National Spherical Torus eXperiment Upgrade

Design Update

NSTX-U Team Meeting – March 4, 2020

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Outline

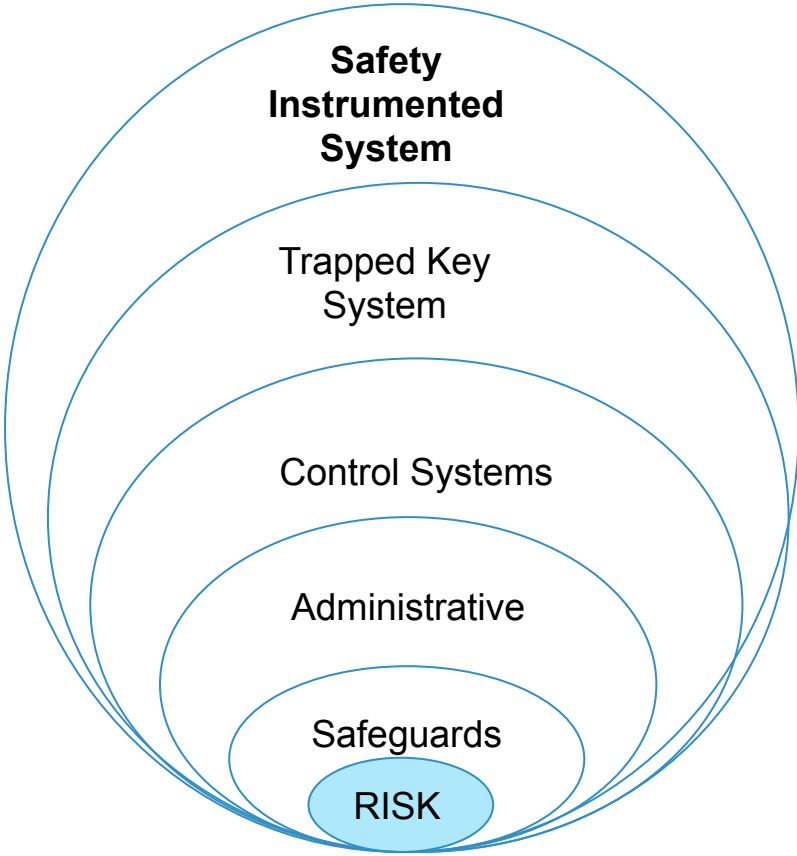
- Safety ← echo John's and Less' Message
- Design Related to Operations Safety
  - Personnel Safety System - three subsystems
  - Oxygen Monitors
- Other Design
  - Bus Work
  - PF-4 Radial Restraints
  - Private Flux Region Fueling
  - Bakeout Systems
  - Vessel Blackening & Duct Shields
  - Magnet Field Scope
  - Peer reviews to close MCS & Passive Plate chits
  - 27" Flange Seal Repairs
  - Central Control System
  - BES Shutter Repair
  - VVIH Field Scope
  - Shorted Turn Protection
  - TF Twist Measurement
  - Machine Instrumentation

Discussed in this talk
Overview in Backup

Layers of Protection - Personnel Safety System

- **PSS is for personnel protection**
  - **Keep the hazards from the people**
  - **Keep the people from the hazards**
- Hazards are mitigated through Independent Protection Layers
- Safeguards, administrative controls trapped key system are effective at mitigating contact hazards
  - Electrical, thermal, vacuum
- Direct Ionizing Radiation requires further risk reduction → mitigated through the PSS Safety Instrumented System (SIS)

Calculation - link



Configuration Managed Safeguards Protect Against Contact Hazards

- Electrical Hazards
  - Covering bus runs
  - Barriers around (but stood off from) the machine proper
  - Cages in the gallery
- Thermal Hazards
  - Covers over the bakeout insulation to ensure it is touch-safe
- Vacuum Hazards
  - Covers over windows

Prototypical Cover with Trapped Key Interface

How to do configuration management?

Procedures, drawings, labels, tamper-proof fasteners, and trapped keys.

