Report of the NCSX Physics Validation Review Panel
26-28 March 2001

D. Anderson, Univ. of Wisconsin
J. Freidberg, MIT
A. Glasser, LANL
J. Harris, Australian Natl. Univ.
T. Jarboe, Univ. of Washington
J. Johnson, Florida A&M Univ.
G. Navratil, Columbia Univ.(Chair)
D. Newman, Univ. of Alaska
S. Okamura, NIFS
W. Peebles, UCLA
S. Pitcher, MIT
P. Politzer, GA
D. Steiner, RPI
H. Weitzner, NYU

I. Introduction and Charge

The NCSX Physics Validation Review Panel met at the Princeton Plasma Physics Laboratory 26-28 March 2001 to review the physics basis of the National Compact Stellarator Experiment (NCSX) Project as charged by the U. S. Dept. of Energy (charge attached in Appendix A). The Panel based its review on the report summarizing the NCSX pre-conceptual design and supporting physics basis prepared by the NCSX Project and two days of oral presentations by the NCSX Project Team.

II. General Findings and Recommendations

The consensus of the Panel is that the physics requirements and capabilities of the pre-conceptual design of the NCSX experiment represent an appropriate approach to developing the design of a Proof of Principle scale experiment that is the central element in a program to establish the attractiveness of the Compact Stellarator (CS) concept.

The Panel also finds that the choice of the Quasi-Axisymmetric (QAS) approach for a PoP class low aspect ratio, high beta stellarator experiment is appropriate because of its promise of improved confinement and its commonalty with the well developed scientific understanding of axisymmetric toroidal plasmas. The choice of studying a QAS configuration is complementary with the domestic and international stellarator research program where a Quasi-Omnigenous Symmetry (QOS) approach at large aspect ratio is being pursued in Germany on W7-X, and a Quasi-Helical Symmetry (QHS) approach at moderate aspect ratio is being pursued in the U. S. on HSX.

Calculations and experimental results from earlier stellarators presented by the NCSX Project make a plausible case that a fusion power system based on the successful development of the CS concept may resolve the two primary physics issues in tokamak based fusion power systems:

reduction/elimination of plasma disruptions in a configuration with economic steady-state operation. These gains are achieved at the cost of increased coil complexity and (given present expectations of plasma confinement) somewhat larger machine size. The CS concept is therefore an important member of the portfolio of innovative confinement concepts being pursued by the U. S. Fusion Energy Sciences Program.

Understanding the behavior of magnetized plasmas in three dimensional configurations is an important scientific frontier area. We find that the NCSX experiment will act as a focus and driver for the intellectual development of this important area of plasma physics in the U. S. plasma community.

1. We recommend this scientific leadership role should be more clearly built into the description and execution of the NCSX program mission.

Although this was primarily a physics review and the presentations concentrated on the physics issues, we wish to take note of the brief engineering discussions. The engineering presentations were well prepared and addressed both the design and assembly issues and possible inventive solutions. We feel that they were particularly effective because they presented both the outstanding difficulties as well as the successes in the engineering design.

As the Project continues to develop the physics basis and the design of NCSX for a Conceptual Design Review, we recommend the following activities be pursued by the Project or in some cases as parallel activities that the NCSX Project should encourage and support:

2. There is concern that the present pre-conceptual design point may be “too small.” This view is due to the marginal parameters in NCSX across a broad spectrum of experimental design factors such as: high energetic NBI ion losses, low base heating power, confinement assumptions needed to reach design beta, very small plasma/pfc distances for some equilibria, and neutral penetration concerns. We recommend that as the Project prepares for a Conceptual Design, the size of the design be carefully considered and well justified at the time of the CDR to allay concerns that critical parameters are being fit within a predefined budget envelope.

3. An attractive vision of a CS based fusion power system has not yet clearly articulated by the Project and a comprehensive fusion reactor design study has not yet been carried out. This situation makes it more difficult to build community enthusiasm for the CS concept and to justify the design requirements in key physics parameters for the PoP program. We recommend the Project devote some effort to developing this reactor vision and also to

strongly support the initiation of a comprehensive fusion reactor design study of the CS concept.

4. Plasma flow in a QAS stellarator has been identified by the NCSX Project as a key physics issue that also connects CS and tokamak confinement physics. The Project should more seriously investigate expected flow drive and damping mechanisms in 3-D plasmas in planning the experimental program on NCSX.

