Machine Core Structures

WBS 1.01.02.01

NSTX-U Recovery Project FDR – March 17-19, 2020

Presenter: Mark Smith

D. Loesser - Cognizant Engineer

Last edit: 3/13/20

Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
5. Chit Closure
6. Procurement, Fabrication, Installation, and Test
7. Risk - Project Risks and Design FMECA
8. Quality, Environmental, Safety, and Health
9. Summary

Overview - WBS 1.01.03.01 &.01A

WBS Title	Machine Core Structures	WBS #	1.01.02.01
Project Cog.	Doug Loesser	Assoc. Proj. Man.	Gary Swider
Design Scope	Design new Centerstack casing; design & fabricate new Inner-PF coil supports, upper & lower vacuum boundary components, ceramic break assembly, & outer Skirt. Perform structural integrity assessment of all structures included in the load path to the test cell floor.		
Technical Impact of Scope	Enables reliable high vacuum; supports coils over full range of EM loads, supports inner plasma facing components.		
Design Status	FDRs completed: Casing → 12/28/2018 (link): MCS → 8/5-6/19 (link) chits: CS Casing (link), MCS (link) calculations: CS Casing (link), MCS (link) drawings: CS Casing (link), MCS (link) SoW/Tech Spec: CS Casing (link), MCS (link)		
Fabrication Status	Fabrication of components has started		
Installation Status	Once components are fabricated and coils arrive, the coils will be integrated in their supports		

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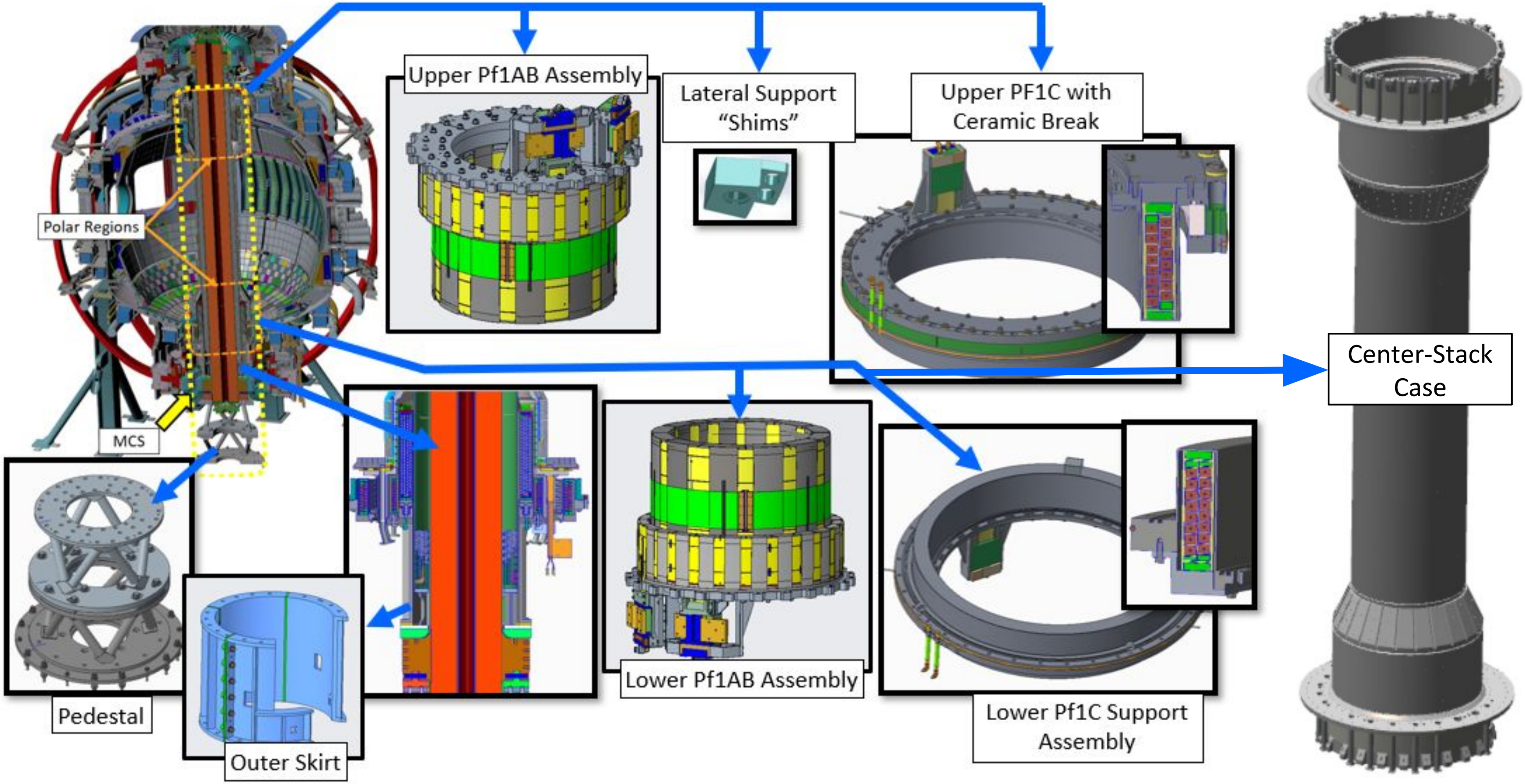
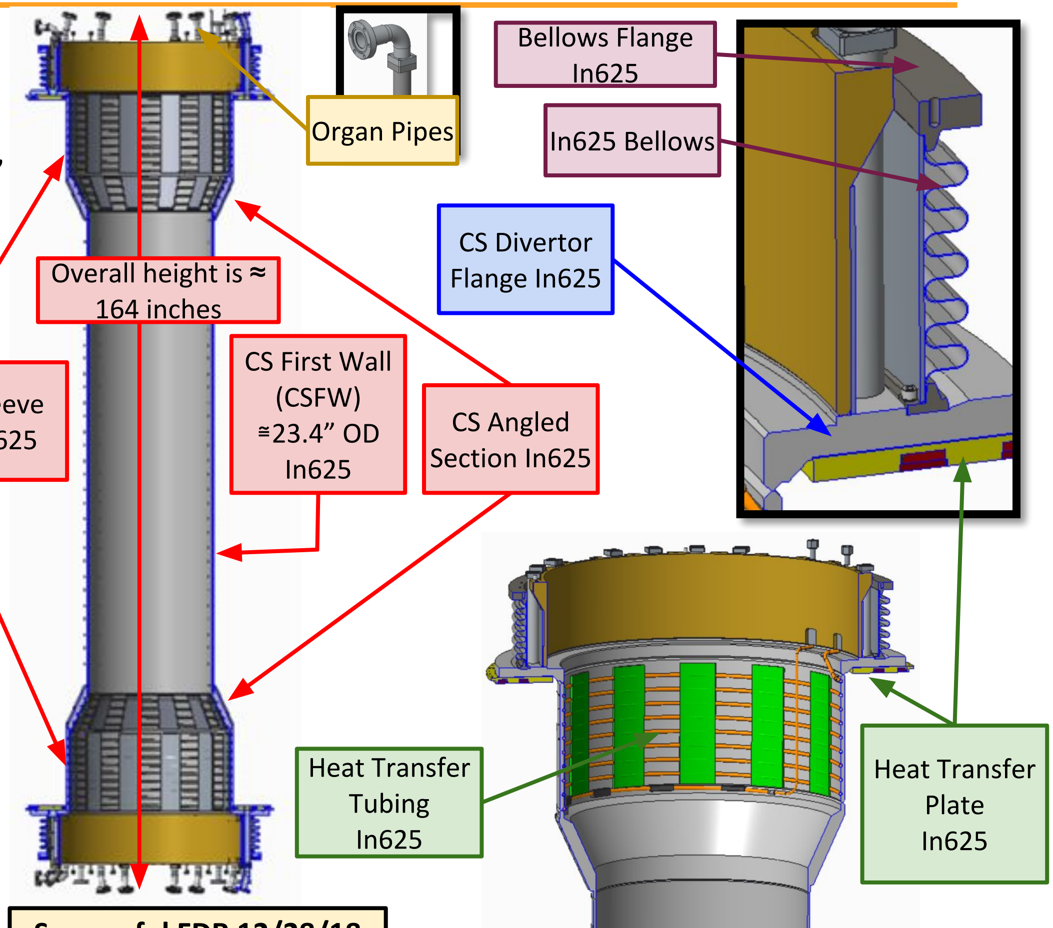
Overview Machine Core Structures Scope



