NSTX-U Program Advisory Committee Report

Dr. Jonathan Menard, NSTX-U Director
Dr. Richard Hawryluk, Interim Lab Director
Princeton Plasma Physics Laboratory

Recommendations of the NSTX-U Program Advisory Committee

Dear Dr. Menard and Dr. Hawryluk:

The NSTX-U Program Advisory Committee (PAC) met at your request at PPPL on January 9-10, 2018, to hear presentations made by the NSTX-U team. This letter is the response of the PAC to your charge.

NSTX-U PAC-39 Members - November 2017

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Charge for NSTX-U PAC-39

January 9-10, 2018

BACKGROUND:

The NSTX Upgrade (NSTX-U) facility operated in FY2016 and rapidly accessed H-mode, exceeded NSTX record pulse duration and magnetic field, commissioned a new 2nd more tangential NBI (12MW total) and most major core plasma diagnostics, and discovered several new fast-ion physics effects using the new 2nd NBI. However, the failure of a divertor poloidal field coil ended NSTX-U operations in July 2016 after completing 10 weeks of a planned 18 week run campaign. The coil failure and other preceding technical issues motivated 2 extensive reviews in 2017 including an “Extent of Condition” review to identify NSTX-U design and/or component deficiencies and an “Extent of Cause” review to identify deficient PPPL practices and procedures. In response to the findings of the Extent of Condition review, NSTX-U initiated a “Recovery” plan/project to implement a Corrective Action Plan (CAP) to remedy the identified deficiencies. The Recovery includes six major scope areas: (1) rebuilding all six inner-PF coils with a mandrel-free design, (2) replacing plasma facing components that cannot be qualified for the full range of mechanical and projected thermal loads, (3) improving the “polar regions” at the machine top and bottom, (4) implementing mechanical instrumentation to assess the quality of mechanical models and trend machine behavior, (5) technical improvements related to bake-out performance and safety, and (6) improving neutron shielding of the test cell. To effectively manage this scope, PPPL is following DOE Order 413.3B Program and Project Management guidelines and has carried out a conceptual design review (CDR) for core tokamak scope. PPPL has also carried out a cost and schedule review and has initiated preliminary design reviews (PDRs) to prepare the Recovery project to be baselined. The Recovery schedule (pre-baseline and with incomplete resource leveling) indicates NSTX-U plasma operations would resume between November 2019 (early finish) and July 2020 (80% confidence).

When complete, the Recovery project and other improvements will significantly enhance NSTX-U reliability and safety and provide the highest-performance ST device in the world program and position NSTX-U to become an increasingly flexible and robust user facility. However, the delays in the NSTX-U operations schedule and advancements in the broader fusion program motivate consideration of the mission elements and long-term strategy of the NSTX-U program and facility in the world context.

CHARGE:

The NSTX-U research program requests PAC-39 comments and recommendations on:

1. The quality and importance of recent NSTX/NSTX-U research results and highlights
2. Uniqueness and timeliness of important questions NSTX-U will answer for fusion science
3. How/whether NSTX-U will be world-leading in scientific areas when operation resumes in 2020
4. Important scientific and technological findings since the original physics design of NSTX-U (2009) and/or since the last 5 year plan was written (2014), and how such findings influence the impact of medium-term research on NSTX-U (2020-2025) and the long-term NSTX-U vision (2025-2030).

The NSTX-U research program requests a written debrief of key comments and recommendations at the end of the PAC-39 meeting and a full written report within one month of PAC-39 completion.

Major Findings

Finding: The High Field ST Pilot Plant is a Compelling and Exciting Vision that can motivate the NSTX-U Program

To reach fusion energy, the world needs to demonstrate the fundamental viability of the fusion reactor concept – that net electricity can be generated ($Q_{eng}>1$), and that challenging issues associated with high duty cycle nuclear operation, materials and breeding can be resolved. These steps are vital to developing low cost of electricity devices, and to trigger the adoption of fusion energy by the private sector. A pilot plant represents an exciting approach to meet this challenge, demonstrating that the energy loop can be closed for net electricity, and pursuing the required nuclear testing and breeding development missions, through phased operation. This would essentially provide a single step to fusion energy (the pilot), but the approach requires research to develop the concept and viable techniques for the pilot.

