Report of NSTX Program Advisory Committee
(PAC-31)

April 17-19, 2012

Committee Members Present:
Jean Paul Allain (Purdue University), remote participant
Clemente Angioni (IPP, Garching, Germany)
Nobuyuki Asakura (Japan Atomic Energy Agency)
Houyang Guo (Tri Alpha Energy, Inc. and IPP, Hefei, China)
Donald L. Hillis (Oak Ridge National Laboratory)
Michael E. Mauel (Columbia University)
Hendrik Meyer (Culham Centre for Fusion Energy, UK)
Thomas Rognlien (Lawrence Livermore National Laboratory)
John S. Sarff (University of Wisconsin) – Chair
Mickey Wade (General Atomics)
François Waelbroeck (University of Texas)
Randy Wilson (Princeton Plasma Physics Laboratory)
Dennis Whyte (Massachusetts Institute of Technology), remote participant

Ex-officio:
John Mandrekas (Fusion Energy Sciences, DOE)
Jon Menard (Princeton Plasma Physics Laboratory)
Masayuki Ono (Princeton Plasma Physics Laboratory)

Committee Members Absent:
Paul Bonoli (Massachusetts Institute of Technology)

1. Introduction

The NSTX Program Advisory Committee (PAC) held its 31st meeting at the Princeton Plasma Physics Laboratory (PPPL) during April 17-19, 2012. The NSTX program has transitioned from normal operation to a multi-year NSTX-U upgrade outage period. As had been explained to the PAC at its 30th meeting by teleconference, the NSTX toroidal field coil failed in July, 2011. Soon thereafter the decision was made to begin the Upgrade earlier than originally scheduled, but to keep the duration of the outage the same so that NSTX-U operations could also begin sooner than scheduled. The NSTX program has also begun preparations for a new 5-year research proposal for FY 2014-2018.

The PAC was asked to answer the following questions:

1. Are the planned NSTX-U team science activities appropriate during the Upgrade outage?
    a. Comment on progress toward research milestones
    b. Comment on the NSTX-U team plans and preparations for collaboration with other facilities to prepare for NSTX-U operation and contribute to fusion science generally.

2. Are the plans, preparation, and progress for the next 5 year plan strongly supportive of the NSTX-U and FES missions? Consider two time periods:
    a. Initial operation of NSTX-U, i.e. the first 1-2 run years
    b. Longer term, i.e. years 3-5 of NSTX-U operation = later stages of 5 year plan

The NSTX Team presented their research plans in 12 presentations over two days. These included a summary of results and analysis of NSTX data, a program overview that described plans for FY 2012-2014, collaborations, and planning for the 5-year research proposal for FY 2014-2018, a status report on the NSTX-U upgrade project, and research plans for eight Topical Science Groups (TSGs). The PAC thanks the NSTX Team for their effort in preparing comprehensive and informative presentations.

The PAC commends the NSTX Team for another productive year. Despite the failure of the toroidal field coil, a shorter run period of 4.2 weeks yielded 839 shots at an NSTX record rate. The publication rate and number of invited presentations at major plasma conferences has been maintained at a high level. It is impressive that five young researchers now working on NSTX have received Early Career Awards.

While there is substantial progress in all areas of NSTX research, the PAC is particularly impressed by the progress and breadth of the advanced scenario and control modeling. This modeling is clearly providing valuable guidance not only for NSTX-U projections but for current NSTX research as well. Below we indicate a few important scientific results reported this year, not intended to be exhaustive, rather only indicative of the program's achievements:

- Improved theoretical understanding of micro-tearing instability and its role in governing heat transport, which complements growing experimental evidence
- Further increase in energy confinement with lithium evaporation; this improvement is not yet saturated
- Identified the role of oxygen in increasing deuterium retention for a lithium-graphite surface
- Measured the fast ion redistribution from MHD instabilities, and initiated full-orbit calculations to understand the physics
- Detailed analysis of the NSTX disruption database has been undertaken, including development of warning algorithms that predict 99% of disruptions

The PAC commends the NSTX Team for its rapid response in diagnosing the cause of the toroidal field coil failure, assessing options, and developing the plan for an early start and completion of the Upgrade schedule. The careful technical analysis of the failure has provided a good explanation of the cause, and this has improved the design for the toroidal field coil in the new center column of NSTX-U. The Team successfully managed an accelerated schedule for the Upgrade so that it would be possible to start NSTX-U operations in FY 2014. The PAC agrees that this was the correct course of action to minimize the impact of the coil failure on the productivity of the NSTX Program.

It appears to the PAC that the Upgrade is on schedule, and first operation of NSTX-U would indeed be possible in FY 2014. Unfortunately the proposed DOE-FES budget for FY 2013 includes funding reductions that are expected to cause a one-year delay in the completion of the

Upgrade. Recent staff retirements and possible staff reductions associated with the reduced budget will also make it more difficult to have an experienced staff ready for the restart of experimental operations. Hence the opportunity to take advantage of the accelerated upgrade schedule is in jeopardy.

The PAC is very pleased to see that the NSTX team has initiated a substantial design effort for a cryo-pump. Previous PACs had urged this analysis, and it is encouraging that initial results suggest that a cryo-pump compatible with device and plasma performance requirements could be constructed.

The PAC remains impressed by the comprehensive approach to understand the role of lithium coatings, including improved measurement and analysis capabilities on NSTX, supporting “lab” (or test-stand) experiments, collaboration with LTX and other fusion experiments, and theory and modeling. Clearly the NSTX Program is a world leader in lithium coating research.