CenterStack Casing - Scope

- CS Casing provides:
  - primary vacuum interface,
  - support for plasma facing components,
  - Support for Upper PF-1A & B Coils.
- Weldment made from In625 and 316SS.
- Casing fabrication contract includes the full weldment, and installation of Heat Transfer Tubing (HTT) and Heat Transfer Plate (HTP)

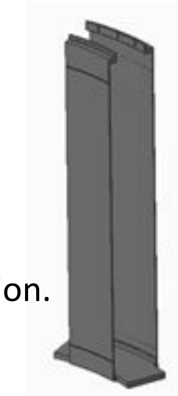
→ Casing manufacturing covered in talk by Viola
→ HTT & HTP design and manufacture covered in talk by Cai

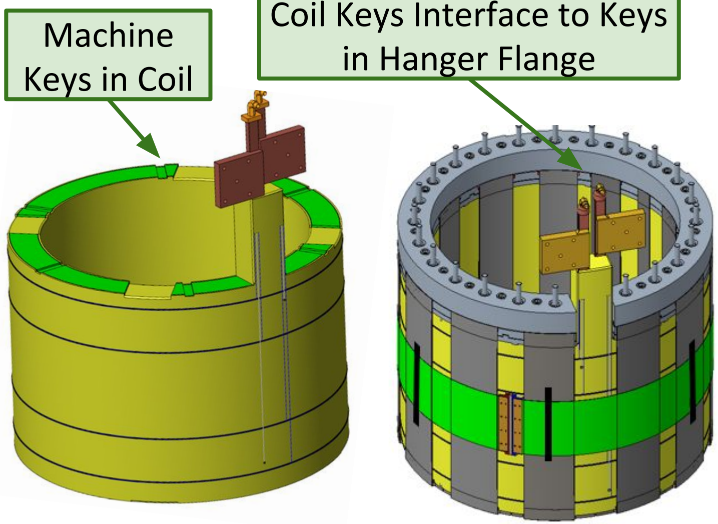


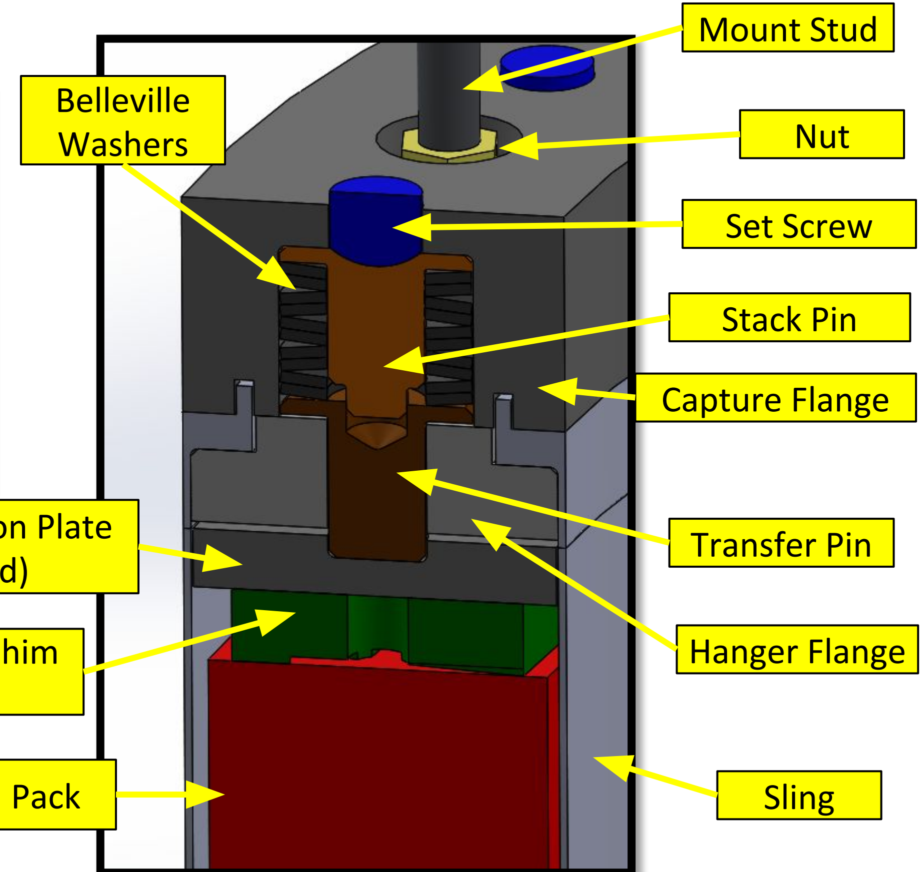
Successful FDR 12/28/18

PF-1a & -1b Sling Supports - Scope

- PF-1a and PF-1b coil supports:
  - Support against upward/downward vertical loads
  - Support against side-loads and moments
  - Provide significant vertical pre-load
    - mitigates coil thermal stresses
- Solution –
  - Support coils in In718 slings
  - Belleville stack used to provide pre-load
  - Use keyed interfaces to maintain coil position.



