NSTX-U

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NSTX Upgrade for Establishing Physics and Technology Basis for FNSF

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for the NSTX-U Team

2014 TOFE Meeting

November 10 – 13, 2014

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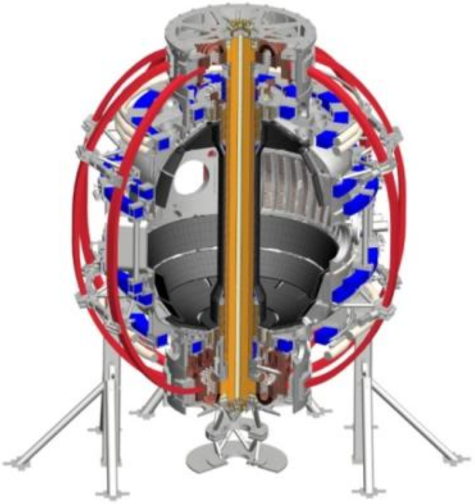
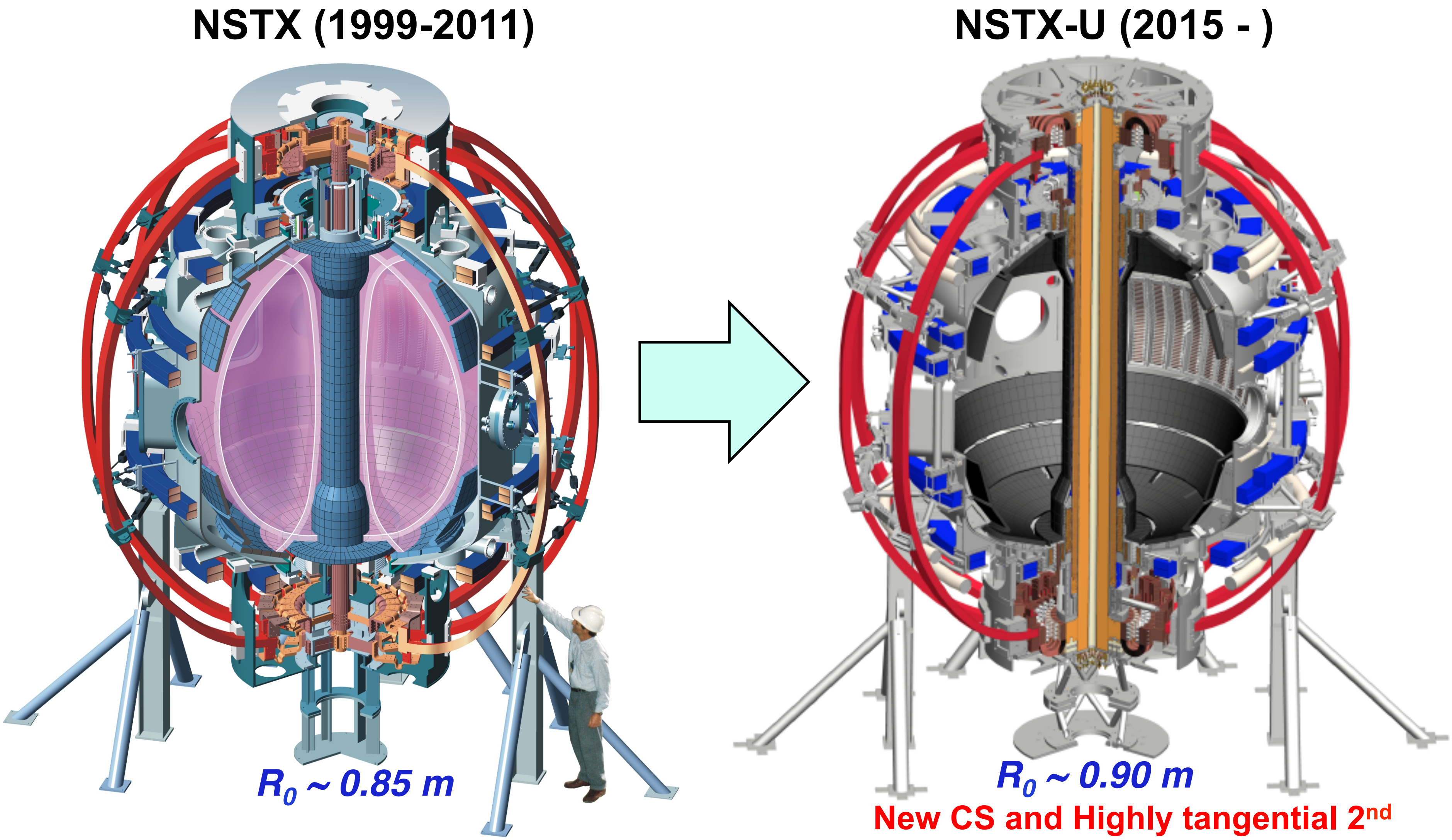


Talk Outline

- **Introduction and Motivation for NSTX-U**
- **NSTX Upgrade Project**
- **NSTX-U ST-FNSF Targeted Experiments**
- **Summary**

NSTX-U is nearing its first plasma

New center-stack and 2nd NBI are major upgrade scopes



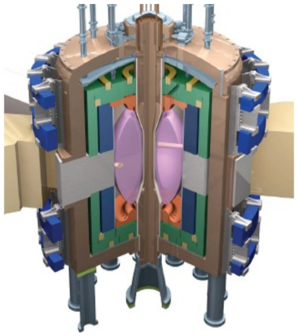
$R_0 \sim 0.85$ m

$R_0 \sim 0.90$ m

New CS and Highly tangential 2nd NBI for non-inductive operations

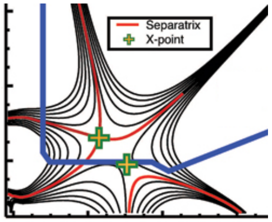
NSTX Upgrade Mission Elements

- **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**

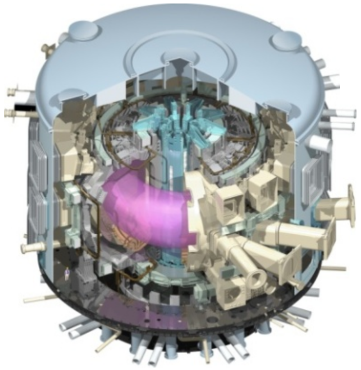


ST-FNSF

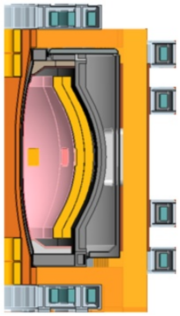
Liquid Lithium



"Snowflake"



ITER

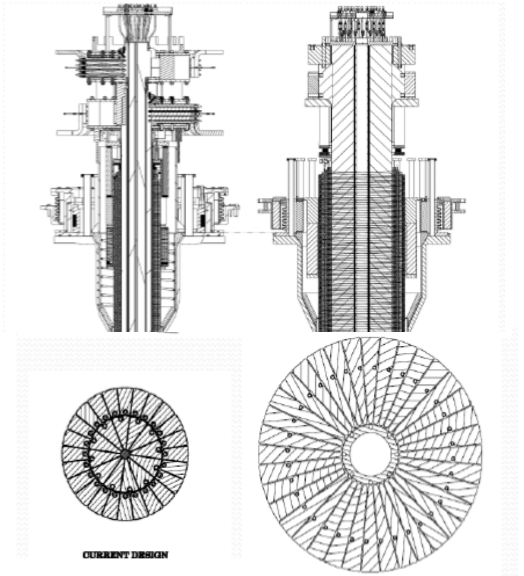


ST Pilot Plant

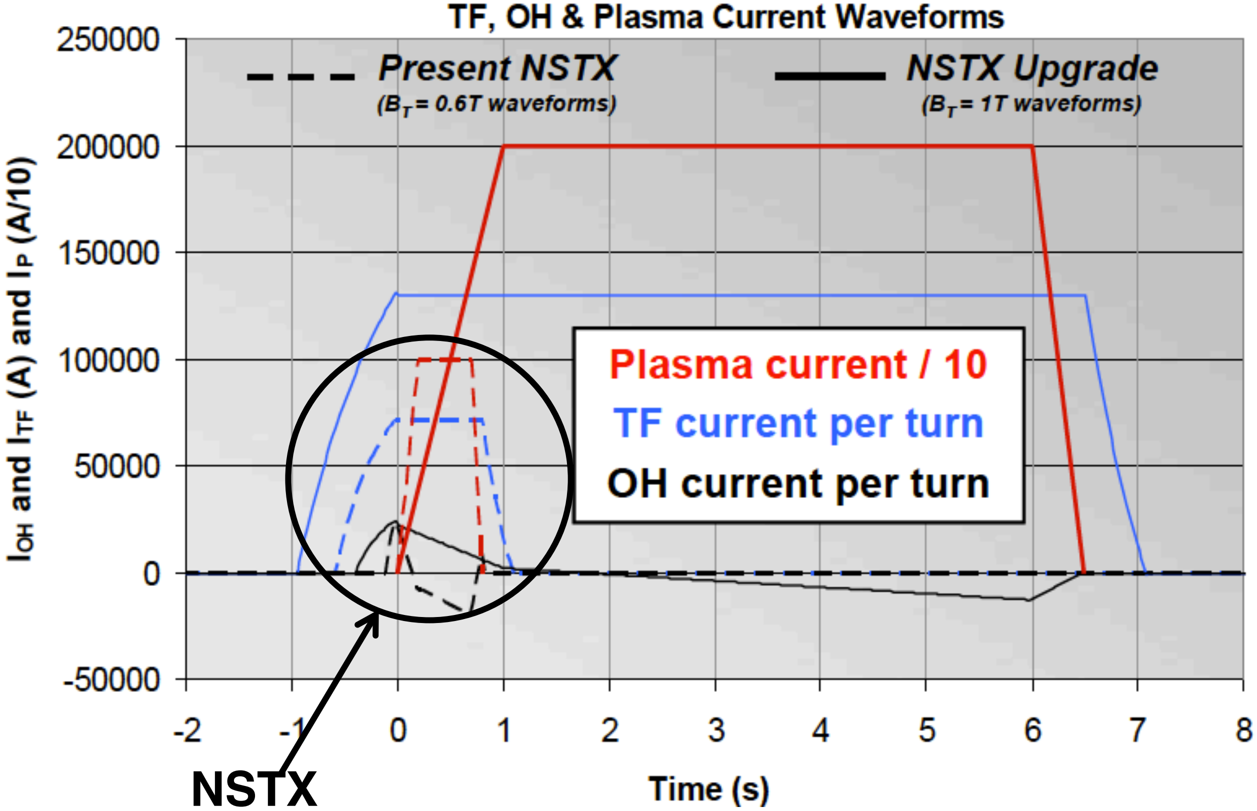
Substantial Increase in NSTX-U Device / Plasma Performance

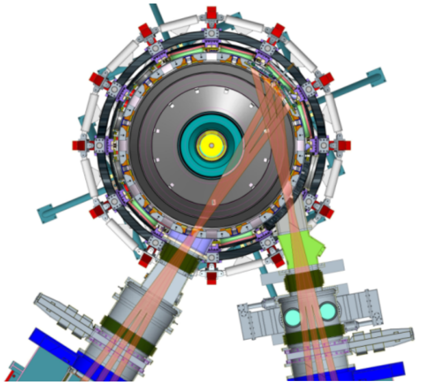
~ X 2 B_T, I_p and P_{NBI} and ~ x 5 pulse length from NSTX

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



TF OD = 20cm TF OD = 40cm





Present NBI New 2^{nd} 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

New CS together with highly tangential NBI injection provides ~ 2x higher CD efficiency for sustained 100% non-inductive operations needed for FNSF

An ST is a low-aspect-ratio, high β_T tokamak
Higher β_T enables higher fusion power and compact FNSF

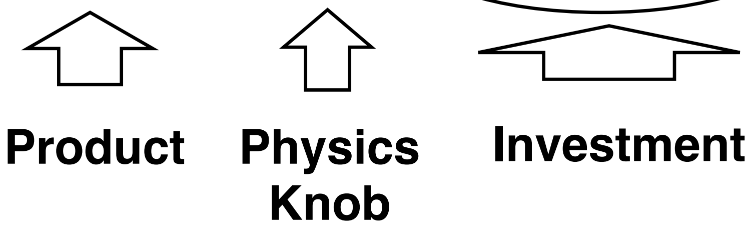
Aspect Ratio $A = R/a$

Elongation $\kappa = b/a$

Toroidal Beta $\beta_T = \langle p \rangle / (B_{T0}^2 / 2\mu_0)$

$$P_{fusion} \propto \langle p \rangle^2 \times Vol$$

$$P_{fusion} \propto \beta_T^2 \; \boxed{B_{T0}^4 \times Vol}$$



Product

Physics Knob

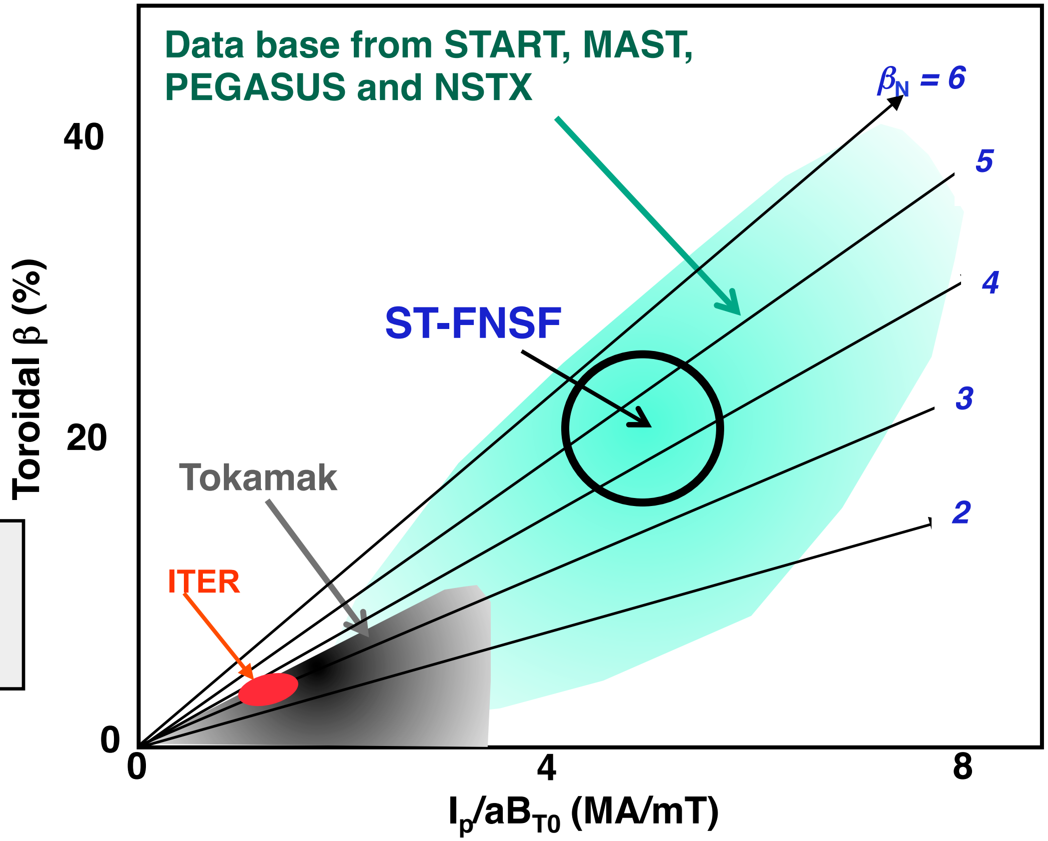
Investment

High neutron wall loading W_n possible in a compact FNSF

$$W_n \propto P_{fusion} / Area$$

$$W_n \propto \beta_T^2 \, B_{T0}^4 \, a \quad \text{(not strongly size dependent)}$$

⇨ *W_n ~ 1-2 MW/m^2 with R ~ 1 m ST-FNSF feasible!*



There have been several studies of ST-FNSF showing the potential attractiveness of this approach

Projected to access high neutron wall loading at modest R_0, P_{fusion}

$W_n \sim$ 1-2 MW/m^2 , $P_{fus} \sim$ 50-200MW, $R_0 \sim$ 0.8-1.8m

Modular, simplified maintenance

Tritium breeding ratio (TBR) near 1

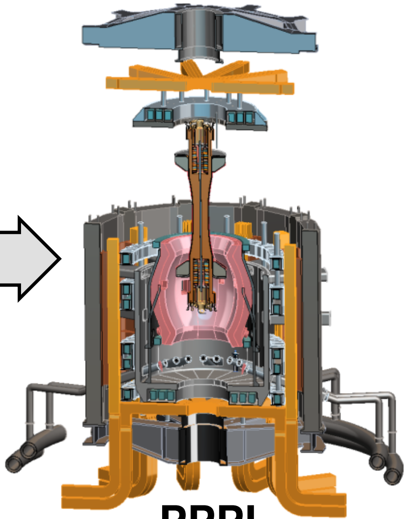
Requires sufficiently large R_0, careful design

NSTX-U to address ST-FNSF R&D needs

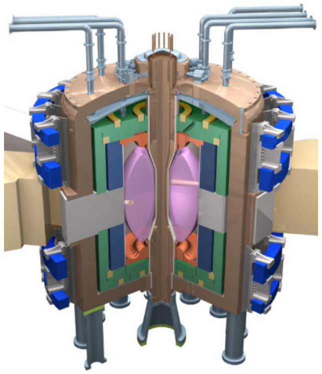
- ✓ Non-inductive start-up, ramp-up, sustainment
- ✓ Confinement scaling (especially electrons)
- ✓ Stability and steady-state control
- ✓ Divertor solutions for (ss) high heat flux

