Report of NSTX Program Advisory Committee
(PAC-35)

June 11-13, 2014

Committee Members Present:
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Ex-officio:
Steve Eckstrand (Fusion Energy Sciences, DOE)
Jon Menard (Princeton Plasma Physics Laboratory)
Masayuki Ono (Princeton Plasma Physics Laboratory)

Committee Members Absent:
None

1. Introduction

The NSTX Program Advisory Committee (PAC) held its 35th meeting at the Princeton Plasma Physics Laboratory (PPPL), June 11-13, 2014. The NSTX facility is nearing the completion of a major upgrade to double the toroidal magnetic field to 1 T, double the plasma current capability to 2 MA, double the neutral beam heating power to 14 MW, and greatly increase the pulse length from 1 s to 7 s. A primary aim for these upgrades is to assess confinement and stability for the spherical tokamak (ST) at lower collisionality and high β_N and to explore future high performance scenarios. The upgrades will also enable much greater plasma control to investigate non-inductive plasma sustainment and formation, issues that are critical to resolve for the ST configuration and its applicability for next-step options like a fusion nuclear science facility (FNSF). We congratulate the NSTX-U team on the favorable review of their 5-year research proposal for FY 2014-2018.

The PAC congratulates the NSTX-U team on successfully solving many key technical challenges associated with the Upgrade project. The work is 87% complete, and while the schedule is tight, there is good probability that CD-4 will be achieved by Jan 2015, and that a full 18 weeks of operation could be completed in FY 2015.

The PAC congratulates the team for undertaking successful collaborations during the Upgrade outage period. We were presented at PAC-31 an ambitious plan for collaborations and analysis of NSTX data at the outset of the Upgrade project. This plan has been successful, and the impact is clear in key metrics for scientific productivity (publications, invited talks, etc.). The joint work on other facilities (DIII-D, C-Mod, MAST, EAST, KSTAR, MAGNUM-PSI, QUEST) are reported by these collaborators to be helpful and welcome. Indeed, these collaborations have brought back to NSTX-U new ideas and new capabilities, e.g., advanced plasma control.

The PAC is very pleased to see the strengthened connection between the NSTX-U experimental program and the PPPL Theory Department through the new Partnership. Following our previous recommendation, one of the presentations (S. Kaye) was dedicated to describing this new partnership. Additional comments are given in answer to charge question 3 below.

The PAC was charged to answer the following questions:

1. Assess the operational preparation and research priorities and preliminary plans for the first two run-years of NSTX-U with emphasis on the first run year.

2. The NSTX Program has been asked by DoE Fusion Energy Sciences (FES) to develop and implement ideas to "Expand engagement with university scientists to enhance the NSTX-U program". Please comment on and/or expand the preliminary set of ideas (to be presented at PAC-35) to make NSTX-U more attractive and/or available to university scientists – including early career researchers and students.

3. Comment on progress and plans for establishing and expanding the partnership between the NSTX-U program and the PPPL theory department.

The NSTX-U team detailed their research plans in 13 presentations over two days. These included an overview of the research program, an update on the Upgrade status, and progress and plans for: the facility and diagnostics, research operations, and the NSTX-U–Theory partnership. There were also presentations related to a number of topical areas: non-inductive startup and ramp-up, development of plasma-facing components (PFC), scrape-off layer (SOL) and divertor physics, pedestal physics, turbulence and transport, macro-stability, energetic particle physics, and RF physics. The PAC thanks the NSTX team for their effort in preparing comprehensive and informative presentations. We applaud having younger members of the NSTX-U team represent the program as presenters; they are a talented and energetic crew who are a clear asset to the NSTX-U program.

2. Comments Pertaining to the Three Charge Questions

The PAC offers the following general comments pertaining to the three charge questions. We also offer additional specific comments related to each of the topical areas in Section 3 below.

1. Assess the operational preparation and research priorities and preliminary plans for the first two run-years of NSTX-U with emphasis on the first run year.

The PAC anticipates that the past practice of relatively short-term scheduling is likely to be insufficient now and for the future NSTX-U program. We therefore recommend adopting a new planning process that incorporates a longer term run schedule. This will (1) better support integrated and increased collaborations anticipated for the NSTX-U program, (2) help develop the rationale that drives the hardware schedule, and (3) maximize the productivity of the first year of operation, which clearly has a very tight schedule.

Particle control remains a critical issue in achieving low-collisionality, long-pulse discharges in NSTX-U. The PAC strongly recommends developing a clear plan to understand particle transport and particle sources and sinks to ensure confidence in the design and implementation of the cryo pump. Such a plan will also increase confidence in achieving important metrics such as low collisionality that validate the primary motivation for the Upgrade within the first two years of operation.

While it is clear there is great eagerness to test the new capabilities of NSTX-U, the PAC urges thorough experimental investigations at each of the operational steps from bare first-wall surfaces to boronization to added lithium. The PAC was presented a very informative time chart (S. Gerhardt) summarizing the readiness of various facility capabilities and diagnostics. We agree that TRANSP analysis capability defines a necessary criterion for research readiness, but it is not sufficient to understand in detail the impact of the various wall conditions and coatings. The PAC recommends more thorough analysis, planning, and preparations that factor in the diagnostic and control capabilities required to support detailed investigation of each of the wall condition operational steps noted above. To support this, we recommend developing metrics for gauging success at each step in wall condition. We also recommend producing a thorough plan and anticipated schedule well in advance of the Research Forum, in part to maximally inform collaborator research proposal preparations. We note that the next opportunity for careful diagnosis of steps in wall conditions like this will not occur until 2018.

