Report of NSTX Program Advisory Committee
(PAC-29)

January 26-28, 2011

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Committee Members Absent:
James W. Van Dam (University of Texas)
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1. Introduction

The NSTX Program Advisory Committee (PAC) held its 29th meeting at the Princeton Plasma Physics Laboratory (PPPL) during January 26-28, 2011. This PAC meeting follows the December 2010 DOE CD-2 approval for the NSTX Upgrade Project, which set the upgrade outage period to begin on April 2012 and end on September 2014.

This PAC meeting was charged to answer two questions regarding the NSTX research plan:

1. Do the proposed research priorities and milestones for the FY2011 and 2012 run campaigns exploit all feasible opportunities for new, major results prior to the Upgrade outage period? Further, do the priorities and milestones support needed preparation for the NSTX Upgrade?

2. Are the NSTX and NSTX Upgrade research plans well aligned with the OFES vision for fusion research in the coming decade? – a vision emphasizing 4 research themes: (i)

Plasma dynamics and control, (ii) Materials in a fusion environment and harnessing fusion power, (iii) Validated predictive capability, and (iv) 3D magnetic fields.

The NSTX Team presented their research plan to the PAC in 12 presentations over two days. These included a summary of accomplishments from the previous run period, a program overview including the schedule and plans for the NSTX Upgrade Project, and detailed descriptions of the experimental plans for eight topical science groups (TSGs). This PAC meeting occurred during a heavy winter snowstorm, which closed the lab for one day, and we are especially grateful to the NSTX Team for their extra effort to maintain the PAC schedule.

The PAC commends the NSTX Team for another very productive run period. NSTX completed all FY2010 milestones, including the Joint Research Target, on or ahead of schedule. Additionally, the highest weekly number of plasma shots (191 per week) was achieved during the 15.4 run-weeks as a result of improved plasma operations due to lithium conditioning. The NSTX Team published more than 50 peer-reviewed scientific articles, including four in *Physical Review Letters*, and presented ten invited talks at the APS-DPP Meeting and eight talks at the IAEA Fusion Conference in Daejon, Korea. Especially noteworthy was that half of the invited talks and journal publications were first-authored by non-PPPL collaborators. During the Closing Ceremony of the IAEA Fusion Energy Conference, the *Nuclear Fusion* Journal Prizes for the past two years were awarded. The 2009 Prize went to Steven Sabbagh (Columbia University) for his paper about record plasma beta values in NSTX and an analysis of Resistive Wall Mode stability. The PAC is also pleased to congratulate J.-K. Park for his 2010 Marshall Rosenbluth Award for Outstanding Doctoral Dissertation and for Drs. Steve Sabbagh and Jon Menard for their award of Fellowship in the APS.

The NSTX experiment also had numerous operational and scientific successes: the Liquid Lithium Divertor (LLD) was installed, the beam-emission spectroscopy (BES) diagnostic became operational, divertor diagnostics and supporting personnel were greatly enhanced, the successful demonstration of multi-state active feedback control to sustain high β_N discharges, the demonstration of energy-efficient coaxial helicity injection (CHI), the reduction of peak heat flux during "Snowflake" divertor studies, the important measurement of the scaling of the scrape-off-layer (SOL) width with I_p, both with and without lithium conditioning, the routine production of enhanced pedestal H-mode (EPH) discharges, and the good integration of divertor diagnostics with modeling and plasma material interaction (PMI) physics.

The PAC recognizes the success of the NSTX lithium divertor research program that has gained technical experience and also advanced our understanding of lithium as a plasma facing material. However, the use of the LLD as a future divertor for NSTX Upgrade remains uncertain. The LLD showed no increase of deuterium pumping as its surface temperature was increased above the lithium melting point. Experiments showed only small reduction in carbon impurity fraction and the plasma density did not become stationary. Because of the importance of divertor issues to the next NSTX-U five-year plan, the PAC offers several near-term and long-term suggestions. These are:

- The NSTX Team should install the full complement of inner-divertor molybdenum tiles before the next run period and devote sufficient run time and research effort to evaluate the impact of the tiles, both with and without Li deposition.