Radiation-tolerant magnets, design

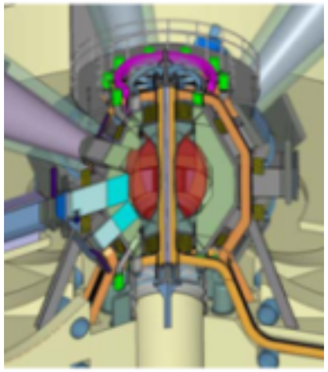
Example ST-FNSF concepts



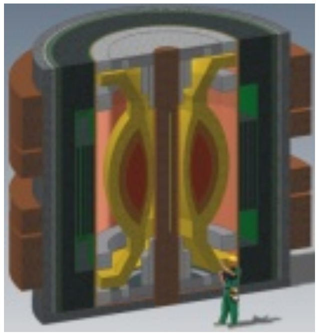
PPPL



ORNL



Culham (UK)



UT Austin

ST-FNSF by T.G. Brown and J. Menard at this conference

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- Introduction and Motivation for NSTX-U
- **NSTX Upgrade Project**
- NSTX-U ST-FNSF Targeted Experiments
- Summary

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

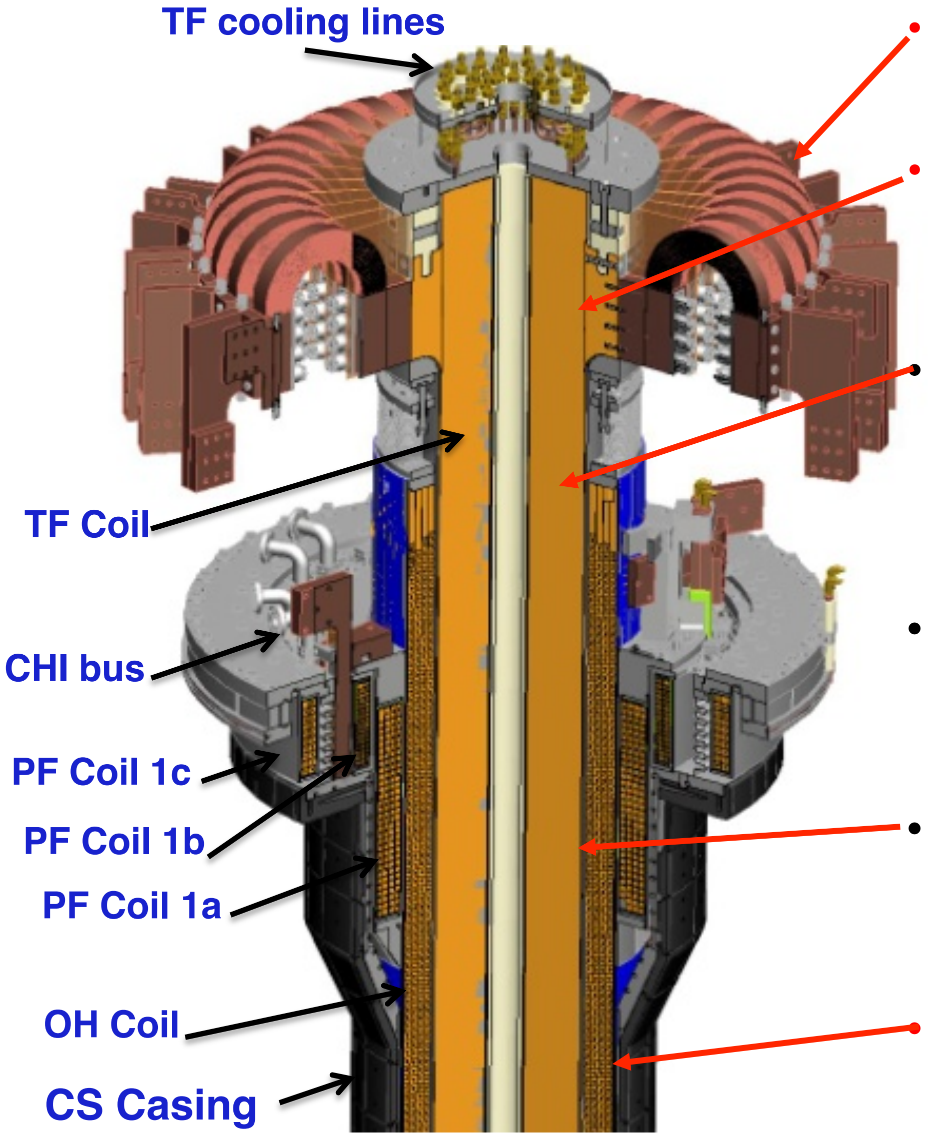
Ancillary Sys

NSTX-U Analyses – P. H.Titus at this conference

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

Innovations and Challenges in Manufacturing New Center-Stack

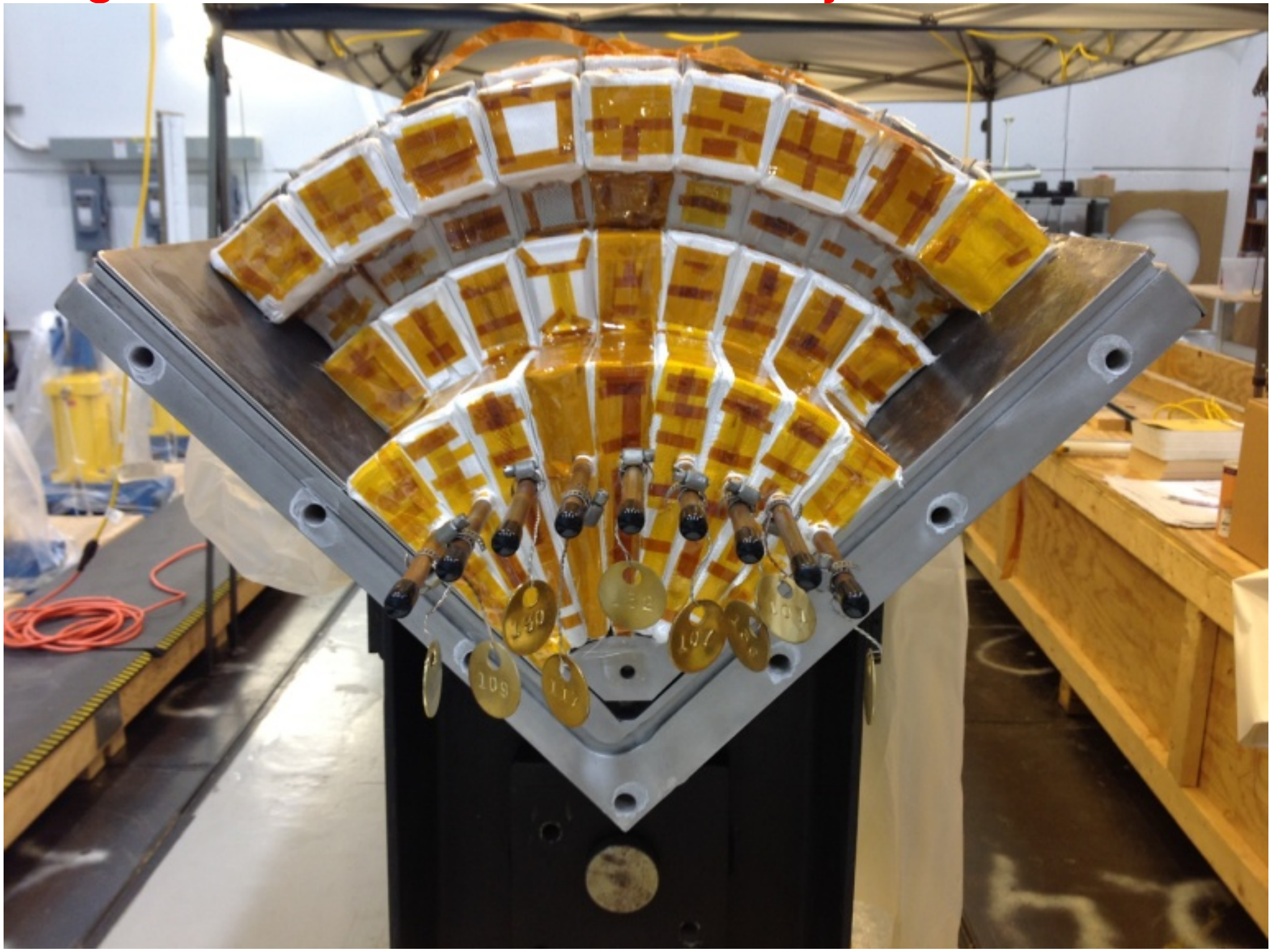


- **TF Flex-bus** - **EDM cuts from solid copper chromium zirconium block**
- **Friction stir welding enabled joining of two different copper alloys without annealing in TF lead area.**
- **Copper cooling tubes were soldered into the TF conductor assemblies using solder paste with non-ionic "R" flux (instead of Zn-Cl-based flux) .**
- **Vacuum Pressure Impregnation performed with CTD-425 (Cyanate Ester / Epoxy Blend Resin. (highly exothermic).**
- **Water soluble "Aquapour" was applied to provide 0.1" gap between TF and OH coils.**
- **Radially very thin Rogowski and magnetic sensors.**

Assembly of Inner TF Quadrants

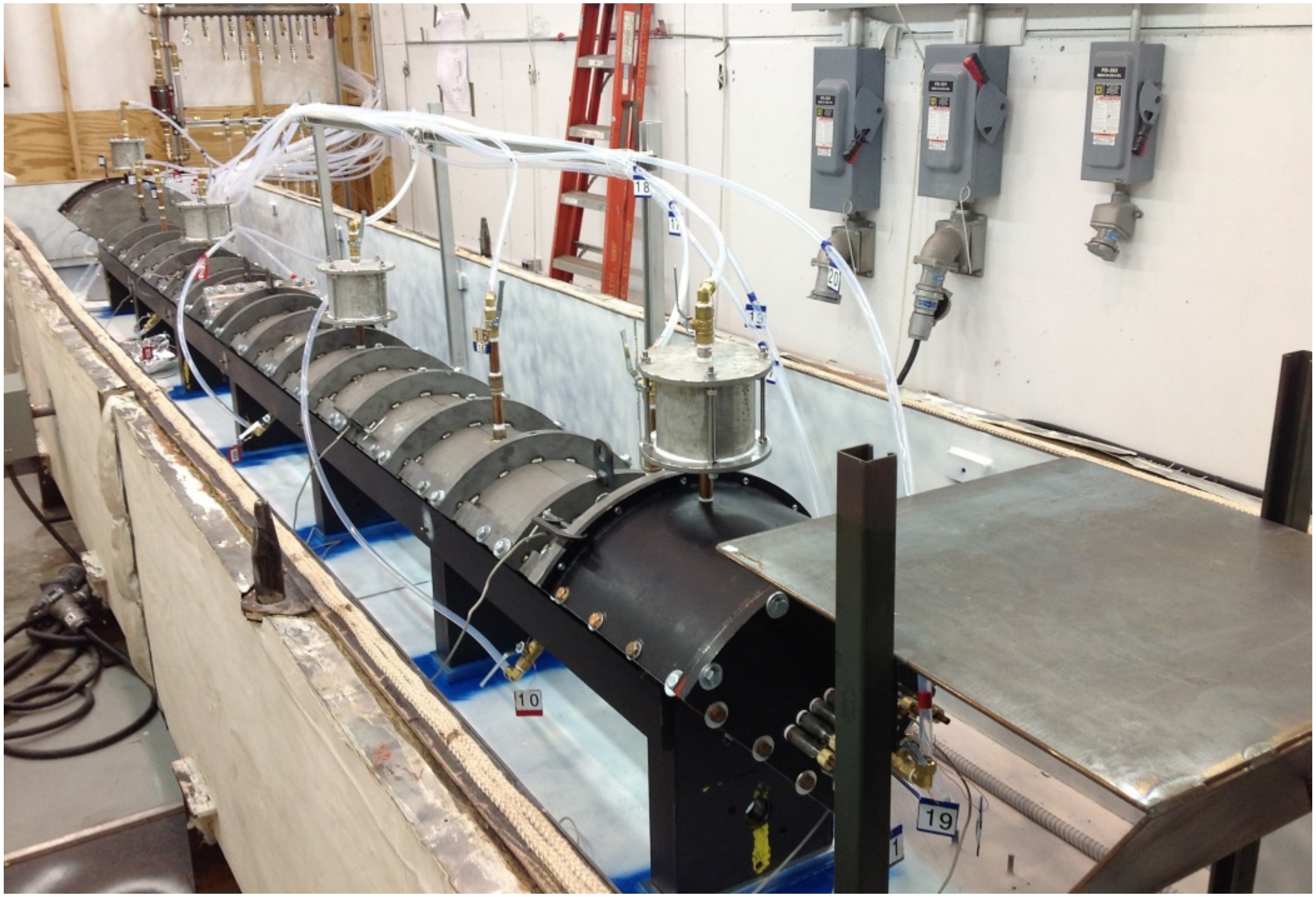
(9) individual conductors into each Quadrant mold

Quadrant manufacturing technique was used to maintain precision for the long length and relative ease of assembly



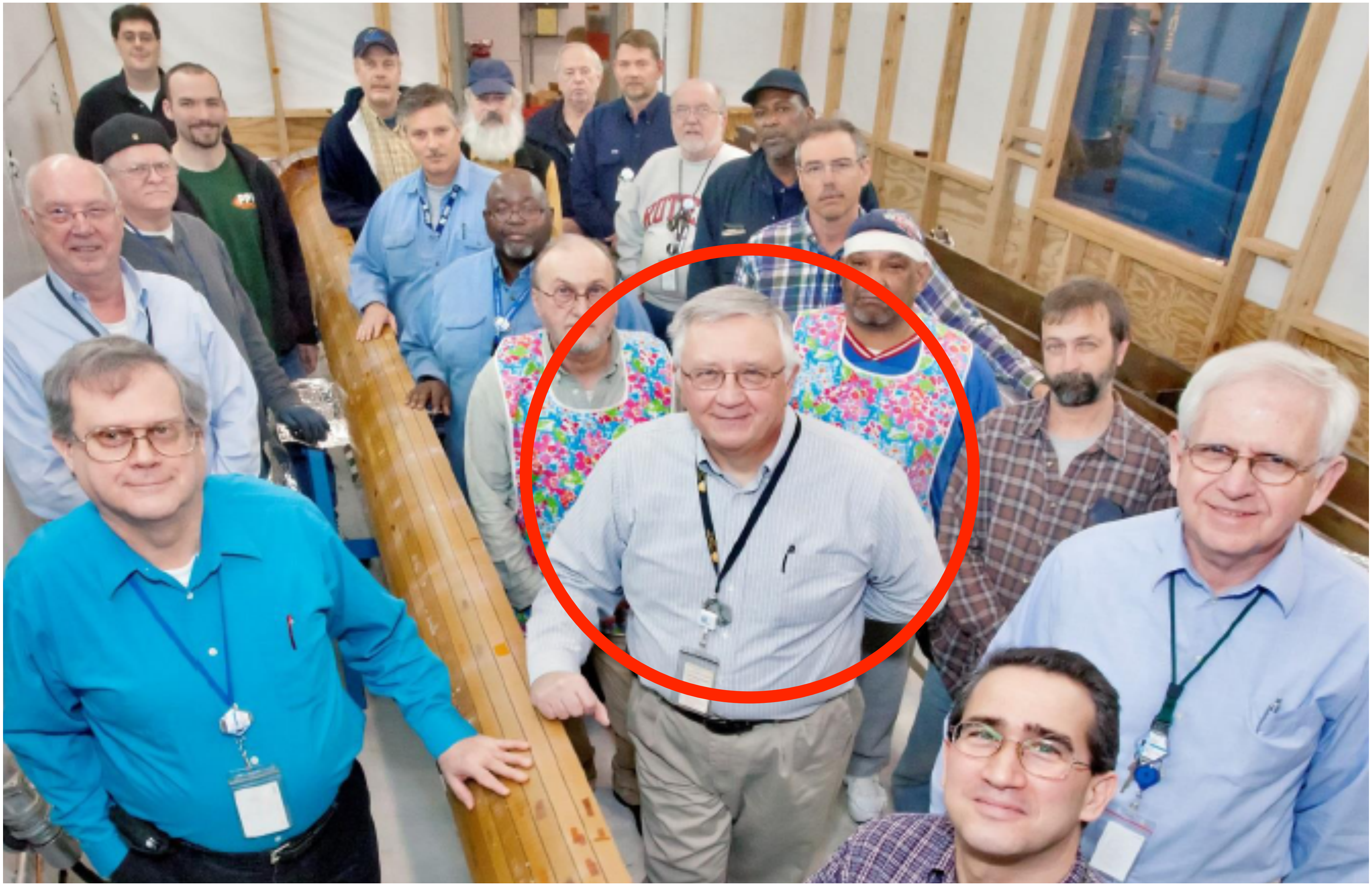
Assembled TF mold ready for Vacuum Pressure Impregnation with CTD-425 resin

This is first of six VPI operation conducted on NSTX-U. Care must be taken due to the highly exothermic nature of the Cyanate Ester / Epoxy Blend Resin. Raised temperature very slowly ~ 2 days.



