NSTX-U

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National Spherical Torus Upgrade Project: Status and Plans

Masayuki Ono

for the NSTX-U Team

17th International Spherical Torus Workshop
University of York, September 16 - 19, 2013

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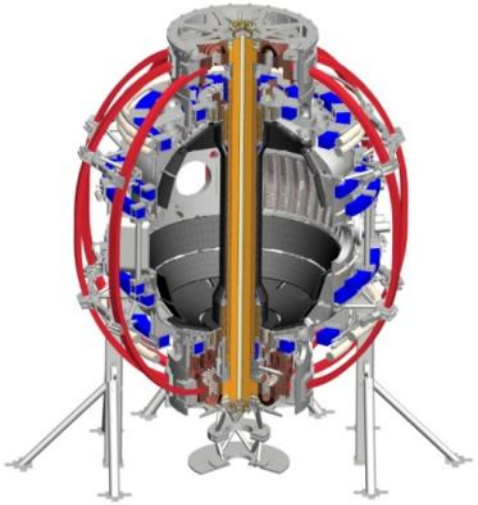
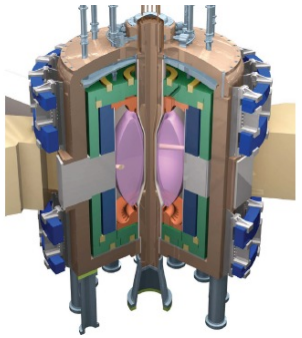


Talk Outline

- NSTX Upgrade Project and Operational Preparation Status
- NSTX-U Facility / Diagnostic Five Year Plans
- Summary

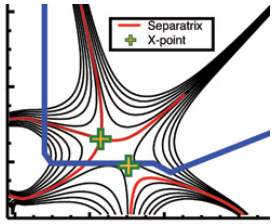
NSTX Upgrade Mission Elements

- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**
- **Develop solutions for the plasma-material interface challenge**
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
- **Develop ST as fusion energy system**

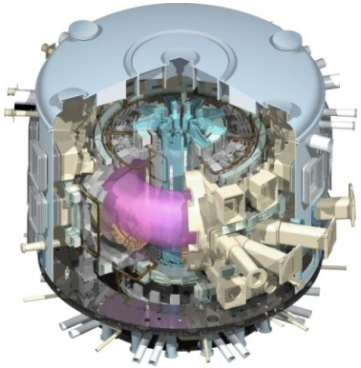


ST-FNSF

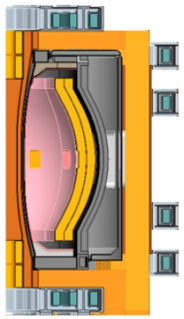
Lithium



"Snowflake"



ITER



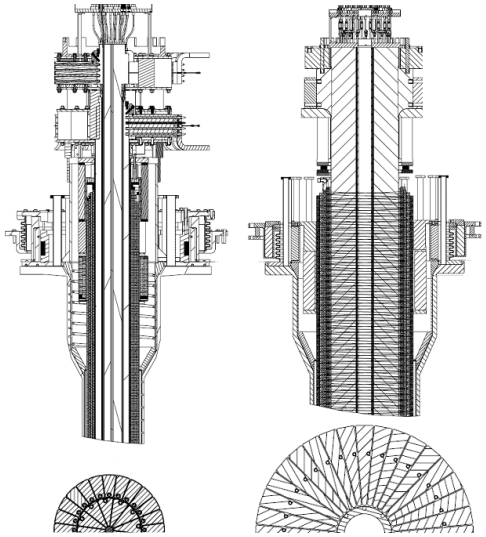
ST Pilot Plant

Substantial Increase in NSTX-U Device / Plasma Performance

To provide data base to support ST-FNSF designs and ITER operations

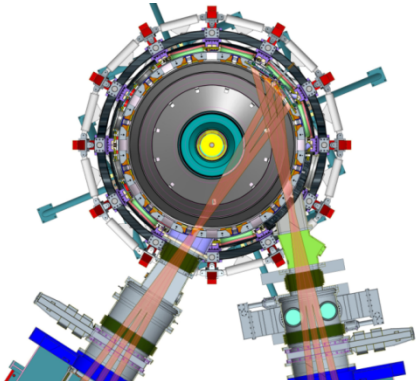
Previous center-stack

New center-stack



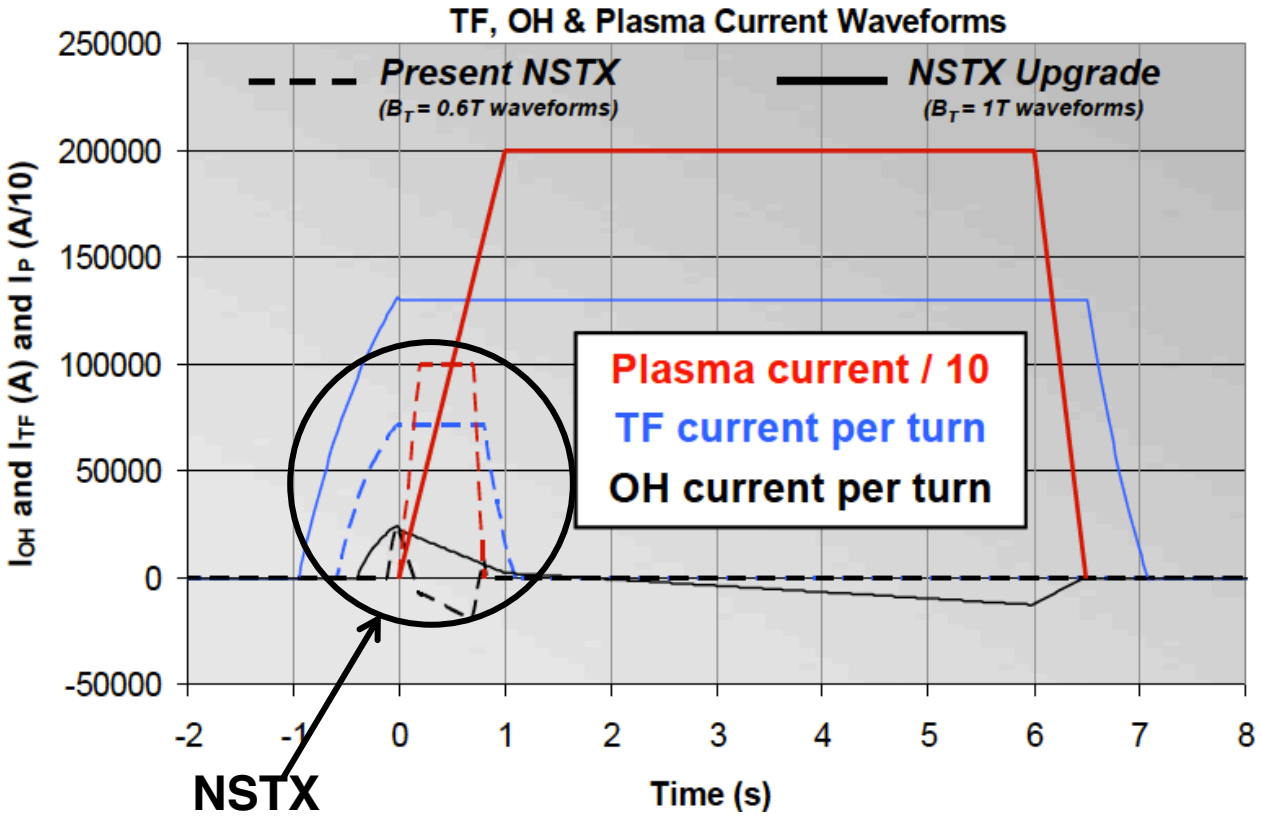
TF OD = 20cm

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

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

NSTX-U average plasma pressure $\propto B_{T0}^2 \beta_T (T^2\%)$ ~ TFTR, JET

NSTX Upgrade Project Progress Overview

R. Strykowsky, E. Perry, T. Stevenson, L. Dudek, S. Langish, T. Egebo, M. Williams and the NSTXU Project Team

New Center Stack Project Scope

- Inner TF bundle
- TF Flex bus
- OH coil
- Inner PF coils

Center stack

- Enhance outer TF supports
- Enhance PF supports
- Reinforce umbrella structure
- New umbrella lids

Structure

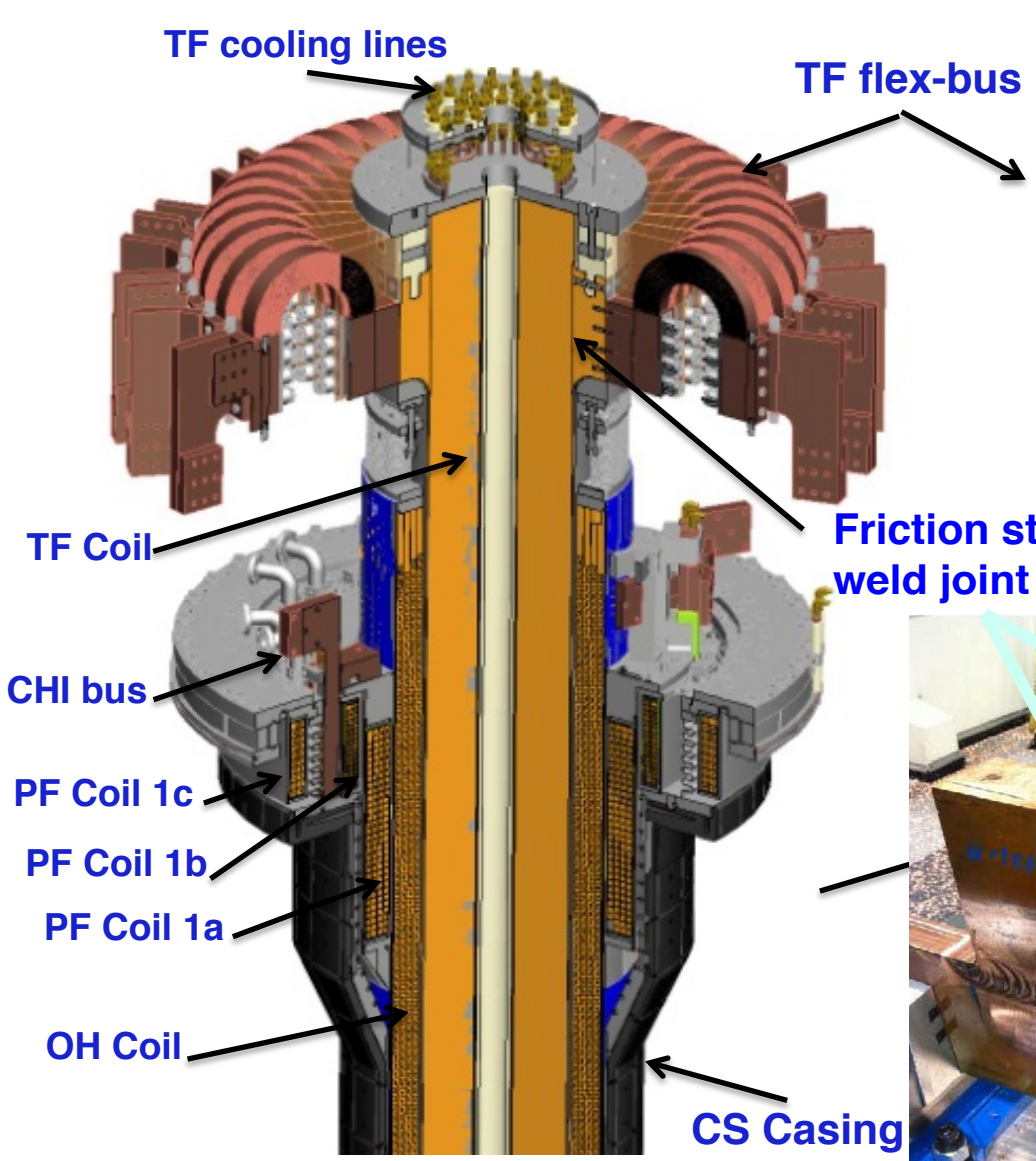
- Power systems
- I&C, Services, Coil protection