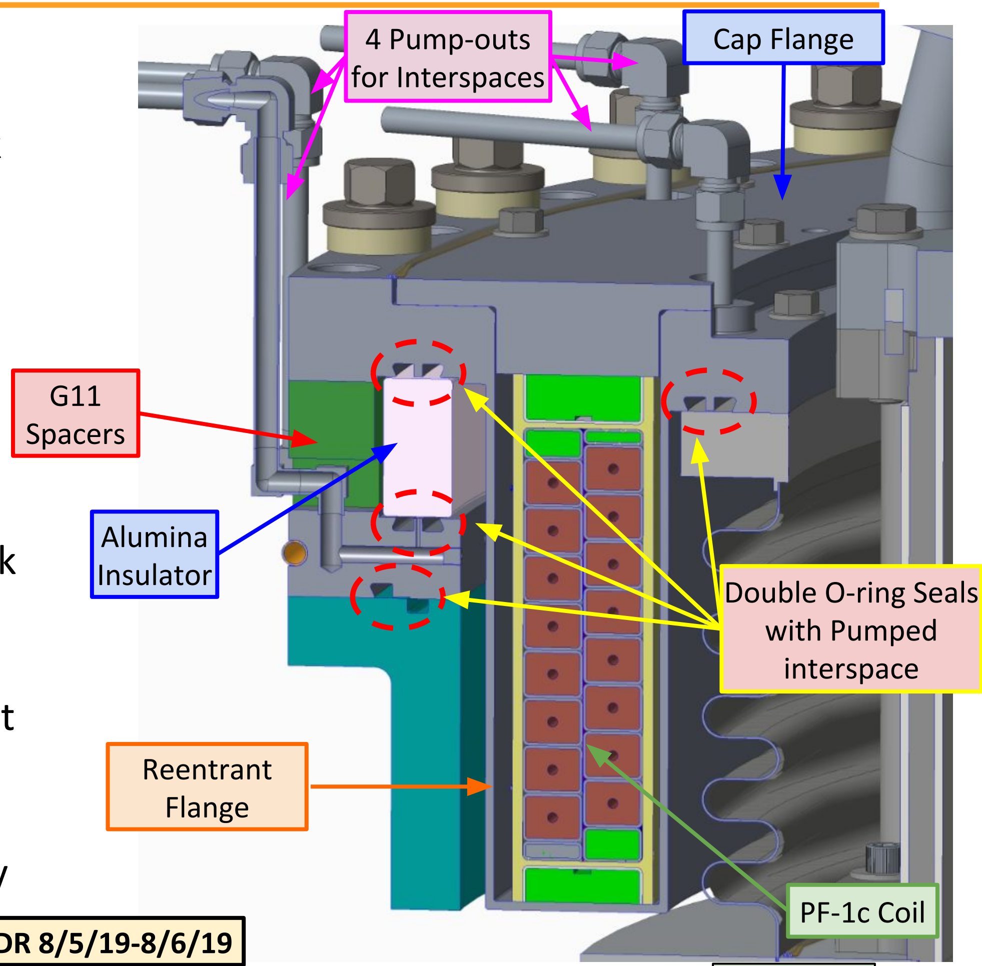




Successful FDR 8/5/19-8/6/19

PF-1c Supports and Ceramic Break - Scope

- PF-1C contained in a reentract In625 housing
  - Made from In625
  - Double O-ring interfaces to ceramic break and bellows flange
- Flange cap contains keys to allow coil radial expansion & maintains coil position.
- Double O-rings on all vacuum interfaces
  - dovetail grooves trap O-rings during component assembly
  - Two pump-out ports for each interspace.
- Bolts have sealing feature preventing water leak ingress compromising the ceramic break standoff.
- Ceramic break floats between O-rings, space set by G-11 spacer
  - Cooling water on ceramic break assembly
  - Note: No ceramic break in lower assembly



Successful FDR 8/5/19-8/6/19

Outer Skirt - Scope

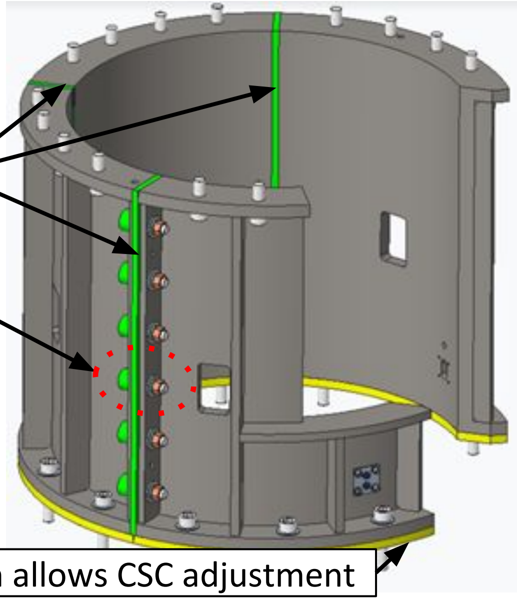
Outer skirt interfaces to the Lower PF-1a/-1b common flange and TF bundle; supports the CSC, PF-1a U/L, and PF-1b U/L against electromagnetic loads.

New outer skirt being designed:

- To accommodate larger Recovery loads.
- To include toroidal insulating breaks.

New Outer Skirt

The Outer Skirt is a 4 part weldment made from In625 with G7 dielectric breaks between each section. The sections are bolted together with hardware + dielectric bushings.



Successful FDR 8/5/19-8/6/19

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Requirements Defined and Met

Source	Requirements	Comment	met
NSTX-U-RQMT-GRD-001	Highest level machine parameters	Defines 2 MA, 1 T, 5 second, 10 MW operating point.	✓
NSTX-CRIT-0001	Design Criteria	Provides the project definition of margin for loads vs. allowables.	✓
NSTX-U-RQMT-SRD-004	Lifting and Fitup	Lifting provisions, clearances, temporary support provisions	✓
NSTX-U-RQMT-SRD-004	Coil Thermal Isolation	Maximum coil ground wall temperature, including allowance for response time in loss-of-coolant scenarios.	✓
NSTX-U-RQMT-SRD-004	Upper Ceramic Insulator	Requirements for ● Location & material ● Requirement to mechanically “float” the insulator ● Electrical isolation	✓
NSTX-U-RQMT-SRD-004	Large Vacuum Seals	No single elastomer seals allowed, leak check capability required.	✓
NSTX-U-RQMT-SRD-004	Bakeout Provisions	Requirements for electrical connections for DC current supply.	✓
NSTX-U-RQMT-SRD-004	Heating/Cooling Provisions	Requirements to ● support range of bakeout temperatures ● provide heating and/or cooling capabilities on horizontal and vertical target (HTP and HTT), consistent with pressure/temperature parameters of bakeout system ● accommodate thermal growth	✓

