General Comments (1)

- The PAC congratulates the NSTX Team for a productive year. Despite the failure of the TF coil, a shorter 4.2 run weeks prior to the planned outage yielded 839 shots at a record rate. The publication rate and number of invited talks for the Team has been maintained at a high level. Five young researchers working on NSTX received Early Career Awards.

- The PAC commends the NSTX Team for its rapid response in diagnosing the cause of the TF failure, assessing options, and developing the plan for an early start and completion of the Upgrade schedule. Also, the design for the TF coil in the new center column has been improved as a result of the careful analysis of the failure.

- The Upgrade appears to be on schedule, and first operation of NSTX-U would be possible in FY 2014. Unfortunately the proposed DOE-FES budget is expected to delay completion of the Upgrade by one year. Retirements and possible additional staff reductions will also make it more difficult to have an experienced staff ready for the re-start of experimental operation. This results in a lost opportunity to take advantage of the accelerated upgrade schedule.

General Comments (2)

- The PAC is very pleased to see that the NSTX Team has initiated a substantial design effort for a cryo-pump. Initial results suggest that a pump compatible with device and plasma performance requirements could be constructed.

- The PAC is impressed by the comprehensive approach to understand the role of lithium coatings, including improved measurement and analysis capabilities on NSTX, supporting “lab” experiments, and theory and modeling. Clearly the program is a world leader in lithium coating research.

- The PAC remains concerned that a solution to obtaining stationary plasmas with low collisionality suitable for the high level objectives in PFC/PWI research has not been identified. The cryo-pump is not certain, neither in design nor funding, and deuterium pumping by lithium on metal substrates is known to be different than for carbon.

- The PAC is 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 priorities: FNSF scenario development, heat flux control solutions, and exploring role of 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, 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.

General Comments (3)

- The PAC is impressed by the progress and breadth of the advanced scenario and control modeling. This is clearly providing valuable guidance not only for NSTX-U projections, but for current NSTX research as well.

- A number of important scientific results this year, for example:
  - Improved theoretical understanding of micro-tearing instability and its role in governing heat transport; compliments growing experimental evidence
  - Further increase in energy confinement with lithium evaporation; this improvement is not yet saturated
  - Identified role of oxygen in affecting deuterium retention for lithium-graphite surface
  - Measured fast ion redistribution, and initiated full-orbit calculations to understand the physics
  - Detailed analysis of the NSTX disruption database, including development of warning algorithms that predict 99% of disruptions

  Note: The selection above is intended to be representative, not exhaustive. Many other results could have been listed.

General Comments on 1st Charge Question (1)

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*

- The revised milestones with emphasis on analysis and projections to NSTX-U and future facilities are appropriate and compelling. The PAC suggests that milestones that leverage NSTX contributions to ITER physics and operations be moved earlier if possible, e.g, 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.

- The collective list from the topical science areas is long, and it is not clear resources (funding, personnel, etc) are really available to support this list. Prioritization appears necessary.

General Comments on 1st Charge Question (2)

- A large portion of the collaborations favor research on DIII-D and C-Mod, because these facilities have mature diagnostics and other capabilities. However, the proposed DOE-FES budget makes it uncertain that the proposed collaborations can be adequately supported. 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.

- In some cases the collaboration calls for the temporary relocation of NSTX team members to other laboratories. While this is well motivated, there is a danger individuals could drift from their home team identity. The PAC suggests a proactive strategy to maintain the NSTX team environment.

- Additional comments specific to the topical science areas are described below

General Comments on 2nd Charge Question

2. *Are the plans, preparation, and progress for the next 5 year plan strongly supportive of the NSTX-U and FES missions? (refer to the information below for mission elements)*
   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 PAC urges identifying a few high priority and high impact goals that can be achieved in the first year of NSTX-U operation (both for NSTX-U and fusion science generally) . The plan for initial operation appears tentative, while the new capabilities are substantial.

- 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 program. We also agree with the assessment of the priorities as outlined in the response to our question on priorities.

