NSTX Centerstack Scope

L. Dudek

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Columbia U
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INL
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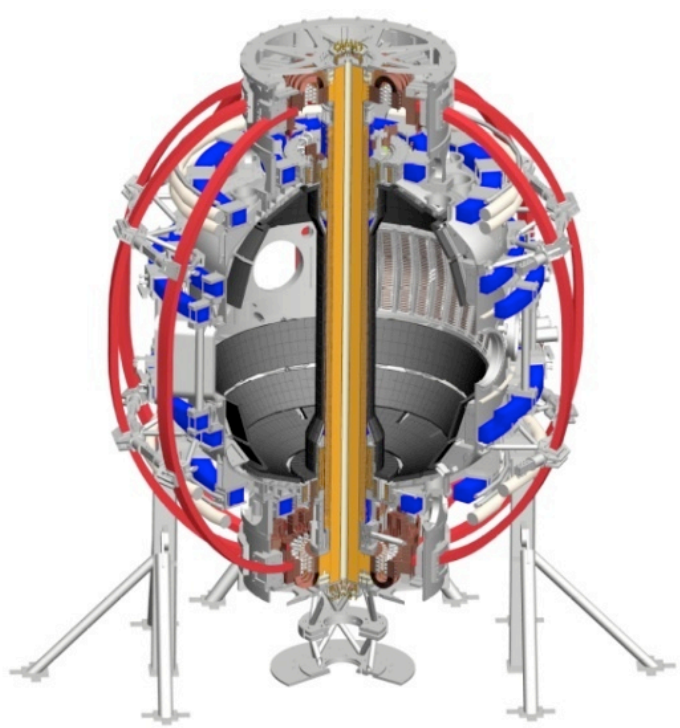
X Science LLC

NSTX Upgrade
Readiness For Operations Review
PPPL
December 9-11, 2014



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

- General Requirements
- WBS Elements / Cost Accounts
  - Vacuum Vessel & Coil Support Structures
  - Magnets
  - PFCs
  - Power
  - Bakeout
  - I&C
- Solutions to Remaining Challenges
  - Aquapour
  - OH Cooling Wave
- Remaining Tasks and PTPs
- Readiness to Operate
- Instrumentation
- Maintenance Inspection Plan
- FMEA
- Summary

NSTXU Centerstack General Requirements

- Requirements defined in GRD: **NSTX-CSU-RQMTS-GRD**
  - Replacement of the Center Stack Core
  - Modification of the NSTX to meet extended performance parameters at higher fields, higher current and longer pulse length
  - Modify as necessary the Supporting Subsystems and Equipment to meet extended performance parameters
  - Design Point Spreadsheet - Provides specific detailed parameters including 96 operational scenarios to be used when performing analysis in the evaluations above and for designing the upgrade components
    - Physics operations parameters
    - Physical dimensions of the Centerstack Radial Build
    - TF, OH, and PF Coil Design Parameters (Diameters, Conductor sizes, Insulation dimensions, No. Turns, Coolant Flows, Voltages, Currents, etc)
    - Coil and Plasma Waveforms
    - PF/OH Coil Forces
    - PFC Heat Loads
    - Force Influence Matrices
    - Circuit Impedances
    - Pulse Spectrum

GRD: Replacement of the Centerstack Core

- 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
  - Microtherm thermal insulation
  - Center Stack Casing (CSC)
  - Plasma Facing Components (PFC) associated with CS Casing including the Inboard Divertor (IBD)
  - TF, OH, PF1A Upper (PF1AU), PF1A Lower (PF1AL), and PF1B Lower (PF1BL) coil electrical leads
  - CS and Supply piping for heating and cooling of CS Casing and IBD
  - Pedestal which supports Center Stack Assembly from floor

GRD: NSTXU Extended Performance

- New Performance Parameters
  - Plasma Current (I_p): 2 MA, 5 sec flat top
  - Toroidal Field (B_t): 1.0 T at R_0=0.9344m
  - Total Pulses: 20,000 per Pulse spectrum Table 24
  - T_{Pulse}: 5.0 sec, T_{Rep}: 2400 sec

- Structural Improvements to meet the higher field, higher current and longer pulse length
  – TF outer leg supports
  – PF coil supports
  – Vacuum vessel if required (VV)
  – Internal hardware including Passive Plates and Outboard Divertor

GRD: Modification to Supporting Subsystems and Equipment

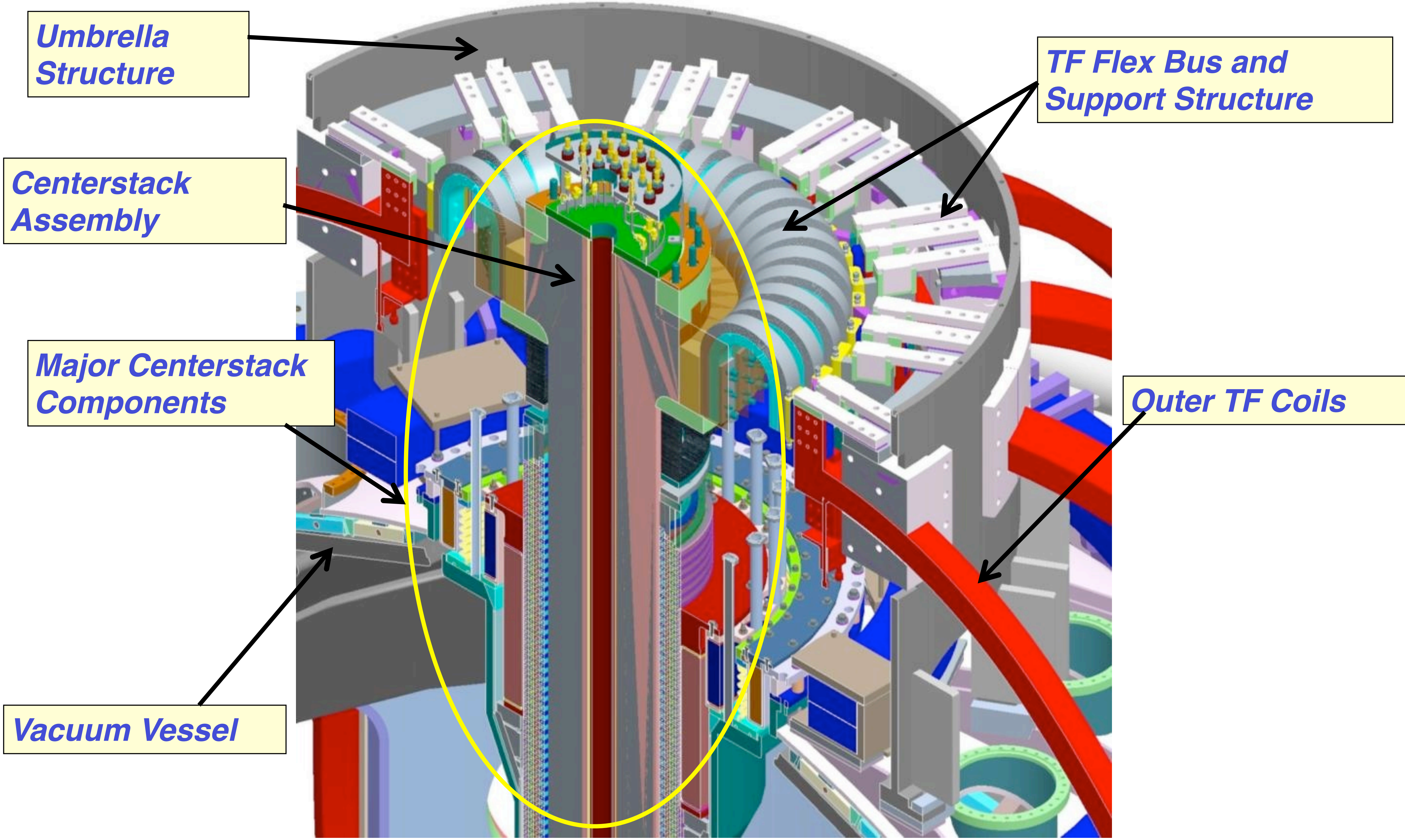
- Evaluate and modify as required the following for compatibility with higher field, current and longer pulse length
  - Internal hardware including Passive Plate supports and Inboard Divertor
  - Auxiliary Systems
    - Vacuum Pumping Systems
    - Cooling water Systems
    - Gas Injection Systems
    - Bakeout System
  - Diagnostic Systems
  - Electrical Power Systems
  - I&C Systems
- Electrical Systems Upgrades required to meet new coil power requirements
  - Power Systems
  - CS Bakeout system
  - I&C systems
- Center Stack Diagnostics Sensors relocated to the new Centerstack assembly
- Auxiliary Systems
  - Cooling water system mods
  - CS and Supply piping for inboard gas injection

Cost Accounts

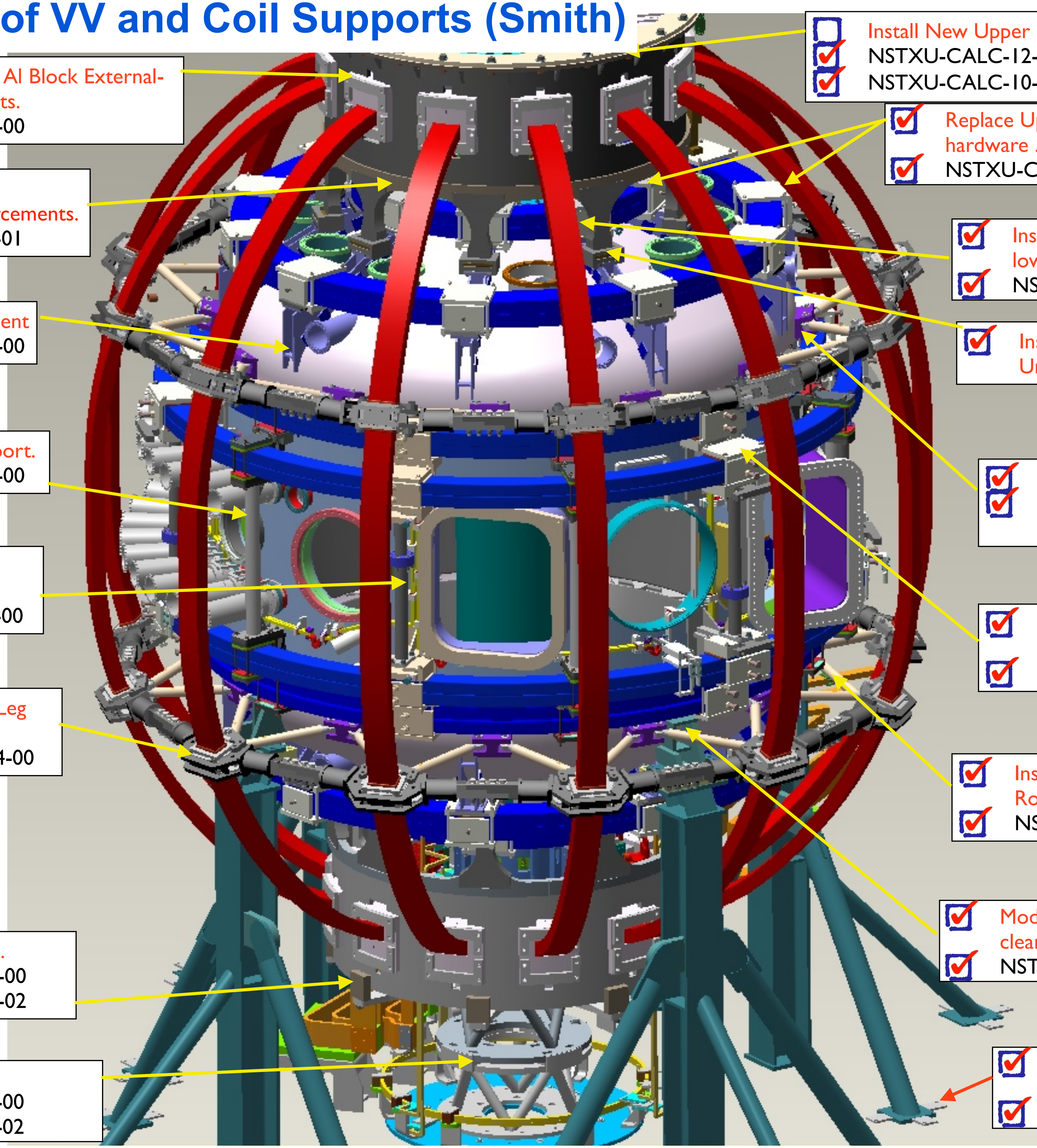
WBS	CAM	Budget	Actuals	Earned	SPI	CPI	% Complete
1000 CSU Analytical Support	CLOSED	$705	$686	$705	1.00	1.03	100%
1001 CS Plasma Facing Components	Tresemer	$2,110	$1,933	$2,108	1.00	1.09	100%
1002 Passive Plate Analysis & Upgrade	CLOSED	$925	$697	$925	1.00	1.33	100%
1200 Structures & Supports	CLOSED	$3,805	$4,505	$3,805	1.00	0.84	100%
1300 Center Stack	CLOSED	$2,986	$3,473	$2,986	1.00	0.86	100%
1301 Outer TF Coils	CLOSED	$471	$477	$471	1.00	0.99	100%
1302 Center Stack Assembly	Raftopoulos	$909	$971	$854	0.94	0.88	94%
1303 TF Joint Test Stand & Test	CLOSED	$353	$225	$353	1.00	1.57	100%
1304 Inner TF Bundle	CLOSED	$4,045	$4,146	$4,045	1.00	0.98	100%
1305 Ohmic Heating Coil	CLOSED	$6,611	$11,112	$6,611	1.00	0.59	100%
1306 Inner PF Coils	CLOSED	$944	$1,077	$944	1.00	0.88	100%
1307 CS Casing Assembly	Raftopoulos	$1,384	$1,687	$1,384	1.00	0.82	100%
1310 CSU Magnets Systems	CLOSED	$442	$442	$442	1.00	1.00	100%
3200 Water Cooling System Mods	Atnafu	$420	$278	$260	0.62	0.93	62%
3300 Bakeout System Mods CSU	Raki	$160	$154	$136	0.85	0.88	85%
3400 Gas Delivery System Mods	Blanchard	$102	$87	$92	0.90	1.06	90%
4100 Center Stack Diagnostics	CLOSED	$836	$840	$836	1.00	0.99	100%
4500 MPTS VV Modification	CLOSED	$1,137	$1,595	$1,137	1.00	0.71	100%
5000 CSU Power Systems	Raki	$5,735	$4,277	$5,399	0.94	1.26	94%
5200 DCPS*	Stevenson	$2,692	$4,113	$2,671	0.99	0.65	99%
5501 Coil Bus Runs	Atnafu	$2,051	$2,076	$1,678	0.82	0.81	82%
6100 Control Sys Data Acquisition	Sichta	$1,216	$964	$889	0.73	0.92	71%