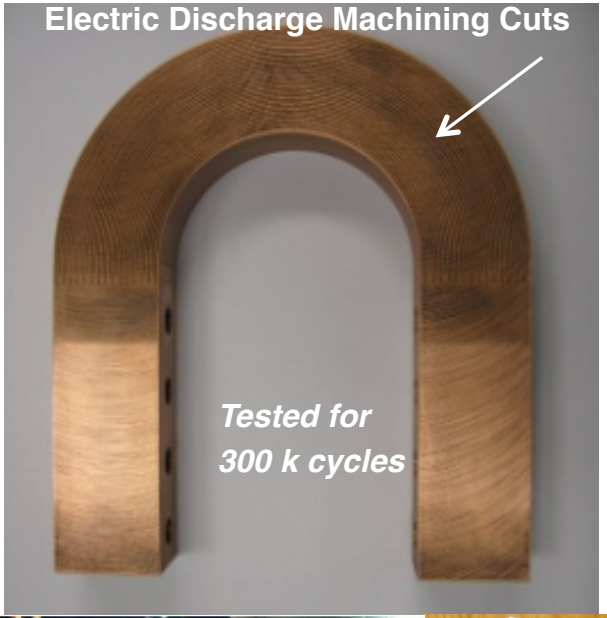
Ancillary Sys

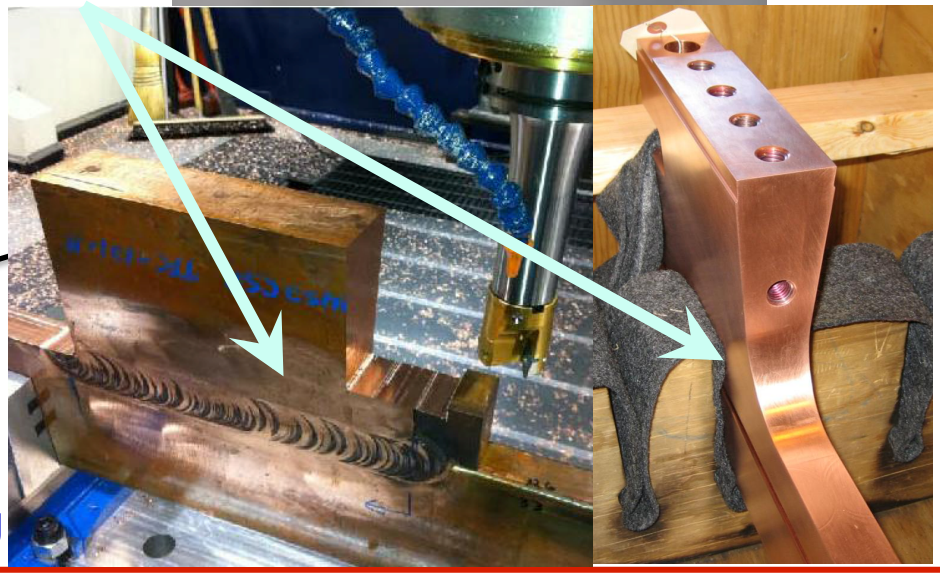
2nd NBI Project Scope

- Decontaminate TFTR beamline
- Refurbish for reuse
- Relocate pump duct, 22 racks and numerous diagnostics to make room in the NSTX Test Cell
- Install new port on vacuum vessel to accommodate NB2
- Move NB2 to the NSTX Test Cell
- Install power, water, cryo and controls

Improved Center-Stack Design to Handle Increased Forces
Identical 36 TF Bars and Innovative Flex-Bus Design



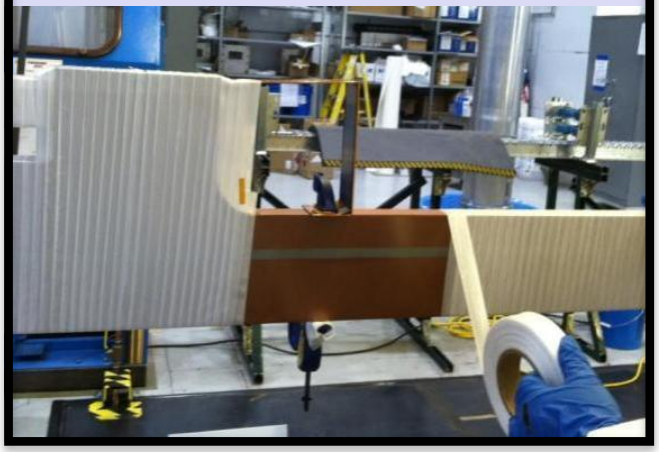




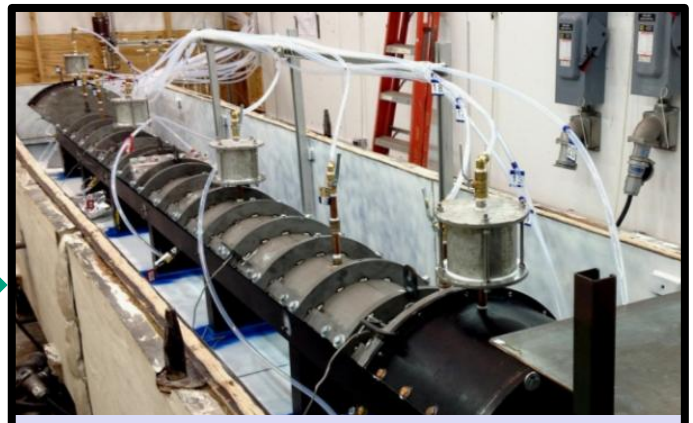
Center Stack Fabrication & Assembly Proceeding Well
Innovative manufacturing techniques developed

Cooling tube soldered with resin-based flux into inner TF conductor

Conductor being wrapped with fiberglass insulation



Insulated conductor being placed into mold



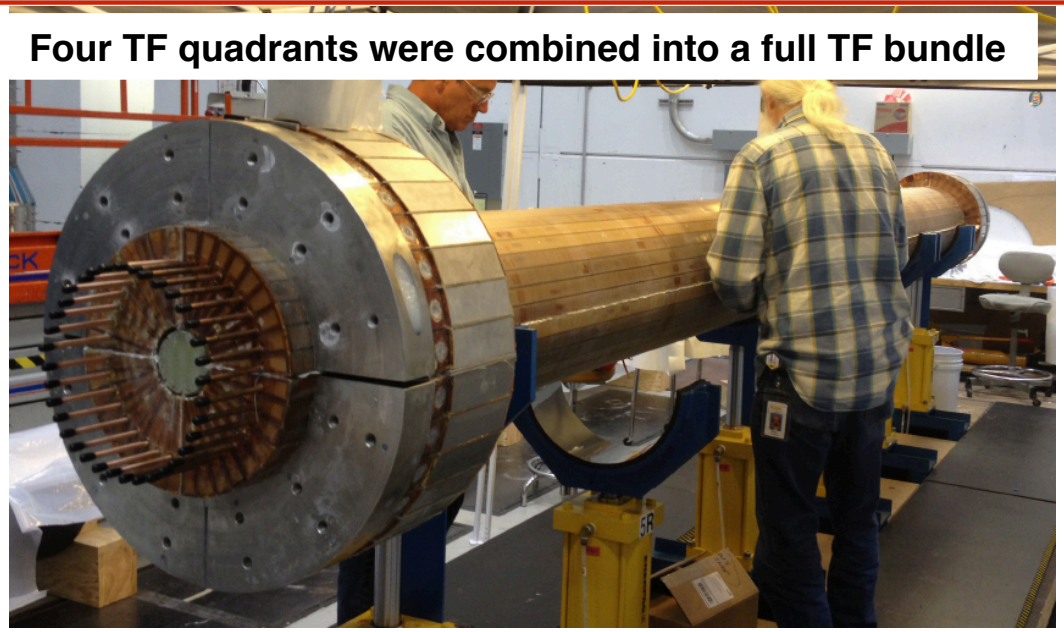
Assembled TF mold ready for Vacuum Pressure Impregnation with CTD-425

Three Quadrants successfully VPI'd !

