

Report of NSTX Program Advisory Committee (PAC-37)

January 26-28, 2016

Committee Members Present:

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Theodore Biewer (Oak Ridge National Laboratory)
Ian Chapman (Culham Centre for Fusion Energy, UK), remote participant
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Charles Greenfield (General Atomics)
John Sarff (University of Wisconsin-Madison) – Chair, remote participant
George Sips (JET Exploitation Unit, Culham Science Centre, UK)
Dan Thomas (General Atomics)
François Waelbroeck (University of Texas at Austin)
Graham Wright (Massachusetts Institute of Technology)
Steve Wukitch (Massachusetts Institute of Technology)
Xueqiao Xu (Lawrence Livermore National Laboratory)
Dennis Youchison (Oak Ridge National Laboratory)

Ex-officio:

Mark Foster (Fusion Energy Sciences, DOE)
Josh King (Fusion Energy Sciences, DOE)
Jon Menard (Princeton Plasma Physics Laboratory)
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Committee Members Absent:

Kouji Shinohara (Japan Atomic Energy Agency)

1. Introduction

The NSTX Program Advisory Committee (PAC) held its 37th meeting at the Princeton Plasma Physics Laboratory (PPPL), January 26-28, 2016. The PAC was informed that the NSTX-U upgrade project has officially been completed, and we applaud this as a major achievement. The upgrade proceeded on budget and on schedule, and rapid progress has been made in producing research-grade plasmas since completion of DOE Critical Decision CD-4. The upgrade brings important new facility capabilities, in particular doubling of the toroidal magnetic field to 1 T, doubling the plasma current capability to 2 MA, doubling the neutral beam heating power to 14 MW, and greatly increasing 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).

At its 36th meeting last year, the PAC was informed that an electrical arc in the new magnet system occurred during test shots in April 2015. Since then, comprehensive reviews were

conducted and the damage was successfully repaired. These reviews established more rigorous engineering and operational procedures, and they even created new research capabilities. These new procedures should serve the NSTX-U program well going forward.

The research plan for the first year of NSTX-U targets operations with maximum plasma current of 1.4 MA and maximum toroidal field of 0.8 T, which will limit electromagnetic forces to one-half their full NSTX-U design values. This is a significant step beyond NSTX capability that should allow, for example, a factor of 2-3 reduction in the plasma's collisionality. The PAC is confident that NSTX-U's scientific productivity will be high for the 18 run weeks in FY 2016. Operation with the full NSTX-U design values of 2 MA and 1 T is planned for FY 2017.

The NSTX-U program remained scientifically strong throughout the multi-year upgrade process. Many of the collaborations established during this period will continue, and the PAC urges continued programmatic attention to nurturing these collaborations. A focus on the exciting new plasmas created in NSTX-U will of course be natural for an upgrade project, but the collaborations established over the past several years are highly important for both the U.S. and international fusion programs.

The PAC was charged to answer the following questions:

1. Please assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign? Are there any major missing elements, or new opportunities?
2. Please assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs.
3. Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support "integrated predictive capability".
4. Please comment on the present team prioritization of planned facility enhancements including: divertor cryopump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research.

The NSTX-U team detailed the status of the project and their research plans in 10 presentations over two days. These included an overview of initial NSTX-U plasma operations, an overview of research program progress and plans, an overview of the NSTX-U facility and diagnostics, and progress and plans for the science groups. There were also presentations related to specific topics: non-inductive startup and ramp-up, conversion to high-Z plasma facing components, and disruption studies. There was also a presentation on the NSTX-U / PPPL Theory partnership status and plans. The PAC thanks the NSTX team for their effort in preparing comprehensive and informative presentations.

2. Comments Pertaining to the Four Charge Questions

In this section the PAC summarizes several overarching comments and recommendations regarding the charge questions. Additional comments are included in Section 3, organized according to the NSTX-U science group topics.

1. Please assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign? Are there any major missing elements, or new opportunities?

In your presentations to the PAC, you commented a number of times on how the new organization structure for the NSTX-U program with three overarching science groups (core, boundary, integrated scenarios) has been effective in helping you define priorities and optimize the run plan. The PAC noted the benefits of this new organization, and we anticipate this will be a very effective foundation for the NSTX-U program going forward. Our report is organized on the new science group structure, and most of our comments in response to charge question #1 follow in Section 3. One general observation we emphasize here, the PAC is concerned that the milestones for FY 2017 rely heavily on progress in FY 2016. NSTX-U is off to a great start, but you are still bringing up a largely modified facility and many new capabilities. The challenges for attaining sufficient progress in FY 2016 may be greatest in the boundary science area where careful sequencing and scheduling are required.

2. Please assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs.

Broadly speaking, the NSTX-U program is well aligned with priorities and initiatives identified in recent community strategic planning meetings and workshops. There were many NSTX-U team members involved in these workshops. The NSTX-U program has long had a competition between a vision for future applications based on the ST (FNSF in particular) and other programmatic needs, especially ITER. We see this tension again this year, cf. charge question #4.

As for ITER, while the NSTX-U program is well connected via ITPA, your present research could impact ITER urgent needs:

- NSTX-U has unique capability to investigate massive gas injection at different locations in the poloidal plane. We recommend this be highest priority for NSTX-U's ITER-related research activities in the near term.
- The digital coil protection system (DCPS) is likely to be a good model for ITER. You have already been in contact with ITER about this new system, and the PAC anticipates ITER will be enthusiastic to understand details.
- Active prediction and avoidance of disruptions has been an important area of NSTX research, including advances in real-time control using methods embedded in the plasma control system (PCS) that could be good models for ITER.
- NSTX-U run plans include novel pellet-pacing experiments for ELM control using lithium, B₄C, and vitreous graphite materials.
- NSTX-U is likely to provide useful data and methodologies for the development and understanding of ELM control physics using resonant magnetic perturbations (RMP).

3. Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support “integrated predictive capability”.

The PAC is very pleased to see that the NSTX-U / PPPL theory partnership is officially established following the one-year trial period. We view the partnership as an important and auspicious inflection point in the role of the theory division in the laboratory. The partnership is showing itself to be effective in ensuring that the capabilities of the PPPL theory division are optimally utilized in support of the NSTX-U program. In particular, the PAC found encouraging the prominent role played by members of the theory division in the Science Group structure. As a means of continuing the improvement in the participation of the theory division, we recommend diversifying the participation of the theory division in the partnership beyond the application of codes.

The PAC was impressed by the achievements of the partnership over the past year. Our comments on particular achievements are included in the sections below on the activities of the various science groups. We found that the partnership contributes strongly to all NSTX-U priorities except for the role of solid vs. liquid metal PFC. The PAC considered the question of whether NSTX-U should work through the partnership to increase PPPL theory contributions in this priority area. We did note, however, that the theory division is participating effectively in NSTX-U external collaborations. Such collaborations provide an alternative means of ensuring the needed theory support in the priority areas.

The PAC feels that a 5/10-year plan for how the partnership will develop to ensure future impact on the NSTX-U program would be beneficial.

Support for integrated predictive capability

The PAC believes that the partnership will have a highly beneficial effect on support for integrated and predictive capabilities. In particular, we expect that the partnership will lead to improved protocols and workflows for preparing experimental data for simulations. It is important that these improvements be made available equally to external collaborators.

We recommend that PPPL theory fully utilize the opportunities provided by the partnership for the validation of codes and their benchmarking (e.g. XGC vs. GTS in the core). The goal for integrated predictive capability obviously extends beyond NSTX-U and PPPL. While the partnership is founded on several flagship codes and modeling capabilities, it is essential to maintain strong collaborations for a goal as large as predictive capability, both to and from the PPPL-based research activities.

The PAC understands that PPPL draws a distinction between theory codes and experimental codes such as TRANSP, and that the “flagship” denomination is only applied to theory codes. The PAC nevertheless feels that broadening the contributions by the theory partnership to TRANSP and predictive TRANSP would be beneficial to NSTX-U and the broader community as well as to the goal of improving our integrated predictive capability.

4. *Please comment on the present team prioritization of planned facility enhancements including: divertor cryopump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research.*

The PAC agrees that all of the planned facility enhancements could bring valuable and important new capabilities to NSTX-U. We also agree with your assessment that the divertor cryopump is the highest priority. The plan for finalizing the physics and engineering design appears sound, but it is not conservative. The PAC urges that sufficient resources be dedicated to finalizing the design and completing the construction no later than the one-year outage planned for 2018.

In order to prioritize the other possible facility enhancements, the PAC recommends careful consideration of the capabilities provided by each enhancement in the context of requirements for the research program in a longer-term view. For example, while the impact of the non-axisymmetric control coils (NCC) is clear in the plans presented by the team, it is less clear that the team has considered how high-Z walls will affect the science program. The relative priority of the enhancements could be strongly impacted by planned operation with a metal wall. This should be considered in collaboration with partners with relevant experience. Recent research, e.g., experiments on ASDEX Upgrade and JET, shows that core rf heating is essential with an all-metal-wall boundary. Neoclassical transport is accentuated in the ST, and the effect of impurities related to a metal wall could be even more challenging than seen in higher aspect ratio tokamak plasmas. There is presently no capability for core rf heating in NSTX-U that is compatible with large heating by neutral beam injection. The gyrotron opens the possibility for electron Bernstein wave (EBW) heating in dense NSTX-U plasmas, but the physics basis for EBW is still in development. The PAC therefore strongly recommends increased emphasis on high-harmonic fast-wave injection (HHFW), as described in Section 3. More generally, experiments in 2016-18 that help distinguish the relative impact of the possible enhancements should be planned.

3. Comments and Recommendations for the NSTX-U Science Groups

In this section we provide our comments and recommendations for NSTX-U research as they pertain to the core, boundary, and integrated scenario science groups.

3.1 Core Science

The experimental plan of the Core Science Group (SG) is comprehensive and coherently structured and is planned around key strengths, towards the achievement of the FY16 Milestones. The PAC agrees with the prioritization of the proposals. In particular, the research plans to map the impact of the upgraded I_p and B_T and the 2nd NBI, the plan to explore stability at high β , low v^* and to study AE character at very large β_{fast} and v/v_A , are extremely exciting. These are high impact, unique capabilities and rightly prioritized.

The core SG is also well aligned with the FESAC / FES initiatives, and includes important ITER relevant research elements. In particular, the research thrusts of the Macro-stability topical science group (TSG) respond to urgent ITER needs. A special mention has to be given to the impressive progress in disruption prediction, avoidance and mitigation (DPAM), which is

entirely aligned with the FES strategy, directly addressing critical ITER priorities, and is well coupled with theory.

The PAC is pleased to acknowledge the increased link between theory and experiments enabled by the NSTX-U / PPPL theory partnership, which significantly strengthens the research in the topical areas of the Core Science Group.

Turbulence and Transport

The domain of parameters that become accessible as a consequence of the upgrade allows investigations in turbulence and transport which are an essential element of the NSTX-U mission. The exploration of the plasma confinement properties at the values of low collisionality and high beta that become achievable in NSTX-U will provide critical answers for strategic decisions for the next steps in fusion energy science. The investigation of turbulence and transport is a key component of this research and puts NSTX-U at the forefront in this area.