CAM Tim Stevenson to give detailed talk about the Digital Coil Protection System (DCPS)

General Arrangement



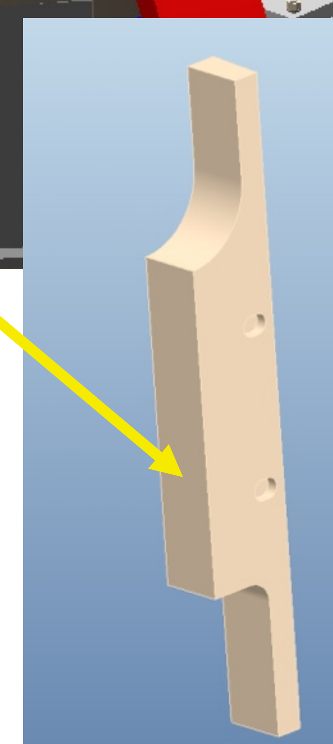
Overview of VV and Coil Supports (Smith)

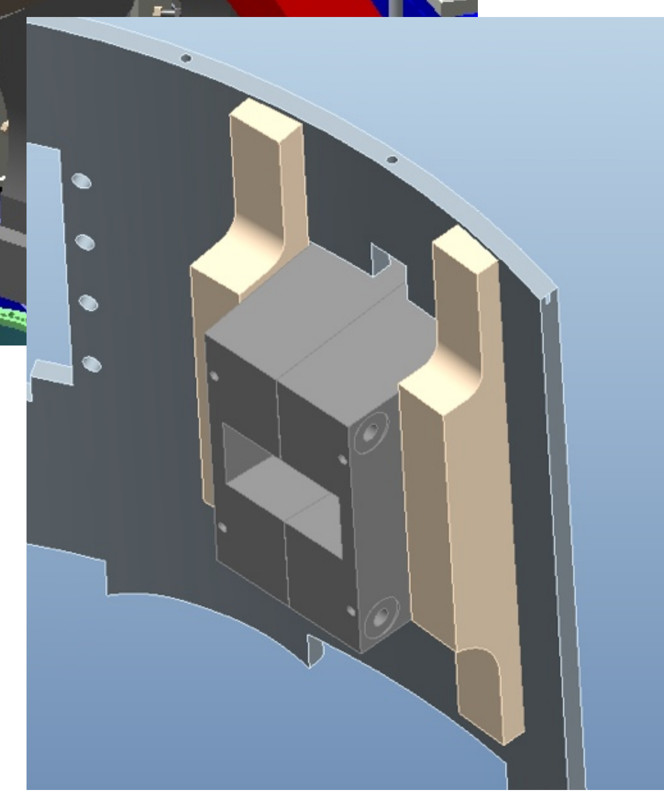


Umbrella Reinforcement

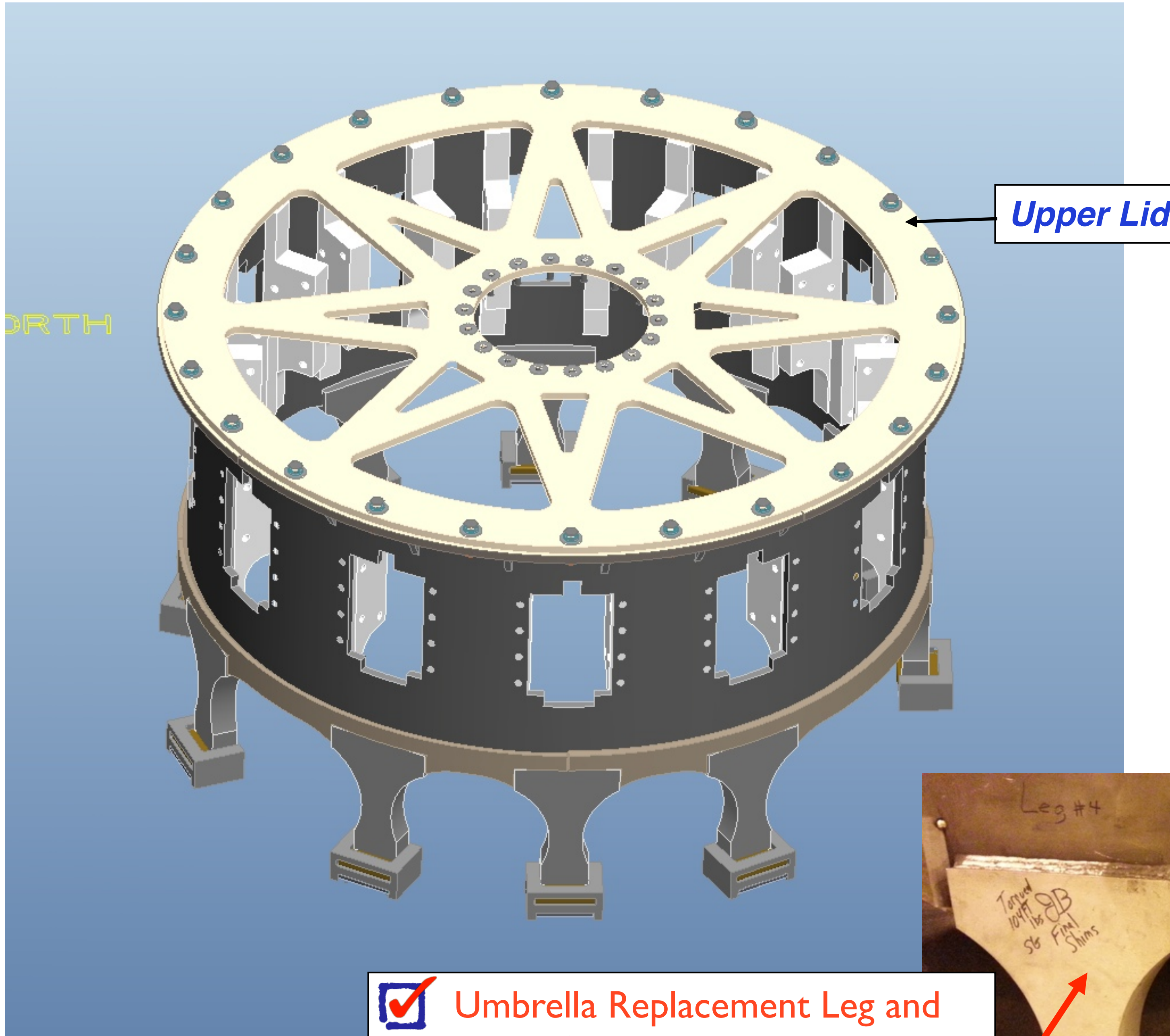
The Umbrella Structure & Outer Leg Supports Have Been Strengthened To Handle 4X Larger Forces of the Upgrade

- ☑ Upper & Lower Al Block External-Internal Reinforcements.
- ☑ NSTXU-CALC-12-06-00 Upgrade TF to Umbrella Structure Aluminum Block Connection (Titus), (Smith)
- ☑ NSTXU-CALC-132-04-00, - Analysis of TF Outer Leg, (Zhang), (Titus)

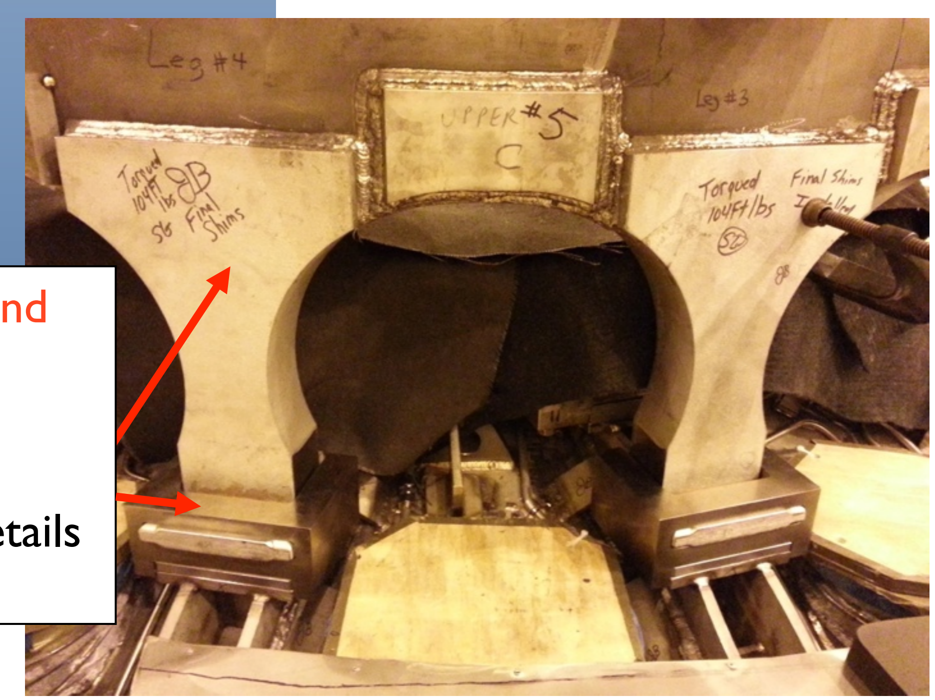




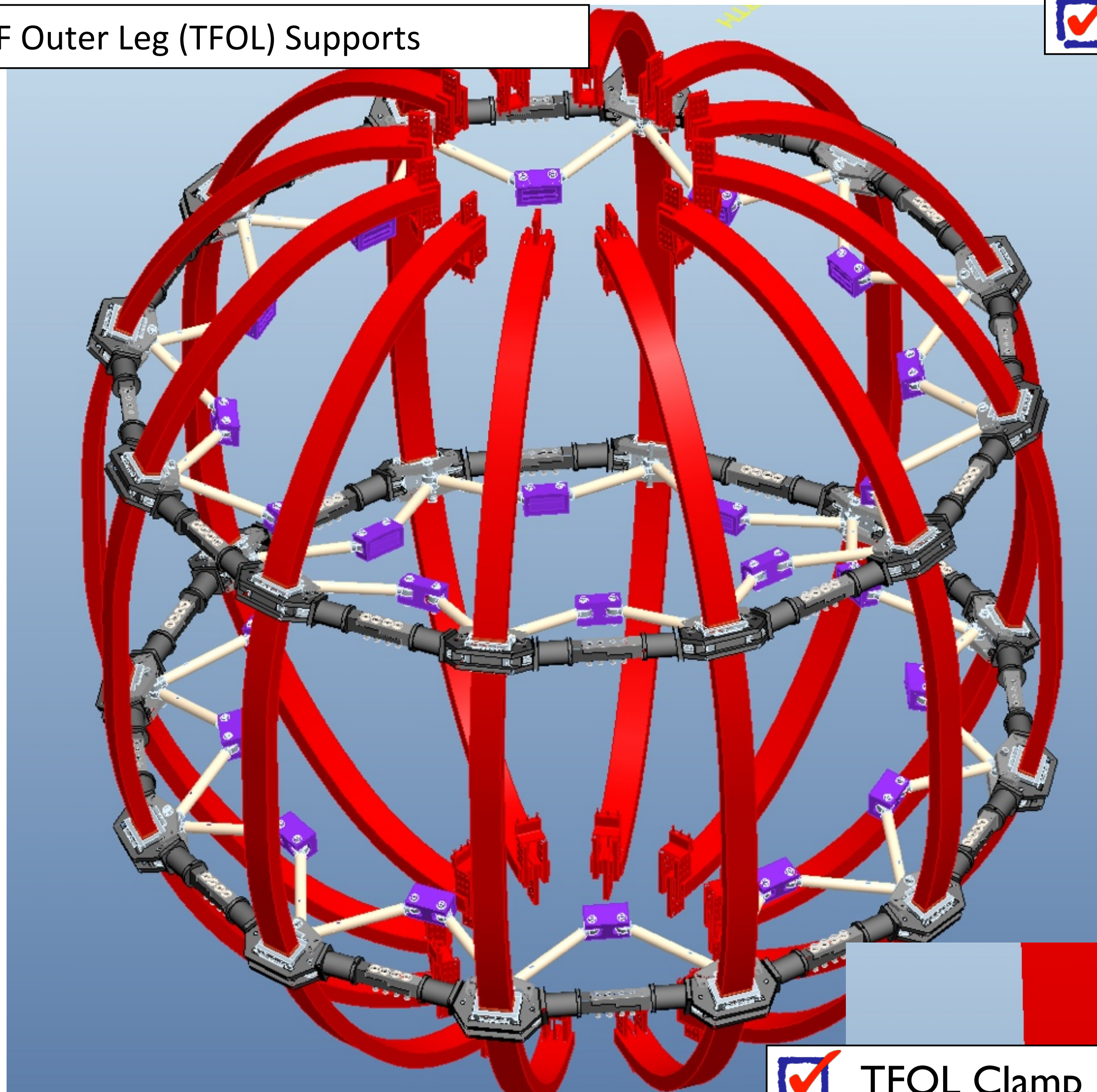
Umbrella Lid Reinforcements

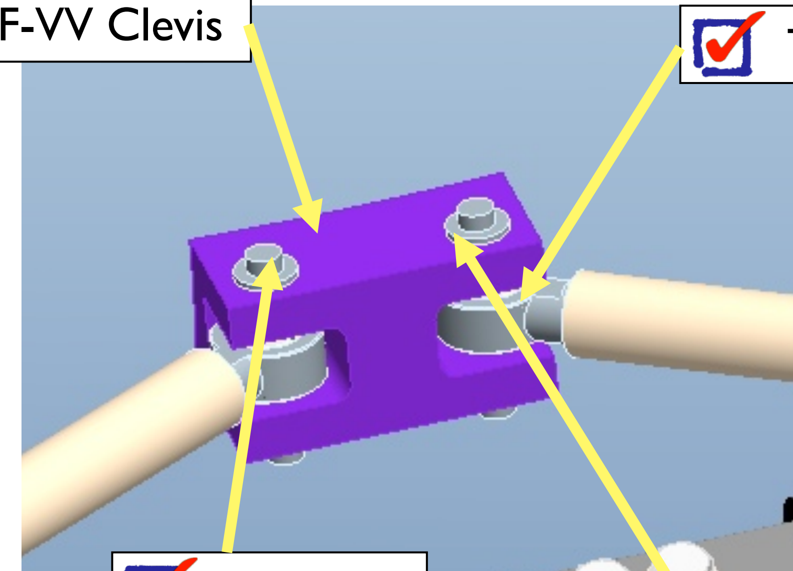


- ☑ Umbrella Replacement Leg and sliding foot
- ☑ NSTXU-CALC-12-07-00 Umbrella Reinforcement Details (Titus)

