NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Progress toward commissioning and plasma operation in NSTX-U

Masa Ono and the NSTX-U Team

(Presented by S.A. Sabbagh)

FEC IAEA Meeting
St. Petersburg, RU
18-23 October 2014

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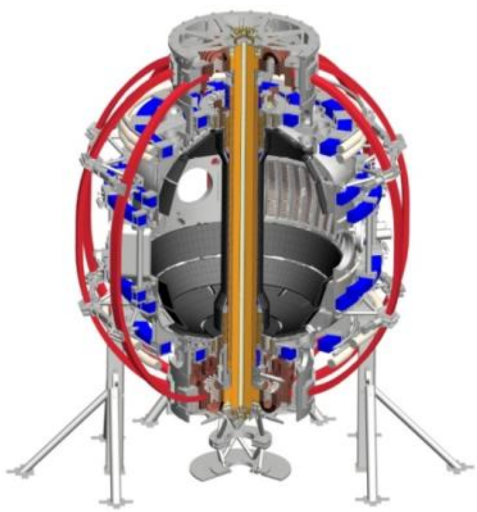

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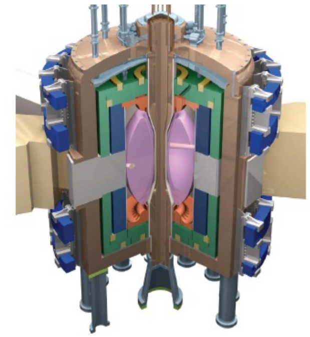
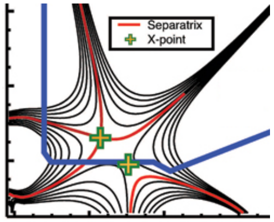
NSTX Upgrade Mission Elements

- **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**

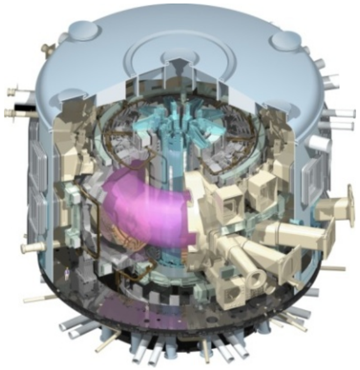


ST-FNSF

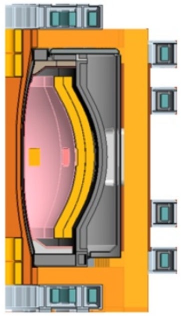
Liquid Lithium



"Snowflake"



ITER



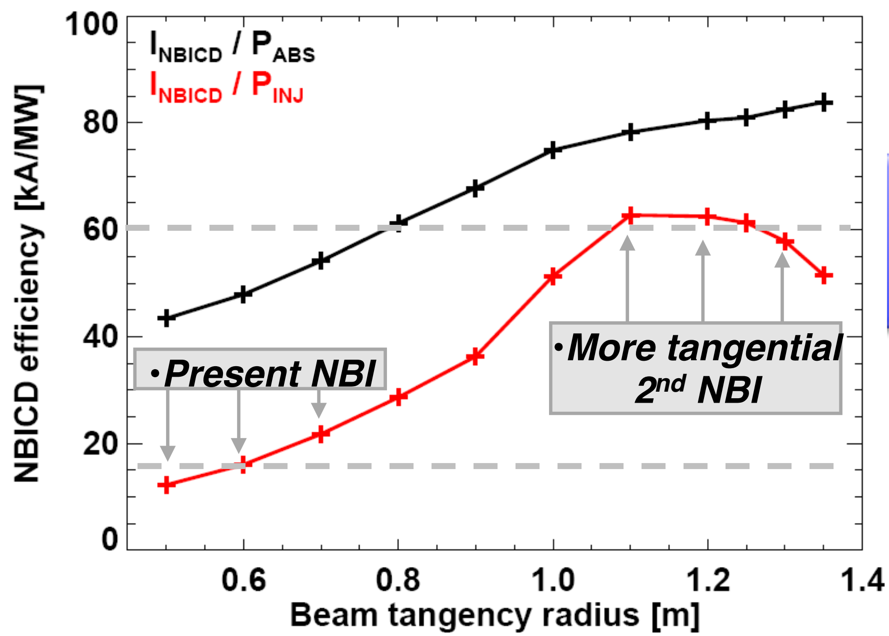
ST Pilot Plant

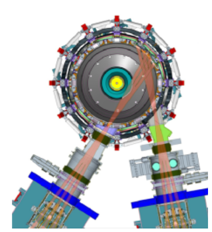
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new centerstack (CS) + more tangential 2nd NBI

- **New CS provides higher TF (improves stability), 3-5s needed for J(r) equilibration**
- **More tangential injection provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
  - 1.5-2x higher current drive efficiency

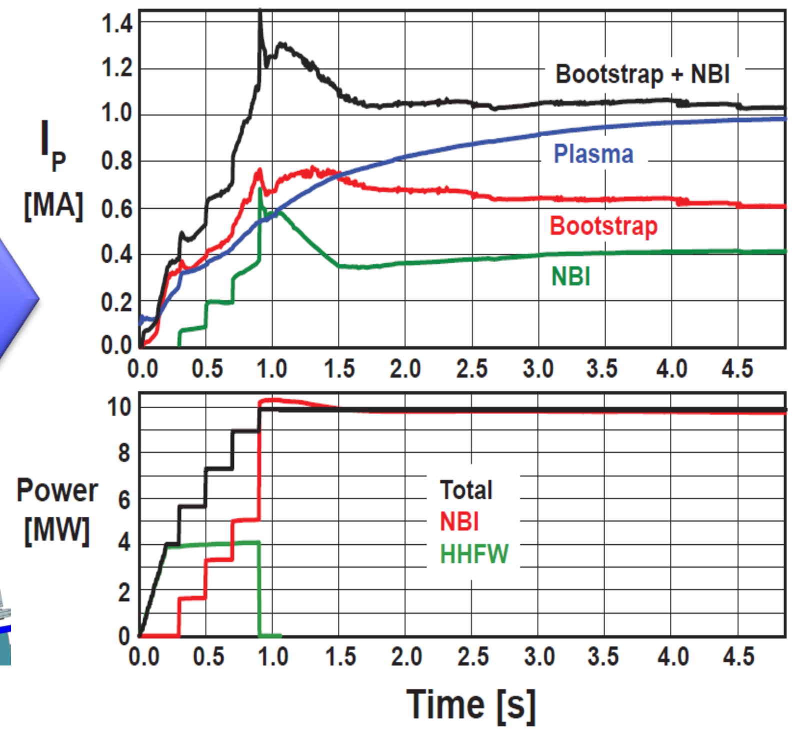
E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5\times10^{19}m^{-3}$, $\overline{T}_e$ = 0.83keV



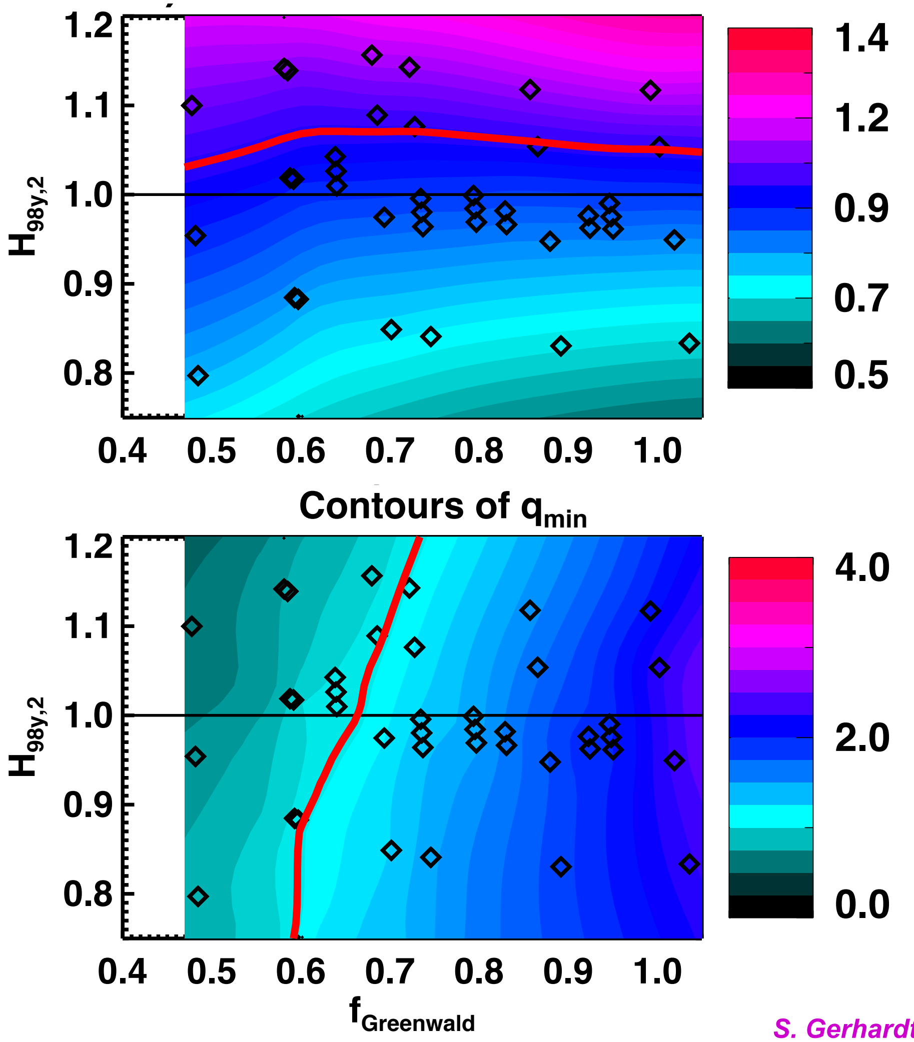


•TSC simulation of non-inductive ramp-up from I_P = 0.1MA, T_e=0.5keV target at B_T=1T