- Before deposition of Li, the PAC recommends re-establishment of an ELMing H-mode baseline with boronized carbon (and Mo) plasma facing surfaces. The purposes of these experiments are (i) to observe density and impurity control with more conventional ELM-regimes and plasma material interactions, (ii) to contrast and better understand the impact of Li in NSTX, and (iii) to provide discharge performance characteristics that will inform your divertor planning for the NSTX Upgrade.

- During these pre-lithium runs, take the opportunity to demonstrate two-feed antenna, full-power HHFW heating and demonstrate the compatibility of HHFW with NBI and your NSTX Upgrade discharge targets.

- Since a primary focus of the NSTX Upgrade five-year plan must be the demonstration of stationary, high-performance, non-inductive spherical torus (ST) discharges that will inform next-step fusion development choices, the PAC suggests the NSTX Team launch a serious cyropump and divertor geometry design study and develop an alternative to insure against uncertainties associated with the use of any next generation LLD in the NSTX Upgrade.

Finally, in time for the PAC-31 meeting, the PAC asks that the NSTX Team describe their planning for the post April 2012 outage activities including design and scoping studies for the upgrade project, planning for start-up and initial discharges, and longer-term discharge scenarios needed to achieve the project goals. The PAC sees an opportunity to optimize how personnel will be assigned, how collaborators will contribute, and how best to use the many experts on the NSTX Team to continue ST research and maximize preparations for the Upgrade.

In the remainder of this report, the PAC presents answers to the two specific charge questions and makes several observations and recommendations pertaining to the eight topical science groups (TSGs) and research thrust areas.

2. Specific Comments Pertaining to the Two Charge Questions

The PAC makes the following comments pertaining to the two charge questions.

1. *Do the proposed research priorities and milestones for the FY2011 and 2012 run campaigns exploit all feasible opportunities for new, major results prior to the Upgrade outage period? Further, do the priorities and milestones support needed preparation for the NSTX Upgrade?*

   The PAC endorses the NSTX research priorities and milestones for the upcoming run period and supports your emphasis on boundary physics, edge turbulence, pedestal, and divertor physics studies. Since our PAC meeting precedes the March 2011 date for the NSTX Research Forum, the PAC expects sharper focus on a limited number of high-priority experiments will occur based on input from the Forum. We urge the NSTX Team to make sure that the most important physics areas are investigated thoroughly instead of investigating many areas with less focus.

Regarding preparation for the Upgrade, the PAC endorses plans to emphasize divertor physics, the study of upper-null Snowflake, and the installation and study of Li-coated molybdenum tiles. Additionally, because of uncertainties associated with impurity accumulation, the PAC recommends the next run period include studies that inform your divertor planning for the Upgrade. These could include: (i) exploration and development of ELMing H-mode discharges with and without Li deposition, (ii) studies of impurity transport and confinement, and (iii) further investigations of impurity control techniques, like central electron heating and divertor gas puffing.

Finally, the PAC reinforces your plans to give priority to measurements and experiments that will become excluded in the post-upgrade configuration. These include experiments using the high-k_r microwave scattering diagnostic and scaling experiments to very low aspect ratio.

2. *Are the NSTX and NSTX Upgrade research plans well aligned with the OFES vision for fusion research in the coming decade? – a vision emphasizing 4 research themes: (I) Plasma dynamics and control, (II) Materials in a fusion environment and harnessing fusion power, (III) Validated predictive capability, and (IV) 3D magnetic fields?*

   The PAC views the NSTX research plan as appropriately aligned with the new vision that has emerged from DOE/OFES. NSTX has significantly advanced and will continue to advance our understanding of plasma dynamics and control, validate predictive capability of our models of plasma dynamics and transport, help to determine the optimal level of 3D magnetic field in toroidal magnetic traps, and contribute to next-step efforts, like various Fusion Nuclear Science Facility (FSNF) or Component Text Facility (CTF) concepts, that will investigate fusion materials and components.

   The PAC believes a high priority goal of the present NSTX research program is to build confidence in the capabilities of the upgraded NSTX facilities. Similarly, the PAC believes one high priority goal of the NSTX Upgrade Program should be to determine the credibility of the ST as a next-step FNSF or CTF. The contributions from NSTX to each of the four OFES vision areas should be guided, in part, by the need to resolve key "gaps" concerning the effectiveness of the ST configuration in future fusion devices. The PAC particularly endorses the long-term goal to demonstrate non-inductive, stationary, and high performance ST discharges in the NSTX Upgrade.

