NSTX PAC-29

Meeting Debriefing
Friday, January 28, 2011

- General Observations
- Charge 1a: Opportunities for New Science Results
- Charge 1b: Opportunities to Support Upgrade
- Charge 2: NSTX aligned with OFES Vision
- Task Group Comments

General Comments (i)

- 2010 extremely productive (amazing; congrats)
  - 4 PRLs, 10 DPP invited talks, 8 IAEA talks, 57 scientific publications
  - 2941 plasma shots in 15.4 run weeks w all milestones completed on or ahead of schedule
- High-beta control (!); CHI start-up (!); BES (!); Snowflake (!); ELM triggering (!); EP H-mode (!); λ_q SOL scaling (!); Divertor diagnostic and modeling very good (!)
- NSTX continues to benefit from theory-experiment-simulation involvement, inter-machine studies, strong collaborator participation; and doctoral students
- NSTX responded very well to PAC suggestions (thank you!)

General Comments (ii)

- NSTX Li research program is successful, advancing understanding and technical experience with Li.

  However, the LLD as a future divertor for NSTX-U (and for fusion) remains uncertain.

- The PAC continues to support installation of Mo tiles in order to inform your decision for the NSTX-U divertor.

  However, the PAC urges NSTX (1) install the full ring of Mo tiles (being aware of critical installation requirements) and (2) to devote sufficient run time and research effort to evaluate the impact of the tiles and the effectiveness of Li deposition

General Comments (iii)

- Because of the importance of divertor issues to your next 5-year plan, the PAC also recommends the upcoming run begin with “non-Li” start-up w/ Boronized C; this will…
  - re-establish an ELMing H-mode (having density & impurity control) base-line without Li; and
  - demonstrate two-feed, full-power HHFW wo/Li, and investigate the compatibility of HHFW with NBI, your Upgrade plans, etc
- Finally, since a primary focus of the NSTX-U 5-year plan must be demonstration of high-performance, non-inductive ST discharges to inform next step fusion development choices.

  The PAC suggests you launch a serious Cryopump/Divertor geometry design study (well before 5-year plan) and develop conventional alternative to insure against the uncertainties associated with an advanced LLD design for NSTX-U

General Comments (iv)

- In time for the PAC-31 meeting, prepare a plan for outage activities including initial Upgrade discharge plans, design and scoping studies for Upgrade success, and Upgrade discharge targets
- Plan to optimize how personnel will be assigned, how collaborators will contribute, and how best to use Outage period to maximize ST research and preparation for Upgrade

(1a) Do the research priorities/milestones exploit opportunities for new and major results prior to outage?

FY2011-12 NSTX research milestones
(**base** and *incremental*)

	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	4 / 10	10
1) Transport & Turbulence		R11-1 BES, High-k Measure fluctuations responsible for turbulent electron, ion, impurity transport	
2) Macroscopic Stability Assess sustainable beta and disruptivity near and above the ideal no-wall limit		R11-2 2^{nd} SPA, RWM state-space control Assess ST stability dependence on aspect ratio and boundary shaping (with ASC TSG)	IR12-1 *Real-time rotation, 2^{nd} SPA, RWM state-space control, HHFW* *Investigate magnetic braking physics and toroidal rotation control at low ν^* (with ASC TSG)*
3) Boundary/Lithium Physics Assess H-mode characteristics as a function of collisionality and lithium conditioning		R11-3 Snowflake, MPTS, Lithium Assess very high flux expansion divertor operation (with ASC TSG)	R12-1 MAPP, BES, High-k, Lithium Assess relationship between lithium-conditioned surface composition and plasma behavior
4) Wave-Particle Interaction Characterize HHFW heating, CD, and ramp-up in deuterium H-mode			IR12-2 *Tangential FIDA, BES, reflectometer* *Assess predictive capability of mode-induced fast-ion transport*
5) Solenoid-free start-up, ramp-up			R12-2 CHI, NBI, HHFW Assess confinement, heating, and ramp-up of CHI start-up plasmas (with WPI/HHFW TSG)
6) Advanced Scenarios & Control			R12-3 SGI, Lithium, HHFW Assess access to reduced density and ν^* in high-performance scenarios (with MS, BP TSGs)
7) ITER urgent needs, cross-cutting		R11-4 BES, High-k, 2^{nd} SPA H-mode pedestal transport, turbulence, and stability response to 3D fields (cross-cutting with T&T, BP, MS)	
Joint Research Targets (3 US facilities): Understanding of divertor heat flux, transport in scrape-off layer		FY11 JRT MPTS, MSE-LIF Characterize H-mode pedestal structure	FY12 JRT BES, High-k Understand core transport and enhance predictive capability

