Report of NSTX Program Advisory Committee
(PAC-23)

January 22-24, 2008

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1. Introduction

The NSTX Program Advisory Committee (PAC) held its 23rd meeting at the Princeton Plasma Physics Laboratory (PPPL) during January 22-24, 2008. The purpose of the meeting was to give advice and comment regarding the NSTX research plan for FY 2008 and the draft NSTX 5-year plan for the years FY 2009-13. In response to budget uncertainties, the 5-year plan is split into two periods: the period from FY 2009 to FY 2010 and the three-year period from FY 2011 through FY 2013. This division results from a recent DOE request to the newly constituted ST Coordinating Committee (STCC) and the NSTX research team to formulate a focused and prioritized research plan for FY 2008-10 to address the most critical needs for the design of next-step STs while also preparing for the possibility that operation of NSTX would cease after FY 2010 to accommodate construction and operation of the National Compact Stellarator Experiment (NCSX).

In particular, the PAC was asked to answer three questions regarding the NSTX research plan:

1. Does the FY 2008 research plan provide the correct balance and focus to optimize the contributions of NSTX in the areas of: next-step ST development, resolution of remaining ITER design issues, and fundamental toroidal confinement science?

2. Do the proposed research and upgrade plans for FY 2009–10 maximize NSTX contributions toward ST development and fundamental toroidal confinement science?

3. Does the proposed 5yr plan appropriately address high-priority issues for next-step STs and toroidal confinement science beyond those that can be addressed by the end of FY 2010?

The NSTX Team presented their research plan to the PAC in 12 presentations over two days. These included a summary of accomplishments from the FY 2007 run, an overview of the FY 2008 run plan, an overview of the research program through FY 2010 and beyond, an overview of the facility and diagnostic installation plan, and detailed descriptions of the plans for the topical science groups (TSGs).

The PAC commends the NSTX Team for a tremendously productive FY 2007 run period. NSTX operated for 63 days, completed 43 experiments, achieved important milestones, and completed several ITPA tasks. Especially noteworthy were the eight invited presentations at the APS-DPP Annual Meeting. These results informed and built confidence in the proposed NSTX research plan and included:

1. Combined feedback control of error fields and resistive wall modes (RWM) to maintain plasma rotation and plasma high-beta performance.
2. Understanding fast ion loss from multiple nonlinearly interacting Alfvén modes.
3. Measurement and understanding of the structure and spectrum of Alfvén cascades.
4. Measurement of high-k fluctuations during Type I ELMs and understanding the role of electron transport in ELM severity.
5. Using deuterium gas puffing to create a partially detached divertor (PPD) that resulted in a significantly reduced divertor heat flux.
6. Successful use of the lithium evaporator (LITER), the use of which correlated with lowered densities and recycling, and increased energy confinement via broader, higher electron temperature profiles.
7. Improved high-harmonic fast-wave (HHFW) core heating achieved when the density at the antenna is below the onset for surface wave excitation.

The PAC is also grateful for the clear and informative presentations delivered by all participants. These presentations make apparent that the NSTX Team has responded energetically, rapidly, and responsibly to DOE/OFES guidance to develop a focused and prioritized research program. We also appreciate the many references to prior PAC recommendations and the efforts made by the NSTX Team in addressing these recommendations.

In addressing the charge, the PAC made four general recommendations dealing with the research priority and focus, three comments stemming from the charge questions, and several specific recommendations pertaining to the six topical science groups (TSGs). These are presented below.

2. General Recommendations

The PAC makes four general recommendations pertaining to the NSTX near-term and five-year research plans. These are:

1. The PAC endorses the prioritization of both your research goals and your key hardware upgrades. The NSTX Team made correct and sound choices to prioritize near-term research and corresponding upgrades.