3. Comments and Suggestions Pertaining to Topical Science Groups

In addition to the observations and comments related to the specific PAC charge, PAC members have reviewed the plans for each of the Topical Science Groups. Specific and technical comments have been prepared for each Topical Science Group, emphasizing the upcoming FY 2011-2012 run period prior to the start of the Upgrade outage.

3.1. Boundary Physics

As in the previous year, the NSTX team provided separate presentations on general boundary physics and lithium-coated divertor operation and physics. Our PAC report follows this same division, though some obvious overlap will occur owing to the strongly linked nature of the topics.

The accomplishments of the Boundary Physics group during this last year are very impressive. Many scientific papers have been published with at least three *Physical Review Letter* publications in the boundary area.

The recommendation by last year's PAC that the boundary increase the number of personnel has resulted in more than five new postdocs, researchers, and students working on some aspect of boundary physics, with three visiting researchers planned to participate from ASIPP in China in FY11-12. The group was very responsive to the FY10 JRT on divertor heat-flux width scaling, coordinating the experimental planning between Alcator C-Mod, DIII-D, and NSTX, providing important NSTX data using the infrared camera, and coordinating the final report to OFES. They are also strongly involved in the FY11 JRT on pedestal structure, which began in Oct. 2010.

The heat-flux reduction capability of the Snowflake divertor has been demonstrated for a wider range of discharge conditions and associated transport modeling has begun. In order to control the influx of carbon, studies have been performed to understand the effect of the timing of a fueling gas-puff, where early fueling may limit high divertor plasma temperature and thus sputtering; clarifying work on divertor plasma parameters and impurity generation/shielding is needed here. The enhanced H-mode $H_{95} \sim 1.7$ has been shown to depend on the toroidal magnetic field at the X-point with a possible explanation of ion orbit loss sensitivity to this field strength. Especially notable edge diagnostic improvements include eight additional edge Thomson scattering channels prepared for installation in FY11, improved soft X-ray measurements for edge impurities, and BES for edge and core turbulence.

As the NSTX Team looks forward to the next two years before the NSTX shutdown for the upgrade, the PAC believes a number of issues deserve high-priority attention. Some of these topics are mentioned in the FY11-12 milestones (see above), but even those are worth listing again.

- Develop effective strategy for particle control, *e.g.*, perform a serious cryo-pump design study

- Interpretation of plasma/material interactions (pumping/heat-flux), in the presence of mixed-materials (C, Mo, Li) (R12-1)

- Identify/characterize impurity sources (spatial/temporal) and determine SOL/edge screening efficiency, including clarification of the divertor plasma characteristics and impurity generation mechanism; consider ELMing vs. ELM-free for impurity control

- Consider performance of “conventional” divertors as backup to advanced Snowflake or Super-X configurations. For all divertor options, examine impact of divertor geometry for pumping and heat-flux control, *e.g.,* open vs closed divertor and tilted divertor plates.

- Obtain measurements of n_e, T_e, and T_i in the divertor and the midplane, though T_i is most challenging; include mean and fluctuation levels for assessment of importance of turbulent or “blobby” SOL transport (repeated from last year). These investigations will help to understand divertor heat-flux-width scaling and if there is any transport mechanism specific in the ST plasma.

- Clarify the nature and implications of Li reduction of heat-flux width, λ_q; is this reduction due to a sheath-limited SOL? What are the implications for divertor power handling with a Li divertor for the Upgrade with higher power and longer pulse length? In addition, determination of the power balance in the divertor (exhaust power from main plasma, radiation loss power and target heat load) is desirable.

- Establish pre-lithium baseline discharges with boron (Snowflake, Mo tiles, HHFW)

- Provide data and participate in comparison with theory/simulations including neoclassical and turbulent transport in the edge/SOL.

- With the new installation of Mo tiles on the inner divertor, and reuse of the Mo trays on the outer divertor, it is desirable to initially obtain baseline discharges without lithium evaporation (but with boron conditioning) and then move to lithium coatings. In all cases, measurements should be made of Mo influx in the divertor and edge/core, as well as plasma parameters in the divertor and edge.

3.2. Lithium and Divertor Physics

We commend the substantial increase in PMI science capabilities in NSTX, including (i) suite of excellent diagnostics: MAPP, heat flux, divertor spectroscopy, *ex situ* analysis, and (ii) rapid ramp- up of students and collaborators.

