NSTX Center Stack Upgrade Overview

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Princeton Plasma Physics Laboratory
NSTX Upgrade Project

Office of Science Review
LSB, B318
December 15-16, 2009

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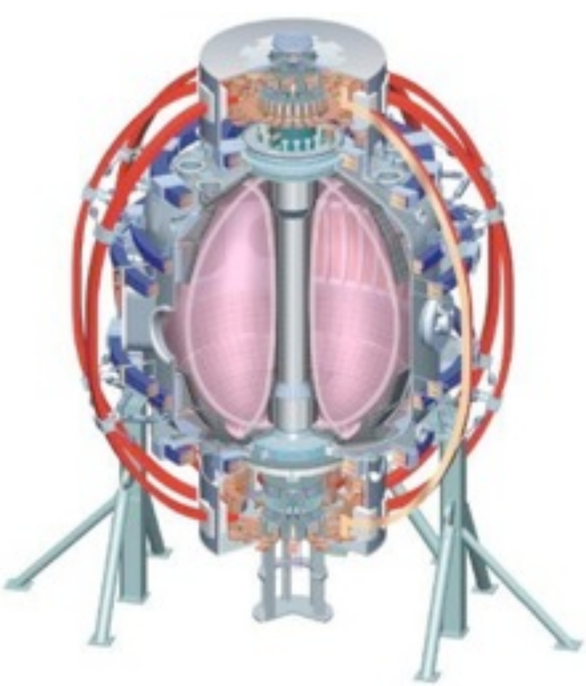

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Wednesday, December 2, 2009

Outline

- Introduction
- Scope
- Upgrade Description
  - Core
  - PF / TF Coil Structures
  - Power Systems
- Cost Estimates
- Risk
- Summary

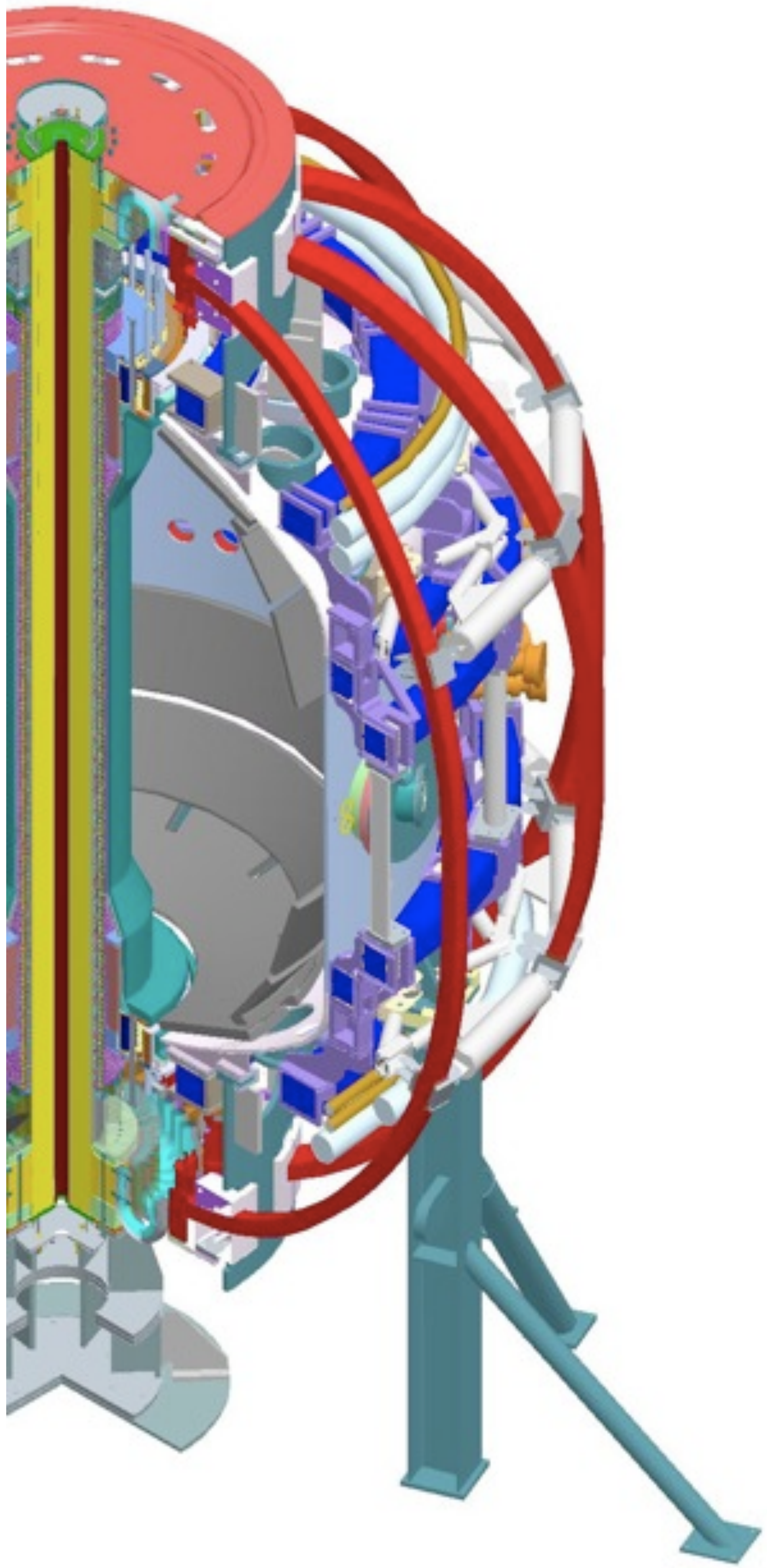
Introduction

- Purpose
  - To expand the NSTX operational space and thereby the physics basis for the next-step ST facilities
  - To achieve higher levels of performance and pulse duration
- Requirements Summary

	NSTX	NSTX-CSU
Plasma Major Radius [m]	0.8540	0.9344
Aspect Ratio	1.266	1.500
Plasma Current, I_P [MA]	1.0	2.0
Toroidal Field B_t [T]	0.55	1.0
Pulse Length, T_{pulse} [s]	1.0	5.0
Rep Rate $T_{repetition}$ [s]	600	2400
Center Stack Radius $R_{centerstack}$ [m]	0.1849	0.3148
Antenna Rad, $R_{antenna}$ [m]	1.5740	1.5740

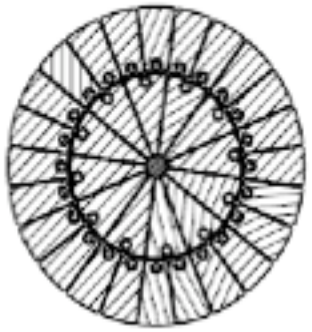
NSTX Upgrades Scope

- Changes to the Central Core:
  - Toroidal Field (TF) inner leg bundle including flags, hubs, and flexible connectors
  - Ohmic Heating (OH) coil
  - Poloidal Field (PF) coils PF1A Upper, PF1A Lower, and PF1B
  - Center Stack Casing (CSC), Insulation, Plasma Facing Components
  - TF, OH, PF1A Upper (PF1AU), PF1A Lower (PF1AL), and PF1B Lower (PF1BL) coil electrical leads
  - CS and Supply piping for heating and cooling of CSC and IBD
- Structural Improvements
  - PF Coil & TF outer leg supports
  - Pedestal which supports Center Stack Assembly from floor
  - Vacuum vessel if required (VV)
- Electrical Systems
  - Power Systems, CS Bakeout system, I&C systems
- Center Stack Diagnostics Sensors
- Auxiliary Systems
  - Cooling water system mods
  - CS and Supply piping for inboard gas injection

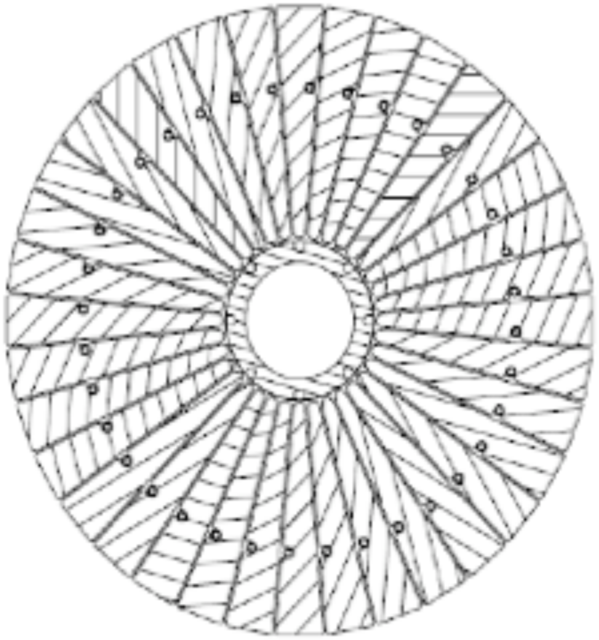


TF Design Parameters

	Base Design	Upgrade Design
Operating Voltage	1013 volts	1013 volts
Number of turns	36	36
Number of layers	2	1
Cooling	Water	Water
Operating current	71,168 amps	129,778 amps
Turn insulation	0.0324 in.	0.0324 in.
Dielectric strength- turn insulation		3.8 KV [3] half-lapped layer glass
Groundwall insulation	0.054 in.	0.090 in.
Copper mass	2260 lbs	10,900 lbs
Outside diameter	7.866 in.	15.752 in.
Insulation scheme	B-stage CTD-112	S-2 glass and VPI CTD-101K
Cooling hole size ID	0.186 in.	0.305 in.



