9 December 1996

Dr. Ronald R. Davidson, Director
Princeton Plasma Physics Laboratory
P. O. Box 451
Princeton, NJ 08543

Subject: Report of the NSTX Program Advisory Committee – November 1996

Dear Ron:

The newly chartered NSTX Program Advisory Committee (PAC) met for the first time at the Princeton Plasma Physics Laboratory on 21-22 November 1996. In this letter we report on our activities at this meeting and on our initial response to your charge to the committee (copy attached) which asked us to provide comments and advice in 3 areas: (1) Initial NSTX research priorities; (2) Physics requirements for the NSTX design; (3) Preparation for NSTX research. In preparing this report, we were provided with considerable background information by the NSTX Program and Project (as indicated in the attached agenda) and we thank the NSTX team for their well structured and clear presentations.

NSTX Research Program Priorities

Proceeding with a Spherical Torus proof-of-principle program as part of the US fusion effort was endorsed in recommendations by the Fusion Energy Sciences Advisory Committee at its July 1996 meeting together with the FESAC Scientific Issues Subcommittee (SciCom) report on Alternative Concepts. In its report, the SciCom identified the following six issues which should be addressed in a proof-of-principle spherical torus program:

1) Extension of the data base to determine the dependence of plasma confinement on aspect ratio
2) Achievement of high beta by auxiliary heating
3) Development of techniques for clean, efficient, non-inductive start-up
4) Development of efficient current drive techniques for low aspect ratio
5) Achievement of high bootstrap current fraction in advanced operation

6) Long pulse, fully relaxed operation

The mission of the NSTX research program has been defined to be: "prove the physics principles of the Spherical Torus." As described to the PAC by the NSTX Program, the physics program objectives of NSTX which support this proof-of-principle mission have been divided into the following 4 areas, with more detailed physics goals identified for each:

- Confinement and Transport
  - characterize global scaling and local transport properties of plasmas at low aspect ratio
  - identify and characterize microinstabilites which play a role in confinement
  - explore turbulence suppression and transport barrier formation

- MHD Stability and Mode Control
  - identify β limiting processes in low aspect ratio plasmas
  - develop methods to control beta limiting MHD modes and extend the operating β limit

- Non-inductive current drive
  - develop technique(s) for non-inductive start-up of an ST plasma
  - create a near-steady state plasma sustained completely by non-inductive means

- Divertor/SOL Physics
  - effect of large mirror ratio on power handling and SOL
  - characterize H-mode/SOL properties of ST plasma with a natural divertor

The committee concurs that these mission elements are the appropriate primary objectives for the NSTX program, which if achieved would address the 6 issues identified as critical in the FESAC SciCom report. However, the PAC recommends that these detailed physics goals be further refined to more clearly illustrate the unique Spherical Torus contribution to these physics areas. As an example, we have taken the detailed physics goal of "power handling" listed in the NSTX Program presentations under Divertor/SOL Physics and expanded this to highlight 2 unique physical effects expected in an ST.

A plan for the first few years of operation of NSTX was presented to the PAC which is based on a strategy of advancing confinement/beta studies and high harmonic fast wave (HHFW) heating and current drive using inductive start-up techniques in parallel with an effort to develop non-inductive start-up techniques. Machine performance milestones (heating power, β_N, I_p, and pulse length) were established at 3 points during the five-year plan. We endorse this strategy proposed by the NSTX Program and recognize that this research plan acknowledges important fusion concept development issues. We also recommend that the NSTX Program prepare a version of this plan which highlights the

specific physics issues being studied leading up to the achievement of the identified machine performance milestones.

We were asked specifically in our charge to comment on the relative emphasis among the ST physics areas in the first few years of the NSTX research program. The PAC recommends the following priorities:

1) Studies of Transport, Beta, Heating and sustaining current drive, using inductive start-up
2) Non-inductive start-up studies
3) Divertor & SOL studies

While we recognize that it is critically important to the development of the ST concept to discover means for non-inductive start-up, obtaining early results on the transport, beta limits, heating and current drive using the inductive start-up capability of NSTX should get somewhat higher priority. The PAC also recommends that the physics program effort be tightly focused on pursuing the physics areas which are unique to the ST.

