Report of NSTX Program Advisory Committee
(PAC-33)

February 19-21, 2013

Committee Members Present:
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Nobuyuki Asakura (Japan Atomic Energy Agency)
Theodore Biewer (Oak Ridge National Laboratory)
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Hendrik Meyer (Culham Centre for Fusion Energy, UK)
Thomas Rognlien (Lawrence Livermore National Laboratory), remote participant
John Sarff (University of Wisconsin-Madison) – Chair
Joseph Snipes (ITER Organization)
François Waelbroeck (University of Texas)
Randy Wilson (Princeton Plasma Physics Laboratory)
Graham Wright (Massachusetts Institute of Technology)

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 33rd meeting at the Princeton Plasma Physics Laboratory (PPPL), February 19-21, 2013. The NSTX facility is currently undergoing 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 increases the pulse length from 1 s to 7 s. A primary aim for these upgrades is to assess confinement and stability at lower collisionality and high β_N and to explore future high performance scenarios critical for the spherical tokamak (ST). 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). The NSTX program is also completing its preparation of a new 5-year research proposal for FY 2014-2018.

With this context, the PAC was asked to answer the following questions:

1. Assess the NSTX-U 5 year plan with respect to how well it addresses the key physics issues needed to evaluate the potential of the ST to provide high-performance plasmas for use in a future fusion research facility. Example future fusion research facilities include a toroidal plasma-material-interface facility, a fusion nuclear science facility, or a Pilot Plant/DEMO;
2. Assess the plans to investigate key tokamak physics issues for ITER;
3. Assess plans to contribute to model validation and the development of predictive capability;

In addressing charges 1-3 above, please comment in particular on the strength of planned NSTX-U contributions to boundary physics and plasma-material-interaction research.

4. Comment on possible improvements to the NSTX-U 5 year plan presentations including logic and format.

The NSTX-U Team presented their research plans in 14 presentations over two days. These included an overview of the NSTX-U 5-year plan research program, a report on the project status and 5-year plan facility overview, and a presentation on the 5-year plan contributions to ITER. In addition, the PAC heard presentations for research plans in a number of topical areas: scenarios and control, macroscopic stability, turbulence and transport, boundary physics and plasma-material interactions, particle control, energetic particle physics, high-harmonic fast-wave and electron cyclotron heating (ECH), and solenoid-free startup-up and ramp-up. There was also a separate presentation on non-axisymmetric control coils (NCC), a proposed new plasma control capability. The PAC thanks the NSTX Team for their effort in preparing comprehensive and informative presentations.

The PAC congratulates the NSTX-U team for preparing a 5 year plan that is compelling in its opportunities for making important contributions to fusion plasma science, informs the development of the ST configuration, and contributes to the development of ITER. We hope that the comments contained in this report will be valuable to further improve the written document and the presentations made to the imminent proposal review panel.

The PAC is pleased to hear that the upgrade project is going very well and that there are no major technical issues that impede its completion. We were informed that the project is on schedule, and operation of NSTX-U could commence in the Fall of 2014. However, initial operation in this time frame is in jeopardy due to budget constraints. This is a challenging time for the fusion program in terms of funding, and we hope that the great technical progress made by the NSTX-U team will allow initial operation of the upgraded NSTX facility as soon as possible.

The PAC notes excellent ongoing progress in the analysis of key scientific issues, such as particle and heat flux control, that increase the plausibility for success in the scientific research plan and methods proposed for NSTX-U. We also note that the NSTX-U team remains scientifically productive during this period while there is no experimental operation, through ongoing analysis of existing data, collaborations with other programs, and participation in major scientific meetings and activities like ITPA

2. General Comments Pertaining to the Four Charge Questions

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

1. Assess the NSTX-U 5 year plan with respect to how well it addresses the key physics issues needed to evaluate the potential of the ST to provide high-performance plasmas for use in a future fusion research facility. Example future fusion research facilities include a toroidal plasma-material-interface facility, a fusion nuclear science facility, or a Pilot Plant/DEMO .

The NSTX-U research plan is clearly aimed to address the key scientific issues that define the potential of the ST. The proposed work addresses high priority issues that have been identified in planning processes such as the FESAC Toroidal Alternates Panel (TAP) and MFE Research Needs Workshop (ReNeW) reports. The proposed work also clearly identifies the new opportunities made available through the upgrade of the NSTX facility. The PAC agrees with the assessment that NSTX-U, together with MAST-U and other national and international facilities, should provide the essential experimental capabilities needed to inform decisions on next-step options that could be based on the ST configuration.

The PAC agrees that the NSTX-U program's highest priority goal should be to use the new capabilities made available in the upgrade (larger toroidal field and plasma current capability, plus a second neutral-beam injector) to demonstrate high performance 100% non-inductive steady-state scenario plasmas. The upgrade provides substantial new territory to explore, and NSTX-U will be among the world leaders in this area of research.

Non-inductive plasma formation is a recognized critical issue for the ST's viability for future fusion applications. For example, this is called out as the #1 priority scientific issue for the ST in TAP. The PAC believes that the gap in demonstrating non-inductive startup and ramp-up is now larger than the gap in demonstrating 100% non-inductive sustainment in the ST. We also note that the new capabilities in NSTX-U, most importantly the off-axis NBI, greatly improve the opportunity to demonstrate current ramp-up from a seed current (generated through several possible methods) using NBI overdrive. Further, the key physics of non-inductive ramp-up, such as energetic particle confinement, stability and transport, is particularly well aligned to the strengths of the NSTX-U research program in developing predictive science. Thus, while the PAC agrees that 100% non-inductive sustainment should be the highest priority, it is essential that non-inductive ramp-up in particular be given more urgent emphasis in the NSTX-U program (run time, manpower, diagnosis, etc). The ST's viability for future fusion applications based on the tokamak configuration is more uniquely connected to this scientific issue.

The NSTX-U research plan and proposal calls for a staged approach in transitioning from a dominantly graphite first-wall to complete metal plasma-facing components (PFCs) somewhere in the time frame 2019-2023. The plan also calls for using a mix of materials during the next five years to make step-wise assessments of these different materials in the NSTX-U plasma environment. The PAC is concerned that this step-wise approach will make it challenging to understand the physics and issues associated with identifying the appropriate PFC materials for an application like FNSF, for which graphite appears an unlikely solution and tungsten is considered the front-runner.

Under the base-funding scenario presented to the PAC, the research plan emphasizes physics investigations enabled by the upgrade, in particular accessing plasmas with reduced collisionality and demonstration of high-performance steady-state scenarios. The PAC agrees with this strategy, and it is clear that that the program will be constrained to implement metal PFCs in later years of NSTX-U operation. However, under the incremental funding scenario, a more aggressive approach toward the implementation of metal PFCs, including the possibility of a flowing liquid lithium module, *may* be compatible with achieving other high priority goals that are key to informing the ST's readiness for next steps. (For example, the PAC has previously urged that the NSTX-U team pursue as a high priority a cryo-pump for greater assurance in achieving particle control as a high priority.) While tokamak operating scenarios are notoriously sensitive to wall conditions (particular at low density and high performance), and carbon PFCs are known to be forgiving such that an early transition to high-Z PFCs could make scenario development more challenging, there is an obvious tension between the need to establish the readiness of the ST for next step applications and specific scenario development tasks that will have to be addressed. With this balance of priorities in mind, the PAC recommends considering an aggressive strategy for installation of metal PFCs (for the incremental funding scenario only), and perhaps replacing the present plan in the 5-year proposal with one along the lines described in Jon Menard's answer to our question on this point. This approach would strengthen the case for research goals included in the NSTX-U PFC/PMI thrusts: 1) *Understand lithium surface-science for long-pulse PFCs*, 2) *Unravel the physics of tokamak-induced material migration and evolution,* and, 3) *Establish the science of continuous vapor-shielding.* If an aggressive approach is not feasible, then the implications of carbon to the three research thrusts above must be addressed in more detail. At a minimum, we would like a more detailed report on the plan toward a complete metal first-wall and its impact on the research program at the next PAC meeting.