Current TF Bundle 7.9 inch diameter

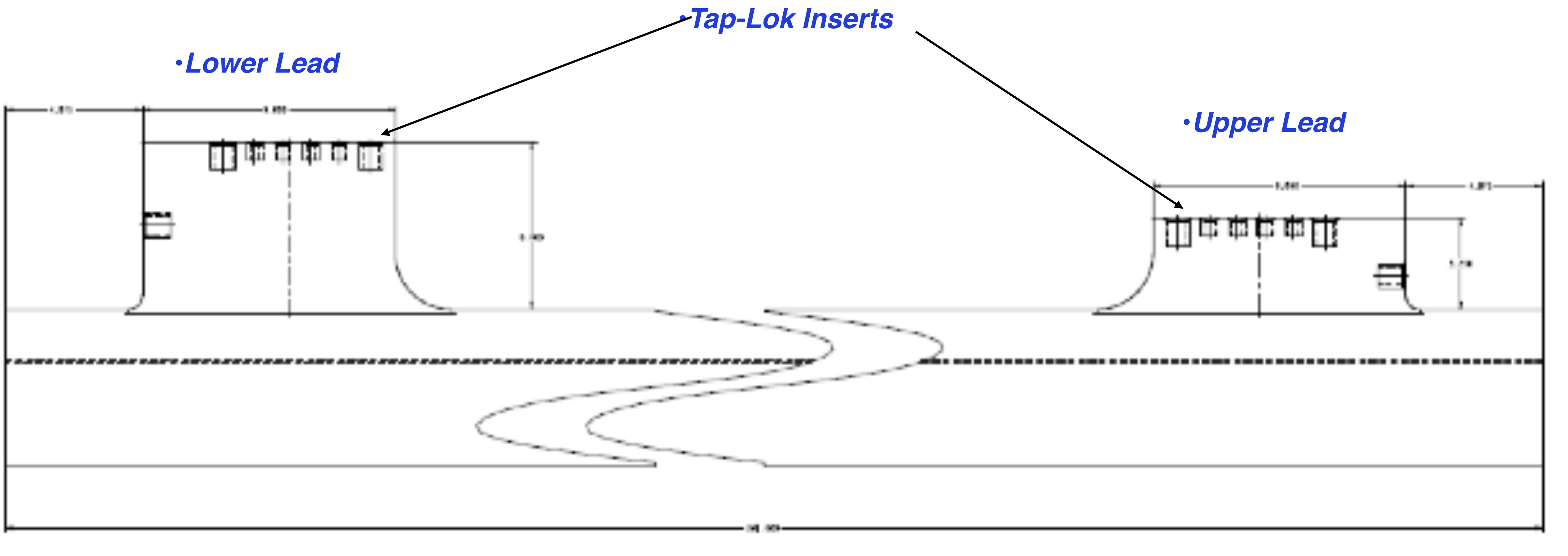


Upgraded TF Bundle 15.7 inch diameter

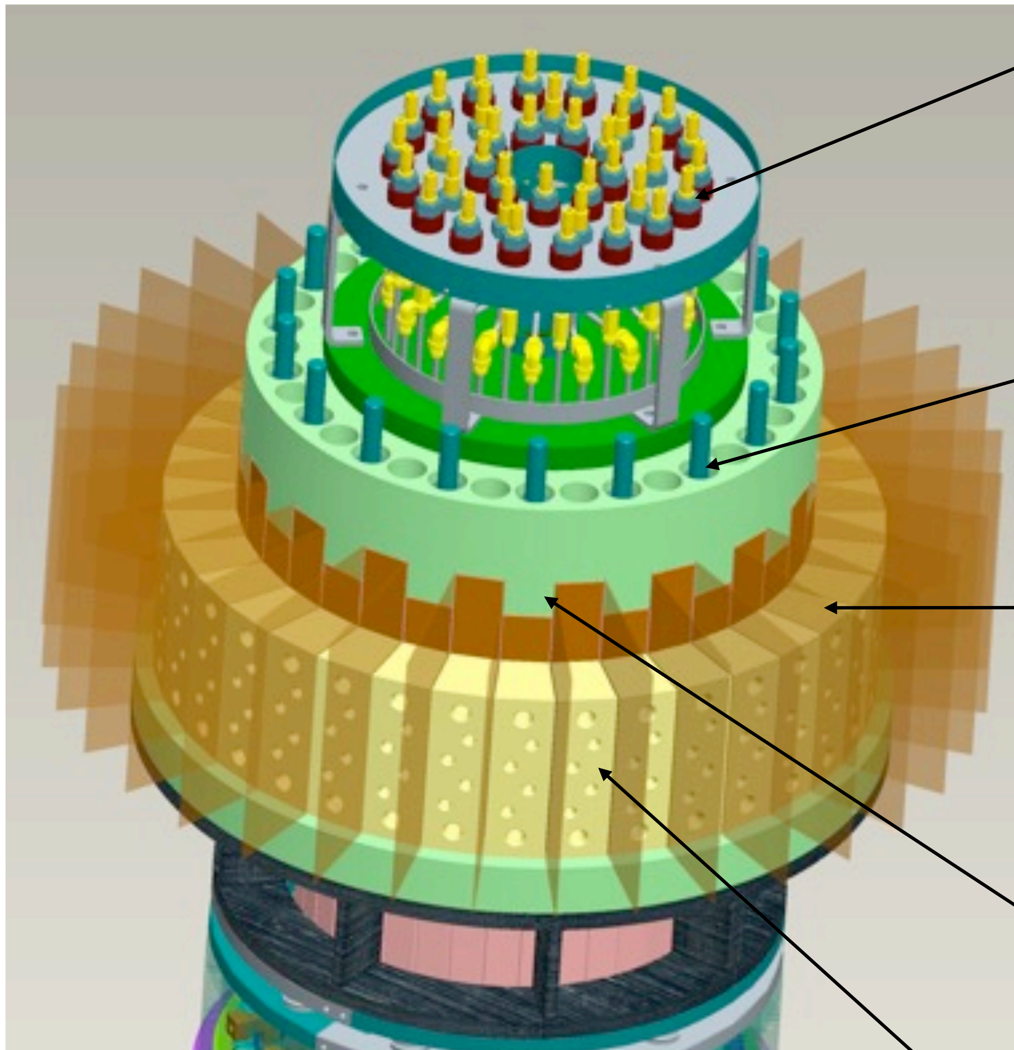
**** Reference: Per half-lapped layer- 1260 volts [VPI impregnated glass]***

Conductor Lead Extensions

- Lead extensions will be added to the TF bundle via Friction Stir Welding [FSW]
- The upper coil lead is shorter in height than the lower to allow for installation of the PF1A coils and Center stack casing
- Lead extensions will be fabricated using higher strength copper [Cu-Cr-Zr]
- Tests were performed by Edison Welding Institute to qualify procedure [OFHC to OFHC]
- Additional tests using C18500 are being scheduled
- Due to the serial nature of the fabrication of these conductors this work is on critical path
  - **Plan is to submit this to DOE for approval as early procurement**

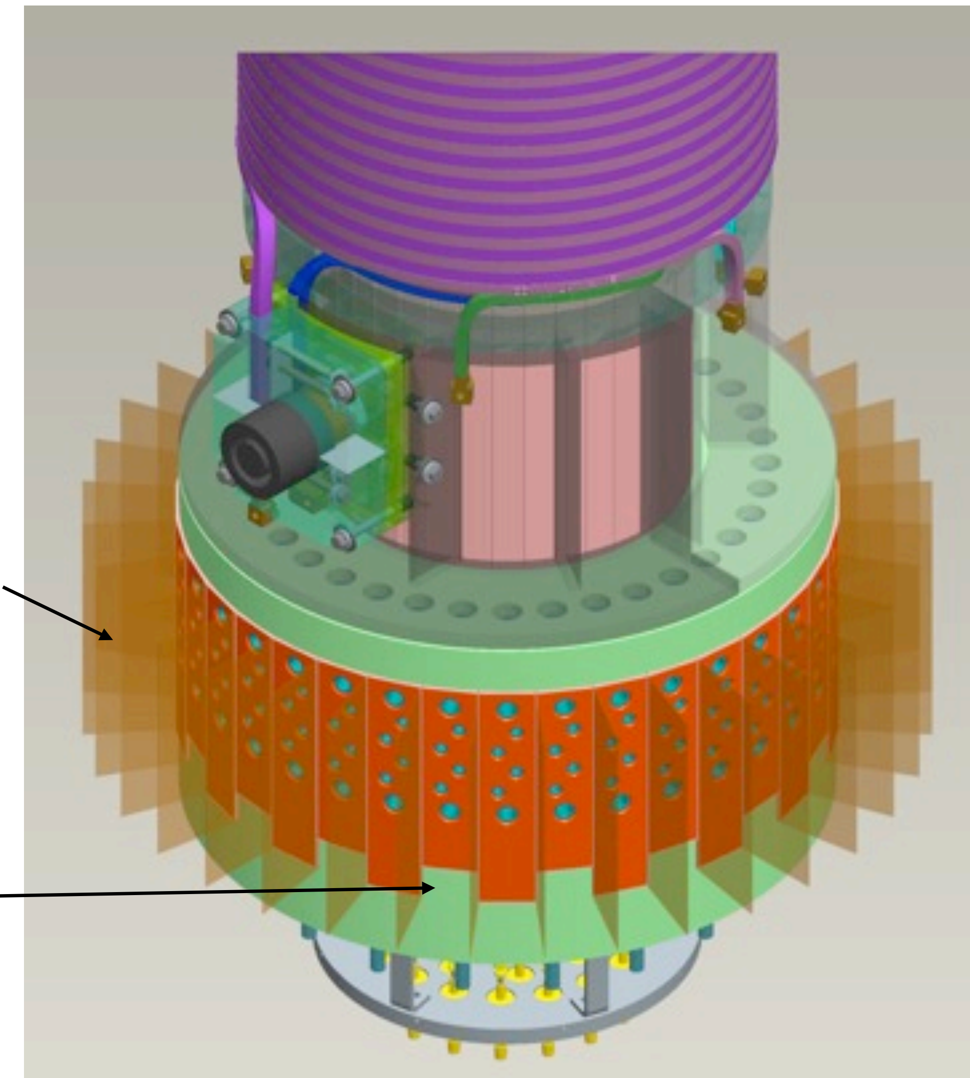


Inner TF Bundle End Details



•Upper TF Bundle

- Quick disconnect cooling tube connections
- Umbrella lid interface
- G-10/Kapton flash shield between lead areas
- G-10 Interlocking top plate
- Lead extensions [Upper only]



