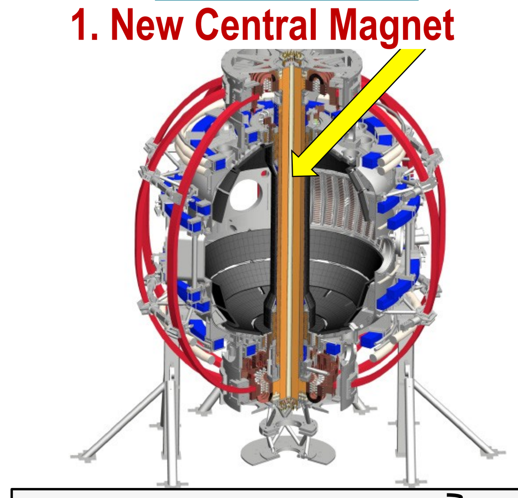
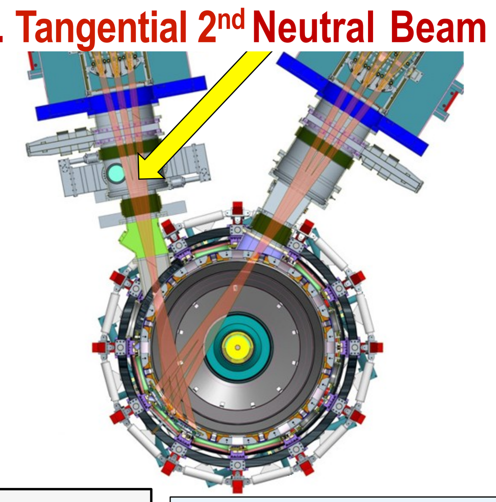
NSTX-U designed to address key ST / fusion questions →
Will access new physics with 2 new tools:

Transport and Stability Physics at Low Collisionality	Sustainment Without a Transformer
1. New Central Magnet	**2. Tangential 2nd Neutral Beam**



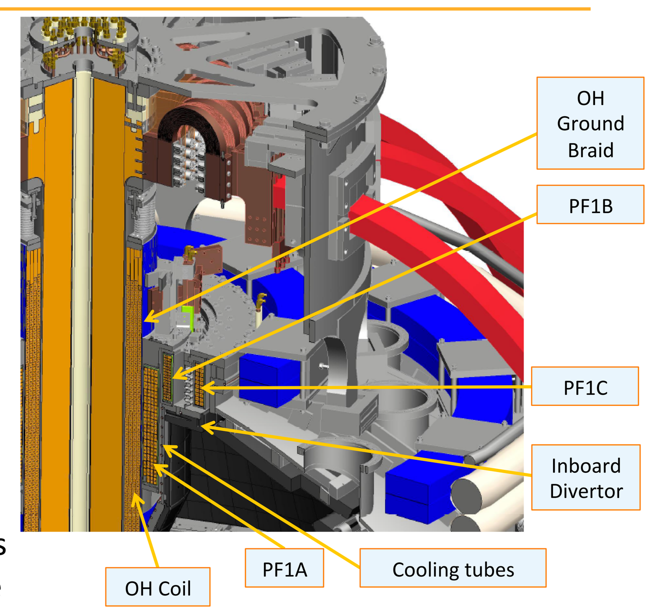


2× field, current, power
4× heat flux, 5× pulse length
Up to 10× higher $nT\tau_E$
} Relative to NSTX-U

NSTX-U Completed in 2015, Operated for 10 run weeks in 2016

What is NSTX-U "Recovery"?

- A number of issues hindered operations in FY15&16.
  - 4/15: OH "Arc Flash" incident
  - 9/15: Inadequate inboard divertor bake
  - 5/16: CS cooling tubes wrong material, induced current/motion, breaches
  - 5/16: Bent PF1AU bus bar
  - 6/16: Internal short in PF1AU coil
- FY2017: DOE requested PPPL to review "Extent of Condition" and submit Corrective Action Plan (CAP) as a laboratory Notable Outcome
- **Recovery = Implementation of Extent of Condition CAP**