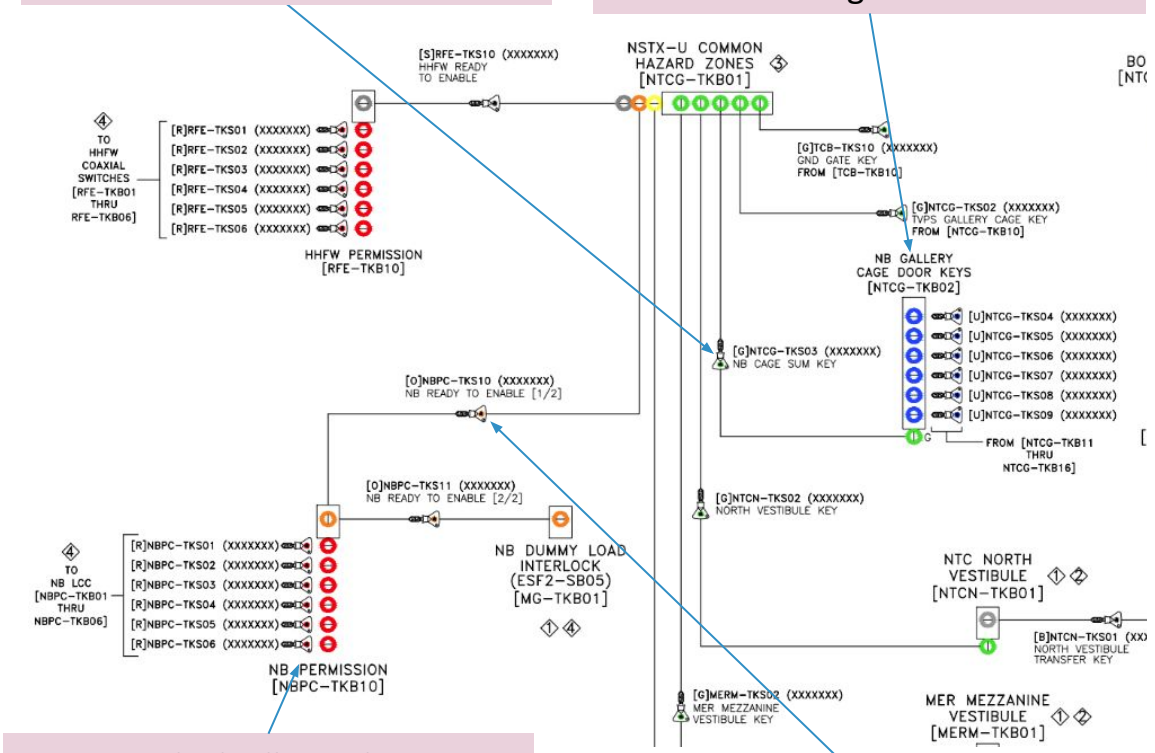
Trapped Key System Ensures the Configuration is Correct

Trapped Keys dedicated to personnel safety.

The keys required to turn on the sources of hazardous energy can only be extracted from their key blocks if all the safeguards are in place, test cell locked, etc

2: ... to extract the green key.

1: Ops personnel must lock these cages...



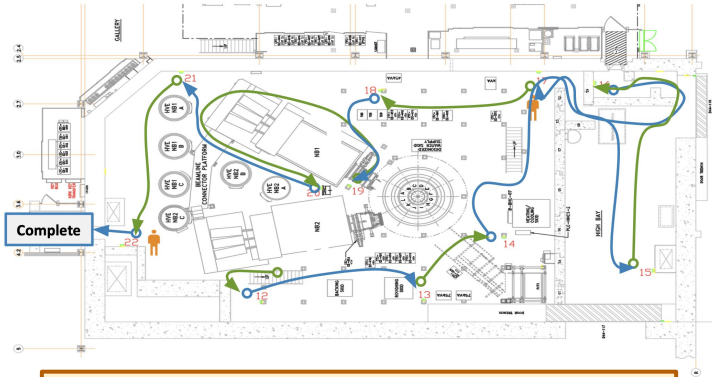
4: ...which allows the NB controls to be energized

3: When all the keys are accumulated, can get the this key...

PSS-Safety Instrumented System

- Follows consensus standards IEC 61508/61511
- Functionally
  - Door interlocks in test cell, MER mezzanine, cable spread room, etc
  - E-stop buttons
  - Inconsistent state monitoring - Ex: ensure at least one electrical break is always present when test cell is in “Access”.
  - Engineered Search and Secure - route enforced by placement of search stations
- Design Features
  - Redundant safety-rated door switches, redundant safety-rated breaker-trip mechanisms
  - Safety-class PLC
  - Fail safe design, including major upgrade to D-site breakers to ensure fail-safe behavior
  - Dedicated labeling, tamper-proof fasteners

Combined E-Stop & Search and Secure Station



Lower Level Search and Secure Route

Oxygen Deficiency Monitors will Be Added to the Test Cell

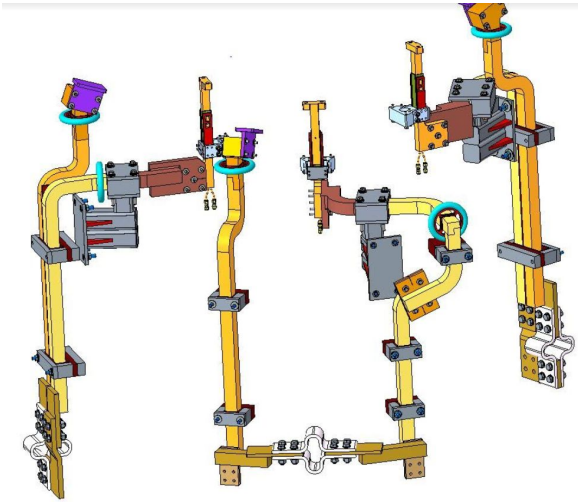
- Sources of oxygen deficiency conditions in the test cell and vicinity:
  - LHe supply for the beamlines
  - LN2 supply for the beamlines
  - SF_6 in the beam power supplies
- Adding *redundant* oxygen monitoring at numerous locations
  - At elevation (primarily to detect He as it stratifies)
  - Between beamlines (primarily to detect LN2)
  - Under machine (primarily for LN2, but also Ar from the Argon Purge System)
  - In shield door pit (primarily for SF6 accumulation)
- Also installing sensors in the gallery, at floor level and elevated
- You will receive additional training, but the simple message is: if you hear the alarm, you need to leave

