# Report of NSTX Program Advisory Committee (PAC-16)

### September 9 and 10, 2004

**Committee Members Present:**
James W. Van Dam—chair (University of Texas)
Cary B. Forest (University of Wisconsin)
Charles M. Greenfield (General Atomics)
Donald L. Hillis (Oak Ridge National Laboratory)
Thomas R. Jarboe (University of Washington)
Mitsuru Kikuchi (Japan Atomic Energy Research Institute)
Brian Lloyd (UKAEA Culham)
T. K. Mau (University of California, San Diego)
Michael E. Mauel (Columbia University)
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:**
Martin Greenwald (MIT)
William M. Nevins (Lawrence Livermore National Laboratory)
Paul W. Terry (University of Wisconsin)

## 1. Introduction

The NSTX Program Advisory Committee (PAC) held its 16th meeting at the Princeton Plasma Physics Laboratory on September 9 and 10, 2004. The PAC had a new chair (J. Van Dam) and several new members (D. Hillis, B. Lloyd, T. Mau, M. Mauel, and P. Terry).

At this meeting, the PAC heard presentations about recent research results and about program priorities. The PAC appreciates that the talks were well prepared and well presented.

From the presentations, it was evident that the NSTX Team had decided to re-categorize its research program in terms of the scientific issues being proposed by the FESAC Priorities Panel. The PAC compliments the Team for adopting this modern approach. The new categories, apart from each being expressed as an explicit statement about an issue, clearly map from four of the previous five categories. Non-inductive operation is no longer a category per se, but is subsumed within the category having to do with macroscopic stability; the PAC trusts that this does not portend a de-emphasis on the subject of long-pulse/steady-state issues, which are critically vital to the NSTX mission of assessing the attractiveness of the ST as a fusion energy concept. Another observation about categories, which almost goes without saying, is that cross-cutting issues—e.g., pedestal physics and 100% non-inductive operation—are not adequately defined in terms of a single topical science area.

The activities of the PAC at this meeting were largely focused on responding to the charge to the Committee: viz., to review and recommend adjustments to the research priorities and collaboration opportunities that were proposed in the draft of the NSTX Program Letter for 2005-2007. At the same time, the presentations about recent results provided background for addressing this charge.

At future PAC meetings, we look forward to hearing presentations by the NSTX team that describe overall progress to meet program goals.

In what follows, we first respond to the charge for this PAC meeting and then offer comments about the recent NSTX research results.

## 2. NSTX Program Letter

About one-third of the NSTX research program is conducted through collaboration activities involving non-PPPL scientists from the US and abroad. These collaborations are funded by three-year grants from the DOE Office of Fusion Energy Science, totaling about $5M per annum. Each year some fraction (30-40%) of these grants comes up for review. This year the grants that are from university and industry groups and that involve neither construction nor implementation of diagnostics are up for renewal.

The solicitation announcement (http://www.sc.doe.gov/grants/FAPN04-24.html) promises that "updated information on the NSTX research priorities and collaboration opportunities during the next three years" will be provided for new and renewing submitters of proposals. Originally, the draft for the Program Letter from the NSTX Team proposed to give this advice by assigning to each research element within the four research areas a rating (high/medium/low) for research priority and a separate rating (high/medium/low) for collaboration opportunity, with asterisks added to the latter for those research elements involving work that would come up for renewal this year. These types of ratings are the same as those used in the 1999 Program Letter.

The members of the PAC, however, were confused by the multiple meanings apparently associated with the two rankings and the asterisks. To simplify matters for those who will submit proposals, the PAC therefore recommends deleting the rankings and the asterisks, and simply listing the high-priority research elements that are especially relevant to this year's solicitation. A fairly comprehensive list of ST scientific issues is already given in the solicitation announcement; our recommendation is to highlight a subset. Of course, innovative ideas on other scientific problems should also be welcomed.

We recommend that the Program Letter use the four revised tables that are contained in this PAC report. Language in the body of the Program Letter should be modified so as to be in accord with the revised tables.

In composing these revised tables, the PAC everywhere deleted the statement "Compare with theory and modeling." Proposals should be free to use whatever means—experiment, theory, modeling, or some combination thereof—are considered appropriate.

To avoid confusion, the Program Letter should specify whether "2005-2007" means calendar or fiscal year periods.