2. *Assess the plans to investigate key tokamak physics issues for ITER.*

The NSTX-U program is capable of making important contributions in the development of burning plasma science and support for ITER. Generally speaking, the principal contributions to ITER lie in physics connections that inform operational scenarios, since the window for impact on ITER design is closing fast. In this regard, the NSTX-U team has identified a set of important contributions for predictive physics understanding in the set of topics listed below:

- Plasma rotation and mode locking
- Disruption prediction, avoidance, and mitigation
- Vapor shielding of material surfaces during disruptions
- Edge-localized-mode (ELM) control using a variety of ITER-relevant tools
- Mitigation of high heat flux through a radiative divertor
- Impurity ion transport

- Energetic particle mode physics
- High-harmonic fast-wave research

Research on these topics are very likely to be impactful for developing physics scenarios for ITER, although the research must be done in collaboration with other experiments, e.g., through NSTX-U's participation in ITPA.

3. *Assess plans to contribute to model validation and the development of predictive capability.*

There are important examples of opportunities to develop predictive science through NSTX-U research evidenced in the presentations made to the PAC. This was especially clear for research on energetic particle effects and turbulence and transport. However, the presentations were not uniform in exposing the scientific approach that was illustrated in Stan Kaye's answer to our question on "NSTX-U's best examples of advancing model validation and predictive capability." The PAC recommends ensuring that opportunities for model validation and the development of predictive capability are clear in the written proposal document. Also, more coverage of the research approach to this should be visible in the presentations to better expose the opportunities.

To support a discussion and elucidation of model validation and development of predictive capability, the PAC recommends including a presentation that summarizes theory and simulation plans connecting the NSTX-U experimental program and the theory community, in particular the PPPL Theory group. This presentation should aim to reveal the balance of theory, simulation, and experiment in developing predictive science through the NSTX-U research program We would appreciate such a presentation at future PAC meetings as well. Obviously there is a danger that simply adding more material in the presentations will make them more time consuming overall, which is very likely not the best strategy. The presentations in total must strike the right balance in topics and details presented.

4. *Comment on possible improvements to the NSTX-U 5-year plan presentations including logic and format.*

There are at least three key additional capabilities described in the presentations and proposal that are contingent on funding scenarios: cryo-pump(s), 1-2 MW ECH/EBW, and a full/partial NCC coil set. From the PAC's perspective, most of the presentations appeared to assume the optimistic +10% funding scenario. In both the presentations and proposal, it would be helpful to better delineate what physics research will be accomplished with and without these additional capabilities (as allowed in various funding scenarios), to more clearly expose the advantages they bring. This will be especially important in the review of the 5-year research proposal where reviewers will want to understand various capabilities given funding options.

The NCC coils offer great potential for investigating 3D physics. The discussion of this capability was mostly confined to macro-stability. The PAC sees the NCC coils as a versatile tool with potential to investigate 3D physics broadly. This is not fully apparent in the presentations. Similarly, the prospects for HHFW operation in NSTX-U appear greatly improved, and HHFW could be viewed and planned as a more versatile tool for a variety of physics studies, including heating, rotation studies, and perhaps impurity particle control.

The plans for boundary physics studies, plasma-material interactions, and particle control were separated into four separate talks. While these areas of research are particularly rich topics for NSTX-U, they collectively consumed a lot of time. The PAC believes these presentations could be compressed without losing key information or risking miscommunication of the importance of this research. The tradeoff is leaving adequate time for discussion, both during presentations, and in PAC/panel executive sessions.

3. Comments and Suggestions Pertaining to Topical Research Areas

We summarize below recommendations for each topical research area. The order is as presented at the PAC meeting. Some topics are combined along the lines of previous convention for NSTX topical group research areas.

3.1 Scenarios and Control

The NSTX-U Advanced Scenarios and Control Topical Science Group (ASC TSG) has a programmatic goal to "*develop the basis for integrated, steady-state operation and axisymmetric control for next-step STs, while helping resolve key scenario and control issues for ITER.*" This is supported by an operational goal to "*establish stationary, 100% non-inductive operation, and partial inductive operation up to* I_P*=2 MA, for 5 seconds over a wide range of Greenwald fractions*." The PAC finds that these goals are appropriate for the NSTX-U program, and stated in the proper order, in that developing operational scenarios for an ST FNSF, the defining role of NSTX-U, are given the highest priority. The secondary (presumably lower priority) goal helps to establish ITER's operating point. Although NSTX-U is not unique for this, it can make important contributions.

The ASC TSG has four research thrusts, on which we comment below:

Thrust ASC-1: Scenario Physics

- Develop and assess 100% non-inductive operation
- Extend the high-current, partial-inductive scenarios to long-pulse

Thrust ASC-2: Axisymmetric Control Development

- Develop methods to control: heat flux for high-power scenarios, rotation and current profile control, improved shape and vertical position control

Thrust ASC-3: Disruption Avoidance By Controlled Plasma Shutdown

- Detect impending disruptions
- Develop techniques for automated termination

Thrust ASC-4: Scenario Physics for Next Step Devices

- Determine the optimal, simultaneous q- and rotation profiles
- Study the conditions for classical beam current drive
- Explore and validate integrated models for projections to FNSF

Thrust ASC1: Scenario Physics

The scenarios chosen are appropriate and probably achievable with the in-progress upgrades, primarily the additional off-axis NBI. These scenarios do not make use of NSTX-U's HHFW capabilities, which are not usually combined with NBI. It is not clear how or whether the impact of divertor conditions on core performance is considered. Access to the scenarios – in particular following a non-solenoidal current ramp – has not been addressed.

Recommendations:

- Evaluate and consider experimentally testing whether HHFW heating could provide useful additional flexibility in the scenarios that can be achieved. In particular at the higher plasma current in NSTX-U (~ 2MA) it is expected that RF-accelerated beam ions will be better confined.
- Investigate core-edge consistency in the context of these integrated scenarios.
- Plan for full discharge – including breakdown, ramp-up, flattop, and ramp-down – ST FNSF scenario demonstrations, presumably late in the 5-year proposal period.

Thrust ASC2: Axisymmetric Control Development

The NSTX-U Team is among the world leaders in development and exploitation of the Snowflake Divertor. The profile control work described in the proposal is not unique to NSTX-U, but NSTX-U can play an important part working with Lehigh (profile control) and DIII-D (plasma control system and similar research lines).

The PAC endorses the efforts included in this thrust and the NSTX-U Team's associated collaborations with other institutions.

Thrust ASC3: Disruption Avoidance By Controlled Plasma Shutdown

The NSTX-U Team's work on disruption prediction is unique and world leading, but to date has only considered data from one device. Implementation in the NSTX-U PCS is the obvious next step, as is implementation on other devices.

Recommendations:

- In addition to obvious importance to NSTX-U, disruption prediction will have to work on ITER with little or no tuning. The next step for this approach should be to implement it for at least one other tokamak to determine how portable it is.
- The PAC endorses the approach being taken with respect to the NSTX-U research program.

Thrust ASC-4: Scenario Physics for Next Step Devices

This appears to be an integration thrust combining elements of Thrusts ASC1 and ASC2 with an added emphasis on validated modeling,

Recommendations

- Experiments done within the first two thrusts will provide opportunities to begin the model validation efforts inherent to Thrust ASC4. The NSTX Team should consider this in planning and carrying out those experiments.

3.2 Macroscopic Stability and the Non-Axisymmetric Control Coil Applications

Comments pertaining to Charge Question #1 (future ST facilities)

The five-year plan proposes a compelling program aimed at answering the stability and control questions related to the potential of the ST to provide high-performance plasmas for use in a future fusion research facility. In particular, NSTX-U will address the key question of the role of lowering the collisionality on locked modes (LM), resistive wall modes (RWM), Alfvén eigenmodes (AE) and neoclassical tearing modes (NTM). It will also address the controllability of the current profile during ramp-up and the role of Alfvénic instabilities during fully non-inductive operation, including their possible role in triggering RWMs by depleting the population of EPs. The second NBI beam will enable greatly improved control of the safety factor and rotation profiles. The prospect of closed-loop rotation profile control is particularly enticing. Lastly, the planned NCC offers considerable promise for advancing our understanding of 3D physics, particularly in the context of the low collisionality operation. We note that due to the timeline for the installation of the NCC, careful consideration of the results on other machines and deliberate utilization of the features unique to NSTX-U will be required to allow the new coils to realize their potential for discovery.