Requirements Defined and Met

Source	Requirements	Comment	met
NSTX-U-RQMT-SRD-004	Coil Support Structures	Requirements for • Restraint against vertical and side loads • Thermal isolation • Minimization of toroidal conductivity • Pf1A & B Coil pre-load & pre-load monitoring • Diagnostic routing through support structures	✓
NSTX-U-RQMT-SRD-004	Lateral load bearing Structures	Requirement to support CSC under Halo load, not to load O-rings, and accommodate instrumentation.	✓

Requirements Defined and Met

Source	Requirements	Comment	met
NSTX-U-RQMT-RD-003	Disruptions	Provides guidance on computation of halo and eddy currents, including fatigue considerations, as an input to analysis.	✓
NSTX-U-RQMT-RD-005	Diagnostic provisions	Thermocouple, Flux loop and Rogowski counts, routing, and locations.	✓
NSTX-U-RQMT-RD-008	Machine Instrumentation	Defines preload and Lateral Support shim sensors.	✓
NSTX-U-RQMT-RD-010	Magnetic Materials	Defines allowable magnetic permeability.	✓
NSTX-U-RQMT-RD-011	Alignment Requirements	Alignment tolerances between TF bundle and inner-PF coils.	✓
NSTX-U-RQMT-RD-012	Preload Requirements	Provides pre-load requirements for PF-1a and PF-1b coils; provides coils side loads due to non-axisymmetric conditions.	✓
NSTX-U-RQMT-RD-013	Thermal Loads	Provides 5 scenarios for heating during plasma ops, as well as bakeout, as input to analysis .	✓
Design Point Spreadsheet	Vertical Loads	Provides static and dynamic (VDE) vertical loads on coils and structures	✓

Charge question: 1

MCS Interfaces are Defined

- Interface control documents defined to manage interfaces among **S**ystem **B**reakdown **S**tructure entities.

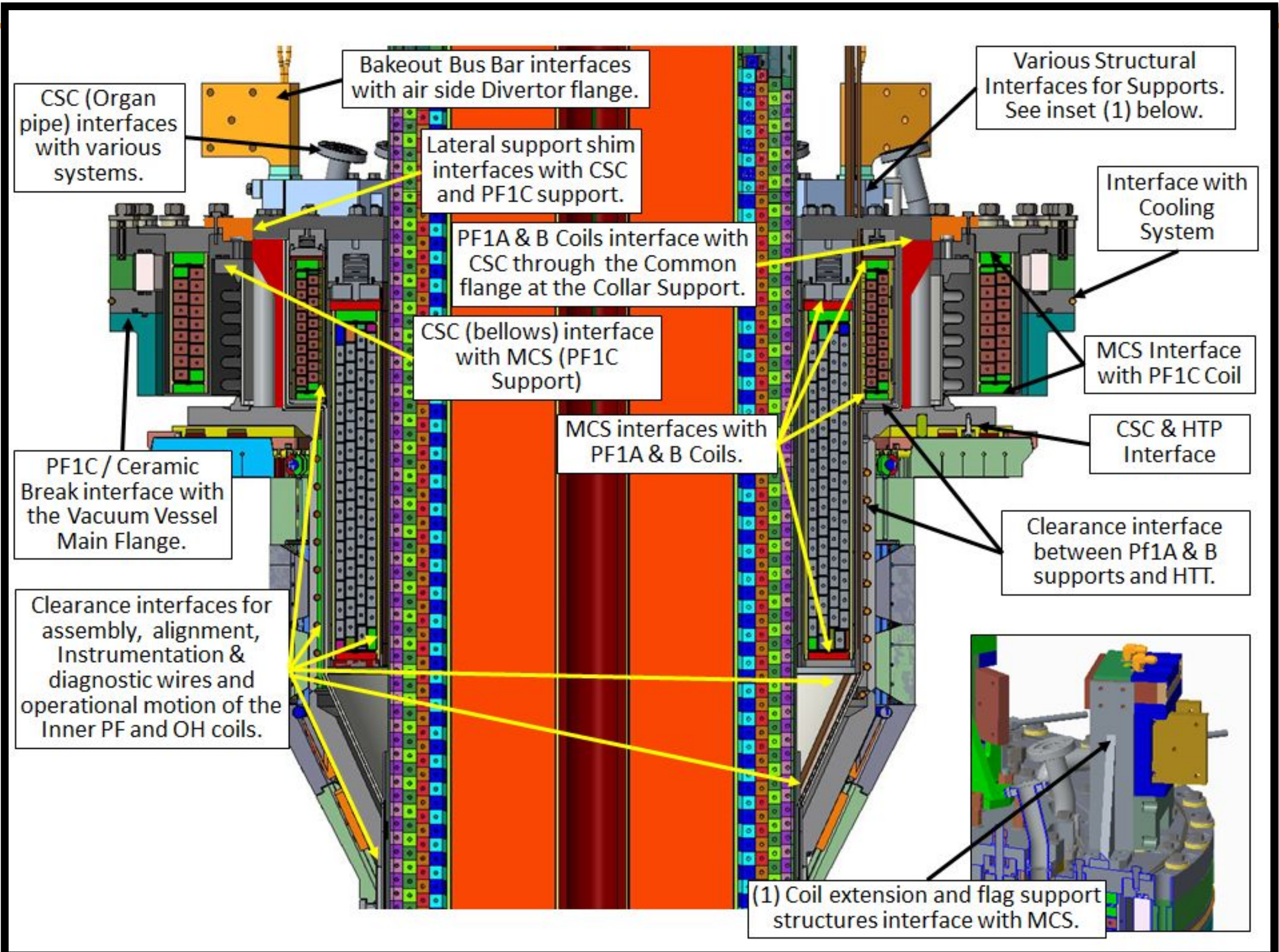
Ex: CSC and the Baking, Cooling and Vacuum systems. Refer to the Interface Control Plan on the Review Website for the project philosophy for interface control.

