



U.S. DEPARTMENT OF
ENERGY

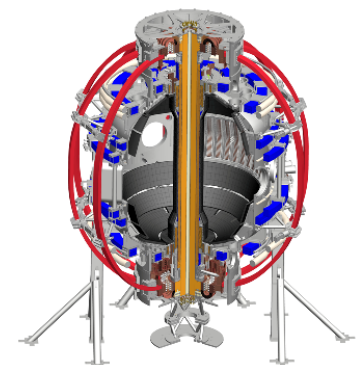
Office of
Science



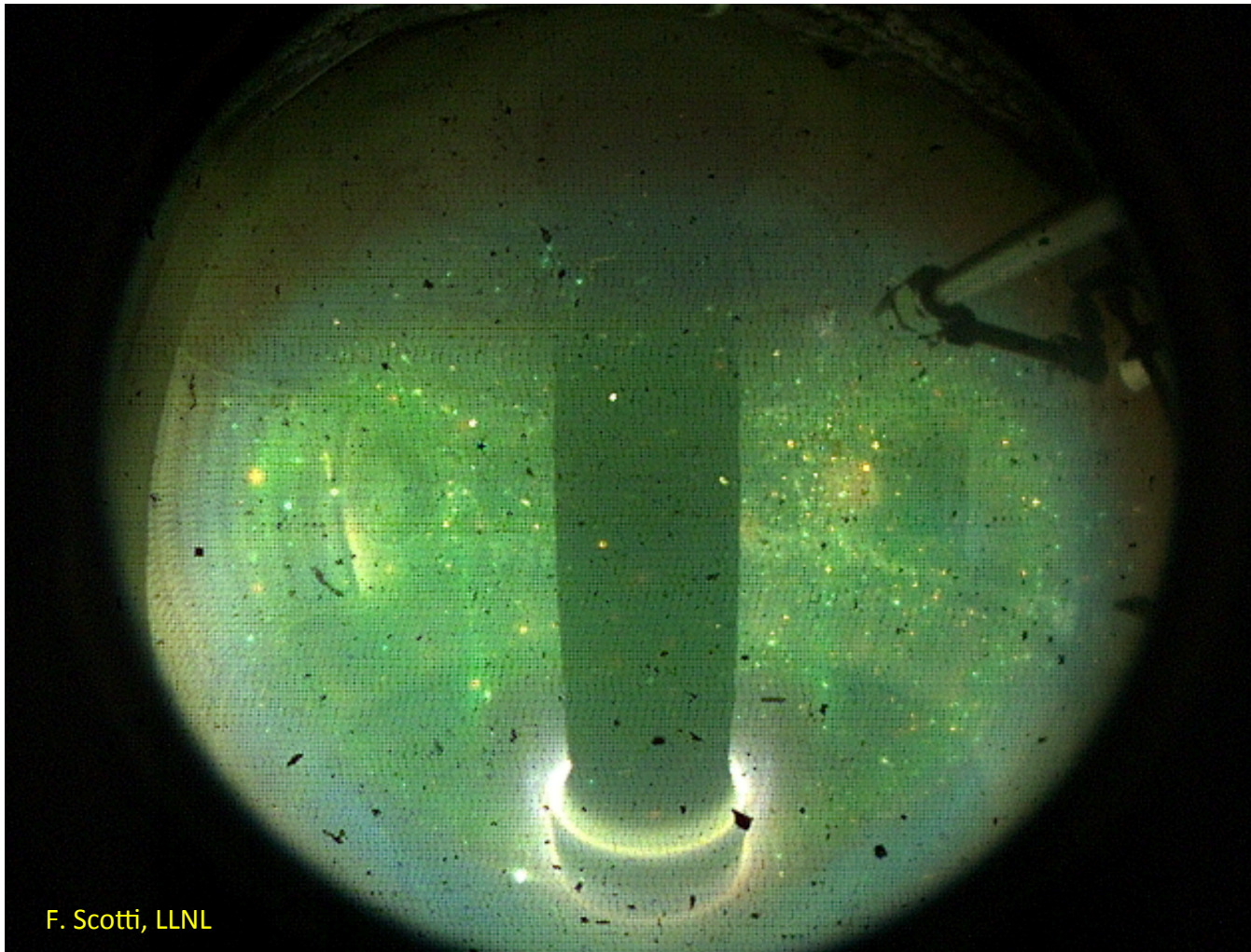
NSTX-U Facility and Project Plans

Stefan Gerhardt & the NSTX-U research,
engineering, and operations teams

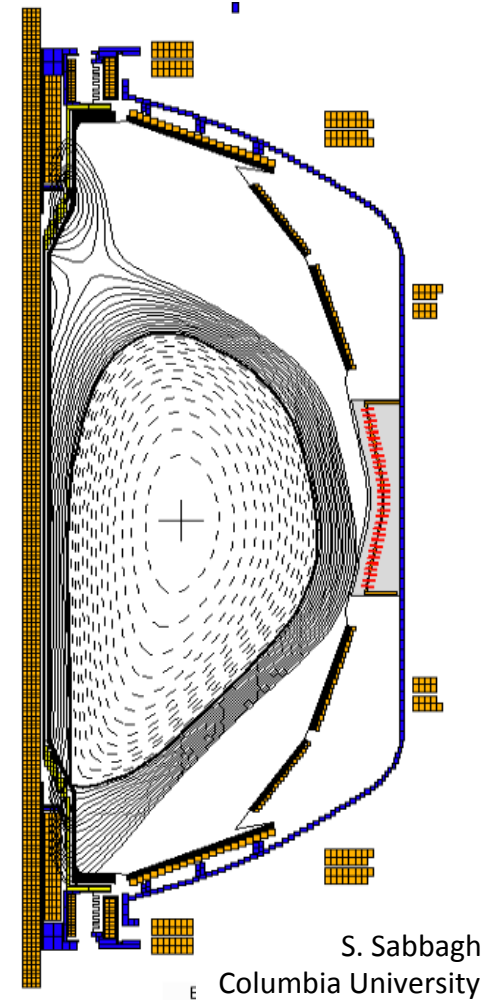
18th ST Workshop
Princeton University
November 3rd, 2015



!! NSTX-U is an Operating Facility !!



F. Scotti, LLNL



S. Sabbagh
Columbia University

Outline

- Introduction to the Upgrade
- Building the Upgrade
- First Plasma Results
- Plans for the First Campaign
- Future Plans

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5 highest priority goals of NSTX-U 5 year plan: (simplified)

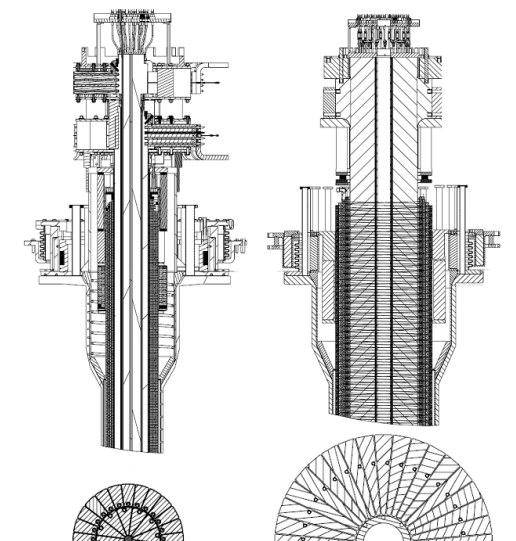
- Advance ST for Fusion Nuclear Science Facility (FNSF)
 1. Demonstrate 100% non-inductive sustainment at high- β .
 2. Develop and understand non-inductive start-up and ramp-up
- Develop solutions for plasma-material interface challenge
 3. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment
 4. Begin to assess high-Z PFCs + liquid lithium PFCs
- Explore unique ST parameter regimes to advance predictive capability
 5. Access reduced ν^* and high- β to dramatically extend ST physics understanding



Many more details in the program talk by J. Menard

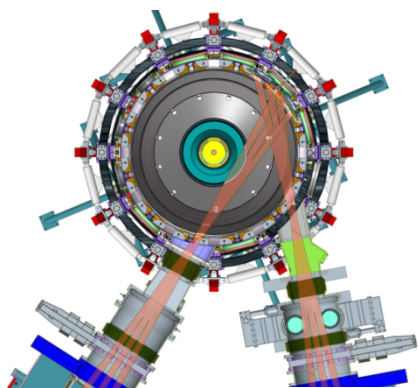
A New TF/OH Magnet Assembly and an Additional Neutral Beamline are the Key Components of the Upgrade

Previous center-stack **New center-stack**

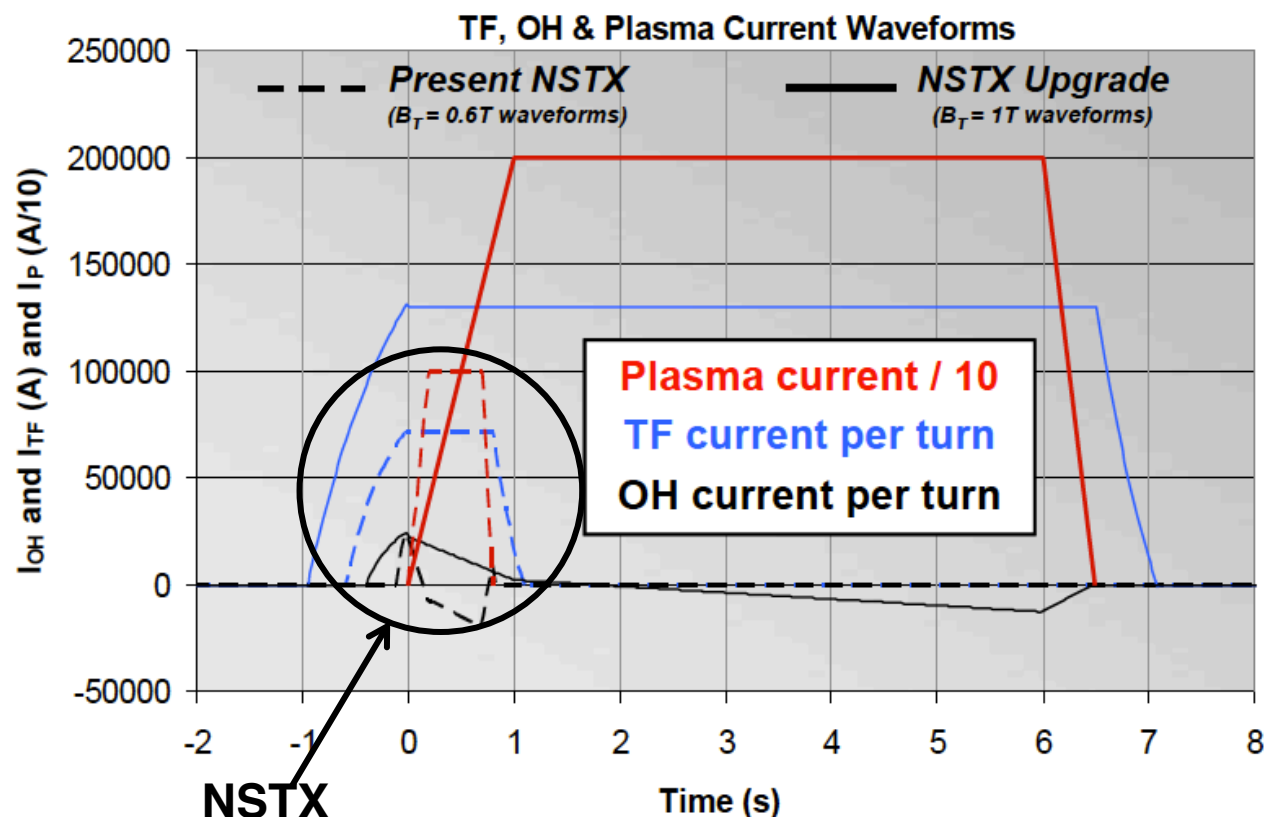


TF OD = 20cm

TF OD = 40cm



Present NBI **New 2nd NBI**



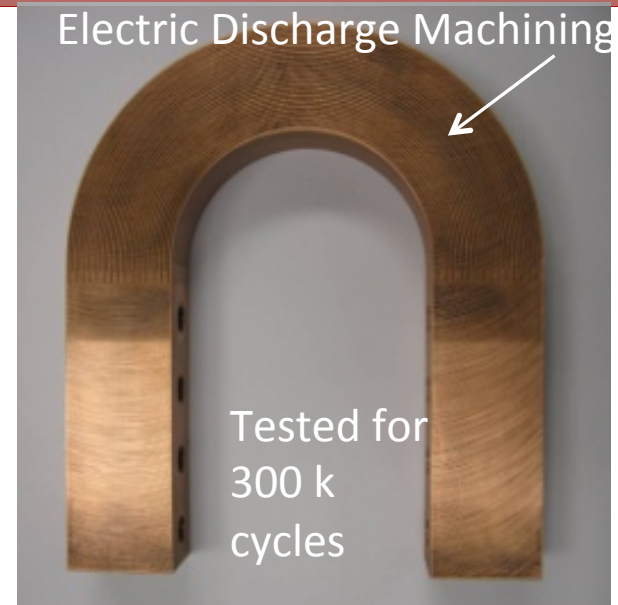
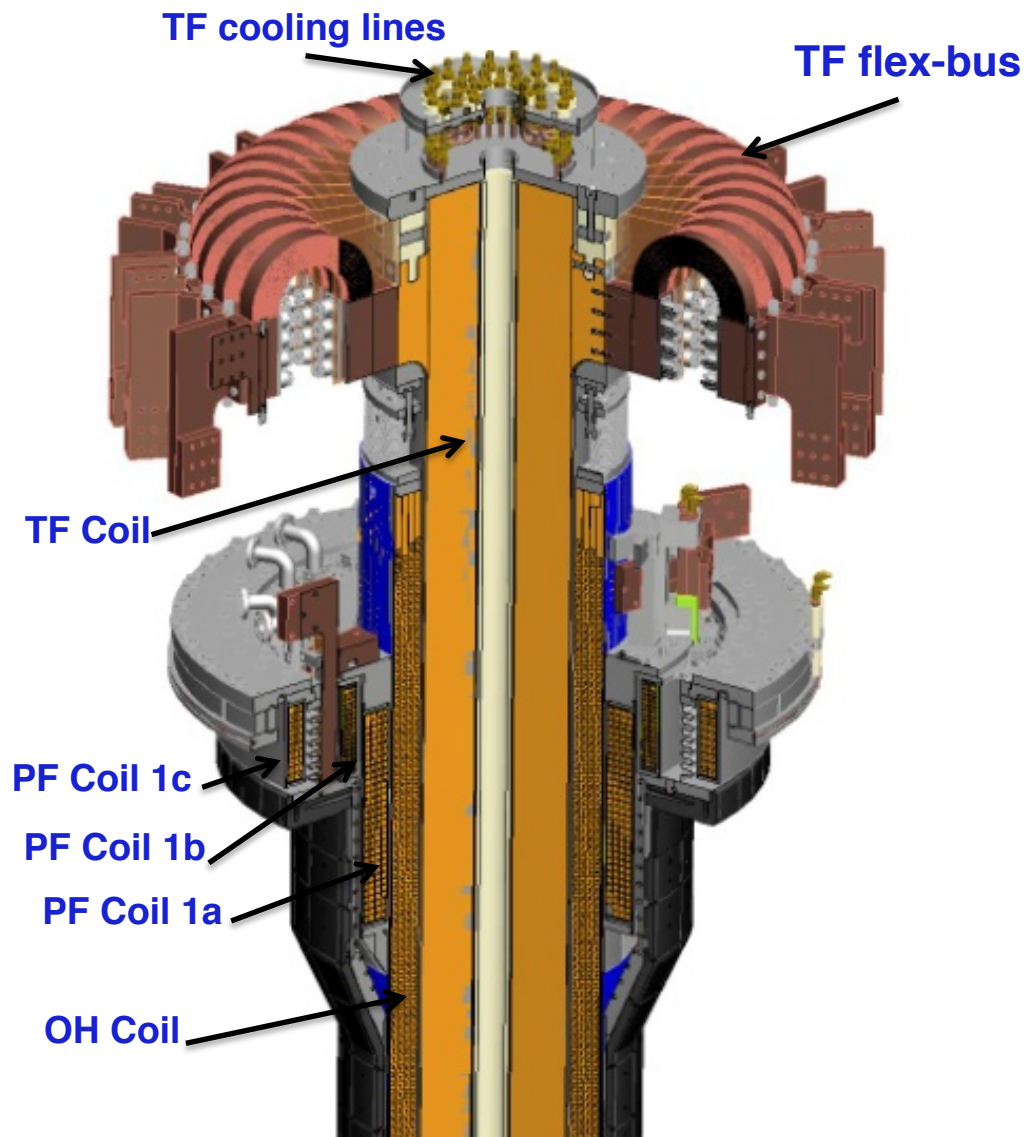
~ 10 increase in $n\tau T$ from NSTX

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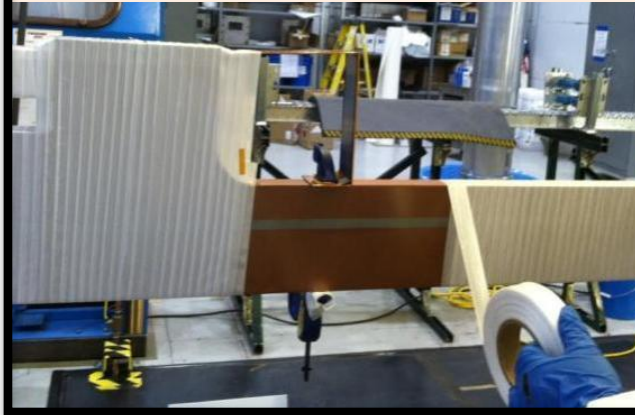


New Center-Stack uses Innovative Design to Handle Increased Forces

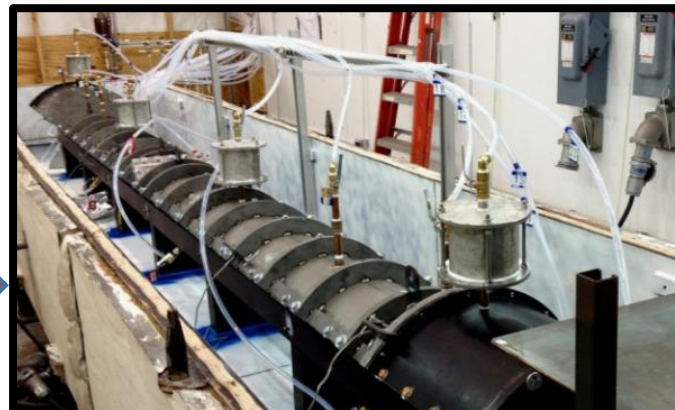


CS Step #1: Manufacture TF Quadrants

Conductor being wrapped with fiberglass insulation



Insulated conductor being placed into mold



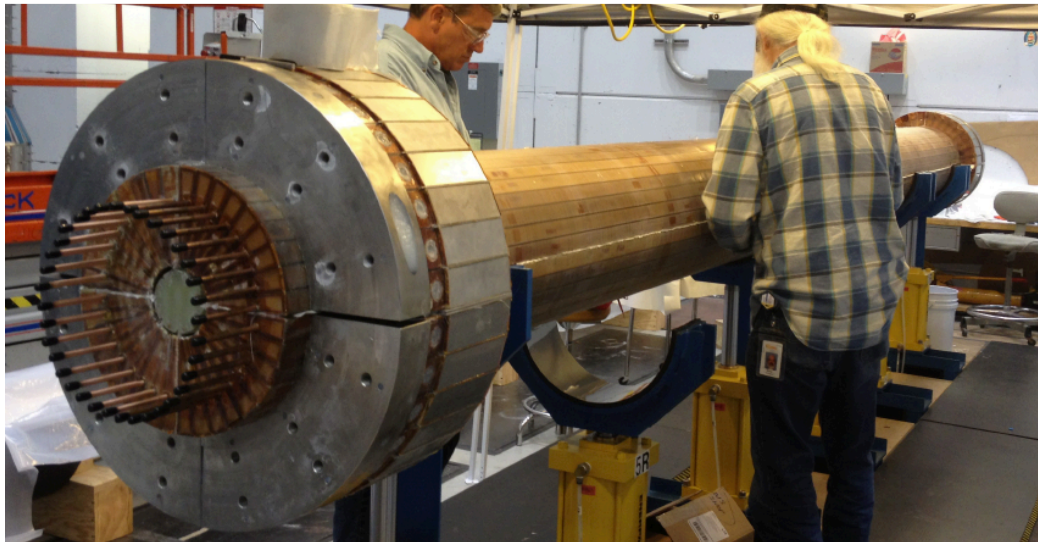
Assembled TF mold ready for Vacuum Pressure Impregnation with CTD-425



All four Quadrants successfully VPI'd !