100% non-inductive operating points projected for a range of toroidal fields, densities, and confinement levels

$B_T = 1.0$ T, $I_P = 1$MA, $P_{inj} = 12.6$MW



Projected Non-Inductive Current Levels for κ~2.85, A~1.75, f_{GW}=0.7

B_T [T]	P_{inj} [MW]	I_P [MA]
0.75	6.8	0.6-0.8
0.75	8.4	0.7-0.85
1.0	10.2	0.8-1.2
1.0	12.6	0.9-1.3
1.0	15.6	1.0-1.5

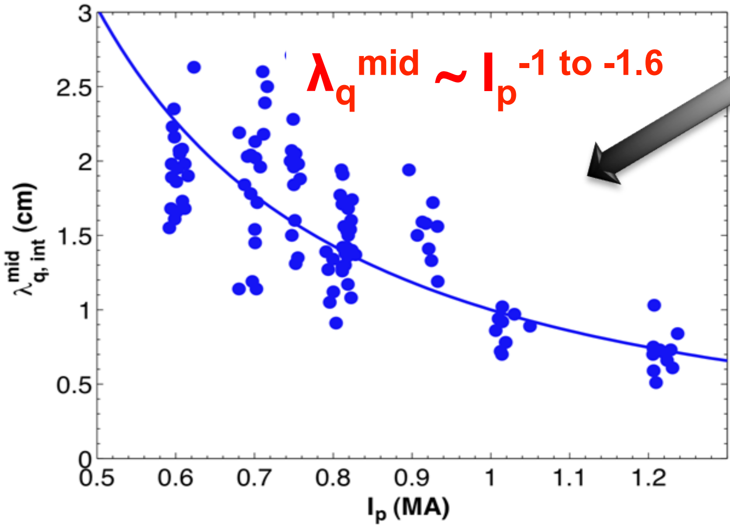
From GTS (ITG) and GTC-Neo (neoclassical):

$\chi_{i,ITG}/\chi_{i,Neo} \sim 10^{-2}$

Assumption of neoclassical ion thermal transport should be valid

S. Gerhardt, et al., Nucl. Fusion 52 (2012) 083020

NSTX-U will investigate detachment and high-flux-expansion "snowflake" divertor for heat flux mitigation

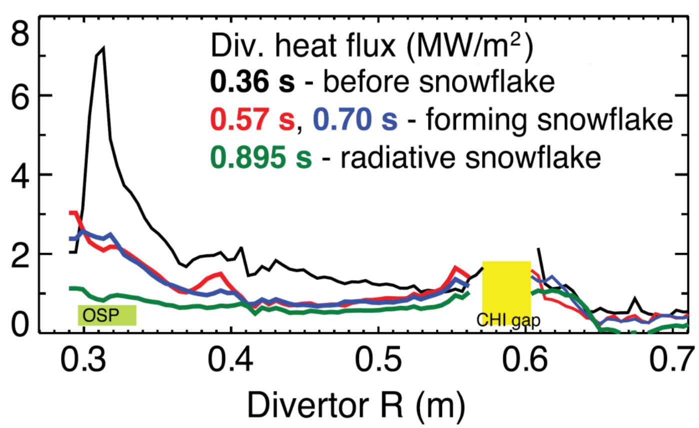


Divertor heat flux width decreases with increased plasma current I_P

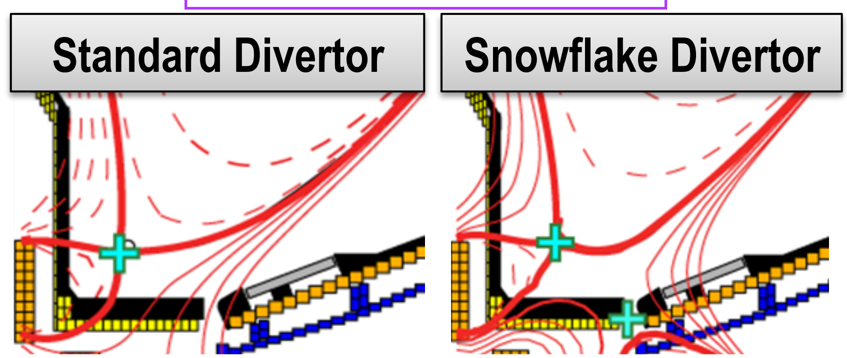
30-45MW/m^2 in NSTX-U with conventional LSN divertor at full current and power

Can reduce heat flux by 2-4× in NSTX via partial detachment at sufficiently high f_{rad}

NSTX data



Soukhanovskii EX/P5-21



Snowflake→ high flux expansion = 40-60 lowers incident $q_\perp$, promotes detachment

NSTX-U: U/D balanced snowflake has < 10MW/m^2 at I_P = 2MA, P_{AUX}=10-15MW

NSTX Upgrade Project Progress Overview

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

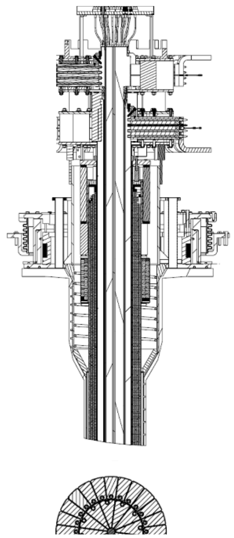
2nd NBI Project Scope

- 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

Substantial Increase in NSTX-U Device / Plasma Performance

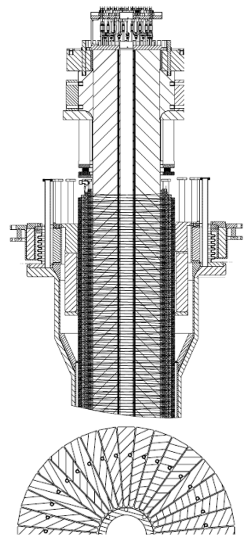
To provide data base to support ST-FNSF designs and ITER operations