One of the grants up for renewal this year involves diagnostics work. The PAC wonders whether this grant could be given a one-year extension in order to synchronize it with other diagnostic grants.

As previously noted, the new overall categories for NSTX research are now based on science issues. However, many of the research elements within the categories are not yet described in terms of science issues. An example is the category related to Waves and Energetic Particles, several of whose research elements are techniques (EBW, HHFW, NB). It would be better if these research elements were described in terms of science issues. Since the deadline for the Program Letter is imminent and since the tables in their present format are still helpful to potential submitters of proposals, the PAC is content that the NSTX Team might consider this suggestion in the future.

## 1) Understand the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained magnetic configurations.

| Research Elements |
|---|
| Develop equilibrium reconstruction and tool development for between-pulse and post-pulse analysis<br>– Take into account sonic flow, energetic ions, very high beta, and other non-ideal affects important for low aspect ratio<br>– Integrate diagnostic data to obtain accurate equilibrium<br>– Identify effects of bootstrap and diamagnetic currents |
| Develop real-time plasma control capability for important ST objectives, including:<br>– Solenoid-free current initiation, ramp-up, and sustainment scenarios/techniques<br>– Precise control for highly shaped plasma |
| Characterize and understand effects on neoclassical tearing modes and on other internal stability modes from:<br>– Plasma profiles<br>– Sheared sonic flows<br>– Externally driven, localized currents<br>– Low aspect ratio |
| Characterize and understand effects on external beta-limiting modes from:<br>– Nearby passive conductors<br>– External and plasma-induced non-axisymmetric fields<br>– Plasma rotation and its damping<br>– Active non-axisymmetric magnetic field modifications<br>– Plasma shape modifications<br>– Low aspect ratio |
| Characterize and understand effects on H-mode pedestal and ELM properties from:<br>– Edge stability<br>– Flow effects on edge phenomena<br>– Low aspect ratio |
| Characterize and understand magnetic reconnection and stability associated with<br>– Co-axial helicity injection<br>– Outer poloidal-field-only plasma initiation |

## 2) Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas.

| Research Elements |
|---|
| Characterize and understand low- and high-k core plasma turbulence mechanisms in a variety of confinement regimes<br>– Includes linear and nonlinear gyrofluid and gyrokinetic simulations taking into account the effects of sonic flows and order-unity beta |
| Characterize and understand low- and high-k edge plasma turbulence mechanisms in a variety of confinement regimes<br>– Include flows, field structure, and electromagnetic effects |
| Update and apply neoclassical transport model to low aspect ratio plasmas<br>– Sonic flows<br>– Flow shear<br>– Radial electric field effects<br>– Finite orbit effects<br>– Very high beta |
| Characterize and understand core transport coefficients and fluxes and their parametric dependences in a variety of confinement regimes<br>– Including transport barriers, driven and spontaneous flows, etc.<br>– May include both dimensional and dimensionless approaches |

## 3) Learn to use energetic particles and electromagnetic waves to sustain and control high temperature plasmas.

| Research Elements |
|---|
| Characterize and understand EBW coupling, power deposition, and current drive<br>– Emission<br>– Launching<br>– Mode conversion<br>– Propagation<br>– Absorption by passing and trapped electrons<br>– Current generation<br>– Effect of electron transport on current drive efficiency |
| Characterize and understand HHFW coupling, power deposition, and current drive<br>– Launching, launcher-sheath-edge interactions<br>– Propagation, absorption by electrons, hot thermal ions, and fast ions<br>– Current generation<br>– Linear mode conversion, nonlinear mode coupling<br>– Effect of electron transport on current drive efficiency |
| Characterize and understand NBI power deposition and current drive<br>– Effect of finite gyroradius and large guiding center orbits<br>– Resulting effects on fast ion driven bootstrap currents<br>– Effects of fast ion driven instabilities on driven currents |
| Characterize and understand current initiation and current ramp-up by rf waves (HHFW and/or EBW), and the transition to NBI-driven plasma<br>– Breakdown modeling<br>– Control system development<br>– RF heating of electrons on open flux surfaces<br>– RF heating at low electron temperatures |
| Characterize and understand interactions between fast-ion driven modes and the fast ions, including effects of:<br>– Fast ion energies, density, and profiles<br>– Plasma profiles<br>– Low aspect ratio |