CS Step #2: Assemble Full TF Bundle

Four TF quadrants were combined into a full TF bundle



Center-Stack Casing with tile studs

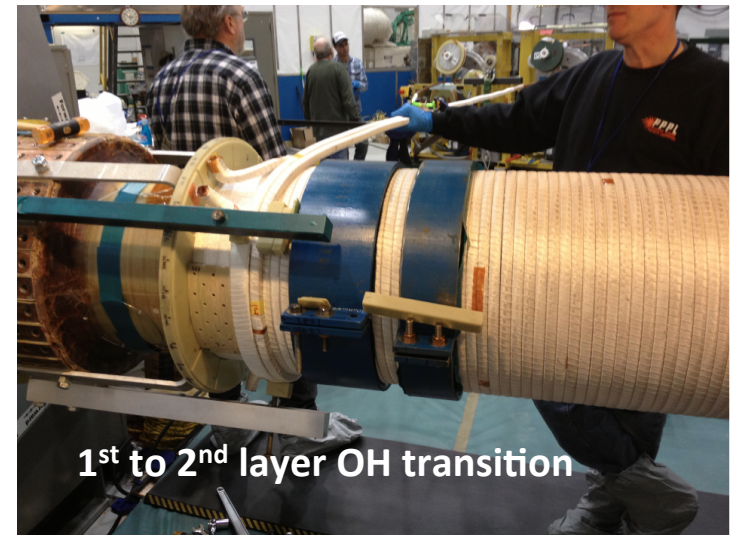
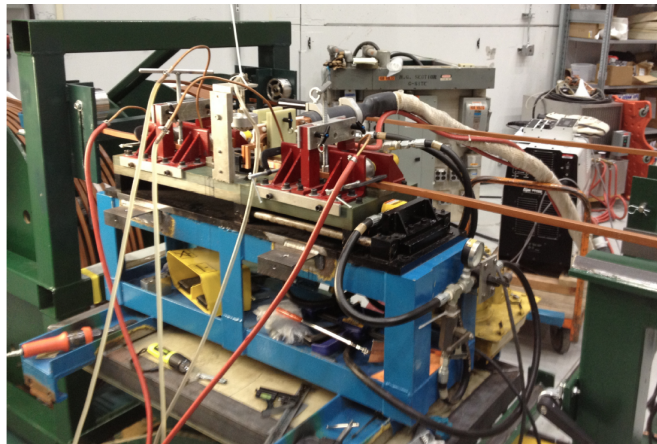


TF bundle with ground wrapping lowered into VPI mold



CS Step #3: Wind OH Coil on TF Bundle

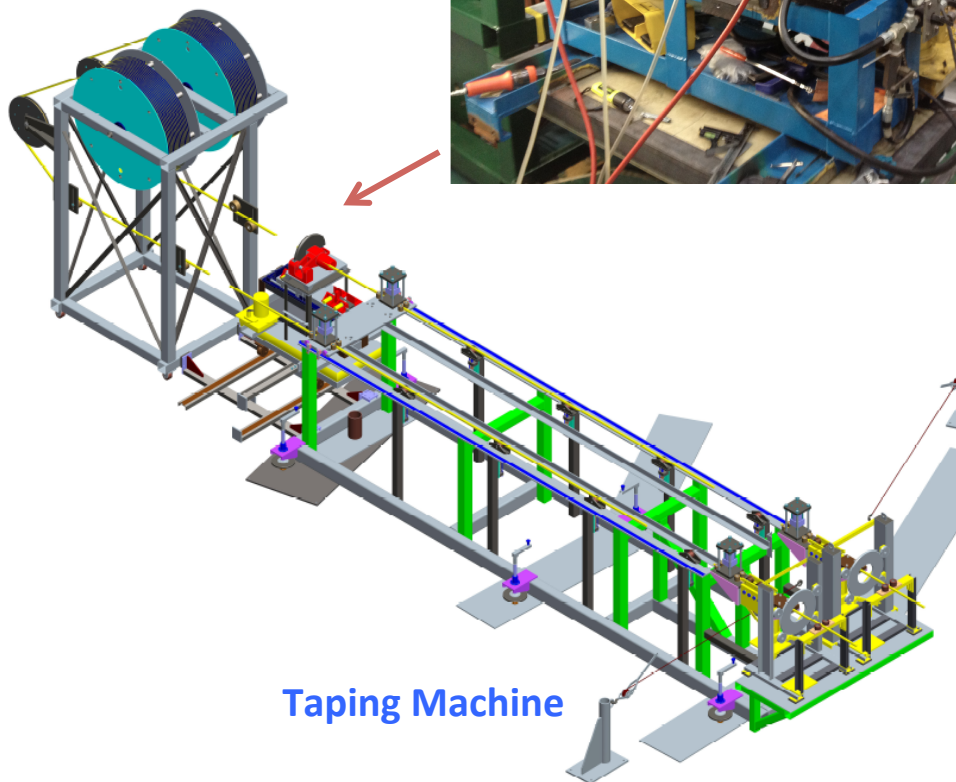
In-line Induction
brazing station



1st to 2nd layer OH transition



1st layer OH winding 2/3 complete



Taping Machine

CS Step #4: Add Diagnostics and Fit Casing

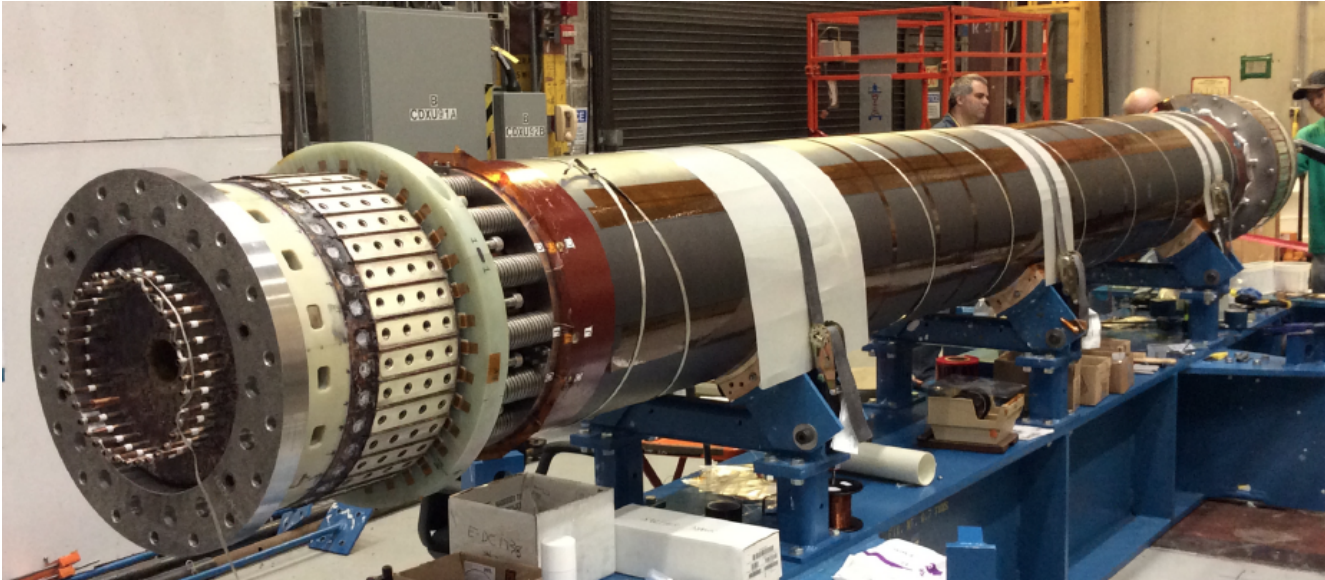
OH winding over TF completed



CS Casing lowered onto Center Bundle



CS center bundle (TF+OH) completed



CS Step #5: Install in NSTX-U!

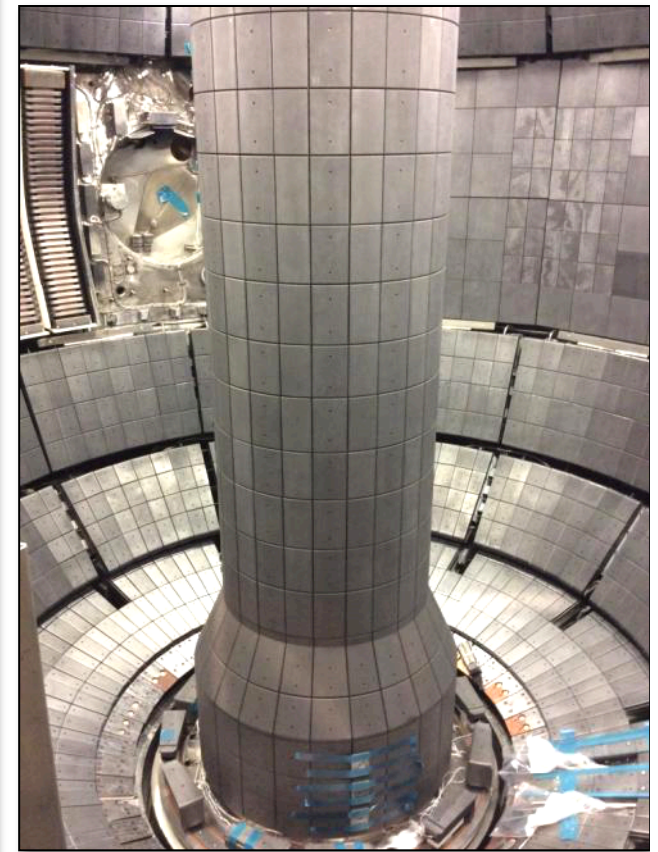
Over the shield wall



Over the machine



Inside NSTX-U!



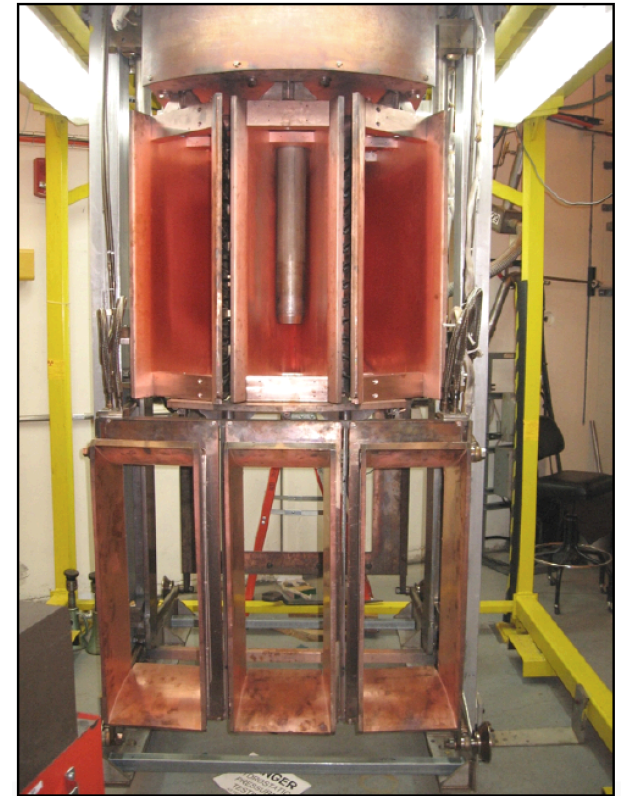
NB Step #1: Get Beamline Components Ready to Move to NSTX Test Cell

Beamline had been used for tritium operations on TFTR, was still located in the TFTR test cell.

Decontamination of the TFTR beamline



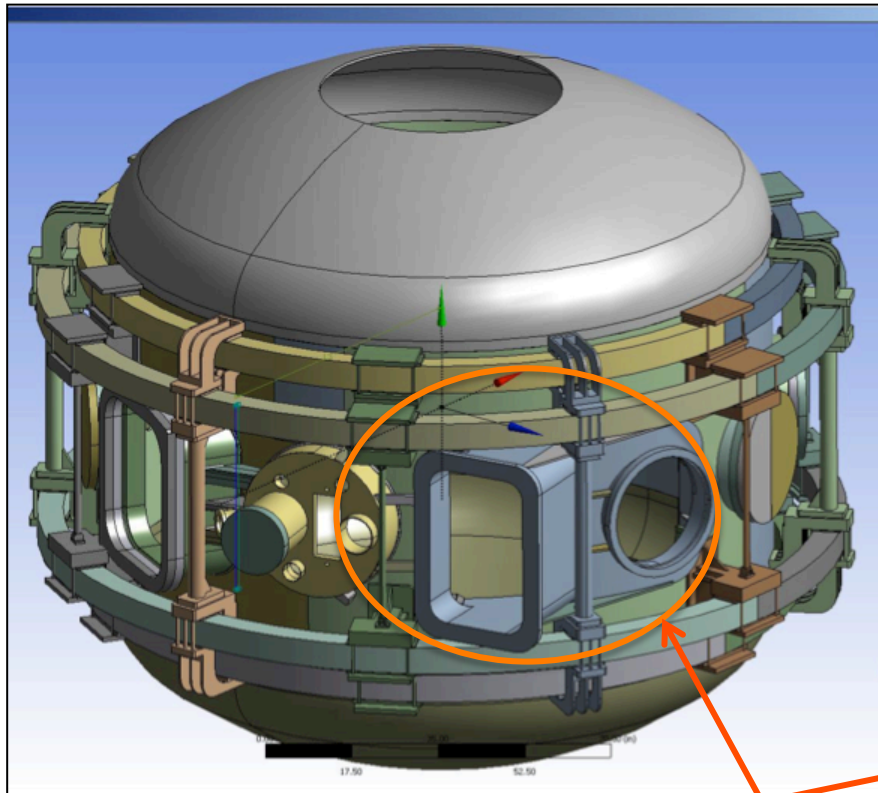
Refurbish the calorimeter and other beamline internals



New primary energy ion dump



NB Step #2: Modify the NSTX Vessel to Accommodate the More Tangential Injection

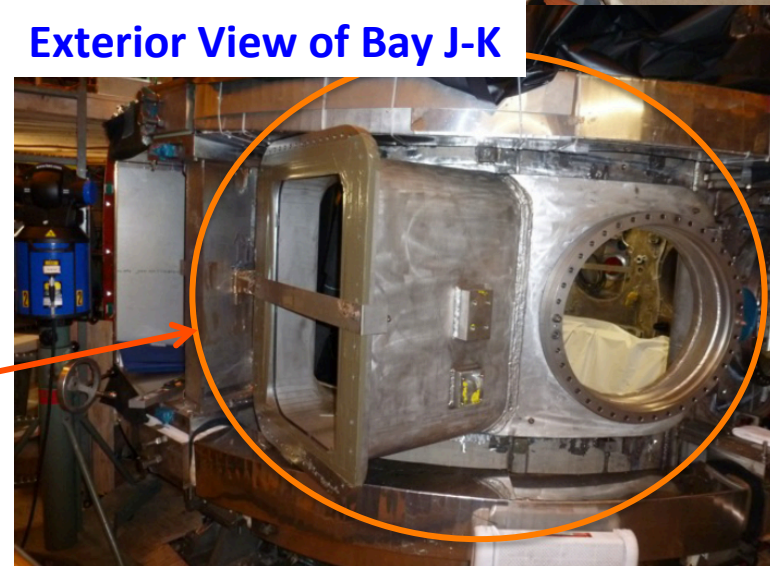


JK cap

Interior View of Bay J-K



Exterior View of Bay J-K



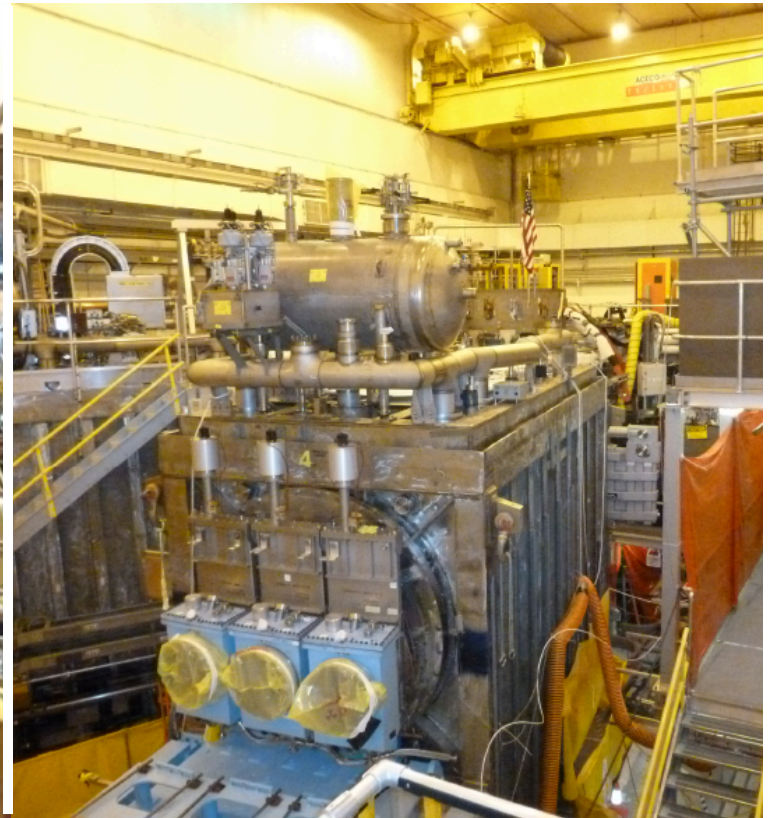
NB Step #3: Move the Beamline and Its Internal Parts Into the NSTX Test Cell