Laser Spectroscopy Based Oxygen Deficiency Monitor

Can detect oxygen deficiency in the presence of any displacing gas

Inner-PF Bus Work

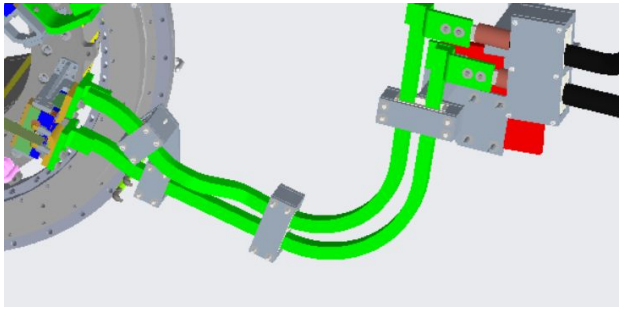
- Hard bus for PF-1a U/L, -1b U/L, and -1c U/L, bakeout all redesigned
- New water-cooled flex for PF-1b designed



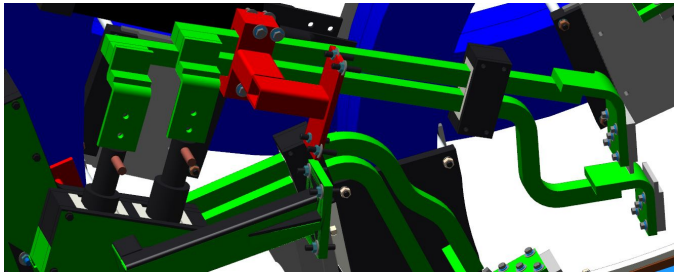
Lower Bakeout Bus Work

- Stresses are due to EM, thermal loads on the coil and leads, displacements of structures - significant design challenge
- Attempted to follow same routes as previous → should not result in new interferences with legacy installations

PF-1bL Bus and Supports



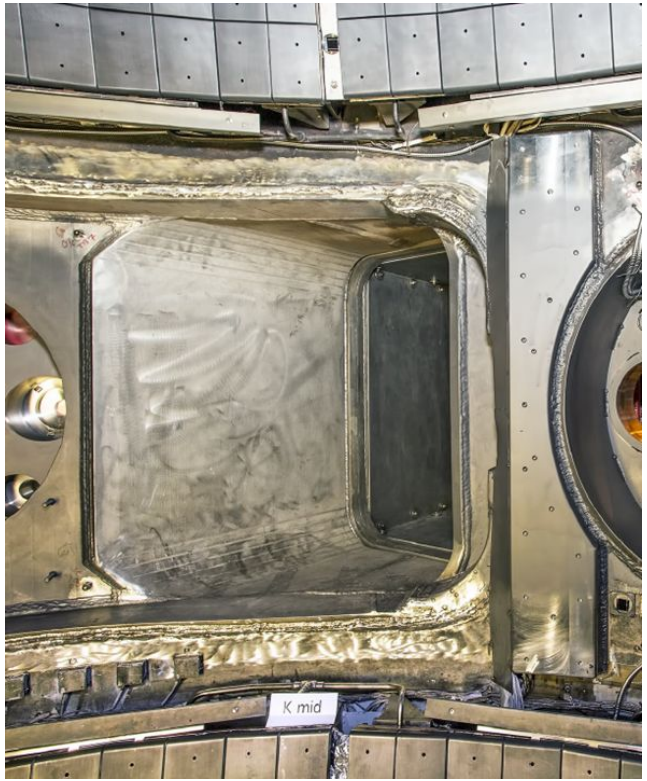
PF-1aL Bus and Supports



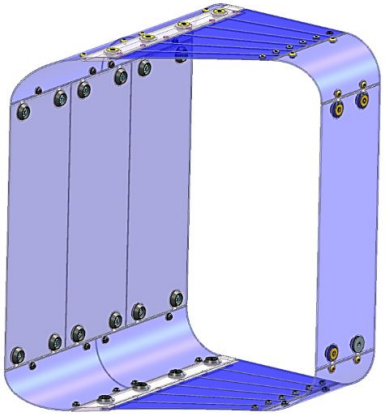
Cai, Brooks, Rana, Titus, Wang, Khodak, Sheckman, Winkelman, et al, FDR link, link, wrapping up design at phase III FDR this Friday

