February 27, 2001

Dr. Robert J. Goldston, Director
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Subject: Report of the 10th NSTX Program Advisory Committee Meeting – February 2001

Dear Rob:

The NSTX Program Advisory Committee (PAC) met at the Princeton Plasma Physics Laboratory on 8-9 February 2001 (agenda attached). We received a status report on action items from our last meeting (neutral beam injection and fast ion losses, MSE issues and plans, CHI results and plans, local measurements, and HHFW results and plans). In addition, our activities at this tenth meeting of the PAC focused on two areas in response to your charge to the committee (copy attached): (1) To comment on the recently updated NSTX program plan for the years 2001-3; and (2) to advise you on the key elements of the NSTX Program Letter.

The PAC was impressed with the NSTX program's progress over the last 5 months, including achieving the FY 2000 milestone of injection of 4 MW of HHFW power, applying up to 4.5 MW of neutral beam heating, obtaining ion temperature and flow velocity profiles from the charge exchange recombination emission spectroscopy (CHERS) diagnostic originally used on TFTR, achieving a toroidal average beta of β_T=22% (β_N~4.2), and obtaining an energy confinement times of up to 100 ms with evidence of both H-mode and internal transport barriers. Some intriguing fast particle physics results have already been achieved. The high harmonic fast wave (HHFW) system clearly demonstrated electron heating, with central electron temperatures in excess of 1 keV. A boronization system was installed ahead of the original schedule and gave excellent results. The multi-pulse Thomson scattering system has become a reliable workhorse on the NSTX experimental research program providing routine high-quality density and electron temperature profile data crucial for the on-going research program.

The NSTX Program Plan

The NSTX program plan presented to the PAC shows a near-term emphasis on energy confinement and MHD stability limits, while the important issues of non-inductive current ramp-up (unique to spherical tokamak reactors) and current sustainment (a critical issue for spherical tokamak reactors) are delayed until 2004 and 2005 respectively. The PAC notes that the order in which the NSTX research milestones are scheduled to be addressed has not been altered, and that the delay in achieving milestones is, in part, due to funding limitations which have limited NSTX run time to 13 weeks/year. Nevertheless, the PAC was concerned by the delay of milestones relating to non-inductive current ramp-up and sustainment beyond the FESAC 5-yr assessment point (that is, ~2004), and this single issue dominated the PAC-10 deliberations.

The PAC believes that the NSTX program should focus on issues unique to the spherical torus. Non-inductive current ramp-up and sustainment are critical issues. Is helicity injection current drive (CHI) going to work—and, if not, are there viable alternatives for current ramp-up? What is the schedule and relative priority for these alternatives? Can the plasma current in a spherical torus be sustained non-inductively at a reasonable cost in recirculating power? All of these issues must be successfully resolved if our vision of a spherical torus reactor is to be realized. Hence, the PAC was disappointed to see these important milestones delayed beyond 2003.

The NSTX program noted that this delayed schedule was still consistent with the FESAC 5-year goal of preparing for participation in a burning plasma experiment. Non-inductive current ramp-up and sustainment are less critical to a burning plasma experiment based on the spherical torus concept due to the reduced requirements for pulse length and neutron fluence. Energy confinement, MHD stability limits, and power and particle exhaust are critical to the success of such an experiment. Hence, it is true that the revised schedule for meeting the NSTX milestones would be well aligned with the FESAC schedule and the reduced goal of a burning plasma experiment.

However, the PAC's reaction to this was mixed. Some members were intrigued by the possibility that the spherical torus concept may offer a low-cost route to achieving a burning plasma, while other members were alarmed that the NSTX schedule delays work on some of the critical physics issues for ST power reactors beyond the FESAC assessment point. The PAC concluded that it had not received sufficient information on the prospects of spherical tori as a low-cost route to a burning plasma experiment to resolve this issue.

It is not clear to the PAC that a physics base, sufficient to support a proposal to FESAC for a burning plasma experiment based on the spherical torus will be available by FESAC's the 5-year assessment in (or about) 2004. Even if the NSTX Team believes it likely that such a physics basis could be available, it may (or may not) wish to revise its program strategy accordingly. As a first step the PAC invites the NSTX Team to take 6 months to review its strategy relative to a burning plasma experiment, presenting the result of this review at the next PAC meeting.