We note that the NSTX group, together with their Columbia collaborators, has played a leading role in RWM control. The new capabilities offered by NSTX-U combined with the existing expertise gives high confidence that the group will be able to answer the questions pertaining to the sustained stability properties of a future nuclear fusion research facility.

Comments pertaining to Charge Question #2 (ITER relevance)

The 5-year proposal offers the promise of many contributions of relevance to the operation of ITER. As pointed out in the presentations, spherical tori exert a high leverage in testing models of plasma behavior by providing data for plasma parameters lying outside the ranges explored in the other machines.

The work on state-space control for EF and RWM stands out as having good potential for leading to advances that can be incorporated in ITER. Other contributions of NSTX-U are likely to be too late to influence the design of ITER, but will nevertheless be important in guiding experimental planning.

The relevance of NSTX-U team expertise to issues of concern to ITER is attested by the active and prominent role played by the team in ITPA activities, particularly as concerns RWM physics and active mode control more generally.

Comments pertaining to Charge Question #3 (developing predictive capability)

The NSTX-U group has been a leader in advancing the modeling of the role of kinetic effects in RWM stability and the calculation of braking by NTV, both of which play a critical role in determining the achievable beta. The five-year plan places a great deal of emphasis on the evaluation of the NTV for the new coil and also the extension of the NTV modeling to lower collisionality. The focus on NTV is understandable in view of the group's leadership in this area, but seems to have driven out consideration of the role of resonant forces in contexts other than locked modes. This is surprising since at least one of the codes that are cited in support of the NTV picture (POCA) shows that resonant interactions dominate over non-resonant NTV forces (Kim, PoP 2012). The preoccupation with neoclassical transport has also led to the omission of two PPPL codes (M3D-C1 and XGC-0) from the list of codes being used to investigate rotation control (NTVTOK, IPEC, POCA, FORTEC-3D).

Development of a predictive capability for rotation control is likely to require broadening the scope of the physics beyond NTV. In particular, the figures of merit (FOM) used to design the coils are dominantly focused on NTV (the only FOM independent of NTV is the beta gain). It would be helpful for the presentation to describe the empirical basis for the chosen figures of merit. To place these remarks in perspective however, the FOM provide a qualitatively stronger foundation for designing the NCC than the vacuum field analysis that was used to design both the ITER coils and the coils used successfully on DIII-D.

Lastly, we take note of the interesting work performed by the NSTX-U team and collaborators in the interpretations of the observations of ELM pacing with the NSTX coil set (Canik, NF 2012). This work recalls earlier work at PPPL on the observations of secondary ballooning mode (BM) instabilities nonlinearly excited by long wavelength modes (Park, PRL 1995), and invites the use of nonlinear MHD codes to examine the stability of coil-triggered BM with greater accuracy than permitted by stellarator equilibrium codes.

Comments pertaining to Charge Question #4 (5-year plan improvements)

The NCC, in combination with other NSTX-U capabilities, presents unique opportunities and leverage to help resolve basic physics issues associated with 3D shaping. The five-year plan could be improved with respect to how it communicates the breadth of the NCC program. In particular, the presentations emphasize mode-control aspects of NCC at the expense of edge/SOL physics (there are no references to NCC in either Maingi or Soukhanovskii's talks). Other aspects that could be developed further are: interaction of NCC with "snowflake", effect of NCC on HHFW coupling (i.e., SOL losses), and effect of Li on NCC ELM pacing.

3.3 Turbulence and Transport

The 5-year plan of NSTX-U presents a very comprehensive research program to answer strategic open questions in order to assess the potential of the ST to provide high-performance plasmas for use in a future fusion research facility. A general remarkable feature of the research thrusts is that they appropriately combine different but equally important scientific goals. The empirical characterization of the global confinement, exploring the new parameter domains which will be accessible by NSTX-U and which are relevant for the operation in future devices, is combined with specific investigations aiming at reaching a physical understanding of the observed transport based on first principles models and related codes. These research goals are complemented by the development and the verification and validation of reduced transport models which can be applied to predictive transport modeling and which play an essential role to reach a predictive capability for the design, the scenario development and the performance of future devices. The PAC is also glad to acknowledge that the suggestions presented in the report of the PAC 31 have been coherently included in the research plan, which allows the research program to address in a more consistent and comprehensive way the challenge of an integrated understanding of the multi-scale and multi-channel problem of transport. In addition, the research activities are also effectively planned in time, by taking into account the development of the capabilities of the device and the availability of the different fluctuation diagnostics. The PAC endorses the general research program and the goals of the 5-year plan, and is confident that many critical open questions in turbulence and transport will be answered by the NSTX-U experiment and the planned related theoretical modeling activities. The PAC also presents a set of suggestions, which are particularly intended to give guidelines that could be useful in the need of establishing a prioritization of the research topics and for the identification of research activities in which NSTX-U can perform leading research at an international level.

Comments pertaining to Charge Question #1 (future ST facilities)

In the perspective of the application to the prediction of the behavior of future devices, it is suggested to give emphasis to the dependence of transport produced by the different turbulence regimes potentially present in a ST as a function of collisionality, beta, and the toroidal angular velocity. Critical issues that deserve investigation are the impact of rotation (ExB shear and parallel velocity shear) on electromagnetic turbulent transport and the role of low k turbulence in producing ion heat, particle/impurity and momentum transport. In this framework, the PAC acknowledges the interesting new results obtained with simulations that identify experimentally relevant regimes of "hybrid" low-k instabilities, like for instance KBM and TEM.

The planned fluctuation diagnostics provide an appropriate and effective combination of measurements in the low and high k spectral ranges for core turbulence studies. Recent research has recognized the critical role of concurrent multi-field and multi-scale fluctuation measurements to identify the role of different instabilities and turbulent regimes to produce transport. To this end it is important to establish if planned diagnostics (the BES, the reflectometry, the polarimetry and the new high-k scattering system for 2D k-spectra) can concurrently access the same radial locations and plasma parameters. The simultaneous application of all of the diagnostics can be expected to be a critical requirement to make fundamental progress. The ongoing investigation of the parameter domains where the different instabilities are expected to occur provides an appropriate background to assess whether the diagnostics can access the various plasma parameter domains in the various NSTX-U scenarios that are foreseen for both specific transport experiments as well as for long-pulse high performance scenarios in a later phase.

In the critical topical area of electron heat transport, the PAC agrees with the identified need of successfully developing an energetic particle mode model for electron heat transport, which is essential to achieve the high priority goal of the prediction of the electron temperature. However, the PAC is concerned that the timeline on this specific research topic is not sufficiently aggressive, if a validated predictive capability has to be reached within 5 years. The PAC suggests that higher priority is given to these studies, in order to be in the condition of developing a model for GAE/CAE driven electron heat transport well before the end of FY17. A more aggressive timeline will provide additional time in the following years for a comprehensive validation (this is also relevant in the answer to charge 3).

The PAC endorses the priority given to impurity transport studies. The observation that impurity transport is often consistent with neoclassical transport raises concerns on the possibility of avoiding central accumulation of high–Z impurities like W, which could be used as PFC in a later phase of NSTX-U operation. Thereby, during the first years of operation with CFC and Li, it is suggested to consider as high priority the investigation of the transport of heavy impurities. In particular, the PAC suggests the investigation of potential tools that are available in NSTX-U to control accumulation. Very interesting experiments can be based on laser ablation of high-Z impurities which can be well monitored by the ME-SXR diagnostics. This research activity can explore the impact of auxiliary central wave heating with HHFW (and EBW if this will become available) to control impurity accumulation, and compare the effect of more perpendicular with respect to more tangential NBI sources, investigating also the impact of varying the plasma toroidal rotation velocity with the external 3D coils. In this context, but also under a more general perspective, it can be considered that operation in NSTX-U which tries to reproduce the conditions expected in a future fusion reactor, in particular reaching lower collisionality, high beta and operating at reduced toroidal rotation, might reveal a limited role of neoclassical transport with respect to low-k turbulence. This could have at least beneficial effects on the control requirements of heavy impurities, if not on the overall plasma confinement.