FY2016 Program: The organization of experiments around multi-TSG experimental proposals (XPs) is very effective in order to explore the impact of the major upgrades (that is, increased I_p/B_T and 2nd NBI heating system) from several standpoints, covering both global confinement aspects as well as local physics on multiple transport channels. In the following years, a wider range of more specific experiments becomes possible, also focusing on local transport / fluctuation measurements, in combination with the availability of an increased number of diagnostics. These possibilities will certainly be exploited by the NSTX-U Team and by external collaborators.

Recommendation on experimental proposals for FY2016-FY2018: The PAC recommends emphasis and priority be given to experiments which can also assess the probability of achieving long term goals. In particular, the characterization of the impact of rotation on the relative role of neoclassical and turbulent high Z impurity transport as well as the possibilities of affecting high Z impurity (and bulk plasma) transport by the application of HHFW should be considered with high priority. In this context, the PAC underlines that Neon is not sufficiently high Z to investigate the properties of high-Z (and heavy) impurities like W or Mo which could be used as plasma facing components in NSTX-U in a later stage. Krypton or Xenon would be more appropriate than Neon.

Theory partnership: A strong connection between theory and experiment in the field of turbulence and transport is indispensable to make progress in this area. The stronger connection allowed by the partnership is therefore of strategic importance. The application of PPPL flagship global GK codes in the framework of turbulence and transport studies opens extremely interesting new possibilities of research and of theory validation. This activity would certainly benefit from the simultaneous application of non-PPPL codes which already include increasingly realistic physics ingredients, in particular electromagnetic effects and higher order rotation effects, even though in local versions. Emphasis should also be given to the development of synthetic diagnostics for direct comparisons with fluctuation measurements (this element was not mentioned at this PAC meeting, but it is likely already taken into consideration). In particular, in the low-k range of fluctuations, synthetic diagnostics for quantitative comparisons with the combination of measurements from BES, reflectometry and microwave

polarimetry might allow the assessment of the relative role of electrostatic and electromagnetic turbulence towards lower collisionality and higher β , in comparison with the theoretical predictions.

Macroscopic Stability

The NSTX-U macroscopic stability topical science group makes leading contributions with many unique features and continues to be well connected to the PPPL theory group and collaborators. The main headlines in the macroscopic stability TSG are well formulated and in many cases address key issues for ITER and FES strategy. Particularly notable is the work on disruption prediction, avoidance and mitigation which, despite being relatively new, is making a high impact and answering important questions for ITER.

FY2016 Program: The NSTX-U team remains at the forefront of macrostability studies, especially resistive wall modes (RWM), rotation braking studies and neoclassical toroidal viscosity (NTV) modeling. This will be cemented by the upgraded capabilities of NSTX-U. The main focus of the 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 a physics basis for optimizing stability through equilibrium profile control by 3D fields; and (iii) understanding disruption dynamics and developing techniques for disruption prediction, avoidance, and mitigation. The planning of the first campaign has been thorough and the priorities are clear and appropriate. The increase in current, field and heating power result in very exciting plans to explore stability at high β , low v^* . These are high-impact, unique capabilities and rightly prioritized.

The flexibility in massive gas injection is world-leading. The PAC is excited to see the results from this flexible system and believe they can have very high impact, even if the DMVs and their location are not exactly ITER-like. Early experiments will be to characterize the halo current toroidal asymmetry and loading on the center column, using 18 newly installed shunt tiles and commission the new MGI system. Following commissioning of the MGI, experiments will characterize density assimilation vs. poloidal location of MGI system, including injection in the private flux region. These studies should be given highest priority within macrostability TSG due to the near-term timescales for providing input to ITER and should proceed as soon as possible.

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. Furthermore, this may be especially important 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. PAC is pleased to see that a previous recommendation to increase effort on NTMs is reflected in the program.

Recommendation: Only one day has been assigned for MGI experiments. In order to fully exploit this unique capability, it is likely that more than one run-day will be needed and this should be accounted for in the planning if DMV commissioning proceeds smoothly.

Recommendation: The macrostability TSG has a large fraction of the run-time. Consider adding the word “stability” to the lists of R16-1 or R16-3 to give appropriate acknowledgement to step-change NSTX-U provides in Macro-stability, e.g. “assess the H-mode confinement, stability, pedestal, SOL characteristics at higher I_p , B_t and P_{NBI} ”.

Recommendation: NSTX-U plasmas are likely to rotate very rapidly, so the team should exploit this unique capability. Consider formation of a working group to assess stability at wide range of plasma rotation, with the data collected parasitically. This will need to include developments in modeling capability of rapidly rotating plasma equilibria for stability analysis with flow.

Recommendation: It is important to think well in advance about how high-Z walls will affect the macrostability program in the future. For instance, how will you incorporate high-Z impurity measurements in the core into the DECAF model and how will the disruption prediction model change? How will you access high β without active mode control when islands could lead to impurity accumulation? There are many other issues and it is important to engage collaborators in this planning.

Theory partnership: It remains commendable that the macrostability topical science group headlines explicitly focus on enhancing the understanding of the physics which underlie these areas, as well as providing effective empirical tools. This necessitates a close and concerted connection to theory and modeling, which has always been the case with both the PPPL theory group and collaborators, and the PAC is encouraged to see that this continues to strengthen. Indeed, macroscopic stability is one of the strongest NSTX-U topical groups in this respect.

Energetic Particles

The energetic particles TSG is largely responsible for two of the five NSTX-U high-level research goals (“Study energetic particle physics prototypical of burning plasmas” and “Advance concept for Fusion Nuclear Science Facility (FNSF) by demonstrating 100% non-inductive ops at high performance”). Indeed, NSTX-U is the most capable machine for studying energetic particles in the world in FY2016.