Response to the First Charge

The PAC found the NSTX program plan to be responsive to the reports of the FESAC Panel on Priorities and Balance, to the Integrated Program Plan Activity, and to the recent NRC report on the fusion program. The PAC notes that milestones 1 through 3 were met on schedule. We have therefore restricted our attention to the remaining 6 milestones (that is, the milestones numbered 4 through 9).

Milestone #4: Particle and Energy Confinement. Diagnostics are critical to meeting this milestone. The multi-point Thompson scattering system (MPTS) is already supplying reliable profiles of electron density and temperature. The charge exchange recombination emission spectroscopy (CHERS) system is beginning to supply data on the ion temperature and toroidal flow velocity; Early measurement of Z_{eff}, derived from ultrasoft X-ray arrays are in hand (led by Johns Hopkins University), with more information expected from Bremsstrahlung measurements; measurements of the radial electric field and q-profile via the motional Stark effect are still 1-2 years off. Existing measurements of the temperature and density profiles have enabled transport analysis of 3 NSTX shots. This analysis revealed anomalies (for example, heat pinches) suggesting that further work in this area is required. We expect that papers analyzing the confinement in NSTX based on both the MHD and kinetic energies (that is, profiles of n_e,. T_e, and T_i) will be available during this calendar year. The PAC believes that the understanding of confinement in NSTX is best advanced by developing quiescent scenarios with good profile measurements to enable reliable characterization of the local transport. Overall, the PAC believes that the NSTX Team is well positioned to meet this '01 milestone.

Milestone #5: High Harmonic Fast Wave. The PAC commends NSTX on its progress to date, including integration of HHFW into NSTX physics program by, for example, using HHFW during the current ramp to produce an improved target plasma for subsequent neutral beam injection. The PAC believes that the NSTX Team is on track to meet this FY '01 milestone as written. However, the PAC does have some concerns:

Physics Issues: All of the results shown are at the very slowest launched spectrum (peaking at $k_{\|}\approx 14\ m^{-1}$). It is necessary to understand why a faster launched spectrum does not appear to heat in the very limited number of experiments attempted to date. Is this due to parasitic ion absorption? This issue is critical for moving on to HHFW current drive experiments, as current drive phasing (90º between antenna elements) produces just such a fast launched spectrum ($k_{\|}=7\ m^{-1}$). The NSTX Team must continue to emphasize the *quantitative* understanding of electron damping. Such an understanding is necessary for both transport analysis (which requires a well-characterized source) and developing a baseline experimental understanding of damping on thermal ions (prior to the introduction of fast beam ions into HHFW heating scenarios).

Technology Issues: If the NSTX Team is to achieve its goals of high-β and non-inductive current sustainment, then HHFW system must become a tool which is routinely available to experiments unrelated to the physics and technology of RF launchers. At present the *routine* launched power and RF pulse length are well below the design goals. We expect more from this system in view of the low launched power density demanded from the rather large NSTX HHFW antenna. The NSTX Team should aim to make the HHFW system as reliable as the neutral beam system. Can the HHFW system produce a clean 1.3 MW pulse for as long as the neutral beam? Can an H-mode be obtained with HHFW alone at the same power as an H-mode is obtained with neutral beams alone?

Any shortcomings of the HHFW system (as compared to the neutral beam system) could prevent the HHFW from fulfilling its promise as a versatile tool for controlling the NSTX plasma. However, serious current drive experiments await the MSE system, so there still remains a window in time to resolve the physics and technology issues.

***Milestone #6: MHD Stability at High-*β.** NSTX has already achieved $\beta_T \approx 20\%$ without active external control. While reliable measurements of the q-profile (which requires the MSE diagnostic) will not be available, we do not anticipate that this will be a barrier to meeting this 9/02 milestone. Hence, the PAC believes that the program is already well on its way to meeting this milestone (that is, $\beta_T \approx 25\%$ without active external control). The PAC does look forward to reconciliation between the EFIT, MHD, and kinetic estimates of the stored energy since this experimental uncertainty is presently greater than the theoretical or modeling uncertainty in the β-limits. Looking to the future (that is, beyond 9/02) we hope to hear more about strategies for active control of resistive wall modes; and we anticipate that neoclassical tearing modes may become an issue in NSTX as the research moves toward full non-inductive current sustainment (and, thereby to scenarios with large bootstrap current fractions).