NSTX can rightly claim to be in the worldwide lead for lithium PMI in major confinement devices. While the performance of LLD was a disappointment, we note that NSTX has the tools in place to properly assess the PMI science of what did and did not work, and what is the correct way to move forward for both Lithium enabling capabilities in NSTX extending to a possible FNSF or CTF in the future.

Given the present evidence, we agree with the NSTX strategy to install Mo tiles but this must be properly integrated into the entire run plan to provide several go/no-go decisions on Upgrade. These include (i) assure proper mechanical installation/alignment, (ii) cleaned Mo surfaces, even if it takes dedicated runs, (iii) optimized lithium deposition rates (*e.g.* ~ 0.1–1 micron), (iv) thermography, recycling, MAPP, and material mixing. Make diagnostics and quantitative assessment of Li/Mo/C PMI critical to this campaign.

NSTX is not ready to make a key programmatic decision about developing a more aggressive LLD (*e.g.* true liquid filling in capillary). Experiments to date using the LLD were probably not a true test of the full potential of liquid Li PFC. But weak-to-null results makes it too risky to the overall NSTX strategic decision to push forward. This necessarily reduces the immediate impact of NSTX towards use of lithium as a next- step PMI surface. A more definitive test of clean- as-possible liquid lithium test on the new inboard divertor Mo (and LLD) as outlined above is timely to this critical programmatic decision.

Given the central role of PMI to the NSTX/ST program, continue the investments and upgrades to PMI science capabilities in Upgrade regardless of the divertor path selected. These include divertor Thomson scattering, material probes, investigations of the Snowflake at small angles between the magnetic field and divertor surface, and similar research tasks.

3.3. Macro-stability Research

The NSTX program continues its influential role in the international macroscopic stability program. The program in RWM studies is particularly notable for its international leadership. During the past year, the group has made significant advances towards low-l_i, high β_N operations. The demonstration of ELM triggering by RMP and of the effects of current ramps on plasma response have provided a useful perspective on the effects of RMP. Validation of kinetic MHD theory is laying the foundation of a unified picture of RWM and building confidence in extrapolations to NSTX-U and ST applications.

We find that the stability research is well aligned with OFES and ITPA priorities. The group has also been responsive to the recommendations of PAC-27, participating in experiments establishing the dependence of NTM threshold on the ion banana width. It has also contributed to the validation of models for the Rutherford equation by providing data on the role of the curvature term.

We believe that an unusually good interaction between experimentalists and theorists has played an important role in enabling the success of the Macroscopic Stability program and, in particular, in building the basis for confident extrapolations to future devices. We congratulate J.-K. Park on his early career award and express our strong support of the plans to extend IPEC to include resonant-layer physics.

We encourage the group to explore further the commonalities between RWM and RMP physics, in particular as regards kinetic effects on the plasma response. We approve of the plans for NSTX to address ITER-relevant questions relating to the forces during disruptions, and encourage the group to give these experiments suitable priority before the shutdown.

3.4. Turbulence and Transport

The position of NSTX for studying turbulent transport has been strengthened thanks to the first BES and SXR measurements achieved in 2010. Also a new Frequency Modulated Continuous Wave (FMCW) reflectometer has started operation. These new tools complement the existing set of diagnostics, in particular high k microwave scattering measurements. This comprehensive set of diagnostics has been very useful to clarify a number of issues. It is highly recommended that this set be fully exploited during the next 2 years, before the outage and removal of the high-*k* scattering diagnostic.

Several important results have been found in 2010. Dedicated experiments have shown that the level of high-*k* fluctuations decreases with collisionality, whereas the confinement is known to degrade with collisionality on NSTX. On the other hand, non-linear gyrokinetic simulations indicate that the electron diffusivity driven by microtearing modes does increase with collision frequency. Hence microtearing turbulence appears to be a serious contender for explaining electron transport in NSTX plasmas. Nevertheless other observations indicate that ETG and GAE may play some role in the confinement. Therefore the PAC encourages the NSTX team to pursue its investigations to clarify the relative role of microtearing, GAE and ETG modes. The combination of low and high k fluctuation measurements will certainly be useful in that matter. Regarding this point, the PAC was very pleased to see that the NSTX team is making progress in designing a new high-*k* diagnostic, which will replace the present one in FY 13 or 14.

