U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

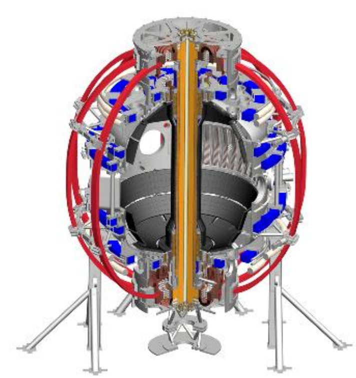
Present and Future ORNL Contributions to NSTX-U Research

M.L. Reinke, J.W. Ahn, T. Gray, J. Canik,
J. Caughman, S. Diem, C. Lau, J. Lore

FES Quarterly Review
2/8/16

OAK RIDGE National Laboratory

PPPL



Present ORNL Research on NSTX-U Focuses on Boundary and RF Physics

- boundary physics elements
  - power and particle exhaust
    - lead SOL heat flux width experiments
    - physics design of cryo-pumping system
  - H-mode pedestal physics
    - impact of lithium on recycling and edge microstability & turbulence
  - effects of 3D fields on edge the edge plasma
    - ELM control via pulsed and steady 3D perturbations
    - modification of divertor characteristics with 3D fields
- RF heating and current drive program elements
  - support HHFW design, operations, experiments & modeling
  - diagnose RF/plasma/antenna interactions, supporting experiments and modeling towards high power & reliability
  - assist in design and evaluation of ECH/EBW options

FY16 ORNL Diagnostic Activities

- responsible for NSTX-U infrared imaging diagnostics that measure heat flux to PFCs
  - wide-angle, 30 Hz IR camera for 3D structures
  - upper/lower divertor 1.6 kHz for outer strike point
- key tools to understand local HHFW/SOL interactions
  - fast (20 μs/sweep) X-mode reflectometer for n_e profile, fluc.
  - RF-compensated double probe, probes for local n_e, T_e
- developing prototype divertor IR-imaging bolometer
- contributing to analysis for other NSTX-U tools
  - AXUV diode-based P_{RAD} measurements (JHU/PPPL)
  - VUV/SXR impurity spectroscopy (LLNL)
  - tangential IR camera viewing RF antenna (PPPL)
  - centerstack & upper divertor spectroscopy (UT-K)

Complementary ORNL Modeling Expertise

- 2D and 3D fluid boundary modeling tools
  - SOLPS, EMC3-EIRENE
- edge turbulence simulation
  - GS2 and GENE gyrokinetic codes to study impact of Li on pedestal
  - exploring ways to extend to fluid turbulence modeling (BOUT++)
- 3D equilibrium and perturbed plasma response
  - VMEC (+STELLOPT code suite for transport, stability)
  - collaboration with IPEC/GPEC, M3D-C1 teams on simulating combined magnetic + transport response using EMC3-EIRENE
- using MHD codes for linear stability of pedestal (ELITE)
- tools for modeling RF physics and technology
  - AORSA, COMSOL

interest in linking multiple tools to give a "pedestal-to-wall" picture for exhaust solutions

Near-Term Research Priorities

- leading high priority, FY16 milestone experiments
  - XP 1514 "Heat Flux and SOL Width Scaling in NSTX-U" **Gray**
  - XP 1536 "Resonant ELM frequency behavior as a function of q95 with 3D fields" **Lore, Ahn**
  - XP 1557 "Interaction of applied 3D fields with detachment" **Ahn** (ITER/ITPA), XP 1558 "effects of 3D gas puffing" **Lore**
- important contributions to characterization of HHFW SOL losses in H-mode plasmas (XP 1510)
  - assisting in XPs on HHFW current drive (1566), RF/NBI interactions (XP 1533) led by PPPL
- experiments that prepare for facility enhancements
  - XP 1528 "Characterize Plasma Near Plenum Entrance" **Canik**
  - assisting with XP 1526 "high-Z reference discharge" for testing of FY17 role of high-Z tiles **Gray**

FY17+ Diagnostic Extensions

- expand IR coverage to look at inner strike point and center-stack & more (30 Hz cameras)
- extend fast IR by using multi-color optics, test spectrally resolved IR to improve heat flux on coated PFCs
- development of radiated power diagnostics for core and boundary using resistive bolometers
  - 24-ch tangential midplane (never done on NSTX)
  - re-engineering lower x-point views for divertor radiation
- investigating active/passive emission spectroscopy to enhance diagnoses of RF/plasma interactions
- exploring potential of fiber-optic temperature sensing to avoid EM interference on bolometry and tile calorimetry

Longer-Term Research Contributions

- ORNL excited to contribute and lead aspects of the exploitation of a high-Z NSTX-U
  - high-Z experience via research on DIII-D, JET and C-Mod
  - diagnostics (IR, bolo) & boundary modeling for low-Z seeding
  - RF tech. (HHFW, EBW), diag./modeling for high-Z control
  - *can ORNL help accelerate the PFC changeover and use NSTX-U as a platform for large scale materials tests?*
- continue strong emphasis on the impact of 3D fields on pedestal and boundary physics (NCC upgrade?)
- enhance integration of boundary modeling expertise with wider NSTX-U pedestal/boundary diagnostics
  - ORNL collaborators key leaders in 2D and 3D boundary modeling for NSTX, need to continue and extend for NSTX-U

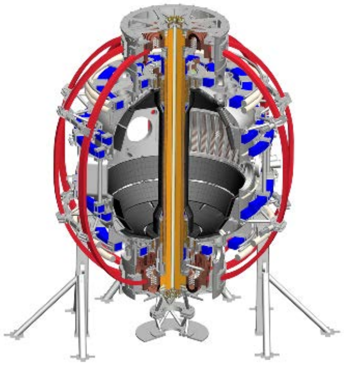
NSTX-U Program FY2016 Q1 Report

Jon Menard, Stan Kaye, Masa Ono (PPPL)

For the NSTX-U Team

PPPL and FES
February 8, 2016

*This work supported by the US DOE Contract No. DE-AC02-09CH11466



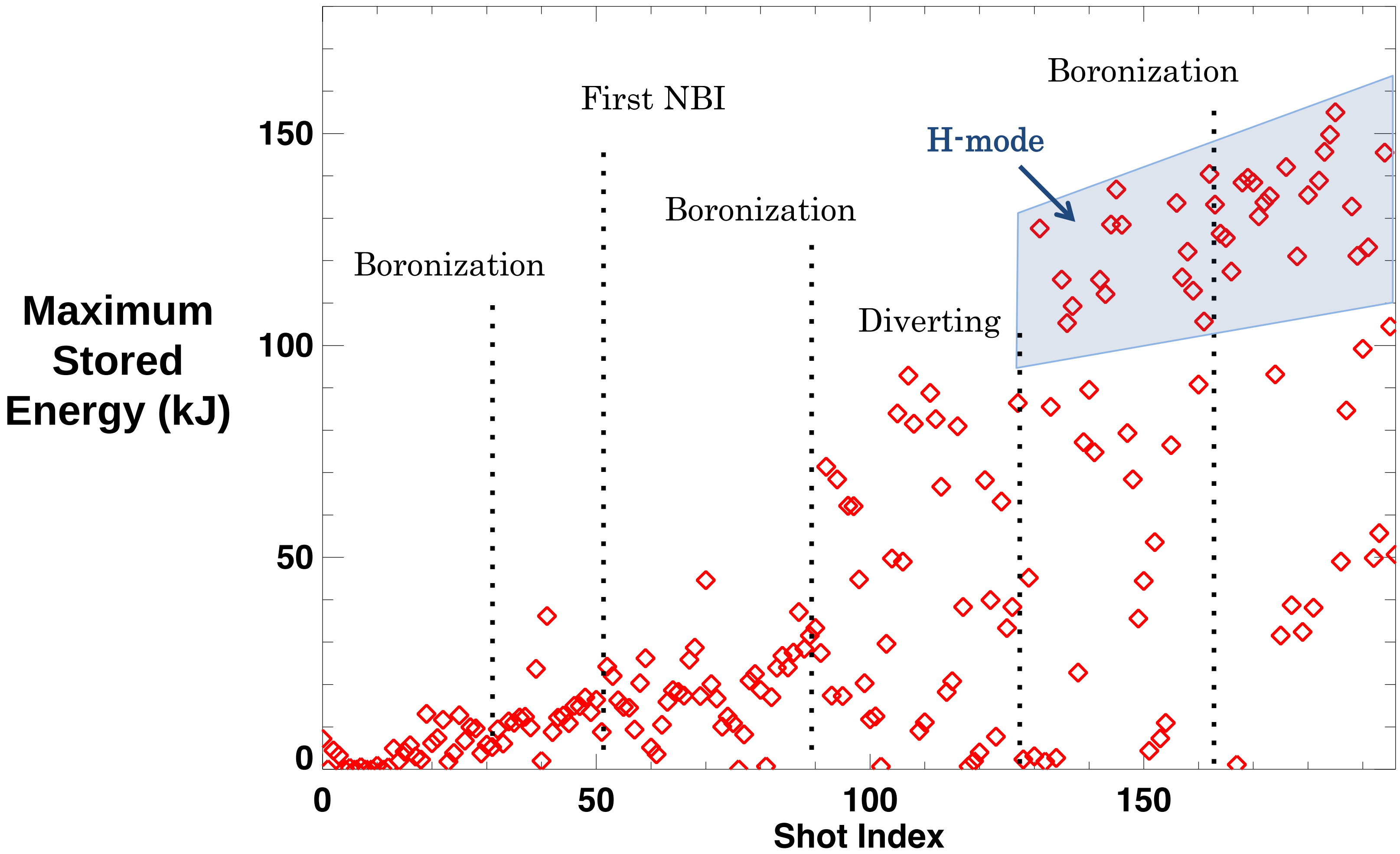
Outline

- Overview of initial operation of NSTX-U
- PAC-37 charges, recommendations
- Run Coordination status

Summary of NSTX-U Plasma Operations

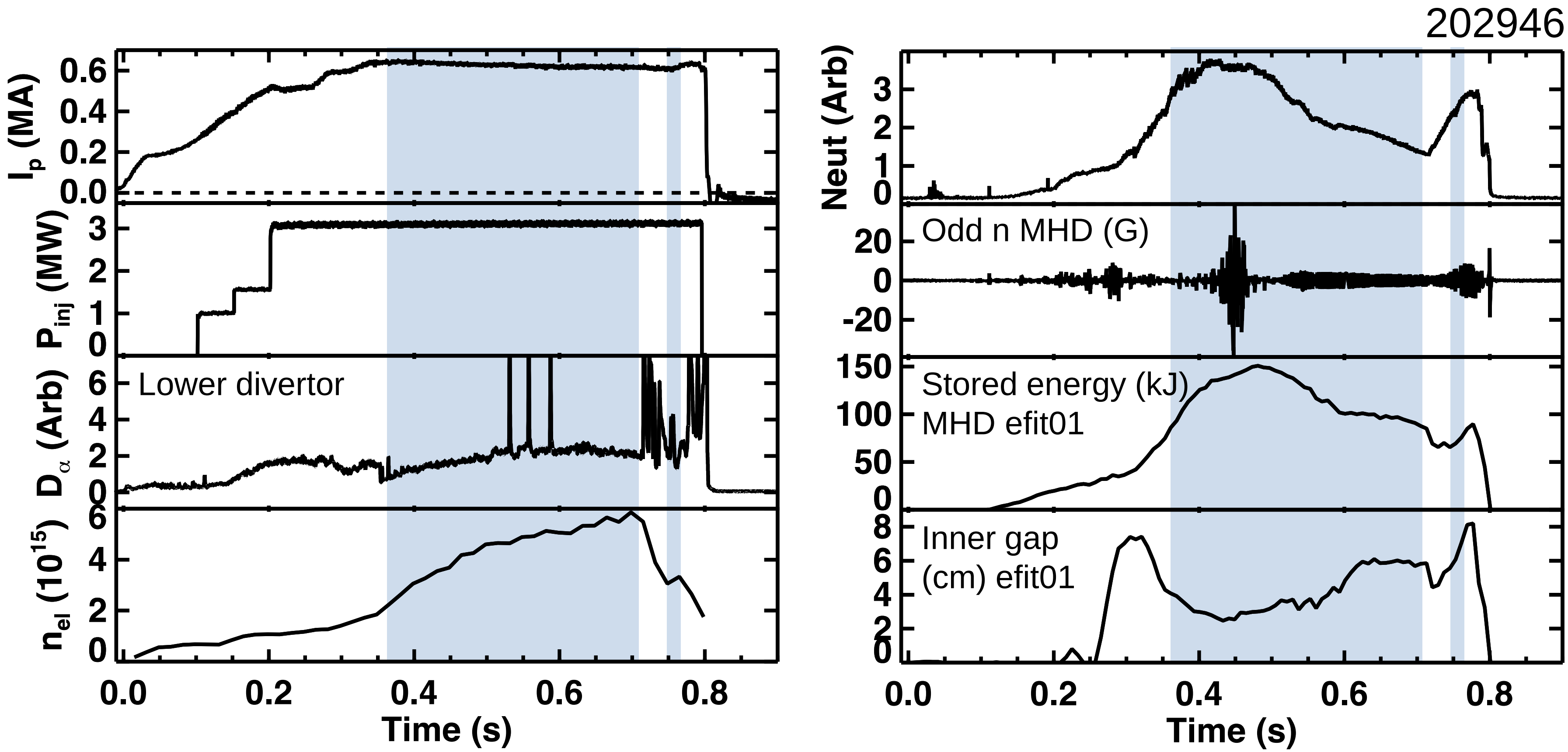
- CD-4 milestone (I_p > 50kA) completed August, 2015
  - I_p ~ 150 kA with GDC and CS bake
- 2.5 days of operation following full vessel bake, before boronization (December, 2015)
  - I_p = 500 kA flattop with inner-wall limited L-mode
  - Progress enabled by I_p, gap and Z feedback control
- 2.5 weeks of operations in January, 2016
  - Neutral beam heating: up to 4MW total from four sources
  - Diverted L-mode and H-mode operations at I_p = 600 kA
    - Good progress toward goal: 1.4 MA, 2s ELMy H-mode by week 8
  - Three boronizations completed

Significant progress over the first few weeks in commissioning NSTX-U

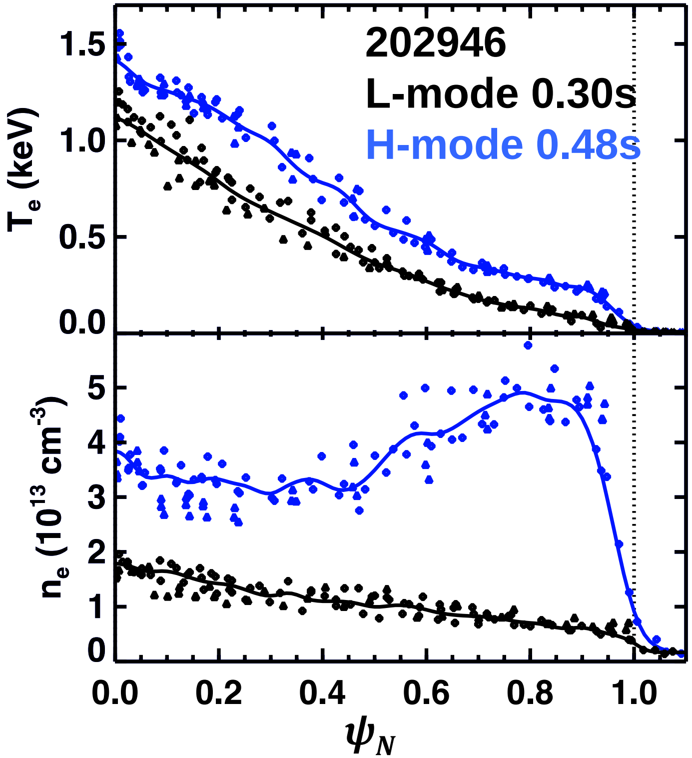


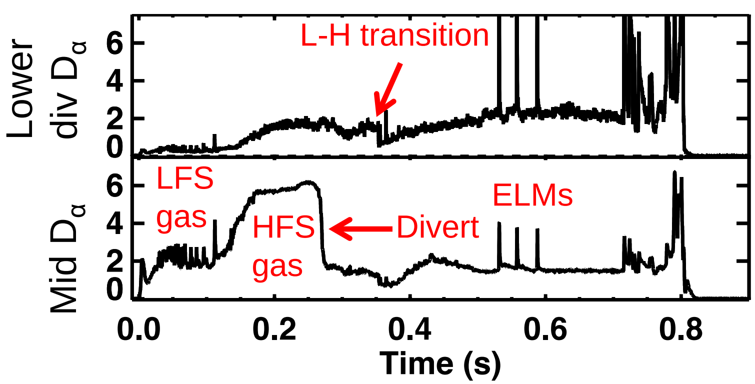
Reliable H-mode access has been achieved on NSTX-U

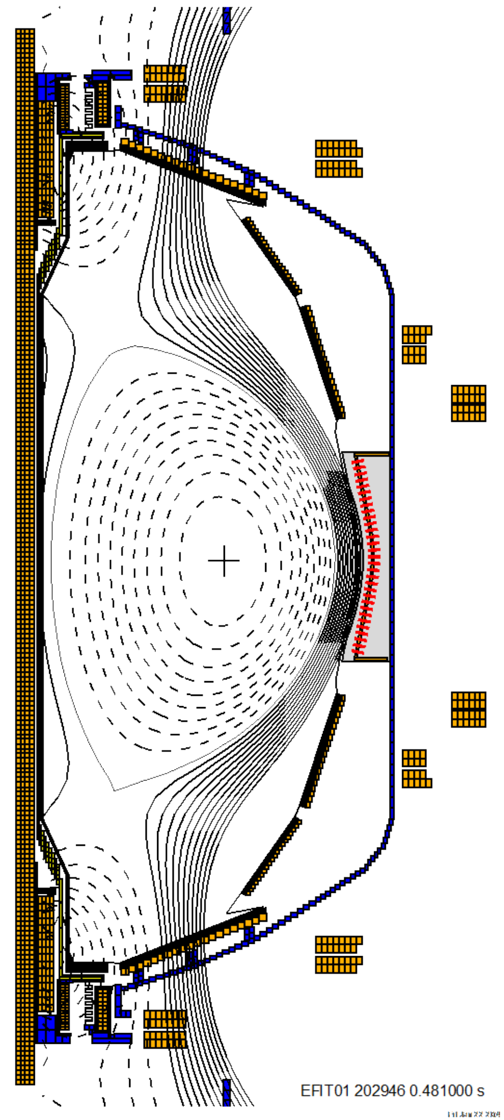
- H-mode with NBI > 1.5 MW at I_p > 500 kA, B_T = 0.65T
  - H-mode achieved with only 0.9 MW NBI in a few cases
  - B_T exceeds maximum in NSTX