FY2016 Program: The new flexibility in NBI geometry will enable a very broad capability for tailoring the fast ion distribution function. This directly addresses one of the three high level milestones for FY2016: “Assess effects of NBI injection on fast ion $f(v)$ and NBICD profile” (R16-2). While the characterization of Alfvén eigenmodes will make the most of the very wide operational space in terms of v/v_A and β_{fast} , the PAC is also pleased to see that, following a previous recommendation, the program includes experiments to control Alfvén eigenmodes as well. This is potentially very high impact for burning plasmas in ITER.

Recommendation: The Toroidal Alfvén Eigenmode Antenna is (currently) a unique capability deserving of exploitation. Please provide an update on status and future plans for TAEA at the next PAC.

Theory partnership: There are excellent links between the PPPL theory group and other collaborators and the Energetic Particle TSG. This is very important to exploit fully the NSTX-U capability, and perhaps even more important in this field. Perhaps the biggest change in ITER

plasmas will be the presence of a dominant alpha particle population, so it is essential to robustly demonstrate validation of predictive modeling against experimental data, and NSTX-U can lead this.

Recommendation: In support of the capability of flexible NBI for AE experiments, it is important to have a vision for the necessary developments to fully model AE evolution in order to validate these models against the NSTX-U data to reliably extrapolate to ITER and FNSF-ST. Please provide a detailed vision for this modeling. Some issues include whether M3D-K can capture nonlinear wave-particle interaction, collisional damping or fast ion orbit widths?

Comments related to Charge Question #4

The generic definition of the TSG objectives and research thrusts for 2016-2018 are largely comprehensive. However, the PAC recommends particular emphasis be given to the definition of an appropriate experimental plan (combining objectives of both T&T and MS TSGs) to inform the best strategies to effectively allow / ease operation under the long-term goal of high-Z PFCs. An ST with dominant NBI heating is in a particularly unfavorable domain of parameters for operation with high-Z PFCs. High toroidal rotation largely enhances high-Z neoclassical transport and strong rotational shear reduces turbulent transport. In addition, core particle source from NBI and low bulk plasma diffusivity unavoidably leads to central peaking of the density profile. This is a potential showstopper towards the long-term goal of long, stationary (steady-state) operation with high-Z PFCs.

The current plan to control the high-Z concentration by means of the ELM frequency might be insufficient and will likely severely limit the operational space and the possibilities of achieving high performance. Something needs to be done to control central accumulation; otherwise the requirements in (low) pedestal-top concentration become too constraining. These considerations should also be taken into account in the definition of the prioritization of the facility enhancements, in particular NCC versus enhancements to increase coupled RF power (ECH/EBW and HHFW). The cryopump remains the obvious highest priority.

The proposed NCC will significantly enhance the research area in Macro-stability, allowing a broader spectrum of mode control and finer rotation profile control, and will provide an important tool for many NSTX-U experiments as well as macroscopic stability. The PAC encourages the finalization of the NCC design as soon as possible to enable this project to proceed when there is availability of funding and engineering effort. Furthermore, increased possibilities of controlling / reducing plasma rotation (as allowed by the NCC) are also of high interest in the framework of turbulence and transport studies. Finally, by allowing a strong reduction of the plasma rotation, the NCC are also beneficial in reducing the neoclassical transport component of the high-Z impurities, but also affect other transport properties, with potential reduction of global confinement.

However, from a comprehensive perspective, the experience acquired in existing devices with metal walls and dominant NBI clearly indicate that any long term plan towards full high-Z PFCs should be accompanied by a complementary plan to ensure sufficient central wave heating power (HHFW, ECH/EBW, etc.). The PAC considers this to be an indispensable tool towards the achievement of the long term goal of stationary operation with high-Z PFCs. Thereby, the PAC

recommends that the experimental research over the years 2016-2018 take these elements into consideration, and gives emphasis to research which can better inform the correct prioritization of the enhancements. In particular, the HHFW capabilities and impact on physics program should be investigated as soon as possible since this might also affect the decision on the priorities of the enhancements. This recognizes that EBW/ECH experiments are not likely to be realized in less than a few years time.

Recommendation on the integration of the enhancements in the scientific program: As for the program overall, the Core Science Group should consider how the long-term program requires the capabilities provided by each of the proposed facility enhancements. While the impact of the NCC is very clear in the plans presented by the team, it is less clear if the team has considered how high-Z walls will affect the core science program. It is essential that when deciding which enhancements are most important that this long-term need in the presence of a metal wall is considered. This should be considered in collaboration with partners with relevant experience.