A high field spherical tokamak (ST) represents a potentially lower capital cost path to a more compact pilot plant, and thus a compelling possibility to meet this challenge with a more affordable and viable device. Such an approach would provide a distinctive position for the U.S. program, while other partners are presently focused on much larger scale devices. It may therefore be a compelling path for the U.S. to pursue that could enable the U.S. to take the lead on and ownership of key reactor technology. PPPL has substantial intellectual ownership of this vision as applied to the ST.

This vision would be heavily leveraged by a number of transformative technologies. The exploration of these for an ST pilot plant requires research programs that both engage spherical tokamak facilities and other elements. Key aspects include:

- Advances in high field and high temperature superconductors can raise performance and may enable demountability to facilitate the nuclear research mission of the pilot.
- Advanced PFC solutions such as liquid metal walls.
- High efficiency, reactor compatible current drive techniques to reduce required fusion performance and device scale, and aid discharge ramp up (a key issue for the ST).
- Development of and physics projection capabilities for a fully non-inductive stable reactor core.

The vision articulated for the ST pilot plant incorporates recent advances in ST physics and provides an appropriate framework for prioritizing NSTX-U choices for the next five years. These are well reflected in the NSTX-U research plan, which provides key, distinctive and needed capabilities to meet the challenges involved, complementing those available elsewhere. In particular, its core performance parameters will enable evaluation of regimes at higher equivalent fusion performance, pressure and density than those elsewhere, with potentially higher bootstrap fraction, more coupled ions and electrons, more relevant pedestal, and lower fast ion fraction that is possible on MAST-U. Its abilities to explore high beta electron transport and stability issues above the no-wall limit are particular strengths, while the exploration of high harmonic fast wave would be important for the ST approach. This will help develop candidate reactor solutions and the physics basis to project to the reactor scale. The proposal for a liquid lithium divertor solution is particularly exciting and could lead to a transformational breakthrough for all fusion reactor paths; this should be pursued with vigor.

Therefore, this plan for research to explore the development of the spherical tokamak as a possible core for a compact pilot plant is strongly endorsed.

It should be noted that although the detailed exploration of the arguments conducted by the PAC in discussion with the NSTX-U team identified many key and distinctive needed contributions to this vision from NSTX-U (such as those discussed above), this was not immediately evident in presentations made to the PAC; effort is needed to specifically and quantitatively set out more clearly the elements that are present that make NSTX-U distinct from other facilities, particularly MAST-U, in the talks and documents offered by the team.

The PAC Recommends leading with this vision when presenting arguments for the program and the recovery and improving linkage of underlying physics issues and facility capabilities to this vision.

Finding: NSTX-U has many unique aspects

NSTX-U remains the world-leading spherical tokamak in many aspects of its capabilities and strongly complements the capabilities of MAST Upgrade. When compared with MAST-U, NSTX-U will have the following unique aspects:

- It will be able to operate at higher pressure and field, which will enable NSTX-U to address the key goal of assessing ST confinement scaling at higher field and determining whether an ST can be non-inductively sustained. This is fundamental to the long-term strategy of developing a reactor based on the spherical tokamak concept, and NSTX-U will be the world's best facility to address the totemic issue.
- NSTX-U will operate for longer pulses, which will enable the team to develop sustained high beta scenarios
- NSTX-U will have a close-fitting wall, whilst MAST-U will remain a more open geometry with only small stabilizing plates with limited poloidal extent. This will enable NSTX-U to develop sustained high beta scenarios which would not be possible without the wall stabilization.
- Higher density non-inductive scenarios will be possible on NSTX-U
- NSTX-U will be the only spherical tokamak with a high-harmonic fast wave heating system, which will be key for developing high beta scenarios at very high plasma pressures, as well as for tailoring the super-Alfvenic particle population.
- MAST-U will not apply wall conditioning with lithium, which means that NSTX-U will be unique in assessing the lithium conditioning and the wider pedestals the Li may provide.
- Both machines will have a wide shaping flexibility with similar ranges of triangularity and elongation accessible in principle. However, the vertically-displaced nature of the MAST-U NBI system means that when applying full beam power, the MAST-U shaping flexibility is significantly restrained to avoid NBI shine-through, meaning that only NSTX-U can apply a wide range of plasma shapes concomitant with high heating power.