10 Major Scope Areas Define the Recovery

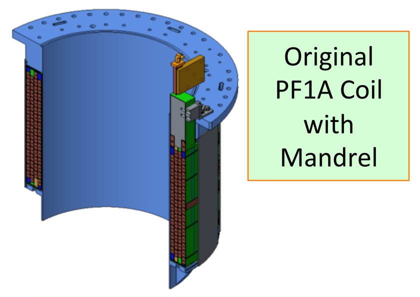
Improved Reliability	Safety and Compliance	Transition to Ops

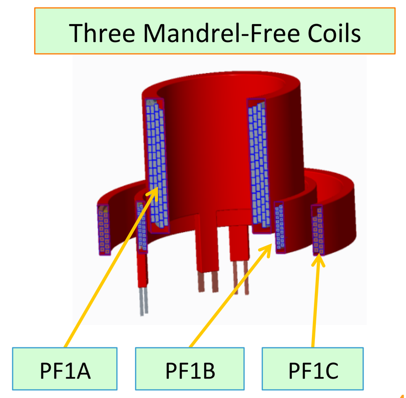
1. Rebuild all six inner-PF coils with a mandrel-free design
2. Replace plasma facing components that do not meet updated requirements
3. Improve the "polar regions" (machine top and bottom)
4. Remedy issues with the passive plates
5. Implement mechanical instrumentation to assess quality of mechanical models, trend machine behavior
6. Improve hot He distribution system used during bakeout; eliminate the safety issues identified with the bakeout medium temperature water system
7. Improve the test cell neutron shielding and access control system
8. Reassemble the machine (KPP #1)
9. Implement the Accelerator Safety Order
10. Commissioning: Bakeout (KPP#2), Test Coils (KPP#3), Create First Plasma (KPP#4)

- Goals consistent with ultimate performance target of I_P=2 MA, B_T=1 T, P_{inj}=10 MW, and τ_{pulse}=5 seconds
- Early finish date of February 2021.

New Inner PF Coils are Designed to Improve Testability and Manufacturability

- Reminder of path:
  - Build 6 new PF-1 coils (PF-1a/1b/1c, upper & lower)
  - Use designs that facilitate turn-to-turn testing
    - Previous coils fabricated on permanent mandrels
    - New coils: removable mandrels
- New coil design simplifies fabrication relative to the previous inner-PF coils
  - Simplified winding pattern
  - No braze joints
  - Softer copper
- Prototyping is a key element of our plan





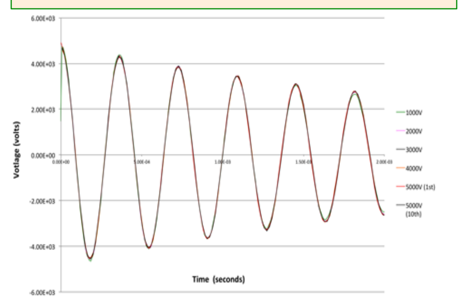
We are Completing the Prototyping Phase on Coils

<u>Our approach</u>: Any vendor that makes production coils must first be qualified by making a prototype coil, having that coil go through a rigorous inspection and test procedure

- Have completed prototype coil fabrication at four locations
- Have completed prototype coil evaluation at PPPL

Prototype Tests Have Been Successfully Completed

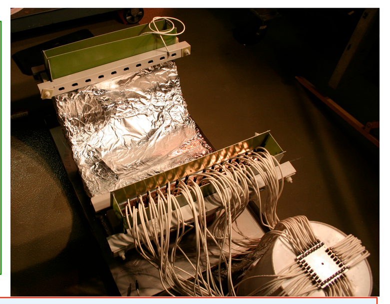
Surge tests showing similar ringing waveforms from 1 kV to 5 kV ← Assess turn insulation



Vendor # →	1	2	3	4
R_{20} (mΩ)	5.67	5.66	5.67	5.7
Inductance (mH @ 10 Hz)	1.8	1.79	1.79	1.81

Section and inspect coil ← Assess VPI quality and workmanship

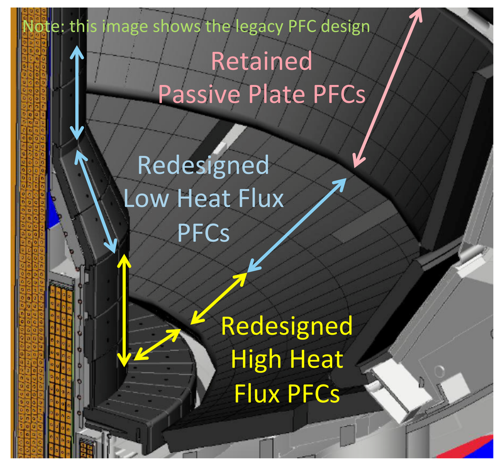
High-voltage tests on ground and turn insulation ← assess ground and turn insulation

