, ANU, the INLS, and Princeton University. This research program provides excellent education and training opportunities to graduate and undergraduate students.

15. Signature

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No.

A. **Purpose and Goals**

As a fusion reactor, the field-reversed configuration (FRC) is recognized to have many attractive features, such as linear magnet geometry and high-β operation space. However, there are major fundamental physics challenges to the development of the FRC into a practical fusion reactor. These include achieving adequate energy confinement, generating stability against certain modes (especially the internal tilt), and finding appropriate methods to sustain the plasma configuration and to heat the ions and electrons to fusion-relevant temperatures. The purpose of the proposed research program is to perform experimental studies of a new class of rotating magnetic field shapes (odd parity) that are predicted to solve several of these problems.

Rotating magnetic fields (RMFs) have been successfully used, particularly in rotamak devices, to make plasma, drive toroidal current, and obtain field reversal. Rotamak experiments, however, have produced only warm electrons, $T_e < 50$ eV, and showed energy loss at a rate consistent with simple ion-acoustic flow on open field lines. In fact, theory clearly shows that the standard RMF geometry, that of even parity, opens the field lines of an FRC. Recently, however, we proved the exciting result that specially shaped transverse fields, those of odd parity, maintain the closure of an FRC's flux surfaces. An experimental test of whether closed field lines will improve the FRC's energy confinement time is the primary goal of the proposed experiments.

The second goal of the proposed experiments is to study particle heating by the RMF. Recent theoretical work showed that odd-parity RMFs would heat both electrons and ions. For example, RMFs of strength *ca.* 20 G are predicted to heat the ions in a 20 kG, 10-cm radius FRC to fusion-relevant temperatures, above 20 keV, and electrons to about 10 keV. A working FRC is far more complex than the theoretical heating model used, in part because of the field penetration question. Hence, the predicted odd-parity RMF plasma-heating physics requires detailed experimental tests in an FRC.

The theoretical ion heating studies also showed the provocative feature that ions heated into betatron orbits were localized near the FRC's midplane. This has good implications for stability. A goal of the experiment is to approach the conditions where this can be tested.

B. Approach

Experimental tests of odd-parity RMF require reliable, flexible, definitive techniques. Our approach is to use standard commercially available technologies/equipment to provide reliability and flexibility. To be low cost, modest-sized, low-power components are necessary. Low cost also mandates use of existing components, or commercially available ones, to minimize technology development efforts and costs. Our FRC experiment, to be operated onto the existing MNX facility, will have a relatively small volume and low power compared to past and present FRC experiments. But its power/volume will match or exceed that of most other rotamak experiments. The small volume and low power will also reduce safety concerns.

For these experiments to succeed, detrimental plasma-wall and atomic-physics effects must be minimized. For example, in most rotamak experiments, the FRC separatrix lay

outside the vacuum vessel wall. Intense wall recycling took place and the plasma remained only partially ionized. Ion cooling occurred by charge exchange. The experimental facility and methodology we have chosen avoids these complications by employing a separate plasma formation region about a meter away from the ultra-high vacuum FRC section. This will also allow operation at low plasma density, essential for reducing the plasma collisionality and response and allowing tests of physics principles in a system with several dimensionless parameters, e.g., the ratio of collisional mean-free-path to system size, comparable to a reactor. Helium will be used as the working gas.

We will employ non-invasive techniques for diagnosing the FRC, so as not to alter its parameters or compromise the confinement benefits obtained with closed field lines. These diagnostics will include external magnetic measurements of β, spectroscopic measurements of ion and electron temperature, and microwave measurements of density. A staged implementation of these diagnostics is part of the research plan. For the most part, conventional diagnostics, whose interpretation is universally accepted, will be used to guarantee the definitiveness of the measurements. If the plasma confinement and heating are excellent, the installation of more advanced and complex diagnostics will be sought. An example is the measurement of the internal magnetic field by motional Stark effect (MSE). We note that there is already an MSE system installed on MNX, as part of an NSTX diagnostic development program.

C. **Progress (FY2002)**

In preparation for FRC/RMF experiments, we are continuing theoretical studies of odd parity RMF effects on ions and electrons. Results on ion heating have been published and those on electron heating will soon appear. We constructed and tested the first odd-parity RMF antenna, coupling 30 W at 13 MHz into a weakly ionized plasma: T_e = 1.2 eV, n_e = 10^{12} cm^{-3}, and n_n = 10^{17} cm^{-3}. Selected accomplishments, achieved this year, are summarized below.

(i) Ion heating by odd-parity RMF

A *Phys. Rev. Lett.*, coauthored by S.A. Cohen and A.H. Glasser, showed that explosive ion heating occurred when (even) small-amplitude odd-parity RMFs, with frequency in the ion-cyclotron range, were applied to the FRC. The heating mechanism is a hybrid of ion-cyclotron resonance and stochastic magnetic pumping (Fermi acceleration). The chaotic behavior displayed by the ion orbits is under continuing investigation.

(ii) Electron heating by odd-parity RMF

A paper, coauthored by A.H. Glasser and S.A. Cohen, was accepted by *Phys. Plasmas*. It showed that appreciable electron heating (to ~ 10 keV) occurred when (even) small-amplitude low-frequency odd-parity RMFs were applied to the FRC. Electron heating occurs due to non-adiabatic scattering events from magnetic field non-uniformities and azimuthal acceleration near the O-point field null. Current drive was also examined. The chaotic nature of the electron trajectories was demonstrated by the calculation of the Lyapunov exponents.

(iii) Stability of particle orbits

Graduate student Alexandra Landsman presented a paper on the stability of particle orbits in the FRC. Her results clearly explain the localization of betatron orbits in the FRC midplane and the linear stability of these orbits.

(iv) Operation of the first RMF antenna

Graduate student Ethan Schartman performed the first operations of the odd-parity RMF antenna, built by graduate student Tom Kornack. Undergraduate student Jonathan Sapan performed the circuit analysis necessary to build the RF coupling circuit and assisted Mr. Schartman in the antenna operations.

(v) Diagnostics

The first set of diamagnetic coils were built and tested. A heterodyne interferometer was installed in the MNX laboratory.

(vi) Education/student research activities

In 2001, a total of 8 students performed research on the FRC project. In addition to the three graduate students and one undergraduate whose work was described above are: K. Stokke (1st-year graduate student) probe measurements on helicon plasmas; E. Lieberman (Princeton University junior) mathematical theory of field closure maintained by odd-parity fields; R. Gondhalekar (Cambridge University junior) control system for diagnostics; E. Torbert (Princeton University senior) an experimental study of transitions to chaotic states.

D. **Future Goals (remainder FY2002 and FY2003 and FY2004)**

In the present fiscal year, we are completing RF design and construction tasks for the odd-parity RMF system. We have selected a method to allow tuning the antenna circuit across a broad frequency range (5-30 MHz). Our approach relies heavily on the use transmission lines in a tank circuit for impedance matching and frequency control. We are studying ways to balance the orthogonal antenna circuits in phase and amplitude. A major re-orientation of the layout of the MNX laboratory equipment began in the summer. Operations were resumed in September. Installation of the RMF components in the MNX vacuum system will be completed in March.

Once the final RMF section is installed, RMF experiments with low-density plasma can begin. The RMF power will be gradually increased to 100 W. The plasma will remain linear. Studies of RF coupling and plasma diagnosis with passive spectroscopy, microwave interferometry, and diamagnetic loops will be made. The axial B field, B_a, will be low, about 100 G. Studies of confinement and heating at RF power up to 1 kW will be begin in September.

We await a decision from DOD on a proposal we submitted to procure a 200 kW RF power supply to extend our parameter space for experimentation. If this proposal is not approved, we shall rebuild a disused RF supply to provide 100 kW in 10 ms pulses at a duty factor of 1%. However, this will delay the high power (ion heating) part of the program by about 1.5 years, attributable to the funding being below the amount requested in the original proposal. As part of this proposal, we are requesting incremental funding to restore the funding to the level named in our original proposal.

The remaining experimental research period (FY 2003 and 2004) has two phases, each of approximately equal duration. In FY2003 we will increase the RMF power to 5 kW. If the power coupling is successful, β should reach 1, an FRC form, and B_a rise above 200 G. This will allow studies of energy confinement of an FRC formed by odd-parity closure-preserving RMFs. Electron heating studies are an important part of this research phase. Late in the next phase (FY2004), the RMF power would be increased to 100 kW (or 200 kW, pending the DoD proposal), permitting first studies of ion heating. The external magnetic field is expected to exceed 1 kG and the ion temperature would then climb above 100 eV, assuming classical cross-field transport.

(i) RF equipment

The RF power supplies/amplifiers at PPPL, whose capabilities are in the range we need, (from 5 kW CW at a fixed frequency of 13.6 MHz, to 100 kW for 10 ms pulses, tunable between 2 to 30 MHz), will need refurbishment for use in the FRC experiments, as described in the original proposal.

(ii) Diagnostics

Diamagnetic loops have been built and installed in the flux conservers, to provide axial measurements of β.

With helium as the working gas, T_e can be measured with an iCCD/spectrometer system by line-ratio techniques to T_e values somewhat above 50 eV. Above 100 eV, windowless Li-Si detectors could be used to measure T_e. The same iCCD system would measure T_i by Doppler broadening. Impurity radiation could be used between for temperatures between 20 and 100 eV.

The plasma density will be measured by a microwave interferometer.

If the external field exceeds 1 kG, a request would be made through PPPL management to DOE to use the MSE system intended for NSTX. This would be used for non-invasive measurement of the internal magnetic field.

(iii) Plan for theoretical work

The Hamiltonian code ($RMF_{2.00}$) of Dr. A. Glasser will be used to study heating in our small FRC. The electrostatic potential term will be examined for its effects on heating, confinement, and current drive.

E. Relationship to Other Projects

A multi-institutional theory proposal is being prepared for submission in the soon-to-be-announced DOE ICC theory solicitation. It will cover continuing work with the $RMF_{2.00}$ code, analytic studies of particle dynamics using Melnikov's techniques and Poincare plots, and MHD aspects of the RMF problem. This is included in the following discussion of incremental funding

F. Incremental Effort: FY2003 - FY2004

(i) Experimental work

A request is made for an additional $160K to restore the FRC funding to that level stated in the LAB 00-07 proposal. The funding would be used to increase manpower, that is, research and technical staff will be hired into the experimental program, to build, test and run

the RF equipment, to run the additional diagnostics, to develop FRC operational scenarios, and to maintain the experimental facility. Without this additional funding, the ion-heating goal stated in the original proposal would be delayed 1.5 years and the operation of the interferometer would be delayed by a year.

(ii) Theoretical work

Incremental support of $382K ($150K for PPPL and $232K for other institutions) is proposed for theory work. The theory work would be performed at a number of institutions including PPPL, LANL, NYU, Princeton University Department of Mechanical and Aerospace Engineering, INLS, and ANU. Funding for this theory workscope will be requested in a proposal to be submitted to DOE in response to the soon-to-be-announced ICC solicitation. The following paragraphs describe the theoretical studies to be performed with the contributors to these studies noted in parentheses at the end of the paragraph.

Motivated by the highly successful theoretical efforts with the Hamiltonian code, incremental funding is sought in FY2003-004, to support additional staff. Exciting and unexpected results shown the Hamiltonian code include electron heating and current drive. These are very promising areas meriting further study. A most surprising result was that RMF would drive electron motion in the direction opposite of the RMF's direction of rotation. Another major discovery was that the radial motion of both ions and electrons was controlled by the (transformed) Hamiltonian invariant, K. Additional research staff are needed to study these. (PPPL, LANL)

Also, the Lyapunov exponents and the Poincare plots of the system, necessary to address particle confinement and the development of particle distribution functions for subsequent heating and energy extraction research, will be studied. The Lyapunov and Poincare activities will describe our research results in terms familiar to the community of scientists who study dynamical processes in higher dimensional systems. This will allow shared benefits between the fusion community and dynamical systems scientists. (PPPL, LANL, PU-MAE, ANU)

Symbolic dynamics studies will be initiated with the aim of answering three very basic questions that the experiments cannot easily address by standard diagnostic techniques. These questions are: Has a true closed-field FRC been formed from the initial mirror geometry? Does a toroidal field (non-zero helicity) exist in the FRC? Is there a clear difference between even- and odd-parity RMF? The spectrum of the symbolic dynamics, called the symbolic cycle distribution (SCD), may show characteristics that are distinct for the pairs of conditions named in the three above-named questions. The SCDs produced by the RMF and hybrid codes would then be compared with those generated by analysis of time-series data from the FRC experiment. (PPPL, PU_MAE, INLS)

Hybrid (MHD electron and kinetic ion) code studies of RMF effects will be made and focus on the novel parameter range and geometry in our experiment. Emphasis will be on RMF penetration in 3-D and electron heating. Ion heating and stabilization studies will take place in the latter part of the program. This delay is advisable because of the need for faster computational capabilities for the computationally intensive 3-D stability calculations. (PPPL, NYU, LANL)

F. Schedule/Milestones

FY2002	
Dec	Install FRC components on MNX
Aug	Increase RMF power to 5 kW
FY2003	
Oct	Study confinement time in odd-parity RMF-formed FRC
Feb	Study electron heating in FRC
FY2004	
Feb	Extend pulse length beyond 1 ms
July	Increase plasma radius to 4 cm, to increased magnetic flux.
FY2003/4 Incremental	
2003	Test and operate 100 kW RMF unit
	Lyapunov exponents calculated for ions and electrons in PPPL Experiment
2004	Symbolic dynamics studies of RMF code
	Poincare plots of ion and electron orbits
	Ion heating studies at 100 kW

1815 FRC ROT MAG. FIELD 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.3	.4	1.3	.4	1.3
Engineers					
Administrators					
Graduate Students			1.0		1.0
Technicians	.1	.1		.1	
Clerical					
Subcontractors					
TOTAL FTEs	.4	.5	2.3	.5	2.3
OPERATING COSTS $(000):					
PPPL Labor	48.0	76.2	145.5	79.8	148.2
Subcontract Labor					
Overtime					
Travel	2.5		8.6		6.5
Energy					
Stockroom					
Miscellaneous Expenses	.4				
Procurements/ICOs	15.0	13.0	203.1	8.3	202.2
Organizational Burden	6.6	8.5	8.6	8.8	8.7
Other					
General + Administrative	38.4	59.3	176.4	60.1	176.6
TOTAL OPERATING COSTS	110.9	157.0	542.2	157.0	542.2
TOTAL OPERATING OBLIGATIONS	108.9	157.0	542.2	157.0	542.2
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	110.9	157.0	542.2	157.0	542.2
GRAND TOTAL OBLIGATIONS	108.9	157.0	542.2	157.0	542.2

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1205	0	2/11/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Paul Trap Simulator Experiment	AT 50 15 03 3

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Ronald C. Davidson Phone: 609-243-3552 Email: rdavidson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Periodic focusing accelerators and transport systems have a wide range of applications ranging from basic scientific research in high energy and nuclear physics, to applications such as heavy ion fusion, spallation neutron sources, tritium production, and nuclear waste treatment, to mention a few examples. Of particular interest at the high beam currents and charge densities of practical interest are the combined effects of the applied periodic focusing field and the intense self fields produced by the beam space charge and current. Under the auspices of the Office of Fusion Energy Sciences solicitation DOE-007, we initiated fabrication of the Paul Trap Simulator Experiment (PTSX) to simulate the collective processes and nonlinear dynamics of an intense charged particle propagating beam through a periodic focusing field configuration. Following an assembly of the PTSX experimental facility, experimental operation is planned to begin in April, 2002.

The key technical milestones for PTSX during FY 2003 and FY 200 are the following:

(a) Complete suite of experiments on emittance-dominated one-component plasmas (December, 2002).
(b) Begin experiments on space-charge-dominated one-component plasmas (January, 2003).
(c) Complete installation of laser-induced fluorescence diagnostic and begin experimental operation (March, 2003).
(d) Complete initial suite of experiments on space-charge-dominated one-component plasmas (September, 2003).
(e) Complete suite of experiments on space-charge-dominated one-component plasmas (March, 2004).
(f) Complete experimental investigations of halo particle excitations (September, 2004).
(g) Complete preparation of scientific reports (September, 2004).

15. Signature

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Paul Trap Simulator Experiment

A. Purpose and Goals

Periodic focusing accelerators and transport systems have a wide range of applications ranging from basic scientific research in high energy and nuclear physics, to applications such as spallation neutron sources, tritium production, heavy ion fusion, and nuclear waste transmutation. Of particular interest, at the high beam currents and charge densities of practical interest, are the combined effects of the applied focusing field and the intense self fields produced by the beam space charge and current on determining detailed equilibrium, stability, and transport properties. Through basic experimental studies, analytical investigations based on the nonlinear Vlasov-Maxwell equations, and numerical simulations using particle-in-cell models and nonlinear perturbative simulation techniques, considerable progress has been made in developing an improved understanding of the collective processes and nonlinear beam dynamics characteristic of high-intensity beam propagation in periodic focusing and uniform focusing transport systems. Nonetheless, it remains important to develop an improved basic understanding of the nonlinear dynamics and collective processes in periodically-focused intense charged particle beams, with the goal of identifying operating regimes for stable (quiescent) beam propagation over hundreds, even thousands, of lattice periods of the periodic focusing magnetic field, including a minimum degradation of beam quality and luminosity. High-intensity accelerator systems and beam transport lines are typically large physically and expensive to operate. Under the auspices of Department of Energy Program Announcement LAB00-07, we have initiated construction of the Paul Trap Simulator Experiment (PTSX). The purpose of this facility is to carry out detailed experimental studies on a compact Paul trap configuration that fully simulates the collective processes and nonlinear transverse dynamics of an intense charged particle beam propagating through a periodic quadrupole magnetic field configuration. The proposed experimental studies include detailed investigations of: (a) beam mismatch effects and envelope instabilities, (b) collective wave excitations, (c) chaotic particle dynamics and production of halo particles, (d) mechanisms for emittance growth, and (e) determination of the effects of the distribution function on stability properties.

B. 2000-2001 Publications

"Paul Trap Simulator Experiment to Simulate Intense Beam Propagation Through a Periodic Focusing Quadrupole Field," R. C. Davidson, P. C. Efthimion, E. Gilson, R. Majeski, and H. Qin, American Institute of Physics Conference Proceedings **606**, 576 (2002).

"Guiding-Center Vlasov-Maxwell Description of Intense Beam Propagation Through a Periodic Focusing Field," R. C. Davidson and H. Qin, Physical Review Special Topics on Accelerators and Beams **4**, 104401 (2001).

"Paul Trap Experiment for Simulating Intense Beam Propagation Through a Quadrupole Focusing Field," R. C. Davidson, P. Efthimion, R. Majeski and H. Qin, Proceedings of the 2001 Particle Accelerator Conference, 2978 (2001).

"Paul Trap Configuration to Simulate Intense Beam Propagation Over Large Distances Through a Periodic Focusing Quadrupole Field," R. C. Davidson, P. C. Efthimion, R. Majeski, H. Qin and G. Shvets, Nuclear Instruments and Methods in Physics Research **A464**, 502 (2001).

"A Paul Trap Configuration to Simulate Intense Nonneutral Beam Propagation Over Large Distances Through a Periodic Focusing Quadrupole Magnetic Field," R. C. Davidson, H. Qin, and G. Shvets, Physics of Plasmas **7**, 1020 (2000).

C. Approach and Technical Progress

The layout and scientific objectives of the Paul Trap Simulator Experiment are described in detail in the Research Proposal submitted in response to Department of Energy Program Announcement LAB00-07, and in the 2000-2001 publications identified above in Section B. To briefly summarize the Paul trap simulator configuration, a long nonneutral plasma column ($L \gg r_p$) is confined axially by applied dc voltages $\hat{V} = const.$ on end cylinders at $z = \pm L$, and transverse confinement is provided by segmented cylindrical electrodes (at radius r_w) with applied oscillatory voltages $\pm V_0(t)$ over 90° segments. Here, $V_0(t+T) = V_0(t)$, where $T = const.$ is the oscillation period, which produces an oscillatory quadrupole focusing force on a particle with charge q and mass m near the cylinder axis. Because the transverse focusing force is similar in waveform to that produced by a discrete set of periodic quadrupole magnets in a frame moving with the beam, the Paul trap configuration offers the possibility of simulating intense beam propagation in a *compact* experimental facility. The nominal operating parameters in the experiment are: cesium ions ($A = 133$); plasma column length $2L = 2m$; wall radius $r_w = 10$ cm; plasma radius $r_p = 1$ cm; maximum wall voltage $\hat{V}_0 = 400$ V; end electrode voltage up to $\hat{V} = 500$ V; and voltage oscillation frequency $f_0 = 1/T = 220$ kHz for $^{137}Ba^+$ ions. The proposed experimental studies include detailed investigations of: beam mismatch effects and envelope instabilities; collective wave excitations, chaotic particle dynamics and production of halo particles; mechanisms for emittance growth; and effects of distribution function on stability properties.

