Fifth Report of the National Compact Stellarator Experiment
Program Advisory Committee
November 14-15, 2001

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The National Compact Stellarator Experiment (NCSX) Program Advisory Committee (PAC) met on November 14-15, 2001 to advise the Director of the Princeton Plasma Physics Laboratory, Robert Goldston, on two items. The primary charge was to advise on progress in the design of NCSX and preparations for the Conceptual Design Review (CDR) of the NCSX Program. The PAC was also asked to comment on the theory, computation and international collaboration components of the PPPL Stellarator Program and their overall coordination.

The PAC recognized that significant progress has been made in the NCSX design since the Physics Validation Review (PVR) in March 2001, particularly in the design of the stellarator core. The change from 21 modular coils to 18 has resulted in increased diagnostic access and optimization of these coils has resulted in smoother coils with a reduced current density. This opens the possibility for 2T operation, which may be important for achieving low ν^*_i conditions. Beam access can now be achieved without an extended leg on the modular coils located at the field period joints. Small toroidal field background coils have been added at the midplanes of the modular coils and shown to increase flexibility without compromising access or adding ripple components non-commensurate with the N=18 modular coil ripple. A wide range of configurations is also attainable through variations of the current ratios in the different modular coil types, PF, and TF coil sets; significant questions remain as to the sensitivity of the equilibria to intended and unintended variations in these currents and the effectiveness of the beam heating in these varied configurations. PIES runs have shown the ability to trim out or minimize natural islands through minor variations in the coil geometry; utilization of the trim coils have also been shown to be able to reduce island size, but to the committee's knowledge these investigations have not been performed with the reduced trim coil set proposed nor completely integrated into the engineering design. The NCSX Team is making a good concerted effort to address issues raised in previous PAC's and at the PVR, as documented in their September 2001 report to DoE and the "PVR Recommendations Tracking Log" in preparation for the CDR.

The major concern to the PAC was that there has not been a convergence of coil sets used for the calculation of the physics attributes of NCSX with those that are tractable from an engineering point of view. As an example, the 'physics design' coil set has a projected interference between coils in the finite-build, while the 'engineering design' coil set (without such interference) results in ~50% increase in neutral beam loss when the

equilibrium is determined to preserve stability to ballooning and kink modes. The PAC unanimously agreed that a single design must be presented at the CDR. The NCSX Team must develop a clear strategy, plan, and timeline for arriving at a unified engineering/physics design for the device for the CDR. This plan must include enough time to perform the needed physics and flexibility calculations for this unified design. While design improvements will certainly occur after the CDR, the device as then-presented must be physically realizable and able to fulfill the primary missions of the NCSX. There was a reasonable level of confidence expressed by the engineering team that the engineering design can be rapidly brought into agreement with the physics design using the spline representation tools in-hand to modify the coil set to eliminate the interference problem. Should this prove difficult to achieve, the physics accessible with the present engineering design needs to be critically examined.

A shortcoming of the presentations to the PAC was the lack of identifiable trade-offs between the engineering and physics designs and the impacts on the experimental goals. As an example, and as mentioned before, keeping the same ballooning and kink stability limits (jointly) led to a 50% increase in beam loss and a factor of ~15 increase in epsilon-effective**3/2 in the core. What were the relative roles of ballooning and kink in this situation? Clearly, as demonstrated from W7AS, tearing modes are a real problem. The kink and vertical stability are real issues in current-carrying plasmas. The situation with respect to ballooning is still unclear experimentally in stellarators. Analysis of results from code optimization runs should attempt to focus more on learning the drivers and trade-offs versus the demonstration of existence of a set of state variables (e.g. coil currents) satisfying a broad set of criteria.

The presentations to the PAC were heavily oriented to improvements in the physics and engineering design of NCSX, of which there were many. The CDR committee will be charged, however, with evaluation of the physics program achievable in a single design proposed and the likelihood that it can be executed with that facility and available resources in a timely manner. NCSX has a broad range of physics objectives. Design efforts have focused on simultaneous achievement of a large set of these objectives. Attention should be given to a prioritization of these objectives and how, if design tradeoffs are necessary, they can still be achieved in a perhaps less integrated fashion. The presentations to the CDR should concisely state the mission of the device, followed by a prioritization of the objectives, and a clear, logical, mission-driven experimental plan to achieve these objectives. This plan should emphasize the diagnostics needed to get the measurements required for each objective, their interface to the NCSX device, analysis tools needed to interpret the measurements, and the timeline for estimation of deliverables. As many of these systems are being implemented out of the operating budget, this schedule should be correlated with the requested funding profile. The committee recognizes that much has already been done in this area and that PPPL is aware of its importance, but wants to emphasize that clearly presenting this material would make a compelling case to the CDR that NCSX should move forward and can complete its mission within the time and budget envelope proposed.