Beam Box being lifted over NSTX



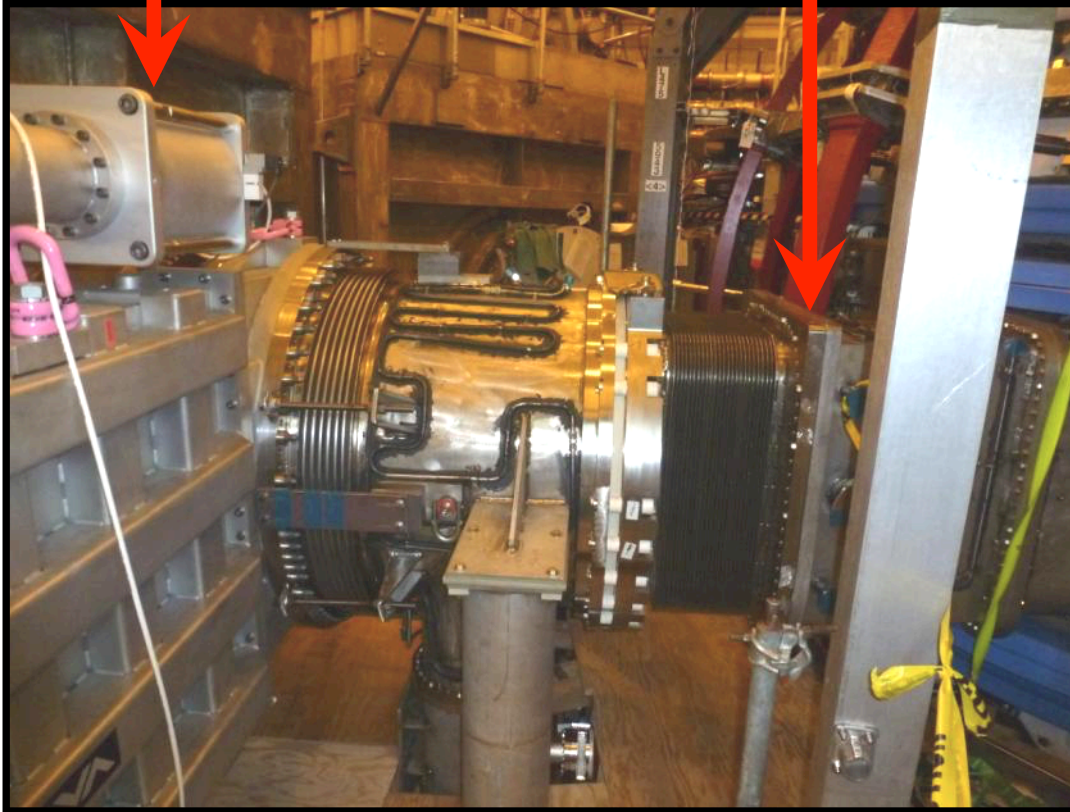
Beam Box placed in its final location and aligned



Beam Box being populated with components

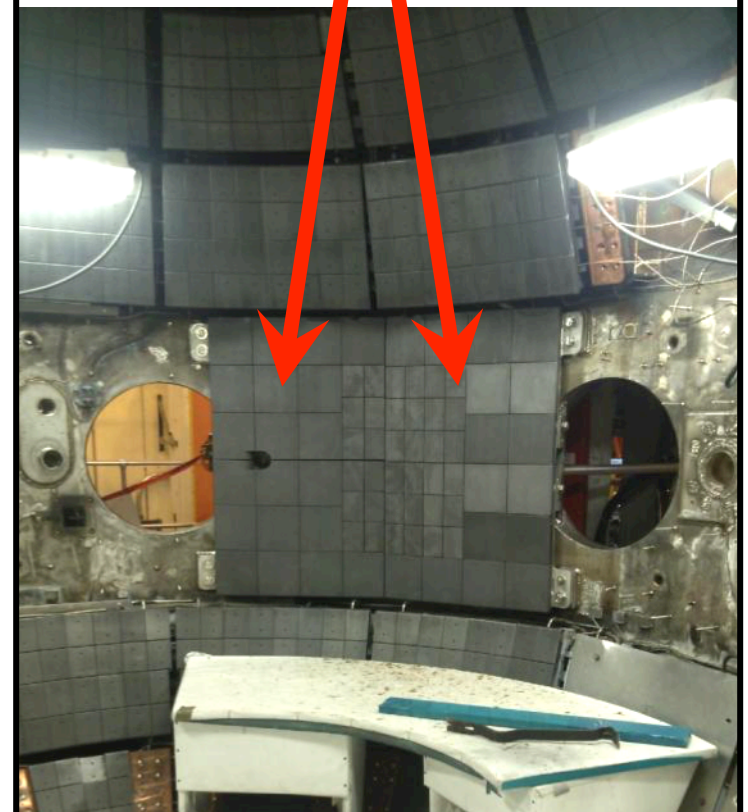
NB Step #4: Add the Armor, Drift Duct, Services

Neutral Beam & Torus
Isolation Valve



Vacuum Vessel Bay J/K
Port

Neutral Beam Armor
Installed



Very significant jobs to add liquid N₂ and liquid He plumbing, cooling water for sources and beamline internals, vacuum pumping, high-voltage cabling and power supplies

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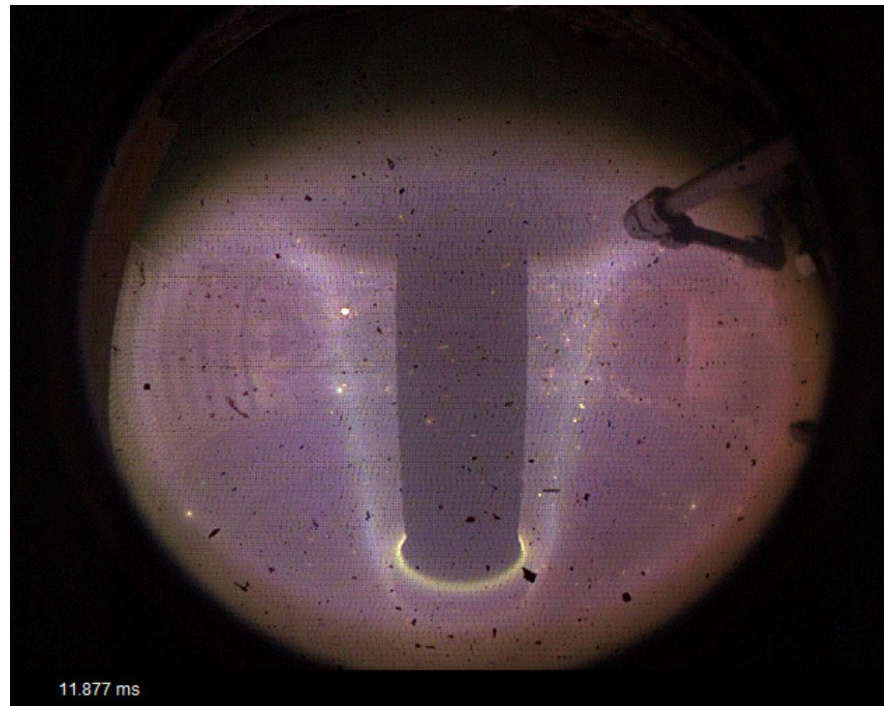
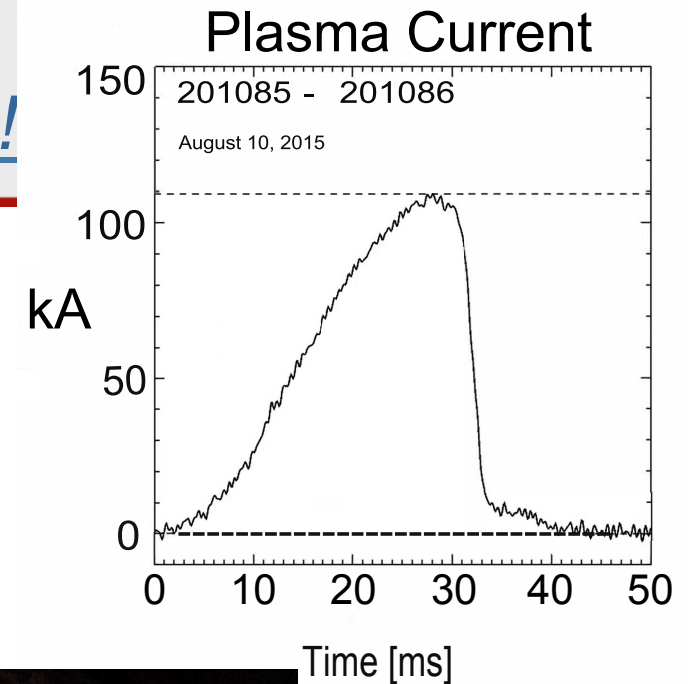
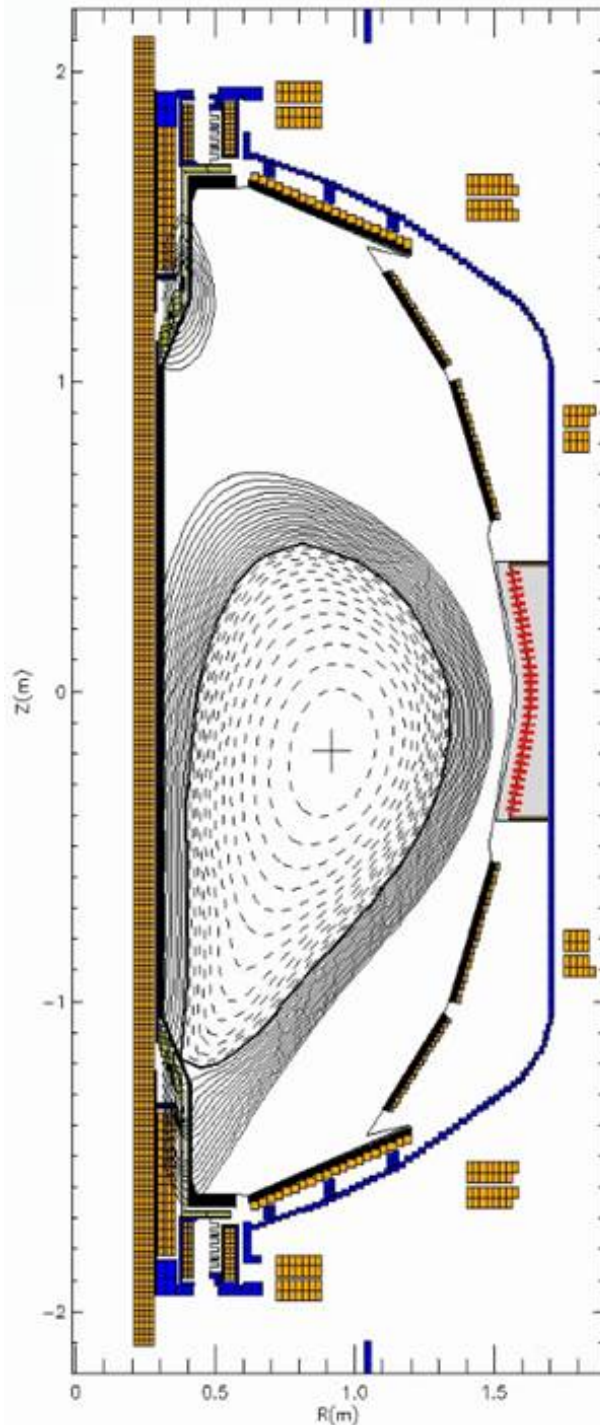
Context on Initial Operations

- To declare the construction project complete, we did the following:
 - demonstrated an $I_p=50$ kA plasma.
 - demonstrated NB #2 operations with at least a 40 kV beam.
- In order to get to these quickly, we did only a CS 350 C bake.
 - All the graphite on the outboard divertors & passive plates was unbaked, and therefore a source of water.

8/10/2015
!! 110 kA Plasma !!

EFIT Reconstruction
of the Plasma Shape
Available on Very 1st
Shot!

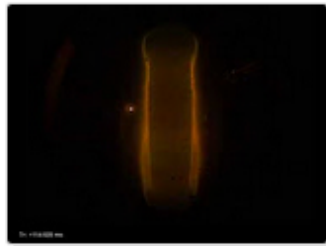
[S. Sabbagh
Columbia University]



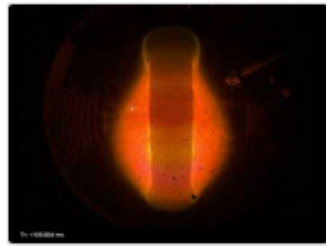
Fast Color
Camera
Image
[F. Scotti, LLNL]

“Middle” Movie Frame for Each Shot Shows Shot-to-Shot Progress on First Run Day

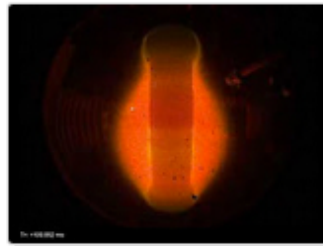
Shot #2



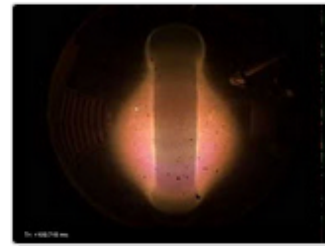
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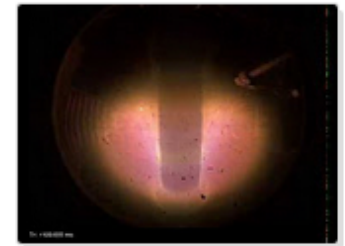
nstx_2_201074.mov



nstx_2_201075.mov



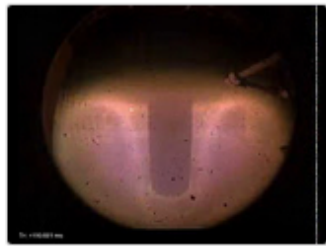
nstx_2_201076.mov



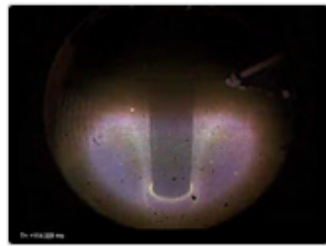
nstx_2_201077.mov

Shot #6

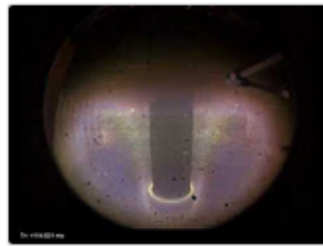
Shot #7



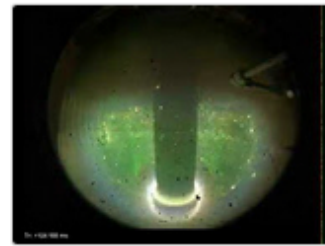
nstx_2_201078.mov



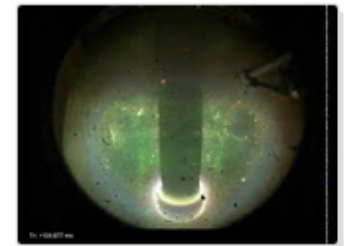
nstx_2_201079.mov



nstx_2_201080.mov



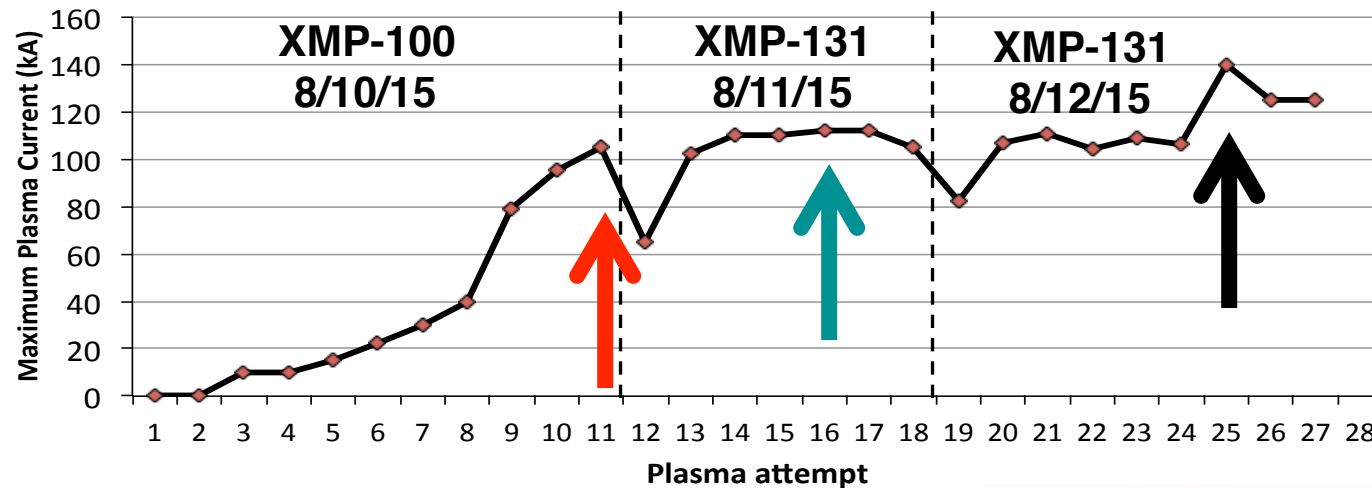
nstx_2_201084.mov



nstx_2_201085.mov

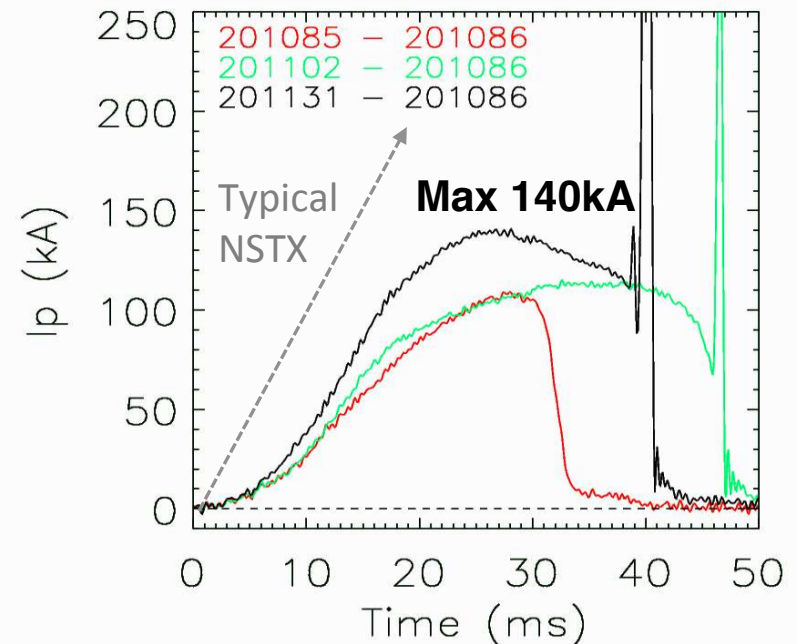
Shot #11

Continued Improvement in Plasma Current and Duration in 28 Plasma Shots over 3 Days



