Mission, Experimental Plan, and Preparations

1 INTRODUCTION AND PURPOSE

This document describes the Mission and Experimental Research Plan for the National Compact Stellarator Experiment (NCSX) Project, being designed and constructed at the Princeton Plasma Physics Laboratory (PPPL) of the Department of Energy. The Mission is discussed in Section 2 as a set of research goals. The Experimental Research Plan is described, in Section 3, to accomplish the mission in a phased approach, allowing a flexible investigation of the issues and building upon other research developments occurring in parallel. The diagnostics required to carry out the research plan are also discussed. It is expected that the details of the Experimental Research Plan will evolve as the construction and research proceeds. Section 4 presents the plan for preparing for NCSX research.

2 NCSX MISSION

The mission of NCSX is to acquire the physics knowledge needed to evaluate the compact stellarator as a fusion concept, and to advance the understanding of 3D plasma physics for fusion and basic science.

NCSX research will investigate the effects of three-dimensional plasma shaping, of internally- and externally-generated sources of rotational transform, and of quasi-axisymmetry on the stability and confinement of toroidal plasmas. In particular, NCSX will seek to answer the following questions:

- What are the beta limits and limiting mechanisms in a low aspect-ratio stellarator? Can pulse-length-limiting instabilities, such as external kinks and neoclassical tearing modes, be stabilized by external transform and 3D shaping for $\beta \sim 4\%$? Is high-b compatible with equilibrated profiles?
- How do externally-generated transform and 3D shaping affect disruptions and their occurrence?
- Can the collisionless orbit losses typically associated with 3D fields be reduced by designing the magnetic field to be quasi-axisymmetric? Is flow damping reduced? Is the resulting transport and confinement similar to actually axisymmetric systems? How does the transport scale in a compact stellarator?
- Do anomalous transport control and reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? Do zonal flows saturate turbulent transport in a quasi-axisymmetric stellarator at levels similar to tokamaks?
- Are equilibrium islands and neoclassical tearing-modes reduced or eliminated by choice of shear?
- How do stellarator edge-field characteristics such as islands and stochasticity affect the boundary plasma and plasma-material interactions? Are 3D methods for controlling particle and power exhaust compatible with good core confinement.
- How do the Alfvenic-eigenmode spectrum and stability of a quasi-axisymmetric stellarator differ from those of a tokamak or a non-symmetric stellarator?

It is appropriate and necessary for a Proof-of-Principle class experiment to investigate a broad range of issues. These issues are listed above in approximate priority order. However, they are strongly interconnected and mutually supporting. As an example, transport control and enhanced confinement may be required to access the beta-limits. Control of the plasma boundary, edge neutral and impurity influx is often instrumental in achieving enhanced confinement.

NCSX will acquire and contribute a data base for accomplishing the Fusion Energy Sciences Advisory Committee milestone of 1999: “Determine attractiveness of a Compact Stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation." This database will provide the basis for designing follow-on experiments, and for evaluating the compact stellarator as a fusion energy concept.

3 EXPERIMENT STRATEGY AND PLAN

NCSX research will pursue the mission in a series of phases, corresponding to the increasing capability of the facility. The planned phases are:

I. Initial Operation – initial plasma operation and system shakedown

II. Field-line Mapping – validation of the coil manufacture and assembly

III. Ohmic – operation with inductive current and ohmic heating only

IV. Auxiliary Heating – operation with 3MW of NBI, installation of PFC liner.

V. Confinement and Beta Push – operation with ~ 6MW of auxiliary heating, 2nd generation PFCs

VI. Long Pulse – plasma and heating pulse lengths of at least 1.1 sec, pumped divertor. Possible further upgrade of heating power.

The phases are separated by upgrades to the facility to add heating and diagnostic systems, and to install internal plasma-facing components (PFCs), almost certainly requiring a venting of the vacuum chamber. Phases IV, V, and VI may contain multiple experimental campaigns spanning several years and may include additional iterative improvement of diagnostics and plasma-facing components, based upon research results.

The envisioned experimental activities for each phase are summarized in following tables, along with the required diagnostic measurements. The experimental activities are color coded by general research area: stability, transport, flux-surface integrity, edge and power and particle handling. The highest priority activities are those needed for subsequent phases and are indicated in *italic.* Activities started in a specified phase will likely continue into later phases. The diagnostic plan is further discussed in the Engineering Design Document, WBS 3.