•Lower TF Bundle

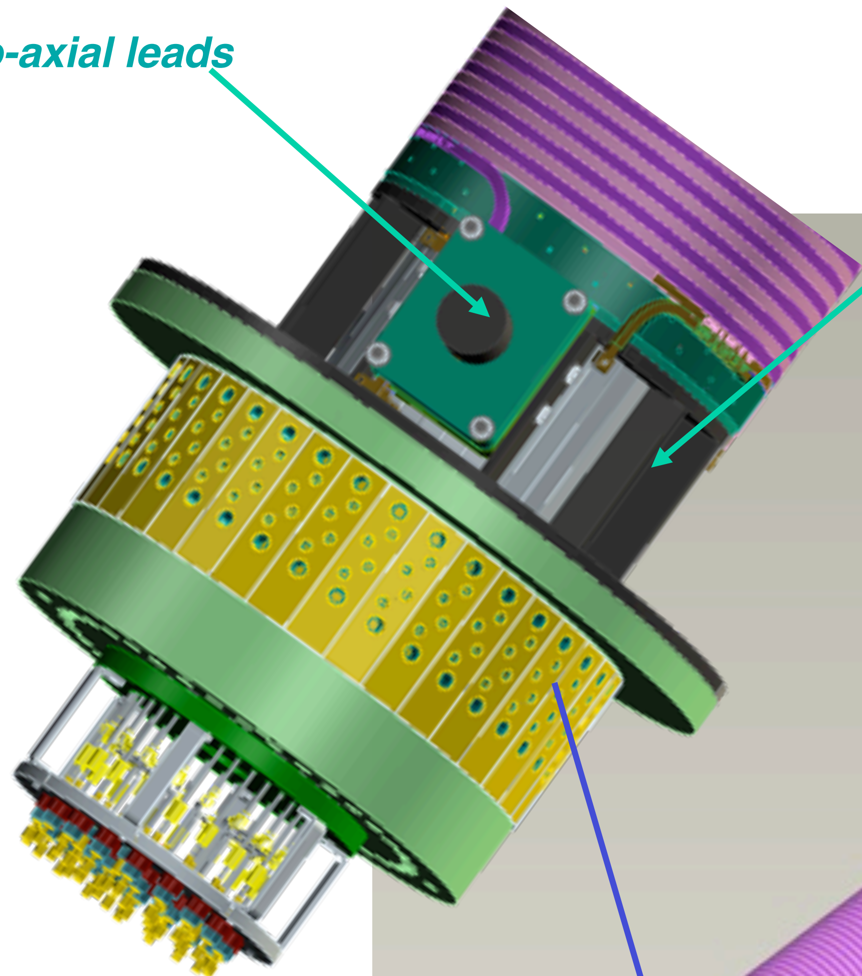
Ohmic Heating Solenoid

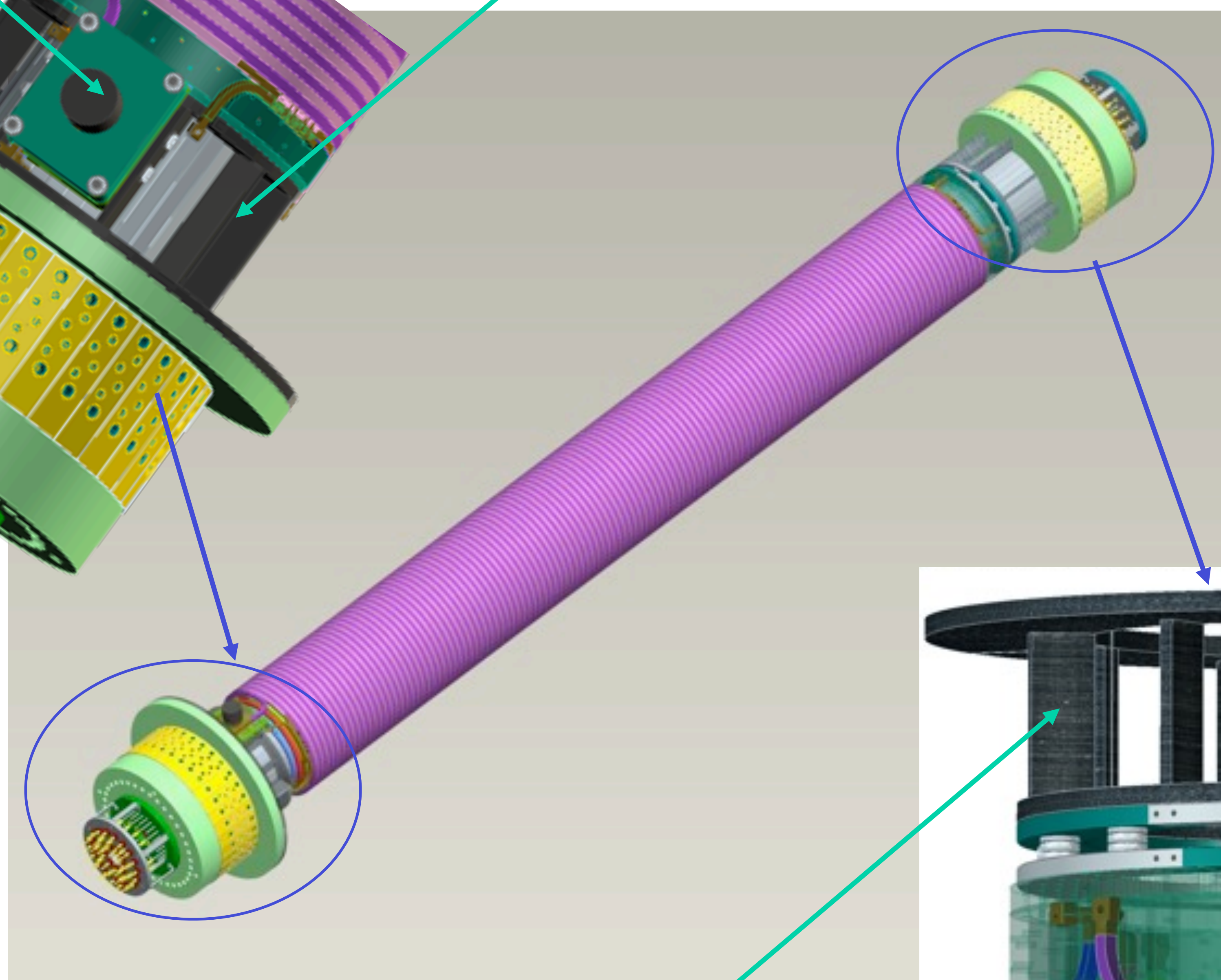
•*Design Parameters*

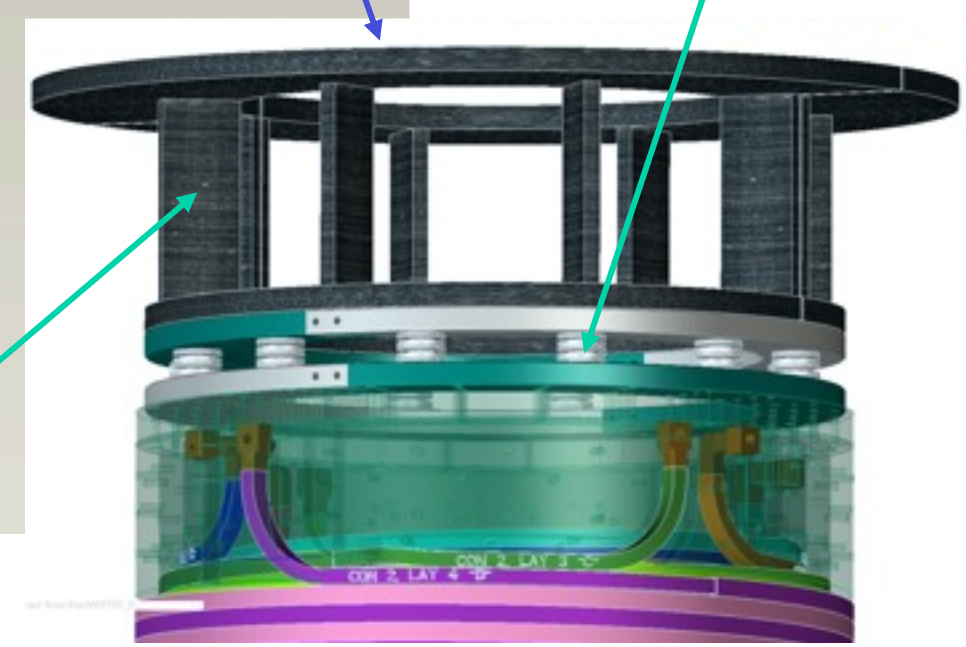
	Base Design	Upgrade Design
Operating Voltage	6077 volts	8100 volts
Number of turns	964	1148
Number of layers	4	4
Cooling hole diameter	0.188 in	0.175 in
Operating current	24,000 amps	24,000 amps
Groundwall insulation	0.054 in.	0.090 in.
Turn insulation	0.0268 in	0.0480 in
Turn insulation dielectric strength		16.4 KV
Outside diameter	12.304 in	22.10 in
Copper mass	2340 lbs	6400 lbs
Cooling paths	8	8

**** Reference: Per half-lapped layer- 7.6 KV [Kapton] and 1260 volts [VPI impregnated glass]***

OH Solenoid End Details

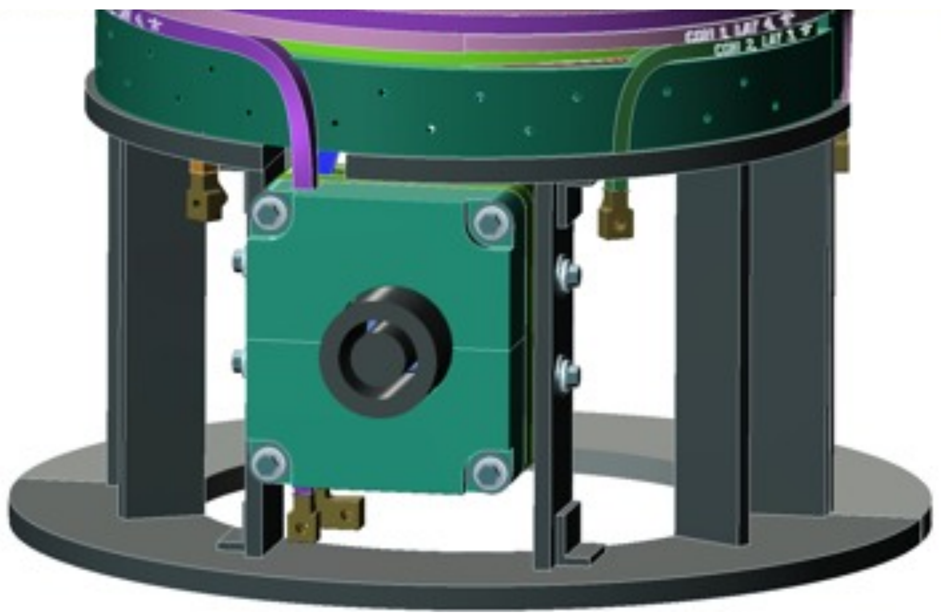


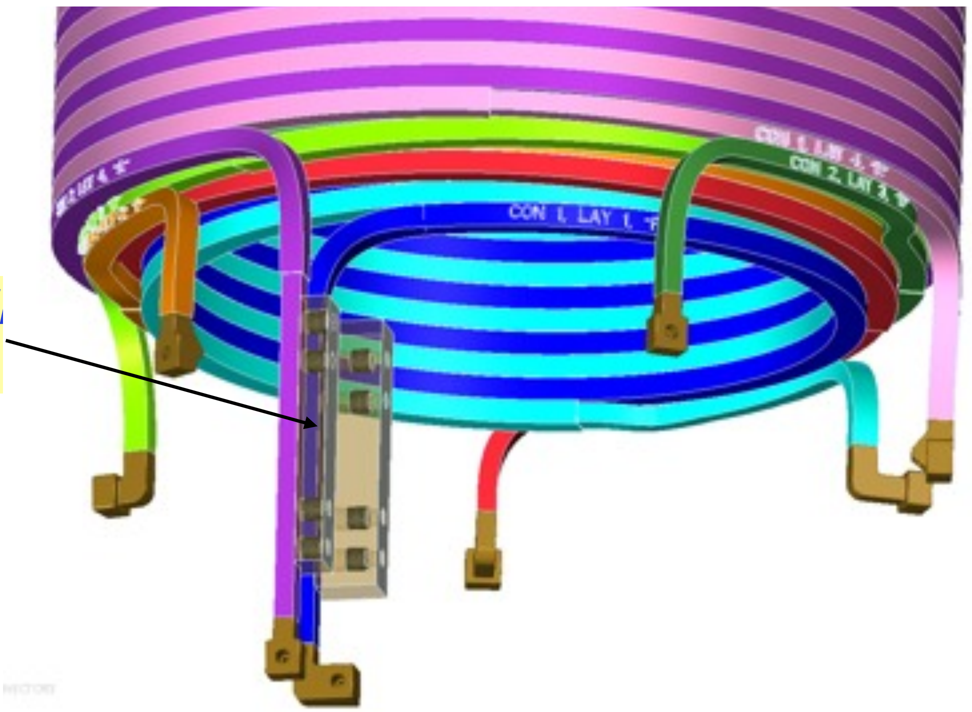




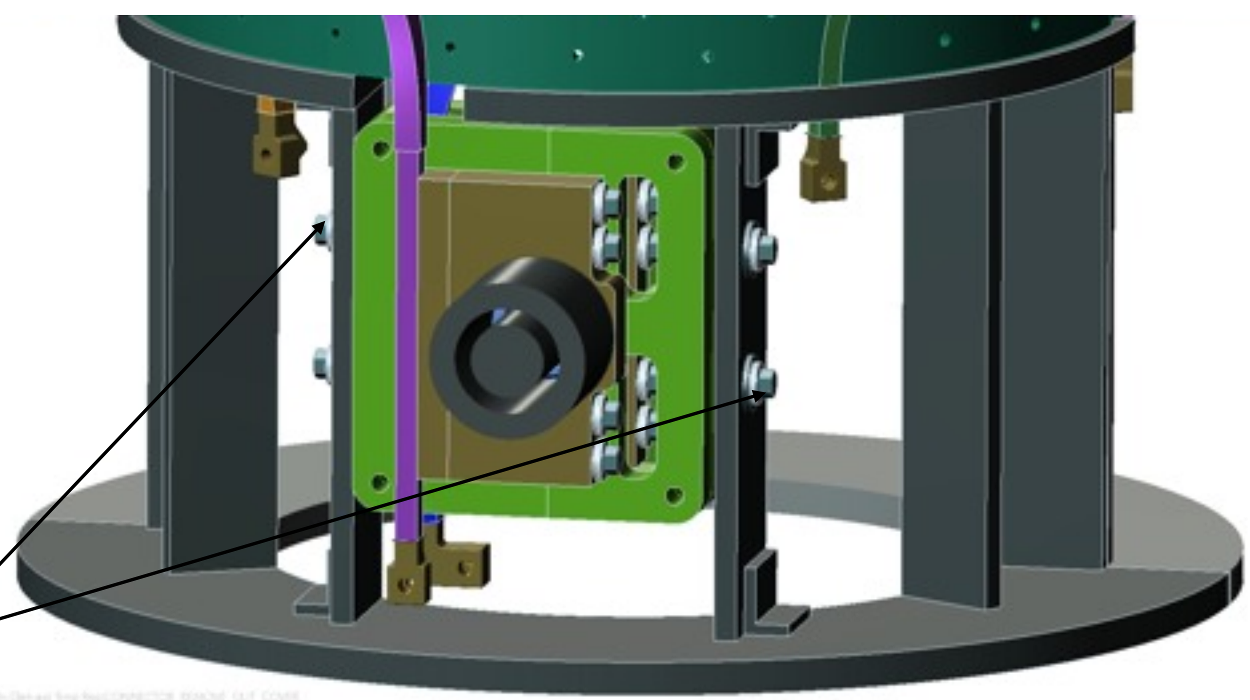
- Co-axial leads
- OH is supported between the upper and lower TF leads
- Belleville washer package to maintain preload [Pre-load requirements presently being analyzed]
- OH is supported between the upper and lower TF leads

