Report of NSTX Program Advisory Committee (PAC-17)

January 20 and 21, 2005

Committee Members Present:
James W. Van Dam (University of Texas)—chair
Charles M. Greenfield (General Atomics)
Martin Greenwald (MIT)
Donald L. Hillis (Oak Ridge National Laboratory)
Thomas R. Jarboe (University of Washington)
T. K. Mau (University of California, San Diego)
Michael E. Mauel (Columbia University)
William M. Nevins (Lawrence Livermore National Laboratory)
Paul W. Terry (University of Wisconsin)
Michael A. Ulrickson (Sandia National Laboratory)
Michael C. Zarnstorff (Princeton Plasma Physics Laboratory)

Ex-officio:
Martin Peng (Oak Ridge National Laboratory)
Masayuki Ono (Princeton Plasma Physics Laboratory)

Committee Members Absent:
Cary B. Forest (University of Wisconsin)
Mitsuru Kikuchi (Japan Atomic Energy Research Institute)
Brian Lloyd (UKAEA Culham)

1. Introduction

The NSTX Program Advisory Committee (PAC) held its 17th meeting at the Princeton Plasma Physics Laboratory on January 20 and 21, 2005.

At this meeting, the PAC heard several presentations about research results and plans. The PAC appreciated that there were two major presentations that directly addressed the charges concerning the research and facility plans for FY 2005-2007 and the run-time plan for FY 2005, and that other presentations addressed comments in the PAC-16 report. Further, the PAC appreciated that the talks were clear and concise and that they were available on the NSTX web page prior to the meeting.

Although the experimental facility has been in a planned outage since the preceding PAC meeting (PAC-16, September 2004), new results were presented at this meeting, based on analysis of experimental data. The PAC feels that NSTX has made impressive progress during the past year.

The PAC's general response to the two charges for this meeting is that, overall, both the research and facility plans for FY 2005-2007 and the run-time plan for FY 2005 are very good. More detailed comments are offered in the following sections of this report.

2. FY05-07 Research and Facility Plans

The first charge to the PAC at this meeting was as follows: *Does the proposed research and facility plan for FY05 – 07 appropriately address the evolving priorities of the U.S. Fusion Energy Sciences Program?*

In the cover letter to the PAC describing the two charges, the phrase "evolving priorities" in this first charge was referenced against ITPA high-priority research activities and the priority recommendations of the FESAC Program

Priorities Panel. The PAC noted, however, that the latter have not yet been publicly released; hence a detailed comparison of NSTX plans with the Priorities Panel recommendations is inappropriate at this time. Also, while ITPA and Priority Panel priorities can be useful for NSTX, nevertheless, because the ITPA priority research activities are highly focused on tokamaks and the Priority Panel scope of interest is the overall program (with ITER in mind), the PAC feels that research specific to spherical tori (ST) should also be kept prominent as an important "evolving priority" for the NSTX program.

Concerning NSTX research in general, the PAC thinks that the NSTX team did a good job of addressing critical issues, given the budgetary constraints. The presentations to the PAC showed the relationship of the NSTX program to the setting and fulfilling of science milestones for the national program, to the ITPA goals, and to support (where appropriate) for ITER needs. The PAC feels that NSTX has made strides in identifying how ST-specific features, such as low aspect ratio and high beta, can be used to test and extend generic toroidal physics understanding. The PAC noted that NSTX has gone beyond its original motivation of investigating the ST as a fusion concept; at the same time, the PAC thinks that NSTX currently has a good balance of activities that explore the ST as a fusion concept and of more generic explorations of toroidal physics. The NSTX program also has a good combination of fundamental scientific studies and explorations of new fusion-relevant technologies (e.g., diagnostics, active control, new heating methods, and new plasma-wall concepts). From the presentations, the PAC did get the impression that the proposed research plan may be overly ambitious. Also, the presentation of the proposed program seemed to put too much emphasis on what would be done with the incorporation of incremental funding; the program with such funding should be more clearly distinguished from that without, and this was done in response to the PAC's questions.

Concerning the linkage of NSTX research with ITPA high-priority research activities, the PAC took note that support in several areas was described in the presentations. In particular, there are 13 joint ITPA experiments that have potential NSTX participation, in the areas of confinement, transport, pedestal and edge, divertor and scrape-off layer, macroscopic stability, and steady-state physics. One of the PAC members commented that conventional tokamak programs are increasingly initiating such joint experiments with spherical tori in general and NSTX in particular, and that NSTX (along with MAST) is now accepted as a major player in ITPA activities. While NSTX can certainly contribute to ITPA, it should carry out the research specifically needed for spherical tori—such as solenoid-free startup and sustainment, radio-frequency current drive with EBW and HHFW, and heat and particle handling at the divertor.