Previous center-stack

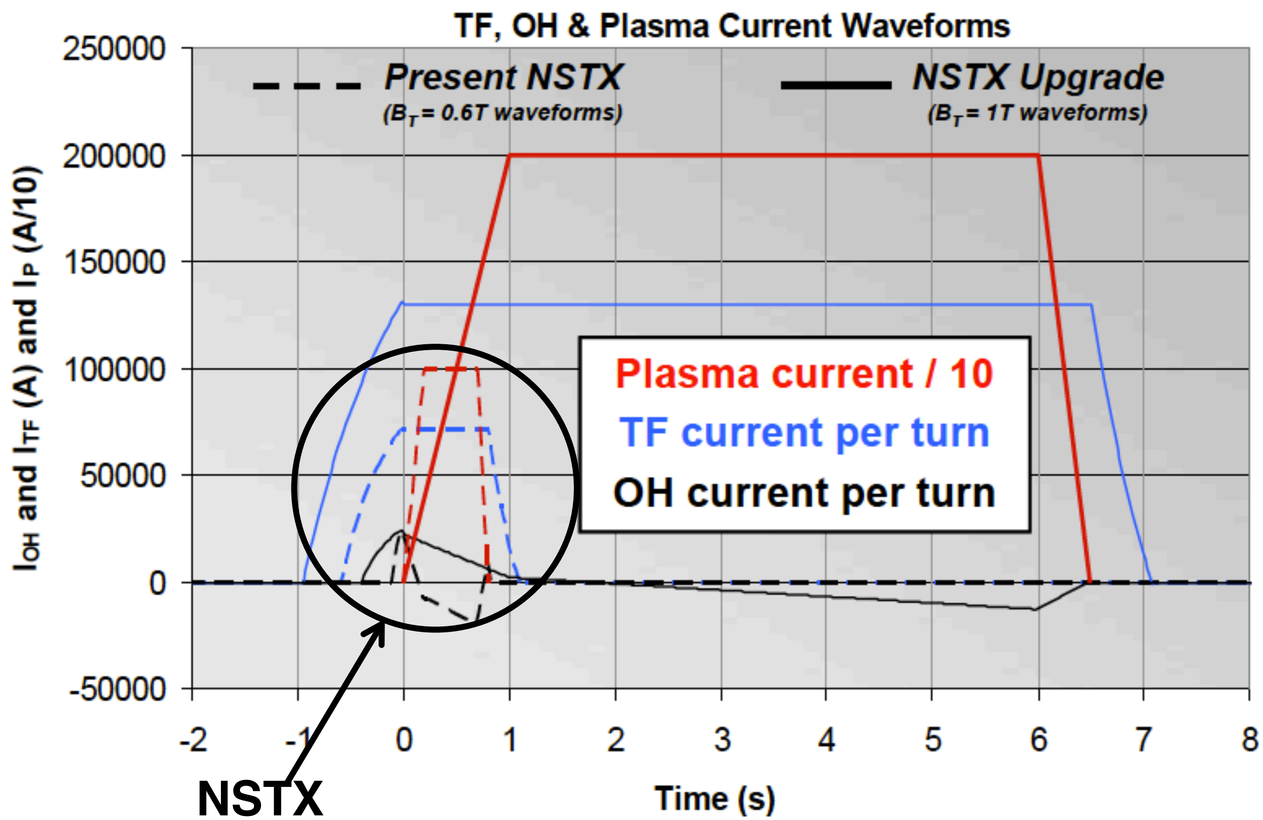


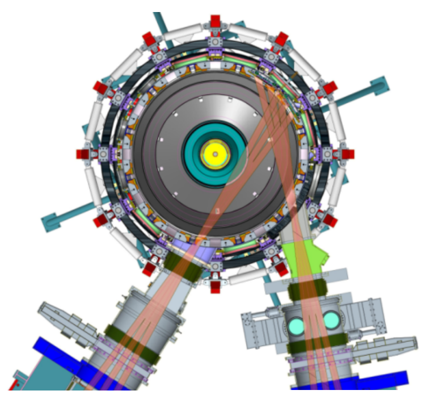
TF OD = 20cm

New center-stack



TF OD = 40cm





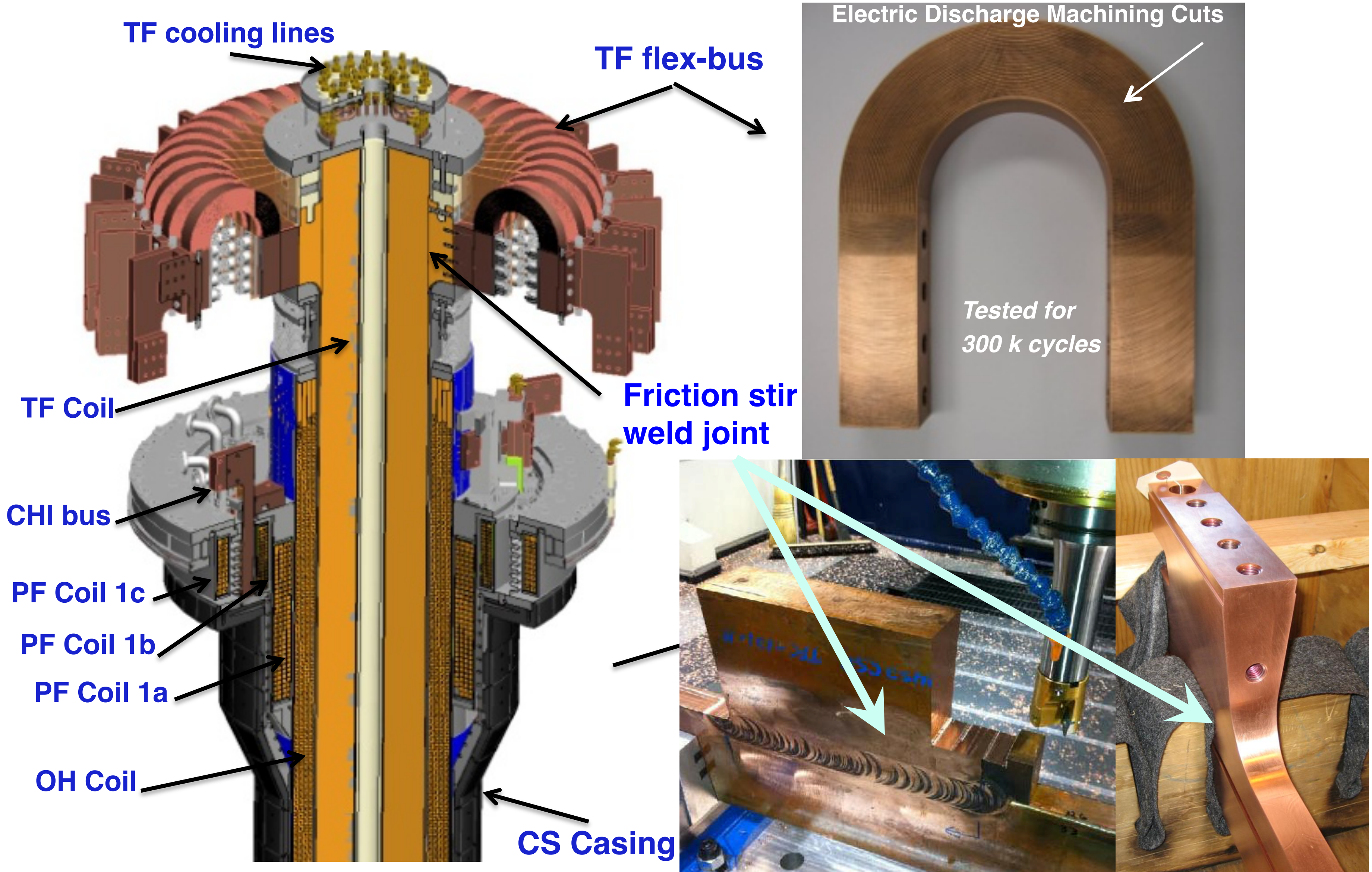
Present NBI New 2nd NBI

	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 5 - 10 increase in $n\tau T$ from NSTX

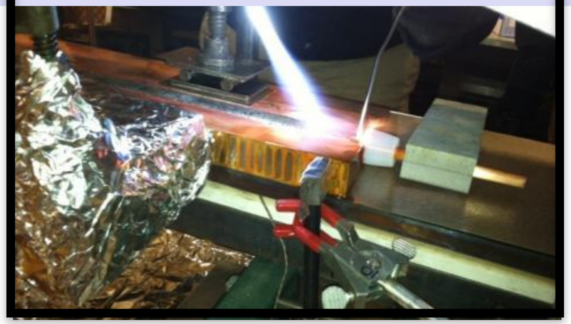
NSTX-U average plasma pressure $\propto B_{T0}^2 \beta_T (T^2\%)$ ~ Tokamaks

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

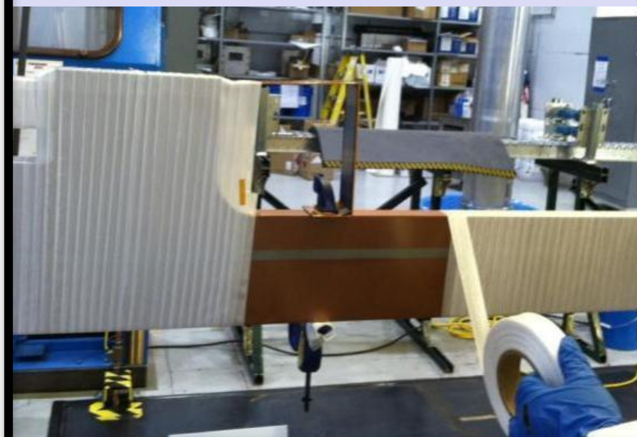


Center Stack Fabrication & Assembly Proceeding Well
Innovative manufacturing techniques developed

