Report of NSTX Program Advisory Committee (PAC-25)

February 18-20, 2009

Committee Members Present:
Riccardo Betti (University of Rochester)
Paul Bonoli (Massachusetts Institute of Technology)
Jeffrey Brooks (Purdue University)
Ronald H. Cohen (Lawrence Livermore National Laboratory)
Xavier Garbet (CEA Cadarache)
Donald L. Hillis (Oak Ridge National Laboratory)
Haruyuki Kimura (Japan Atomic Energy Agency)
Richard P. Majeski (Princeton Plasma Physics Laboratory)
Michael E. Mauel (Columbia University)—Chair
Hendrik Meyer (UKAEA Culham)
John S. Sarff (University of Wisconsin)
James W. Van Dam (University of Texas)
Mickey Wade (General Atomics)

Ex-officio:
Stephen A. Eckstrand (DOE Office of Fusion Energy Sciences)
Jon Menard (Princeton Plasma Physics Laboratory)
Masayuki Ono (Princeton Plasma Physics Laboratory)

Committee Members Absent:
Jiangang Li (Institute of Plasma Physics, Hefei, China)
Bruce Lipschultz (Massachusetts Institute of Technology)

1. Introduction

The NSTX Program Advisory Committee (PAC) held its 25th meeting at the Princeton Plasma Physics Laboratory (PPPL) during February 18-20, 2009. This is the first PAC meeting since the successful peer review of the NSTX 5-Year Plan for the years FY 2009-13. This PAC Meeting also marks the 10^{th} anniversary of the start of NSTX plasma physics operations, and we congratulate the NSTX Team on the growing research capability of the NSTX facility and the many significant research contributions during the past decade.

The purpose of the meeting was to give advice and to comment regarding the NSTX research plan for FY 2009 and also for the midterm period leading to installation of an upgraded toroidal field center stack (CS) and a second neutral beam injection line. These two upgrades are significant. They will allow NSTX to explore longer-pulse ST discharges at reduced collisionality and with relaxed profiles and to study more fully non-inductive current ramp up and current profile control. Because installation of these upgrades might begin as early as FY 2012 and require an outage period of up to two years, NSTX research and research planning for the FY 2009-11 time period has increased importance.

The PAC was asked to answer three questions regarding the NSTX research plan:

1. Does the research plan provide the correct balance and focus to optimize the contributions of NSTX in the areas of: next-step ST development, ITER high-priority research needs, and fundamental toroidal confinement science?

2. Does the research plan fully exploit the upcoming (FY2009-2011) facility and diagnostic upgrades?

3. Is the NSTX research plan responsive to the four highest priority ST physics issues identified in the FESAC-TAP report - namely: start-up and ramp-up, plasma-material interface, (electron) energy transport, and integration?

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 2008 run, an overview of the FY 2009 run plan, an overview of the research program through FY 2011 and beyond, an overview of the facility and diagnostic installation plan, and detailed descriptions of the plans for eight topical science groups (TSGs).

The PAC commends the NSTX Team for a productive and effective FY 2008 run period. The FY2008 run was a tremendous success by every measure. NSTX achieved more than 16 run weeks (exceeding its target) and completed 43 experimental proposals and 12 machine proposals. Management of the run was particularly effective. Each week was planned 1-2 weeks ahead so that experiments could be scheduled to achieve optimal use of diagnostic and facility systems. The planning was made further effective by scheduling up to four experimental proposals on each run day. We are pleased that run time was held in reserve and allocated to critical areas, including six extra days for boundary physics, five extra days for ITER/ITPA support, and four extra days each for macrostability and for turbulence and transport. Especially noteworthy were the 16 NSTX-related presentations at the IAEA Fusion Conference, the eight NSTX-related invited presentations at the APS-DPP Annual Meeting, and also the recognition of NSTX as demonstrated in the APS-DPP tutorial talk on spherical tokamaks presented by A. Sykes (UKAEA).

The FY 2008 results informed and built confidence in the proposed NSTX research plan. They included:

1. Routine use of combined n = 3 error field control and n = 1 feedback control to reliably extend duration of high β_N plasmas, and allow operation above the no-wall stability limit for flat-top periods beyond 1.5 s.
2. Investigation of fluctuations over a broad range of wave numbers and yielding observation of strong dependence of energy confinement on collisionality, new studies of the suppression of fluctuations during reversed magnetic shear, and important observations of the anomalous momentum pinch.
3. Successful installation and operation of a second lithium evaporator (LITER) and the lithium powder dropper to reduce recycling, increase electron temperature, suppress ELMs (as well as ELM excitation with external magnetic perturbations), and improve

HHFW heating efficiency. Lithium deposition resulted in the achievement of record core electron temperatures in NSTX.

