Seventh Report of the National Compact Stellarator Experiment
Program Advisory Committee
July 13-14, 2004

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The National Compact Stellarator Experiment (NCSX) Program Advisory Committee (PAC) met on July 13-14, 2004 to advise the Director of the Princeton Plasma Physics Laboratory, Robert Goldston, on two items: the planned research preparation activities in FY05 through FY08, and the planned goals and capabilities for research campaigns in FY08 through FY10. After an introduction and overall update of the project by Hutch Neilson, Mike Zarnstorff presented the proposed Research Plans. This was followed by detailed presentations on the specific preparations for magnetic diagnostics and equilibrium reconstruction, electron-beam mapping of magnetic structure, general diagnostics preparation, and edge physics studies. The formal presentations concluded with an update on the ARIES-CS study.

This report is structured in two main sections: 1) our response to the overall status of the project and main research goals, plans, and capabilities, and, 2) response to the detailed areas of preparation presented at the meeting and mentioned above.

Overall Status of the Program and Research Plans

Findings:

The committee is pleased with the progress that the Project has made since the last PAC meeting. The NCSX team has been very responsive to comments and recommendations made by PAC-6 and other reviews since that time. Examples are the development of winding and potting techniques, the decision to make the vacuum vessel bakeable to 350C (which the committee views as a significant design improvement), and increased number of diagnostic ports and in-vessel space for divertor and scrape-off layer flexibility.

NCSX has over-arching goals of finding conditions for high–beta, disruption free operation, and finding conditions for good stellarator confinement in conditions that can be extrapolated to reliable steady-state operation. Achieving the goals that NCSX has delineated will make important contributions to answering questions being formulated by the FESAC Priorities Planning efforts.

Specifically, the high priority goals outlined for NCSX include:

- Dependence of confinement on the effective ripple
- Demonstrate that quasi-axisymmetry can be achieved
- Potential for confinement improvement by toroidal currents and the benefit of current-generated rotational transform.
- Investigate the mitigation of current driven instabilities due to external transform.
- Determine the nature of the limiting beta in stellarators to both pressure-driven and current-driven modes.
- Characterize edge configuration and explore potential divertor solutions.

We agree to the phased approach defined by important technical milestones corresponding to these broad goals. A primary finding of the committee is, however, that these broad goals need to be broken down to specific experimental plans. The present planning is at too high a level to provide focus for research forums or help set program priorities. This topic is discussed further in the comments and recommendations sections below.

The presentations at the meeting did not address the theory and computational recommendations raised in PAC-6. The effectiveness of the research preparations for NCSX and the capabilities during operations depends on a more extensive theoretical and computational activity than was apparent from the presentations. An integrated theory and computational effort proportional to the scale of the planned experimental program is critical to the preparations for each of the main research areas. These efforts would greatly increase the quality of the information and potential for success for NCSX for the decisions that are needed in the 2012 timeframe. Among the research areas that require extensive theoretical and computational attention are the underlying turbulence and transport in a 3-D configuration, MHD equilibrium and stability, wave particle interactions, edge/scrap-off layer physics, and required diagnostic design. The project execution and planning would clearly benefit from increased support from the theory program.

Comments:

The research program would benefit from a distilled and concise list of research milestones for each phase of the program. Having a long and detailed list of physics goals and opportunities is important, but is not sufficient for prioritization purposes and focusing the research program. As an example, on NSTX, there are 3-5 physics milestones to be met per year spread across various topical groups. These goals are clearly delineated to the research team at the beginning of each run period, and leaders of each task group have a responsibility to try to achieve them. Proper formulation of these goals forces the research team to think about its present capabilities and what resources and upgrades may be needed. For NCSX, stating such goals clearly for the various research phases will be beneficial to potential participants in the program and help guide the planned research forums. Experiments planned for Phases 3 & 4 should show clear links or paths to the broader stated NCSX-specific goals to ensure that demonstrable progress is made on the stated desired 2012 time frame in the OFES Strategic Plan.