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

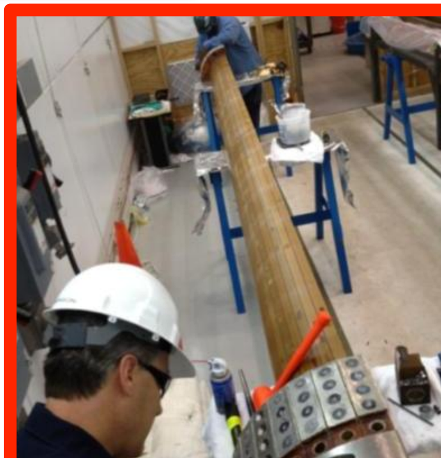


Conductor being wrapped with fiberglass insulation



Insulated conductor being placed into mold

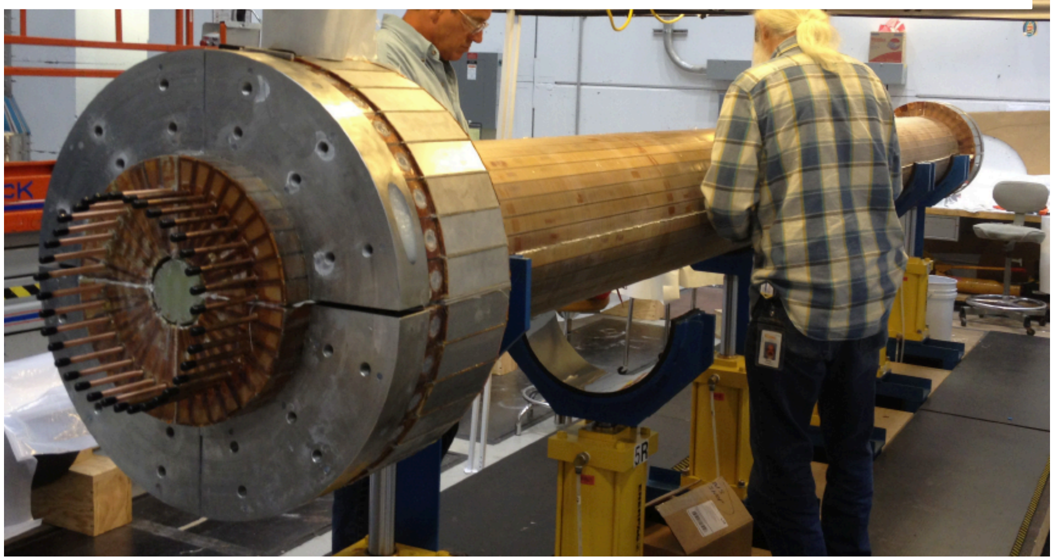
Assembled TF mold ready for Vacuum Pressure Impregnation with CTD-425



All four Quadrants successfully VPI'd !

TF Bundle Manufacturing Stages

Four TF quadrants were combined into a full TF bundle



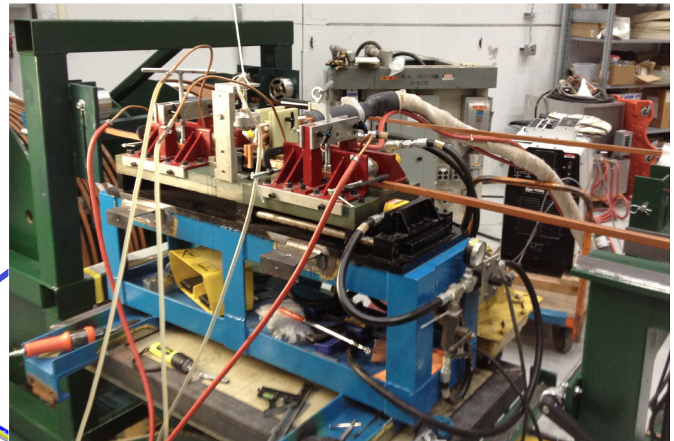
TF bundle with ground wrapping lowered into VPI mold