The NSTX team has also made progress in the understanding of mechanisms underlying the L-H transition and its interplay with the core. BES and FMCW measurements show a fast decrease of the level of fluctuations in the edge, followed by a slower decay in the core. Also it appears that the L-H power threshold is sensitive to the major radius at the X-point, in accordance with predictions of the XGC0 code. Among the various unresolved issues, one may quote the large difference in the level of fluctuations that is observed with and without Li, the dynamics of the L-H transition and its propagation to the core, and the conditions for the onset of the EP H mode. These issues certainly deserve some attention, given the central importance of this topic for MFE. The PAC endorses the vigorous plan that is envisioned to clarify these points.

The PAC congratulates the NSTX team for its findings in the field of momentum transport, in particular the edge localisation of the intrinsic torque. The determination of means to control rotation appears to be a sound objective given the importance of the subject for ITER.

Progress on impurity transport is also noticeable. This is an important issue in view of long pulse operation on NSTX. Preliminary measurements using the new SXR diagnostic are encouraging. This activity should be amplified in order to assess impurity transport in the core. Molybdenum should be given special attention, as it is a possible choice for divertor tiles. Also the PAC recognizes the effort that has been done to develop techniques for controlling the impurity content, in particular ELM triggering, unfavourable ion ∇B direction and Snowflake divertor. The PAC encourages the NSTX team to pursue and amplify this activity. The use of HHFW for controlling impurities in the core should be further investigated.

The strengthening of the interaction between theoreticians and experimentalists is visible through the extensive use of comprehensive modelling tools to model turbulent transport. The involvement of theoreticians to prepare and exploit experiments on NSTX appears to be fruitful. Also the PAC has noticed the strong involvement of other U.S. and foreign laboratories, in particular for the development of turbulence diagnostics. As in the past years, the PAC encourages the NSTX team to pursue its effort in that direction.

3.5. Wave-Particle Physics: Energetic Particles and HHFW

This TSG investigates wave-particle physics and separate recommendations are made for energetic particle physics and high harmonic fast-wave (HHFW) heating.

Energetic Particles

The PAC felt that significant progress was made in energetic particle research during 2010. The NSTX Team continues to exploit a combination of unique capabilities / opportunities in this area: A neutral beam injection (NBI) system that can produce fast ions (with $V > V_{Alfven}$) in high beta NSTX plasmas, and an array of diagnostics to diagnose Alfvénic instabilities such as FIDA, ssNPA, the new Scintillator Fast Ion Loss Probe (sFLIP), BES, and an upgraded reflectometer system. Furthermore the NSTX Team has taken advantage of a suite of sophisticated MHD codes that are available locally such as the linear kinetic MHD NOVA-K code, the non-linear M3D-K code, the powerful nonlinear HYM code, the ORBIT code, and the full-orbit following particle code SPIRAL. Using this array of diagnostics and simulation capability they have made impressive progress in establishing the connection between enhanced thermal / fast ion losses and Alfvénic instabilities. Evidence of fast ion redistribution by Global Alfvén Eigenmodes (GAE's) was obtained using the upgraded reflectometer system with 4× the spatial resolution and coverage, where GAE avalanches appear to trigger TAE bursts. The NBI system was also used to trigger large TAE avalanches, which resulted in up to a 30% enhancement in fast ion losses. Finally the HYM code was used to simulate the frequency and mode number spectra of edge localized Compressional Alfvén Eigenmodes (CAE's) and core localized GAE's. Good agreement was found with experiment for both the GAE and CAE mode structures with poloidal mode numbers, $m \sim 1–3$ and $m \sim 8–10$, respectively.

The PAC agrees with plans of the Wave-Particle Group to continue to validate simulation capability in this area, as this will aid assessment of fast ion losses for NSTX-U. In particular we think it is important to pursue eigenfunction modeling with the HYM code using GAE experiments, comparison of non-linear M3D-K against experiment (mode structure, bursting and chirping behavior), and extend the NOVA-K + ORBIT simulations to include the use of the SPIRAL code. The PAC recommends this validated simulation capability be applied to H-mode plasmas in both NSTX and NSTX-U, especially considering the effect of redistribution of NBI ions due to MHD activity on current profiles in the Upgrade. Because of the increased toroidal field range in NSTX-U, we note that it may be possible to explore the transition regime between $V > V_{Alfven}$ and $V < V_{Alfven}$.