Center Stack Is Coming Together

TF Bundle is nearing completion

Four TF quadrants were combined into a full TF bundle

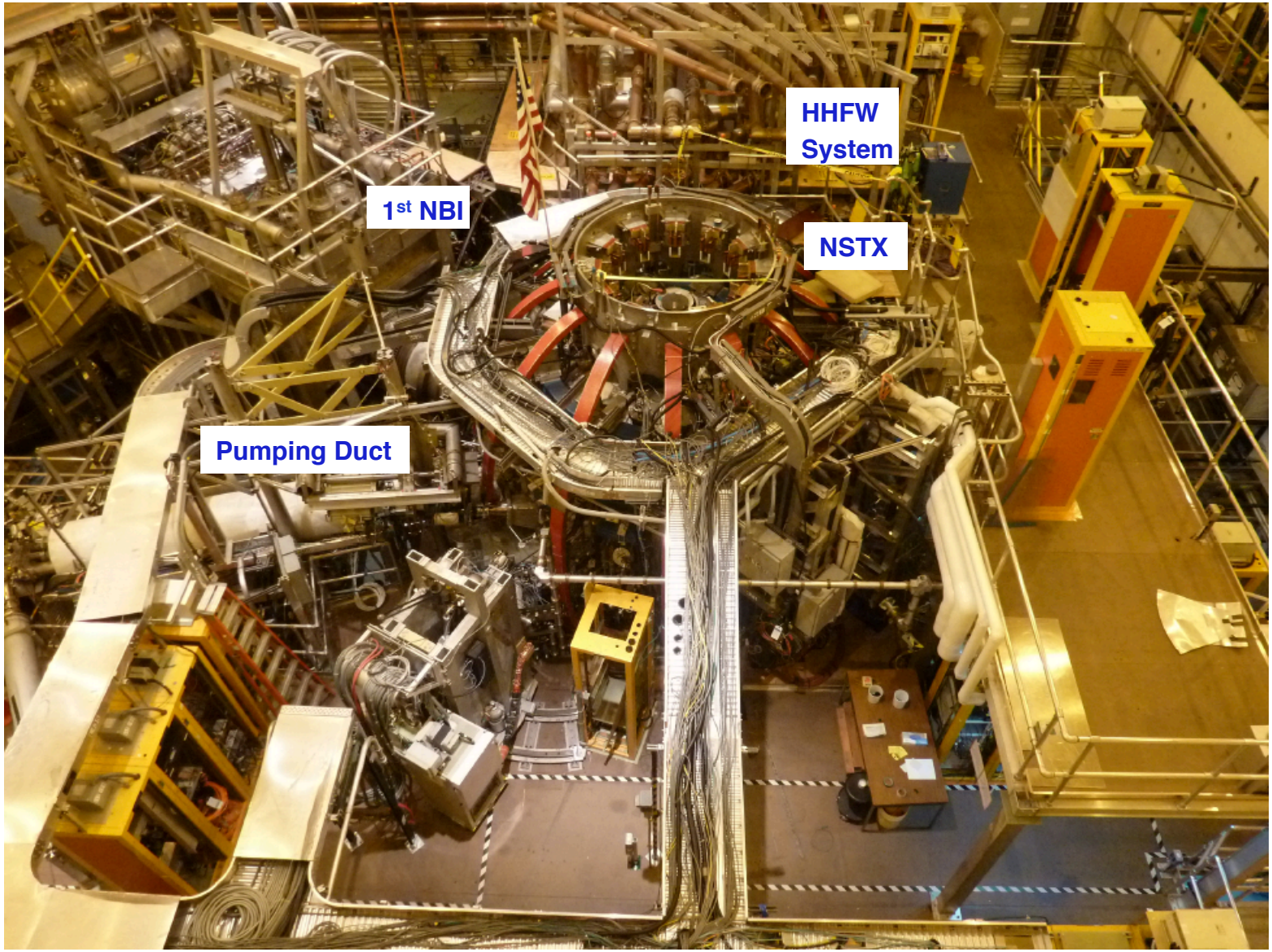


TF bundle with ground wrapping lowered into VPI mold

Center-Stack Casing with tile studs

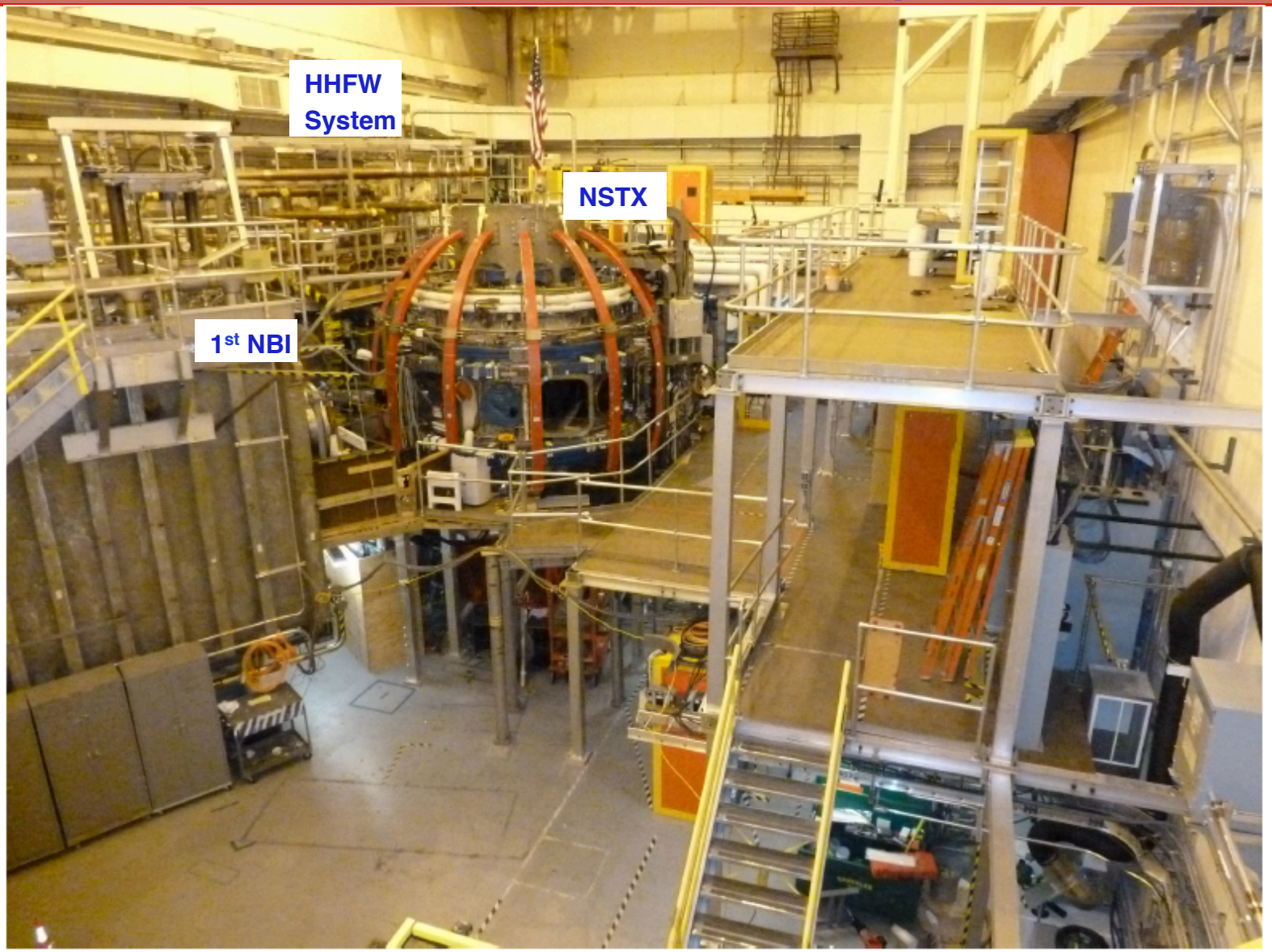
Aerial View of the NSTX Test Cell (Oct. 2011)

Beginning of the NSTX Upgrade Construction Activities

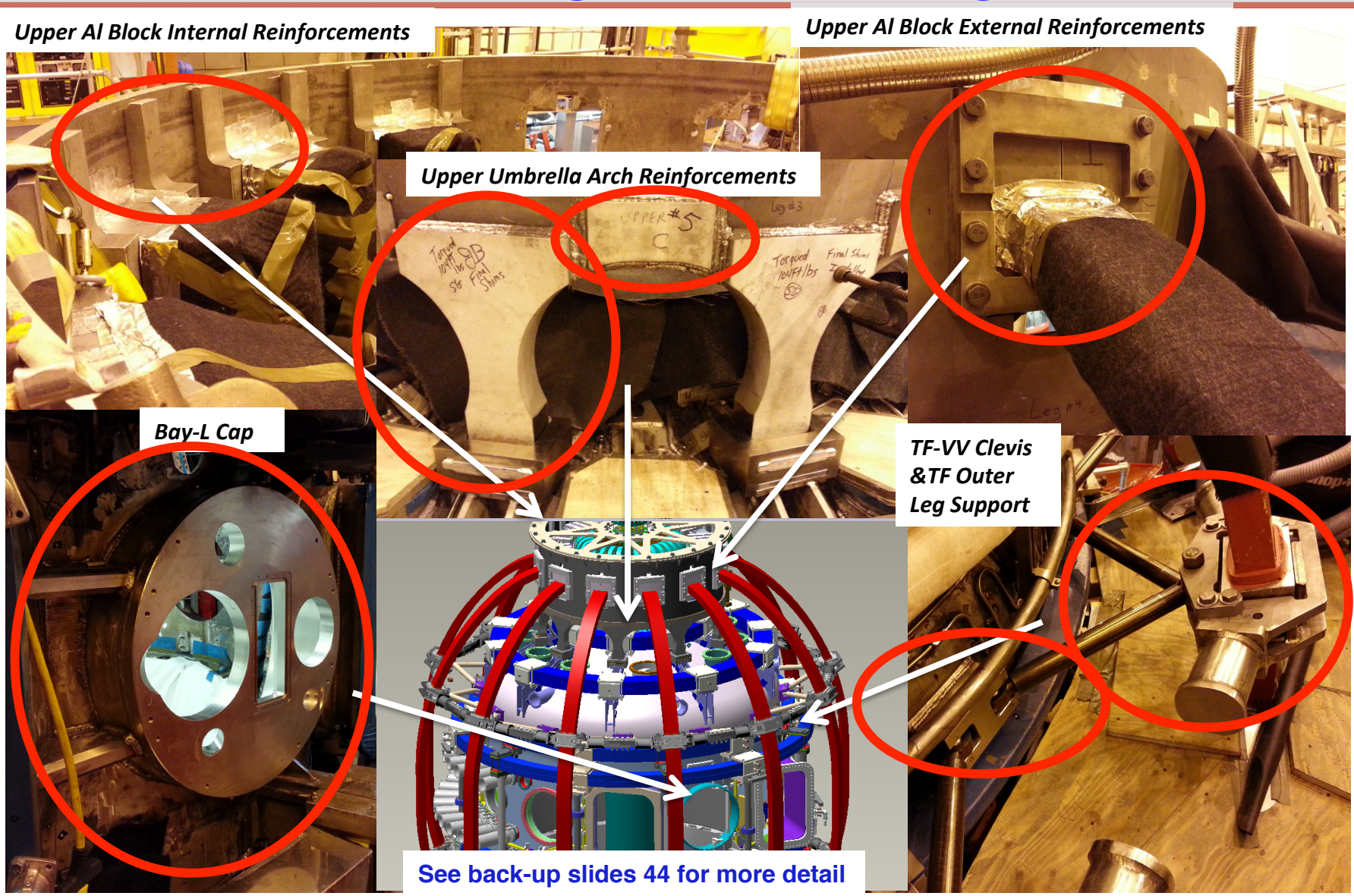


Aerial View of the NSTX Test Cell (Feb. 2012)

Space for the 2nd NBI cleared and 3rd floor platform added



Support Structural and Vacuum Vessel Upgrades
Must handle 4 x higher electromagnetic loads

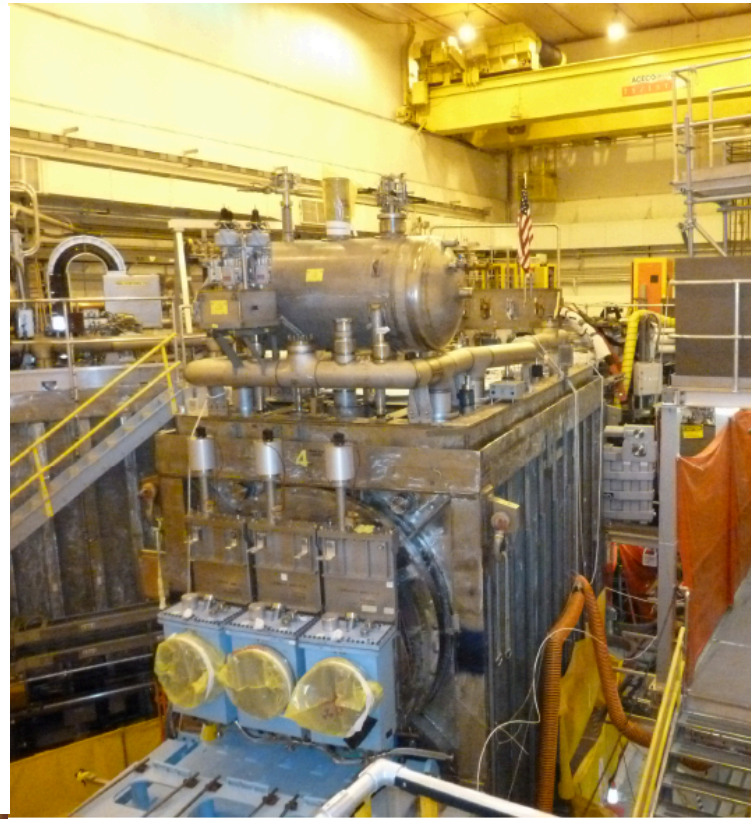


Relocation of the 2nd NBI beam line box from the TFTR test cell into the NSTX-U Test Cell Complete.