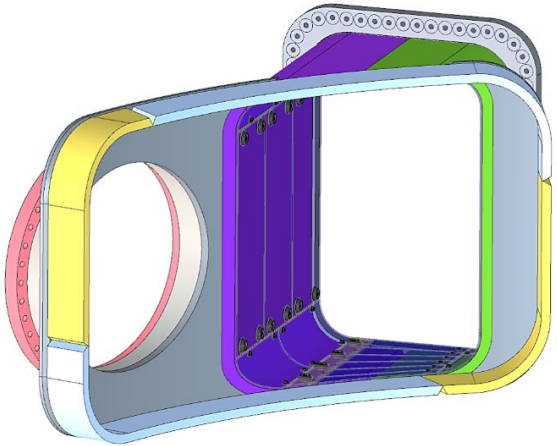
Enhanced Duct Shielding for Bay K

Bay K Duct
NB#2 Comes Through Here



- Neutral beam #2 is injected into plasma via this duct.
- If the pressure in the duct is too high, beam can become ionized.
- Charged beam particles bend in the magnetic field, striking the side of the duct
- New segmented TZM Moly duct shields can handle all thermal, disruption loads in the duct

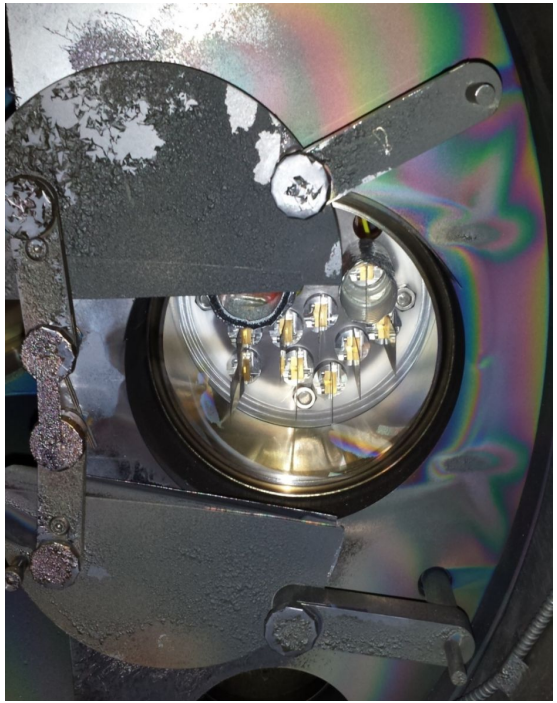




Blackened Custom Plates Will Be Used to Provide Vessel Blackening

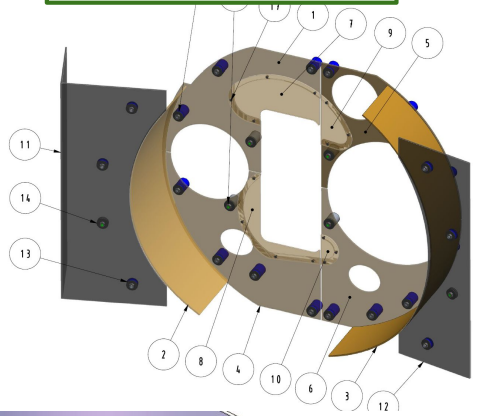
Must blacken portions of the vessel walls to prevent light from reflecting into various key diagnostics

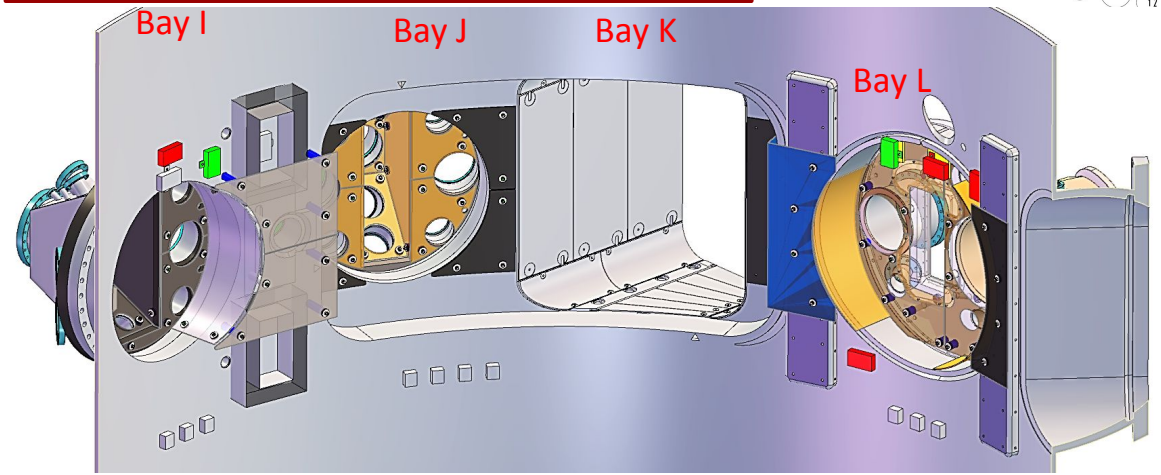
Aerodag flaking off in 2016 → not acceptable



- Custom SS plates with “Black Oxide” Coating
- Good vacuum and lithium comparability
- Analysed to be compatible with disruption and head loads