Co-axial Bus Leads



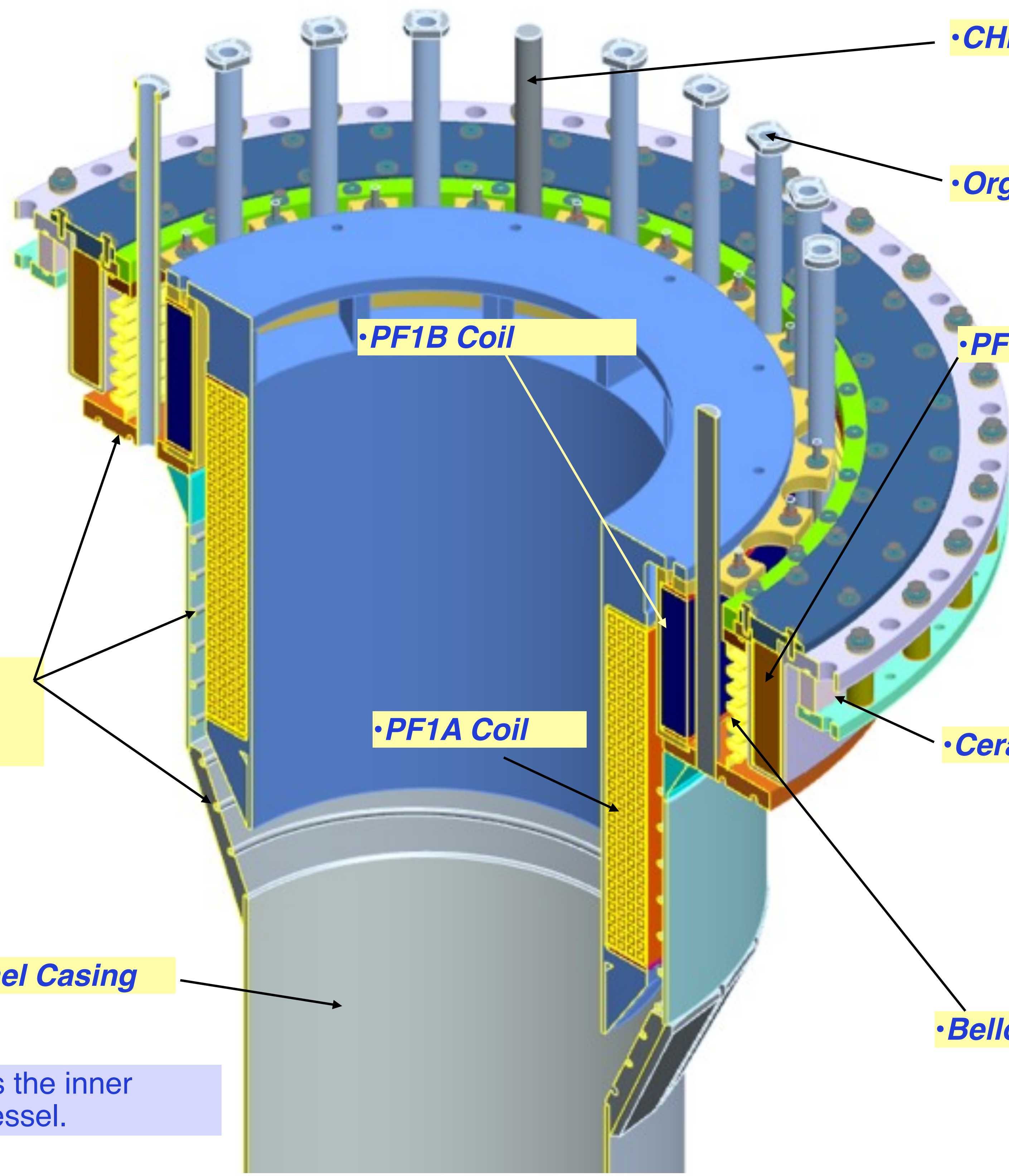


•*Leads will be brazed to coi*
conductors



•*Leads will be supported via stainless steel structure that also provides vertical support for the OH solenoid*

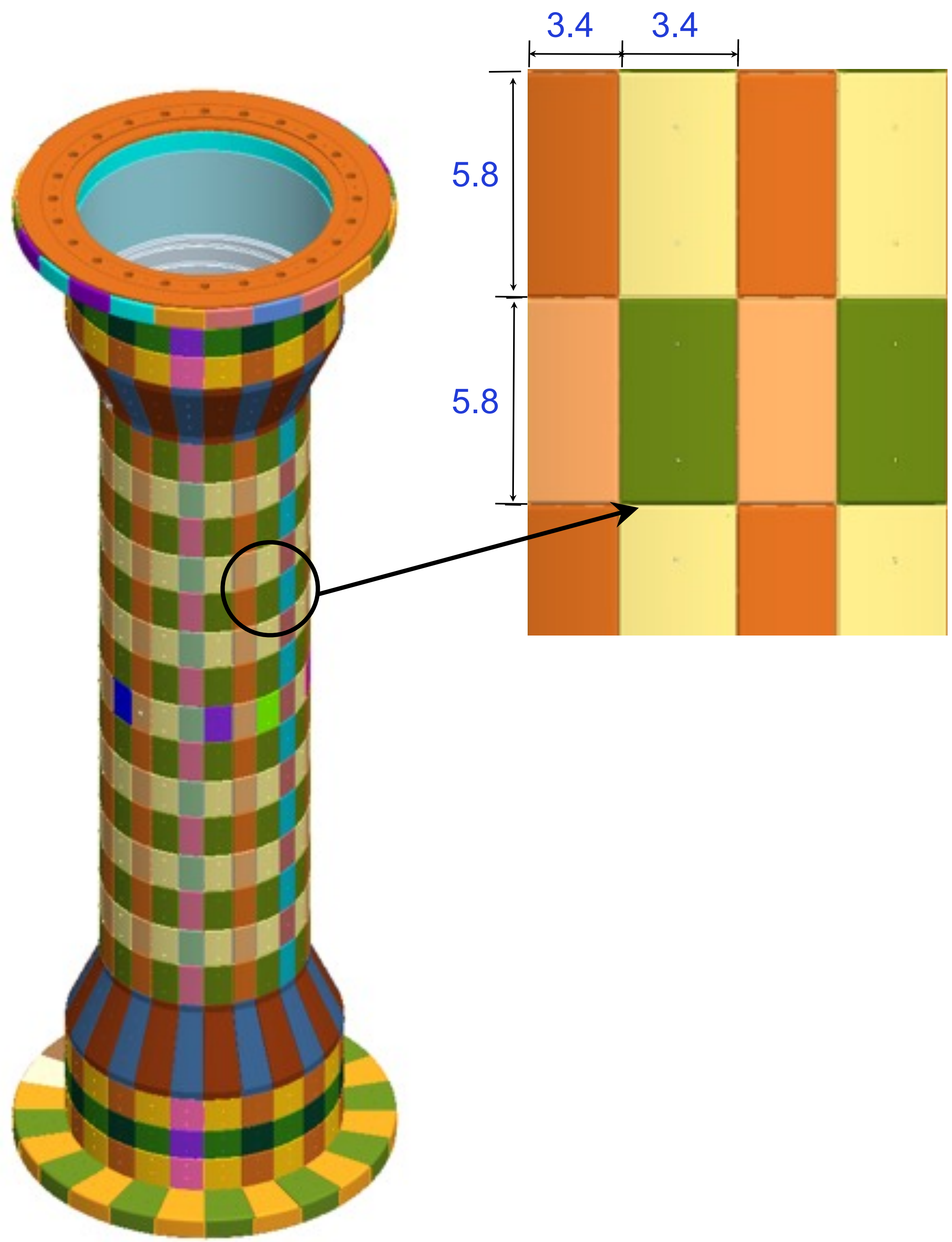
Center Stack Casing Components



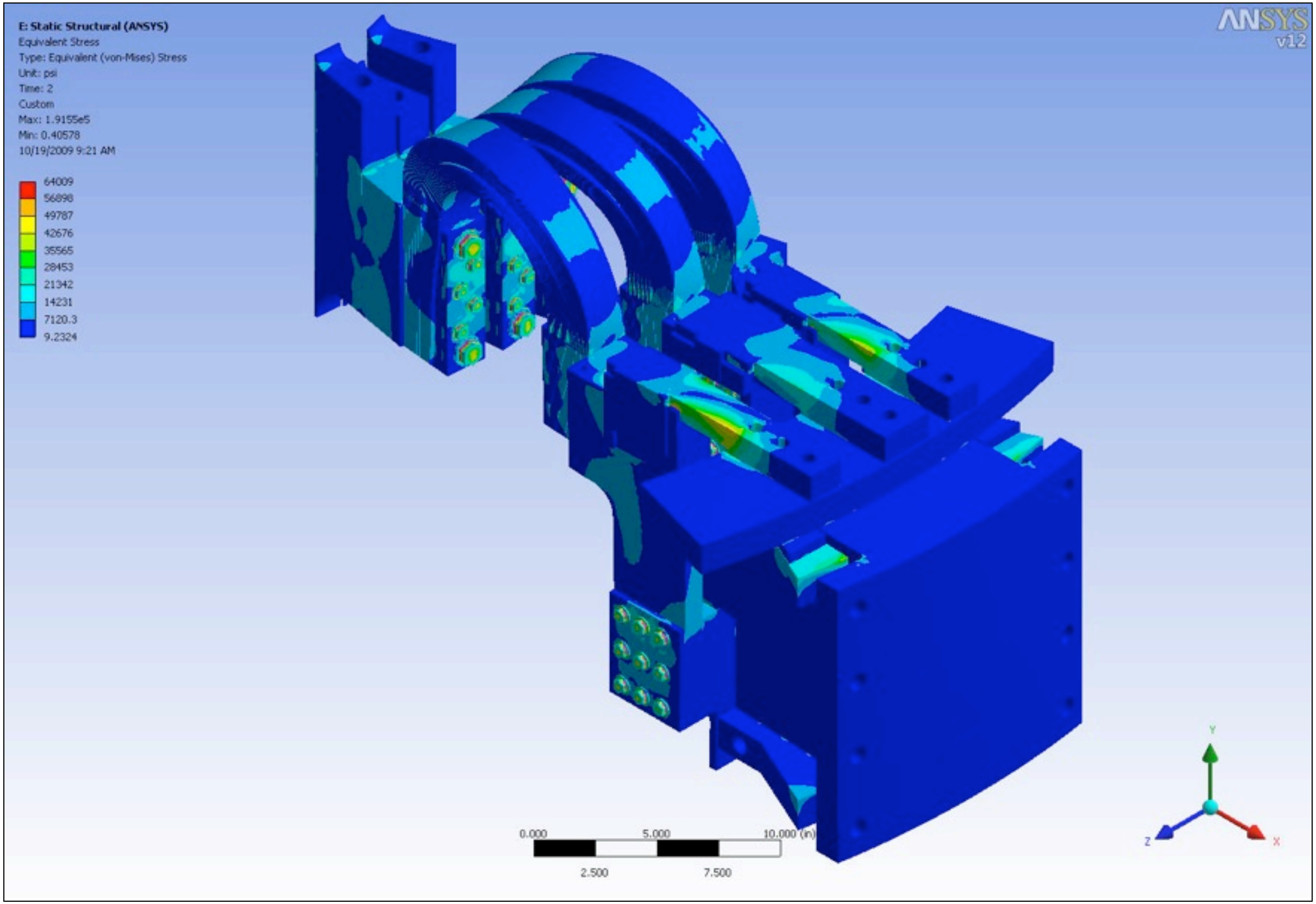
•Centerstack casing provides the inner vacuum wall for the NSTX vessel.