TFTR NBI beam box and components successfully tritium decontaminated.

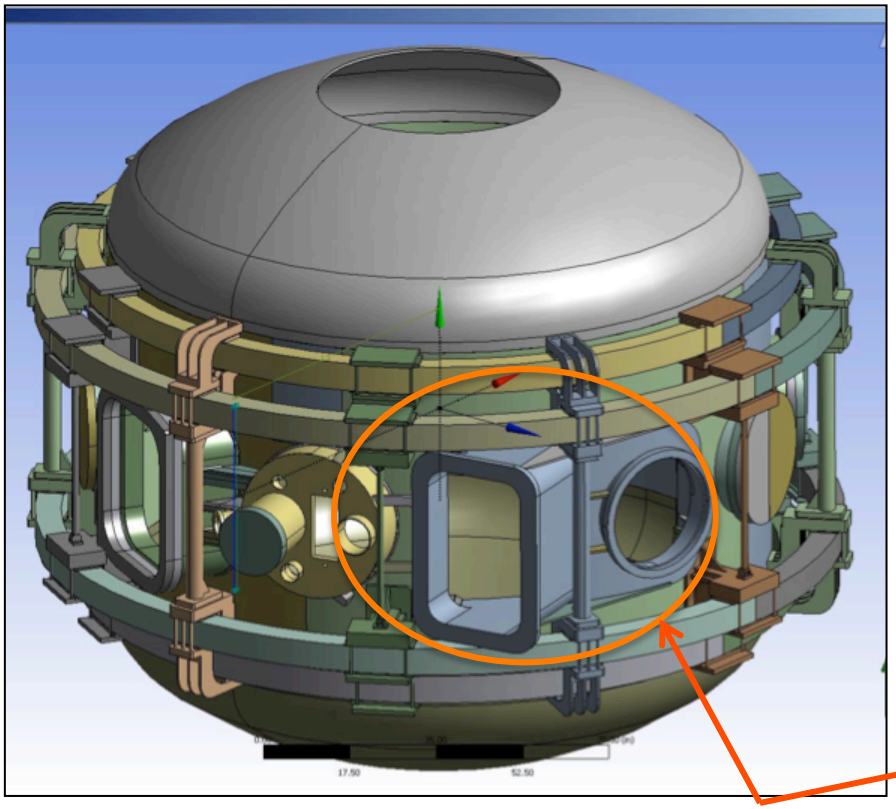
Beam Box being lifted over NSTX

Beam Box placed in its final location and aligned



Beam Box being populated with components

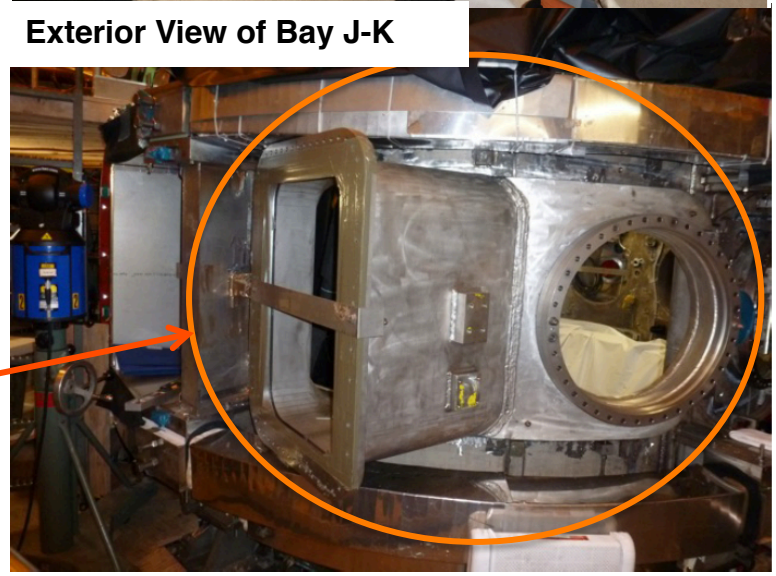
Highly Tangential 2nd NBI Enabled by JK-Cap
Outer Wall Radius Moved Outward to Avoid Beam Clipping



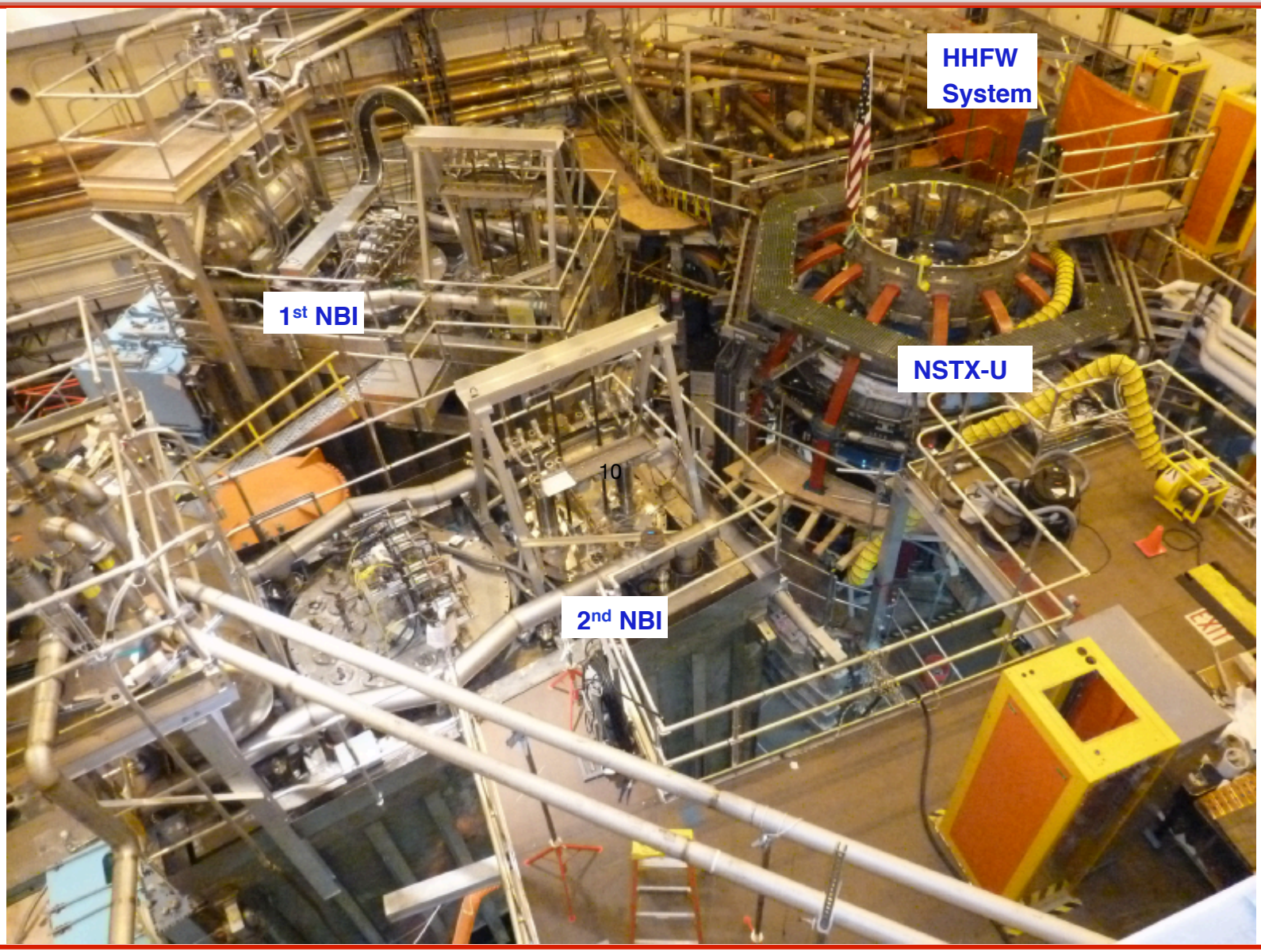
JK cap

Interior View of Bay J-K

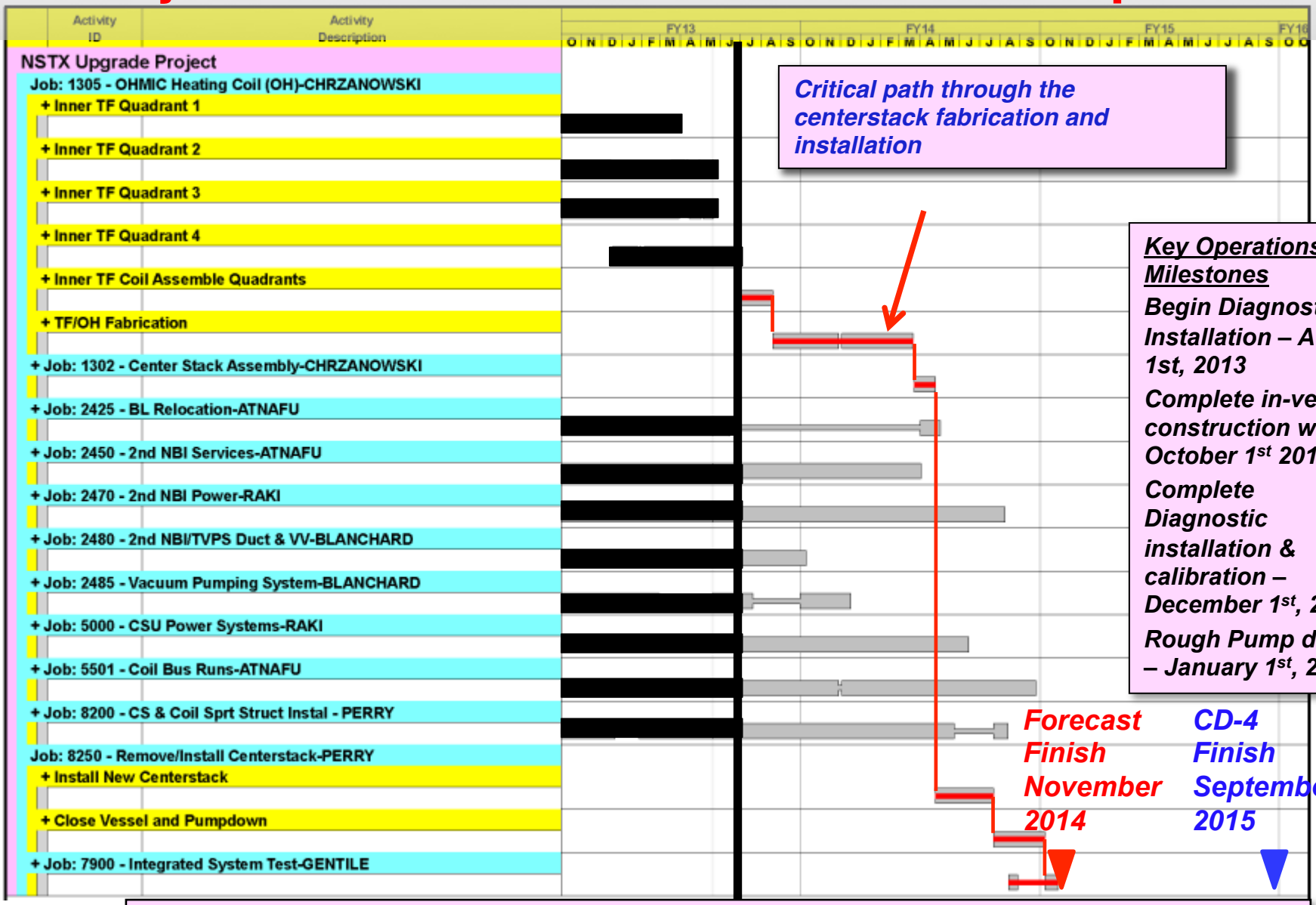
Exterior View of Bay J-K



Aerial View of the NSTX-U Test Cell (Aug. 2013)