Completion of First TF Quadrant
NSTX-U PPPL Magnet Fabrication Team

Much thanks to Jim Chrzanowski for 40 years of pioneering fusion magnet manufacturing



The quadrants assembled with S-2 glass tape between layers & pre-insulated G-10 core

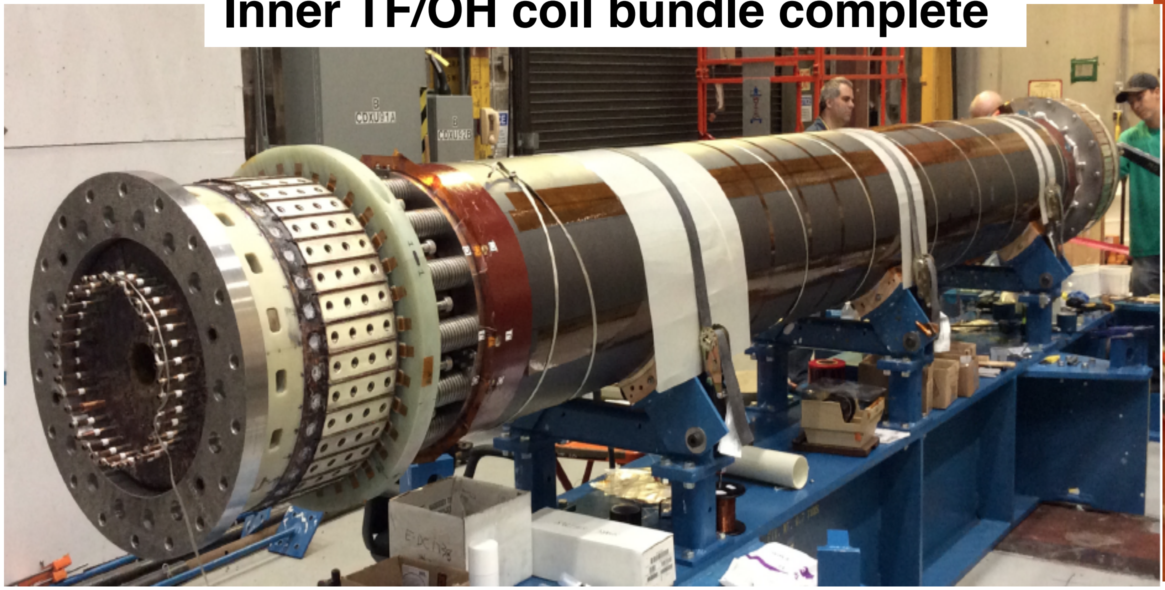
Full TF Bundle in oven after successful VPI

A movie of OH coil winding at PPPL

Center-stack Components Fabricated
Center-stack assembly complete

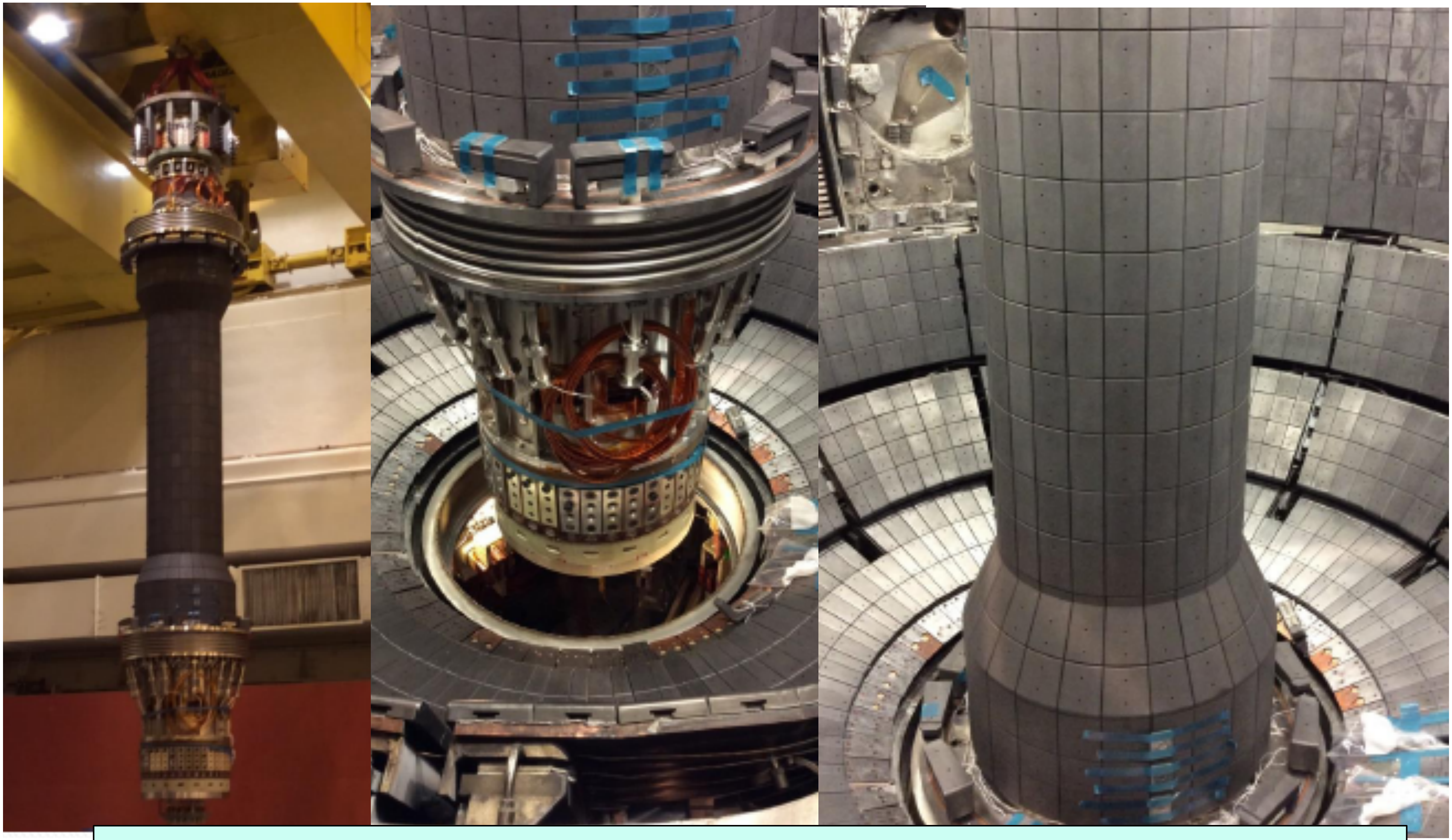
Vacuum Pressure Impregnation of OH Complete

Inner TF/OH coil bundle complete



CS casing installed over the TF/OH coil bundle

New Center-Stack Installed In NSTX-U (October 24, 2014)



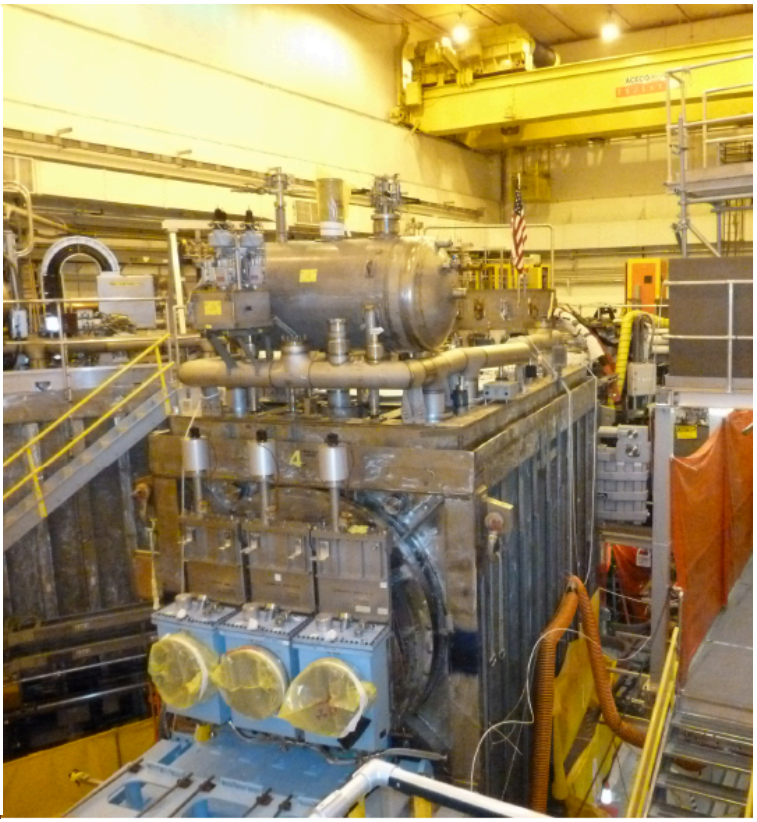
First plasma scheduled in Mar. 2015 and research operation in May 2015.

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

TFTR NBI beam box / components successfully tritium decontaminated.

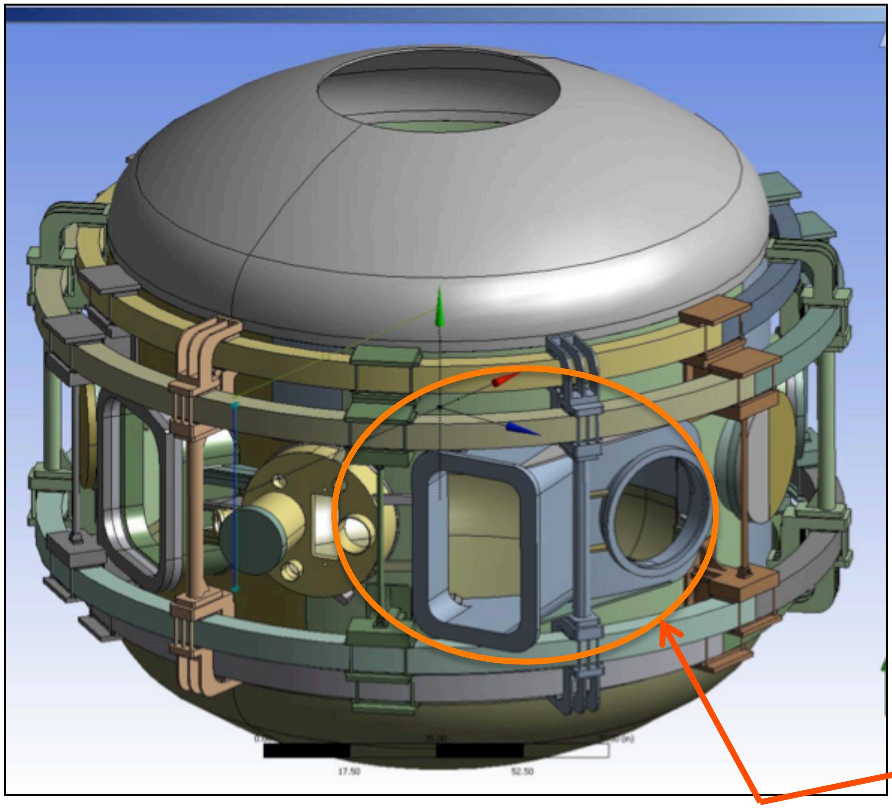
Beam Box being lifted over NSTX

Beam Box placed in its final location and aligned



Beam Box being populated with components

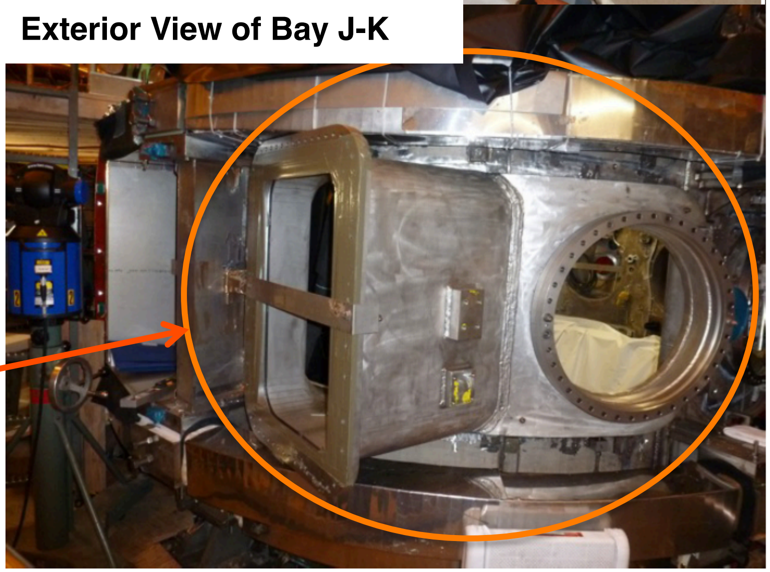
Highly Tangential 2nd NBI Enabled by JK-Cap
Outer Wall Radius Moved Outward to Avoid Beam Clipping



JK cap

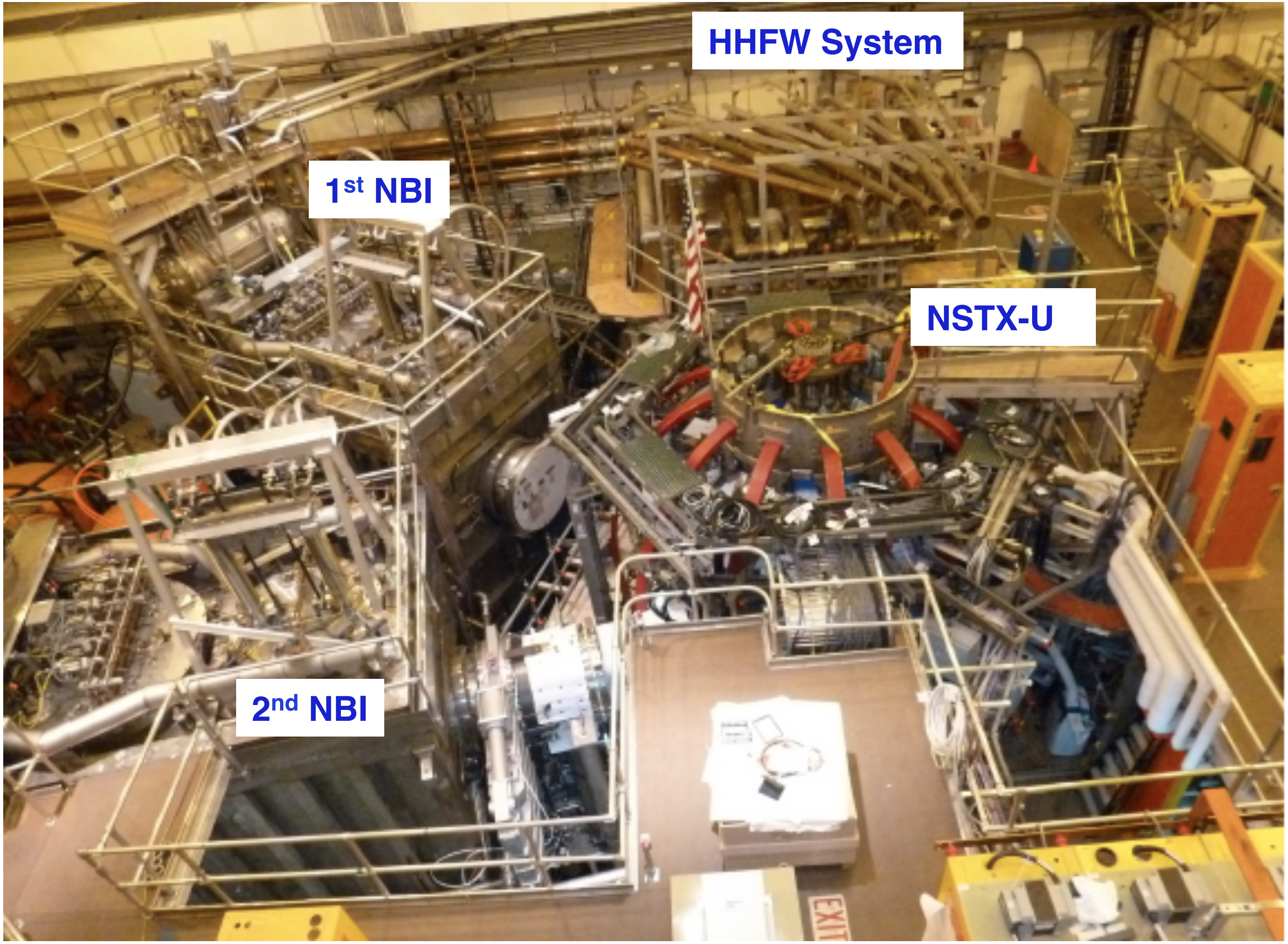
Interior View of Bay J-K

Exterior View of Bay J-K



NSTX Upgrade Project Is Nearly Complete

Recent aerial view of NSTX-U Test Cell (Oct. 27, 2014)