3.2 Boundary Science

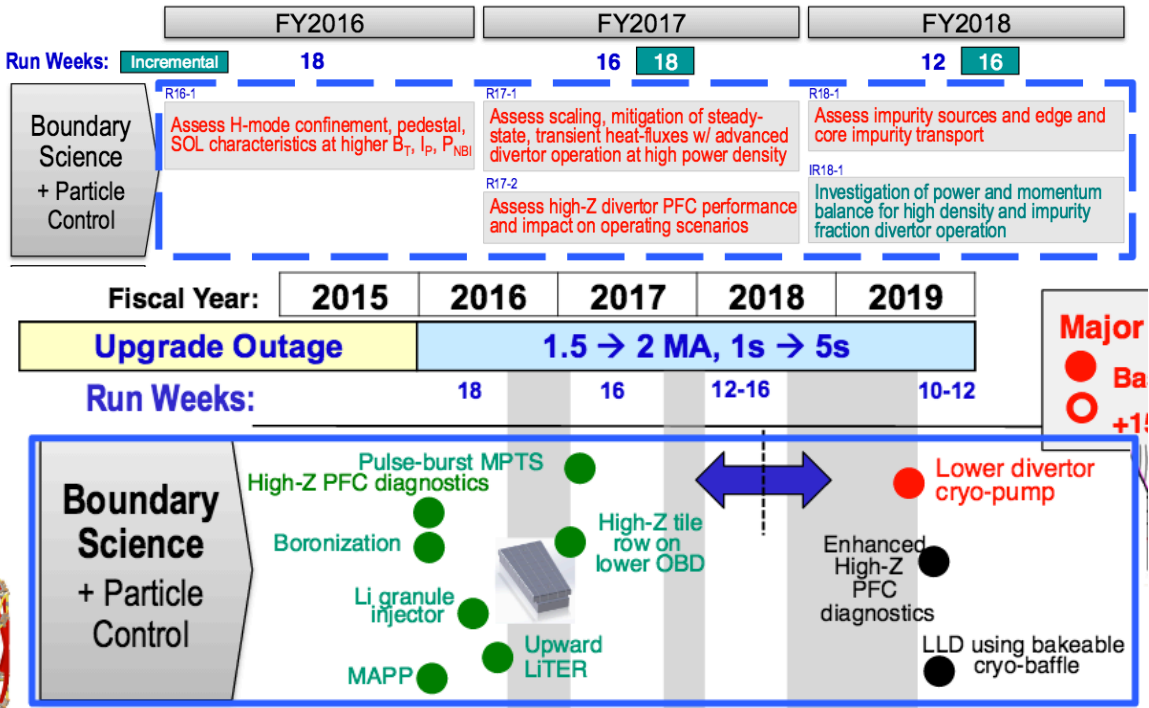
The PAC is pleased that NSTX-U continues to have a strong focus on boundary plasma physics and plasma-material interactions. The NSTX-U team has done an excellent job leveraging the uniqueness of NSTX-U and in-house expertise to produce highly relevant scientific capabilities particularly for the boundary and the wall. Given the aggressive scientific plan presented, we fully expect NSTX-U to be a key contributor to the nuclear fusion science community both nationally and internationally.

The PAC found the boundary science experimental plans for NSTX-U to be comprehensive with no major gaps or missed opportunities. It is clear that the Boundary SG used the research thrusts outlined in the NSTX-U five-year plan to prioritize their experimental work as the outline of their plans and milestones map well to NSTX-U thrusts. The new alignment of the Boundary SG and its respective Topical Science Groups (e.g. Pedestal structure, SOL/divertor, Materials & PFCs) as well as the Particle Control Task Force have excellent coverage of the breadth of science in the boundary and are focused on the issues most pertinent and important to NSTX-U and, in some cases, the larger fusion science community as well.

The PAC commends the NSTX-U team for moving the transition to high-Z and liquid Li PFC earlier in the 5-year plan with the planned installation of a high-Z toroidal row in the lower divertor for the FY2017 campaign and the high-Z, heated cryo baffle with pre-filled Li reservoirs as well as an additional row of high-Z tiles in the upper divertor for the FY2018 campaign. This will help to further establish and maintain NSTX-U's global uniqueness as well as make important contributions to clarify a ST-FSNF concept.

Comments related to Charge Question #1

As mentioned above, there are no major gaps in the NSTX-U experimental campaign. The plans for FY2016 follow a controlled approach (e.g. slowly ramping up plasma performance, extended period of boronizations before introducing Li) that was previously recommended by the PAC.



The Boundary SG schedule for milestones and upgrades

The PAC’s main concerns lie more in the potentially over-aggressive timeline for some milestone completions and experimental plans. The incremental changes to larger high-Z coverage of the wall and introduction of liquid Li will affect the boundary science in an irreversible way. Therefore, the experimental timeline may be the most critical for the Boundary SG. The PAC is concerned that the necessary machine capabilities and equipment/upgrade/diagnostic availabilities may not line up with the timelines proposed to meet some of the Boundary SG research goals. NSTX-U is encouraged to identify all critical paths in their project plans and revise the scheduling and resource allocations accordingly so all elements are consistent. Some examples of specific concerns for the next several experimental campaigns are listed below.

- *R17-1: Assess scaling, mitigation of steady-state, transient heat-fluxes with advanced divertor operation at high power density.*

The PAC is concerned about the disconnect between the development of control of divertor radiation feedback, implementation of divertor radiation diagnostics, snowflake control development, time to test appropriate control algorithms and the R17-1 milestone. These elements seem highly unlikely to occur on the specified timescale. The support indicated in the extensive list of Divertor/SOL-TSG XPs in the master XP list seems to attempt to address this, but it is unclear the capabilities, in terms of both control and diagnostics, will be there. A clearer plan for the timely delivery of these elements should be developed, as they will affect the milestone.

- *R17-2: Assess high-Z divertor PFC performance and impact on operating scenarios*

For the FY2017 experimental campaign, there will only be a single toroidal row of high-Z tiles. While this may be sufficient to determine how high-Z tiles perform under NSTX-U heat

fluxes, it seems doubtful that the impact of a high-Z wall on operating scenarios in NSTX-U can be appropriately assessed with only a single row of high-Z tiles. Carbon could very likely still be the dominant plasma impurity at this stage. This aspect of R17-2 could be more thoroughly addressed with larger high-Z coverage in FY2018 and beyond.