2. The NSTX Program has been asked by DoE Fusion Energy Sciences (FES) to develop and implement ideas to "Expand engagement with university scientists to enhance the NSTX-U program". Please comment on and/or expand the preliminary set of ideas (to be presented at PAC-35) to make NSTX-U more attractive and/or available to university scientists – including early career researchers and students.

The PAC applauds the concerted effort to engage NSTX-U collaborators in a fruitful planning discussion on expanding engagement with university scientists. While this is a specific request from FES to the NSTX-U program, it is in fact a larger fusion community issue. The PAC was informed that the planning discussion was organized through three meetings jointly with 22 FES-funded NSTX-U collaboration grantees (university, laboratory, industry). The specific suggestions identified for possible FES and PPPL action are good examples that are either essential to stabilize or to improve the environment for university collaborations on NSTX-U (J. Menard overview presentation slides 40-43).

The PAC agrees the NSTX-U Innovative Research Award (NIRA) is a good idea that should be implemented. We were informed through the question-answer period that university-based collaborations involving NSTX-U research are already substantial, e.g., totaling 76 individuals. Hence, if targeted exclusively to university researchers, the NIRA would increase university collaborations 10-20% beyond that which is currently underway. The PAC advises that in considering support for collaborative Ph.D. student research, duration of more than three years might be necessary to make such support tenable.

Looking beyond the specific suggestions presented to the PAC toward the larger community issue, establishing a university program dependent *primarily* on collaboration at a major fusion user facility is compelling but very challenging. There are few such programs in existence in the U.S. fusion program. The PAC suggests that PPPL and/or FES could help facilitate the establishment of such university-based collaborative programs, keeping in mind the following considerations:

- The base for stable university collaboration is a tenured faculty member(s) who is responsible for the supervision of Ph.D. education. This base is often greatly enhanced by the addition of professional scientists/engineers. The faculty member(s) must be vested in the students' research activities.

- Tenure promotions typically demand demonstration of scientific leadership in addition to scientific productivity. Structuring the scientific management of the NSTX program to include university faculty/researchers would help demonstrate scientific leadership and integrate university participation with less concern for additional financial support, i.e., the university faculty member(s) becomes an integrated, co-leader of the Research team. We note that university scientists already hold leadership positions in the Topical Science Groups.

- Competition for tenured faculty positions is fierce. Guaranteed financial support for startup and initial salary can significantly influence hiring decisions. This model has been successful in other research communities and other fusion projects, e.g., MAST/Culham and its nearby universities. PPPL and/or FES could seek to establish tenure-track positions through such support, perhaps targeting universities in close geographic proximity to facilitate graduate student educational needs. (Proximity is not likely essential, however.)

The three points above only touch on the essential criteria for successful and sustainable university participation at FES user facilities. We recommend that PPPL/NSTX help drive a national conversation on the role of universities in fusion and plasma physics research, together with other laboratories and universities.

3. *Comment on progress and plans for establishing and expanding the partnership between the NSTX-U program and the PPPL theory department.*

The PAC was impressed with the results of the very productive partnership that was initiated in order to increase the participation of the PPPL theory Department in the NSTX-U project. We congratulate the co-leaders of the partnership (A. Bhattacharjee and S. Kaye) along with the participating theorists and NSTX-U team members for making that initiative so successful.

The partnership focused on addressing topics critical to achieving the priorities of the NSTX-U Five Year Plan. It included research on non-inductive operation, the exploration of parameter regimes unique to ST (with the goal of advancing predictive capabilities), and investigations aimed at developing solutions for the plasma-material interface. Achievements included the study of a mechanism channeling power from the beams to the electrons through CAE and KAW; the simulation of VDEs using the new finite thickness wall in M3D-C1 while radiation distributions, runaway electron current and resulting edge profiles are being modeled with DEGAS2 and XGC1; the investigation of the role of Kelvin-Helmholtz destabilization in turbulent transport; the demonstration of the inverse scaling of blob turbulence with plasma current; and the identification of the role of neoclassical effects in setting the width of the SOL heat flux.

The PAC recommends that PPPL maintain the partnership regardless of the continuation of the incremental funding that was used to seed it. This should be a high priority.

In order to encourage the theory-experiment partnership, we recommend that the NSTX-U team include details of theory and modeling requirements for an experiment when proposals are made. We also recommend that NSTX-U scientists strengthen their familiarity with the goals and priorities of the theory division in order to increase their effectiveness at communicating the import of NSTX-U experiments to the problems being addressed by Princeton theorists. For example, do the strong flows leading to KH destabilization also affect the dynamics of the zonostrophic instability? What do the analytic reconnection rates established by A. Bhattacharjee and collaborators imply with regard to the regimes (plasmoid, SP, Hall-MHD) pertaining to CHI? Do microtearing modes and NCC fields offer case studies for ghost surfaces? Enhancing communication with the theory group will stimulate self-motivated collaborations leading to impactful discoveries, and it will increase the prestige and effectiveness of the NSTX-U team.

The PAC also suggests that the NSTX-U/Theory partnership produce a set of target milestones for theory work in the next three fiscal years (like slide 13 from J. Menard's talk) especially highlighting the synergy with the experimental milestones. We further request that the team show a timeline of the long-term planning for the development of modeling capabilities, as in slide 12 of M. Ono's talk. We look forward to seeing such milestones at future PAC meetings.

3. Comments and Suggestions Pertaining to Topical Research Areas

We summarize below recommendations for each topical research area organized according the presentations made to the PAC.

3.1 Advanced Scenarios and Control

The PAC commends the preparations that the NSTX-U team is making in the area of scenario preparations and the development of control systems required for NSTX-U. The progressive build-up of the NSTX-U operation and control capabilities during FY-15 and FY-16 is clear and well aligned with the 5-year plan for NSTX-U. In this 5-year plan NSTX-U should (1) develop the basis for integrated, steady-state operation and axisymmetric control for next-step STs and (2) establish stationary, 100% non-inductive operation, and partial inductive operation up to 2 MA, for 5 seconds over a wide range of Greenwald fractions, collisionality, and β values.