- Internal interfaces are interfaces within an SBS element and managed by the respective COGs. This typically is managed via the controlled CAD model. EX: Interfaces between the sub-components of the PF1A supports: flanges, slings, etc.
- MCS is a WBS term. MCS are embedded in the Magnet SBS, sub-level CSA.

MCS is included in the following ICDs

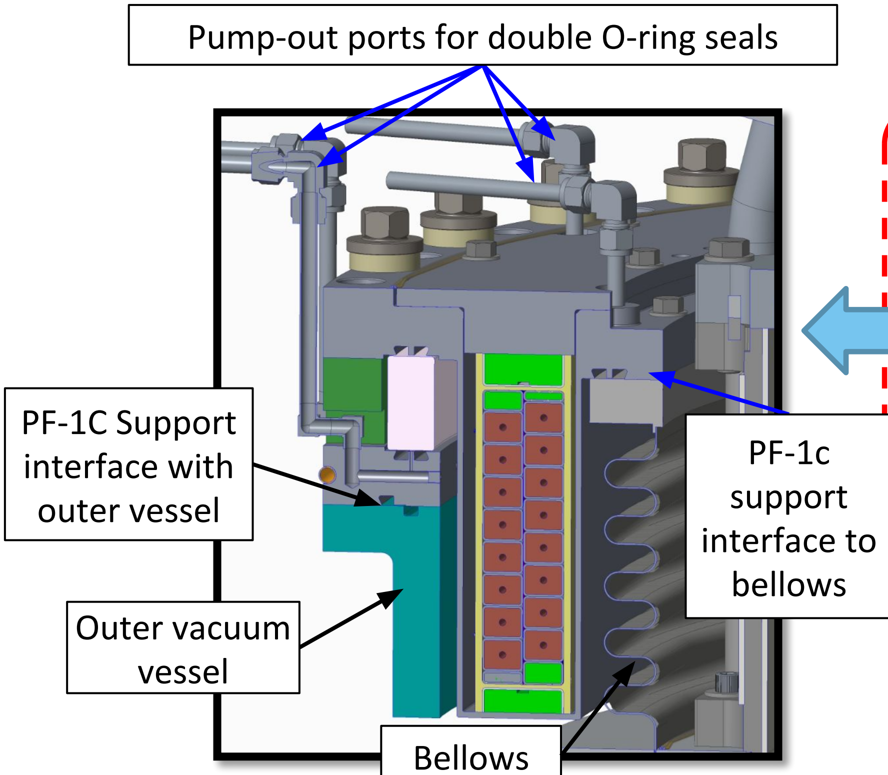
1. PFCs - *Mostly CSC interfaces.*
2. Vacuum Vessel - Interface at the nozzle
3. Test Cell Pedestal Being bolted to floor
4. Coolant System — Ceramic Break cooling
5. Bakeout - OH Heating on Horizontal flange
6. Diagnostics — Flux Loops, rogowski coils etc
7. Integrated Machine Operations — Instrumentation Strain gauges
8. Vacuum Pumping - IVPS
9. Gas Delivery — Interfaces at the Organ Pipes for MGI, Private Flux Injectors High Field Injectors.
10. Magnets — PF1* structure e.g., Slings : this is an internal interface, but due to the criticality complexity along with the multiple COGs involved, an ICD was created for this interface.