4. Measurement of the impact of Alfvén modes on core electron transport.
5. Operation of the new poloidal CHERS and fast-ion deuterium-alpha (FIDA) diagnostics.

The PAC is also grateful for the clear and informative presentations delivered by all participants. These presentations described significant research capabilities of the NSTX Facility and showed the energy and inventiveness of the NSTX National Team. We appreciated 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 arrived at three general observations and recommendations that deal with the size, importance, and future of the NSTX research program. We also made specific comments stemming from the charge questions and made recommendations pertaining to the eight topical science groups (TSGs) and research thrust areas. These are presented below.

2. General Observations and Recommendations

The PAC makes three general observations and recommendations for the NSTX Research Program. These are:

1. The PAC believes that the number of personnel on the NSTX National Team has not kept pace with the increased capability of the NSTX research facility. This year marks the 10th anniversary of the start of plasma physics studies with the NSTX device. During the past 10 years, the NSTX facility was continuously improved and outfitted with new diagnostic systems, plasma control and interface systems, and improved heating and fueling systems. Today's NSTX Facility and Research Program are large and significant. Furthermore, with the successful completion of its 5-Year Plan, NSTX is now embarking on a timely and appropriate upgrade program that includes (i) a new center stack for higher toroidal fields and longer discharge pulses and (ii) a second neutral beam injector for higher heating powers and additional plasma current drive. The PAC strongly supports the long-term vision for NSTX as described in the 5-Year Plan, because these upgrades will significantly enhance its ability to fulfill its mission.

   However, as the research capabilities of NSTX have expanded, the size of the NSTX national team has not. The PAC believes that there is a shortage of people to run, analyze, plan, maintain, and carry out the NSTX research mission. To address this shortage, the PAC recommends that <u>PPPL should use the opportunity provided by the start of an exciting 5-Year Plan to expand the staff and strengthen collaborations at NSTX.</u>

2. <u>The PAC encourages the NSTX Team to more fully embrace their top-level research and programmatic priorities in annual research NSTX planning.</u> The PAC endorses the prioritization and balance of the top-level NSTX research goals and the key NSTX hardware upgrades as presented during PAC-25. However, the PAC believes that even more could be done to insure that these top-level priorities are reflected in the annual research plan. While the PAC recognizes the importance of a broad research program that addresses the full range of scientific questions that can be addressed with NSTX, the

PAC believes more can be done to achieve top-level research priorities when allocating resources for the NSTX run plan. Considering the programmatic importance of resolving technical and scientific issues prior to the installation of the center-stack and NBI upgrades, the NSTX Team should consider ways to insure that highest priority research efforts are emphasized, especially research involving lithium divertor and boundary physics, the use of HHFW heating, and integrated scenario development. Indeed, during the next three years, experiments should be planned to resolve technical questions and reduce scientific uncertainty associated with the longer-pulse, higher-power discharges planned for the post-upgrade period.

3. The PAC recommends that the NSTX Team consider ways to devote additional resources to the investigation and development of a high heat flux divertor for NSTX. A high heat flux divertor with sufficient particle control is critical to the NSTX Program. Therefore, the PAC recommends even greater emphasis be placed in the research program, run plan, and diagnostic implementation plan for addressing Li divertor issues.

   For next year's PAC meeting, we request that the NSTX National Team make an explicit presentation detailing what will be the heat flux targets required in post-upgrade discharges and identification of high-heat flux divertor options compatible with reasonable density control targets.

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 research plan provide the correct balance and focus to optimize the contributions of NSTX in the areas of: next-step ST development, ITER high-priority research needs, and fundamental toroidal confinement science?*

   The PAC endorses the top-level balance and priorities as presented during our meeting. As explained, the highest priority for NSTX is next-step ST development including the research needed for the upcoming NSTX upgrades. While NSTX should continue to make unique and strong contributions to resolving issues identified by ITER/ITPA and to understanding fundamental toroidal physics, with scarce run-time resources, higher priority should be given to support upcoming NSTX upgrades and ST development. For the FY2009 run, the NSTX Team should consider allocating "cross-cutting" and "reserve" run days to experiments that enhance understanding of the effects of Li, maximize the effectiveness of HHFW, and further develop the plans for post-upgrade divertor options. In subsequent years, the run plans should reflect the critical importance of research supporting ST development paths and the NSTX upgrades in the 5-Year Plan.