The PTSX facility and associated diagnostic suite constitute an enormously flexible facility for simulating a wide range of nonlinear collective processes important in the propagation of intense charged particle beams over large distances. Most importantly, the flexible source geometry and ability to vary the voltage waveform $V_0(t)$, either dynamically or from experiment to experiment, permit detailed studies to be carried out over a wide range of density $\hat{n}$, average radius r_p, and choice of equivalent waveform for the quadrupole focusing field. Furthermore, a laser induced fluorescence (LIF) diagnostic capability will permit a detailed investigation of the evolution of the density profile, rms column radius, transverse emittance, and velocity distribution function. An important dimensionless parameter s that measures the beam intensity and the self-field intensity is defined by $s \equiv \hat{\omega}_p^2/2\hat{\omega}_q^2$, where $\hat{\omega}_p$ is the plasma frequency, and $\hat{\omega}_q$ is the effective transverse focusing frequency. In the moderate-intensity beams encountered in high energy and nuclear physics applications, the self-field parameter s typically satisfies $s \leq 0.2$, corresponding to emittance-dominated beams which are a few or several Debye lengths in diameter. On the other hand, for space-charge dominated beams of interest for heavy ion fusion, the self-field parameter s can approach unity, corresponding to a very low transverse emittance, and near balance of the applied focusing force and the repulsive space-charge force. The PTSX facility has the capability to

investigate collective nonlinear processes for values of the self-field parameter ranging from moderate self-field intensity to very high intensity. Furthermore, the waveform for $V_0(t)$, which simulates the quadrupole focusing magnetic field, can be dynamically varied during an experiment, e.g., slowly varying amplitude at fixed frequency, or slowly varying frequency at fixed amplitude.

Excellent technical progress has been made during FY 2001 and FY 2002 in the design and fabrication of the Paul Trap Simulator Experiment facility. Highlights of this progress include: thorough preparation of laboratory space for siting the facility; procurement, assembly and pumpdown of the PTSX vacuum chamber to the 10^{-9} Torr pressure range (July, 2001); successful development of cylindrical electrode cutting techniques at PPPL, and identification of ion source vendors (September, 2001); successful identification of vendors for cylindrical electrode fabrication and plating (November, 2001); and installation of the electrode assembly and ion source (February, 2002). Initial experimental operation is planned for April, 2002. The detailed scientific program on PTSX is summarized in Section D.

D. Future Accomplishments (FY2003–FY2004)

The proposed experimental program on the PTSX facility will focus on a variety of investigations of collective nonlinear processes of fundamental interest in the physics of intense charged particle beams propagating in periodic focusing field configurations. The proposed studies are described in the Research Proposal submitted in response to the Department of Energy Program Announcement LAB00-07 and include the following task areas.

(a) The PTSX facility will be used to determine the effects of different waveforms for $V_0(t)$, at fixed amplitude and frequency, on equivalent beam propagation through periodic quadrupole field geometry. Waveforms ranging from sinusoidal to a (near) step-function lattice with variable fill factor will be used. Particularly important will be a determination of the conditions for quiescent, stable, matched-beam propagation over large (equivalent) distances, and the dependence of the density profile and distribution function using the laser-induced fluorescence diagnostic on the choice of waveform for $V_0(t)$ and the intensity parameter s.

(b) At fixed values of frequency $f_0 = 1/T$, if the focusing field amplitude is overly strong, it is expected that the plasma column will be subject to the so-called envelope instability in which the beam envelope and rms radius develop large-amplitude oscillations. This can lead to loss of equilibrium, beam mismatch, and ejection of so-called 'halo' particles from the core. Using a sinusoidal waveform for $V_0(t)$, experiments will be carried out to intentionally excite the envelope instability in order to determine its detailed nonlinear evolution and saturation, dependence on the intensity parameter s, and its effect on the production of halo particles. These experiments will provide an excellent opportunity to test and validate theoretical models of the envelope instability.

(c) A critical problem in accelerator physics is the unwanted production of halo particles by beam mismatch induced, for example, by faulty magnet sets which have the incorrect field intensity, or are misaligned, etc. To test this effect in the Paul trap simulator, we will intentionally spoil the voltage waveform $V_0(t)$ for a few or several periods in order to induce a mismatch. The detailed nonlinear effects on density profile, distribution function, and rate of halo particle production will be investigated as a function of degree of mismatch and self-field intensity parameter s.

(d) In related experiments, at fixed frequency $f_0 = 1/T$ and specified waveform (sinusoidal, say), we will adiabatically vary the amplitude of the oscillatory voltage pulse to simulate beam propagation through long transition regions where the focusing field amplitude is slowly varying (e.g., increasing slowly to compress the transverse dimension of the beam). Important in this regard will be a quantitative determination of how slow (i.e., over how many lattice periods) the transition has to be to assure quiescent (stable) beam propagation, and a determination of the corresponding effects on the transverse emittance, rms beam radius, and distribution function.

(e) Nonneutral plasmas and intense charged particle beams support a wide variety of collective oscillations that depend on the details of the distribution function, the focusing field strength, the self-field intensity parameter s, and geometric effects such as the proximity of the conducting wall. These oscillations typically involve various combinations of the frequencies $\hat{\omega}_q$ and $(\hat{\omega}_p^2/2)^{1/2}$, modified by geometric effects (r_p/r_w). We will carry out a series of experiments on PTSX that investigate detailed properties of collective excitations either excited externally, or occurring naturally as the result of beam mismatch, imperfections in the voltage waveform, or as a consequence of an instability. In addition to testing and validating theoretical models of collective oscillations in intense charged particle beams, particular emphasis will be placed on identifying collective modes whose signature will serve as a robust diagnostic for key properties of the beam, such as line density, transverse emittance, etc. We will also investigate the effects of collective oscillations as a mechanism for the production of halo particles. At moderate mode amplitudes, the associated nonlinearities induce chaotic particle motion, and theoretical predictions indicate that particles near the outer edge of the beam can be ejected to about $1.5r_p$. The laser-induced fluorescence diagnostic is sufficiently sensitive to detect a small population of ions ejected from the core.

(f) Depending on the ion source used in the Paul Trap Simulator Experiment, there is considerable flexibility to alter the input 'beam' density profiles, ranging from radially decreasing or uniform profiles, to slightly hollow, to hollow, to multiple beamlets (using masking techniques). During FY 2004 of the proposed research, we will investigate a variety of physics phenomena related to the input profiles from the ion source. Particular emphasis will be placed on determining the equilibrium properties of normal, slightly hollow, and hollow profiles, and their effects on emittance growth and the distribution function. We will also use a masked multiple beamlets source (4 to 8 beamlets) to investigate multiple beamlet propagation and subsequent beam merging, including the effects of adiabatically increasing the strength of the focusing field over several oscillation periods T.

Finally, the Paul Trap Simulator Experiment benefits from ongoing accelerator physics and nonneutral plasma research activities at the Princeton Plasma Physics Laboratory. There activities include: (a) theoretical and numerical studies in support of the Spallation Neutron Source project and the Los Alamos Proton Storage Ring (PSR) experiment; (b) analytical studies and computer simulations of space-charge-dominated beam propagation in heavy ion fusion applications; and (c) basic experimental investigations of the confinement and nonlinear dynamics of nonneutral plasmas in the Electron Diffusion Gauge (EDG) experiment, a Malmberg-Penning trap configuration.

The proposed funding level corresponds to the guidance funding level of \$315 K in each of the fiscal years FY 2003 and FY 2004. In addition, in the enhanced case, incremental funds of \$100 K are requested in FY 2004 to provide improved diagnostic capability and the flexibility to investigate alternate (e.g., higher-order multipole) electrode configurations and alternate (e.g., multiple beamlet) source configurations.

E. Milestones for FY 2003 and FY 2004

E.1 Milestones at Guidance Funding Level

1. Complete suite of experiments on emittance-dominated one-component plasmas (December, 2002).
2. Complete installation of laser-induced fluorescence diagnostic and begin experimental operation (March, 2003).
3. Complete initial suite of experiments on space-charge-dominated one-component plasmas (September, 2003).
4. Complete suite of experiments on space-charge-dominated one-component plasmas (March, 2004).
5. Complete experimental investigations of halo particle excitation (September, 2004).

E.2 Additional Milestones at Incremental Funding Level

6. Determine effects of alternate source configurations (e.g., multiple beamlet) on the dynamics and confinement of one-component plasmas (July, 2004).
7. Determine influence of alternate electrode configurations (e.g., higher-order multipole) on the dynamics and confinement of one-component plasmas (September, 2004).

1205 PAUL TRAP EXPERIMENT 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.4	.5		.5	.4
Engineers					
Administrators					
Graduate Students	1.0	1.0		1.0	
Technicians	.2	.7		.7	
Clerical					
Subcontractors					
TOTAL FTEs	1.6	2.2		2.2	.4
OPERATING COSTS $(000):					
PPPL Labor	100.6	144.0		150.6	37.3
Subcontract Labor					
Overtime					
Travel	2.1				
Energy					
Stockroom					
Miscellaneous Expenses		5.0		7.0	
Procurements/ICOs		29.8		18.6	25.6
Organizational Burden	15.4	18.5		19.3	2.6
Other					
General + Administrative	70.9	117.7		119.5	34.5
TOTAL OPERATING COSTS	189.0	315.0		315.0	100.0
TOTAL OPERATING OBLIGATIONS	147.0	315.0		315.0	100.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment	174.1				
TOTAL EQUIPMENT COSTS	174.1				
TOTAL EQUIPMENT OBLIGATIONS	160.0				
GRAND TOTAL COSTS	363.1	315.0		315.0	100.0
GRAND TOTAL OBLIGATIONS	307.0	315.0		315.0	100.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1215	0	3/01/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
Studies of the Effect of Segmented Electrodes on Physical Processes and Fundamental Limitations of Hall Plasma Thrusters	AT5030500

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Nathaniel Fisch Phone: 609- 243-2643 Email: nfisch@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The proposed research seeks to extend the scientific understanding of Hall thrusters, or, more generally, the insulating properties of magnetized plasma. We propose to research a family of segmented electrode Hall thrusters, operating in the range of 1 kW, with the object of understanding the fundamental physics underpinning these devices. In the process, we will develop methods of localizing steep voltage drops that potentially challenge accepted limits on the magnetic insulation properties of plasma. It is a related objective to characterize the waves and instabilities that arise as these limits are approached. Finally, it is our objective to suggest, on the basis of these investigations, better configurations for Hall thrusters.

The proposed work scope for this effort was submitted in response to DOE Program Announcement LAB 00-07 "New Programs in Fusion Energy Sciences" in 2000. This project has been funded in FY 2001 and FY2002.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

A. Approach and Technical Progress

In the last year, we upgraded of our vacuum facility by installing cryo pumps (very nearly complete). We made significant progress in diagnosing the harsh thruster plasma regime. We put into place a fast movable emissive probe and double probe inside the thruster channel. This allowed us to distinguish probe-induced perturbations. We also characterized the thruster performance in regimes exhibiting plume angle reduction through the placement of external electrodes. We built a high-frequency probe setup for comparing to theoretical predictions. Our preliminary observations show 7.5 MHz oscillations, and harmonics thereof. These interesting measurements may indicate structures rotating with the E x B velocity. We demonstrated the importance of wall materials with different secondary electron emission coefficients, identifying in the process important and to some extent unforeseen, physics issues associated with the secondary electron emission. To support our experimental campaign, we collaborated on theoretical modeling carried out by collaborators at the University of Michigan. Also, we identified some very interesting variations on the theme of cylindrical geometry E x B Hall-type acceleration.

Although we will be able to pursue the interesting issues associated with these effects somewhat, a modest increase in budget would enable us to pursue these issues more deeply. Also, at the time that the project is set to expire in 2004, we should just be beginning to understand the very interesting effects associated with magnetic insulation. The diagnostics we will have in place will also allow us to study in detail cross-field transport, as well as other limits to magnetic insulation. Accordingly, a continuation into Year 4 may yield very interesting new physics. We intend to submit a follow-up continuation proposal and the FY04 scope of work is part of this future proposal.

B. Future Accomplishments (FY2003-FY2004)

In FY 2003—2004, we will work towards challenging the accepted limits on Hall thruster technology. We hope to have accomplished extremely fine measurements of the details of the thruster plasma so that we can identify the microscopic behavior of this type of insulating flow. We should have in place both fast probe and spectroscopic measurements that will give us detailed potential profiles in a variety of magnetic configurations. By conducting parametric studies in magnetic field structure, gas flow rates and discharge voltages, as well as using different wall materials, we will develop a working model of plasma behavior and plasma-surface physics, and should find hard limits on magnetic insulation.

C. Milestone Schedule

FY 2002

1. Compare physics of cylindrical thruster with annular thruster. Develop working model of the plasma flow, basic instabilities, and efficiency scaling (September 2002)

FY 2003:

1. Develop working model of basic instabilities, and efficiency scaling and complete set of experiments identifying plasma-wall effects (May 2003).

2. Perform detailed measurements of plume characteristics (September 2003).

FY 2004:

1. Develop working model of limitations of magnetic insulation in Hall thrusters and describe physics for different configurations of magnetic insulation (May 2004).

2. Diagnose and compare to theory microscopic plasma processes as these limits are challenged (September 2004).

Incremental Funding

With the additional $60K of funding in FY 2004, we will build a hybrid-type of thruster that includes magnetically trapped and electrically trapped electrons to neutralize the ion space charge, rather than simply neutralizing the space charge by electrons impeded by a radial magnetic field. We anticipate significant value in understanding this configuration for its interesting plasma physics, for its potential as a new type of thruster, and it potential in providing better understanding by supplying an important reference point to the limits of magnetic insulation in related geometries that we will be studying in any event.

Incremental Milestones

a. Build, operate, and characterize cylindrical design thruster with hyprid trapped electrons (January 2004).

b. Initiate characterization of fluctuations, conductivity, and performance of hybrid trap and compare to related configurations (September 2004).

D. Relationship to Other Projects

The research carried out under the Lab 00-07 funding is complementary to other research carried out on the Hall thruster facility. The other research is funded by AFOSR, DARPA, and the NJ Commission on Science and Technology. The primary aim of the other sponsored research projects is to develop new technology in the area of Hall thrusters: for AFOSR, the aim is to miniaturize the cylindrical Hall thruster that we proposed for low power applications; for DARPA, the aim is to explore a novel ion/Hall tandem thruster that we proposed; and for the NJ Commission on Science and Technology the primary aim is to develop through our segmented electrode innovations a superior Hall thruster with technology transferable to grow the NJ aerospace industry. What these other projects do not pursue, and which is the aim of the DOE Lab 00-07 project, is the vigorous development of general scientific principles that must accompany the technological progress, namely the scientific understanding of the limits of magnetic insulation, characterization of waves, instabilities, and transport parameters in general E x B flows, and the development of suitable diagnostics to explore the detailed physics. The simultaneous pursuit of the other more technologically oriented projects has enabled us, by leveraging resources, to upgrade our vacuum facility in the last year and to pursue our quest for scientific understanding on the most interesting devices.

The research also leverages cooperation on numerical studies of Hall thrusters through cooperation with Dr. Michael Keidar of the University of Michigan. There is also a small Binational Science Foundation Grant for US-Israeli Cooperation, awarded to Professor Amnon Fruchtman of Holon Technological Institute that has enabled the PI to pursue with Professor Fruchtman related theoretical ideas on Hall thruster plasma flows.

E. 2000—2001 Publications

Plume reduction in segmented electrode Hall thruster, Y. Raitses, L. A. Dorf, A. A. Litvak and N. J. Fisch, Journal of Applied Physics **88** (3), 1263--1270 (August, 2000).

Variable Operation of Hall thruster with Multiple Segmented Electrodes, N. J. Fisch, Y. Raitses, L. A. Dorf and A. A. Litvak, Journal of Applied Physics **89** No. 4, 2040--2046 (February, 2001).

A Study of Cylindrical Hall thruster for Low Power Space Applications, Y. Raitses, N. J. Fisch, K. M. Ertmer and C. A. Burlingame, 2000-3421, 36th AIAA/ASME/SAE/ASEE JPC, (July, 2000).

Variational Principle for Optimal Accelerated Neutralized Flow, A. Fruchtman and N.J. Fisch, Physics of Plasma **8**, 56--58 (January, 2001).

Resistive Instabilities in Hall Current Plasma Discharge, A. A. Litvak and N. J. Fisch, Physics of Plasma **8**, 648--651 (February, 2001).

Control of the Electric Field Profile in the Hall Thruster, A. Fruchtman, N.J. Fisch, and Y. Raitses, Physics of Plasma **8**, 1048--1056 (March, 2001).

Parametric Investigations of Non-Conventional Hall Thruster, Y. Raitses and N. J. Fisch, Physics of Plasmas **8** 2579--2586 (May, 2001).

Effects of segmented electrode in Hall Current Plasma Thrusters, Y. Raitses, M. Keidar, D. Staack and N. J. Fisch, Report PPPL-3634 (December, 2001), submitted to J. Appl. Physics (October, 2001).

High-frequency Probing Diagnostic for Hall Current Plasma Thrusters, A. A Litvak, Y. Raitses, and N. J. Fisch, Report PPPL-3622 (October, 2001), to appear in Review of Scientific Instruments (2002).

1215 HALL PLASMA THRUSTER 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.8	.5		.5	.1
Engineers					
Administrators					
Graduate Students					
Technicians	.2	.3		.3	.1
Clerical					
Subcontractors					
TOTAL FTEs	1.0	.8		.8	.2
OPERATING COSTS $(000):					
PPPL Labor	102.2	89.5		93.6	29.1
Subcontract Labor					
Overtime					
Travel	3.0	4.0		4.1	2.0
Energy					
Stockroom					
Miscellaneous Expenses	5.9				
Procurements/ICOs	28.1	28.1		22.6	3.8
Organizational Burden	14.3	12.5		12.8	2.4
Other					
General + Administrative	82.3	77.9		78.9	22.7
TOTAL OPERATING COSTS	235.8	212.0		212.0	60.0
TOTAL OPERATING OBLIGATIONS	208.0	212.0		212.0	60.0
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	235.8	212.0		212.0	60.0
GRAND TOTAL OBLIGATIONS	208.0	212.0		212.0	60.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1220	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Turbulence in Liquid Metals	AT5030500

6. WORK PROPOSAL TERM: Begin: 10/1/02 End: 9/30/03

7. CONTRACTOR WORK PROPOSAL MANAGER:
Hantao Ji Phone: 609-243-2162 Email: hji@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This experiment (LMX or Liquid Metal Experiment) is being funded as a program under LAB 00-07 solicitation, New Programs in Fusion Energy Science. FY2003 will be the third year of the program.

The goal of LMX is to investigate the fundamental physics of magnetohydrodynamic (MHD) effects on surface waves and turbulence in liquid metal. MHD turbulence has been regarded as an essential element of many intriguing phenomena observed in space and laboratory plasmas, and it has been a primary subject of basic plasma physics research. Recent interests in the application of liquid metal to fusion devices also add new demands for a better understanding for MHD physics of electrically conducting fluids. This proposal calls for an extensive study of MHD effects on fluid turbulence and surface waves using liquid metal, which can be well approximated by MHD models. Table-top size devices using easy-to-handle metals, such as gallium, will be used for the proposed experiments. Three basic physics issues are being addressed: (1) when and how do MHD effects modify surface stability, either in linear regimes or nonlinear regimes such as solitary waves? (2) when and how do MHD effects modify a free-surface flow, such as by surface deformation? (3) when and how do MHD effects modify thermal convection? A successful experimental investigation of these basic physics issues with detailed diagnostics would significantly advance our physics understanding of electrically conducting fluid, and therefore, the MHD nature of liquid lithium applications to fusion devices, and even laboratory and astrophysical plasmas.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Purpose

Turbulence has been one of the primary subjects of many subfields of physics, including plasma physics. It exists essentially everywhere in the universe, from hydrodynamic flows to astrophysical objects. In fact, turbulence is regarded as an essential element in many intriguing phenomena in plasmas, such as transport enhancement, self-organization etc. Addition of a magnetic field to the highly non-linear Navier-Stokes equation makes turbulence in magnetohydrodynamic (MHD) models even more complicated to understand.