- Centering plasma and shrinking outer gap lengthened discharge
- Reducing prefill fueling increased I_p ramp rate (Wed)

Performance Will be Dramatically Better Now that We Have Completed the Full Vessel Bake



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Facility Status as of 10/31/2015

- Coils
 - OH, TF and PF coils systems fully operational.
 - In final stage of recommissioning the external midplane 3D field coils and their supplies.
- Vessel pumped down, 3 week bakeout complete
- Neutral Beams
 - 6 sources have completed low-voltage conditioning
 - 3 sources on each of 2 beamlines
 - Three sources on the new beamline are now make beam at modest voltages.
- HHFW system fully reinstalled and undergoing vacuum conditioning

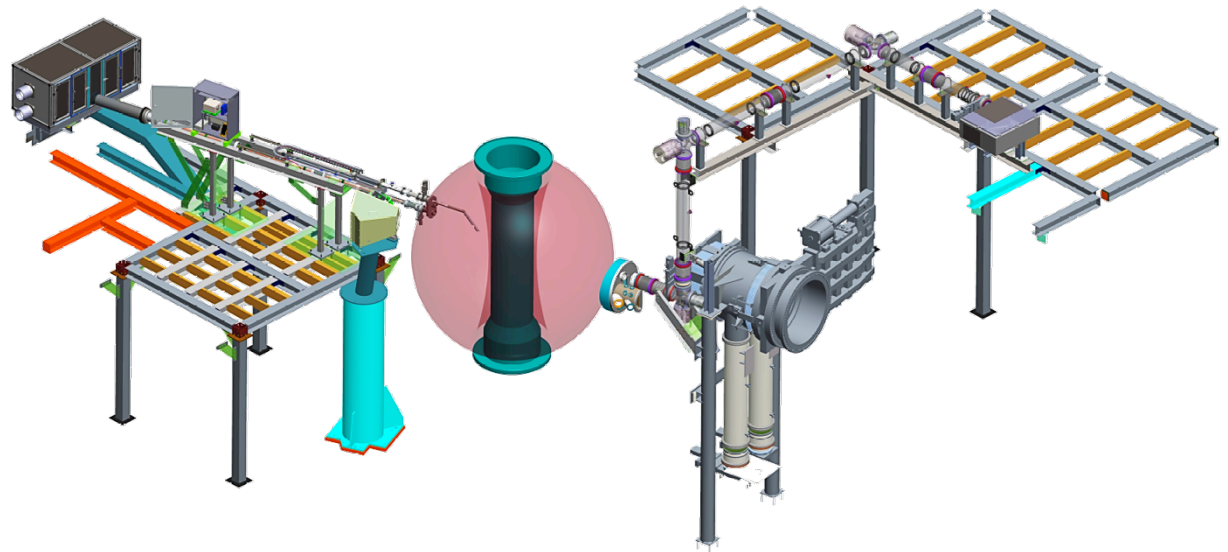
Many New and/or Improved Diagnostics Ready to Support Operations

- Re-Aimed 42 Channel Thomson Scattering

- Tangential FIDA
- New SSNPAs
- 48 channel BES
- Multiple Energy SXR
- Materials Analysis Particle Probe
- Many more...

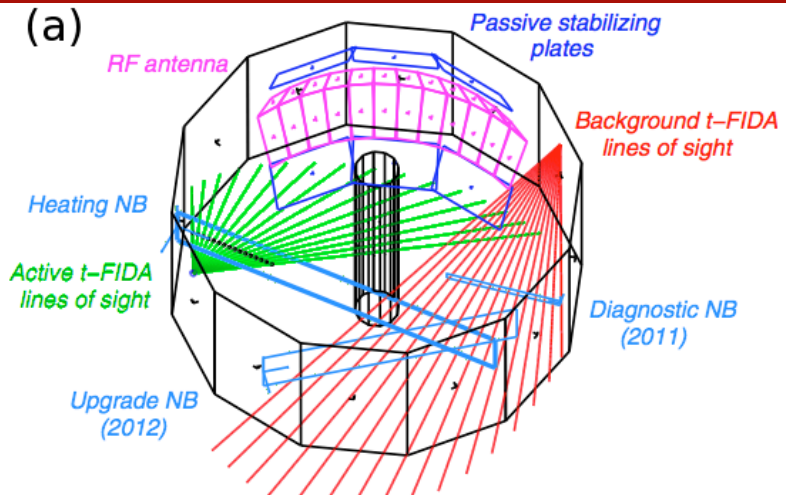
Key Features

- 42 radial channels
- Improved spatial resolution compared to NSTX
Outer edge pedestal and ITB
- Major beam path modifications to accommodate larger CS and new NB box
- Collection optics hardware modified, improved imaging
- Two 30-Hz Nd:YAG lasers provide baseline capability
Provision for third laser

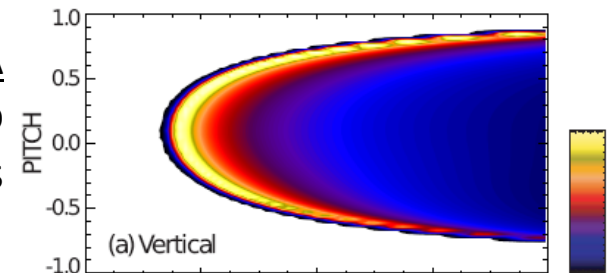


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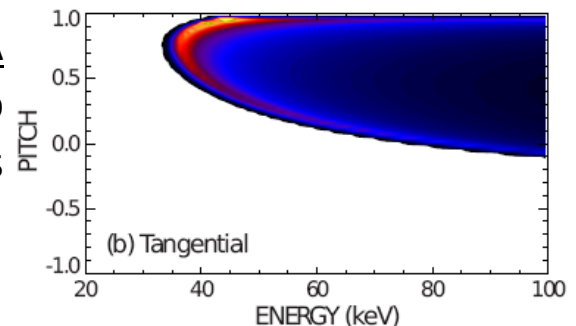
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Vertical FIDA
Strong Sensitivity to
Trapped Particles



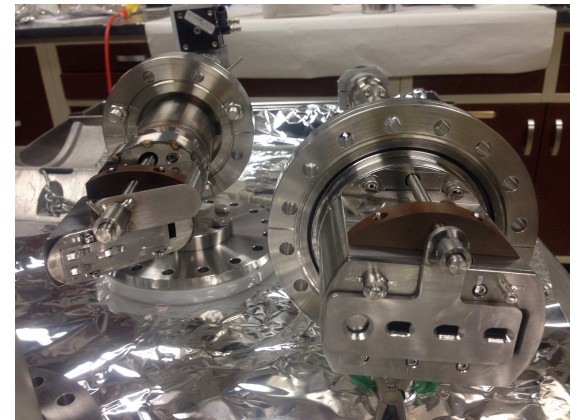
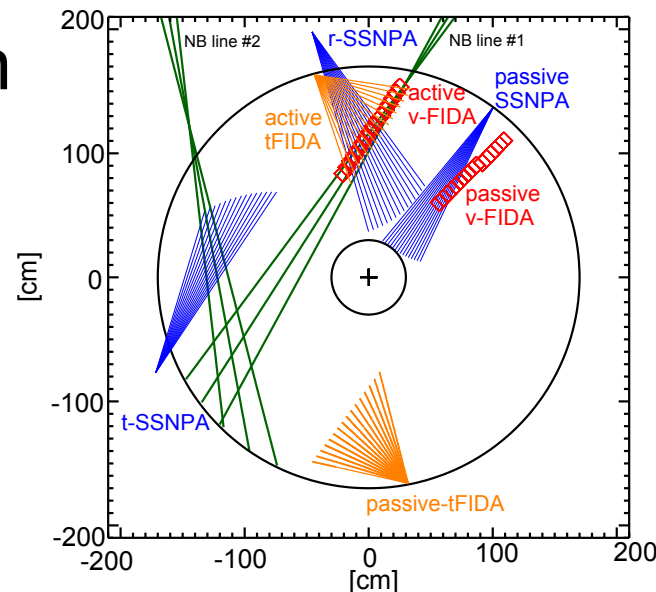
Tangential FIDA
Strong Sensitivity to
Co-Passing Particles



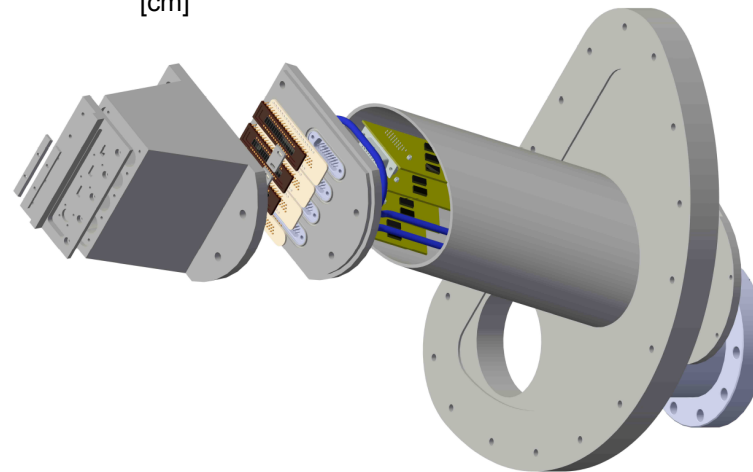
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SSNPAs are Installed and Ready for Operation



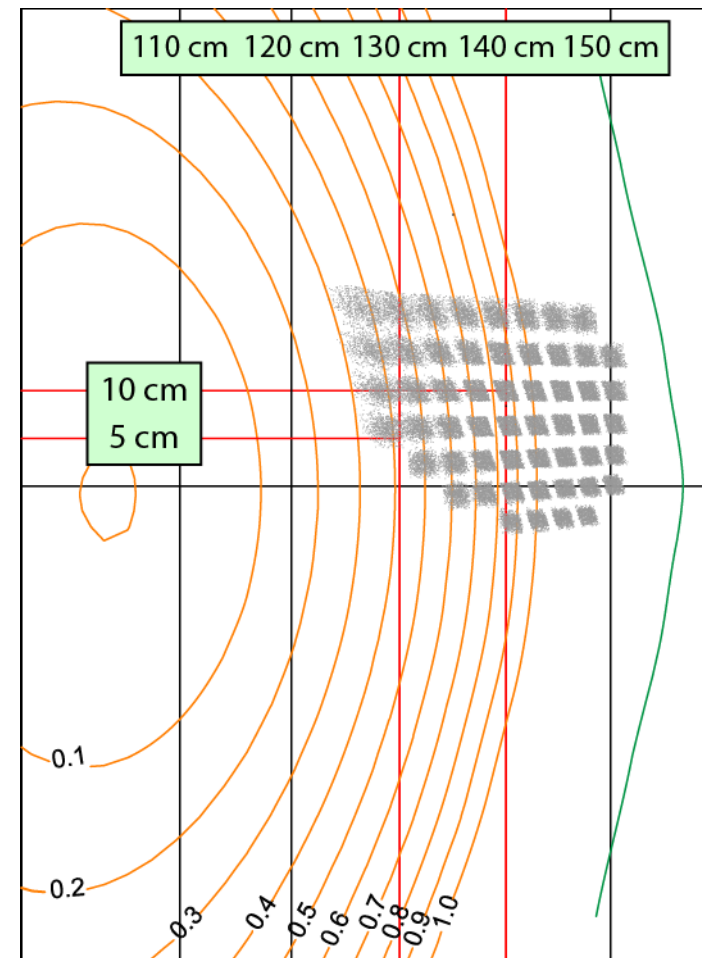
*D. Liu, W. Heidbrink,
UC-Irvine*



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Expansion from 32 to 48 detection channels
2D pedestal/SOL imaging with 54 bundles



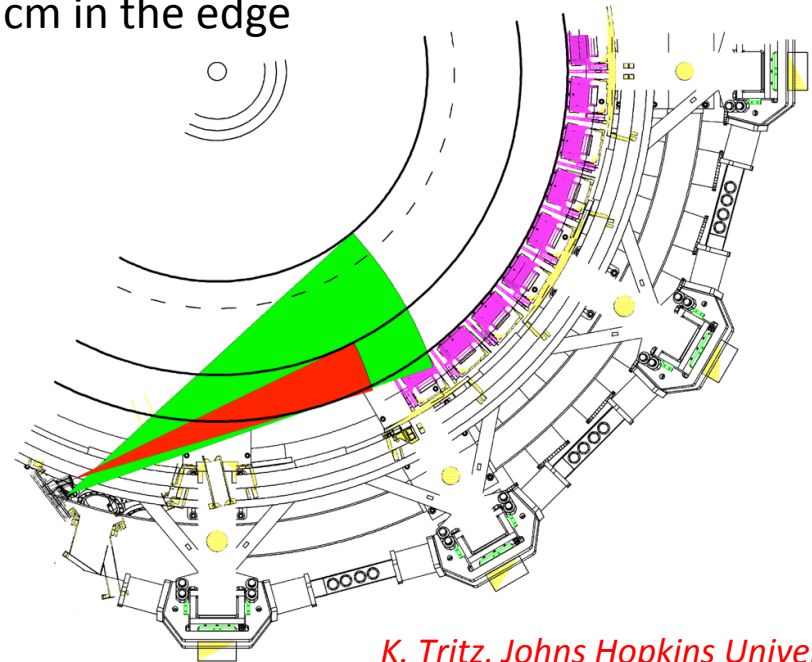
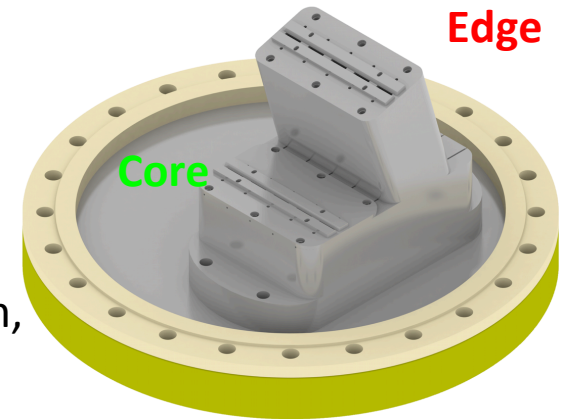
D. Smith, G. McKee, U. of Wisconsin-Madison

Many New and/or Improved Diagnostics Ready to Support Operations

- Re-Aimed 42 Channel Thomson Scattering
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Goal: Fast T_e profiles from edge to core, using multi-energy X-ray emissivity

- 100 channels for edge and 100 for core, 10 kHz
- Bolometry, Be 5 μm , 15 μm , 50 μm & 150 μm filters
- 3 cm spatial resolution in the core, 1 cm in the edge

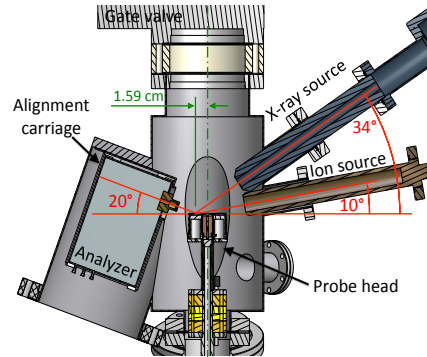


K. Tritz, Johns Hopkins University

Many New and/or Improved Diagnostics Ready to Support Operations

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Undergoing Final Installations to Support Operations

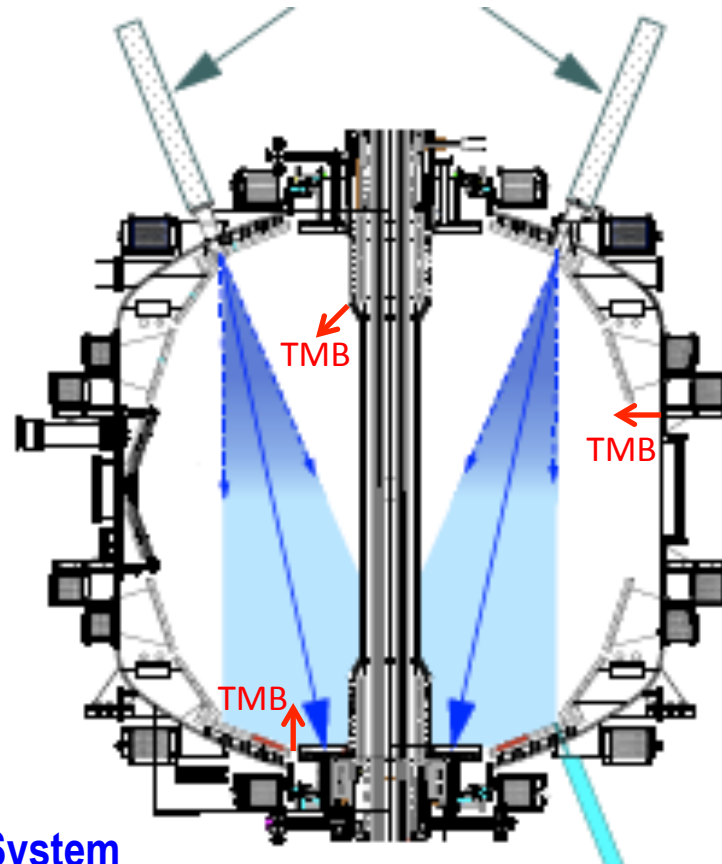


J.-P. Allain, C.F. Bedoya-Arroyava, U. of Illinois Urbana-Champaign

Many New and/or Improved Diagnostics Ready to Support Operations

- Re-Aimed 42 Channel Thomson Scattering
- Tangential FIDA
- New SSNPAs
- 48 channel BES
- Multiple Energy SXR
- Materials Analysis Particle Probe
- Suite of 3 new EUV spectrometers
- Many more...
- Toroidal and Poloidal CHERS
- Dual MSE systems
- Synthetic Aperture Microwave Imaging (York University, CCFE)
- Multiple fast and slow IR camera systems
- Multiple divertor visible and NIR spectrometer systems.
- Multiple divertor filtered visible cameras.
- EUV Spectrometers
- ...