During FY14, the preparation for control of the current profile and rotation (involving collaborators) has been excellent, addressing milestone R14-3. Control-oriented models for the current diffusion are used for a dynamic observer and the design of a controller, to be tested in FY16 for combined β_N and l_i control. The proposed control of the rotation profile in NSTX-U uses non-resonant, neoclassical toroidal viscosity (NTV) physics and variations of the core neutral beam injection profile, supported by extensive TRANSP simulations.

Especially for scenario development and their control, the commissioning schedule prior to FY15 operation is aggressive and has the potential for significant delays. Hence, the scheduling of the 18 week run plan in FY15 should continue to take into account completion of key systems. Providing a best estimate for when systems become available during FY15 and FY16 is essential for optimum use of NSTX-U. Key would be prioritizing to make sure critical systems are ready to meet their high level objectives.

In the preparation of the start of NSTX-U operations in FY15, a lot of work has been devoted to installing (new) diagnostics. A new digital coil protection system will be commissioned and be a key part of extending the NSTX-U operation. The extensive work on these systems required for operation is noted by the PAC.

The research activities on advanced scenarios and plasma control for the first 2 years cover the developments of (1) long-pulse and high current scenarios, (2) fully non-inductive scenarios, (3) first attempts at profile control, 4) heat flux control, 5) disruption avoidance and 6) neutral beam current drive (NBCD) studies. The PAC praises the team in preparing these research opportunities at NSTX-U. Validation of NBCD should be given high priority in the first two years of operation, starting at 600-800 kA using (initially) inductive ramp-up of the plasma. Power control with strike point control, radiation control and snowflake control are key new developments, but care should be taken not to fragment the research in the area of heat flux control.

Particle and density control at NSTX-U will have new capabilities such as gas valves under real-time control, impurity seeding and new real-time density measurements. However, the cryopump will not be available until at least FY17, and it is not yet known whether lithium alone will provide adequate particle removal. The preparation (algorithms) for real-time density control (including its profile) is not clear. For the experimental program in FY15 and FY16 priority should be given to documenting what can be used to provide active particle control long pulse, high power plasmas. A second priority should be developing the necessary basis for the design of a cryopump for NSTX-U in combination with new the capabilities of the device, such as the snowflake divertor.

The development of disruption avoidance in NSTX-U and the characterization of disruption mitigation with Massive Gas Injection at several poloidal locations should be seen as an important part of the US (and worldwide) effort to define a robust disruption mitigation system for ITER. This aspect should be given more emphasis for NSTX-U, especially in preparation for the Joint Research Target (JRT) in 2016.

In their presentations to the PAC, the NSTX-U team did not provide details on the study, optimization, and control of NBCD at NSTX-U in collaboration with DIII-D. This area is well coordinated; DIII-D has announced a second national campaign that includes a joint experiment with PPPL for “testing the prospects of neutral beam current drive to produce fully non-inductive and current overdrive in preparation for follow-on experiments on NSTX-U.” Sufficient priority should be given to this collaboration during the first 2 years of operation.

3.2 Solenoid-Free Start-Up and Ramp-Up

One of the most critical issues that must be resolved for an FNSF-ST is that of initiating the plasma and ramping to full current without relying on a solenoid to drive current. The PAC commends the NSTX-U team for addressing this issue using capabilities that are unique to the NSTX-U device.

The initial current ramp, to approximately 400 kA, will be driven using Coaxial Helicity Injection (CHI). This was demonstrated in NSTX, with as much as 200 kA driven current. Credible scalings predict this should reach 400 kA or more in NSTX-U. Previous attempts at handing off the resulting cold plasma to other tools to complete the current ramp (solenoid, fast wave [FWCD], and/or neutral beam current drive [NBCD]) met with limited success. NSTX-U plans to obtain a 28 GHz gyrotron to heat the electrons in the CHI plasma to a level where these other tools can efficiently drive current. Ultimately, a combination of FWCD and NBCD is planned to complete the current ramp noninductively.

There are several challenges involved in the full nonsolenoidal ramp scenario. Previous experience in NSTX has already demonstrated sufficient plasma control to form closed flux surfaces and avoid contact between the CHI plasma and the walls. Also, in the past the NSTX team did not usually mix fast wave and neutral beams as the rf tended to be absorbed by beam ions.

The plans for the first two years of NSTX-U operation appear to address the right issues. The PAC cautions that sufficient experimental time will need to be made available to develop the current ramp. Early experiments will need to determine the limits of CHI plasma formation, and in particular determine the maximum achievable current without use of the solenoid. Although separate experiments can and should be done to develop a FWCD/NBCD current ramp starting at 400 kA (presumably using the solenoid to get there), a full demonstration of nonsolenoidal startup will have to wait for availability of the 28 GHz gyrotron.

The PAC is, however, concerned at the early stage of development of this gyrotron coupled with its importance for the entire current ramp scenario. We urge that this development be expedited as much as possible, as it appears to set the critical path for a full current ramp demonstration.

The PAC further commends the NSTX-U team for the extensive effort that is underway to apply modeling tools including NIMROD, TSC, and TRANSP to the problem. We look forward to results of further simulations including more realistic assumptions for fast wave coupled power. These tools will also be very useful for both prediction and interpretation of the upcoming experiments.