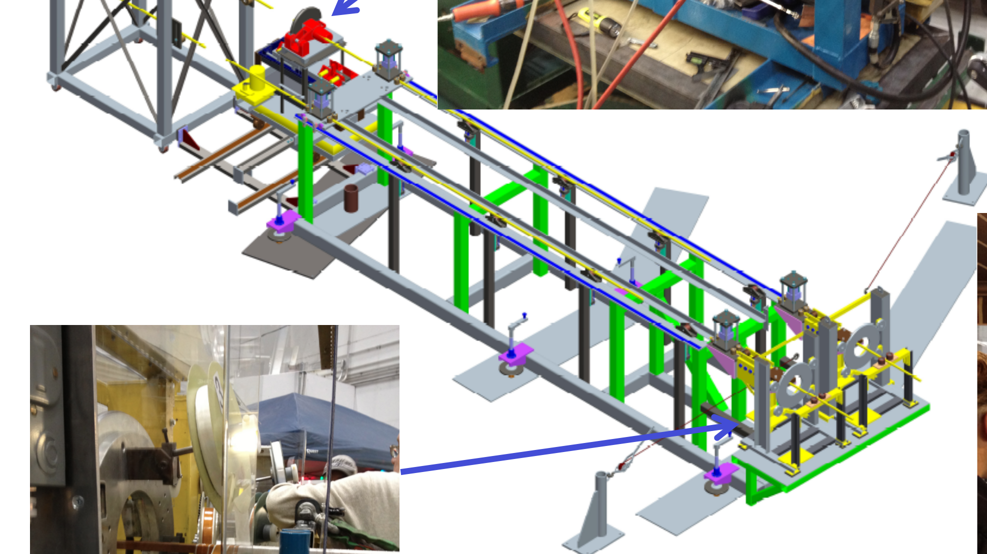
Center-Stack Casing with tile studs

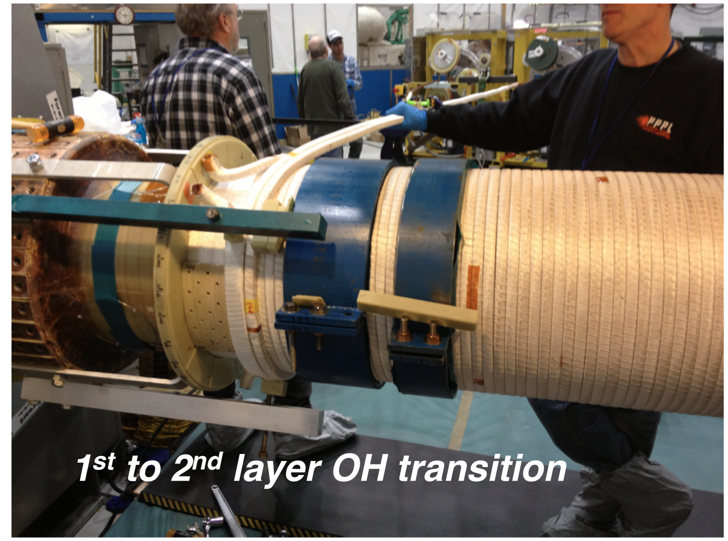
OH Winding Operation

OH Conductor Induction Braze & Taping Machine

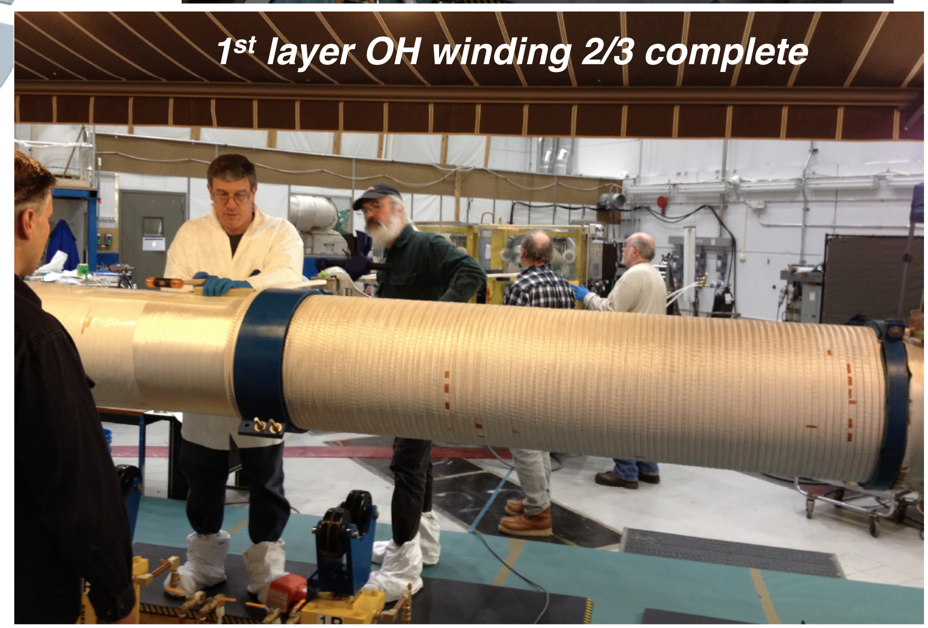
In-line Induction braze station







1st to 2nd layer OH transition

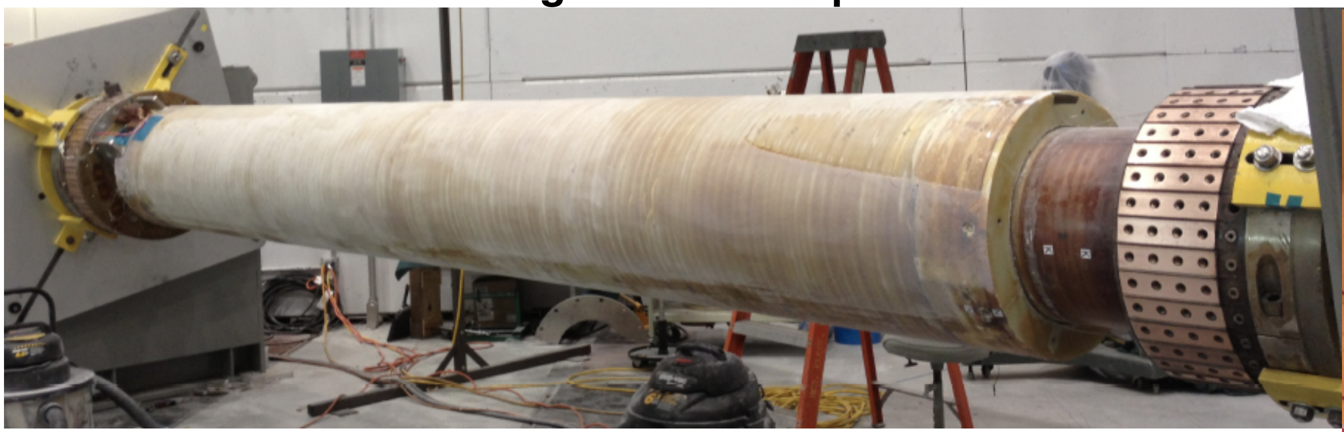


1st layer OH winding 2/3 complete

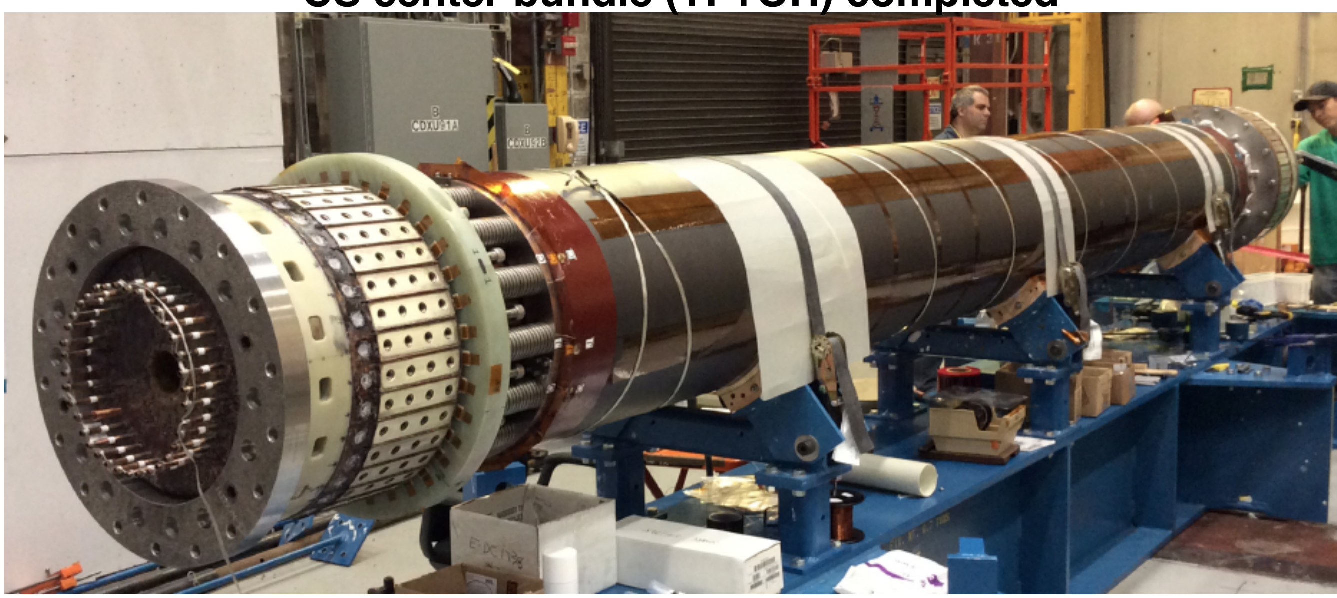
Taping Machine – Three fiberglass tapes, first two with kapton