While there is very good progress in understanding the effects of lithium coatings on particle control, and the option for a cryo-pump is promising, the PAC remains concerned that a solution to obtaining stationary plasmas suitable for the stated high-level objectives has not been identified for NSTX-U. A key measure of success for the NSTX-U upgrade will be attaining plasmas with low collisionality, for which density control is the strongest leverage. The cryo-pump is not certain, neither in design nor funding, and deuterium pumping on metal substrates is known to be different than for carbon substrate, the present plasma-facing component (PFC) material of NSTX. We note that the PFC and plasma-wall-interaction (PWI) research plan calls for the eventual use of metal substrates in NSTX-U, both molybdenum and tungsten.

The PAC is also concerned that the 5-year program plan has potential competing priorities with regard to the implementation of the PFC and particle control upgrades to support the three highest level goals: FNSF scenario development, divertor heat flux control solutions, and exploring the role of plasma collisionality in ST performance. The PAC recommends that the NSTX-U Team develop an implementation strategy that provides definitive results at minimum risk on each of these goals, even if that requires deferral of one with respect to the others. This strategy should be developed in the 5-year plan and presented at the next PAC meeting.

2. General Comments Pertaining to the Two Charge Questions

The PAC makes the following general comments pertaining to the two charge questions. We also make numerous specific comments on the charge questions related to each of the Topical Science Group areas that appear in Section 3 below.

1. *Are the planned NSTX-U team science activities appropriate during the Upgrade outage?*
    a. *Comment on progress toward research milestones*
    b. *Comment on the NSTX-U team plans and preparations for collaboration with other facilities to prepare for NSTX-U operation and contribute to fusion science generally.*

As a consequence of the reduced operation in FY 2011-12 and accelerated upgrade schedule, the NSTX Team revised their milestones for emphasis on analysis and projections to NSTX-U and future facilities. The PAC finds the revised milestones appropriate and compelling. We suggest that milestones that leverage NSTX contributions to ITER physics and operations be moved earlier if possible, e.g., research on fast ion transport and disruption avoidance.

The PAC applauds the formulation of a compelling collaboration strategy that advances both NSTX-U and fusion science more broadly, with a high bar for measure of success, e.g., publications in Physical Review Letters and other prominent journals. However, the collective list of future collaborations described in the TSG presentations is long, and it is not clear that resources (funding, personnel, etc.) are really available to support the long list. It appears to the PAC that prioritization is necessary. A related observation is that a large portion of the collaboration plans favor research on DIII-D and Alcator C-Mod, because these facilities have mature diagnostics and other capabilities. However, the proposed DOE-FES budget for FY 2013 makes it uncertain that the proposed collaborations can be adequately supported on these facilities. Also, MAST is approaching its scheduled shutdown for upgrades, making it a limited term option for collaboration. These factors could severely hamper the compelling collaboration strategy formulated by the NSTX team. This further emphasizes the need for prioritization of collaborative activities.

In some cases the collaboration calls for the temporary relocation of NSTX team members to other laboratories. While this is well-motivated and likely essential, there is a danger that individuals could drift from their Home Team identity. The NSTX management mentioned this issue, and the PAC suggests developing a proactive strategy to maintain the NSTX team environment.

2. *Are the plans, preparation, and progress for the next 5 year plan strongly supportive of the NSTX-U and FES missions? Consider two time periods:*
    a. *Initial operation of NSTX-U, i.e. the first 1-2 run years*
    b. *Longer term, i.e. years 3-5 of NSTX-U operation = later stages of 5 year plan*

Overall the PAC finds the emerging 5-year plan to be supportive of both NSTX-U goals and the FES mission. Next to ITER, the upgrade of NSTX represents the second largest investment in US fusion facility capabilities in the next few years. The PAC therefore urges identifying a few high priority and high impact goals that can be achieved in the first year of operation, both for NSTX-U and fusion science generally. The plan for initial operation as presented appears tentative, while the new capabilities and investment are substantial.

During the meeting, the PAC asked the NSTX Team to identify the research priorities for the 5-year plan. With regard to FNSF, we framed this question to encourage a priority assessment of NSTX-U contributions to resolving critical path issues independent of magnetic configuration, and not necessarily specific to the ST-FNSF concept. Five research thrusts were identified in the Team's response, which in priority order are (1) demonstrate 100% non-inductive current sustainment with plasma performance that extrapolates to $\geq$ 1MW/m^2 neutron wall loading in a FNSF, (2) access reduced ν^* combined with the ability to vary the safety factor and plasma rotation profiles to dramatically extend ST plasma understanding, (3) develop and utilize a high-flux-expansion divertor magnetic configuration for heat flux mitigation, (4) develop and understand non-inductive start-up and ramp-up to project to ST-FNSF operation with small or no solenoidal induction, and (5) assess high-Z plasma-facing components, plus flowing liquid lithium, to develop a high-duty-factor integrated PFC/PMI solution for an FNSF and beyond. The PAC agrees with this assessment, and notes that all 5 research thrusts are vital to assess the ST configuration for future fusion applications, and represent major contributions to fusion science generally. The PAC recommends that the 5-year plan be organized as a staged approach aimed to succeed in accomplishing the highest priorities for the NSTX-U research program.

3. Comments and Suggestions Pertaining to Topical Science Groups

We summarize below observations and recommendations for each of the TSG areas.

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, e.g., analysis of a cryo-pump and its projected use for particle control.