   These choices were based on four criteria: (i) whether the research would answer key questions relevant to next-step devices, (ii) uniqueness, (iii) likelihood that the research can achieve results by the end of FY 2010, and (iv) whether the upgrade is consistent with budget constraints. The NSTX research priorities are: (i) to increase and understand neutral-beam driven current (NBICD), (ii) to increase and understand H-mode energy confinement, and (iii) to understand and sustain high β_N operation and non-inductive current start-up and ramp-up. The PAC agrees that achieving all three of these research goals would fill knowledge gaps and greatly improve confidence in the extrapolation to next-step ST devices. The PAC also feels that NSTX is well prepared to make progress along each of these high-priority research goals. They build upon and continue recently successful research efforts.

   The NSTX Team identified three upgrade priorities: (i) complete installation of beam-emission-spectroscopy (BES) diagnostic in FY 2009 and FY 2010, (ii) implementation of the liquid-lithium-divertor (LLD) in a three-year lithium research effort that begins this year with the second LITER, the LLD target plates for the FY 2009 run, and a still unspecified LLD enhancement for the FY 2010 run, and (iii) installation of a double-feed upgrade to the HHFW system for the FY 2009 run and a “resilience” system to maintain HHWF coupling during ELMs for the FY 2010 run. The PAC endorses these upgrade priorities.

2. The PAC encourages the NSTX Team to fully embrace their FY 2008-2010 priorities in NSTX organization and planning. As explained above, the PAC endorses the NSTX research and upgrade priorities. The NSTX Team should consider organizational and planning decisions that strengthen the research associated with these priorities and that measure and highlight progress. For example, the NSTX Team should consider allocating “cross-cutting” and “reserve” run days in FY 2008 to experiments that enhance understanding of the effects of Li and that maximize the effectiveness of HHFW. The NSTX Team should formulate additional and explicit milestones that will measure your progress in the key research associated with the LLD and the HHFW. Program management should consider adding a FY 2008 milestone for demonstrating and understanding the effects of the second LITER, and consider adding FY 2009 milestones to measure progress with the LLD and the dual-feed HHFW antenna.

   Finally, some of the most important NSTX research and upgrade priorities cut across the topical science groups (TSGs). The NSTX Team would benefit from identifying an organizational structure, with clearly defined leadership and responsibilities, for the "cross-cutting" efforts associated with your key upgrade priorities (the LLD, the HHFW, and the BES), and key research priorities (NBICD, H-mode confinement, sustained high-β_N operation and non-inductive current start-up and ramp-up.) Although the NSTX Team should not abandon those efforts that advance scientific investigations broadly and are well suited to the TSGs, the need to focus on priorities is urgent. As a consequence, the PAC urges the NSTX Team to identify one or more additional organizational structures to aid the implementation of priority upgrades and the coordination of high-priority research. The PAC acknowledges that this might be accomplished in several ways; the important point is that the chosen way should empower certain individuals with leadership and responsibility for each of your high-priority activities.

3. The PAC believes a research plan of at least three years is warranted in order to complete critical research in several areas. The spherical tokamak (ST) configuration has strong merit as a platform for next-step fusion test development while providing cost-effective toroidal confinement research. In particular, NSTX is contributing essential data on the role of aspect ratio in toroidal confinement. These observations motivate the PAC to comment generally on the importance of continuing the on-going NSTX research. The PAC believes the NSTX Team has defined a highly focused and prioritized program through FY 2010 that responds well to DOE/OFES guidance. The research plan presented to the PAC builds upon recent NSTX results, brings unique and important research tools to a world-class research device (*e.g.* combined BES and high-k fluctuation measurements, LLD, and HHFW), and addresses critical research topics pertaining to sustained high-performance ST discharges. The PAC believes a "full three-year" research program extending through the end of FY 2010 is fully warranted. A shorter period of operation would be a tremendous waste of a valuable resource. The PAC also acknowledges that three years is too short for NSTX to maximize scientific confidence for ST next steps, but NSTX can and should make significant headway in addressing all three research priorities and in benefiting from all three of the planned key upgrades.

4. The PAC believes NSTX has a wealth of topics, ideas, and opportunities to justify the additional operation contained in the full five-year plan through FY 2013. The PAC believes the FY 2011-2013 experiments have great promise (i) to address critical scientific questions, (ii) to achieve important performance milestones that impact next-step STs and other toroidal research initiatives, and (iii) to complete exciting ongoing research tasks (*e.g.* non-inductively sustaining high-beta, high-confinement ST discharges).