High Harmonic Fast Wave Heating Physics

Significant progress was made in the high harmonic fast wave heating (HHFW) area in 2010 despite degraded antenna performance due to increased lithium usage. In particular, RF only H-mode plasmas were produced with $T_e(0) \approx 3$ keV, $P_{RF} = 1.4$ MW, $I_P = 300$ kA, $I_{RFCD} \approx 85$ kA, $I_{BS} \approx 100$ kA and $f_{NI} \approx 60\%$. These results are extremely encouraging in that they extrapolate to fully non-inductive plasmas (at 300 kA) using $P_{RF} \approx 3$ MW, which is well below the arc-free power limit of the antenna straps. We are interested in knowing if this extrapolation leads to an MHD stable current profile. We also commend the use of state of the art simulation capability in this area. Good agreement was obtained between simulated and measured FIDA signals using the fast ion distributions from coupled AORSA and ORBIT RF simulations of HHFW-fast ion experiments. These simulations included the effects of ion finite orbit width (FOW) and demonstrated the importance of this effect in obtaining agreement between simulation and experiment. Especially impressive were the 3-D AORSA full-wave simulations with the 2-D NSTX wall boundary that reproduced the experimentally observed dependence of surface wave excitation on toroidal field (B_ϕ) and toroidal wavenumber (k_ϕ) in HHFW experiments.

In the upcoming experimental run period it is highly recommended that baseline antenna operation with boronization be carried out before the start of the lithium campaign, thus providing information on performance of the upgraded antenna system in the absence of lithium. This will allow a more direct comparison to pre-reconfiguration performance. Production of RF + NBI H-modes at higher plasma current should be done to establish their feasibility and assess the level of parasitic losses in combined HHFW-NBI experiments. Also, observations of density pump-out in H-mode plasmas should be pursued to determine if this is a carbon pump-out effect or not. In light of the fact that the magnetic field for the Upgrade will be 1 T and the harmonic resonances will be correspondingly lower, it is again recommended that the NSTX Team revisit the absorption and propagation physics of HHFW in NSTX-U. We encourage them to use the AORSA+ORBIT RF simulation capability to assess HHFW-NBI interaction at lower harmonic number in these plasmas and to use 3-D AORSA simulations to assess surface wave excitation, accounting for any differences that are expected in the scrape off layer plasma of NSTX-U

3.6. Solenoid Free Start-up and Ramp-up

Start-up and ramp-up of the plasma current without the use of a central inductive solenoid remains a critical issue for the development of the ST. The NSTX program has a well-defined scenario using a staged sequence. First, transient coaxial helicity injection (CHI) is used to form the plasma and drive several hundred kA of plasma current. Second, the high-harmonic fast wave (HHFW) system is then used to heat the plasma and increase the current by bootstrap current over-drive. Lastly, when the plasma current reaches 500 kA, neutral beam injection is added to further heat and ramp the bootstrap current. The CHI and HHFW stages are still in development separately, which is appropriate given the technical challenges for each. The PAC encourages experiments that remain focused on CHI and HHFW separately rather than trying to integrate the two steps at this point. This will make better use of limited run time and allow better understanding of the physics and technical challenges for each process.

Several key advances in CHI operation were achieved in 2010. The current produced by the combination of transient CHI and subsequent inductive ramp-up achieved a record current, with reduced transformer flux usage. The “absorber” coils were utilized to suppress arcing, helping maintain higher quality plasmas. Operation with lithium injection also seems to help improve plasma quality. The NSTX team addressed a PAC-27 concern that the upgrade called for the removal of the absorber coils. The CHI experiments in 2010 not only showed the effectiveness of these coils, but the upgrade design has been modified to maintain this capability. Further, the designed coils will be even more flexible than those presently installed. The PAC is also pleased to see that TSC modeling has been performed not only to better understand ongoing experiments but also to project the current with higher toroidal field as will be provided in the upgrade. The projected larger plasma current could be helpful to simplify the start-up and ramp-up scenario.

Further TSC modeling in support of ongoing experiments is encouraged. The PAC is also very pleased to see the new collaboration on NIMROD modeling of the CHI process. This is very likely to yield a reliable physics basis that includes the dynamics of plasma relaxation.