While the initial experiments on NCSX won't begin for another four years and the real experimental program won't begin until a year after that, it is understandable that a detailed program plan is still in development. However, effort is needed before the first Research Forum to flesh out the program in more detail so potential collaborators can understand how they can best contribute to the research program and help guide diagnostic timelines. The target audience includes U.S. experimentalists, theorists, and foreign stellarator experimental programs that have experience (and perhaps equipment and personnel) to contribute.

The committee concurs that a research forum in early 2005 would be helpful to the project, but only if the detailed planning is accomplished prior to the meeting. The project should consider whether they would like advice from the PAC prior to the announcement/scheduling of that event, and what format/structure would be needed for the desired input.

The mechanism proposed for assembling the national collaborative team is similar to that used for NSTX. Experience at PPPL in this regard will help in the effective formulation of this team, drawing upon both the successes and shortcomings from the NSTX activities. The project management should encourage key personnel from participating institutions to be brought into the project early. This should begin at (or before) the first research forum. Also, national collaborative team assembly in NSTX funded many early collaborators at 1/3-2/3 of requested (needed) levels; this process insured broad collaborator participation, but at below needed levels. This resulted in underutilized capabilities (e.g. diagnostics available only for a small number of experiments). Project management should consider critical project needs to insure full coverage of critical areas. How will research areas to be done by host institutions and ones to be done by collaborators be decided? That process should be determined prior to the research forums.

Single neutral beam operation in Phase 3 presents challenges to NCSX. While W7-AS was able to obtain significant results, they utilized ECRH for plasma start-up, in contrast to the OH requirements for NCSX. NCSX will have additional difficulties in bringing up the machine in single NBI operation. The 1.5MW phase of operation has potential competing risks of (1) unstable iota profiles (co-injection) and (2) enhanced fast ion loss (counter-injection). If there are any delays between commissioning the first and second beams, the program may only have one beam for some time. More thought needs to be given to potential accomplishments during this initial brief phase in planning for the research forum. Potential topics include exploration of conditions for disruption immunity, plasma flow and fluctuation levels, and possible benefits of low effective ripple on global energy confinement. Some of these topics are included in the general goals listed by the project of this phase. The committee agrees that the primary mission of this phase is to show that NCSX has operational capability and can accomplish its mission.

The project realizes that careful priority setting is required to effectively utilize the available funds in the research preparation category, especially in the FY05-06 periods. These funds cover the long-lead diagnostics and facility upgrade preparations, program planning, and the initial research team formation steps. The committee agrees that the level presented is highly constraining. The highest priority should be given to more detailed specific development of the program, from which priorities and timelines on the other elements can be determined. Wherever possible, the project should endeavor to resource level the research preparation budget to increase funds in the critical earlier planning stage. This ability may be limited given the construction funding requirements and the given baseline funding of the project. The committee recommends that the project team investigate ways to pull others into the planning process to help define its goals and specific experimental campaigns without any significant cost increases.

The project reported an annual operating budget for the 'matured' NCSX of $28.2M, split roughly evenly between science and facilities costs. This budget was derived based upon experience from NSTX and factoring in efficiencies from joint operations of the two devices. NCSX will be at least as complicated as NSTX to operate and, factoring in the cryogen costs and additional computation/modeling for control and interpretation of results, should have a stand-alone budget on the order of NSTX. The project should consider the impact on physics goals, program schedule, and capabilities of failing to achieve their projected levels of efficiencies in operation of the two devices.

In the present NCSX research schedule, the first 100 magnetic sensors and the first subset of PFC's are supposed to be installed during a period of just 3 months between the 2nd and 3rd research phases. The installation of the internal magnetic diagnostics and PFC's in CMOD took 2 years of full-time work, much of it actually spent inside the vacuum vessel. The same job in NCSX appears much more complicated, and there is concern the allotted time, from the schedule presented, may be insufficient. The committee understands that the NCSX Team has already recognized this issue, and we encourage them to allot as much time as possible for this installation. Additionally, the engineering team should examine mechanisms and potential impacts of direct PFC attachments to the VVSA.