   For this reason, the PAC urges the NSTX Team to submit a full 5-Year plan as requested by the DOE/OFES. Furthermore, the PAC recommends that PPPL management should consider all possible options that would allow NSTX to complete a 5-Year plan.

3. Specific Comments Pertaining to the Three Charge Questions

In addition to the general recommendations above, the PAC makes the following comments pertaining to the three charge questions.

1. *Does the FY 2008 research plan provide the correct balance and focus to optimize the contributions of NSTX in the areas of: next-step ST development, resolution of remaining ITER design issues, and fundamental toroidal confinement science?*

   The PAC views the NSTX Forum (November 27-29, 2007) as successful. The national process for the solicitation of ideas and proposals for FY 2008 experiments appears to be working well, and the NSTX Team should continue to encourage broad national participation in experiment proposal and planning. Each Topical Science Group (TSG) has prepared a FY 2008 research plan that is appropriate. The PAC generally endorses the run time priorities within each TSG.

   The PAC believes the initial allocation of run time between the TSGs shows recognition of high-priorities and balance. For example, the initial allocation of run days has a relative increase in the fraction of days devoted to boundary physics, non-inductive start-up, and ramp-up. The PAC encourages the NSTX Team to further strengthen high-priority activities in the FY 2008 run plan. The critical importance of the LLD for the achievement of FY 2010 goals suggests strengthening efforts to understand the underlying behavior of lithium in NSTX, in support of the role of lithium in the achievement of density reduction and other discharge performance goals. The PAC recommends that a FY 2008 milestone be defined to highlight new results from the dual LITER. Additionally, research that would directly benefit the utilization of future key upgrades and key research goals should have priority in the allocation of "cross-cutting" and "reserve" run days. Examples include experiments using the dual-LITER and experiments that yield new HHFW understanding.

   NSTX has been providing and will continue to provide unique physics supportive of ITER and the fundamental understanding of toroidal confinement. The planned FY 2008 contributions to outstanding ITER design issues include understanding ELM mitigation using resonant magnetic perturbations (RMPs), control of vertical displacement events (VDEs), and assessment of resistive wall mode (RWM) control coil topology. These experiments are relevant and responsive to ITER needs.

2. *Do the proposed research and upgrade plans for FY 2009–10 maximize NSTX contributions toward ST development and fundamental toroidal confinement science?*

   As explained in the general comments, the PAC supports the upgrade and research priorities of the NSTX plan through FY 2010. These plans were presented and organized into six Topical Science Groups (Turbulence and Transport, Boundary Physics, Wave-Particle Physics including energetic particles, Macrostability, Current Start-up and Ramp-Up, and Integrated Scenarios).

   In Sec. 4 of this report, the PAC makes technical observations and comments concerning each of the TSGs. These comments address details of the FY 2009-2010 research plan not already contained in the general PAC recommendations.

3. *Does the proposed 5yr plan appropriately address high-priority issues for next-step STs and toroidal confinement science beyond those that can be addressed by the end of FY 2010?*

   The long-term goal of the NSTX research program is to significantly reduce the uncertainty in extrapolating discharge performance to next-step experiments. As presented to the PAC by the NSTX Team, the centerpiece of the FY 2011-2013 plan would be the demonstration of 100% non-inductive current drive (NICD) with NBI and bootstrap current. This would be achieved by maintaining and controlling the plasma current profile for more than three current relaxation times (τ_{CR}). ELM control, central safety factor control with HHFW, and a long-pulse liquid lithium divertor (LLD) capable of handling high divertor heat flux are expected to be central to achieving this integration goal.