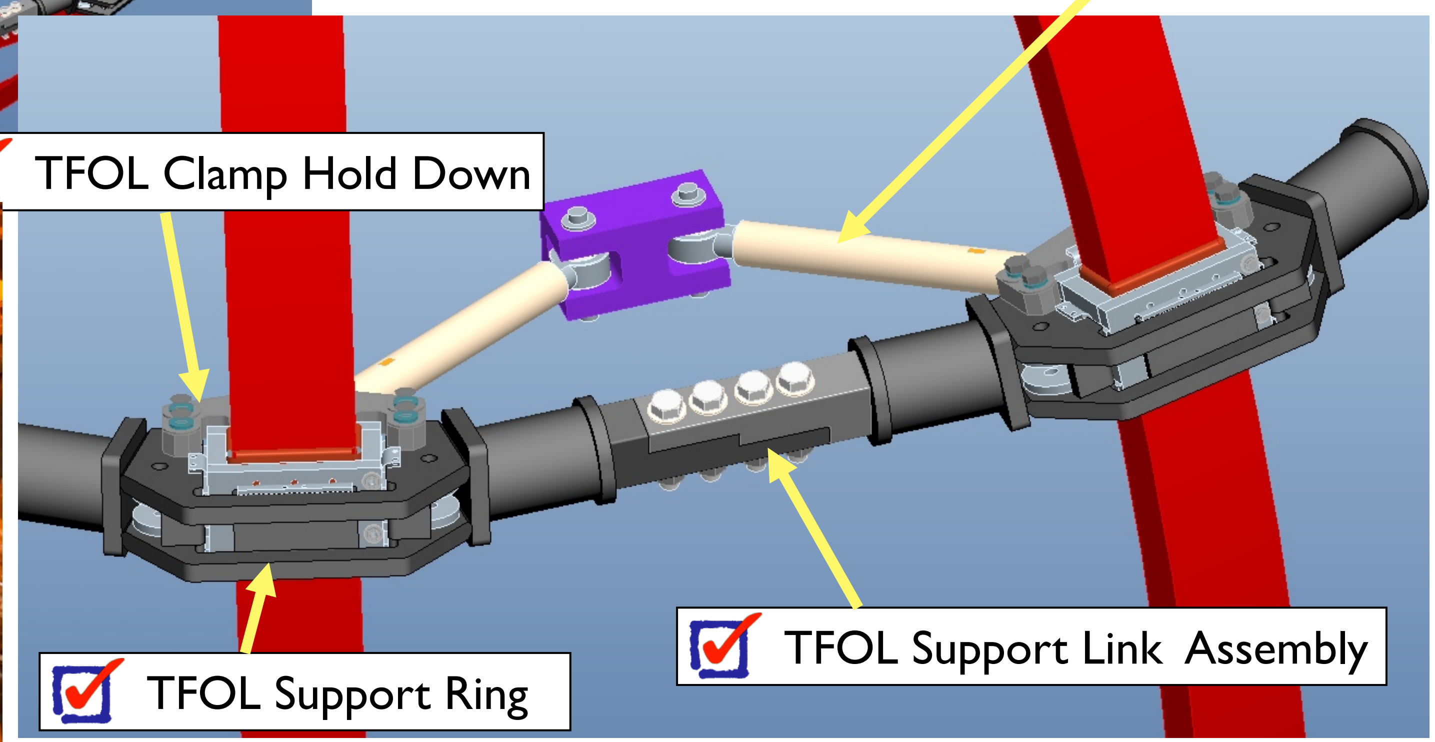


TF Outer Leg (TFOL) Supports



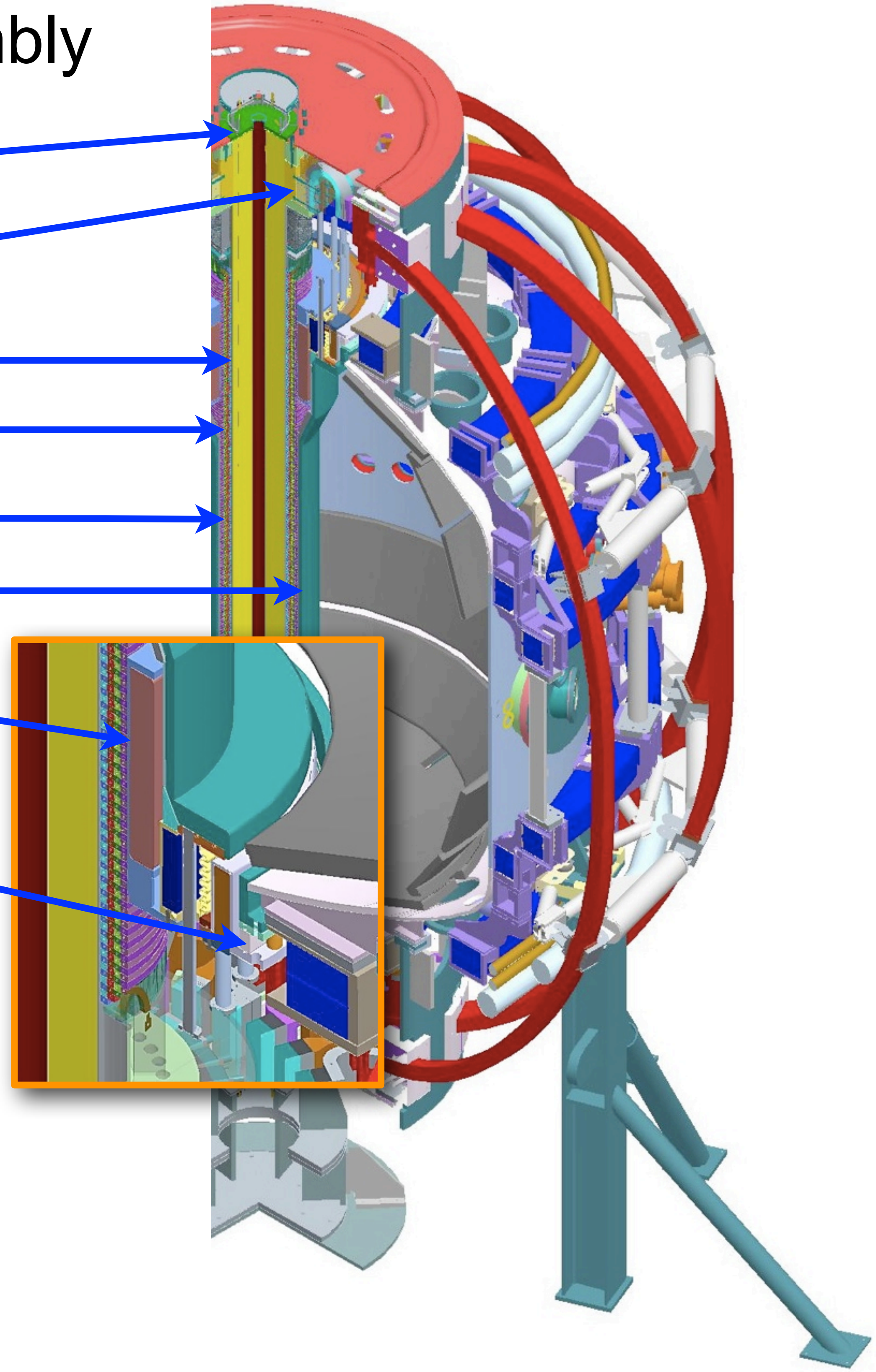


- NSTXU-CALC-132-11-00- Ring Bolted Joint - (Rogoff, Zatz)
- NSTXU-CALC-132-04-00 Analysis of TF Outer Leg (Zhang, Titus)

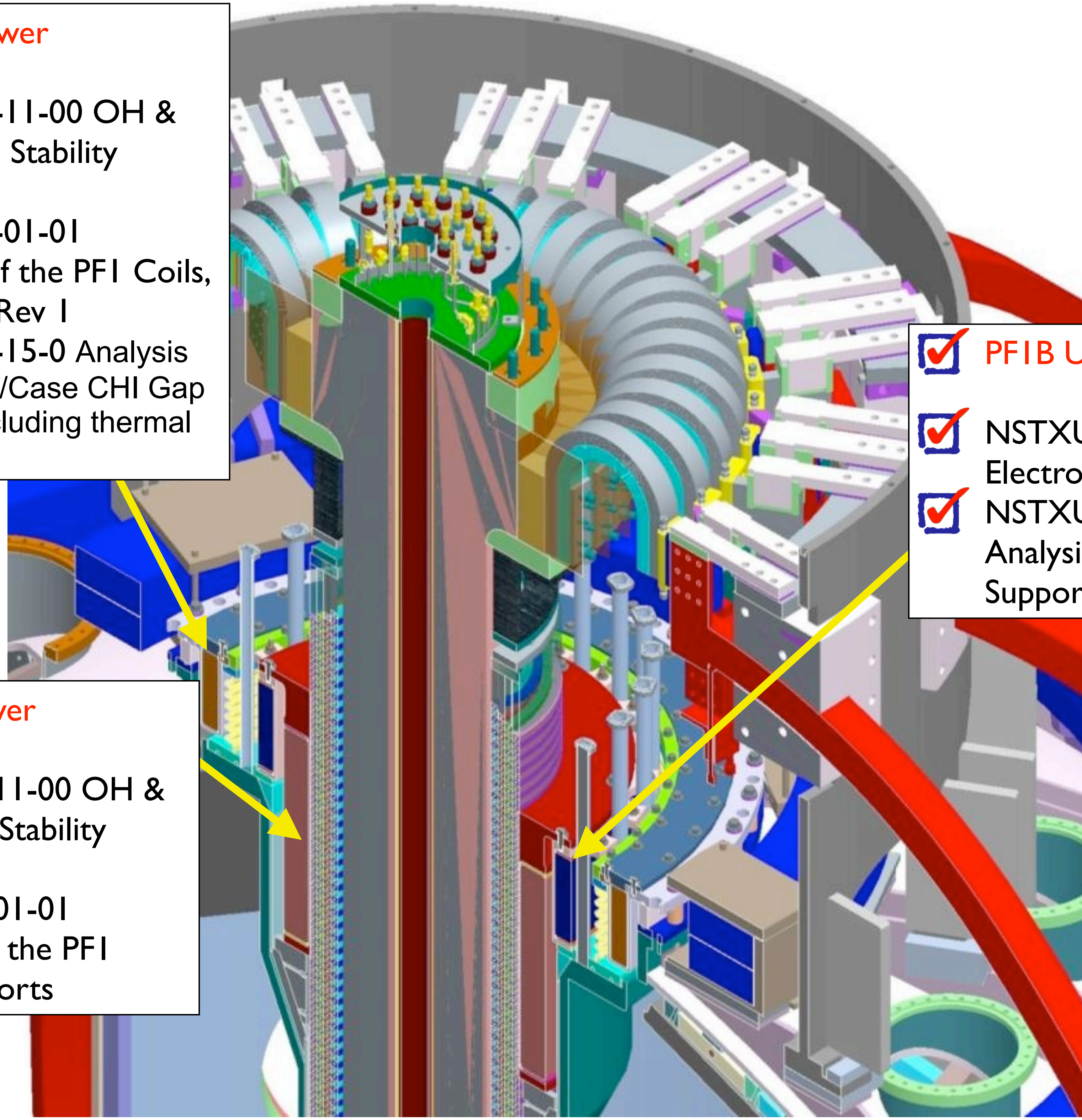


The New Central Core (Chrzanowski, Raftopoulos)

- Design, Build and Install New CS Assembly including :
  - New TF Hub Assembly
  - New TF Stub and Flex Assemblies
  - New Inner TF Bundle
  - New Ohmic Heating Coil
  - New Inconel Casing & Insulation
  - New PFC Tiles
  - New Poloidal Field 1a, b & c Coils
  - New Ceramic Break



- R&D Activities to support above work
  - TF electrical joint testing
  - OH braze joint testing
  - Stir Welding Tests



☑ PF1C Upper and Lower

☑ NSTXU-CALC-133-11-00 OH & PF1 Electromagnetic Stability Analysis

☑ NSTXU-CALC-133-01-01 Structural Analysis of the PF1 Coils, leads and Supports, Rev 1