3.3 Plasma-Facing Component Materials and Development (Lithium and High-Z)

The topical science area in plasma-facing component (PFC) development focused their responses on addressing the three charges, particularly the plans and priorities for the first two years of NSTX-U operation (FY15-16). The responses are guided by the 5-Year Plan research thrusts outlined in Ch. 5 of the NSTX-Upgrade Research Plan for 2014-2018.

We congratulate the NSTX-U team for conducting critical collaborations in support of PFC lithium and high-Z material research during the upgrade. We also appreciate scheduling of high-Z tiles (bulk-W lamellae in FY16) and cryo-pump installations (FY17) according to the PAC-33 recommendations. The Materials Analysis and Particle Probe (MAPP) diagnostic and its implementation in FY15 is important for plasma-material interface (PMI) studies without influence of discharge history. Overall, there has been excellent work on fundamental surface science with university (e.g. Princeton U.) and international (e.g. DIFFER Magnum-PSI) collaborations to support experiments in the identified thrusts.

Following are suggestions for FY15-16 experiments according to the Research Thrusts identified in the 5-Year Plan:

Thrust MP-1: Understand lithium surface-science for long-pulse PFCs

One challenge for operation at longer pulses in NSTX-U plasmas will be to predict the important coupling of surface chemistry evolution and D recycling and retention. This challenge is driven by plasma-induced erosion/re-deposition inducing changes to chemistry faster than equilibrium time scales. In addition, PFC temperature increases near the high heat-flux region of the outer strike-point can also introduce complexities in correlating lithium surface evolution to plasma performance. Therefore, it is critical for surface science laboratories to complement experiments in NSTX-U and in particular to the extent possible provide for conditions relevant to plasma shot operation (e.g. D energy, fluence, temperature, etc.). Therefore, experiments planned for lithium coating deposition at high temperature should be conducted closer to NSTX-U wall operation conditions, e.g. including D irradiation, to understand effects on hydrogen dynamic retention. It would be especially useful to study the pumping performance of Li-C surfaces at the total D fluence levels expected in NSTX-U over its 3-5 sec. operation.

Thrusts MP-1, 2: Systematic study of Li surface-science in NSTX-U and Physics understanding of tokamak-induced material migration and evolution

In addition to the need for in-situ studies of plasma-surface interactions (i.e. "in-situ" defined as surface science experiments under "realistic" conditions found in NSTX-U with both model and realistic materials systems), a systematic approach to connect plasma performance to the interface of the plasma and the wall surface must be established carefully. In particular, with an essentially new device in NSTX-U, erosion and re-deposition conditions must be identified with new plasma configurations. Whereas fast start-up and plasma confinement studies by wall conditioning such as the Li evaporation systems (LITERs) will be in high demand, systematic investigation of the effects of lithium deposition (amount and coverage) on the scrape-off layer (SOL), divertor, and pedestal plasma is important, i.e. providing enough time of initial operation with Li-free conditions for FY15, in particular in the context of boronization steps.

Sufficient time for systematic studies introducing lithium conditioning in a methodical way would be desirable. This approach is important both in the assessment of the impact of more lithium coverage (e.g. with the introduction of the granule injector and upward-facing evaporator system) and running fiducial experimental shots that elucidate boronization contemplating future use of a cryo-pump. From the standpoint of the engineering design of a cryo-pump system planned for FY17, it will be critical to evaluate particle balance under both non-lithiated conditions and those with different Li coating conditions providing a unique database that steps into FY16, which will focus on the introduction of the high-Z material tiles (i.e. introduces yet another PFC interface with the plasma). From the standpoint of the edge plasma, non-Li wall conditions (i.e. under higher hydrogen recycling conditions) would be desirable to study ELM-pacing with the Li dropper and/or injector systems and compare systematically with progressively higher Li wall coverage using evaporator systems. This approach would elucidate the role of the lithiated wall versus the direct Li-particle injection into the plasma edge for pacing ELMs. From the standpoint of the planned outboard high-Z material tiles, a systematic methodology will enable understanding and a more quantitative evaluation of Li coverage and uniformity using the various Li coating techniques and their effect on recycling and reduction in sputtering/surface damage when applied to high-Z materials such as tungsten or TZM.

Thrust MP-2: Physics understanding of tokamak-induced material migration and evolution

Code development is key aspect for this thrust in FY15. Systematic MAPP studies correlating with plasma performance are desirable and in particular the team is commended for initiating collaborations to compare edge/wall computational modeling (WallDYN) with plasma edge diagnostics. This requires a high level of coordination and it is recommended that all those involved, including those operating plasma-edge diagnostics (e.g. optical spectroscopy systems including those with optical chords to MAPP samples, MAPP and in-situ QCMs), work closely together in designing experimental proposals that methodically work from non-Li conditions to predominantly lithium-based surfaces in NSTX-U. It is also not clear how various computational modeling codes will be used and specifically the surface response where the lithium and boron chemistry with graphite can be complex. This should be clarified.

Thrust MP-3: Establish the science of continuous vapor-shielding

Similar to our comments above, it would be desirable to provide enough coordination with surface-response models and plasma edge models to elucidate the role of Li coatings at high temperature on high-Z substrates, ultimately leading to an assessment of the vapor-shielded regime. A strategy and plan with metrics should be developed to verify the success of vapor-shielded regime and the role of carbon and other impurities on Li coatings integrated to high-Z substrates.

Additional comment on active study of high-Z transport and control

The present plan should provide useful data on the mechanical stability of the new tiles but limited and perhaps confusing information on plasma-material interactions owing to the small surface area available. The initial coverage (presently only one row in outboard lower divertor in FY16) should be reconsidered before installation in FY16. The detailed shaping of W-lamellae should also be considered. Different options to consider include: 1) expand the poloidal coverage to more than one toroidal row in FY16 and 2) add toroidally separated high-Z tiles at various wall locations to better validate the lamellae design in a variety of loading condition (i.e., small-scale melting has tended to be the most limiting factor in W PFC deployment). Study of W transport and control, such as melting layer and accumulation control, will be necessary before major replacement of wall PFCs (FY19). These results will also contribute to ITER/ITPA R&D. In addition, installation of the laser blow-off system for FY16 would allow important controlled injection of high-Z to study its transport throughout the discharge.