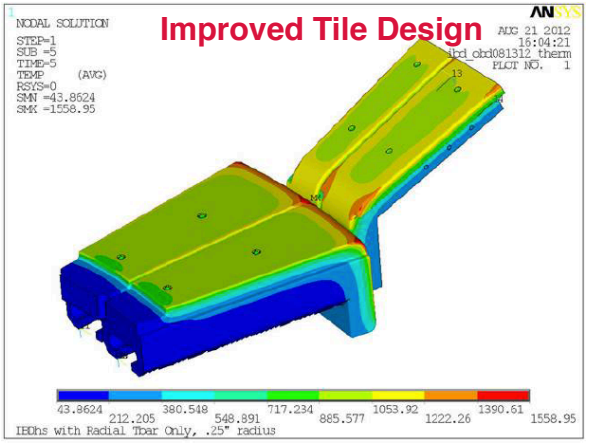
Project on Track for October 2013 Completion



Engineering and Research Operations Activities
In Preparation for the NSTX-U Operations

- **Improving the PFC geometry in the vicinity of the CHI gap to protect the vessel and coils due to ~ 10x higher divertor heat loads**

New gap overhung tiles to provides necessary protection. Gap tiles being fabricated by the vendor.



- **Replacing electronics that control rectifiers - The new Firing Generator (FG) will deliver firing pulses with greater resolution, precision, and repeatability, critical for the new 8-parallel, 130kA TF system configuration.**

More than half of the 68 FG production units have now undergone power testing in rectifiers, and test results for all units have been identical, giving us confidence that we can rely on bench testing for the remaining ones. Power testing will continue to confirm current balancing on multiple rectifiers. Target completion date of Nov. 2013.

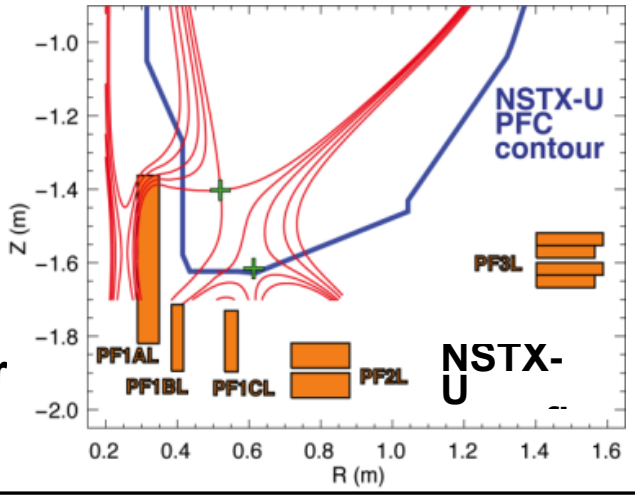
Transrex AC/DC Convertors

NSTX-U Plasma Control System Upgrade

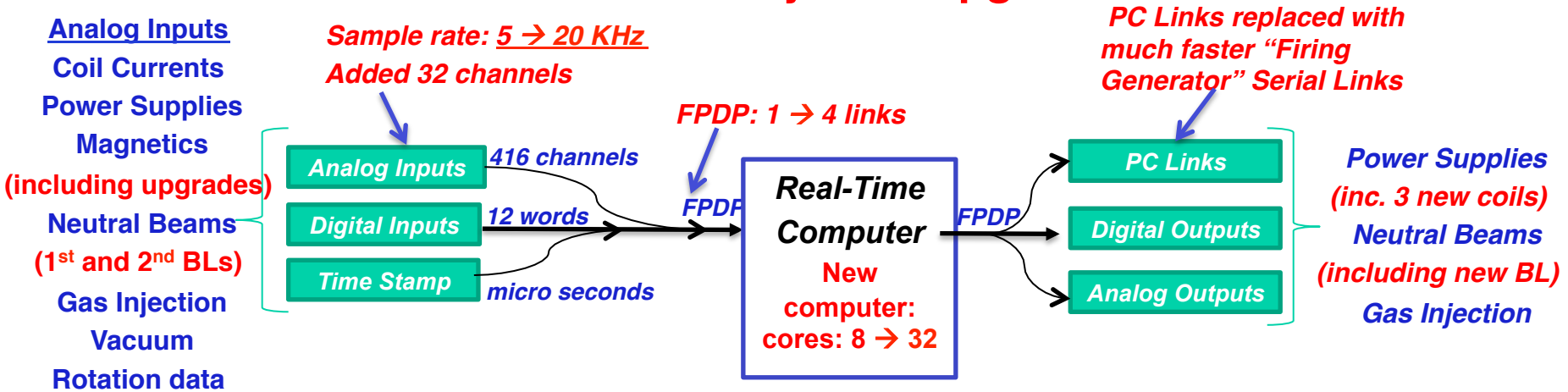
Enables real time up-down symmetric divertor control

NSTX-U PF Coil Power System Upgrade

- The first-year power supply capabilities of NSTX-Upgrade will yield considerable experimental flexibility, via up-down symmetric PF-1C coils
- By powering upper and lower PF-1A & PF-1C coils, it will be possible to generate up-down symmetric snowflake divertors
- The new configuration should provide better control for the CHI absorber region.



Plasma Control System Upgrade



NSTX-U diagnostics to be installed during first 2 years

Half of NSTX-U Diagnostics Are Led by Collaborators

MHD/Magnetics/Reconstruction

- Magnetics for equilibrium reconstruction
- *Halo current detectors*
- *High-n and high-frequency Mirnov arrays*
- Locked-mode detectors
- RWM sensors

Profile Diagnostics

- 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)
- *MSE-CIF (18 ch)*
- *MSE-LIF (20 ch)*
- *ME-SXR (40 ch)*
- Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics

- *Poloidal Microwave high-k scattering*
- *Beam Emission Spectroscopy (48 ch)*
- Microwave Reflectometer,
- *Microwave Polarimeter*
- Ultra-soft x-ray arrays – multi-color

Energetic Particle Diagnostics

- *Fast Ion D_α profile measurement (perp + tang)*
- Solid-State neutral particle analyzer
- Fast lost-ion probe (energy/pitch angle resolving)
- Neutron measurements

Edge Divertor Physics

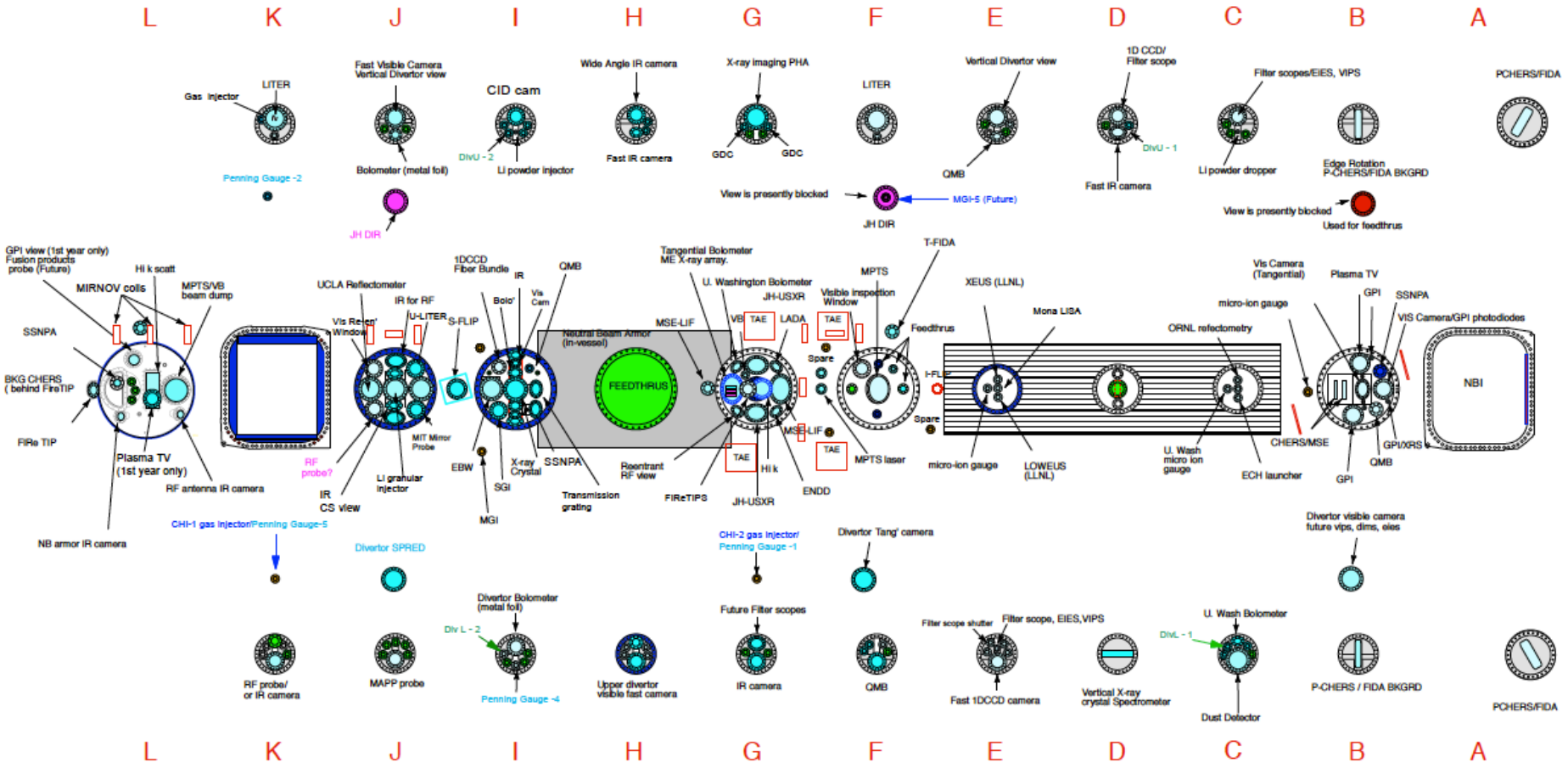
- Gas-puff Imaging (500kHz)
- Langmuir probe array
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- *1-D CCD H_α cameras (divertor, midplane)*
- *2-D divertor fast visible camera*
- Metal foil divertor bolometer
- AXUV-based Divertor Bolometer
- IR cameras (30Hz) (3)
- *Fast IR camera (two color)*
- Tile temperature thermocouple array
- *Divertor fast eroding thermocouple*
- Dust detector
- Edge Deposition Monitors
- Scrape-off layer reflectometer
- Edge neutral pressure gauges
- *Material Analysis and Particle Probe*
- *Divertor VUV Spectrometer*