Centerstack Plasma Facing Component Upgrades

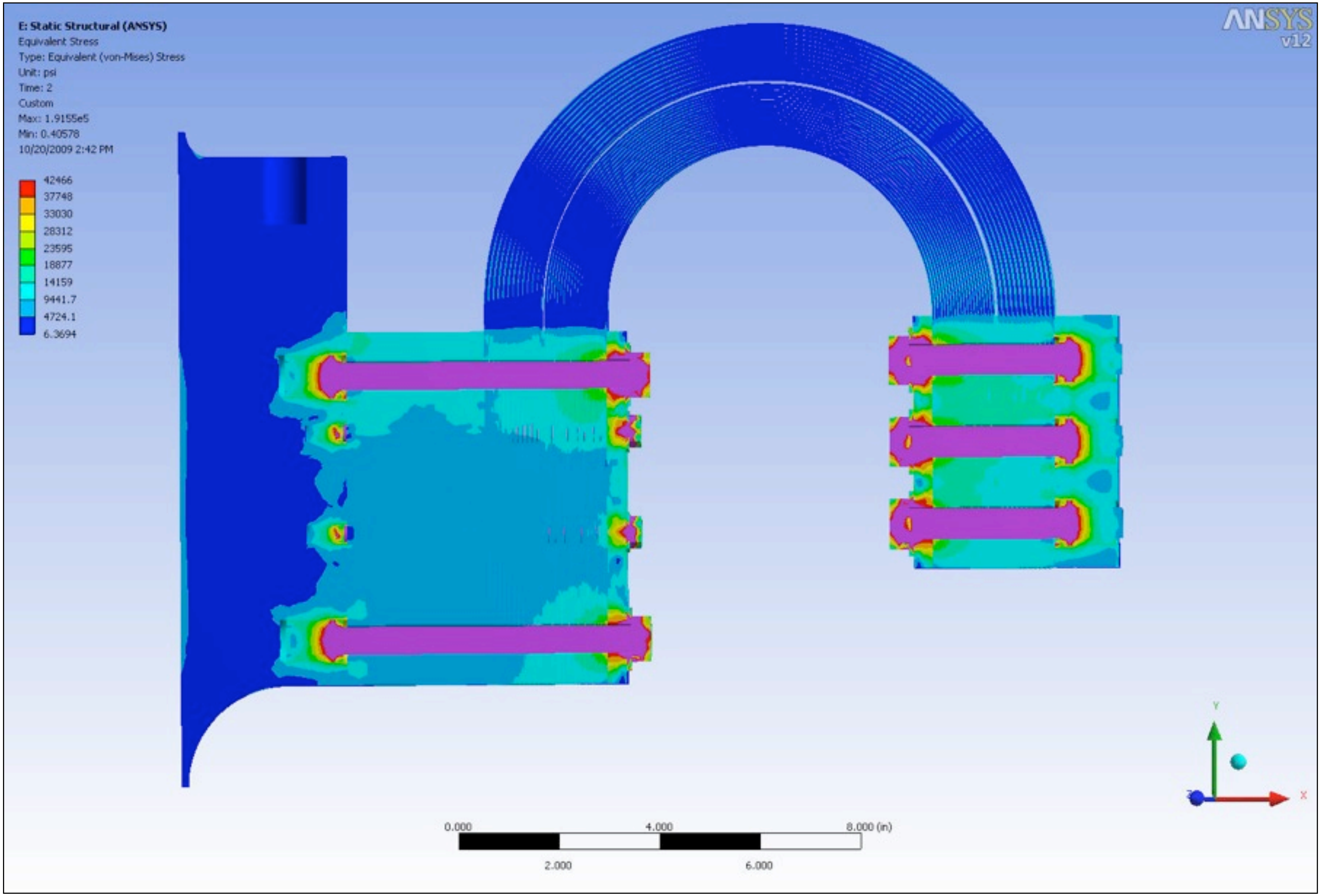
- Surfaces of Centerstack will be protected from the plasma with a layer of CFC tiles
- Larger CS Diameter but fewer, larger tiles
  - ~900 => ~600 tiles
- Diagnostics & gas injection incorporated into tile designs
  - Essentially same scheme as original, increased diagnostics where useful
  - New gas injection scheme
- Materials
  - Moving toward all CFC for better thermal and mechanical properties
- Fastening Scheme
  - Simplifying scheme where possible.
  - Rails & T-bars
  - Finding solutions to reoccurring issues such as stripped Allen keys, insufficient tolerances, plus ease-of-installation and removal.



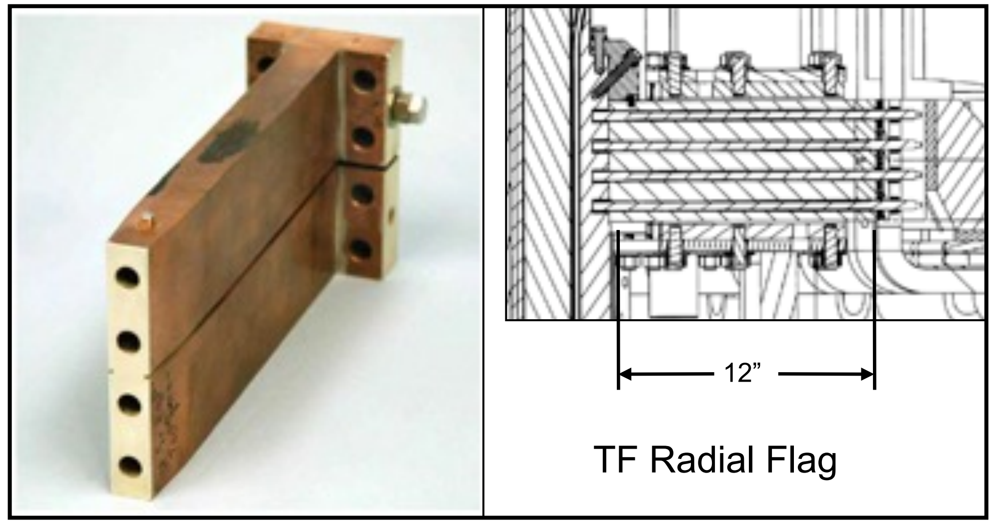
Single Segment 3-Strap Structural Model Results: von Mises Stress

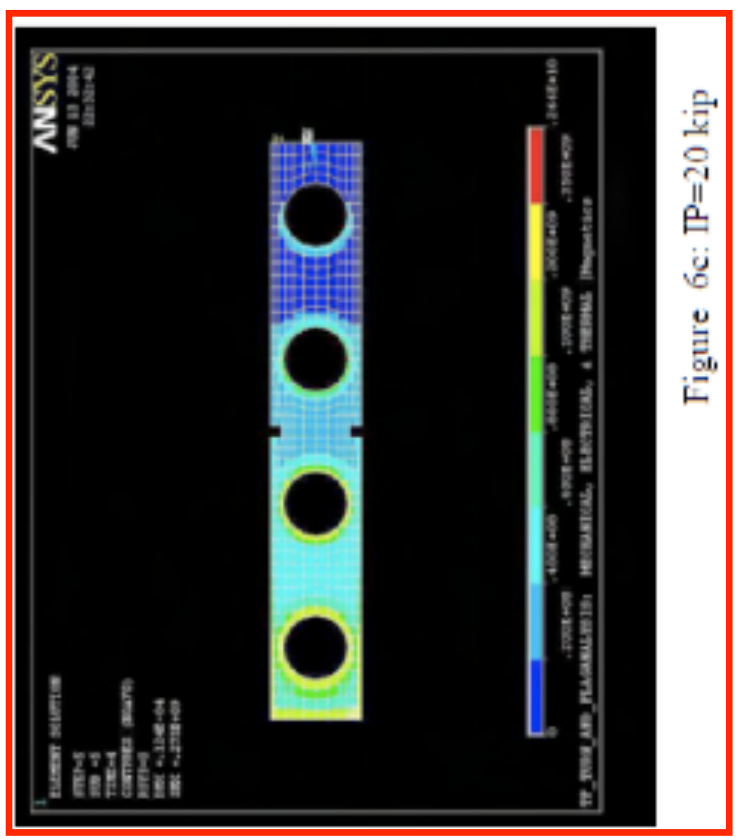


Single Segment 3-Strap Structural Model Results: Copper Flag Thread Stress



Issues with Current Joint Design





ANSYS Model Results:
Contact Pressure

Pitting Damage - 2005

- In-situ voltage/ current measurements indicate separation above .45T
- Pitting damage corresponds with ANSYS coupled field model lift-off areas (R. Woolley, 2005)
- Inconel 718 bolt pretension limited to 5000 lbf/ ea due to low shear fatigue strength of C10700 copper threads

Current Joint Design vs Upgrade Comparison

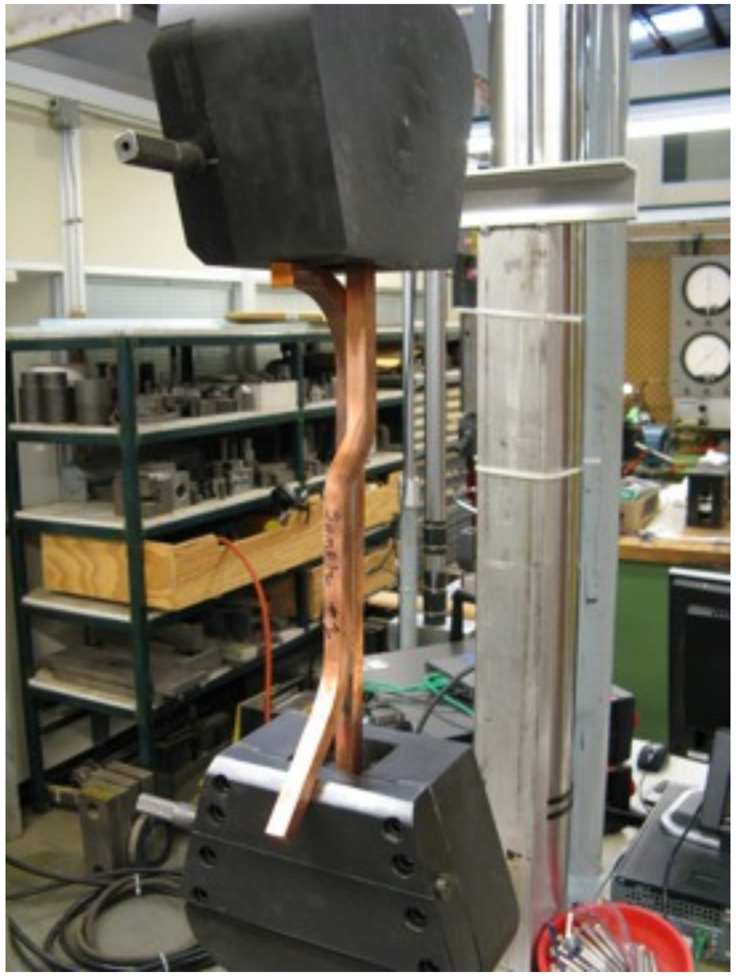
Table I - Design Operating Points				
Design	Total Current (A)	Maximum TF (Tesla)	Maximum PF (Tesla)	On-Time Pulse Duration (sec)
Current	72,000	0.6	0.1	0.5
Upgrade	130,000	1.0	0.3	7.0

Table II - Joint Mechanical Parameters							
Design	Joint Contact Area (in^2)	Total Bolt Force (lbf)	Average Initial Contact Pressure (psi)	Minimum Operating Local Contact Pressure (psi)	Calculated In-Plane Mating Torque (in-lbf)	Max. TF In-Plane Separating Torque (in-lbf)	Lift-off Torque Margin
Current	3.382	20,000	5,914	0	12,500	17,500	-0.29
Upgrade	12.739	94,000	7,379	~2500	90,875	30,143	2.01