A central element of the CDR is the expected cost and schedule of NCSX. The NCSX Project has actively engaged potential vendors through small 'manufacturing studies' contracts for key elements (and potentially largest cost-drivers) of the stellarator core, namely the modular coils and the vacuum vessel. The PAC agrees with this philosophy as a means to ensure potential design improvements and that problems are brought to light early, and as a means to ensure the largest possible set of competitors for the procurement process. Information from these studies should serve to increase the confidence level of the cost and the design of the core elements at the CDR.

The PAC is especially supportive of the revised design of the vacuum vessel. The new design significantly increases the spacing between the vessel and the plasma, providing more room for plasma shape changes between various operational scenarios, for plasma facing components, for installation of RF antennas, and for implementation of a divertor. Control of neutrals is clearly a critical component for successful operation in keeping moderate densities for low ν^*_i and to minimize rotation damping: both key features needed for the NCSX mission. The neutral problem may be exacerbated in NCSX due to the significant prompt loss of beam-produced ions and the moderate na product in the bean-shaped cross-section.

The Project recognizes this importance and has opted for a phased approach to eventual implementation of a divertor. This has been the historical precedent and makes sense given the complexities of the 3-D divertor structure in stellarators and its dependence upon the machine operating parameters. The minimal intrusions of the PFC support structure and the new vessel configuration leave a wide window open for the divertor design. While the design efforts have correctly focused on unification of engineering and physics design of the coil set and core plasma properties, more attention needs to be directed towards the edge as the magnetic design gels. The project has started addressing these issues. The initial modeling results presented were encouraging; care should be taken that the calculation boundary conditions are commensurate with neutral pressures in existing stellarator and tokamak experiments. Given the successful impact of divertor operation on W7AS and the stellarator edge modeling tools developed at Garching, there is confidence that a divertor can be implemented in NCSX given sufficient attention. There is a need to incorporate the divertor planning into the diagnostics and run plan of NCSX. Specific measurements need to be detailed and sequenced to provide the necessary information, in a timely manner during operations, to provide for the phased-in divertor upgrade. As the modeling and divertor design progresses, it needs to be established that the required parameters for divertor operation are compatible with the desired core plasma parameters.

The high beta mission of NCSX can almost assuredly be executed using neutral beams in low field, high-density operation. The PVR endorsed predominantly beam heating as this has been demonstrated effectively in the present generation of stellarators. The integrated plan is to achieve high beta and low ν^*_i simultaneously. This requires keeping the density at moderate levels. Even with implementation of a divertor, it may be difficult to limit the density using neutral beam heating. The NCSX Team should, as part of the experimental plan, elucidate projected performance and achievable goals under these

conditions. The vacuum vessel redesign provides access for high-field mode conversion heating antennas, as recommended by the PVR. Investigations of RF wave propagation and heating are tentatively set to begin in the 5th operating phase of the program. Earlier scoping studies could provide data to ascertain whether this is a viable option and provide time for implementation should this be desirable.

A large range of flexibility can be achieved in NCSX through programming of the currents in the three modular coil types, coupled with variations in the PF and auxiliary TF coil sets. The existence of a diverse set of plasma configurations has clearly been shown. What is less clear is the sensitivity of the plasma configurations and machine performance to these variations. There were no presentations on the changing of the heating effectiveness between these configurations. A series of 'snapshots' were presented showing an evolution of configurations from low beta to high beta operation. A method should be developed for the CDR to clearly show the needed variations in all of the coil currents and that these are plausible within the timescale of an NCSX discharge.
A longer-range issue, which will be critical to operations, is the sensing of the plasma state and control of these currents to regulate machine performance.

The PAC heard two brief presentations on the PPPL theory and computation efforts and collaborations. A relatively small group have been highly focused on theory and computational issues related to the design of the NCSX and QPS experiments; these efforts have produced a leap in the capabilities of analysis of current-carrying stellarators and resulted in exciting designs for two new stellarators that interface well to the worldwide effort. The Team is commended for these efforts and achievements. Collaborations are in progress to apply and benchmark these codes on existing stellarator experiments and to improve their performance for application to open issues (e.g. full-torus PIES). Formidable tasks remain in the years before operation of NCSX to develop the analysis and control tools needed for successful operation, such as a 3-D version of the EFIT code. It is noted that a proposal has been submitted to begin this development. The level of effort in theory and computation needs to be examined in the light of future NCSX Program needs.