As electrically conducting media, liquid metals can be well approximated by the MHD model. Because they can be confined by well-defined boundaries, liquid metals are an ideal medium to study MHD turbulence in the laboratory, despite limitations due to size and flow speed in practice. The existence of a gravitational force makes a liquid metal experiment similar to experiments in water. In this sense, it is a natural extension from typical water-experiments to a liquid metal experiment in order to study MHD effects on well-studied fluid turbulence. The existence of wide-ranging (although incomplete) knowledge of fluid turbulence should help to understand MHD aspects of turbulence.

The primary purpose of LMX is to address the following three important physics subjects:

I. When and how do MHD effects modify surface stability, either in linear regimes or nonlinear regimes such as surface turbulence or solitary waves?
II. When and how do MHD effects modify a free-surface flow, such as by surface deformation?
III. When and how do MHD effects modify thermal convection, either during onset of a convection instability or turbulent convection?

All these three subjects in the proposed research have direct relevance to fusion applications of liquid lithium, which can be made to flow in a reactor chamber with a free surface and a high speed, and are subject to a large heat flux and a strong magnetic field. In addition, interfacial phenomena between two fluids are also relevant to astrophysical processes, such as breaking of gravity waves for efficient mixing of fuels and ashes, which determines speed and magnitude of nuclear runaway reactions in nova and super-nova explosions.

Approach

Our philosophy in LMX is to design physics experiments with minimum complications from liquid metal handling and required apparatus yet with maximum controllability. Gallium is chosen because of its low melting point, relatively high conductivity, and easy handling. A table-top-sized apparatus has been built to generate

surface waves in an arbitrary angle with respect to applied magnetic field. Special attention is paid to minimize or control boundary effects by minimizing wave reflection and by varying the distance to the boundaries. Electric current can be introduced either in the wave propagation direction and/or its perpendicular direction. A mechanical pump has been acquired to drive a moderately fast liquid gallium free-surface flow across magnetic field.

Reliable diagnostics are crucial to generate high-quality data to be compared with theories or simulations. An ICCD camera is used to monitor overall behaviors of liquid gallium surface. A laser reflection system has been developed to measure surface deformation with high accuracy (~0.1mm) at multiple locations (up to 7x7=49 locations). PC-based data acquisition and controls ensure high reproducibility of experiments.

Progress in FY01 and FY02

(1) Construction of experimental apparatus. In order to ensure experimental reproducibility with maximum controllability, a high quality experimental apparatus has been built. A large (19”x19”) gallium tank made of plastic material is placed inside in a larger water tank heated from below to ensure uniform temperature of the liquid gallium. A coil system has been built to generate magnetic field up to 600 G. The coil current is generated by a power supply, which is controlled by a PC. A PC-controlled wave driver system is constructed to drive waves with various angles with respect to the magnetic field. The wave driver system has been optimized to generate uniform 1D waves in liquid gallium, which has large surface tension force. An upgraded version of multi-laser reflection system, capable of up to 7x7 beams, has been built to measure surface deformation accurately at multiple locations. Water and gallium containers have been rebuilt with installation of variable depth profiles (“beach”) in order to minimize wave reflection from boundaries. A PC-based LABView system has been developed to provide full automation of experimental sequencing, including waveforms of magnetic field and driven surface waves. A data acquisition system that can acquire images from a high-speed ICCD camera is also fully controlled by the LABView system.

(2) Experimental results. Liquid gallium surface waves have been successfully generated as a function of frequency and magnetic field with varying angle from the direction of wave propagation. The waves have been measured accurately by the multiple-point laser reflection system, including their frequency, wavelength, and amplitude.

(2.1) Dispersion relation. The wavelength as a function of frequency, or the dispersion relation of the waves, has been determined. It is found that in the low frequency range, or gravity wave regime, the measured dispersion agrees well with the linear theory. However, in the large frequency range, or capillary wave regime, the

measured dispersion corresponds to a much lower surface tension coefficient compared to the published value. It has been confirmed that the decrease of surface tension is caused by surface oxidization of liquid gallium.

(2.2) Magnetic damping. The wave amplitudes have been measured as a function of space and magnetic field. It is found that the wave amplitude is suppressed by a magnetic field applied along the propagation direction but not in the perpendicular direction. At B=600G, the wave amplitude at a location 10 cm away from the wave driver is suppressed by a factor of two. This magnetic damping of driven surface waves can be well explained by the linear wave theory, which includes the VxB term in Ohm's law to dissipate wave energy ohmically.

(3) Theoretical and computational collaborations. Close interactions with theory and simulations are an important component of LMX. Analytic theory efforts in collaborations with Prof. R. Kulsrud (PPPL) and Dr. H. Rappaport (U of Texas) are underway. Two weeks of support to Dr. H. Rappaport has been provided as a subcontract. Inclusion of the VxB term in the linear theory has been made to predict magnetic damping. In addition, close collaborations with Prof. R. Rosner (U of Chicago) have been established to compare experimental data with direct numerical simulations, in connections with surface wave phenomena in astrophysical situations.

(4) Fusion technology collaborations. Close collaborations with APEX program under fusion technology programs have been established, especially with Prof. M. Abdou (UCLA), Dr. R. Kaita (PPPL), Dr. N. Morley (UCLA), and Dr. G. Antar (UCSD). Comparisons between experimental data and MHD calculations and exchange of diagnostics are planned.

(5) Presentations and publications.

(5.1) An invited talk was given at First International Symposium on Free Surface Flow and Interfacial Transport Phenomena held at Yugawara, Japan, May 10-11, 2001.

(5.2) An oral talk was given at the mini-conference on lithium wall during APS DPP meeting at Quebec City in 2000.

(5.3) A seminar was given at UCLA on Jan. 2001.

(5.4) A senior thesis was written by Will Fox at Physics Department of Princeton University (April 2001).

(6) Education. LMX has supported two summer students (Lauren Bell from Howard U and David Pace from U of Pacific) and one senior thesis (Will Fox), which won Shenstone prize from Princeton University.

Expected Progress in Future

1. Remainder of FY02

Analysis of the obtained high quality data will be finished and presented as an invited talk at the 6th International Symposium on Fusion Nuclear Technology (7-12 April 2002) at San Diego. A full paper, summarizing both experimental and theoretical results, will be written and submitted to a physics journal. Moving of LMX experimental apparatus from a basement to a newly refurbished laboratory in L-wing building will be completed. The coil system will be upgraded to generate > 1kG of magnetic field using a new power supply, which will be engineered to be controllable by a PC. New safety equipment and procedures will be installed and established. Two dimensional surface waves and large amplitude waves will be generated and investigated.

Later in this fiscal year, we will move on to experimentally study free-surface flow when magnetic field and/or electric current are applied with various geometries. A gallium flow loop will be constructed by using a gallium pump and two hotplates, each heating a container at a different height. A nozzle is attached at the higher container to permit liquid gallium to flow out. The liquid gallium can be either guided into a duct with the upper side open to form a free-surface flow or it can be allowed to free fall into the lower container. Achievable flow speed will be on order of 2m/s, resulting in a few of 10^5 of Reynolds number (Re), which is large enough for the flow to be in the turbulent regime.

2. FY03

The MHD effects on the liquid metal flow with a free surface will be examined. Either a uniform magnetic field or a localized magnetic field by small permanent magnets will be applied. A magnetic field of 1kG will result in a Hartman number (Ha) of several hundred, which should be large enough for the flow to be affected by Lorentz force. An electric current can be driven along or across the flow by electrodes. An important question is when and how is the conventional Hartman flow modified by existence of a free surface.

The surface stability of a driven flow or stream will be studied first as a function of flow speed (or Re), strength of magnetic field (or Ha), and imposed current. A convective instability may result from a high-speed flow. MHD turbulence along the flow will be measured by probes and possibly by ultrasonic methods. Modification of nature of turbulence due to MHD effects, such as transition from 3D turbulence to 2D turbulence, will be the focus of the experiments.

Later in this fiscal year, we will move on to experimentally study MHD effects on thermal convection. Maintaining a fixed vertical temperature gradient is important for study of thermal convection. The hotplate can provide heating from below and cool air can

be pumped in to maintain a lower temperature at the top. Since the viscosity of gallium is extremely small, a wide range of Rayleigh number up to a few of 10^5 can be achieved without a large heating power.

3. FY04 (Request for proposal renewal)

Detailed physics experiments will be performed to study MHD effects on thermal convection in a static liquid gallium. Linear thermal stability will be studied by increasing the temperature difference systematically with an imposed magnetic field and current. The onset of a convective instability can be determined by observing convection from the surface or by a sudden decrease in temperature difference. The depth of the liquid metal layer can also be another controlling parameter. When convective cells rise to the surface, their behavior can be affected by surface tension, which strongly depends on the wavelength. Therefore, the container size and liquid depth can be changed to study effects of surface tension force on the convection. A uniform magnetic field will be applied by external coils either vertically or horizontally. A magnetic field of 1 kG will result in Chandrasekhar number of more than 10^5, which should be large enough to affect convection stability.

Later in this fiscal year, the onset of thermal convection in a flowing free-surface liquid metal will be studied. The thermal convection could also in turn affect free-surface flow. The MHD effects on fully turbulent convection will be another focus of the experiments when heat flux is greatly increased. Both surface deformations and magnetic fluctuations will be measured to characterize effects from magnetic field and current.

4. FY04 (Incremental)

One of the important implications of the experimental and theoretical results on the linear surface waves concerns stability of the liquid metal walls suspended by Lorentz force, a scheme proposed by the fusion chamber technology community. It has been suggested that the perturbations with wavenumbers parallel to the imposed electric current are not affected by the Lorentz force, therefore they are subject to Rayleigh-Taylor instability. Experimental studies of linear and nonlinear stability of suspended liquid gallium are important not only for its academic interests but also for the development of fusion technologies. The current setup for magnetic coils and current supplies only can provide a Lorentz force (jxB) of 1/10 of gravity force (ρg). It is proposed to upgrade both magnetic field (3kG) and electric current (1kA) using existing PPPL equipment so that the Lorentz force is comparable to the gravity force. Experiments will be carried out to study linear and nonlinear stability of both static and flowing liquid gallium suspended by the Lorentz force. The stability will be measured by surface deformation as functions of time and space.

Milestones

FY02

- Move the experiment and upgrade the magnetic field – March 2002
- Complete experiments and data analysis of MHD surface waves and set up experimental apparatus to study MHD free-surface flows – September 2002

FY03

- Perform experiments on MHD effects on free-surface gallium flow – March 2003
- Complete experiments and data analysis of free-surface flow – September 2003
- Setup experimental apparatus and obtain initial data on MHD effects on thermal convection – September 2003

FY04

- Perform experiments on MHD effects on thermal convection in a static liquid gallium – March 2004
- Perform experiments on MHD effects on thermal convection in a free-surface gallium flow – June 2004

FY04 (Incremental)

- Upgrade magnetic field to 3kG and current to 1kA – March 2004
- Study surface and flow stability with larger magnetic field and currents – September 2004

1220 LIQUID METALS		03/01/02		
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists	.2	.2	.2	.1
Engineers				
Administrators				
Graduate Students	.5	.5	.5	.5
Technicians	.4	.1	.1	.4
Clerical				
Subcontractors				
TOTAL FTEs	1.1	.8	.8	1.0
OPERATING COSTS $(000):				
PPPL Labor	75.3	52.8	55.3	67.9
Subcontract Labor				
Overtime				
Travel	3.0	3.0	3.5	2.0
Energy				
Stockroom	4.0			
Miscellaneous Expenses				
Procurements/ICOs	32.6	22.4	18.6	42.6
Organizational Burden	9.9	6.4	6.6	4.8
Other				
General + Administrative	62.3	48.4	49.0	62.7
TOTAL OPERATING COSTS	187.1	133.0	133.0	180.0
TOTAL OPERATING OBLIGATIONS	129.1	133.0	133.0	180.0
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	187.1	133.0	133.0	180.0
GRAND TOTAL OBLIGATIONS	129.1	133.0	133.0	180.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1210	0	3/1/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
Stellar Flare Plasma Diagnostic	AT5030500

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Manfred Bitter Phone: 609- 243-2582 Email: mbitter@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

There exist large uncertainties in the theoretical predictions of density-sensitive line ratios for the spectra of helium-like and neon-like ions, which are used for the diagnosis of stellar flares. These uncertainties have led to misinterpretations of experimental data in the astrophysical literature. The goal of the present work is to measure these density-sensitive line ratios in a plasma environment under controlled conditions at NSTX. For this purpose, a high resolution X-ray crystal spectrometer that covers the wavelength range from 4 to 24 Å will be installed at NSTX. The measurements will be performed in close collaboration with astrophysicists from Columbia University and the Chandra Observatory and with researchers from MIT.

The proposed work scope for this effort was submitted in response to DOE Program Announcement LAB 00-07 "New Programs in Fusion Energy Sciences" in 2000. This project has been funded in FY 2001 and FY2002.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The *n=3* ➔ *n=2* L-shell spectrum of mid-Z neon-like ions and the *n=2* ➔ *n=1* K-shell spectrum of helium-like ions dominate the X-ray emission over a wide range of plasma conditions in the sun and a variety of cosmic sources. This is also true in tokamaks and laser produced plasmas. The ratios of the inter-combination and resonance lines, e.g. the ratio of the transitions **3C**: $2p^5 3d\ ^1P_1$ ➔ $2p^6\ ^1S_0$ and **3D**: $2p^5 3d\ ^3D_1$ ➔ $2p^6\ ^1S_0$ in neon-like ions and ratios of the transitions **w**: $1s^2\ ^1S_0$- $1s2p\ ^1P_1$, **y**: $1s^2\ ^1S_0$- $1s2p\ ^3P_1$, and **z**: $1s^2\ ^1S_0$- $1s2s\ ^3S_1$ in helium-like ions are sensitive to the electron density or the electron temperature and are therefore of interest for the diagnosis of stellar flares. Unfortunately, there exist large discrepancies in the theoretical predictions for these line ratios, which have led to misinterpretation of the experimental data in the astrophysical literature. For instance, the **3C/3D** ratio of FeXVII has been used for opacity measurements of stellar atmospheres (Waljeski et al.Astrophys, J. **429**, 909 (1994)). However, the opacity values claimed cannot be justified in view of the large theoretical uncertainties in the predictions for the so-called zero-density limit (Brown et al. Astrophys. J. **502**,1015 (1998)).

The goal of the present effort is therefore to measure density-sensitive line ratios from helium- and neon-like ions, which are of interest for the diagnostic of stellar flares, in a controlled plasma environment at NSTX. For this purpose, a high-resolution X-ray crystal spectrometer that covers the wavelength range from 4 to 24 Å will be installed on NSTX. This instrument has been previously used on the Princeton Large Torus (PLT) experiment (P. Beiersdorfer et al., Rev. Sci. Instrum. **60**, 895 (1989)). The measurements on NSTX will be performed in close collaboration with astrophysicists from Columbia University and the Chandra X-ray Observatory and with researchers from MIT.

Complementary measurements will be performed at the Electron Beam Ion Trap (EBIT) at the Lawrence Livermore National Laboratories (LLNL) to investigate the role of individual excitation processes and for an accurate determination of wavelengths. The excitation processes can be controlled at EBIT by scanning the energy of the electron beam.

APPROACH

The choice of an appropriate port and the experimental arrangement of the spectrometer at NSTX are essential for reliable measurements of line ratios. They were determined by the following considerations: The spectrometer is a curved crystal spectrometer in the Johann configuration, which offers the advantages that an entire spectral range can be observed simultaneously and that each spectral line is reflected from the entire crystal. The spectrometer is therefore well suited for reliable measurements of line ratios. However, because of the focusing properties of the Johann geometry each spectral line is emitted from a different volume element in the plasma and for reliable measurements of line ratios it is therefore necessary that the electron temperature and density - which determine the X-ray emissivity - are the same in each volume element. This condition is fulfilled if the sightlines of the spectrometer are dispersed in the toroidal direction at a common major radius, since the electron temperature and density are invariant along the toroidal magnetic field.

The spectrometer will therefore be installed at a port on the bottom of the NSTX vacuum vessel and oriented in such a way that the sightlines are dispersed in the toroidal direction. Moreover, each sightline will end at the ceiling of the NSTX vacuum vessel to avoid intersections with the center stack and eliminate geometrical effects. In this way, the length of each sightline through the plasma will be the same. This would not be the case if some of the sightlines did intersect the center stack and other sightlines would pass by the center stack. The work on the design interface to the NSTX vacuum vessel has been done with the NSTX team, which is supporting this effort.

TECHNICAL PROGRESS

- The spectrometer interface and support structures have been designed.
- Mechanical parts have been fabricated and delivered.
- Designs for the substantial in-vessel work, which requires a modification of the water-cooled divertor and protective plates, have been completed.
- The detector, a Reticon photo diode array, has been tested at LLNL and is operational.
- A spherically bent mica crystal for the measurement of spectra in the wavelength range below 20 Å has been purchased.

FUTURE ACCOMPLISHMENTS

The plan for the remainder of FY2002 is to complete the fabrication of the new in-vessel hardware and to install the in-vessel hardware and crystal spectrometer during the next major NSTX outage from June to September 2002.

During FY2003, the spectrometer will be operational at NSTX and will be used to measure spectra of intrinsic impurities, such as iron, and spectra of helium-like neon, which can be easily injected with the available gas injection systems.

In FY2004, the diagnostic will be fully established and ready for collaborative experiments with the astrophysics community. Since the present grant (LAB 00-07) expires at the end of FY2003, we will apply for a renewal or extension of the present grant. Incremental funding of $100,000 is being requested in FY2004 for the installation an impurity injector (a laser ablation system) to enable the study of other impurities of interest to the astrophysical community. The basic engineering design of the mechanical parts and the laser (~ value $20,000) from the impurity injector previously used on TFTR are still available at PPPL.

MILESTONE SCHEDULE

	Base	Actual
FY2002 Milestones		
Installation of the new in-vessel hardware and spectrometer on NSTX (Subject to NSTX run schedule)	JUN 02	
FY 2003 Milestones		
First spectra from intrinsic impurities of NSTX plasmas and spectra of helium-like neon, which can be easily injected, will be recorded	JAN 03	
FY2004 Milestones		
Diagnostic will be fully established and ready for collaborative experiments with the astrophysics community	JAN 04	
FY2004 Incremental Milestones		
Design, fabricate, assemble and install impurity injector on NSTX	MAR 04	
Measure density-sensitive line ratios in the spectra of non-intrinsic elements on NSTX	SEP 04	

1210 STELLAR FLARE PLASMA 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.3	.3		.3	
Engineers					.1
Administrators					
Graduate Students					
Technicians	.1				.2
Clerical					
Subcontractors					
TOTAL FTEs	.4	.3		.3	.3
OPERATING COSTS $(000):					
PPPL Labor	47.0	39.9		41.7	35.9
Subcontract Labor					
Overtime					
Travel	5.0	5.0		5.0	
Energy					
Stockroom	1.0	1.0			1.0
Miscellaneous Expenses					
Procurements/ICOs	22.0	6.9		5.6	24.3
Organizational Burden	3.9	3.0		3.1	4.3
Other	5.8				
General + Administrative	39.3	33.2		33.6	34.6
TOTAL OPERATING COSTS	124.0	89.0		89.0	100.1
TOTAL OPERATING OBLIGATIONS	84.0	89.0		89.0	100.1
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	124.0	89.0		89.0	100.1
GRAND TOTAL OBLIGATIONS	84.0	89.0		89.0	100.1

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1225	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Application of Lithium to a Tokamak Wall	AT6010301

6. WORK PROPOSAL TERM: Begin: 10/1/02 End: 9/30/04

7. CONTRACTOR WORK PROPOSAL MANAGER:
Richard P. Majeski Phone: 609-243-3112 Email: rmajeski@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The purpose of this proposal is to develop the liquid lithium walled tokamak as an Innovative Confinement Concept. The proposed program would install a heated, conducting shell and a system for coating it with lithium in the Current Drive eXperiment – Upgrade (CDX-U). The resultant device, the Lithium Tokamak eXperiment (LTX), would test theoretical predictions of the effects of an absorbing boundary on tokamak operations, including the production of low gradient electron temperature profiles, and wall-stabilized low-shear current profiles. These modifications are predicted to extend the operationl beta limit of conventional aspect ratio tokamaks to the range of 20-30%.