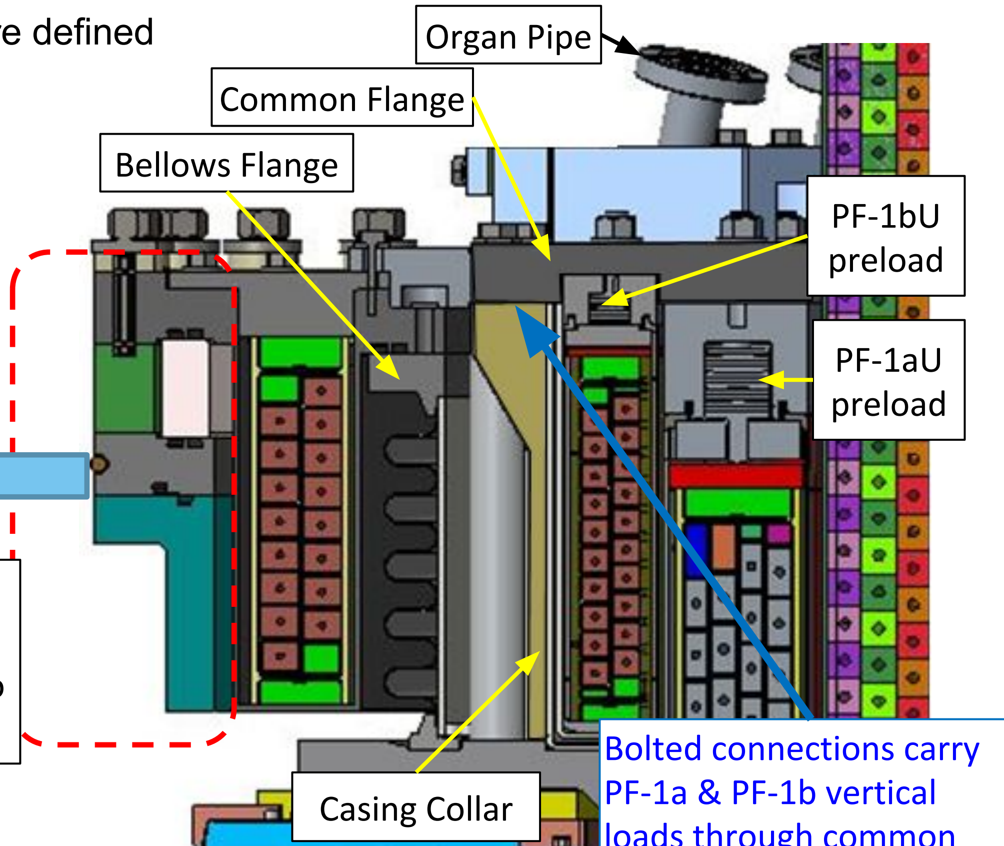
MCS Interfaces are Defined



MCS Interfaces are Defined

PF1ABC Coil interfaces with the MSC structures are defined in the Magnets Center Stack Structures ICD.