The planned experiments for transient CHI emphasize more delivered energy, further optimization of the absorber coils, and full use of lithium injection capability during CHI. The PAC agrees with this strategy. We urge that more complete diagnosis of CHI plasmas be high priority in these experiments. It is clear that data such as Thomson scattering profiles have been essential to understand how CHI works. The NIMROD work will provide a theoretical context for which more complete data will be needed for validation. The approach used for understanding spheromak plasmas on the SSPX experiment is an excellent research model that can be replicated on NSTX. The PAC also notes that the milestone calling for an assessment of confinement in CHI plasmas means that complete diagnosis needs to be implemented as soon as possible. This will also better expose the unique qualities of CHI plasmas, such as the ability to attain low density. Understanding these plasmas could have a broader impact on NSTX operation and particle control. The PAC agrees that the NSTX plan for adding molybdenum tiles on the inboard divertor will be interesting for CHI experiments, as this will provide a metal cathode surface that seemed to be preferred in HIT experiments. The PAC urges measurements of impurity content in the core to assess quantitatively the effect of the plasma-electrode interaction, which may lead to high-Z impurity production.

Significant progress on non-inductive sustainment using HHFW was made in 2010, despite the limited operation of the antenna associated with large amounts of lithium use. About 60% non-inductive sustainment was achieved in 300 kA discharges using 1.4 MW of HHFW. This allows a projection of about 3 MW required for full sustainment, which is within the HHFW system's capabilities, but leaves little extra power for achieving bootstrap current over-drive (4 MW total available). The PAC recommends maintaining a focus on non-inductive sustainment in steady current conditions to optimize HHFW, which has a number of issues discussed above in section 3.5. Here we emphasize the importance of HHFW experiments early in the campaign before large amounts of lithium are used to facilitate high power antenna operation with the modified antenna-grounding scheme.

The PAC continues to support NSTX's collaboration with the DIII-D group on outer poloidal-field-coil (PF) start-up. We also agree that a test in NSTX of the plasma gun helicity injection method as developed by the Pegasus group would be highly valuable to complete before the upgrade outage begins.

3.7. Advanced Scenarios and Control

The PAC notes significant progress on several fronts towards integrated high performance plasmas in preparation for NSTX-U including: (i) validation of current drive predictions in ST plasmas, (ii) demonstration of new shape control capabilities, including simultaneous X-point height and strike-point position control and outer squareness control, (iii) production of long pulse, high performance plasmas at aspect ratio/elongation expected in NSTX-U, (iv) demonstration of the compatibility of Snowflake divertor and high operation, and (v) improved documentation of the enhanced pedestal H-mode (EP H-mode), which looks to be a potential path to high confinement operation.

Regarding plans for the upcoming run period, the PAC believes the control research plan is appropriate based on near-term needs. In the area of scenario development, the PAC suggests a balanced approach between the searches for a low-fueling/low core impurity ELM-free H-mode solution with the development of non- ELM-free scenarios for impurity/ density control.

During the upcoming operating period prior to the outage, the PAC recommends that experiments emphasize experiments that will form the basis for rapid exploitation of the new tools to be available in NSTX-U. The emphasis in scenario development research should continue to focus on techniques for long-pulse density and impurity control including exploration of non- ELM-free H-mode scenarios. Additionally, increased emphasis should be placed on determining the compatibility of HHFW (in particular plasma-antenna gap) and long-pulse, high power NBI. Near-term EP-H mode experiments should focus on operation space and control methods for achieving this regime more reliably.

The PAC recommends the NSTX team take steps to reduce the uncertainties with regard to long-pulse, high performance operation on NSTX-U. In particular, the NSTX Team needs to develop a path forward for density/impurity control in high-performance plasmas. While the proposed increased coverage of Li/Mo may be successful in suppressing the density/impurity buildup, the PAC notes that the results obtained to date in NSTX are very reminiscent of ELM-free H-mode operation in conventional aspect-ratio tokamaks, which have essentially abandoned this operation regime because of the uncontrolled density/impurity buildup. In this regard, the PAC recommends that the NSTX team begin to evaluate other options for density control in NSTX-U including divertor cryopumps and non- ELM-free H-mode scenarios.