Coil winding tests are well underway and will be extended with the delivery of the prototype coil winding forms and "twisted racetrack" form in the near future. The team is building experience and well aware of potential issues. The committee advises that the winding team consider using non-metallic clamps and screw jacks to minimize the release of metallic chips that could present problems in the finished coil. The flexible rope material generally does not require as much clamping force as a more conventional conductor.

Recommendations:

Develop a concise list of specific research milestones and experimental activities for each phase of the program. This will aid planning for diagnostics/upgrades, provide focus for the upcoming research forums, and help the project set priorities.

Secure adequate theoretical and computational support in the near term for developing the specific NCSX experimental plans and activities. Consider methods to provide DoE guidance on theory and modeling needs of the NCSX Project.

Estimate the human and computational resources needed during the period up to 2012 for the cost effective utilization of the NCSX facility with respect to needs for theory and modeling, and computer support plans for analysis (not just DAQ/control).

Ensure research preparation needs are adequately covered by the proposed budget profile. Examine ways to move funds earlier (if needed and/or possible) within DoE approved overall profile; any options considered should **not** impact the machine construction schedule. How could collaborations help in defining research preparation? Determine possible contingencies in operating plan/program if joint machine operation savings fall short of projections.

Examine the timetable and milestones for PFC design and implementation with respect to the overall experimental program.

Committee Response to Detailed Preparations

The committee's findings, comments, and recommendations on magnetic diagnostics, electron-beam mapping, general diagnostics preparations and edge – modeling are presented below for each topical area, respectively.

Magnetic Diagnostics and V3FIT

Findings:

Equilibrium reconstruction is key to the success of NCSX operation & achievement of its physics goals. Significant progress has been made in understanding methods to accomplish this task and progressing toward defining measurement needs. The project is commended for its progress in this area and for recognizing the importance of this need and aggressively pursuing its resolution.

The project has developed a strategy to set up a database of calculated VMEC equilibria and to use mathematical tools to select the appropriate number and location of magnetic sensors. Methodologies will be checked through application to signals from existing devices and intense investigation on the CTH device scheduled to become operational later this year.

Comments:

Large-scale computational efforts are needed to generate the required database. The team should perform simulations that show the sensitivity of the magnetic signals against variations in the current and pressure profiles. Integrated analysis by combining magnetic and available kinetic data is an important task and serves to constrain the potential equilibrium solutions from the magnetic data alone. Error propagation and consistency checks should be possible using Bayesian probability approaches. Specifically, it is important to understand the accuracy of the reconstruction and how this can be assessed.

Under the present approach, it was made clear that more computer resources need to be devoted to accomplish the goals within a reasonable amount of time. The issue of the size of the database required should be re-examined to ensure this level of computation is necessary for NCSX diagnostic design. If so, then additional resources should be pursued and brought to bear on the problem.

Flux loops embedded in the coil structure are a central element to the reconstruction. Model loops should be included in the reduced-scale coil winding test, specifically to find out if their design presents any unanticipated problems. (For example: mechanical and electrical survival during the winding and potting procedures, fragility of leads, cryogenic issues, etc.)

For the plasma current measurement, it was not clear if the primary rogowski would measure plasma current only, or a combination of plasma and vessel currents. High temperature flux loops and B-probes are relatively straightforward, but a 350C flexible mandrel with insulation for a rogowski is more challenging.

The importance of vessel and other eddy currents in machine operation, equilibrium, islands, and equilibrium reconstruction were not discussed in detail. For instance, while there are breaks in the modular coil shell, there may be other current paths through supports or safety grounding. If these paths are low impedance for grounding purposes, currents may be significant and should be measured. The project might want to measure such currents for fault detection. The issues of hard and/or soft grounding should be examined from the viewpoints of safety, machine performance monitoring and physics impact.