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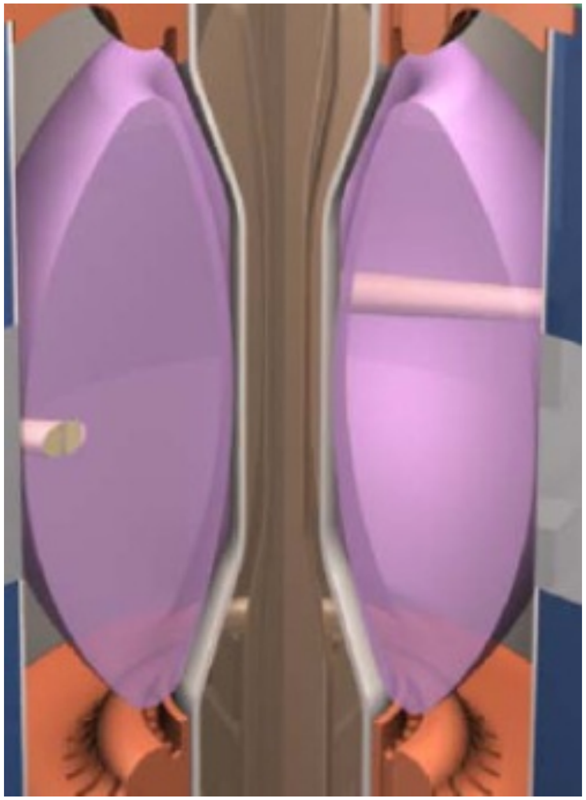
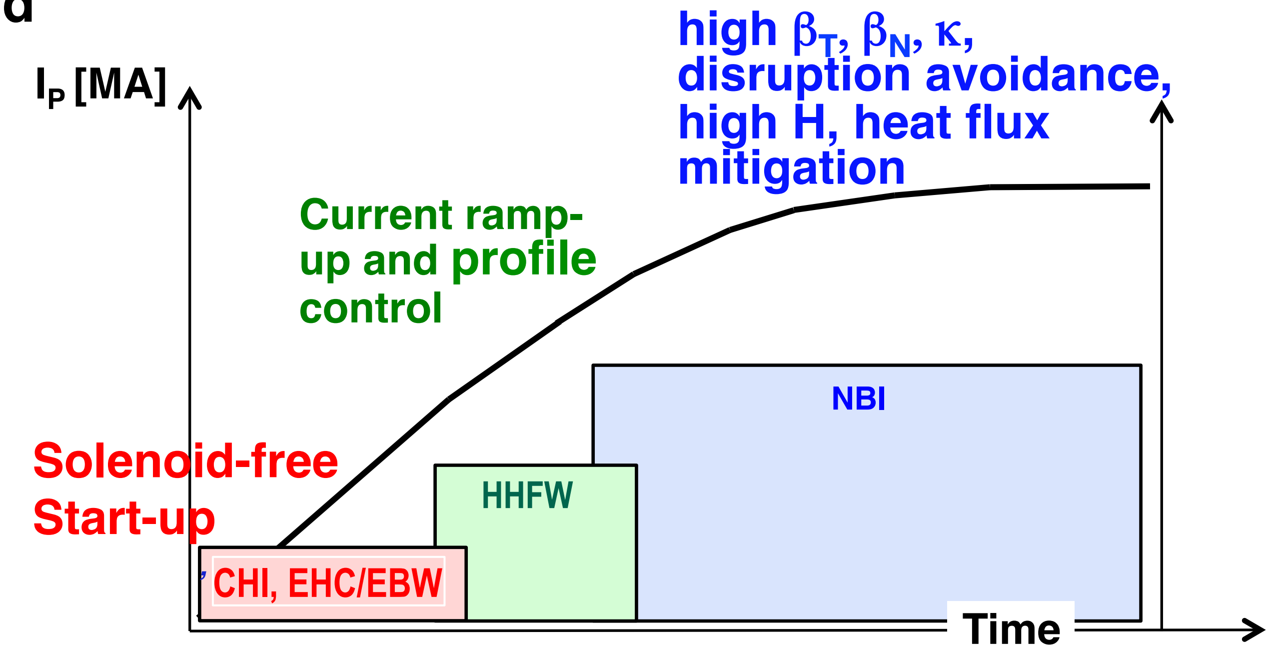
NSTX-U Addressing Critical Issues for FNSF Solenoid-free high beta operation

Compact ST-FNSF has no/small central solenoid



~ 1-2 MA of solenoid-free start-up current needed for FNSF

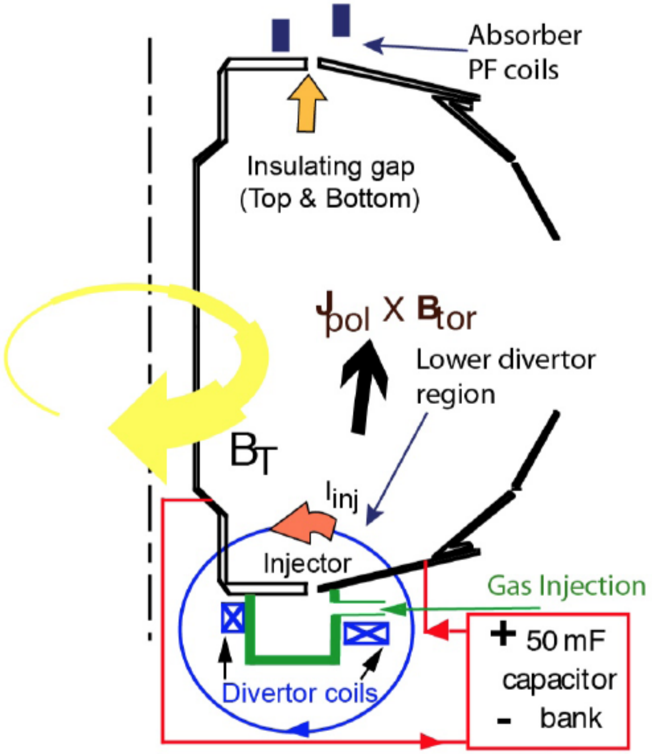
ST-FNSF Scenarios to be tested in NSTX-U

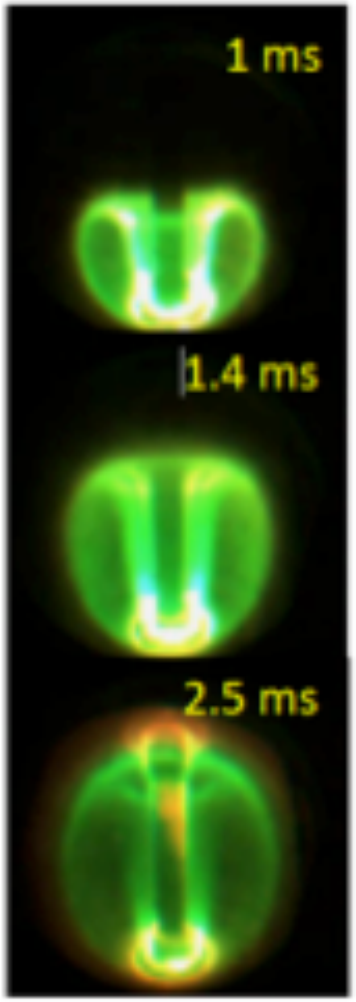


- Tools are in place in NSTX-U to test:
  - Coaxial Helicity Injection for start-up
  - HHFW for current ramp-up
  - NBI for 100 % non-inductive operation
  - Advanced divertor for heat flux mitigation

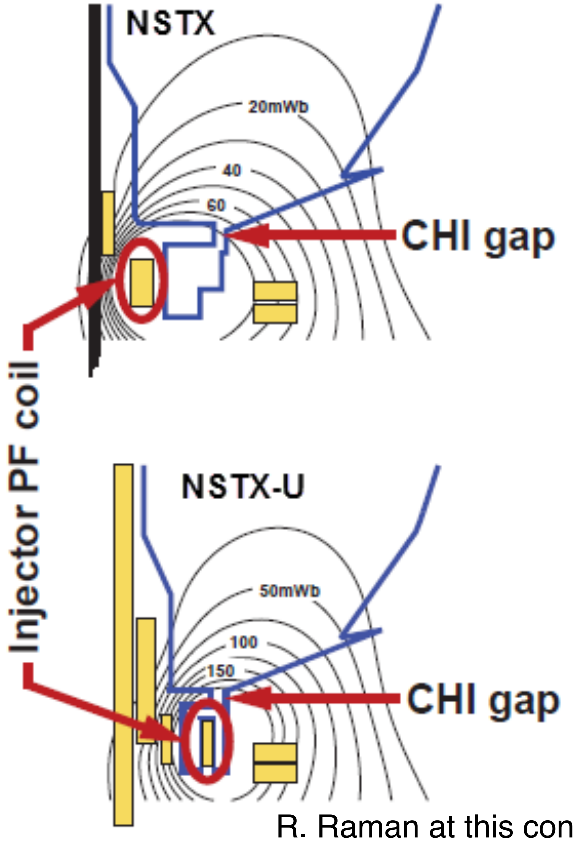
Helicity Injection Is an Efficient Method for Current Initiation
FNSF needs ~ 1-2 MA of start-up current

CHI achieved solenoid-free 160 kA ST plasma in NSTX





Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports ~ 0.4 MA current

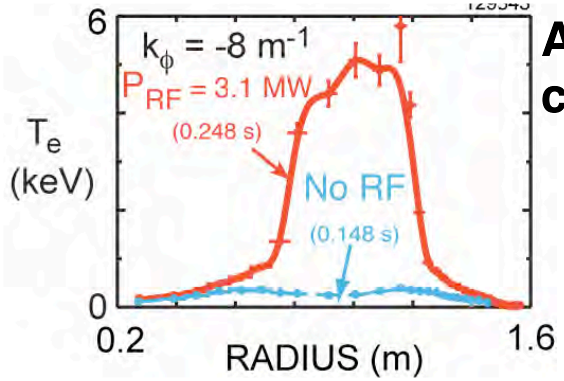


R. Raman at this conference

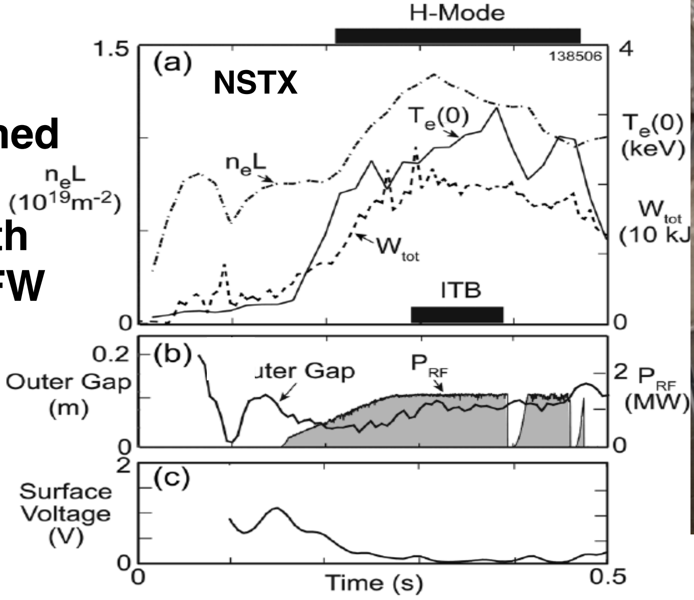
CHI projects to achieve ~0.4 MA of start-up current in NSTX-U

Current Ramp-Up with HHFW for FNSF
Up to Ip level sufficient for NBI heating and CD

Efficient HHFW electron heating due to high β_e achieved in NSTX.



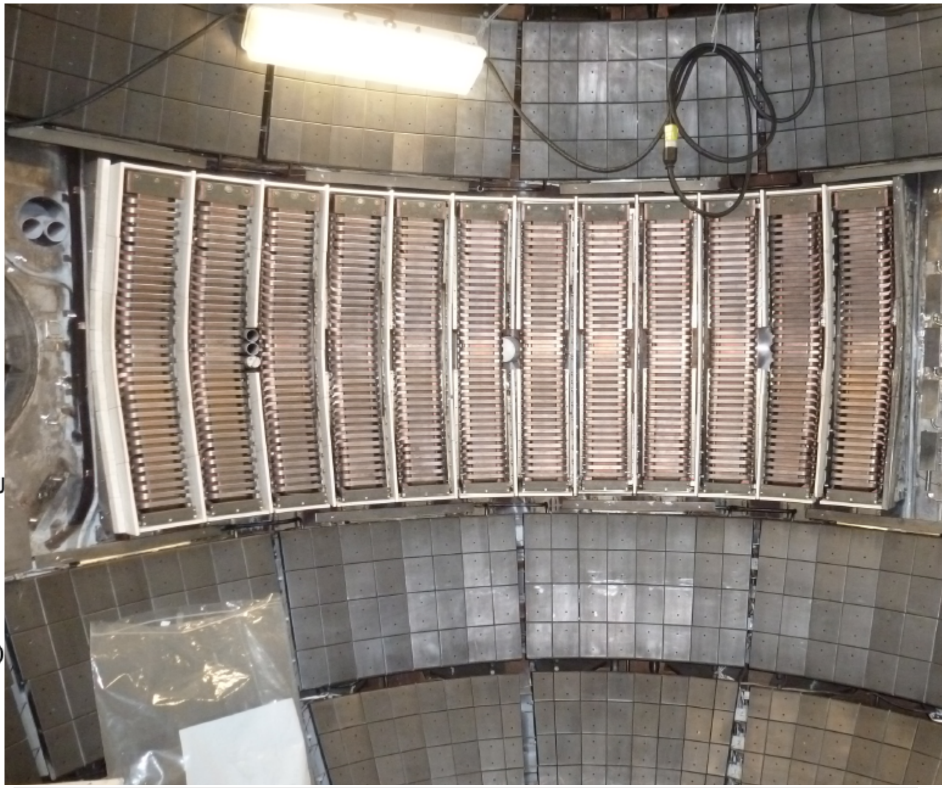
Near sustained discharges obtained with modest HHFW power.



G. Taylor et al., PoP (2010), (2012)

HHFW current ramp-up will be tested in NSTX-U at higher power ~ 4 MW.

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

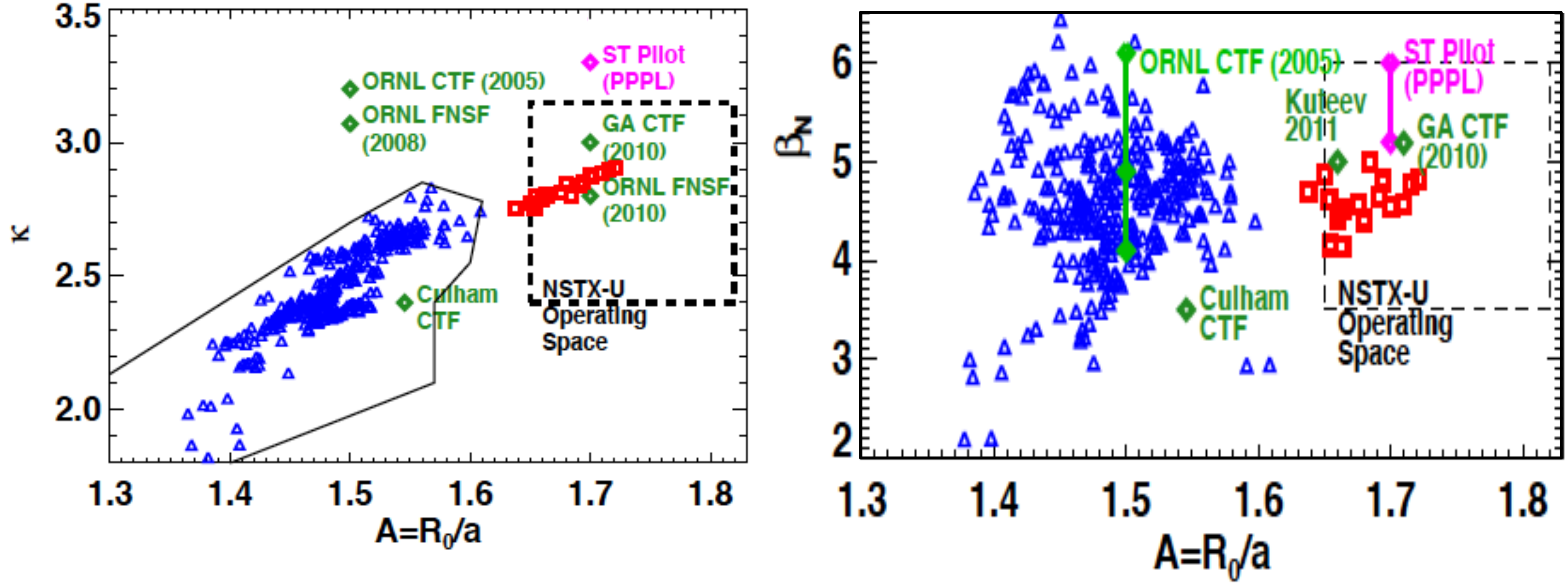


- **Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.**

NSTX has accessed A, β_N, κ needed for ST-based FNSF

Requires $f_{BS} \geq 50\%$ for plasma sustainment

$$f_{BS} \equiv I_{BS} / I_p = C_{BS}\, \beta_p / A^{0.5} = (C_{BS}/20)\, A^{0.5}\, q^*\, \beta_N \;\propto A^{-0.5}\, (1+\kappa^2)\, \beta_N^2 / \beta_T$$

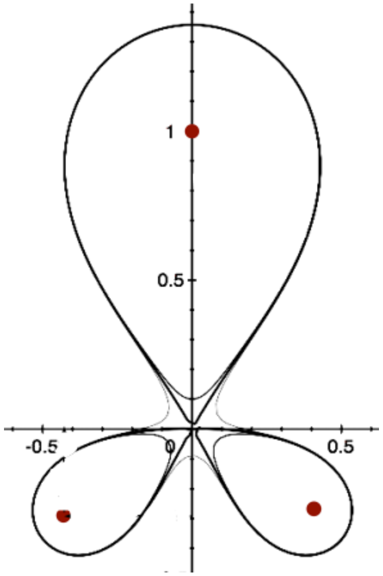


S.P. Gerhardt et al., NF (2011)

- NSTX achieved f_{BS} ~ 50% and f_{NI} ~ 65-70% with beams.
- NSTX-U expects to achieve f_{NI} ~100% with the more tangential (~ x1.5- 2 more current drive efficient) NBI.

