National Spherical Torus eXperiment Upgrade

NSTX-U Recovery Project Progress Towards First Plasma

IAEA - FEC - 2021

S. Gerhardt for the NSTX-U Recovery Team

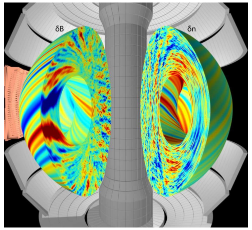
PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

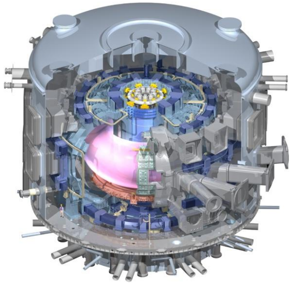
Low aspect ratio "Spherical Torus / Tokamak" (ST) vital for toroidal science and fusion energy development

- ST accesses unique regime of high β_T
  - Fundamental changes in nature of turbulence, MHD stability
    - Enhanced electromagnetic and super-Alfvénic effects
  - STs can more easily measure electron-scale turbulence
    - Important transport channel at all aspect ratio
  - Neutral beam fast-ions in present STs mimic DT α populations
    - Study burning plasma science
- Expanded parameter space crucial for model validation
- ***If physics results favorable, STs could provide more economical fusion development & energy systems***
  - Potentially reduced magnet and device size and cost

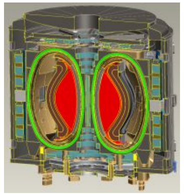
Electromagnetic turbulence



ITER



Pilot Plant

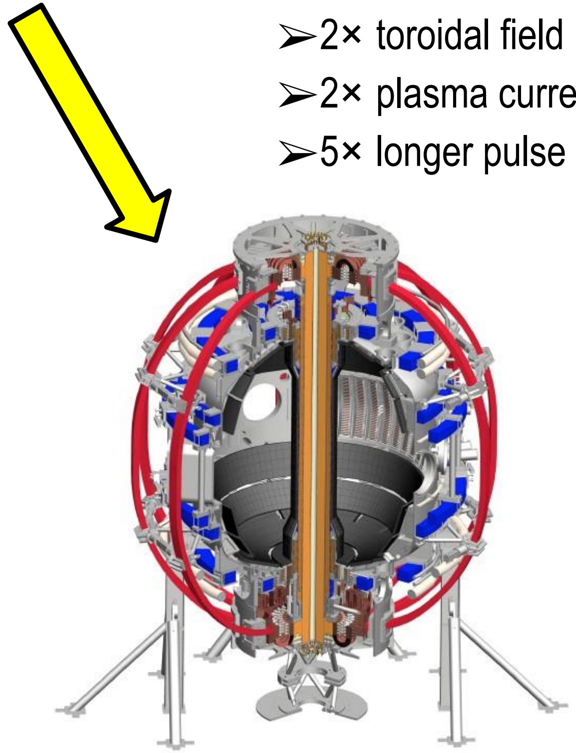


Five year research plan developed by all collaborating institutions and approved by DOE
Available at: https://nstx-u.pppl.gov

NSTX ⟹ NSTX-U: Two major upgrades

1. New Central Magnet

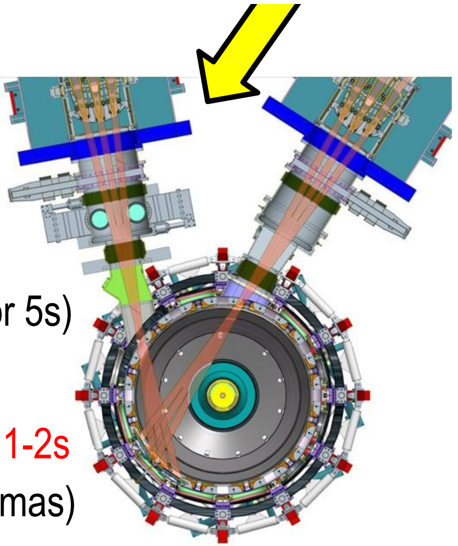
- ➢2× toroidal field (0.5 → 1T)
- ➢2× plasma current (1 → 2MA)
- ➢5× longer pulse (1 → 5s)



→ Unique regime

Study new transport and stability physics

2. Tangential 2nd Neutral Beam



- ➢2× heating power (5 → 10MW for 5s)
  - Tangential NBI → 2× η_{cd}
  - Up to 15MW NBI + 4MW RF for 1-2s
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)
- ➢4× divertor heat flux (→ ITER levels)

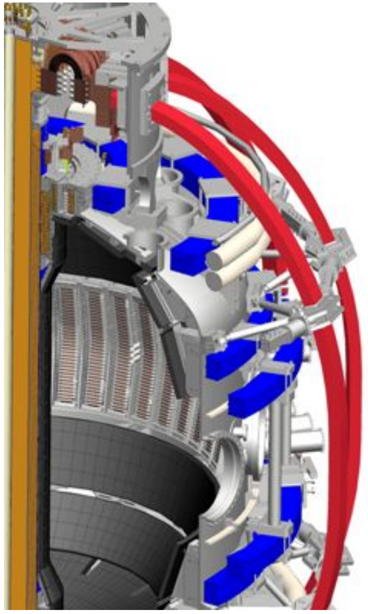
→ Sustain plasma without transformer

Not yet achieved at high-$\beta_{T,}$ low ν^*

Essential for any future steady-state ST

NSTX-U and MAST-U are presently the most capable devices in the world-wide ST research program

NSTX-U



Similar features:

- Major radius R = 0.8-1m
- Plasma current up to 2MA
- Pulse durations 1s → up to 5s
- Strong neutral beam heating

Having both NSTX-U and MAST-U important to confirm unique ST results

MAST-U (UK)

Complementary Research:

Core emphasis

- Higher magnetic field, aux. power (NB+RF), pressure
- 2× higher self-driven current

Boundary emphasis

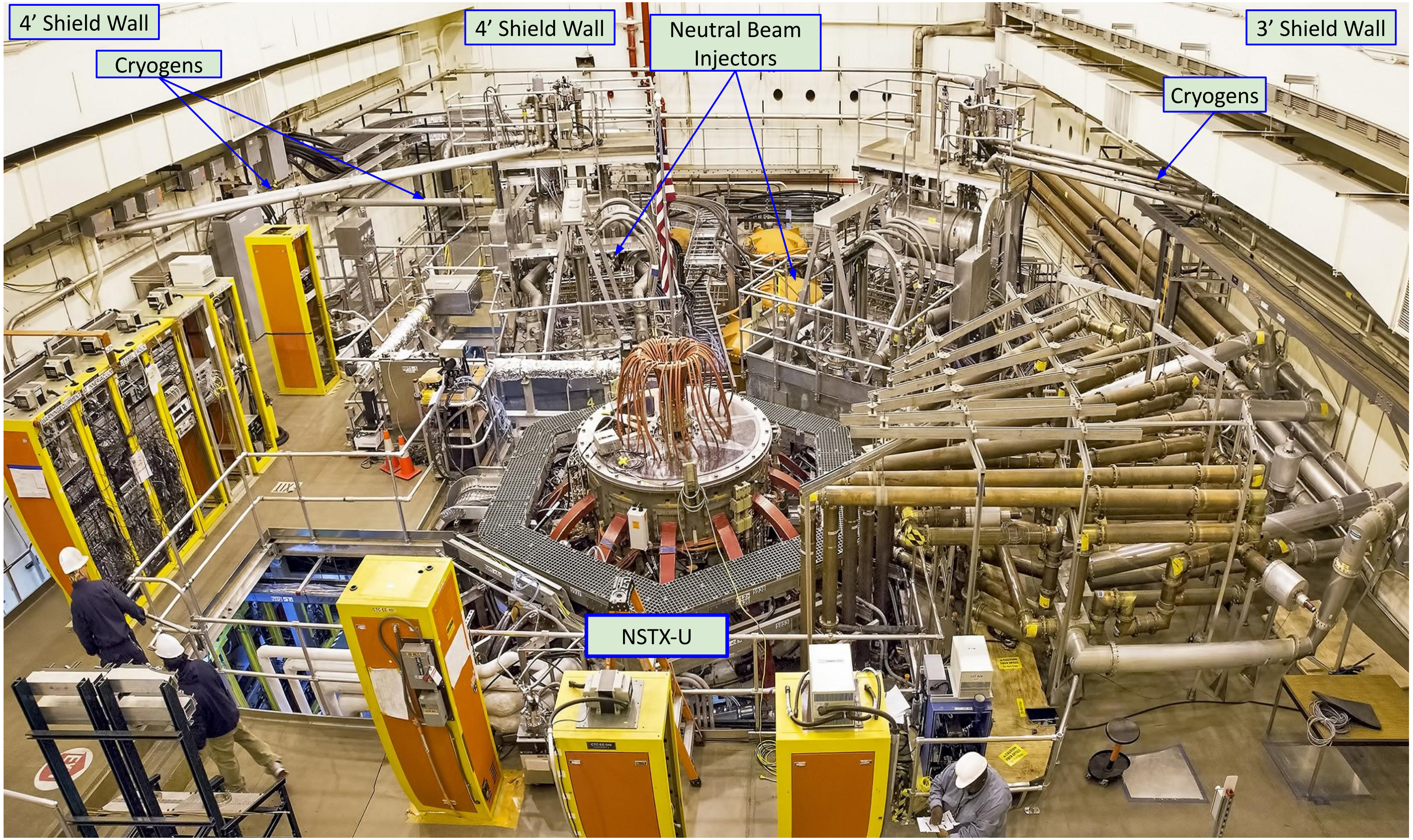
- Highly-flexible “long-leg” divertor for power exhaust research
- Off-midplane 3D magnetic field coils