The PAC was very impressed with the progress of the NSTX-U team's investigation of a cryo-pumped divertor and the application of a snowflake divertor configuration that could possibly include detachment or a radiative divertor for the control of the large heat fluxes expected for NSTX-U during its long pulse operation. The PAC strongly recommends that, if particle control becomes an issue, the cryo-pump design and implementation must be accelerated. In addition, pumping will be more efficient with increasing particle recycling in a divertor geometry with close-fitting side walls. Optimization of the divertor geometry should be studied to improve particle control.

The PAC suggests that a much clearer plan is needed to better clarify the evolution from carbon to all-metal walls. Effects of the high-Z wall on the PWI and plasma performance should be determined without influence of Li layers, i.e., prior to Li studies on the metal walls. The PAC also notes that the 5-year transition from an all-carbon machine to an all-metal machine is very ambitious, especially considering the possible reduction in key staff in coming years. A more systematic evaluation of the PFC assessment plan is needed to determine whether all of the steps described are needed. One suggestion to consider is the elimination of the Mo phase and going directly to W.

The snowflake divertor introduces new physics that must be addressed, such as the role of "leading edges" for operation with high-Z materials in a low-aspect-ratio device. What is the specific strategy to deal with this challenge? It is also recognized that a systematic understanding of the plasma performance will be needed which spans the operational space between the complete snowflake to the partial snowflake configuration in order to arrive at a compact and functional NSTX-U divertor design. The PAC also recommends that the NSTX-U team review and prioritize the divertor diagnostic capability that will be needed for NSTX-U to fully understand the snowflake configuration.

Research of high-Z impurity shielding in the edge and SOL plasmas and active control of the core accumulation will be essential in the high power and long pulse plasma when high-Z PFCs are installed. Control methods, such as gas puffing, central heating, and possibly new ideas should be investigated together with developments of spectroscopic measurement and transport modeling.

Comments specific to Charge Question 1

Research progress: The PAC sees that important progress has been made in Boundary and Divertor Physics on NSTX especially in the following areas: a detailed comparison between a conventional divertor geometry and that of a snowflake divertor configuration. The NSTX snowflake divertor has provided a strong reduction of heat flux, and initial cryo-pump modeling looks promising for the snowflake divertor configuration. Projections for NSTX-U are for a mapped midplane-heat-flux width of $\lambda_q \sim 3$ mm and a peak heat flux of 20 – 30 MW/m^2. The PAC is pleased to see that the NSTX team is developing a PFC assessment plan for NSTX-U in an attempt to transition to full metal coverage for FNSF relevant PMI development (Mo, W, etc.). In addition, significant progress has been made on pedestal stability analysis for a small ELM regime and enhanced-performance H-modes.

Collaboration plans: The PAC commends the NSTX-U team for its development of several important domestic and international collaborations, such as: 1) development of snowflake control algorithms with the DIII-D Plasma Control System (PCS); 2) Assessment of high-Z PFCs for NSTX-U through a C-Mod collaboration on molybdenum; 3) A key international collaboration with ASIPP in Hefei, China and MIT on Pedestal/SOL turbulence measurements with gas-puff imaging (GPI); and 4) A possible collaboration with ASDEX-U is planned for small-ELM-regime analysis and for the effects of 3-D magnetic fields on divertor-plasma detachment. For item (1), it would also be very useful to include the assessment of snowflake operation on the larger aspect-ratio DIII-D tokamak and compare existing results from NSTX; a key question is how the favorable snowflake operation scales to standard tokamak geometry.

The PAC observes that the NSTX-U team needs a systematic plan to define the PFC strategy. Currently, the strategy for PFC choices is a bit confusing. The group needs to identify early the type of Mo and W used for studies well before NSTX-U. For example: Is it TZM? Porous or non-porous? What about the influence of impurities from these materials on the lithium coating surfaces? The NSTX-U team needs to clearly separate the science of high-Z PWI from Li PWI and utilize laboratory experiments where possible to address many of these issues. The NSTX-U team needs to address the engineering issues of high-Z tile edge design and configuration, especially leading edges that intercept parallel plasma flow along the magnetic field, **B**. This is an important issue to reduce erosion and melting, in particular, for the snowflake divertor, where **B** will make a shallow incident angle with the material surface over a very wide area.

Comments specific to Charge Question 2

Years 1-2 operation: The PAC recommends that the NSTX-U team investigate the high flux expansion snowflake divertor under a condition of detachment. Due to the high heat flux expected in the longer pulse lengths and higher heat loads on the divertor, it will be important to investigate large heat-flux reduction that could be obtained during detachment in a snowflake configuration. It is also recommended that a study to investigate divertor power exhaust in the presence of high-Z divertor components be carried out. Performance of the divertor plasma will change from the previous experiments where carbon was the intrinsic impurity. Radiation control with seeded impurities will likely be necessary to handle the high heat flux in the SOL and divertor for high-Z PFC.

Scaling of the divertor heat-flux width and understanding of the underlying physics is a central issue that should receive focused attention in the operation of NSTX-U, first by comparing with NSTX results, and then pushing to higher plasma current. Likewise, the dependence of H-mode performance on current and plasma beta is planned, which will help increase the understanding of these parameters for fusion devices. Coupling these measurements with theory/simulation should be a high priority to move toward a predictive understanding in these areas as emphasized in NSTX-U and OFES mission/vision statements.

It is also important that the NSTX-U team begin a cryo-pump design for the larger particle flux and longer plasma discharges that will be compatible with the NSTX-U vessel and divertor geometry, as well as the snowflake shapes. Therefore, a full assessment of the cost and capability of a cyro-pumped divertor system should be established prior to initial NSTX-U operation. At the same time, future development of the divertor design appropriate for a ST configuration will be necessary in order to provide particle and heat control in steady state discharges. For the assessment, strategy of the pumped divertor study including compatibility with Li injection/handling systems, development in the upper and lower divertors, and PFCs study will need to be clarified.