4 of 9 FY11-12 milestones involve boundary physics:
R11-3, R11-4, R12-1, FY11 JRT

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(1a) Do the research priorities/milestones exploit opportunities for new and major results prior to outage?

- Short answer: "yes"

  The PAC endorses your emphasis on boundary, edge turbulence, pedestal, divertor studies

- The PAC expects the Research Forum will provide some focus and priority among the research topics, and we urge the NSTX to use the prioritization from the ResForum to make sure that most important physics areas are investigated throughly (instead of investigating many areas with less focus.)

- Also, carefully complete your $R/a \approx 1.4$ "to do list" (as part of your of scaling studies to Upgrade)

(1b) Do the research priorities/milestones support needed preparation for NSTX-U?

- Short answer: "yes"

  The PAC endorses your plans to emphasize divertor physics, the study of upper-null snowflake, your planned installation and study of Li-coated/Mo-tiles,

- Additionally, because of uncertainties associated with impurity accumulation, the PAC recommends (1) you explore and develop an ELMing H-mode option (wo/Li and w/Li) for NSTX-U long-pulse, high-performance discharges, (2) work to improve your understanding of impurity transport and confinement, and (3) investigate impurity control techniques, like central electron heating, gas puff, etc.

(2) NSTX/NSTX-U well-aligned with OFES vision areas

A vision for U.S. fusion research in the coming decade has emerged from OFES emphasizing 4 research themes:

- **Plasma dynamics and control**
  - Perform detailed measurement of underlying processes, connect to theory, develop integrated understanding, demonstrate advanced scenarios in tokamaks
- **Materials in fusion environment, harness fusion power**
  - Understand and control processes beyond the last closed flux surface, including open field line physics, plasma-surface interactions, coupling between SOL & PSI
  - Determine the fusion nuclear science facility (FNSF) geometry
  - Determine the materials the FNSF will be made from and should test
- **Validated predictive capability**
  - Increase emphasis on validation of physics models incorporated in simulation
  - Increase confidence in extrapolating tokamak/ST in support of ITER, next-steps
- **3-D magnetic fields**
  - Determine the optimum level of 3D field in toroidal magnetic configuration accounting for both physics and engineering complexity in the optimization
    - Enhance the theory of 3-D equilibria, stability, and transport research
    - Increase emphasis in 3-D fields near-term on domestic facilities

(2) NSTX/NSTX-U well-aligned with OFES vision areas

- Short answer: “yes”, but…
- NSTX is charged to determine the credibility of the ST for a FNSF/CTF. NSTX/-U program priority must be to resolve key “gaps” to next step ST devices.

  The contributions from NSTX/-U to each of the four vision areas must be guided by this priority.
- NSTX-U must demonstrate NI/stationary discharges that illustrate ST/CTF/FNSF; $2\pi R$ creates challenges for ST divertor

Topical Science Groups

- Boundary Physics
- Li Research
- Transport
- MHD
- HHFW & Energetic Particles
- Solenoid-free start-up
- Advanced Scenarios and Control
- ITER/Cross-Cutting/Enabling Physics

Boundary Physics NSTX Topical Science Group – 1

- **2010 accomplishments are impressive**
  - Completed FY10 divertor heat-flux-width JRT; engaged in FY11 pedestal JRT
  - Snowflake divertor formation and performance clearly demonstrated
  - Work to understand gas puff timing to control carbon
  - Increased personnel working in Boundary Physics area
  - Numerous important publications, including several PRLs
  - Continued study of improved H-mode (H_{95}~1.7); B_{tX} and R_X dependence
  - Prepared 8 additional edge Thomson channels for FY11