Project Has Finished Design and Started Fabrication/Installation

- NSTX-Upgrade Project - new magnets and heating systems added to legacy NSTX facility (2010-2015)
- A number of issues hindered NSTX-U operations in FY15&16.
  - Culminated in June 2016 operations halt due to an internal short in coil
- Extent of Condition (2017) $\longrightarrow$ Defined Recovery Project scope
  - ***<u>Objective is to achieve a high-reliability user facility</u>*** - ***I_P=2 MA, B_T=1 T, P_{inj}=10 MW, t_{pulse}=5 sec***
- Project Baseline Review (August 2019)
  - Defined the Project Baseline
  - Released specific long-lead scope elements for fabrication
- Project Final Design Review (March 2020)
  - Validation of the final design by external committee
- Project CDE-3 Review (May 2020)
  - Released the balance of the Project for fabrication/installation

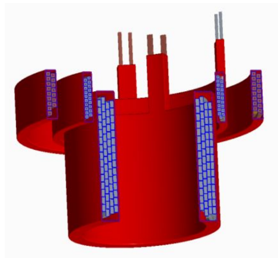
<u>NSTX-U Recovery is Now Squarely in the Construction/Installation Phase of the Project</u>

NSTX-U Within the Test Cell (2016)

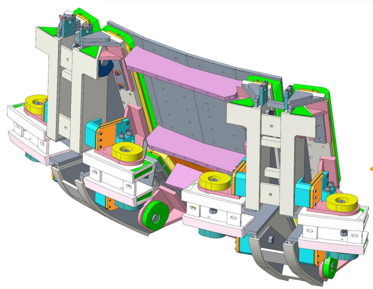


Significant Project Scope Resides in the Machine Core

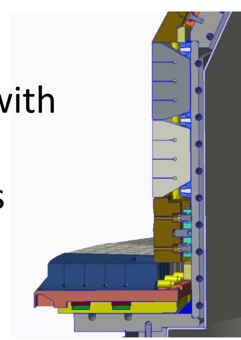
Six new inner-PF coils (PF-1a, -1b, -1c, upper and lower)

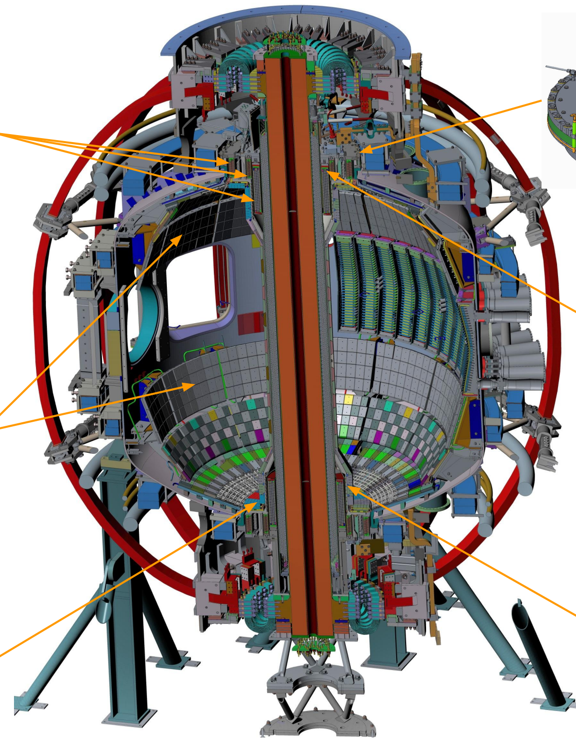


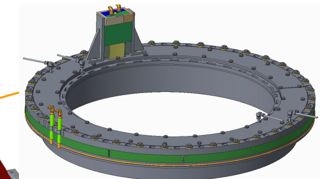
Repairs to passive plate bracketry to allow operation at full EM load



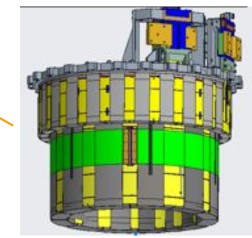
New graphite tiles with improved heat flux handling capabilities