5. The link between primary experimental physics objectives and the critical diagnostics needed to achieve these objectives is not yet well defined. Careful definition of this important part of the science mission and experimental program of NCSX is essential and should be completed as part of the conceptual design.

6. The review lacked a full discussion of the status of QAS vis-à-vis the large range of stellarator possibilities. While the advantages of QAS were made clear, there was essentially no discussion of its limitations. The presentation of these comparisons would likely increase the desirability of diverse stellarator experiments and enhance understanding of the role of the CS in the portfolio of toroidal magnetic configurations by the broad fusion science community.

III. Equilibrium & Stability Modeling; Coil Design

The "robustness" of the NCSX was discussed extensively in the review. There is no precise criterion for the robustness of the proposed configuration. We understand it to mean that acceptable plasma states exist for a reasonably broad range of states near the evolution path from vacuum to the final state, and that the results are not unduly sensitive to changes in profile, coil currents, plasma evolution, *etc*.

For equilibria obtained from VMEC, which assumes good flux surfaces, the NCSX team was successful in calculating beta limits against external kinks, ballooning and Mercier modes, over a wide range of parameters, and found stable configurations at high beta (~4%). They also showed evolution from zero to high beta, describing a stable startup trajectory. Acceptable equilibria with edge currents and edge pressure gradients were also shown. These results bolster confidence in the robustness of the configurations.

The NCSX team has investigated the sensitivity of the equilibria to the onset of islands, using the PIES code, but these useful and valuable studies were incomplete, being limited by the very long run-times required by the PIES code. As detailed below, the Panel felt that prior to the CDR additional detailed investigation of the flux surface quality using realistic coil geometry was essential.

The NCSX team made an effort to investigate tearing stability, but due to the tools available, the NCSX team was limited to treating this in the cylindrical approximation. There are presently no codes capable of treating tearing modes reliably in two or three dimensions for equilibria too far from cylindrical.

Recommendations for short-term developments, before CDR:

1. Examine island formation, destruction of flux surfaces, and maintenance of QA symmetry, using *finite model* coil configurations close to the final design.
2. Study the effects of coil construction errors, and other field perturbations, on flux surfaces in particular, and equilibrium and stability in general.
3. Carry out, where appropriate, calculations of island formation and destruction of surfaces in the full torus, dealing with perturbations that break the 3-fold symmetry.
4. Develop additional self-consistent startup evolutions, using the final coil set, with realistic, time-dependent collisionalities, especially in the evaluation of the bootstrap current.
5. Use these self-consistent start-up scenarios in PIES and other codes to examine flux surface quality and stability properties at a number of points along the evolution path.

Recommendations for longer-term development:

6. Develop real-time reconstruction of the last plasma surface from external magnetic measurement, for purposes of real-time control.
7. Develop a 3D counterpart to the EFIT code for reconstructing equilibrium profiles from internal and external experimental measurements. Identify the critical measurements necessary to accurately reconstruct the equilibrium so that they can be integrated into the NCSX machine design.
8. The NCSX Project should promote the development of 3D tearing mode theory and computation.

IV. Experimental Plans and Scenario Modeling

Confinement assumptions and heating power.

The modeling for NCSX considers two very reasonable assumptions: either the confinement follows ISS95 stellarator scaling, or it follows tokamak L-mode scaling (ITER 97P). If the ISS95 is used, NCSX would require an enhancement factor of two to three to meet its goal of $\beta = 4\%$ and low collisionality (so that the bootstrap current approximates that in reactor conditions) with 6 MW of NBI power. If ITER 97P scaling is used, NCSX could achieve the mission targets without enhancement over L-mode. Determination of the confinement characteristics thus becomes a major part of the experimental program.

Since the configuration of NCSX is new and unique, it is not possible to say *a priori* how confinement will scale. Prudence dictates that sufficient heating power be provided to meet mission goals for L-mode or two to three times ISS95 confinement. Issues surrounding RF heating—choice of scheme, antenna configuration, *etc.*— will require time, effort and experimentation to resolve.

1. The Panel recommends that the NCSX team plan on using 6 MW of NBI power as the primary heating source.

NBI configuration and pulse length.

The present machine size restrictions imposed by the cost envelope result in significant beam orbit losses ~15% for co-injection and 20-30% for counter-injection. This lowers the absorbed heating power somewhat, and also reduces the room for maneuver in setting up configurations with balanced momentum input or sheared rotation.