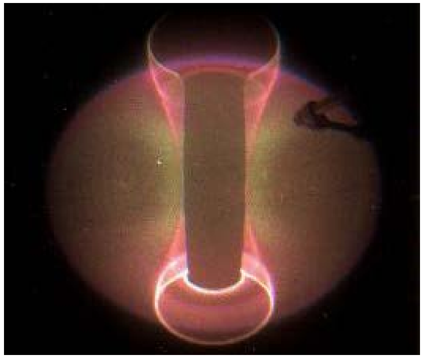
Excellent diagnostic availability has enabled rapid progress



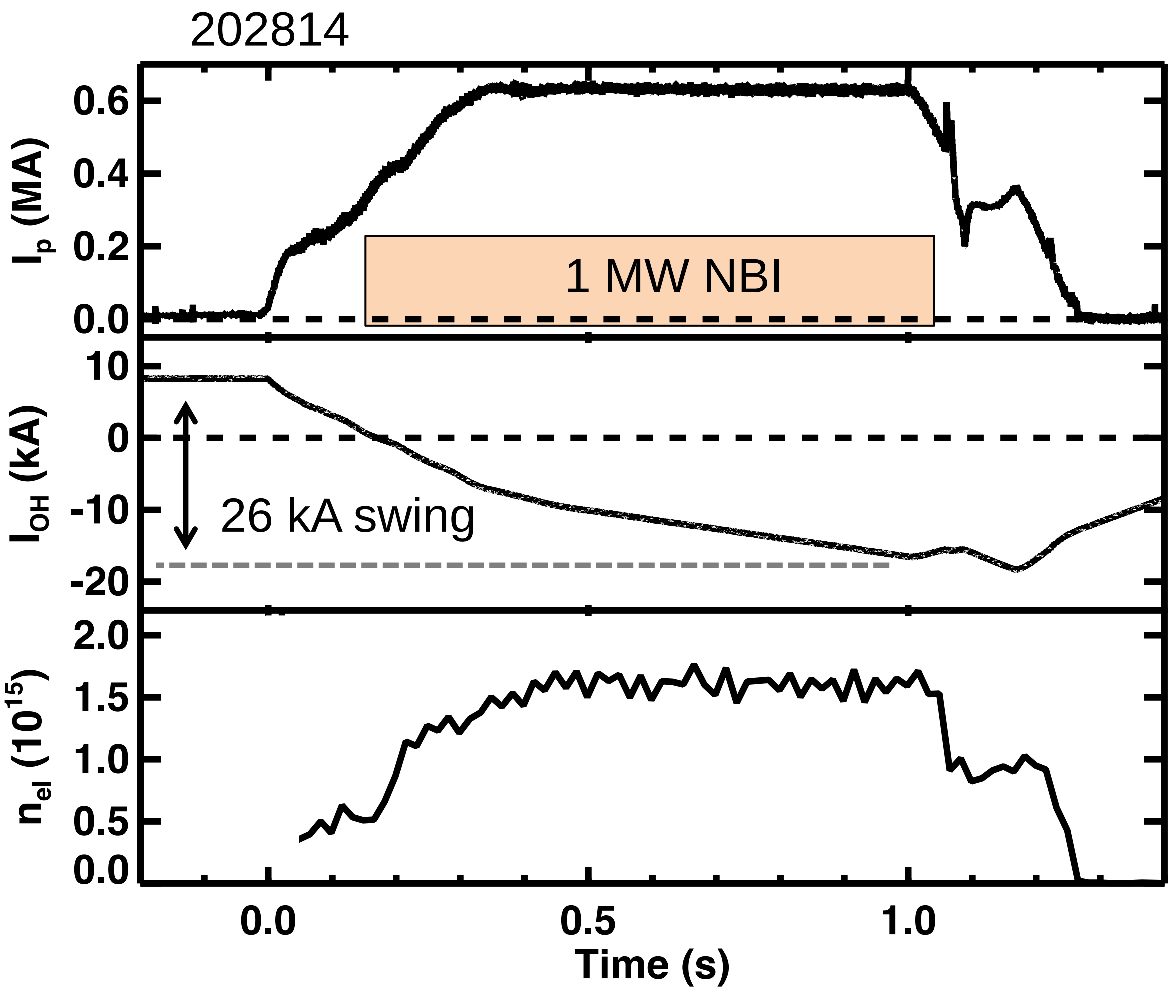


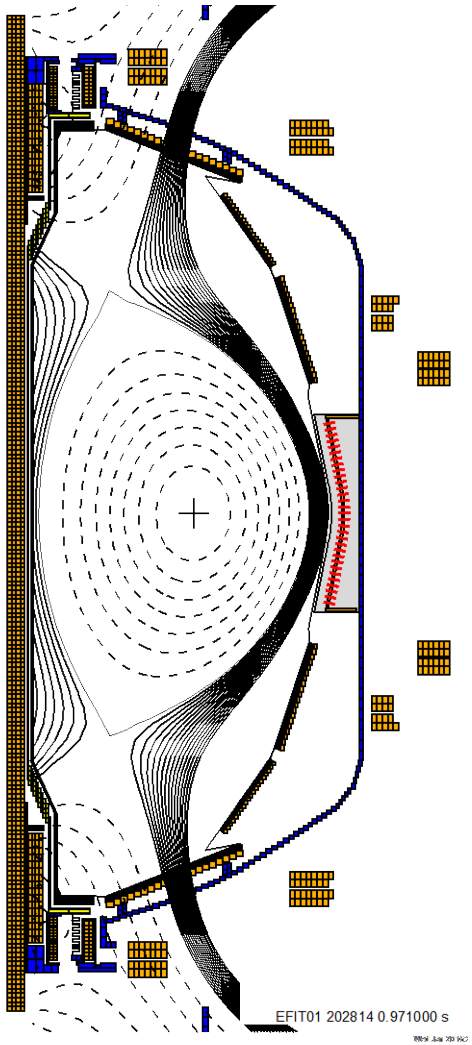


I_p	0.58 MA
B_{T0}	0.61 T
P_{NBI}	3 MW
P_{OH}	0.2 MW
A	1.6
κ	1.53
l_i	0.97
δ_{lower}	0.55
W	151 kJ
β_T	7.86%
β_P	1.22%
β_N	4.66
τ_e	50 ms



Stationary diverted L-mode operations has also been achieved





These discharges have already been used to support research operations

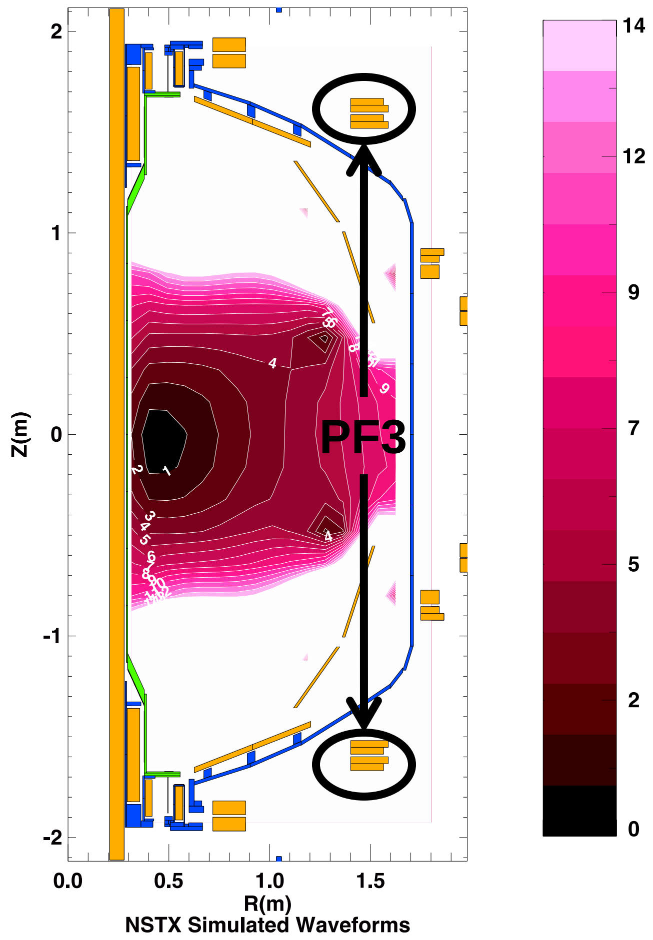
Significant progress has been made on a number of commissioning activities

- XMP-101: Inductive startup on NSTX-U
- XMP-106: Magnetics calibration
- XMP-126: Initial I_p and R control
- XMP-105: Initial n=0 control
- XMP-118: Boronization characterization
- XMP-127: Neutral beam checkout
- XMP-132: Automated rampdown development
- XMP-107: Neutron calibration transfer
- XMP-133: Increase elongation in L-mode
- XMP-116: Initial H-mode access in NSTX-U
- XMP-121: Six SPA and RWM coil checkout
- XP-1506: Low-beta locked mode studies

Inductive startup scenario informed by vacuum field modeling

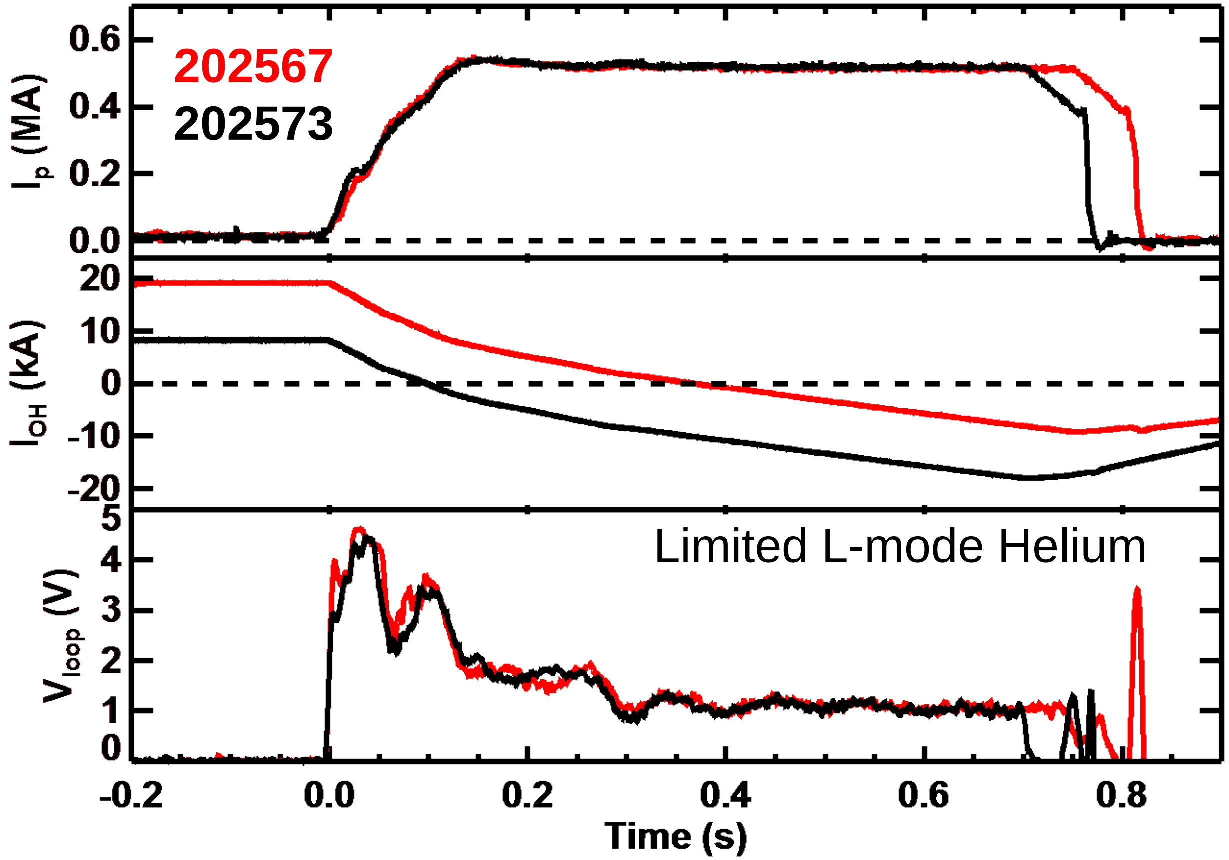
- Solenoid provides confining B_Z
  - Bipolar PF3 coils null this field
  - V_{loop} via ramping OH and PF3 fields
- Null properties sensitive to fields from induced wall currents
  - LRDFIT wall model used to prepare scenarios in advance
  - About 200 kA total wall current at breakdown
- PF3 and PF5 coils provide additional B_p following breakdown
  - Must maintain passive R and Z stability

Simulated B_p fields at breakdown



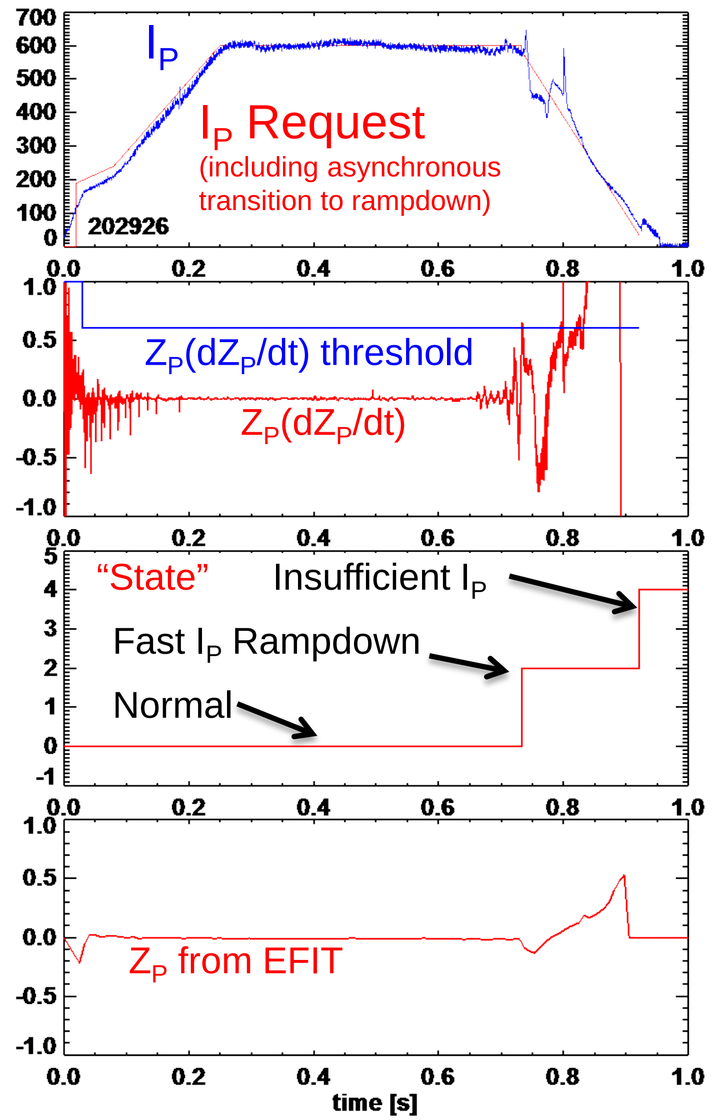
Routine startup at two OH precharge levels has been demonstrated

- Goal: scalable scenario for arbitrary OH precharge
  - Some experiments desire flexible precharge to optimize constraints from coil heating and coil current limits



New capability: automated rampdown used in routine operations

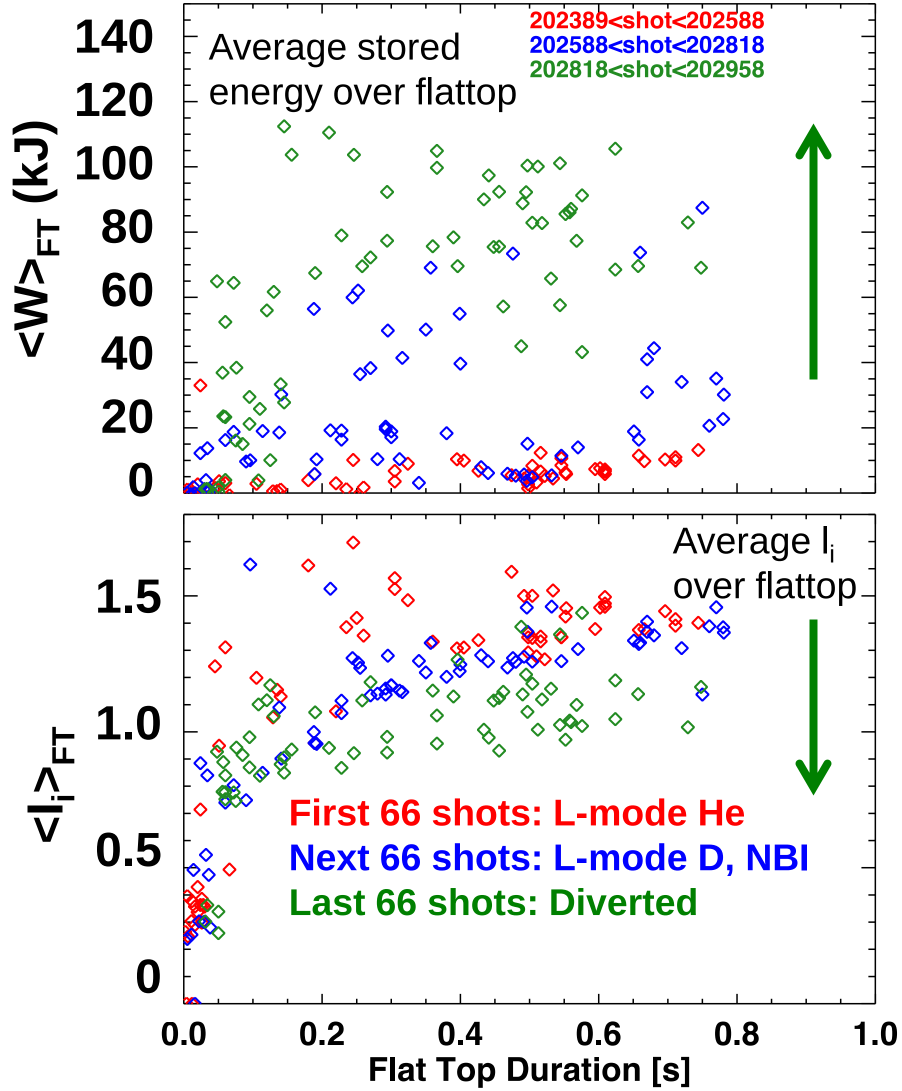
- Plasma control system detects loss of control
  - OH solenoid near maximum current
  - Vertical oscillations exceed threshold
  - Abs(I_p - $I_{p\ request}$) too large
- Feedback control switches to new “states” that attempt to gently end the discharge
- See S. Gerhardt’s PAC talk