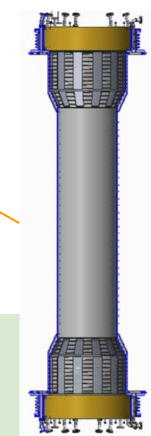






PF-1a, -1b, -1c support structures and double O-ring seals



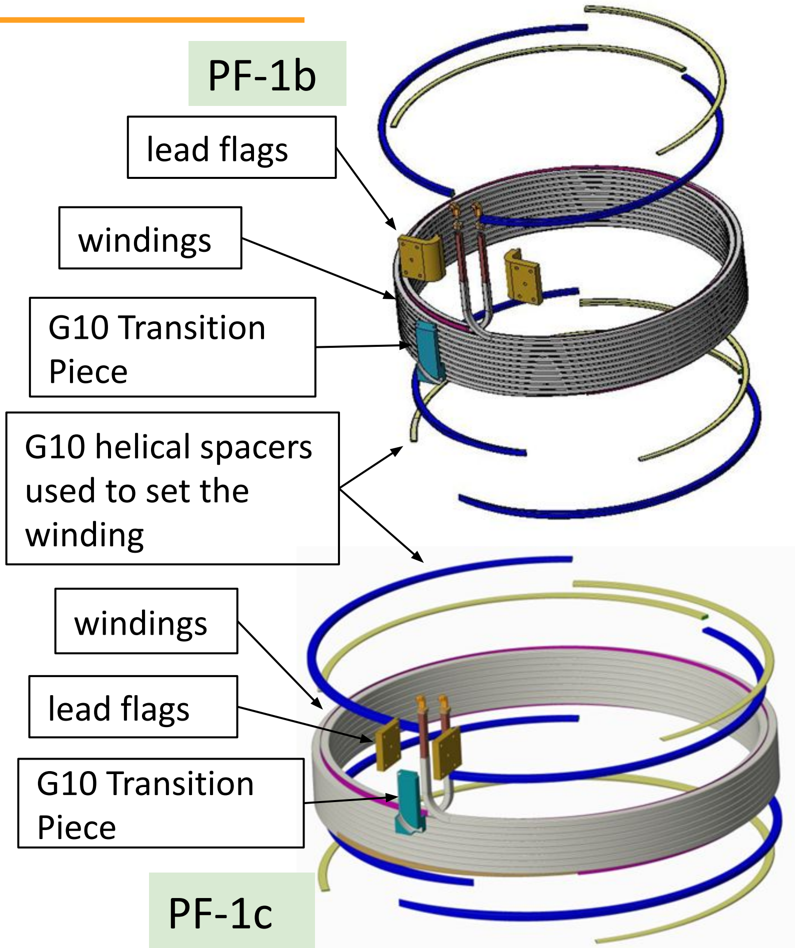


New Center Stack Casing With **Improved Heating/Cooling Features**

Numerous additional scope elements - not all addressed in this poster

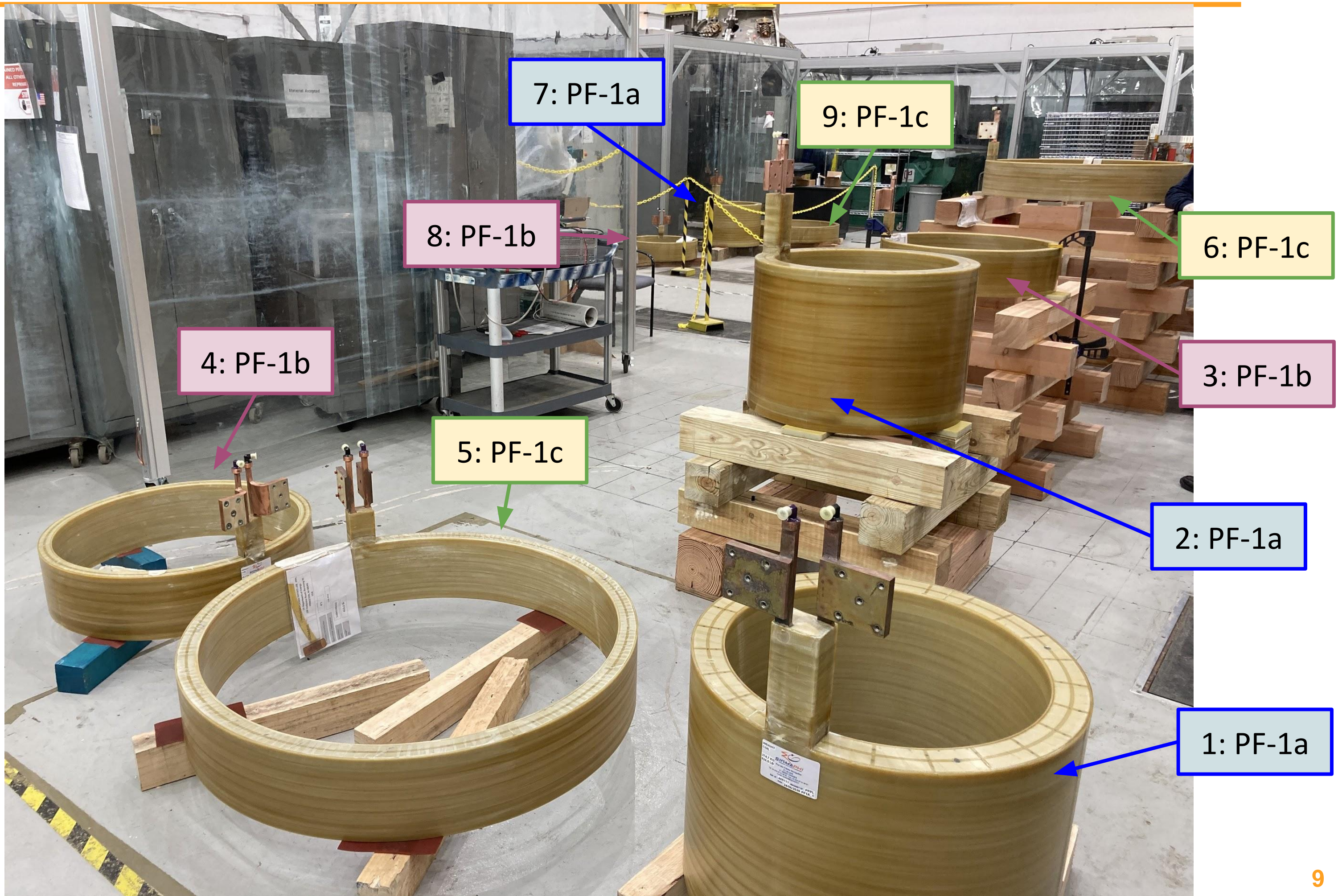
Inner PF Coils - Design Parameters

		PF-1a	PF-1b	PF-1c
Coil Terminal to Terminal Voltage	kV	2.03	2.03	2.03
Current	kA	19.7	20.0	20.2
# of Layers		4	2	2
# of Turns		61	20	16
Turn-to-Turn Voltage	V	33	101	127
Turn-to-Turn Insulation Safety Factor		2168	709	567
Layer-to-Layer Voltage	V	1013	2026	2026
Layer-to-Layer Safety Factor		76	38	38
Max Turn-to-Ground Voltage	V	2026	4052	4052
Turn-to-Ground Safety Factor		54	27	27



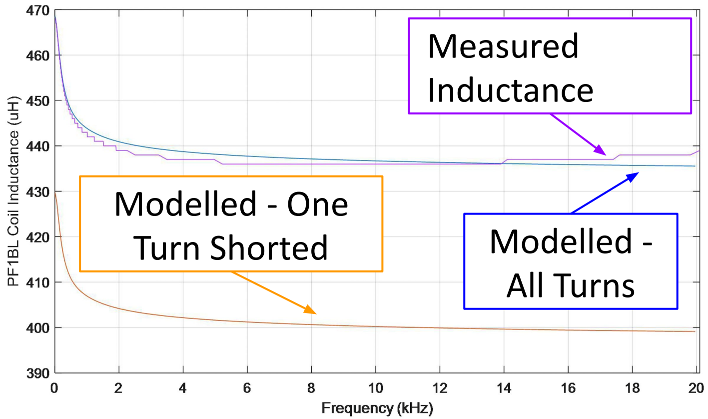
All Coils Are Complete!

- Prototype coils fabricated by 4 vendors, including PPPL.
- Electrical tests, destructive testing and inspection, to assess quality between vendors
- Contract awarded to Sigmaphi (Fr)
- *All coils built and delivered*

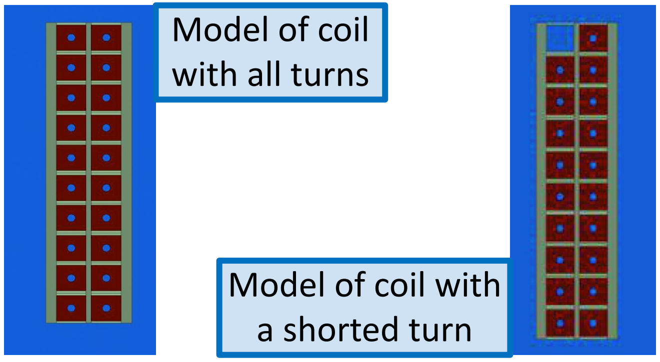


Magnets Pass Comprehensive Electrical Tests to Ensure Good Turn-to-Turn Insulation