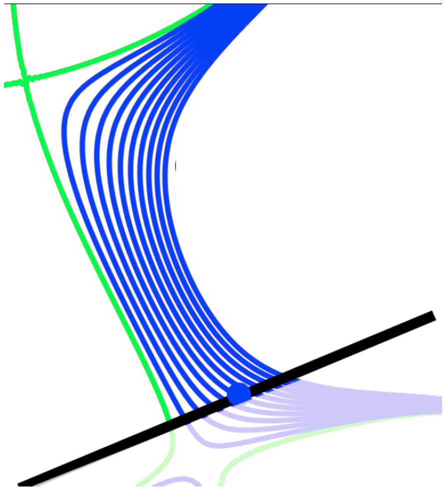
Divertor flux expansion of ~ 50 achieved with Snow Flake Divertor with large heat flux reduction in NSTX

Snow-flake



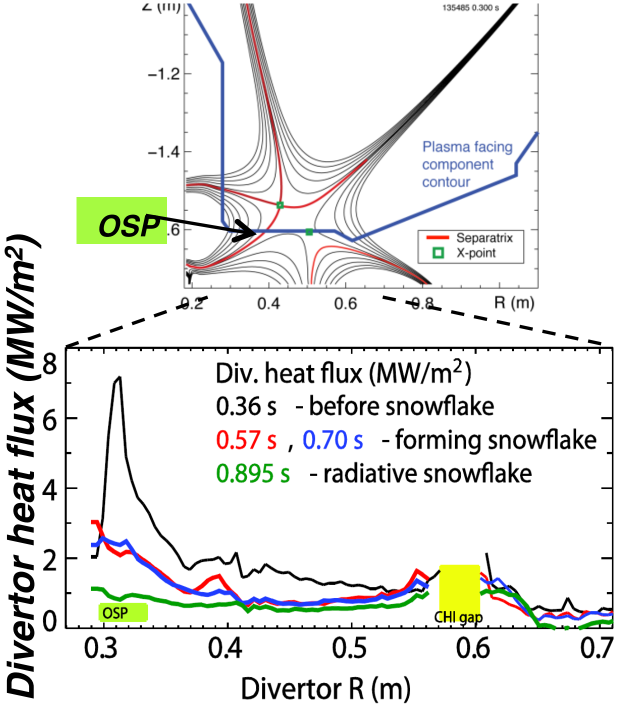
D. Ryutov, et al., PoP (2007)

X-Divertor: CREST



P.M. Valanju, et al., PoP (2009).

Snowflake divertor in NSTX



V. A. Soukhanovskii et al., PoP (2012)

NSTX-U will investigate novel divertor heat flux mitigation concepts needed for FNSF and Demo.

- **Up-and-down symmetric Snow Flake / x-Divertors**
- **Lithium + high-z metal PFCs**

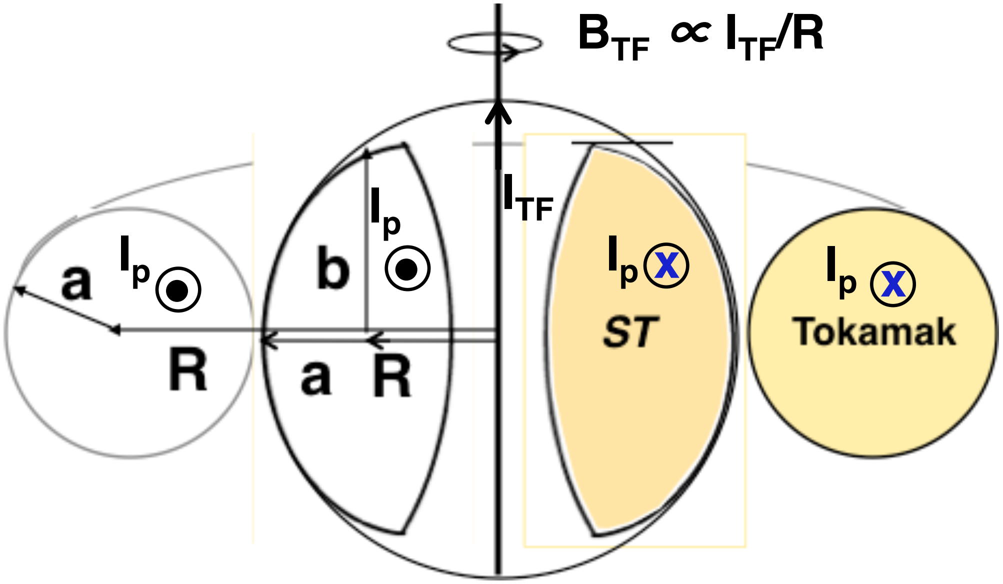
Summary of NSTX-U

- NSTX-U's main mission is to establish basis for FNSF while providing data for ITER operation and PMI solutions.
- Unique ST features include high beta and compact geometry which would be suitable for compact FNSFs.
- ST-FNSF can be compact, low tritium consumption, and lower cost, satisfying the FSNF criteria of Abdou report.
- With new center-stack and 2nd tangential NBI, NSTX-U plans to demonstrate 100% non-inductive operation at high beta needed for FSNF.
- The new center-stack was completed and installed in NSTX-U. The pump down is planned this month.
- 2nd NBI is nearly complete and the commissioning is planned in Jan. 2015.
- NSTX-U plan to have the first plasma in Mar. 2015 and commence research operation in May 2015.

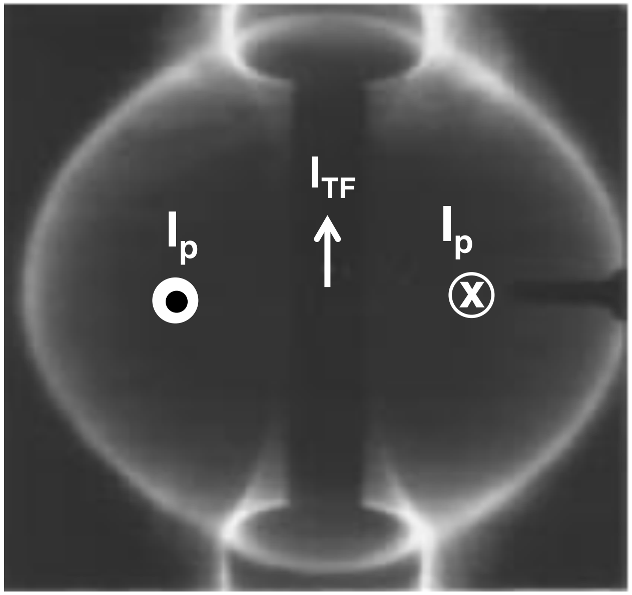
Back-up Slides

ST is a low aspect ratio tokamak with A < 2
Natural elongation makes its spherical appearance

Aspect Ratio A = R/a | ***Elongation $\kappa = b/a$*** | **“natural” = “without active shaping”**



Camera image from START



A. Sykes, et al., Nucl. Fusion (1999).

Note: ST differs from FRC, spheromak due to B_{TF}

Y-K.M. Peng, D.J. Strickler, NF (1986)

ST can be compact, high beta, and high confinement

Higher elongation κ and low A lead to higher I_p, β_T and τ_E

Aspect Ratio $A = R/a$

Elongation $\kappa = b/a$

Toroidal Beta $\beta_T = \langle p \rangle / (B_{T0}^2 / 2\mu_0)$

- **ST has high Ip due to high κ and low A**

$$I_p \sim I_{TF} (1 + \kappa^2) / (2 A^2 q^*)$$

S. Jardin et al., FS&T (2003)

- **Ip increases tokamak performance**

$$\tau_E \propto I_p$$

$$\beta_T \equiv \beta_N I_p / (aB_{T0})$$

- **ST can achieve high performance cost effectively**

$I_p \sim I_{TF}$ **for ST due to low A and high κ**

⇧

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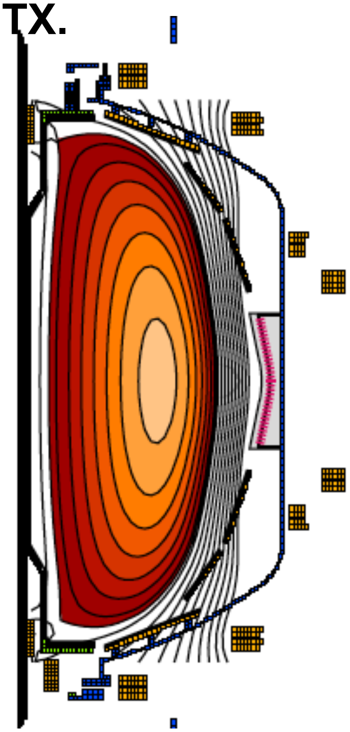
High κ ~ 3.0 equilibrium in NSTX.



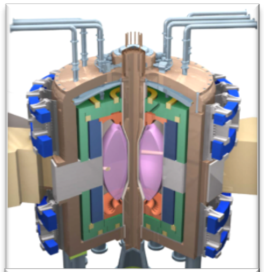
D.A. Gates et al., NF (2007).

Fusion needs FNSF(s) (modest cost, low T, and reliable) to Test and Qualify Fusion Components

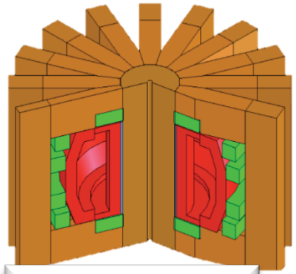
Fusion needs to develop reliable/qualified components which are unique to fusion:

- Divertor/PFC
- Blanket and Integral First Wall
- Tritium Fuel Cycle
- Remote Maintenance Components
- Advanced Power Generation

FNSFs



FNSF-ST



FNSF-AT

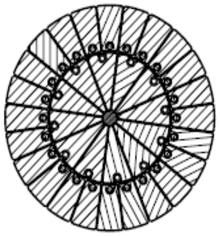
- **Without R&D, fusion components could fail prematurely which often requires long repair/down time. This would cripple the DEMO operation.**
- **FNSF can help develop reliable fusion components.**
- **Such FNSF facilities must be modest cost, low T, and reliable.**

If the cost of volume neutron source (FNSF) facility is "modest" << ITER, DEMO, it becomes highly attractive development step in fusion energy research. M.A. Abdou, et al., FTS (1996)

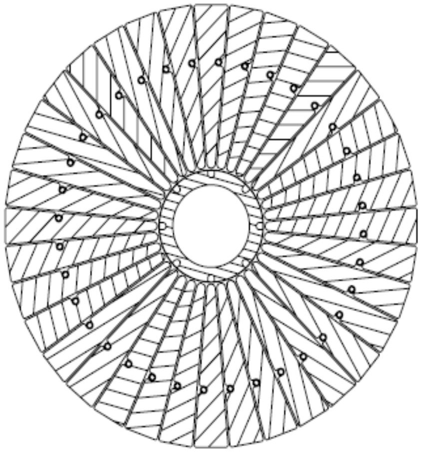
Inner TF Bundle Comparisons- Physical

Description	Present Design	Upgrade Design
Operating Current	1013 volts	1013 volts
Number of Turns	36	36
Number of Layers	Double	Single
Cooling	water	water
Maximum T/T Voltage stress	970 volts	28 volts
Maximum T/T voltage/mil	14.9 volts/ mil	0.432 volts /mil
Maximum volt/mil across leads	14.9 volts/mil	9.65 volts/mil
Turn to Turn Insulation thickness	0.0648 inch	0.0648 inch
Groundwrap insulation thickness	0.054 inch	0.222 inch
Insulation Scheme	B-stage (Pre-preg)	Vacuum Pressure Impregnation
Outside Diameter	7.866 inch	15.572 inch
Cooling Hole Inside Diameter	0.186 inch	0.305 inch
TF Conductor material	C10700	C10700

- *TF Bundle Failure Review 9/7/2011*



- ***Current TF Bundle 7.9 inch diameter***



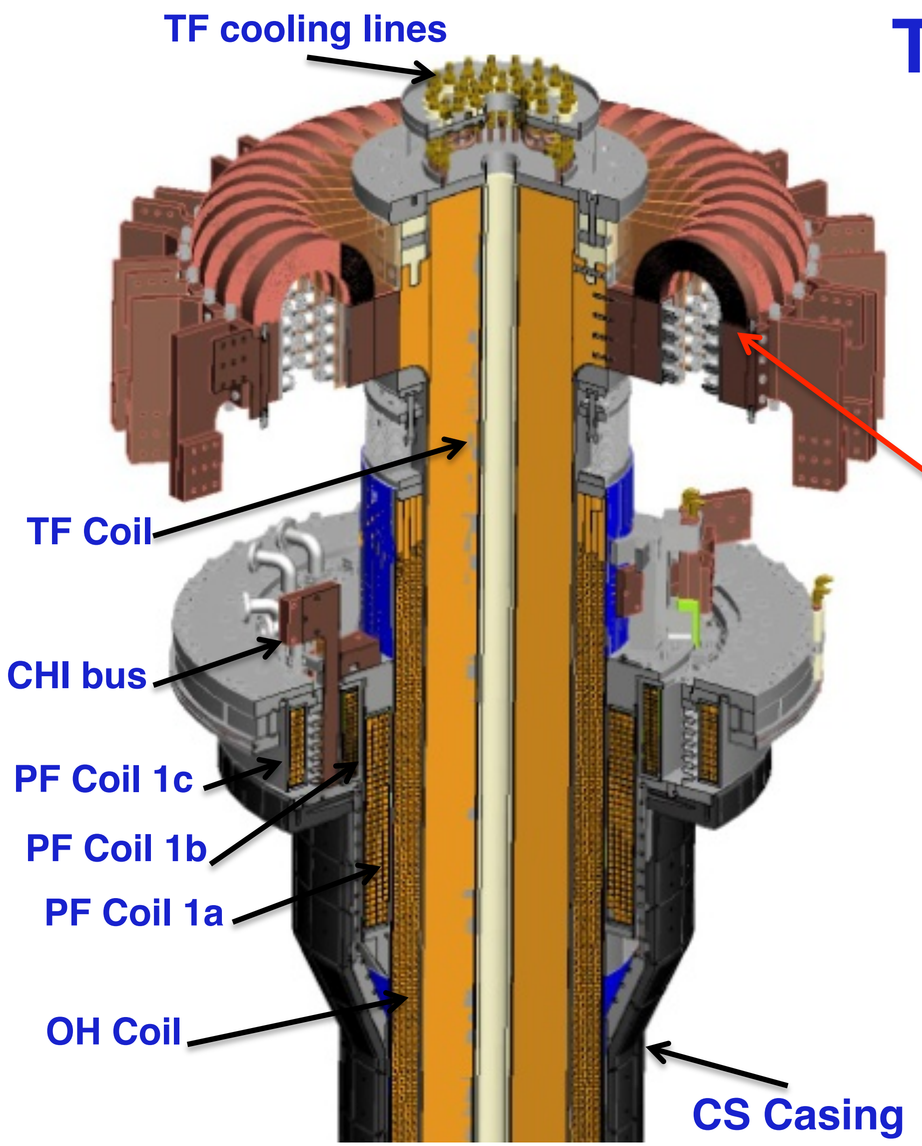
- ***Upgraded TF Bundle 15.7 inch diameter***

TF Bundle Comparisons- Materials

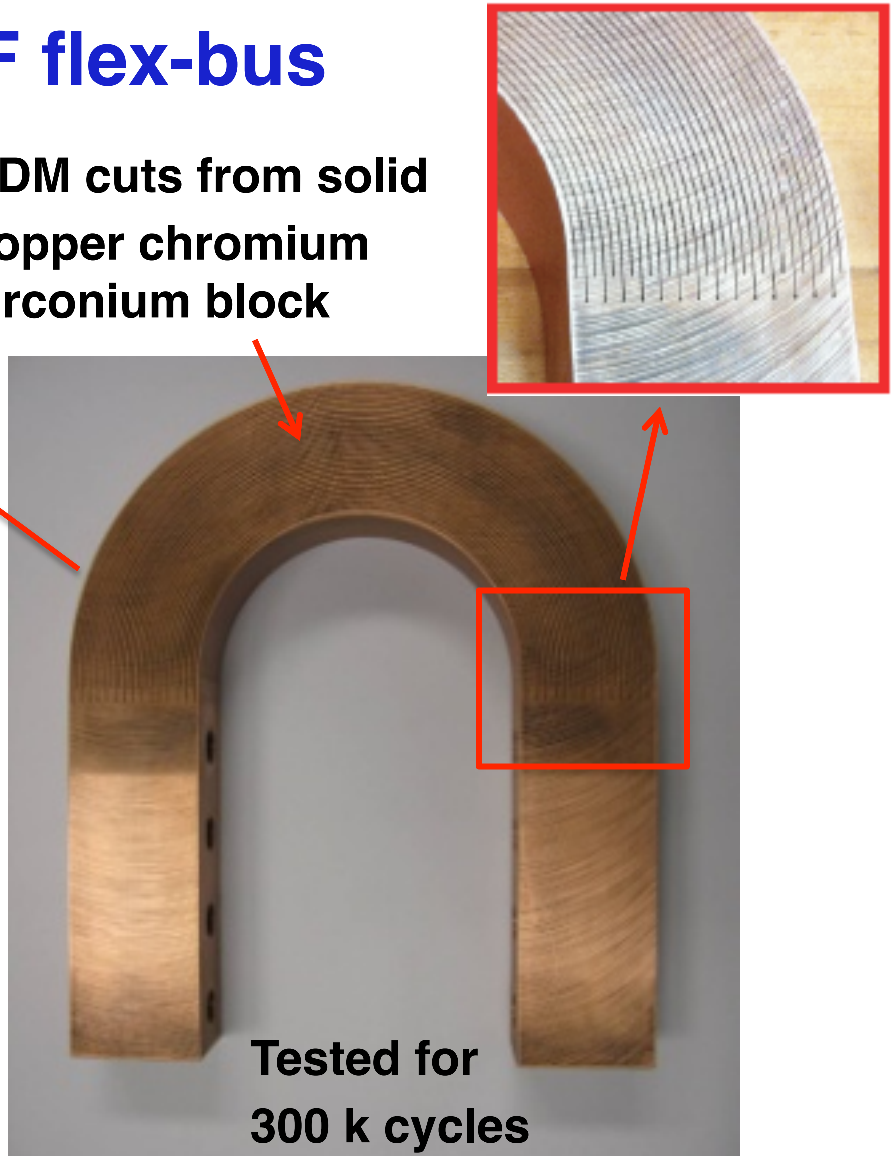
Material	Existing TF Bundle	Upgraded TF Bundle
Copper Conductor	C10700 (OFHC w/ Silver)	C10700 (OFHC w/Silver)
Primer	DZ-80 (Ciba-Geigy)	CTD-450 (Cyanate-Ester primer)
Insulation Scheme	CTD-112P B-stage tape B-stage did not have ample resin to fill all voids between conductor corners	VPI w/CTD-425 Cyanate Ester Hybrid Provides good resin fill minimizing/eliminating void areas between conductor corners
Solder	95%-5% Tin-Antimony	95%-5% Tin-Antimony
Cooling tube	ACR (0.032 inch wall)	Type K (0.035 inch wall)
Flux	“NOKORODE” Paste flux (Contains Chlorides that may of contributed to insulation failure)	Rosin Flux (Does not contain Chlorides-organic material)