At the next meeting of the NSTX PAC, we request an update on the progress in developing a more detailed research plan for NSTX.

Physics Requirements of the NSTX Design

The second element of our charge was to provide an assessment "on a continuing basis" of the operational objectives and the design requirements of NSTX. At each of our next few meetings, the PAC will select a specific aspect of the NSTX design for a detailed examination, beginning with the NSTX diagnostic systems at our next meeting. This process of carrying out a "rolling review" will allow the PAC take a close look at and provide recommendations on each of the major elements of the NSTX device prior to start of experimental operation in FY99. In addition, as part of our initial assessment of the NSTX design requirements, a sub-committee of the PAC will review and provide comments on the draft NSTX General Requirements Document (GRD) and Project Requirements Document (PRD) at our next meeting. This sub-committee will be chaired by Ed Lazarus and include Ken Gentle, Gerald Navratil, Steve Scott, and Yuichi Takase.

Since this was the PAC's initial exposure to the NSTX design, a number of questions and issues were raised. In many cases the NSTX Project is aware of and working on resolving these, but due to limited resources this work is still in progress. Below are summarized a list of these issues, and where appropriate, our recommendations.

Non-inductive start-up

As mentioned previously, the development of techniques for the non-inductive start-up of an ST is a critical issue. While the PAC endorses the plan to test coaxial helicity injection (CHI) as the primary approach to non-inductive start-up of NSTX, we view CHI as a high risk/high pay-off approach. Given the great importance of

this issue, we believe it would be prudent for the NSTX Program to identify and plan for the development of alternative approaches for non-inductive start-up. The use of ECH for non-inductive start-up, as demonstrated on CDX-U, has already been identified by the Program as one possibility. We recommend that the NSTX program actively seek out additional ideas and evaluate their suitability and requirements to test these on NSTX.

With respect to CHI, experimental work on DIII-D using CHI was unsuccessful largely because the strike point control was inadequate to maintain contact with the biased electrode. We recommend that the capability of the NSTX control system (equilibrium coil set and magnetic diagnostics) be reviewed to assure adequate strike point control.

Neutral Beam Heating and Associated Diagnostics

There is a strong consensus by the PAC that adding neutral beam heating and the associated diagnostics (notably MSE for *q*-profile measurements) are essential for achieving the goals of the NSTX Program. However, the required timing of adding these systems is still somewhat unclear. Based on the information available, we believe that a delay of 6 months or less after start of operations in installing NBI/MSE would have little impact on the program, while a delay beyond 2 years would have severe program impact. In order to understand the impact of a delay in the availability of NBI and associated diagnostics on NSTX, we recommend that the NSTX Program more clearly identify when NBI and associated diagnostics are critically needed in the proposed physics program and also examine the option of use of a diagnostic neutral beam for MSE measurements as an interim solution.

The MSE diagnostic is a particularly important diagnostic for the NSTX and we recommend that because of the critical viewing access required for this system, that it be carefully analyzed for expected spatial resolution, signal-to-noise, neutral beam voltage requirements, interference with operation of other heating beams, need for beam modulation, *etc.* Since beam emission spectroscopy (BES) is also a likely upgrade diagnostic, the access requirements (which differ from MSE in general) should be assessed prior to fabrication of the vacuum chamber.

RF Heating and Performance Modeling

A number of questions were raised relative to the plans to implement high harmonic fast wave (HHFW) heating and current drive on NSTX. The strong magnetic field strength gradients in an ST present special challenges and the modeling of NSTX operation with these systems is only beginning. In this context we recommend the Program consider the following questions/issues:

- What is the back up approach in the physics program plan if HHFWCD is unsuccessful?
- If HHFW heating doesn't work in some configurations, what T_e can be achieved with NBI?

We agree with the NSTX Program that carrying out additional modeling studies is important during this next year and we highlight three areas identified during our discussions:

- Additional modeling is needed beyond the present Solovev equilibria studies for cases with the level of plasma diamagnetism expected in well-aligned/high bootstrap fraction equilibria.
- Additional modeling of start-up scenarios with NBI only HHFWCD only, and NBI/HHFWCD is needed.
- The current profile control capability of HHFWCD should also be investigated. In particular, to what degree can the driven current profile be controlled (including the effects of the anti-current drive component of the spectrum)?
- For well-aligned/bootstrap sustained plasmas used as a design basis for NSTX, what values of H and $\chi(\rho)$ are required to sustain these profiles?