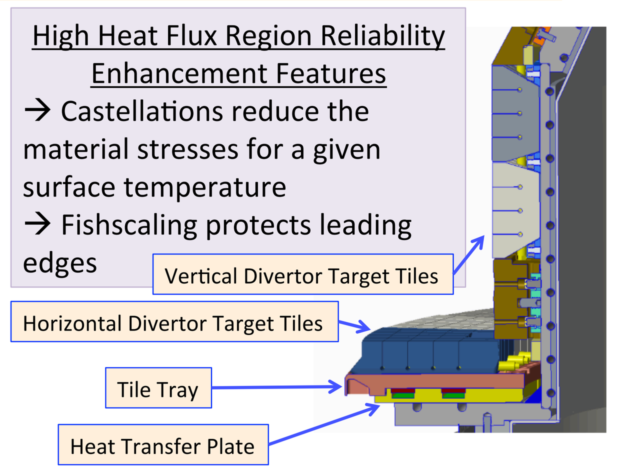


<u>4 of 4 coils have successfully completed the battery of tests</u>

2 vendors directly qualified, 2 with provisional need for improvements

Plasma Facing Component are Being Designed to Meet Full Performance Thermal and EM Loads



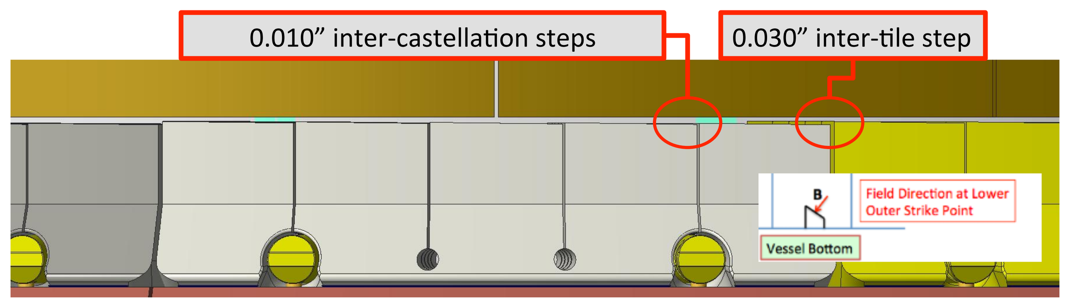


High Heat Flux- Full EM loads, with aggressive heat flux requirements:
~5.5 MW/m^2, 5 seconds @ 5 degrees incident angle, no toroidal leading edges

Low Heat Flux Region- Full EM loads, but modest heat flux requirements:
~3 MW/m^2, 5 seconds @ 8 degrees incident angle, leading edges allowed

Manufacturing and Physics Optimization has Led to the Choice of Final Fishscale Angles