3.4 Scrape-Off Layer (SOL) and Divertor

Overall, it is good and appropriate that this topical group is becoming more integrated to the central mission of the NSTX-U program. This topical area faced a similar challenge to the rest of the NSTX-U team with the prolonged shutdown for the upgrade. The boundary / SOL team is congratulated on what appears to have been a very productive collaboration with DIII-D in further development and exploration of the snowflake divertor configuration for divertor heat flux control.

Moving to NSTX-Upgrade, the proposed diagnostic set is appropriate to both support the NSTX-U overall mission and advance the edge physics in the first few years of operation. The team is also contemplating more aggressive diagnostic deployment in the long term. The development and installation of divertor Thomson scattering would be a great addition to the diagnostic battery, and one that seems possible with the rather open divertor geometry of NSTX-U. The set of PMI diagnostic tools has been improved, particularly with MAPPS. Continued deployment and improvement to PMI diagnosis should be considered. Overall we continue to encourage the team to involve boundary modeling as new results come in from NSTX-U. For example, UEDGE modeling of both conventional and advanced divertors will not only improve physics understanding but also inform divertor design. This fits in well to the NSTX-Theory partnership.

The issue of achieving stationary particle/density control should be the highest priority in the near-term for SOL/divertor research. However the near-term priority for the NSTX-U program was stated as being heat flux control. It is recommended that heat flux is not the highest priority since it appears unlikely that administrative energy-limits will be surpassed for the PFCs. It is noted that these prioritizations may not be mutually exclusive because the team may need to focus on snowflake development and its ability to achieve high-recycling divertors in a variety of plasma shapes regardless. In addition, the same experiments can provide needed SOL characterizations versus operating parameters (B, Ip, etc.).

It is vital that this topical group, and NSTX-U overall, assure the necessary near-term effort to fully characterize the requirements and feasibility of the cryopump through measurement and modeling. The cryopump installation will be perturbing to the NSTX-U schedule, but it will likely be the central tool in obtaining the device mission goal of stationary high-performance plasmas.

3.5 Pedestal Physics and Control

The PAC was impressed with the focused work of the NSTX-U team during the upgrade shutdown to advance understanding of the pedestal behavior from existing NSTX data and by participating in related experiments on C-Mod, DIII-D, MAST, and EAST. Among the notable results/activities discussed are: KBM analysis for NSTX and C-Mod data, pedestal recovery dynamics in DIII-D, EP H-mode analysis for NSTX shots, demonstration of LPI ELM pacing in EAST, leading 2014 JRT study, and work on EM effects in XGC1.

Before commenting on the specific FY15-16 plans presented, the PAC wishes to emphasize that a very central goal for NSTX-U research should be to understand particle transport, sources, and sinks, and thus density profiles. As reported several years ago (Canik et al., Phys. Plasmas 2012), lithium has a large effect on the pedestal profile and thus ELM stability. While that paper reports differences without and with lithium in the turbulence levels and considers some characteristics of micro-instabilities given the measure profiles, it does not answer the fundamental question of why the pedestal plasma profiles change so much with lithium injection, which presumably alters the material surface properties (recycling) and perhaps line radiation. This issue couples the pedestal to the SOL/divertor/wall on one side and the core on the other; thus it requires integration of these regions in some fashion. The PAC did not see a detailed plan for how this fundamental question of particle transport and profile formation will be addressed, but believes finding the explanation should be very high priority, given that density control for NSTX-U is so crucial and such understanding could have broad scientific impact for other fusion devices. Furthermore, in early NSTX-U operation, power handling is not likely to be a limiting factor.

Comments and recommendations on three high-level pedestal-related activities for FY15-16 for each are given below, identified by milestone number:

R15-1: Assess H-mode energy confinement, pedestal, and scrape off layer characteristics with higher BT, IP and NBI heating power

This research is key to understanding how the ST pedestal properties will scale to more FNSF-relevant parameters, and is strongly encouraged, especially related to the particle transport issue just mentioned. It is important to obtain NSTX-U data first without wall conditioning to understand the effect of boron and lithium. One of the issues noted in the PAC-33 report is the understanding the different scaling of pedestal width with poloidal beta compared to MAST, which should be revisited. In general, it will be important to make comparisons between NSTX behavior and that of NSTX-U. In preparation, it would be helpful to identify NSTX discharges to be used for such baseline comparisons.

While scaling of the LH transition power threshold is perhaps implicit in such studies, such plans should be articulated.

Diagnostics cited for pedestal measurements were MPTS, BES, bolometers, and ME-SXR. While these mainline measurements are very useful, the PAC would welcome more extensive use of high-*k* scattering (for turbulence) and CHERS (for E_r, T_i) in the pedestal if possible, or development of plans to improve their applicability. The installation of a laser blow-off system in FY16 will provide a key tool to help understand transport of high-Z ions through the edge region.

The overarching pedestal research goal given during the pedestal presentation was "develop predictive capability for pedestal structure and evolution." Such predictive capability was also mentioned in the talk on "Theory Partnership," which apparently focuses on XGC1 and perhaps a developing continuum kinetic code for pedestal turbulence. Given the overarching nature of this goal, the specific plans here could/should be better articulated/developed. What about pedestal analysis from other previously used codes, e.g., SOLPS, UEDGE, NEO, etc.?