- *New refrigeration unit availability for cryopump*
It was mentioned that a new refrigeration unit is likely needed for the cryopump upgrade. However, there was no mention if this additional consideration would have any impact on the timeline for cryopump operation. The PAC would like confirmation that the new refrigeration unit will be installed, integrated and implemented by the end of the FY2018 planned shutdown period.
- *Availability of upward LiTER for “lithium only” particle control*
In order to understand particle control via lithium surfaces as opposed to additional pumping provided by the cryopump, the upward LiTER is crucial to provide full Li coverage of the wall. Given the technical difficulties encountered with the new orientation, it was unclear if the upward LiTER would be available before the FY2016 vent prior to installation of the high-Z lower OBD row. It is important that the upward LiTER be available with sufficient time for proper assessment of particle control with lithium surfaces before changing the divertor tiles or installing the new cryopump. Full coverage will be required to assess lithium coatings on high temperature substrates and mixed material issues after the high-Z row is installed.
- *Pedestal diagnostic availability for 2016-2017 campaign*
On the timeline provided the pulse-burst MPTS is not available until FY2017 campaign. It was unclear from the presentation the extent to which this improves the pedestal diagnostic situation although pulse burst would be crucial for better ELM understanding. The PAC is concerned there are not sufficient pedestal specific diagnostics to complete scientific missions in FY2016 and perhaps FY2017 campaigns.
- *Availability of granule injector before lithium coverage*
The granule injector for ELM pacing will rely on B₄C and vitreous carbon as well as lithium. It was not clear to the PAC how the injector schedule is impacted by LiTER lithium, cryopump, or high-Z OBD operations. Presumably due to the small material quantities involved in the injector experiments, they may be completely independent, but this should be verified.
- *Diagnostics to resolve the questions regarding RF coupling through the scrape-off layer.*
The PAC is concerned that the diagnostic coverage at the antennas and through the scrape-off layer may be insufficient in resolving the questions of RF through the scrape-off layer. This could be crucial in understanding the effectiveness of HHFW for NSTX-U.

The following paragraphs outline further specific comments and concerns on areas of the Boundary SG experimental plan.

The PAC congratulates the Boundary SG team with coming up with a novel way to get liquid Li into NSTX-U sooner with the Li pre-filled high-Z tiles. The PAC also recognizes that while the pre-fill Li components are novel, they are also very ambitious. Some initial work and testing of the pre-fill concept was shared with the PAC via back-up slides and private conversations and we are encouraged the work is already under way, but we emphasize the need for appropriate time and resources to be put into this project to finish it on a timeline that is acceptable for fabrication and installation. Not only is there work to do in the wicking optimization and surface wetting but also for viable methods to reliably load the Li into the internal cavities and to keep the system clean. We also recommend exploring 3-D printing or advanced manufacturing as a potential method to create the complex internal cavity structures.

The PAC is impressed with the experimental plan for the advanced divertor work with a focus on snowflake configurations. We recognize that this is important work, especially for the ST community. We recommend close collaboration with MAST Upgrade for the snowflake work, especially in the FY2016 campaign where snowflake divertor configurations will be run in an all-carbon device, similar to snowflake divertor configurations in MAST Upgrade. This should give excellent coverage of the parameter space across both machines for comparison and comprehension.

While the PAC supports the Boundary Group's intended emphasis on the stated high level Research Priorities, we also wish to encourage the Boundary SG and Pedestal TSG not to discount the energetic particles as an integrated problem for the boundary. The effects of energetic particles with respect to erosion and core effects in a ST wall environment may be challenging and informative, particularly as you study the secular changes in the main wall as you progress through the planned transformation to high-Z and liquid Li.

In the longer term, the BN limiter for the HHFW antenna will need to be replaced with a high-Z limiter as NSTX-U moves to full high-Z coverage, but this is not reflected in the graphic displaying the timeline for the transition. The HHFW limiter upgrade occurs in FY2019 after the one-year shutdown and falls under the purview of Integrated Scenarios SG. Having a low-Z limiter defeats the purpose of a high-Z wall and may not survive high power density, long-pulse operations needed to assess heat flux mitigation and advanced divertor configurations. Given previous issues with the low-Z antenna limiters during short pulses in NSTX, a thorough engineering approach needs to be taken with the high-Z limiter and the PAC recommends this work start earlier than 2019.

Comments related to Charge Question #2

The PAC recognizes a close alignment of the Boundary SG research program with the two tier-one FESAC initiatives on transients and PMI. In particular the emphases on ST pedestal structure, SOL widths, and progressive integration of high-Z materials into a lithium environment are supported. The accelerated move to high-Z and liquid Li PFC also aligns well with FESAC priorities and will allow NSTX-U to contribute to those FESAC initiatives much sooner.

The Boundary SG alignment with ITER is less clear. There is interest with ELM pacing as demonstrated through the contributions to ITPA. However, given the scope of open questions

and needs for ITER, the PAC feels there is room to contribute across a wider range of topics for the boundary and PFCs. The improved scaling of the SOL width, detachment physics and radiative divertor physics all seem like topics that could be of high interest to ITER. The PAC recommends communicating with the ITER team the NSTX-U research plans along these lines as an outreach to develop stronger collaborative ties between NSTX-U and ITER.

Comments related to Charge Question #3

The NSTX-U/PPPL theory partnership for the Boundary SG appears to be more dependent on external collaborators than in the other SGs. The PAC recognizes that there is a paucity of edge plasma and plasma wall modelers in general in the community, which necessitates external collaboration. However, this can also be viewed as an opportunity to grow in-house expertise in a field that is in high demand. In any case, the PAC appreciates the high quality of collaborators the NSTX-U Boundary SG has been able to attract and secure.

The PAC cautions that when working towards integrated modeling and predictive capabilities that the theory collaborators need to be in close contact with both their experimental counterparts from the Boundary SG and the theorists and modelers from the other NSTX-U SGs. It appears that the NSTX-U/PPPL theory partnership has been very successful in opening the channels of communication between in-house experimentalists and theorists, and these channels of communication must also be open to external collaborators.