   The PAC agrees that achievement of 100% non-inductive current sustainment for several current diffusion ties will indeed greatly increase the scientific confidence in the ST concept and provide critical information for decisions on potential next-step ST options. Together with other proposed research to address other high-priority issues for extrapolation of the ST concept, such as solenoid-free start-up, I_p ramp-up, boundary control, and high heat flux handling, the NSTX five year plan provides good justification for additional experimental operation through the FY 2013 program year

   At the end of the FY 2010 run year, NSTX will have ready significant new tools to make additional progress in all high-priority research areas and contribute broadly toward toroidal confinement science. These follow-on experiments would be valuable. However, the second neutral beam line would be extremely valuable for achievement of the FY 2013 long-term performance target, and will likely be required for high-performance discharges created at the high toroidal field possible with sub-cooling.

4. Specific Comments and Suggestions Pertaining to TSGs

In addition to the general recommendations and comments listed above, members of the PAC have reviewed the plans for each of the Topical Science Groups. Specific and technical comments have been prepared for each TSG emphasizing the FY 2008-2010 run periods, but also commenting on the 5-Year Plan through FY 2013.

4.1 Turbulence and Transport

The NSTX Team is pursuing a wide-ranging and important set of studies in the area of turbulence and transport. These include momentum transport and rotation effects as part of the FY 2008 Joule milestone, and coordinated studies of heat, momentum and particle transport. Research is directed towards obtaining predictive capability for energy confinement in STs, but also towards advancing the general understanding of transport in magnetized plasmas. In the latter area, work on electron transport is particularly appropriate, given the characteristics of NSTX. The measurement of high *k* turbulence and comparison with models to investigate anomalous electron transport in a machine with approximately neoclassical ion transport are extremely important. The PAC remains very interested in the measurement of k_r and k_θ at high k. The addition of BES for simultaneous characterization of the fluctuation spectrum at low k is a welcome development, and the plans to utilize that capability are appropriate. The ability to measure δB in the context of electron thermal transport remains important. With a large number of significant studies to be conducted in a short amount of time, further prioritization may be needed.

Some additional comments are in order. The observation that global confinement studies have given way to local transport studies is correct. Therefore, to have impact, NSTX global confinement studies must be clearly linked to local transport studies and conceptual understanding, for example, through coordinated modeling and theory efforts. The combination of low-k BES with high-k diagnostics to study phenomena across electron/ion scales should be matched with the development of modeling efforts that seek to address disparate scales and the significant physics likely occurring across those scales. Predictive capability and validation need to be backed up with specific plans like the joint design of experiments by experimenters, modelers, and theorists, and the development and implementation of validation metrics. NSTX has attractive possibilities for validation relating to multiple measures of turbulence and transport phenomena.

Planned work with lithium provides unique opportunities for particle transport studies that should not be missed. Where possible these should be combined with other resources known to affect particle transport, like RMPs. NSTX's combination of neoclassical ions and anomalous electrons also offers unique opportunities for transport studies. Comparisons with MAST, where χ_ϕ appears to be more closely correlated with χ_i ($\chi_\phi \leq \chi_i$), would be instructive for characterizing transport across STs, as well as helping to advance understanding of momentum transport. Related questions should be pursued like understanding the role of pinch anomalies in momentum transport when χ_ϕ remains smaller than a neoclassical χ_i.

4.2 Boundary Physics

The presentations highlighted a few of the interesting boundary physics results of the past year. The capability to reduce the peak heat loads though D2 gas puffing (partially detached divertor) were encouraging in light of the concentrations of heat loads in an ST. Likewise, the LiTER experiments showed that covering of a large fraction of the vessel with Li can remove ELMs, improve plasma quality, lower the density, and enhance EBW coupling to the core plasma. Although we did not hear details, we understand that other important research programs, including ELMs studies and SOL turbulence research, were fruitful.