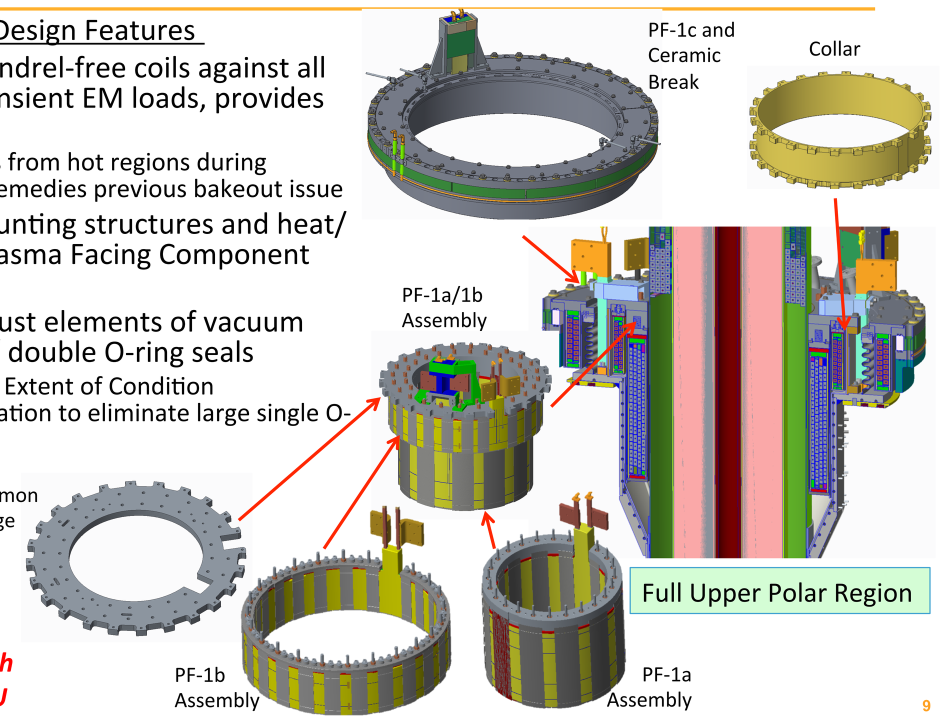
- Fish-scaling protects the leading edges of tiles against overheating
  - Prevents large carbon sources and potential edge cracking from thermal stresses
  - Required angle depends on the maximum incident angle, dimensions and tolerances
- Steeper fish-scale angles:
  - Facilitate a loose tolerance budget ← Good
  - Allows for erosion while preserving leading edge shielding ←Good
  - Results in increased heat flux in the non-shadowed regions ← Not Good
- Trade-off study → Requirement to “robustly” shield leading edges
  - Results in ~0.7-1 degree fishscale angle
  - Factor of ~1.5-2 heat flux enhancement at 1 degree incident angle



Polar Region Design Developed to Robustly Support the Coils and Provide a Highly Reliable Vacuum Boundary

<u>Design Features</u>

- Supports mandrel-free coils against all static and transient EM loads, provides preload
  - Isolates coils from hot regions during bakeout ←remedies previous bakeout issue
- Provides mounting structures and heat/ cooling for Plasma Facing Component (PFC) Tiles
- Provides robust elements of vacuum boundary, w/ double O-ring seals
  - Response to Extent of Condition recommendation to eliminate large single O-ring seals



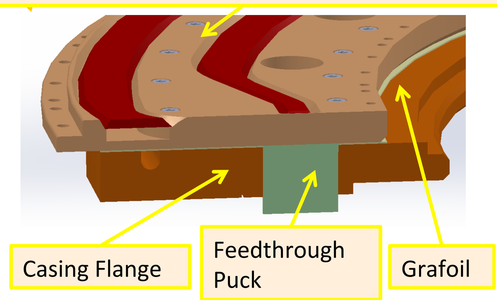
Polar Region = North and South Poles of NSTX-U

New Heating/Cooling Features are Being Added to the CS Casing

Requirements:

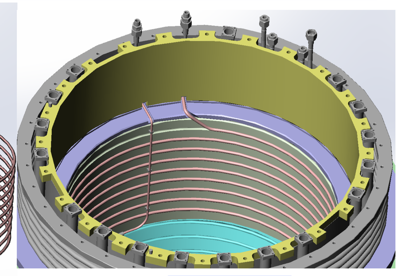
- Remove heat from tiles during normal operation, supporting a 20 minute repetition rate
- Add heat to tiles during bakeout, supporting >300 C bakeout for all tiles
- No use of water in the vacuum boundary

2: Inconel 625 Heat Transfer Plate- vacuum side cooling channels for hot or cold He