2. *Does the research plan fully exploit the upcoming (FY2009-2011) facility and diagnostic upgrades?*

   The PAC supports the upgrade and research priorities of the NSTX plan through FY 2011 and also the upgrades included in the 5-Year Plan. The PAC also believes that exciting results are to be expected from the FY2009 run plan. As explained in the NSTX presentations, experiments in the upcoming runs have the potential to produce significant performance breakthroughs by demonstrating large non-inductive current fractions which are sustained at high-normalized beta and which appear transiently during periods of non-inductive current drive. Additionally, the PAC anticipates significant progress resulting from the two major new NSTX capabilities: experiments using the liquid lithium divertor (LLD) and the use of HHFW as a research tool for comparative discharge studies. Because of the importance of boundary and pedestal physics, the PAC suggests that the installation of additional multipoint Thomson scattering channels should be accelerated.

Additional comments are presented within Sec. 4 of this report. These comments address details of the FY 2009-2010 research plan not already contained in the general PAC recommendations.

3. *Is the NSTX research plan responsive to the four highest priority ST physics issues identified in the FESAC-TAP report - namely: start-up and ramp-up, plasma-material interface, (electron) energy transport, and integration?*

   The PAC believes the NSTX Research Plan is appropriately responsive to the FESAC-TAP report. In the high priority area of I_p start-up and ramp-up, the PAC recommends that increased emphasis should be placed on current ramp-up because the increased effectiveness of the HHFW provides an exciting opportunity to explore the potential of bootstrap “over-drive”. NSTX should continue to explore non-inductive plasma current start-up in collaboration with related efforts using MAST, Pegasus, and DIII-D. In the longer term, after the installation of the center-stack and NBI upgrades, the NSTX research program will become even more “aligned” with the FESAC-TAP research goals.

4. Specific Comments and Suggestions Pertaining to Topical Science Groups

In addition to the general recommendations and comments listed above, PAC members have reviewed the plans for each of the Topical Science Groups. Specific and technical comments have been prepared for each Topical Science Group, emphasizing the FY 2009-2011 run periods.

4.1. Boundary Physics

The boundary physics (BP) topic science group at NSTX simultaneously addresses ST physics, ITER needs, and toroidal physics. These include the important topics of (i) power and particle management, (ii) SOL width and turbulence characterization, and (iii) pedestal and ELM physics, which are both cross-cutting issues and also ST specific. The BP topic is getting an appropriately high fraction of dedicated run days and also “piggy-back” run days. The PAC recognizes impressive results in FY 2008, including (i) partial detachment via shaping/flux expansion, (ii) SOL width characterization, (iii) blob propagation and connection to simulation, and (iv) ELM characterization, elimination with Li, deliberately reintroduced. Additionally, we recognize that considerably more connection to theory/modeling is evident today than during past years. One reason for this good trend is reliance upon theory efforts of collaborators.

We believe NSTX would benefit from more cross-talk between the BP group and other topical groups, especially RF (but also transport/turbulence, MHD, and integrated scenarios). Additionally, the central stack (CS) and 2nd NBI upgrade will challenge existing PFCs on NSTX with high heat loads of 20-30 MW/m^2 and may present a major challenge. We note that shape control efforts have been proceeding nicely, and it will be wise to continue to pursue novel concepts to spread the heat load, such as the X-divertor, snowflake, and asymmetric bias. Investigations should focus on the goal of candidate solution for 5 sec pulse after the major upgrades, and we believe NSTX will benefit from the modeling of NSTX performance of divertor heat loads for standard and novel configurations.

The NSTX presentations made a compelling case for more edge Thomson channels. These channels should not be part of the incremental funding request. The additional channels are required for the FY 2011 Joule Milestone, and we recommend installation to advance at least 6 – 8 months, if possible.

The PAC suggests that the following research issues may be helpful to NSTX BP planning. Issues related to long-pulse operation are most important, such as impurity transport/buildup, long-pulse pumping capability of solid Li, density control, and ELMs. The PAC also suggests that more systematic characterization of differences/similarities of effects on edge plasma with different Li approaches (LITER, dropper, LLD) would be a good goal and a unique contribution. We endorse further studies to understand Li elimination of ELMs (a unique capability) and to expand research to control particle rise. With the CS and NBI upgrades, new power levels will require more emphasis on experiments and modeling in the boundary physics area. Since much of the boundary area research is performed by collaborators, the NSTX program would benefit from additional collaborator support after the upgrades.