- **2011-12 plans address many key Boundary Physics issues**
  - Connect well to OFES research themes, esp. theme II on PMI
  - Target BP issues to allowing Upgrade to reach research goals
    - Assess very high flux expansion divertor operation (R11-3: with ASC)
    - H-mode pedestal transport, turbulence, and stability response to 3D fields; esp. improved H-mode & its ELM stability (R11-4: with IUN, T&T, MS)
    - Characterize H-mode pedestal structure (FY11 JRT: BP, T&T)
    - Assess relationship between lithium conditioned surface composition and plasma behavior; MAPP operational (R12-1: Lithium TSG)

Boundary Physics NSTX Topical Science Groups – 2

- **Issues for special emphasis/attention**
  - Develop effective strategy for particle control, e.g., a serious cryo-pump design
  - Interpretation of PMI (pumping/heat-flux,) with mixed-materials (C, Mo, Li)
  - Impurity sources (spatial/temporal) and edge screening; ELMing vs ELM-free
  - Careful attention to divertor geometry for pumping/heat-flux; open vs closed, tilt; consider performance of "convention" divertors
  - SOL n_e,T_e, and T_i measurements in divertor/midplane; include mean/ fluctuations for theoretical interpretation/scaling; run more on outer tray?
  - Li reduction of λ_q; sheath-limited SOL? Implications for Li power handling?
  - Establish pre-lithium baseline with boron (snowflake, Mo tiles, HHFW)
  - Comparison with theory/simulations including neoclassical and turbulence

Lithium & Plasma-Material Interactions

- We commend the substantial increase in PMI science capabilities in NSTX
  - Suite of excellent diagnostics: MAPP, heat flux, divertor spectroscopy, ex-situ analysis, etc.
  - Rapid ramp-up of students and collaborators.
- NSTX can rightly claim to be in the worldwide lead for lithium PMI in major confinement devices.
- The performance of LLD was a disappointment BUT…
- we note that NSTX has the tools in place to properly assess the PMI <u>science</u> of what did and did not work, and that's the correct way to move forward for both Lithium's enabling capabilities in NSTX & → FNSF, etc.

Lithium, LLD & Moving Forward

- Given the present evidence, we agree with the NSTX strategy to install Mo tiles but this <u>must</u> be properly integrated into the entire run plan to provide several go/no-go decisions on Upgrade
  - Assure proper mechanical installation/alignment
  - <u>Cleaned</u> Mo surfaces, even if it takes dedicated runs
  - Optimized lithium deposition rates: ~ 0.1-1 micron?
  - Thermography, recycling, MAPP: 3-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).
  - Was this LLD a true test of liquid Li PFC? Probably not. But weak-null result 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 IBD Mo (and LLD) as outlined above is timely to this critical programmatic decision.
- Given central role of PMI to NSTX/ST program continue investment and upgrades to PMI science capabilities in Upgrade regardless of path.
  - Divertor TS, material probes, Snowflake at small B angle, etc.

Turbulence and transport

- **FY 2010– a very successful year**:
- First BES and SXR measurements
- Clarification of the scaling of turbulent transport and density fluctuations with collisionality
- First measurements of impurity transport. Progress in controlling impurity influx and transport
- Determination of intrinsic torque density profile
- Progress in understanding LH transition and interplay with core confinement- sensitivity to X point major radius.

Turbulence and transport
Work plan 2011-2012 - recommendations

- **Fully exploit the present set of diagnostics before removing the high k scattering diagnostic; continue to design of a new high k diagnostic**
- **Electron transport** : clarify the respective roles of ETG, GAE and microtearing modes by comparing low and high k measurements.
- **Impurity transport** fully use SXR to assess impurity transport – pursue effort to prevent impurity accumulation (ELM pacing, snowflake divertor, RF heating, …).
- **Edge turbulence/LH transition**: understand low $\delta n/n$ and power threshold with Li, dynamics of the LH transition - clarify conditions for onset of EP H mode
- **Code validation**: increase the effort to implement synthetic diagnostics adapted to NSTX diagnostics.