☑ NSTXU-CALC-133-15-0 Analysis of the PF1C mandrel/Case CHI Gap thermal response including thermal shield design

☑ PF1B Upper and Lower

☑ NSTXU-CALC-133-11-00 OH & PF1 Electromagnetic Stability Analysis

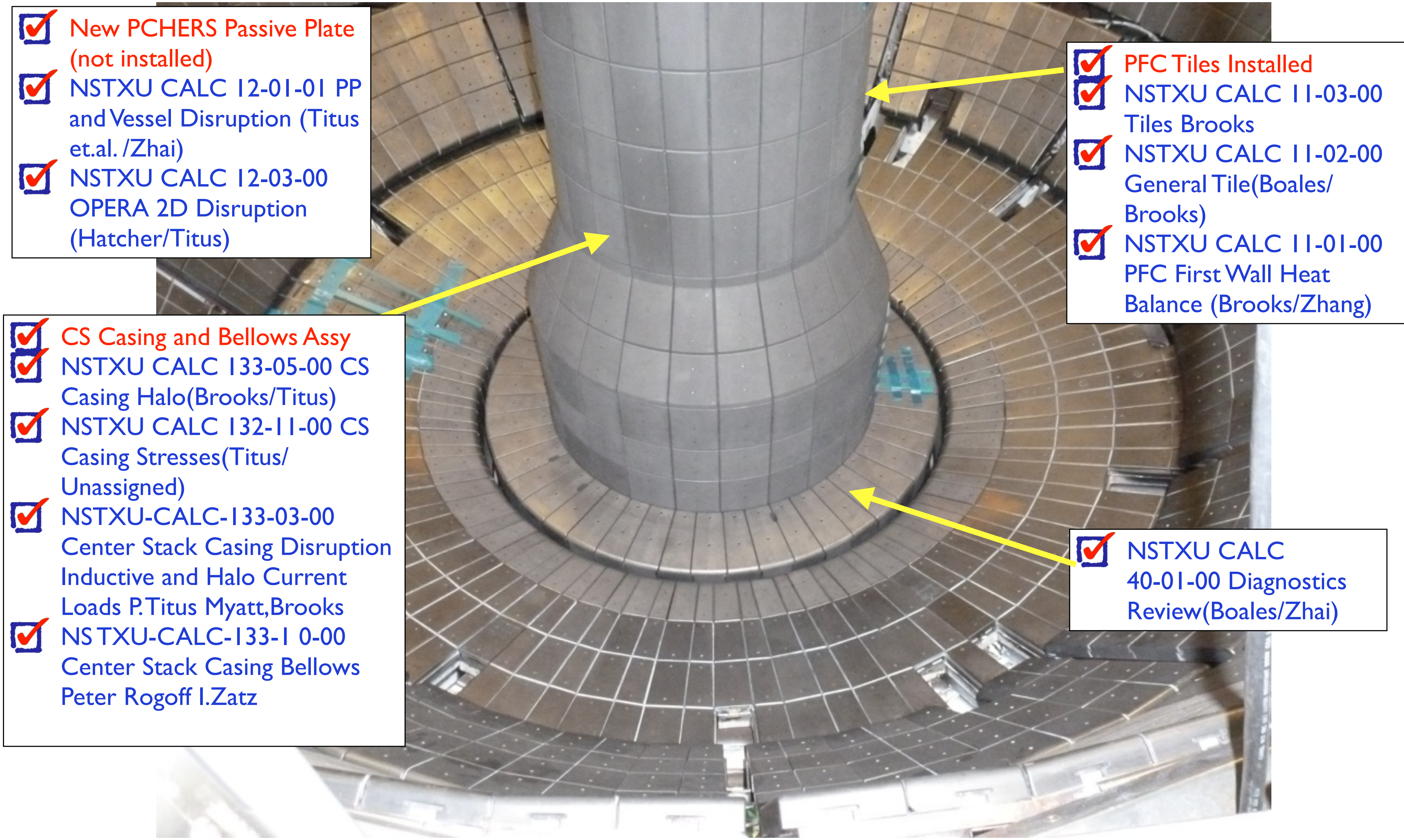
☑ NSTXU-CALC-133-01-01 Structural Analysis of the PF1 Coils, leads and Supports

☑ PF1A Upper and Lower

☑ NSTXU-CALC-133-11-00 OH & PF1 Electromagnetic Stability Analysis P.

☑ NSTXU-CALC-133-01-01 Structural Analysis of the PF1 Coils, leads and Supports

PFC's (Tresemer)



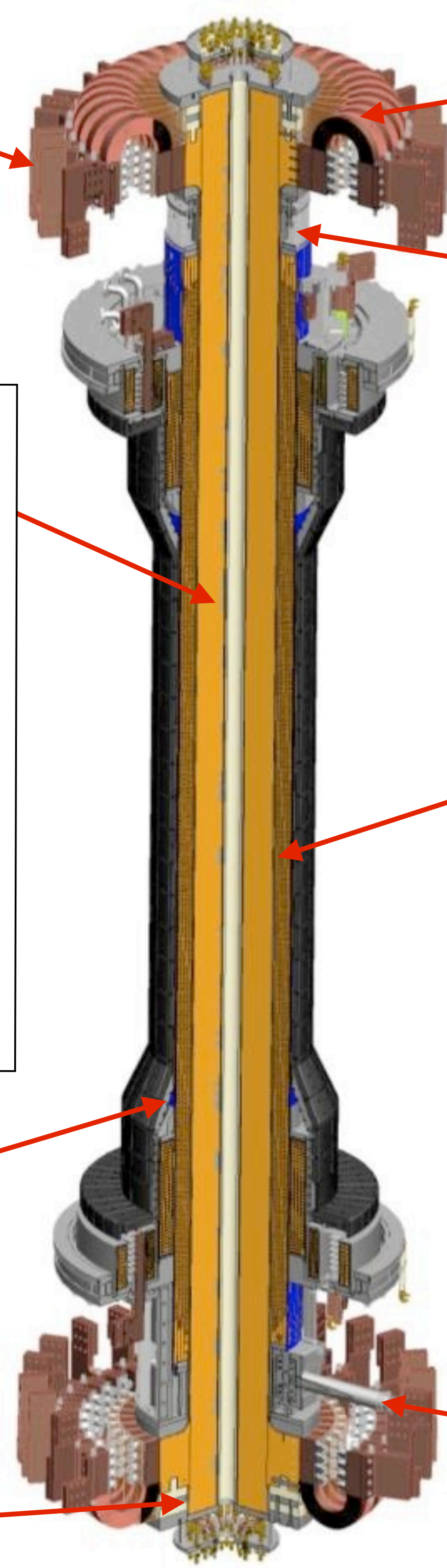
TF Bundle, OH and Extensions

- ☑ TF Lead Extensions
- ☑ TF Lead Finger Supports
- ☑ NSTXU-CALC-132-14-00 TF Strap Assembly Fingers

- ☑ TF Flex Joints Fabrication
- ☑ NSTXU CALC 132-06-00 TF Flex Joint (Willard)

- ☑ OH Preload Assembly
- ☑ NSTXU CALC 133-04-00 OH Preload Bellevilles(Rogoff/Zatz)

- ☑ TF Bundle and Conductors
- ☑ 1.1.0 NSTXU-CALC-132-03-00 Torque Egns for Design Point (Woolley/ Titus)
- ☑ NSTXU CALC 132-10-00 TF Cooldown FCOOL (Zolfaghari/Kalish)
- ☑ NSTXU CALC 132-05-00 TF Coupled EM-Thermal (Zhang)
- ☑ NSTXU-CALC-132-08-00 Determination of shear Forces Between the TF conductors and Insulation and the G-10 Insulating Crown. A. Zolfaghari T.Willard
- ☑ NSTXU-CALC-132-07-00 Maximum Torsional Shear Stress P.Titus R.Woolley



- ☑ OH Coil Assembly
- ☑ Thermal Stresses on OH-TF Coils NSTXU-CALC-133-02-00
- ☑ NSTXU-CALC-133-06-00 OH Coolant Hole Optimization A. Zolfaghari
- ☑ NSTXU-CALC-133-08-00 OH Stress Analyses A. Zolfaghari
- ☑ NSTXU-CALC-133-09-00 OH Fatigue and Fracture Mechanics P.Titus I.Zatz
- ☑ NSTXU-CALC-133-11-00 OH & PF1 Electromagnectic Stability Analysis P. H.M.Fan Titus / Zolfaghari

- ☑ CS Casing
- ☑ NSTXU CALC 133-05-00 CS Casing Halo(Brooks/Titus)

- ☑ NSTXU CALC 132-08-00 TF Collar Pin/Shear (Zolfaghari)

- ☑ NSTXU CALC 133-07-00 OH Coax (Mardenfeld)

Decision to Use Aquapour

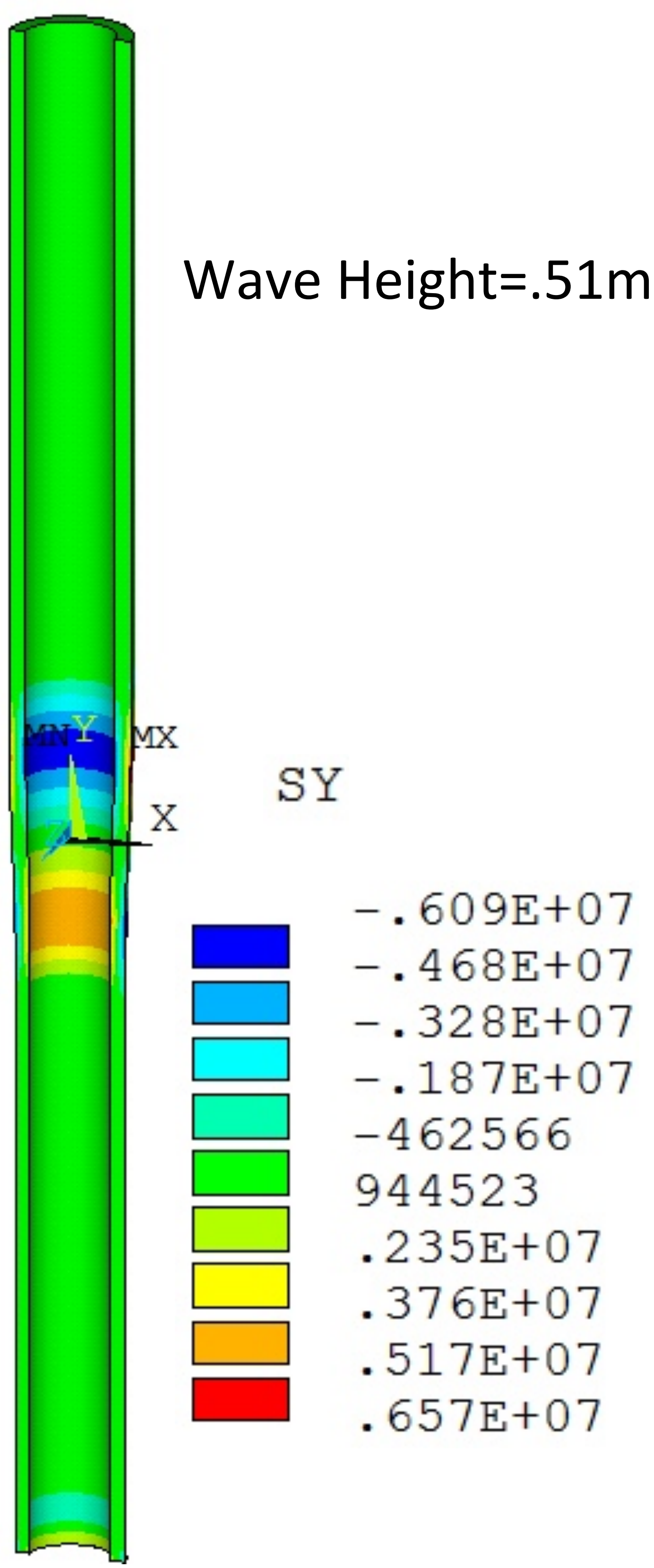
- The Conceptual Design of the TF/OH assembly utilized an OH coil wound directly onto the TF Bundle.
- During the PDR held in June 2010 the upgrade project noted that a gap of ~0.015” inches should be maintained between the OH and TF to ensure that thermal growth during operations would not be an issue.
- A variety of methods to achieve this were explored and a 0.10” thick Aquapour layer was selected as the approach to be taken.
- Aquapour is a plaster-like substance for use in epoxy molds that is easily moldable and hard once cured. It can be quickly removed with water once potting is complete.
- An R&D program was initiated to understand how to use the material. The test program lasted several months and demonstrated the ability to install, wind on, and remove the Aquapour material.
- The risk of not being able to remove the Aquapour was identified early on and was added to the risk registry along with the mitigation plan to run with it, if necessary.