Concerning the linkage of NSTX research to FESAC Priorities Panel recommendations, the PAC noted that NSTX research is well aligned with the four main scientific theme areas of the Panel's Interim Report.

The PAC commends the good linkage between the NSTX and MAST research programs. One of the presentations described several areas of complimentary research and comparison studies. Specifically, it was noted by the PAC that NSTX is able to explore very high beta operation with its passive stabilization capability, while MAST, with its large vessel size and in-vessel poloidal field coils, can investigate different divertor solutions and long-pulse issues.

In the following sections, detailed comments are offered concerning the NSTX research and facilities plans. For convenience, we will use the categories that correspond to the six Experimental Task groups of NSTX.

Research Plans: Macroscopic Stability

The PAC is very impressed with the progress on equilibrium reconstruction, which includes rotational effects and kinetic data (essential for reversed shear) and which has now begun to incorporate data from the new Motional Stark Effect diagnostic. The PAC feels that this is among the most precise such work being done in the world today. The reconstruction capability is rapid (between shots) and reliable (2000 shots without a miss). The highly accurate magnetic diagnostics on NSTX, which interface with the equilibrium computations, also deserve praise. The PAC noted that there are plans to nearly double the number of channels for the MSE diagnostic in FY 2005. Currently it has four channels; eight channels are installed and ready for operation; and the number will be upgraded to 14 (contingent on budgetary considerations). The higher number of channels will be useful to resolve equilibrium profiles with shear reversal. The PAC also found interesting the report of the first observation of resonance with AC error fields. The PAC commends the continued research on stabilization of resistive wall modes.

Research Plans: Wave-Particle Interactions

Electron Bernstein Waves (EBW)

Due to the important role of electron Bernstein waves in future advanced operation of NSTX, the PAC is concerned that the planned EBW system is initially earmarked for only 1 MWand would not come online until 2010 under the "base budget" level of funding. Full implementation of the EBW system is 4 MW, which is what is required to sustain operation at 40% beta. Hence, EBW implementation should be given higher priority to ensure the timely attainment of long pulse, high-beta operation on NSTX. The PAC noted that EBW tests on MAST will help NSTX in deciding whether to pursue EBW or high harmonic fast waves (or both); emission experiments on NSTX and modeling results will also help provide a basis for such a decision.

Fast Ion MHD

The effects of fast-ion MHD on flux-balance transport analysis and driven currents should be investigated further. The neutral particle analyzer data from NSTX seems to show that fast-ion MHD could be more complicated than what is indicated from the D-D neutron rate. This issue has implications for transport coefficients and for projection to future ST devices and also ITER. The PAC noted that the effect of instabilities on fast ions and current drive profiles is an important issue and not necessarily unique to spherical tori.

High Harmonic Fast Waves (HHFW)

HHFW current drive is of considerable programmatic interest for the spherical torus. (In addition, fast-wave current drive is a crucial ITER need.) The PAC recommends that the CQL-3D code be incorporated with TRANSP; this will allow integrated modeling for some important scenarios involving HHFW, EBW, and NBI and also aid the analysis of experiments. Resources should be applied to accomplish this soon. Code comparisons for NSTX and DIII-D, with both fast wave RF and neutral beams included in the computations, are also encouraged.

One idea from the PAC is to test whether RF sheaths on antenna structures, touted as a probable cause for the observed HHFW absorption at the edge, could be minimized by realignment of the antenna current to be perpendicular to the magnetic field, e.g., with a simple comb-line structure.

Related to edge coupling degradation, efforts should be made to map out the observed regimes of HHFW heating and current drive, in terms of the launched wave spectrum and plasma beta, in order to facilitate the modeling and design of NSTX current ramp-up scenarios. The PAC recommends increased effort in FY 2005 on HHFW theory and modeling of the problem of poor coupling to the core at low parallel wave numbers and in the presence of neutral beam ions.