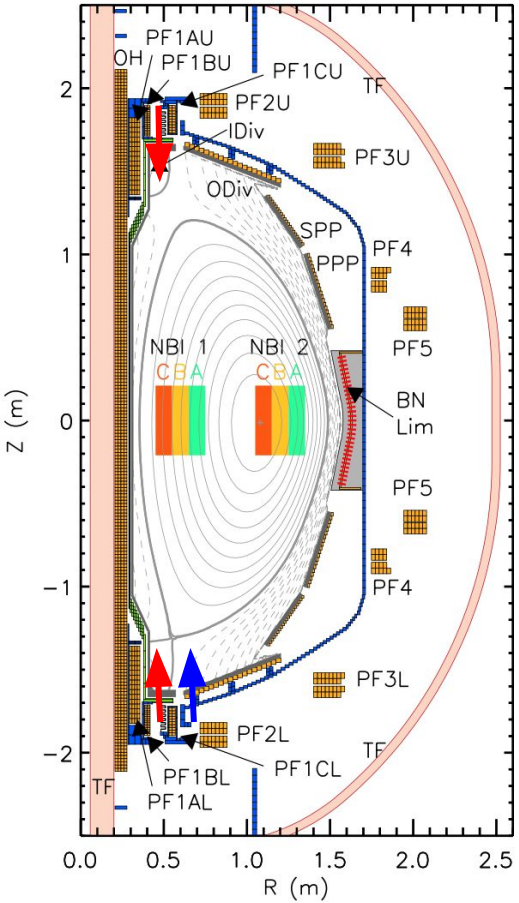
Bay I Plates



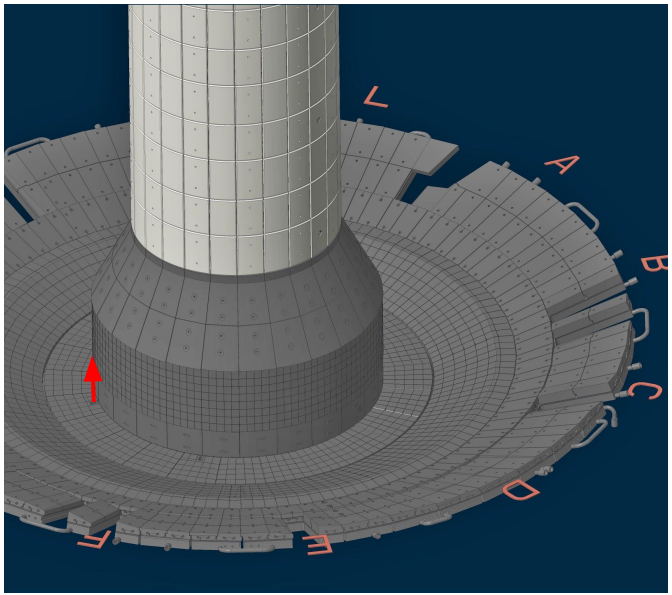


Private Flux Region (PFR) Fueling Design Complete

- Piezo-valves that inject gas into the “private flux region”
- 1 each top and bottom
- PCS control of injector open/close.
- Will allow studies of enhanced photon radiation to limit heat to the PFCs
  - Including comparison to similar outboard target injectors



← PFR Injection location relative to plasma (red)
OBD injection location (blue)



Injection location relative to PFCs

Machine Instrumentation

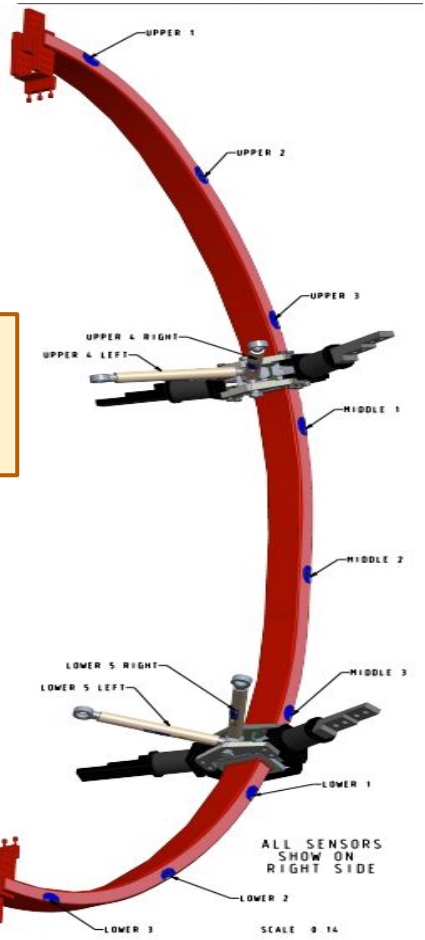
Machine instrumentation program is defined to assess the mechanical behavior of the machine:

- Model validation
- Trending over time
- "Out of family" detection

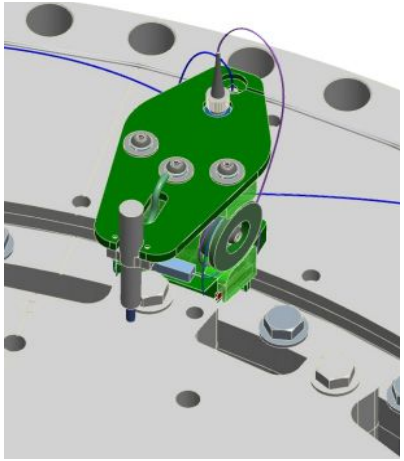
All fiber optic based.