Aquapour Experience

- The Aquapour layer was successfully formed on the TF Bundle as planned during fabrication, and the OH Coil was wound with no issues.
- Electrical tests indicated both the TF Bundle and OH VPI were of high quality
- Once the OH solenoid had been VPI'd and the outer OH surface cleaned attempts at removing the Aquapour commenced.
- It was soon discovered that epoxy from the VPI had migrated into the Aquapour fill. The depth of infiltration is unknown.
- For nearly 2 weeks unsuccessful attempts to remove the Aquapour were made using various methods including hand tools and electrically heating the OH coil
- Decision was made to run with the Aquapour in place
- A peer review of external and internal reviewers was held to elicit help with the mitigation plans.
- Additional analysis ("*NSTX Upgrade OH-TF Aquapour Interaction*" NSTXU-CALC-133-16) and another look at the Physics program has revealed that the Physics Program is mostly unaffected by the presence of the Aquapour (S. Gerhardt to present details)

OH Cooling Wave Calculation

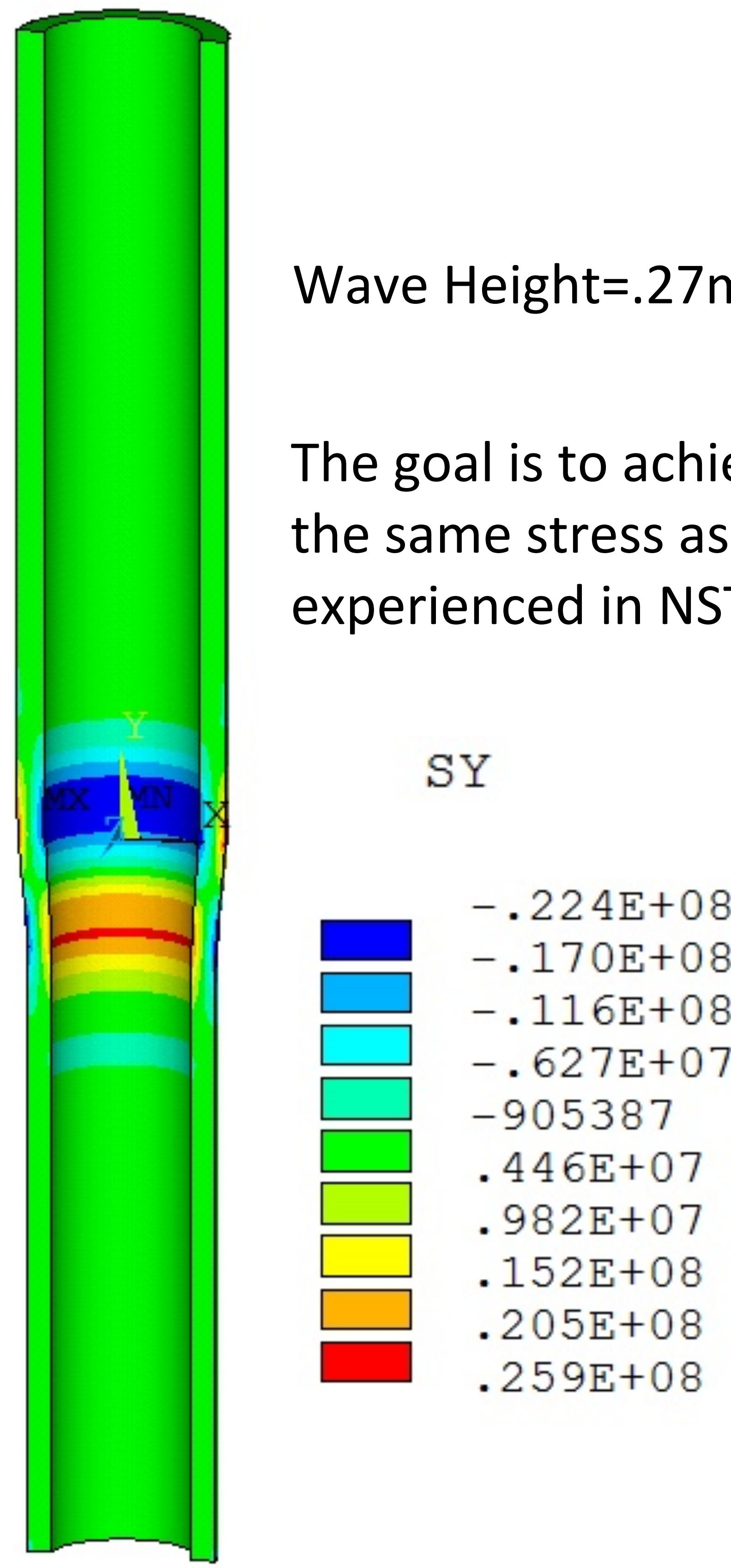
Wave Height=.51m



NSTX

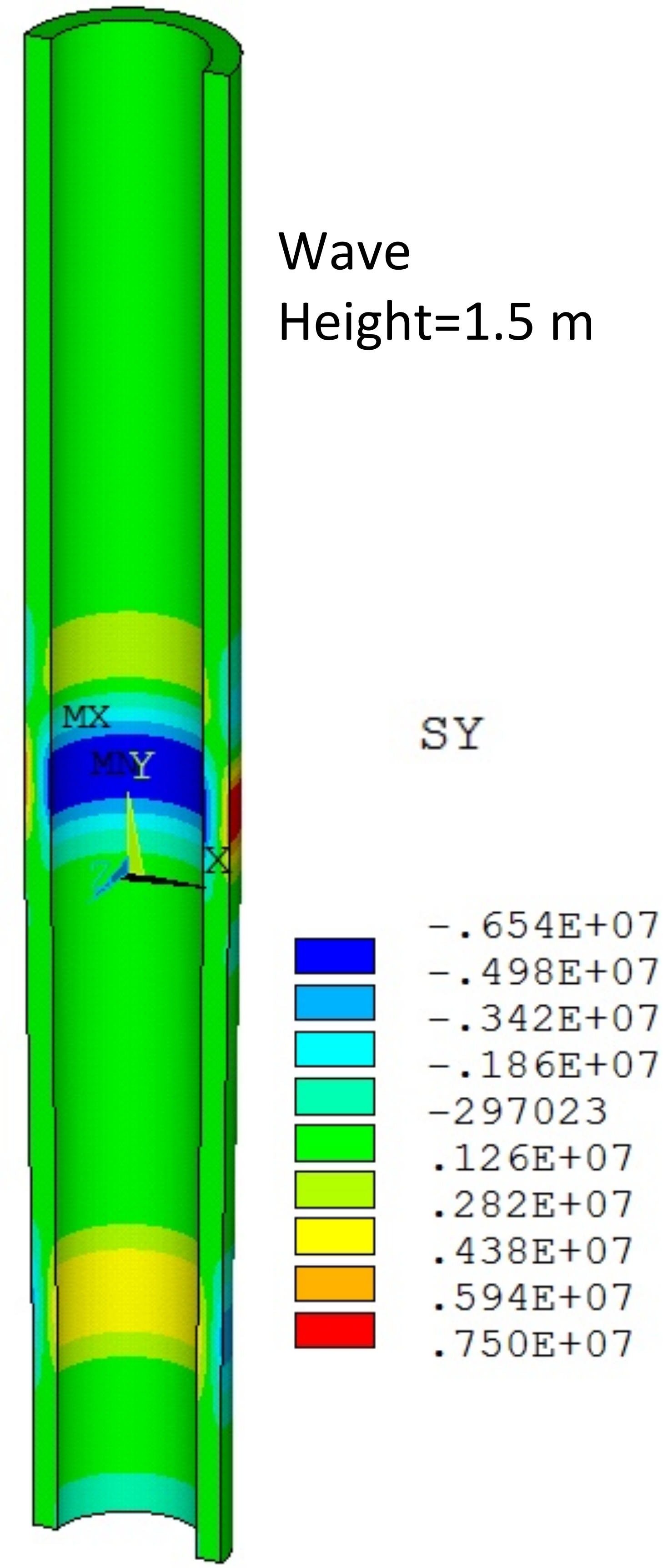
Wave Height=.27m

The goal is to achieve the same stress as experienced in NSTX



NSTX U

Wave Height=1.5 m



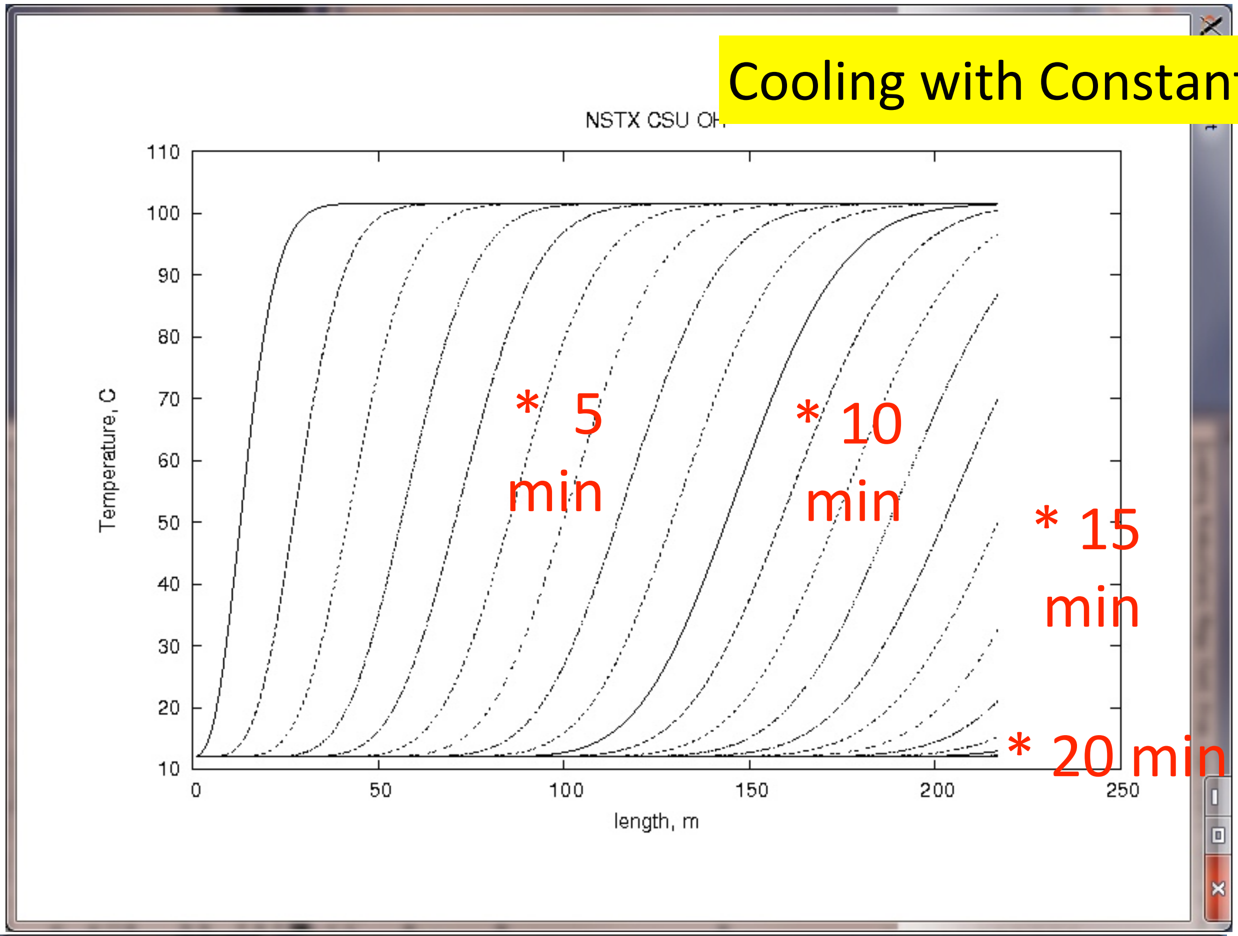
NSTX U

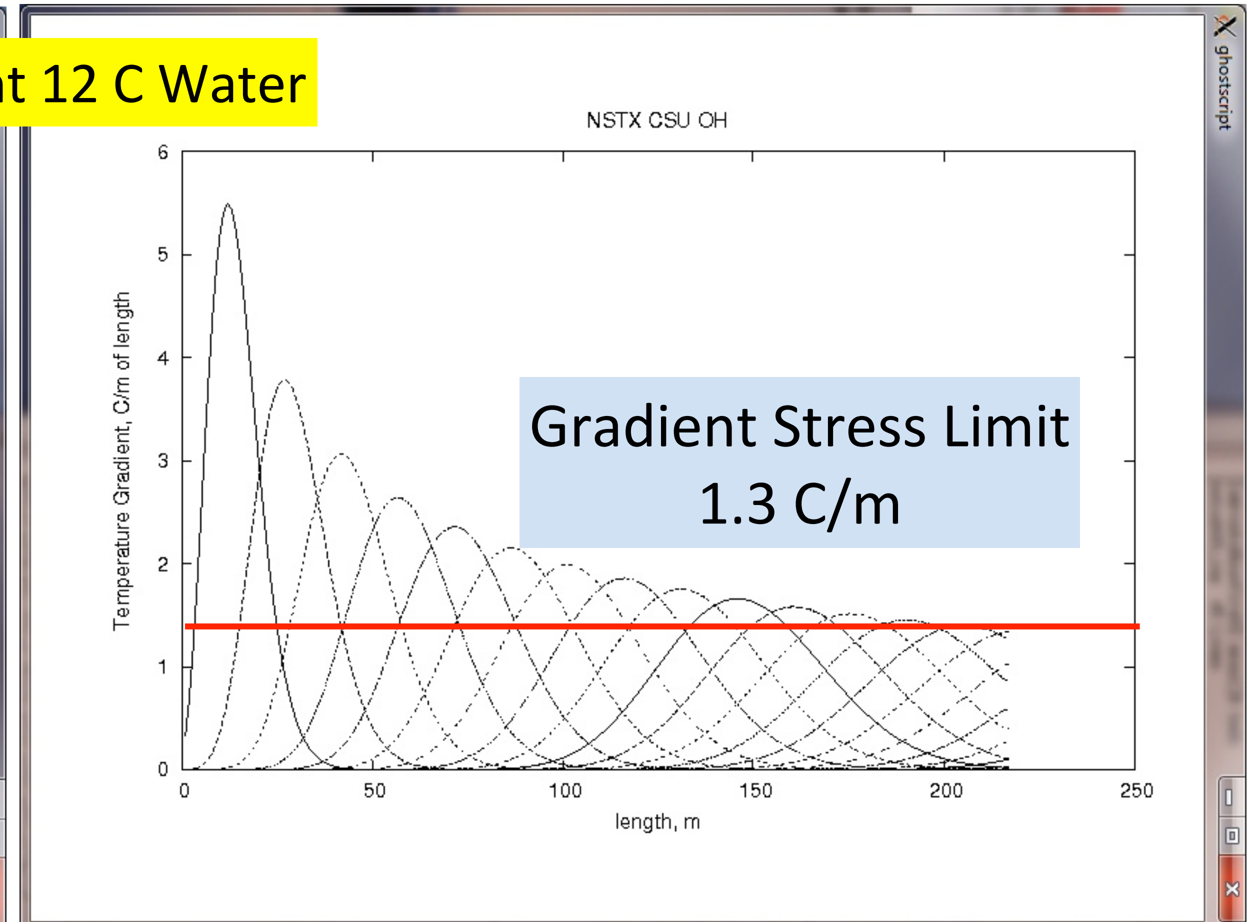
The OH Cooling Wave

- The copper/glass bond may delaminate due to the stresses predicted in the analysis.
- Delamination alone would not cause the coil to fail but repeated mechanical motion during pulses may cause a short.
- Solution: A water heating system is being designed to provide a more gentle cooling cycle by starting the cooling with hot water and gradually cooling to 12c over 300s
- In addition a series of tests are being performed by the resin manufacturer to determine if the coil will delaminate and eventually fail electrically