Operations will restart with continued goal of developing fiducial ELMy H-mode discharge

- H-mode operations open path to lower l_i
  - Permits larger κ and I_p range
  - Target l_i ~ 0.5 via an earlier L-H transition, larger NBI power and improved wall conditions

- Target fiducial for FY2016 is an ELMy H-mode discharge at I_p = 1.4 MA



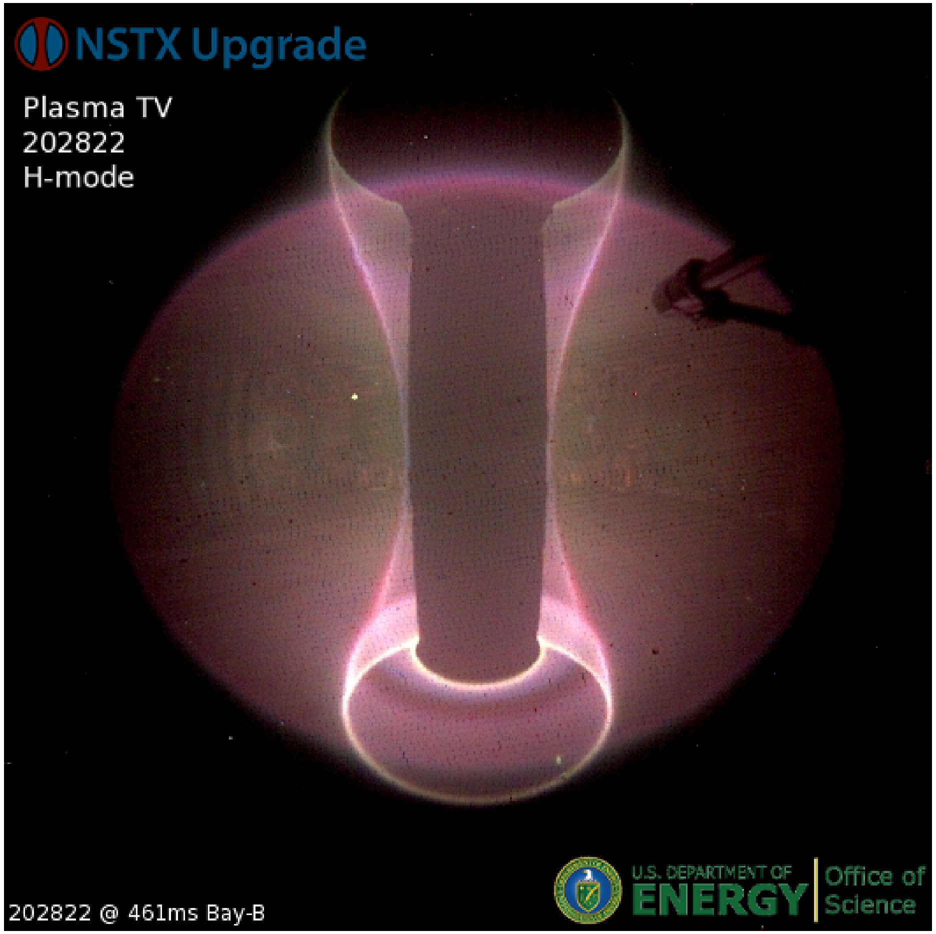
Ongoing commissioning activities will prepare NSTX-U for research program

- Near-term activities include …
  - Optimization of vertical control (see S. Gerhardt's PAC talk)
  - ISOFLUX shape control
    - rtEFIT has been successfully running and is ready to support operations
  - Error field identification and correction
    - Low-beta error field measurements have been completed
  - Diagnostic commissioning and calibration
    - MPTS, CHERS, MSE, NPAs, FIDA
  - NBI power modulation for β control from PCS
    - PCS control of beam termination has been used
  - MHD spectroscopy and RWM control
    - Real-time mode detection in PCS is nearly complete

- Covered in more detail in Jon Menard's PAC talk

Plasma operations on NSTX-U is off to a great start!

- First days of NSTX-U have produced H-mode and stationary diverted L-mode discharges
- Control and diagnostic capabilities established quickly
- Research program starting in parallel with commissioning activities



Outline

- Overview of initial operation of NSTX-U
- PAC-37 charges, recommendations
- Run Coordination status

PAC-37 held Jan 26-28 – 4 charge questions:

- Please assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign
  - Are there any major missing elements, or new opportunities?
- Please assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs.
- Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support “integrated predictive capability”.
- Please comment on the present team prioritization of planned facility enhancements including:
  - Divertor cryo-pump, non-axisymmetric control coils (NCC), 28GHz gyrotron, conversion to high-Z PFCs + liquid metals research

The following slides are an abridged version of the full PAC-37 debrief comments

PAC Comments on 1st Charge Question

1. Please assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign. Are there any major missing elements, or new opportunities?

- "You commented a number of times on how the new organization structure for the NSTX-U program with three overarching science groups (core, boundary, integrated scenarios) has been effective in helping you define priorities and optimize the run plan. The PAC sees the benefits of this new organization, and we anticipate this will be a very effective foundation for the NSTX-U program going forward."
- "The PAC is concerned that the milestones for FY17 rely heavily on progress in FY16. The challenges for attaining sufficient progress in FY16 may be greatest in the boundary science area."

PAC Comments on 2nd Charge Question

2. Please assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs.

- "NSTX-U program is well aligned with priorities and initiatives identified in recent community strategic planning and workshops"
- "As for ITER, while the NSTX-U program is well connected via ITPA, your present research could impact ITER urgent needs:
  - Unique capability to investigate massive gas injection at different locations in the poloidal plane, **which should be highest priority**
  - The digital coil protection system (DCPS) is likely to be a good model for ITER
  - Active prediction and avoidance of disruptions in the PCS
  - Novel pellet-pacing experiments for ELM control using lithium, B4C, and vitreous graphite
  - NSTX-U is likely to produce important input to RMP control physics and development"

PAC Comments on 3rd Charge Question

3. *Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support "integrated predictive capability"*

- "The PAC is very pleased to see that the theory partnership is officially established following the one-year trial period. We strongly endorse continuing the partnership."
- "The goal for integrated predictive capability obviously extends beyond NSTX-U and PPPL. While the partnership is founded on several flagship codes and modeling capabilities, it is essential to maintain strong collaborations for a goal as large as predictive capability, both to and from the PPPL-based research activities."

PAC Comments on 4th Charge Question (1)

4. Please comment on the present team prioritization of planned facility enhancements including: divertor cryo-pump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research.

- "The PAC agrees that all of the planned facility enhancements could bring valuable and important new capabilities to NSTX-U."
- "The PAC agrees with your assessment that the divertor cryo-pump is highest priority. The plan for finalizing the physics and engineering design appears sound, but it is not conservative. The PAC urges that sufficient resources be dedicated to finalizing the design and completing the construction no later than the one-year outage planned for 2018."

PAC Comments on 4th Charge Question (2)

4. Please comment on the present team prioritization of planned facility enhancements including: divertor cryo-pump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research.

- “Recent research, e.g., ASDEX Upgrade and JET, shows that core RF heating is essential with an all-metal-wall boundary.
- Neoclassical transport is accentuated in the ST, and the effect of impurities related to a metal wall could be even more challenging.
- There is presently no capability for core RF heating in NSTX-U that is compatible with large NBI heating.
- The gyrotron opens the possibility for EBW heating, but the physics basis is still in development.
- The PAC strongly recommends increased emphasis on HHFW, as described in slides following.”

Other PAC comments highlighted by JEM (1/4)

- “TRANSP should be listed in the set of flagship codes.
  - Broadening the contributions by the theory partnership to TRANSP and predictive TRANSP would be beneficial to NSTX-U and the broader community as well as to the goal of improving our integrated predictive capability.”
- “Macrostability TSG research thrusts respond to urgent ITER needs. Hugely impressive growth in DPAM aligned with FES strategy and ITER priorities, and well coupled with Theory. Well done!”
- “In FY 16, organization of experiments around multi-TSG XPs is very effective in the investigation of the impact of major upgrades Ip/BT and 2nd NBI, covering global confinement aspects as well as local physics on multiple transport channels.”

Other PAC comments highlighted by JEM (2/4)

- “The PAC recommends emphasis be given to experiments which can also assess probability of achievement of long term goals: In particular characterization of impact of rotation (neoclassical vs turbulent) and HHFW on high Z impurities (and bulk plasma). Neon may not be sufficiently high Z.”

- “Recommend Core SG to widely look at the effect of rotation on stability. This can probably be captured parasitically. NSTX-U is likely to rotate very rapidly, so you should exploit this unique capability. Perhaps a small working group to oversee this is warranted, including theory where flowing equilibria may be needed in analysis”

Other PAC comments highlighted by JEM (3/4)

- “Commend the NSTX-U team for moving the transition to high-Z and liquid Li earlier in the 5-year plan. This is important in terms of mission of clarifying a ST-FNSF and to further establish and continue NSTX-U’s global uniqueness.”
- “The completion of some (boundary) milestones seems overly aggressive and the PAC is concerned some may not be able to completed on this aggressive schedule due to limitations of machine capabilities and availabilities. For example, can the impact of high-Z on operation scenarios in 2017 be assessed with only a single row of high-Z?”
  - The PAC recommends accelerated development of control of divertor radiation feedback, implementation of divertor radiation diagnostics, snowflake control development, as well as time to test appropriate control algorithms, in order to meet the R17-1 milestone

Other PAC comments highlighted by JEM (4/4)

- “The integrated modelling work done in preparation for experiments on plasma control and current drive studies, both using TRANSP, is impressive.
  - Examples are the preparation for experiments on several different control schemes and the modelling of fully non-inductive start-up.”
- “The run-time allocation is reasonably well balanced and addresses the main research milestones set-out for 2016. However, the time allocated to HHFW and CHI is marginal.”
  - “HHFW should have increased experimental and simulation effort to find a path to avoid SOL losses and minimize absorption on beam ions”
- “The PAC congratulates the NSTX-U Team on the design, implementation, and routine use of an active disruption avoidance scheme based on a “state machine. This is well aligned with the recommendations of the recent FES Transients Workshop, and we recommend that this continue to be used as an expanding platform incorporating additional disruption causes beyond the present VDE emphasis.”

PAC-37 written report expected early March

- Nominal schedule (from J. Sarff):
  - Feb 5, drafts for the PPPL/NSTX-U theory partnership and science group sections of the report submitted
  - Feb 10, J. Sarff circulates first draft of the combined report
  - Feb 17, comments due on first draft (track-changes)
  - Feb 22, J. Sarff circulates second (and hopefully final) draft
  - Feb 26, send final version to NSTX-U team

- After final written report is received, Program will have TSG/SG meetings in mid-March to discuss the recommendations and develop responses

Outline

- Overview of initial operation of NSTX-U
- PAC-37 charges, recommendations
- Run Coordination status

Experimental proposal preparation and execution well underway

- 29 eXperimental Machine Proposals (XMP) for commissioning / calibration identified and/or written
  - 11 of the 29 already being executed (see Battaglia listing)
  - Expect ~5-6 run weeks of XMP
- 27 eXperimental Proposals (XPs) written, reviewed for highest priority (P1a) experiments ~6 run weeks

►~1/2-2/3 of FY16 run-time has XMP/XP ready

- Additional allocations:
  - High priority experiments - P1b,c ~3.5-4 run weeks
  - Priority P2a,b ~ 1.5-2 run weeks
  - Reserve ~1 run week
- For more info see: Master Spreadsheet of XMPs and XPs

Research Operations Goals for first 2 run-months
(still consistent with Forum guidance / assumptions)

- Machine Commissioning – ~1 month (run weeks 1-4)
  - Develop basic breakdown, current ramp, shape/position control, diverted plasmas, H-mode access, basic fuelling optimizations.
  - Diagnostic commissioning
  - Boronized PFCs
  - Mostly XMPs
  - Goal: 1 MA, 0.5 T, NBI-heated H-mode (i.e. ~NSTX fiducial levels)

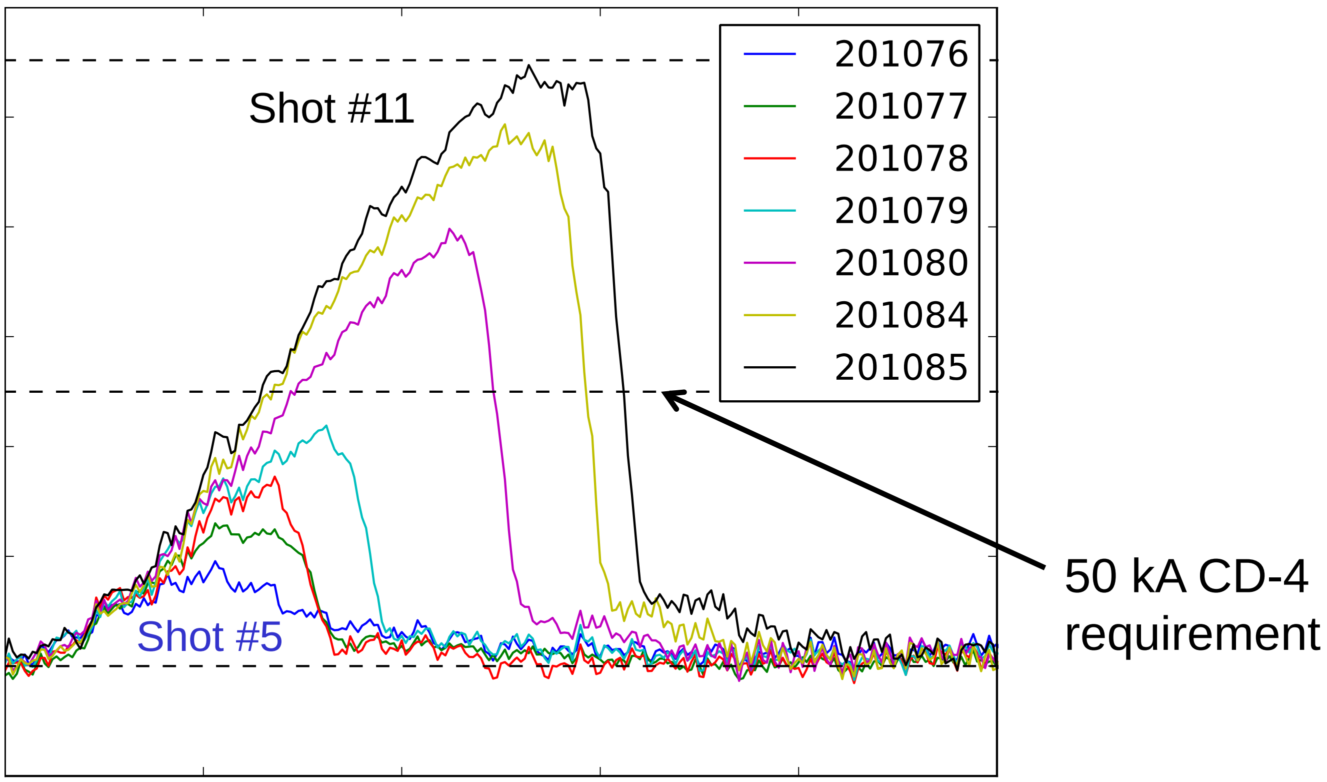
We are here at ~2.3 run weeks

- 1st Month of Science Campaign (run weeks 5-8)
  - Boronized PFCs, possibly begin Li coatings (end of period)
  - Operations and basic profile diagnostics, neutron rate,…
  - HHFW available for commissioning
  - 6 beam sources up to 90 kV
  - Operation up to 1.4 MA and 0.65 T, 2 seconds