Years 3-5 operation: During this period, the PAC feels that the NSTX-U team should provide an assessment of a partially detached snowflake divertor with full cryo-pumping to see if this configuration provides sufficient heat-flux reduction and particle control for NSTX-U long pulse operation.

3.2. Lithium Research

The continuing analysis of NSTX data reinforces that use of lithium evaporation can have a substantial impact on the overall plasma behavior. High-level goals are to demonstrate the following: superior plasma performance, high divertor-heat-flux handling, and reduction of PFC sputtering and neutron-damage. Research areas required for scalable understanding are surface chemistry, online prototype testing, and tokamak integration.

The reduction of peak heat flux with Li deposition was documented, as well as the narrowing of the heat-flux radial profile for the same power as no-Li discharges. Just where the remaining power went is not well understood, though likely it is distributed via impurity radiation. If possible, more data analysis should be performed and more modeling to build a consistent picture. Such analysis also relates to understanding if Li is playing a substantial role in the apparent detached divertor plasma operation obtained in the snowflake configuration that yields very low peak heat flux.

The observed development of a small-ELM-like regime on some discharges following the cessation of Li deposition is very interesting, especially because such discharges show low impurity accumulation, presumably due to the returning edge MHD fluctuations. The result suggests an optimum Li coverage exists to allow such regimes. More analysis of such discharges is encouraged, particularly for understanding what coverage is optimal and how this coverage can be maintained under different discharge conditions.

Simulation work with XGC0 indicates that low Li core concentrations during normal Li deposition can be explained by neoclassical transport given the inward transport of carbon during ELM-free discharges induced by Li deposition. While interesting, the net impurity increase (mainly C) without ELMs makes this regime unattractive.

Hydrogenic and impurity particle recycling/transport in the inboard divertor and wall can contribute to the overall sources of these particles, and it is thus important to understand such processes in this region when designing PFCs appropriate for ST tokamaks. Simulation and experiment studies such as local Li coating and divertor pumping from the private region will help evaluate their influence on divertor and core plasmas. It is also important to measure influx profiles of intrinsic D and Li, and seeded impurities.

The collaborative simulation and lab work (Purdue, ORNL, PPPL) on the role of oxygen in pumping D on a lithiated carbon surface is very good science and shows the potential complexity of such multi-material systems. Given this insight, an integrated quantitative model is still needed to explain the experimental D-alpha and neutral pressure signals. The data so far suggests that Li deposition alone does not provide adequate pumping for general particle control, though better Li coverage is planned for NSTX-U that may help.

The use of lithium for particle control could be supplemented or possibly replaced by a cryo-pump. The cryo-pump analysis presented was very welcome and impressed the PAC. The next step of full 2D modeling with B2+EIRENE (SOLPS) is very appropriate. In the results presented, the goal was to show that the particle input from the neutral beams could be pumped by such a system, but did not consider the possibility of outgassing from walls that may add a significant particle source at times, especially if the walls heat up during the discharge. Given that the reduced analysis presented showed the pump could remove about twice the neutral beam input, there is a question of its adequacy if there is a substantial extra gas load.

Comments specific to Charge Question 1

Research progress: The PAC sees that important progress has been made in documenting the impact of Li deposition on NSTX discharge behavior including the following: continuous improvement of energy confinement time with deposition level, reduced divertor heat flux and profile width, and the observation of a small-ELM-like regime with much reduced impurity accumulation some 20 discharges after Li deposition is stopped. Li deposition does correlate with decreased D-alpha and neutral pressure in the divertor, indicating that significant D pumping occurs. A fundamental understanding of the important role of oxygen in deuterium pumping on lithiated graphite surfaces has been developed. Projecting forward to NSTX-U, operation with Li is especially uncertain given the likely transition to refractory high-Z metal PFCs over the first 5 years under higher heat fluxes for longer discharge times, and there is little experience/understanding of how Li behaves on such surfaces. The LTX and EAST collaborations will help.

The PAC is pleased to learn of the initial analysis of the capability of a cryo-pump in NSTX-U showing that it could pump the expected neutral beam particle input and that the snowflake divertor configuration appears even move favorable than the standard X-point divertor. Additional work investigating outgassing from Li layers due to the realistic increased surface temperature should be included in divertor pump design. A SOLPS analysis should now be used to verify the reduced-model analysis in preparation for an eventual engineering design.

Collaboration plans: There are important collaborations either underway or planned to contribute to the much needed improved understanding of Li as a plasma-facing component (PFC). For the fundamental behavior of Li layers on materials, the local PPPL/Princeton University (PU) collaboration leverages PU expertise on thin-film physics and the planned work with Purdue U to test Li-coated materials in the Magnum-PSI (FOM-DIFFER, The Netherlands) linear plasma device this year. For tokamak operation with Li, the MAPP probe will be lent to the PPPL LTX to analyze Li on various metallic surfaces. A key international collaboration is with ASIPP in Hefei, China for implementing and studying Li dropper and granule injectors on EAST and a flowing model on HT-7. It is planned to apply the granule injector technology developed at ASIPP on NSTX-U. Given the proximity of LTX, the PAC encourages a clear articulation of what Li physics is common to the two devices and to develop/present an appropriate collaborative plan related to Li issues.