These experiments would be performed in conjunction with the fusion technology program's ALPS and APEX efforts.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSES AND GOALS

Experiments on CDX-U and the PISCES device at UCSD have established that liquid lithium has very desirable properties as a plasma-facing component in a tokamak. In particular, it has been shown that plasma recycling on liquid lithium is low to nonexistent. A tokamak with a perfectly nonrecycling wall would therefore constitute a fundamental experiment in plasma science – an innovative confinement concept which tests the consequences of introducing *absorbing boundary conditions* to a confined plasma. Analyses by S. Krashenennikov of UCSD and L. Zakharov of PPPL have shown that a perfectly nonrecycling, conducting wall would have a profound effect on the equilibrium and beta limits of a tokamak discharge. Ohmically driven discharges would have virtually flat temperature profiles. The resultant q profile would lack a q=1 surface and the associated sawtoothing, and the tokamak could be stably operated with $q(a)<2$. A conventional aspect ratio tokamak would have a greatly enhanced beta limit. For example, Zakharov has calculated that the beta limit for TFTR under these conditions, which typically operated with β~2%, would be increased to >25% - a tenfold increase in beta which would have produced an approximate *hundredfold* increase in fusion power output.

In a reactor, a plasma-facing surface of liquid lithium flowing at 10 – 20 m-sec^{-1} would serve as the perfectly conducting wall. In a near-term pulsed experiment, a conducting shell could serve as the conducting wall. If the shell is coated with several hundred angstroms of lithium and heated to the melting point of lithium (180 ^{o}C), then a near-term test of these predictions would be feasible at modest cost.

The purpose of this proposal for incremental funding is to perform an experimental test of the consequences of an absorbing, conducting wall in CDX-U. This innovative confinement concept mission – LTX or the Lithium Tokamak eXperiment - would be pursued in tandem with the present technology mission of CDX-U.

APPROACH

CDX-U would be modified to incorporate the following features:

1. A conformal, conducting copper shell 1 cm thick, which would produce a wall time of ~140 msec. The shell will be faced with thin stainless steel or another material resistant to attack by liquid lithium, and installed inside the CDX-U vacuum vessel.

2. A system to heat the shell to 250 – 300 ^{o}C. Most of the CDX-U liquid lithium limiter experiments were performed at 250 ^{o}C.
3. An internal, cooled heat shield to maintain the centerstack temperature below 85 ^{o}C, and the vacuum vessel wall temperature below 150 ^{o}C at all points.
4. A system for vacuum deposition of lithium on the inner, plasma facing, surface of the shell. A suitable system based on commercial e-beam deposition systems is under separate development.
5. A modified poloidal field coil set for improved equilibrium control.
6. Fast gas jets or a multiple pellet injector (refurbished PBX-M system) for fueling.

Funding for this proposal is requested at the level of $650k for FY03, and $550k for FY04. This is an incremental request; it is assumed that the baseline fusion technology budget request for CDX-U is also funded. The fusion technology mission for CDX-U will continue in LTX.

PUBLICATIONS AND STUDENT TRAINING

CDX-U has an extensive history of student involvement. The LTX experiment will continue and expand upon the educational mission whenever feasible.

EXPECTED PROGESS IN FY03-04

Tasks in FY03:

1. The design of the heated shell and the heat shield will be completed.
2. Procurement of the vacuum deposition system will be completed.
3. Design of the new poloidal field coil set and support structure will be completed.

Tasks in FY04:

1. Refurbishment of the PBX-M pellet injector (ORNL) will be completed.
2. The conformal shell, heat shield, and poloidal field coils will be completed.
3. Following completion of the initial recirculating liquid lithium limiter experiments, the conformal shell, poloidal field coils, and support structure will be installed.
4. The e-beam deposition system will be installed.

Experiments in LTX will begin in late FY04 or early FY05.

MILESTONE SCHEDULE FOR FY03-04

Activity	Date complete
Complete engineering design of PF coil set. Let contract for coils.	March 2003
Complete engineering design of conformal shell and heat shield. Begin fabrication.	May 2003
Procure e-beam systems.	August 2003
Poloidal field coils complete	September 2003
Shell and heat shield complete	December 2003
Vent for LTX modifications	January 2004
Internal vessel tasks complete. Vessel reassembled.	July 2004
PF support structure, PF coils installed.	August 2004
Begin commissioning of LTX	September 2004

1225 LITHIUM TOKAMAK EXP 03/01/02				
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists		.2		.2	
Engineers		.3		.1	
Administrators					
Graduate Students		.5		.5	
Technicians		1.5		1.0	
Clerical					
Subcontractors					
TOTAL FTEs		2.5		1.8	
OPERATING COSTS $(000):					
PPPL Labor		224.5		170.4	
Subcontract Labor					
Overtime		30.0		30.0	
Travel		7.0		7.0	
Energy					
Stockroom		20.0		20.0	
Miscellaneous Expenses		6.6		6.5	
Procurements/ICOs		104.7		103.8	
Organizational Burden		25.7		19.5	
Other					
General + Administrative		231.5		192.8	
TOTAL OPERATING COSTS		650.0		550.0	
TOTAL OPERATING OBLIGATIONS		650.0		550.0	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS		650.0		550.0	
GRAND TOTAL OBLIGATIONS		650.0		550.0	

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1080	0	3/01/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
Electron Bernstein Waves (EBW) Diagnostic	AT5010802

6. WORK PROPOSAL TERM: Begin: March 1, 2002 End: September 30, 2004

7. CONTRACTOR WORK PROPOSAL MANAGER:
Philip C. Efthimion Phone: 609- 243-3212 Email: pefthimion@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Under a Diagnostic Initiative (Notice LAB 98-17) Grant, PPPL developed an electron temperature diagnostic based upon measuring electron Bernstein waves (EBW). Significant progress has been achieved during the past 3 years. The results include:

(1) determining the EBW emission source is localized at the electron cyclotron layer;
(2) observing that the mode conversion efficiency depends on the density scale length at the mode conversion layer, consistent with theory;
(3) using an in vessel antenna with a local limiter near the mode conversion layer to achieve ~ 100% tunneling efficiency and inferring the electron temperature profile from the measured EBW emission; and
(4) realizing higher harmonic EBW can be developed into a local density fluctuation diagnostic.

Here we propose to complete the diagnostic development by designing and installing a toroidally steerable in-vessel antenna, with a local limiter, on NSTX. This steerable antenna will allow us to verify that we can establish the ~100% mode conversion on NSTX and will allow a comparison between the X-mode and the O-mode EBW mode-conversion processes on NSTX.

The proposed work scope for this continuation effort was submitted in response to DOE Program Announcement 01-25 "Development of Diagnostic Systems for Magnetic Fusion Energy Sciences" in August 2001. This project has been funded in FY 2002.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

Many magnetically confined plasma devices cannot take advantage of standard ECE diagnostics to measure temperature. They either operate at high density relative to their magnetic field (e.g. $\omega_p >> \Omega_c$ in spherical tori) or they do not have sufficient density and temperature to reach the blackbody condition ($\tau > 2$). Here we propose to develop a radically different ECE diagnostic based upon the measurement of electron Bernstein waves (EBW) to ascertain the local electron temperature in these plasmas. The EBW can propagate at high densities, where $\omega_p >> \Omega_c$. One can reach the blackbody condition with a plasma density $\approx 10^{11}$ cm^{-3} and $T_e \approx 1$eV. This makes it attractive to most magnetized plasma devices including stellerators, ST's, modest size tokamaks, mirror machines, dipoles, reversed field pinches, semiconductor processing plasmas, and many plasmas for non-fusion applications. With increased interest in modest size confinement experiments to improve the β of fusion plasmas, an inexpensive diagnostic to measure electron temperature evolution would be very useful.

Having made excellent progress to date showing the EBW diagnostic measurement of temperature is feasible on CDX-U, we propose here to complete the EBW diagnostic development. The in vessel antenna we built, installed and operated on CDX-U in FY2001 and FY2002 provides a path forward for accessing the EBW emission without the need for correction of the data. The antenna has its own limiter to optimize the density scale length to achieve 100% tunneling efficiency. In FY2002 we plan to complete the studies with the in vessel antenna on CDX-U. There are two possible explanations for the 100% emission levels and we would like to complete the experiments on CDX-U to determine the exact process. Based upon that knowledge, an appropriate antenna and limiter will be designed and installed on NSTX in FY2003. This diagnostic will participate in the NSTX experimental program in FY2003 and FY2004 to validate its usefulness and robustness.

APPROACH

The serious issue with using EBW is the wave accessibility for the emission measurement. Simple accessibility arguments indicate the wave may be accessible by either direct coupling or mode conversion through an extremely narrow layer ($\approx$ 1-2 mm) near the plasma edge. We continue to investigate the accessibility of the EBW emission on CDX-U with electromagnetic and electrostatic antennas.

The critical task for the remainder of FY2002 and for FY2003/4 is to complete the development of an antenna whose coupling efficiency is relatively insensitive to the plasma edge conditions. The diagnostic needs to follow core temperature changes and not be sensitive to the plasma edge conditions. We designed, fabricated and installed an antenna probe assembly that fits into the CDX-U vacuum vessel and makes measurements of both electromagnetic and electrostatic EBW emission. This antenna probe has many features and controls that allow us to better understand the emission process and to control it. These issues are continuing to be examined on CDX-U in

FY2002. In FY2003 the experimental research will move on to NSTX to test the antenna concept on a hotter and denser plasma. Again the accessibility will be examined. Electron temperature measurements will characterize auxiliary heating experiments and MHD. The EBW measurements will be compared to those from the Thomson scattering system. Proof-of-principle will be achieved by effectively contributing electron temperature measurements to the NSTX experimental program and by comparing favorably to Thomson scattering measurements in FY2003/4.

TECHNICAL PROGRESS

We have built instruments for CDX-U and NSTX, and during FY2001 and FY2002 we measured EBW emission on CDX-U and NSTX using electromagnetic antennas. We have found the following: (1) The emission source is localized at the electron cyclotron layer, which is important for a local temperature diagnostic. (2) The radiation is predominantly X-mode polarized on CDX-U, as expected. (3) The mode conversion efficiency depends on the density scale length at the mode conversion layer, consistent with theory. (4) Using the complex probe antenna in CDX-U, which incorporates a local limiter near the mode conversion layer, we achieved ~ 100% tunneling efficiency and consequently inferred the electron temperature profile from the measured EBW emission. There were two publications describing this work in FY2001. In addition, our results have significant ramifications toward EBW current drive and heating in moderate and high β plasmas. The fact that we can ascertain the electron temperature profiles from mode converted EBW indicates that heating and current drive can be applied to moderate and high β plasmas. This has spurred the interest in such experiments on NSTX and a significant effort to model various EBW heating and current drive scenarios.

FUTURE ACCOMPLISHMENTS

The major accomplishment being targeted by our proposed research program in FY2003/4 is the demonstration of the viability of the EBW electron temperature diagnostic on NSTX. The NSTX plasma parameters provide an excellent proof-of-principle test bed for this new diagnostic in a high β plasma regime. Specific accomplishments we are targeting are the demonstration of ~100% EBW mode conversion efficiency, independent of the plasma density conditions and that the emission is directly proportional to local T_e. Results from this research are also directly relevant to the development of EBW heating and current drive for high β plasmas.

MILESTONE SCHEDULE

FY2002 Milestones

Complete measurements with the complex probe antenna on CDX-U.	SEP 02

FY2003 Milestones

Based upon the CDX-U research, design, fabricate and install a suitable antenna on NSTX.	JUN 03

FY2004 Milestones

Complete measurements with new antenna on NSTX.	JUN 04
Determine if emission is now just proportional to Te and no longer sensitive to density conditions.	SEP 04
Compare EBW emission mode converted to O-mode emission and EBW emission mode converted to X-mode	SEP 04

1080 EBW DIAGNOSTIC		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists	.1	.3	.3
Engineers		.1	
Administrators			
Graduate Students	.5		
Technicians		.2	.2
Clerical			
Subcontractors			
TOTAL FTEs	.6	.6	.5
OPERATING COSTS $(000):			
PPPL Labor	29.8	67.8	70.8
Subcontract Labor			
Overtime			
Travel	5.0	5.0	5.0
Energy			
Stockroom	1.0	1.0	1.0
Miscellaneous Expenses			
Procurements/ICOs	12.5	19.1	15.8
Organizational Burden	1.5	8.3	8.0
Other			
General + Administrative	25.2	58.7	59.3
TOTAL OPERATING COSTS	75.0	159.9	159.9
TOTAL OPERATING OBLIGATIONS	75.0	159.9	159.9
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	75.0	159.9	159.9
GRAND TOTAL OBLIGATIONS	75.0	159.9	159.9

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1081	0	3/1/02

4. WORK PROPOSAL TITLE:
3-D Imaging Diagnostic

5.BUDGET AND REPORTING CODE
AT5010802

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:

Hyeon Park	Phone: 609-243-3604	Email: hpark@pppl.gov
Ernesto Mazzucato	609-243-3157	emazzucato@pppl.gov

8. HEADQUARTERS ORGANIZATION:
Office of Science

9. OPERATIONS OFFICE:
Chicago Operations Office

10.CONTRACTOR NAME:
Princeton University
Princeton Plasma Physics Laboratory

11. DOE HQ ORGANIZATION CODE:
SC

12. DOE OPS OFFICE ORGANIZATION CODE:
CH

13. CONTRACTOR CODE:
15

14. WORK PROPOSAL DESCRIPTION:

The preliminary ECEI/MIR system will be installed on TEXTOR in August 2002 (when plasma operations are planned to resume on TEXTOR and physics experiments will begin). Responsibilities for the system will be shared among three institutes (UC-D, FOM and PPPL). PPPL will perform characterization of the combined ECE/MIR system including design and fabrication of large mirror optics. Initially the ECEI and MIR subsystems will focus on "filamentation" physics and density fluctuation measurements separately. Development of a dichroic splitter for the two systems and additional microwave components will allow us to operate two subsystems simultaneously. Physics analysis of the two systems will be shared between the three institutes.

The proposed work scope for this effort was submitted in response to DOE Program Announcement LAB 01-25 "Development of Diagnostic Systems for Magnetic Fusion Energy Sciences" in August 2001. This project has been funded in FY 2002.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The primary purpose of this workscope is the development of an imaging system, for simultaneous measurement of T_e and n_e fluctuations in the TEXTOR tokamak, by three primary collaboration participants: PPPL, TEXTOR and the University of California at Davis, CA (UC Davis). ECE imaging (ECEI) systems have demonstrated the capability to measure T_e fluctuations (both random and coherent) in many tokamak devices, including TEXTOR. Based on successful testing of a prototype MIR instrument, we have designed a preliminary MIR system for installation on TEXTOR. The ECEI and MIR subsystems will initially be tested separately in the early stage of physics study. Eventually the two subsystems will be combined to study both fluctuation quantities simultaneously.

APPROACH

Development of a preliminary combined ECEI/MIR instrument using large reflective optics is warranted based on:

(1) Successful application of the ECEI system,
(2) analysis of MIR data obtained from the prototype system installed on TEXTOR in FY2001,
(3) off-line test results obtained from tests performed in a PPPL laboratory with a precisely known corrugated target.

A detailed comparison study between the MIR technique and conventional reflectometry will be completed over a wide range of wave number and fluctuation levels. We anticipate that this MIR diagnostic system will provide a new level physics of fluctuation spectra and profiles on TEXTOR. In August 2002, the combined ECEI/MIR system will be installed and physics studies will begin. After installation, the system will be optimized to simultaneously measure both T_e and n_e fluctuations on TEXTOR. At the same time we will investigate “filamentation” phenomena using the ECEI system, and the study of n_e fluctuations measured by MIR will be analyzed to provide insight into specific physics regimes available on TEXTOR, such as Dynamic Ergodic Divertor operation and the RI mode.

TECHNICAL PROGRESS

The ECEI system was installed on TEXTOR in FY2001 and has successfully demonstrated the measurement of T_e fluctuations and is now part of the ongoing research program to study ”filamentation” phenomena. The ECEI data from TEXTOR has been available for the three primary collaboration participants: PPPL, TEXTOR and the University of California at Davis, CA (UC Davis). The FOM diagnostic team on TEXTOR has been coordinating the installation and integration of the new preliminary ECEI/MIR system on the port where testing of the prototype ECEI system has been performed (20 cm [toroidal] x 45 cm [poloidal]). We have tested two prototype

Microwave Imaging systems; the first one based on the ECEI lens optics and a second based on rudimentary reflective mirrors. Qualitatively, we were able to measure the focal plane and corresponding fluctuation spectra in each system. Based on this experience, we have nearly completed the design of a combined optical system based on large reflective optics and a correspondingly optimized detection system. The imaging system has been set up and tested in an off-line laboratory at PPPL to characterize the system performance and the test results confirmed the design goals. The comparison study between MIR and conventional reflectometry has provided additional detailed confirmation of the basis behind the MIR approach; namely, that conventional reflectometry techniques have potential problems for core measurements, and MIR can alleviate these problems. Complete understanding of the system as designed provides strong confidence in the density fluctuation measurements on TEXTOR.

FUTURE ACCOMPLISHMENTS

In this project, PPPL will focus on the design of the optical system for MIR and ECEI based on reflective mirrors. This set-up will also be used to perform a study of the fundamentals of reflectometry techniques. Here a series of precisely known corrugated targets will be used to investigate the comparative features and limitations of conventional and imaging reflectometry systems. These results will be compared with the 2-D wave simulation results. The expected turbulence spectra will be calculated by gyro-kinetic and/or gyro-fluid simulations, using physics parameters from TRANSP. Additionally, T_e fluctuations measured by ECEI will be compared with the density fluctuations over the various time windows to assess the correlation between density and temperature fluctuations.

We will work closely with the PPPL gyro-kinetic (GK) group (W.W. Lee, Z. Lin, T.S. Hahm) to discuss how to make a tie between GK simulation codes and the experimental 2-D imaging results.

MILESTONES

FY2002 Milestones

	Base	Actual
Complete characterization of the preliminary ECEI/MIR system	JUN 02	
Ship the ECEI/MIR System to Germany and begin installation of the system on TEXTOR	AUG 02	

FY2003 Milestones

	Base	Actual
Fully tested MIR/ECEI System will be ready on TEXTOR	FEB 03	
Initial physics operation of TEXTOR MIR/ECEI System (Subject to TEXTOR run schedule)	APR 03	
Initial application of visualization and analysis tools	JUN 03	

FY2004 Milestones

	Base	Actual
Complete development of analysis and visualization tools for TEXTOR discharges	FEB 04	
Participate in TEXTOR experimental proposal for a specific physics program (Subject to TEXTOR run schedule)	JUN 04	
Complete modifications to improve reliability and make ECEI/MIR system routine diagnostic for TEXTOR	SEP 04	

1081 3D IMAG. DIAGNOSTIC 03/01/02					
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists	.3	.4		.4	
Engineers					
Administrators					
Graduate Students					
Technicians	.2				
Clerical					
Subcontractors					
TOTAL FTEs	.5	.4		.4	
OPERATING COSTS $(000):					
PPPL Labor	51.3	53.1		55.5	
Subcontract Labor					
Overtime					
Travel	15.0	10.0		10.0	
Energy					
Stockroom	1.0	1.0		1.0	
Miscellaneous Expenses					
Procurements/ICOs	67.8	6.8		3.8	
Organizational Burden	4.3	3.7		3.9	
Other					
General + Administrative	59.6	45.2		45.8	
TOTAL OPERATING COSTS	199.0	119.8		120.0	
TOTAL OPERATING OBLIGATIONS	80.0	119.8		120.0	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	199.0	119.8		120.0	
GRAND TOTAL OBLIGATIONS	80.0	119.8		120.0	

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1083	0	3/01/02

4. WORK PROPOSAL TITLE:	5. BUDGET AND REPORTING CODE
X-ray Imaging Crystal Spectrometer	AT5010802

6. WORK PROPOSAL TERM: Begin: December 1, 2002 End: September 30, 2004

7. CONTRACTOR WORK PROPOSAL MANAGER:
Manfred Bitter Phone: 609- 243-2582 Email: mbitter@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Non-perturbing high resolution measurements of ion temperature profiles, $T_i(R,t)$, are needed in present and future, ITER-like, MFE research devices. This task supports work to develop a new type of X-ray Imaging Crystal Spectrometer that will monitor the ion temperature from the Doppler width of X-ray lines from medium-Z elements, like argon or krypton, along multiple sight-lines. This new spectrometer will consist of a spherically bent crystal and a position-sensitive 2D detector. A prototype instrument has been installed on NSTX and is presently operating with a conventional 1D position-sensitive proportional counter, which records spectra of helium-like argon (ArXVII) along a central sight-line through the plasma for Doppler measurements of the central ion temperature. The instrumental layout has been optimized to image a 15 x 80 cm^2 large cross-section of the plasma onto a 10 x 30 cm^2 large 2D detector.