## 4) Learn to control the interface between a 100-million-degree plasma and its normal temperature surroundings.

| Research Elements |
| --- |
| Characterize and understand the plasma edge, including<br>– Plasma particle and heat fluxes, recycling, and impurity fluxes<br>– ELMs and edge transport barriers (H-mode pedestal)<br>– Erosion and re-deposition of divertor and first wall materials<br>– Plasma power distribution<br>– Edge and SOL turbulence, including intermittent ejection of filaments and “blobs”<br>– Effects of varying the aspect ratio (in/out asymmetry)<br>– Plasma edge configurations and conditions, including conditions governing access to radiative divertor regimes |
| Develop control of ELMs and non-diffusive transport<br>– Investigate methods for controlling ELM size while maintaining high plasma performance<br>– Understand heat fluxes to the secondary null in single null plasmas |
| Characterize and understand the effects of wall treatment on in-vessel materials<br>– Lithium coating<br>– Boronization<br>– Carbon composites, boron-nitride, aluminum, etc.<br>– Dust formation and distribution |

## 2. Research Results from FY04 Run Year

We congratulate the NSTX Team on an extremely busy and productive run year. After the facility had been shut down for a year for repairs, the research program came roaring back. We applaud the Laboratory for finding the funds to support three additional weeks of run time, for a total of 21 run-weeks (an NSTX record and an OFES priority).

Quite a few new and exciting physics results were reported to the PAC. It appears that very good progress has been made in almost all areas of the NSTX research program.

The PAC discerned that the FY04 run year had two notable characteristics. The first is that there were a number of "firsts": e.g., the commissioning and first light of the MSE diagnostic, the first measurement of turbulent fluctuations in the core of a low-aspect-ratio plasma, the first application of transient coaxial helicity injection. The second characteristic pertains to the prevalence of cross-machine comparison experiments: e.g., similarity experiments on electron thermal transport (with MAST and DIII-D), joint experiments on RWM stabilization, comparison experiments on the aspect ratio dependence of mode structure for Alfven eigenmodes (with DIII-D), and comparison experiments (with MAST) on confinement and L-H threshold transition physics. The PAC definitely encourages such joint experiments.

The PAC also encourages more theoretical calculations for NSTX. In general, these activities tend to be under-reported in the presentations to the PAC.

### *Macroscopic plasma behavior:*

High beta access

The new, high-speed equilibrium control system is a big success. Already NSTX has shown increased ability to achieve high-beta and high-beta-poloidal discharges.

Results showing that the operation regime in ($l_i$, κ) has been extended by 30%, with numerous data points at high beta ($\beta_t$ > 30%), are noteworthy. Moreover, the sustainment of discharges with ($\beta_t$ > 30% for up to two energy confinement times is an important step toward the NSTX research goals, even though this is still transient, with further effort required to sustain it in quasi steady-state. Implementation of the PF1A coil upgrade next year should allow access to even higher beta values by means of advanced shaping.

Non-inductive current

The achievement of a significant amount (~60%) of non-inductive current drive is quite impressive. This is also promising for the future extension of NSTX performance.

Developing the technology for solenoid-free startup, current ramp, and plasma current sustainment is important for the NSTX program, since one of its primary goals is to assess the ST as an attractive fusion concept. (Solenoid-free startup is also an area rich in reconnection physics and general plasma science.) Hence, it is notable that transient coaxial helicity injection (CHI) for solenoid-free startup was employed for the first time on NSTX. Some good progress has been made with this technique; however, plasma current that lasts beyond the end of the injector current is needed. Operating at 2 kV is an important experiment and will probably help. The PAC supports the view that density control needs to be achieved so that the Greenwald limit is not violated. Puffing gas and putting ECH power in the injector would be helpful for density control.

Poloidal field-only startup has also been begun. Achieving 20 kA is a good start for current that is produced with outer PF coils only. PF induction thus joins CHI as one of the major approaches to solenoid-free startup. The goal now for PF-only startup is to increase the available flux swing; ideas for doing so should be explored.

Equilibrium reconstruction

Progress in using the EFIT code for between-shot equilibrium reconstruction, including rotation and "partial kinetic" data, is striking.