In the framework of particle transport studies, particularly under the consideration of the dominant impact of the density profile on the bootstrap current, for long-pulse non-inductive operation, it is suggested to extend the scope of these studies, exploring also the possibility of perturbative transport experiments (e.g. with gas puff modulation) in order to separately quantify both particle diffusion and convection. This is an essential element in order to establish the relative role of neoclassical and turbulent transport mechanisms in particle transport, and would provide additional insights for an integrated identification of the (low-k) turbulent transport sources as well as other transport channels (like momentum and ion heat transport).

In the framework of rotation studies, the PAC endorses the comprehensive approach presented in the 5-year plan, organized under the realization that all the components of the toroidal momentum flux are essential in the ST research. In fact, a FNSF can be expected to achieve a hot ion regime in the presence of strong external NBI heating and torque, whereas a reactor will have limited external torque, and dominant electron heating. The PAC underlines the importance of the investigation of sources of residual stress, particularly at the edge, including the study of the impact of 3D effects. This research also offers a unique possibility of collaboration with the colleagues of the theory department. Global codes are required to model this physics problem, and those directly developed at PPPL (GTS and XGC-1) are almost unique tools for these applications.

Comments pertaining to Charge Question #2 (ITER relevance)

The PAC acknowledges that the NSTX-U research program in turbulence and transport is of relevance also for ITER. The general consideration is that all of the studies planned to increase the understanding of plasma turbulence and transport have the potential application of improving present capabilities of predicting the behavior of plasma discharges in ITER, and of better defining the scenarios. In this framework, the PAC agrees with the recognized importance of impurity transport studies. In particular, the assessment of the size of impurity transport in the H-mode pedestal is of particular importance for ITER. In contrast to large aspect ratio tokamaks where the transport of impurities in the H-mode pedestal has been found to follow the neoclassical predictions, studies in the NSTX H-mode pedestal suggest that turbulent impurity transport can be large compared to the neoclassical transport. The clarification and understanding of these potential differences, comparing experimental conditions in NSTX-U (and NSTX) with those in large aspect ratio tokamaks, is certainly an important element for a reliable prediction of the behavior of the impurities in ITER.

In addition to impurity transport studies, it is also suggested to give emphasis to the understanding of turbulence and transport in high beta conditions, which can be less easily accessed by large aspect ratio tokamaks. Thereby, it appears of particular interest to compare with a conventional aspect ratio tokamak like DIII-D, in order to investigate differences (and similarities) in plasma turbulence properties and in transport as a function of beta, comparing low and large aspect ratio conditions. This is of critical importance also beyond ITER, since desired operation of a fusion reactor is at very high beta, to limit the cost of electricity.

Comments pertaining to Charge Question #3 and #4 (developing predictive capability, 5-year plan improvements))

The PAC acknowledges that NSTX has covered a world leading position in developing a coherent research program in which the confinement properties of the main core plasma are investigated with accurate profile and fluctuation diagnostics, and simulated with physics comprehensive and realistic numerical simulations. Thereby, it can be expected that NSTX-U will consolidate this leading position, and allow further significant progress in the fundamental understanding of transport in toroidal devices, and extensively contribute to the validation of models and related numerical tools. The PAC acknowledges that in the 5-year plan emphasis is given to both the physical understanding of the observations with first principle (physics comprehensive) models and to the development and validation of reduced physics models. However, the definition of the 3rd thrust appears to give more emphasis to the latter aspect, and risks to hide the former, which is actually equally (if not even more) essential. The PAC suggests that both elements are considered and presented (charge 4) with equal emphasis, in recognition that these are not independent elements in the validation approach. This would increase the overall coherence of the presentation. First, the identification and understanding of critical ingredients are required to appropriately describe transport in NSTX-U. This implies the application of physics comprehensive, realistic, first principles models, which can be compared with a hierarchy of observations provided by fluctuation and profile diagnostics. Once these ingredients are identified and understood, then they can be included in reduced transport models, which have to be developed and verified against the first principle models. The same dependences of transport as a function of plasma parameters must be quantitatively predicted by both reduced and first principle models. Finally, the reduced transport model can be applied over large sets of data and validated by testing whether experimental dependences can be quantitatively reproduced, gaining confidence in the predictive capability of the reduced transport model. The PAC acknowledges that such an integrated validation process, which takes into account both a hierarchy of measured quantities and a hierarchy of theoretical models (from first principles to reduced transport models) is in practice already applied by the NSTX-U Team in the research on turbulence and transport. The PAC suggests that these aspects be more clearly pointed out in the presentation. This would also allow the presentation of the plan for validation to follow more closely the guidelines and best practices for verification and validation that have been described in recent publications.

More specifically, and still in the framework of the plans for validation, the PAC underlines the importance of the further development and application of global nonlinear codes (like for instance GTS and XGC1, which are developed at PPPL). These codes are essential not only to investigate potential effects of turbulence spreading, but also to test appropriately the role of large scale (almost MHD like) modes and finite ρ^* effects on the turbulence level and on the transport components (e.g. in momentum transport). Linear local models can be justified for an easy initial investigation of the linear instabilities at the edge of the plasma (as these models are already utilized and planned to be utilized). However, particularly at the edge, the potentially increasing role of nonlinear effects should also be kept under consideration, in addition to the sizable length of the ion Larmor radius with respect to the characteristic gradient lengths. This could imply (as it has been already observed in several simulations of edge turbulence) that linear modes are of little meaning in that region of the plasma, and suggests the need for making a more regular use of global nonlinear codes in the future, particularly when the problem of the physics of edge turbulence and transport is addressed. This should also motivate the inclusion of complete electromagnetic models in the global codes developed at PPPL.The expected increase of computing resources over the next 5 years will certainly allow nonlinear global codes to be applied on a more regular basis to directly model the experiments.

In case a theory oriented talk will be considered, as suggested by the PAC, these aspects could be also presented in that talk.

3.4 Boundary Physics, Scrape-Off Layer and Divertor, and Plasma-Material Interactions

The PAC was presented with three presentations in this area. An overall strategy, the plans for the pedestal, scrape-of-layer (SOL) and divertor physics topical group and the plans for particle control. A presentation of the plans for Material and Plasma Facing Component (PFC) research is also relevant to this area, since the choices of the PFCs clearly affects the conditions in the Divertor, SOL and Plasma Boundary area. PFC issues will be discussed in Section 3.5 of the report. It is the aim of the NSTX-U team to be one of the world leaders in this area, and previous results vouch for their strong presence in the field.

In particular the work undertaken by the NSTX-U team on the Snowflake (SF) divertor configuration (complementing the pioneering work at TCV) is remarkable, and has been followed by collaborative work on the SF configuration for DIII-D. Together with the use of Li conditioning in NSTX to change the recycling sources just inside the last closed flux surface to improve stability the work has led to a noteworthy insight into the physics of pedestal transport and stability.

The capabilities of NSTX-U and the presented research plan are likely to put the NSTX-U team into a world leading position in this area, although the international competition is strong. NSTX-U will have the unique capability to combine a double null SF divertor with extremely high heat fluxes through the SOL. The upgrades planned to the Li injection system, as well as the cryo-pump, will allow a better control of the recycling sources with the unique capability to compare particle control techniques, e.g. between Li wall conditioning and cryo-pumping. The longer pulse length will allow tests of steady state divertor heat flux mitigation. Higher plasma current and toroidal field will open a wider operating space, bridging the gap (in particular) to an ST-FNFS.

It should be noted, though, that divertor and SOL physics are particularly difficult to scale to larger devices. Hence, a deeper understanding in this area is needed to develop predictive capabilities that will be substantially aided by strong international collaboration. This understanding requires a comprehensive suite of diagnostics and advances in plasma modeling.