Based on run time allocations for FY 2008 it is clear that a diverse number of issues will be addressed and that the general boundary physics program is well organized. We endorse the efforts to better characterize parallel power flows, divertor detachment, turbulence and its role in affecting SOL profiles. However, while the nine experiments slated for run time cover a range in boundary physics topics, only two dealt with the aspects of using LiTER, one dealing with D retention and the other concerning the effects of Li on ELMs. This concerns us because the positive effects of Li evaporation are far from being understood, and the further applicability of the technique requires a thorough understanding of the effects of lithium coatings. As discussed last year and also during this year’s meeting, it is very important to determine the physics behind the changes in plasma performance correlated with the use of Li. Are the positive effects on plasma performance and plasma profiles the result of changes in recycling (pumping)? If the Li pumping is the dominant effect, is the important pumping occurring at the divertor or around the first-wall generally? Is it possible that lithium coatings primarily bind deuterium loaded into the carbon wall, making it unavailable for recycling? Could it be that the positive effects correlating with Li usage are due to suppression of some impurities (e.g. C, O) and/or their replacement with Li in the plasma? Closer collaborations with FTU, which is the largest metal-walled tokamak performing extensive lithium PFC work, may also provide information on the role of carbon-lithium interactions.

Returning to the issue of pumping, such experiments should include particle accounting (i.e., how much gas is injected versus how much is left in the vessel after a shot, as well as post-mortem analysis of the tiles). Experiments should be done with bare walls after a vacuum break (no Li on surfaces) and then , after lithium is introduced, for each shot (which was a direct recommendation from PAC-21).

Based on the importance of this issue for NSTX, STs in general, and all fusion devices, we urge the NSTX staff to devote more resources to understanding the physics that lead to changes in plasma behavior with Li, along the lines of the questions above. By more resources is meant more personnel, more diagnostics, an increased integrated modeling effort, and more experiments. The latter should come from allocation of the ‘cross-cutting’ and ‘reserve’ days, as well as from allocation of the additional 6 run weeks if those become available.

The issue of divertor heat handling is more difficult for an ST than for higher-aspect-ratio devices because an ST has a smaller divertor area relative to the power flowing out of the core plasma. NSTX will provide the best test of the heat-handling capability for STs, as well as for general fusion plasmas. The NSTX Team plans to address this through studies of divertor detachment achieved by means of D_2 gas puffing and through flux-surface spreading. We also recommend studies, if possible, of the efficacy of impurity puffing (*e.g.,* N_2, Ne) for achieving detachment. Comparison of the effectiveness of impurity puffing to enhance divertor radiation with and without a fresh Li surface may lead to some useful information about the effect of Li on core impurities as well.

4.3 Wave-Particle: Heating and Energetic Particles

HHFW and EBW

Significant progress was made during FY07 on both EBW emission studies and HHFW coupling. In the area of EBW emission, the use of lithium conditioning resulted in an estimated 50% or greater transmission efficiency for thermal emission from the core in H-mode plasmas. This factor of 5-6 improvement in coupling has been attributed to a reduction in collisional damping of the EBW in the edge. HHFW experiments at 5.5 kG demonstrated effective heating in helium L-mode plasmas with 2 MW of NBI. Core current drive has now been observed using the MSE diagnostic with 1.8 MW of RF power in 90° antenna phasing.

The FY08 – FY10 plan now understandably de-emphasizes ECH/EBW in favor of HHFW. This is primarily because there is neither the budget nor the time to complete installation of a higher power EBW system prior to FY10, which may be the final run year for NSTX. EBW may not be essential for next step STs but would be valuable as an additional control tool, especially for off-axis current drive. Nevertheless, because of the reciprocity theorem, much can be learnt by studying the inverse emission process, and continued efforts in this direction on NSTX are encouraged. In FY09-10 it is hoped to move the mode conversion layer inside the LCFS to reduce fluctuations in the emission. The effects of increased edge bootstrap current following the L-H transition may then need to be taken into account in order to explain the emission. The plan to continue collaboration on high-power EBW experiments on MAST, which will shortly exploit a 28GHz gyrotron on loan from ORNL for non-solenoidal EBW start-up studies, is welcomed.

An upgrade to the HHFW system is planned, to increase the voltage handling capability of the antenna. This upgrade should result in higher power coupling during both startup and full current operation. The NSTX team should accordingly ensure that sufficient resources are allocated to prepare for and take advantage of this upgrade. In FY08, it is planned to extend the L-mode helium plasma studies to L- and H-mode NBI-heated D plasmas, with a phase scan and MSE measurements to determine the non-inductive current profile. Sufficient run time should be allocated for a thorough study, and the work should be extended to higher neutral beam power.