- *TF Bundle Failure Review 9/7/2011*

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



TF flex-bus

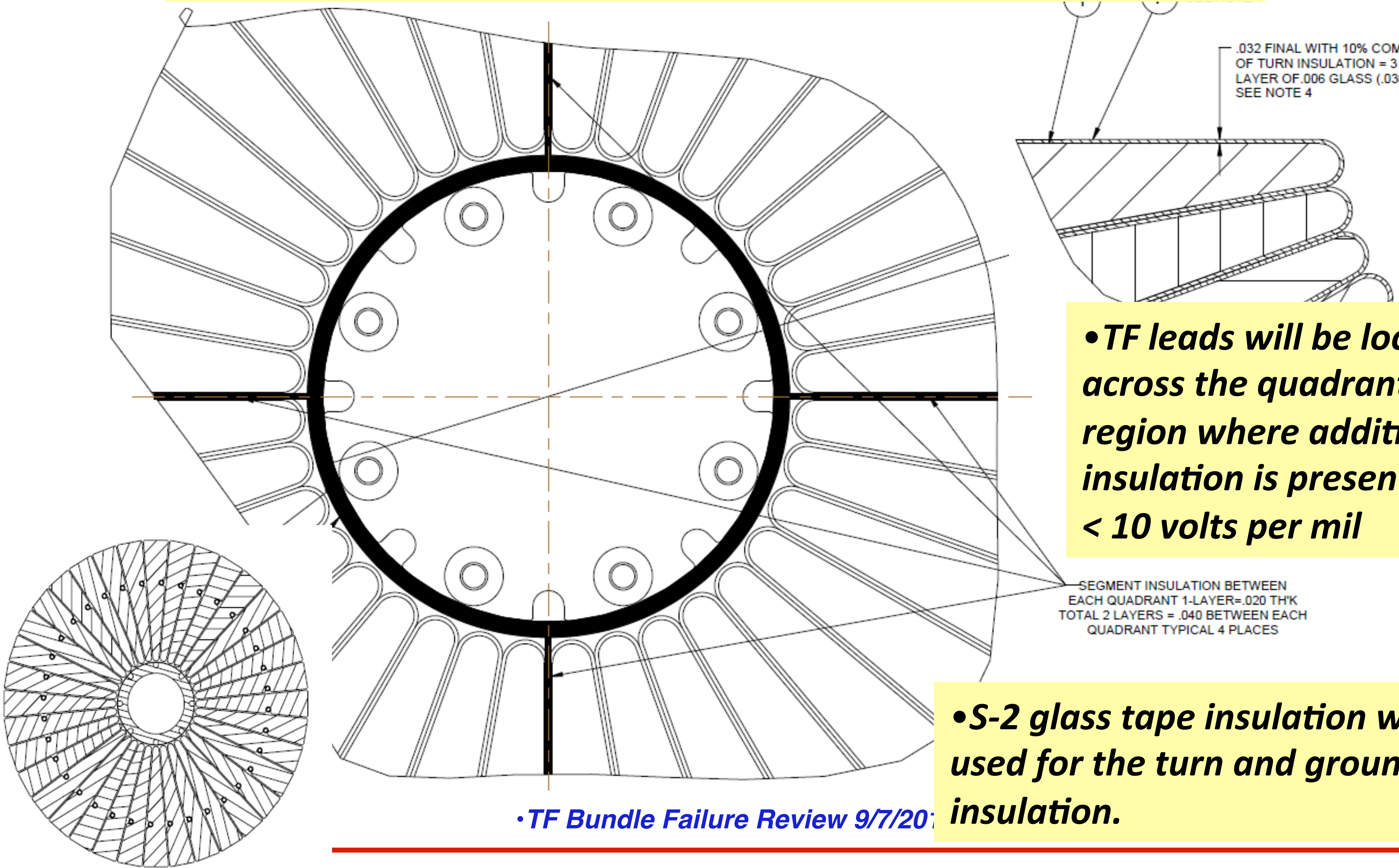


EDM cuts from solid copper chromium zirconium block

Tested for 300 k cycles

Upgrade Design- Insulation Scheme

- ***Maximum turn to turn insulation voltage <30 volts turn to turn***
- ***(< 0.5 volts per mil)***

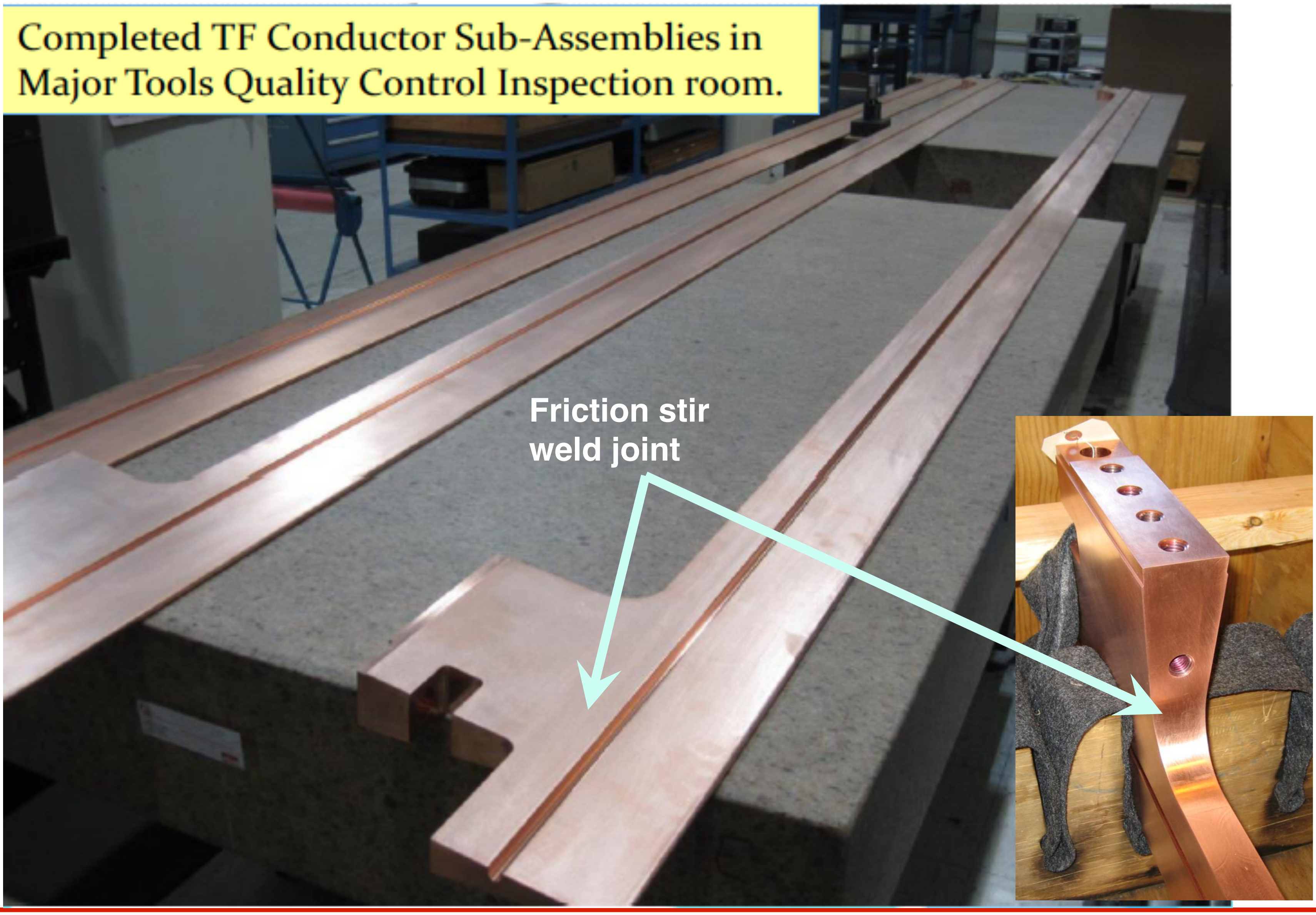


- ***TF leads will be located across the quadrant region where additional insulation is present < 10 volts per mil***

- ***S-2 glass tape insulation will be used for the turn and groundwall insulation.***

- *TF Bundle Failure Review 9/7/201*

36 TF Bars manufactured by Major Tools With innovative friction stir weld joints



Completed TF Conductor Sub-Assemblies in Major Tools Quality Control Inspection room.

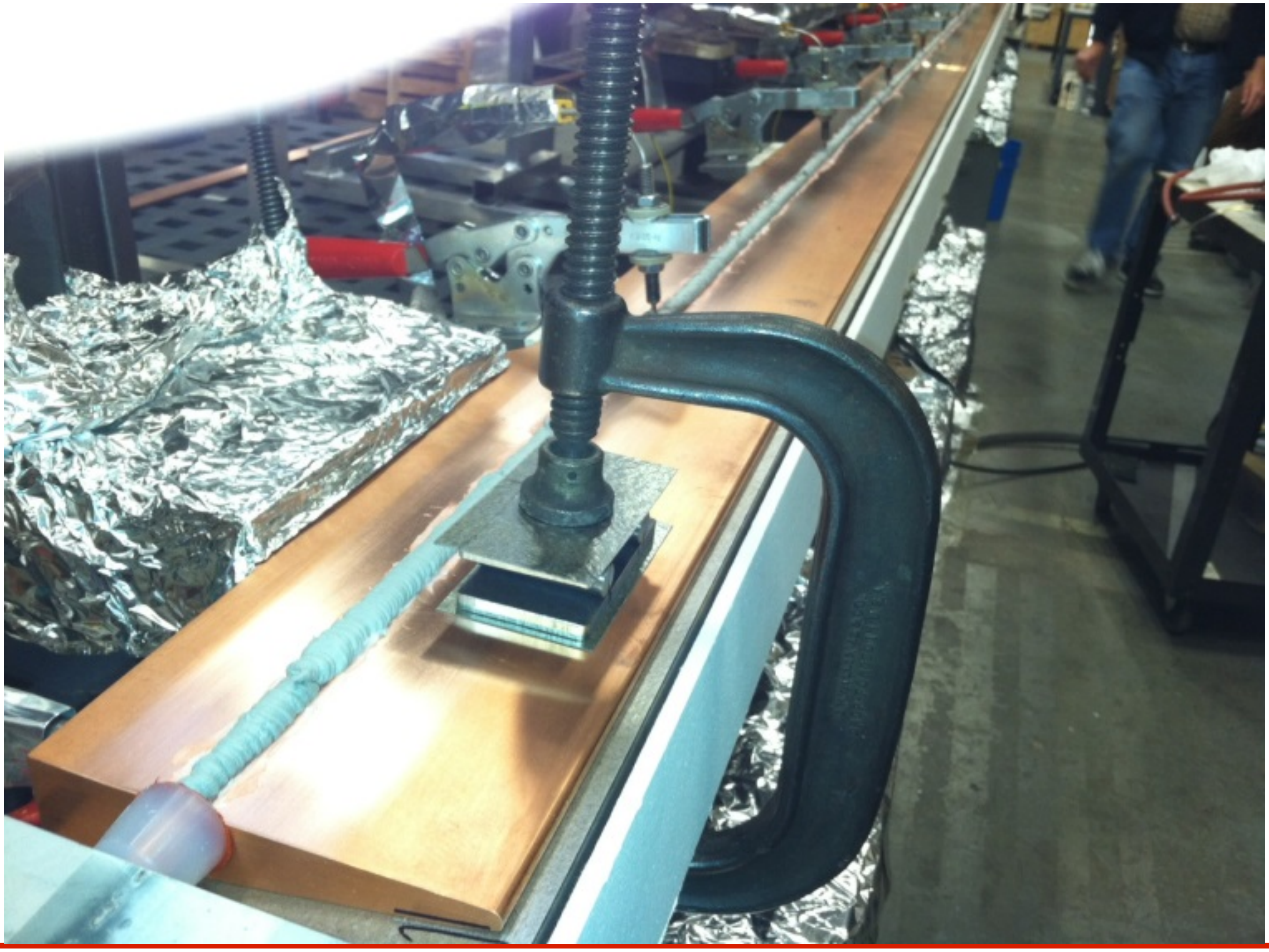
Friction stir welding enabled joining of two different copper alloys without annealing!

TF Conductor Friction Stir Welding

High strength coil leads, Copper-Chromium-Zirconium (CDA18150) were added to each end of the oxygen free silver-bearing copper conductors (CDA10700) by a process known as friction stir welding (FSW). This work was completed by Edison Welding Institute (EWI) in Columbus, Ohio

Copper cooling tubes were soldered into the TF conductor assemblies using solder paste with non-ionic "R" flux

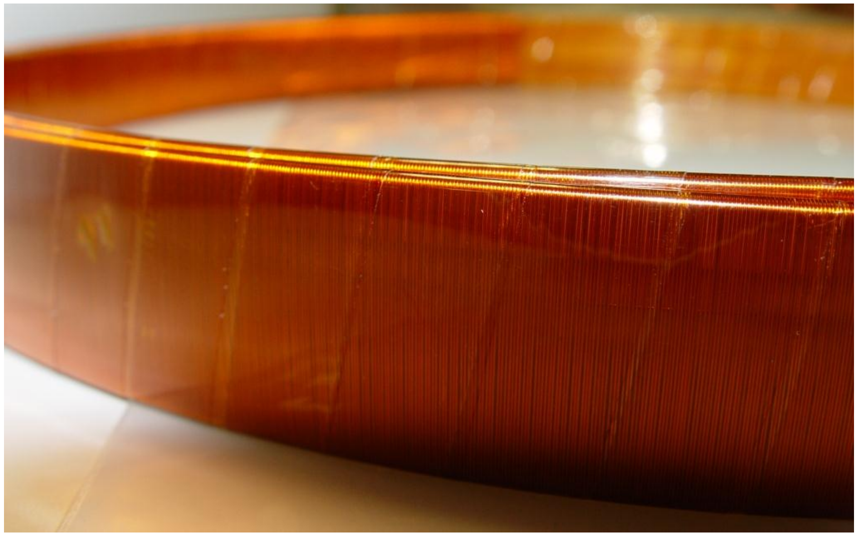
Contaminant from the flux containing Zn and Cl caused gradual insulation deterioration which led to the TF coil failure in NSTX