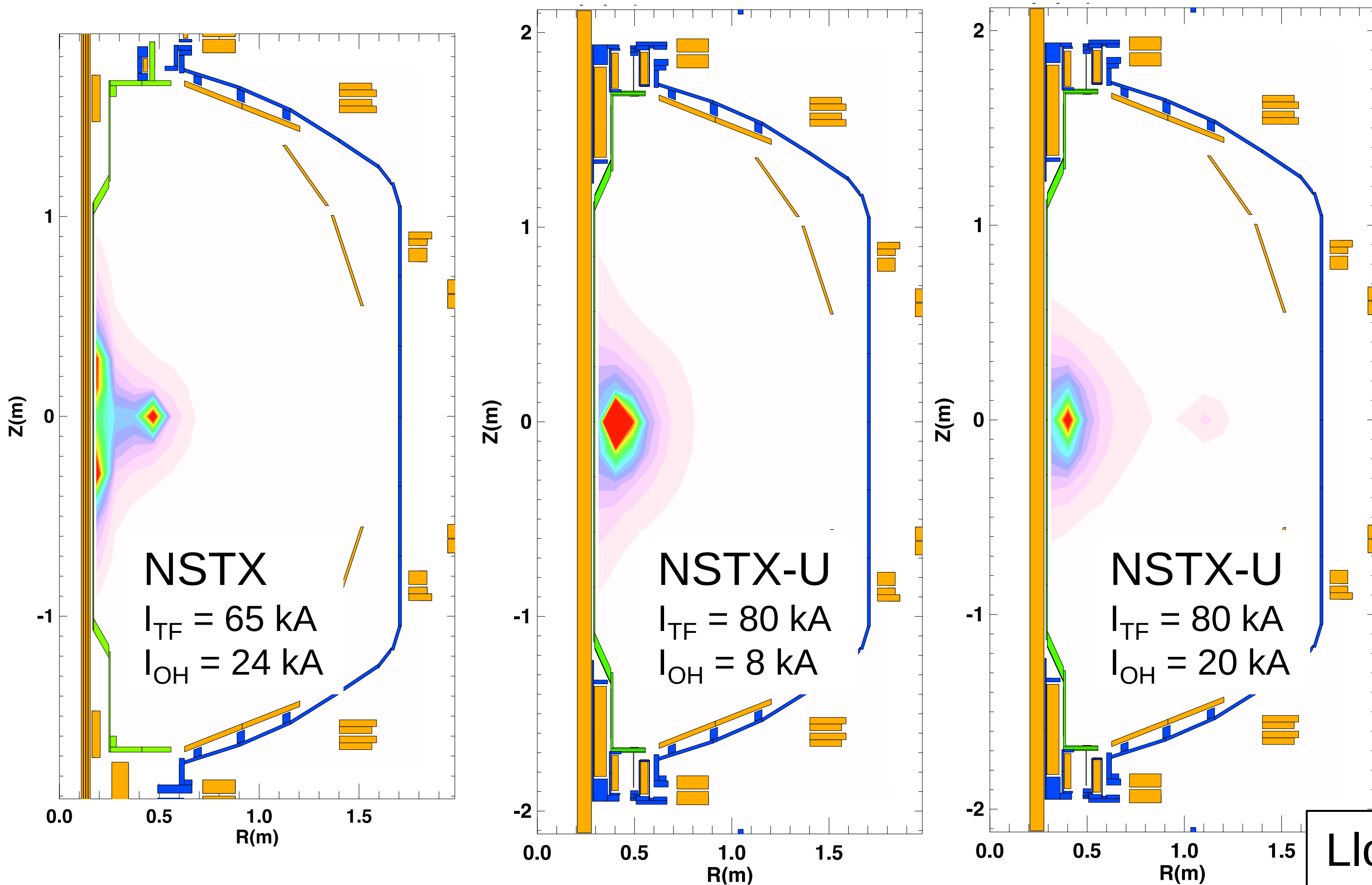
M. Ono talk will cover operational readiness

Backup

Startup scenario identified via calculations enabled rapid progress in achieving CD-4



Loop voltage required for breakdown in good agreement with calculations



Model: V_{loop} = 2.0 V — V_{loop} = 2.4 V — V_{loop} = 3.3V

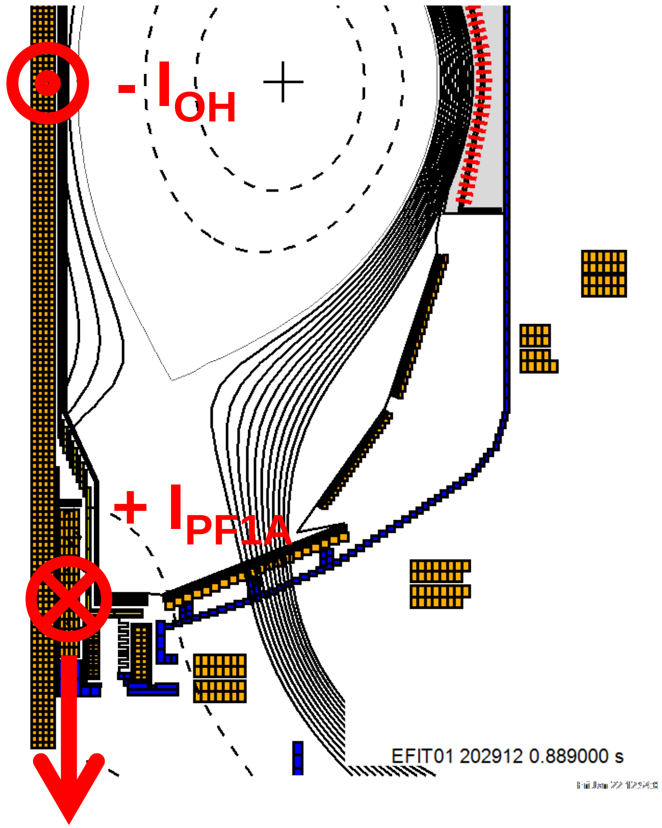
Experiment: V_{loop} **= 2.5 V** — V_{loop} **= 3.7 V**

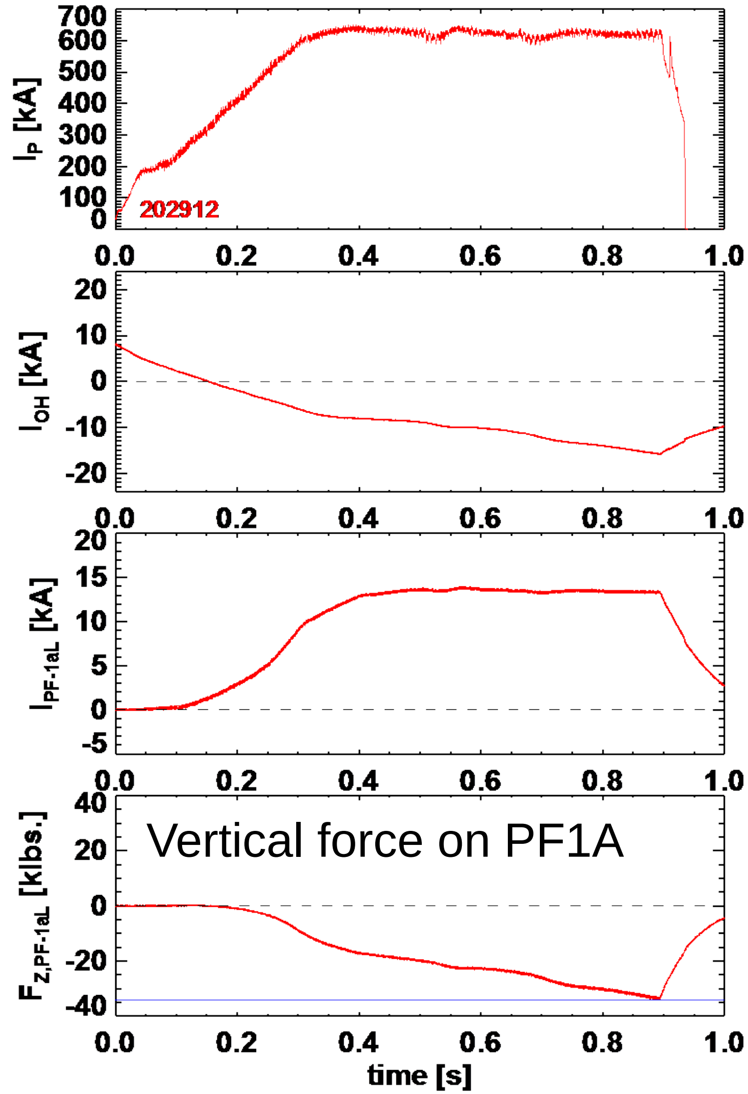
Lloyd parameter:

$$\frac{V_{loop} I_{TF}}{R^2 \langle B_\perp \rangle}$$

Digital coil protection system successful in preventing unacceptable coil operation

Example of a hard shutdown in response to a force limit

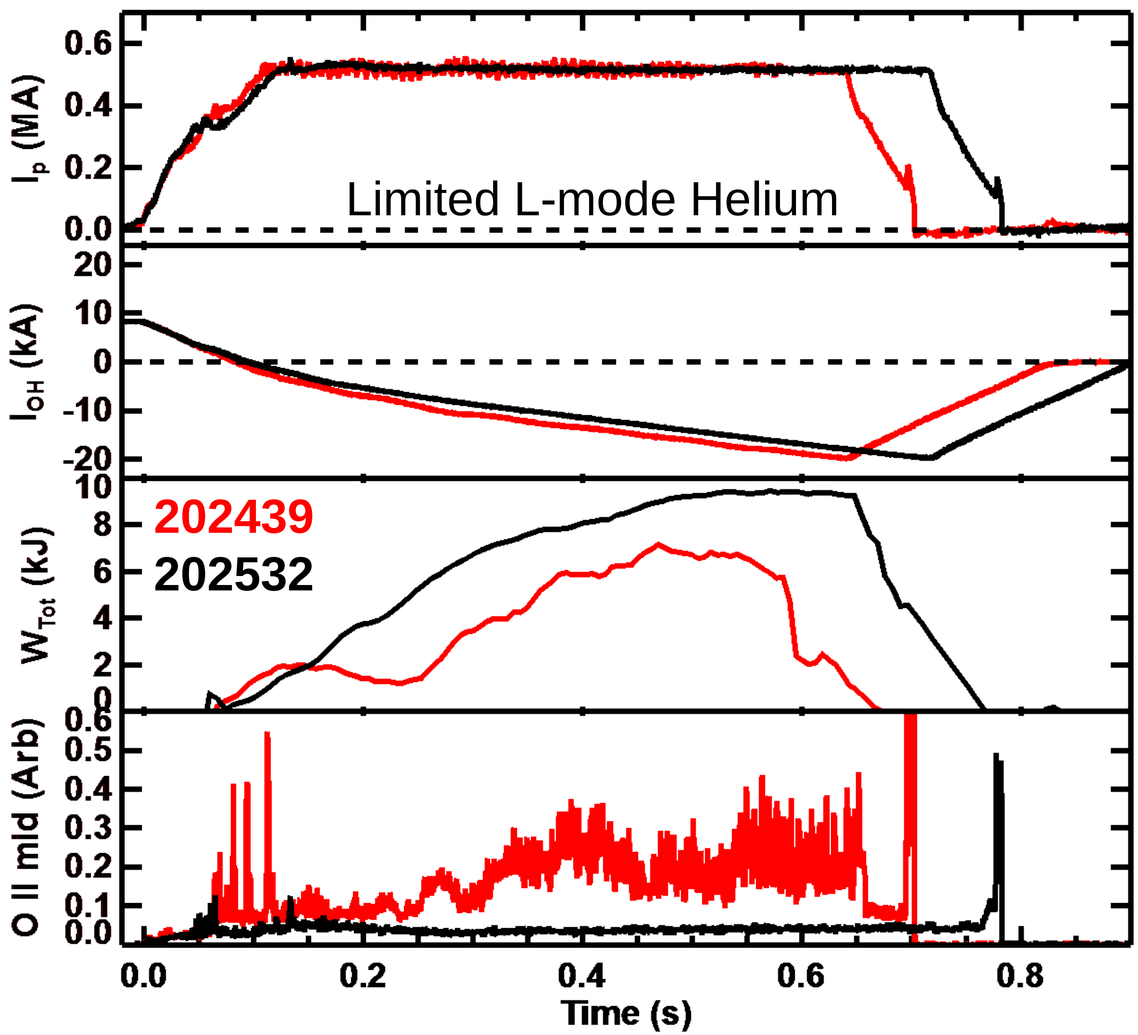




More details in Facility Status talk (M. Ono)

First boronization had positive impact on discharge performance

- Flux consumption and oxygen content reduced
- Measurements of boron deposition and impurity migration have been completed (see M. Jaworski's talk)



Run Time Guidance for XP Prioritization (February 2016)

Similar to Research Forum, but +1 week for XMP, +1 week for XP

Baseline # run weeks:	18		
Estimated total # run days:	90		
Estimated XMP run-days	30		Cross-cutting commissioning, shot development, calibrations
Reserve for multi-TSG XPs	10		
Contingency / director's reserve	5		
Nominal total days for TSG/TFs to prioritize	55		
Minimum # run days per TSG / TF	3.2		
Milestone weighting for FY16 and FY17 runs	0.8	0.2	

Priority #1 fraction 0.75

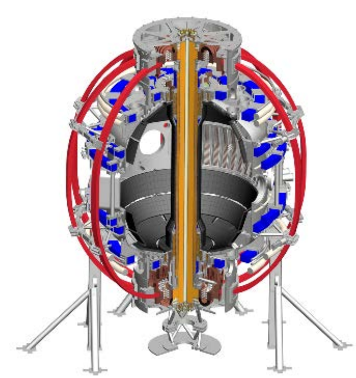
	TSG / Task Force	FY 16 Milestones	FY17 Milestones	FY16 count	FY17 count	Milestone additional runtime	Forum Idea Count Increment	Nominal TSG / TF run days for single TSG XPs	Nominal TSG / TF run days for multi-TSG XPs	Nominal TSG / TF run days for all XPs	Nominal Priority 1 XP run time	Nominal Priority 2 XP run time
Boundary	Pedestal	R16-1		1	0	0.8	0.5	4.5	1	5.5	4	1.5
	Divertor and SOL	R16-1	JRT-17, R17-1	1	2	1.2	1	5	1	6	4.5	1.5
	Materials and PFCs		R17-2		1	0.2	0	3	1	4	3	1
Core	Macroscopic Stability	JRT-16, R16-3		2	0	1.6	1	5.5	1	6.5	5	1.5
	Transport & Turbulence	R16-1	R17-3	1	1	1	0.5	4.5	1	5.5	4	1.5
	Energetic Particles	R16-2		1	0	0.8	0.5	4.5	1	5.5	4	1.5
Scenarios	Advanced Scenarios and Control	Notable, JRT-16, R16-2,3	JRT-17, R17-4	4	2	3.6	1	7.5	1	8.5	6.5	2
	Solenoid-Free Start-up		R17-4	0	1	0.2	0	3	1	4	3	1
	Wave Heating and Current Drive		IR17-1	0	1	0.2	0	3	1	4	3	1
Task Forces	Particle Control	R16-3		1	0	0.8	0.5	4.5	1	5.5	4	1.5
							Total:	45	10	55	41	14

- Some of additional XMP time ***may*** go to HHFW commissioning
- SGs/TSGs should update XP run-time assignments

NSTX-U Project / Facility Status

Masa Ono and Jon Menard

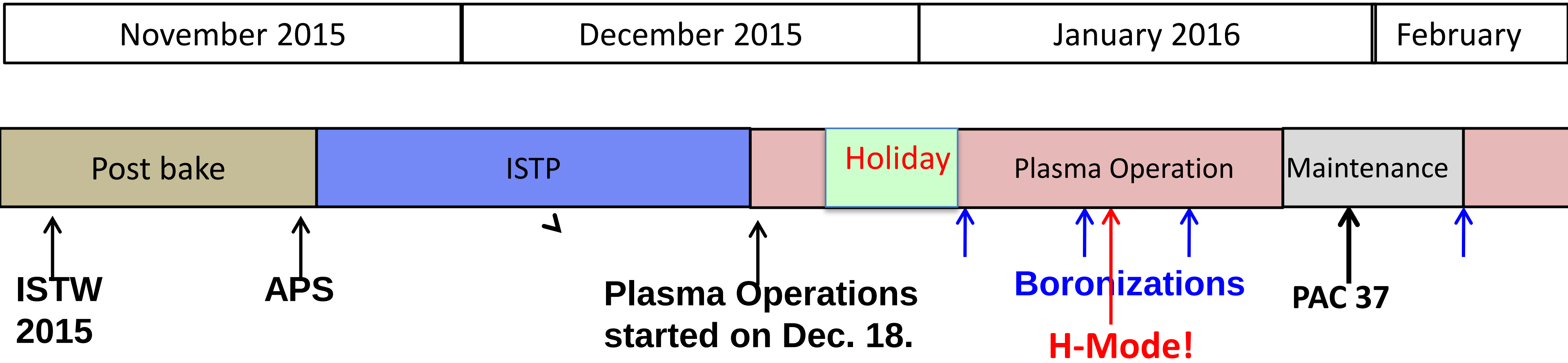
NSTX-U FY 2016 Q1 Review Meeting
February 8, 20156



Outline

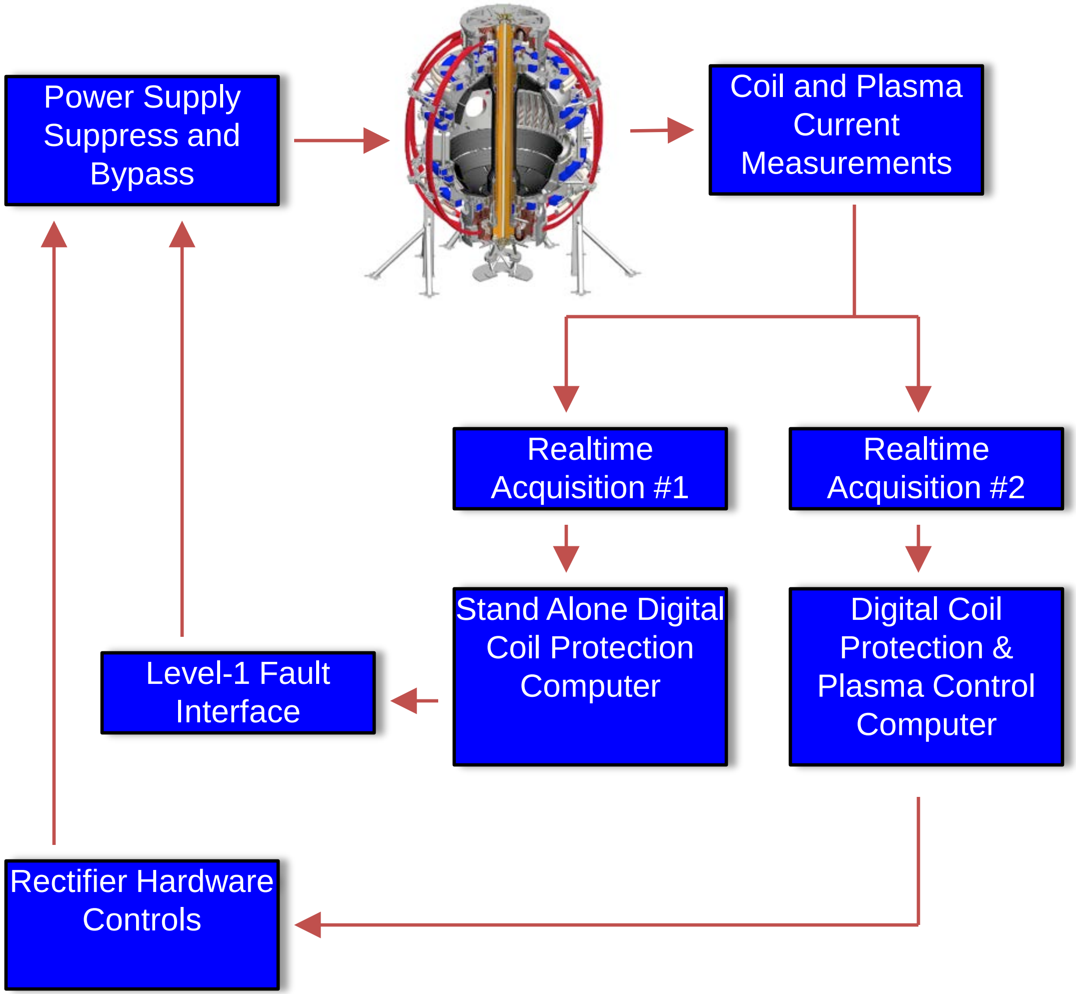
- Facility Operations Status and Plan
- On-Going Facility Enhancement Status and Plan
- Longer Term Facility Enhancement Status and Plan
- Summary
- Back-up: Explanation of Increments

FY 2016 plasma operations started
Expecting to run 18 run weeks in FY 2016



- **After CD-4, we vented briefly to install various items before the bake.**
- **Bakeout was completed with good vacuum pressure in October**
- **During ISTP, MGs experienced control problem during ISTP. The problem resolved and MG#1 is supporting the operations.**
- **Plasma operation started on Dec. 18 and ran for 2.5 days before the holiday.**
- **The first boronization performed on Jan. 4, 2016 and performed four times.**
- **NBI injection started and H-mode access achieved quickly.**

Digital System Provides Electromechanical Coil Protection
DCPS supporting the research operation very nicely



Protects the NSTX-U coils and mechanical structure against electromagnetic loads

Computes forces and stresses in realtime based on reduced models of the full mechanical structure

Redundant systems

Full commissioning of the system went very well; DCPS is now routinely supporting operations.