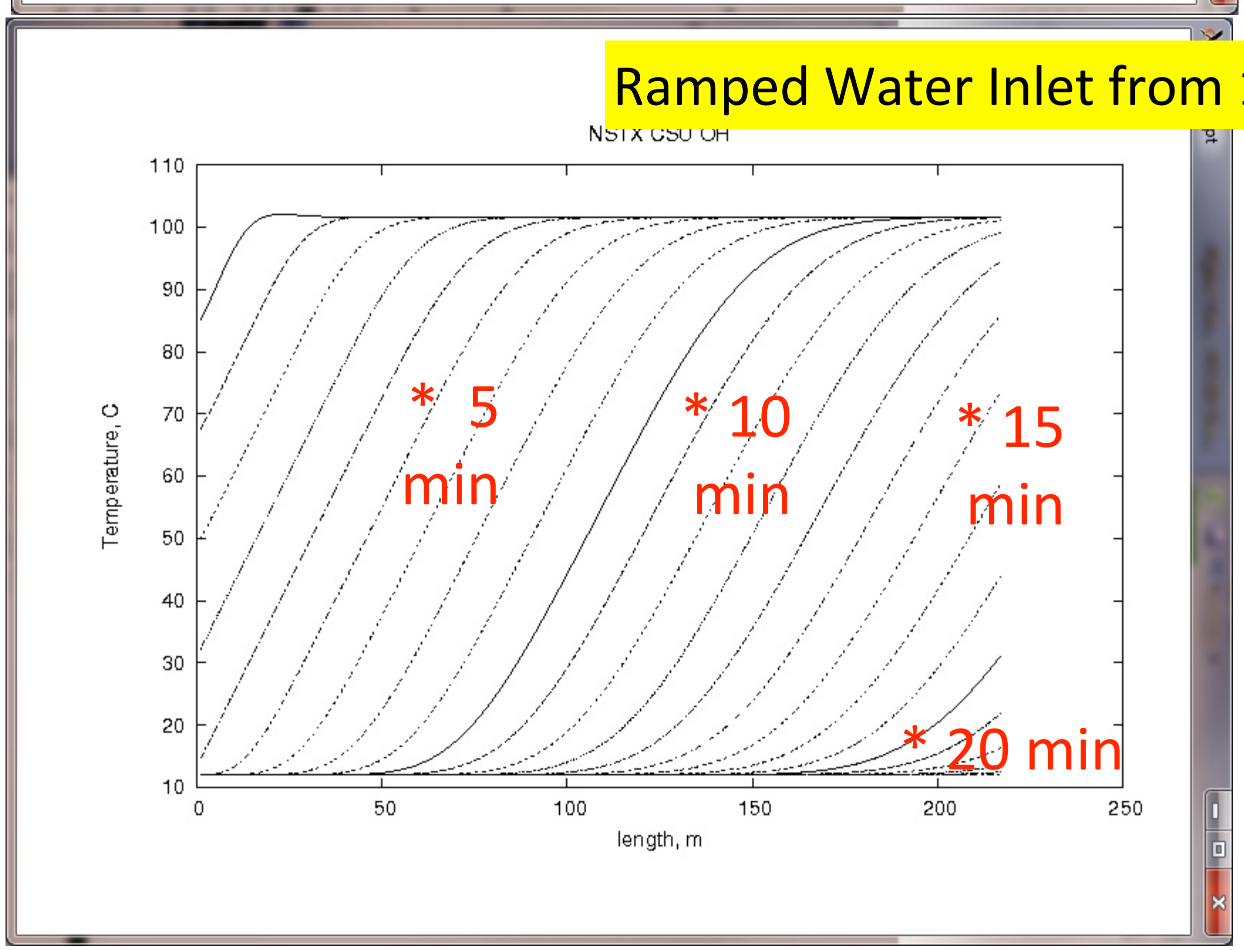
OH Cooling Wave and Gradient in Conductor

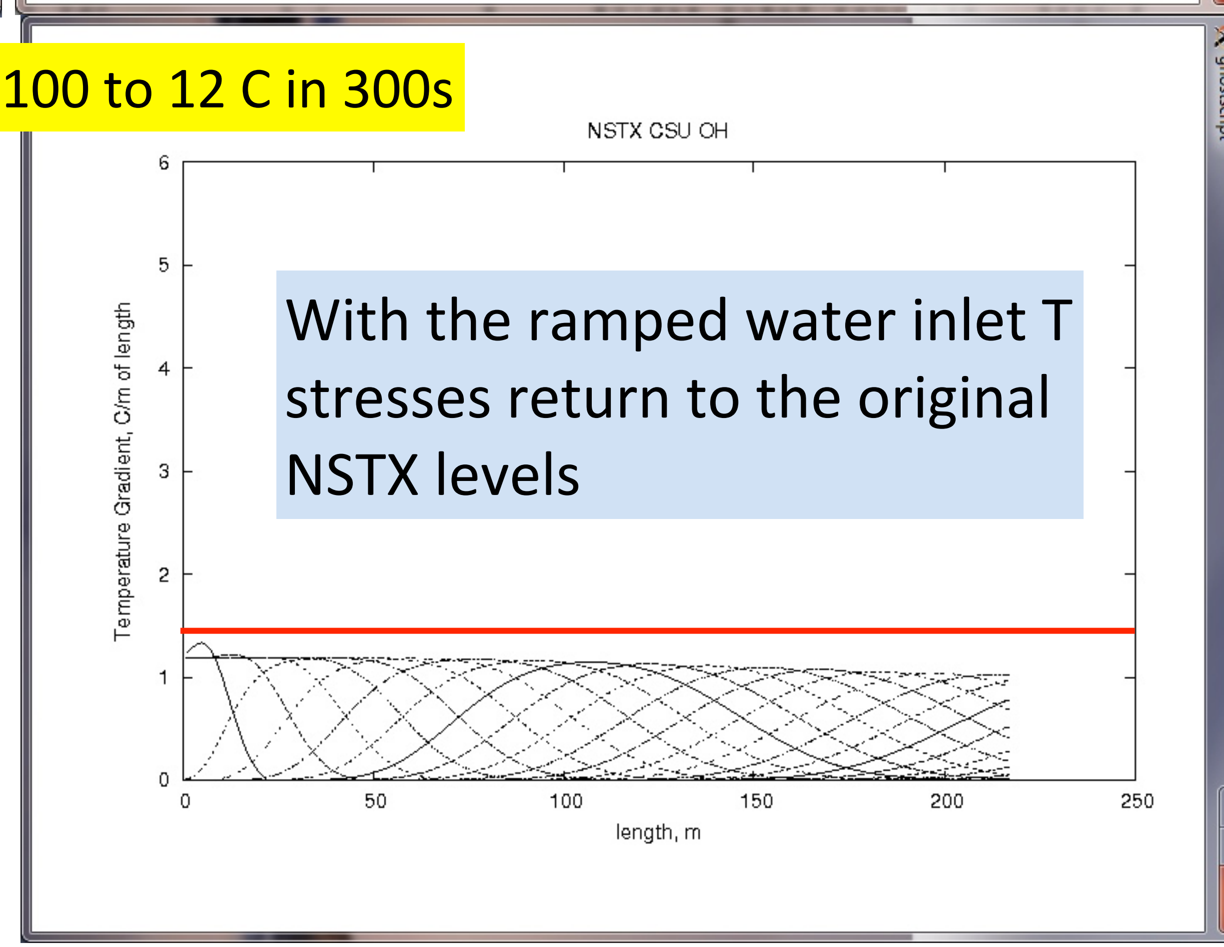
Cooling with Constant 12 C Water





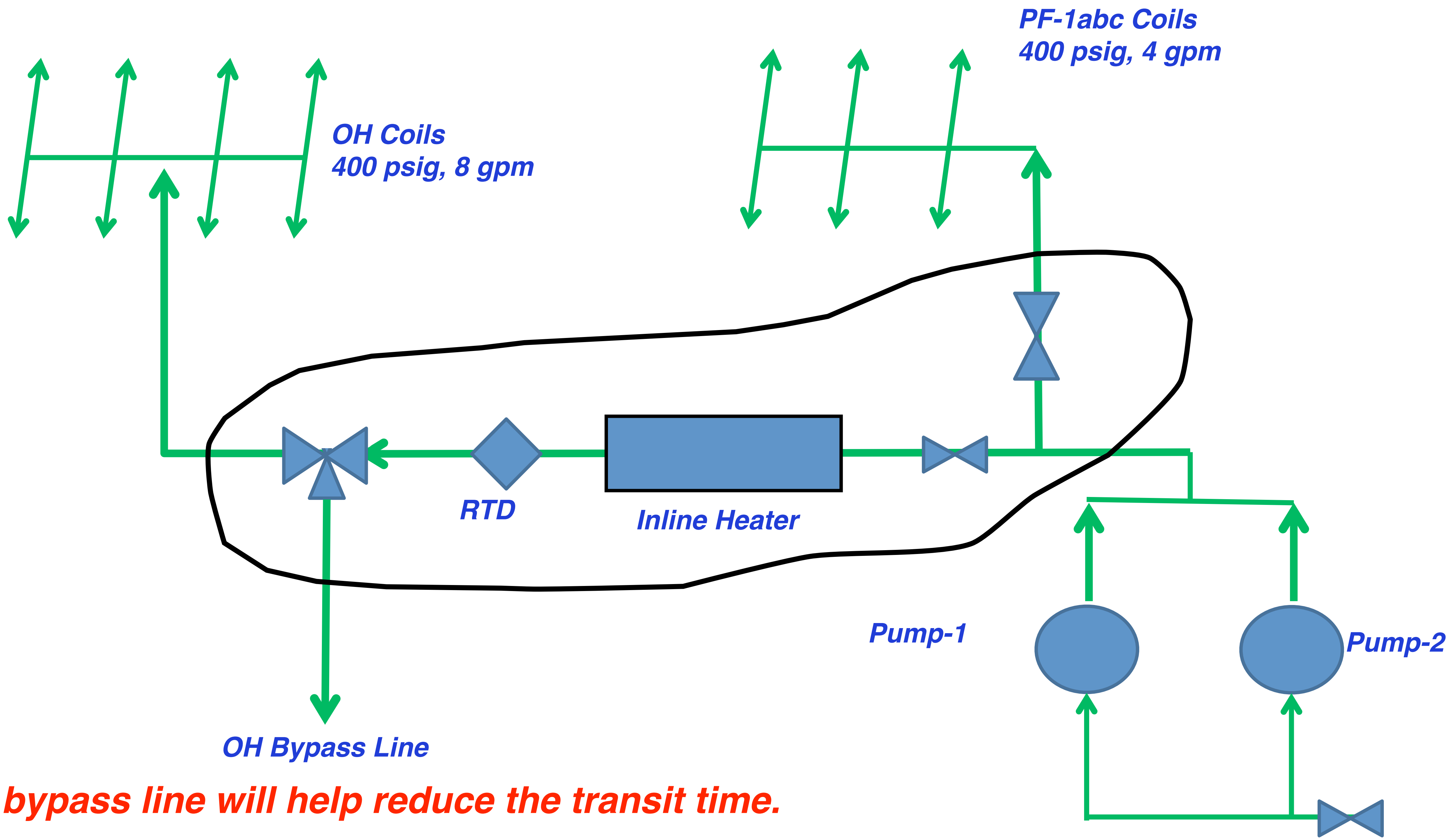
Ramped Water Inlet from 100 to 12 C in 300s





Proposed OH Water Heater Design (Atnafu)

- Inline heater on the high pressure side provides water temp matched to coil temperature after pulse
- Temperature ramps down over 5 mins to cool coil gently
- Detailed design is underway
- Installation planned to be ready for initial operations in March.