Resistive wall mode stabilization

The results concerning stabilization of resistive wall modes (RWM) are very positive. Two (of the planned six) active feedback coils for RWM stabilization have been deployed. Also, new internal sensor arrays permit the observation of mode detail. The good comparison of the new internal magnetic sensors with external sensors bodes well for future efforts on active control of the RWM and other MHD modes. In particular, the reduction in the density at which locked modes occur is an encouraging result. RWM modeling has made good progress, with unstable RWM dynamics shown to be consistent with theory. Furthermore, the observation of resonance with an AC error field was reported. Taking into account the effect of AC resonances in resonance field amplification is important.

Neoclassical tearing modes

As the beta values in the discharges are now routinely large, tearing mode studies are becoming more important. Electron Bernstein waves (EBW) could be useful for stabilization of neoclassical tearing modes. Since EBW propagation characteristics are very sensitive to the vertical position of the launch point, the capability of varying the location of the launch point should be considered, for use as a control knob.

### *Multi-scale transport behavior:*

Just as the macro-stability studies have benefited from the installation of new diagnostics, so also has the investigation of multi-scale transport behavior. High-resolution CHERS, which finds high rotation and large gradients in ion temperature and toroidal shear velocity, has been a significant addition to NSTX. Also, correlation reflectometry came online and allowed, for the first time, the ability to quantitatively characterize long-wavelength turbulence in the core of a low-aspect-ratio plasma (L-mode). This reflects major progress in core transport measurements.

### *Waves and energetic particles:*

Electron Bernstein waves (EBW)

This past year the EBW studies changed from viewing the X-mode to also viewing the O-mode with the installation of a new obliquely viewing antenna. OXB with polarization control of launched wave appears attractive as a coupling technique. Experimental verification of the Ohkawa current is an important experimental goal.

Measurements of equal quantities of emission in X and O mode (due to EBW) suggests that polarization control of the launched wave will further optimize OXB coupling. This is an interesting result. It will be important to follow this up with direct polarization measurements in future experiments.

The proposal for a ~1 MW EBW experiment should be given serious consideration. Interestingly, theory and simulations indicate that EBW can drive significant amounts of off-axis current in NBI-heated high-beta NSTX plasmas, free of interactions with energetic beam ions.

Because of their highly localized deposition, electron Bernstein waves are also suitable for suppressing neoclassical tearing modes (as mentioned earlier) and, potentially, for plasma initiation and current ramp-up.

However, electron radial transport effects can potentially degrade the localization and current drive efficiency for electron Bernstein waves, and this issue should be investigated.

The PAC suggests theory and modeling efforts to address the following issues:

— Investigate the role of electron transport on current drive efficiency and localization.
— Explore the role of the Ohkawa current over a wider parameter range and compare CQL3D results with similar calculations for MAST from BANDIT-3D.
— Consider whether parametric decay instabilities might be an issue for coupling to the EBW.

High harmonic fast waves (HHFW)

High Harmonic Fast Wave RF is one of the scenarios for non-inductive current drive for NSTX. From the observational data, it appears that HHFW does not couple well during neutral beam injection, especially at 7 $m^{-1}$. Additional run time on NSTX should be devoted to studies of the interactions of RF with neutral beam-heated plasmas in order to improve coupling efficiency and make significant progress toward determining the role of HHFW for non-inductive current drive operation for NSTX. In particular, heating by HHFW in H-mode plasmas in the presence of neutral beams needs to be further studied.

HHFW absorption has significant dependence on both the wave number and its direction (co/counter angle). However, the mystery of why the HHFW heating efficiency decreases with $k_{\|}$ is beginning to be understood. This appears to be caused by parametric decay instabilities with the launched fast wave, which results in loss of power at the plasma edge, as shown by RF probe measurements near the edge. This can potentially limit the utility of HHFW as a current drive and heating technique and should be investigated thoroughly. Other possible causes, such as scattering off edge density fluctuations and excitation of coaxial modes, should also be given due attention.

As with EBW, the effect of electron transport on HHFW current drive efficiency is an important issue and should be explored.

As time-resolved, MSE-constrained EFIT comes online, non-inductive current profile analysis should be high priority. Comparisons of measured non-inductive current profiles with modeling results from codes (AORSA, CURRAY) are important.

<u>Fast particle physics</u>
NSTX affords a unique testbed for advancing the understanding of fast particle/wave interactions, as indicated by its active research program in this area. A wide range of Alfvén wave turbulence can be investigated in NSTX, due to its large population of super-Alfvénic fast ions. It was reported that fast ion losses do not exhibit expected scalings with plasma current or beta, but in fact appear to have no dependence. Further study of this would be warranted.