- NSTX-U will have a larger parallel heat flux on the divertor plates, at least for short pulses, which will allow the team to assess divertor scalings in spherical tokamaks at high field and narrow scrape-off layers.
- Finally, the more flexible beam injection tangency, will allow NSTX-U to study fast ion physics a wider range of scenarios with more flexible fast ion distributions than in MAST-U

As well as the benefit of the unique aspects of the NSTX-U programme listed above, the U.S. programme will benefit from the intentional strong complementarity between MAST-U and NSTX-U, which adds value to the programs of both machines. For instance, the wide flexibility in divertor configuration in MAST-U will provide key information on the best divertor concept for a next-step spherical tokamak, whilst NSTX-U's unique ability to operate at sustained high-beta in high-field plasmas will assess the confinement scaling to extrapolate to the next-step ST. Similarly, the cryopumped divertor in MAST-U will allow NSTX-U to make comparisons of performance with real-time density control to inform later facility enhancements.

The PAC recommends the addition of either a cryopump or a faster implementation of a Li metal wall in NSTX-U for addressing the mission critical non-inductive sustainment goals of NSTX-U. The presently proposed means of density control are highly speculative and, indeed, previous experience on NSTX found very limited ability to influence density with some of the techniques proposed here. Density control is important to ensure the full range of high performance scenarios can be accessed, particularly for the optimization of fully non-inductive stationary discharges to arrest q profile evolution. It is also an important control parameter for collisionality assess transport and kinetic physics, as well as pedestal optimization. Cryopumping is the main effective proven technique for density control and could be part of the plan either for the recovery or soon after, perhaps pending an assessment of the benefits of lithium density control as a more attractive solution.

Finding: NSTX-U will both compete worldwide and complement the world program in ST research

During the recovery project the NSTX-U team performed experiments at other facilities that address NSTX-U research goals for guiding future operations, such as major collaborations at DIII-D with a dedicated run campaign and collaborations with MAST-U. These activities contribute to answering key science questions as well as maintaining world-class scientific expertise at PPPL. As a result, the research program at NSTX-U will benefit from these collaborations when the device operation restarts.

Improvements to the power handling of high heat-flux components in the divertor of NSTX-U will complement the flexibility in divertor configuration in MAST-U by assessing ways to exhaust power loads for an ST pilot plant. The ability to control the plasma density is key for the stable performance of ST plasmas and eventually for ST pilot plants. Density control by means of a divertor cryopump is being explored at MAST-U and this work provides a testing ground to assess its importance for NSTX-U. Moreover, with its Li-evaporation program, NSTX-U will be able to provide a direct comparison point to the MAST-U results.

The disruption mitigation system with prediction and avoidance tools at NSTX-U can contribute to mainline tokamak research programs. Other areas of notable contributions to the world-wide fusion research program are: (1) studies of super-Alfvenic fast ions with the incorporation of high quality diagnostics, theory and control tools, (2) real-time control tools at NSTX-U for plasma rotation or beta and (3) research in the understanding of electron transport at low collisionality in the core plasma.

Recommendations: The NSTX-U team should continue their scientific collaborations in order to prepare the start of NSTX-U operations, while maintaining a focus on specific research needed to preserve their world-leading position in the areas of disruption prediction/mitigation, electron transport, fast-ion driven instabilities and real-time control of non-inductive plasmas in ST's. These activities provide the opportunity to accelerate the proposed research program when operations restart at NSTX-U.