- Additional comments specific to the topical science areas are described below

Boundary & Divertor: Topical Science Group 1

1. Are planned NSTX-U team science activities appropriate during Upgrade outage?

- *Progress toward research milestones and PAC-29 recommendations*
  - Presented comparison of conventional and snowflake divertor
  - Projection for NSTX-U of λ_q ~ 3 mm and peak heat flux of 20-30 MW/m^2
  - NSTX Snowflake Divertor has provided a strong reduction of heat flux
  - Developing PFC Assessment plan for NSTX-U to transition to full metal coverage for FNSF relevant PMI development (Mo, W, etc.)
  - Progress on pedestal stability analysis for small ELM and quiescent H-mode regimes
  - Initial cryo-pump modeling results looks promising for snowflake divertor;

- *Plans/preparations for collaborations & contributions to fusion science*
  - Develop snowflake control algorithms with PCS on DIII-D
  - Assess high-Z PFCs for NSTX-U through C-mod collaboration (erosion studies Mo)
  - Pedestal/SOL turbulence measurements with GPI on EAST, C-mod
  - Possible collaboration with ASDEX in small ELM analysis and effects of 3D fields on detachment

Boundary & Divertor: Topical Science Group 1

- *Issues/concerns*
  - NSTX-U needs a more systematic plan that defines what their PFC strategy is
    - Strategy for PFC choices is a bit confusing at present
    - Clearly separate the science of Hi-Z PWI from Li PWI (consider Lab experiments)
  - Need to identify early the type of Mo and W used for studies before NSTX-U. For example: is it TZM? porous or non-porous? what about impurities from these materials to the lithium coating surface? effect on D particle retention?
  - For snowflake and conventional divertor detachment and radiation control with impurity seeding is an important issue especially in high-Z divertor .
  - Engineering issue of high-Z tile edge design and configuration is important to reduce erosion and melting, in particular, for SF-divertor due to shallow incident angle over the wide area.

Boundary & Divertor: Topical Science Group 1

2. Are plans, preparation, & progress for 5-year plan supportive of missions?

- *Short term, run years 1-2*
  - NSTX-U will investigate high flux expansion snowflake divertor with detachment for large heat-flux reduction
  - Perform cryo-pumping physics design for NSTX-U compatible with vessel geometry and snowflake shapes
  - Study divertor power exhaust with high-Z PFC

- *Longer term, run years 3-5*
  - Assess partially detached snowflake divertor + cryo-pump to see if provides sufficient heat-flux reduction and particle control for NSTX-U long pulse operation

Boundary & Divertor: Topical Science Group 1

- *Issues/concerns*
  - If particle control becomes an issue, cryo-pump must be accelerated
  - A clear plan for the evolution from carbon to all-metal walls is needed
  - the snowflake concept must address the role of "leading edges" for high-Z materials operation in a low-aspect ratio device; What is the specific strategy to deal with this challenge?
  - Systematic understanding of the plasma performance from complete Snow Flake to partial Snow Flake is required. Also, control of seeding impurity and detachment is necessary for the compact divertor design.
  - The 5-year transition from an all-carbon machine to an all-metal machine is very ambitious considering reduction in key staff.
  - Review/prioritize divertor diagnostic capability suitable for understanding the snowflake configuration

Lithium & Cryo-Pump Physics: Topical Science Group 2

1. *Are planned NSTX-U team science activities appropriate during Upgrade outage?*

- *Progress toward research milestones and PAC-29 recommendations*
  - Correlated increased Li deposition with increasing τ_E and decreasing divertor heat flux, particle recycling, and neutral pressure
  - For large Li deposition, propose increase of core C and with low Li concentration to neoclassical impurity slows – but what about effect of no ELMs?
  - Found regime of small MHD events (ELMs-?) ~20 shots after LITER evaporation stopped; optimized Li coverage? Sustainable? Small “ELMs” also for small RMP
  - Showed role of O impurity on D pumping within C-Li surfaces – MD sim + lab expt.
  - Initial cryo-pump model looks promising, esp. for snowflake; now use SOLPS