Three Techniques for PFC Conditioning Will Be Used in the First Campaign



1: Boronization System

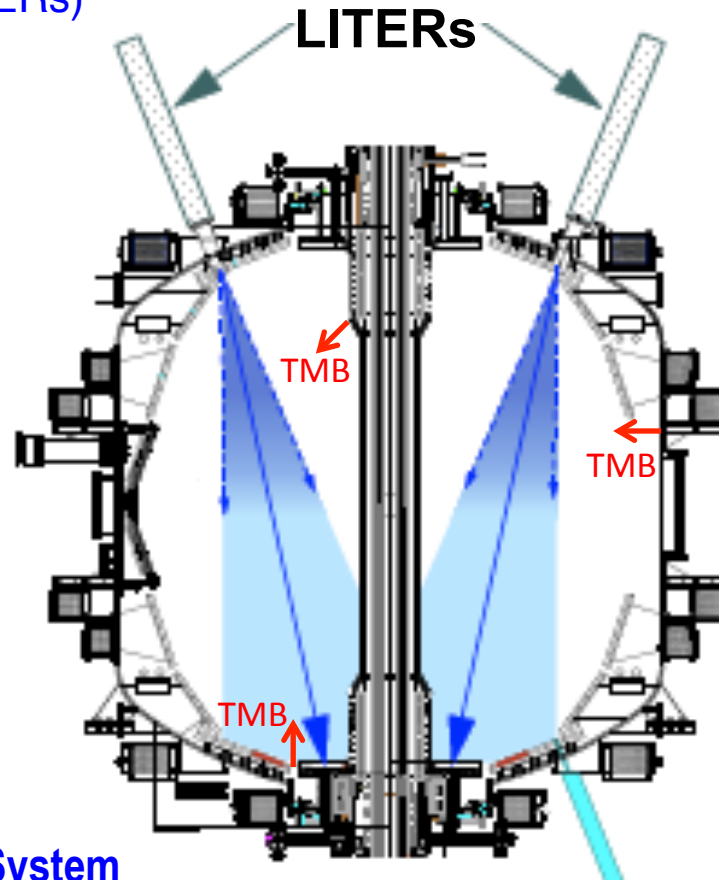
- Boronization with trimethylborane (TMB) will be the initial PFC conditioning technique.
- New system with improved safety, three gas inlet ports for improved uniformity.

Three Techniques for PFC Conditioning Will Be Used in the First Campaign

2: Lithium Evaporator (LITERs)



- Dual system provides evaporated lithium coverage over the full divertor.
- Will be deployed mid-run.



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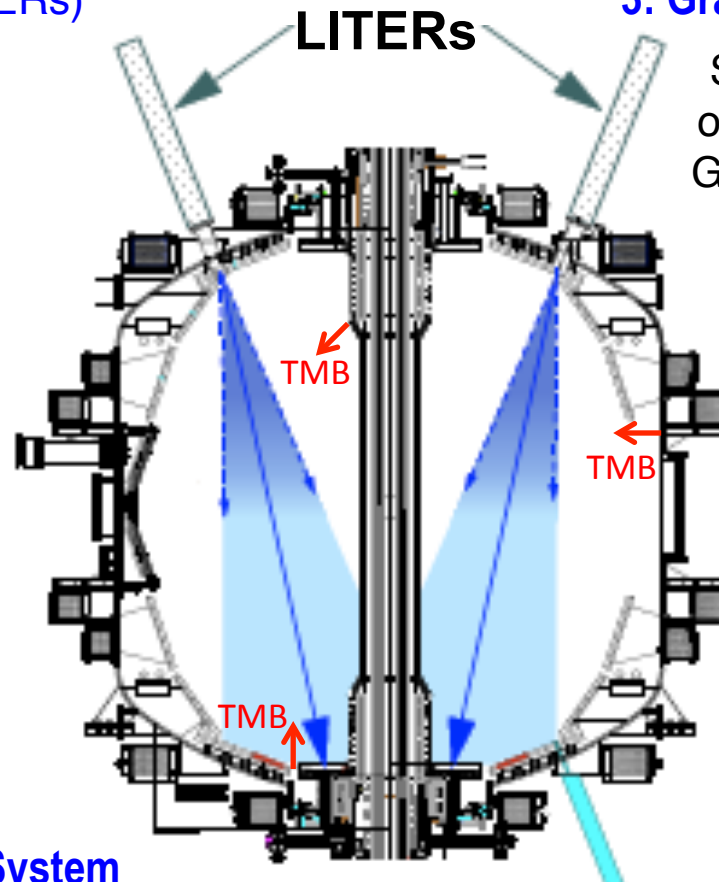
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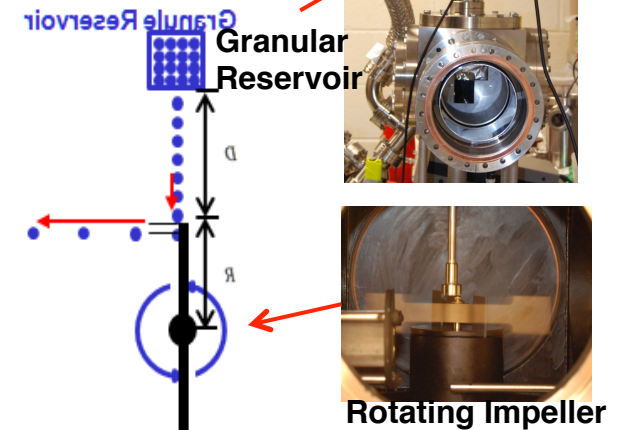
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- New system with improved safety, three gas inlet ports for improved uniformity.



3: Granule injector (GI) for ELM pacing

Successfully tested on EAST and DIII-D
Granules: Li, B₄C, C
f ~ up to 500 Hz



- System in final design and fabrication stages for deployment during the FY16 run campaign

Latest run plan schedule for 2016

- November: Power Supply & Coil Testing
- December: Plasma Operations, Control and Diagnostic Commissioning
- January-May: Physics Experiments
 - Mid-run assessment, probably around April,
- June: Start outage
- Resume operations fall/winter 2016 for FY17

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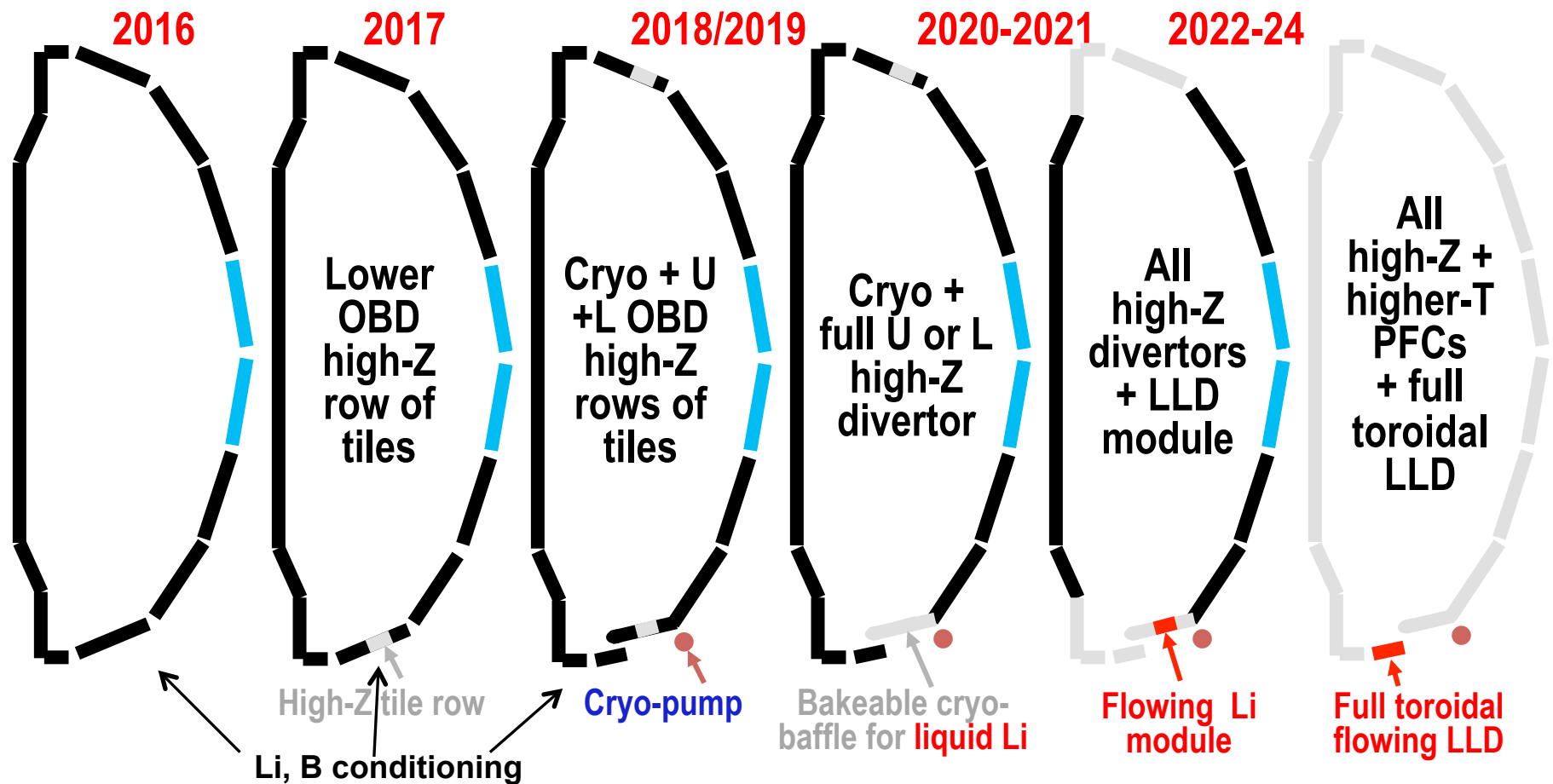


Exciting Facility Enhancements Planned for NSTX-U

- High-Z PFCs
- Cryo-pumped divertor
- New 3D field capabilities
- High power ECH/EBW heating system

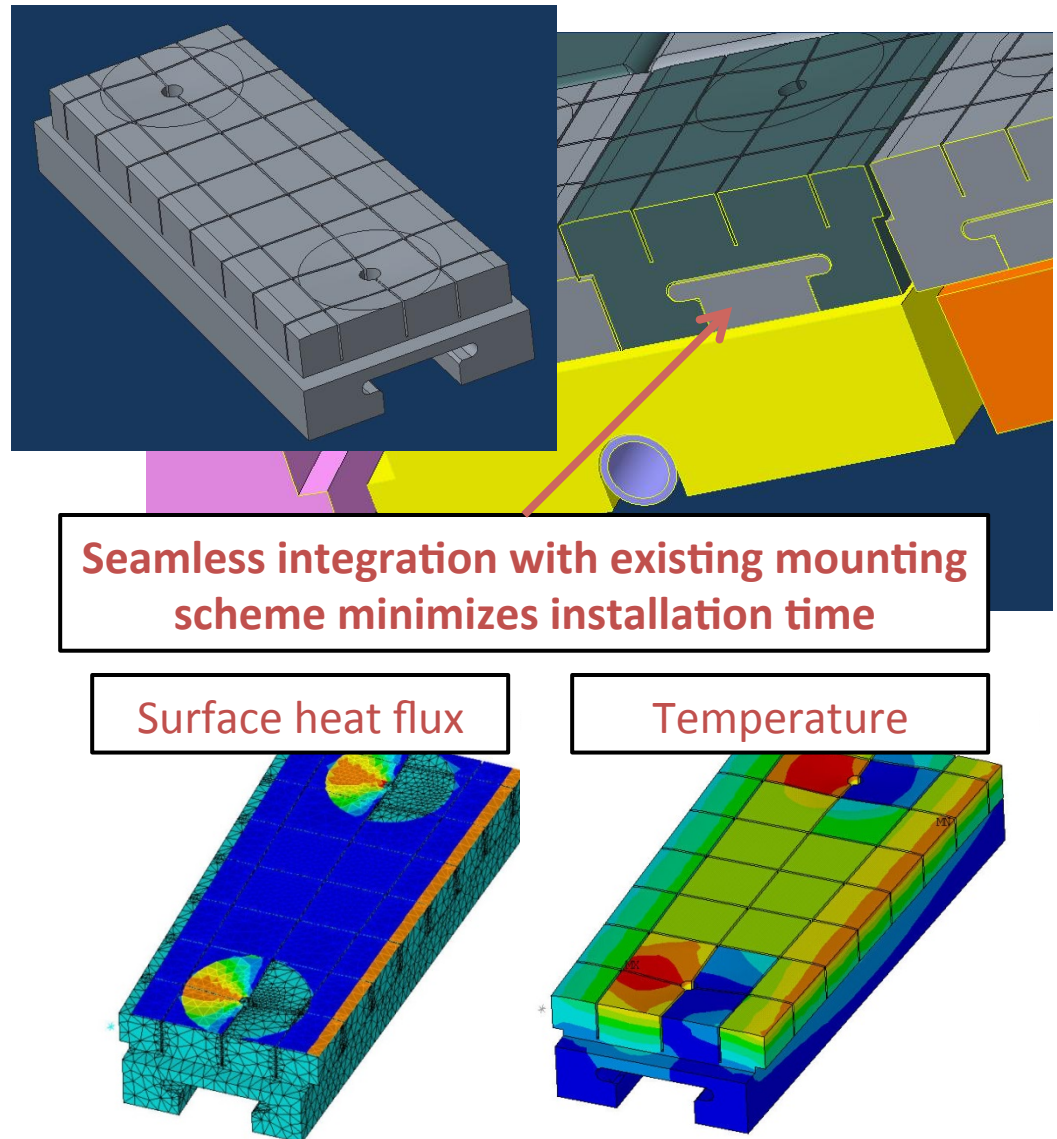
Staged Plan Has Been Developed to Implement High-Z PFCs & Flowing Liquid Metal Systems

C BN Bulk Li High-Z



Single Row of TZM Molybdenum Tiles Will Be Installed for the FY-2017 Run Campaign

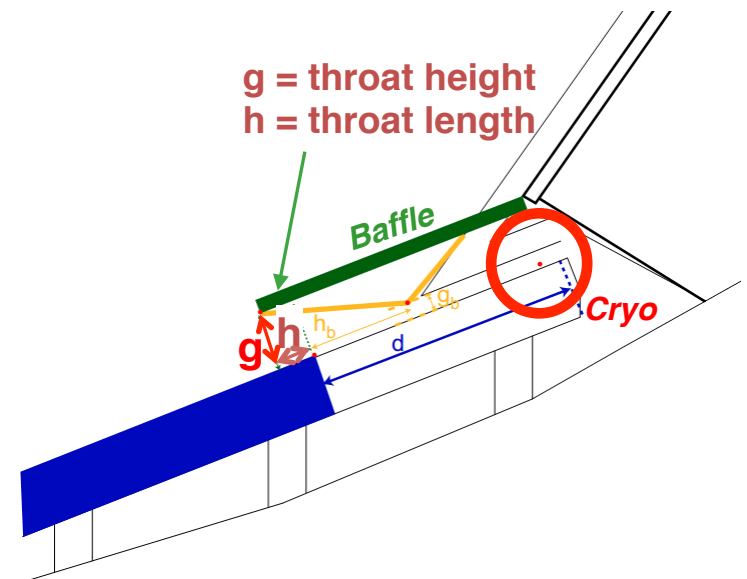
- Goals:
 - Initial assessment of plasma performance with high-Z PFC
 - Develop expertise in analysis, manufacture, installation with the new material
- Design constrained to by a one-for-one replacement of the existing tiles.
- Raw material procurement underway
- Edge and access-way chamfers introduced to reduce heat-flux peaking.