The PAC is concerned, however, about the termination of NSTX-U collaborations in the U.S., with all university and industry physics collaborations ending next month, and diagnostic collaborations due to expire in a year's time. This includes some highly expert world leading research personnel. A particular concern is the absence of a plan or recommendation from the NSTX-U management or FES on how to provide required expertise or manage this issue. The resumption of the NSTX-U research program will require a properly skilled scientific workforce. It is noted that once expertise is lost, or re-deployed to other facilities, it may not easily be recovered. Even if FES cannot commit the funds to this, at this time, **it is incumbent on the NSTX-U management to make and propose a plan for the maintenance of the scientific team and to ensure readiness and plans for eventual scientific operation of NSTX-U.**

It was also noted that the NSTX-U program appeared to divide the team between PPPL and non-PPPL participants, applying different work-structures and metrics to them. This contrasts strongly with the other national facility, DIII-D, where an integrated scientific management structure is adopted that makes no distinction between personnel origin, despite them being present under many different funding models and degrees of certainty. For example, if a collaborator status changes, then plans and personnel can simply be switched out to meet program goals. **It is recommended that the NSTX-U national facility should adopt an integrated scientific management of the facility.**

Further, the present uncertainty over funding of non-PPPL staff is causing extreme insecurity and concern amongst these scientific staff. At best, it seems certain that key experts will no longer be able to work on NSTX-U. This highlights the asymmetry between non-PPPL and PPPL staff, with the latter protected to some degree. This creates divisions within the team. The present approach seems to be to leave these issues to FES, but FES should be assisted with advice and plans from the NSTX-U management. And this advice should be balanced to consider PPPL and non-PPPL participants alike. **Thus, the NSTX-U management should regard themselves as custodians of the entire scientific team, not simply the PPPL personnel, and develop proposals for staffing plans that balance needs of PPPL and non-PPPL participants.**

Finding: The Recovery Project Management will help Expedite Return to Operations

The NSTX-U device experienced a series of technical problems; the most recent of which was the failure of one of the poloidal magnetic field coils, which has rendered the device inoperable and in need of significant repair. The causes of these problems are attributed to technical, operational, and procedural issues. As a result of these incidents, the Laboratory performed a comprehensive analysis of all of the systems on NSTX-U. This process identified actions needed to be taken to form a corrective action plan to ensure reliable and predictable operation. The Department of Energy (DOE) Office of Fusion Energy Sciences (FES) assigned a notable outcome to PPPL supporting this approach: Complete an extensive extent-of-condition review of NSTX-U to identify all design, construction, and operational issues. Prepare a corrective action plan (CAP) to include cost, schedule, scope, and technical specifications of actions.

Twelve Design Verification and Validation Reviews were conducted by external and internal scientists and engineers and focused on identifying issues associated with both the design of the systems and whether the as-built components will meet the design requirements to support operation. In addition, an external Extend of Condition panel examined the Design Verification and Validation Reviews and made recommendations on four high-level programmatic decisions regarding the inner poloidal field coils, limitations to the required bake out temperature needed for conditioning of the vacuum vessel, divertor and wall protection tiles, and coaxial helicity injection.

The PAC recognizes how PPPL has been under severe pressure to develop the Corrective Action Plan. The 17 reviews, over 1000 chits, and the 350-page action plan are a testament to the serious response to the problems. The PAC commends the team for their resilience, fastidiousness and continued enthusiasm in difficult circumstances. The breakdown of the recovery projects into key areas is clear, appropriate, and will help the effective management of the recovery. The PAC is encouraged by the implementation of the CAP to improve PPPL processes and management systems – this may be painful but is important in the long run.

Recommendation: NSTX-U staff should move ahead with speed to complete the recovery activities. It is now in a better position to execute its world leading scientific program. Following the completion of the Extent of Condition reviews, both design work and cost and schedule development were completed and reviewed.