Plasma Monitoring

- FIReTIP interferometer
- Fast visible cameras
- Visible bremsstrahlung radiometer
- *Visible and UV survey spectrometers*
- *VUV transmission grating spectrometer*
- *Visible filterscopes (hydrogen & impurity lines)*
- Wall coupon analysis

New capability, Enhanced capability

NSTX-U facility/diagnostics port assignment
Port flanges designed and being procured



Formulating Strategy Toward Full NSTX-U Parameters

After CD-4, the plasma operation could enter quickly into new regimes

	NSTX (Max.)	Year 1 NSTX-U Operations (2015)	Year 2 NSTX-U Operations (2016)	Year 3 NSTX-U Operations (2017)	Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8	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

- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year 1 data has been accumulated
- 3rd year goal: Full capability

Talk Outline

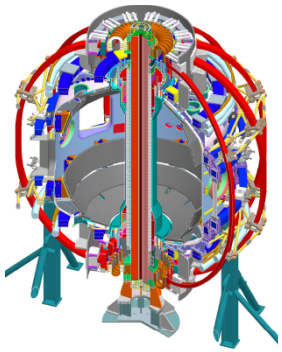
- NSTX Upgrade Project and Operational Preparation Status
- **NSTX-U Facility / Diagnostic Five Year Plans**
- Summary

5 year plan tools with 5YP base funding

2014	2015	2016	2017	2018
Upgrade Outage	1.5 → 2 MA, 1s → 5s			

Run Weeks: 16 | 14 | 14 | 16

New center-stack



2nd NBI

Start-up and Ramp-up
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- up to 0.5 MA plasma gun
- 1 MW ECH/EBW

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson

Materials and PFCs
- High-Z tile row on lower OBD
- High-Z tile row on cryo-baffle
- High-Z PFC diagnostics
- All high-Z PFCs

Liquid metals / lithium
- Li granule injector
- Upward LiTER
- LLD using bakeable cryo-baffle
- Flowing Li divertor or limiter module

MHD
- MGI disruption mitigation
- Partial NCC
- NCC SPA upgrade
- Enhanced MHD sensors

Transport & Turbulence
- δB polarimetry
- High k_θ
- DBS, PCI, or other intermediate-k

Waves and Energetic Particles
- HHFW limiter upgrade
- HHFW straps to excite EHO
- 1 coil AE antenna
- 4 coil AE antenna
- Charged fusion product, neutron-collimator

Scenarios and Control
- Establish control of: Snowflake, $\bar{n}_e$, Rotation
- q_{min}
- Divertor P_{rad}
- Control integration, optimization

Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017

NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

Priority scope

Incremental scope

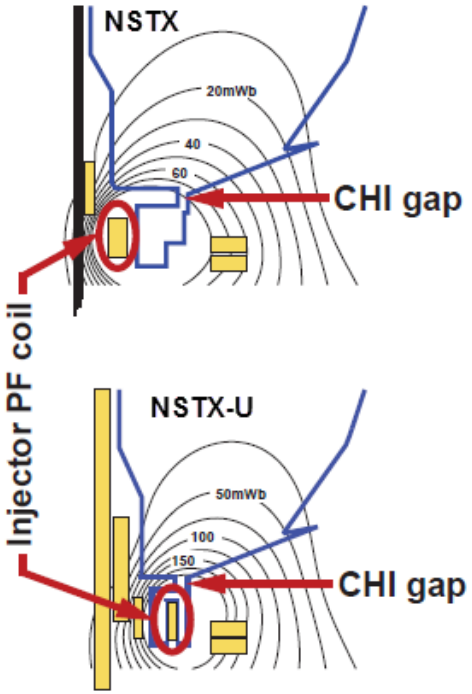
Solenoid-free Start-up

High priority goal for NSTX-U in support of FNSF

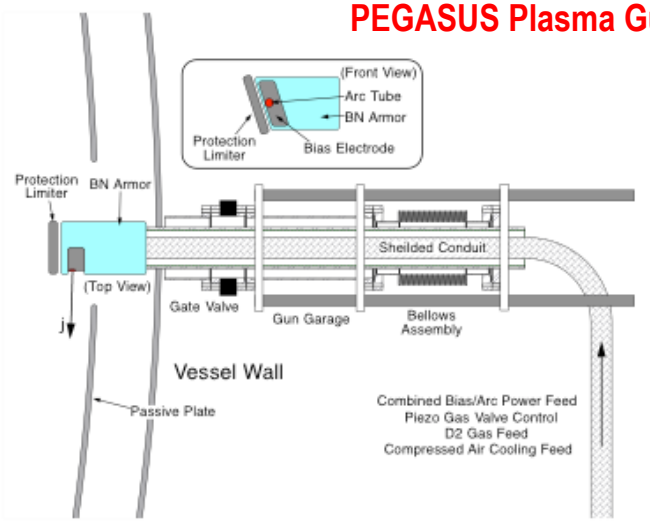
CHI Start-Up

- 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



PEGASUS Point Source



U. Wisconsin

Non-Inductive Start-up Systems Design for Post-Upgrade Operations

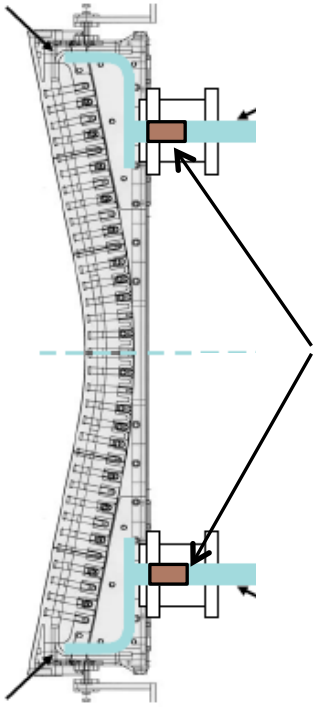
- CHI will start with the present 2 kV capability then enhanced to ~ 3 kV higher voltage as needed.
- PEGASUS gun start-up producing exciting results Ip ~ 160 kA. The PEGASUS gun concept is technically flexible to implement on NSTX once fully developed. High current gun for the NSTX-U will be developed utilizing the PEGASUS facility in collaboration with University of Wisconsin.

Strengthen HHFW Antenna Feeds for Disruption Load

A MW-Class 28 GHz ECH System for Non-Inductive Operation

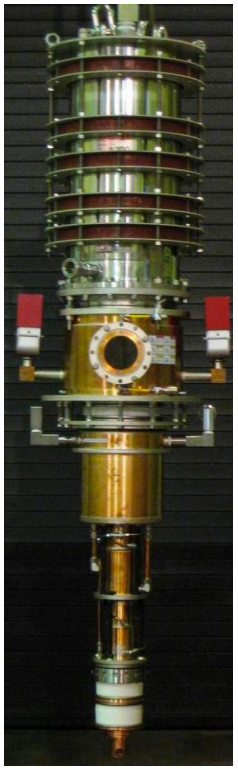
New Compliant Antenna Feeds

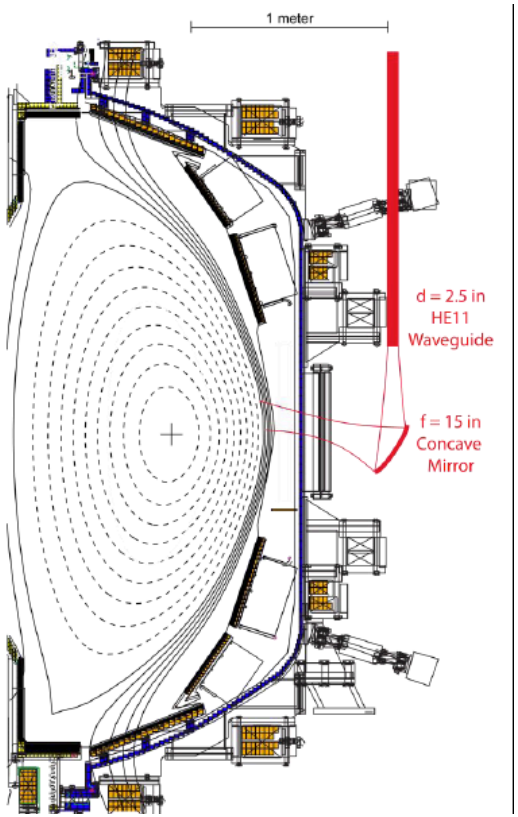
Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions



C-Mod antenna electroformed compliant section

28 GHz, 1.5 MW Tsukuba Gyrotron





28 GHz ECH/EBWH waveguide and mirror concept

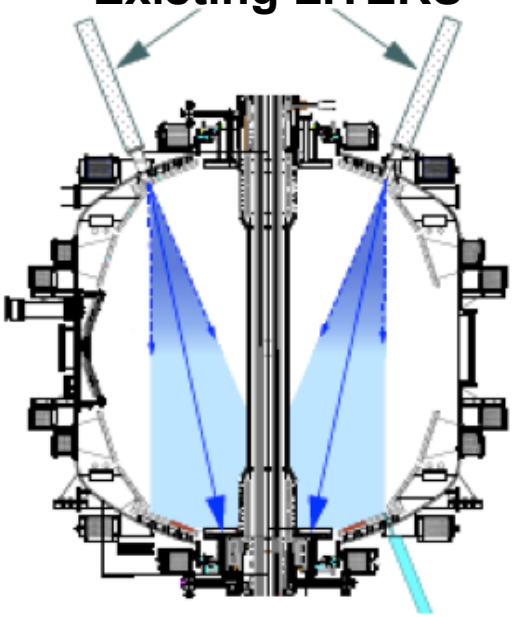
- Successful CDR conducted, prototype feeds being procured.
- Feeds to be tested in the RF test-stand before FDR, installation in spring 2014.

- Start MW-class ECH/EBW system conceptual design for non-inductive operations (MOU with Tsukuba University).