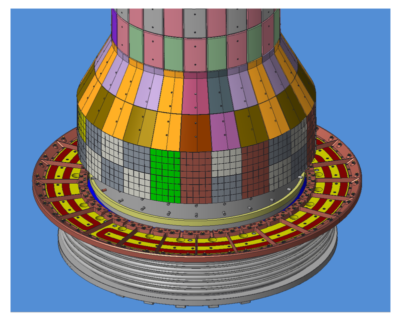


1: Heat Transfer Tubing – no angle section cooling

Formed

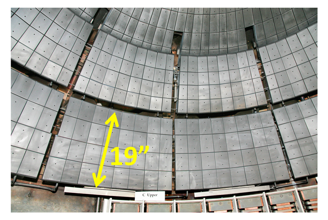


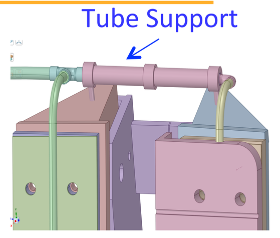
Installed

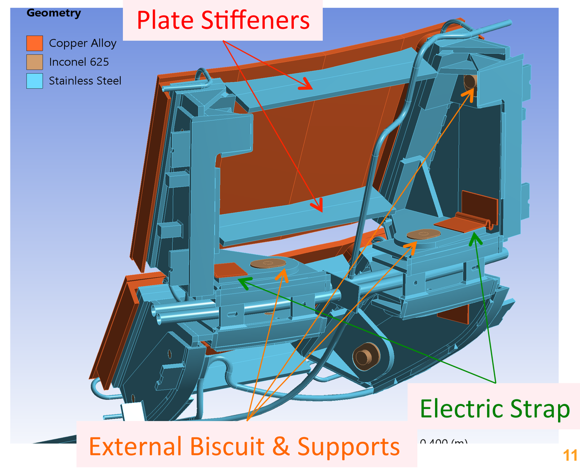


Passive Plate Motion Issues are Remedied with New Designs

- Passive plates are Cu plates covered by graphite tiles
  - provide stabilization to plasma instabilities
- Issues and resolution:
  - Flexing under EM disruption load →plate back stiffeners
  - Unacceptable play in their bracketry →stronger bolts and in-situ fastening augmentation
  - Non-uniform electrical resistivity →Dedicated electrical connections
  - Excessive EM loads on the He lines →Tube support for lines.
- Solutions can be implemented w/o significant disassembly







Strict Alignment Tolerances Defined

Coil	Tilt Tolerance	Shift Tolerance
	mrad	mm
PF-1a	2	3
PF-1b	2	3
PF-1c	4	5
TF Inner Legs	0.4	2

Tolerances between divertor and TF coils and the divertor target.

Ensure minimal non-axisymmetric heat fluxes on divertor PFCs

Tolerances between inner-TF legs and the vertical field coils

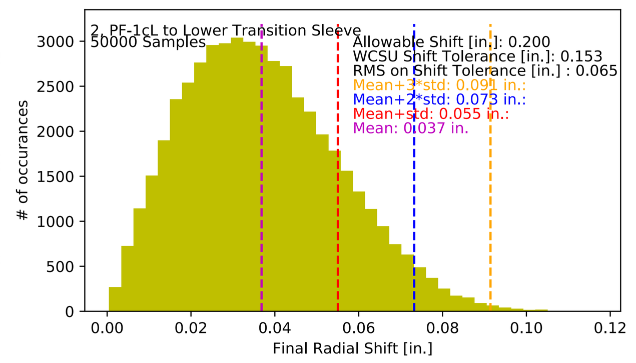
Ensure that global MHD (mode locking, NTV) do not impede operations

Coil	Shift Tolerance	Tilt Tolerance
	mm	mrad
Displacements between PF-5U and PF-5L	2	0.7
Displacements between PF-4U and PF-4L	2	30.7
Displacements between inner-TF axis and PF-5 Axis	1.5	0.5
Displacements between inner-TF axis and PF-4 Axis	2	0.5

Monte-Carlo Analysis Used to Assess Likely Misalignments

- Many mechanical interfaces between the coil Cu and the tiles
  - See slide on “Polar Region”
- Tolerances (shift, tilt) at each mechanical interface recorded
  - Match-machining used at some interfaces to reduce stackup across interfaces
- Use tolerances to complete a Monte-Carlo analysis
  - Accounts for shifts and tilts, with arbitrary toroidal phase of each perturbation
  - Typically use mean+3σ as the definition for meeting requirements

Example Distribution of Shifts between the PF-1c Coil and the Transition Sleeve (Vertical Divertor Target)



An Metrology Network Will to Enable Machine Alignment

- Key need: a means to provide alignment for components both inside and outside the vessel.
- Method: Contract vendors to set up a set of monuments on the outside of the vessel that have known locations in a global coordinate system
  - Multiple loops around machine with their precision hardware to “stitch” together a high accuracy coordinate system.
- Can then align metrology against those monuments as needed.
  - Vendors will also be asked to provide positional measurements of the outer-PF coils and the vessel nozzles.