Completed Center-stack Components
Center-Stack Assembly Started

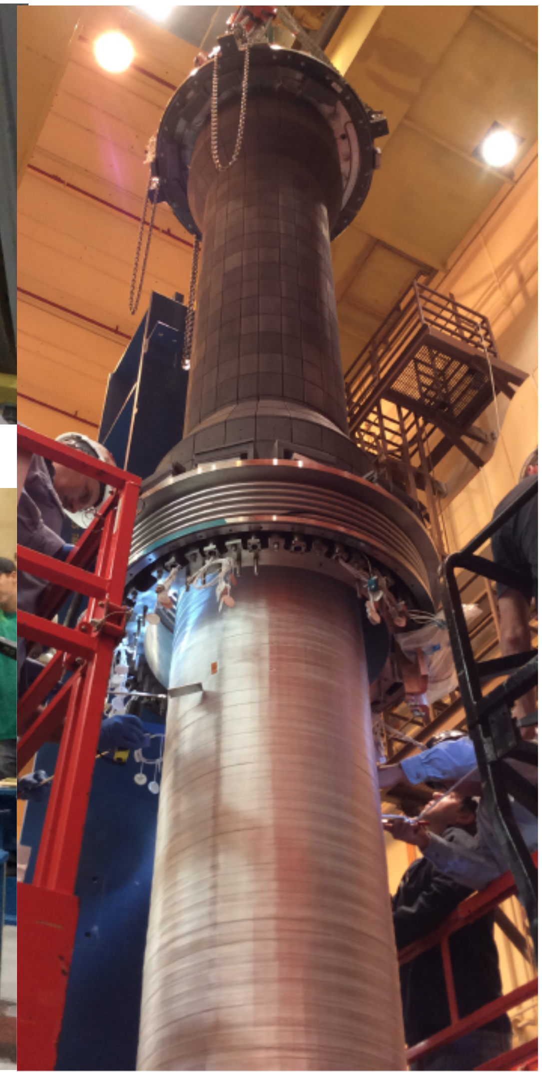
OH winding over TF completed



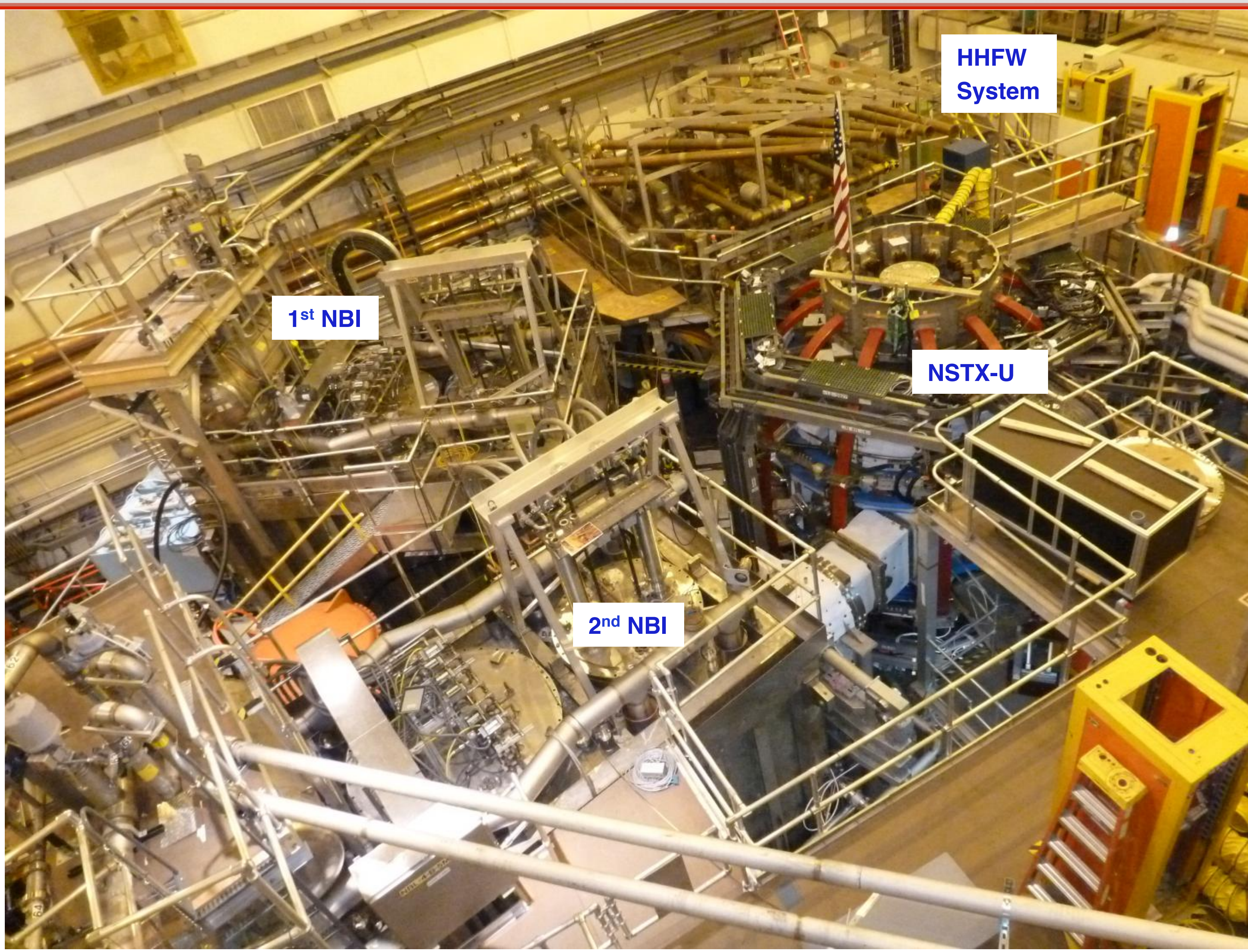
CS center bundle (TF+OH) completed



CS Casing lowered onto Center Bundle

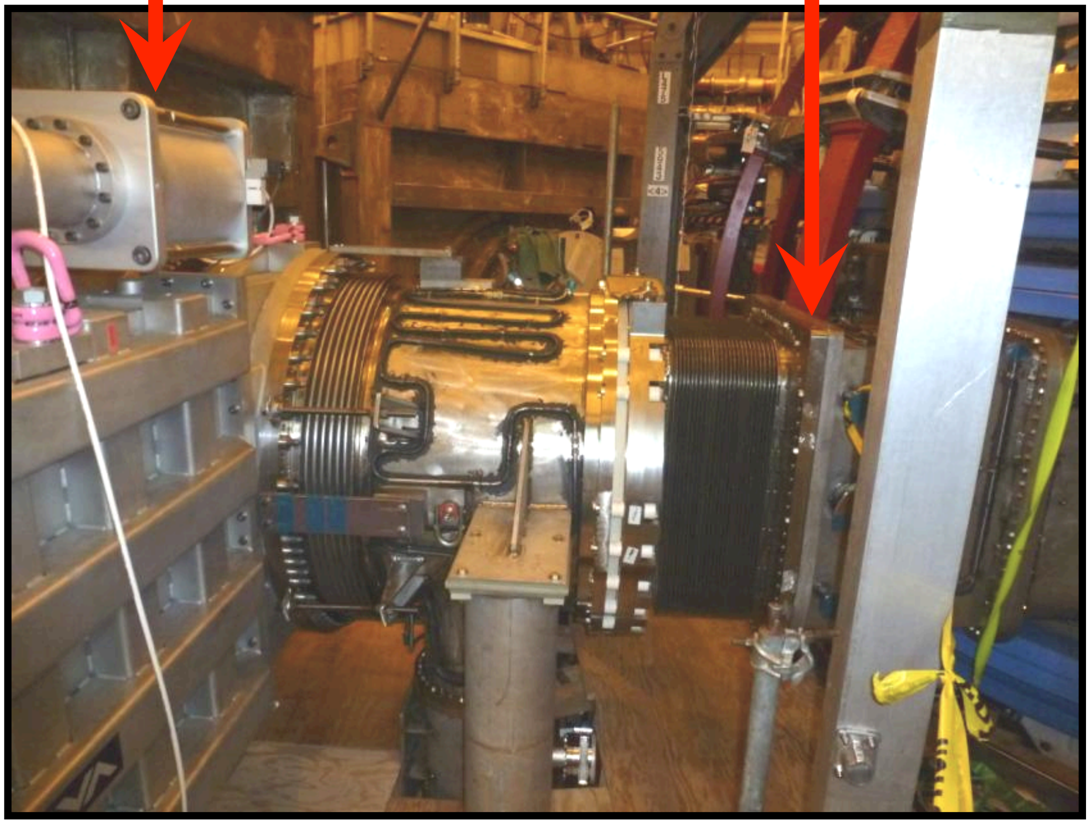


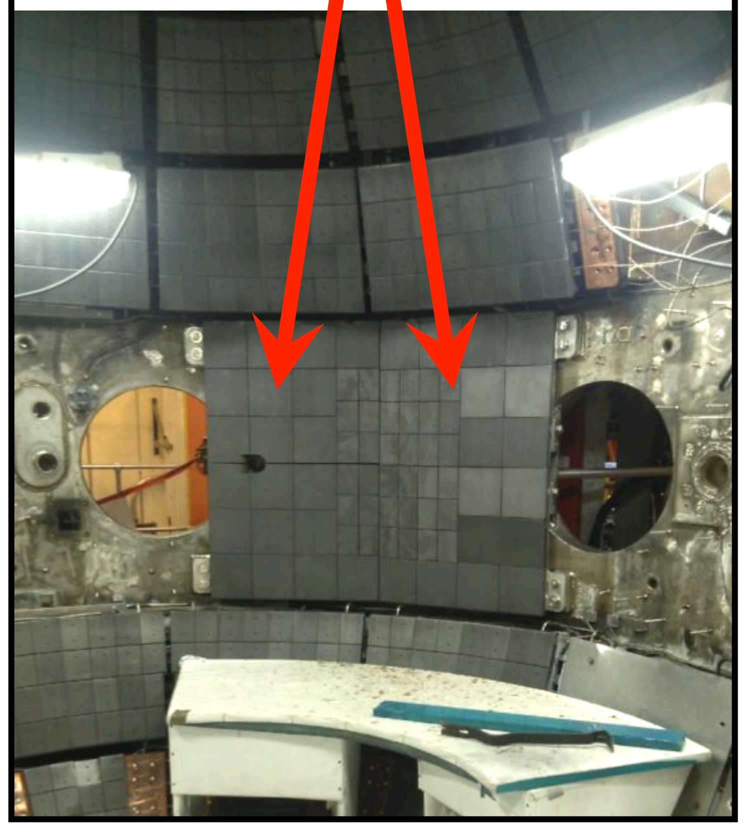
Aerial View of the NSTX-U Test Cell (Sept. 2014)