- *Plans/preparations for collaborations & contributions to fusion science*
  - MAPP being loaned/used on LTX during NSTX-U construction
  - Princeton U surface analysis expert & equipment of Li surface studies
  - Beginning Li-PFC materials in Magnum-PSI device in June
  - Li granule injection to EAST (adding to Li dropper); flowing liquid metal on HT-7
  - Modeling of Li edge plasma with edge transport codes (PPPL, LLNL, ORNL)

Lithium & Cryo-Pump Physics: Topical Science Group 2

- *Major issues/concerns*
  - PFC metals and Li are complicated; study/understand separately
    - LTX research on metals should be leveraged/emphasized for understanding Li
    - How will Li surface-physics simulation & plasma coupling get done?
    - Understanding temperature effects for Li, opportunity with LTX
  - Pumping at inner divertor/PF regions may increase effectiveness of particle control

- *Detailed issues/concerns*
  - Prioritization/specificity needed for colloborations
  - C influx appears independent of Li coatings – why?
  - Sputtering of Li by injected medium-Z radiating impurities?
  - Engineering design/costing of cryo-pump
  - Pumping behavior or Li on metals (data for Li on C); saturation processes
  - Li saturation in Upgrade faster because of higher particle flux; flowing Li fixes?
  - Li has narrow temperature window before too much influx

Lithium & Cryo-Pump Physics: Topical Science Group 2

2. Are plans, preparation, & progress for 5-year plan supportive of missions?

- *Short term, run years 1-2*
  - Progressively test improved Li evaporative systems & coverage; add granule injector
  - Down-select flowing Li-PFC, including PFC material; test offline (where?)
  - With incremental funding, build cryo-pump

- *Longer term, run years 3-5*
  - Add flowing Li system to Upgrade; 1st one quadrant, then full coverage
  - With incremental funding, install and utilize cryo-pump

- *Issues/concerns*
  - If particle control becomes an issue, cryo-pump must be accelerated
  - Behavior of Li on metal substrates is new territory for tokamaks; understanding may be slow

Macroscopic Stability: NSTX-U

- Progress is impressive 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 2 years of operation of NSTX-U seem appropriate. In particular,
  - year 1 focuses mastering changed features such as error fields and shape controls.
  - Year 2 begins the exploitation of new capabilities such as the off-axis NBI and SPAs.
  - The diagnostic development efforts, such as real-time velocity measurements, are promising.
- A notable feature of the 5-year plan of NSTX-U is the relatively low profile of 3D studies (R12-1), despite the identification of this area as a priority by FES and the important new capabilities that the upgrade will provide, particularly as regards reduced-ν_* regimes of operation and the elucidation of differences in the response to RMP in NSTX and DIII-D.
- The PAC assumes that the diffuse nature of 3D studies in the presentations is a consequence of our previous request for a study on cryopump design, and hopes to see this subject receive renewed attention in the future. (issue of limited personnel)

Macroscopic Stability: during shutdown

- The MS plans for the shutdown period focused on 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:
  - Role of kinetic effects in the rotation dependence of RWM stability;
  - 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 (cf Park PoP 2011)? Do rotating modes, such as the LLM, also introduce NTV, and if so, what are its consequences?
- 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 transform a paradigm into a theory is to make it break. The above two paradigms have reached a level of maturity that justifies an aggressive exploration of the limits of their validity.

Transport and Turbulence (T&T)

- PAC fully supports the present highly coherent research approach 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

- PAC strongly encourages to keep this approach in future years and during the NSTX Upgrade period

- PAC acknowledges the progress made by the NSTX team through this comprehensive and coherent research approach, and is impressed by the quality and importance of the results obtained during the last year

- Unifying role of collisionality on confinement, impact of collisionality on μT transport, characterization of pedestal fluctuations with BES, impact of density gradients on high-k fluctuations, application of XGC0 to L-H transition phenomenology, application of neoclassical theory in explaining observations of impurity transport

T&T activities during outage (1)