4.2. Lithium Physics and Related Research Plans

We commend the NSTX team for their response to the challenge of understanding the role of lithium in plasma performance and for some of their specific responses to the 2008 PAC report.

We note the present and planned activities for Liquid Lithium Divertor (LLD) and for lithium-related diagnostics (diagnostic probe, tile sensors, *etc*.), the plans for integrated modeling of NSTX plasma/Li-boundary (HEIGHTS package, UEDGE/DEGAS/REDEP, etc), and the formation of the Lithium Thrust Group with dedicated run-days planned.

We note also the implementation and encouraging initial results from the lithium/canister powder drop technique, pellet injection, with ELM suppression, low core Li accumulation (but high Z_{eff}), etc.

We remain concerned about the pace of Plasma-Material Interaction (PMI) diagnostic and modeling efforts, both in-house and with collaborators, and the over-commitment of PPPL personnel. This point must be emphasized due to the exceptional importance of the LLD to the NSTX program. We repeat the PAC-2008 recommendation to understand the physics behind plasma effects correlating with Li usage, sooner rather than later, and give priority to studies of Li effects in the allocation of reserve experimental run time.

In FY 2008, the NSTX group continued to increase the area of carbon PFCs covered by lithium coatings, through the introduction of a second LIThium EvaporatoR (LITER). In addition, a new technique for introducing lithium to the SOL layer plasma during a discharge ("Lithium dust") was developed and demonstrated toward the end of the 2008 run period. This augmented capability for producing solid lithium wall coatings resulted in several notable results during the 2008 run. Especially interesting is the observation that ELM activity decreases, and eventually ceases entirely, as the total amount of lithium evaporated onto the carbon PFCs is increased. ELM stabilization was predicted to be a consequence of reduced recycling. Stabilization appears to be in agreement with modeling codes, although further experimental work is needed. An undesirable side effect of ELM stabilization is, predictably, an accumulation of high-Z impurities, primarily carbon and metals. Interestingly, the accumulation of lithium in the core plasma is very low and has now been measured at ~0.1%. The impurity accumulation effect can be mitigated through use of the RWM coils for controlled ELM excitation, to flush the core plasma of high-Z impurities. Indeed, successful investigation of ELM control in NSTX, and the compatibility of ELM control with Li, will have broad impact and importance. The use of lithium coatings continues to be associated with increased energy confinement in the electron channel. There is continued evidence for reduced recycling in reduction of the divertor D_α signal, although with continued high-field-side fueling and an influx of carbon density, control has not been achieved.

In order to better address the increasing importance of lithium walls to the NSTX program, a new Lithium Research Thrust area has been initiated, to coordinate lithium-related research for the FY 2009 run period, and to prepare for the installation of the Liquid Lithium Divertor (LLD) in time for the FY 2010 run period. This is a welcome development, since the consequences of the use of lithium coatings in NSTX appear to cut across several of the currently existing topical science areas.

During the FY 2009 run, no new lithium systems will be deployed, although the lithium dust injector (developed at the end of the 2008 run) will be more extensively used. The FY 2009 run therefore presents a good opportunity to develop an understanding of the interplay between lithium coatings, whether applied with LITER or lithium dust, the carbon PFCs, and the edge plasma, prior to the introduction of the LLD in FY 2010. This highlights the need for careful PMI experiments and modeling (with HEIGHTS, UEDGE, DEGAS2, REDEP, etc.) in FY 2009. Both efforts will be aided by data from the new surface analysis station, which will become available during the run.

Specific Recommendations:

1. An assessment of the effect of lithium coatings, in combination with carbon, on recycling should be performed this fiscal year, if at all possible. This will help address questions such as: Is the variation of performance with lithium deposition due to thicker coatings or more extensive coverage, as a function of evaporation rate and total evaporated inventory? What is the role of mobilized carbon? Carbon dust deposited on lithium coatings will be relevant to LLD performance. What role does water play? NSTX is beginning to address PMI specific issues, but more work is needed.

2. NSTX could also address issues related to the physical processes of lithium powder injection function such as powder transport, formation, disassociation, deposition, and burial.

3. A focus on transient gas injection (via the SGI or other fast acting gas puffers) may shed light on τ_p* and global recycling coefficients. Even if a determination of global recycling is not possible, pulsed fueling experiments with lithium coatings will certainly provide qualitative information on the coating performance and should be pursued. For example, the results of transient fueling experiments with evaporative coatings and with powder injection could be compared.