Princeton University and PPPL have been fully committed to performing the Extent of Condition review in a thorough and transparent manner. The Extent of Condition review has served to identify important issues that, when addressed, will significantly improve the NSTX-U research facility and optimize the NSTX-U science mission

Finding: Liquid Metal Wall Research is Compelling

The PAC finds that liquid metal (LM) wall research is compelling for the world fusion community and is particularly unique among spherical tori. The use of LM PFMs has been flagged as a potential fusion energy relevant option in many high-level strategic planning reports – the latest being the 2015 OFES PMI strategic report, because they offer a potential self-healing surface that has immunity to thermo-mechanical stresses and resilience to neutron damage over most solid PFM options. Nonetheless, development of LM PFMs/PFCs in the world community is minimal and the TRL of this option is very low. NSTX and PPPL's long investment in LM, particularly using lithium, has shown benefits to both the plasma boundary (power exhaust solution) and core (higher energy confinement). In addition, lithium provides the only means of density control on NSTX-U, but it is doubtful full operating parameters (10 MW, 2 MA, 1T, 5s pulses) can be reached without the use of solid lithium wall coatings or the addition of a cryopump. PAC-39 therefore finds LM research with lithium a natural fit to the NSTX-U program and would like to see a clear plan to further this research and evaluate the use of LM for potential implementation in an ST Pilot Plant.

The current recovery project replaces the old NSTX PFCs with new graphite PFCs qualified to the high-power operating scenarios of NSTX-U and compatible with thin LITER-evaporated lithium coatings. However, high-Z PFCs will provide better lithium compatibility, can stabilize lithium flows under MHD forces, and may provide a potential tritium-compatible path forward to an ST Pilot plant.**The PAC acknowledges that graphite tiles may be needed to meet the near-term performance requirements of NSTX-U as a *user-facility*; however, this should not delay pilot-relevant PMI studies with lithium and high-Z walls.**

The addition of several rows of high-Z tiles in a high-performance ST can provide a useful PMI platform that also complements conventional aspect ratio devices with high-Z walls. In addition to studying mixed material transport and boundary physics in an ST, these tiles can also function as a substrate for liquid lithium. Such an enhancement will expand the utility of NSTX-U for conducting PMI research supporting any pilot plant in a DT environment. In the meantime, NSTX-U will continue to experiment with solid lithium coatings to mitigate ELMs and provide for better energy confinement.

Recommendations:

A more aggressive PFC development program on NSTX-U should be pursued. A phased approach beginning with the addition of several rows of high-Z tiles in the divertor is highly compelling. These tiles should be carefully designed and instrumented to accommodate potentially very high heat fluxes while minimizing damage (e.g. due to melted leading edges). They should also be used to study high-Z material migration in the ST configuration. Advanced spectroscopic and IR diagnostics will be required to view the tiles, and this must be coupled with divertor and SOL modeling to make NSTX-U an important platform for PMI research aimed at a future ST pilot plant. Such work is also complementary to on-going efforts at conventional tokamaks like DIII-D, EAST, and ASDEX Upgrade.

PAC-39 recommends Li PFM (and LM) research also continue during the intermediate period between now and the end of NSTX-U recovery by exploiting avenues of research on LTX-beta and/or EAST that inform, in particular, core-edge integration scenarios using these PFM methods.

Lithium deployment beyond LITER can begin with the lithium filled high-Z tiles that can replace the high-Z solid rows mentioned above. It is hoped that the lithium can enhance density control as well as improve confinement. **PAC-39 supports an accelerated schedule for the lithium-filled high-Z tiles.** This project will provide important performance data on density control and power handling using lithium. However, development of a flowing lithium system may be considered only if major improvements are made to the safety infrastructure supporting NSTX-U, e.g. complete removal of water from the machine and test cell.

It is requested, in the preparation for the next PAC meeting, that a study should be undertaken comparing the cost, safety and efficacy of a new divertor cryopump to the expanded use of lithium in the spherical torus. A decision can then be made on future directions concerning density control and whether the PMI research will focus on low-Z or high-Z walls. Regardless of the chosen PFC path, an accelerated, staged replacement of the base-line graphite tiles with high-Z tiles, or perhaps graphite tiles with high-Z coatings, is recommended.