The PAC did not see a comprehensive plan for integrated modeling of the boundary and wall at NSTX-U. The XGC code is moving into the pedestal and SOL but future plans for XGC, especially as it pertains to boundary science, were only very briefly touched on with very little detail. WallDYN is a powerful tool but there were no plans presented for integration. Most of the PMI/Edge modeling involving both solid and liquid walls is performed through university collaborations with Princeton University, Auburn and U. Tennessee and leverage SciDac and other BES initiatives. A portion should be integrated into the NSTX-U/PPPL Theory Partnership at PPPL. The PAC recommends stronger collaborations with Purdue and LLNL on the NSTX-U edge modeling. Proper model integration is an enormous effort that needs a well thought-out vision to be successful. The PAC would like to see a report on the vision and future plans for integrated modeling of the boundary and wall at the next PAC meeting.

Comments related to Charge Question #4

From the perspective of boundary science, the prioritization is clear. The top priority is the cryopump and associated high-Z and liquid Li coverage (e.g. high-Z baffle with Li pre-fill). This also includes the eventual move to a full high-Z wall with flowing Li divertor modules as this represents the most likely wall composition for the ST-FSNF.

The secondary priority is the non-axisymmetric control coils (NCC). The NCC have direct impact on the boundary, primarily through ELM control. 3-D fields can also play an important role in heat flux profiles in standard and advanced divertors. Given that these topics are areas of emphasis for the NSTX-U research plan, it is clear that the NCC could be a very useful tool for the Boundary SG. This should be balanced against the resource demands that installation of these coil sets will make on the NSTX-U program, and the fact that the 3-D field effects and

ELM suppression physics can and are being studied on other machines. Thought should be given to the unique ST aspects of this work in striking this balance.

The tertiary priority is the 28 GHz ECH/EBW gyrotron. ECH/EBW has no direct impact or effect on boundary physics. There are secondary effects as it could change impurity transport from the core to the edge, but since ECH/EBW is mainly a tool for the core physics, it has the lowest relevance for the Boundary SG and boundary physics.

3.3 Integrated Scenarios

Initial operation has established a good platform for the FY16 run schedule, with basic control, and the digital coil protection systems working well. The PAC is impressed by the new digital coil protection system (DCPS) that can be expected to maximize the operational space of NSTX-U and is already attracting the attention of ITER and others in the fusion community. Integrated scenario development and control will be important in establishing and developing plasma discharges required for the research program at NSTX-U. The planned operation at 1.4 MA, 0.8 T during FY16 would be a significant step beyond NSTX capability.

Comments related to Charge Question #1

The PAC observes that there is a very good preparation of the experiments planned for 2016 and that the commissioning plan for NSTX-U supports the experiments proposed. The run-time allocation is reasonably well balanced and addresses the main research milestones set-out for FY16. However, the time allocated to HHFW and CHI is marginal and should certainly not be reduced. The PAC recommends that experiments documenting the efficiency of HHFW heating should be allocated increased resources for experiment and simulation to find a path to avoid SOL losses and minimize absorption on beam ions. Furthermore, for FY17, the PAC recommends targeting a demonstration of the transition from a CHI-created plasma to HHFW current sustainment (at least) or ramp-up.

The integrated modeling work done in preparation for experiments on plasma control and current drive studies, both using TRANSP, is impressive. Examples are the preparation for experiments on several different control schemes and the modeling of fully non-inductive start-up. Experiments planned for FY16 on HHFW and NBCD should provide the data needed to complete the modeling of solenoid free startup.

Comments related to Charge Question #2

NSTX-U has unique capabilities for non-solenoidal startup, which is a critical ST-specific gap for an ST-FNSF or reactor. The PAC recommends that fully non-inductive startup should continue to be prioritized in the NSTX-U Program by assigning sufficient runtime.

The PAC congratulates the NSTX-U Team on the design, implementation, and routine use of an active disruption avoidance scheme based on a “state machine.” This is well aligned with the recommendations of the recent FES Transients Workshop, and we recommend that this continue to be used as an expanding platform incorporating additional disruption causes beyond the present VDE emphasis. However, the PAC recognizes that integration of real-time disruption

prediction and avoidance as a routine tool in the control system is not-trivial, and should be given sufficient resources.

NSTX-U should provide results for joint experiments coordinated by the ITPA; for example data from controlled ramp-down studies, coordinated by the IOS-TG of the ITPA. In the future NSTX-U can and should play a proactive role in joint experiments of the ITPA (e.g. disruptions, ELMs and scenario development) with dedicated experiments on NSTX-U in FY17.

Comments related to Charge Question #3

The use of TRANSP for integrated scenario control and full non-inductive scenario developments is essential as is evident from the preparation of the experiments planned in FY16. The PAC recommends TRANSP be supported on par with the theory flagship codes, including appropriate resources for future code and code platform developments.

The PAC strongly encourages the continued external collaboration with RF SciDAC for access to state of the art RF codes. We also encourage the NSTX-U team to continue to develop local capability to utilize RF codes such as TORIC, AORSA, and GENRAY. The inclusion of non-thermal ions will be important for the assessment of HHFW applicability to beam heated discharges. With its suite of energetic ion diagnostics, NSTX-U could provide unique data to validate the RF codes and should seek to collaborate with RF SciDAC to implement equivalent synthetic diagnostic. For RF interaction with the SOL plasma physics, collaboration with RF SciDAC will again be the most effective path forward with the expected development on high fidelity RF antenna-core absorption simulation capability.

Comments related to Charge Question #4

Having a cryopump for density control and a tool for obtaining low collisionality is essential for development of long pulse and steady state scenarios. The PAC advises that from the point of scenario development at NSTX-U the cryopump be given highest priority of the proposed facility enhancements.