Cryopump Physics Design Done in Collaboration with ORNL

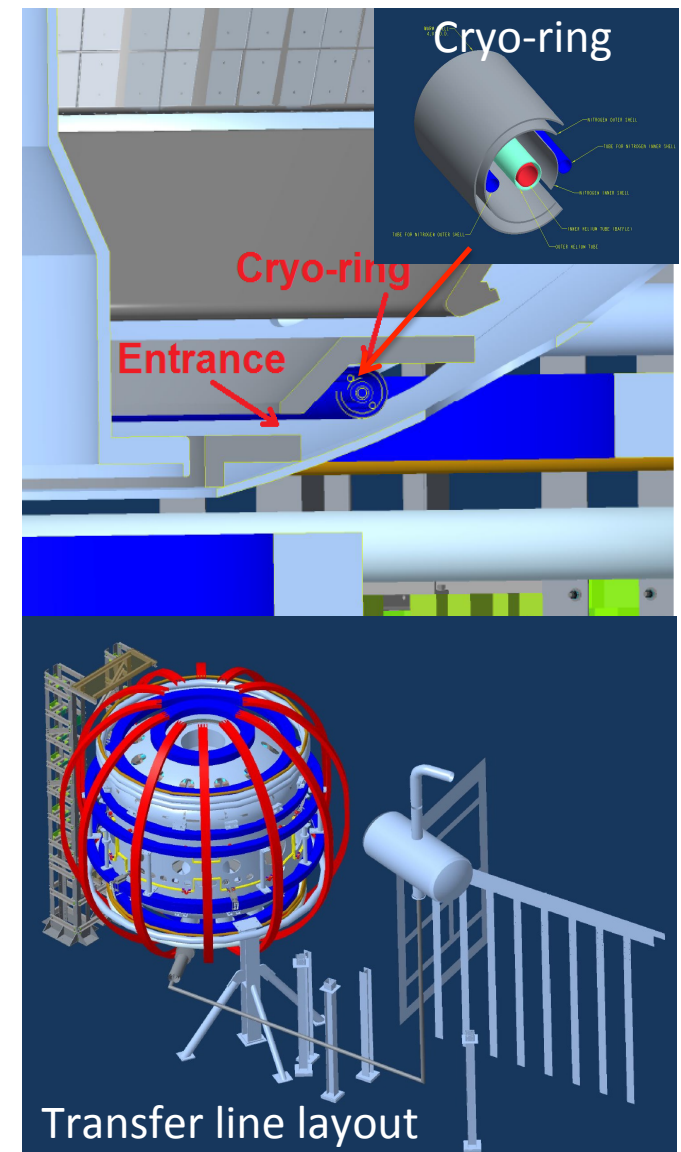
J. Canik, ORNL

- Initial designs used semi-analytic models to determine pump geometry.
 - Conclusion on optimum geometry:
 - duct height $h \sim 2.5$ cm,
 - length $h \sim 2$ cm,
 - Radius of 0.72 m.
 - Allows pressures > 1 mT over a range of plasma shapes and SoL widths.
 - Should allow the full beam fuelling to be pumped.
- Calculation then benchmarked against SOLPS



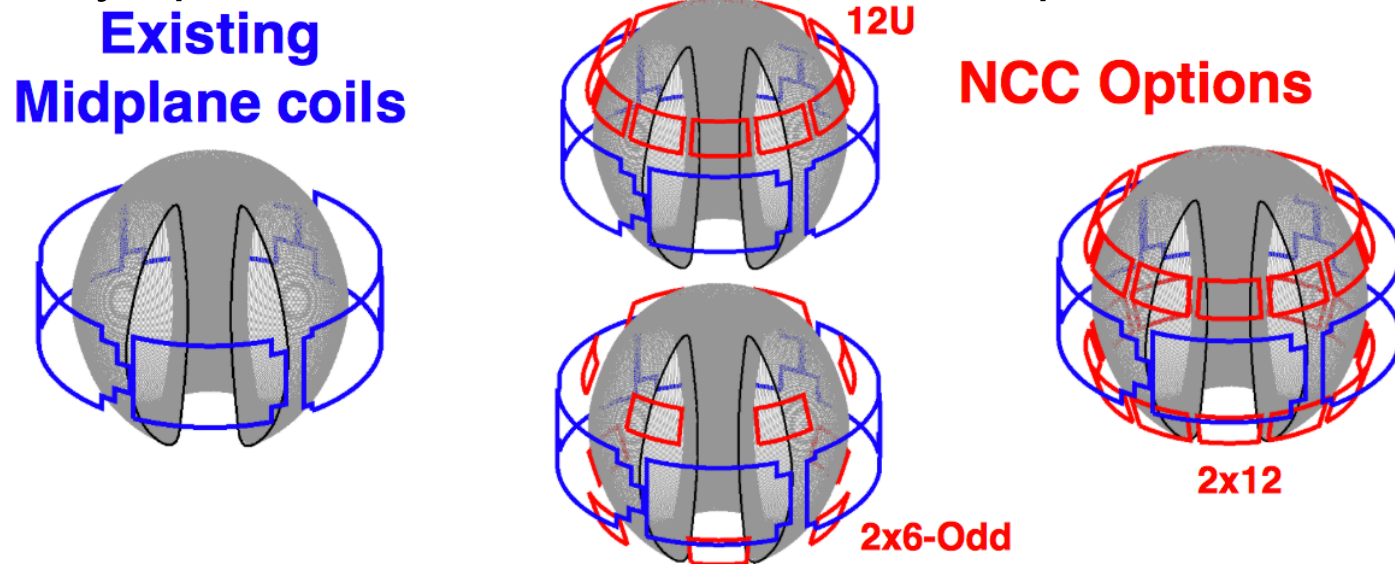
Physics Studies are Transferring to the Initial Engineering Design

- Initial in-vessel geometry has been laid out.
 - Pump radius, throat dimensions taken from the modeling.
 - Is a significant perturbation, requiring a rebuild of basically the entire lower outer divertor.
- 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.



Non-Axisymmetric Control Coils Will Dramatically Improve Our 3D Physics Capabilities

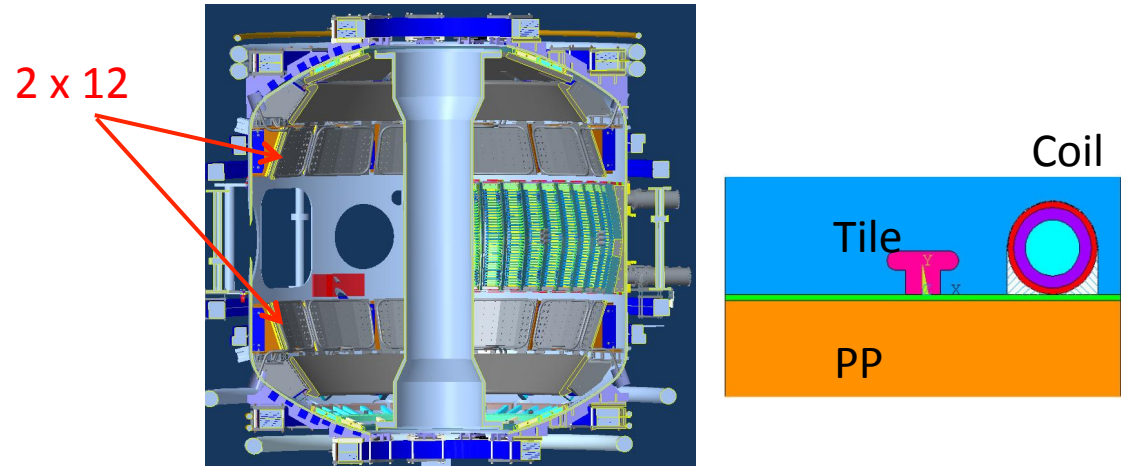
- Three primary options considered for the NCC implementation:



- Metrics under consideration:
 - $n=1$
 - RWM control
 - Ability to scan the relative ratio of resonant to non-resonant $n=1$ contributions
 - $n>1$
 - Variation of available NTV torque profiles.
 - NTV normalized to the Chirkov parameter
- Conclusion: 2x12 is best, 2x6-Odd is a good step in a staged implementation

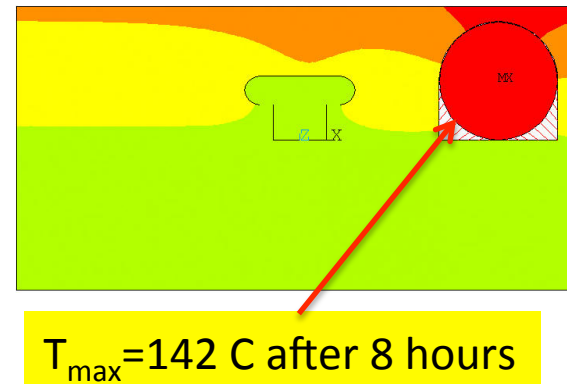
NCC is Undergoing Conceptual Design in Parallel with the Cryopump

- Considering a mineral insulated conductor
- Order of 20' test sample is placed:
 - Both solid and hollow center conductors
- Goal is to assess
 - Manufacturability/formability,
 - electrical characteristics, including end-sealing methods,
 - fabrication lead time and cost.
- Hollow conductor will allow He cooling, but analysis indicates thermal ratcheting with solid conductor is likely manageable.



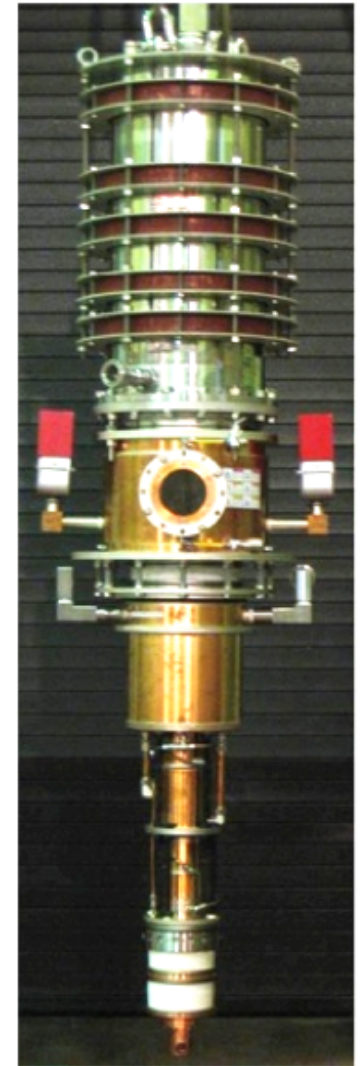
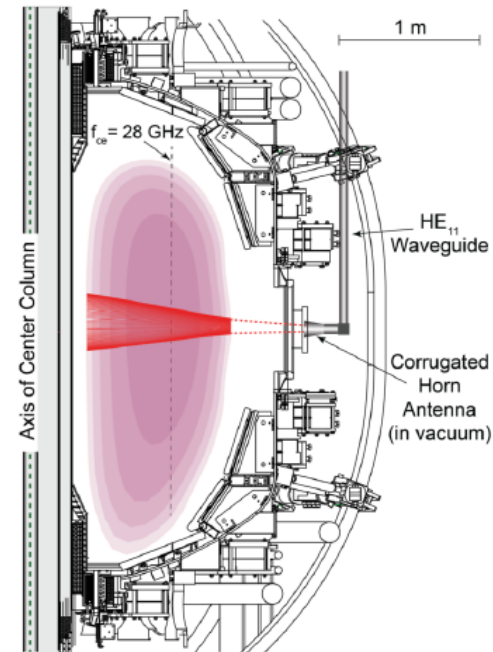
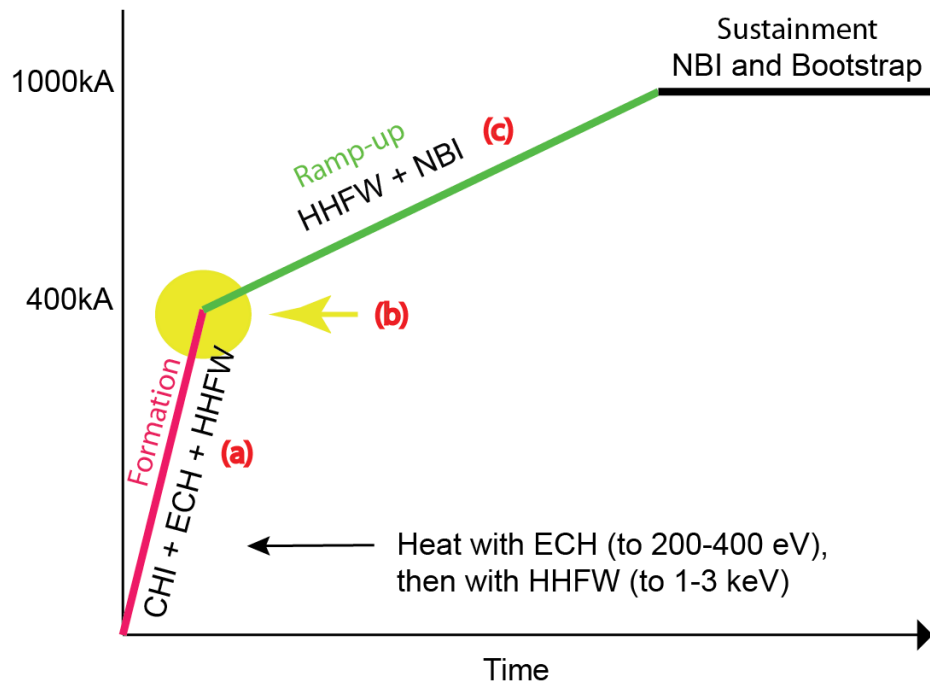
Assumptions In Solid Conductor Calculation

3 kA 5s pulse 1200 s repetition prate



28 GHz Gyrotron System Will Facilitate Non-Inductive Startup Research

- Coupling CHI to NB overdrive will be aided by electron heating



- TSC simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~ 400 eV in 20ms
- 28 GHz, 2 MW tubes developed by Tsukuba University planned to provide this power.
- Have found location for gyrotron, appropriate commercial waveguide manufacturer.

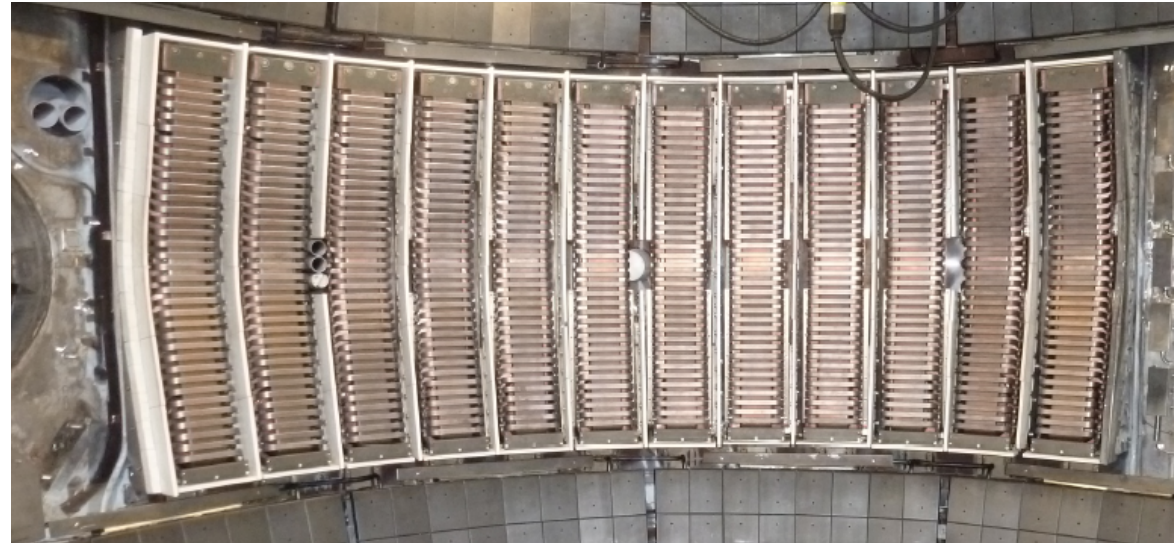
Summary

- The upgrade construction project was successfully completed.
 - Vessel modification & structural supports, moving the beamline, beamline services, fabricating the new OH/TF bundle, DCPS,...
 - First plasma has been achieved.
- Many new and/or improved diagnostic & PFC conditioning systems for the new run.
- Exciting facility upgrades are planned to further increase the scientific productivity of the facility.

Backup

HHFW System is Ready to Support Research Plasma Operations

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



Transmission lines installed & tuned.