Finding: Recent research by the NSTX / NSTX-U is of high quality and important

During the recovery project a number of NSTX-U scientists have continued to advance the ST concept through additional analysis of NSTX-U existing data and collaborations with other research facilities. These efforts have resulted in significant progress for ST research as well as providing insight for the broader toroidal magnetic fusion program. Highlights of this research include, though not limited to:

- Alfven instability induced energetic particle transport and control through collaborations with DIII-D and UCI
- Development of algorithms for NBI control of rotation and stored energy as implemented on DIII-D
- Development of Disruption Event Characterization and Forecasting (DEAF) as part of an international multi-device effort
- Study of ν^* scaling of confinement on conventional aspect ratio tokamaks for improved scaling towards NSTX-U and an ST Pilot plant
- Examination of electromagnetic micro turbulence scaling towards the high β expected in future STs
- Improved understanding of HHFW heating losses in the edge plasma through a collaboration with UCLA's LAPD linear plasma device
- Collaboration with MAST-U on the development of startup scenarios

Recommendations. While the NSTX-U staff research efforts during this down period have been productive and wide ranging, they could be better served by more clearly articulating how these results affect NSTX-U's future capability and research plan, as well as the overall ST pilot plant concept. In addition, before the NSTX-U restart, future research should be more focused on efforts that will directly benefit the NSTX-U and ST program. Some examples of this include:

1. The impact of recent NSTX-U pedestal stability and transport analysis on NSTX-U's projected non-inductive high beta scenario;
2. How improved understanding of kinetic effects on high beta stability affects aspect ratio optimization of a pilot plant;
3. Explore how the aspect low aspect ratio of NSTX-U could be used to examine the physics of divertor heat flux width scaling towards a pilot plant, and;
4. Exploit development of divertor configuration control concepts on MAST-U for use in control of NSTX-U divertor configurations

Comments: Scenario Thrusts and MHD

The unique parameters that can be assessed by NSTX-U rely on the development of plasmas scenarios above 1MA, up to a maximum of 2MA, and the sustainment of these plasmas for up to 5 seconds in (near) fully non-inductive conditions.

The initial operation of NSTX-U in FY2016 showed that rapid progress can be made towards non-inductive operation, rapidly equaling or surpassing results obtained previously in NSTX. More recently, results from collaborative experiment in DIII-D and MAST are outstanding and are preparing advanced scenario control for NSTX-U.

In the area of macroscopic stability, the attainment of regimes with high values of β_N/l_i and the analyses of these regimes that show that these plasmas are not necessarily more unstable is world-leading research. Excellent results were obtained on physics based disruption prediction/avoidance research (DECAF), with a wider relevance than just ST's, showing continued progress in the mission to obtain wall stabilized, high beta operation at NSTX-U. The requirements for an ST and unique research at NSTX-U were well defined in this area.

Recommendations:

1. Postulating the requirements for advanced scenarios at NSTX-U based on the ST mission goals and stipulating the challenges or issues that need to be addressed in the near future. A clear list of objectives for a research plan aimed at demonstrating non-inductive operation in NSTX-U should be developed, with clear milestones and steps of how these can be achieved within the first five years.
2. Emphasizing the uniqueness of the scenario development at NSTX-U with the aim of achieving non-inductive operation at higher toroidal field compared to previous results obtained at NSTX and planned for at MAST-U. Neutral beam heating levels above 10MW will give access to plasma conditions with a high bootstrap fraction. Combined with the unique neutral beam current drive capabilities and flexible deposition and control, this will provide a wide operational window for non-inductive operation. Operation at high input power will allow operation at higher plasma density compared to NSTX and MAST-U.
3. Highlighting the world-class, real-time measurement and control capabilities foreseen when NSTX-U restarts operation, which clearly benefit from the further developments of the control systems and results obtained from collaboration experiments during the recovery project. Emphasizing that the control system at NSTX-U incorporates a unique combination of real-time diagnostics, but also indicating what contributions could be made to control burning plasmas in general.
4. Focusing NSTX-U research on ramp-up and not addressing plasma formation scenarios, which can be done in collaboration with other experiments. Study the role of fast-ion transport in achieving sufficient current-drive, critical for the ramp-up mission.
5. Stipulating the research milestones for NSTX-U in the area of macroscopic stability and the disruption detection/avoidance during the first five years of NSTX-U operation.