Results with – 90° (co-) phasing are clearly relevant to startup and provide benchmarking of 3D RF codes. However, the peaking of the current profile produced by on-axis current drive at 90° phasing and the resultant drop in q_0 is undesirable. Consideration should be given to additional work with symmetric or counter (+ 90°) phasing to heat without additional current peaking, or even broaden the current profile. If absorption at – 150° is very strong and significantly off-axis, it may also be useful for broadening the current profile.

Significant run time will likely be needed to take full advantage of the double-fed antenna upgrade in FY09. Presumably FY09 operations will repeat the most successful wavenumber and target plasma experiments from FY08 at higher power levels. Heating during the current ramp will also require time to develop discharges which maintain a near-constant antenna-plasma gap.

For FY10, the ELM-resistant matching system was not elaborated upon, but if installed will also likely require significant run time to optimize and then capitalize upon.

Since fast wave heating or current drive in either NHTX or CTF would very possibly operate at lower normalized harmonic, we once again recommend that consideration be given to operation at 5.5 kG in hydrogen, perhaps at the end of the FY08 run to minimize impact on machine operations. Note also that the onset n_e for surface wave excitation should decrease as the normalized frequency decreases, for fixed wavenumber, which should further illuminate the role of surface waves in NSTX.

Finally, we note that a termination of NSTX in FY10 will result in the loss of the only HHFW heating and current drive experiment on a large tokamak in the world fusion program. In addition, the loss of operations in FY11-13 will eliminate the possibility of combining ECH/EBW with any of the unique startup capabilities of NSTX, including CHI and outer PF startup with ex-vessel coils, which cannot be explored on MAST. In the event of operation in

FY11-13, a 350 kW ECH system is scheduled for FY 2011 but only with a budget increase. Without that, it falls entirely off the plan for the five years.

Fast particle physics

Further good results on fast particle physics were obtained in FY07. The program directly addressed a Joule milestone as well as the OFES theory program milestone, and in addition it was an ITPA task. This is a good example of fulfilling multiple goals.

The most important FY07 results, in our opinion, were (1) the observation of fast ion loss, measured with the sFLIP diagnostic, which occurred only in the presence of multiple energetic particle modes and (2) the observation of fast ion loss, as indicated by the neutron rate, correlated with a TAE "avalanche."

The synthetic diagnostic in the NOVA code was used to reproduce the radial mode structure seen with reflectometers. However, it was not clear whether these modes were the energetic particle multi modes or the TAE avalanche—or something else. It was stated that the computed mode structure, as verified against the experimental measurements, could then be put into the ORBIT code to simulate fast ion redistribution. However, no results were presented to allow comparison with DIII-D experiments (in which PPPL scientists are heavily involved) where a large discrepancy between the ORBIT prediction for redistribution and the measured result was found.

Another important result in FY07 was the finding that HHFW suppresses CAE/GAE modes that exhibit hole-clump frequency chirping. It would be interesting to check if this result is consistent with the Berk-Breizman nonlinear theory, which predicts that high "collisionality" (which can be supplied by an RF wave) tends to eliminate the instability.

The experimental confirmation that Alfven cascade modes (also known as reversed-shear Alfven eigenmodes) lie in the frequency range between the geodesic acoustic mode and the TAE frequency is a nice piece of work. The beta scan experiments that demonstrated cascade mode coupling to the GAM were the first of their kind (and were reported in an invited talk at APS-DPP 2007).

Predictive capability for fast ion transport (i.e., redistribution and/or losses) is the highest priority for the NSTX fast particle research program in FY08-09. This work is applicable to alpha particle confinement in ITER and also to neutral-beam current drive. The latter is an important topic for next-step ST devices. NSTX has a FY09 milestone to study how the current profile is modified by fast ion-driven modes. Redistribution with avalanche modes is also the highest priority research in FY10 and FY11-13.