With respect to diagnostics, the PAC is pleased to see plans for a divertor Thomson scattering (TS) system as well as improved edge resolution of the main (core region) plasma TS diagnostic and the divertor bolometer. At high plasma β measuring the pedestal width at the low field side mid-plane is particularly challenging. It may be advisable to also improve the resolution of the TS at the high magnetic field side mid-plane. The PAC also believes that better turbulence diagnostics around the X-point region are needed, in particular to understand the transport in a SF configuration. The addition of an X-point gas puff imaging system is a right step in this direction, but more measurements of various fluctuating field components are needed. Without evidence presented, it appears doubtful that core systems, such as beam emission spectroscopy or high-k scattering, have the required resolution/sensitivity in the SOL or the steep gradient region of the pedestal.

With respect to modeling the research plan needs a clearer focus on how the NSTX-U team plans to improve pedestal and SOL modeling and how the data can test these models. For example, SOL modeling with the current 2D fluid codes describes the parallel transport fairly well, but the common model for the perpendicular transport of steady diffusive/convection transport coefficients is too simple to capture the dominant intermittent turbulent transport. Furthermore, the 3D nature of the SOL, in particular in the presence of strong MHD (e.g. during ELMs) or applied 3D fields for ELM mitigation, requires a 3D code.

Turbulence codes that may describe the perpendicular transport on the other hand have often very limited models for the parallel momentum and energy transport.

Comments pertaining to Charge Question #1 (future ST facilities)

The plasma boundary is a critical component for a future high performance ST device (as well as other configurations). The heat flux expected from ST devices will have P/R or P/S values that are up-to a factor 9 and 6 respectively above previous NSTX capabilities. The upgrade will bring this within a factor 4 with respect to P/R and a factor of 2 with respect to P/S to future potential ST facilities such as the ST-FNSF or then ST-Pilot Plant. The power flux projected for NSTX-U will exceed the material limits by up-to a factor of 3 to 6 depending on the material chosen. Here, transient heat loads due to ELMs are of crucial importance. In addition particle control needs to be demonstrated in a future device relevant fashion.

The research plan supports all of these three important areas. The near term program (year 1) without the availability of NSTX-U concentrates on further analysis and inter machine comparison of pedestal micro-stability and pedestal structure, SOL width scaling of detached regimes and modeling of SOL turbulence as well as SF divertor studies on DIII-D. For particle control a key milestone is the design of the cryo-pump. The wider operating space of NSTX-U is used in the mid-term (year 2-3) to further deepen the understanding as well as to establish optimized boundary regimes and divertor configurations. Li wall conditioning facilitates a wide range of the NSTX-U physics studies. This conditioning is a very powerful tool for increasing the understanding of the boundary physics, but it is unclear if this technique, even with constant replenishment using a Li dropper, is applicable to future devices using tritium. The team needs to clarify how the scalability and integration of these optimized boundary regimes to future ST applications can be quantified.

Studies of radiative detachment in the SF and conventional divertor configuration are of particular importance for future devices. The proposed five-year plan is sufficient to address the detachment physics and the PAC agrees that this needs to feature strongly in the plan. The open divertor geometry, however, is likely to prevent the demonstration of impurity retention even in the presence of a cryo-pump as an impurity sink. Impurity retention is an important aspect for a future ST device. The NSTX-U team should consider if it is possible to baffle the divertor volume to demonstrate impurity retention and deuterium compression. The long term planning (years 3-5) addresses the effect of the cryo-pump and ELM mitigation via 3D magnetic perturbation with off-mid plane coils using the capability added later. In particular in the field of 3D perturbations, much work has been done on other devices such as ASDEX Upgrade, DIII-D, KSTAR and MAST. This area, though very fashionable and important, is likely to make less of an impact this late in the program. The NSTX-U team needs to ensure that the physics understanding and experience gained on other devices is efficiently applied. The justification of 3D off-mid-plane coils on the grounds of the boundary and PMI area alone is probably not strong enough given the existence of advanced coil sets on other devices (e.g., MAST). Other ELM mitigation techniques such as Li granule injection and vertical kicks are also proposed exploiting unique capabilities of NSTX-U. Studying the compatibility of the SF divertor in double null configuration with vertical kicks at high elongation may be important for future high performance ST operation.

There are several aspects of NSTX pedestal data that differ from data obtained on other devices, such as

- NSTX shows a pedestal width scaling with beta as $\Delta_p^{ped} \propto \beta_\theta^{1.05}$, much stronger than observed on other devices, which see $\Delta_p^{ped} \propto \beta_\theta^{0.5}$. This includes the similar size device MAST. Also the measured pedestal widths are $\Delta_p^{ped} \leq 0.07\, r/a$, wider than those observed on other ST devices.
- The ELM free regime commonly accessed using Li wall conditioning has not been observed so far on other devices (TFTR, EAST).
- The type-V ELM regime is only observed on NSTX.

A focused approach and a collaborative effort are needed to understand the applicability of the findings to future STs. The plan to compare pedestal conditions where recycling is "controlled" by Li coating combined with cryo-pumping during early collaborations with the standard-aspect-ratio EAST, and later in NSTX-U itself, is very welcomed in this respect. This will exploit a unique Li/cryo-pump ST capability of NSTX-U. In this respect important questions relevant to the performance of future high performance STs are:

- Will Li continue to suppress ELMs at higher power?
- Will the ELM suppressed regime found with Li also be accessible with cryo-pumping?
- Why do ELMs come back with the SF divertor configuration despite Li conditioning?
- Why isn't ELM suppression with Li seen in conventional tokamaks such as EAST?

One important aspect that is not well covered by the five-year plan is the compatibility of boundary and core performance with a reactor relevant wall material. It is likely that neither solid Li nor C is appropriate wall materials. It is also known from recent experience, that the change of the wall material influences the boundary plasma substantially. The change to the full W wall on ASDEX Upgrade has resulted in different boundary plasma, SOL and divertor behavior. The change on JET to the Be/W wall has reduced the achievable pedestal height and the ELM dynamics. On NSTX the introduction of Li has changed the pedestal structure substantially. Whilst the PAC understands the desire to exploit performance upgrades with a "safe" wall it is also important to understand the consequences on the divertor, SOL and boundary physics of a more restrictive material choice. Consequently, the five-year plan shows a stepwise transition from the C wall move to a full metal high-Z wall with liquid Li divertor modules in the lower divertor. This implementation is planned to lead to a full metal wall after the 5-year period (completed in 2019) Within this 5 year period the installation of a row of Mo tiles (2016), planned high-Z trace impurity experiments using laser blow off and finally the installation of the bakeable cryo-baffles for liquid Li (2018-19) are steps in the right direction, but are unlikely to yield results that would enable a decision for a suitable wall material on an ST-FNSF by the end of the five-year plan. The NSTX-U team should clarify how results on conventional tokamaks may help this decision or how the implementation of the full-metal wall could be accelerated in an incremental budget. The planned upgrades for liquid Li plasma facing components won't demonstrate compatibility with double null operations, which is fundamental to future ST devices to achieve tolerable heat fluxes at the inner strike points.

Comments pertaining to Charge Question #2 (ITER relevance)

It is unlikely that NSTX-U results will have a strong impact on ITER design issues, since many of these issues need to be resolved before NSTX-U comes online. The deeper understanding gained on NSTX-U with the access to different parameter regimes can make a strong contribution to the successful operational exploitation of ITER. This deeper understanding is strongly supported by the proposed five-year plan. In particular the insight that can be gained with respect to ELM and pedestal physics (stability and transport), and using the capability to affect the pedestal pressure with Li conditioning, have already allowed and will in the future allow a deeper insight into the pedestal stability. The different access to second stability in the SOL in the ST can test SOL stability issues attributed to ballooning instabilities that are difficult to address in conventional tokamaks alone. The high heat flux density through the SOL achievable in NSTX-U is likely to push the SOL parameter regimes to extremes. Understanding of radiative detachment and scaling of the SOL width in detached conditions are important issues for ITER that feature strongly in the five-year plan. Here, the capability to access lower collisionality and higher plasma current combined with high power densities are unique to NSTX-U and the P/R and P/S values achievable overlap the ITER operating space.