4. NSTX should investigate whether the increase in electron stored energy is due to a confinement increase or whether there is another mechanism.

5. The design, and two alternative constructions, of the LLD is advancing well. Two concerns have been identified. First, the possibility of liquid lithium attacking the brazed material and exposed copper at the lower edge of the LLD needs to be investigated. It is important that formation of a silver-lithium eutectic, with subsequent debonding of the SS-copper braze, be avoided, as well as possible transport of copper back onto the divertor target surface of the LLD. This can be addressed in offline tests. Secondly, fill techniques that result in a thicker layer of lithium on the LLD are desirable. Confining the lithium fill to the LLD surface, rather than involving the surrounding carbon, would also be desirable in order to quantify the effect of the LLD. The PAC is aware that the use of a liquid fill technique places greater stress on the need to avoid degradation of the underlying copper by liquid lithium.

6. The problems in extension of the LLD design to longer pulse and higher power density should be investigated. What would an LLD design for the upgrade look like? Characterization of the surface temperature of the LLD as a function of power deposition profile would provide helpful information, and should be available in FY 2010, from IR cameras and the diagnostic tiles.

7. We note a modeling cross-cut issue: Should/can blob-transport code results be integrated with Li boundary response modeling?

4.3. Macro-stability Research

The NSTX Team made very good progress in several important areas of macro-stability research in the FY 2008 campaign: (1) Feedback control using the nonaxisymmetric coil set succeeded in controlling the n=3 magnetic field error to maintain plasma rotation, while simultaneously providing active control of the n=1 resistive wall mode (RWM). As a consequence, high beta values were maintained for long duration, up to the heating limits of the coils. (2) Experiments carried out in collaboration with DIII-D scientists clarified that the onset of m=2, n=1 neoclassical tearing modes (NTM) depends on the flow *shear* in the vicinity of the q=2 magnetic surface. Also, the data from NSTX and DIII-D indicate that the NTM marginal island width is observed to scale with the ion banana orbit width. (3) Through density control provided by LITER, the collisionality was varied to investigate the ion temperature dependence of the neo-classical toroidal viscosity. (4) Modeling of the RWM stability in NSTX using the MISK code indicates that the influence of plasma flow is non-monotonic, with instability appearing at both low and intermediate values of toroidal rotation. (5) Several experiments were conducted in support of important issues for ITER, including plasma breaking associated with magnetic field errors, tests of the latency introduced by conducting structures in resistive wall mode feedback control, and simulation of feedback control when one of the coils has failed.

The FY 2009 research plan in macro-stability calls for a milestone on understanding RWM stabilization and control versus plasma rotation. This is an important and timely area of research. The PAC makes several recommendations in connection with this milestone: (1) use n=3 magnetic breaking to further reduce the plasma rotation and test n=1 RWM feedback control in low rotation plasmas, (2) maintain a close collaboration with the DIII-D team to explore the differences in RWM stability of low rotation plasmas attained by magnetic breaking (DIII-D) versus magnetic breaking (NSTX), (3) explore the implications of the newly measured poloidal flow on RWM stability (and also neo-classical tearing modes), and (4) increase the effort on theory and modeling, either through collaboration or on-site staff, to help resolve and understand the influence of plasma flow and identify important mechanisms, *e.g.* collisionality, kinetic damping, and Alfven wave damping. We note that theoretical tools like MISK and MARS-K are ready to be fully exploited in such studies.

The PAC endorses the plan to increase research on understanding plasma disruptivity. In connection with this, we recommend that effort to understand the beta "fluctuations", *i.e.* the temporal variations in the plasma pressure, particularly for operation at high-normalized beta, will likely yield important and interesting physics.

The PAC also endorses efforts to explore the impact of fast ions on RWM stability. The capability of LITER and other lithium-based methods for particle control will be helpful to adjust the collisionality.

With respect to longer term NSTX macro-stability research, the PAC recommends that scenario development be initiated for the use of HHFW heating to provide access to high beta. Used in conjunction with neutral beam heating, HHFW could provide a large range of plasma rotation without resorting to magnetic breaking techniques. In particular, it will be important to understand the intrinsic rotation of NSTX plasmas at high beta. We note that the addition of a second neutral beam will be helpful for investigating macro-stability at very high, possibly supersonic, rotation speeds. The stability properties of the plasma might be surprisingly different in this regime. Lastly, the PAC also supports the continuing design of the NCC coil system.