Comments specific to Charge Question 2

Years 1-2 operation: The PAC assumes and recommends that an initial base-line operation of NSTX-U will be performed before the introduction of Li, including snowflake divertor operation. The plan to then test the ability of the Li evaporators to provide sufficient coverage for longer pulses and more uniform coverage by use of additional evaporators, injectors and/or sprayers, and to assess if the impact follows the NSTX experience, is appropriate. Understanding and optimizing the use of Li for divertor heat-flux control addresses the NSTX-U mission element of finding a solution to the plasma-material interface problem at high power, and Li's pumping capability, if improved, could also contribute to the goal of obtaining non-inductive steady-state discharges.

Experience gained from LTX, Magnum-PSI, HT-7 and EAST should be used to guide new capabilities such as ELM control by Li granule injector and flowing Li capabilities. Establishing the pumping capability of Li with fuller device coverage should be a high, early priority, as well as clarifying the role of Li in low heat flux operation with the snowflake divertor. Radiative energy loss by seeding with impurities is a major technique to reduce the high heat flux in SOL and divertor when radiative loss by Li is not sufficient, especially for high-Z PFCs (having no carbon). Compatibility of impurity seeding with Li layers (impurity retention and Li erosion) and the feedback system should be investigated at this stage.

Additionally, better understanding of the small-ELM-like regime with reduced-Li coverage should be a priority because it has the potential to reduce impurity accumulation during Li operation.

A full assessment of the cost and capability of a cryo-pump system should preferably be established prior to initial operation, including its compatibility with Li, to better inform the possible decision to install this capability. This system promises to enable steady-state discharges.

Years 3-5 operation: In this period, the plans call for installation of a flowing Li module – pending lab-based tests and modeling, perhaps limited to one toroidal sector, and a possible cryo-pump. By this time, it should be clear if Li is required for power handling, especially with the snowflake configuration, if Li provides substantial particle pumping, and there should also be an assessment of the compatibility of Li with the cryo-pump. The use of flowing Li on only one toroidal segment is sure to complicate the understanding, and perhaps operation, of the device. There should be a clarification by the NSTX staff of whether this strategy is based on ease of retracting or removing the module if there is a problem with operation or is a cost-saving measure.

3.3. Macro-Stability Research

Similarly to the other topical areas, the NSTX team has made impressive progress in Macroscopic Stability given the limited run time. Notable achievements include the investigation of low-density startup, the observation of the toroidal rotation of halo currents, and advances in the characterization of the effect of non-resonant braking on error field thresholds.

The group's plans for the first 4 years of operation of NSTX-U seem appropriate. In particular, year 1 focuses on reestablishing previous capabilities and mastering changed features such as error fields and shape controls. Year 2, by contrast, begins the exploitation of new capabilities such as the off-axis NBI and SPAs. The diagnostic development efforts, such as real-time velocity measurements, look particularly promising. A notable feature of the plan for years 3-5 of NSTX-U is the relatively low profile of 3D studies (R12-1), despite (i) the identification of this area as a priority by FES and (ii) the important new capabilities that the Upgrade will provide, particularly as regards reduced-collisionality regimes of operation and the elucidation of differences in the response to RMP in NSTX and DIII-D. The PAC assumes that the absence of this topic from the presentations is a consequence of reduced manpower caused by our previous request for a study on cryo-pump design. We hope to see this subject receive renewed attention in the future. In particular, we endorse the plans for the NCC coils and strongly support the planned inclusion of the plasma response in the design efforts.

The presentations provided less detail regarding the plans for the shutdown period, other than for outlining the group's remarkable collaboration program. We view the shutdown period as providing significant opportunities to both broaden and solidify the group's key recent contributions to the fusion program. Specifically, in the past few years the group has played a leading role in bringing about two paradigm shifts:

1. Role of kinetic effects in the rotation dependence of RWM stability
2. Role of NTV in error field penetration.

The consequences of both of these effects are almost certain to extend beyond the particular phenomena that led to their discovery. What is the role, for example, of the precession resonance in the plasma response to RMP?[1] The shutdown period creates an opportunity for the MS group to take the lead in exploring these consequences using existing data as well as through collaborations. The best way to transition a paradigm into a theory is to make it break, i.e. to exhibit explicitly the limits of its validity. The above two paradigms have reached a level of maturity that justifies an aggressive exploration of their range of validity.

3.4. Turbulence and Transport

The NSTX-U team is developing a highly coherent research approach in turbulence and transport studies in which global confinement properties, local transport levels, and turbulence characteristics are investigated experimentally and a consistent physical understanding is sought by means of comprehensive theoretical models and related numerical tools. The PAC fully endorses this approach and strongly encourages the NSTX-U team to keep and further develop this approach in future years and during the NSTX-U operation. The PAC is glad to acknowledge the scientific progress made by the NSTX-U team through this comprehensive and coherent research approach, and is impressed by the quality and importance of the results obtained during the last year. Among the most important results, we would like to mention the identification of collisionality as critical parameter in order to unify confinement behavior in lithiated and un-lithiated H-mode plasmas, the related dedicated study of the impact of collisionality on micro-tearing transport, the characterization of fluctuation properties at the pedestal with BES, the investigation of the impact of density gradients on high-k fluctuations, the application of the XGC0 code on observations of the L-H transition, and the application of neoclassical theory in explaining observations of impurity transport.

During the period of the outage, an appropriate set of scientifically relevant research activities are considered, dedicated to the analysis of data from past NSTX experimental campaigns, with related modeling activities, as well as to the physics design of diagnostics planned for the NSTX-U operation. For the completion of these research activities, the PAC presents specific suggestions that should be useful for a more complete development of the research during the outage period, and to extend the investigations during the NSTX-U operation period.