Some examples...

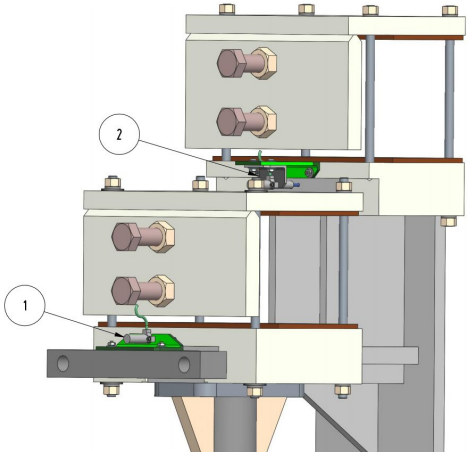
Strain sensors to assess the bending behavior of the TF outer legs



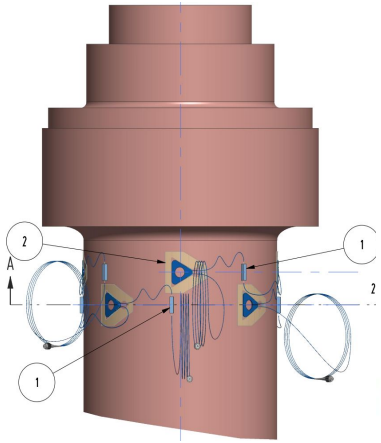
Relative Thermal Expansion of the CS relative to the Outer Vessel



Displacement of sliding joints on PF-4 and PF-5 coils



Stain Rosettes to Measure TF Bundle Twist Under EM Loads



Summary

- Recovery Project engineering team has completed an enormous amount of design
- These elements will make key improvements in the safety and reliability of our operations
- It is exciting to transition to fabrication, construction, installation

Backup

Shorted Turn Protection (STP) Fills Gap in Coil Protection Systems

STP checks the measured current and voltage against realtime models, declares a fault if the behavior deviates beyond thresholds

Measure Current and Voltage - Replacing the present legacy coil voltage measurements with new dividers, custom electronics

Realtime - voltage measurement will be available in realtime to STP system, as well as PCS.

Models - state representation of the NSTX-U coil system includes all mutual couplings (including to the vessel)

Declares a Fault - Voltage will be removed from all coils in the event of a I/V anomaly

Coil Protection Scheme - High Level Summary

Coil Ground Faults	Power conversion ground fault detection (existing)
Coil overcurrent, excessive I^2t, excessive force	Digital coil protection system (existing)
Coil overheating	Cooling water interlocks (existing)
Coil Terminal, Layer-to-Layer Faults	Shorted Turn Protection system (new)

Bakeout - DC Supply Movement

DC supplies drive ~8 kA of current down the CS casing, ohmically heat it

Supplies used to be wheeled into test cell for bakeout - connected at the machine bottom

With elimination of the lower ceramic break, they must connect at the machine top → Locate them there permanently → shorten the time to enter the bakeout configuration

Put these...

...here. (Southwest side of highest platform)

and:

- Reinforce platform
- Run DI water
- Power and control cabling
- Install cable tray for cabling to the machine

PSS-SIS and CCS Upgrade/Replace the Legacy HIS

Hardwired Interlock System (HIS) - a rack full of relays - served two functions

1: Allowed COE to grant permission to enable and arm system (Neutral Beams, Rectifiers, RF)

2: Generate emergency stops via door interlocks, e-stop buttons → opened breakers and line/ground switches in the event of an emergency stop

Control room parts replaced by Central Control System (CCS) - "loop set" will come from this new PLC

Replaced by the new Personnel Safety System

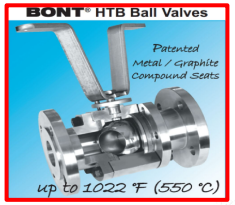
Bakeout - Helium System Instrumentation and Control

Helium system provides gas at ~430 ℃ to piping inside the machine

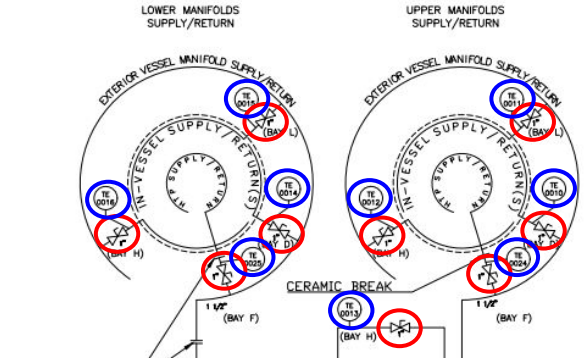
In-vessel piping is functionally unchanged, helium skid unchanged.