Research Plans: Transport and Turbulence

Electron Thermal Transport

Electron thermal transport is a well-chosen topic in terms of its importance in the world program, and the NSTX investigations in this area take advantage of its unique characteristics and of opportunities for collaborative research with other experiments. The emphasis on fluctuation measurements at higher wave numbers is appropriate, given the theoretical focus on the electron temperature gradient-driven mode (ETG) as a natural extension from prior successful ITG work. However, it is not a foregone conclusion that electron thermal transport resides in high-wave-number fluctuations, nor that ETG causes significant electron thermal transport. Hence it is important to develop contingencies if high-k fluctuations are not the source of anomaly for electron thermal transport. NSTX seems to be doing this with respect to measuring both low-k and high-k fluctuations. With the high beta plasmas in NSTX, another mechanism to consider is that of magnetic fluctuations, for which diagnostic capabilities at a variety of scales would need to be developed.

Much of the micro-turbulence theory work reported for NSTX is concerned with the development and enhancement of comprehensive codes, whose results are compared with experimental data. However, comparisons of radial wave number spectra and diffusivity profiles do not provide sufficiently stringent tests of the underlying physics models; more detailed diagnostic measurements would be helpful. Also, for isolating physical mechanisms, the comprehensive code effort should be complemented with the use of reduced codes and analytical theory—e.g., to explain why the simulations show that non-adiabatic electrons enhance the low-k transport.

Momentum Transport

The plans to "develop a fully nonlinear treatment with self-consistent momentum transport" in a simulation code are laudable, but rather ambitious, since not much is yet known about momentum transport in fusion plasmas. This could likely become a multi-year project. Direct experimental measurements of fluxes and flux correlations would be helpful, for example, to obtain a well-characterized χ_ϕ. One suggestion from the PAC is to utilize transient experiments (such as used on C-Mod), with braking coils and neutral beams turned on and off. A particular project would be to develop methods to measure the Reynolds stress, which may govern anomalous momentum transport.

Research Plans: Edge Physics

Scrape-Off Layer and Pedestal Physics

The NSTX team is commended for having a detailed, well-thought-out research plan for SOL and pedestal physics, including new diagnostics (e.g., additional Thomson scattering channels and high-speed infrared camera) and better control of the boundary location. These studies directly address one of the main areas in the FESAC Priority Panel's Interim Report, viz., boundary-plasma interface. Long-pulse and high-power studies are also very relevant.

Cross-field SOL transport is a current topic of high interest, because it may help explain a great deal of edge and divertor phenomenology. One of the high-priority ITER needs is that of SOL/main chamber interactions, which is related to the question of SOL transport. NSTX should take the opportunity to study it.

Edge Turbulence

The possibility that shear Alfvén waves contribute significantly to turbulence in the edge pedestal region may be another consequence of the high-beta nature of NSTX plasmas. The BOUT code appears to observe this, although fluid codes see resistive ballooning instead. Experimental studies on NSTX could help resolve the question through measurements of the basic properties of the turbulence, such as the equipartition of velocity and magnetic field fluctuations and the phase angle. It would also be worthwhile to explore collaborations with other machines (e.g., LAPD and MST) for which shear Alfvén turbulence is known to be important.

Power Footprint on Divertor

Implementation of the fast IR camera will be useful for understanding ELM heat deposition in the divertor, which is a key ITPA and ITER need. If the camera can see the outer regions of the outer divertor plate, it could also study ELM effects on the first wall near the divertor, another issue of interest to ITER. The PAC discussed whether the IR measurements would have adequate resolution to measure the power footprint on the divertor (cf. the JET solution of moving the plasma over an array of thermocouples). NSTX has a plan for checking this question.

Wall Pumping and Particle Control

Given the sensitivity of HHFW and EBW to plasma edge profiles and conditions, along with the desire to study pedestal physics and ELM characteristics, it would be prudent to conduct the lithium pellet preparation experiments as early as possible during the run in order to allow maximal opportunity for realization of particle and density control under a variety of plasma conditions. Injection of lithium pellets may provide sufficient wall pumping capability; however, NSTX should be ready to implement lithium evaporation at the time of the checkpoint near the middle of the run period. If there are plans to use the lithium evaporator technique in other devices, it would be useful to measure the poloidal and toroidal coverage of the lithium coating.

Some density control is obtained from glow discharge cleaning between shots, at least for short pulse lengths; this should be quantified. It would be interesting to explore whether lithium deposition is related to glow between shots.