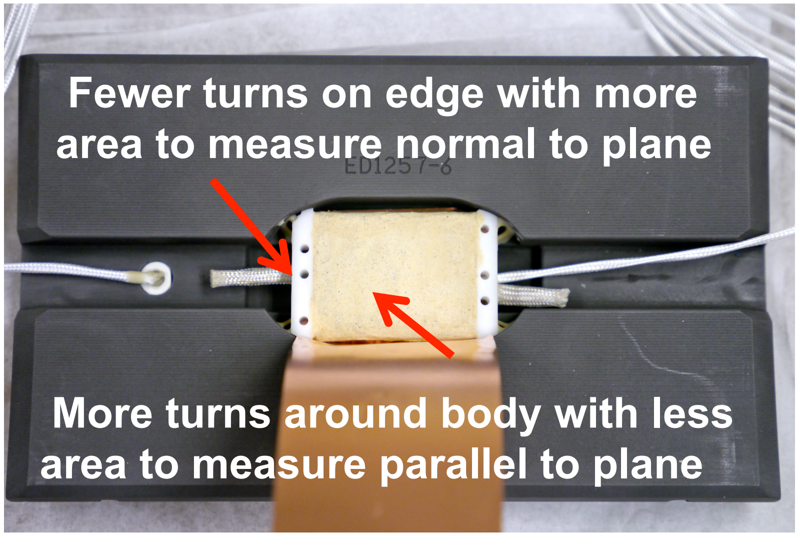


Applying S-2 Glass TF Turn Insulation

Limited Center Stack Space Requires Compact Designs for Magnetic Sensors

Maximize "gain" – wire turns x area – by flattening cross sections





Coil dimensions: 3.8 x 2.3 x 0.5 cm

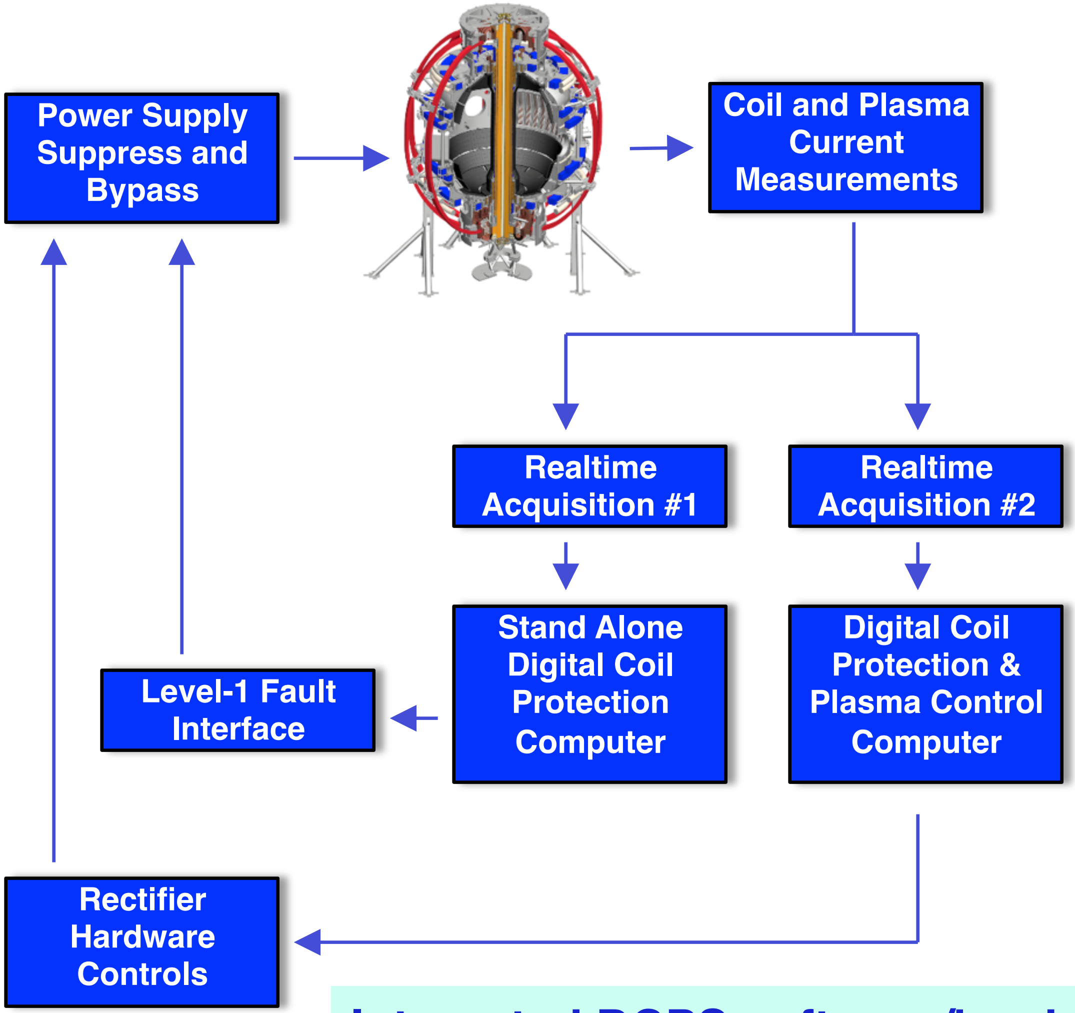
Rogowski coil for measuring plasma currents wound around thin teflon mandrel

- **30 turns of AWG 30 wire per cm**
- **Thickness kept at ~2.5 mm over ~11 m length**

Magnetic pickup coils fit in pockets in graphite plasma-facing components

- **AWG 26 copper wire around MACOR mandrel and coated with high temperature adhesive**
- **Capable for use up to 800°C**

New Digital Coil Protection System (DCPS) Provides Comprehensive Coil Protection



Power Supply Suppress and Bypass

Coil and Plasma Current Measurements

Realtime Acquisition #1

Realtime Acquisition #2

Stand Alone Digital Coil Protection Computer

Digital Coil Protection & Plasma Control Computer

Level-1 Fault Interface

Rectifier Hardware Controls

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

Integrated DCPS software/hardware testing is being performed now in anticipation of FCPC dummy load testing in December.

Formulating Strategy Toward Full NSTX-U Parameters

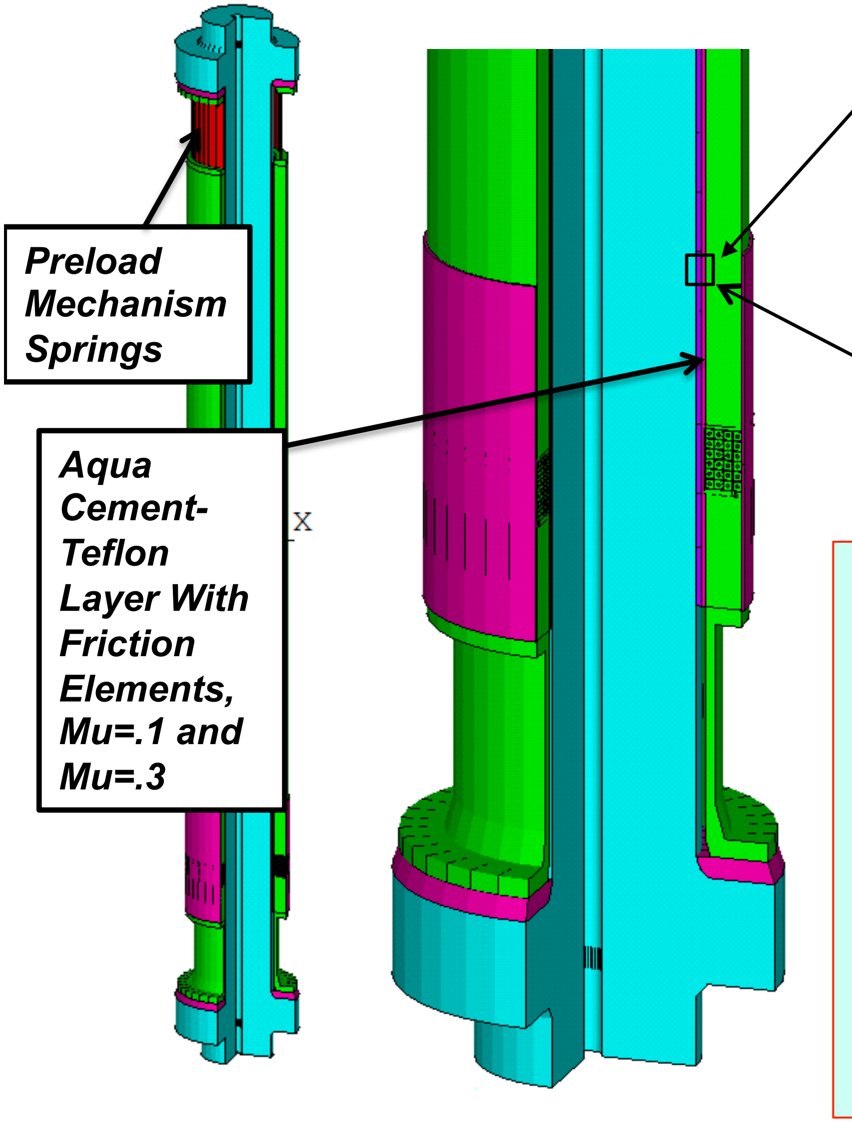
After CD-4, the plasma operation could enter quickly into new regimes

	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**

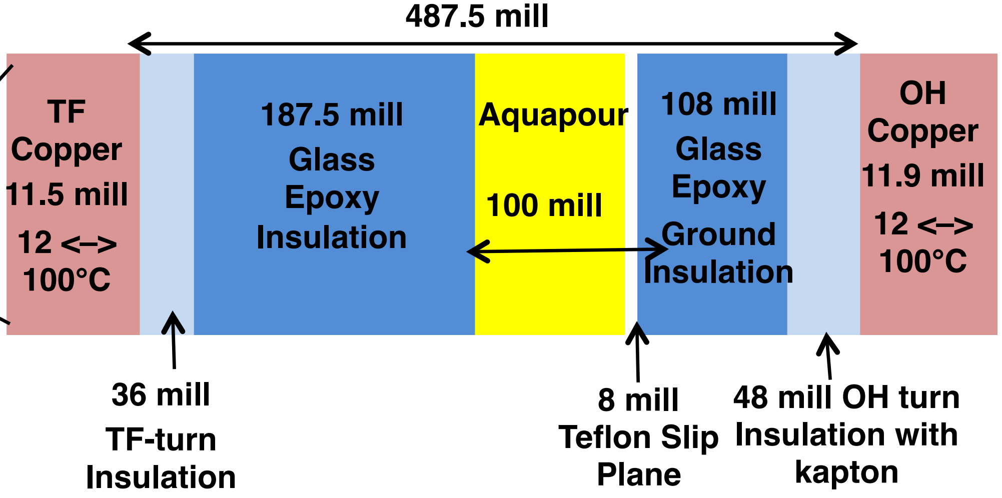
- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year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

Schematics of OH-TF bundle configuration

100 mill gap between OH and TF to provide free OH-TF operation



TF-OH Gap Details


487.5 mill

TF Copper 11.5 mill 12 <–> 100°C

187.5 mill Glass Epoxy Insulation

Aquapour 100 mill

108 mill Glass Epoxy Ground Insulation

OH Copper 11.9 mill 12 <–> 100°C

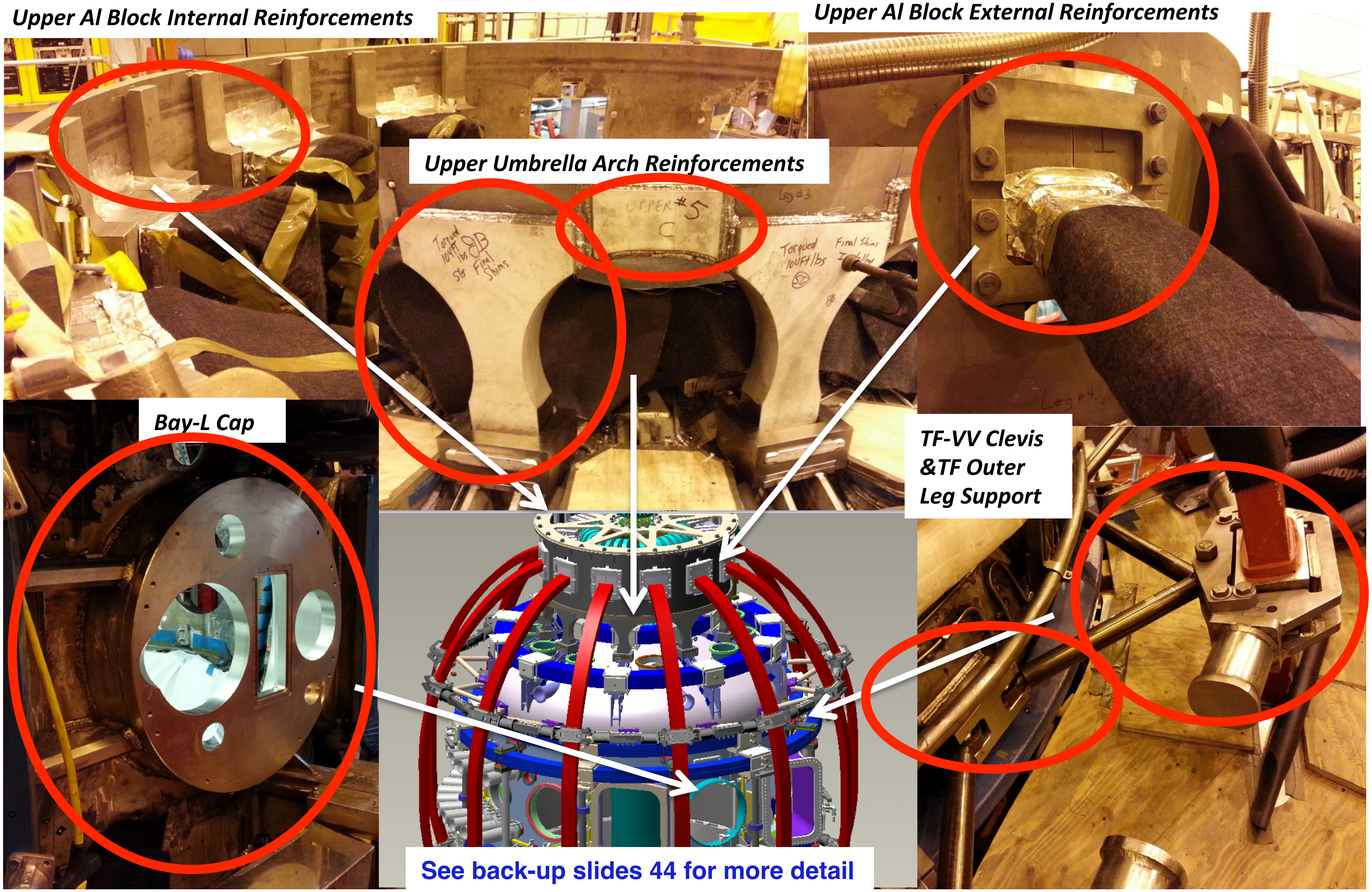
36 mill TF-turn Insulation

8 mill Teflon Slip Plane

48 mill OH turn Insulation with kapton

- Both TF and OH expand about 12 mills during the full parameter operation reaching ~ 100 °C from 12 °C.
- If TF expands more than OH, the gap region could be compressed leading to insulation stress as the TF and OH grow radially and axially.
- The full 1 T, 2 MA, 5 sec (third year) scenario maybe affected since TF temperature could exceed OH by as much 19°C which could cause insulation stress.
- Bringing the temperature gap down to 10°C range reduces the stress to acceptable range.
- This can be accomplished by pre-heating the OH with respect to TF by ~ 10°C.

Support Structural and VV Enhancements Complete
Must handle 4 x higher electromagnetic loads



Upper Al Block Internal Reinforcements

Upper Al Block External Reinforcements

Upper Umbrella Arch Reinforcements

Bay-L Cap

TF-VV Clevis &TF Outer Leg Support

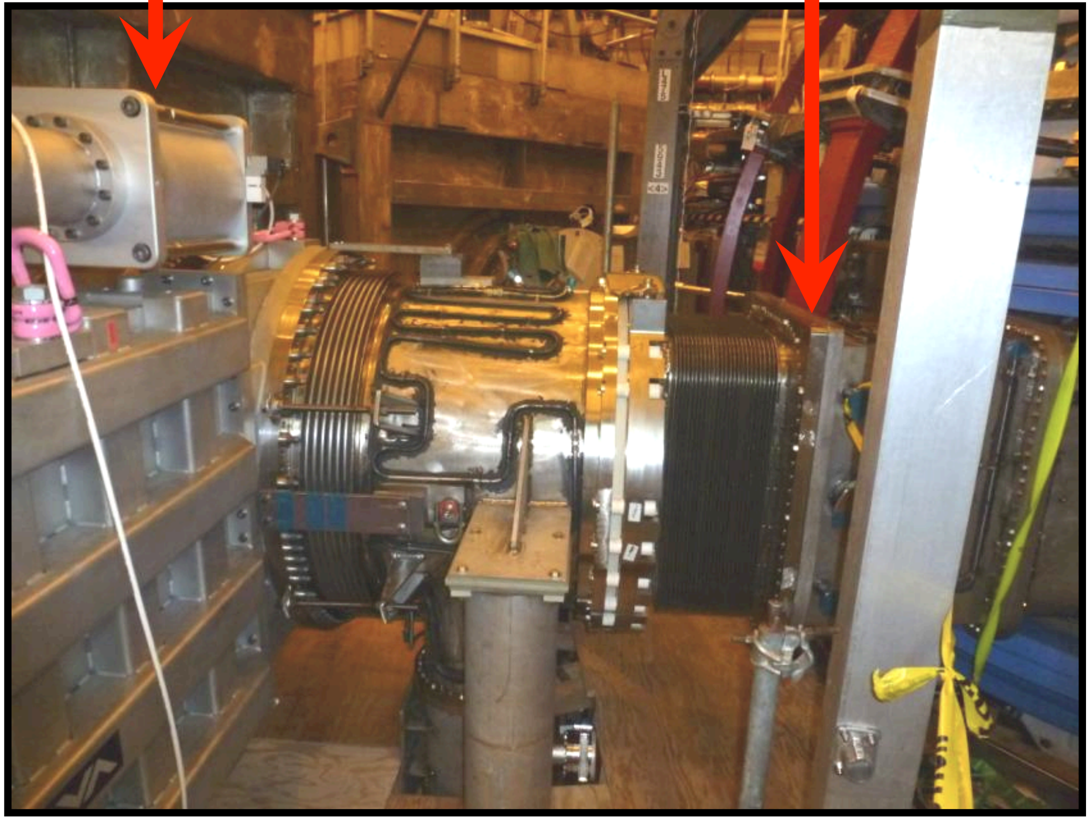
See back-up slides 44 for more detail

Final 2nd NBI Component being Installed

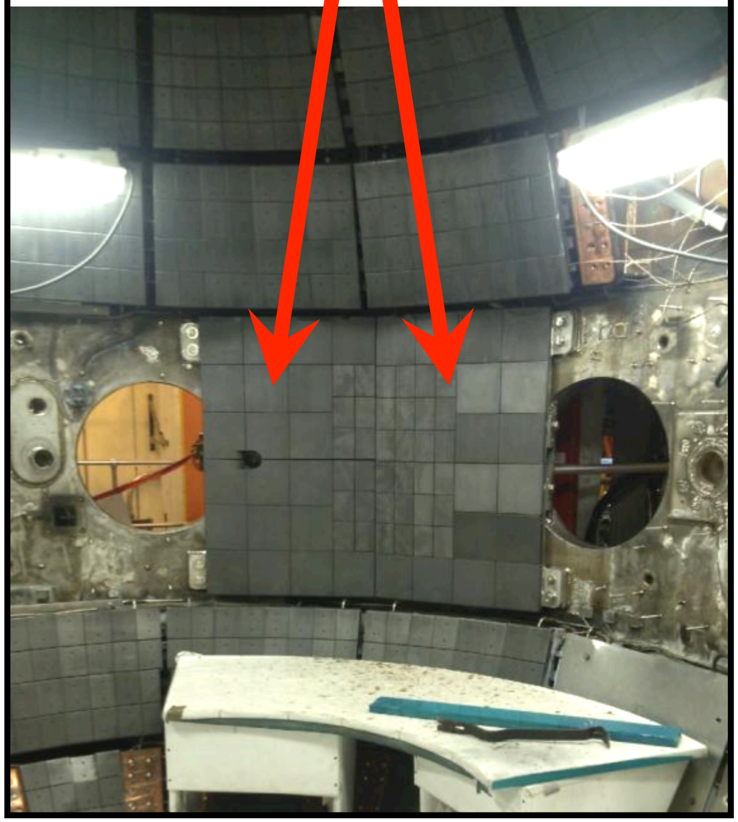
2nd NBI duct with pumping section and NBI armor installed