Recommendations:

Continue development of an understanding of the sensitivity of the magnetic signals to profile variations as compared to experimental needs and what level of constraints are needed in kinetic data to accomplish the needed reconstructions at an appropriate accuracy.

Determine the level of computational resources needed to develop the required database and secure additional resources as required. Look at ways to involve international programs to get more computational power.

Investigate application of techniques to the tokamak community for 3-D events. This could build support for the activity, provide them with useful diagnostics, and provide a testbed for NCSX.

Incorporate model loops in the test coil windings.

Electron-Beam Mapping

Findings:

Mapping of the magnetic surfaces of a basic configuration has been included in the definition of project completion prior to first plasma. Phase 1 operation consists of predominantly field mapping and magnetic diagnostic checkout. Preparation work has included looking at several specific cases for mapping and methods to electrically check alignment of coil sets. The mapping preparations have focused on identifying configurations sensitive to assembly errors which resonate with specific transform values in order to assure that device has been assembled properly. The committee concurs with this approach.

Comments:

There is a need to continue to identify and prioritize cases to map. The goal should not focus on characterizing large numbers of configurations, but identifying resonances or errors that are present and developing methods to correct/ameliorate them. This could be addressed by PPPL or in research forums.

More specific goals for e-beam mapping should be developed soon so that analytic tools can be developed and collaborations set up. The methodology for extrapolating information from field mapping to applying corrections should be pursued. Several groups in the US have experience with electron beam mapping in stellarators (ORNL/Wisconsin/Auburn). The project could collaborate with existing stellarators (e.g. HSX and CTH in the US or H-1NF in Australia) that

have recently, or will soon be doing, mapping. Existing devices could be used as test facilities to debug methodologies/hardware to expedite this element of the NCSX experimental campaign.

Previous committees and reviews have recommended a mapping system, which could be used as needed without a major interruption of the experimental program. This committee concurs for the following reasons:

- allows to check for mechanical changes and error field compensation
- allows to qualify particular configurations not considered in original measurements, but becoming of interest during the conduct of the experimental program.

Recommendations:

Develop definition of "acceptable" flux surface quality in its relationship to the electron beam mapping measurements.

Define more clearly the electron beam field line mapping tasks and goals. Specifically, what measurements are needed to identify the most dangerous resonances and to confirm that the machine has been properly assembled.

Adopt the ability to map at any given time in the experimental program, without significant down time, as a general design requirement for the mapping system.

Investigate possible collaborations to debug hardware and analysis techniques so they are immediately available when NCSX begins operation.

General Diagnostics Preparations

Findings:

There has been significant activity in diagnostics planning and definition of diagnostic locations and layout since the last PAC meeting. The committee is pleased with these activities and that there has been an approximately 50% increase in the available ports in the final vacuum vessel and views this as an important improvement. The diagnostics have been phased in to meet the needs of the general research plan as presently envisaged and presented.

Comments:

The large vertical ports for Thomson scattering and FIR diagnostics appeared marginal in aperture for viewing the outboard side of the plasma in the drawings provided. There is a risk of not being able to diagnose an edge transport barrier in outwardly shifted plasmas because the port isn't wide enough, and for general plasma measurements in the scrape-off layer.

Initial diagnostic design is not scheduled to begin until 2006; this puts serious time pressure on long lead-time systems. While design efforts need to be fit within the available funding profile, starting to setup diagnostic groups as early as possible to define key issues and problem areas could reduce the impact of this late start.