Inductive Start-up

The inductive start-up scenarios presented to us assume a dI_p/dt rate of 5 MA/sec. While 2 to 4 MA/sec has been achieved in smaller tokamaks (*e.g.* C-Mod), conventional large tokamak experience (TFTR, JET, DIII-D) is more typically about 1 to 2 MA/sec. Frequently, higher rates of current rise lead to MHD activity and poor confinement. What is the consequence to the physics program if dI_p/dt in NSTX is limited to a lower value?

Equilibrium Control

We note that the expected values of the plasma internal inductance, l_i , in NSTX are much lower than for conventional tokamaks. The design base cases at high beta with 90% well-aligned bootstrap current have l_i ~ 0.2 and CHI start-up cases at low-beta have l_i ~ 0.1. In the equilibrium control space of κ and δ versus l_i which are possible in the NSTX design, these should be plotted and the 'headroom' and control flexibility quantitatively assessed.

Some reactor studies for low aspect ratio tokamaks suggest that higher elongation, κ, may be needed to achieve the necessary plasma current with high bootstrap fraction. What maximum value of κ can the baseline NSTX equilibrium coil set support?

There has been considerable experience in the design of plasma control systems in the DIII-D and C-Mod programs and we support the NSTX Project's plan to use input from these groups in the design of the NSTX control systems.

<u>Preparation for NSTX Research</u>

A plan to form a set of ST Working Groups (STWGs) was described to us for comment. Based on these presentations and the discussion which followed we identified 4 objectives that the NSTX Program indicated it wished to accomplish through the activities of these STWGs:

1) NSTX national team selection and management
2) development of a detailed physics program for NSTX

3) outreach to the fusion community for input into the NSTX program
4) coordination of proposals to DOE for involvement in NSTX

Because of the very project specific nature of the input desired from these STWGs in support of the NSTX Program, we recommend that these be renamed NSTX Working Groups (NSTXWGs) since they will not be acting to coordinate the broader national effort in ST physics which involves Pegasus, CDX-U, HIT, and related theory and modeling activity.

The use of a set of working groups tasked to accomplish objectives 2 and 3 listed above (which involve community outreach and development of a detailed physics program for NSTX), we believe will be very helpful for the NSTX Program and we encourage the Program to proceed with the formation of these NSTXWGs. However, the PAC believes that combining these activities with objectives 1 and 4 would be very inappropriate. Attempts to use this mechanism for team selection and proposal coordination would generate conflicts of interest. The appropriate method for dealing with these issues is either through the NSTX PAC as described in its charter or through a Research Planning Council established within the NSTX Program. We recommend that the NSTX Program obtain information from the TFTR, DIII-D, and C-Mod programs on how they select and manage their multi-institutional teams, as well as review the plans developed for the formation and management of the TPX National Research Team, as input into the definition of a process for NSTX.

Initial Terms of Membership

As described in the NSTX PAC Charter, the 9 regular members of the committee were assigned initial terms of office with 4 members assigned 18 month terms and 5 members assigned 3 year terms at random, so as to provide for an orderly rotation in PAC membership. The term for each member of the PAC is listed below with terms ending on 31 December 1997 for 18 month terms and 30 June 1999 for 3 year terms:

Ken Gentle	Univ. of Texas	(3 years)
Ed Lazarus	ORNL	(3 years)
Farrokh Najmabadi	UCSD	(3 years)
Gerald Navratil, Chairman	Columbia Univ.	(3 years)
William Nevins	LLNL	(18 months)
Stewart Prager	Univ. of Wisconsin	(18 months)
Steve Scott	PPPL	(18 months)
Ron Stambaugh	General Atomics	(18 months)
Alan Sykes	UKAEA/Culham	(3 years)
Yuichi Takase	MIT	(3 years)

Next Meeting of the TPX Program Advisory Committee

The next regular meeting of the NSTX PAC will be in about 6 months in May 1997, as specified in our charter. At this meeting, we expect to include the following activities as part of our agenda:

- NSTX PAC Comments on GRD and PRD documents
- Report on the initial activities of the NSTXWGs
- Update on the NSTX Physics Research Plan
- Review of Diagnostics Plans for NSTX

In closing, the PAC would like to compliment the NSTX Program again for the excellent overview of the NSTX design and physics program they provided to us at our first meeting, and we recognize they are working hard and are committed to making this project a success. We all look forward to continuing to work together with the leadership of NSTX to develop and carry out a scientifically exciting and successful program of research.