The different and wider parameter regimes in the plasma boundary and SOL will improve the confidence of models with respect to predicting future conventional aspect ratio devices including ITER. There is a strong overlap between the needs of the ST and the needs for ITER and other future devices in the area of boundary, SOL and divertor physics.

The PAC agrees that the emphasis of the research needs to be in a better understanding of the physics issues. A principal difficulty with this research in the ST is that it is unclear how far regimes (or even results) can be transferred to conventional tokamaks. First principle transport models for the pedestal and SOL are in an early stage and may not always include the full physics. For example XGC1 currently only models electrostatic turbulence, which though possibly sufficient in the SOL doesn't apply in the pedestal of NSTX-U and may even not apply in the SOL. Therefore detailed measurements beyond the standard profile and power flow diagnostics are needed. The NSTX-U team should clarify the spatial and temporal resolution as well as the applicable parameter range for turbulence and profile measurements in the pedestal and SOL region.

An important area of ITER research is ELM mitigation. NSTX-U will have several tools to contribute to this research such as the Li granule dropper, the possibility to study vertical kicks, mid-plane 3D n=3 coils and finally the off mid-plane coils available from 2018. The NSTX-U team could emphasize more strongly these capabilities and their relevance to ITER physics understanding in the research plan. Li granules may not be relevant for ITER studies, since they also deposit Li layers in the device, which are not feasible in ITER or other devices using tritium. Furthermore, Li deposition will also change the boundary conditions. The NSTX-U team could consider if other, more ITER relevant, materials can be used with the granule dropper to study ELM mitigation. Possible candidates could include Be, TESPEL or possibly Al. The off axis 3D magnetic perturbation coils planned for installation in 2016/17 can be used for ELM mitigation using resonant magnetic perturbations (RMP). Other devices such as ASDEX Upgrade, DIII-D, KSTAR and MAST are likely to have made substantial progress on the physics basis with off mid-plane coils before these are operated in NSTX-U. The NSTX-U team should clarify the strength/uniqueness of the proposed coil system with respect to existing systems. Also, the figure of merit presented in the presentations, $F_{N-C} = T_{NTV} / C^4_{vacuum,\psi_N=0.85}$, of the ratio of NTV torque to Chirikov parameter to judge the effectiveness of the RMPs seemed disjointed from current research, which shows that the field alignment is more important than the Chirikov parameter. Designated RMP coil sets have recently been designed on ASDEX Upgrade, ITER, KSTAR and MAST and a vibrant international collaboration exists. The NSTX-U team should actively engage in an international effort to design their coil set. The PAC notes, however, that NSTX-U researchers are already involved in ELM mitigation studies on KSTAR.

Comments pertaining to Charge Question #3 (developing predictive capability)

The presented five-year plan highlights several areas where NSTX data are compared to modeling results. Notable are the ongoing comparisons of pedestal profiles to the peeling ballooning mode stability. Initial comparisons of the pedestal width with EPED modeling have also been done, as well as attempts to compare turbulence characteristics with XGC1 electrostatic calculations in the pedestal and the SOLT code in the SOL. With respect to the pedestal width NSTX reports different results from other tokamaks, in particular different from MAST. Comparison with EPED calculations seems to account at least partly for the differences, but more detailed analysis needs to be done. Clearly the improved resolution mid-plane TS and the wider operating space will provide the required insight in comparison with other US devices as planned for year 1.

With respect to comparison and validation of turbulence codes the research plan is less clear. A continuation of the gyro-kinetic electromagnetic turbulence in the pedestal is planned for year 1 with comparisons of the pedestal structure with codes like XGC0 and XGC1 in years 4-5. The comparison of the resulting profiles is not enough to arrive at predictive capability. To get confidence in the predictive capability, more detailed probing of turbulence characteristics need to be done to excel in the field. The NSTX-U team should also strive to collaborate with other pedestal/SOL turbulence simulation groups nationally and internationally. As recommended above*, the NSTX-U team should clarify the diagnostic capabilities of the turbulence measurements such as spatial, temporal resolution and sensitivity in the parameter range of the pedestal.* Modeling of the pedestal turbulence in the ST most likely requires a fully electromagnetic full-f global code.

Simulations of the SOL are planned with 2D fluid codes such as UEDGE, SOLPS (neutrals fluid or Monte-Carlo) and electrostatic gyro-kinetic models such as XGC1. SOLPS coupled to the Monte-Carlo neutral code EIRENE also is used to design the cryo-pump. Comparison to the actually achieved pumping speed with the predicted pumping performance from the SOLPS-EIRENE will provide a good example for the predictive capabilities of the simplified SOL modeling with respect to particle balance. Turbulence needs inherently a 3D description and results from other devices and more recently NSTX have shown that ELMs require a 3D description of the SOL as well. Error fields and RMPs fall into the same category. Therefore, SOL codes need to be extended to 3D geometry (e.g. EMC3). Furthermore, the cross-field transport according to Fick's law assumed in the fluid codes with a more complete description of the parallel processes has been shown experimentally [O. E. Garcia, J. Nucl. Mat. **363** (2007) 575] and theoretically [V. Naulin, J. Nucl. Mat. **363** (2007) 24] to describe, at least, particle transport poorly. New code development is needed in this area to achieve predictive capabilities. Whilst code development as such is not necessarily a part of the NSTX-U program, a clearer path on how the research in the five-year plan will contribute to this development would be useful. The NSTX-U team should clarify how the new data are testing the applicability of the physics models and the assumptions made in the simulations.

Comments pertaining to Charge Question #4 (5-year plan improvements)

The PAC generally commends the NSTX-U team on the clarity and content of the presentations. There is, however, room still for improvement. The presentations in the boundary physics, SOL and divertor physics area are split into four separate presentations (including the Material and PFC presentation). The different presentations follow a slightly different style leading to the feeling of a somewhat disjointed program in this area. The initial strategic overview tries to join the programs together, but a single consistent presentation on Boundary, SOL, Divertor physics and Plasma Material Interactions would be beneficial.

Whilst the link of the planned activities to the main research thrusts is clear from the structure of the presentations it is less clear how the plan links into the high level goal to *Develop and understand integrated plasma exhaust solutions compatible with high core performance for FNSF and ITER.* Compared to the other research areas it also seems odd that this most important area has only two very broad research thrusts.

3.5 Materials, Plasma-Facing Components, and Particle Control

The topical science area in Materials, PFC and Particle Control focused their responses on addressing the three charges and in particular on the strength of planned NSTX-U contributions to boundary physics and PMI (plasma-material interaction) research.

Comments pertaining to Charge Question #1 (future ST facilities)

Attaining plasmas with low collisionality, for which density control is the strongest leverage, remains one of NSTX-U's most important objectives. We applaud the NSTX-U team for reconfiguring their implementation strategy of PFC and particle control upgrades to support exploration of high-performance plasmas for use in a future burning fusion research facility. In particular the decision to use tungsten high-Z materials and the high-level priority of implementing a cryo-pump is noteworthy. The previous PAC-31 pointed out its concern with potential competing priorities in the NSTX-U 5-year program. The three highest-level goals were summarized as: FNSF scenario development, divertor heat flux control solutions and exploring the role of plasma collisionality in ST performance. The PAC remains concerned about these potential competing priorities and the current 5-year plan strategy as presented still makes it difficult to discern which goal is being prioritized over another and how the implementation of the 5-year plan helps achieve such prioritization. For example, the argument that NSTX-U will provide meaningful data on PMI physics for a future burning fusion plasma device is difficult to support given NSTX-U will remain largely a carbon machine for the proposed five years. At the end of the proposed 5-year program, a compelling case for selection of PFC/PMI materials for an FNSF-ST (or similar device) will be difficult to make. Not enough will be known about operations with high-Z walls and the feasibility of Li coatings or flowing liquid Li walls will still be in doubt or uncertain. Given that MAST-U will be a carbon device for the foreseeable future, if progress is to be made on ST operations with high-Z or liquid metal PFC, then this progress must be made on NSTX-U. Two PFC upgrades that address robust fusion material walls (e.g. tungsten and liquid lithium) are not implemented until the end of the 5-year program. In particular two main challenges identified by the PAC with PFC/PMI implementation are: 1) Material mixing (from a largely carbon device) could hamper understanding of the impact of the single-row high-Z in lower divertor and 2) the use of a static liquid lithium module. The PAC recommends consideration of implementing use of tungsten PFCs earlier than the end of the 5-year plan if feasible. As already pointed out in section 2, this option should be only considered in the case of incremental funding scenario, and with appropriate timing, in order not to limit the possibility of developing and achieving the low collisionality scenarios in the first years of operation with carbon PFCs.