- In the framework of gyrokinetic modeling of turbulence, it is suggested to move towards increasingly realistic simulations, including the impact of rotational shear on micro-tearing, the impact of an additional C impurity species in conditions of experimentally measured large effective charges, and consider the impact of these effects on the collisionality scaling, particularly in the case that correlations between parameters are present in the experiments.

- A critical aspect on which particular efforts are suggested to be dedicated is the role of low-k turbulence in producing particle (electron and impurity) and momentum transport. In contrast to ion heat transport, neoclassical transport is very small for momentum and electron particle transport, and high-k (ETG) as well as micro-tearing turbulence (which can produce electron heat transport) cannot produce transport in the particle (electron and impurity) and momentum transport channels. The comparison between conditions in

[1] Note that this question is addressed by J.-K.Park's 2011 paper in Phys. Plasma, which was only briefly alluded to during the review.

which neoclassical transport is expected to produce a significant amount of ion heat transport with conditions in which this is estimated to be smaller with respect to power balance transport levels (e.g. comparisons among L-modes and H-modes) is potentially helpful in this direction.

- Specific parameters that are of interest in the framework of these studies are the local inverse aspect ratio and the electron beta. These are of particular importance in the comparison with observations in large aspect ratio tokamaks, as planned in collaboration activities (e.g. with DIII-D).

- Strongly connected to these research activities, it is suggested to progress towards increasingly accurate calculations of neoclassical transport, establishing the domain of applicability of conventional theory (e.g. the NCLASS and the NEOART codes), in particular with respect to the magnitude of the poloidal Larmor radius and of the impurity rotation velocity, and performing comparisons within a hierarchy of neoclassical models, including, in addition to NCLASS or NEOART, also codes like NEO and XGC0. The application of such a hierarchy of models/codes to observations of ion heat and impurity transport is of extreme interest (size of ion heat conductivity, of impurity diffusivity, and size of impurity convection to diffusion ratio).

- It is suggested to consider the development of a model for *AE induced electron heat transport already during the outage phase (in collaboration with the TSG on Energetic Particles) to be tested against past NSTX results and to be applied then to NSTX-U.

- Finally, in order to be ready for the exploitation of NSTX-U, the preparation of diagnostics for turbulence and transport analyses plays an important role. These diagnostics require good profile measurements, including also current density/safety factor profile (e.g. MSE-LIF) and impurity transport (e.g. ME-SXR) and multi-scale multi-field fluctuation measurements (FIR high-k_θ scattering, BES, polarimetry, reflectometry). When this is deemed necessary, it is suggested to verify that these diagnostics will have the appropriate radial coverage and spectral range for fluctuation measurements in the expected NSTX-U scenarios.

Planned collaborations are considered appropriate and mutually beneficial for laboratories. If priorities have to be identified due to budget or personnel limitations, it is suggested to focus on the exploration of the impact of electromagnetic turbulence in other devices, with particular emphasis on comparisons on the roles of beta and epsilon on transport.

The general plan for turbulence and transport studies in NSTX-U is considered appropriate and effective, and does not appear to require further definition at present. In particular, an approach combining fluctuation measurements at high-k_θ (new FIR scattering) and polarimetry (being tested in DIII-D) in combination with BES (and reflectometry) is certainly very promising to explore and quantify the relative role of low k turbulence (microtearing and ITG/TEM) and high-k turbulence (ETG) in NSTX-U.

During NSTX-U operation, the PAC suggests that high priority be given to establishing the impact of low collisionality, high beta, and rotation on confinement and to related modeling/validation of theory based transport models and turbulence simulations. At the time of NSTX-U operation, new computer capabilities should allow also the investigation of global effects on transport, by means of comparisons of global turbulence simulations with experimental measurements of transport levels and fluctuations.

3.5. Wave-Particle Physics: Energetic Particles and HHFW

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

Energetic Particles

Understanding fast particle driven instabilities and their effect on plasma heating and confinement is one of the most important tasks for ST research towards ITER/DEMO and the FNSF. Appreciable progress has been made on NSTX in this field despite the short run period. This also prevented the exploitation of the newly installed prototype TAE antenna, which now has to be deferred to NSTX-U. The PAC recommends that this capability be retained and active collaboration be pursued to allow rapid exploitation in NSTX-U.

The studies previously concentrating on L-mode because of the better diagnostics have been extended to the H-mode regime allowing projection towards NSTX-U. The modeling of the plasma fast particle interaction using NOVA-K (linear stability, eigenfunction), ORBIT (fast particle response, gyro-center) and SPIRAL (fast particle response, full-orbit) codes has been improved, but is still mostly linear modeling. Of particular interest is that the modeled fast ion redistribution in energy and space during TAE avalanches and a low-frequency kink-like mode does not lead to significant fast ion losses. This needs to be reconciled with transport calculations that seem to indicate an appreciable fast particle loss.

The fast ion redistribution during the kink-like mode has also been confirmed using the new FIDA data. First comparisons between modeled mode structures and experimental data have been shown and the PAC looks forward to seeing more of these quantitative comparisons, in particular with measurements of the fast particle distribution (e.g. FIDA). More evidence of non-linear coupling between *AE's and low-frequency MHD has been found with TAE avalanches destabilizing low-frequency modes and the low-frequency kink-like mode redistributing fast particles such that the CAEs and GAEs drive is increased. Impressive is the modeling of the electron transport due to GAEs that seems to be consistent with TRANSP calculations. The PAC recommends maintaining a strong crosscutting effort between the Transport & Confinement and the Wave & Energetic Particle topical groups, even strengthening it even further. The PAC strongly endorses plans to develop simplified models to be implemented into predictive transport models. This should be a high priority item reflected in the research milestones for the near term program.