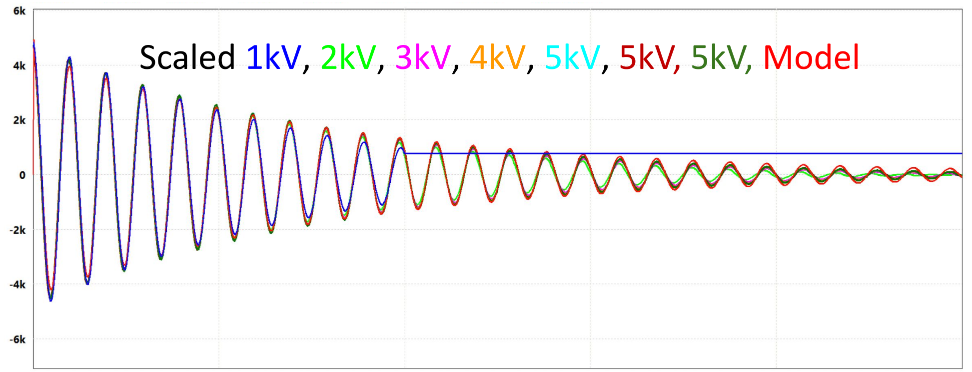
Frequency Dependent Inductance



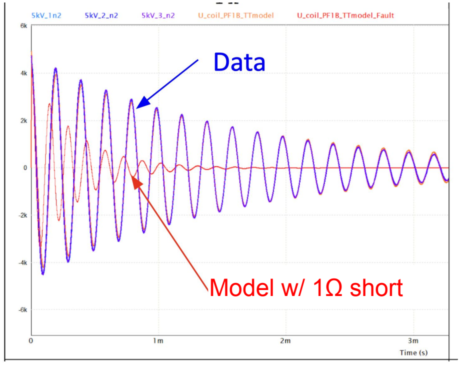
PF1B Coil Inductance vs. Frequency

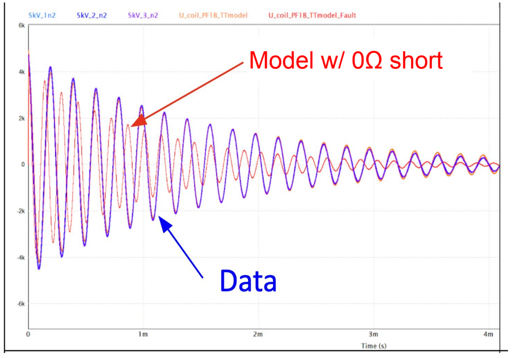


Surge Testing

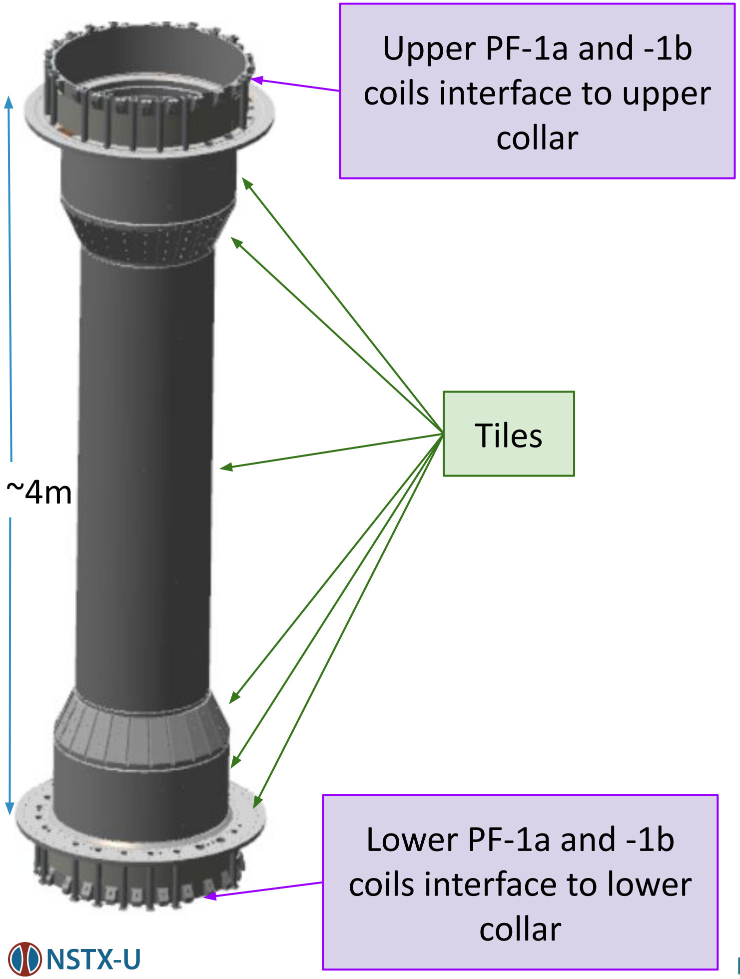


Data is only consistent with having good turn-to-turn insulation





Casing Manufacture



<u>CS Casing provides</u>:

- The high-field side vacuum boundary
- Structural load path for numerous coils
- The mounting surface for plasma facing components
- Heating/cooling function
- Alignment of coils and PFCs

<u>Loaded by many effects</u>

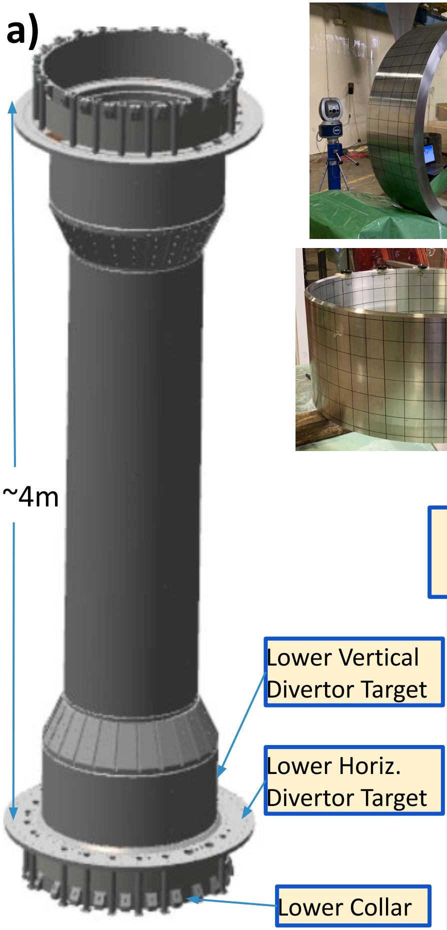
- Electromagnetic loads on magnets
- Disruption loads - vertical from eddy currents and sideways from halo currents

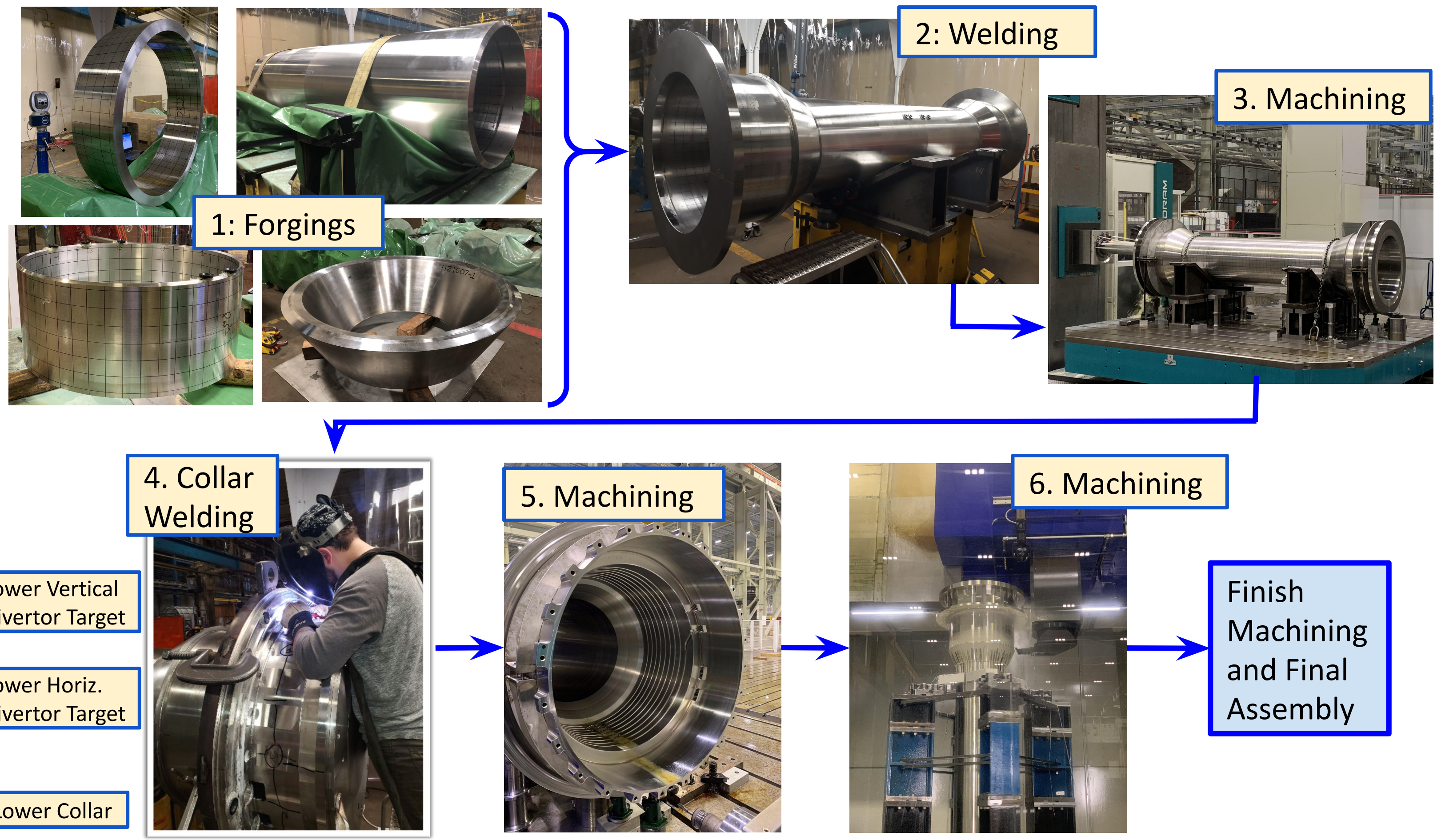
<u>Being fabricated from Inconel 625</u>

- about 50% stronger than 316SS
- 2x as resistive

Casing Manufacture

HOLTEC INTERNATIONAL





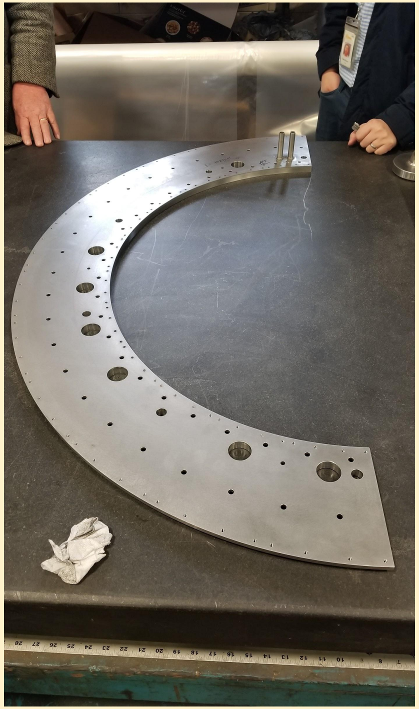
Heat Transfer Plate and Heat Transfer Tubing Fabrication Complete

G.J. OLIVER, INC.

HOLLIS LINE

PTR PRECISION TECHNOLOGIES, INC.