IR15-1: Develop and assess the snowflake divertor configuration and edge properties in NSTX-U

This research is important because it addresses how the use of the snowflake divertor for heat-flux mitigation will impact the pedestal characteristics. Such work will follow some done on NSTX.

Following the discussion above about particle transport and density profiles, attention needs to be focused on how snowflake divertor operation affects particle transport and density profiles. Plans should be more clearly articulated/developed.

R16-1: Assess scaling and mitigation of steady-state and transient heat-fluxes with advanced divertor operation at high power density

The pedestal-related aspect of this research milestone involves ELM stability and ejection characteristics as well as between-ELM pedestal profile evolution and transport. These are key questions that should be addressed, and while some understanding can be developed in FY16, it is a complex topic that will likely continue for some time.

Concerning ELM stability and use of EPED to compare with the pedestal "height and width", it was noted in the pedestal presentation that EPED has some difficulty with very low toroidal mode number ELMs as observed in NSTX. The PAC suggests that other MHD codes can calculate such ELM stability if EPED continues to have this difficulty. However, utilizing the "width" model in EPED with an ELM stability code other than ELITE might involve extra work. It would be helpful to discuss these ideas more thoroughly with EPED's developer to formulate a plan.

For ELM ejection and divertor heat-flux modeling for experimental comparison, the possibility of using JOREK was mentioned. For ELM dynamics, consider also M3D-C1 and/or BOUT++, which should have a similar capability. For LGI ELM pacing, JOREK may have a pellet model that would be useful.

The between-ELM aspect of this milestone is closely linked to R15-1 discussed above, i.e., pedestal structure is linked to transport, sinks, and sources, and the heat flux to divertors involves these same processes into the SOL. Thus, it is important for this linkage to be coordinated with SOL/divertor researchers.

3.6 Transport and Turbulence

The PAC congratulates the NSTX-U team for the recent important results on a broad range of research topics, in particular: turbulence measurements across the L-H transition and comparison with linear gyrokinetic calculations, the test of reduced models for the evaluation of the transport produced by micro-tearing turbulence, the development of increasingly realistic descriptions of the electron heat transport produced by GAE and CAE, and the progress in the physics description of momentum transport, with the inclusion of centrifugal effects and the application and comparison among global codes.

The research on turbulence and transport in NSTX-Upgrade is of extreme interest, since the new capabilities of this device allow the investigation of unexplored regimes of parameters, combining low collisionality with high beta, which are highly relevant for future fusion facilities. The three thrusts on transport and turbulence of the 5-year plan properly identify the long-term research goals, and the proposed milestones for FY15 and FY16 are adequately aligned for a successful accomplishment of the thrusts and leverage the increased scientific possibilities offered by the upgrade.

A particularly important aspect of successful research in this topical area is the strong connection between experimental, modeling, and theoretical studies. The PAC applauds the strong links that are being built between experimental and theoretical research in this topical area, which are strengthened by the improved NSTX-Upgrade and PPPL theory partnership. In particular, the PAC acknowledges the specific consideration which has been given to the suggestions included in the last PAC report, with emphasis on the study of GAE and CAE transport, by means of the application and planned further extension of the HYM code, as well as with the application of global gyrokinetic codes on modeling of the residual stress for momentum transport studies. In addition, the ongoing developments to include electromagnetic effects in both GTS and XGC1 are extremely valuable and are major theoretical upgrades, which are required towards a fully realistic description of NSTX-Upgrade plasmas. The PAC is pleased to learn that a strong link between experimental and theoretical research is already envisaged in the planning of FY15-16 activities.

The PAC agrees with the hierarchy of investigations towards lower collisionality and higher beta plasma regimes that have been planned. These consider first (FY15) the empirical characterization of global confinement properties and assess the impact of the new NBI sources on transport relevant parameters, and progressively move (FY16) to the characterization and related modeling of local transport of multiple channels in combination with the increased availability of multi-field and multi-scale fluctuation diagnostics.

However, the PAC is concerned that in FY15-16 insufficient emphasis is given to experimental studies of particle transport, and related validation of models. As previously emphasized in the PAC-33 report, particle transport plays a critical role towards the development of stationary scenarios for long-pulse operation, in particular at low density, with direct impact on the bootstrap current fraction and on the behavior of high-Z impurities. For this reason, the PAC recommends that higher priority be given to main plasma (electron) particle transport studies in combination with the already planned studies dedicated to other transport channels. In particular, perturbative experiments on particle transport could be considered, assessing the feasibility and extending the collaboration with CCFE for comparative analyses between NSTX-U and MAST-U in this topical area. In addition, in the framework of multi-channel transport investigations, which is of particular importance in assessing the role of the different instabilities in producing transport, main plasma (electron) particle transport should be included as an essential element, given that its specific properties help in discriminating among different transport mechanisms. Development and application of reduced transport models should include the simulation of the plasma density, in combination with the planned validation activity dedicated to the modeling of the ion and electron temperature profiles. In particular, initial studies could be dedicated to assess if a neoclassical particle transport model can reproduce the experimental density profiles in the core (considering the particle source produced by NBI), and in the pedestal, where, however, the role of the source is more difficult to establish. On a longer term (FY16 and beyond) the increased understanding of particle transport could be also considered to investigate the possibility of developing control schemes for the density profile shape, in addition to density control, certainly useful for long pulse operation (e.g. to be applied in experimental campaigns starting from 2018).

3.7 Macroscopic Stability

The NSTX-U macroscopic stability program addresses key issues for ST-FNSF and ITER in the areas of error field control, 3D fields, and disruption avoidance and mitigation. The main headlines in the macroscopic stability Topical Science Group are well formulated, address key issues, and are cogently reflected in all the sub-milestones and work of the NSTX-U team; further the program is delineated in a way which will enhance the position of the NSTX-U team as world leaders in the field.