- All sources are ready.
- Vacuum conditioning in progress

The Research Program Will Initiated By a Sequence of Commissioning Experiments (XMPs)

- XMPs for pre-plasma calibrations (3)
- XMPs to reestablish basic “L-mode” plasma operations (7).
- XMPs for “H-mode” access and advanced plasma boundary control (5)
- XMPs for additional control development and initial diagnostic checkout (6)
- XMPs for advanced diagnostic checkout (6)

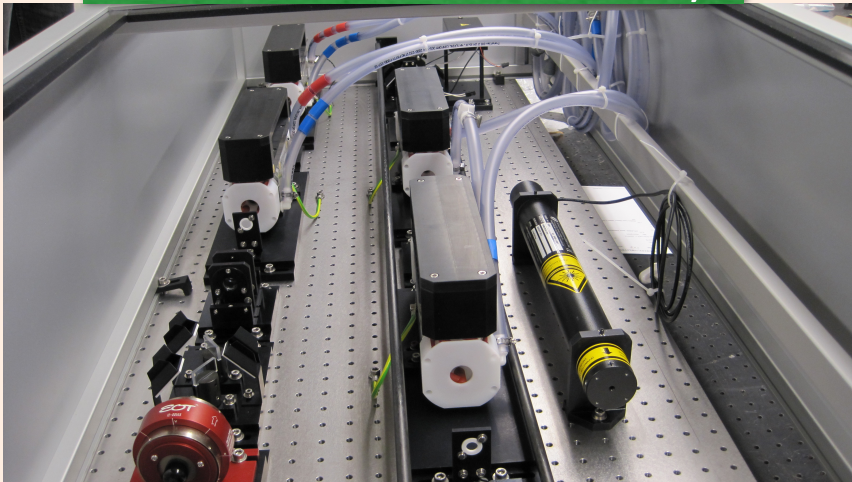
At the completion of this list, we will be ready to execute the critical XPs (I_p & B_T Scaling, Characterization of the 2nd NB Line)

Continually Improving Diagnostics Will Aid in Understanding

2 Examples

Pulse Burst Thomson Scattering

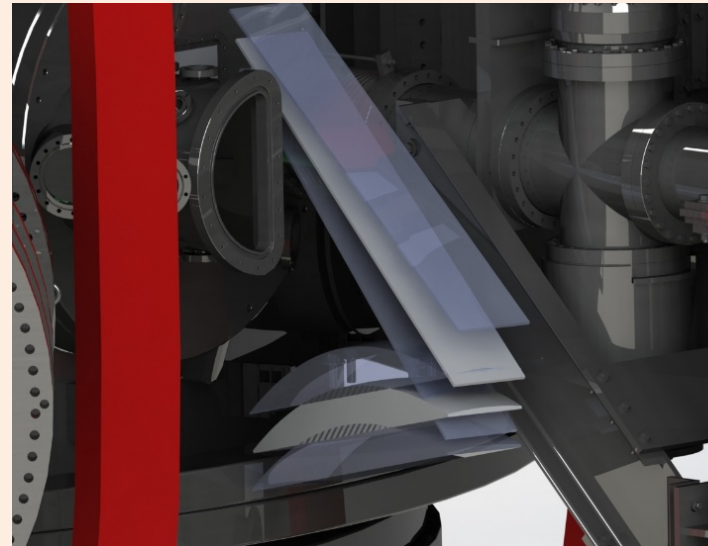
Front view of the laser cavity



- PBLS is capable of 30 Hz normal operation as the baseline
 - This will increase the NSTX-U Thomson rep rate to 90 Hz from 60 Hz.
- PBLS will provide pre-programmed or on-demand bursts of 1 kHz (for 50ms) or 10 kHz (for 5 ms)
 - 50 pulses of 1.5 J each
- Anticipated delivery date: Spring 2016

High-k Scattering

UC-Davis, PPPL

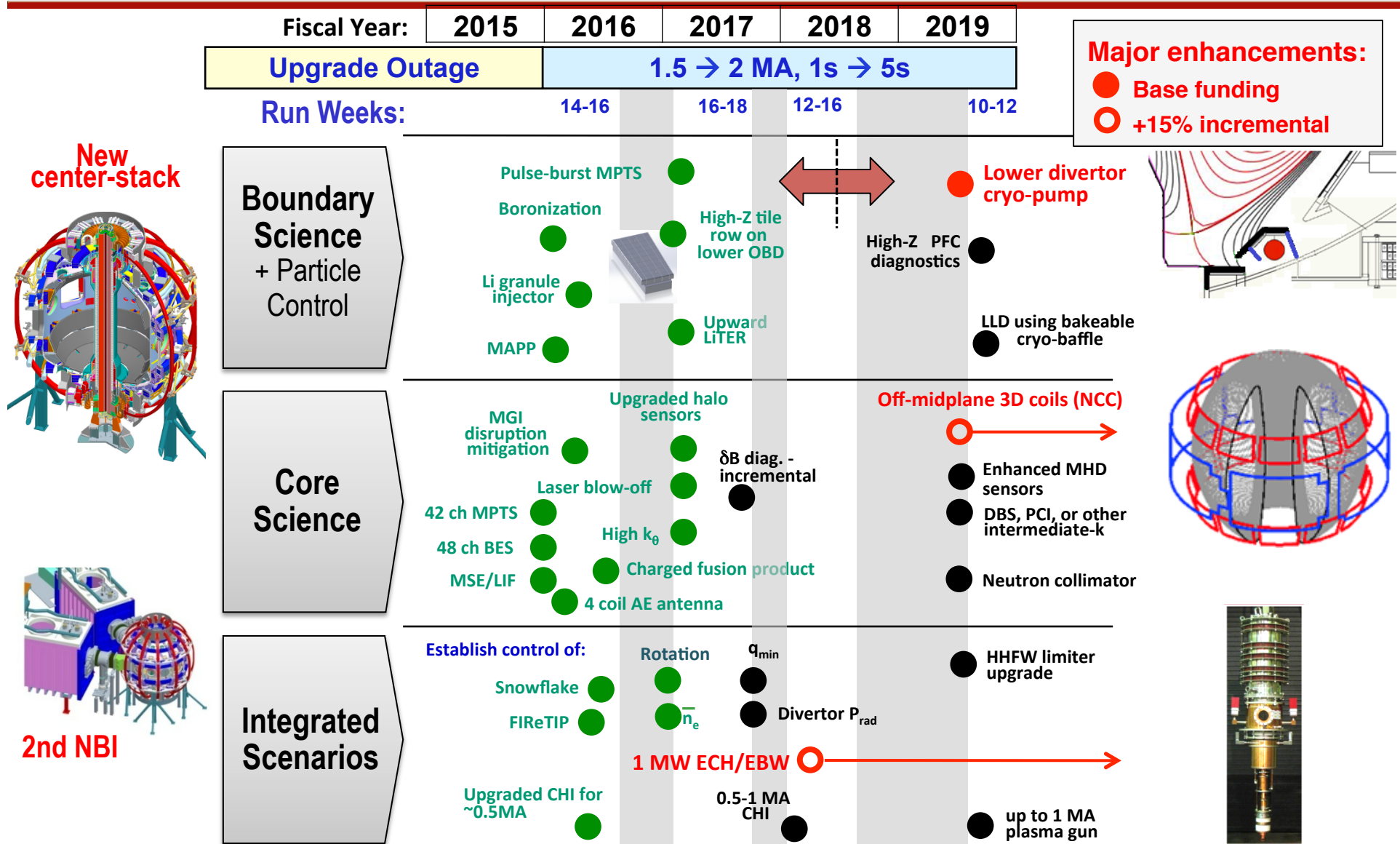


- Innovative schemes allowing measurement of critical wavenumber space features
- Large wavenumber coverage of $k_{\perp} < \sim 50 \text{ cm}^{-1}$, resolution of $\sim 1 \text{ cm}^{-1}$ and 40 MHz response for electron-scale turbulence measurement
- Spatial coverage from the core to the edge with spatial resolution $< 5 \text{ cm}$, allowing detailed comparison with turbulence models

Also laser blow-off, resistive bolometry in main-chamber and divertor, X-ray crystal spectrometer,...

We Have an Aggressive Five Year Facility Enhancement Plan

2015-2016: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH



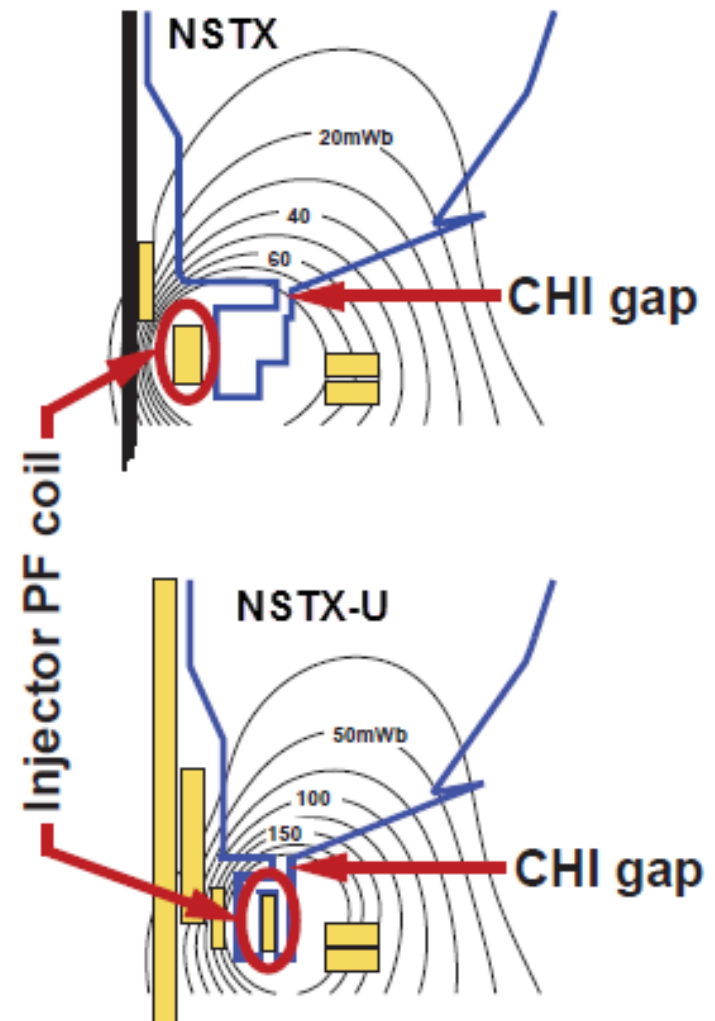
CHI Program Assess Solenoid-Free Start-Up in Support of ST-FNSF

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

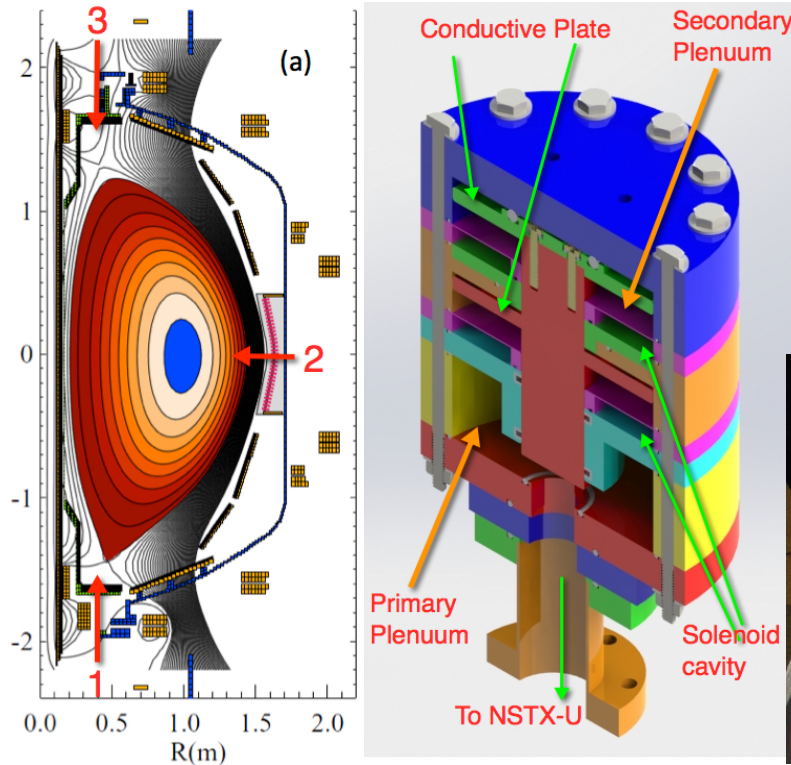
- CHI will start with the present 2 kV capability then enhanced to higher voltage as needed.
- Control system updates for the CHI cap bank have been completed.
- Bank has been fired into a dummy load.



Disruption and Plasma Control Tools for NSTX-U

Massive gas injection system for disruption mitigation study

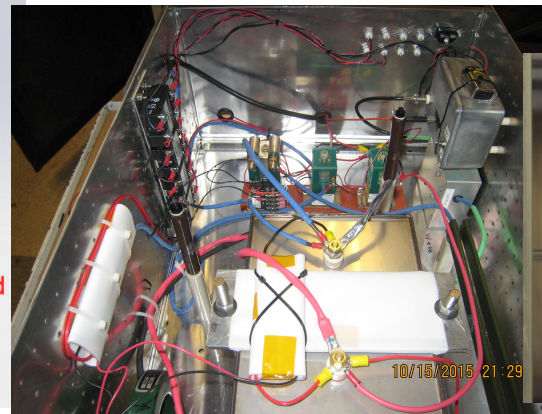
NSTX-U MGI Valve



- 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 $J \times B$ torque) based on the ORNL ITER MGI design

Compact MGI Power Supply for NSTX-U installation

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



Magnets

Solenoid

Magnets

Solenoid

MGI Valve

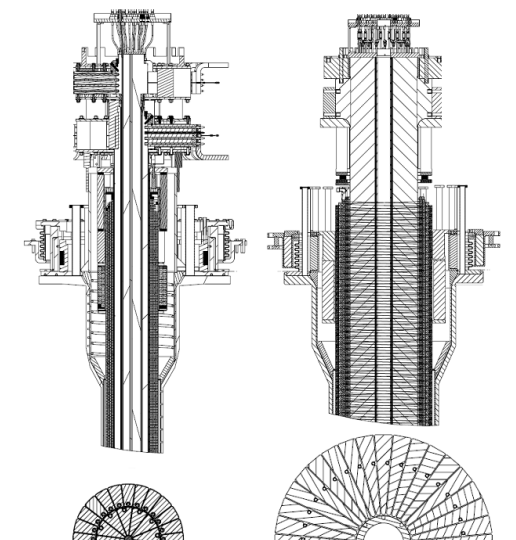
U. Washington

Status:

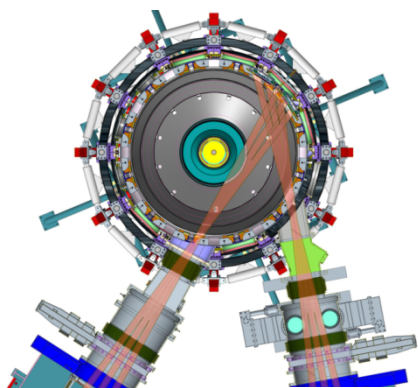
- Conceptual Design Review of MGI system was held on October 16.
- Recommended changes were incorporated into the power system hardware.

A New TF/OH Magnet Assembly and an Additional Neutral Beamline are the Key Components of the Upgrade

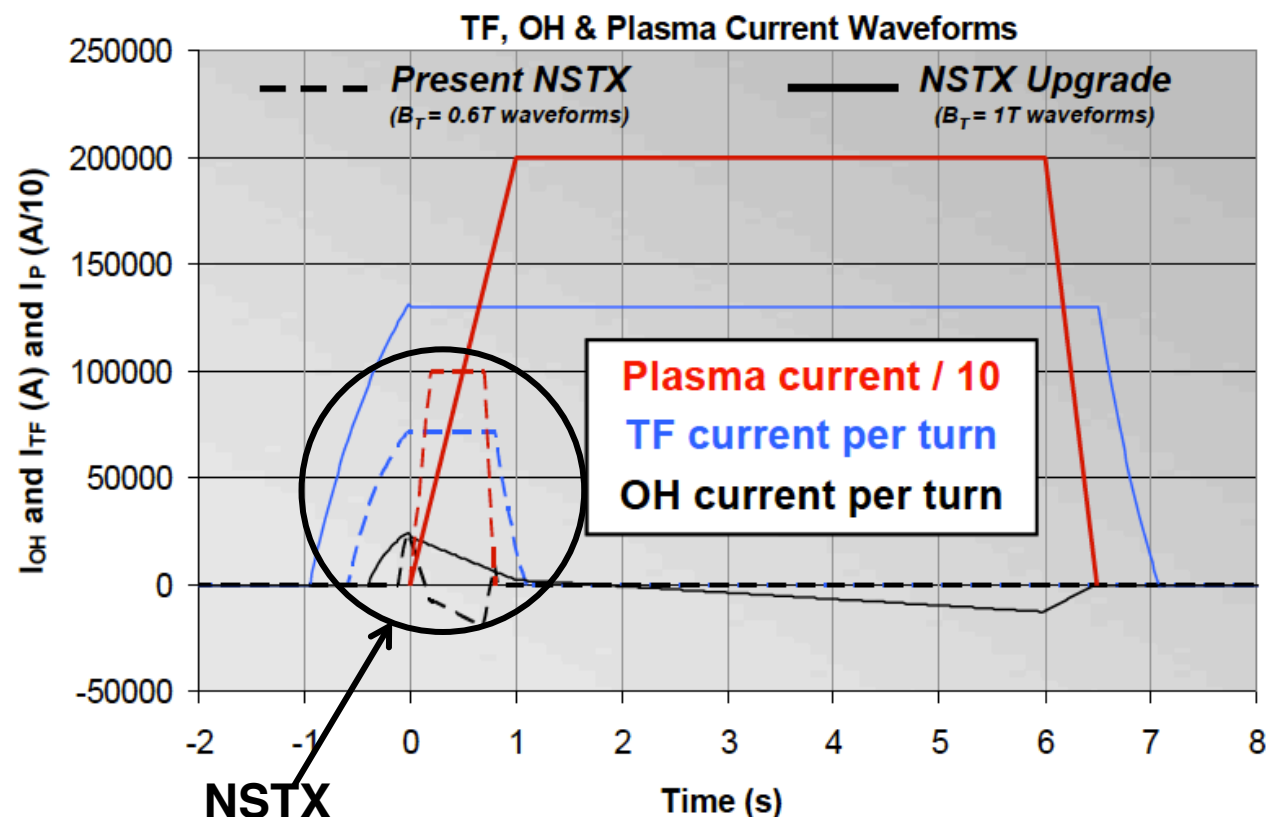
Previous center-stack **New center-stack**