Discussions ongoing with ITER for collaboration

Excellent Progress on Magnetic Diagnostics

- **Plasma current, loop voltage, poloidal flux and field measurements in good shape supporting EFIT.**
  - **All integrators recalibrated**
  - **Rogowski coils fully calibrated, and pickup compensations established**
  - **All Mirnov sensors and flux loops have had their position determinations refined based on calibration shots.**
- **New diamagnetic loop system is now operational also supporting EFIT.**
  - **Based on using the Rogowski return loop as a diamagnetic loop.**
  - **Successfully implemented and eliminated the old TF-coil diamagnetic system.**
- **High-n and high-f array is taking data.**
  - **Used for detecting rotating Kink/Tearing modes, *AE modes.**
- **RWM sensors are writing mode fit data to the tree.**
  - **Realtime RWM sensor codes have also been upgraded, now in testing.**

Significant Progress in Plasma Control System
Now supporting the research operations

- **PCS has been supporting plasma operations.**
  - **Pre-programmed PF control & simple radial and vertical position control, I_P control.**
  - **Gas injection and pre-fill control**
  - **Real-time magnetic sensor calibrations**
  - **Beam control from PCS**
  - **Automatic discharge shutdown following disruption detection.**
  - **rtEFIT running in the background on the control machines**
  - **RWM/EF coil current control from PCS has been restored.**
- **Some older less-reliable real-time digitizers have been replaced, and a new every-shot latency measurement system has been implemented.**
- **Near term PCS steps**
  - **Finish testing rtEFIT and begin to use ISOFLUX shape control**
  - **Finish the recommissioning of the RWM/EF control algorithms**
  - **Then move on to profile control and snowflake divertor control.**

NSTX-U diagnostics to be installed during first year
More than half are led by collaborators

Ready now/commissioning

Magnetics for equilibrium reconstruction
Halo current detectors
High-n and high-frequency Mirnov arrays
RWM / Locked-mode sensors
MPTS (42 ch, 60 Hz)
T-CHERS: $T_i(R)$, $V_\phi(r)$, $n_C(R)$, $n_{Li}(R)$, (51 ch)
P-CHERS: $V_\theta(r)$ (71 ch)
Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
Midplane ME-SXR (200 ch)
Midplane tangential AXUV bolometer array (40 ch)
Ultra-soft x-ray arrays – multi-color
Fast Ion D_α profile measurement (perp + tang)
Solid-State neutral particle analyzer
Neutron measurements
Charged Fusion Product
Fast IR camera (two color)
Material Analysis and Particle Probe
AXUV-based Divertor Bolometer
Tile temperature thermocouple array
Fast visible cameras
Visible bremsstrahlung radiometer
Visible and UV survey spectrometers
VUV transmission grating spectrometer
Visible filterscopes (hydrogen & impurity lines)
Wall coupon analysis
1-D CCD H_α cameras (divertor, midplane)
2-D divertor fast visible cameras (4)
Two-color intensified 2D cameras TWICE (2)
Edge neutral density diagnostic ENDD
IR cameras (30Hz) (3)
Dust detector
Edge Deposition Monitors
Scrape-off layer reflectometer
Edge neutral pressure gauges

Ready by mid-run

Fast lost-ion probe (energy/pitch angle resolving)
Microwave Reflectometer
Beam Emission Spectroscopy (48 ch)
MSE-CIF (18 ch)
MSE-LIF (20 ch)
SAMI edge field pitch diagnoistc
Divertor VUV Spectrometer (SPRED)
Gas-puff Imaging (500kHz)
Langmuir probe array
Divertor fast eroding thermocouple

Ready by end of run

FIReTIP interferometer

Ready next run year

Poloidal FIR high-k scattering
Midplane metal foil bolometer
Metal foil divertor bolometer

New capability,
Enhanced capability

Heating System Operations

- **Both Neutral Beams are still at LHe temperatures. Routine panel regens.**
- **Neutral Beam #2**
  - **N2A Source has operated to 60 kV. High voltage transmission line repairs completed.**
  - **N2B Source has operated to 60 kV. High voltage transmission line repairs completed.**
  - **N2C Source had operated and injected power up to 75 kV.**
- **Neutral Beam #1**
  - **N1A Source had operated and injected power up to 75 kV.**
  - **N1B Source had operated and injected power up to 65 kV.**
  - **N1C Source had operated and injected power up to 85 kV.**
- **RF Systems**
  - **RF HHFW #1-6 dummy load tested to 1 MW 0.5 seconds prior to Holidays.**
  - **Plan to start antenna conditioning after arc fault recovery is completed.**

Still need some dedicated conditioning time needed on all systems.

Latest run plan schedule for 2016

Goal is to operate 18 run weeks

➔FY16 budgets are favorable enough to support 18 weeks

➔ Want as much data as possible for IAEA synopses/meeting, APS-2016

- **December: 0.5 run weeks (XMP)**
- **January: ~ 2 run weeks (XMP, XP), PAC-37**
- **Two week maintenance: Neutral Beam T-line repair, Argon purge system, LITER, Diagnostics**
- **February: ~ 3 run weeks**
- **March ~ 3 run weeks**
  - **Mid-run assessment in March/April**
- **April – June 9.5 run weeks, complete FY16 run**
- **July: Start outage: install high-k, high-Z tiles, …**
- **Resume operations winter 2017 for FY17: ~16 run weeks**

NSTX-U device performance progression

- **1st year:** Limit forces to ½ way between NSTX and NSTX-U, and ½ of the design-point heating of any coil
  - Presently operating at B_T ~ 0.65T
  - Increase to B_T ~ 0.8T after completing engineering analysis
- **2nd year goal:** Full field and current, coil heating to ¾ of limit
- **3rd year goal:** Full capability

Parameter	NSTX (Max.)	Year 1 NSTX-U Operations	Year 2 NSTX-U Operations	Year 3 NSTX-U Operations	NSTX-U Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8 (0.65)	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160
I_P Flat-Top at max. allowed I^2t, I_P, and B_T [s]	~0.4	~3.5	~3	5	5

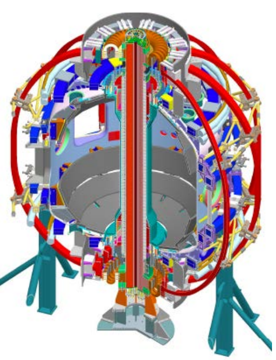
Outline

- Facility Operations Status and Plan
- On-Going Facility Enhancement Status and Plan
- Longer Term Facility Enhancement Status and Plan
- Summary
- Back-up: Explanation of Increments

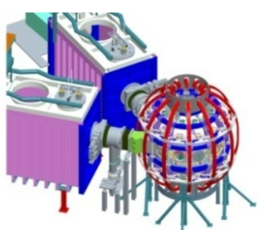
Five Year Facility Enhancement Plan (green – ongoing)

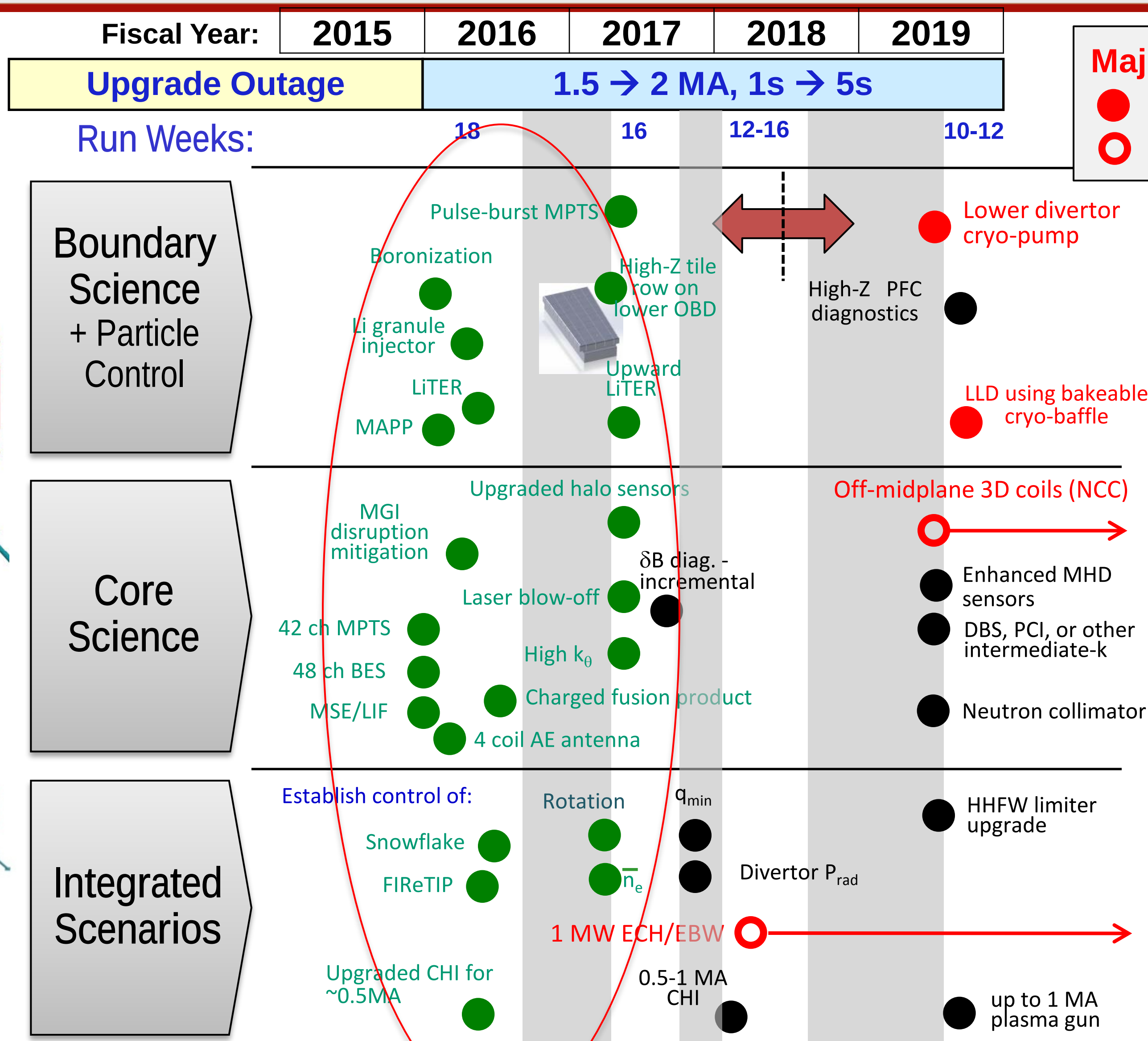
2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

New center-stack

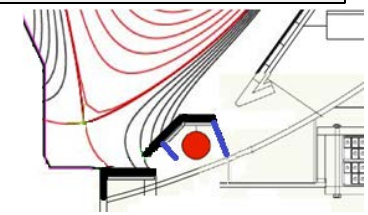


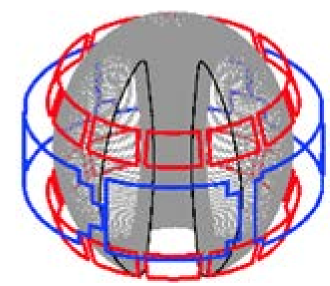
2nd NBI





Major enhancements:
- ● Base funding
- ○ +15% incremental

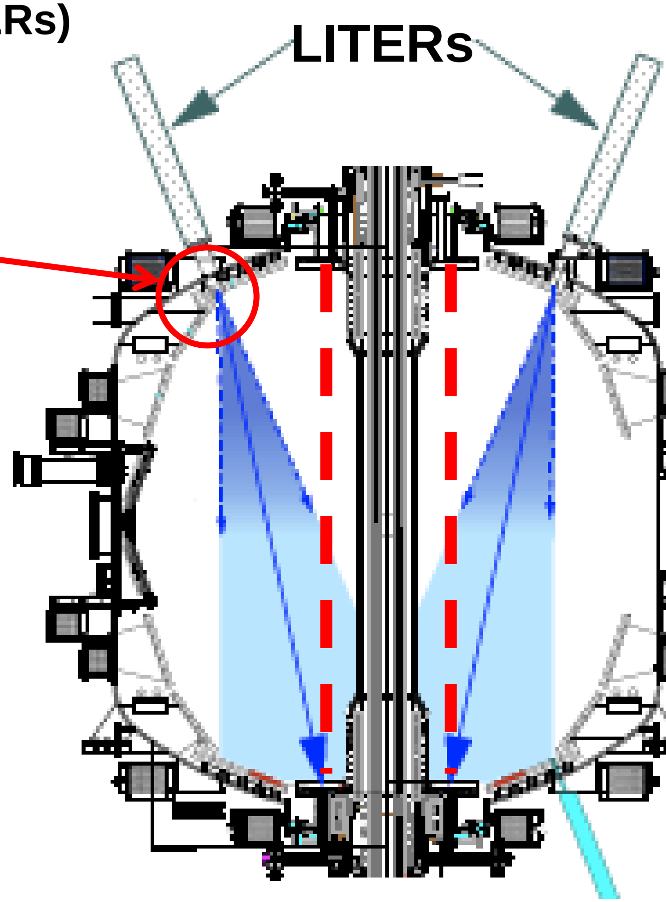




First Year Boundary Physics Tools

Boronization, Lithium Evaporators, Granule Injector

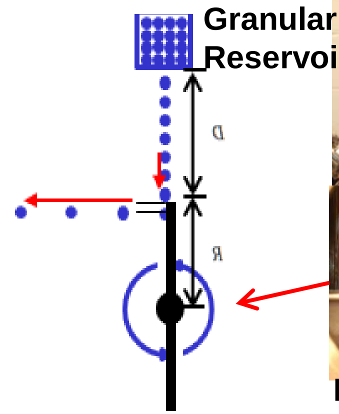
Lithium Evaporator (LITERs)

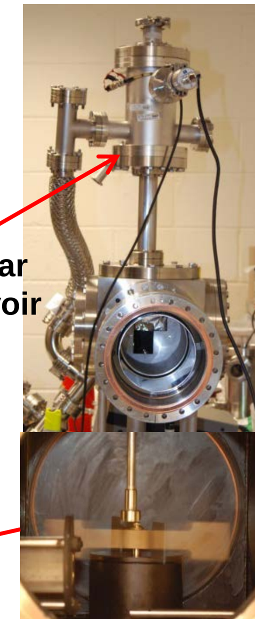


- LITERs filing set up in high bay south of NSTX-U Test Cell
- Argon purge system being implemented for safety

Granule injector (GI) for ELM pacing

Successfully tested on EAST and DIII-D
Granules: Li, B_4C, C
f ~ up to 500 Hz





Rotating Impeller

- Remote control undergoing tests
- Stand complete
- Vacuum interlock requirements identified and implementation plan specified

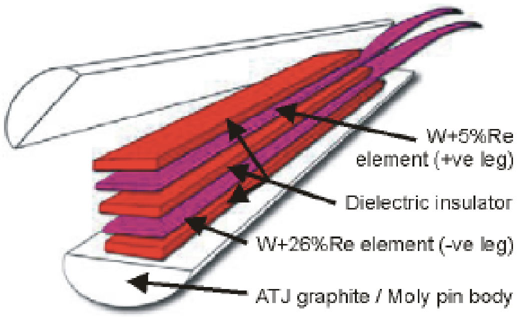
Boronization System

- Multiple injection and glow made more uniform boronization.
- System is working very well. Third boronization complete. Also being used for He glow discharges.