The main focus of the macrostability program for the first two years is in (i) understanding and advancing passive and active feedback control to sustain macroscopic stability at low collisionality; (ii) understanding 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields; and (iii) understanding disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas. It is commendable that these headlines explicitly focus on enhancing the understanding of the physics that underlie these areas, as well as providing effective empirical tools. This necessitates a close and concerted connection to theory and modeling, which exists and has been recently strengthened by the initiative to develop a stronger NSTX-U/Theory partnership. The PAC notes this excellent endeavor and warmly commends this, noting macroscopic stability as one of the strongest NSTX-U topical groups in this respect.

Appropriate weight is attributed to milestones in the macroscopic stability area, focusing on areas where this TSG can also affect NSTX-U plasmas for all experiments. For instance, the FY15 milestone: "Develop physics+operational tools for high-performance (κ, δ, β, EF/RWM)" is cross-cutting, but founded on the physics advances led by the macroscopic stability thrust. Given the urgency and importance of avoiding and mitigating disruptions in ITER, more importance should be placed on this subject. Currently there is a JRT ("Assess disruption mitigation, initial tests of real-time warning, prediction") in FY16; this belies somewhat the importance of this area and the key advances NSTX-U may provide in this field.

Feedback control to sustain stability at low collisionality:

The PAC supports the research plan to develop physics understanding and feedback control of RWMs to high beta, low collisionality plasmas in support of ST-FNSF. The RWMSC with rotational stabilization in the controller model will benefit significantly from the new power supplies for the ex-vessel coils which will allow n>1 mode control and extended rotation studies. The continuing development of the tools to study kinetic stabilization theory and benchmarking exercise is strongly commended. Similarly, a productive collaboration has been established with DIII-D to further test and verify these models, the complementarity of which will enhance the NSTX-U results to come. The historical NSTX focus on RWMs is retained for FY15-16, perhaps at the neglect of NTM stability studies. As NSTX-U begins to run much longer pulses at high beta, NTMs may become more prevalent and important to the pulse performance and sustainment. Consequently, more effort should be invested in developing methods for tearing mode suppression, especially in preparation of later operation with a metal wall since JET and ASDEX Upgrade have reported enhanced high-Z impurity peaking in the presence of NTMs, and the consequent performance degradation and even disruptions associated with this.

Recommendation: Since NBI is the main tool for changing fast ion distribution, the NBI-induced torque will also vary. The PAC suggests the team do modeling of the various mixes of rotation/fast ion profiles that can be achieved at sufficiently high beta and predict RWM damping rates.

Recommendation: More emphasis should be given to NTM stability in preparation for a high-Z wall, especially developing tools to suppress the mode given strong high-Z peaking observed with NTMs in JET. For long pulse with metal walls, this could be an additional driver for the ECH/EBW program.

Application and understanding of 3D fields:

The dynamic error field correction will also benefit greatly from the additional power supplies to allow n>1 mode control. Error field correction is correctly given high priority for the first year of NSTX-U operation. Error field correction will be even further enhanced with the NCC allowing a wide spectrum of fields to be applied.

The NSTX-U team remains at the forefront of rotation braking studies and NTV modeling. This leading position has been strengthened even further during the upgrade project due to continued development of tools such as POCA, MARS-K and PENT as well as experiments on KSTAR.

Dedicated long-pulse KSTAR experiments show no hysteresis in rotation profile with respect to applied 3D field strength. The progress in the rotation controller including NTV torque is also an excellent advance.

Recommendation: The PAC supports the high priority given to error field correction in FY15. We recommend that you utilize metrics other than δB minimization for DEFC (e.g., minimize braking etc. as used for NCC design) and then utilize the best metric for error field correction routinely. There is scope to feed into the new rotation profile controller too.

Understanding and controlling disruptions:

Recent participation in DIII-D MGI experiments have developed very useful collaborations and established experience that will be important for NSTX-U experiments. The enhanced capability to study disruption mitigation with three mitigation valves in different poloidal positions will make a significant impact in the field. Disruption avoidance and mitigation remains a high priority issue for ITER (perhaps the highest priority issue) so the PAC strongly commends the NSTX-U team for developing capability in this area. Early experiments will be to characterize the toroidal asymmetry of the halo current and loading on the center column, using 18 newly installed shunt tiles and commission the new MGI system. In FY16, NSTX-U will characterize density assimilation versus poloidal location of MGI system, including injection in the private flux region. These studies should be given high priority and proceed as soon as possible, even in FY15 if possible.

Recommendation: More emphasis should be given to disruption avoidance and mitigation, elevated even above the JRT for FY16. This is an area of huge importance for future machines, and NSTX-U is well placed to contribute. The PAC commends the emerging links with theory and modeling in this area, and it is keen to see this grow in the near future.

Enhancement for non-axisymmetric control coils (NCC):

The proposed NCC will significantly enhance research in macrostability, allowing a broader spectrum of mode control and finer rotation profile control. The NCC will also provide an important tool for many NSTX-U experiments beyond macroscopic stability. The development of IPECOPT to optimize the equilibrium for both core and edge NTV is a very welcome advance in terms of designing the NCC set. The plan to extend this model to analyze additional figures of merits such as error field correction or RMP for affecting ELMs will no doubt help the finalization of the NCC design. The PAC commends this preparatory code development and encourages the finalization of the NCC design as soon as possible.

Recommendation: The NCC would be a valuable tool for NSTX-U for EFC, rotation tailoring, pedestal/ELM control amongst others. The PAC agrees with the prioritization with respect to other enhancement projects (i.e., that the cryopump and the ECH are higher priority). The PAC supports the NSTX-U team in requesting incremental funding to realize the NCC as soon as possible, noting the risk that beginning work in 2017 for installation and realization after that may reduce the international impact.