Final 2nd NBI Component being Installed

2nd NBI duct with pumping section and NBI armor installed





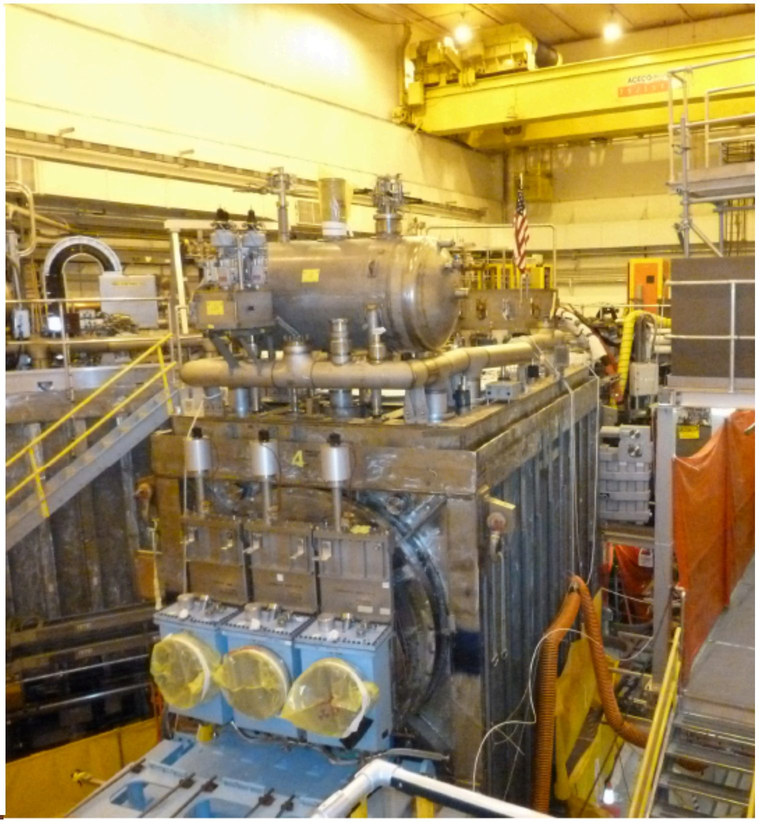
Source installation planned for June

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

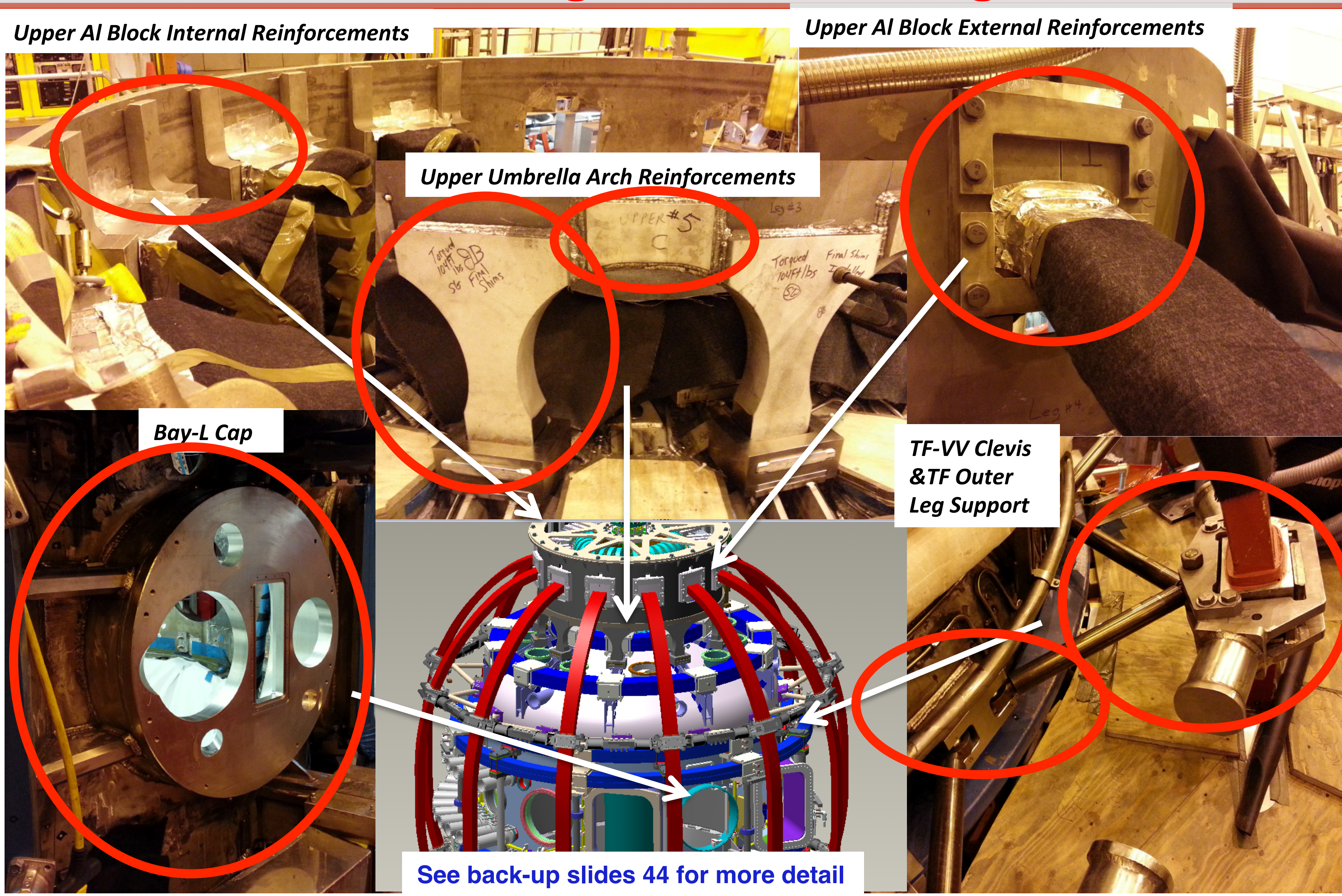
Beam Box placed in its final location and aligned



Beam Box being populated with components

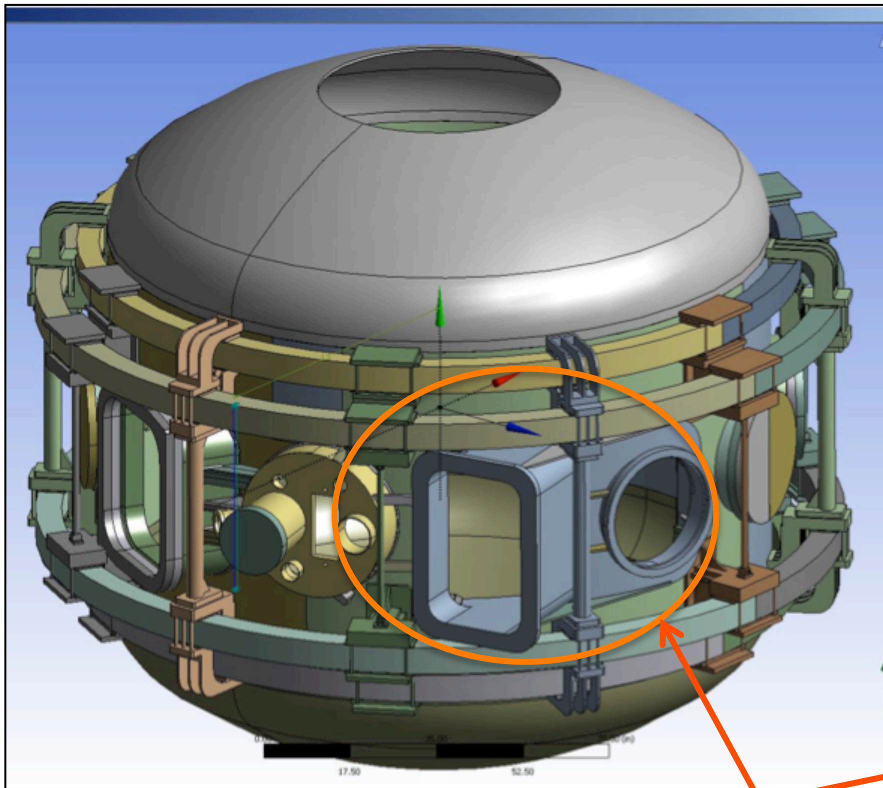
Support Structural and Vacuum Vessel Upgrades

Must handle 4 x higher electromagnetic loads



Highly Tangential 2nd NBI Enabled by JK-Cap

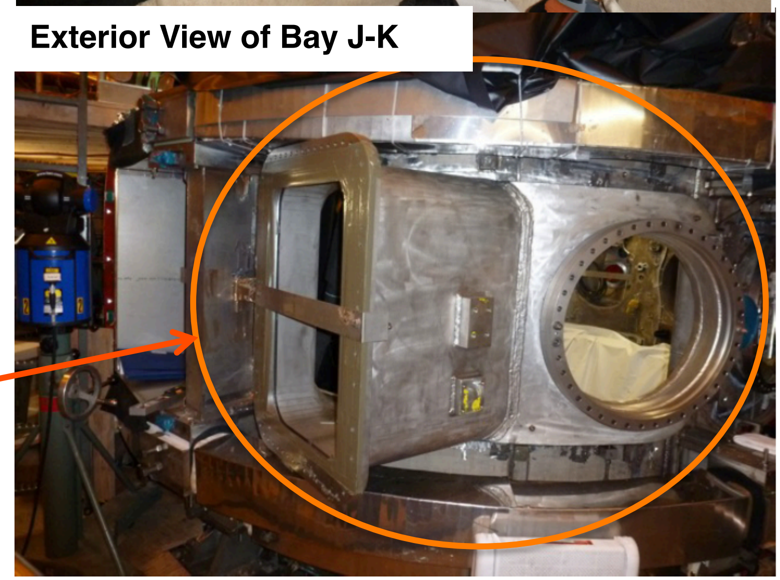
Outer Wall Radius Moved Outward to Avoid Beam Clipping



JK cap

Interior View of Bay J-K

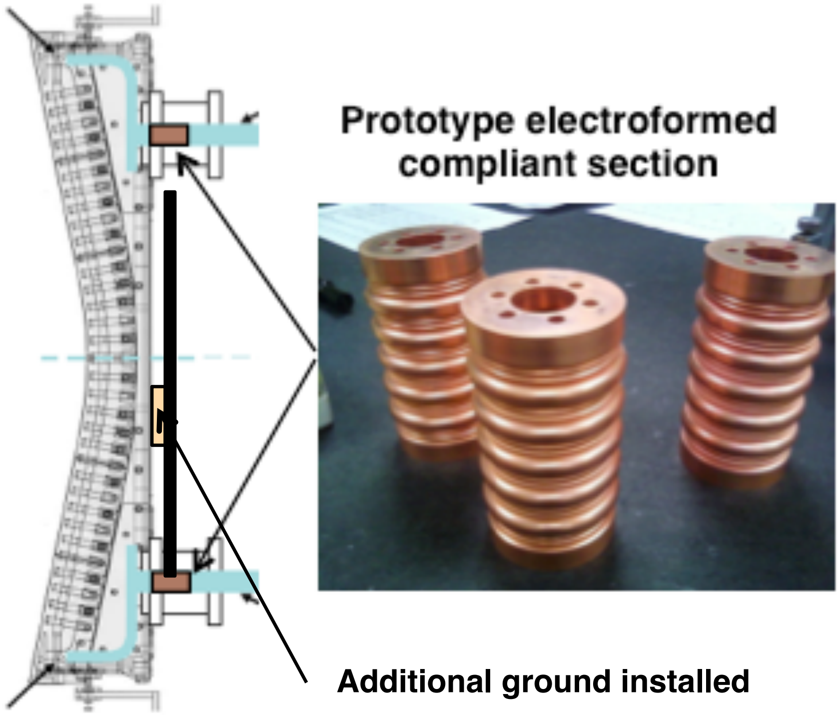
Exterior View of Bay J-K



HHFW System for Electron Heating and Current Ramp-up
Improved Antennas were installed in NSTX-U