3.I INITIAL OPERATION

Short Ohmic pulses will be used to achieve the first-plasma milestone and carry out a brief campaign intended to test the ability to initiate the plasma and checkout the operation of the initial diagnostics.

Experimental Activity	***Required measurements***
Initiate plasma; exercise coil set	Plasma current
Ip > 25 kA	Magnetic diagnostic set: position, loop voltage, stored energy
Checkout magnetic and vacuum diagnostics	Plasma/wall imaging
Initial wall conditioning	Line-integrated density

3.II FIELD-LINE MAPPING

This campaign will test the accuracy of the stellarator magnetic field generation by measuring the magnetic surface shapes in vacuum.

Experimental Activity	***Required measurements***
Map flux surface (cold & room temperature	Electron-beam mapping apparatus
Verify iota and quasi-axisymmetry, to degree possible	Variable energy electron-beam
Verify coil-flexibility characteristics	

3.III OHMIC

This phase will establish good control of the magnetic configuration as well as good vacuum and wall conditions. Physics results on global confinement scaling, density limits, vertical stability, effects of low-order rational surfaces on stability and disruptions, and plasma-wall interactions, all at low beta and temperature, will be produced.

Experimental Activity	***Required measurements***
Plasma control, plasma evolution control	Electron density & temperature profiles
Global confinement & scaling; 3D shaping	Radiated power profiles
Density limit and mechanisms	Magnetic axis position
Characterize Te and ne profiles & variations	Low (m,n) MHD
Vertical stability	Flux-surface topology
Current-driven kink stability	Impurity sources & concentration
Effect of low-order rational surfaces on flux-surface topology	Zeff
Initial study of trim coils	Hydrogen recycling
Effect of contact location on plasma edge, recycling	
Attempt to control contact location	

3.IV AUXILIARY HEATING

This campaign will explore the flexibility, plasma confinement, and stability of NCSX, starting at the initial heating power (3 MW from two neutral beams), magnetic field (at least 1.2 T) and pulse length (at least 0.3 s). The ability to control the discharge evolution to produce current profiles approximating the bootstrap profile will be tested. Physics results on the adequacy of neoclassical transport optimization, density limits, confinement scaling, and enhanced confinement regimes will be produced. Stability of moderate-β plasmas and conditions for avoiding density-limit disruptions will be investigated. Boundary plasma conditions and plasma-wall interactions will be studied. Studies attempting control of neutral influx through boundary modifications and wall coatings will be started. This campaign will develop a database for deciding on the amount and type of any plasma heating upgrades that might be needed and for next steps in the implementation of plasma-facing components. In addition, this campaign will commission a series of new diagnostics systems.

Experimental Activity	***Required measurements***
Plasma control with NB heating and CD	Ion temperature profile
Test of kink & ballooning stability at moderate β	Toroidal and poloidal rotation profiles
Effect of shaping on MHD stability	Iota profile
Initial study of Alfvenic modes with NB ions	Radial electric field profile
Confinement scaling	Fast ion loss
Local transport & perturbative transport measurements	Ion energy distribution
Effect of quasi-symmetry on transport	First wall surface temperature
Density limits and control with auxiliary heating	High frequency MHD (< 5 MHz)
Use of trim coils to minimize rotation damping	SOL temperature and density
Blip meas. of fast-ion confinement and slowing down	Neutral pressure
Initial attempts to access enhanced confinement	
Pressure effects on surface quality	
Controlled study of neoclassical tearing using trim coils	
Wall coatings with auxiliary heating	
Edge plasma and exhaust characterization	
Attempts to control recycling neutral influx	
Wall biasing effects on confinement	
Low power RF loading and coupling studies (possible)	

1.V CONFINEMENT AND HIGH BETA

This phase will attempt to extend enhanced confinement regimes and investigate high-beta stability issues with a full neutral-beam complement (6 MW from four beams) and/or megawatt-level radio--frequency heating. Enhanced confinement will be pursued using the techniques developed on other experiments, including sheared rotation from NBI, reduced recycling by wall coating (B, Li) and conditioning, edge radiation (RI-mode), and by pellet fueling. The dimensional and non-dimensional scaling of confinement will be determined and compared to other configurations. These plasmas will then be used to test directly the predicted beta-limit and study the predicted beta-limiting mechanisms. The configuration requirements to avoid disruptions and the disruption-free operating area at high beta will be documented. The edge design will be iterated, including installation of divertor baffles, to optimize power and particle exhaust and neutral influx.