3.8 Energetic Particle Physics

The PAC agrees that the energetic particle research plan for the next two years is well positioned to take advantage of the expanded set of NSTX-U capabilities: flexible NBI system, higher magnetic field and current, 3D field coils, Alfven Eigenmodes (AE) antenna, and HHFW. NSTX-U also has a state of an impressive suite of diagnostics: expanded reflectometer, high frequency magnetic coils, FIDA, ssNPA, sFLIP, and BES. The impressive experimental capabilities are matched by state of the art simulation and analysis capabilities. The PAC agrees with the overarching research goals: (i) develop and validate predictive/interpretive tools for AE and fast ion dynamics and (ii) assess requirements for fast ion phase space engineering through selective excitation/suppression of AE modes. Developing predictive capability to describe AE and fast ion interaction are important goals for the NSTX-U program that can support ITER and FSNF-ST. The coupling between experiment and theory is very strong and the PAC encourages continued tight coupling.

While it is valuable to do more detailed comparisons of measured and theoretical Alfvén Eigenmode (AE) damping rates, the PAC suggests that higher priority should be placed on demonstrating and evaluating AE control tools over characterization of AE modes. Understanding techniques to control AEs would have an even greater impact on ITER and FNSF. This effort would take advantage of NSTX-U strength in plasma control and suite of actuators: plasma shape, NBI and HHFW heating and current drive systems for density and current density profile control, and NCC fields to vary plasma and mode rotation. A second recommendation is to measure fast ion losses associated with 3D fields, which can be investigated readily in piggy-back experiments. Due consideration should be given to this possibility when planning the experiments, and development of the modeling required to compare to loss detection should be carried out, e.g., tracking particles in 3D fields, including plasma response. We also recommend that a clear plan for experiments using the AE antenna in FY15-16 be developed and presented to the PAC at the next meeting. The AE antenna is anticipated to be a valuable tool for physics investigation of AEs and the related high value/leverage physics needs to be identified and prioritized. For instance, dedicated experiments looking at the beta-damping of AEs would be very important for ST-FNSF.

3.9 High-Harmonic Fast-Wave and Electron Cyclotron Heating

The primary plans for high harmonic fast wave (HHFW) and electron cyclotron heating (ECH) power in NSTX-U for FY15 and FY16 support one of the primary NSTX-U research needs quite well, namely the goal to generate solenoid free start-up and fully non-inductive (NI) discharges that extrapolate to ST-FNSF. The target solenoid-free start-up uses a combination of coaxial helicity injection (CHI) to generate a ~200-300 kA discharge which is then heated to 1 keV using O-mode electron cyclotron heating (ECH) or electron Bernstein waves mode converted from reflected X-mode and HHFW heating and current drive until plasma is sufficiently dense to allow beam current drive and bootstrap current to sustain the plasma. The PAC agrees with the goals for FY15-16 to assess antenna performance and characterize the RF interaction with SOL and fast ions, which are important for NSTX-U and ST-FNSF.

The PAC offers the following suggestions and concerns regarding the plans for HHFW and ECH /EBW power in NSTX-U in FY15 and FY16. In the ECH/EBW area, the plan needs to be better articulated; the information in the presentation at this meeting was insufficient to evaluate the preparation and plan. The gyrotron is pivotal and currently in the incremental budget request. The NI start-up is critical for the NSTX-U program so identification of a gyrotron to purchase or borrow is paramount. The PAC suggests that borrowing a short pulse, ~0.5 s, gyrotron would allow NSTX-U to proceed with the NI start-up and may be possible through collaboration.

In the HHFW area, the PAC recommends developing additional simulation and diagnostic capabilities to address SOL losses. While a good, large computational simulation effort is in place, the identification of the waves in the simulation is of significant physics interest and would influence potential antenna modifications. Additional magnetic probes would be extremely important to experimentally verify the modes potentially responsible for power loss. We recommend developing a clear plan for experiments, simulation, and theoretical studies to evaluate viable RF scenarios to both heat and drive current in NSTX-U and ST-FNSF. Good examples of HHFW heating exist for NSTX, but results for current drive seem to be lagging. While HHFW and EBW are both possible current drive options, we recommend performing simulations to identify if a HHFW scenario can be identified in particular. Experimental investigation of HHFW in inductive ramp-up discharges as soon as possible would be high leverage; the coupling during start-up could prove to be difficult, and the viability of HHFW could be investigated in absence of a complete solenoid-free start-up scenario.

The PAC also recommends the development of a plan for possible HHFW antenna modifications specifically aimed for improved performance (e.g., lower SOL losses). The current plan emphasizes understanding edge losses by revisiting previous experiments with additional diagnostics. We suggest developing a set of possible modifications and build the case for their implementation through simulations and supporting experiments. Since HHFW is strongly dependent on antenna performance, a set of metrics should be developed to evaluate the impact of boronization, Li injection, and other conditions on antenna performance. The present antenna performance appears to limit HHFW utilization significantly, e.g., the maximum voltage of 25 kV in vacuum is too low for reliable operation.

Finally the PAC strongly recommends the research plan for RF simulation validation experiments focus on physics and capabilities that are unique to NSTX-U. HHFW interaction with fast ions could be well diagnosed in NSTX-U due the suite of available diagnostics and access to state of the art simulations. Hence, the PAC suggests the RF-edge plasma validation experiments receive lower priority, since the diagnostics and simulation codes are less developed. For example, magnetic probes are necessary for experimental wave identification, and simulation codes require realistic antenna geometry.

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