NCSX has been designed for low levels of neoclassical ripple transport; as such anomalous transport is expected to be dominant. An important feature of quasi-axisymmetry is the issue of low flow damping, resulting in flows and, potentially, flow shear, which will hopefully result in the creation of transport barriers, and the formation of a pedestal. This may require dedicated high-spatial-resolution edge diagnostics, which weren't explicitly mentioned in the diagnostics tally. With the expected dominant role of anomalous transport, fluctuation diagnostics for determination of fluctuation levels and turbulent fluxes are important. The project has adopted a recommendation from PAC-6 and included a fluctuation diagnostic (TBD) in Phase 5 of the program. BES is being considered as a candidate. The project should consider in its more detailed delineation of the program if earlier implementation of a fluctuation diagnostic would be advantageous, especially given that a diagnostic neutral beam is in the baseline planning for Phase 4.

Early plasmas (even in Phase 3 with 1.5 M NBI) may not have V3FIT equilibria for guidance and the diagnostic set will be limited. Fast visible cameras would be very useful for operations for rapidly diagnosing plasma position and other behavior, as well as providing a useful comparison of the edge location for early V3FIT reconstructions. We note that some visible cameras are in the baseline plan, and the detailed specifications and timing of availability should continue to be evaluated as the project progresses.

The project should consider the torus hall having a calibrated neutron diagnostic at the beginning of Phase 3.

NCSX does not expect to experience significant disruptions and the energy release is expected to be more benign than in tokamaks due to the existence of magnetic surfaces in the absence of plasma current. Are there any particular disruption-related diagnostics that should be added, such as fast strain gauges on tiles or vessel, halo current monitors, or vessel motion?

The project should consider the impact of the 350C bakeout on soft x-ray camera design as soon as possible; can a feasible method of cooling the preamps and detectors be worked out? What is the impact of thermal motions on camera alignment and what methods are available to check alignment?

Recommendations:

Insure that diagnostics adequate to resolve the edge profiles have acceptable access.

Re-evaluate diagnostics phase-in as the prioritized specific experimental plan evolves. Consider whether some level of fluctuation diagnostic is needed/advantageous earlier in the program.

Determine the feasibility of SX cameras mounted to the 350C vacuum vessel.

Define any needed diagnostics for measuring disruption events, specifically as they may need to interface to the vacuum vessel and assembly.

Start setting up diagnostic groups as early as possible, especially for long lead-time systems. This recommendation ties to adequacy of the research preparation budget.

Edge Physics

Findings:

The problems of divertor and boundary plasma control are connected with core confinement performance and transport barriers in tokamak experiments. We expect a similar connection for the Compact Stellarator.

The committee is pleased that the project has made significant progress in code development and benchmarking and in analyzing the boundary region in NCSX. A set of initial diagnostics has been identified for characterizing the edge regions and views are being defined.

Early results show that the edge field configuration is more tokamak-like than in W7AS. The project may need to be careful in extrapolating the W7AS island based system to NCSX.

Comments:

The development of the divertor/boundary control in the CS is a challenging undertaking. The improved core confinement modes are likely to be paced by the development and improvement of the boundary control and divertor.

The magnetic boundary of the CS differs from the high aspect ratio stellarator. The unique boundary properties include an extended stochastic magnetic SOL region (in some equilibria) and large flux expansion regions near the helical edges in others.

The EMC3-EIRENE code solves self-consistently for plasma, neutrals and impurity behavior in the edge and can treat 3-D structures, islands, and stochastic areas. It has been tested on W7-AS, LHD and TEXTOR DED. This is viewed as a valuable tool for application to NCSX. The Wendelstein group has volunteered to train a person in its operation.

The CS SOL plasma and divertor research program should investigate the unique features of the CS boundary and exploit these features in the development of the divertor and boundary control system.

Recommendations:

Continue energetic particle modeling to assist in design of partial PFC system, as well as modeling of the edge magnetic topology and calculation of footprints and peaking factors on the wall.

Ensure that an experienced boundary plasma/ divertor scientist is included in the project team.

Take advantage of the offer to train someone in the use of EMC3-EIRENE at the earliest available opportunity.