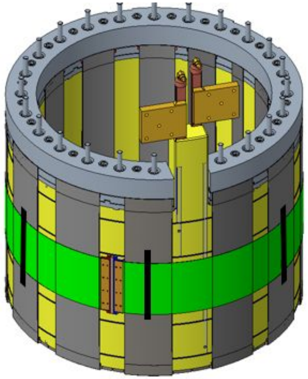
HOLLIS LINE



Provide heat removal for 12 MW/5s pulses every 20 minutes
Will be installed on the Casing as part of the Final Assembly

Magnet Supports are Nearing Completion PF-1a and PF-1b

PF-1a or -1b Assembly: Slings provide preload to minimize insulation tensile strains

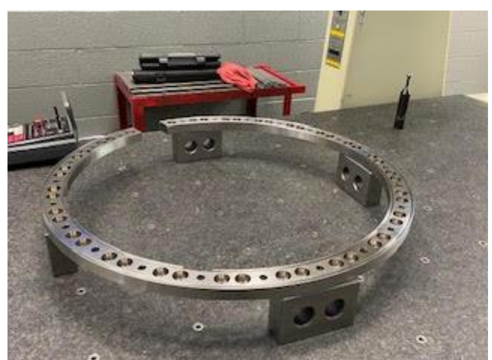


PRECISION ADVANCED MACHINING

PrecisionAdvancedMachining.com

- LARGE 5-AXIS
- BORING
- GRINDING
- TURNING
- MILLING

ISO 9001:2015



Representative Sling/Flange Configuration

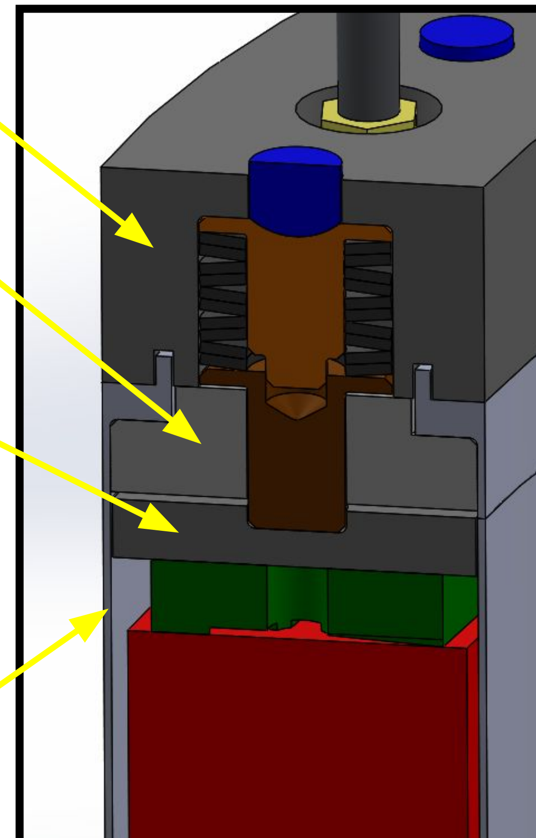
Capping Flange
4 of 4 Total
Complete

Hanger Flange
4 of 4 Total
Complete

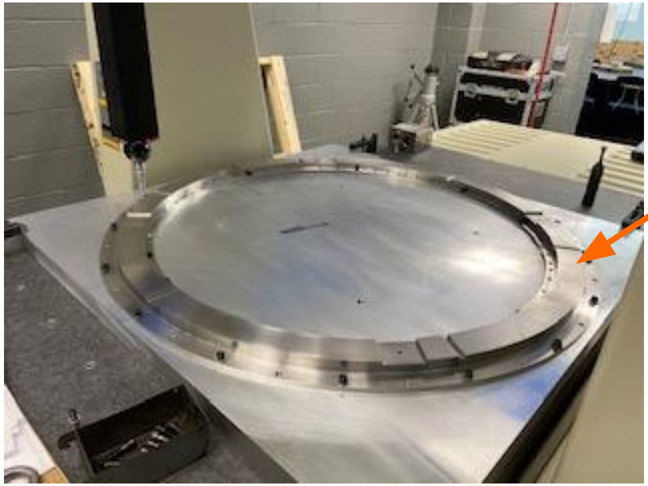
Compression
Flange
4 of 4 Total
Complete