The NSTX facility has unique capabilities (*e.g.*, super-Alfvenic fast ions and very high fast-ion beta) and special strengths (e.g., excellent fast-ion diagnostics, strong coupling of experiment with theory) for research on energetic particle physics. The NSTX scientists who work in this area are world-class. Also, the subject of fast-ion transport is an important issue for ITER and next-step ST devices, as mentioned earlier. However, in view of other ST issues that critically need to be addressed in the next two or three years in order to make a convincing case for an ST next-step facility, the run allocation of 3 days in FY08 seems about right. The continuation of the energetic particle effort during FY09-10 and beyond is also quite appropriate.

4.4 Macro-stability

The NSTX team is commended for significant progress in macro-stability research during the FY 2007 campaign. Two notable accomplishments include: (1) improved RWM and dynamic error field correction that led to a record pulse length for NSTX with sustained plasma rotation and (2) effective use of n=3 non-resonant braking to modify the plasma rotation and its impact on the physics of the critical-rotation threshold for RWM stability and neoclassical tearing modes. The PAC also notes strengthened connections to theory, including experimental comparisons with the predicted neoclassical toroidal viscosity and collaborations on kinetic modifications to MHD, mode locking physics, and the development of advanced RWM feedback algorithms. We strongly encourage these theory and modeling efforts, as they will be essential to provide understanding of macro-stability physics and to improve further the experimental control tools.

Given that the ITER design is expected to be finalized in FY 2008, there are several near-term, high-priority experiments in macro-stability that have been identified by the NSTX Team and the broader community that are included in the FY 2008 program. These are tests of resonant magnetic perturbations for ELM control, experiments to increase the understanding of the neoclassical toroidal viscosity, and tests of an ITER-like RWM coil configuration. Completing these experiments as early as possible in FY 2008 will represent a significant and timely contribution from NSTX to the ITER design decisions.

The PAC notes that the NSTX team has clearly identified important and high-priority research in macro-stability, both in support of next-step ST options as well as in contribution to the science of toroidal confinement more generally. This area of research enjoyed a large amount of run time in FY 2007. Since the PAC is recommending more emphasis in other topical areas for FY 2008, we feel that the clear identification of high priorities in macro-stability research will be beneficial to ensure a productive year in this area of research in FY 2008.

The experiments in FY 2007 on the aspect-ratio comparison of neoclassical tearing mode stability were very efficient and effective, producing interesting comparisons of the marginal island width for stabilization and tearing onset conditions as a function of plasma rotation at different aspect ratios (in particular, comparing NSTX and DIII-D). The PAC recommends that a similar level of run time be devoted to tearing studies in FY 2008, and that the research focus might best be aimed at plasma rotation effects, since rotation is more generally a Joule milestone. Experiments probing dependencies on normalized gyroradius and collisionallity might need to be deferred.

The new set of 12 internal coils (the non-axisymmetric control coils NCC) proposed in the five-year plan appears to be well motivated and will add significant new capability for a wide range of research. The PAC agrees that this upgrade will not be possible if NSTX does not operate past FY 2010. However, if it becomes clear that post-FY 2010 operation is possible, then we recommend pursuing a more detailed design so that the option to install NCC would be available.

4.5 Current Start-up and Ramp-up

The solenoid-free plasma formation and current ramp-up program represents a critical part of the ST long-term development path and also contributes more broadly to the corresponding research in higher-aspect-ratio tokamaks. The solenoid-free plasma startup research on NSTX is unique within the US fusion program. The PAC commends the NSTX Team for responding broadly to the action items and recommendations from the PAC-21 meeting.

The main focus of this research has been the CHI capability, a unique feature for medium-sized devices such as NSTX. Outer PF start-up and Plasma Gun Start-up have been added to the program for FY 2008-2010. For the CHI, there is a concern regarding the scaling of achievable current from smaller devices, such as HIT-II, to the larger NSTX. While HIT-II has been optimized for CHI, some clarification of the expected scaling and maximum current achievable in NSTX would be beneficial. Along these lines, we applaud the attempts to simulate the transient CHI discharges with the TSC code and recommend the continuation of that work. We also appreciate that the CHI program could benefit strongly from the liquid lithium program, in terms of recycling and gas control, while sharing the concern that development and optimization of CHI scenarios using the LLD might consume significant run time. Outer PF start-up and Plasma Gun Start-up have been added to the program for FY 2009-2010 as additional methods for plasma current initiation. These programs will provide alternate tools for coupling to non-inductive CD methods and ramp-up to high beta.