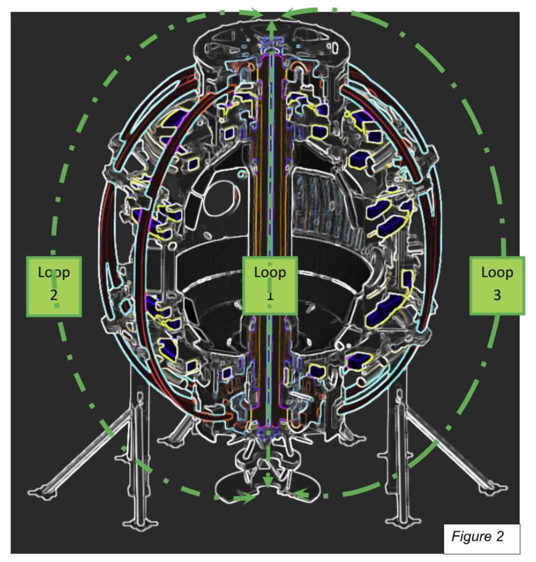
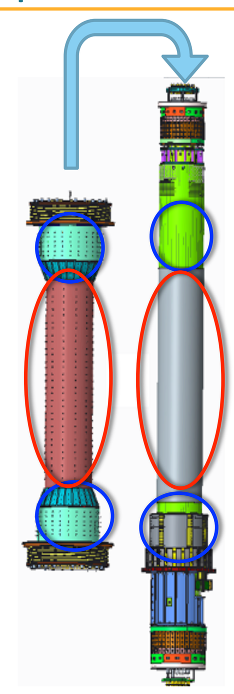


Figure 2

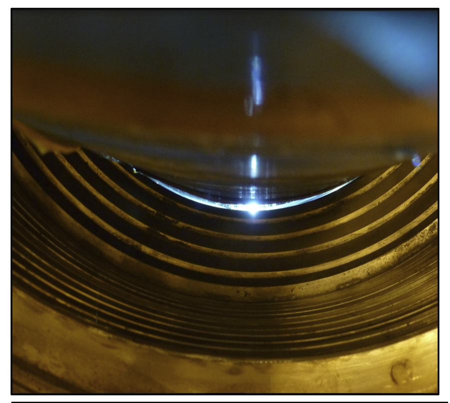
Trial Fit Activity Initiated to Ensure Casing Could be Aligned w/ Adequate Clearances

- Issues from 2016 run
  - Casing was significantly tilted relative to the bundle.
  - Microtherm insulation showed signs of damage when the casing was removed.
- Note: these issues primarily related to the central portion of the casing; largely independent of work on the ends
- Trial fit activity was initiated to assess alignment capability and clearance.



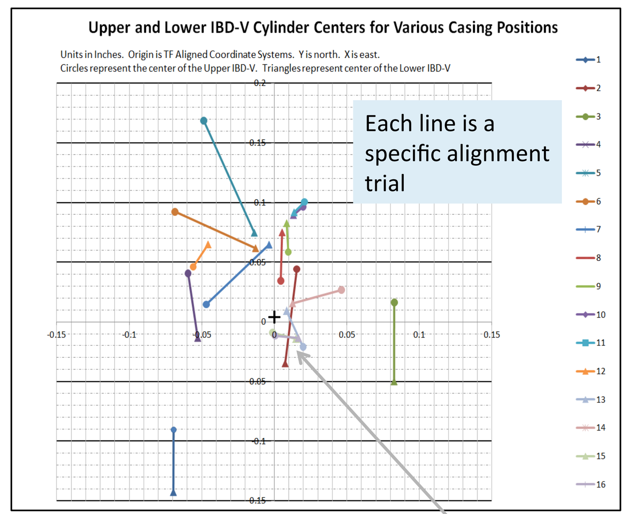
Trial Fit Was Successful in Aligning the Bundle

Image showing light visible the full length of the casing.



	-RD-11 Requirement	Achieved
tilt [mrad]	0.4	0.14

Each line connects points at top and bottom of the casing
Plot origin is centered on the TF coil
Units are inches



Final position of best alignment