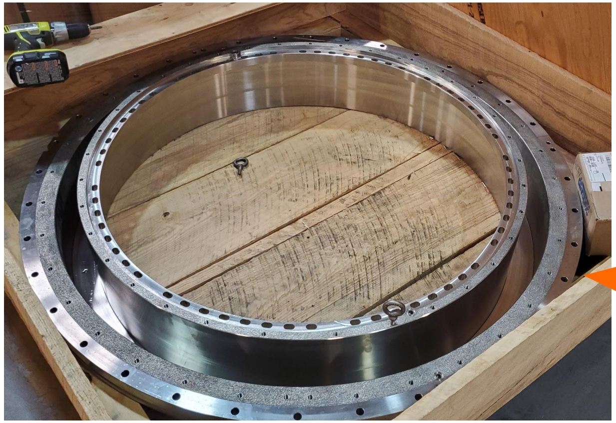
Sling
PF-1b Slings
~80% Complete

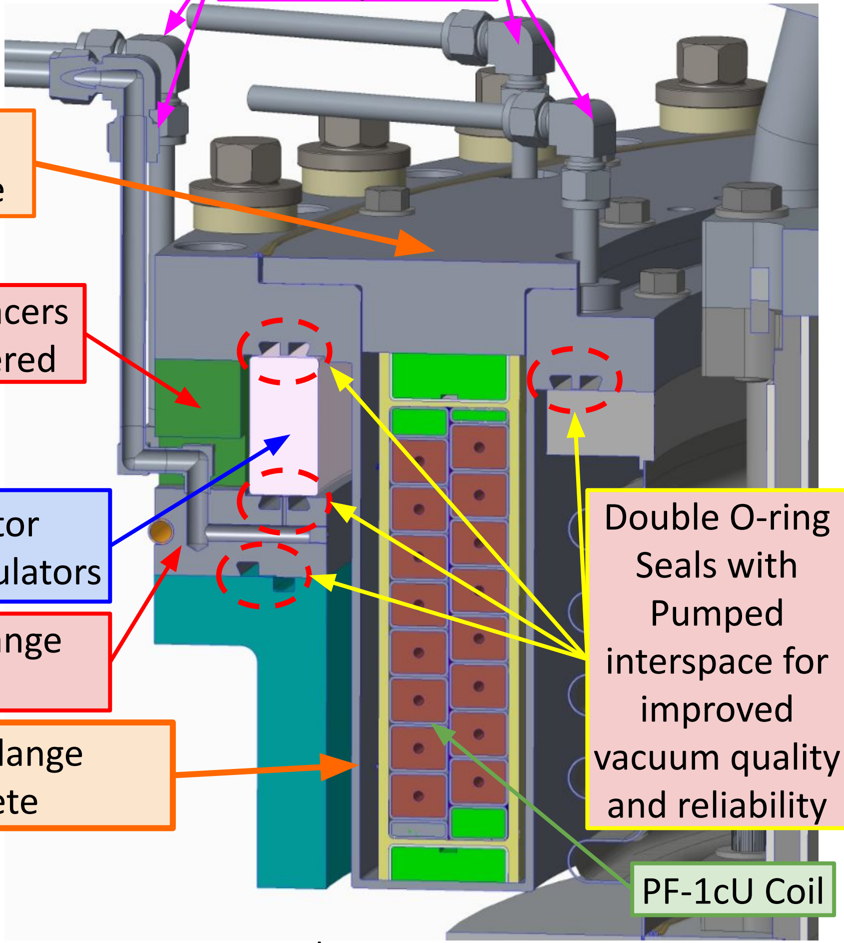
PF-1a Sings
~70% Complete



Magnet Supports are Nearing Completion
PF-1c & Ceramic Break





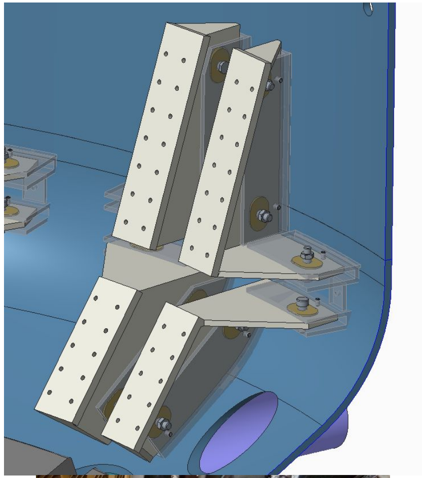


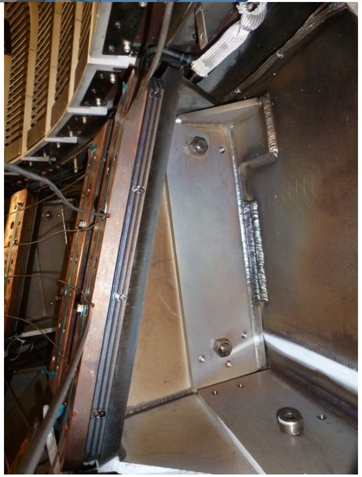
Upper Insulator

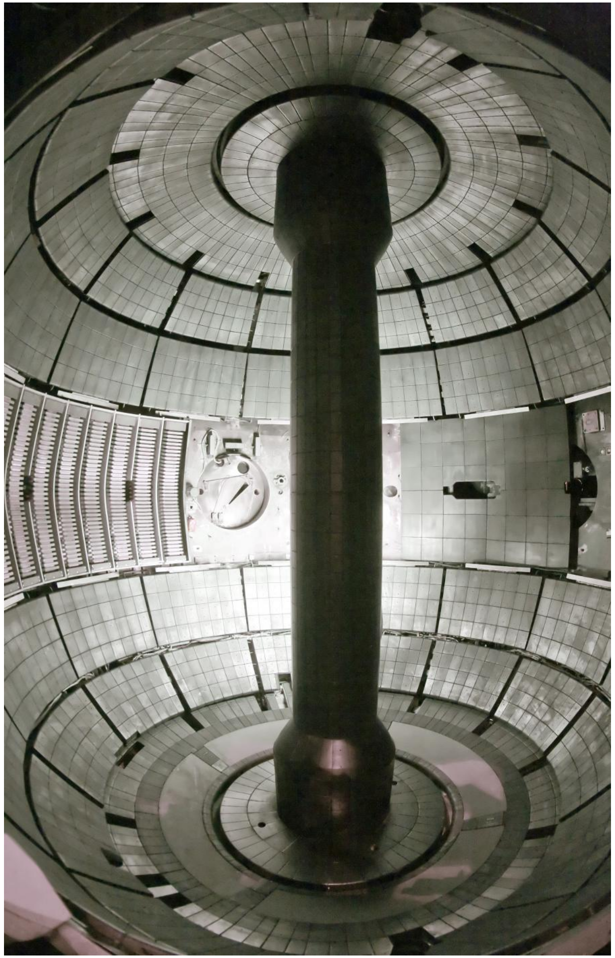
G.J. OLIVER, INC.

Passive Plates are Used to Control the Plasma Stability

- 1” thick Cu plates, mounted to the vessel wall via bracketry
- Slow vertical displacements growth → Facilitate achieving high elongation.
- Pressure-driven external kink is stabilized, resulting in the more slowly growing resistive wall mode.
    - Kinetic effects or feedback with 3D fields can stabilize the RWM
- Critical to the high-β research program



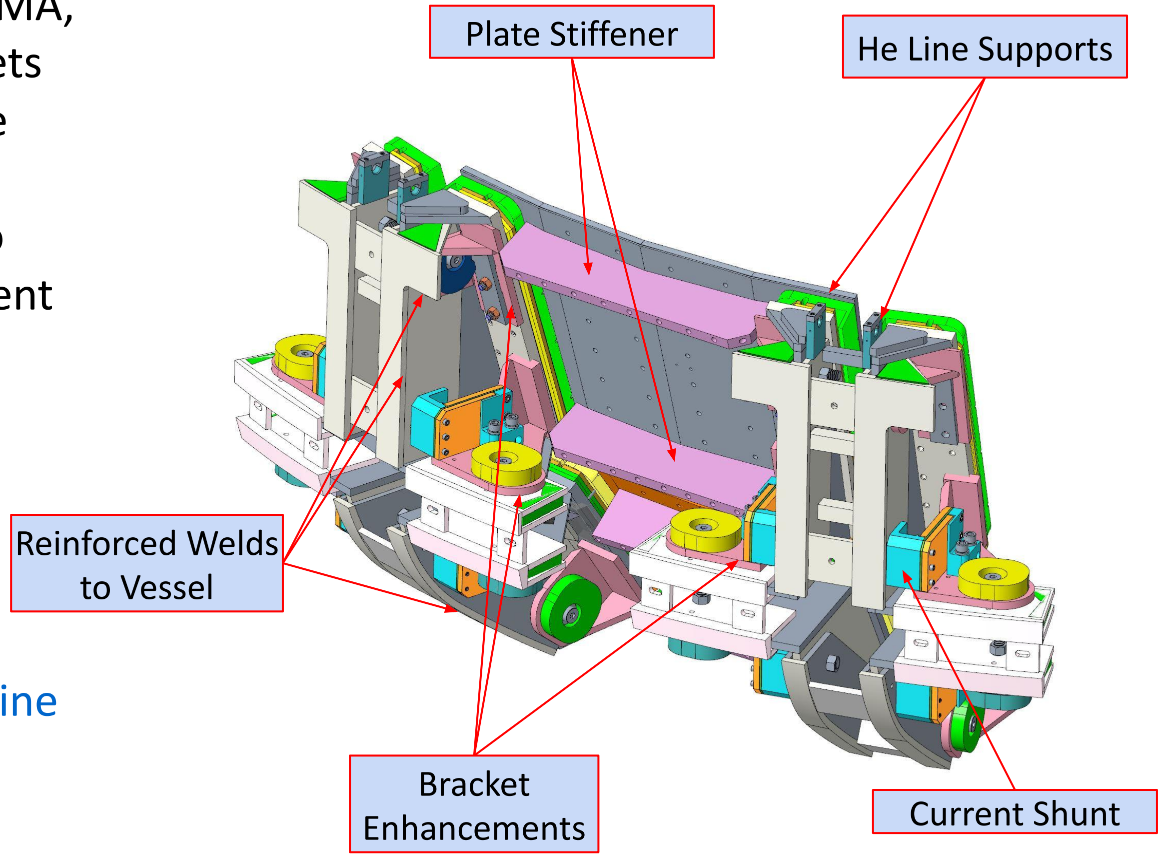




__Concern__: Huge loads on the passive plates, and by extension their brackets, during disruptions

Passive Plates Brackets and He Lines are Being Reinforced

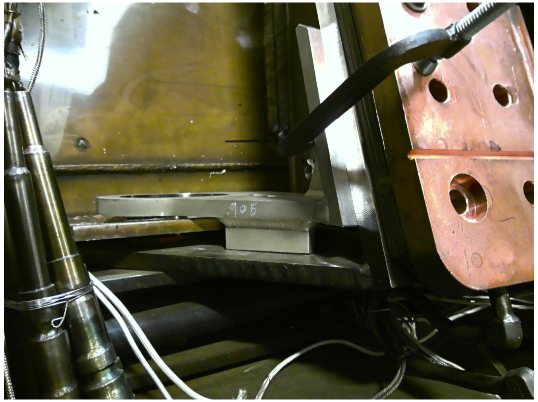
- With larger NSTX-U loads at I_P=2 MA, B_T=1 MA, welds in existing brackets were not projected to survive, He lines had unacceptable currents
- Making targeted modifications to improve structural, improve current carrying capability:
  - He line supports
  - Plate stiffeners
  - Improved brackets
  - Improved welds of legacy brackets to vessel
  - Current shunts to better define current paths