Macroscopic Stability

- Very strong program:
  - RWM control: role of precession drift resonance
  - RMP: Demonstration of RMP triggering of ELM
  - NTM: scaling of threshold
  - Congratulations J.-K. Park on Early Career Award
- Good alignment with OFES, ITPA priorities
- Responsive to PAC-27
  - NTM: dependence of threshold on the ion banana width, contributions to the validation of `Rutherford' models by providing data on the role of the curvature term
  - ITER: study of rotation of halo currents
- Distinguished by uncommonly effective EX-TH interaction.

Recommendations

- Continue exploring commonalities between RWM, RMP physics; involve stellarator designers in RMP research (MHD stability of 3D equilibria w/o stellarator symmetry)
- Give greater priority to halo current studies before shutdown: address ITER questions regarding forces, etc…
- Devote effort to applying state-based controller to EFC and locked-mode avoidance for low-n_e startup (synergy with RMP research, ITER-relevant)
- Assess disruption prediction and mitigation in context of NSTX-U

Energetic Particle Physics

- **Significant progress was made in energetic particle research during 2010:**
  - Unique local capability was exploited:
    - NBI system to produce fast ions (with $V > V_A$) in a high beta plasma (NSTX)
    - FIDA, sFLIP probe, NPA, BES, reflectometer diagnostics
    - NOVA-K, M3D-K, HYM, ORBIT, and SPIRAL codes
  - Establishing connection between enhanced thermal / fast ion losses and Alfvenic instabilities:
    - Some evidence of fast ion redistribution by GAE's (by triggering TAE bursts).
    - Used NBI to trigger large TAE avalanches – saw enhanced ion losses.
  - Simulated edge localized CAE's and core localized GAE's with HYM code – good agreement with measured frequency and mode number.

- **Recommendations:**
  - Agree with plans to continue to validate simulation capability as this will aid assessment of fast ion losses for NSTX-U:
    - Validate eigenfunction modeling with HYM code using GAE experiments.
    - Comparison of non-linear M3D-K vs. experiment (mode structure, bursting and chirping behavior).
    - Continue NOVA-K + ORBIT simulations but extend to non-linear regime using M3D-K and use SPIRAL.
  - Start to apply simulation capability to H-mode plasmas in NSTX and NSTX-U. (Especially consider effect of redistribution on current profiles in upgrade)
  - Consider collaborating with GSEP SciDAC Center to incorporate more realistic representations of fast particle distributions in NOVA-K and M3D-K.
  - Will it be possible to study the transition regime between $V > V_A$ and $V < V_A$ in the Upgrade ?

Energetic Particle Physics

- **Significant progress was made in the HHFW area in 2010 despite degraded antenna performance due to increased lithium usage:**
  - Produced RF only H-mode plasmas 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 $f_{NI} = 60\%$.
  - Commend the use of state of the art simulation capability:
    - Good agreement between simulated and measured FIDA signals using coupled AORSA and ORBIT RF to include FOW effects in the analysis of HHFW-fast ion experiments.
    - Prediction of experimentally observed dependence of surface wave excitation on $[B_\phi, k_\phi]$, using 3-D AORSA full-wave simulations with 2-D NSTX wall boundary

- **Recommendations:**
  - Obtain baseline antenna operation with Boronization before beginning lithium campaign.
  - Revisit RF + NBI H-modes at higher I_P to establish feasibility and assess the level of parasitic losses in combined HHFW-NBI experiments.
  - Pursue density pump-out observation in H-mode Is this C pump-out?
  - Revisit the absorption and propagation physics of HHFW in NSTX-U in light of the fact that the magnetic field for the upgrade will be 1 T and the harmonic resonances will be lower.
  - Use validated simulation capability (AORSA+ORBIT RF) to assess HHFW-NBI interaction at lower harmonic number in NSTX-U plasmas.
  - Use validated simulation capability (AORSA) to assess surface wave excitation in NSTX-U plasmas accounting for different SOL parameters.