Comments: Core Transport and Energetic Particle Studies

Understanding how plasma energy confinement behaves at low collisionality in spherical tokamaks is key to predicting the performance of future STs. The importance of this question is well reflected by the weight it is given in the NSTX-U research plan, which aims at understanding the underlying physics responsible for the transport. NSTX-U, with the highest magnetic field of any ST and flexible heating capabilities, will be in a position to exploit its unique operational space to address this question. Moreover, this research will benefit the broader fusion community by providing validation of drift-wave and electromagnetic instability theory. During the 2016 operational campaign NSTX-U already demonstrated the flexibility of its operational space, which lends itself directly to this goal.

During the Recovery Period the NSTX-U team, through their own efforts and their many collaborations, have done an excellent job on paving the way for the re-start of NSTX-U operations. In particular, the models of electron transport have been greatly developed in preparation of high-beta operation. These will help to guide experiments once operation re-starts and also provides the tools needed to understand and validate the experimental data. The development and use of these codes for electron transport applications is a prime example of cutting edge research by the NSTX-U team.

For the validation of the developed models NSTX-U will need to be prepared with a comprehensive suite of turbulence diagnostics. This need is being addressed by a combination of low- and high-k diagnostics including beam emission spectroscopy, far infrared scattering, Doppler back scattering, and cross-polarization scattering, which will provide a key measurement of the core magnetic fluctuations. This validation of the behavior of this quantity in high-beta plasmas will be a unique measurement to NSTX-U and will support our understanding of the stabilization of ion-scale modes in ST's.

In addition to its turbulence diagnostics, NSTX-U will also be well equipped with fast ion diagnostics, which coupled with the upgrade of the neutral beam injection system and HHFW, will place it in an ideal situation to study energetic particle physics with unprecedented control of the fast ion velocity space in an ST. The use of HHFW system in these experiments would enhance this capability even more. Results from the 2016 campaign, coupled with improved tools for the simulation of fast particles, demonstrate a potential path toward active Alfven Eigenmode control, which should be investigated and exploited after the re-start of NSTX-U. The improvement of the energetic modeling tools during the Recovery Period place the NSTX-U team in an improved position to understand and learn from the experimental data after restart. Moreover, the unique operating conditions (high fast ion pressure and super-Alfvenic ions) will allow NSTX-U to develop and validate models in a regime no other machine can access, and one that is particularly relevant to burning plasmas devices, which will produce significant intrinsic fast ion populations.

Recommendations:

1. Thorough investigation of low- and high-z impurity transport properties as a function of plasma rotation, ion temperature, electron density, and fast-ion velocity space distribution in preparation of the introduction of more relevant wall materials. Exploration of the use of RF

heating, 3-D fields and other actuators to control the impurity behavior is also strongly recommended.

2. The plan should include facility to explore turbulent transport and stability at reactor relevant rotation, to capture and explore the expected physics behaviors and turbulence characteristics of a pilot plant.
3. That the near term plans of characterizing the effects of complex fast ion distributions be broadened to include active control of those distributions combined with predictive model testing for the stabilization of Alfven Eigenmodes other instabilities that can lead to the loss of confined fast particles.
4. Specifying the energetic particle physics questions that are important for STs and a clear list of objectives that NSTX-U plans to achieve in the first five years.
5. Maintaining, if not improving, the capability of HHFW, as it is useful tool for core transport and energetic particle studies as it gives the ability to vary the ratio of Te/Ti and to tailor the fast ion velocity distribution. Moreover, RF heating may prove to be a vital tool for the control of high-Z impurity accumulation.

Comments: Pedestal Physics

The NSTX-U pedestal research program is critical for the success of NSTX-U as well as for the development of the ST concept. The pedestal exerts strong leverage on overall scenario optimization by broadening of both the pressure and current profile. Understanding the scaling of the pedestal profile will be necessary for projecting the performance of an ST pilot plant. NSTX-U has already highlighted aspects of ST pedestal characteristics that may be different from conventional aspect ratio tokamaks. Development of a predictive model for the ST pedestal and its implication for an ST pilot should become the focus of the NSTX-U pedestal research program.