Adding the following capabilities:

- Flow control valves - ability to throttle back flow at each of 9 locations here He enters the vessel → better control, facilitates He cooling during plasma operations
- Temperature measurements at all He inputs and outputs on the vessel → better understanding of the bakeout heat deposition
- He flow measurements to the top and bottom manifolds on the machine → better understanding of He flow



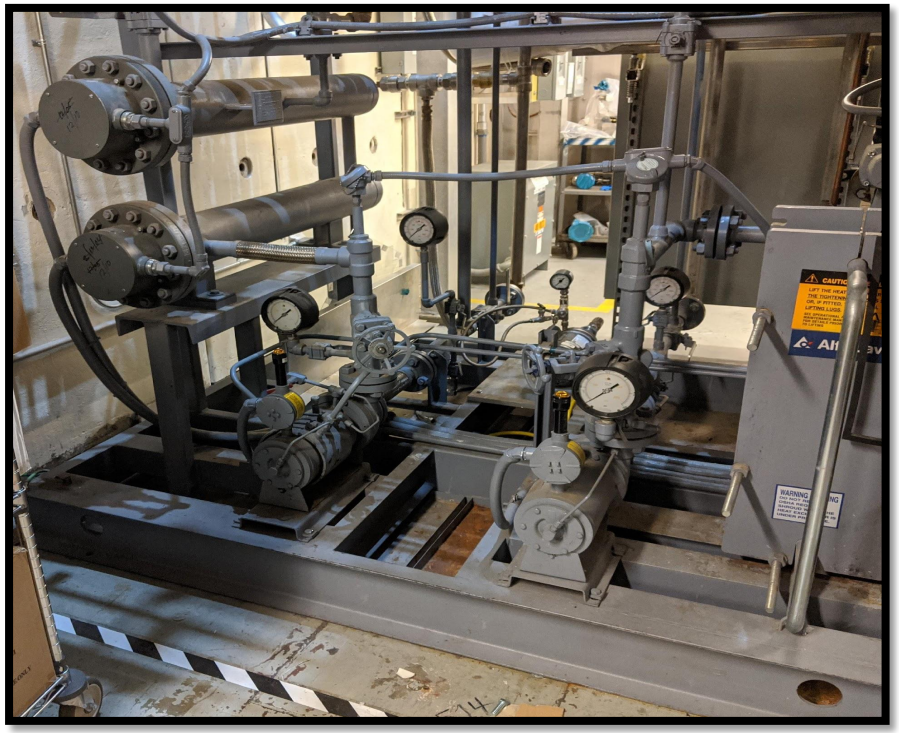
Supply Manifolds



Bakeout - Water System Improvements

Operate the bakeout system with pressurized ~150 ℃ H_2O on the vessel skin - above the atmospheric pressure boiling point

Potential issue → system can rupture if the H_2O flashes to steam (pressure loss, excessive temperature)



Actions:

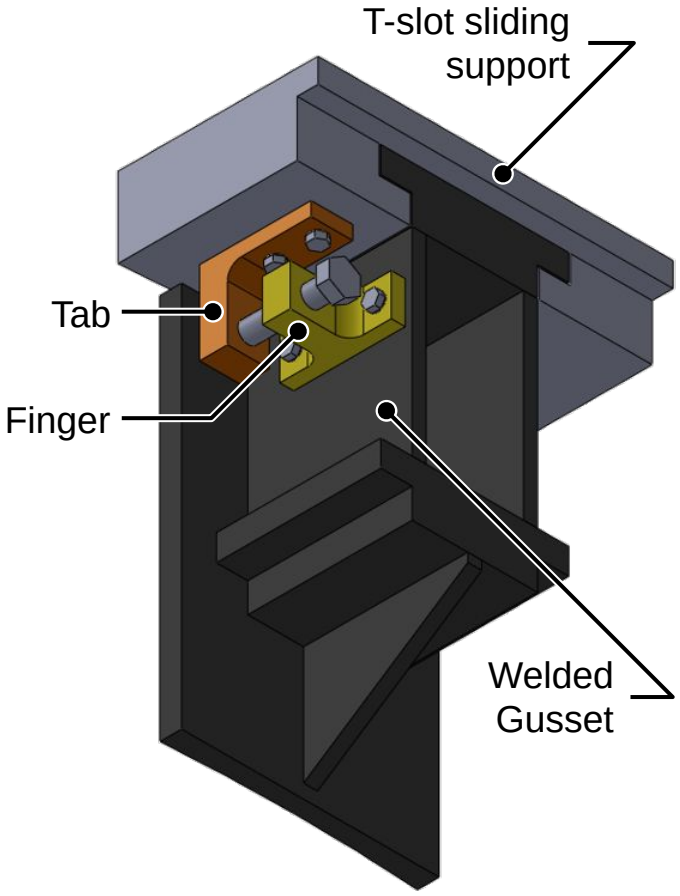
Significantly reducing the volume of water in the system