Neutral Beam & TIV valve

Vacuum Vessel Bay J/K port



Neutral Beam Armor Installed

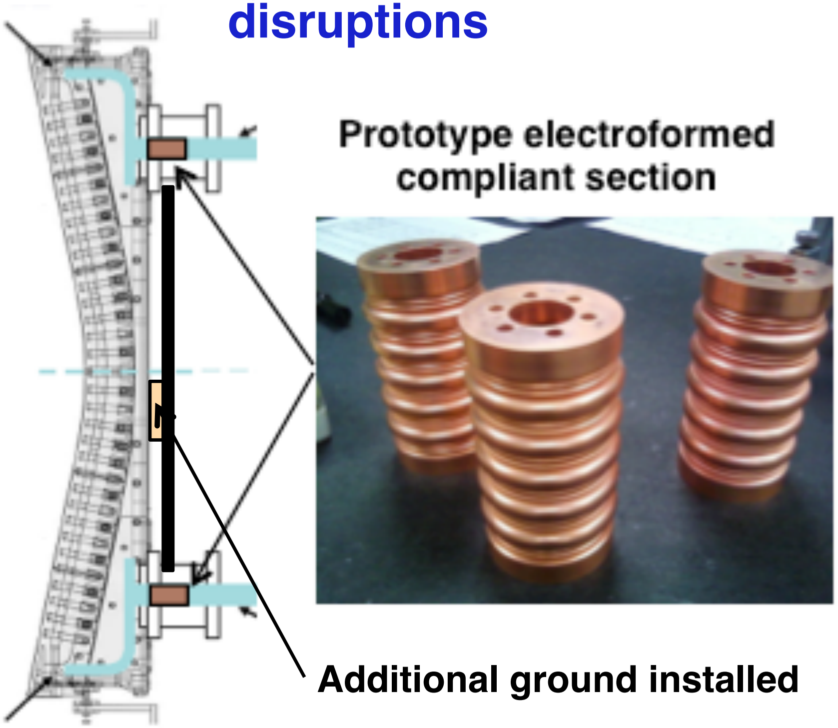


2nd NBI Commissioning planned in Jan. 2015

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

New Compliant Antenna Feeds

Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions

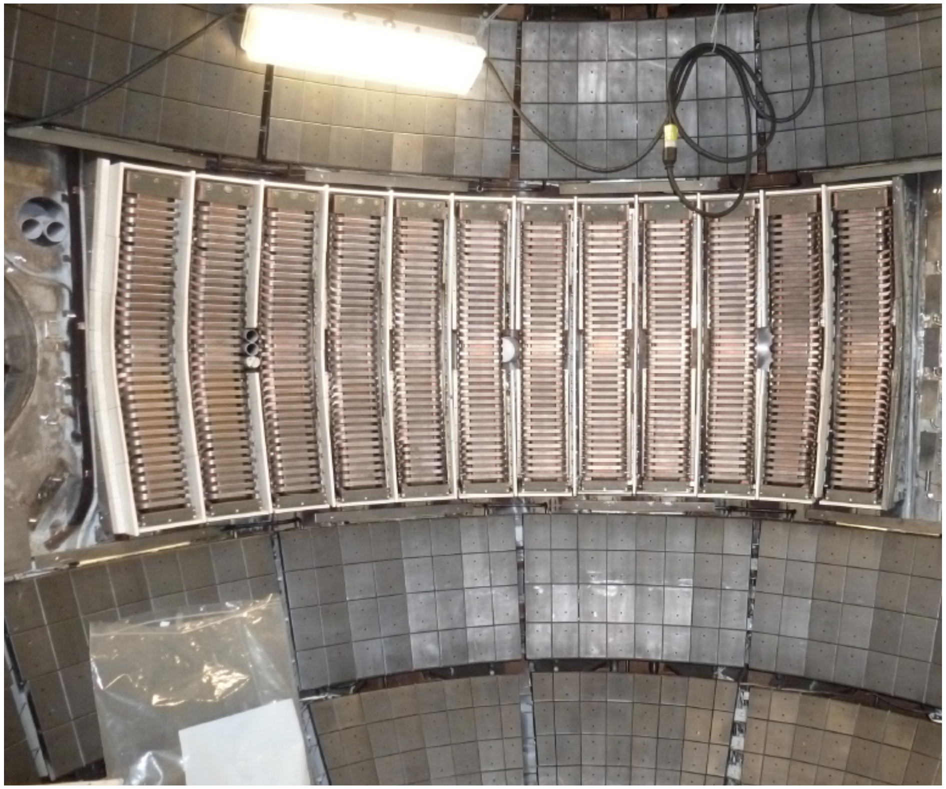


Prototype electroformed compliant section

Additional ground installed

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

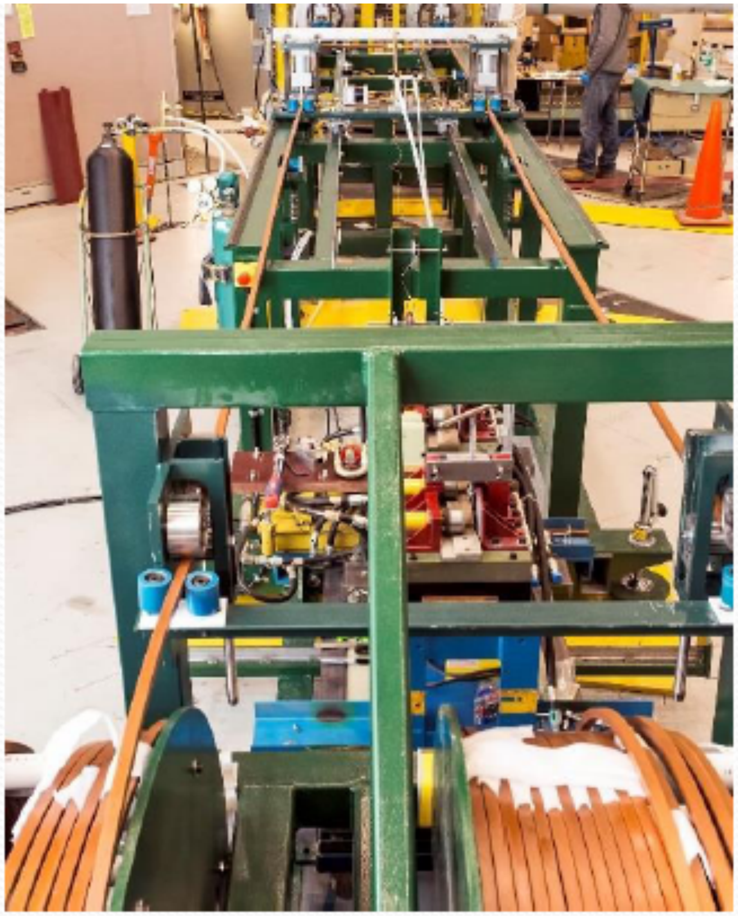
Antennas were re-installed with the new compliant feeds and back-plate grounding



4 MW is available for HHFW heating and current ramp-up

OH Winding Station

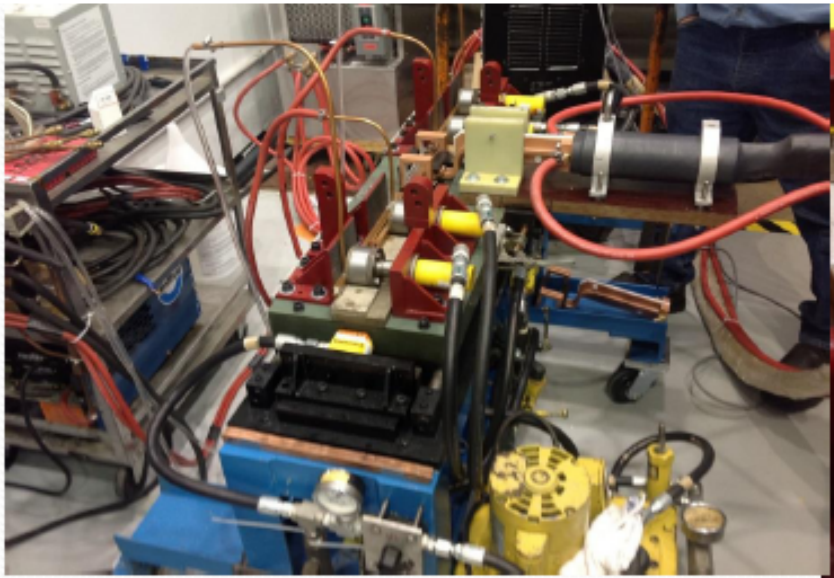
Taping Machine

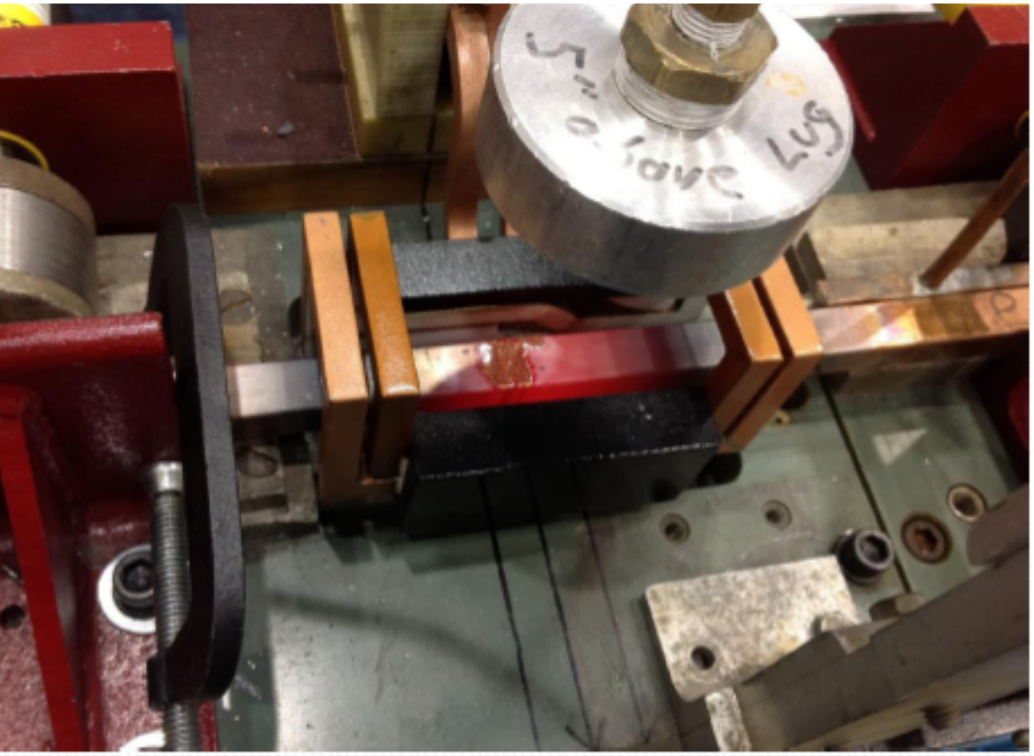


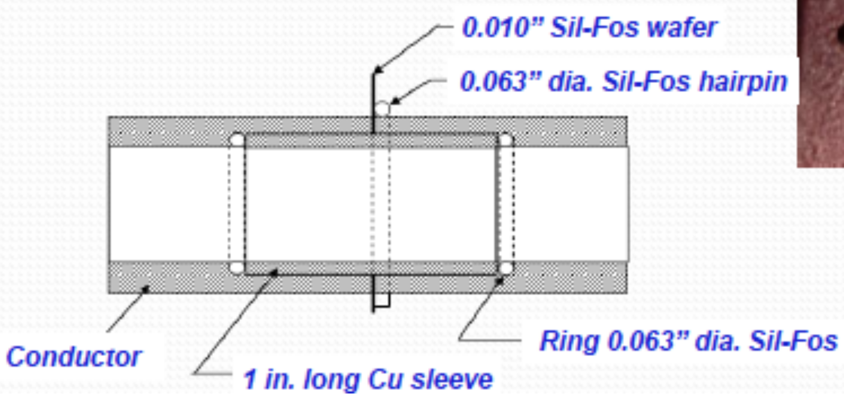
OH primed Conductor

On-line Brazing: 32 in line induction brazes were performed during the OH winding operations

Each braze joint was mechanically loaded (stretched) and helium leak tested to ensure a quality braze joint.





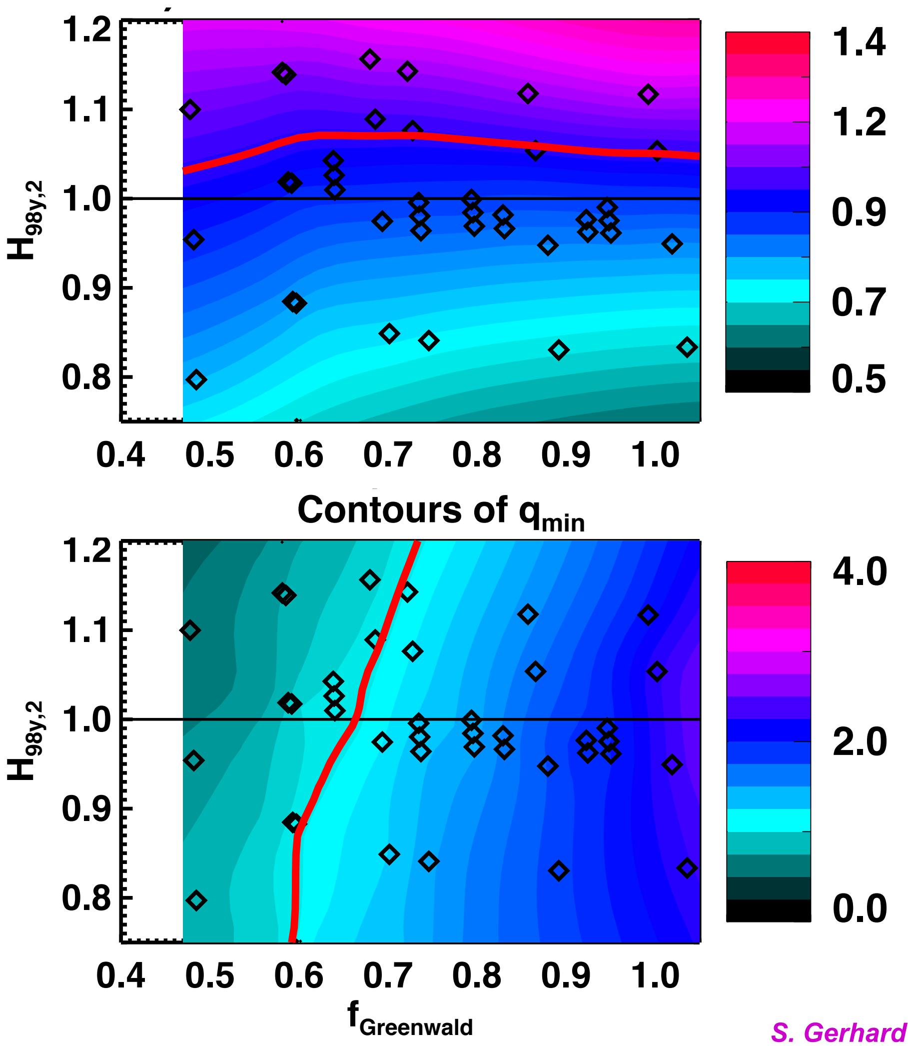


Inconel Center-Stack Casing Fabrication

fabricated by Martinez-Turek, Inc.

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



Contours of Non-Inductive Fraction

Contours of q_{min}

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