- Planned data analysis, Modelling and Physics design considered appropriate

- Specific suggestions:
  - Move towards increasingly realistic GK turbulence simulations (impact of rotational shear on micro-tearing, particularly with respect to collisionality scaling, possible correlations between rotational shear and collisionality)
  - Role of low k turbulence in producing particle (electron and impurity) and momentum transport
  - Role of epsilon and beta on these transport channels (comparison of transport properties with large aspect ratio tokamaks)
  - Accurate calculations of neoclassical transport (domain of applicability of conventional theory, comparisons between NCLASS and XGC0) and consistent application to observations of ion heat and impurity transport

T&T activities during outage (2) & planned collaborations

- Specific suggestions (continued):
  - Consider development of model for *AE electron heat transport already during outage phase (in collaboration with TSG on Energetic Particles) to be tested against past NSTX results (and to be applied then to NSTX Upgrade)
  - To be ready for the exploitation of NSTX-U, preparation of diagnostics for turbulence and transport analysis plays important role
  - Requires good profile measurements (including current density/safety factor profile: MSE-LIF, impurity transport ME-SXR) and multi-scale multi-field fluctuation measurements (FIR high $k\theta$ scattering, BES, polarimetry, reflectometry) with appropriate radial coverage in expected NSTX-U scenarios
- Planned collaborations are considered appropriate and mutually beneficial for labs
- Priority to be given to the exploration of e.m. turbulence in other devices (comparisons on the role of beta and epsilon on transport)

T&T plans for NSTX-U operation

- General plan for turbulence and transport studies in NSTX-U considered appropriate and effective

- Approach combining fluctuation measurements at high kθ (new FIR scattering) and polarimetry (being tested in DIII-D) in combination with BES (and reflectometry) highly promising to explore relative role of high k and low k (μT and ITG/TEM) in NSTX Upgrade

- High priority to be given on establishing the impact on confinement of low collisionality, high beta, and rotation and to related modelling/validation of theory based transport models and turbulence simulations (which at that time will be able to investigate also global effects, what is presently still missing due to computer limitations)

Energetic Particles – Results (1)

Response to PAC-29:

- Despite the drastically reduced run time good progress has been made concerning the PAC recommendations.

Results:

- Considerable progress in the understanding of the detailed physics of *AE modes and coupling to low-f MHD.
  - Good to see detailed simulations of fast ion redistribution supporting observations.
  - FIDA data allows validation and the PAC looks forward to see direct comparisons between modelling and measurements.
- It is interesting to see that modelled FI losses due to the modes (avalanches and n=1 kink) are small.
  - This may be in contradiction with observed current drive and heating calculations.
  - A strong cross-cutting between Wave and Particles and the Transport & Turbulence topical groups should be maintained.

Energetic Particles – Results (2)

- The PAC encourages an increased emphasis of nonlinear modelling benchmarked against existing data to improve predictive capability.

- Further understanding of ways to avoid or control the detrimental fast particle MHD aiding the advanced scenario development should be thought.
  - This could be tested on other devices (DIII-D, MAST or ASDEX Upgrade) in FY13/14.

Energetic Particles – Outage activities

- The PAC strongly supports the plans to develop reduced models to be implemented into transport codes and agrees with the overall strategy.
  - It would be preferable to adopt a more aggressive time scale to develop these models to better predict NSTX-U performance.

- FI physics is the strongest contribution of the ST to ITER/DEMO physics. The PAC is concerned that this is not clearly reflected in the near term future plans or milestones.

- The PAC welcomes the collaborations with MAST and DIII-D during the outage.
  - A benchmarking of the different codes used to model fast ion transport should be pursued to gain confidence in the predictive modelling.

- The link between the HHFW heating and energetic particles may be strengthened further.
  - Enabling HHFW heating with strong NBI is an important goal for the upgrade.

Energetic Particles – NSTX-U

- The generally PAC agrees with the plans for the NSTX-U exploitation.
- A clearer understanding of ITER/DEMO compared to FNSF needs may help to focus the research activities.
- High priority research goals exploiting the new facilities leading to high impact publications should be formulated.