dTMB Gas Cabinet for safety

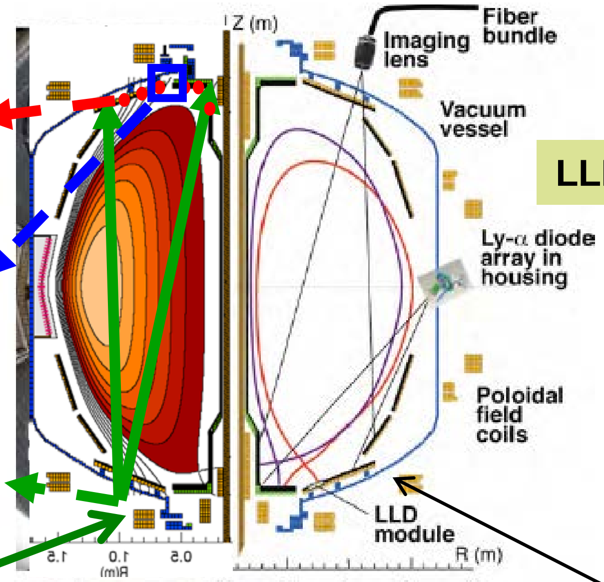
Enhanced Capability for PMI Research
Multi-Institutional Contributions

Divertor fast eroding thermocouples



ORNL

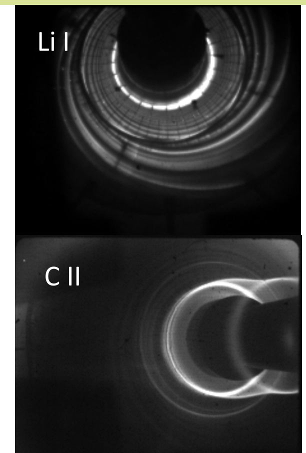
Divertor Imaging Spectrometer



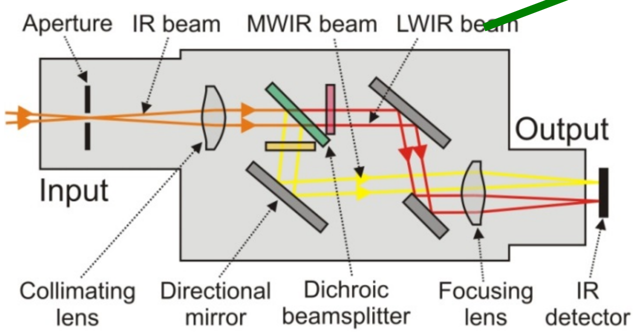
LLNL

Multiple fast 2D visible and IR cameras with full divertor coverage

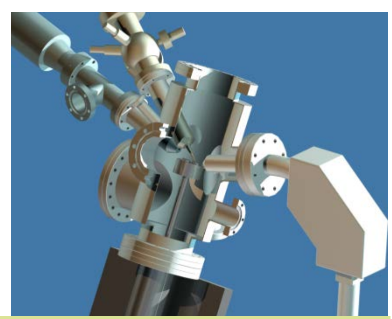
LLNL, ORNL, UT-K



Dual-band fast IR Camera



MAPP probe for between-shots surface analysis – Now taking data

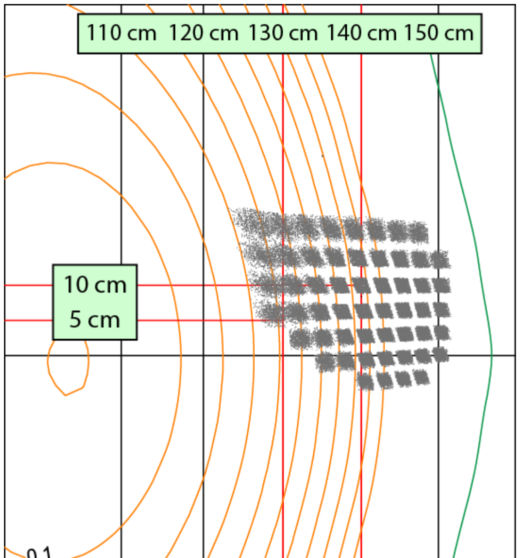


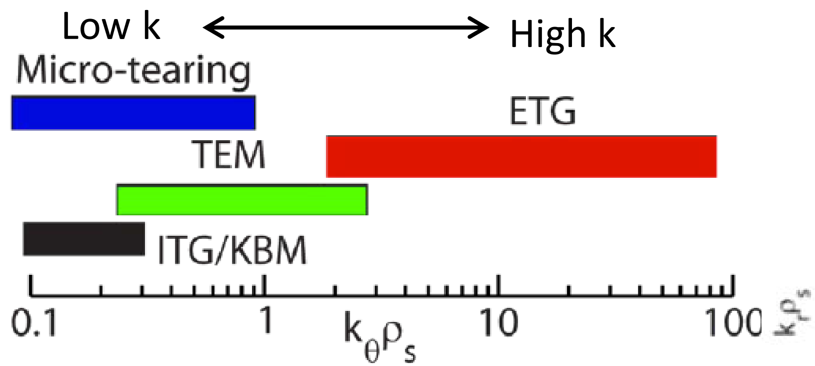
U. of Illinois, PPPL

Microturbulence Diagnostics Being Enhanced

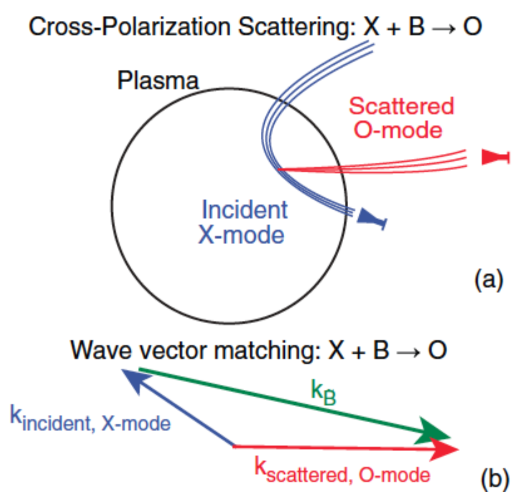
To measure ion to electron gyro-scale, magnetic fluctuations

Beam Emission Spectroscopy
for low k turbulence
48 chs being readied



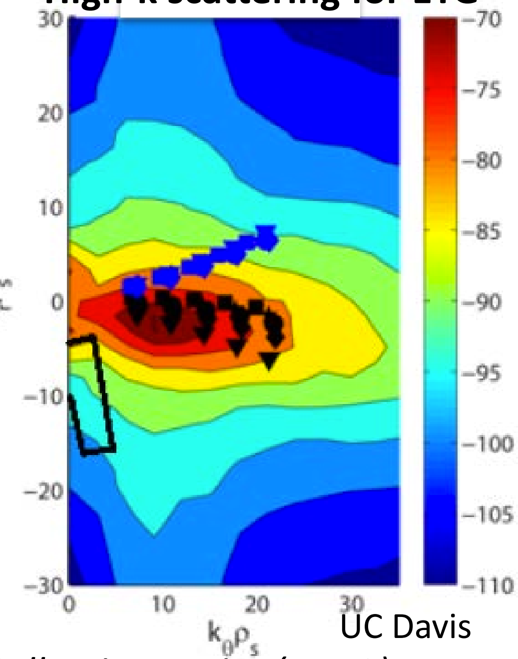


Cross-Polarization Scattering for magnetic fluctuations being developed in collaboration with DIII-D and MAST



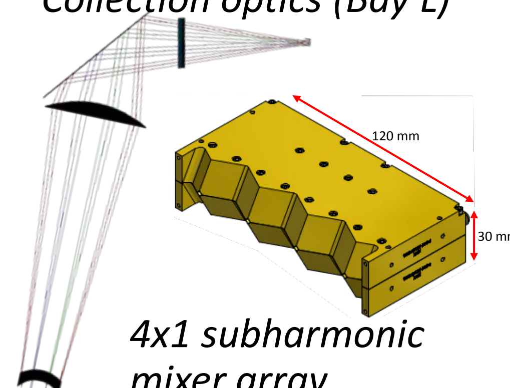
UCLA

High-k scattering for ETG



UC Davis

Collection optics (Bay L)



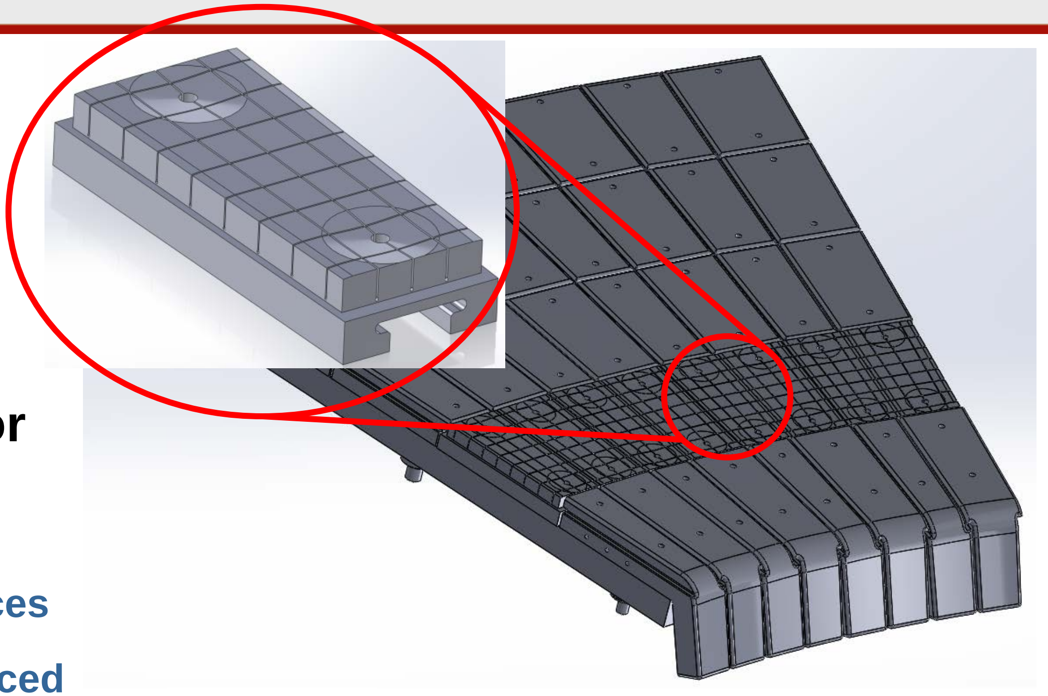
4x1 subharmonic mixer array

Available for FY 17

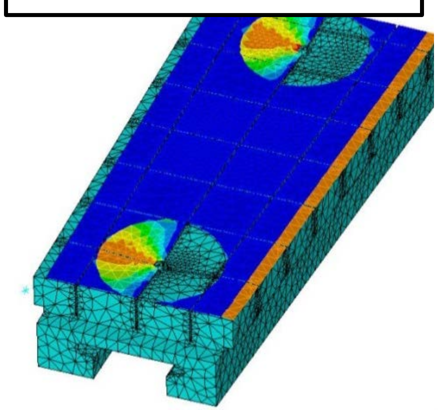
High-Z Tile Design Nearly Complete

(See M. Jaworski's PAC talk for more detail - plan to be ready by the 2016 outage)

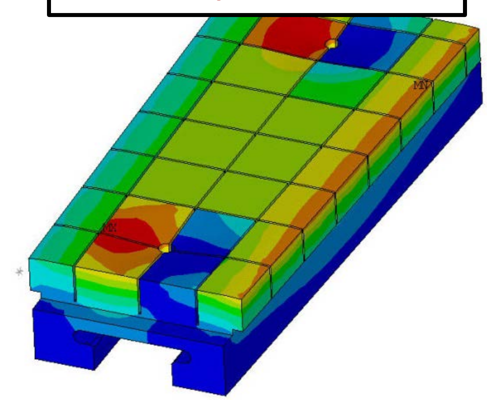
- **Successful PDR held in December**
  - **Final drawings and installation issues nearly complete (FDR mid-Feb.)**
  - **82% of raw materials on-site**
- **Final design rated to 10 MW/m^2 for 1s heat flux for 1000s of cycles**
  - **Installation flexibility introduced to accommodate "as built" vessel tolerances**
  - **Edge and access-way chamfers introduced to reduce heat-flux peaking**
- **Design "lesson's learned" already informing cryo-pump PFC design**
  - **Geometric flexibility emphasized to avoid stress-limited design**
  - **Tight tolerancing in sub-structure emphasized to avoid time-intensive installation tasks**



Surface heat flux



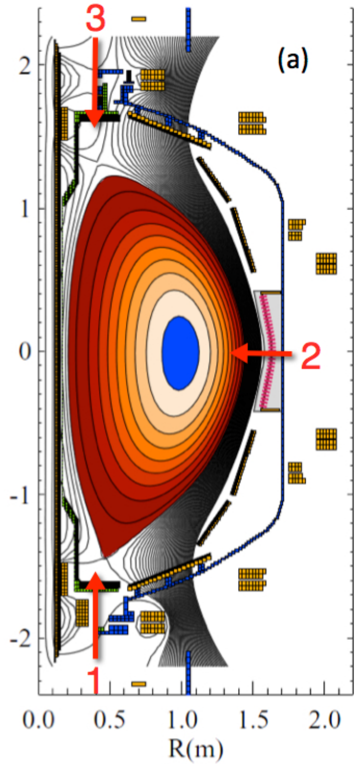
Temperature

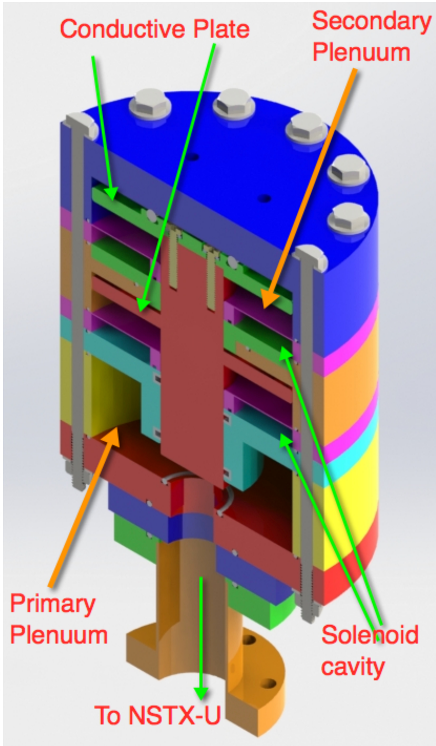


Disruption Mitigation System for NSTX-U

Massive gas injection system at multiple poloidal positions

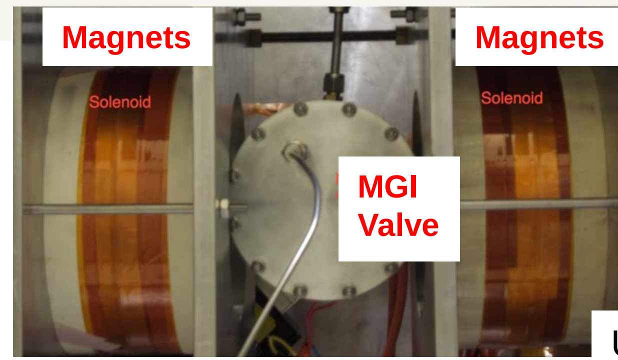
NSTX-U MGI Valve





- Massive gas injector system at multi poloidal location with identical injection set-up
- Compact power supply proto-type tested at UW
- A new double solenoid MGI design (zero net J x B torque) based on the ORNL ITER MGI design

MGI also tested on the U. Washington test stand with magnetic field



U. Washington

- **Conceptual Design Review of MGI system was held on October 16. Recommended changes were incorporated into the power system hardware.**
- **All the MGI components including MGI valves were delivered to PPPL from U. Washington.**
- **Preparation are being made to commission the MGI system on NSTX-U this year.**

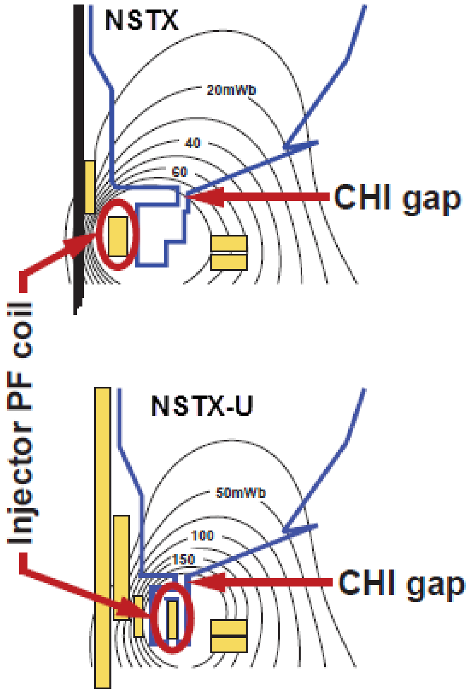
Solenoid-free start-up in support of ST-FNSF

NSTX-U CHI configuration permits ~ 400 kA level start-up

CHI Start-Up in NSTX-U

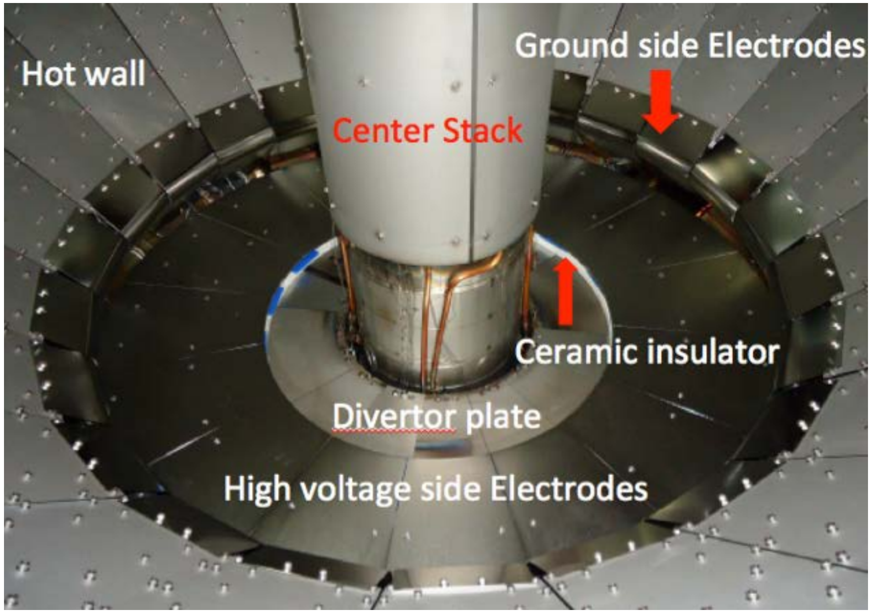
- **Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX**
- **NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation**