Solenoid-free Startup and Ramp-up (1)

- Remains high priority issue to enable future ST applications (FNSF, reactor)
- Excellent progress for CHI in 2010:
  - Further reduced the solenoid flux required in current ramp-up, now saving up to ½ the flux
  - Made effective use of the absorber coils to limit arcing
  - New absorber coils in the upgrade design appear to not only preserve capability but add new flexibility
  - Good progress using TSC modeling to understand present experiments and to project CHI-driven current at higher BT (recommend this continue)
  - Initiated NIMROD modeling to understand the current drive process; this work will likely yield a physics basis for further optimization

Solenoid-free Startup and Ramp-up (2)

- Recommendations:
  - Full non-inductive sustainment of low current plasma by HHFW remains a good near term goal
    - Experiments in 2009 made some progress in determining power requirement and extrapolation for bootstrap overdrive
    - Agree with the plan for “clean” antenna experiments early in campaign
    - Tests with CHI target plasmas should be lower priority
  - Good plan for more CHI energy, higher current in absorber coils, and full use of lithium for impurity control
  - Maintain and extend diagnostics to characterize CHI plasmas. This data is critical for validating modeling via TSC and NIMROD
  - New inner divertor molybdenum tiles will provide a useful test of impurity generation by CHI cathode
  - Begin assessment of confinement properties of CHI target plasma, e.g., taking advantage of low density capability, and assessment of core accumulation of high-Z impurity from the molybdenum cathode.
  - Agree PEGASUS-like plasma gun experiment be performed before outage period, which provides an important alternate approach to startup
  - Maintain collaboration with DIII-D on outer-PF startup development

Advanced Scenarios and Control (1)

- **Progress in 2010: PAC notes significant progress on several fronts towards integrated high performance plasmas in preparation for NSTX-U**
  - Validation of current drive predictions in ST plasmas
  - Demonstrated new shape control capabilities
    - Simultaneous X-point height and strike-point position control
    - Outer “squareness” control
  - Produced long pulse, high β plasmas at aspect ratio/elongation expected in NSTX-U
  - Demonstrated compatibility of snowflake divertor and high β operation
  - EP-H mode looks to be a potential path to high confinement operation

- **2011-12 Plans:**
  - Control research seems appropriate based on near-term needs.
  - Scenario development should balance search for low-fueling/low core impurity solution with development of ELMing scenarios for impurity/density control

Advanced Scenarios and Control (2)

- **PAC recommendations on 2011-12 plan to take best advantage of NSTX-U upgrades:**
  - 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
  - HHFW: Increase emphasis on determining 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.
- **PAC concerns:**
  - Path forward to density/impurity control in high β plasmas is extremely uncertain. NSTX team should take a balanced approach in assessing possible solutions:
    - Increased Li/Mo coverage
    - Divertor cryopumps
    - ELMing H-mode scenarios
  - Best cases of bootstrap current (high βp, high q95) achieved 50% bootstrap current. Off-axis NBI provides ~ 350 kA @ 6 MW. PAC recommends detailed modeling of non-inductive capability in NSTX-U

ITER urgent needs, Cross cutting and enabling

- Welcome the formation of the new ITER/CC TSG.
- Most critical areas have been identified:
  - Particle and impurity control in support of NSTX-U.
  - Effect 3D perturbation on pedestal and edge transport and turbulence in support of ITER.
  - Coordinated ELM research (ITER, NSTX-U).
- NSTX would be well placed to address additional ITER urgent needs that also benefit NSTX-U.
  - Contribute to the new disruption DB including heat loads on wall/targets. (NSTX-U halo current distribution)
  - Improve the understanding of the effect of ELMs/disruptions on divertor and first wall structures.
  - Improve understanding of SOL plasma interaction with the main chamber (in particular impurity and particle source distribution and effect of high Z impurities/transport).
- Compatibility of 3D perturbation with Snowflake divertor.
- Strongly recommend to evaluate the cryo-pump/divertor geometry as available option for particle control in the Upgrade.
  - Compare wall pumping (with and w/o Li) with envisioned cryo-pump system.
  - Assess long pulse performance with LITER/LLD pumping.