4.4. Turbulence and Transport

NSTX is an excellent position for making progress in the domains of electron heat transport, momentum transport, and particle transport. One reason is that long-wavelength instabilities are stable in most NSTX H-mode plasmas, so that ion transport is close to neoclassical. Moreover NSTX is equipped with an excellent microwave scattering experiment, which allows measurements of high-wave-number density fluctuations, *i.e.* in the range of ETG instabilities. A promising BES diagnostic will be progressively installed, to be completed in FY 2011. Finally, the program on turbulence and transport derives benefit from a theory group on site and collaborations with several institutions.

Several outstanding results have been obtained in FY 2008. The most striking achievements are the observation of a strong dependence of $B\tau_E$ on collisionality and the evidence of a momentum pinch velocity, thanks to transient braking experiments. Other achievements are the suppression of high-k fluctuations with negative magnetic shear and the effect of GAEs on electron transport.

Finally, it has been shown that the neoclassical ion transport observed in H-mode plasmas is consistent with stabilization of low-k modes by shear flow.

The near-term program is focused on the understanding of electron transport (FESAC-TAP recommendation). Several micro-instabilities may underlie electron turbulence in NSTX, namely, ETG, microtearing modes, and GAEs. The direct comparison of high-*k* fluctuation measurements (microwave scattering) to gyrokinetic simulations (with an appropriate synthetic diagnostic) should bring information on the role of ETG modes. Moreover, an assessment of fast electron transport is foreseen, with the help of an X-ray camera. This initiative is strongly encouraged, since it should help to clarify the role of electromagnetic fluctuations with tearing parity. The plan to reduce the amplitude of the various driving or damping terms (fast ions for GAEs, collisionality for microtearing modes) is sound. The implementation of a BES diagnostic is highly welcome since it will give information on the possible role of low-*k* instabilities such as microtearing or Alfvén eigenmodes. In addition, the PAC recommends an assessment of the interplay between edge plasmas with Li PFCs and electron transport. On a longer term, the PAC suggests exploring ways to measure magnetic field fluctuations. Also, the impact of doubling the magnetic field and current should be evaluated. In particular, since the ion gyroradius will likely be smaller at higher magnetic field, it appears mandatory to verify that the microwave scattering diagnostic will still be able to measure high $k\rho_s$ fluctuations.

Regarding the other items proposed for FY09-11, the programme for studying ion heat transport as a possible cause of confinement degradation when NBI will be upgraded makes sense, in particular once the new BES diagnostic is operational. However it is also recommended to investigate impurity transport. Impurity peaking appears clearly as a potential limitation in discharges with Li coated PFCs. Hence it might have detrimental effects in future experiments with LLD. One solution to solve this problem, already tested on NSTX, is to mimic ELMs with external coils. Another solution would be to look for conditions where ITG/TEM turbulence is weakly excited – this might actually be a natural consequence of increasing core heating power with HHFW. The program that is proposed for studying momentum transport looks sensible, thanks to the variety of control knobs offered by the set of external coils. BES measurements should prove useful to test the role of residual low-*k* fluctuations in momentum transport.

The program to study the LH transition is attractive. The future upgrades will allow an extension of the domain of explored parameters. It is recommended, however, to investigate in somewhat more detail the physics of turbulent transport suppression at the LH transition and the residual transport after the transition. Regarding this question, correlation length measurements by reflectometry appear very promising. Also, CHERS measurements of the poloidal velocity should be very helpful.

As a final recommendation, the NSTX staff is encouraged to pursue its efforts to strengthen the interaction between theoreticians and experimentalists and also to continue its fruitful collaborations with US and foreign laboratories.

4.5. Energetic Particles

NSTX is an excellent test bed for fast ion physics. Energetic particles in NSTX are super-Alfvénic and high beta. Fast particle diagnostics are excellent, and the program has good theory and simulation support.

Highlights from the FY 2008 run include: (i) measured neutron rate reductions correlated with fast-ion avalanche loss and kink-induced radial redistribution, (ii) the apparent role of GAEs in causing core electron transport, and (iii) several invited talks at IAEA and APS-DPP in FY 2008.

The PAC encourages NSTX to push forward important cross-cutting research in the topics of (i) fast ion effects on RWM stability (with MHD TSG), (ii) simulation of multi-mode avalanches, also with rotation shear, and (iii) consideration of simulating alpha heating with on-axis 2nd harmonic HHFW on protons (with HHFW TSG).