### ***Plasma boundary interface:***
<u>Detachment</u>
It was reported that the inner divertor can be detached, which thus reduces the heat flux to the divertor. A challenge is to search for ways to achieve outer divertor detachment. The PAC encourages collaboration with MAST to compare results on detachment.

<u>ELM studies</u>
Apparently a new type of ELM has been observed on NSTX. The Hiroshima divertor fast camera has been useful in these studies. ELM severity is seen to depend strongly on elongation. The PAC looks forward to studies with the ELITE code of ELM and edge pedestal stability at low aspect ratio. Such studies are underway at MAST, and the PAC encourages close collaboration with both the MAST team and the DIII-D team in this area.

<u>Boronization</u>
The PAC notes that further optimization of boronization procedures has contributed to improved access to high performance operation. However, there can be problems with over-boronization. Daily/morning (or almost daily) boronization may lead to problems with the flaking of coatings, as has been observed on COMPASS from long-term boronization. UFO’s may be an indication of potential problems. An eye should be kept on the inventory of coatings like B, Li, etc.

<u>Recycling</u>
Two new systems for particle control (lithium pellets and supersonic gas injector) were commissioned on NSTX. So far there are only some initial results, with more results expected to be forthcoming next year.

The realization of current drive scenarios will probably require the control of recycling in NSTX. Currently most of the emphasis is on solutions that require pumping via lithium evaporation, lithium coatings, or lithium pellets. More evaluations may be necessary to determine how thicker lithium layers will interact with various materials inside NSTX and whether flaking will be a problem with continued application of lithium. Some additional effort should probably be focused on evaluating the feasibility of a pumped divertor for continuous particle removal.

The PAC took special note of the fact that a decision point is approaching in FY06 for deciding between a lithium module or a cryopump. Meanwhile, in FY05, deposition techniques with lithium pellets will be seriously pursued, while a lithium evaporator has been delayed for one year due to resource constraints. The PAC is concerned that NSTX should have a strategy and a schedule of planned activities geared toward preparing for this decision point. Perhaps this was simply neglected in the presentations to the PAC. We suggest that this issue be dealt with at the next PAC meeting.

### ***Facility and diagnostic upgrades:***
Many of the interesting and high-quality results of the past year were obtained as the consequence of the installation of new diagnostics and various upgrades to the facility.

Quite a few new diagnostic capabilities (new or upgraded) were added during FY04. Especially impressive are the control system upgrade, the 8-channel MSE diagnostic, the fast tangential X-ray camera, the 51-channel CHERS diagnostic, edge rotation measurements, upgraded correlation reflectometry, and the divertor visible camera.

The PAC noted the decision to delay purchase of additional CHERS spectrometers and detectors by one year due to resource constraints.

Motional Stark effect diagnostic (MSE)

The PAC was very impressed with the progress made on the MSE diagnostic. This is a crucial measurement for NSTX in evaluating current profiles. It will greatly facilitate the analysis of non-inductive current drive profiles and improve the understanding of equilibria and the evaluation of stability and transport. MSE had first light in January 2004. Eight channels were successfully operated, although it was limited to four detectors. So far it has yielded initial measurements for current profile evaluations. The PAC looks forward to its use in EFIT equilibrium reconstruction.

TF flag joints

The PAC appreciated the report from the NSTX management about the observation of excessive TF flag displacements, which indicates a need to repair the TF joints. The PAC agrees that the decision to replace the epoxy in all the flag joints during the upcoming machine outage is a prudent step.

PF1A coil upgrade

NSTX has also decided to take advantage of the center stack removal to implement the PF1A coil upgrade a year ahead of schedule. The new coil will help provide enhanced shaping capability (simultaneously high elongation and triangularity), for access to even higher beta regimes. Early implementation of the PF1A coil upgrade is quite reasonable in view of its improved plasma control capability. The PAC does note that divertor/neutral control (not yet implemented on NSTX) could also be an important research element, along with advanced shaping. (The extra demand on resources resulting from the early PF1A coil upgrade has meant that the lithium evaporator and an upgrade to CHERS have had to be delayed by one year, as mentioned above.)