Sincerely yours,

Gerald A. Navratil, Chairman
for the NSTX Program
Advisory Committee

cc: M. Ono
M. Peng
S. Kaye
R. Goldston
W. Dove
J. Willis
J. Hoy

M E M O R A N D U M

TO: NSTX Program Advisory Committee

FROM: Ronald C. Davidson

SUBJECT: Charge to the NSTX PAC

DATE: October 31, 1996

Thanks again for agreeing to serve on the NSTX Program Advisory Committee (PAC) which will have its first meeting at the Princeton Plasma Physics Laboratory on November 21 and 22. Gerald Navratil has kindly agreed to be the first chair of the committee.

Attached for your consideration is the charge to the committee, which I hope you can begin to address at your first meeting. Also enclosed is local travel information.

Again, thanks for agreeing to serve on the NSTX PAC. It is my expectation that this committee will play a critical role in establishing research priorities on NSTX and in helping to determine the research program.

Attachments (2)

cc: Robert J. Goldston, PPPL
Dale M. Meade, PPPL
Masa Ono, PPPL
Martin Peng, ORNL
N. Anne Davies, DOE/OFES
John W. Willis, DOE/OFES
Jerry Wm. Faul, DOE/PG

CHARGE TO THE FIRST NSTX PROGRAM ADVISORY COMMITTEE MEETING NOVEMBER 21-22, 1996

1. Initial NSTX Research Program Priorities

   The NSTX facility is designed to be capable of investigating the physics principles of spherical torus (ST) plasmas in the areas of

   i) Noninductive ST plasma formation,
   ii) Heating and current sustainment,
   iii) Magnetics and stability limits,
   iv) Transport and fluctuations, and
   v) Divertor and scrape-off-layer.

   What should be the relative emphasis among these areas for the first 2-3 years of the NSTX Research Program?

2. Physics Requirements for the NSTX Design

   The NSTX physics design requirements are driven by a set of operational objectives, which in turn are defined by the NSTX physics mission. On a continuing basis, we request that the PAC address the following questions: Are the operational objectives appropriate for the NSTX physics mission? Do the design requirements support the operational objectives?

3. NSTX Research Preparation

   A number of Spherical Torus Working Groups (STWG's) composed of fusion researchers in the U.S. are being formed for FY 1997 to provide input to coordinated proposals for the NSTX research preparation activities during FY 1998. What actions should the NSTX Program consider to ensure the national balance among the collaborating institutions? What level of support should be made available to these activities in FY 1998?

National Spherical Torus Experiment
Program Advisory Committee

TFTR Conference Room (LOB-318)
Princeton Plasma Physics Laboratory

November 21-22, 1996

AGENDA

Thursday, November 21, 1996

9:00 AM	Welcome and Introduction	R. Davidson, PPPL
9:20 AM	DOE Comments: Commitment, Mission, Budget, and Schedule	W. Dove, OFES
9:35 AM	NSTX Mission	M. Peng, ORNL
10:15 AM	NSTX Physics Design	S. Kaye, PPPL
11:15 AM	NSTX Near-Term Project Activities	M. Ono, PPPL
12:15 PM	Lunch	
1:15 PM	NSTX Medium-Term Project Activities	M. Ono
2:15 PM	NSTX Research Plan	S. Kaye
3:15 PM	Program Advisory Committee Caucus	
4:15 PM	Program Advisory Committee Feedback	G. Navratil, Columbia (PAC Chair)

Friday, November 22, 1996

9:00 AM	Plans for Building National NSTX Research Team: Formation of ST Working Groups	M. Peng
11:00 AM	Discussion of Plans for the Next Meeting	G. Navratil
12:00 Noon	Lunch	
1:00 PM	PAC Feedback and Preparation of Report	G. Navratil
3:00 PM	Adjourn	