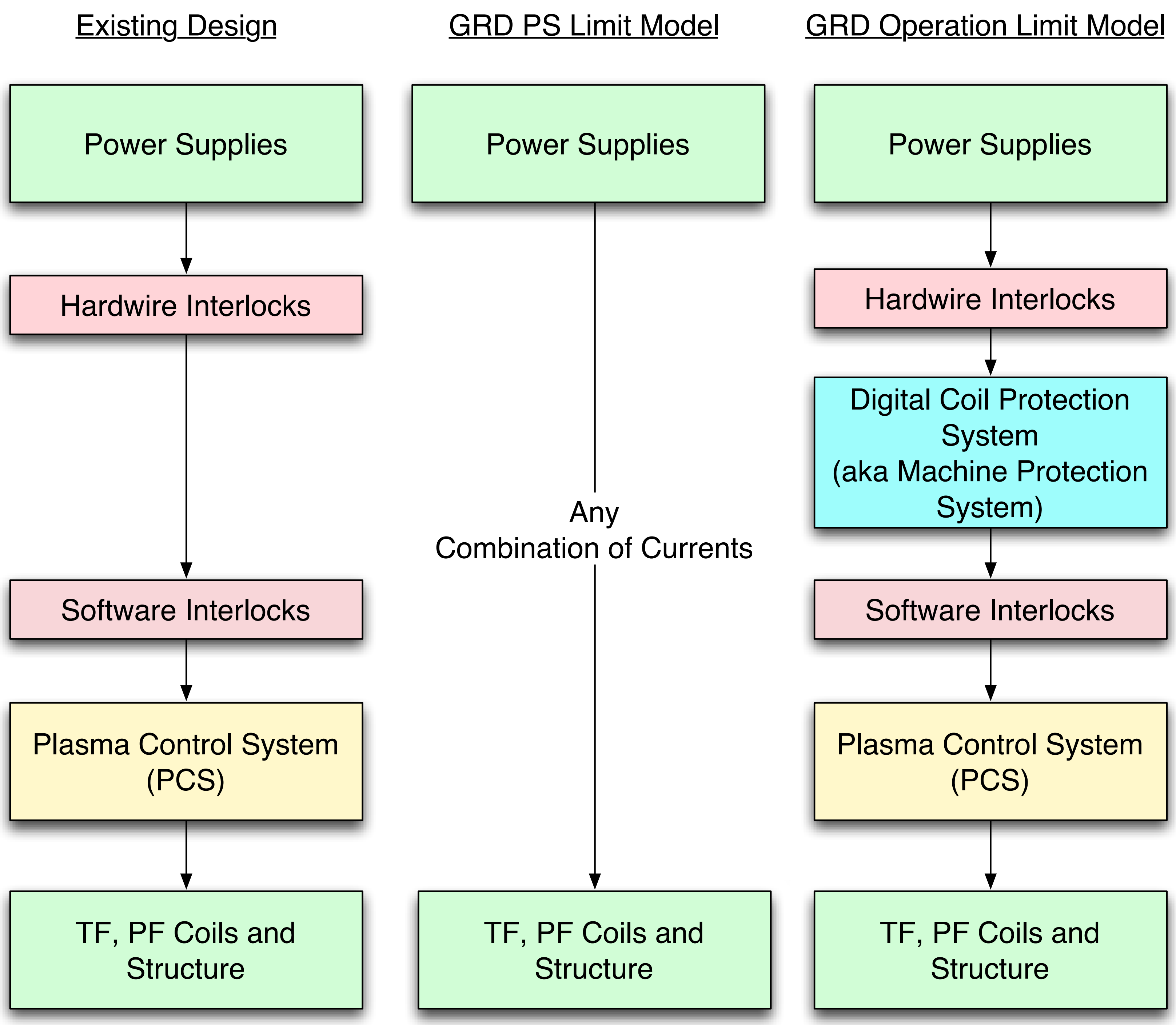
Table III - Joint Electrical/ Thermal Parameters						
Design	Current Density (A/in^2)	Initial Electrical Resistance (W)	Heat Generated I^2R (W)	Thermal Power Density (W/in^2)	Initial Thermal Resistance (W/C)	Zero-Heat Capacity Temperature Rise (C)
Current	21,289	1.48E-07	7.66E+02	2.27E+02	1.18E-02	9.1
Upgrade	10,205	3.93E-08	6.63E+02	5.21E+01	3.14E-03	2.1

Additional Planned R&D Activities

- Layer to layer TIG-Braze joint tests [OH]
  - Preliminary tests demonstrate good joint strength
- In-line braze joint tests [OH]
- Additional Friction Stir Welding [FSW] tests- OFHC to CU-Cr-Zr [TF leads]
- TF Joint tests
  - Build test stand
  - Mechanical & possibly full current tests



Choosing the Appropriate Lorentz Loading Design Basis



TFTR Coil Power Supplies

Individual Coil Current settings and other hardwired interlocks such as thermal, water flow, etc

Predictive redundant protection provides both thermal and stress protection. Will abort shot if a predicted combination exceeds capacity

Individual Coil Current settings and other software interlocks such as thermal, water flow, etc

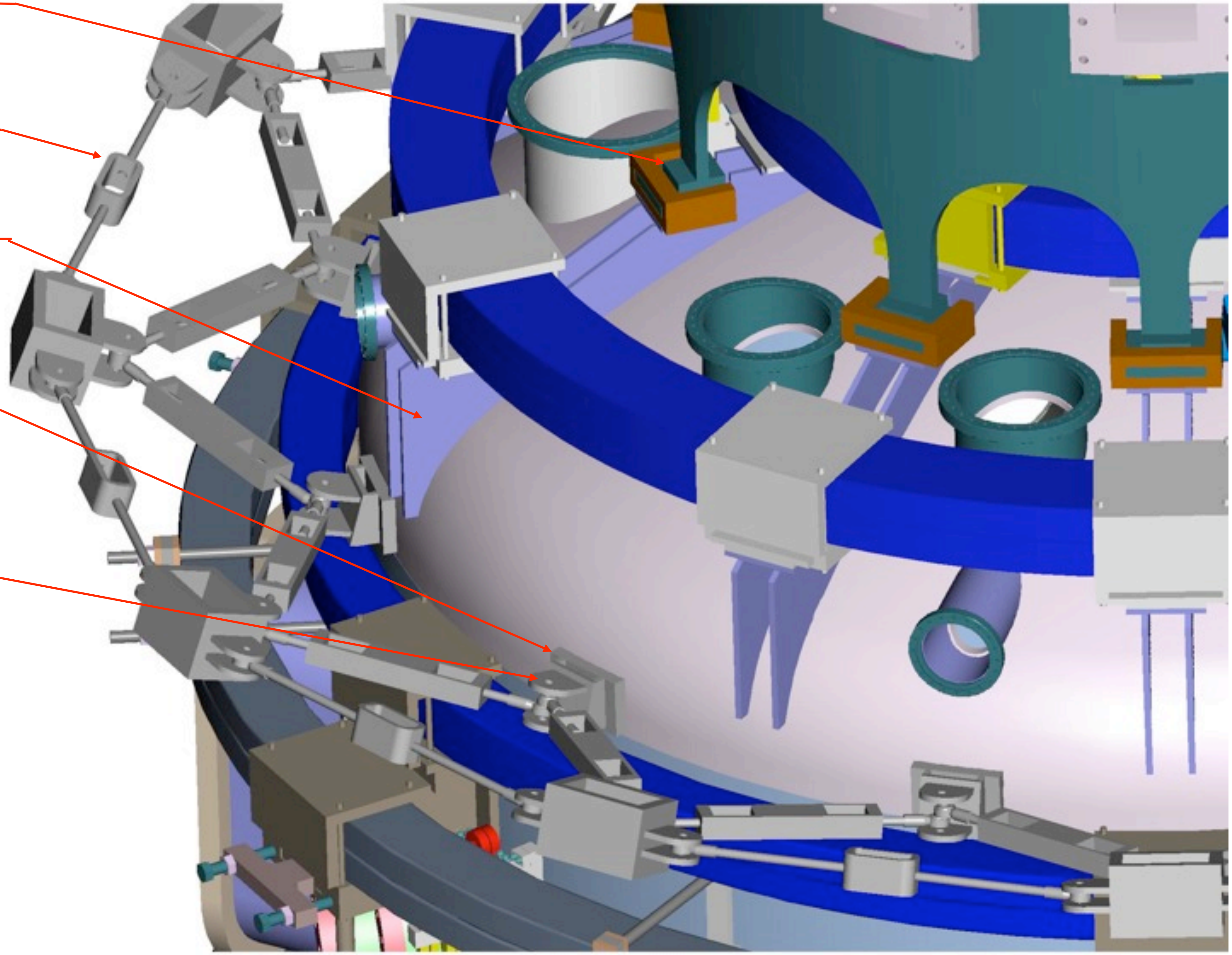
Feedback Control to maintain plasma Parameters

Coil electrical and mechanical capacity
Structural Supports strength

GRD PS Limit Model	GRD Operation Limit Model	
PF 4 & 5: 542,105 # OH: 545,134#	PF 4 & 5: 82,845 # OH: 12,100 #	Required Design Loads

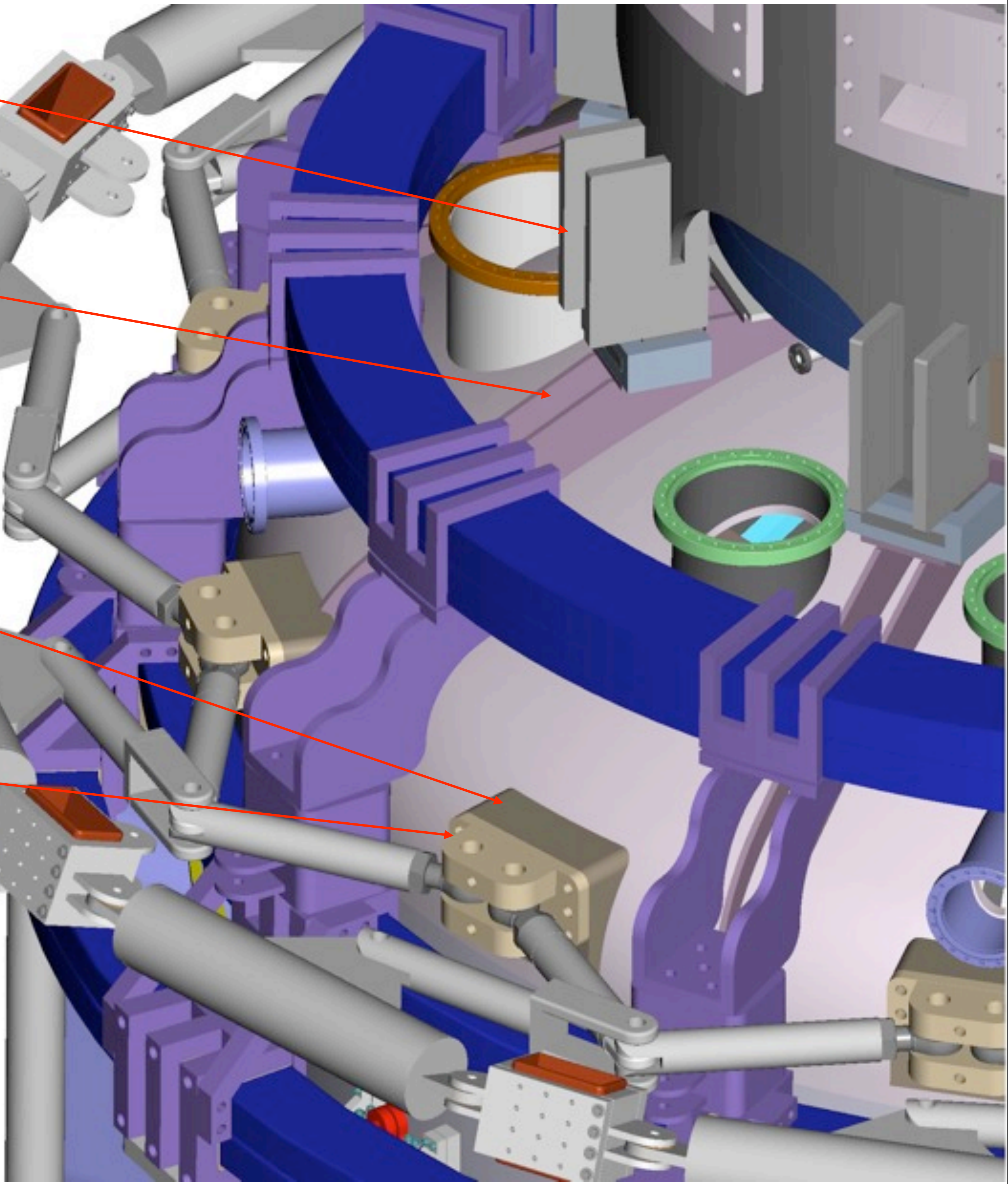
Existing TF & PF Support Details and Integration

- Existing Umbrella Structure legs
  - with Sliders
- Existing TF Ring
- Existing Ribs
- Existing VV Pads
- Existing TF Support Clevis