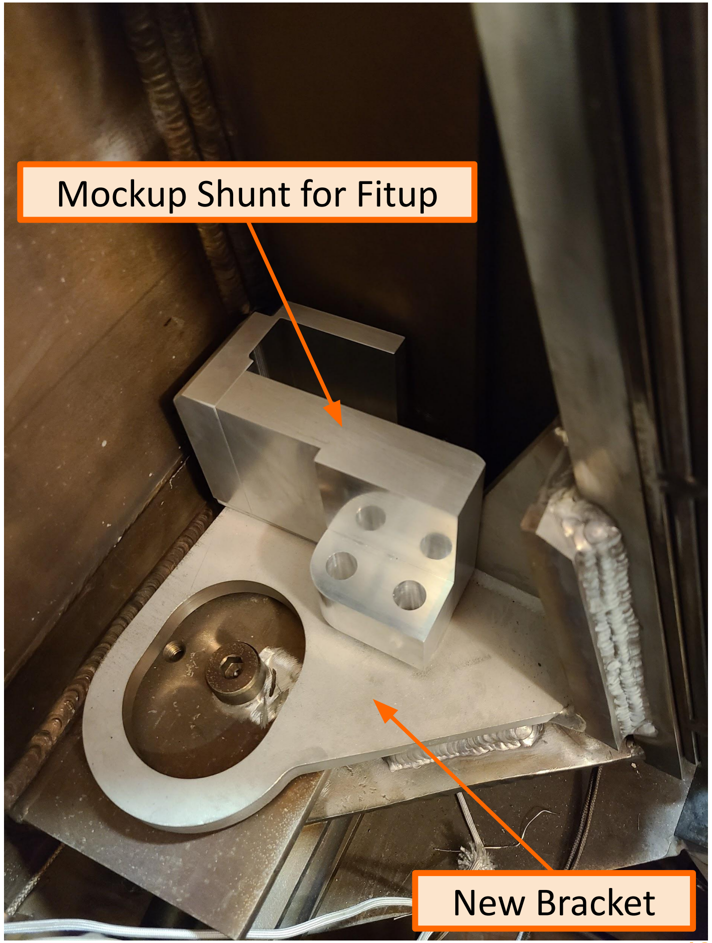


Passive Plates - Progress

Brackets -240 of 240 fabricated
Biscuits - 240 of 240 fabricated

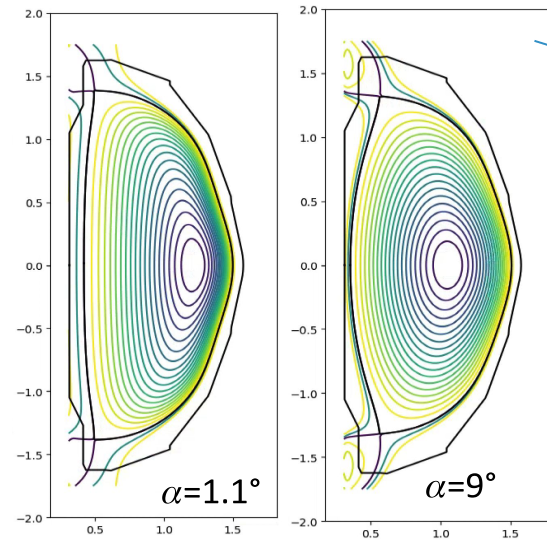
Now installing brackets

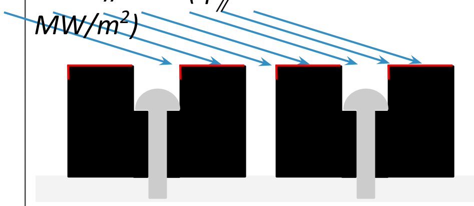




Plasma Facing Components Have to Meet Demanding Requirements - T_{surf}

- Halo current loads - ~800 lbs on divertor PFCs
- Large heat fluxes over a range of incident field line angles
  - Large heat fluxes in excess of $q_\perp$~ 50 MW/m^2 expected to be possible in LSN scenarios designed to compress flux.
- Sublimation accelerates above ~1600 C - will contaminate the plasma





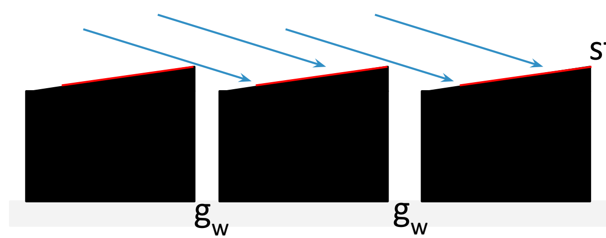
Solutions to avoid hot spots

- Shield the tile gaps
- Don't have front-surface fastener access

manufacturing tolerances ~0.005"

step = $(g_w+\delta g_w)\tan(\alpha)+\delta h+d_{erosion}$

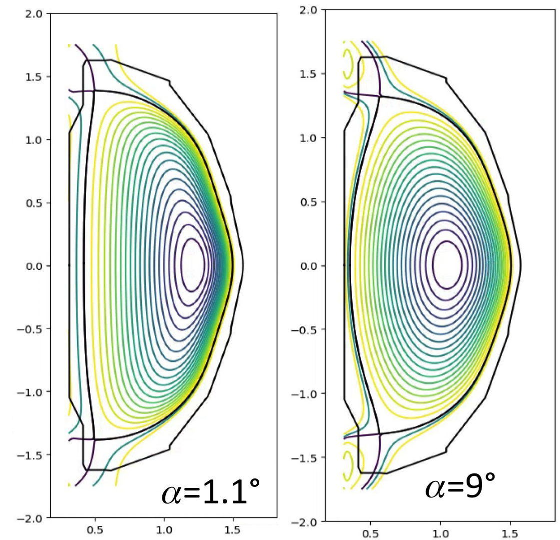
~0.02"   5°   0.003"



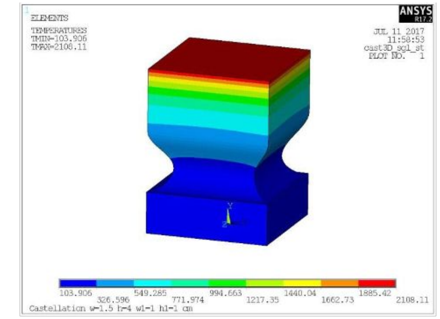
Step Height = 0.01"
Ramp Angle <1°

Plasma Facing Components Have to Meet Demanding Requirements - Stress

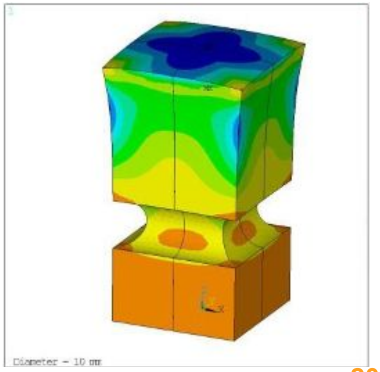
- Halo current loads - ~800 lbs on divertor PFCs
- Large heat fluxes over a range of incident field line angles
    - Large heat fluxes in excess of $q_{\perp}$~ 50 MW/m^2 expected to be possible in LSN scenarios designed to compress flux.



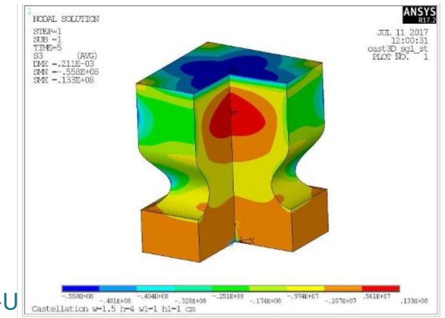
Model Tile
1: Temperature Distribution



Model Tile
2: Thermal Growth

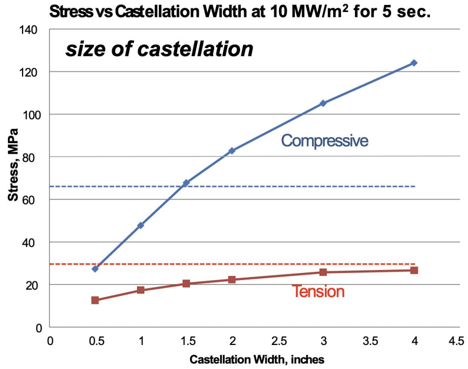


Model Tile
3: Compressive Stresses



Model Tile
4: Compressive Stresses as a Function of Tile width

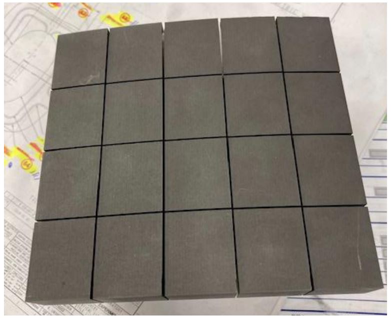
<~1.5" tiles have acceptable compressive stresses



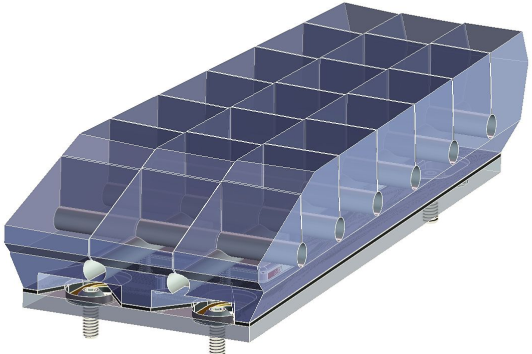
Plasma Facing Components are Moving Through Fabrication

Tile Summary Status		
	# done	# parts
Tiles	1021	1465
Metals	4163	4612

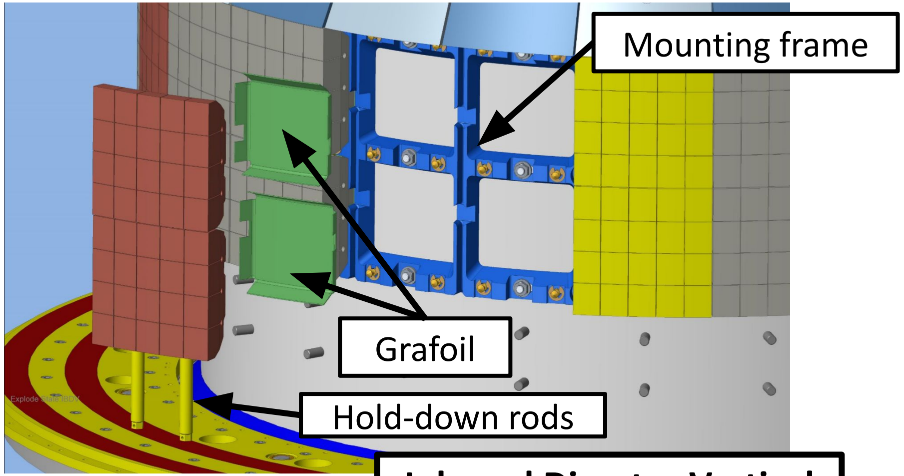
MWI



Stillwater TECHNOLOGIES LLC.