The activities planned for the long outage period in general reflect strategically important issues. The PAC agrees with the emphasis to first expand the non-linear modeling capability by coupling SPIRAL to the HYM code. Modeling of the saturated modes is particularly challenging and can be benchmarked against existing data. Also the concentration on optimal fast ion diagnostic design seems prudent. The funding of these “new” diagnostics in the financially challenging budget situation remains a cause for concern. Therefore, the PAC encourages a physics driven priority list to be developed. The analysis of NSTX-U scenarios with respect to the expected fast ion physics is important due to the importance of the contribution of the ST in this area with respect to ITER/DEMO physics. The modeling should be used to guide the NSTX-U research plan as well as the diagnostic strategy. The PAC is concerned that the proposed time line is not aggressive enough with only one research milestone in FY 2014, not reflecting the importance of the field with respect to NSTX-U and other future tokamaks. The PAC recommends to accelerate the time line in particular with respect to developing simplified models of the *AE induced fast ion transport. The collaborations indicated with DIII-D and MAST seem to be appropriate and more concrete plans should be developed well in advance, in particular with respect to diagnostics and TAE antenna exploitation. The reduced run periods of these devices, however, may limit the possibilities.

An important aspect for future devices is the avoidance of detrimental fast particle driven MHD. Here, a further understanding of such operating regimes should be established within the NSTX database. The assumptions for a deeper understanding and the access to these regimes could be tested on other devices with the appropriate actuators and diagnostics (e.g. ASDEX-Upgrade, DIII-D and MAST). This should be done together with the Advanced Scenarios topical group.

The HHFW coupling in the presence of strong NBI heating is important for the NSTX-U goals and has not been demonstrated on NSTX. The PAC feels that the link between the HHFW team and the fast particle modeling team could be strengthened further.

The plans presented for the early exploitation of NSTX-U include the most important issues and reflect the capabilities well. In view of developing a strong research plan a clearer understanding of the ITER/DEMO needs compared to the needs for the FNSF with respect to energetic particle physics may help to focus the research activities. The PAC recommends formulating high priority research goals leading to high impact publications to further aid the development of the NSTX-U research plan.

High Harmonic Fast Wave Heating Physics

Significant progress was made in the high harmonic fast wave heating (HHFW) area in 2011 despite the lack of experimental time. The in-depth analysis of the heat deposition in the divertor has led to an understanding that the energy is coming from wave fields excited between the antenna and the last closed flux surface, not from fields that are field line connected to the antenna. This is an important new result in this field. Of course, the NSTX antenna was deliberately designed to minimize direct interaction with field line sheaths by placing insulators to intersect the field lines. The experimental results and the 3D modeling give hope that in NSTX-U operation, at higher toroidal field, it will be easier to avoid these SOL losses.

During this analysis of the SOL losses it was also observed, that for HHFW only H-mode discharges the heat footprint during the ELMs was extremely narrow. If this turns out to be characteristic of electron heated discharges it would be of extreme importance to future devices.

This finding should be explored on other devices with pure electron heating and revisited on the Upgrade. It should also be investigated for the inter-ELM period.

Continued progress has been made in interpreting the FIDA data and comparing with theoretical modeling for HHFW plus NBI heating. The data and modeling are coming into reasonable agreement.

So, while there is undoubtedly much more that can be done with existing data the NSTX RF team should turn increasing attention to modeling NSTX-U discharges. In particular, modeling of the SOL behavior at higher field and modeling of the interaction between the HHFW and the new NBI should be undertaken. Addition of new SOL diagnostics should be considered where appropriate to further evaluate the effects of RF in the SOL plasma. Modeling of the performance of HHFW for achieving fully non-inductive operation in the Upgrade including minimum temperature requirements for heating the CHI plasma should be performed.

During the outage the team should take advantage of the opportunities to continue and extend their research on other facilities to verify the universality of their findings. The PAC recognizes that the NSTX team proposed doing this and wishes to encourage it.

The NSTX HHFW group has proposed new initiatives for application in the Upgrade as well as indicating a desire to take advantage of the need to make technical changes to the system to accommodate the Upgrade. The PAC supports these initiatives and suggests that collaboration with MIT in the areas of antenna analysis and design of an Edge Harmonic Oscillation (EHO) antenna be pursued.

In the area of ECH/EBW the NSTX team should complete the conceptual design of such a system. In addition, a physics basis for ECH in the start-up plasma, e.g. density limit, power requirements, etc. should be performed taking advantage of any experiments on MAST and other smaller ST's. The role of EBW heating in fully non-inductive operation should be re-assessed for the parameters of NSTX-U.

3.6. Solenoid Free Start-up and Ramp-up

Start-up and ramp-up of the plasma current with a small or without the use of a central inductive solenoid remains a critical issue for the development of the ST. CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up to 1 MA in NSTX-U. The approach to this is to use Electron Cyclotron Heating (ECH) to heat the initial 100 kA CHI target plasma temperature Te >100 eV, then use the high-harmonic fast wave (HHFW) to increase Te to 1 keV and initiate H-modes to continue ramping up current to 400 kA, assisted by the bootstrap current. Finally, neutral beam injection will be added to further heat and ramp the current to the desired goal, i.e., 1 MA.