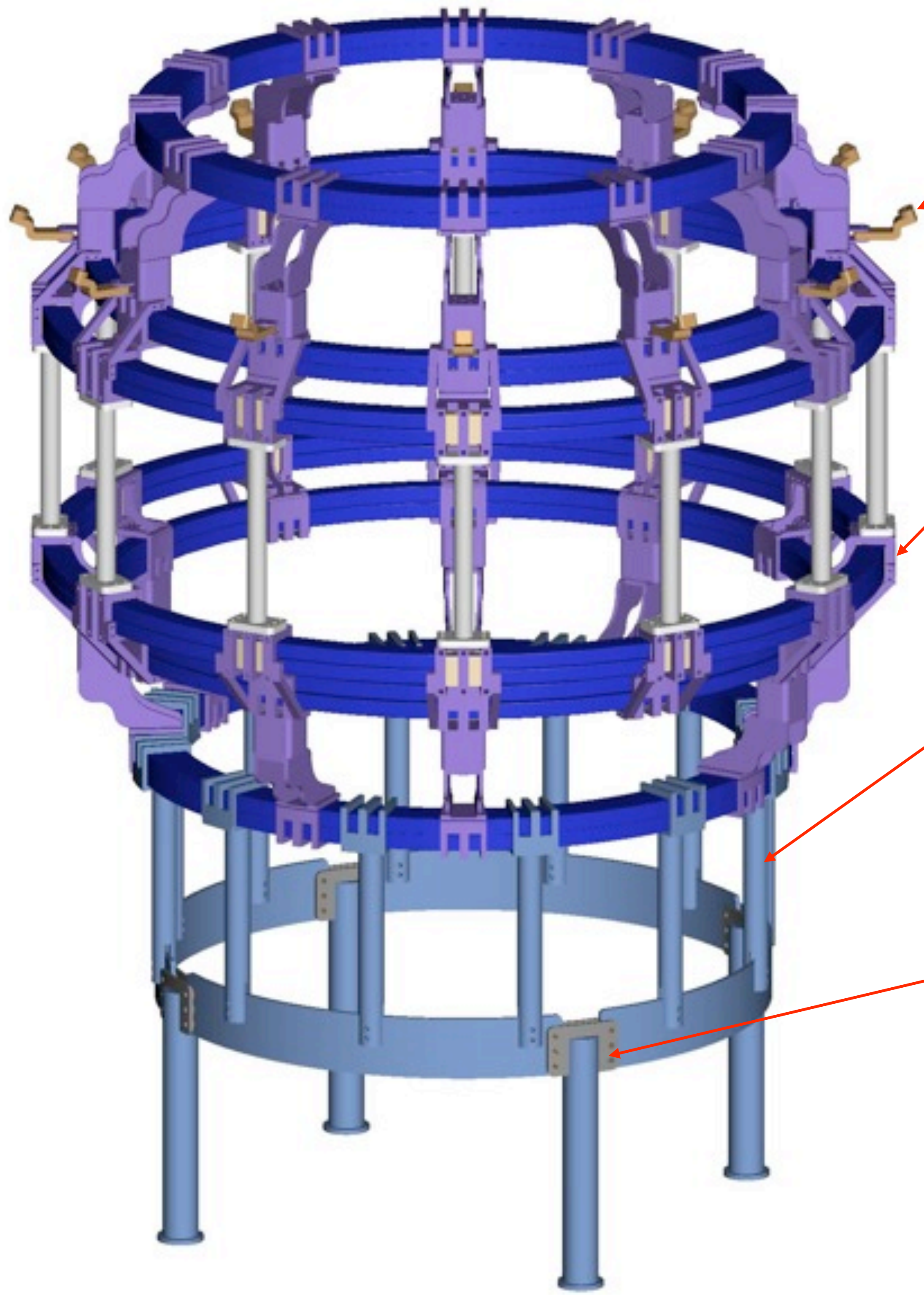


New Coil Supports Designed to use same Real Estate as Existing

- Reinforced Umbrella Legs
- Modified Ribs
- New Stronger TF Ring
- New VV Pads
  - welded to vessel
- New Clevis

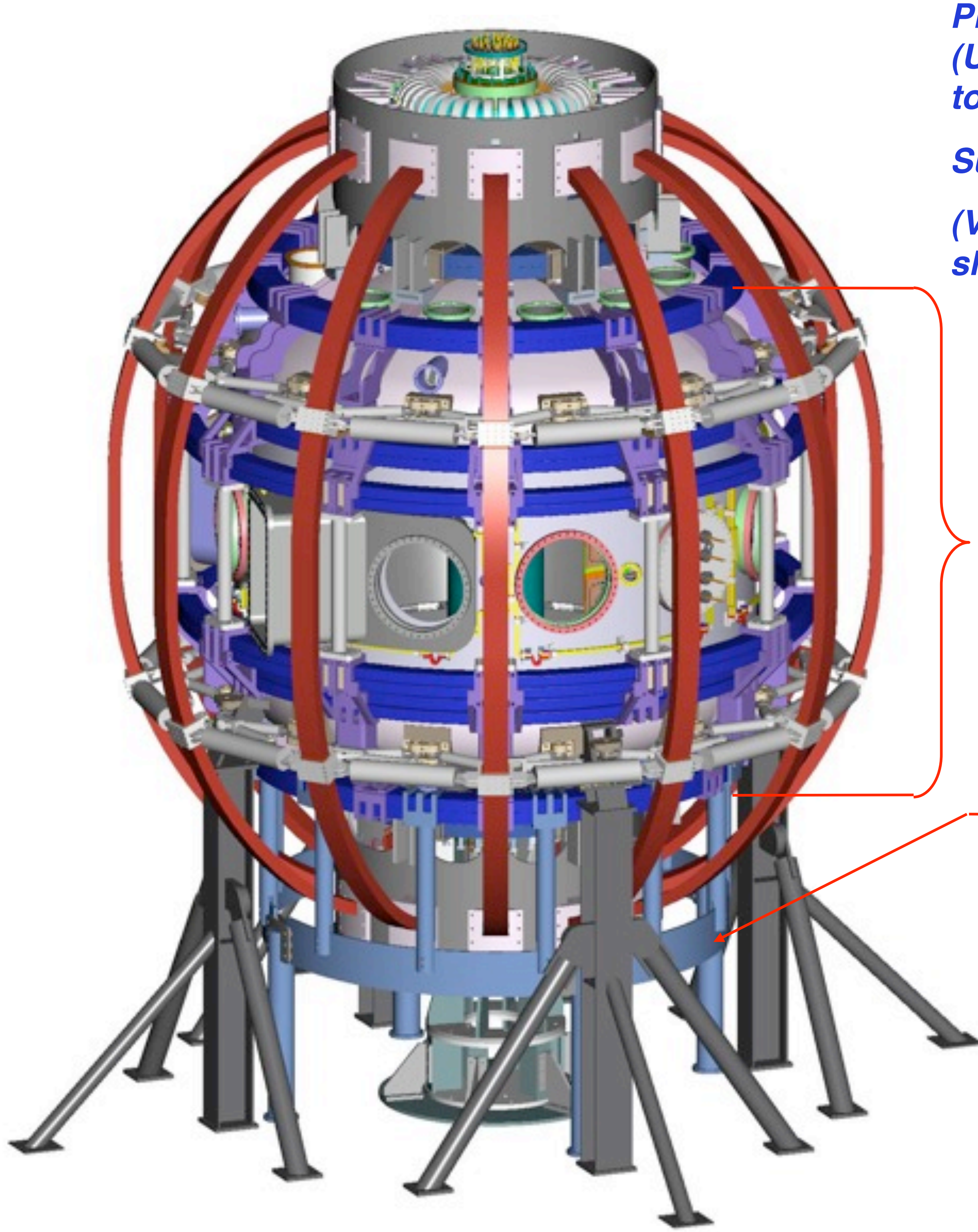


PF Cage – Coils Assembly with bottom support



- Stabilizers
  - Attached to TF Clamp
- Cage Assembly
  - Supported by Cage Support
- Cage Support
  - Can be installed and removed in sections
- Bushings for insulation break

NSTX Main Assembly with PF Cage Support



PF Cage = PF3, PF4 & PF5 Coils (Upper and lower) Bundled together.

Supported by Cage support.

(VV Heating/Cooling Manifold not shown.)

NSTX CSU Calculation Index October 2009

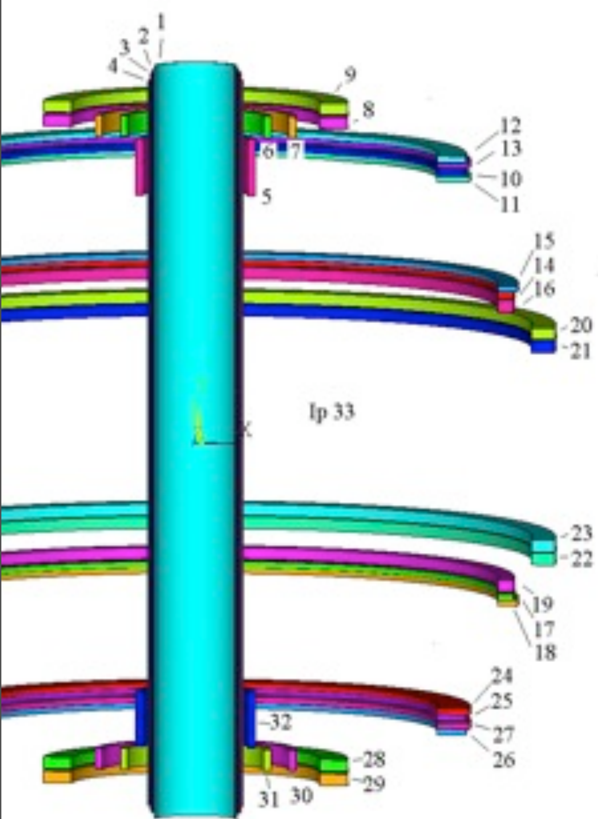
The list has been recently updated. Latest Listing:

http://nstx-upgrade.pppl.gov/Engineering/WBS_Specific_Info/Design_Basis_Documentation/Calculations/index_Calcs.htm