The proposed work scope for this effort was submitted in response to the DOE Program for Development of Diagnostic Systems for Magnetic Fusion Energy Sciences Experiments, LAB 01-25. This project will be funded in FY 2003 and FY2004.

15. Signature:

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Contractor Work Proposal Manager

Human/Animal Subjects: No

PURPOSE

This task addresses the need for non-perturbing high resolution measurements of ion temperature profiles, $T_i(R,t)$, in present devices and future ITER-like devices for MFE research. Such measurements can be performed with a new type of X-ray Imaging Crystal Spectrometer that will be developed with a spherically bent quartz crystal and a position-sensitive 2D detector. It will permit the observation of temporally and spatially resolved spectra of highly charged ions from trace impurities like argon or krypton along multiple sightlines through the plasma using only one crystal. In addition to ion temperature profiles, this X-ray Imaging Crystal Spectrometer will provide profiles of the electron temperature, $T_e(R,t)$, and profiles of the impurity ion charge state distribution, which is of interest for ion transport studies. The advantages of this diagnostic are that it can provide data for all experimental conditions, which include plasmas with pure Ohmic heating as well as plasmas with RF and neutral beam heating. In contrast to other techniques like charge-exchange spectroscopy, the X-ray Imaging Crystal Spectrometer does not require the injection of neutral beams, which perturb the plasma and are not expected to penetrate to the hot core of large, ITER-like devices. The purpose of the present proposal is to demonstrate the 2D imaging properties for Bragg angles near 45°, which are essential to the concept of this instrument (see M. Bitter et al., Rev. Sci. Instrum. **70**, 292 (1999)). This proof of principle requires development and testing of large 2D detectors. By providing profiles of plasma parameters with a high spatial resolution of about 5 cm, the X-ray Imaging Crystal Spectrometer will solve a longstanding problem in X-ray spectroscopy and lead to a breakthrough in X-ray diagnostics of extended plasma sources that are used in MFE research. Once this potential is successfully demonstrated, the proposed X-ray Imaging Crystal Spectrometer is expected to replace present arrays of single-chord crystal spectrometers, which have less capability for profile measurements and which require more valuable diagnostic real estate on MFE devices.

APPROACH

A prototype of the X-ray Imaging Crystal Spectrometer, which utilizes a spherically bent quartz crystal with a radius of curvature of 375 cm and an active area of 6 x 3 cm^2, has recently been installed on NSTX. The layout of this instrument has been optimized to image a 15 x 80 cm^2 large cross-section of the plasma onto a 10 x 30 cm^2 large 2D detector, which will be purchased to demonstrate the imaging properties of the spectrometer. So far, spectra of helium-like argon (ArXVII) have been measured on NSTX with a conventional 1D position-sensitive multi-wire proportional counter along a central sightline through the plasma with a temporal resolution of 10 ms. These spectra were used for Doppler broadening measurements of the ion temperature and have demonstrated the satisfactory performance of the spherically bent crystal. It is planned to first use a 10 x 30 cm^2 large position-sensitive multi-wire proportional counter, since proportional counters of this size are a reasonable extrapolation from those presently in use. Although the count rate of these proportional counters is limited to about 300,000 photons/sec, their signal-to-noise ratio is very high and better than that of any solid state detector. The measurements with a 2D proportional counter will, therefore, both demonstrate the imaging properties of this instrument and set a benchmark for the development of other detector technologies. These may provide a higher throughput and be more suitable for high radiation environments if their performance compares favorably with that of proportional counters.

FUTURE ACCOMPLISHMENTS

The main goal for FY03 is the development of a large (10 cm x 30 cm) 2D position-sensitive multi-wire proportional counter with sufficient spatial resolution of 0.2 mm in one direction to provide the spectral information and a coarser resolution of a few millimeter in the other direction providing the spatial information in the plasma. Multi-wire proportional counters (MWPC's) can be developed to any specified size utilizing proven technologies. MWPC's also have a high detection efficiency of nearly 100% for 3 keV X-rays and high signal-to-noise ratio. One limitation of the MWPC is that their count rate capability is only a few hundred kHz. A 2D position-sensitive MWPC will therefore be an excellent detector for a proof of principle experiment but, because of its count rate limitation, it will not be the optimal final detector. However, an MWPC will allow us to obtain spectra of high resolution with a high signal to noise ratio and this will define the standards for the development of future (large) detectors with a higher count rate capability of several MHZ.

The first 2D spectra will be obtained with a new MWPC at the end FY03 and new software will be developed for the analysis of 2D spectra in FY03 and FY04.

A 2D detector with higher count rate capability will then be developed in FY04.

MILESTONE SCHEDULE

FY2003 Milestones

Complete design and award a contract for a new 2D multi-wire proportional counter	MAR 03

FY2004 Milestones

Installation of a new 2D multi-wire proportional counter and data acquisition system on the NSTX X-ray Imaging Crystal Spectrometer. Ready to collect and store data. (Subject to NSTX run schedule)	DEC 03
Proof of principle demonstration of the new X-ray Imaging Crystal Spectrometer. Initial data analysis complete.	MAR 04
Complete development of a large 2D detector with a count rate capability of several MHz	SEP 04

1083 CRYSTAL SPECT DIAG 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists		.3		.4	
Engineers					
Administrators					
Graduate Students					
Technicians		.1		.1	
Clerical					
Subcontractors					
TOTAL FTEs		.4		.5	
OPERATING COSTS $(000):					
PPPL Labor		51.5		68.6	
Subcontract Labor					
Overtime					
Travel		8.0		6.0	
Energy					
Stockroom		1.0		1.0	
Miscellaneous Expenses					
Procurements/ICOs		65.9		60.9	
Organizational Burden		4.0		5.2	
Other					
General + Administrative		64.4		73.0	
TOTAL OPERATING COSTS		194.8		214.7	
TOTAL OPERATING OBLIGATIONS		194.8		214.7	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS		194.8		214.7	
GRAND TOTAL OBLIGATIONS		194.8		214.7	

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1028	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
National Undergraduate Fellowship	AT5010702

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Pamela Lucas Phone: 609 243-3049 Email: plucas@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. OE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The Princeton Plasma Physics Laboratory (PPPL) proposes to continue the National Undergraduate Fellowship Program in Plasma Physics and Fusion Energy Sciences, which provides outstanding undergraduate students attending United States colleges and universities an opportunity to conduct research in the disciplines that comprise the plasma sciences in general and fusion research in particular. The goal of the program is to stimulate students' interest and encourage further study in one of the fields relevant to fusion research while providing capable assistants to fusion research projects.

The program is widely advertised in colleges and universities around the United States. New recruiting approaches include an electronic application process; targeted recruiting aimed at physics departments that graduate the largest percentage of women and underrepresented minorities, as well as increasing the number of members of the university fusion community on the selection committee. Each year, up to 25 students are selected competitively by a committee of researchers. Following a one-week course in Plasma Physics taught at PPPL, students are offered 9-week summer research assignments alongside practicing scientists and engineers in projects sponsored by DOE. Students are paid a stipend and a living allowance. The research is carried out not only at the large laboratories, such as PPPL, but also at colleges and universities, including those represented by the UFA. These sites encompass a broad range of research in physics and engineering.

It is generally recognized that achievement and implementation of fusion power and advancements in plasma sciences will require several decades of intense research and development. The scientists and engineers who will be carrying out this vital program ten and twenty years from now will be, primarily, those now in college and graduate school. To guarantee a continuing supply of excellent research workers trained in appropriate disciplines requires that we maintain strong educational interest in plasma physics and fusion technology.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

1028 UNDERGRAD FELLOWSHIP 03/01/02			
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists			
Engineers			
Administrators	1.0	.8	.8
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	1.0	.8	.8
OPERATING COSTS $(000):			
PPPL Labor	73.2	57.3	63.9
Subcontract Labor			
Overtime			
Travel	45.0	35.0	35.0
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs	182.7	106.7	98.7
Organizational Burden			
Other			
General + Administrative	116.6	97.0	98.3
TOTAL OPERATING COSTS	417.5	296.0	295.9
TOTAL OPERATING OBLIGATIONS	299.9	296.0	295.9
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	417.5	296.0	295.9
GRAND TOTAL OBLIGATIONS	299.9	296.0	295.9

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1036	0	3/01/02

4. WORK PROPOSAL TITLE
PPPL - Trenton Partnership

5. BUDGET AND REPORTING CODE
AT5010702

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Pamela Lucas Phone: 609 243-3049 Email: plucas@pppl.gov

8. HEADQUARTERS ORGANIZATION:
Office of Science

9. OPERATIONS OFFICE:
Chicago Operations Office

10. CONTRACTOR NAME:
Princeton University
Princeton Plasma Physics Laboratory

11. DOE HQ ORGANIZATION CODE:
SC

12. DOE OPS OFFICE ORGANIZATION CODE:
CH

13. CONTRACTOR CODE:
15

14. WORK PROPOSAL DESCRIPTION:

Since 1990, the Princeton Plasma Physics Laboratory has maintained partnerships with local public school districts aimed at improving the teaching and learning of science, mathematics and technology. PPPL proposes to continue its educational alliances with these districts, including Trenton, improving teacher professional development in science and exposing students to scientific research. The focus of the partnership will continue to be teachers and students. Teacher workshops will allow teachers the opportunity to work with PPPL scientists to explore in greater depths the subjects they teach. Hands-on science workshops for students and parents, a research enrichment program, as well as school year internships will expose students to careers in science and scientific research.

PPPL scientists and staff will serve as a resource to local teachers and administrators in matters related to science education and scientific literacy and will provide hands-on activities and demonstrations, offer technical assistance and technology implementation, career exploration and judge science fairs. Special tours and programs and loans or grants of equipment and materials are also included.

PPPL will continue to partner with other regional stakeholders in the effort to improve math and science performance in the local school districts through the Eisenhower Professional Development Grant "Teaching Science Matters". This effort is coordinated with other regional educational initiatives and involves industrial, community, and non-profit partner institutions to offer sustained and intensive, high quality professional development to teachers. These and other regional partnerships provide significant leveraging of programmatic resources.

Science education staff will continue to serve in an advocacy roll in support of science education through participation in local boards and supporting various educational initiatives in support of professional development opportunities for teachers' and scientists' involvement in education.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

1036 TRENTON PARTNERSHIP 03/01/02					
	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists					
Engineers					
Administrators	1.3	1.1		1.1	
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	1.3	1.1		1.1	
OPERATING COSTS $(000):					
PPPL Labor	95.1	87.9		91.9	
Subcontract Labor					
Overtime					
Travel	6.0	3.0		3.0	
Energy					
Stockroom					
Miscellaneous Expenses					
Procurements/ICOs	59.5	35.6		30.5	
Organizational Burden					
Other					
General + Administrative	75.6	70.5		71.3	
TOTAL OPERATING COSTS	236.2	197.0		196.7	
TOTAL OPERATING OBLIGATIONS	200.0	197.0		196.7	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS	236.2	197.0		196.7	
GRAND TOTAL OBLIGATIONS	200.0	197.0		196.7	

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1037	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Plasma Science Institute/CPEP	AT5010702

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Pamela Lucas Phone: 609 243-3049 Email: plucas@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

PPPL will continue to conduct the Plasma Science and Fusion Energy Institute “Plasma Camp” as a 2-week intensive summer program for high school physics teachers from around the country. The Institute is centered on plasma physics and fusion energy sciences and is designed to demonstrate the relevance of the chosen topics to current 9-12th grade curricula. The goals of the project are to increase teachers' content knowledge in areas of plasma sciences, to increase teachers' capacity for and confidence in their ability to implement inquiry-based teaching methods in their classrooms, and to increase teachers' capacity to infuse examples, demonstrations, and investigations into students' study of other areas of classical physics. Participants include new teachers and veterans of past workshops and all participants write curricula based upon their theoretical and experimental work. One participant noted, “Helping students discover the beauty and complexity of the physical world is a great endeavor…working with scientists doing research on fusion and bringing part of this knowledge to students is an experience all physics teachers should have.”

Building on the success of the Institute, selected teachers from the Institute developed a Plasma Science Academy for high school students. The Academy meets an expressed need for such training on the part of program participants. In addition, the intent of this endeavor is to extend the Institute by "field testing" the plasma sciences curricula developed by participants while at the same time offering a unique opportunity for high school students not found in typical summer laboratory experiences. The first Plasma Academy was held during the summer of 2001. The initial audience included students from groups traditionally underrepresented in science. Follow up sessions are planned for throughout the FY02 school year and the program will be offered again in the summer of 2003.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

1037 PLASMA SCI INST/CPEP 03/01/02			
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists			
Engineers			
Administrators	.3	.3	.3
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs	.3	.3	.3
OPERATING COSTS $(000):			
PPPL Labor	22.0	22.9	24.0
Subcontract Labor			
Overtime			
Travel	10.0	10.0	10.0
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs	39.2	33.2	31.9
Organizational Burden			
Other			
General + Administrative	29.0	32.9	33.1
TOTAL OPERATING COSTS	100.2	99.0	99.0
TOTAL OPERATING OBLIGATIONS	100.0	99.0	99.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS	100.2	99.0	99.0
GRAND TOTAL OBLIGATIONS	100.0	99.0	99.0

Dir Alloc Ovrlaid/Indr incld

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1029	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Upgrading Museum Displays	AT5010702

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
John DeLooper Phone: 609-243-3047 Email: jdelooper@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

Communicating the benefit and promise of plasma science and fusion research is a responsibility of the Office of Fusion Energy Sciences and the fusion community. Information communicated via web sites and brochures are easily updated and distributed. Changes in more permanent displays, like those at museums, are not readily updated and often out-of-date. This proposal describes a program to evaluate the extent of the problem and to begin to remedy this situation. Incremental funds of $50K for FY 2003 and $100K for FY 2004 are requested.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

The purpose of this proposal is to provide up-to-date information on plasma science and fusion research by the use of museum displays. Current permanent displays, such as those at museums, are not readily updated and often out-of-date. To address this issue, the following actions are proposed:

During the summer of FY02, an ERULF student will be assigned to survey the major museums throughout the United States. This survey will determine: whether the museum has a fusion and/or plasma display; whether or not it is up to date; and the facilities willingness to host a new fusion/plasma display. The student will also do some preliminary studies for what should be included in the display to communicate the plasma science and fusion research effort. The ERULF program will cover the cost of this effort.

During FY03, PPPL will develop a small self-contained plasma science and fusion display (occupying < 100 ft^2 of floor space). The display will have at least one hands-on plasma device (e.g., a plasma ball or a fluorescent lamp), which visitors can touch and play with. The goal of the design will be to explain the OFES program while minimizing the cost of the display. As part of this process, the objective is to develop the design of a plasma/fusion display in the first half of FY03 and then test the display at a museum close to PPPL (potentially the Liberty Science Center). This design would be iterated based upon the feedback from the public. This testing phase will also allow PPPL to assure that the design is reliable and that it does not turn into a piece of "junk" after a few weeks of use and abuse by the public. A preliminary concept is to develop several of these displays, which would be a traveling exhibit (however, our approach may change depending on the survey information obtained during FY02). The traveling display would be offered to museums for free (a major selling point) and because it wouldn't be "permanent" it would allow an opportunity to update the device when it travels to the next facility.

During FY04, PPPL will develop two traveling displays (current plan, may change depending on survey results) at museums (the selection of the museums will be based on the data collected by the ERULF student – most out-of-date, most willing to accept display). When the display is first installed, Dr. Hulse, a PPPL Scientist, will travel to the museum and give a lecture on fusion and plasma science as the introduction and opening of the display.

The goal is to build and install the display at a minimum cost. The budget requested also includes funding for providing OFES brochures and handout materials on each of the displays.

Schedule/Milestones:

FY03

January	Develop preliminary display for OFES Review
March	Determine museum that will get display for testing (potentially Liberty Science Center).
September	Revise display and concepts based on test case (maybe several versions)

FY04

January	Determine 2 museums who will get display
September	Install displays and have opening ceremony and lecture by PPPL scientist for each unit. Determine whether to build additional units and how much effort should be available to maintain existing exhibits.

1029 MUSEUM DISPLAY		03/01/02	
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists		.1	.1
Engineers			
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs		.1	.1
OPERATING COSTS $(000):			
PPPL Labor		10.7	10.3
Subcontract Labor			
Overtime			
Travel		4.0	4.0
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs		18.2	55.5
Organizational Burden		.7	.7
Other			
General + Administrative		16.4	29.5
TOTAL OPERATING COSTS		50.0	100.0
TOTAL OPERATING OBLIGATIONS		50.0	100.0
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS		50.0	100.0
GRAND TOTAL OBLIGATIONS		50.0	100.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1038	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Plasma Science Education Laboratory	AT5010702

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Andrew Post-Zwicker Phone: 609-243-2150 Email: azwicker@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

An innovative laboratory dedicated to plasma science education at the pre-college and undergraduate level is proposed. The Plasma Science Education Laboratory (PSEL) will be the first of its kind, a cutting-edge education facility that brings the beauty and complexity of plasmas to a greatly expanded range of teachers and students who now rarely have the chance to study plasma physics in a hands-on manner.

The PSEL builds on PPPL experience developing successful, innovative hands-on science education programs centered upon weaving plasmas into existing curricula. It will enable science education and outreach programs to take fuller advantage of the scientific and technical capabilities of PPPL in support of the educational missions of the DOE and OFES. Nothing of this nature currently exists at any DOE facility, and the creation of such an educational facility at PPL will make PPPL a national leader in science education, and will serve as a prototype for developing similar centers at other laboratories. The new laboratory/classroom space and associated equipment will allow the Science Education Program (SEP) to provide a solid basis for continuing and expanding its existing highly successful activities, and will form the basis for the creation of new programs, including additional outreach programs for underrepresented populations. Incremental funds of $100K for FY 2003 and $50K for FY 2004 are requested.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Purpose

- Make PPPL a national leader in science education, especially at the pre-college level.
- Create a unique laboratory and classroom space dedicated to bringing plasma science to a broad population.
- Build a variety of plasma sources of varying levels of complexity that will be the core of all educational activities.
- Recruit a group of "Master Teachers" to develop and teach these new opportunities along with PPPL staff.

Approach

Crucial to the success of this new plasma science educational laboratory (PSEL) is an integrated teaching approach that has students at all levels learn physics in the same manner that a research scientist does physics. (Learning physics by doing physics.) The success of this approach is well documented in physics education research journals[1] but is still not commonly used with students. At the core of this method is a research-based experience (in the laboratory) woven together with the necessary theoretical basis (in the classroom) and the use of advanced computational tools with an emphasis on visualization of the underlying principles. This is consistent with the scenario proposed under a recent DOE Scientific Simulation Initiative for plasma science[2]

This is also the scenario that was used for the past several years with the Plasma Camp workshop and independent student research performed under the supervision of Dr. Andrew Post-Zwicker. As documented in the "Background" section, this method is extremely successful and forms the "proof-of-principle" basis for the scope of this proposal.

The increase in Science Education Program activities will be supported by a group of "Master Teachers" to both develop and assist in the teaching of new workshops, as part of this proposal. A summer "educational internship" will be created to bring new master teachers to PPPL to assist in the various programs. These master teachers will be veterans from Plasma Camp and, thus, well versed in basic plasma physics theory and experimentation.