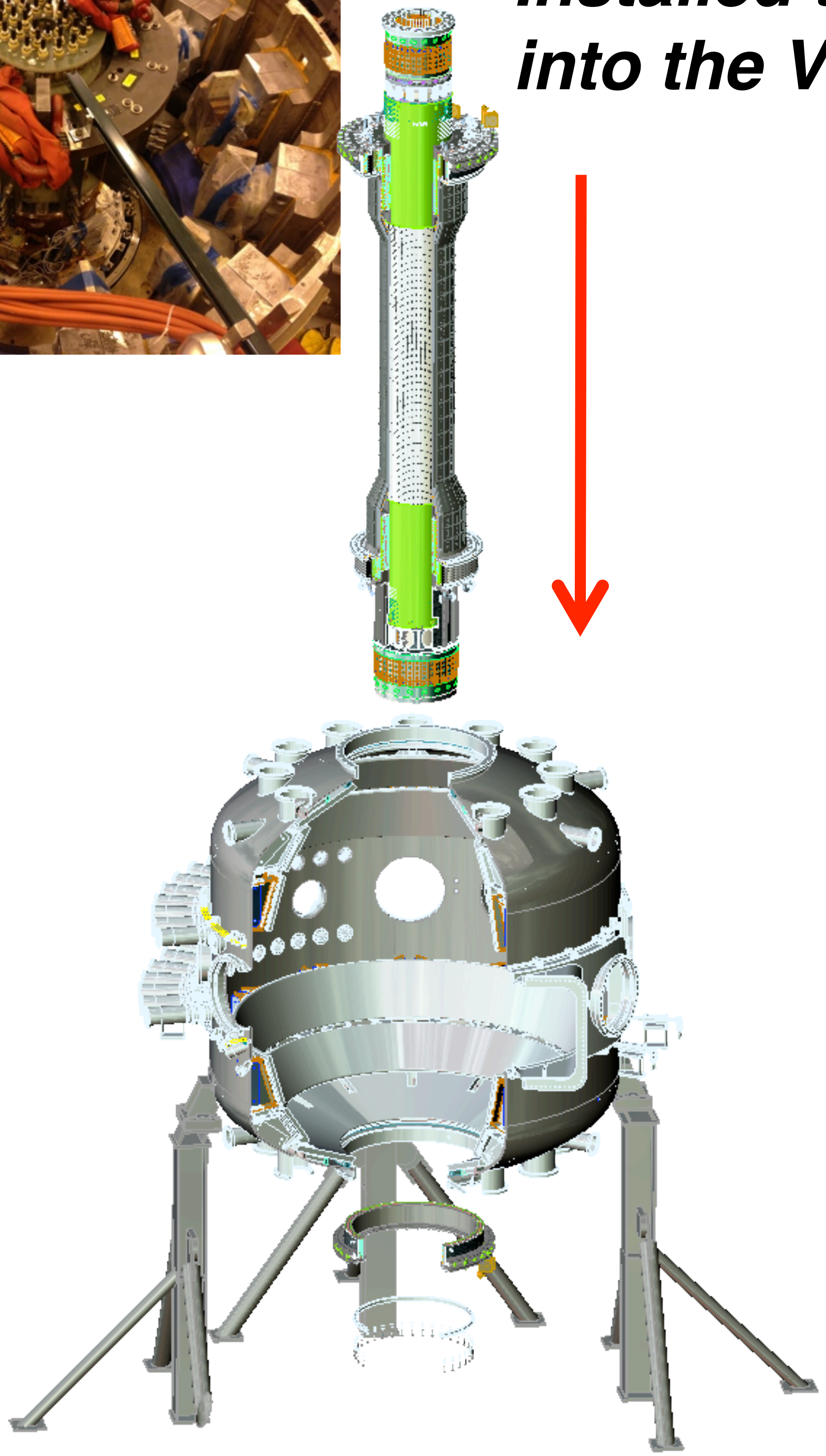
- ***The bypass line will help reduce the transit time.***

OH Coil Insulation Strain-Controlled Tests and Elevated Temperature Creep Tests

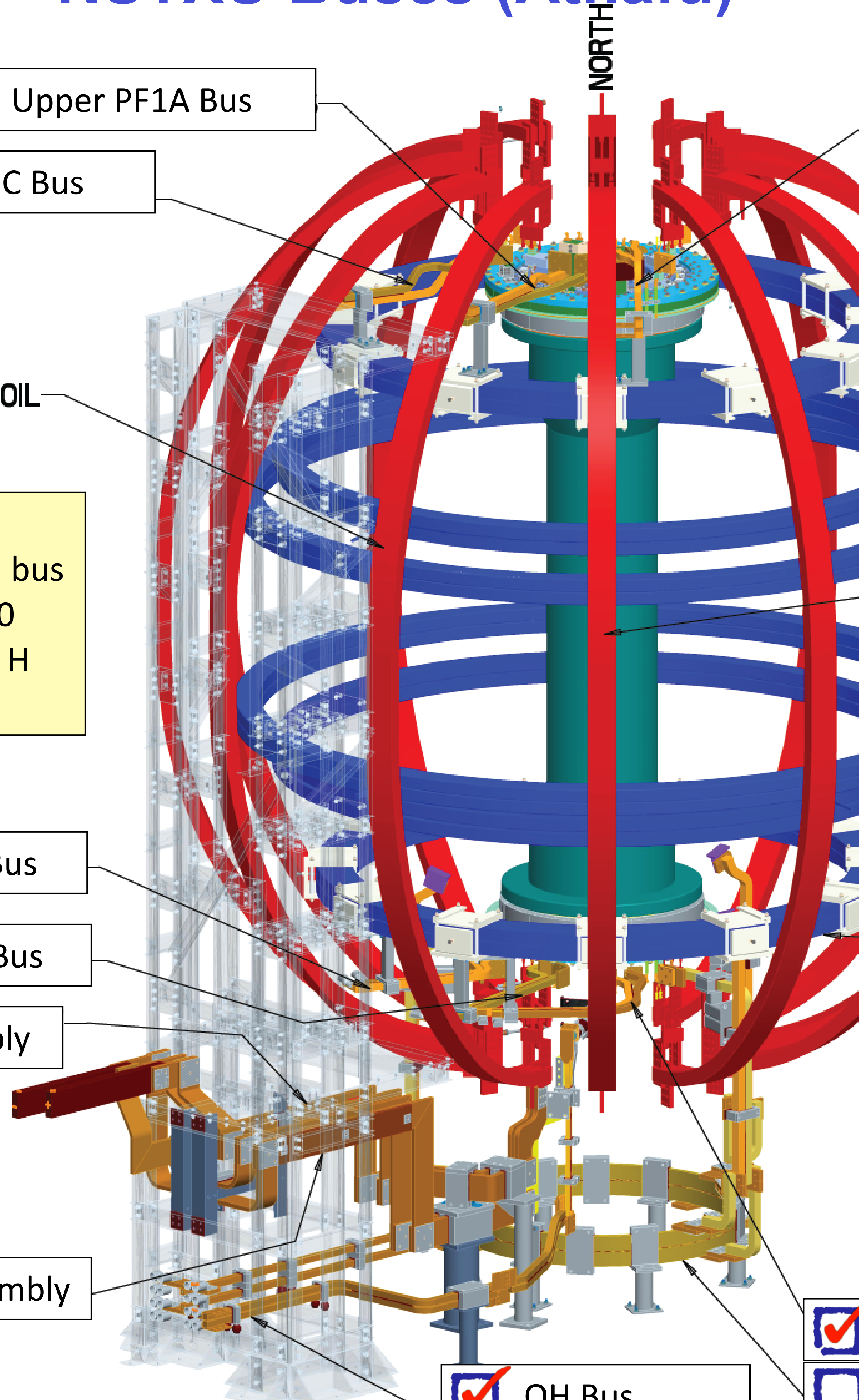
- Tests are being performed by the resin Mfr, CTD, include:
  - Two 3x4 copper turn specimens for strain-controlled testing of NSTX-U OH coil insulation.
    - To determine if turn-to-turn delamination will occur by OH coil cooled from its peak of 100 C by 12 C water
    - For qualification of possible future frictional interactions with the TF
    - Electrical tests to be performed to see effect of mechanical strain on the electrical insulation
  - Two 10-layer stacks of copper insulated like the OH turns for elevated temperature creep tests.
    - The purpose of this test is to determine if creep will occur at 110 C and 120 C
    - This test is being performed to determine if the operating temperature of the OH coil can be increased to accommodate preheating of the OH coil so that it is mechanically decoupled from the TF coil with the Aquapour remaining in place between the OH and TF
    - The goal is to demonstrate that preload will not be lost at a rate that is difficult to overcome with the adjustments in the preload mechanism

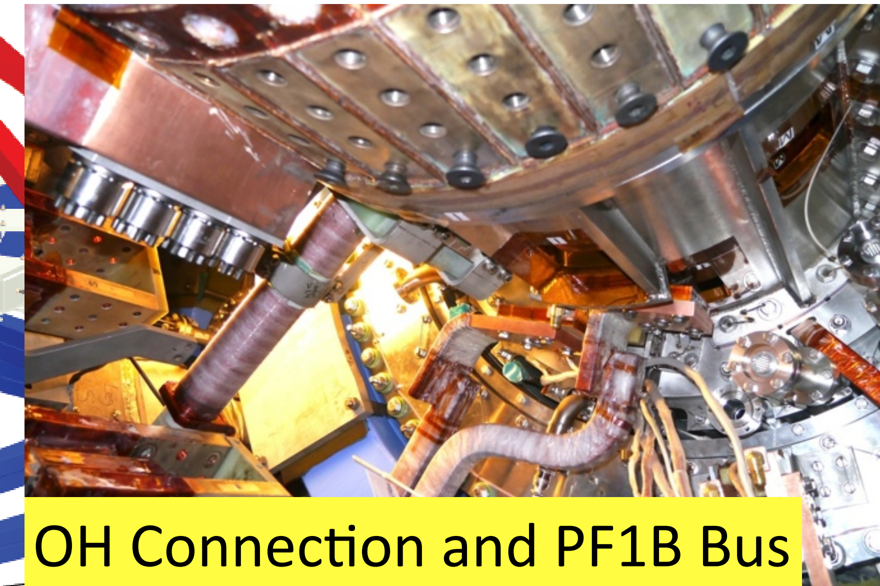
Assembly & Installation of CS Completed

Installed the completed Center Stack Assembly into the Vacuum Vessel (October 2014)



NSTXU Buses (Atnafu)

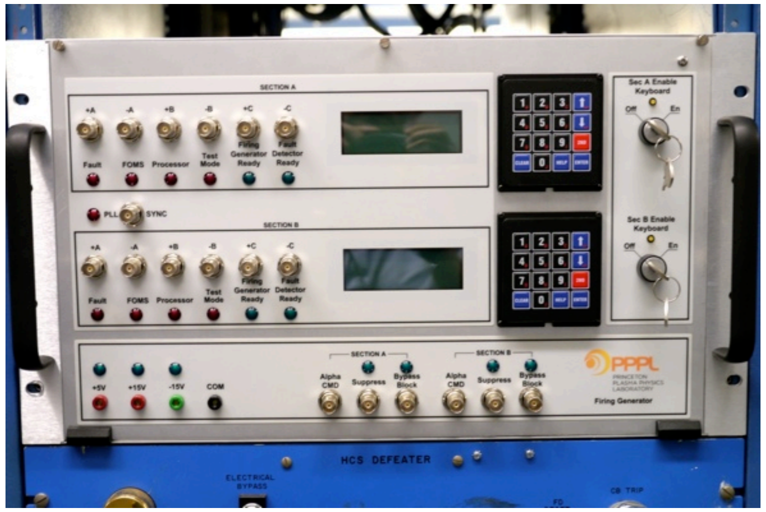



OH Connection and PF1B Bus


TF Leads

Electrical Power System (Raki)

- Upgrade Requirements
  - TF : 129.8 kA, 1kV, ESW 7.08 sec every 2400 sec (7.05kA rms) ;
  - OH : 24kA, ESW 1.474 sec every 2400 sec ; 6kV
  - PF1a: Eliminate Ripple reduction reactors
- Tasks Summary
  - ☑ Redesigned TF Circuit increasing parallel branches from Four TO Eight branches
  - ☑ Provided two +/- 0 to 155A fiber optic DCCT for TF
  - ☑ Increased the number of parallel cables feeding TF from Five TO Eight.
  - ☑ Redesigned the Power Cable Termination Structure to have higher size bus for TF
  - ☑ Redesigned OH Power Loop using the old PLT TF coils as the current limiting reactors.
  - ☑ Redesigned the Hardwired Control system for TF & OH using PLC
  - ☑ Redesigned PF1a circuit eliminating the ripple reduction reactors.
  - ☑ Designed and installed a new TF turn to turn fault detection system.
- Calculations Supporting Tasks
  - ☑ NSTXU-CALC-53-01-00 Modification of the TF Coil Power System PSCAD Model
  - ☑ NSTXU-CALC-53-02-00 Modification of the OH Coil Power System PSCAD Model
  - ☑ NSTXU-CALC-53-03-00 TF Cabling from the Transition Area to NSTXU Test Cell
  - ☑ NSTXU-CALC-53-04-00 TF Cabling from the Rectifiers to SDS
  - ☑ NSTXU-CALC-53-05-00 Current Unbalance in the Eight Parallel Branches
- Status
  - ☑ Design and installation completed
  - ☐ Testing is in progress.
    - ☐ PTP-ECS-70 -ECS HCS Upgrade Preliminary Test procedure - Zhao
    - ☐ PTP-ECS-71 - ECS HCS OH Upgrade Preliminary Test procedure - Zhao



Bakeout (Raki)

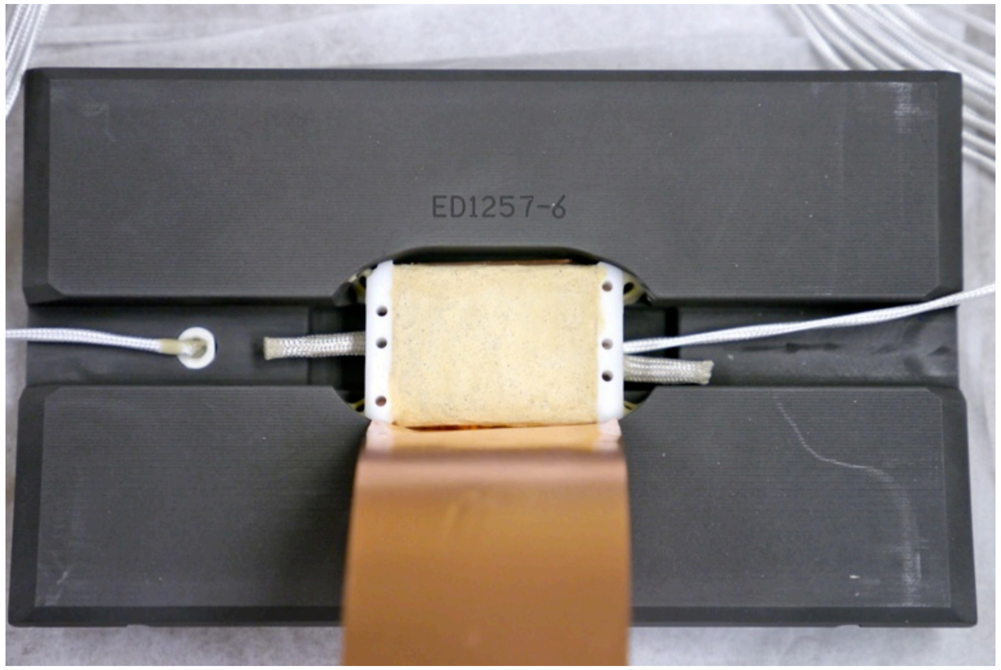
- Requirement
  - To provide a low voltage power supply and related cabling to pass current to the CS Casing to heat to 350C
- Progress
  - Work is 85% complete
  - ☑ Power supply has been purchased and is in place ready for use
  - ☑ Dummy load is fabricated and available for use
  - ☐ Only remaining work is to checkout the power supply with the dummy load.