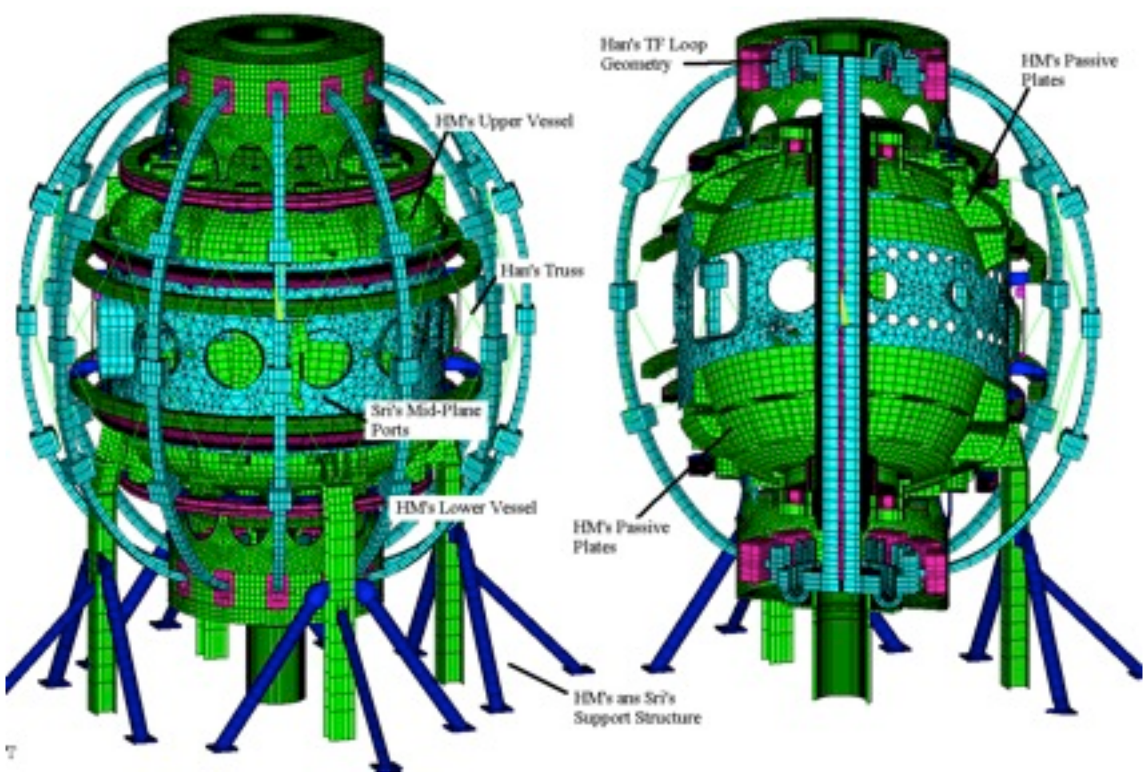
Project Memos

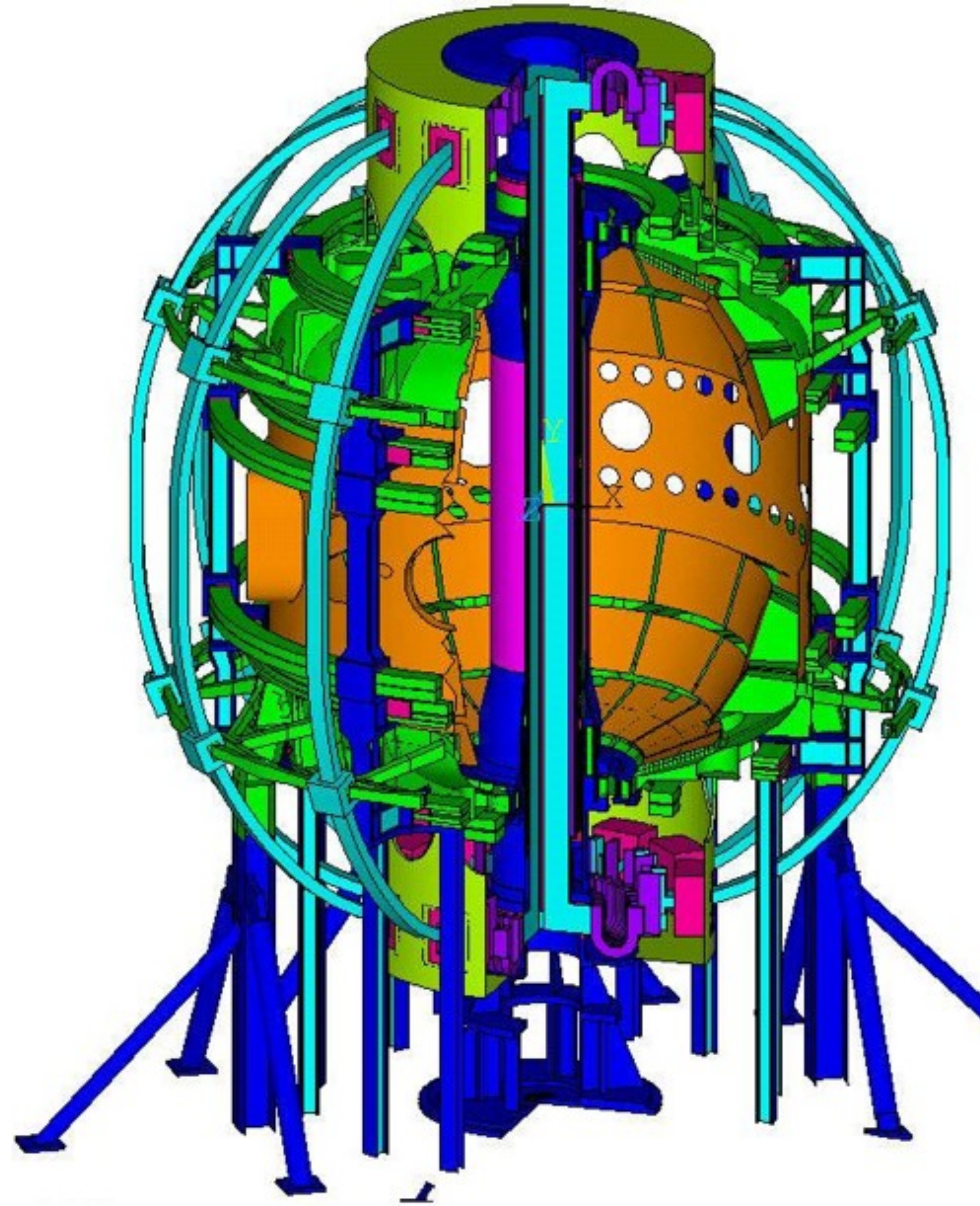
WBS	Originator	Calculation Number/Revision	Subject	Finalized?
1 - Torus Systems				
11- Plasma Facing Components				
12 - Vacuum Vessel/Supports	Avasarala	NSTX-CALC-12-01-00 (Unsigned)	Disruption Analysis Of Vacuum Vessel	No
13 - Magnets	Titus	NSTX-CALC-13-01-01 (Unsigned)	Global Model - Description, Mesh Generation, and Results	No
	Titus	NSTX-CALC-13-02-00 (Unsigned)	Maximum and Minimum Loads on the NSTX OH and PF Coils, and Coil Groupings	No
	Hatcher	NSTX-CALC-13-03-00 (Unsigned)	NSTX Influence Matrix	No
131 - Poloidal Field Coils	Woolley	NSTX-CALC-131-01-00 • Body of Calculation • OH&PF coil set geometry • Poloidal field vectors and poloidal fluxes throughout NSTX given any user-input set of coil and plasma currents	NSTX CSU Poloidal Fields (06262009)	YES
132 - Toroidal Field Coils	Titus	NSTX-CALC-132-01-00 (Unsigned)	Coupled Electromagnetic-Thermal Diffusion Analysis	No
	Titus	NSTX-CALC-132-02-00 (Unsigned)	Coupled Electromagnetic-Thermal Analysis (04202009)	No
	Woolley	NSTX-CALC-132-03-00	Out-Of-Plane (OOP) PF/TF Torques on TF Conductors in NSTX CSU	YES
	Han	NSTX-CALC-132-04-01 (Unsigned)	Analysis of TF Outer Leg	No
	Han	NSTX-CALC-132-05-01 (Unsigned)	TF Coupled Thermo Electromagnetic Diffusion Analysis	No
	Willard	NSTX-CALC-132-06-00 (Unsigned)	TF Flex Joint and TF Bundle Stub	No
	Titus	NSTX-CALC-132-07-00 (Unsigned)	Maximum TF Torsional Shear	No
133 - Center Stack	Myatt	NSTX-CALC-133-01-00 (Unsigned)	Structural Analysis of the PF1 Coils & Supports	No
	Avasarala	NSTX-CALC-133-02-00 (Unsigned)	Thermal Stresses on the OH-TF Coils	No
	Titus	NSTX-CALC-133-03-00 (Unsigned)	Center Stack Casing Disruption Inductive and Halo Current Loads	No
			OH Coil Cooling Optimization in the	

Global Model Is Used for...



- Selecting Worst Cases
- Scoping Studies
- Cross-Checking other Models





NSTX Fatigue Criteria Document

- NSTX CSU is designed for approximately 3000 full power and 30,000 two-thirds power pulses.
- A fatigue strength evaluation is required for those NSTX CSU components with undetectable flaws that are either cycled over 10,000 times or are exposed to cyclic peak stresses exceeding yield stress.
- Any NSTX component without cyclic tensile loading and loaded only in compression shall not require a fatigue evaluation.

NSTX GRD:

For engineering purposes, number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of ~ 60,000 pulses based on the GRD specified pulse spectrum.

- ***We need to reconcile the Criteria and GRD***
- ***Definition of the Aged Condition for "Used" Components?***
- ***Because of the increase in loads, Minors Rule and Non-Linearity of Fatigue, Previous Stress Cycles Will Add Little***

Analysis Summary

- Design basis loading is evolving because of GRD guidance on Worst Case vs Normal +Machine Protection System. Cost savings are likely as we remove extreme load scenarios via inclusion in MPS.
- TF Inner Joint Field and displacement boundary conditions have been passed to a detailed model of the joint
- TF reinforcements for in-plane and out-of plane loads have been designed to Worst Case loads and remain in the territory currently used by the present TF supports – Loosening or disassembly is not required for bake-out. Reinforcements of the umbrella structure are needed.
- Centerstack TF and OH assembly meets normal operational loads, Belleville support system maintains OH coil contact at lower support to eliminate motion at leads and coolant connections.
- As of the CDR no modifications of the vessel or passive plates are needed for disruption loads. More disruption cases are being run, and more detailed models of the passive plate support hardware are being modeled.
- Active cooling being incorporated into the new centerstack divertor areas has been sized. Tile surface temperatures for long pulse full power operation are high and require further evaluation.
- Inner PF's and structure are undergoing improvements as a part of the normal design process to meet Normal and Halo loads.
- Analysis work continues to complete treatment of all details of the design and optimize and economize the design concepts.

PWR SYSTEM UPGRADE FOR NEW CENTER STACK

- REQUIREMENTS
  - TF : 129.8 kA, 1kV, ESW 7.08 sec every 2400 sec (7.05kA rms) ;
  - OH : 24kA, ESW .9 sec every 2400 sec ; 8kV
  - PF : Existing configuration will meet requirements
- CONSTRAINTS:
  - Constraints analyzed to project realistic estimate
    - NSTX machine is located in NTC - is small in area.
    - Constrained space in the basement of NTC
    - FCPC Building has limited space & equipment is virtually crammed inside. No basement in this building.
      - Thus real estate availability is very limited and design of upgrades has to meet these limitations
      - TF has now four parallels. Thus short circuit current about 250kA. Upgrade dictates doubling parallels - short circuit current also gets doubled – the forces are four times more. Hence power loop components require appropriate upgrade. Also additional protective measures are required.

TF POWER LOOP DESIGN

- Four additional PARALLELS of Transrex power supplies to be connected to existing four parallels
- Each parallel will have two 1 kV Transrex power supply sections in series.
  - Current Limiting Reactors (CLRs) will be connected between the supplies
  - One section of the supply will be used as a Diode
- Existing four Safety Disconnect Switch (SDS) of TF with additional parallel supplies will be used.
  - two parallels to be fed via each switch.
- Four more DC reactors (270uH) to be used in the additional 4 parallels.
  - Since upgraded OH circuit needs reactors of higher inductance,
  - the existing 270uH OH CLRs will be reconnected in the TF Circuit.

TF POWER LOOP DESIGN – Contd.

- DCCTs
  - Existing eight DC Current Transducers (DCCT) will be repositioned to detect current in each of the eight parallels
  - Eight additional DCCTs will be purchased and installed
  - Two new DCCTs to detect total TF Coil Current
- CABLING
  - Reconnect existing cabling as needed.
  - Install additional power cabling within FCPC - nearly 6000 feet of 1000 mcm 5kV power cables. Limited space makes bus installation difficult
  - Reconnect existing power cabling in Transition Area (TA) - in TFTR Test Cell Basement- to NSTX Test Cell for TF use.
  - Provide Control Cabling as needed

OH PWR. LOOP DESIGN & PF PWR. LOOP DESIGN BASIS

- EXISTING OH PWR LOOP DESIGN:
  - 6kV Anti-parallel configuration
  - 24kA for 0.4 seconds every 600 seconds
- UPGRADE - OH PWR LOOP DESIGN:
  - 8kV Anti-parallel configuration
  - 24kA for 0.9 sec every 2400 seconds
  - Work Required
    - 2kV installed standby is available in each of the anti-parallel branches. Hence these supplies will be switched into the circuit.
    - The DC CLR values will be optimized to the new requirement based on PSCAD analysis. Thus new reactors of the required values will be purchased and installed.
    - All the other equipment and cabling in the power loop will be used AS IS
- PF DESIGN:
  - Existing PF circuits will be used AS IS for the upgrade except for PF1a wherein the ripple reduction reactors will be eliminated.
- Digital Coil Protection System
  - A redundant Digital Coil Protection System (DCPS) is being provided to prevent power supplies from delivering power in excess of what the Coils and Coil support system can handle.

Cost Estimates

- Cost estimates were generated by the Job Managers with input from engineers closest to the work
- Estimates are conservative
- Depending on the work estimated, they are based on
  - Previous NSTX construction
  - Quotes from Vendors or suppliers
  - Engineering Judgement
  - Published cost data (eg RS Means)
- Additional detail to be presented by R. Strykowsky

Centerstack Upgrade Risks at CD-1

- The latest Risk Registry now has 34 risks identified
  - Vendor Performance (9)
  - Coil Fabrication (8)
  - Installation Difficulty (7)
  - Design error (4)
  - Analysis (3)
  - Other (3)
- Risk: OTF and PF Support Installation Difficulty
  - Design is being tailored to improve installation
    - Modular
    - Utilize space occupied by existing supports
  - Careful planning
    - Coordinate carefully with NB upgrade
    - Methodical removal of existing equipment

Summary

- The upgrade requirements are challenging but a conservative conceptual design is being presented
- The design is well defined and is ready to proceed to the preliminary design level
- The upgraded TF joint, which was problematic with the original design, has evolved into a robust design with major improvement in margin
- The cost estimates are based on the conservative design which is being presented