Background

During the last four years, "Plasma Camp" has proven a highly successful model for expanded efforts. It has created a group of teachers that weave plasma physics into their introductory courses. Rather than teach a section on "plasma", these teachers use

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[1] "Learning to think like a physicist: A review of research-based instructional strategies," A. Van Heuvelen, Am. J. Phys. **59**, 891-897 (1991).
"Teaching Physics: Figuring Out What Works", E. F. Redish, N. Steinberg, Physics Today, 52, 24-30 (1999)

[2] "Advanced Computation in Plasma Physics", W.M. Tang, DPP APS Meeting, 2001 (Invited).

plasma to as a teaching tool throughout the entire curriculum. Thus, topics as diverse as collisions, thermodynamics, electricity, magnetism, atoms, light, etc. are all explored using plasma sources (fluorescent light bulb, plasma globe, DC glow discharge tube) as the basis for hands-on learning. We have also supported and mentored several high school students performing independent plasma physics research.

These activities resulted in invited and contributed papers at APS meetings, publications (both refereed and non-refereed), and numerous awards at the national and international level for the student research. These include such high-profile and prestigious awards as a multiple prize winner in the International Science and Engineering Fair and a semi-finalist in the Intel National Science Talent Search. Further, three manuscripts for publication in refereed journals are currently in preparation. These activities are listed below:

Presentations at APS Conferences

Sophia Gershman, Watchung Hills Regional High School, **The Use of a Glow Discharge and Other Plasma Sources in Teaching Introductory Physics**, DPP 2001 meeting. (Invited talk)

Sophia Gershman, Watchung Hills Regional High School and Andrew Post Zwicker, PPPL, **The Use of the Plasma Chamber in Teaching Introductory Physics**, 2001 April meeting. (Contributed talk)

Andrew P. Post-Zwicker and Nicholas R. Guilbert, **On the Efficacy of a Research-Based Experience for Introducing Plasmas into the High School Physics Classroom,** Bulletin of the American Physical Society, Seattle, WA, (1999). (Poster)

Andrew Post Zwicker**, Using the Internet for Plasma Physics Education,** DPP 1997 meeting. (Invited talk)

Refereed Journals

N.R. Guilbert, Sophia Gershman, and A.P. Post-Zwicker, **The Creation of Contemporary Physics Curricula for the High School Classroom Utilizing a Research Experience Professional Development Workshop – A Case Study in Plasma Physics**, In preparation, to be submitted to the Journal of Science Education.

Sophia Gershman, N.R. Guilbert, and A.P. Post-Zwicker, **Teaching Introductory Physics with a Plasma-Centered Curriculum**, In preparation, to be submitted to the American Journal of Physics.

A.P. Post-Zwicker, Sophia Gershman, and N.R. Guilbert, **A Simple Glow Discharge Tube for Introductory Physics Laboratories**, In preparation, to be submitted to the American Journal of Physics.

N.R. Guilbert and A.P. Post-Zwicker**, 'Plasma Camp': A Different Approach to Professional Development for Physics Teachers,** Journal of the National Consortium of Specialized Secondary Schools of Mathematics, Science, and Technology, **4**(2) 11 (1999).

N.R. Guilbert, **Deconstructing a Plasma Globe**, The Physics Teacher, 37 11, (1999).

Other Publications

A.P. Post-Zwicker and N.R. Guilbert, **A New Model for Bringing Contemporary Physics Topics into the High School Classroom**, Newsletter of the Forum on Education, American Physical Society, Fall, 1998.

Student Research Topics

2001 – 2002

Interactive Plasma Display
Erik Kaiser, Marine Academy of Science and Technology, Sandy Hook, NJ

Analysis of Striations in a DC Glow Discharge Plasma
Frank Provenzano, New Rochelle High School, New Rochelle, NY

Semifinalist, 61st Annual Intel Science Talent Search

2000 - 2001

Glow Discharge Optical Emission Spectrometry for the Relative Calibration of Helium Emission Line Intensity vs. Concentration
Matthew Siegel, New Rochelle High School, New Rochelle, NY

Semifinalist, 60th Annual Intel Science Talent Search

Isolating Plasma Species - Initiating Internal Electrostatic Fields for Plasma Heating
Garrett Young, Home Schooled, Branchburg, NJ

Second Place Physics, 2001 International Science and Engineering Fair
Third Place Physics, 2000 International Science and Engineering Fair
First Place, New Jersey Regional Science Fair (2000 & 2001)

Visualization of a Charged Particle in a Magnetized Plasma
Garrett Young, Home Schooled, Branchburg, NJ

First Prize Physics, Mercer Community College Science and Engineering Fair

1999 – 2000

Plasma Impurities in a Transverse Magnetic Field
Jeremy Ehrhardt, Mercer Community College

First Place, New Jersey Regional Science Fair

Relationship to Existing Projects

The creation of this laboratory/classroom space will not only facilitate the creation of new and innovative educational activities, it will also have an immediate and significant impact on the existing activities. Most of the activities are limited in scope due to the current lack of adequate laboratory space. In particular, the creation of a Plasma Science Education Laboratory will allow:

1. Expansion of the existing laboratory mini-course for National Undergraduate Fellowship students during their one-week plasma course at PPPL.
    a. Size of current laboratory limits existing experimental section of course
2. Expansion of existing Plasma Camp workshop for high school physics teachers.
    a. Current workshop is limited to 12/year due to inadequate laboratory space
3. Increase in the number of workshops for K-12 teachers from surrounding school districts.
    a. Based on an existing partnership with Princeton University who will lead this effort
4. Creation of a laboratory mini-course for Energy Research Undergraduate Laboratory Fellowship students (Funded by Office of Science)
    a. No course exists due to size constraint of existing grad lab
5. Creation of a new program for pre-service teachers
    a. Funding from DOE Office of Science is secured
6. Creation of a new workshop for community college teachers
    a. Partnership with Portland Community College, Portland, OR is in place (NSF funding secured)
    b. Workshop to create plasma laboratory course for community colleges educating technicians for plasma-related industrial jobs

Milestone Schedule

FY03

December	Finish construction of new laboratory/classroom facility
June	Begin the creation of a visualization predictive code of a DC glow discharge tube for educational purposes

FY04

May	Complete construction of an advanced plasma sources
August	Create and run pilot program for community college teachers

1038 PLASMA SCI ED LAB	03/01/02			
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists				
Engineers				
Administrators				
Graduate Students				
Technicians		.1		
Clerical				
Subcontractors				
TOTAL FTEs		.1		
OPERATING COSTS $(000):				
PPPL Labor		13.7		4.8
Subcontract Labor				
Overtime				
Travel		5.9		6.0
Energy				
Stockroom				
Miscellaneous Expenses				
Procurements/ICOs		48.2		23.2
Organizational Burden		1.5		.5
Other				
General + Administrative		30.8		15.6
TOTAL OPERATING COSTS		100.1		50.1
TOTAL OPERATING OBLIGATIONS		100.1		50.1
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS		100.1		50.1
GRAND TOTAL OBLIGATIONS		100.1		50.1

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1393	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
D-Site Caretaking Operations	AT5501

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
A. von Halle Phone: 609-243-2618 Email: avonhalle@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The purpose of the D-Site Caretaking job is to provide the resources required to maintain the radiological safety of the unused D-site experimental areas.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Current operations through FY02

As the TFTR systems were turned over to caretaking operations, administrative procedures establishing proper conduct of operations were updated and streamlined as appropriate. Examples include:

- Chain of Command for ops, maintenance, and balance of plant
- Operations, maintenance, and emergency response procedures
- A work scheduling and permit system
- Management oversight

Other administrative procedures governing conduct of operations issues remain in effect during caretaking operations. These include:

- Configuration control
- Shift turnovers
- Standards for logkeeping
- Communication
- Lockout/Tagout

Certain other aspects of the operation of the TFTR facility have remained unchanged upon entering the caretaking phase. The vacuum vessel, neutral beamlines, ion sources, tritium processing systems and the various vacuum appendages of TFTR still retain significant inventories of adsorbed and implanted tritium which continue to slowly outgas into internal volumes. These volumes must be routinely monitored and processed to keep amounts of readily releasable tritium at safe levels. Tritium monitors and daily surveys of machine areas are used to verify nuclear boundaries and to allow for quick remediation when the boundary of contamination does expand. The caretaking effort is also responsible for responding, in a timely fashion, to the sometimes unpredictable changes that may occur within the nuclear boundary.

Procedures for accurately documenting site tritium inventories remain in force. The HVAC systems and the Liquid Effluent Collection (LEC) system also remain fully operational and safety system operations and surveillances remain intact. Full operation of the REML and Health Physics oversight of many caretaking activities is required. AC power system maintenance and operations is required throughout caretaking.

The CICADA operations center was closed out upon completion of operations in support of bulk tritium removal. The safety computer has been phased out and has been replaced, for access control only, by the PPPL Security Computer (LINX). Other CICADA control system operations are required throughout caretaking operations and include:

- Maintenance and support of the video systems in the test cell and tritium areas.
- Maintenance and support of the TFTR public address system.
- Maintenance and support of TRECAMS.

Maintenance and surveillance of mothballed equipment is also required throughout the caretaking period. These requirements and activities include the procedures and manpower necessary to provide periodic inspections and maintenance of:

- Vacuum, Cryogenic, and Water systems.
- The Motor Generator Sets.
- The Experimental Power Systems (NB, FCPC, and ICRF).
- Oil filled equipment.
- System safety status.

FY03 and FY04

With the completion of D&D, responsibility for all of D-Site with the exception for maintaining the radiological safety of the TFTR Test Cell, Basement and Tritium Area will become the responsibility of NSTX. The D-Site Caretaking job will maintain the radiological safety of the TFTR experimental area. This scope of work would not be expected to be part of the NSTX Project but is needed to ensure safe operation of the Laboratory in compliance with regulations.

Some mothballed/unused equipment preserved for future projects remains in the TFTR Test Cell and Test Cell Basement. These include, for example, the TFTR neutral beamlines and ion sources and tritium processing systems. Although tritium inventories have been removed as part of the D&D project, the neutral beamlines, ion sources and tritium processing systems still retain low levels of adsorbed and implanted tritium, which continue to slowly outgas into internal volumes. These volumes must be routinely monitored to assure that there has been no uncontrolled increase or release of tritium contamination. Tritium monitors and surveys of machine areas are used to verify proper control of tritium contamination. Any measurement of surface tritium contamination will require prompt decontamination operations.

Procedures for accurately documenting tritium contamination remain in force. The HVAC systems and the Liquid Effluent Collection (LEC) system also remain fully operational and safety system operations and surveillances remain intact. Operation of the Princeton Environmental Analytical & Radiological Laboratory (PEARL) and Health Physics oversight of caretaking activities is required. The Health Physics staff will also provide on-going environmental monitoring of tritium in the groundwater and biota as well as document stack releases. This is especially important in our interactions with members of the local community as well as state regulatory authorities.

Supervision and oversight of TFTR test cell and test cell basement activities and conditions is required and include:

- Maintenance and support of the video systems in the test cell and tritium areas
- Maintenance and support of the Tritium Remote Control and Monitoring System (TRECAMS), used to monitor tritium releases
- Remaining neutral beam ion source maintenance and inspection
- Unused cryogenic system maintenance and inspection
- Unused neutral beam systems maintenance and inspection
- Test cell crane inspections and minor repairs
- Tritium monitor calibration and repair

Funding for D-Site Caretaking Operations was not included in the Congressional Budget Request for FY 2003. PPPL did include this activity in last year's Field Work Proposal submission for FY 2003 funding, and we feel that this is an important activity which should be directly funded.

1393 D-SITE CARETAKING	03/01/02			
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists				
Engineers	3.0	.4		.4
Administrators	.8	.1		.1
Graduate Students				
Technicians	11.0	1.2		1.2
Clerical	.3			
Subcontractors	.6			
TOTAL FTEs	15.7	1.7		1.7
OPERATING COSTS $(000):				
PPPL Labor	1238.0	187.3		195.8
Subcontract Labor	44.0			
Overtime	107.8			
Travel				
Energy	284.7			
Stockroom	19.9			
Miscellaneous Expenses	88.3			
Procurements/ICOs	175.6	109.6		97.9
Organizational Burden	149.7	27.3		28.5
Other				
General + Administrative	1067.3	175.9		177.7
TOTAL OPERATING COSTS	3237.0	500.1		499.9
TOTAL OPERATING OBLIGATIONS	3202.0	500.1		499.9
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	3237.0	500.1		499.9
GRAND TOTAL OBLIGATIONS	3202.0	500.1		499.9

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
4801 - 4810	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Environmental Restoration/Waste Management	AT5507 – FY02 / Various - FY03/04

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Scott B. Larson Phone: 609-243-3387 Email: slarson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The Environmental Restoration and Waste Management activities performed at PPPL include the following:

- Technical, financial, regulatory, and administrative management of soil and ground water remediation projects.
- Management of generated hazardous, low level radioactive, mixed low level radioactive, asbestos and regulated solid wastes and recyclable materials in accordance with established regulations, which includes collection and treatment, storage and disposal.
- Waste minimization and pollution prevention activities.
- Environmental Compliance.
- Cleanup actions in response to spills or other environmental impacts.

* The Congressional Budget Guidance for FY 2003 does not fund Waste Management (ER/WM) as a separate program; instead it distributes Waste Management funding as part of our project B&R lines. At this point in the planning process, we have not precisely determined how to allocate the cost of ER/WM to the various B&R lines which contain ER/WM funding; therefore, our project budgets do not include ER/WM costs. We have, as an alternative, developed a separate FWP for Waste Management.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

ENVIRONMENTAL RESTORATION

This activity supports the PPPL technical personnel and program management for all environmental restoration activities at PPPL. These personnel are responsible for the technical, financial, regulatory, and administrative issues related to soil and ground water remediation. In addition to the environmental restoration program outlined below, these personnel are also responsible for cleanup actions conducted in response to spills or other environmental impacts. All environmental restoration work is overseen by the New Jersey Department of Environmental Protection (NJDEP), as required by a Memorandum of Understanding (MOU) between NJDEP and Princeton University.

Under EM-40 funding PPPL completed a site-wide Remedial Investigation (RI) and Interim Remedial Actions addressing soil and ground water contamination at the site. Contaminated soil was removed and a No Further Action Determination was received from NJDEP. Ground water contamination consists primarily of the chlorinated organic chemical tetrachloroethylene (PCE), trichloroethylene (TCE) and their degradation products. Contamination is limited to shallow ground water on the PPPL site and is not migrating off-site. Limited natural degradation of contaminants has been documented at the site. The approved ground water remedy relies on PPPL's existing foundation dewatering system to control and extract contaminated ground water as well as natural attenuation processes. Under the approved remedy PPPL conducts quarterly monitoring of selected wells and building sumps to monitor system performance. PPPL submits an annual Remedial Action Monitoring Report to NJDEP as required under New Jersey's Technical Requirements for Site Remediation (NJAC 7:26C). Long-term ground water monitoring is expected to continue for a minimum of ten (10) years until contaminants have degraded to below regulatory levels.

Environmental Restoration Milestones

MILESTONE	PLANNED DATE
Conduct quarterly groundwater monitoring	Quarterly
Submit Groundwater Monitoring Report*	Annual

*Actual submittal date dependent on NJDEP approval of monitoring program.

ENVIRONMENTAL COMPLIANCE

Environmental Compliance regulations impose requirements on the generation, management, and disposal or release of waste products (effluents) generated as a result of routine facility operations. Generation of zero wastes from processes is very seldom possible; therefore, the Environmental Compliance management system at PPPL establishes practices that eliminate or limit the generation of waste products, minimize pollution, and save operating funds. This activity maintains all environmental permits for air and water releases. All monitoring required by the various permits is performed under this activity. The Environmental Compliance function cuts across and supports all

Laboratory activities: experimental projects, facility operations, and environmental programs.

WASTE MANAGEMENT

The goal of the activities that are carried out by the Waste Management Branch of ER/WM is the proper management of hazardous, low level radioactive, mixed low level radioactive, asbestos and regulated solid wastes and recyclable materials generated at the Laboratory. This activity also includes waste minimization/pollution prevention activities, asbestos removal, and program support. Within this activity are four main scope elements: waste collection & treatment, storage, and disposal, and asbestos project management.

- Waste Collection and Storage includes the collecting, sorting, characterizing, and storing of all waste streams.

- Waste Treatment includes resources and materials required for "lab packing" and sorting of hazardous wastes, elemental neutralization and other RCRA-exempt treatment of all waste streams, compaction, size reduction, and dismantlement of low-level radioactive wastes, solidification of tritiated waste, and crushing of scintillation vials.

- Waste Transportation and disposal includes resources required to transport and dispose of all generated waste streams.
- Asbestos Management, Removal and Disposal includes subcontractor costs for the removal, transportation and disposal of asbestos.

- Program support includes providing financial management and project control support to waste management activities; and producing monthly reports for the DOE, senior Laboratory management, and waste operations staff. This activity also includes the resources in support of the treatment, storage, and disposal of the waste streams not directly related to these specific activities.

Technical Objective: The objective of this activity is to properly manage an estimated 100,000 lbs of hazardous waste, 1,125 cubic feet (31 cubic meters) of low level radioactive waste, 70 cubic feet (2 cubic meters) of mixed low level radioactive waste, 300 cubic yards of asbestos waste, 130 tons of regulated solid waste and 70 tons of recyclable materials generated by PPPL in accordance with state, federal, and local regulations and DOE orders.

Waste Management Milestones

MILESTONE	PLANNED DATE
Submit Solid Waste Information Forecast to Hanford	6/30/03
Collect, store, package, and dispose of hazardous, low level radioactive, mixed low level radioactive, asbestos, and regulated solid wastes and recyclable materials.	9/30/03
Submit Biennial Generators Report to NJDEP	3/31/04
Submit Solid Waste Information Forecast to Hanford	6/30/04
Collect, store, package, and dispose of hazardous, low level radioactive, mixed low level radioactive, asbestos, and regulated solid wastes and recyclable materials.	9/30/04

FY 2003 Congressional Budget

The FY 2003 Congressional Budget figures reflected a level of activity that has changed following the completion of the TFTR D&D Project. As a result, the authorized funding level can be decreased from $3,103K to $2,700K allowing these funds to be reallocated to other PPPL programs, while still maintaining appropriate controls for environmental and waste management programs.

Drivers:
OSHA
29 CFR 1910.120 Requirements for Hazardous Waste Workers

RCRA
New Jersey Administrative Code 7:26-1 through 10. (NJ Hazardous Waste Management Regulations)
40 CFR 260 through 268 (Federal Hazardous Waste Management Regulations)

TSCA
40 CFR 761 also New Jersey Administrative Code 7:26-8 (PCB Regulation)

DOT
49 CFR 171-178 (Hazardous Materials Transportation Regulations)

DOE
DOE Order 5820.2A Radioactive Waste Management
DOE Order 435.1 Radioactive Waste Management

EPA
10 CFR 835 (Radiation Protection)

WASTE MANAGEMENT		03/01/02		
	FY02	FY03		FY04
		Baseline	Incremnt	Baseline Incremnt
STAFFING(FTEs):				
Physicists				
Engineers				
Administrators	8.2	7.7		7.7
Graduate Students				
Technicians	5.5	3.6		3.6
Clerical	1.3	1.0		1.0
Subcontractors	.1			
TOTAL FTEs	15.1	12.3		12.3
OPERATING COSTS $(000):				
PPPL Labor	1165.2	1053.0		1100.4
Subcontract Labor	18.7			
Overtime	8.0	2.0		2.0
Travel	26.3	20.9		18.9
Energy				
Stockroom	2.0	1.6		1.6
Miscellaneous Expenses	23.5	20.8		20.8
Procurements/ICOs	1041.0	622.4		565.6
Organizational Burden	24.7	32.3		33.8
Other	5.8	1.1		1.1
General + Administrative	1028.5	946.2		955.6
TOTAL OPERATING COSTS	3343.7	2700.3		2699.8
TOTAL OPERATING OBLIGATIONS	3149.7	2700.3		2699.8
EQUIPMENT COSTS $(000):				
Equipment - Direct				
Equipment - G+A				
Fabricated Equipment				
TOTAL EQUIPMENT COSTS				
TOTAL EQUIPMENT OBLIGATIONS				
GRAND TOTAL COSTS	3343.7	2700.3		2699.8
GRAND TOTAL OBLIGATIONS	3149.7	2700.3		2699.8

Dir Alloc Ovrlaid/Indr incld FabEq Labor Alloc Overlaid.