U. Washington



- **CHI will start with the present 2 kV capability then enhanced to higher voltage as needed.**
- **Control system updates for the CHI cap bank have been completed, and the system is ready for remote testing.**
- **The CHI control room procedure has been updated.**

QUEST CHI Experiment to test high-Z electrode operation



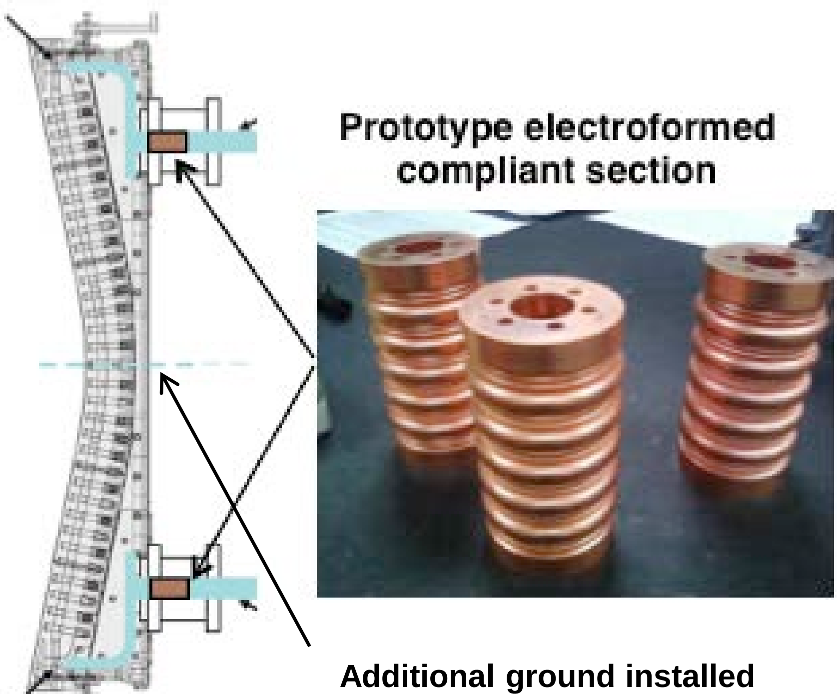
- **An ST-FNSF like CHI configuration will undergo plasma tests on QUEST after FY 2016 NSTX-U operation**
- **CHI electrodes installed in QUEST, CHI power supply and gas injection system fabricated at U-Washington**

HHFW system will be ready for operation in March

All sources are ready to start antenna conditioning

New Compliant Antenna Feeds

Allow HHFW antenna feedthroughs to tolerate 2 MA disruptions



- Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.
- RF diagnostics also installed.

Antennas were re-installed with the new feeds and back-plate grounding

Transmission lines installed & tuned.

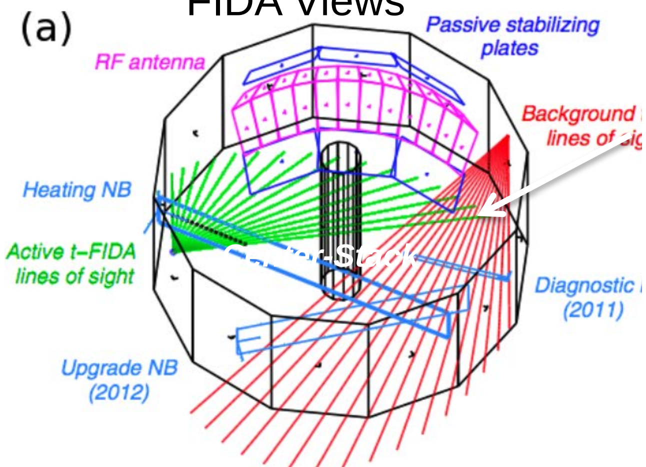
- **All sources will be ready to support HHFW operation in March.**

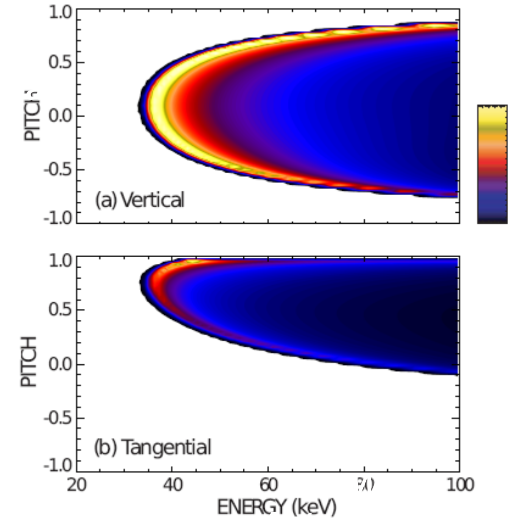
Enhanced FIDA will measure NBI distribution function
For NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics

- **Both vertical (perpendicular) and new tangential (parallel) FIDA systems are ready.**
- **Both FIDA systems have 10 ms, 5 cm, ≈ 10 keV resolutions.**

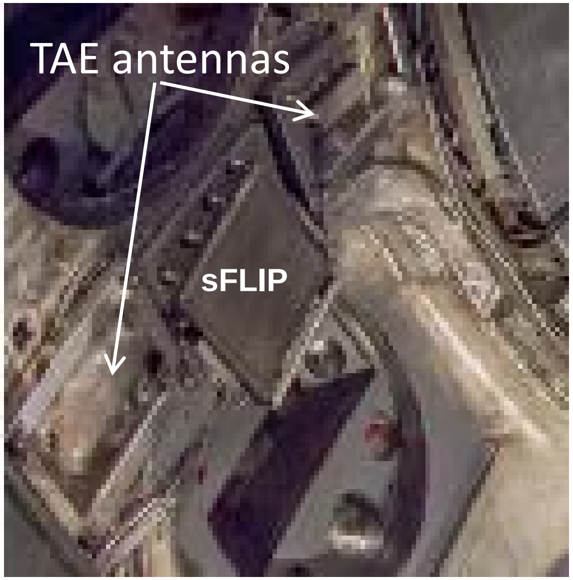
FIDA Views





FY 2016 - 2017 Energetic Particle Conceptual Design and Diagnostic Upgrade

- SS-NPA installed but investigating pick-up problem. UCI
- sFLIP is installed for lost ion measurements
- Active 2 X 2 TAE antennas installed. Initially passive spectroscopy then active excitation at few kW level.
- Proto-type charged fusion product (CFP) profile diagnostic to be installed this year. FIU
- 8+8 reflectometry array available for AEs. UCLA



Outline

- Facility Operations Status and Plan
- On-Going Facility Enhancement Status and Plan
- Longer Term Facility Enhancement Status and Plan
- Summary
- Back-up: Explanation of Increments

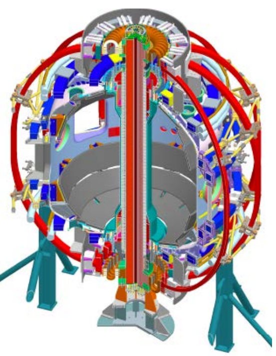
Five Year Facility Enhancement Plan (green – ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

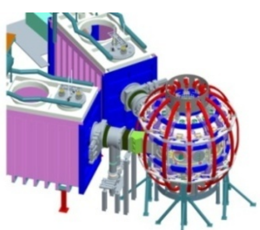
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack



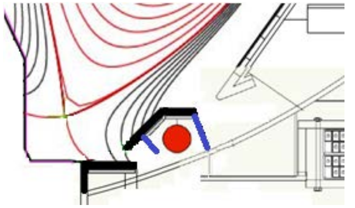
2nd NBI



Boundary Science + Particle Control

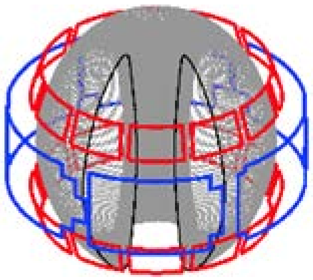
- Pulse-burst MPTS
- Boronization
- High-Z tile row on lower OBD

- Li granule injector
- Upward LiTER
- LiTER
- MAPP
- Lower divertor cryo-pump
- High-Z PFC diagnostics
- LLD using bakeable cryo-baffle



Core Science

- Upgraded halo sensors
- Off-midplane 3D coils (NCC) →
- MGI disruption mitigation
- δB diag. - incremental
- Laser blow-off
- Enhanced MHD sensors
- 42 ch MPTS
- DBS, PCI, or other intermediate-k
- High k_θ
- 48 ch BES
- Charged fusion product
- MSE/LIF
- Neutron collimator
- 4 coil AE antenna



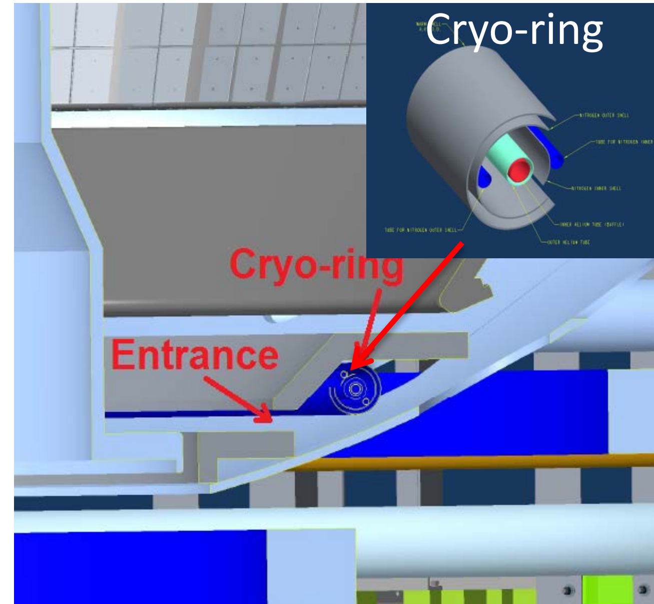
Integrated Scenarios

- Establish control of:
- Rotation
- q_{min}
- HHFW limiter upgrade
- Snowflake
- FIReTIP
- $\bar{n}_e$
- Divertor P_{rad}
- 1 MW ECH/EBW →
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- up to 1 MA plasma gun

Divertor Cryo-pump Design Activities Started

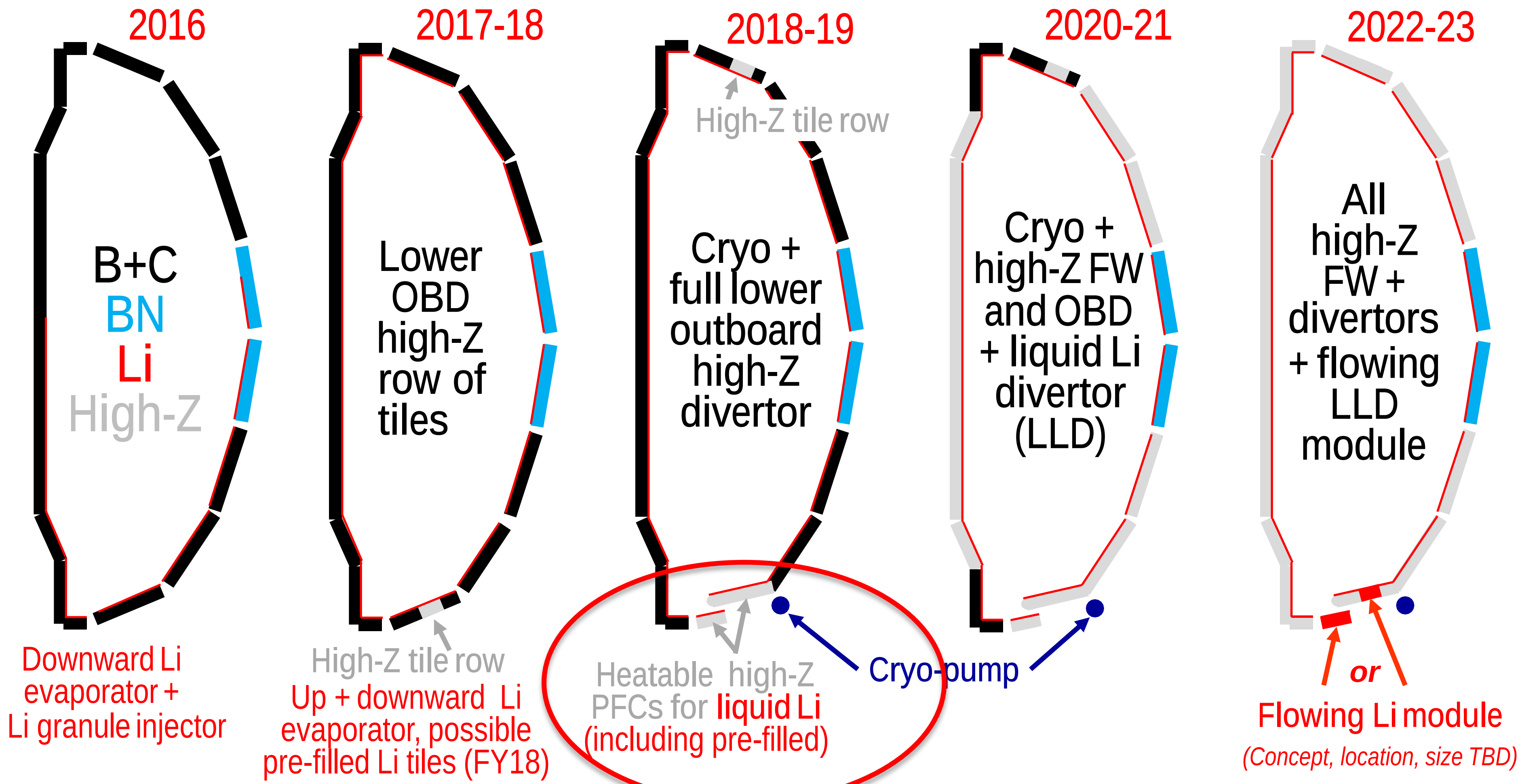
Physics Design Described at PAC 33 by J. Canik, ORNL

- **Initial in-vessel geometry has been laid out. MIT will design cryo-ring.**
  - **Pump radius, throat dimensions taken from the modeling.**
  - **Is a significant perturbation, requiring a rebuild of basically the entire lower outer divertor.**
  - **High-Z tile research will contribute to the choice of PFCs (see M. Jaworski's talk)**
- **Specification in progress for the Liquid He refrigerator.**
  - **Likely suitable model found**
  - **Location in room adjacent to NSTX-U has been identified.**
- **Ex-vessel liquid He plumping and transfer Dewar is under design.**



NSTX-U boundary / PFC plan: add divertor cryo-pump, transition to high-Z wall, study flowing liquid metal PFCs

- 5yr goal: Integrate high τ_E and β_T with 100% non-inductive
- 10yr goal: Assess compatibility with high-Z & liquid lithium PFCs

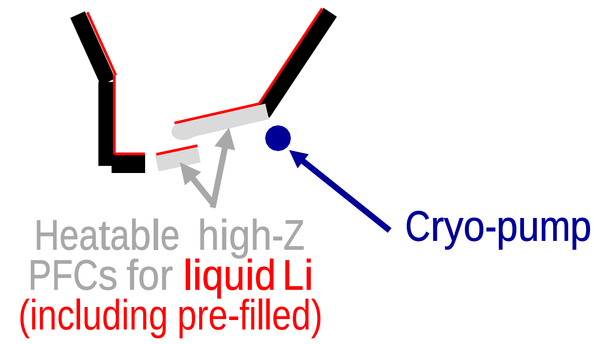


High Z, Liquid Lithium, and Cryo-Pump Enhancements

We are assessing the viability of supporting two separate enhancements: (1) Cryo-pump and (2) heatable high-Z PFC with liquid Li capabilty:

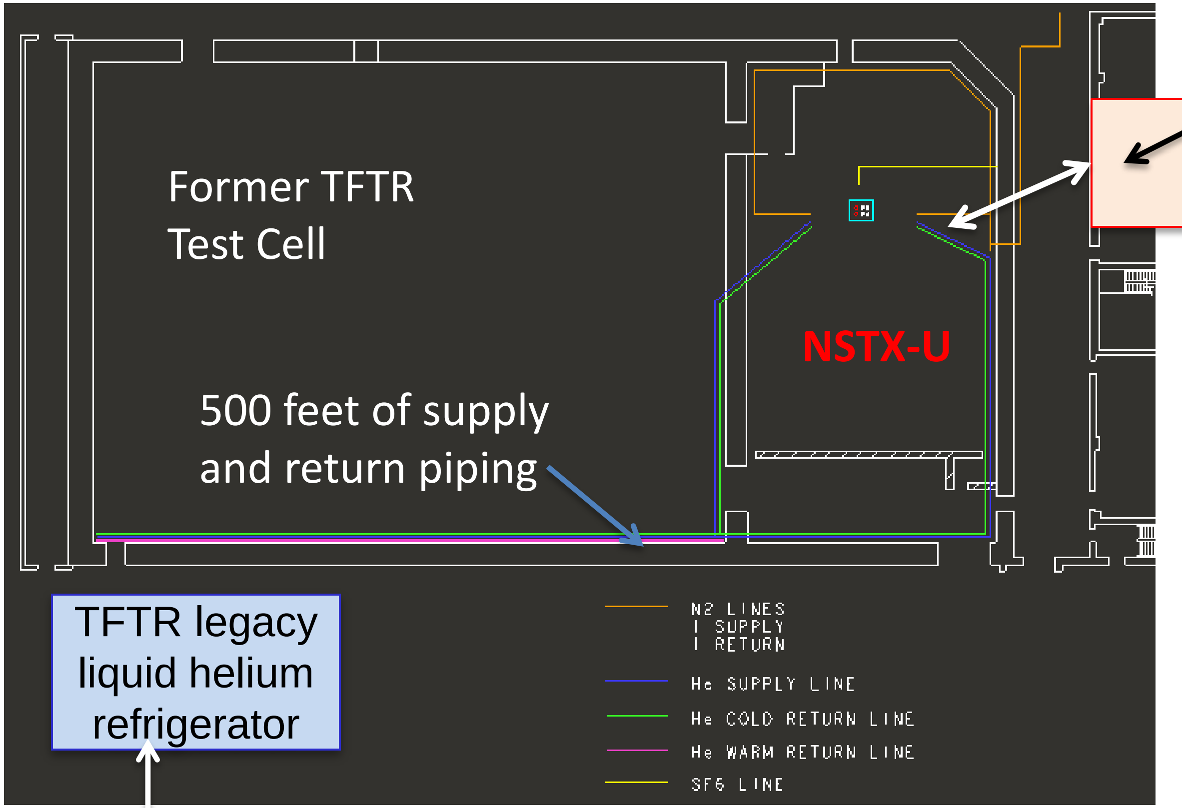
- Heatable high-Z PFCs with liquid lithium divertor capability ~ $ 6-7 M

- Cryo-pump system ~ $ 6- 7 M



Also as a part of facility reliability enhancement, a cryo-plant (helium refrigerator) upgrade is envisioned (~ $2.5M). The existing helium refrigerator is 35 years old and it if fails may cause loss of NSTX-U plasma operation in a given year. It is also located far from NSTX-U which causes more than 50% heat loss. The existing system could become a back-up refrigerator and support other cryogenic needs at PPPL.