The PAC recommends the development of a decision tree for assessing and developing effective tools for non-inductive start-up using CHI, HHFW current drive, NB current drive and the possible benefits of ECH to increase the electron temperature for current drive. At the present time, the path towards solenoid free startup is not fully resolved. A number of potential options exist and the PAC urges the NSTX-U team to aggressively pursue experiments to elucidate which are viable/necessary techniques. The PAC recommends assessing the HHFW for non-inductive start-up, including a new antenna to avoid edge losses and pursuing the necessary simulations to optimize the ECH design. The PAC notes that ECH/EBW research on NSTX-U will be a unique research opportunity since MAST-U does not plan to pursue this for at least 5 years. Furthermore, the PAC recognizes that significant flux saving in ramp-up (even when not fully non-inductive) will have a significant positive impact on long pulse operation of NSTX-U. Non-inductive start-up is critical for the NSTX-U program and acquiring a gyrotron may prove to be paramount. The PAC recommends continued ECH/EBW modeling, engineering design and analysis for implementation of a 1 MW, 28 GHz gyrotron system.

The PAC identifies a need for developing a longer-term strategy for integrated scenario development and control for NSTX-U operation with a high-Z wall that includes actuators and real-time measurement capabilities. The PAC recommends an ECH/EBW actuator be evaluated for control (core heating, CD, high-Z control). In addition, the HHFW should have both experiments and simulations to evaluate its applicability for high-Z impurity control in dominantly neutral-beam heated discharges.

Comments related to the Topical Science Groups in the area of Integrated Scenario Science

For the three TSG's in the integrated scenarios group, the PAC has the following observations and recommendations:

Advanced Scenario and Control

Integrated scenario development is central to the research program at NSTX-U. The development path of scenarios at NSTX-U is clear with the aim of establishing operation at a toroidal field of 0.65 T to 0.8 T in FY16, followed by operation with pulse lengths up to 3 s at 1 T in FY17 and up to 5 s at 1T in FY18.

Several advanced control schemes are being developed for NSTX-U, most of them will be tested in a first series of experiments in FY16. The PAC strongly recommends continuing the work on high-fidelity control simulations, using TRANSP, for testing the proposed control schemes in experiments on control of the plasma stored energy, q-profile, rotation profile, MHD (NTM) and plasma shapes. At its next meeting the PAC would like to see a strategic plan on the development and requirements of control schemes at NSTX-U for FY17-FY18.

Solenoid Free Start-up and Ramp-up

The PAC reiterates that NSTX-U is uniquely positioned to establish the physics, techniques and technologies to generate solenoid free start-up and fully non-inductive discharges that extrapolate to ST-FNSF. The target solenoid-free start-up uses a combination of coaxial helicity injection (CHI) to generate a ~200-400 kA discharge which is then heated to 1 keV using a gyrotron for ECM/EBW, followed by HHFW heating and current drive until plasma is sufficiently dense to allow beam current drive and bootstrap current to sustain the plasma.

The NSTX-U team has some examples of good HHFW heating but current drive seems to be lagging. The PAC urges the NSTX-U team to investigate HHFW in inductive ramp-up discharges as soon as possible. Coupling HHFW during the start-up could prove to be difficult and early investigation would allow one to answer whether HHFW coupling in start-up is viable. Further, one can perform these studies in experiments using inductive start-up and they would contribute to an assessment whether ECH would be essential for non-inductive start-up.

The PAC commends the NSTX-U team for the extensive effort that is underway to apply modeling tools and looks forward to first experimental results on the capabilities of CHI, together with studies of HHFW current drive and NBCD at low plasma current to guide future simulations. Giving sufficient time to these experiments in FY16-FY18 is essential.

Wave Heating and Current Drive

The plans for the Wave Heating and Current Drive TSG are well aligned with the overall NSTX-U mission elements: To explore unique ST parameter regimes to advance predictive capability – for ITER and beyond and advance the ST as a possible FNSF/ Pilot Plant. Experimentally, a recommendation is to develop a clear experimental and simulation plan to evaluate viable RF scenarios to heat and drive current in NSTX-U and ST-FNSF.

For HHFW, the PAC agrees that the experimental goals for FY16 to characterize the RF interaction with SOL and assess the interaction with fast ions. The PAC recommends the NSTX-U team evaluate and improve HHFW antenna performance (lower SOL losses) and consider modifying the antenna to eliminate unwanted E_{\parallel} field by aligning the antenna (rotate it $\sim 30^{\circ}$). In addition to characterizing the antenna performance, the maximum voltage and power limits and their dependence on boronization, lithiumization, disruptions, and vacuum vents should be investigated.

The present antenna performance seems to be significantly limiting HHFW utilization and a vacuum maximum voltage of 25 kV is too low for reliable operation. Further, the PAC recommends identifying discharges where the field alignment of the antenna could be scanned to investigate the role of antenna misalignment in SOL losses. The present antenna is misaligned by $\sim 30^{\circ}$ and scanning from 10° - 45° and examining wave penetration would be particularly instructive. Additional magnetic probes would be extremely important to experimentally verify the modes potentially responsible for power loss.

The PAC also commends the NSTX-U group for collaborating with RF SciDAC to develop additional simulation capability to address SOL losses. While a good computational simulation effort is in place, the identification of the waves in the simulation are of significant physics interest and their identification would influence potential antenna modifications. A dispersion solver would greatly facilitate wave identification.

The PAC recommends addressing an emerging requirement to provide central electron heating for high Z impurity control. From ASDEX Upgrade and JET experience, central electron heating is essential with high Z PFC and a clear RF solution for the ST is yet unknown. In an ST, neoclassical transport is accentuated, and the effect of impurities related to a metal wall could be even more challenging. There is presently no capability for core RF heating in NSTX-U that is compatible with large NBI heating. The addition of a 28 GHz gyrotron opens the possibility for EBW heating, but the physics basis is still in development. The PAC strongly recommends increased emphasis on HHFW to evaluate its applicability for core impurity control.

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