Milestone #7: Innovative Techniques for Start-up and Sustainment of I_p. The current strategy for non-inductive current ramp-up is coaxial helicity injection (CHI). The Team has made impressive technological strides, injecting 260 kA into NSTX while keeping the neutral pressure within a range consistent with OH current drive, without excessive impurity generation. However, it appears that (essentially) all of the injected current is on open flux surfaces. The project believes that it will be possible to form closed flux surfaces through a combination of plasma shaping and the application of a toroidal loop voltage using NSTX's central solenoid. This strategy may require the installation of additional PF coils to maintain a good poloidal field null in the insulating break at the top of NSTX. The PAC encourages this modification to the NSTX PF system if it is found to be necessary and cost effective. The PAC would also encourage the project to consider additional diagnostics for CHI experiments—e.g., measurements of asymmetries in the injected current, or of the MHD activity which is thought to be necessary to moving current from open to closed flux surfaces. The PAC is pleased to see the CHI-OH integration experiments and is pleased that the NSTX Team is cognizant of past divertor biasing experiments on DIII-D.

Recommendation: Given the importance of innovative methods for current initiation to the ST program, the PAC reiterates a recommendation from its first meeting (PAC-1)—the project should consider possible alternatives to CHI for plasma start-up, and articulate a path forward for the ST should CHI prove more challenging than expected. This might include some combination of HHFW current drive, bootstrap current ramp-up, or the use of EBW/ECH current drive.

Milestone #8: Edge Heat Flux. The PAC notes that issues relating to power and particle exhaust were (appropriately) given an initial low priority within the NSTX program, and that the effort in this area is now being increased as planned. As such, it is now an appropriate time for the NSTX

Team to articulate a research program for this area. Issues to be addressed might include

1) The structure of the scrape-off layer (SOL) in ST's—Past thinking on the scrape-off layer of ST's has emphasized the possible importance of mirror trapping to the structure of the ST SOL.

2) Exploration of particle control in ST plasmas—particle control is important both to plasma performance in H-mode, and also to scenarios for current ramp-up by bootstrap current overdrive.

3) Determination of the optimal divertor (or limiter?) configuration for a ST reactor.

Key to these efforts will be careful measurements of the profiles of density and temperature in the scrape-off layer and of the profile of heat flux onto material surfaces.

Milestone #9: Integrated Scenarios at High- β ***and High*** τ_E. This FY '03 milestone includes most of the elements of the original Phase II goals: to demonstrate $\beta_T \approx 25\%$ with a 40% bootstrap current fraction for pulse lengths long compared to the energy confinement time. Achieving this is expected to require enhanced plasma confinement, but no active mode control. The plans for facility and diagnostic upgrades appear to be more than adequate to meet these goals given the promising initial results. This includes profile diagnostics for $T_e(r)$, $T_i(r)$, $Z_{eff}(r)$, $n_e(r)$, etc. which will allow local transport analysis, and the characterization of confinement and transport. Sufficient magnetics and MHD diagnostics exist or are planned to allow determination of stability boundaries and to chart interesting scenarios for integrated high-β, high-τ_E operation.

11 MW of heating power appears to be sufficient to achieve the target value of β. With experience, it should be possible to control the discharge evolution through a combination of neutral beam and HHFW heating power. No plans have yet been presented for density control beyond programming the gas puffing. Also, time is needed for exploration and optimization of

relevant operating modes and conditions (e.g., H-mode , MHD activity, power deposition, etc.) The PAC's only critique is that it is not clear why these goals have been delayed until FY '03. They comprise essentially the original Phase II goals of non-inductive assisted operation. Given the rapid pace of development to date in experimental performance facility capabilities, and necessary diagnostics, there would appear to be no show-stopper to achieving the integrated performance goal before '03.

Response to the Second Charge

The PAC believes that the NSTX program has initiated a fair process for choosing collaborators with their solicitation for letters of interest from present and prospective NSTX Team members, and the use of the NSTX Research Forum to provide information to the community on collaboration opportunities. We trust that the program will continue to follow the procedures outlined in the PAC-9 report regarding peer review, etc.

The PAC was not able to provide a comprehensive review of the 8 tables relating to Research Priorities and Collaboration Emphasis, and will limit itself to a few comments on the proposed collaborations. If the project requires detailed comments on this much material in the future it is important to insure that the PAC Chairman appreciates the magnitude of the task well in advance of the PAC meeting.