A new efficient 400 W liquid helium (L-He) refrigerator to minimize down time risk and reduce operating cost



TFTR legacy liquid helium refrigerator

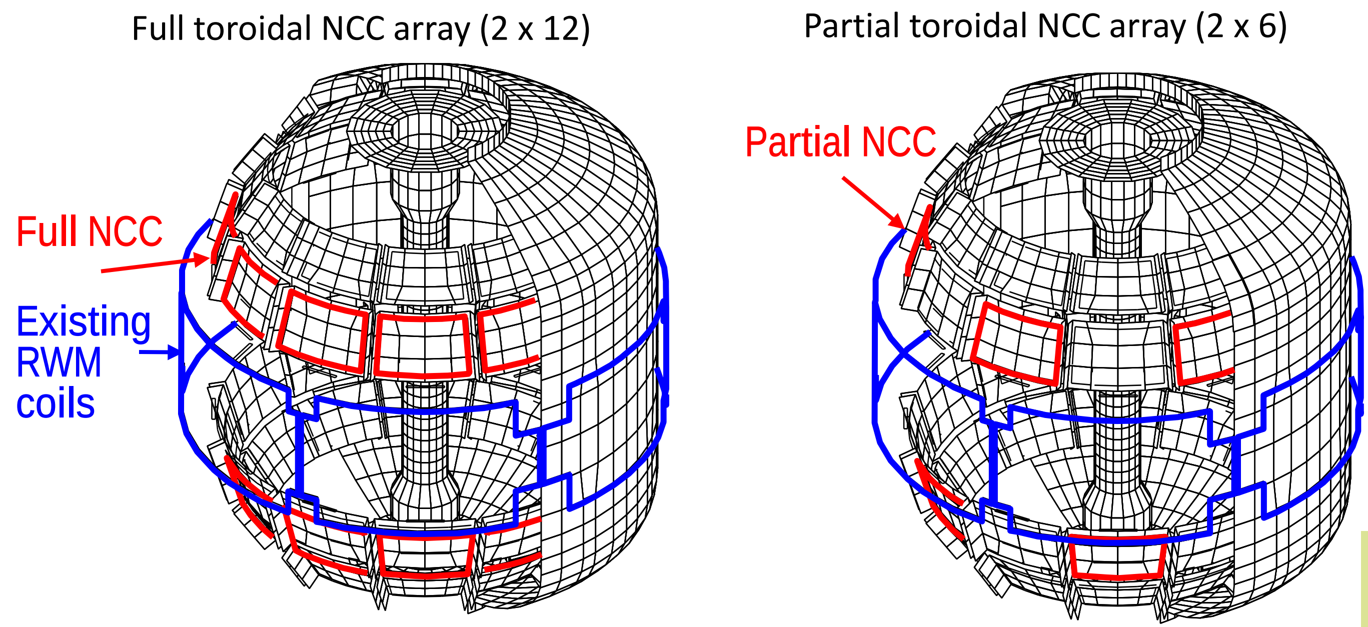
Proposed 400 W L-He refrigerator ~ $2.5M

- 35 years old for NBI #1 and 2 operating at near capacity
- If a failure occurs, the risk is estimated to be 6 months to 1 year of down-time.
- Back up L-He on NSTX-U without causing down time or as a site credit for future projects if needed.

- Located near NSTX-U, accommodates all envisioned loads (NBIs and cryo-pump) by benefit of less piping and heat loss.
- The unit would reuse power and space previously used for a previous 225 Watt refrigerator.
- The existing NBI controls PLC and operations staff can operate this system with only minor adaptations.
- The existing NBI tank Farm and liquid Nitrogen systems would support this 400 Watt refrigerator.

Flexible Mid-Plane Feedback Coils for MHD Studoes

NCC will greatly enhance MHD physics studies and control



Columbia U
General Atomics

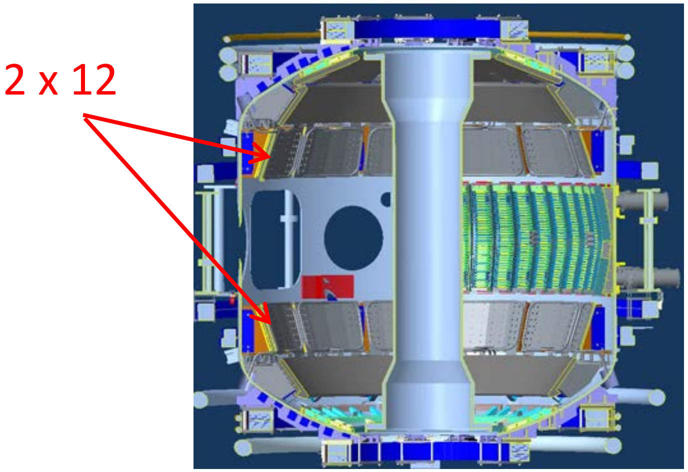
- 6-channel Switching Power Amplifier (SPA) powers independent currents in existing EFC/RWM Coils.
- NCC (a facility enhancement) can provide various NTV, RMP, RWM, and EF selectivity with flexibility of field spectrum (n ≤ 6 for full and n≤ 3 for partial)

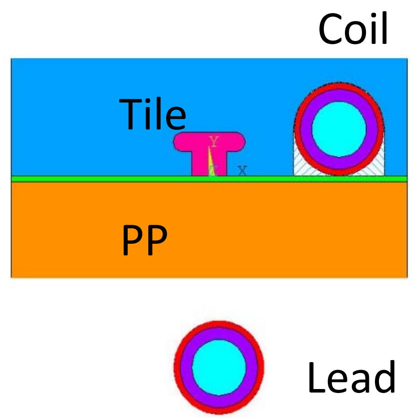
Base – Engineering design work on NCC to be performed in 2016 – 2017 to develop reliable cost and schedule.

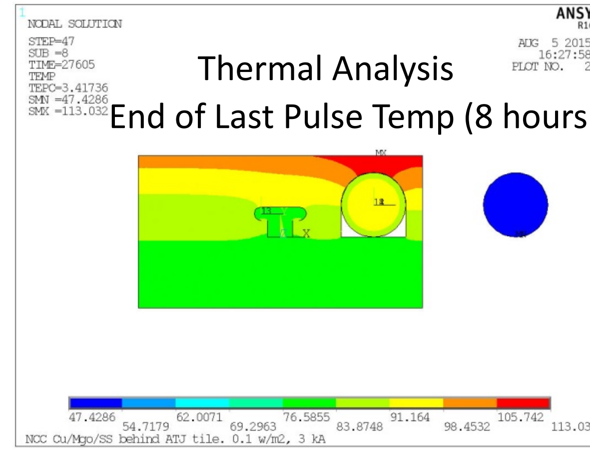
NCC Coils Design Activity Made Significant Progress

NCC Physics Design Presented by J-K Park at PAC 33

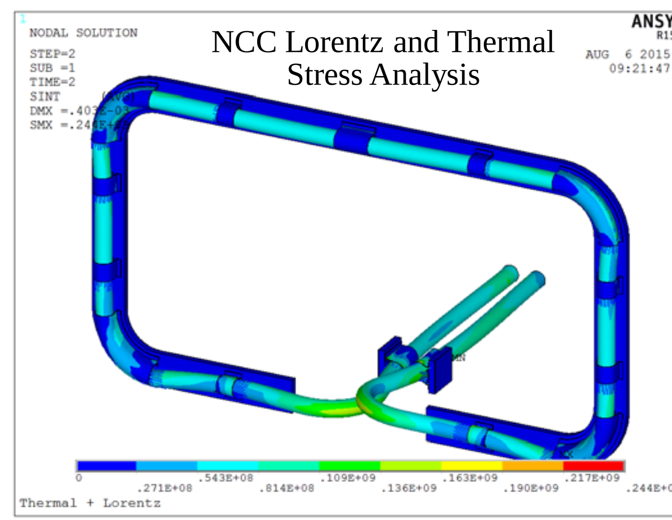
NCC = Non-axisymmetric Control Coil







3 kA,0.1 MW/m2 Plasma Heating,5s pulse,1200 s reprate



With Lead Clamp, 50 C Heat-up, 3kA+ Background Field

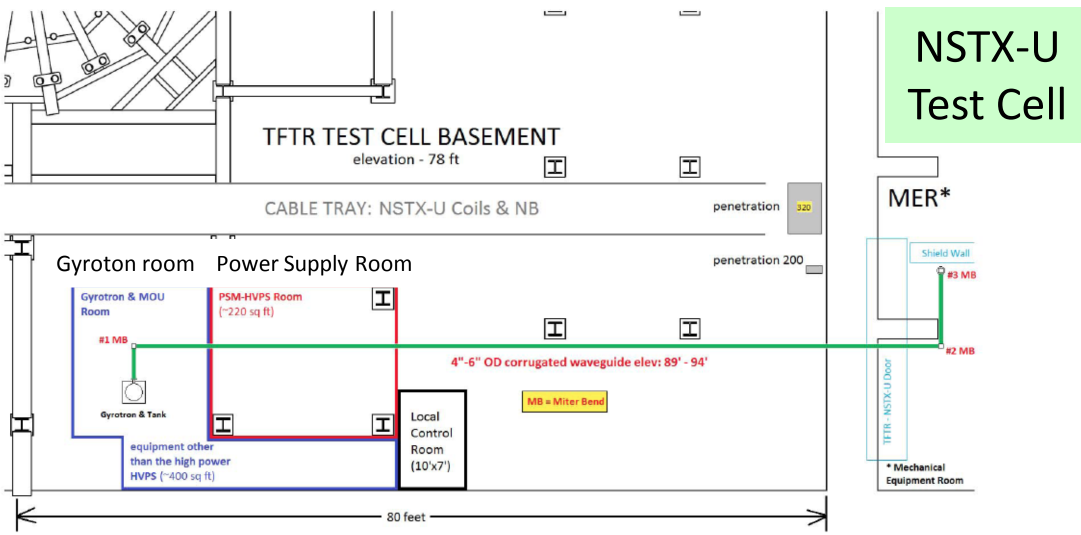
- **Selected candidate conductors and test sample received for R&D.**
- **The R&D selection criteria include thermal capability, manufacturability, impact on interfacing objects, fabrication lead time and cost.**
- **Helium cooling system or no direct cooling options will be quantified.**
- **Cost and schedule will be prepared as part of the CDR which is targeted for May, 2016.**

28 GHz ECH System Design Progressing Well

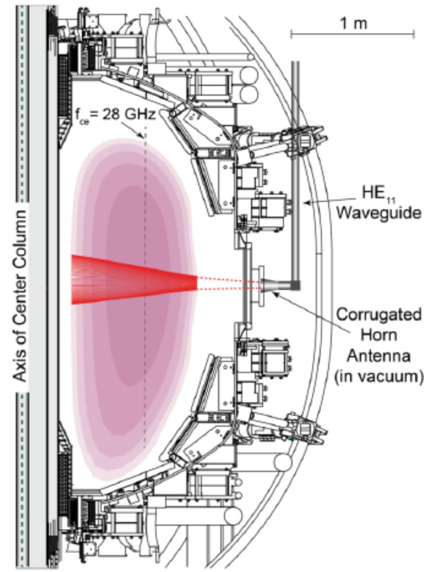
Develop engineering design and cost/schedule this year

- **CHI can form a 200-400 kA seed plasma, but it is too cold for HHFW absorption.**
- **Use of ECH can "bridge the T_e gap" to where HHFW and then NB current drive can support the ramp and sustain the current – crucial for OH solenoid-free compact STs - Talk by F. Poli at this PAC.**
  - **Good first pass absorption predicted.**
- **Goal of first ECH power in 2019 run with 15% incremental funding.**

28 GHz Gyrotron Room



Gyrotron will be located in the TFTR basement. Stray magnetic fields was measured to be negligible



28 GHz 1 MW Tube by Tsukuba

<u>28 GHz Gyrotron Development</u>

- **2nd generation 1.5 MW 28/35 GHz gyroton being developed at Tsukuba University. (See back-up slide)**
- **The gyrotron is being constructed. Will be tested this summer.**

Highest Priority for Incremental Funding
See back-up slide for more detail

1) Supporting our 18 run-week milestone

2) Improving reliability of critical systems that support operation

3) Supporting our collaborator needs to install their hardware

4) Any additional funds available will be used to support the major enhancements (Divertor Cryo-Pump and High-Z)

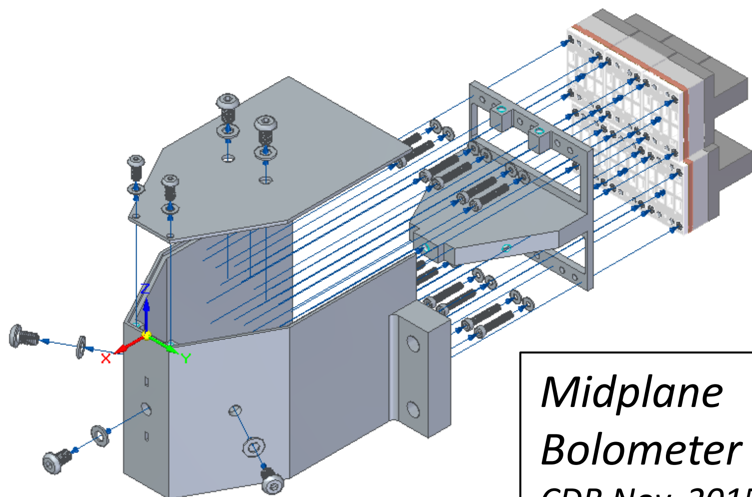
Summary of Facility and Diagnostics
Research operations successfully started

- **Research preparation progressing well. Team is vigorously preparing diagnostics and research tools for the first year of plasma operations.**
- **Research operation started on December 18, 2015. Very good progress on the plasma control system. Routine H-mode obtained shortly after the second boronization.**
- **After two week maintenance period, the plasma operation is restarting this week with all NBI and new capabilities and diagnostics.**
- **Engineering design work continuing for the major facility enhancements: divertor cryo-pump, high-Z tiles, ECH, and NCC.**
- **Considering two enhancements: the divertor cryo-pump in parallel with the heatable high-Z PFCs with LL divertor capability.**
- **400 W L-He refrigerator is also being considered for risk reduction.**

Back-up Slides

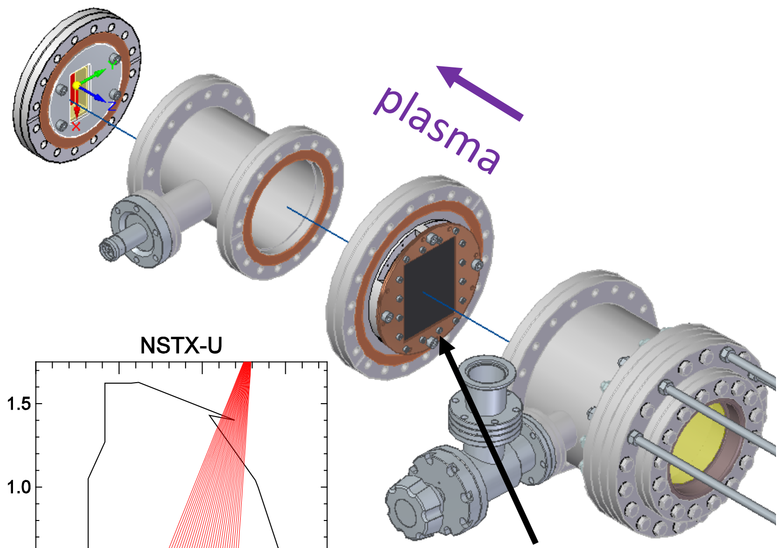
NSTX-U Developing Tools for Measuring Core and Boundary Radiation

- **Redesign and expand bolometer diagnostics to support FY17 operations**
  - **16 ch of lower divertor viewing for boundary radiation**
  - **24 ch tangential midplane core radiation**

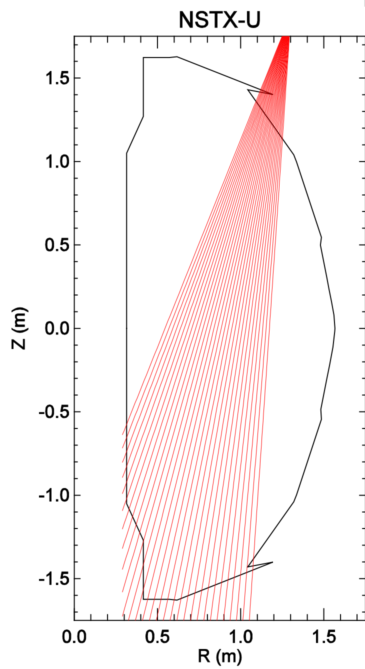


Midplane Bolometer
CDR Nov. 2015

Prototype IR video bolometer (IRVB) with NIFS and DIFFER



thin Pt foil, heated by radiation, imaged by IR camera



testing 32-ch system for viewing lower x-pt late in FY16 campaign

M. Reinke, ORNL