Recent NSTX-U research efforts have documented several pedestal dependencies that appear to significantly deviate from standard aspect ratio tokamak data. These results should be expected to impact the development of NSTX-U and ST pilot plant scenarios. This data analysis has shown:

- Unique edge MHD stability with stronger dependence of pedestal pressure on triangularity and greater access to peeling (edge current) limited pedestal stability for higher pedestal operation at higher density.
- Stronger pedestal width dependence on pedestal β than the EPED model which accurately predicts pedestal width in conventional aspect ratio tokamaks. This data would suggest local transport instabilities other than KBM may be in play in STs.
- Significant widening of the pedestal with lithium injection and the subsequent reduction in recycling.

Recommendations: The NSTX-U pedestal research program is important and technically strong. However, the PAC recommends several actions for the pedestal program to strengthen the overall NSTX-U project and relevance to the wider toroidal magnetic fusion program.

1. In general NSTX-U pedestal research should be organized and articulated around the potential impact on NSTX-U and ST pilot plant operational scenarios. This includes the exploitation of unique ST edge stability space, unique ST pedestal turbulent transport and the impact of pedestal pressure on global stability and pedestal current on non-inductive scenarios. Presentations on NSTX-U pedestal research, particularly those justifying the program, should include this impact on the core scenarios as a more obvious part of the presentation.
2. Pedestal research should also be more tightly coupled with the core plasma transport research. NSTX-U has shown indications of important pedestal transport that is not KBM. Develop and present plans to leverage the increasing sophistication of core transport models for prediction of pedestal profiles. Any additional understanding of pedestal transport will reduce uncertainty in ST concept development and be of great benefit to the wider fusion community.
3. Exploit the use of lithium conditioning to examine the role of pedestal fueling from edge recycling on the pedestal density transport and resulting density profile. As well as the obvious impact on ST scenario development this is a critical and challenging issue for the wider fusion community. Any new insights would be welcomed. This research will likely require additional diagnostics and interpretive modeling. Develop a plan to address this issue.
4. The NSTX-U program should also highlight how it can examine issues of ELM control in STs. One of NSTX-U key physics goals is to investigate if the continued favorable low-collisionality confinement trends could lead to more compact ST reactors. The low collisionality and high pedestal pressure make ELM control critical. In particular, how ELM control affects pedestal characteristics in STs and in turn scenario performance.

Comments: Divertor Physics

The NSTX-U divertor physics research effort has recently focused on preparing for future operations at higher fields and power that may stress in-vessel components. This effort has resulted in a credible design of novel castellated PFCs that are expected to enable the full exploration of the proposed NSTX-U operational scenarios. The design is based on conservative estimates of divertor heat flux and disruption forces derived from international multi-machine scalings.

In presenting NSTX-U research plans it is understood that collaborations have played a large role in divertor physics research and that their future participation is uncertain. Nevertheless, the program should strive to develop a vision of how divertor research on NSTX-U can contribute to the ST concept and wider tokamak boundary solution. The PAC suggests the following topics can be emphasized.

1. NSTX-U can address how this critical factor of divertor heat flux width scales with aspect ratio. The local theoretical effort with the XGC suite of codes can be leveraged to determine diagnostic measurements and parametric scans that may provide insight into the underlying transport processes that result in our existing empirical scaling. Improved confidence in scaling would be of great benefit to the ST development program, but also to the wider fusion community.
2. The divertor research program should aim to integrate with the pedestal research effort to better understand divertor plasma compatibility with ST high performance core plasmas. Issues such as the required physical separation of detached divertor plasmas from the X-point can be

examined for differences from the experience of larger aspect ratio tokamaks. Pedestal density transport research will also require the expertise of divertor researchers for diagnostic and interpretive analysis of fueling from recycling. Impurity transport is also an issue critical for both topics.

3. Finally NSTX-U can provide valuable contributions to the wider fusion effort on developing boundary solutions for PFC heat flux and erosion control. This critical issue for fusion development will not be solved by any single facility. NSTX-U has complementary configurations, plasma conditions and diagnostics that are needed for developing a physics basis that can be applied to tokamaks of varying aspect ratio.