1) The PAC was pleased to note the intent of the NSTX program and OFES to stagger the terms of NSTX collaborations such that only about 1/3 of them will require review in any given year. However, we note that this same plan had been articulated when the present collaborations were initiated. We hope that this time the OFES will meet with greater success in staggering the length of the various collaborations.

2) Regarding the tables, the PAC suggests that greater priority (i.e., a mark of "H") should be given to measuring profiles in the scrape-off-layer. It is difficult to see how progress can be made in, for example, modeling turbulence in the SOL without well-characterized equilibrium profiles.

In closing, we express our congratulation to the NSTX National Research Team for their very successful completion of the ’00 experimental campaign.

Sincerely yours,

William M. Nevins, Chairman
for the NSTX Program Advisory Committee

National Spherical Torus Experiment
Program Advisory Committee
10th Meeting

Agenda

Princeton Plasma Physics Laboratory
Conference Room LSB-318
February 8-9, 2001

Thursday, February 8, 2001

8:30	Coffee & Donuts	
9:00	PAC Executive Session	
9:30	Goldston	Welcome and Charge to the PAC
9:40	Priester	Comments from DOE
9:45	Nevins	Agenda

I. Research and Facility Plans

9:50	Peng	Research Progress and Milestones Toward the FESAC Checkpoint
10:30	Coffee Break	
10:40	Ono	NSTX Device Status and FY 2001-3 Plans
11:30	M. Bell	FY 2001-3 Operations and Diagnostics Plans
12:00	Lunch	
1:00	Kaye	FY 2001-3 Physics Analysis Plans
1:30	Synakowski	FY 2001-3 Research Program Plans
2:50	Coffee Break	

II. NSTX Program Letter

3:00	Peng	Results of Research Forum and Elements of Program Letter
4:10	PAC Caucus	
5:40	Adjourn	
6:30	PAC Party at Goldstons	

Friday, February 9, 2001

8:30	Coffee & Donuts	

III. Resolution of PAC-9 Actions

9:00	Kaye	Neutral Beam Injection and Fast Ion Losses
9:15	Levinton	MSE Issues and Plans
9:35	Raman	CHI Results and Plans
9:55	LeBlanc	Local Measurements
10:15	Wilson	HHFW Results and Plans
10:30	Coffee Break	
10:40	PAC Caucus	
12:00	Lunch	
1:00	PAC Caucus	
2:00	Nevins	Briefing for PPPL Director
3:00	Adjourn	

Charge to the Tenth NSTX Program Advisory Committee Meeting, February 8 - 9, 2001

New results on a broad number of physics topics have emerged from experiments on NSTX since the last PAC meeting. These have excited the research team and offered new opportunities for accelerating scientific progress. The Reports of the FESAC Panel on Priorities and Balance (see attached pages 7-13 of document) and the Integrated Program Plan Activity (see attached pages 34-37 of document) have identified a set of important goals for the national ST program. In response, last year the NSTX Program identified a set of milestones in support of these goals. Recently, the NSTX Research Forum has contributed valuable input on the activities required to achieve our goals. As a result, the NSTX research program plan for 2001-3 was recently updated and I therefore ask the PAC to review and advise me on the NSTX research program plan during the meeting:

1) Does the research program planned for FY 2001-3 effectively take advantage of the growing capabilities of the NSTX facility and adequately address the key research milestones (see NSTX Research Milestone, 12/00, attached)? Do the requested increments in diagnostics and operation capabilities for these years take advantage of the new scientific opportunities anticipated from NSTX in these years?

A process of rolling reviews was set up by DOE guidance and discussed at the FY 2001 Research Forum. A schedule was described for review and renewal of proposals for NSTX research participation during 2002-5. The Laboratory will submit a Program Letter to DOE in March 2001, which identifies NSTX research priorities and collaboration emphasis, in support of this proposal review and renewal process. I ask the PAC to review and advise me on the key elements of the NSTX Program Letter.

2) Do the proposed NSTX research priorities for 2002-5 properly address the key scientific goals identified by FESAC? Does the proposed NSTX collaboration emphasis appropriately maximize the capabilities and expertise of the NSTX National Research Team in achieving the scientific goals?