Significant progress has been made in developing CHI target plasmas and demonstrated record-low flux consumption on NSTX to achieve 1 MA. Impressive progress has also been made on the modeling front: TSC was used to reproduce NSTX CHI discharges and develop initial start-up scenarios for NSTX-U; NIMROD was used to understand flux closure mechanisms and the early dynamic phase of CHI. The projected scenarios heavily rely on ECH to bridge the gap between CHI target plasma and desired conditions for HHFW coupling. The PAC endorses ECRH (> 1 MW, 28 GHz) for current start up during the initial phase of NSTX-U operation. This would greatly enhance start-up and current ramp-up capabilities for direct application of NBI or preheating to >400 eV to facilitate HHFW coupling. This new RF capability could also be used for non-inductive EBW start-up to current levels comparable to CHI start-up alone. This possibility and the impact on the NSTX-U design should be investigated further to strengthen the physics case for a 28 GHz ECRH system. More insight into the capabilities of EBW start-up will be gained by the planned collaborative experiments on MAST within the Wave-Particle Physics TSG. ECRH would also offer a useful tool for additional heating and current profile control. The PAC supports further MHD modeling using TSC, NIMROD, TRANSP, and possibly M3D-C1, in support of NSTX-U, and recommends further exploring the compatibility of low li CHI target plasmas with ECH and HHFW during the initial start-up phase. This will also very likely yield a reliable physics basis for current ramp-up that includes the dynamics of plasma relaxation and compatibility with high plasma performance.

The PAC is pleased to see ongoing collaborations with the broad ST community during the outage, in particular, with QUEST in developing metal electrode for CHI, to gain information for future use of metal divertor plate electrodes in NSTX-U, and with PEGASUS on plasma gun development, assessing the feasibility to scale these to NSTX-U.

3.7. Advanced Scenarios and Control

The PAC notes significant progress on several fronts over the past year towards preparing for advanced scenarios and control research on NSTX-U including: (i) scenario modeling that have elucidated the range over which fully non-inductive operation on NSTX-U is anticipated; (ii) improved capabilities for producing and controlling important configurations for NSTX-U including higher aspect ratio and snowflake divertor configurations; (iii) the development of new diagnostic capabilities for real-time control; and (iv) the development of physics-based pre-disruption detection capability.

Regarding plans for the ongoing outage period, the PAC agrees that the participation of NSTX-U staff on plasma control research on KSTAR and DIII-D are appropriate. In particular, participation on snowflake divertor experiments on DIII-D is highly encouraged. In addition, we recommend that NSTX-U staff pursue participation in off-axis neutral beam current drive and fully non-inductive scenario research on DIII-D (and other devices as appropriate) to develop hands-on experience in preparation for future experiments on NSTX-U.

With regard to the plans for the first two years of NSTX-U operation, the PAC believes the focus on obtaining discharges at intermediate I_p = 1.2-1.5 MA is appropriate as this extends the range of operation beyond that of NSTX and provides a platform for assessing the effect of collisionality on plasma transport and performance. The PAC also agrees with NSTX-U plans to focus on the development of divertor heat flux control techniques for higher current operation. However, as discussed below, we believe that density control should be emphasized more strongly in plans. Continued development of real-time disruption detection algorithms and real-time control of rotation and current density are encouraged but at a lower priority than the above goals. In addition to these activities, the PAC also recommends that a focused activity be included in the plans for this time frame to validate that the off-axis NBI is working as expected in terms of heating, torque, current drive, and energetic particles.

During the 3-5 year time frame after the outage, the extension of NSTX-U operation to fully non-inductive operation and I_p = 2 MA also are appropriate. As part of this plan, the PAC encourages NSTX-U management to establish a program-level objective of demonstrating fully non-inductive operation with $I_p > 0.6$ MA. An important aspect of this capability will be the requisite density control and the PAC encourages the testing of advanced density control techniques that can provide this capability.

The PAC is concerned with what appears to be competing priorities with respect to assessing collisionality effects on transport, scenario development, and PFC research. It is the PAC's belief that density control is a critical enabling tool for the first two of these. A simple non-dimensional analysis indicates varying the collisionality at fixed ρ^*, β, and q requires the density to be held constant as plasma current/field is increased and to be accompanied by a temperature increase that scales as I_p^2. Hence, the factor of 2 increase in I_p/B_T that is enabled by NSTX-U upgrades will have to be accompanied by a factor of 2 improvement in density control beyond what was achieved in NSTX. Improved density control beyond this would expand the available collisionality space even further. In addition, the ability to achieve fully non-inductive operation and maximize off-axis neutral beam current drive will be greatly enhanced by good density control. While delivering this level of density control may be possible with Li divertor operation, this capability has not been demonstrated thus far in NSTX. The PAC recommends that the NSTX-U team develop an implementation strategy that provides definitive results at minimum risk on each of these, even if that requires deferral of one of these goals with respect to the others. This strategy should be presented at the next PAC meeting in their 5-year plan.

Respectfully submitted,

Jean Paul Allain
Purdue University

Clemente Angioni
IPP Max Planck Institute, Garching

Nobuyuki Asakura
Japan Atomic Energy Agency

Paul Bonoli
Massachusetts Institute of Technology

Donald L. Hillis
Oak Ridge National Laboratory

Houyang Guo
Tri Alpha Energy, Inc. and IPP, Hefei, China

Hendrik Meyer
Culham Centre for Fusion Energy, UK

Michael E. Mauel
Columbia University

Thomas Rognlien
Lawrence Livermore National Laboratory

John S. Sarff (Chair)
University of Wisconsin

Mickey Wade
General Atomics

François Waelbroeck
University of Texas

Dennis Whyte
Massachusetts Institute of Technology

Randy Wilson
Princeton Plasma Physics Laboratory

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