Central I&C (Sichta)

- Requirement
  - ~4x longer pulse length drives upgrades for data acquisition, networking, and real-time controls.
- Progress
  - Job is 75% complete (Nov. 2014). Remaining scope: $18k M&S, 320 hrs installation, 500 hrs programming, 850 hrs testing. Ready for ISTP Feb, 2015.
  - ☑ Plasma Control algorithms for NSTX-U are in good shape. The physics requirements for PCS have undergone several revisions.
  - ☑ The engineering specification for Power Supply Real-time Control (PSRTC) software was approved in Nov. Most of the programming has been completed, and unit and system testing are underway.
  - ☐ Digital Coil Protection System software will (also) run on the computer performing the Power Supply Real-time Control (PSRTC) software; this will complement the DCPS system operating at D-Site. The “FCC DCPS” software remains to be integrated into the software framework. This was ECP'd into 6100.
  - ☐ Postponement of (Transrex rectifier) Fault Detector project has spurred a small ECP to purchase (15) additional CAMAC memory modules.

Diagnostics (Kaita)

- Replace Centerstack Diagnostics
  - ☑ Rogowski Coils
  - ☑ Mirnov Coils
  - ☑ Flux Loops
  - ☑ Langmuir Probes
  - ☑ Thermocouples
- Evaluate Diagnostics
  - ☑ NSTXU CALC 40-01-00 Diagnostics Review (Boales/Zhai)



Auxiliary Systems

- Gas Injection Systems (Blanchard)
  - ☑ Relocate existing center stack gas injection system to the new center stack
  - ☑ Pre - Ops Test Procedure: PTP-NSTX-GIS-008 - Fueling Gas Delivery System Pre-Op Testing - (Blanchard)
- Coil Cooling water modifications (Atnafu)
  - ☑ Increase in cooling water pressure by upgrading the pump for the OH coil to provide 600 psig (up from 400 psig)
  - ☑ Upgrade the existing cooling water system to cool the outer TF coil legs separately from the inner
  - ☑ Added 8 flow control valves to OH Coil Cooling system to equalize water passage transit times
  - ☐ OH Water Heater requirement to reduce the cooling wave effect
  - – Calculations supporting design
    - ☑ NSTXU-CALC-133-06-00 OH Coolant Hole Optimization A. Zolfaghari
  - – Pre - Ops Test Procedures
    - ☑ PTP-WS-08 - NSTX De-Ionized Water/ System Testing - (Kalish/Herskowitz)

Remaining Tasks and PTP's

- Complete PF, TF, OH and CHI Bus Bar installations
- Complete connections of the Water Cooling system
- Install the TF Flex Connections to the Outer TF Legs
- Complete design of OH Water Heating System and Install & Comission
- Complete (16) PTPs:

System	Title / System	Author	Status	Run	
Vacuum Vessel and Support Structure					
	NSTX-OP-G-05 -Procedure to vent vacuum spaces behind TIV's	Blanchard	Okay	12/19/14	Current
	NSTX-OP-G-151 -Daily Hi-Pot Test of the NSTX Inner/Outer Vacuum Vessel	Winston	Okay	In-use	Current
	NSTX-OP-G-165 -Venting, Purging and Safing NSTX Vacuum Vessel for Entry	Winston	Okay	In-use	Current
	NSTX-OP-G-170 -Venting and pumping down NSTX for calibrations and diagnostics	Blanchard	Review/Sign-Off	12/19/14	
	OP-VV-732 - Leak Checking of NSTX	Winston	Review/Sign-Off	11/1/14	
Plasma Facing Components					
	NSTX-OP-G-155 - NSTX Boronization using TMB	Blanchard	Revision Required (new system)	3/1/15	
	NSTX-OP-G-157 -TMB GDC Daily	Blanchard	Revision Required (new system)	3/1/15	
TVPS					
	NSTX-OP-G-158 - TVPS Start-Up after an outage	Blanchard	In review	11/1/14	
Gas Delivery Systems					
	PTP-NSTX-GIS-008 - Fueling Gas Delivery System Pre-Op Testing	Blanchard	In review	12/19/14	
Bake-Out Systems					
	NSTX-OP-G-156 - NSTX Integrated Machine Bake-out Operations	Cropper	Revision Required	1/15/15	
Cooling Systems					
	PTP-WS-08 - NSTX De-Ionized Water/ System Testing	Kalish/Herskowitz	Revision Required	11/1/14	
Coil Systems					
	PTP-NSTX-CL-28 - HiPot of NSTX Coil Sys from SDS in FCPC	Ramakrishnan	Revision Required	12/19/14	
	PTP-CL-NSTX-26 - NSTX Coil System Preoperational Tests	Chrzanowski	Okay	11/1/14	Current
	D-NSTX-OP-G-141 - Changing Polarities on NSTX Coil Systems	Baker	Okay	In-use	Current
MPTS					
	NSTX-OP-G-142 - MPTS Personnel Safety Interlock Test Procedure	Camp	Review/Sign-Off	12/19/14	
Diagnostics					
	NSTX-OP-G-05 - Procedure to vent vacuum spaces behind TIV's	Blanchard	Okay	12/19/14	Current

Centerstack Upgrade is Ready for Operations

- The centerstack design is supported by:
  - 67 independently checked calculations
  - 26 Project level reviews by 69 independent external reviewers from 22 institutions
  - Over two dozen additional internal Design and Peer reviews (per eng-033).
  - Chits documented in comprehensive log and independently tracked by QA for closeout
  - Design, fabrication, and installation was conducted using
    - Written specifications, statement of works and procedures
    - Material Certifications for critical components
    - Material Testing performed for critical components and processes
      - Flex connectors, Friction Stir Welding, E-Beam welding, High strength fasteners
    - All welds were 100% visually inspected, in some cases for critical areas like conductors welds were radiographed, UT inspected and / or Dye Penetrant inspected
  - All of the work has been performed Safely with an excellent safety record.

NSTX-U Instrumentation

- **Motivations**:
  - Monitoring
    - CHI Gap thermal loads
    - OH Preload system.
  - Trust but Verify
    - FEA is robust, conservative and comprehensive, however the global stiffness matrix is complex and assumptions that went into the FEA model should be validated.
    - Design & Analysis imposed requirements upon installations that should be verified.
    - Quantify impacts of NSTX-U as-built deviations from CAD/FEA models.
    - Enhance inspection program by providing service history of highly stressed components.
    - Provide data to validate DCPS algorithms

Working Group Developed List of Instrumentation Over the Past Year

- **Needed for CD4**
  - ☑ OH preload monitoring (Installed)
- **Not needed for CD4**
  - CHI Gap thermal loads (PF-1C thermocouples installed)
  - Umbrella lid strains (validate global model)
  - Halo currents in CS tiles ("Shunt" tile installed)
  - Passive Plate Accelerometers
    - In-vessel (already Installed)
    - Ex-vessel
  - PF4/5 coil displacement
  - Outer TF Strut loads (validate global model)
  - J-K Cap twist displacement (validate global model)
  - TF Outer leg bending stress
  - CS Case halo loads at top flange (Bumpers installed)
  - TF flex strap displacement

Inspection Maintenance Plan

NSTX-U Inspection Plan

No.	Item	Inspection Procedure	Annually	After 5,000 shots	After 10,000 shots
1	**PF 4-5 Support Bracket to VV Welds**	Visual inspection for cracks or other signs of fatigue	Inspect for Cracks		
2	**PF 4-5 Support Bracket Studs**	Visual inspection for cracks or other signs of fatigue	Inspect for Cracks	Replace studs with new hardware	
3	**Umbrella feet bolts**	Inspect bolts for torque, report any loose bolts. Retorque as required.	Torque, Looseness		
4	**Vacuum Vessel Dome Rib welds below the Umbrella Feet**	Visual inspection for cracks or other signs of fatigue	Inspect for Cracks		
5	**TF Flex Connectors**	Resistance Check and Verify Fastener Torques or Separate and Inspect surfaces	Resistance Check and Verify Fastener Torques	Separate and Inspect surfaces	
6	**Passive Plates, biscuit clearances and arcing**	Inspect biscuit clearances and arcing			
7	**Inspect Clevis Pin Connections for signs of Fatigue**	Inspect Clevis around Pin Connection for cracks			Inspect for Cracks
8	**OTF Leg Reworked (Mechanical) Flag Joints**	Pass a current through joints and measure voltage drop. Check the torque on the bolts, or look at the compression of the Bellevilles at each inspection. Visual inspection.	Annually and Major outage		
9	**OTF Leg Flags Braze Joints**	UT inspection.	Annually or Major outage		
10	**PF, CHI, TF Buss Joints**	Inspect and / separate - inspect	Joint resistance and verify fastener torques		
11	**TF-VV Clevis Weld: Inspect clevis's adjacent to VV Support Legs**	Visual inspection of welds for cracks and fatigue.	Inspect for cracks		
12	**Socket Head Capscrews connecting SS TF Bundle end plate to insulating ring**	Inspect for torque and looseness	Inspect for torque, looseness		
13	**PF 1A, PF 1B, and TF bus Bars max stress locations per Kodiak calc (details to be provided by Neway)**	Inspect for signs of fatigue	Inspect for cracks		

FMEA and Mitigation plans

- Comprehensive FMEA has been developed (NSTX Failure Modes & Effects Analysis / NSTX-FMEA-71-9):

System	Total Failure Modes	Major Category*
PFC	17	8
VV & Structures	11	7
Magnets	41	29
Vacuum Pumping System	26	
Water Cooling System	22	
Bakeout	33	1
Gas Fueling System	73	
Diagnostics	13	
Power System	49	6
I & C	11	1
Totals	**296**	**52**

Major Category: Time to correct/repair 1 < 12 month and Cost $100k < $5000K

FMEA Sample: Magnets

Failure Mode	Effect	Detection/Recovery	Mitigation Plans
Inner / Outer PF, Inner / Outer TF: Delamination/ debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None/Shutdown and repair or replace	Copper for inner TF, OH available. OTF spare available.
Electrical failure of groundwall insulation at single location	If non-CHI ops, or CHI ops and outer VV grounded, small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground. If CHI ops and outer VV energized by CHI PS, small leakage current between CHI and affected PF circuit.	Power supply system ground fault detector. / Shutdown, repair if possible, or replace.	Copper for inner TF, OH available. OTF spare available.
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics, unusual electrical impedance and response to power supply excitation. / Shutdown, repair if possible, or replace.	Copper for inner TF, OH available. OTF spare available.
Loss of contact pressure leading to excess electrical contact resistance and /or open circuit condition under load at coil terminals or coil leads	Excess joint resistance and heating, arcing, melting, if lead(s) become physically disconnected, could be displaced from normal point of connection, possible diversion of current into other metallic path(s), possible destruction of coil.	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement); Magnetic diagnostics, unusual electrical impedance and response to power supply excitation. / Shutdown, repair if possible, or replace.	Copper for inner TF, OH available. OTF spare available.
TF Flexes- Inner to Outer TF coil- laminates begin to develop cracks	If crack propagates through entire laminate- Outer laminate in particular- the laminate could short to the umbrella lid or adjacent TF flexes	During visual maintenance inspections / Replace	Spares on hand
Loss of contact pressure on flexible joints connecting inner TF Bundle to outer legs	Excess joint resistance and heating, possible contact surface melting, arcing, could lead to open circuit condition	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement) / Shutdown and repair	Spares on hand

Summary: FMEA and Mitigation Plans for Major Events

System	Types of Failures	Mitigation Plans
PFC	Damage due to CHI disruptions	Spare tiles and tile mounts on hand
VV & Structures	Misalignments, buckling	Preventative measures including inspections, instrumentation
Magnets	Electrical shorts or mechanical damage	Repair or replace using spare raw materials on hand
Bakeout	Failure to shutdown power supply	Manual backup potable water cooling option available to prevent coil damage
Power System	Failure to detect overloads, overcurrents, and shutdown	Multiple levels of redundancy provided, Troubleshoot and repair
I & C	SDS interlock switch indicates SAFE when in UNSAFE condition	Overall SLD “Safe” status not achieved, since SLD”Safe” status not issued if air supply still available / Troubleshoot and repair

Summary

- Project design and fabrication was based on the General Requirements Document
- Each element of the design has been verified through analysis to demonstrate it meets the General Requirements and the operating scenarios
- Specifications, SOWs and Material certifications and inspections ensure the fabrication and manufacture of the parts meet the design
- In areas where the design margins are below the criteria for full lifetime pulses maintenance and inspection plans are being used to track the performance of the design
- Plans are in place to achieve full power parameter in 2-3 years of operations

Thank You for Your Attention