The theory and computation efforts at PPPL have been heavily weighted toward the computational end with a few notable exceptions. While these computational tools and studies have been critical and instrumental in achieving the present designs (and will be needed for operations), first principles understanding of the science behind 3D systems are needed. Only modest efforts are underway throughout the community on 3D systems. What needs to be achieved is the perception across the community of the opportunities, excitement, and challenges offered by research in these areas to attract researchers to these topics and build support for both theoretical and experimental 3D studies. The simple existence of a world-class experiment is not sufficient, nor is this solely PPPL's responsibility; rather action is required from the stellarator community as a whole.

PPPL should, however, play a pivotal role. The 3D Workshop at ORNL in January has been called precisely to identify areas where exciting opportunities and needs exist for theory in three-dimensional systems. PPPL should have a strong presence at this

workshop and articulate not only the needs of the NCSX experiment and program, but also their vision of the needs across the program for furthering the understanding of 3D plasma behavior. The vast PPPL experience with tokamak research and stellarator knowledge gained from the NCSX design puts them in an ideal position to establish connections across the program; this opportunity should be exploited to the maximum extent possible. Most phenomena of interest in tokamaks happen in three dimensions. Application of stellarator codes to tokamak (or alternates such as the ST and RFP) analysis, where appropriate, will serve to strengthen the perceived value of stellarator research to the community. The goal of the Workshop is to produce a document presenting the needs and opportunities in 3-D theory. This document, as developed from the community, should be used to help refine and coordinate the theory and computational efforts at PPPL as a national program.

The PAC saw significant international collaborations on both tokamaks and stellarators as presented. These collaborations centered mainly on diagnostics, analysis tools and design efforts. There will be a period of several years between the completion of the engineering design of NCSX and the beginning of experimental operations. Advantage should be taken of this interval to develop the experience needed not only in diagnostics and analysis, but also in device operation. Experience on larger devices of the NCSX-class is presently available only through international collaboration. With the scheduled shutdown of W7AS in July 2002, it is imperative that plans be set forth and executed immediately for participation on this device, if this is to happen at all. There is a wide range of international devices available for obtaining diagnostic and analysis experience. Plans should include increased participation on these devices as well (such as CHS, H1-NF, TJ-II); somewhat smaller programs welcome the participation and can be more flexible in adapting programs to needs of collaborators. US programs offer unexploited opportunities as well. Specifically, CTH will be online well before NCSX and is designed to explore issues in current-carrying stellarators. As such it will offer an ideal facility for operations experience and in the development of current measurement and equilibrium reconstruction methods. Preparations for these collaborations should begin soon. A plan needs to be developed outlining the experience needed to maximize the productivity of NCSX when it begins operation and then identify how this intellectual infrastructure can be gained within the worldwide program.

Detailed recommendations on the two formal charges, and their basis, have been put forth in the above narrative; views of the committee on what it perceives as some of the longer-range issues related to the charges are also expressed. The primary recommendations of the PAC relative to the charges can be summarized as:

1) The NCSX Team must develop a clear strategy, plan, and timeline for arriving at a unified engineering/physics design for the device for the CDR.

2) The presentations to the CDR should concisely state the mission of the device, followed by a prioritization of the objectives, and a clear, logical, mission-driven experimental plan to achieve these objectives for the design presented.

3) A method should be developed for the CDR to clearly show the needed variations in all of the coil currents, that these are plausible within the timescale of an NCSX discharge, and the sensitivity of the configurations/performance to these variations.

4) Divertor planning should be incorporated into the diagnostics and run plan of NCSX and refined calculations of the effects of neutrals presented.

5) PPPL needs to articulate not only the needs and level of effort required in theory and computation for the NCSX experiment and program, but also their vision of the needs across the program for furthering the understanding of 3D plasma.

6) Input from throughout the fusion community on 3-D needs should be used to help refine and coordinate the theory and computational efforts at PPPL as a key element and resource of a national program.

7) Collaborations should be developed from a strategic viewpoint emphasizing the development of skills required to bring NCSX into operation and to analyze results.