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
9101	0	3/1/2002

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
General Plant Projects	AT5508

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
J. W. Anderson, Jr. Phone: 609-243-2207 Email: jwanderson@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This work funds the PPPL General Plant Projects program. This program is a critical element of PPPL's capital projects programming strategy to provide for safe and reliable facility operation. The needs of the program are driven by the evolving needs of the Laboratory's experimental initiatives, the size (square footage area and replacement plant value) of its facilities, and the ages of its infrastructure.

15. Signature:

_____
Contractor Work Proposal Manager

16. Human/Animal Subjects: No

PURPOSE

The General Plant Projects program provides for care of the DOE facility so as to provide for safe and reliable facility operation, as mentioned above, and ascertain that the investment made at PPPL is appropriately maintained.

BACKGROUND

PPPL develops the General Plant Project (GPP) plan in accordance with established procedures. These procedures provide the methodology for evaluating and managing the risks and benefits associated with the Laboratory infrastructure. Proposed projects are formulated, evaluated, and developed under the guidance of the PPPL Technical Resources Committee. Plans and issues are discussed and shared with the Princeton Area Office staff through routine communication and periodic project meetings.

APPROACH

The Laboratory maintains a queue of proposed projects that address ES&H issues, as well as programmatic support. The list of backlogged projects is dynamic and is rank-ordered on an annual basis using a capital asset management risk model. The list of projects under the Milestones section represents our current assessment and is reviewed at least annually.

PROGRESS

During the previous year (FY-01) the following projects were completed as part of this program:
Roofing Systems Replacements
Underground Utilities Replacement Phase II
Fuel Delivery Containment Area
Replacement of C-Site Emergency Electrical Cable
Expansion of LSB East Parking Lot

FUTURE ACCOMPLISHMENTS

A major multi-year project scheduled for completion in FY-2002 is replacement of the central chilled water plant, which provides house and process water-cooling for the Laboratory.

The current year's program also provides for completion of efforts to replace additional failed roofing systems and also for completion of phases III and IV of the underground utility replacement project.

Significant future considerations include repairs to the elevated water tower, a possible cross-connection between the C and D-Site cooling towers, replacement of additional roofing systems, and upgrade of the C and D-site fire protection systems.

MILESTONE SCHEDULE

Baseline Projects:	
Upgrade LSB Elevator Controls	Jun-02
Upgrade D-Site MG Building Fire Alarm System	Sep-02
CS Building Roofing System Replacement	Sep-02
Upgrade ESU Personnel Living Quarters	Sep-02
Upgrade Central Chilled Water Plant	Sep-02
Replace Underground Utilities Phases III and IV	Sep-02
Repair Elevated Water Tower	Sep-03
Install Replacement Roofing Systems	Sep-04
Upgrade C and D-site Fire Protection Systems	Sep-04
Replace Wall Heaters in Laboratory and Theory Wings	Sep-04
Incremental Projects:	
Install C-Site Cooling Tower Interconnect	Sep-03
Install C-Site Replacement Roofing Systems	Sep-03
Elevator Upgrade Project	Sep-04

EXPLANATION

The GPP program is designed to be flexible in order to meet dynamic infrastructure and mission needs. As a result, annual priorities and milestones (for projects) can only be set once budget authority is finalized.

The items scheduled for completion above represent those currently listed as having the highest priority as recognized using the Laboratory and DOE procedures for managing risks and benefits within the laboratory infrastructure. For example, an independent specialist has inspected the elevated water tower and prepared a report listing necessary improvements. Some of these items if unattended may lead to degradation to a point where it could impact both, safety and experimental operations. The Incremental Projects reflect important projects that the Laboratory must address soon in order to maintain effective stewardship of the Laboratory infrastructure. They have been reviewed in accordance with the established risk ranking methodology and represent high priority projects that would definitely reduce risks (programmatic as well as ES&H related) if pursued promptly. The interconnect project would improve the reliability and availability of process cooling water necessary to support NSTX RF System operations. There are still a number of significantly degraded roofing systems at C-Site that require replacement. Lastly, there are three elevators of original (circa 1958) design and construction that merit upgrades to ensure that the existing single shaft hydraulic systems do not fail and adversely affect soil under the affected buildings.

RELATIONSHIP TO OTHER PROJECTS

Delaying these GPP projects will lead to higher maintenance costs, higher energy costs, and the possibility of a failure, which would to materially impact the Laboratory's operations.

INCREMENTAL FUNDING REQUEST

Incremental funding of $200K has been requested in order to reduce the open project list and meet our commitments to maintain the infrastructure at a level that allows reliable dependence on Laboratory facilities.

IMPACT OF CONGRESSIONAL BUDGET

If the FY03 actual funding remains at the Congressional Budget figure of $995K, there will be an adverse effect on infrastructure capital improvement projects in FY03. It will likely require the postponement of several important General Plant Projects that have been determined to provide critical ES&H or experimental program support functions to the Laboratory.

9101 GENERAL PLANT PROJS 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists					
Engineers					
Administrators	.9	1.0		1.0	
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs	.9	1.0		1.0	
COSTS $(000):					
PPPL Labor	104.7	109.7		114.6	
Subcontract Labor					
Overtime					
Travel					
Energy					
Stockroom					
Miscellaneous Expenses					
Procurements/ICOs	1936.3	750.5	147.1	744.6	147.1
Organizational Burden					
Other	28.2				
General + Administrative	547.0	339.9	53.0	340.9	53.0
TOTAL COSTS	2616.2	1200.1	200.1	1200.1	200.1
TOTAL OBLIGATIONS	1370.0	1200.1	200.1	1200.1	200.1

U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1075	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Laboratory Support Equipment	AT5508

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Marie Iseicz Phone: 609-243-2456 Email: miseicz@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

This proposal provides funds for capital equipment that supports the Laboratory at large. The types of capital equipment that may be procured with these funds are upgrades to the scientific/engineering and administrative computer systems, equipment for the Laboratory's engineering technical shops, and special purpose vehicles to support the Laboratory's infrastructure activities such as Facilities Maintenance and Materiel Control.

Requests for support capital equipment, including appropriate justifications, are submitted to Laboratory management (Budget and Human Resource Committee) for consideration. An updated analysis of the Laboratory's needs is performed at the beginning of each fiscal year. On the basis of that assessment, a request will be made to DOE to transfer funds (in excess of the funds initially provided for this equipment) from other projects to support these Laboratory needs. Laboratory management must grant approval for an item of support capital equipment to be procured.

14. Signature

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Contractor Work Proposal Manager

15. Human/Animal Subjects: No

1075 LAB SUPPORT EQUIPT	03/01/02		
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists			
Engineers			
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs			
OPERATING COSTS $(000):			
PPPL Labor			
Subcontract Labor			
Overtime			
Travel			
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs			
Organizational Burden			
Other			
General + Administrative			
TOTAL OPERATING COSTS			
TOTAL OPERATING OBLIGATIONS			
EQUIPMENT COSTS $(000):			
Equipment - Direct	244.0	58.8	58.8
Equipment - G+A	61.0	21.2	21.2
Fabricated Equipment	150.0		
TOTAL EQUIPMENT COSTS	455.0	80.0	80.0
TOTAL EQUIPMENT OBLIGATIONS	115.0	80.0	80.0
GRAND TOTAL COSTS	455.0	80.0	80.0
GRAND TOTAL OBLIGATIONS	115.0	80.0	80.0

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
3501	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
NSF Collaborations	AT5015020

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Philip C. Efthimion Phone: 609-243-3212 Email: PEfthimion@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University, Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:
Three Physics Frontier Center proposals have recently been submitted to NSF in which PPPL is included as a co-investigator. These proposals are for an Interdisciplinary Center for Magnetic Reconnection (Center at U. Maryland), an Interdisciplinary Center for Magnetic Self-organization in Laboratory and Astrophysical Plasmas (Center at U. Wisconsin), and a Center for Liquid Metal Studies of Dynamos (at University of Wisconsin-Madison). Each of these centers is discussed in further detail in the following section.

Proposals submitted by National Laboratories to the National Science Foundation (NSF) are not viewed as competitive because NSF only supports faculty for the summer months they are not paid, while NSF would be required to fully support staff members at National Laboratories that work on NSF research projects. To allow proposals from PPPL to be well received at NSF, the funding provided in this proposal will support PPPL staff's time while working on NSF programs.

15. Signature:

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Contractor Work Proposal Manager

16. Human/Animal Subjects: No

Projects in Conjunction with the National Science Foundation

Several proposals for which PPPL has been included as a co-investigator have been submitted to NSF for consideration. PPPL support for these projects would be provided from the DOE funds requested here.

Physics Frontier Center Proposals

'Interdisciplinary Center for Magnetic Reconnection (Center at U. Maryland)'
PPPL Principal Investigator: M. Yamada

The proposal brings together an internationally recognized, interdisciplinary team of experimental and computational scientists and theorists to address the outstanding physics issues in magnetic reconnection. The recent exciting finding in numerical simulation on the role of Hall effects in driving fast reconnection in collision-free plasmas, the exploration of the structure of the current layer which defines the "dissipation region" in new generation of dedicated laboratory reconnection experiments such as the upgraded MRX, and the development of a new class of advanced computational tools has made the topic ripe for rapid advancement. Issues such the enhanced "anomalous" resistivity, self-generated turbulence and energetic particle production will be addressed in a tight collaboration between theory, computation and experiments. A central goal of the project is to advance physics understanding of magnetic reconnection combining efforts from the state-of-the-art numerical tools such as adaptive techniques to connect local kinetic and global MHD models and the state-of-the-art experimental apparatus with advanced diagnostic tools.

A significant upgrade of the MRX facility is planned to address the science issues for collisionless reconnection of greatest interest in space, astrophysical and laboratory applications. With a larger capacitor bank, the peak electron temperature is expected to reach 30-50 eV, allowing the experiment to access the collisionless regime. The increased temperature will allow the experiment to more deeply access the collisionless regime. The upgrade will increase the size of the vacuum vessel so the separation between the two flux cores can be increased to 1.5 m. This will allow us to study the effects of plasma boundary and to reduce the down-stream plasma pressure, which might have been limiting the outflow speed. The increased outflow velocities could also generate the slow shocks, which are seen in some MHD and kinetic simulations to develop. In this high temperature plasma, the existence of the self-induced out-of-plane magnetic field, which is a signature of dispersive wave, will be experimentally investigated. The measurement of the structure of slow shocks in a laboratory reconnection setting has not previously been successfully achieved. The upgrade of the MRX experiment should sufficiently raise the outflow velocity to force the formation of slow shocks to drive these large velocities. If the slow shocks are seen to develop, the jump conditions across the shock will be tested and compared with the Rankine-Hugoniot conditions.

PPPL Requested Funding from DOE: $830K/year for a five-year period starting 7/01/02

Milestones

Present MRX experimental studies of resistive regime with $T_e < 15$ eV and $S < 1000$	Mar. 2003
Complete design for MRX upgrade	April 2003
Complete MRX upgrade, consisting of an additional 1 MJ capacitor bank and a larger vacuum vessel	Dec. 2003
Complete initial examination of Phase II collisionless reconnection regime with $T_e > 15$ eV and $S > 1000$;	Sept. 2004

'Interdisciplinary Center for Magnetic Self-organization in Laboratory and Astrophysical Plasmas' (Center at U. Wisconsin)
PPPL Principal Investigator: M. Yamada

The proposed Center will advance understanding of a subset of major plasma physics questions critical in the laboratory and cosmos by establishing new connections and collaborations between researchers in the various areas, and by defining specific collaborative problem-oriented tasks. The Center will focus on phenomena associated with magnetic self-organization. In magnetic self-organization a system is driven such that excess free energy excites magnetic instabilities that relax the system by restructuring at the large scale. Magnetic self-organization covers a significant but tractable set of astrophysical phenomena and underlies plasma behavior in the set of laboratory toroidal plasmas in which the confining magnetic field is sufficiently weak that magnetic fluctuations determine macroscopic behavior. The Center will focus on six physics topics, associated with magnetic self-organization, that are of enormous importance to space, astrophysical and lab plasmas: magnetic reconnection, dynamo, angular momentum transport, ion heating, magnetic chaos and transport, and magnetic helicity conservation and transport. These phenomena are often coupled and part of one process of magnetic self-organization, the unifying theme of the Center.

Three core institutions will provide complementary expertise and functions, and will assume dominant responsibility for the success of the center. The University of Chicago provides astrophysical and computational expertise, PPPL mainly provides experiment in local processes of self-organization, and the University of Wisconsin mainly provides experiment in global self-organization. The key activities, applied to each of the six topic areas, are to compare results from different experiments, to perform joint experiments, to apply and evolve theoretical and computational tools developed in one venue to other situations, and to convene topical workshops.

PPPL will study the physics of global reconnection in the controlled merging of two plasma toroids with high electron temperature ($T_e > 30$ eV) in MRX. Magnetic helicity in each initial torus can be varied systematically from co-helicity (same sign of helicity in the two toruses) to counter-helicity (opposite sign of helicity in the two toruses). Conversion from toroidal flux to poloidal flux or vice versa is expected to occur during the merging process as the plasma relaxes. In the case of counter-helicity merging,

substantial amount of toroidal flux is expected to be annihilated to heat ions, which may in turn affect the reconnection process. In addition, kinetic helicity and even cross-helicity may play a role in determining the final global relaxed state.

PPPL Requested Funding from DOE: $430K/year for a five-year period starting 7/01/02

Milestones

Complete design activities to accommodate global merging experiments	Mar. 2003
Complete present MRX experimental research in resistive regime with $T_e < 15$ eV and $S < 1000$	May 2003
Complete installation of merging experiment apparatus	Sept. 2003
Complete experiments for studying the helicity conservation principle	Sept. 2004
Assess the status of reconnection global physics	Sept. 2004

'A Physics Frontier Center for Liquid Metal Studies of Dynamos'
Principal Investigator: H. Ji

This proposed Center is for laboratory experiments using liquid metals to study magnetic field generation. The origin of planetary and stellar magnetic fields is a long standing question in physics; there exists a great amount of theoretical and numerical work addressing the mechanisms for field generation and the effects these fields have on other processes. The proposed Center will provide the first coordinated effort to experimentally search for answers to these questions. The overall scientific goal of the center will be to perform liquid metal experiments and make precision measurements testing theoretical predictions from models used in astrophysics and geophysics.

The major experimental research components of the proposed center are: (1) understanding the origin of magnetic field or self-generation of magnetic fields from laminar and turbulent velocity fields (the dynamo problem); (2) understanding of magnetohydrodynamic (MHD) turbulence in rotating systems driven by thermal convection in planetary dynamos; (3) understanding of magnetic field generation by differential rotation in accretion disks, and (4) the role of magnetic fields on angular momentum transport in astrophysical accretion disks; (5) development of new diagnostics for use in MHD experiments; and (6) validation of numerical MHD models via detailed comparison with experiments and detailed benchmark calculations.

The center will serve four purposes. First, the center will provide a solid framework for collaboration between experimental groups such that ideas and techniques can be shared. Second, the center will foster cross-disciplinary interactions between plasma physics, nonlinear dynamics, astrophysics, and geophysics by convening workshop-style meeting involving all four subfields of physics. Thirdly, the center will provide explicit support for theoretical and numerical studies applied in common to the liquid metal experiments and to naturally occurring systems. Finally, an outreach program is proposed, which will

develop a common public lecture for explaining the background and goals of the present experimental work on liquid metal dynamos to undergraduate and high-school students.

The participating institutions include the University of Wisconsin (Madison), the University of California (Santa Cruz), the University of Maryland, Princeton University (which includes PPPL) and the New Mexico Institute of Mining and Technology (NMIMT). The center has unique facilities for carrying out these challenging experiments, including a new sodium facility at Madison, ongoing convection and mechanical experiments at Maryland, a new Couette flow experiment at NMIMT, and a proposed gallium experiment at PPPL.

Rapid angular momentum transport in accretion disks has been an outstanding problem in astrophysics for more three decades. Classically estimated viscosity of neutral fluid is too small to account for the fast accretion rate accompanied by angular momentum transport. It has been recently recognized that MHD effects play important roles in this process. More specifically, magnetorotational instability (MRI) has been identified as a powerful mechanism to transport angular momentum. Although much theoretical and computational work has been done on this instability, there are no experimental studies on this subject. In the gallium experiment, we propose to demonstrate and study this instability in laboratory for the first time. Theoretical and numerical work indicates that the MRI can be triggered in a small rotating gallium disk with moderate speeds.

At PPPL, the rotating gallium disk experiment serves as a major experimental base to study effects of magnetic field on the flow stability in a geometry similar to accretion disks. The proposed work described in this section of the FWP focuses experiments to be carried by H. Ji, a graduate student, engineers, and technicians, who are not covered by both proposals for NSF.

The proposed research is based on a close collaboration between laboratory experiments and astrophysics led by Prof. J. Goodman in the Astrophysical Sciences Department of Princeton University. A separate proposal, titled “Laboratory Study of Magnetorotational Instability in a Gallium Disk”, has been submitted for NSF to support Professor Goodman and a postdoctoral student. This project is also a major component of a proposed Physics Frontier Center for NSF.

PPPL Requested Funding from DOE: $250K/year for a five-year period starting 8/01/02

Milestones

Establish reference cases using the prototype water experiment for hydrodynamic effects on angular momentum transport.	Dec 02
Optimize and complete detailed design of gallium disk Experiment.	Sep 03
Complete construction of the gallium disk experiment.	Mar 04
Implement diagnostics to detect MRI.	Sep 04

Additional Proposals in Conjunction with the National Science Foundation

PPPL may submit other proposals to NSF for consideration for which PPPL will request DOE support. One possible area of research is modeling and experiments pertaining to solar and magnetospheric plasma phenomena. There is a strong overlap of the plasma physics research conducted at PPPL and solar and magnetospheric physics. Experimental investigations of relevant magneto-hydrodynamic (MHD) phenomena relevant to solar coronal activities in laboratory facilities will continue to make significant contributions to the solar community. Other areas of common interest to the fusion and magnetosphere communities are magneto-hydrodynamic (MHD) waves on transport and its effect on transport and a self-consistent treatment of wave heating and particle acceleration including induced current flows and fluctuations.

3501 NSF COLLABORATIONS 03/01/02			
	FY02	FY03	FY04
		Baseline Incremnt	Baseline Incremnt
STAFFING(FTEs):			
Physicists		.9	.9
Engineers		.3	.3
Administrators			
Graduate Students			
Technicians			
Clerical			
Subcontractors			
TOTAL FTEs		1.2	1.2
OPERATING COSTS $(000):			
PPPL Labor		148.5	148.8
Subcontract Labor			
Overtime			
Travel		9.3	8.8
Energy			
Stockroom			
Miscellaneous Expenses			
Procurements/ICOs			
Organizational Burden		14.0	14.2
Other			
General + Administrative		109.1	109.1
TOTAL OPERATING COSTS		280.9	280.9
TOTAL OPERATING OBLIGATIONS		280.9	280.9
EQUIPMENT COSTS $(000):			
Equipment - Direct			
Equipment - G+A			
Fabricated Equipment			
TOTAL EQUIPMENT COSTS			
TOTAL EQUIPMENT OBLIGATIONS			
GRAND TOTAL COSTS		280.9	280.9
GRAND TOTAL OBLIGATIONS		280.9	280.9

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U.S. DEPARTMENT OF ENERGY

FIELD WORK PROPOSAL

1. CONTRACTOR NO.	2. REVISION. NO.	3. DATE PREPARED
1043	0	3/01/02

4. WORK PROPOSAL TITLE	5. BUDGET AND REPORTING CODE
Plasma Colloquium Travel Grant Program	AT5030500

6. WORK PROPOSAL TERM: Begin: End:

7. CONTRACTOR WORK PROPOSAL MANAGER:
Nathaniel J. Fisch Phone: 609-243-2643 Email: nfisch@pppl.gov

8. HEADQUARTERS ORGANIZATION: Office of Science	11. DOE HQ ORGANIZATION CODE: SC
9. OPERATIONS OFFICE: Chicago Operations Office	12. DOE OPS OFFICE ORGANIZATION CODE: CH
10. CONTRACTOR NAME: Princeton University Princeton Plasma Physics Laboratory	13. CONTRACTOR CODE: 15

14. WORK PROPOSAL DESCRIPTION:

The purpose of the Plasma Colloquium Travel Grant Program is to increase the awareness of plasma research. The new results and techniques of plasma research in fusion plasmas, plasma processing, space plasmas, basic plasma science, etc., have broad applicability throughout science. The benefits of these results are limited by the relatively low awareness and appreciation of plasma research in the larger scientific community. Whereas spontaneous interactions between plasma scientists and other scientists are useful, a focused effort in education and outreach to other scientists is efficient and is needed. The academic scientific community is the focus of this effort, since that permits access to a broad cross-section of scientists and future scientists including undergraduates, graduate students, faculty, and research staff.