It appears that the wetted area of the divertor plates is reduced in plasmas with high elongation and high triangularity, because the heat flux is squeezed into a small area. For long pulse and high power, this would exacerbate heat and particle loads on the divertor. Other consequences are that particle pumping with a cryo-pump would be made more difficult and the optimum position for lithium flow would be complicated. The trade-off between particle pumping and stability benefits with high elongation and high triangularity should be looked at.

An idea proposed for long-pulse pumping is to put a cryo-pump either below the CHI injector slot or above the CHI absorber slot. The CHI voltage can provide an $E\times B$ flow into the CHI gap and on into the cryo-pump cavity. CHI voltage can act as the pre-pump to feed the cryo-pump with high-pressure gas, thus lowering the cryo-pump cost. Also, cryo-pumping in the absorber would augment CHI by preventing density build-up in the absorber.

Neutral Transport Modeling

A suggestion from the PAC is to take the supersonic gas injector to the point where it condenses via nozzle expansion, for possibly better penetration with micro-droplets.

Research Plans: Solenoid-Free Startup

Solenoid-free operation is a critical need for NSTX (due to the small area available for transformer flux) and for future reactor-class spherical torus experiments, and is also relevant for tokamaks (operating in the AT mode). NSTX is investigating two solenoid-free startup methods: coaxial helicity injection (CHI) and poloidal-flux only inductive startup. In FY 2005 the primary goal with CHI is to form a startup closed-flux current with the use of a capacitor bank. With the improvements of lower pre-ionization at lower fill, higher capacitor bank voltage, and faster bank turn-off, this goal should be achievable. The key measure of success will be the formation of closed-flux current, persisting after the injector current ceases. The primary goal of PF-only startup will be the demonstration of plasma current generation, to be subsequently optimized. With increased HHFW power, local pressure enhancement, and higher toroidal field capability, this goal should also be achievable. Both of these solenoid-free startup methods will benefit from the opposite-polarity power supply capability that will be added to the PF5 coil.

Research Plans: Integrated Scenario Development

The PAC is interested in whether realistic scenarios could be developed with higher bootstrap fraction than at present. It appears that the bootstrap current is limited because the amount of neutral beam current drive is fixed by the heating needed to achieve the desired beta value. Higher bootstrap fraction may involve replacing some NBI power with HHFW. This might be used to justify future consideration of a counter beam. At the same time, however, reduced neutral beam current drive goes hand in hand with reduced rotation, thereby raising concerns about resistive wall mode stability, which would need to be studied.

Facility Plans

The PAC had a few comments concerning plans for the facility. First, the PAC felt that the NSTX team is handling the toroidal field flag joint repairs well; hopefully the full TF capability will be restored fairly soon. Second, the problems reported at this meeting concerning cracks in the motor generators are somewhat alarming; the repair and refurbishment could be rather expensive. However, the NSTX plan to deal with the MG problem appears to be adequate, in terms of schedule adjustment and resource shifting.

3. FY05 Run-Time Plans

The second charge to the PAC at this meeting was as follows: *Does the proposed FY2005 experimental run plan make good use of the available capabilities to achieve the FY2005 research milestones and support the FY2006 and FY2007 plans?*

The PAC felt that the NSTX team has generally done a good job of planning how to distribute run time and resources to achieve their FY 2005 milestones and support out-year plans. The capabilities of the machine are still ramping up, and the FY 2005 program appears to set aside time to take advantage of new capabilities, as needed. Also, the run plan is reasonably balanced in allocating an appropriate amount of experimental time to meet NSTX milestones, investigate ST-specific topics, and also address ITPA commitments on high-priority research activities. Apparently the NSTX Research Forum was helpful for digesting the various demands on run time and formulating reasonable research proposals.

The PAC wondered whether the FY 2005 program is overly ambitious. With the fairly long and detailed list of tasks (78 bulleted items for 71 run days) in the run plan, the question arises whether enough experimental days will be available to accomplish these tasks and, at the same time, meet the NSTX milestones. The level of effort that will be needed to repair the motor generator problem could also have an impact on the aggressive research program if the repairs were to take longer than expected. The PAC is confident, however, that NSTX management will focus and prioritize the research effort appropriately in the event the operational period is compressed.

Specifically concerning Transport and Turbulence, the PAC feels that this year’s milestone of characterizing the safety factor gradient and electron temperature gradient effects on electron thermal transport will make good use of the MSE diagnostic and the additional Thomson scattering channels. Also, the high-k scattering to be commissioned this year will support next year’s milestone of measuring high-k turbulence. Hence the machine is on its way to meeting the milestones in this Experimental Task area.