Although a staged plan to implement high-Z PFCs is considered important, waiting until the end of the 5-year plan for a high-Z divertor may not yield enough knowledge on the use of high-Z materials in an ST for timely impact to a next-step device decision, if in fact this is the desired outcome. Lithium coatings have been used routinely in NSTX, however it is not clear if this is a necessary condition to produce and to sustain longer-pulse and high performance plasmas in NSTX-U. The risk of lithium coatings and conditioning is whether these approaches are realistic for a next-step device like an FNSF-ST. The use of lithium coatings on high-Z substrates for vapor shielding testing is also very compelling. However, given that NSTX-U will mostly be a carbon device the impact of these studies will be difficult to ascertain under the current NSTX-U 5-year plan strategy.

PPPL is one of the world leaders in advanced liquid-metal PFC research. The use of liquid metals in a next-step device is uncertain. Having NSTX-U as a platform to determine the feasibility and performance of liquid metal PFCs is critical. However, under the current 5-year plan implementation of a liquid lithium divertor module is not completed until the last year of the plan and in a static mode. Not having the option of a flowing liquid Li module until the 2019-2023 may generate more questions than answers given the known limitations to static liquid-metal systems as reactive as lithium. The PAC also notes that no discussion was presented on mitigating the expected mixed-material scenario on the liquid-metal divertor module with the presence of carbon and oxygen expected in NSTX-U. Furthermore, the NSTX team should consider increasing dedicated experimental time in NSTX-U for PFC/PMI work and in particular for conditions without lithium coatings to establish credible fiducial shots and conditions at each stage of introducing a new PFC scenario (e.g. high-Z row, high-Z divertor, LLD, etc…). This is particularly important for scenarios where comparisons between lithium vs boron conditioning are attempted.

Leveraging external table-top PFC/PMI experiments (e.g. linear plasma devices and surface analysis facilities) is critically important. In particular to understand complex PMI issues in NSTX-U as it progressively transitions from an all-carbon device to a full high-Z metal device. The NSTX-U team does a great job of demonstrating these key connections in the 5-year plan but is encouraged to be more specific on how these experimental facilities are addressing specific questions that cannot be answered in NSTX-U alone.

Comments pertaining to Charge Question #2 (ITER relevance)

Installation of metal tiles at the divertor (hopefully bulk tile) is expected to contribute to ITER/reactor issues. Active study of high-Z PFC and control for ITER should be required. Although a lot of PMI work such as erosion, deposition and melting dynamics has been done, the issue of controlling high-Z accumulation by a variety of tools in NSTX-U (HHFW, center NBI, gas puff/injection, low Z conditioning, and potentially EBW etc.) as well as development of the transport modeling will contribute to ITER physics and reactor operation. This knowledge base can also help accelerate implementation of more high-Z PFC coverage in NSTX-U. However, this reinforces the need for earlier implementation of W tiles in NSTX-U. At the same time, introduction of Material probe (MAPP) is excellent for high-Z surface analysis without influence of discharge history. Thus its early integration in NSTX-U is recommended. When investigating Li vapor shielding, it will be important to keep the connection towards ITER-relevance, provided that NSTX shows how dynamic and atomic process of Li at the transient heat load are similar to those of Be for ITER. Modeling will play a key role in strengthening this relevance. It will be important to plan how specific vapor shielding experiments project towards ITER. Thus close interaction with ITER teams focused on off-normal event modeling and design is highly recommended.

Comments pertaining to Charge Question #3 (developing predictive capability)

Modeling in combination with controlled linear devices or table-top experiments should be pursued more and can be done immediately before the Upgrade is completed or when any high-Z components are installed in NSTX-U. Identifying key model validation with laboratory experiments and in particular in the area of surface response codes (e.g. advanced dynamic BCA codes coupled to atomistic codes [e.g. quantum-classical molecular dynamics]) is critical given the strong coupling of surface response and particle control at the plasma-material interface. Development of high-Z impurity transport modeling is also important.

Additional comments regarding Li research in NSTX-U

Particle control by repetitive Li injection and/or Li evaporation (LITERs) is an important contribution to fusion energy science by the NSTX team. More systematic and quantitative research is preferable to provide the database for Li coating and LL divertor design since hydrogen-isotope retention is still the largest unknown issue. At the same time, transport and PWI modeling of Li, mixed-material (Li+C) and co-deposition needs further development. In particular:

- Quantitative analysis (hydrogen isotope retention, mitigation of Li and mixed-material layers) over the whole PFC surface and how this contributes to improvement of NSTX-U operation and LLD scenario for NFSF-ST.
- Particle balance results from existing and future experimental discharges for comparisons between Li and cryopump particle control scenarios.
- As for Li application to a larger device, evaluation of erosion rate (gross erosion) in the experiments as a function of the plasma temperature and surface temperature is also an important database. It should be quantified and modeled.
- Demonstration of Li vapor-shielding under high heat load is desirable before any major installation of a flowing liquid-lithium system in NSTX-U.
- The performance of vapor-shielding is essential for application of the LLD. Response of Li (recycling and radiative cooling processes) against steady-state high heat flux and transient heat pulse needs to be investigated.

- At the same time, compatibility of LLD with seeding impurity (recycling rate and sputtering rate) should be demonstrated. Research of He pumping scenario will be necessary for meaningful extrapolations to a next-step device.

3.6 Energetic Particle Physics, High-harmonic Fast-Wave, and Electron Cyclotron Heating

Energetic particle research as articulated for the NSTX-U Five Year Plan seems well poised to take advantage of the unique set of NSTX-U capabilities including the NBI system, higher magnetic field and current, and 3D field coils. Gaining an understanding of and being able to predict fast ion behavior are important goals for the NSTX-U program that can improve the possibilities for an FSNF-ST as well as support burning plasma research on ITER. The coupling between experiment and theory in this area is particularly strong and has served the NSTX Project well, and should continue to benefit NSTX-U. The PAC agrees with the stated FY14 milestone to assess reduced models for AE-induced fast ion transport using models for quasilinear relaxation of the fast ion profile for given AE's and using a model for resonant fast ion transport in NUBEAM/TRANSP to complement existing "diffusive/convective" models. The improvements planned for numerical tools such as the implementation of a 3D 'halo' model in TRANSP for the analysis and simulation of charge exchange data and improved descriptions of neutral beam force and rotation in M3D-K, NOVA-K, HYM should be valuable. Finally the complement of diagnostics, including upgrades seems adequate for the NSTX-U Energetic Particle mission (e.g. FIDA, NPA, sFLIP, reflectometer, and BES).

While it is valuable to do more detailed comparisons of measured and theoretical Alfvén Eigenmode (AE) damping rates, the PAC would like to suggest that an even greater impact could be made utilizing the control expertise on NSTX-U by demonstrating AE control and this goal did not come out very strongly in the energetic particle presentation. Given the strong emphasis of the NSTX-U program on plasma control, it would make sense to emphasize control of AE's. Possible actuators include 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. In collaboration with theory, it would also be valuable to develop a predictive capability for the stability of AE's and then include this capability into the control system to learn how to navigate high performance regimes and avoid excessive fast ion loss due to AE's. Can a reduced model be developed to predict AE stability in real-time for event handling? Such AE prediction and control would be very valuable for use in operating ITER burning plasmas.