This proposal requests funds to continue the Travel Grant Program that was established in 1997. Under the program, distinguished lecturers, who are selected by the Colloquium Travel Committee of the American Physical Society's Division of Plasma Physics, are available for talks at U.S. colleges and universities. The lecturers' travel expenses are supported by this grant. In addition, a small fraction of the funds are used to publicize the program.

14. Signature

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Contractor Work Proposal Manager

15. Human/Animal Subjects: No

1043 PLASMA COLLOQ TRAVEL 03/01/02

	FY02	FY03		FY04	
		Baseline	Incremnt	Baseline	Incremnt
STAFFING(FTEs):					
Physicists					
Engineers					
Administrators					
Graduate Students					
Technicians					
Clerical					
Subcontractors					
TOTAL FTEs					
OPERATING COSTS $(000):					
PPPL Labor					
Subcontract Labor					
Overtime					
Travel		15.4		15.4	
Energy					
Stockroom					
Miscellaneous Expenses					
Procurements/ICOs					
Organizational Burden					
Other					
General + Administrative		4.6		4.6	
TOTAL OPERATING COSTS		20.0		20.0	
TOTAL OPERATING OBLIGATIONS		20.0		20.0	
EQUIPMENT COSTS $(000):					
Equipment - Direct					
Equipment - G+A					
Fabricated Equipment					
TOTAL EQUIPMENT COSTS					
TOTAL EQUIPMENT OBLIGATIONS					
GRAND TOTAL COSTS		20.0		20.0	
GRAND TOTAL OBLIGATIONS		20.0		20.0	

Dir Alloc Ovrlaid/Indr incld

EXHIBIT 1

INDIRECT RATES AND BENEFITS

	FY 2002	FY 2003	FY 2004
PPPL Staff Benefits	29.0%	29.5%	30.0%
Hourly Staff Benefits	10.0%	10.0%	10.0%
Vacation Accrual	0.5%	0.5%	0.5%
Site G&A Rate	60.0%	63.5%	63.5%
MHX G&A Rate	25.0%	36.0%	36.0%
Offsite G&A Rate	30.0%	30.0%	30.0%
Engineering Burden Rates			
Computer Division	10.5%	11.5%	11.5%
Fabrication, Ops & Maintenance	9.0%	11.0%	11.0%
Electrical Division	8.5%	9.5%	9.5%
Mechanical Division	14.5%	14.5%	14.5%
Overtime	9.0%	11.0%	11.0%
Research Department Burden	8.0%	7.0%	7.0%
Health Physics Burden	23.0%	50.0%	50.0%

NOTES

The staffing figures (FTEs) include those Laboratory and subcontract employees (where PPPL management directs the subcontract employee) directly engaged in the tasks described in this proposal. The FTEs associated with both operating, capital equipment and GPP funded tasks are included in the staffing figures. The FTEs for employees engaged in non-OFES funded tasks and indirect activities in support of these tasks are not included. Indirect funded staffing levels are budgeted at 171 FTEs (including 19 graduate student FTEs) in FY 2003 and in FY 2004. Total Laboratory FTEs for FY 2002 and FY 2003, including all direct (including non-OFES directly funded activities) and indirect funded activities, are 442 and 450, respectively. The above staffing figures include approximately 29 FTEs for graduate students supported by PPPL in FY2003 and approximately 30 FTEs for graduate students in FY2004.

The Laboratory's staffing level is forecasted to decline in FY2003 (compared to FY2002) both for direct and indirect funded staff. The lower direct funded staffing level in FY2003 is primarily driven by a lower overall funding level for the Laboratory, as the loss of TFTR D&D funding (due to the project being completed in FY2002) is only partially offset by increases in NCSX and NSTX funding, and smaller increases in a number of the Laboratory's other projects. Overall, the Laboratory's funding from the OFES program is expected to decrease by approximately $5.3 million in FY2003, compared to FY2002. The reduction in indirect funded staff is necessary in order to maintain our indirect liquidating rates at competitive levels, notwithstanding a declining funding base. The Laboratory's direct staffing level is expected to increase slightly in FY2004 due to an increase in NCSX funding; indirect staffing is projected to remain unchanged in FY2004.

It is expected that the Laboratory will be able to decrease currently on board staffing levels to align with the reduced staffing levels projected for FY2003 and FY2004. The required reduction in staff will be accomplished by significantly reducing term appointments coupled with the prudent management of reduction opportunities created by routine attrition and/or retirements. It is expected that a number of skill mix issues may surface, but we believe that these will be manageable without requiring the implementation of an involuntary reduction in force.

Labor rates are escalated at an average rate of 4.1% per year for FY 2003 and FY 2004. This rate is comprised of the projected merit pool increase of 3.9% for all Laboratory staffs, a .5% increase for promotions and special adjustments, reduced by a "breakage factor" of .3%. The "breakage factor" is for salary changes that normally occur throughout the fiscal year, and therefore result in increased labor costs for only a portion of the fiscal year. Escalation rates of 2.0% are assumed for all other expenses for both FY 2003 and FY 2004, unless there exists clear evidence that the effective inflation rate is different than this baseline assumption. The benefits and other indirect rates utilized in this Field Work Proposal are shown in Exhibit 1. All rates shown in Exhibit 1 are provisional; changes to the liquidation base or the indirect expenses may necessitate adjustments to these rates.

PPPL's G&A rate structure for FY 2003 is expected to increase. The site rate is expected to increase by 3.5 percentage points and the MHX rate is expected to increase by 11.0 percentage points. The projected increase in the Laboratory's FY 2003 G&A rates is largely driven by the reduction in the Laboratory's funding levels that is described above, and the corresponding decrease in the G&A liquidation base. The decrease in the G&A liquidation base, coupled with the higher cost of labor and benefit inflation and general inflation, is projected to be only partially offset by lower costs expected to be incurred in support of the Laboratory's Business Systems Upgrade Project and reduced staffing levels in various G&A activities. It is noteworthy that the Laboratory's G&A expense pool, which is labor intensive, is projected to be impacted by labor/benefits inflation of approximately 4.5% in both FY 2003 and FY 2004; the 4.5% rate is the combined impact of salary and benefits inflation (largely medical benefits). We are maintaining our G&A liquidating rates for FY2004 at the same levels as in FY2003, as the increased liquidation from the expected increase in NCSX funding is expected to be offset by inflation (both labor and benefits inflation and general inflation). It is noteworthy that the G&A rates included in this Field Work Proposal are projected to over-liquidate by approximately $.7 million and $1.0 million in FY2003 and FY2004 respectively. Nevertheless, due to the number of planning uncertainties, including the possibility of lower than anticipated funding in the Laboratory's science programs and the potential for a significant shortfall in funding for the Safeguards and Security program, we believe that maintaining these levels of "contingency" are prudent at this point in our planning process.

Liquidation from our incremental funding requests is not included in the calculation of our indirect rates. Therefore, any incremental funding received will have the impact of reducing the indirect rates utilized in the FWP submission.

The Congressional Budget Guidance for FY2003 does not fund Waste Management (ER/WM) activities as a separate program; instead, it distributes Waste Management funding as part of several of our project B&R lines. At this point in the planning process, we have not precisely sorted out how to allocate the cost of ER/WM activities to the various B&R lines, which contain the ER/WM funding; therefore, our project budgets do not include ER/WM costs. We have, as an alternative, developed a separate Field Work Proposal for our Waste management activities, geared to the $2.7 million of funding guidance. We have also included an ER/WM line for each program B&R line that included ER/WM funding in the B&R Line Summary Table located in the back of our FWP book; the ER/WM funding included in this table totals to $2.7 million, and resulted from "ratioing" the original number OFES had in the Congressional budget for ER/WM activities to the $2.7 million agreed to as final guidance. We will work with our DOE colleagues during the next several months to develop a methodology for allocating the cost of our ER/WM activities to the various B&R lines, which carry the ER/WM funding.

Some tasks which do not continue into FY2003/2004 are not addressed in this proposal; however, the budget for these tasks are included in the Laboratory budget summaries for FY2002/2003.

Princeton Plasma Physics Laboratory
FY 2004 Budget Request
Fusion Energy Sciences

(dollars in thousands)	FY 2002	FY 2003	FY 2003		FY 2004	
	March AFP	Cong. Budget	Baseline	Increment	Baseline	Increment
NSTX	21,845	27,131	26,461	1,400	26,461	3,640
Advanced Projects						
National Compact Stellarator Exp. (NCSX	2,720	10,239	9,542	3,800	13,800	300
Quasi-Poloidal Stellarator (QPS)	99	246	246	60	1,025	40
Next Step Options	707	814	814	1,500	814	4,200
ARIES - MFE	117	104	104	-	155	-
ARIES - IFE	49	103	103	-	52	-
Socioeconomic Energy Studies	84	99	99	60	99	60
APEX	152	141	141	30	141	30
Subtotal	3,928	11,746	11,049	5,450	16,086	4,630
Collaborations - US						
DIII-D	3,796	4,016	4,016	404	4,016	431
Alcator C-Mod	1,826	2,152	2,152	-	2,152	-
Alcator C-Mod Lower Hybrid	495	500	600	631	600	552
International Collaborations	2,874	2,953	2,953	1,155	2,953	1,111
Subtotal	8,991	9,621	9,721	2,190	9,721	2,094
Theory						
Tokamak Theory	2,229	2,289	2,318	350	2,318	400
Alternate Theory	1,520	1,186	1,550	700	1,550	750
FRC Theory	178	41	195	-	195	-
Computational Physics	355	364	364	-	364	-
SciDAC - Wave Plasma Int	203	182	239	-	182	-
Advanced Scientific Computing	1,260	1,181	1,300	-	1,300	-
Modeling Center for Extended MHD Code	89	89	89	-	89	-
Global Simulation of Microturbulence	129	79	79	-	79	-
National Transport Code	-	-	-	200	-	200
Transport Task Force	20	20	20	-	20	-
Subtotal	5,983	5,431	6,154	1,250	6,097	1,350

Princeton Plasma Physics Laboratory
FY 2004 Budget Request
Fusion Energy Sciences

(dollars in thousands)	FY 2002	FY 2003	FY 2003		FY 2004	
	March AFP	Cong. Budget	Baseline	Increment	Baseline	Increment
Plasma Science & Technology						
Offsite University Research Support	750	848	848	300	848	300
CDX-U	749	708	708	-	708	-
Lithium Tokamak Experiment	-	-	-	650	-	550
Heavy Ion Fusion/Beam Propagation in H	1,149	1,093	1,093	1,377	1,093	2,077
MRX	575	591	591	600	591	600
MNX	188	197	197	-	197	-
Hall Plasma Thrusters	208	212	212	-	212	60
Stellar Flare Plasma Diagnostic	84	89	89	-	89	100
FRC Rotating Magnetic Field	109	157	157	542	157	542
Paul Trap Experiment	307	315	315	-	315	100
Turbulence in Liquid Metals	129	133	133	-	133	180
Subtotal	4,248	4,343	4,343	3,469	4,343	4,509
Diagnostics						
EBW Diagnostic	75	108	160	-	160	-
3-D Imaging Diagnostic	80	108	120		120	
X-Ray Imaging Crystal Spectrometer	-	-	195	-	215	-
Subtotal	155	216	475	-	495	-
TFTR						
D-Site Caretaking Operations	3,202	-	500	-	500	-
Decontamination & Decommissioning	15,452	-	-	-	-	-
Subtotal	18,654	-	500	-	500	-
Science Education	600	592	592	150	592	150
Environmental Restoration/Waste Manageme	3,150	3,103	2,700	-	2,700	-
GPP	1,370	995	1,200	200	1,200	200
NSF Collaborations	-	298	281	-	281	-
Plasma Colloquim Travel	-	20	20	-	20	-
Snowmass	299	-	-	-	-	-
Laboratory Support Equipment	115	80	80	-	80	-
Total Fusion Energy Sciences	**69,338**	**63,576**	**63,576**	**14,109**	**68,576**	**16,573**

Princeton Plasma Physics Laboratory
FY 2004 Budget Request by Budget and Reporting Code - Fusion Energy Sciences

(dollars in thousands)			FY 2002	FY 2003	FY 2003		FY 2004	
			March AFP	Cong. Budg.	Baseline	Increment	Baseline	Increment
AT5010200	OPE	Doublet III-D	2,009	3,220	2,560	-	2,645	-
	EQU	Doublet III-D	380	-	818	404	-	-
	OPE	Waste Management	-	225	139	-	147	-
AT5010300	OPE	Alcator C-Modification	1,517	1,660	1,823	-	1,931	-
	EQU	Alcator C-Modification	160	-	108	-	-	-
	OPE	Waste Management	-	128	104	-	103	-
AT5010701	OPE	International	2,624	2,953	2,723	192	2,542	194
	EQU	International	250	-	230	963	411	917
	OPE	Waste Management	-	192	155	-	143	-
AT5010702	OPE	Other - Science Education	600	592	592	150	592	150
	OPE	Waste Management	-	38	34	-	33	-
AT5010802	OPE	Electron Berstein Waves Diagnostic	75	108	160	-	160	-
	OPE	3-D Imaging Diagnostic	80	108	120	-	120	-
	OPE	X-ray Imaging Crystal Spectrometer	-	-	195	-	215	-
	OPE	Waste Management	-	14	27	-	27	-
AT5015010	OPE	NSTX	7,586	7,691	8,939	256	9,009	267
	EQU	NSTX	760	1,114	929	-	829	499
	OPE	Waste Management	-	474	510	-	508	-
AT5015020	OPE	Experimental Plasma Res - NCSX	2,720	394	751	280	769	300
	OPE	Experimental Plasma Res - QPS	99	246	246	60	84	40
	EQU	Experimental Plasma Res - QPS	-	-	-		941	-
	OPE	Exp Plasma Res - Offsite Univ Research	750	848	848	300	848	300
	OPE	Exp Plasma Res - FRC Rot Mag. Field	109	157	157	542	157	542
	OPE	Exp Plasma Res - FRC Theory	178	41	195	-	195	-
	OPE	NSF Collaborations	-	298	281	-	281	-
	OPE	Waste Management	-	125	145	-	147	-
AT5015033	OPE	Heavy Ion Fusion	1,099	994	1,093	377	1,093	377
	EQU	Heavy Ion Fusion	-	99	-	-	-	-
	OPE	Waste Management	-	62	62	-	62	-

Princeton Plasma Physics Laboratory
FY 2004 Budget Request by Budget and Reporting Code - Fusion Energy Sciences

(dollars in thousands)			FY 2002	FY 2003	FY 2003		FY 2004	
			March AFP	Cong. Budg.	Baseline	Increment	Baseline	Increment
AT502010	OPE	Tokamak Theory	2,229	2,289	2,318	350	2,318	400
	OPE	Advanced Scientific Computing	1,260	1,181	1,300	-	1,300	-
	OPE	Computational Physics	355	364	364	-	364	-
	OPE	Transport Task Force	20	20	20	-	20	-
	OPE	National Transport Code	-	-	-	200	-	200
	OPE	Waste Management	-	246	228	-	225	-
AT502020	OPE	Alternative Concept Theory	1,520	1,186	1,550	700	1,550	750
	OPE	Waste Management	-	99	88	-	87	-
AT502040	OPE	Wave Plasma Interactions (Sci DAC)	203	182	239	-	182	-
	OPE	Global Simulation of Microturbulence	79	79	79	-	79	-
	OPE	Magnetohydrodynamic Code Development	89	89	89	-	89	-
	OPE	Presidential Young Investigator Award	50	-	-	-	-	-
	OPE	Waste Management	-	13	23	-	20	-
AT503050	OPE	Other - MRX	575	591	591	547	591	559
	EQU	Other - MRX	-	-	-	53	-	41
	OPE	Other - MNX	188	197	197	-	197	-
	OPE	Other - Paul Trap Experiment	147	315	315	-	315	100
	EQU	Other - Paul Trap Experiment	160	-	-	-	-	-
	OPE	Other - Hall Plasma Thrusters	208	212	212	-	212	60
	OPE	Other - Turbulence in Liquid Metals	129	133	133	-	133	180
	OPE	Other - Stellar Flare Plasma Diagnostic	84	89	89	-	89	100
	OPE	Plasma Colloquim Travel Grant Program	-	20	20	-	20	-
	OPE	Waste Management	-	81	89	-	88	-
AT50 Subtotal - Science			28,292	29,167	31,888	5,374	31,871	5,976
AT5501	OPE	D-Site Caretaking Operations	3,202	-	500	-	500	-
	OPE	TFTR D&D	15,452	-	-	-	-	-
	OPE	Waste Management	-	-	28	-	28	-

Princeton Plasma Physics Laboratory
FY 2004 Budget Request by Budget and Reporting Code - Fusion Energy Sciences

(dollars in thousands)			FY 2002 March AFP	FY 2003 Cong. Budg.	FY 2003 Baseline	FY 2003 Increment	FY 2004 Baseline	FY 2004 Increment
AT5502	OPE	Doublet III-D	1,267	796	638	-	751	-
	EQU	Doublet III-D	140	-	-	-	620	431
	OPE	Waste Management	-	149	36	-	40	-
AT5503	OPE	Alcator C-Modification	149	492	221	-	221	-
	EQU 01CH	Alcator C-Mod Lower Hybrid System (MIE)	495	500	600	631	600	552
	OPE	Waste Management	-	10	13	-	13	-
AT5505	OPE	NSTX	12,624	18,326	15,945	820	16,376	1,184
	EQU	NSTX	875	-	648	324	247	1,690
	EQU 91HH	NSTX Neutral Beam	-	-	-	-	-	-
	OPE	Waste Management	-	1,120	907	-	920	-
AT5506	EQU	NCSX Equipment (MIE)	-	9,845	8,791	3,520	13,031	-
AT5508	OPE	Other - Env. Restoration/Waste Mgt.	3,150	-	-	-	-	-
	EQU	Other - Laboratory Support Equipment	115	80	80	-	80	-
	GPP	Other - General Plant Projects	1,370	995	1,200	200	1,200	200
AT55 Subtotal - Facility Operations			38,839	32,313	29,607	5,495	34,627	4,057
AT6010301	OPE	Plasma Technologies - CDX-U	749	708	708	-	708	-
	OPE	Lithium Tokamak Experiment	-	-	-	650	-	550
	OPE	Waste Management	-	51	40	-	39	-
AT6010401	OPE	Fusion Technologies - APEX/Jupiter II	152	141	141	30	141	30
	OPE	Waste Management	-	12	8	-	8	-
AT6010501	OPE	Advanced Design - Next Step Options	707	814	814	1,500	814	4,200
	OPE	Advanced Design - ARIES MFE	117	207	104	-	155	-
	OPE	Adv Design - Socioeconomic Studies	84	99	99	60	99	60
	OPE	Snowmass	299	-	-	-	-	-
	OPE	Waste Management	-	64	64	-	62	-
AT6010502	OPE	ARIES-IFE Beam Transport & Focusing Studies	99	-	103	200	52	200
	OPE	Heavy Ion Fusion - NTX & IBX	-	-	-	800	-	850
	EQU	Heavy Ion Fusion - NTX & IBX	-	-	-	-	-	650
AT60 Subtotal - Enabling Research & Development			2,207	2,096	2,081	3,240	2,078	6,540
Total AT			**69,338**	**63,576**	**63,576**	**14,109**	**68,576**	**16,573**

* The FY 2002 budget for obligations shown on the detailed budget pages in this proposal include both current and prior year obligations. This summary only includes current year obligations.