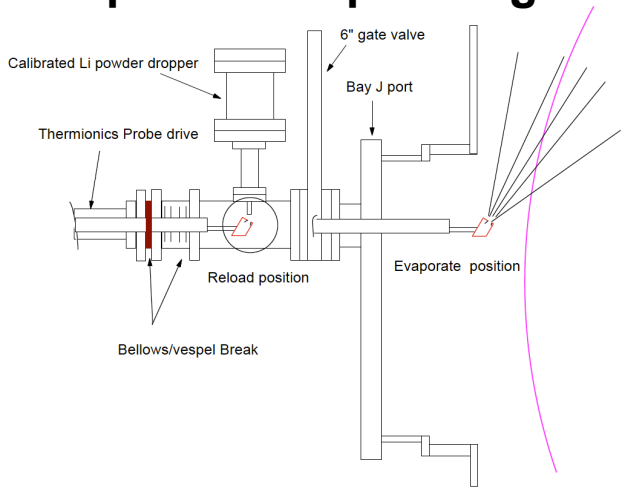
Tsukuba U and MIT

NSTX-U Lithium Capability During Initial Two Years
Lithium Evaporators and Granular Injector

Existing LITERS



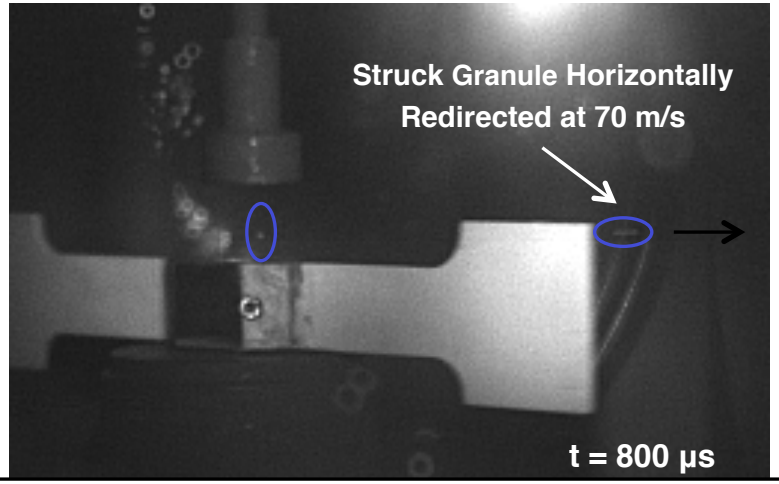
New Upward Evaporating LITER

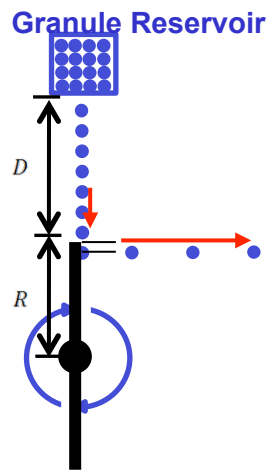


- **Upward Evaporating LITER to increase Li coverage for increased plasma performance**

NSTX-U lithium granular injector for ELM pacing

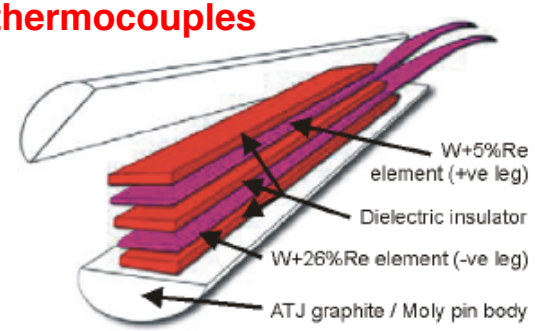
- **High frequency ELM pacing with a relatively simple tool.**
- **ELM pacing successfully demonstrated on EAST (D. Mansfield, IAEA 2012)**



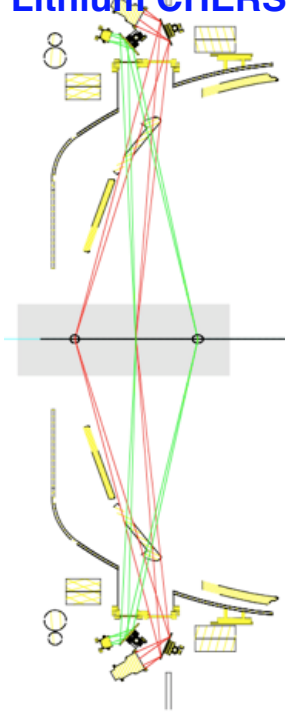


Baseline Capability for PMI Research
Supporting divertor and lithium research

Divertor fast eroding thermocouples

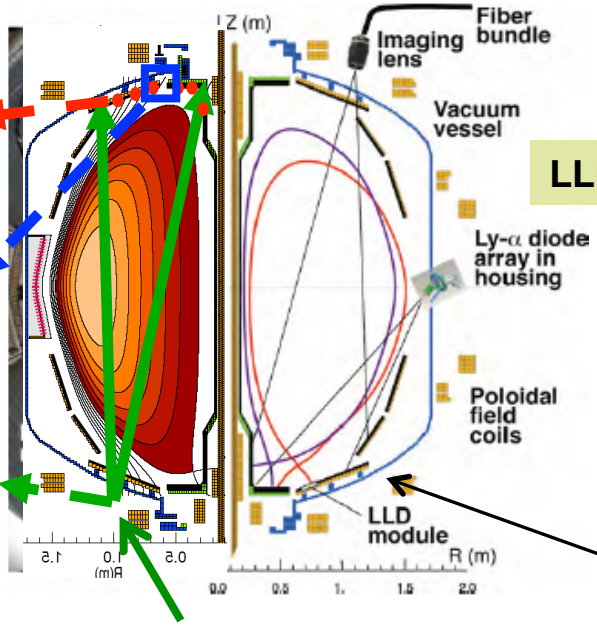


Lithium CHERS



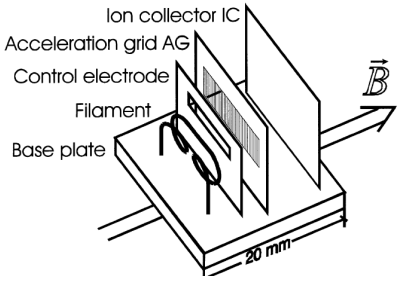
Divertor Imaging Spectrometer

LLNL

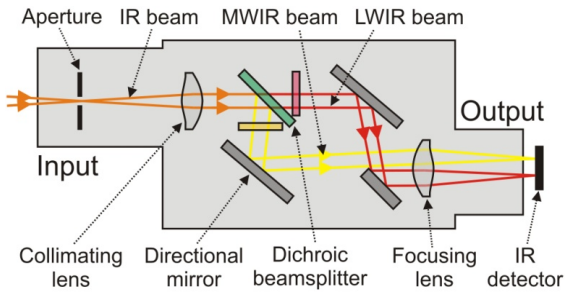


ORNL

Divertor fast pressure gauges

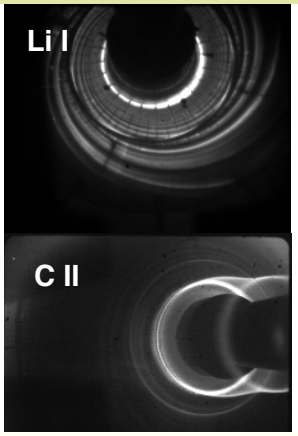


Dual-band fast IR Camera

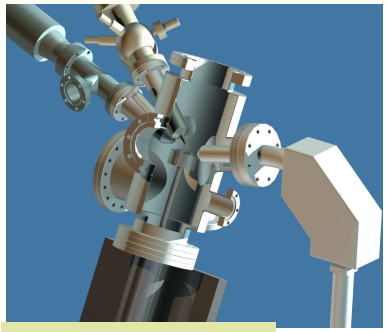


Two fast 2D visible and IR cameras with full divertor coverage

LLNL, ORNL, UT-K



MAPP probe for between-shots surface analysis

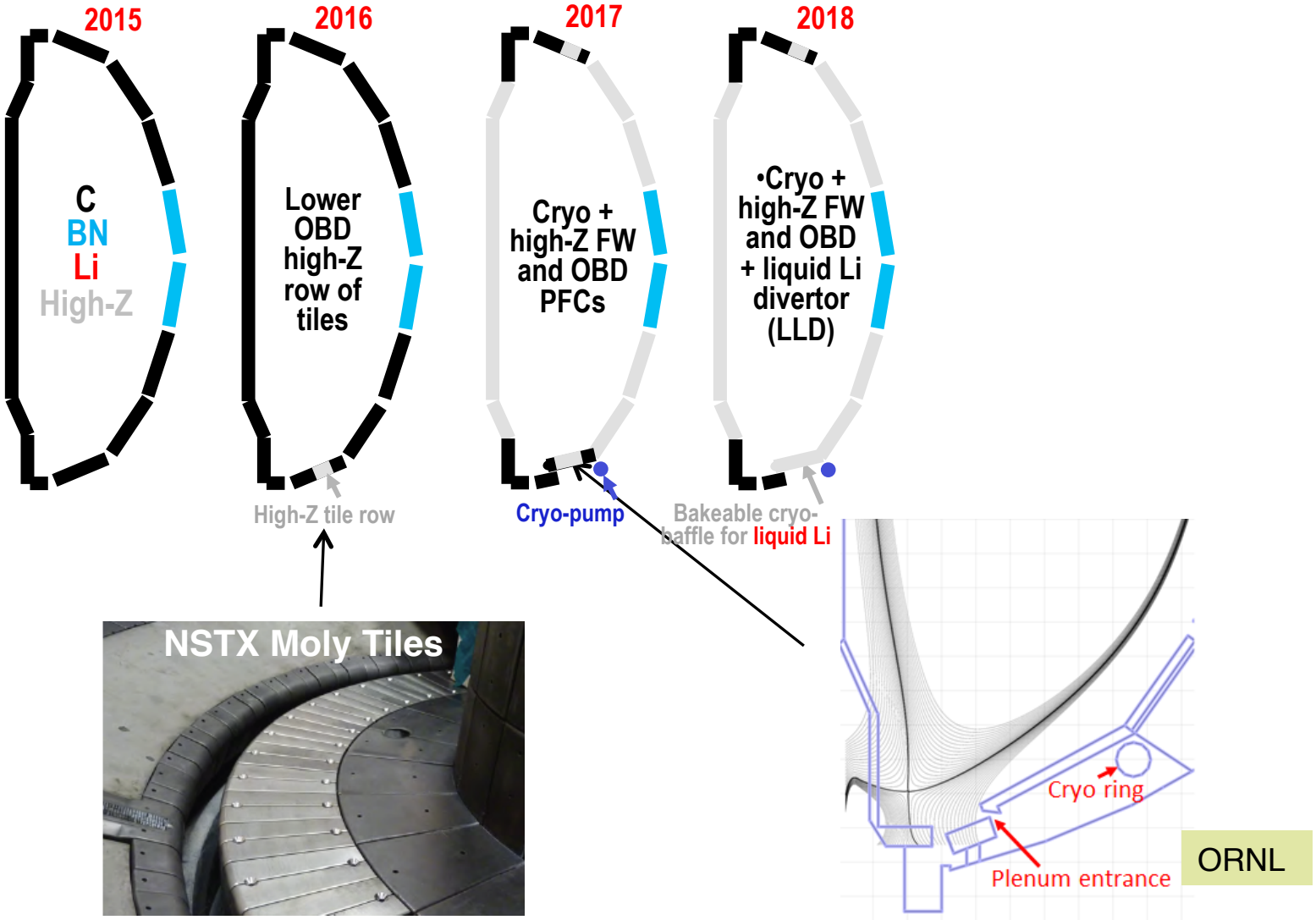


Purdue U.