Currently, PF start-up is scheduled to begin in FY 2009. The PAC believes that outer-PF start-up could possibly begin in FY 2008, since pre-ionization is probably already good enough from CHI to initiate the outer-PF ramp-up. The PAC suggests investigating an earlier start for outer-PF start-up, as it appears to be a promising technique. The Plasma Gun also looks promising, and the PAC endorses the continuation of this work. With the Plasma Gun coming online in FY 2010, it is uncomfortably close to the end of the three-year time period.

In a three-year program horizon, the current focus on CHI is appropriate. The PF Startup and Plasma Gun will be more difficult to master in a 3-year time frame, and it may be difficult to make progress on all three approaches with the limited run time available. We recommend that the NSTX team weigh carefully the benefits of CHI, PF, and plasma gun startup techniques, taking into account the availability of run time and resources. All of the techniques would benefit from an extended operational period lasting until FY 2013.

4.6 Integrated Scenarios

The PAC is encouraged to see the progress during FY 2007 on sustaining very-high-κ operation for an extended duration and developing plasma ramp-up scenarios that allow access to higher central q (less current penetration) at the end of the current ramp. The range of current profiles obtained appear to present a variety of opportunities in the development of high-bootstrap-fraction plasmas with good stability properties. The PAC also notes that the NSTX Team has demonstrated improved density control (albeit transiently) using the LITER system, which bodes well for integrated scenario development.

An important by-product of the very-high-kappa capability is the ability to provide key information on vertical stability issues for ITER. This is a key issue for ITER, in which NSTX can play an important role in the scaling of the maximum controllable displacement from present-day devices to ITER. While there appears to be experimental time provided for this research in the FY 2008 plan, a description of the exact research to be done was not provided to the PAC, giving the impression that this is lower-priority research. The PAC encourages the NSTX team to place relatively high priority on providing this critical information to ITER.

The PAC agrees with the NSTX team that the demonstration of sustained fully non-inductive operation is an important goal for NSTX in support of next-step ST devices and tokamak development in general. The PAC believes that demonstration of such operation (even at a limited level) in FY 2010 is an important milestone in advancing the discussion of next-step ST devices.

As noted in the PAC-21 report, this demonstration requires the integration of several physics elements that are currently at the limits of parameter space on NSTX (namely, $\beta_N > 7$, electron temperature 60% above presently obtained value in similar discharges, moderate density control, and current density profiles with $q > 2$). The NSTX team made progress on each of the goals in FY 2007 through improved RWM stabilization, the use of lithium for density control, and improved startup.

The NSTX approach to push further towards the required operating space involves the use of liquid lithium for enhanced density control and improved confinement and HHFW for electron heating. The PAC is concerned that each of these enabling elements are presently at a limited level of maturity. In this regard, the PAC recommends that the NSTX team develop a multi-year plan that both develops these individual elements to the necessary level and combines these elements systematically into a self-consistent integrated scenario. The PAC realizes that each of these activities is a first-of-a-kind activity, so the development of such systems may require increased resources (manpower and experimental time) and an extended research program to develop the necessary knowledge base. While the PAC believes some level of integration may be possible in FY 2010, NSTX operation beyond FY 2010 will likely be required (rather than simply desired) in order to demonstrate this important capability.

The PAC is concerned that there appears to have been limited progress on refining the modeling of scenarios that were presented at PAC-21 since the scenarios presented this year are the same as those presented at PAC-21. The development of self-consistent scenarios will require several iterations between experiments and scenario simulation/modeling in order to identify the most favorable development path. In particular, it is important to establish the credibility of the models through comparison with experimental data. NSTX is now equipped with sufficient profile diagnostics that modeling of the obtained data can and should be an integral part of scenario development.

Respectively Submitted,

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