# Fourth Report of the National Compact Stellarator Experiment Informal Program Advisory Committee 1-2 August 2000

D. Anderson, I. Bernstein (absent), A. Boozer (chair), M. Fujiwara (absent), J. Harris, C. Hegna, S. Knowlton, J. Lyon, E. Marmar, H. Neilson (ex officio), W. Nevins, P. Politzer, D. Ross (substituting for R. Hazeltine) E. Synakowski, F. Wagner (absent), H. Weitzner (absent but represented by Paul Garabedian)

The Informal National Compact Stellarator Experiment (NCSX) Program Advisory Committee (PAC) met on August 1 and 2, 2000 to advise the director of the Princeton Plasma Physics Laboratory, Robert Goldston. Advice was sought on: (1) the choices that are being made for the machine configurations and (2) the progress that is being made in addressing the technical issues raised in the June 1999 meeting of the PAC and in the August 1999 meeting of the Fusion Energy Sciences Advisory Committee (FESAC). The primary issues raised by the PAC were (a) the flexibility of the coil set for supporting many plasma states, (b) the existence of magnetic surfaces, (c) the achievable physics program versus technical capabilities of the device, and (d) the need to explore confinement enhancement techniques. The issue raised by FESAC was the robustness of the equilibrium configuration throughout the plasma evolution. The Committee had comments on these issues as well as on broader questions in the development of a design.

The NCSX management wishes to have a Physics Validation Review (PVR) on the NCSX design in December 2000 and a design, cost, and schedule review in April 2001. The PAC feels this schedule is aggressive, requires a quick decision on the plasma configuration and a careful focusing and planning of activities. However, the PAC concurs that the NCSX project needs to complete a design proposal.

The PAC was pleased with the progress that had been made, particularly in the last few months, in finding a more robust three-period plasma configuration, LI-383. Rapid progress is being made in studies of plasma configurations. Additional configurations, which would provide more choices for attractive designs, could presumably be found if these activities were continued, even for a few more months. For example, an interesting, but relatively unstudied, two-period configuration was presented. Unfortunately, if the December schedule for a PVR is to be met, the project has no choice but to narrow its design focus to one type of plasma. Of the plasma types that have been studied, the LI-383 type appeared to be the most developed for reaching the project goals.

Much of the time between the June 1999 and the August 2000 meetings of the PAC was spent by the project on tool, rather than design, development. The improvements in three computational tools were particularly evident in the presentations. A large speed-up in the PIES equilibrium code makes the study of magnetic surface quality feasible. An improved free-boundary VMEC equilibrium code permits direct calculations of effects of coils on the plasma. The CoilOpt code has successfully

produced designs for modular coils. The time spent developing these tools appears well justified.

The first recommendation of the PAC is that the physics capabilities of NCSX be the first consideration in design choices. The NCSX will be a platform for physics studies, not a reactor prototype. The physics issues to be studied in NCSX must be chosen carefully. For example, the beta limit given by the standard ballooning analysis may be too conservative for stellarators and drive their design to more extreme shaping than required. The chosen physics issues will define many of the machine properties, such as the required flexibility of the coil set for supporting multiple configurations of physics importance. As noted by the PAC in June 1999, flexibility is key to the value of the NCSX experiment. The NCSX goals presented to the PAC provide a reasonable starting point for defining the required flexibility but, at their the present level of development, are just a starting point. The project has not yet dealt in depth with the issue of the required flexibility or how it will be achieved. Much work remains to be done before the PVR.

The second recommendation is that studies of magnetic surface quality be pursued with high priority. The results on magnetic surface quality shown to the PAC enforced a smooth magnetic surface at the plasma boundary. Nonetheless, these studies found the C-82 configuration, which was the primary focus of design studies in 1999, had unacceptable magnetic surface quality. The new LI-383 configuration appears to have acceptably robust magnetic surfaces. However, the magnetic surface issue will remain open until free-boundary PIES studies have been completed for an actual coil design using a variety of plasma states (magnitudes and profiles of plasma pressure and current). The work on tuning out islands is encouraging and will be important in the design of coils. A deeper understanding of the cause of magnetic islands might lead to more efficient methods for eliminating them.