The more flexible NBI system (6 sources at different tangency) will give a great flexibility over the fast-ion distribution function. This will be important to understand the driving mechanisms for the energetic particle modes and the critical issue of the fast ion redistribution and losses due to these modes. Whilst the higher fast-ion content may make AE stability and dynamics more critical on NSTX-U, the broader deposition due to the more tangential beams will lead to lower gradients reducing the source driving instability. Additional control of the rotation profile with the NCC can also provide control of the energetic particle modes. These additional control actuators could provide a particularly valuable means for energetic particle profile control and should be emphasized. In combination with the wide array of energetic particle diagnostics, the sensors and actuators provide the means to control the energetic particle profile and energetic particle modes.

High Harmonic Fast Wave and Electron Cyclotron and Bernstein Wave Heating

The applications planned for high harmonic fast wave (HHFW) and electron cyclotron heating (ECH) power in NSTX-U target one of the primary NSTX-U Research needs quite well, namely the goal to generate fully non-inductive (NI) discharges that extrapolate to neutron wall loading in an FNSF ($\geq$ 1MW/m^2). In particular up to 6 MW of HHFW at 30 MHz is planned for heating and bootstrap current enhancement during start-up, ramp-up, and H-mode sustainment. Electron cyclotron heating at 28 GHz and at the 1-2 MW level will be added in an Upgrade budget and will be used to heat low density start-up plasmas and for EBW heating of over-dense H-mode plasmas, via the O-X-B mode conversion scheme. For the EBW heating the proposed 28 GHz system is not optimal, since it relies on access to the 2nd harmonic resonance. EBE studies on MAST suggest that this resonance may not be accessible in H-mode at high density due to the strong edge current, although these results may also be explained by enhanced collisional damping due to the lower T_e. Testing this physics is an important contribution to enable EBW heating schemes in future devices. The higher toroidal magnetic field ($B_T \sim$ 1T) in NSTX-U is expected to improve HHFW coupling and the higher current ($I_P \sim$ 2 MA) should improve confinement of fast ions from NBI heating, thus limiting interaction of the lost ions with the HHFW antenna; a problem that had been seen in NSTX.

The research plans in HHFW will not only contribute to model validation and predictive capability in the area of wave-particle interactions but should also ensure success in NSTX-U applications. The NSTX-U Five Year Research Plan emphasizes understanding antenna coupling and absorption of HHFW on thermal and beam ions, which are high priority physics issues for HHFW. Specifically plans were described to use the 3D AORSA field solver to study HHFW coupling and interactions of the HHFW with the SOL. These studies should help identity antenna configurations and SOL parameters that may suppress the surface wave excitation found in NSTX. The development and validation of a full orbit width "Hybrid" CQL3D continuum Fokker Planck code started during the NSTX Project will continue on NSTX-U, as well as benchmarking of the new code against FIDA diagnostic data. Developing an accurate description such as this of the HHFW-fast ion interaction could be crucial for optimizing the use of HHFW in the presence of NBI. The AORSA and TORIC full-wave solvers will be used to assess HHFW absorption on thermal and beam ions. An important corollary activity in this area will be the benchmarking of TORIC against the more complete AORSA solver, thus validating the use of TORIC in TRANSP for time dependent transport analyses of NSTX-U discharges with HHFW heating. In the area of ECH / EBW it was pointed out that plasmas produced with CHI should be amenable to EC heating.

An exciting research plan in ECH / EBW was presented to the PAC, which should help to achieve the goal of solenoid-less start-up. It was pointed out that plasmas produced with CHI are characterized by $T_e(0) \sim$ 5 eV, and that ~25% single pass absorption of ECH O-mode power can be expected at these temperatures and densities (3-4$\times$10^{18} m^{-3}), which should lead to rapid heating to ~200 eV. This part of the research plan also called for the testing of EBW heating via the O-X-B conversion scheme, with detailed modeling of the O-X-B conversion scheme to be carried out, including the use of a realistic SOL model, including edge fluctuations. An interesting idea suggested by the PAC was to consider the use of high field side launch for the EBW scheme as for example studied on MAST, whereby a polarizing mirror would be placed on the high field side to produce the O-X conversion before the EC power was coupled to the plasma. This may give non inductive start-up currents of the same order of magnitude as suggested for CHI/ECH start-up.

The PAC has the following suggestions and concerns regarding plans for HHFW and ECH / EBW power in NSTX-U that could improve the Five Year Plan in this area. It was not clear from the presentations if detailed modeling plans exist for simulating the ICRF antenna structures including the 3D solid geometry of the antenna in the presence of a SOL plasma. This would likely involve using antenna codes such as Microwave Studio, COMSOL, or VORPAL with a plasma model. Presumably these types of antenna simulations could be used to improve the electromagnetic design of the antennas themselves as well as for understanding how the antennas interact with plasma. The PAC also shares a concern that enough time will be spent to assess problems with coupling the HHFW into CHI produced plasmas and into ramping plasmas, as this coupling could be difficult because of the evolving plasma position and and shape. The NSTX-U Team should therefore give careful consideration to what balance is needed between CHI, HHFW, ECH, EBW, and NBI in the scenario development and control program. For example, a dedicated effort may be needed to ensure that the HHFW can be effectively coupled into start-up plasmas. Also, because of the ease of coupling of ECH / EBW power into start-up plasmas, the NSTX-U team should recognize the potential for this method to be a "game-changer" in producing start-up plasmas.

3.7 Solenoid Free Start-up and Ramp-up

Non-inductive start-up and ramp-up of plasma current startup is a unique and critically important issue facing next-step ST development. One of the high-level goals for NSTX-U is to develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid. A clear scenario has been proposed: CHI is used as an initial current seed for subsequent current ramp-up to 1 MA in NSTX-U using RF heating and NBI current over-drive. Local helicity injection is also being developed in collaboration with the PEGASUS group as an alternate method for the initial plasma current formation.

Very impressive progress has been made on the development of CHI, producing 200 kA of plasma current in NSTX with the injector flux of ~ 50 mWb. The projected start-up current will be doubled with augmented tools available for NSTX-U, i.e., 2.5 × injector flux, 2 × TF, enhanced power supply with injector voltage increased from 1.7 to 3 kV, etc. The objective is to use Electron Cyclotron Heating (ECH) to heat the initial 400 kA CHI target plasma temperature to $T_e = 200 \sim 400$ eV, then use the high-harmonic fast wave (HHFW) to further increase Te to 1-3 keV, finally ramping up the current to 1 MA with newly implemented tangential neutral beam injection (NBI), assisted by the bootstrap current. Significant progress has also been made on the modeling front: (1) Modeling of the helicity injection startup in NSTX using the 3D NIMROD code has shown promising results, now starting to show flux closure on experimental time scales; (2) TSC simulation has demonstrated the possibility of ramping up the non-inductive plasma current from the initial CHI target (400 kA) to the desired goal (1 MA), with the proposed heating and current scenario aforementioned.

The PAC supports the plans of continuing MHD simulations (NIMROD, TSC-TRANSP, NUBEAM, GENRAY) of the start-up and ramp-up of CHI-initiated discharges in NSTX, further extending to NSTX upgrade and beyond. This will also very likely produce rich physics results on the dynamics of plasma relaxation, RF heating of low inductance CHI plasmas, as well as fast particle trapping and current drive during the current ramp-up process, which are unique to ST. The PAC is pleased by the progress in developing local helicity injection with retractable plasma guns in collaboration with the PEGASUS team and assessing the feasibility to scale it to NSTX-U. We support the plan to implement this on NSTX-U at the earliest possible date. The PAC also applauds the ongoing collaboration efforts with QUEST in Japan in the development of metal electrode for CHI, to gain information for future use of metal divertor plate electrodes in NSTX-U.

However, the PAC is concerned by the level of effort on and resources allocated to this important area of research and development, which is a key component for developing ST toward FNSF and DEMO. The PAC urges the NSTX-U team to establish more balance between non-inductive start-up/ramp-up and non-inductive sustainment of high performance scenarios (see general comments in Section 2). The NSTX-U team should also develop a concept design for a system enabling the suggested non-inductive start-up in an ST-FNSF.

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March 22, 2013