Concerning Edge Physics, the PAC thinks that lithium evaporation looks promising for particle control; however, since it is still a new method, acceptable cryo-pump geometries should continue to be evaluated, so that at the 2007 decision point, no time be lost in providing particle control for long-pulse NSTX operation. For the 1-2 second discharges planned for the near term, additional studies of more aggressive boronization and helium glow discharge cleaning between shots may provide the needed particle control. The new Thomson channels mentioned in the preceding paragraph also support Edge Physics milestones for this year.

Concerning Solenoid-Free Startup, the PAC recognizes the importance of this part of the NSTX program and supports the approach being taken. There is a concern that eight days of run time in FY 2005 may not permit enough progress for the FY 2006 and FY 2007 assessments to be positive. However, the 14 days of contingency in the FY 2005 plan could allow for more time if used effectively. The PAC appreciated the fact that the research program has contingency plans in case the method of coaxial helicity injection does not work on NSTX.

Concerning Integrated Scenario Development, the FY 2005 milestone of 50% bootstrap fraction and low (but not zero) loop voltage appears to be achievable, since it is not a huge extrapolation from what has already been achieved.

4. Future PAC meetings

Schedule:
At a previous meeting (PAC-15, January 2004), common consent had been reached that a single annual PAC meeting would be sufficient, since NSTX has now developed into a mature program. At the present meeting, the PAC affirmed this sentiment. The PAC, furthermore, suggested that the NSTX management consider a two-day format spread over three days (i.e., beginning at noon of Day One and ending at noon of Day Three) for the annual meeting. If the NSTX program were to desire feedback from the PAC about the mid-year collaboration proposal renewal process, this could probably be accomplished by means of a teleconference call.

Topics:
At a future meeting, the PAC would like to hear about the NSTX overall plan for solenoid-free startup and sustained-pulse operation (from plasma breakdown, through initiation and ramp-up, to current flat top), including a discussion of the requirements for high bootstrap current fraction and a discussion of the role of current drive tools needed for long-term NSTX integrated scenario goals and their development schedule (with decision points).

APPENDIX A — PAC-17 Charge

National Spherical Torus Experiment
Program Advisory Committee
17th Meeting

Princeton Plasma Physics Laboratory
Conference Room LSB-318
January 20-21, 2005

CHARGE

Substantial evolution in the priorities of the U.S. Fusion Energy Sciences Program has occurred during 2004. Key elements in this evolution include the recent scientific recommendations of the FESAC Priorities Panel, and the approaching U.S. participation in the ITER Project with the associated increased importance of the International Tokamak Physics Activities (ITPA). The NSTX Program plans for FY2005 – 2007 and the specific FY2005 run plan need to be examined in light of these developments. The NSTX Team is preparing to present to the PAC for advice an updated description of these plans. It would be helpful if the PAC could address the following two questions:

1) Does the proposed research and facility plan for FY2005 – 2007 appropriately address the evolving priorities of the U.S. Fusion Energy Sciences Program?

2) Does the proposed FY2005 experimental run plan make good use of the available capabilities to achieve the FY2005 research milestones and support the FY2006 and FY2007 plans?

APPENDIX B — PAC-17 Agenda

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AGENDA

Thursday, January 20, 2004

8:30	Coffee & Donuts, PAC Caucus	
8:45	Rob Goldston	Welcome and Charge to the PAC
8:50	Steve Eckstrand	Comments from DOE
8:55	Jim Van Dam	Agenda and Plan of Meeting
9:00	Martin Peng	Actions Items and Introduction
9:20	Ed Synakowski	Research Plan for FY2005 – 2007
	(10:00 Coffee)	
11:00	J. Manickam	Planned Contributions from Theory and Computation
12:00	Lunch	
1:00	Masa Ono	Facility Plan for FY2005 – 2007
2:30	Bob Kaita	Plans for Particle Control
3:00	Coffee	
3:15	Jon Menard	FY2005 Run Plan
4:45	PAC Caucus	
6:00	Adjourn	
7:00	PAC Dinner	Residence of Michelle and Martin Peng

Friday, January 21, 2005

8:30	Coffee & Donuts	
8:30	Steve Sabbagh	Equilibrium Reconstruction Accounting for MSE Data
9:00	Coffee & PAC Caucus	
12:00	Lunch	
1:30	Jim Van Dam	Debriefing
2:00	Adjourn	