The rapid time scale on which the choice between saddle and modular coils must be made (September 2000) unsettled the PAC. Issues that should determine the choice include flexibility, magnetic surface quality, technical risk, maintainability, and cost. Limited data on these issues was available to the PAC. The engineering and physics basis of this choice requires refinement.

Although 6MW in neutral beams is a reasonable complement of heating power, it is marginal for heating the plasma to a beta of 4%, the level desired by the project. At least one beam in a counter injection orientation would allow NCSX to better address certain physics issues (avoidance of beam driven currents, plasma rotation, and modifications to the radial electric field). However, the confinement of beams, particularly counter-injected beams, is an issue. The pulse length of the existing beams, 0.3 s, is short, and a pulse extension would broaden the accessible range of physics studies. High Harmonic Fast Wave (HHFW) heating has attractive properties. However, the PAC concurs with the program management that HHFW is too risky technically to be a primary heating method. The maintenance of the required port space and low-level studies of HHFW studies are reasonable, but these studies have low priority in the

immediate future. HHFW experiments are ongoing on NSTX and, if successful, may justify a reconsideration of this topic.

The physics studies described to the PAC assumed a confinement comparable to that of the best stellarator experiments. For NCSX parameters the assumed confinement is only comparable to tokamak L-mode, but it would be useful for the project to outline the effect on the physics program if confinement were more typical of stellarators, one times the ISS-95 scaling law. The capability of the LI-383 type configurations for supporting the sharp edge pressure gradients, which arise in H-modes, should be assessed. H-modes are important in their own right and are a possible method of enhancing confinement.

Two features of the LI-383 type configurations require thought on program strategy. The first is an assessment of the risk of, or alternatives to, ramping the plasma current through an edge q-value of two. The risks could be assessed by comparisons to the experimental W7-AS results and the close correlation found in that machine to the predictions of a modified theory of tearing modes in a cylinder. The flexibility of the coil set may be adequate to make q less than two in the vacuum state, which would allow the issue to be avoided. Making q less than two in the vacuum state may entail a loss of quasi-symmetry, which is inconsequential in the vacuum. However, this strategy might imply an ability to change the coil currents during an experiment to restore quasi-symmetry. The ability to change coil currents may be generally useful, and the associated technical issues (coil inductances and eddy currents in structures) should be studied.

The second issue raised by LI-383 type configurations is neutral penetration at the thin waist of the plasma. The importance of neutral penetration has not been assessed by either numerical simulation or by comparison to experiments. Before the PVR, the project should have estimates of the penetration and be able to discuss the implications on the control of the plasma edge, such as the location of limiters.

Two questions were posed to the PAC. (1) Are the right configuration choices being made? The time scale of reviews forces choices at a time when rapid improvements in the physics design are being made. Plasmas of the LI-383 type appear, on present knowledge, to be a good basis for an experiment. The PAC was not presented with sufficient information to make a recommendation on the choice between a saddle and a modular coil design. The time scale on which the NCSX management wishes to make the choice (September 2000), which is driven by the dates of the reviews, concerns the PAC. The PAC notes that these reviews are of the preconceptual design and hope the choice will be revisited during the conceptual design if significant issues remain. (2) What is the status of the progress towards addressing the technical issues raised by the PAC and the FESAC? On the issues of flexibility, magnetic surfaces, and robustness: initial and apparently encouraging results have been obtained on the consistency of LI-383 type configurations with magnetic surfaces (if the boundary is held fixed) and on the existence of equilibria with a variety of plasma pressure and current profiles. However, work is just beginning on establishing flexibility requirements and finding coil sets that

satisfy these requirements. If a fixed boundary equilibrium has good surfaces, then a coil set can presumably be tuned to achieve good surfaces. However, the consistency of any set of coils with good surfaces, over any range of equilibria, has yet to be demonstrated. On the issue of the coupling of the physics program and the machine specifications: the PAC looks for greater clarity in the relation between the physics goals and the machine requirements. On the issue of confinement improvement: the understanding of the PAC is that testing the beta limits in NCSX will require a confinement multiplier of 2.6 relative to ISS-95 scaling, even at the lowest magnetic field consistent with adequate beam and plasma confinement (1 Tesla). While this confinement is consistent with results from some stellarator experiments and the tokamak L-mode database, the possibility that confinement will prevent a thorough exploration of the NCSX beta limit remains a concern.