Adding redundant circulation pumps

Adding temperature and pressure interlocks with automatic system blow-down

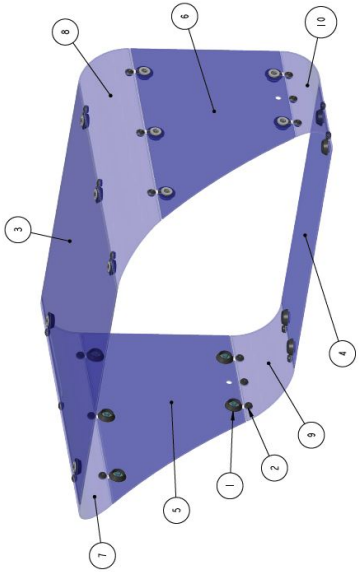
Scope: PF-4 Radial Constraining Pin

- PF-4 pin will be installed on both sides of the existing T-slot supports for both the Upper and Lower PF-4
  - Needed to bring in-field conditions into compliance with analysis modeling assumptions
- Restricts outward radial motion of the coils at two locations during operations
  - Same use case as existing PF-5 pin
- Requires minor modifications to existing welded gusset support and T-slot sliding support

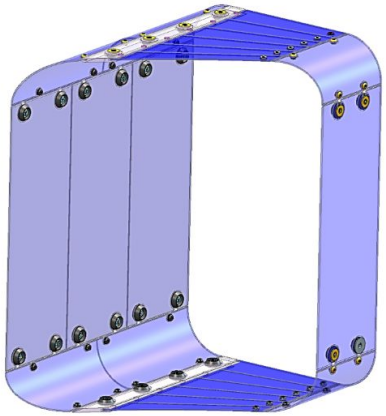


NBI Duct Guard - Final Design

- NSTX-U structural design requirements qualify parts for thermal and EM loads.
- Stress due to EM loads is inversely proportional to electrical resistivity of material used.
  - TZM Molybdenum: (6.85 μΩ·cm)
  - 316 Stainless Steel: (74 μΩ·cm)
- EM and thermal analysis progression since CDR show high stresses due to eddy current effects and thermal gradients.
- Segmenting the duct guard is necessary to qualify parts for NSTX-U EM loads and fatigue cycling.



NB Duct Guard at Bay K
Design Presented at CDR

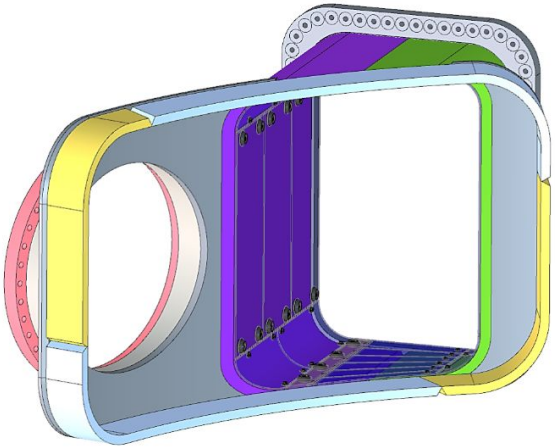


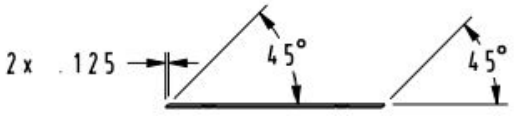
NB Duct Guard at Bay K
Design Presented at FDR

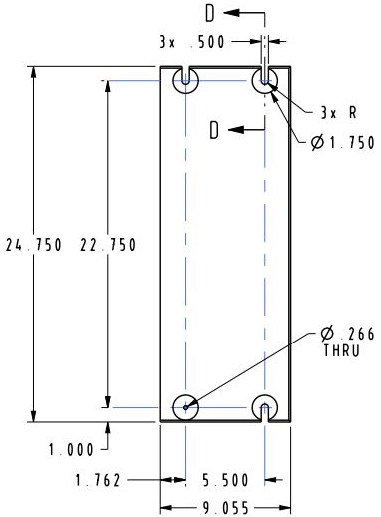
NBI Duct Guard - Final Design (cont.)

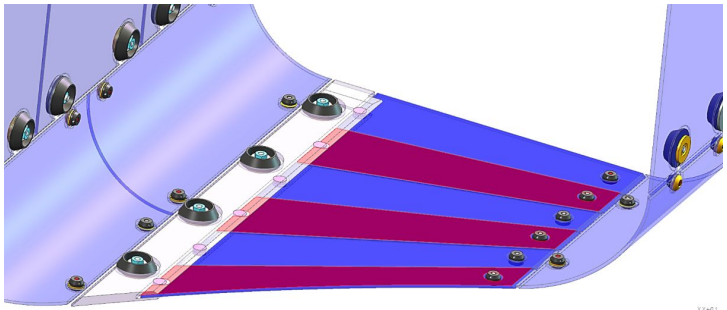
NBIDUCTGDCDR 07	**Please assess if there are practical means to install one or more TCs behind the plate, respecting the requirement for maximum duct** No nearby feedthroughs for easy thermocouple install.	**CLOSED**

- Full 360 degree coverage of neutral beam duct at Bay K.
- 24x plates, each electrically isolated.
- Custom sloped molybdenum washers.
- Downstream plates shadowed by upstream plates using chamfers.









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