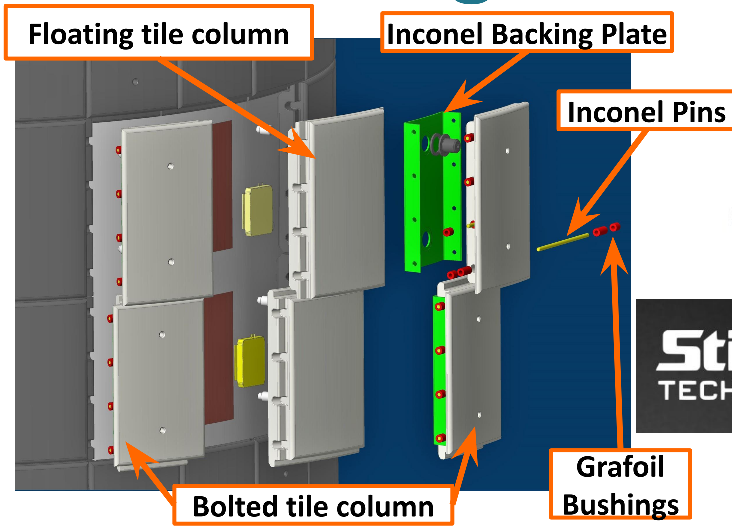


Outboard Divertor Row 1/2



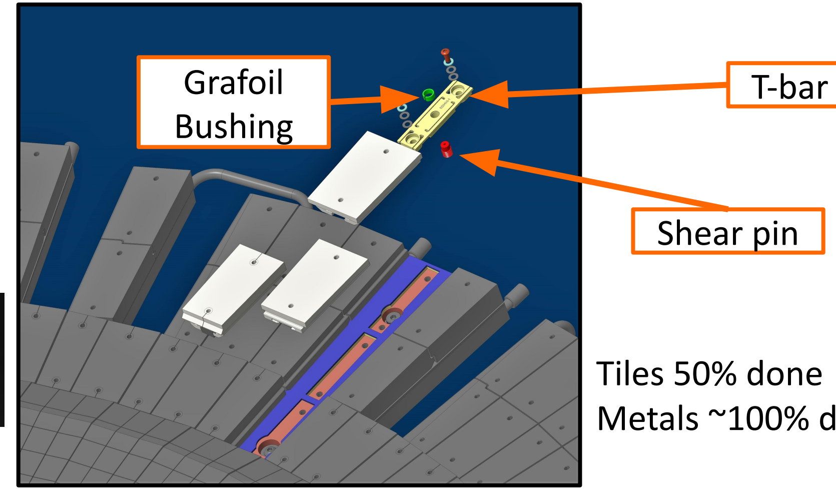
Inboard Divertor Vertical

Plasma Facing Components are Moving Through Fabrication - Low Heat Flux

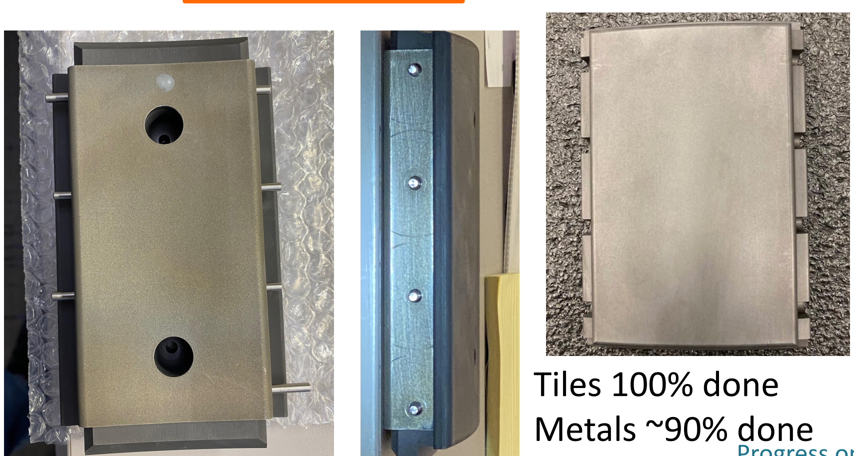


MWI

Stillwater TECHNOLOGIES LLC.

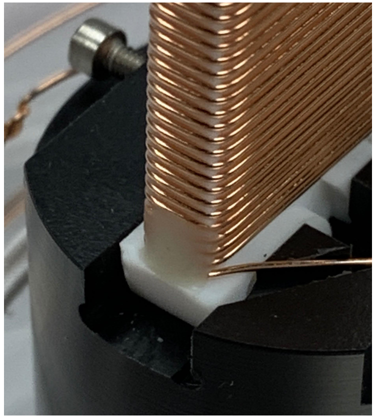


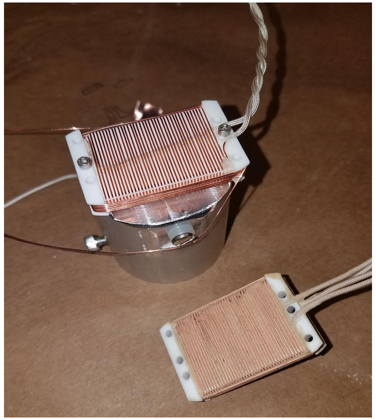
Tiles 50% done
Metals ~100% done



Tiles 100% done
Metals ~90% done

Diagnostics Being Fabricated for Installation in PFC Tiles



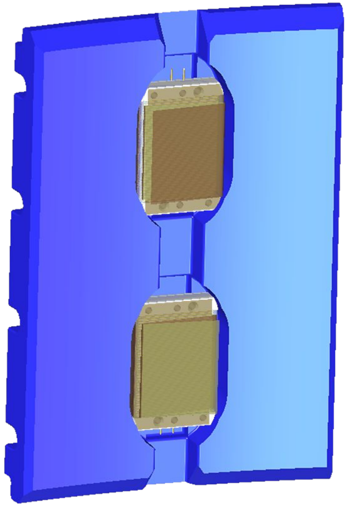


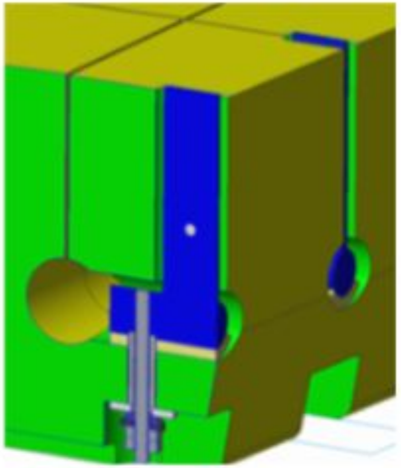
Rail Langmuir Probe

- Designed to fit in small slots in gaps between castellations
- Provides temperature data while maintaining high heat flux capability
- Arrays in all high heat flux tile regions

Mirnov Sensors

- use bare copper in order to achieve simultaneous high temperature and vacuum requirements
- Mandrels have fine grooves to locating the windings
- High temperature cement and fiberglass sleeving for insulation





Test Cell Nuclear Shielding Improvements are Complete

Poured Walls

Roof Blocks

Complete Labyrinth

Scope:

- Construct a labyrinth at the test cell southeast door
- Improve shielding at large wall penetrations

Shielding validated by before-and-after challenges with a portable D-T neutron generator

Other Safety Related Systems on Project

NTC Access Control

- Constructing a redundant and fail safe access control system for the test cell and other experimental areas
- Upgrade of medium-voltage breakers to have a fail-safe trip mechanisms
- Satisfies the requirements of IEC 61508/61511

Oxygen Deficiency Hazard Mitigation

- Adding redundant alarming ODH monitors to areas with significant risk of ODH condition.
- Adding additional ventilation fans to cryogenic areas to reduce probability of small leaks creating ODH conditions

Along with shielding, these systems are critical safety upgrades that bring NSTX-U to the standards expected by the US accelerator community --- NSTX-U is classified as an accelerator within the DOE

Project Schedule

- COVID-19 has resulted in Project delays
  - PPPL curtailed on-site operations March-June of 2020
  - On-site construction and fabrication activities since July 2020 done with limits on on-site staff, various COVID controls
  - Numerous and various vendor impacts
- Near-term critical path is set by the CS casing manufacture
  - Tiles, passive plates, and assembly of coils in slings are all near-critical path
- Once casing is delivered, the critical path shifts to machine reassembly followed by commissioning.
- Now anticipating first plasma in the later half of CY2022 - August of 2022 early finish

Summary

- Project is well into the fabrication/installation phase
  - Magnet fabrication is complete
  - Test cell nuclear shielding improvements complete
  - CS Casing, PFCs, passive plate components all making strong progress
  - Passive plate in-vessel work ongoing
- Anticipating first plasma in the later half of CY2022