Waves - Results

- Response to PAC-29
  - Most of the recommendations involved things to do during the FY 11-12 run that did not take place
  - One recommendation involved modeling of NSTX-U plasmas- This work needs to proceed

- Recent Results
  - Excellent analysis of SOL losses and “surface” wave excitation
    - Demonstrated conditions under which good heating can be achieved- “should” be easier after upgrade (higher B)
  - Interesting result on narrow heat footprint during rf only H-modes
    - Is the between elm footprint also narrower?
  - Good progress on modeling of FIDA data
    - Can this be extended to predictions for NSTX-U NBI set (CD and AE activity)

Waves - Outage Activities (1)

- Investigations on D-IIID and EAST should provide insight
  - Same harmonic range on D-IIID
  - Li on EAST

- Continued Code work should focus on NSTX-U performance

- Consider diagnostics for SOL measurements
  - Increased probe coverage

- Assess the impact of SOL power loads on the NSTX-U divertor in particular with metallic surfaces.

- Collaboration with MIT on Antenna modeling/design changes – minimize antenna sheaths

Waves - Outage Activities (2)

- Modeling of role of HHFW in non-inductive operation
  - Minimum required temperature for coupling to CHI start-up
  - Interaction with beams at lower harmonic number

- Detailed modeling/design of ECH system
  - ECH part of start-up - density limit?
  - EBW role
  - Cost/schedule - Do you need 1 MW
  - Take advantage of MAST

- Consider MIT collaboration on EHO antenna

Waves - Research Goals during NSTX-U operations

- Need to establish role of HHFW in the upgrade
  - Demonstrate performance in non-inductive sustainment
  - Demonstrate performance in start-up

- If ECH added - need plan

- If EHO/*AE antenna added need plan

Solenoid-free Start-up and Ramp-up – (1)

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. A possible scenario has been identified for NSTX-U employed several current drive tools.

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.

Solenoid-free Start-up and Ramp-up – (2)

The projected scenarios heavily rely on ECH to bridge the gap between CHI target plasma and desired conditions for HHFW coupling.

The PAC strongly 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. It 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.

Solenoid-free Start-up and Ramp-up – (3)

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.

Solenoid-free Start-up and Ramp-up program addresses a critical issue that is unique to the ST development for fusion energy. The initial and longer term plans for NSTX-U operation are clearly laid out and will enable a critical assessment of this approach.

Advanced Scenarios and Control (1)

- **Progress in 2011-12: PAC notes significant progress on several fronts:**
  - Impressive progress on scenario modeling that has elucidated the capabilities to achieve fully non-inductive operation in NSTX-U
  - Developed physics-based pre-disruption detection capability
  - Developed diagnostic capabilities for real-time control (rotation - CHERS and current profile – MSE-CIF)

- **Comments:**
  - **Plans during Outage:**
    - Collaborations on other devices such as KSTAR and DIII-D on various aspects of plasma control are appropriate
    - Participation on snowflake divertor experiments on DIII-D is encouraged
    - Should 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

Advanced Scenarios and Control (2)

- **Comments (cont'd):**
  - **Years 1-2 of NSTX-U operation:**
    - Focus on intermediate I_p = 1.2-1.5 MA seems appropriate
    - Development of divertor heat flux control techniques for higher current operation is appropriate, but density control should be emphasized more strongly in plans (see next page)
    - Testing of disruption detection algorithms and real-time control is appropriate but should proceed at lower priority to above goals
    - *Should include focused activity on validation of off-axis NBI (heating, torque, current drive)*
  - **Years 3-5 of NSTX-U operation**
    - Focus on fully non-inductive and I_p = 2 MA operation are appropriate
    - *Advance density control capabilities to extent possible in planning (see next page)*
    - *Should establish program-level objective of fully non-inductive operation with Ip > 0.6 MA*

Advanced Scenarios and Control (3)

- **PAC suggestions:**
  - Modeling indicates range of achievable collisionality in NSTX-U is fairly limited – factor of 3-4 lower than presently possible
    - → Need improved density control to achieve lower f_{GW} to expand range of collisionality
  - Co-mingling of scenario development and PFC research in program plan introduces large amount of uncertainty in achieving objectives of either
  - Disruption detection algorithms that identify disruption precursors sufficiently early to **avoid** disruptions, not just mitigate them, would be an enormous advance