TF OD = 20cm **TF OD = 40cm**



Present NBI **New 2nd NBI**

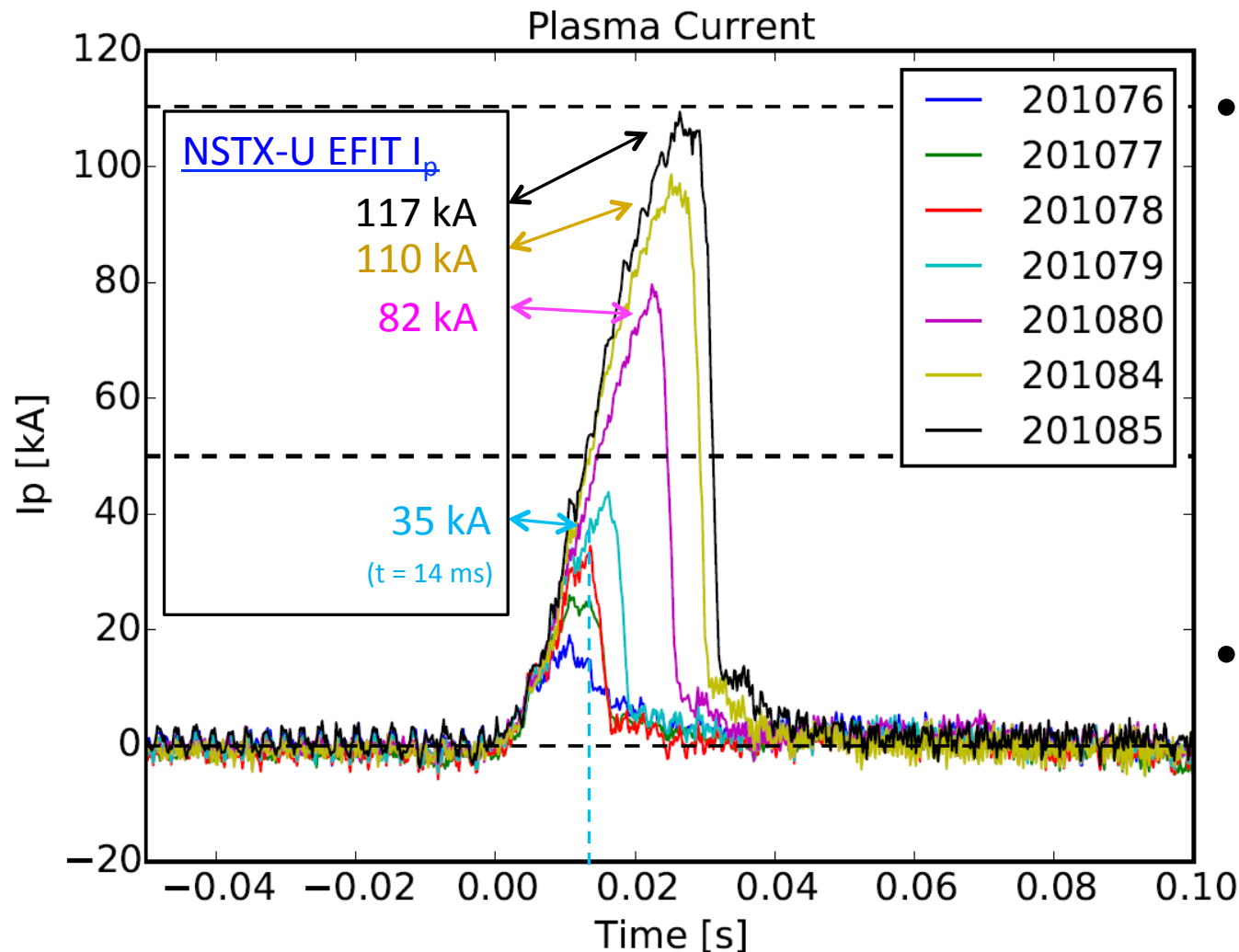


	R_0 (m)	A_{min}	I_p (MA)	B_T (T)	T_{TF} (s)	R_{CS} (m)	R_{OB} (m)	OH flux (Wb)
NSTX	0.854	1.28	1	0.55	1	0.185	1.574	0.75
NSTX-U	0.934	1.5	2	1	6.5	0.315	1.574	2.1

~ 10 increase in $\kappa\tau T$ from NSTX

Measured plasma current compares well to NSTX-U EFIT reconstructed current

Shots from 8/10/2015

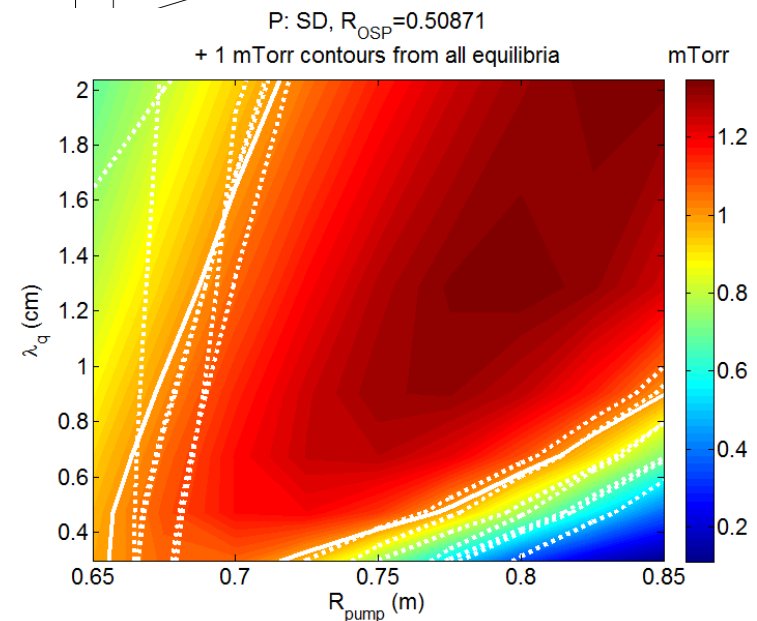
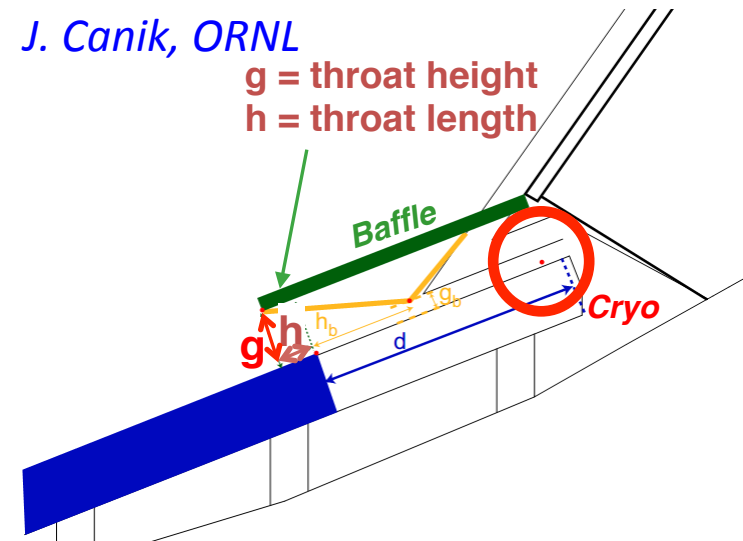


- In highest V_{loop} shots, reconstructed total wall current exceeds 0.4 MA
- Achieved highest current on last shot of day.

Cryopump Physics Design Done in Collaboration with ORNL

- Initial designs used semi-analytic models to determine pump geometry.
 - Conclusion: duct height $h \sim 2.5$ cm, length $h \sim 2$ cm, Radius of 0.72 m is optimum.
 - Allows pressures > 1 mT over a range of plasma shapes and SoL widths.
 - Should allow the full beam fuelling to be pumped.
- Calculation then benchmarked against SOLPS

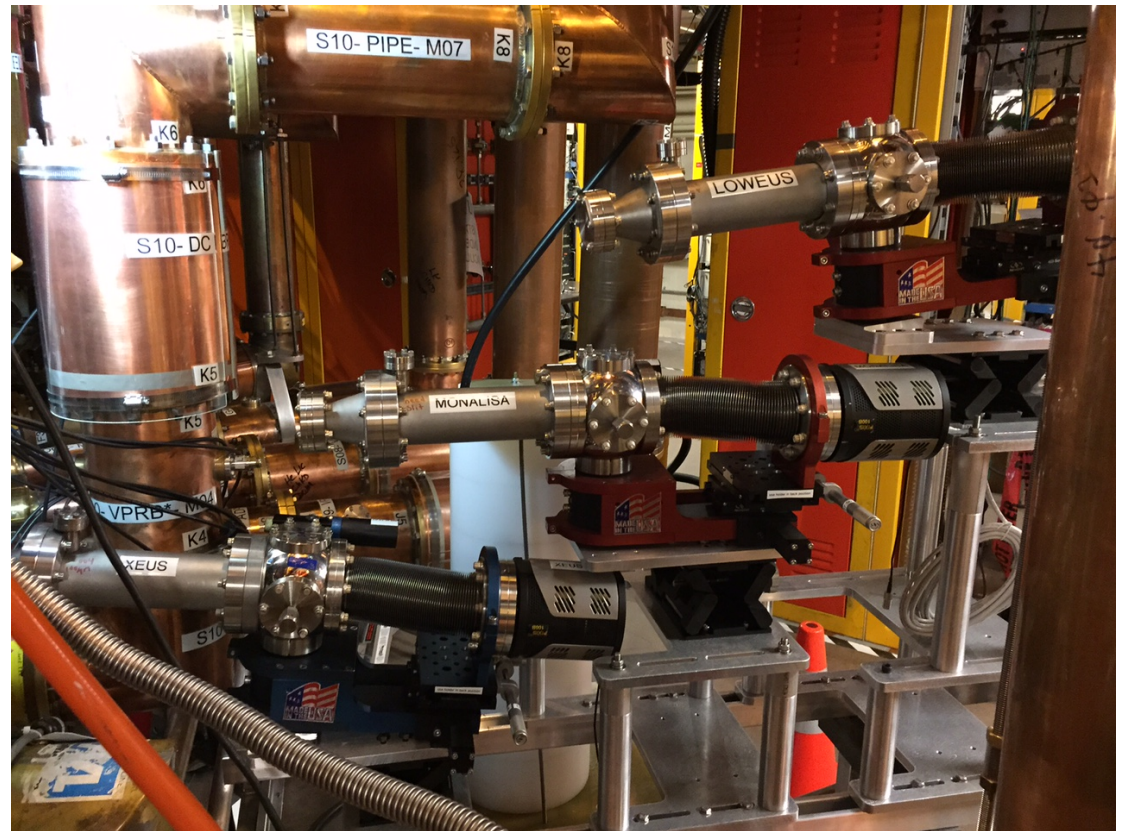
J. Canik, ORNL



Many New and/or Improved Diagnostics Ready to Support Operations

- Re-Aimed 42 Channel Thomson Scattering
- Tangential FIDA
- New SSNPAs
- 48 channel BES
- Multiple Energy SXR
- Materials Analysis Particle Probe
- Suite of 3 new EUV spectrometers
- Many more...

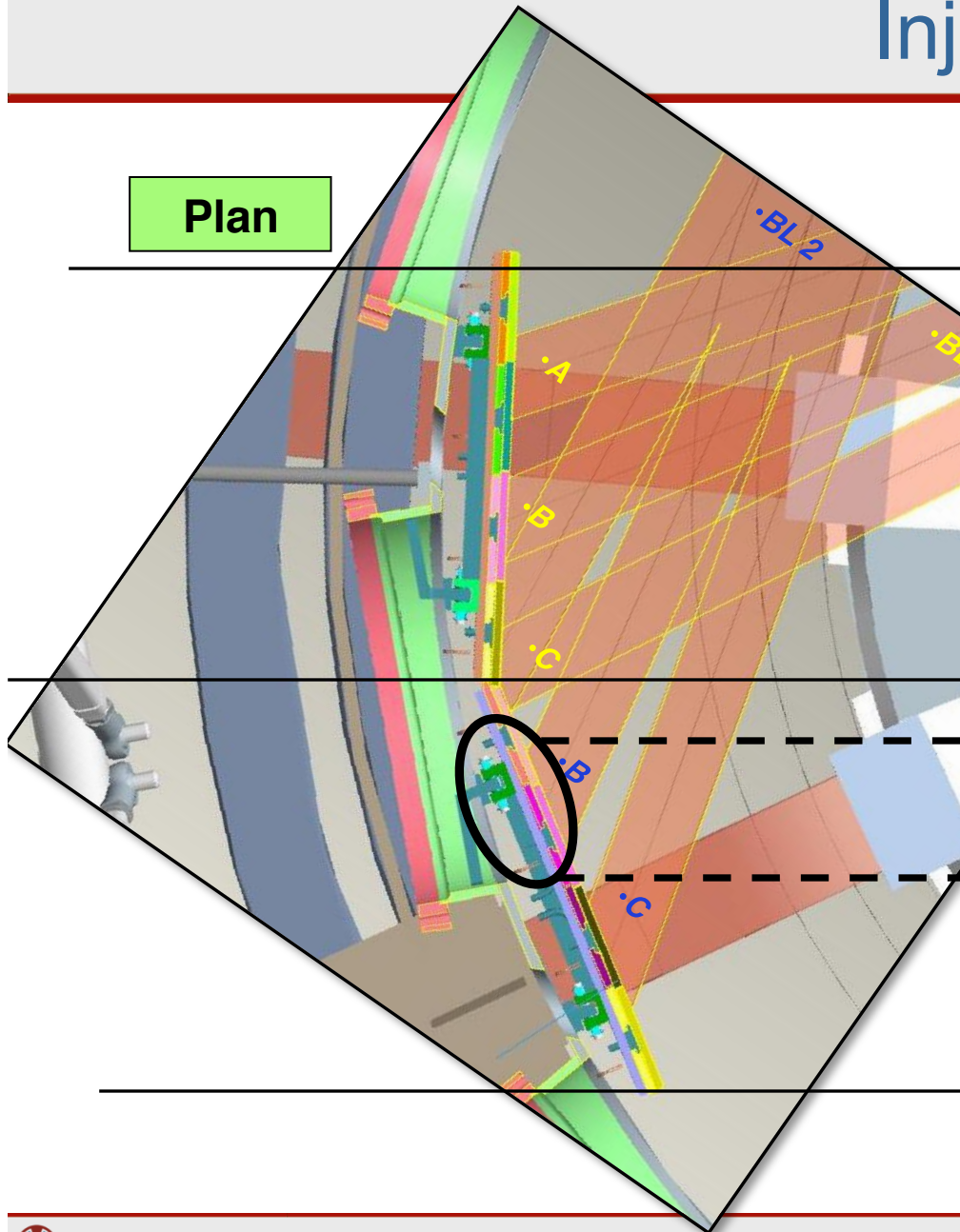
0.5-44 nm aggregate spectral resolution
5 ms time resolution
Presently undergoing final installations



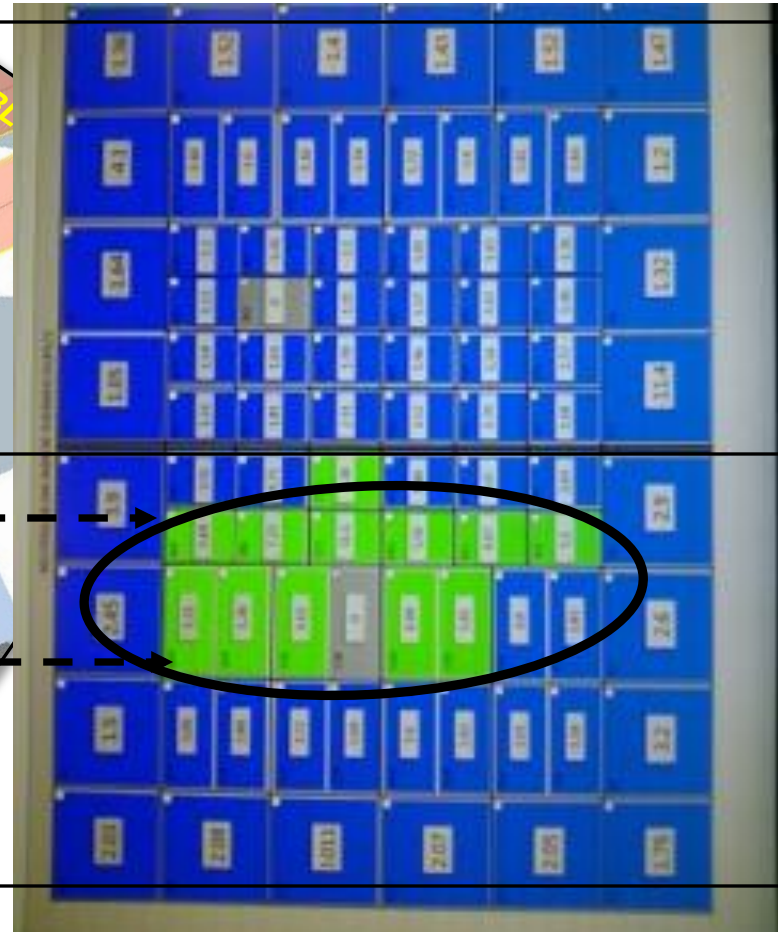
M. Weller, V. Soukhanovskii, LLNL, A. Brereton PPPL

40kV Beam from NB2 Successfully Injected into Armor

Plan

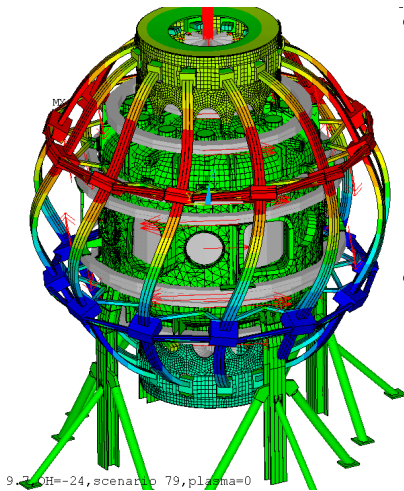


Actual

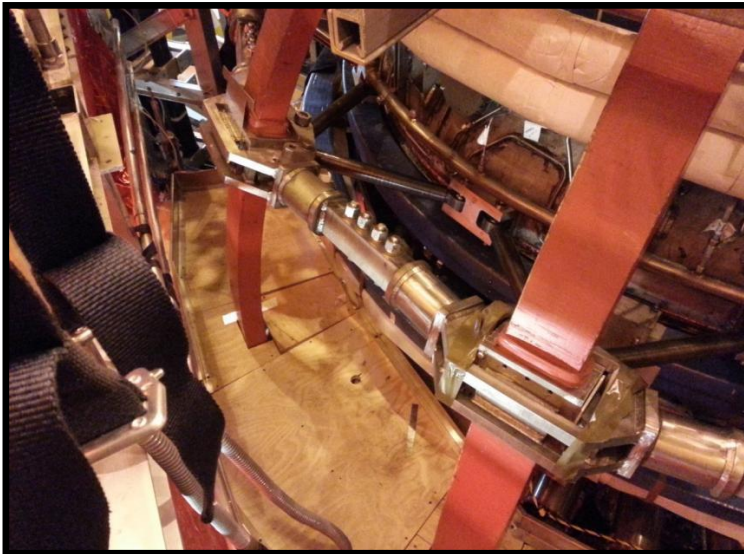


Engineering Design Accounts for Large Forces at Full Field and Current

1: Structural Reinforcement



- Determine EM loading from expected plasma equilibria and disruption scenarios
- Design appropriate mechanical supports to allow those operating points



2: New Digital Protection System

- Written in C++, operating on computers running special realtime LINUX.
- Compute:
 - Forces on coils or combinations of coils.
 - Stresses internal to coils.
 - Torques on the TF inner and outer legs.