Experimental Activity	***Required measurements***
Stability tests at β >~ 4%	Core fluctuations & turbulence
Detailed study of β limit scaling	Core He density
Detailed study of β limit mechanisms	Edge/div. Radiated power profiles
Disruption-free operating region at high- β	Divertor recycling
Active mapping of Alfvenic mode stability (w/ antenna)	Edge temperature & density profiles
Enhanced confinement: H-mode, RI mode, pellets, hot-ion regimes	Divertor target temperature
Scaling of local transport and confinement	Divertor target Te, ne
Turbulence studies	Divertor impurity concentration
Scaling of power or other thresholds for enhanced conf.	
ICRF heating efficiency (possible)	
Perturbative ICRF meas. of transport (possible)	
Divertor operation optimized for power handling and neutral control	
Trace He exhaust and confinement	
Scaling of power to divertor	
Control of high- β plasmas and their evolution	

1.VI LONG PULSE

This phase will be preceded by an upgrade to the heating systems (to allow pulse lengths of ~1 sec, and power of as much as 12 MW) and a possible upgrade of the plasma-facing components for improved power and particle exhaust handling for long pulse. These upgrades will allow equilibration of the current profile to the bootstrap current, and will be used to document the high-beta disruption-free operating area in long-pulse operation (compared to the current-profile relaxation time).

Experimental Activity	***Required measurements***
Long-pulse evolution control	More detailed divertor profiles
Equilibration of current profile	
Beta-limits with ~equilibrated profiles	
Edge studies (3rd generation PFCs & divertor)	
Long-pulse power and particle exhaust, w/ divertor pumping	
Compatibility of high-β, high confinement, and divertor operation	

2 PREPARATION FOR PHYSICS EXPERIMENTS

During the period (FY2003-07), during the NCSX fabrication project, a parallel research preparation activity will be carried out so that NCSX research will be able to proceed as effectively as possible after First Plasma (March, 2007). This is very similar to the approach followed on NSTX. The goals of NCSX research preparations are to prepare analytical and hardware tools that will be needed after first plasma, and to build the NCSX research team.

The NCSX research preparation effort will focus on four areas: plasma control, boundary control, diagnostics, and radio-frequency heating. In FY2003-2005, while operation is still a few years away, the emphasis will be on preparation of physics analysis tools and applying them to the physics design of hardware upgrades. Starting in FY-2006, the effort will expand to begin the engineering and fabrication of long-lead hardware upgrades. These include diagnostics needed for the Ohmic phase (Phase III) which will begin 6-8 months after First Plasma, and additional diagnostics, plasma-facing components, and trim coils needed for the initial auxiliary heating phase (Phase IV), which will begin 14-16 months after First Plasma. The specific research preparation tasks are described in the document "**NCSX Research Preparation Costs**."

The NCSX research group will be a national collaborative team from many institutions, similar to NSTX. This will include the development and operation of the various diagnostic systems as well and the organization and execution of experiments and research campaigns. Starting in 2005, a series of Research Forums will be held to build interest in NCSX research, nucleate the research team, develop research plans and identify areas of common interest, and identify groups interested in participating in diagnostic development. This process will be similar to the Research Forum series established by NSTX for similar purposes.

Before NCSX research begins, collaborative research projects will be established with existing U.S. and International stellarators to investigate topics of mutual interest, to debug analysis techniques, and to give stellarator experience to team members used to axisymmetric configurations. Some of these collaborations have already begun on Wendelstein 7-AS, LHD, and with the German and Japanese theory and modeling groups.

3 SUMMARY

NCSX's mission is to acquire the key physics knowledge needed to assess the compact stellarator concept and its resistance to disruptions at high beta without the need for instability feedback control or significant current drive. NCSX offers novel tools for exploring the effects of 3D shaping and mixed internal vs. external sources of rotational transform on plasma stability, transport, and edge solution. An exciting and thorough research program has been developed to exploit these tools over the course of several operating years, with facility upgrades. Diagnostic measurement needs have been identified to carry out the program. A research preparation program has been planned to develop the analysis tools and upgrade designs, and to assemble the collaborative research team needed to effectively and efficiently begin NCSX research after First Plasma is attained.