In addition to existing energetic particle research plans, the PAC recommends increased emphasis on resolving the discrepancy (NSTX, DIII-D) between measured and simulation mode amplitudes to reproduce fast ion losses.

4.6. RF Heating with HHFW

Significant progress was made in the high harmonic fast wave (HHFW) heating and current drive program on NSTX in 2008. Core electron heating was obtained in deuterium NBI heated H-modes in conjunction with Lithium (Li) wall coatings. This improved heating, with $T_e(0)$ increases up to 2 keV, was believed to be correlated with a reduction in edge density (due to Li conditioning) and improved linear wave coupling. Good electron heating, with >1 MW of power was also obtained in the early current ramp-up phase (300 kA) of NSTX. HHFW heating was used effectively as a tool to investigate electron temperature gradient driven modes, where record electron temperatures of $T_e(0) \approx 5$ keV were produced with HHFW power, thus providing strong electron temperature gradients for transport studies. MSE measurements of core HHFW current drive were also made, consistent with significant modification of the central safety factor, with $q(0)$ dropping from 1.0 to 0.6. Favorable comparisons of the MSE data with simulation from the AORSA and TORIC solvers were also made, which has started to validate the predictive capability of these models. In general there has been an excellent interaction between experiment, theory, and simulation in this area.

The results from the FY 2008 campaign using the HHFW system and the upcoming HHFW antenna upgrade have established an exciting application capability for HHFW in current ramp-up and start-up studies on NSTX. The HHFW upgrade, to a double-ended center-ground antenna configuration, should allow increased power handling under low-load conditions. With this added capability, it is recommended that the NSTX Team start developing plasma scenarios (preferably in FY 2009) that can be used for HHFW heating in current ramp-up and start-up plasmas. A focus of these early studies could be establishing the capability to couple HHFW power to ramping plasmas, for example. It is recommended that additional run days be used for this, if more run time becomes available. The Wave-Particle Group should also revisit the absorption and propagation physics of HHFW in NSTX-U in light of the fact that the magnetic field for the upgrade will be 1 T. This can be done with combined full-wave and Fokker Planck solvers such as AORSA/TORIC and CQL3D. Possible concerns that should be investigated are wave absorption from a fundamental hydrogen resonance layer that will be located at about $r/a \approx 0.75$ to the high field side, a second-harmonic hydrogen resonance at the axis, and mode conversion to the ion Bernstein wave, which may occur at low harmonics of the deuterium ion cyclotron frequency in a high beta plasma. At this toroidal field, energetic protons, in the MeV range may be produced efficiently by the second harmonic resonance heating of residual minority protons in the plasma, although this should be verified by modeling. This heating scheme, or an alternative which produces an energetic ion population, will allow study of a variety of research items related to alpha particle heating in the ST. This is a cross-cutting study to be carried out with the Wave-Particle Group. The Wave-Particle Group should also continue to assess the level of parasitic losses in combined HHFW-NBI experiments, especially given the need to understand the interaction of RF waves with energetic particles in future burning plasma devices. The Wave-Particle Group has investigated RF losses in HHFW heating experiments on NSTX due to parametric decay instability and surface wave excitation in detail. We encourage the Boundary Physics Group to become more involved in the area of RF-edge interactions (*e.g.* sheaths) to determine if RF sheath losses are important in NSTX and to aid in developing mitigation techniques if needed. We also agree with the need to develop increased protection against ELM-induced transients in the antenna loading, and ELM-resistant antenna matching techniques, over the next 2-3 years. Finally, in view of the increased utilization of HHFW heating in NSTX, it is recommended the project consider additional experimental staffing in this area.

4.7. Current Start-up and Ramp-up

The PAC recognizes significant progress during FY2008, including the successful coupling of CHI-formed discharge to inductive ramp with NBI heating, as recommended by PAC-23, and the achievement of full equilibrium control during this phase.

The PAC also congratulates NSTX team members on being joint recipient (along with members of MAST and DIII-D staff) of the 2009 DIII-D Torkil Jensen Award for an innovative proposal for solenoid-free startup on DIII-D.