2. The Panel recommends that these marginal conditions in the current design, which may limit control of flow shear and optimization of absorbed power, be carefully considered and clear solutions (*e.g.* flexibility in re-orienting the beam lines) be identified prior to the CDR.

The Panel notes that ironically the fast ion losses could result in E_r profiles that enhance confinement, as has been seen in W-VII-A and H-1.

The experimental scenario modeling presented indicates that the base NBI pulse length of 300 ms is barely adequate to raise the plasma parameters to the mission target range.

3. The Panel thus recommends that the NCSX team plan to increase the NBI pulse length to 500 ms or more as soon as possible.

Role of RF heating

Mode conversion heating is an attractive option for increasing the heating power at modest cost, but time and resources will be required to develop this heating method for routine use in the NCSX configuration.

4. The Panel recommends that provision to accommodate suitable antennas on the high-field side of the torus be made in the base machine design, with actual deployment of the antenna system coming after the experiments with NBI are well in hand.

HHFW heating offers interesting possibilities, and is in parallel development on NSTX. However, considerable uncertainties remain, and very substantial funding would be required to develop this heating method for NCSX.

5. The Panel therefore recommends that work on HHFW for NCSX be deferred to a later stage in the NCSX program.

Active modulation of coil set currents.

The introduction and exploitation of independent, dynamic control of the different modular coil currents in NCSX has greatly enhanced the flexibility of the device and represents an insightful injection of "tokamak thinking" into the operation of a stellarator. The experimental scenario modeling indicates that this technique will play an important role in achieving the goals of the compact stellarator program.

The time scales for evolution of the profiles and changes to the coil currents are comparable to the toroidal time constant of the vacuum chamber ~10 ms.

6. The Panel recommends that calculations of the circuit and image current responses be coupled into the development of experimental discharge control scenarios.

Neutral penetration into narrow plasma cross-sections.

The combination of machine size restrictions (imposed by cost constraints) and the strong shaping required to produce high external rotational transform result in "pinched" plasma waists of as little as ~20 cm across in the poloidal planes where the NCSX plasma is vertically elongated. Experimental experience indicates that neutrals might be able to penetrate to the core in these locations, and soak up valuable plasma heat and momentum input. Careful design of the limiter and divertor structures might alleviate this, of course. However, the work carried out has not gone far enough yet to allay the Panel's fears that this could be a serious problem.

7. The Panel recommends that, now that the general magnetic configuration has stabilized, an intensive investigation of the neutral penetration issue be carried out. This would involve detailed study of the 3-D field structure and application of existing edge physics models in appropriate frames of reference, and comparison with relevant experimental results,

especially those from Wendelstein 7AS, which has a similar edge topology. The Panel notes that this project would be an excellent target for expanded collaboration with the US edge physics and stellarator community as well as with overseas stellarator programs.

Diagnostic access and plans.

As the NCSX architecture has only stabilized recently, it is understandable that the diagnostic planning to date has necessarily been limited.

8. The Panel recommends that prior to the CDR the NCSX team develop a matrix relating the key program physics issues to the diagnostic requirements to investigate them, as well as the geometric access required to perform the measurements. This will facilitate setting priorities, staging, and even port allocation, and will also catalyze the expansion of collaborative relationships with the US and international fusion communities by providing accessible entry points.

The Panel has some comments and recommendations on specific diagnostics:

9. Because of the special concerns about flux surface robustness at low aspect ratio, the unique magnetic geometry of NCSX, and the anticipated use of trim coils to fine tune the magnetic configuration in the presence of both predictable and discovered perturbation fields, the Panel recommends the deployment of a system for convenient, rapid electron-beam flux surface measurements as part of the permanent operational equipment of the machine. Such a system should use retractable components so that it can be operated without causing major interruptions to plasma operation.

10. Experience on other toroidal confinement experiments indicates that measurements of the changes in the magnetic field induced by the plasma provide the basis for the reconstruction of equilibria, physics analysis, and ultimately optimal control of plasma performance. The Panel recommends that the development of magnetic diagnostics and analysis be integrated with the configuration and engineering design process.

11. The QAS configuration was chosen in large part because of its predicted capacity to support sheared flows like those developed in enhanced confinement tokamak plasmas in which turbulent energy transport is greatly reduced. The Panel thus recommends that measurements of turbulence and flow with sufficient spatial resolution to address key physics questions should play a more prominent role in the diagnostics program than appears to be the case at present.