Additionally, the PAC recommends detailed modeling of non-inductive capability in NSTX-U. Results presented at this PAC indicate that the most favorable experimental case (*i.e.*, with high β_p, high q_{95}) achieved ~ 50% bootstrap current. Separate calculations indicate that off-axis NBI will provide ~ 350 kA @ 6 MW. Simple current drive balance suggests that the maximum plasma current in which fully non-inductive current drive could be obtained is ~ 700 kA. Scenario modeling with realistic transport models should be done to determine the expected limitations.

3.8. ITER urgent needs, Cross cutting and enabling

The PAC welcomes the initiation of this new TSG recommended in PAC-27 to coordinate the research toward ITER and NSTX-U that cuts across the different TSGs. Work in this TSG has already begun to address the most important cross cutting and enabling issue for the NSTX-U, namely the particle and impurity transport. For the upgrade scenarios with stationary density with $n/n_G < 1$ need to be demonstrated. With respect to ITER the issue of pedestal and SOL transport and turbulence in the presence of 3-D magnetic field perturbations was identified to be the highest priority and NSTX is well equipped to contribute to this work. Indeed the demonstration of ELM pacing in otherwise ELM free discharges using short bursts of magnetic perturbations was a great experimental achievement and the PAC commends the NSTX team for this. Here, the new aspect was the pacing of the ELMs, since ELM triggering with 3-D perturbations was observed on other devices much earlier. This method has also shown potential to control the carbon accumulation by flushing out edge impurities. Also the performance of the Snowflake divertor showed potential to ameliorate the problem. However, despite the considerable effort the team has directed towards this task so far this none of this research has lead to stationary discharges and particle/impurity control remains the most pressing issue for the exploitation of NSTX-U.

As the use of neither liquid (LLD) nor solid lithium (LiTER) so far did provide the much needed solution to the particle/impurity accumulation problem in the ELM free high performance discharges the PAC encourages the team to research more conventional fallback solutions such as stationary type-I ELMy H-mode or small ELM regimes together with a cryo-pump alongside the more experimental solution (liquid Li, Li dropper, Li pellets etc.). These ELMy H-modes fit well into the coordinated ELM research identified as priority for the TSG. Indeed, a combination of the different methods (LiTER, LLD, Snowflake, ELM pacing, low density CHI start-up) with the right balance may provide the final solution that allows a confident extrapolation towards NSTX-U long pulses.

In this context, the PAC agrees that the installation of Mo tiles at the inner divertor to serve as a possible substrate for a liquid Li PFC remains a high priority in order to allow for an informed decision about the PFC material in the upgrade. However, it is important that if technically possible full toroidal Mo coverage is provided, and enough time is devoted to characterizing the PFC choice. Here, it is important to allow for comparison discharges on clean as well as boronized C and Mo surfaces before the first Li evaporation. The PAC also recommends quantifying the wall pumping with and without Li (solid or liquid). This should be compared to studies of possible cryo-pump performance in different divertor geometries as conventional fallback solution.

In previous years NSTX has strongly contributed to addressing urgent ITER needs (e.g. vertical control). Although, the investigation of the effect of 3D fields on the pedestal and SOL transport and turbulence is a key issue for ITER and NSTX has a good set of diagnostics and actuators to investigate this, other devices (AUG, DIII-D, MAST) are better positioned to study this physics due to their off-mid plane coils and better variability of the perturbation spectrum. Nevertheless this is important research and the NSTX team has not only the experimental capability, but also the theoretical expertise to progress this area. Nevertheless, the PAC feels that the NSTX team should also consider strongly contributing the following other urgent ITER needs:

1. Contribution to a new disruption DB including conventional and advanced scenarios and heat loads on wall/targets.

2. Understand the effect of ELMs/disruptions on divertor and first wall structures.

3. Improve understanding of SOL plasma interaction with the main chamber.

4. Predict ELM characteristics and develop small ELM and quiescent H-mode regimes and ELM control techniques.

These areas provide a large overlap with the NSTX-U needs. In the case of disruptions (items 1, 2) a characterization of halo currents, toroidal peaking factors and first wall heat loads is important since disruption forces in the upgrade will be much higher than in the current device.

Also the NSTX team should work on viable ramp down scenarios to avoid disruptions in the first place. With respect to (items 2, 3) emphasis should be given to the characterization of impurity and particle sources.

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