The PAC recommends that high priority be placed on providing adequate resources to leverage DIII-D run time towards this important ST goal. Additionally, concerning plans for 2009-2011, we suggest continued efforts to reduce impurity influx during high-current CHI initiation and identification of a specific quantitative objective to focus and measure research progress. One possible measure is the achievement of at least 150 kA low-Z plasma current, allowing ramp-up using other techniques. The PAC is particularly concerned with the challenges of ramping the plasma current from the post-formation phase to current flattop non-inductively. Because of this concern, the PAC recommends increased emphasis on ramp-up scenario development utilizing the HHFW and NBI. This effort should be complemented with improved modeling of this phase, including realistic breakdown scenarios and transport/stability considerations. The PAC encourages continued evaluation of the plasma gun as an alternative plasma-initiation technique. The NSTX Team should continue to pursue collaborative strategies for I_p startup (*e.g.*, outer PF, EBW/ECH for early heating) and to develop long-term strategies for NSTX.

4.8. Integrated Scenarios

The PAC compliments the NSTX Team for the progress made during the FY 2008 run towards demonstration of ST integration goals. These include the following:

(i) Considerable progress towards long pulse, high performance ST scenarios, by combining various control techniques enabling sustained high $\kappa = 2.7$ operation;

(ii) Demonstrated sustainment of $\beta_N > 5$ for 3-4 τ_{CR} with the use of improved n=3/n=1 EF control and Li wall conditioning;

(iii) Quick response to the critical ITER issue of vertical stability.

The PAC endorses the NSTX FY2009 integration priorities: (i) strike point control in preparation for LLD (although consider IR, rather than magnetics, as sensor), (ii) push towards low n_e, low ν* NBCD scenario using Li conditioning, and (iii) recognizing that high NBCD fraction and low ν* are the largest leveraged extrapolation parameters pointing towards next-step devices such as NHTX and ST-CTF.

The PAC makes the following suggestions for the FY 2009-11 period:

(i) The NSTX team should give stronger emphasis towards the development of scenarios with controlled fuelling/density in order to address edge/exhaust and heat load issues. The PAC suggests development of H-mode scenarios without the mid-plane CS fuelling and/or investigate density pump-out instigated by resonant magnetic perturbations as density control tool. This should be preferred to pushing towards higher β_N, since NSTX scenarios already exceed the β_N of future conceptual ST devices. Density control is needed to access low ν^* and large NBCD fraction.

(ii) The NSTX Team should work towards the integration of HHFW heating and potentially current drive into standard scenarios. This would give NSTX a unique tool for controlling, *e.g.* impurity accumulation, the q-profile, the T_e profile, and the plasma rotation. The additional electron heating would also allow access to low ν^* regimes at high T_e. For this, the PAC suggests development of a long pulse scenario with good HHFW coupling based on the Li induced ELM-free H-mode. A key question to answer would be if ELMs reappear at high power or low ν^* in these scenarios, and if yes whether they trigger low-n MHD?

(iii) In addition to the impressive integrated SN scenario the PAC recommends to apply similar techniques in DN, since SN operation might not be possible in future devices due to the high target power loads. It should to be investigated whether the same control techniques (*e.g.* density and ELM control via Li) can be transferred to DN, and for example whether ELMs are reintroduced to the changed plasma edge profiles. Again a key question would be if ELMs could trigger detrimental low-n MHD?

(iv) Non-solenoid I_p ramp-up techniques such as HHFW bootstrap overdrive, and NBCD should be integrated into standard scenarios (if possible high performance) to investigate if stable q-profiles can be maintained throughout the discharge.

(v) The TSC modeling is seen as important for the development of integrated scenarios and optimizing the current ramp-up towards a "relaxed" current profile. This is in particular important with respect to the planned upgrade. It is important to maintain staff/expertise in this area and to work aggressively towards the implementation of a realistic transport model in TSC. Studies exploring the current evolution in high-β, long-pulse discharges should be continued.

Respectfully submitted,

Riccardo Betti
University of Rochester

Jeffrey Brooks
Purdue University

Paul Bonoli
Massachusetts Institute of Technology

Ronald H. Cohen
Lawrence Livermore National Laboratory

Xavier Garbet
CEA Cadarache

Donald L. Hillis
Oak Ridge National Laboratory

Haruyuki Kimura
Japan Atomic Energy Agency

Jiangang Li
Institute of Plasma Physics, Hefei, China

Bruce Lipschultz
Massachusetts Institute of Technology

Michael E. Mauel (Chair)
Columbia University

Richard P. Majeski
Princeton Plasma Physics Laboratory

Hendrik Meyer
UKAEA Culham

John S. Sarff
University of Wisconsin

James W. Van Dam
University of Texas

Mickey Wade
General Atomics

April 1, 2009