12. The three-dimensional nature of the stellarator configuration places additional demands on diagnostic development, favoring the use of multi-view and large area imaging systems. The

Panel recommends that greater consideration be given to the specifications of such systems in preparation of the detailed experimental program.

V. Project Management; Cost & Schedule; FESAC Goals

Project Management

The PPPL/ORNL partnership has been successful in developing the NCSX pre-conceptual design.

1. However, looking forward to the CDR and beyond, we recommend that a more inclusive management approach be adopted to successfully implement the CS PoP program with NCSX playing the primary organizing role. The NCSX management should try to involve all elements of the US and international stellarator activities to form a truly National CS Program with international collaborations. This should include both experimental and theoretical activities. For example, (i) more direct contact and collaboration with existing stellarator experiments is needed to solidify the physics and operational base for the Conceptual Design; (ii) opportunities exist to benchmark the PIES code against similar codes (*e.g.* HINT at NIFS in Japan) and against experimental stellarator results; (iii) serving as a focus for or supporting organizing efforts in the theory community to more effectively address 3D magnetized plasma physics; and (iv) making plans to begin establishing a national experimental research team to carry out experiments on NCSX.

Proposed Budget and Cost Estimation

The NCSX Project Team reviewed with us the methodology used in constructing the cost estimations of the pre-conceptual design. We find that cost estimates were reasonably accurate for this phase in the project design, the methodology was appropriate, and that the work breakdown structure was adequately defined.

Plans for Preparation of the Conceptual Design

The methodology and approach adopted for the management of the pre-conceptual design are appropriate for finalizing the cost and schedule for the conceptual design. However, as noted under comments on Project Management, more direct contact and collaboration with existing stellarator experiments is needed to solidify the basis for the Conceptual Design.

FESAC 10-year Goals

The FESAC Program & Balance Report of September 1999 sets out a 10-year goal to “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." We find that the CS PoP program plan presented to us by the Project is aimed at meeting this goal, and that NCSX is the central element in that plan. However, we note that other supporting elements are called out including theory and modeling support, and CE level experimental programs (some of which are already funded projects by DOE).

2. In addition to these elements listed by the NCSX Project, we recommend that a comprehensive CS fusion reactor design study be included in the PoP plan as an important element in achieving this FESAC 10-year goal to determine the attractiveness of the CS concept.

As noted in the previous section on Project Management, the realization of this FESAC goal will require an evolution of the management approach by NCSX that tries to involve all elements of the US and international stellarator activities to form a truly National CS Program with international collaborations. Given the projected start of plasma studies in NCSX of late in 2006, the Panel concludes that there will necessarily be a delay of several years in meeting this FESAC objective.

We note that the PoP Panel endorsed classification of the CS as a PoP program. We recognize that construction of NCSX would be a relatively costly investment over many years by the Fusion Energy Sciences Program.

3. Therefore, we recommend the OFES and FESAC address the larger programmatic issues to determine whether or not to proceed with construction of NCSX and, if so, on what time scale. These include the issue of program balance within available fusion program budgets, needs of present elements in the program, and opportunities for other new starts and collaborations.

Appendix A – Charge to the Physics Validation Review Panel

A) What is the Scientific and/or Technical Merit of the Proposed Research? In particular,

- Does the proposed experiment address important problems in plasma science, plasma technology, fusion energy science, or fusion energy technology?

- How does the proposed experiment compare with other research in its field, both in terms of scientific and/or technical merit and originality?

- What is the likelihood that it will lead to new or fundamental advances?

B) How appropriate is the proposed Method or Approach? In particular,

- Are the physics requirements for the proposed facility appropriate for the mission?

- Has a sound physics basis been established for developing the conceptual design?

- Does the proposed research employ innovative concepts or methods?

- Does the applicant recognize significant potential problems and consider alternative strategies?

C) Are the project personnel, management arrangements, research environment and institutional support adequate to carry out the proposed program? Does the proposed experiment take advantage of unique facilities and capabilities and/or make good use of collaborative arrangements?

D) How reasonable, appropriate and adequately defined is the proposed budget?

E Are the plans for developing the conceptual and engineering designs and for finalizing cost and schedule appropriate?

F) How well does the proposed research address the FESAC 10-Year goal to determine the attractiveness of a Compact Stellarator?