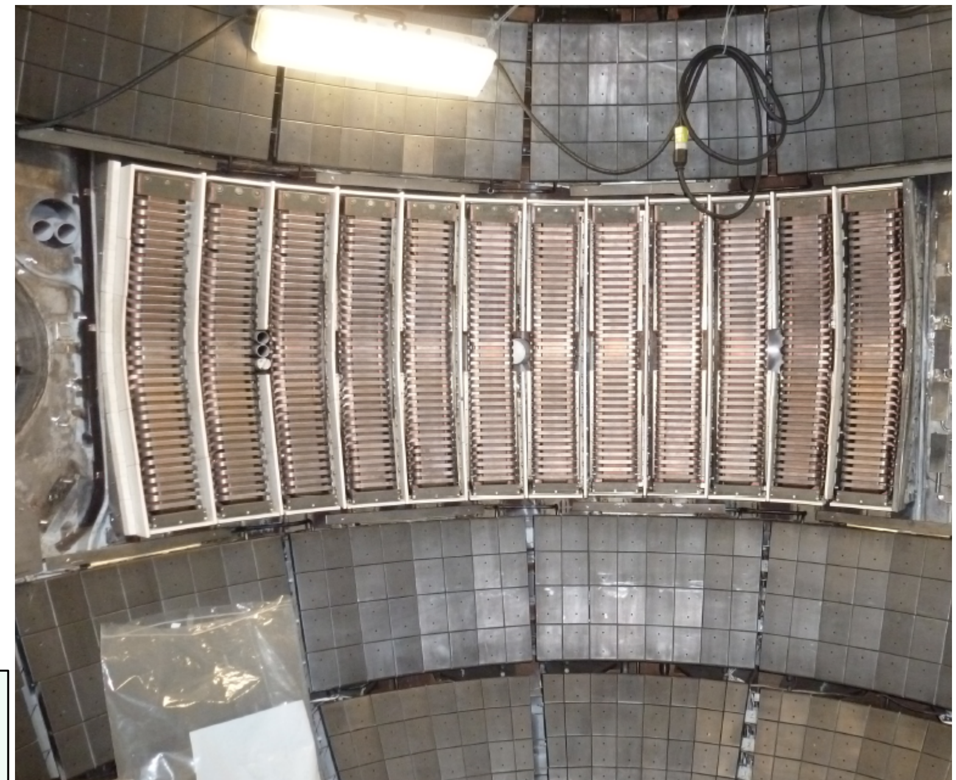
New Compliant Antenna Feeds

Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions

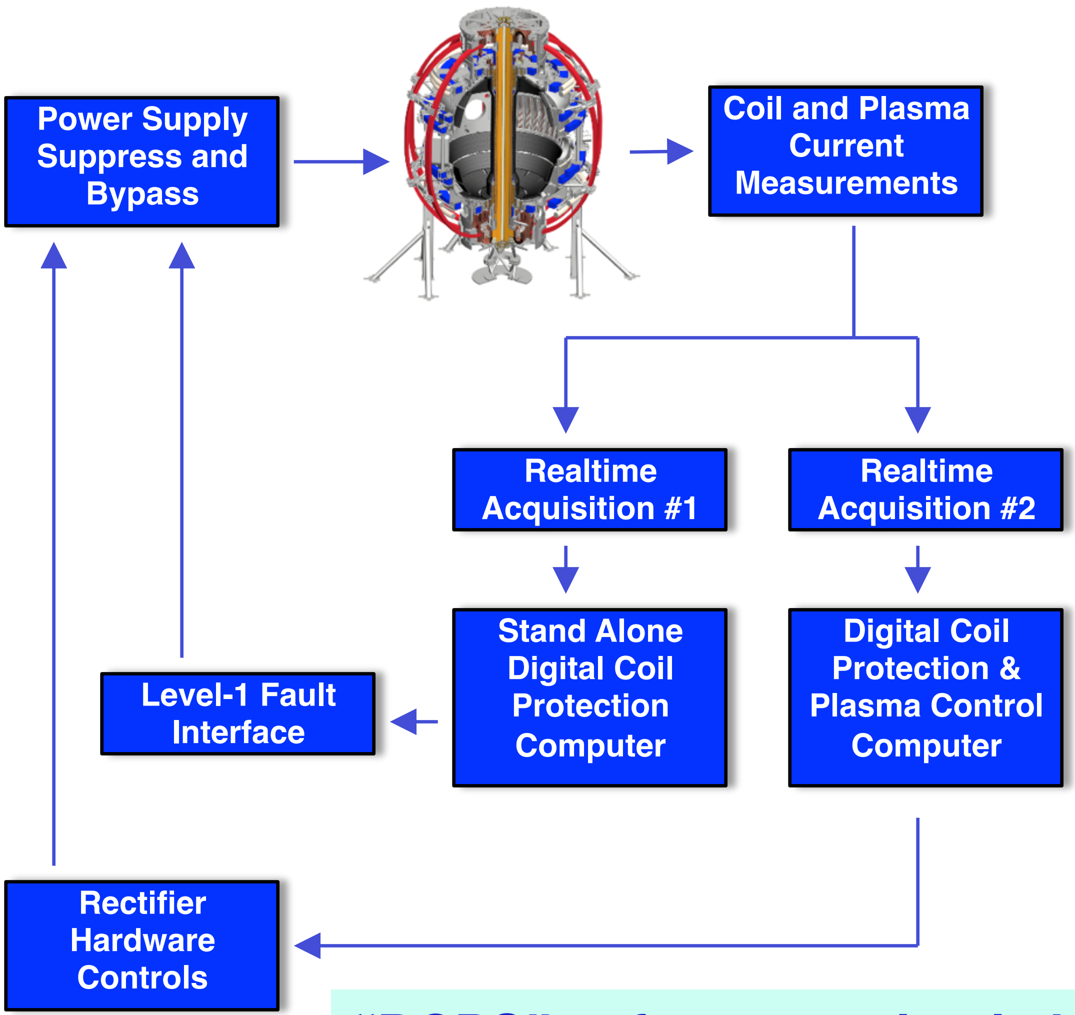


- **Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.**

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



New Digital System Provides Comprehensive Coil Protection



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 system will be a key part of early operations

"DCPS" software testing is being performed right now and the hardware to follow in mid-August.

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 FIR 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 Upgrade Project Milestones on Track
First plasma on February 15, 2014

Level	Milestone	DOE Commitment Date	Forecast	Actual
Level I	**Receive CD-2 Approval**	**Jan-11**		**Dec-10**
Level II	Project FDR	Jun-11		Jun-11
Level I	**Receive CD-3 Approval**	**Jan-12**		**Dec-11**
Level II	Receive First Delivery Machined Inner Tf Conductor	Jun-12		Apr-12
Level II	Nstx Complete Operations	Jul-12		Sep-11
Level II	Begin Upgrade Outage	Aug-12		Sep-11
Level II	Award Neutral Beam (NB) Vessel Cap	Jun-13		Feb-11
Level II	Begin Inner Tf Quadrant Fab (Apply Turn Insul #1	Apr-13		Jun-12
Level II	Complete Assy and Pot Of 4th Inner TF Quadrant	Oct-13		Jun-13
	Install NB Sources		Aug-14	Aug-14
Level II	Complete Fabricate & Test Inner TF/OH Coil Assy	Jul-14		Jul-14
Level II	NB Cap Installed	Oct-14		Jan-13
	Deliver Center Stack to the NSTX TC		Sep-14	
Level II	Lift In New Centerstack	Jan-15	Nov-14	
	Pumpdown		Dec-14	
Level II	Complete ISTP	Aug-15	Feb-15	
Level II	Resume Operations	Sep-15	Feb-15	
Level I	**CD-4**	**Sep-15**	**Feb-15**	

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

Facility and Diagnostic Enhancements to support the exciting 5 year research plan

2014	2015	2016	2017	2018

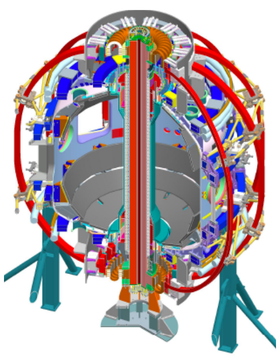
Upgrade Outage | **1.5 → 2 MA, 1s → 5s**

Run Weeks: 16 14 14 16

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

New center-stack



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

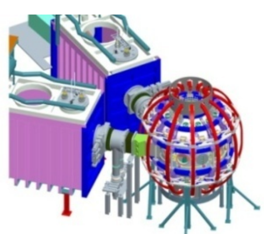
MHD
- MGI disruption mitigation
- Partial NCC
- Enhanced MHD sensors
- NCC SPA upgrade

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

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

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

2nd NBI



Legend: ← ● Priority scope; ● Incremental scope