(see back-up slides # 53 and 54)

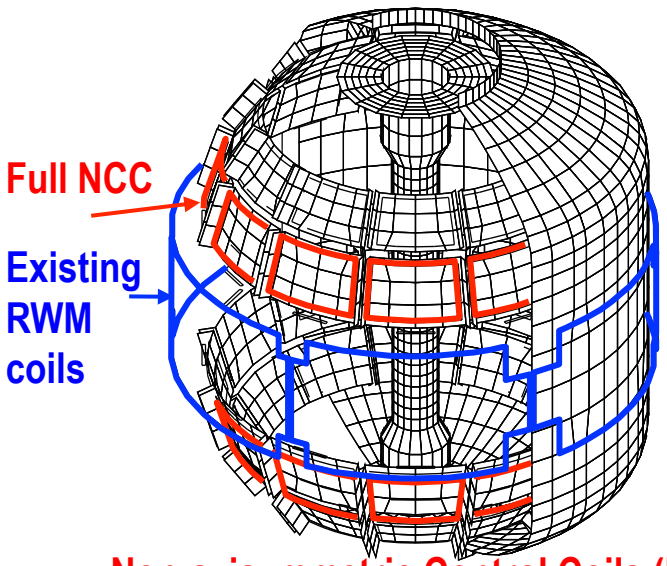
Boundary Facility Capability Evolution

NSTX-U will have very high divertor heat flux capability of ~ 40 MW/m^2



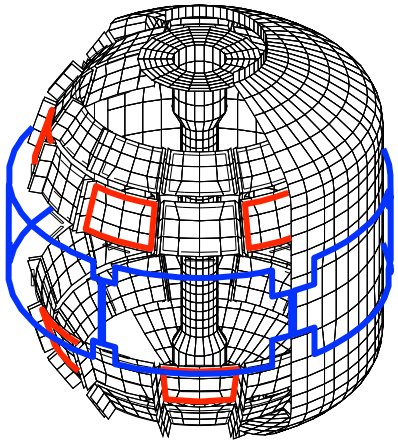
New MHD and Plasma Control Tools for NSTX-U

Sustain β_N and Understand MHD Behavior Near Ideal Limit



Non-axisymmetric Control Coils (NCC)

Partial NCC option (2 x 6 odd parity)

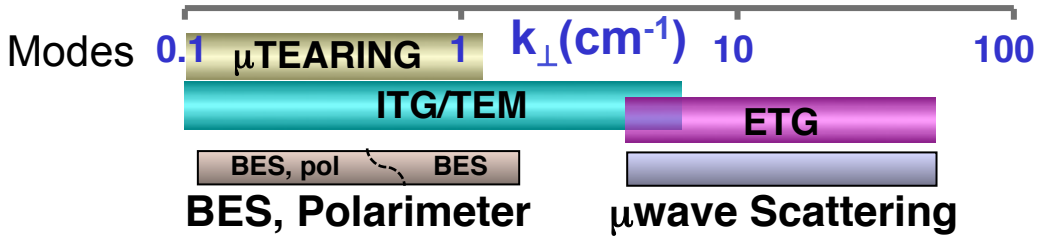


Columbia U., GA

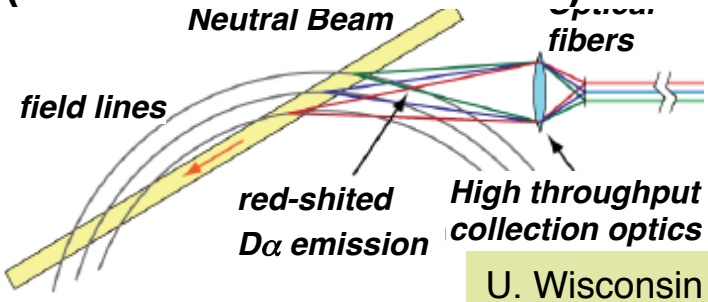
- NCC can provide expanded RWM, NTV, RMP, and EF physics studies with more flexible field spectrum (n ≤ 6, or n ≤ 3 depending on set).
- 2nd 3-channel Switching Power Amplifier (SPA) commissioned in July 2011 to power 6 independent currents in existing midplane RWM and NCC coils.
- An extended MHD sensor set to measure theoretically predicted poloidal mode structure and to improve mode control.
- A Real-Time Velocity (RTV) diagnostic in a new plasma rotation control system for active instability avoidance by controlling rotation profile.
- Multi-poloidal location massive gas injector system will be implemented.

Transport and Turbulence

BES together with high-k to provide comprehensive turbulence diagnostic



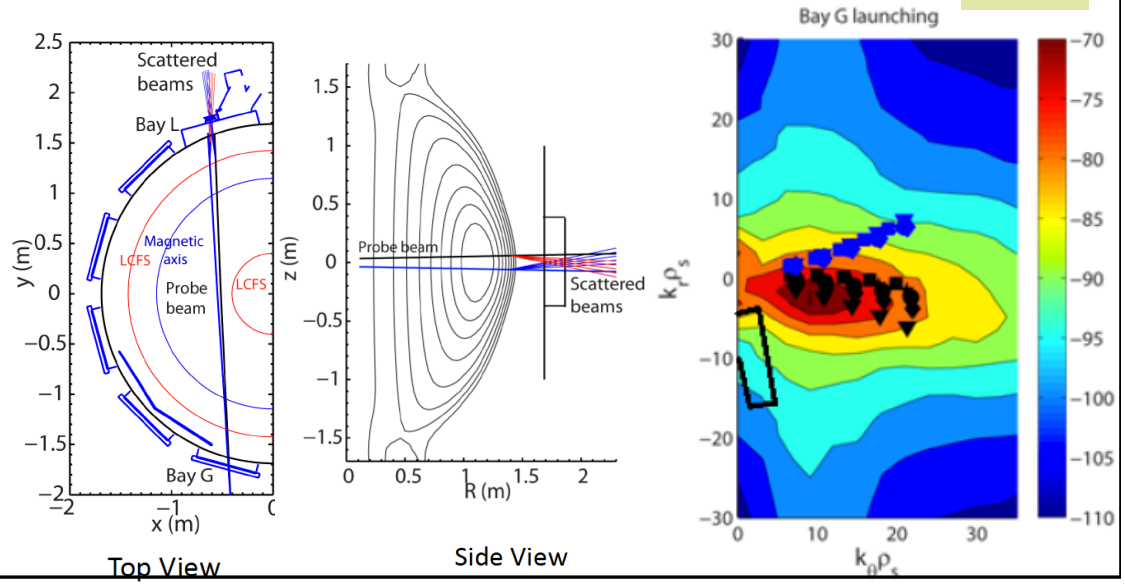
48 ch BES available for NSTX-U (24 ch BES available in 2011)



U. Wisconsin

New high-k scattering system for allowing 2-D k spectrum

UCD



A 288 GHz polarimetry system for magnetic fluctuation measurements is being tested on DIII-D.

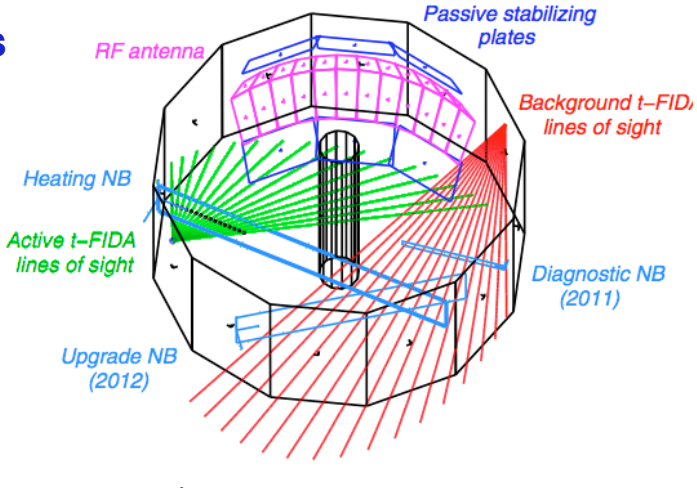
UCLA

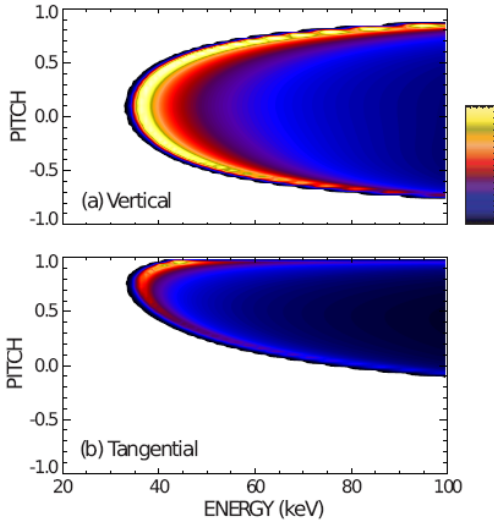
Energetic Particle Research Capabilities
For NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics — UCI

- Vertical FIDA system measures trapped or barely passing (co-going) particles.
- New tangential FIDA system measures co-passing fast ions
- Both FIDA systems have time resolution of 10 ms, spatial resolution ≈ 5 cm and energy resolution ≈ 10 keV.

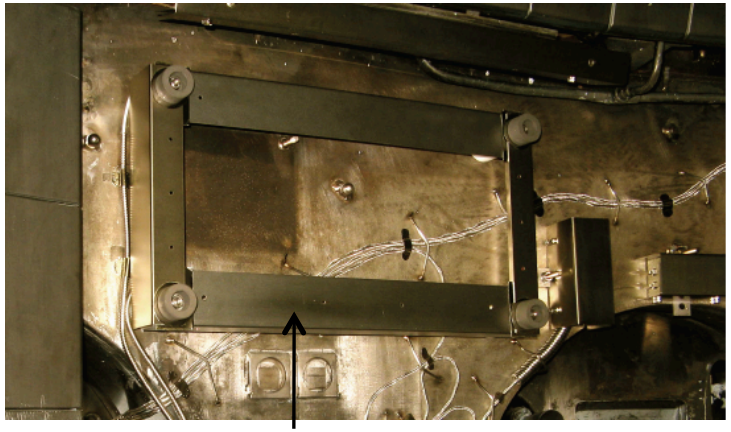
FIDA Views





FY 2013 - 14 Energetic Particle Conceptual Design and Diagnostic Upgrade

- Solid State-NPA enhancement — UCI
- Charged Fusion Product Array — FIU
- Proto-type active TAE antenna



5-turn radial active TAE antenna installed in 2011

Optimized NSTX-U Five Year Plan Has been Developed

Exciting Opportunities and Challenges Ahead

- **NSTX Upgrade provides significant advance in ST plasma performance**
  - A new center-stack to enable 1T, 2 MA, 5 sec operation
  - 2nd NBI for doubling the heating power and efficient current drive for fully non-inductive operation
  - High power density and innovative divertor solutions for world leading PMI research
- **NSTX upgrade outage activities are progressing well**
  - NSTX operations technical staff were shifted to the Upgrade Project tasks.
  - NSTX Upgrade Project is thus far progressing on budget and on schedule.
  - Diagnostics were being reinstalled on NSTX-U.
  - NSTX-U operational preparation activities are starting.
- **Exciting 5 Year Plan (FY 2014 – 18) has been developed**
  - Aiming to provide necessary data base for FNSF design and construction.
  - Strong contribution to toroidal physics, ITER, and fusion energy development.