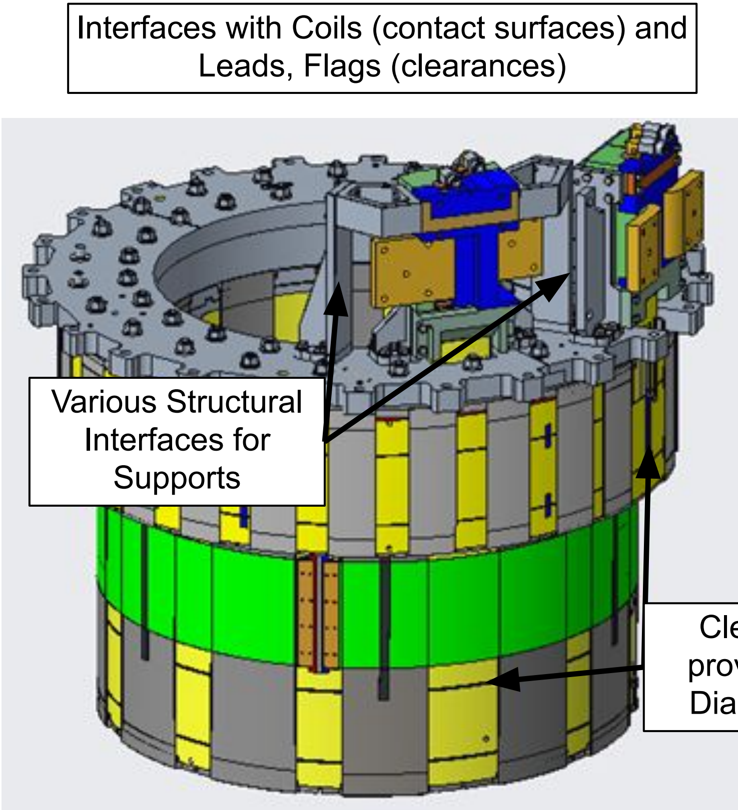


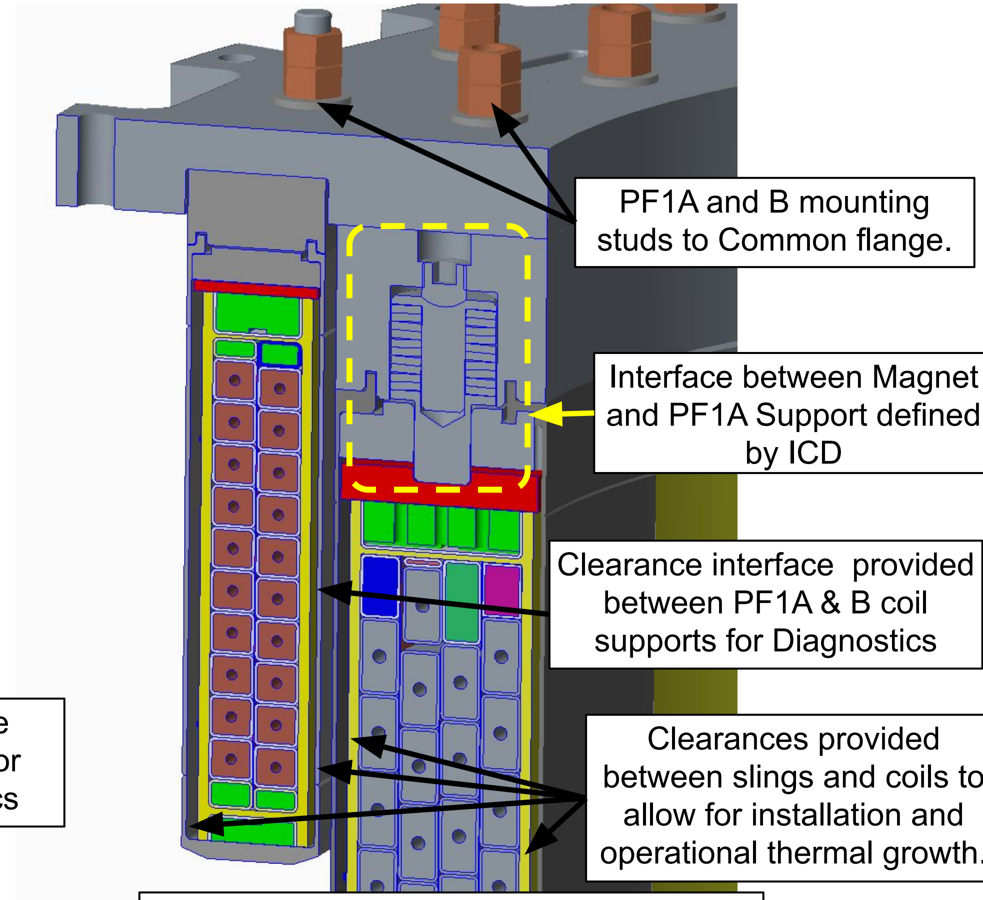


Bolted connections carry PF-1a & PF-1b vertical loads through common flange to casing collar (bolt not shown).

MCS Interfaces are Defined

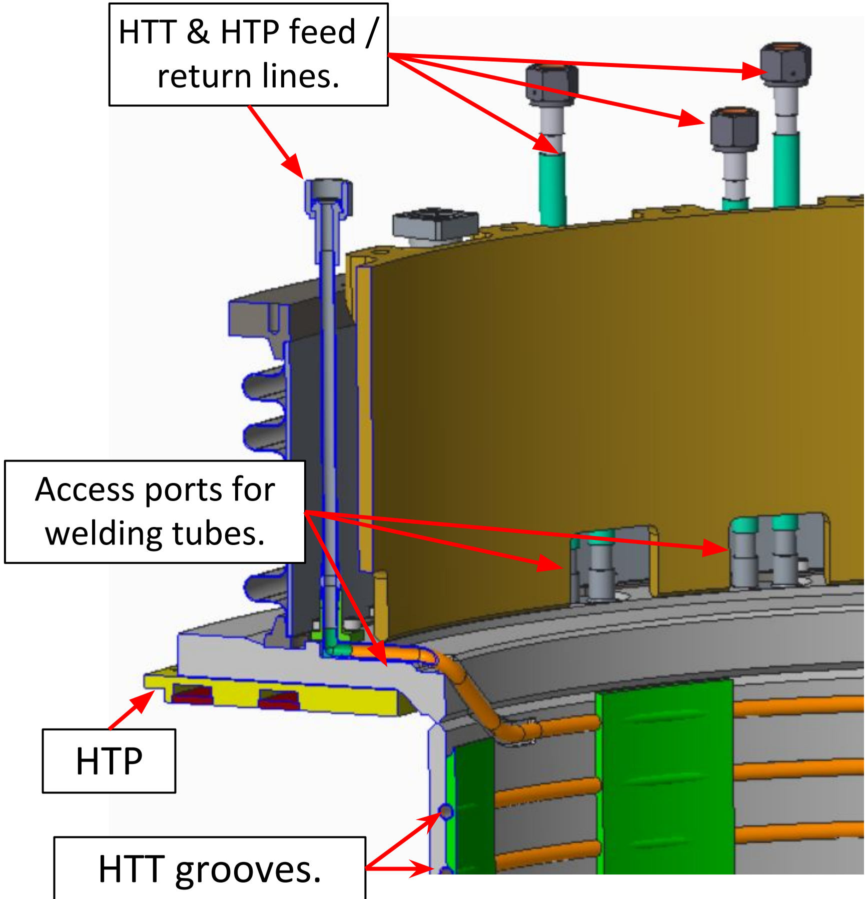
PF1AB Coils in Combined Assembly

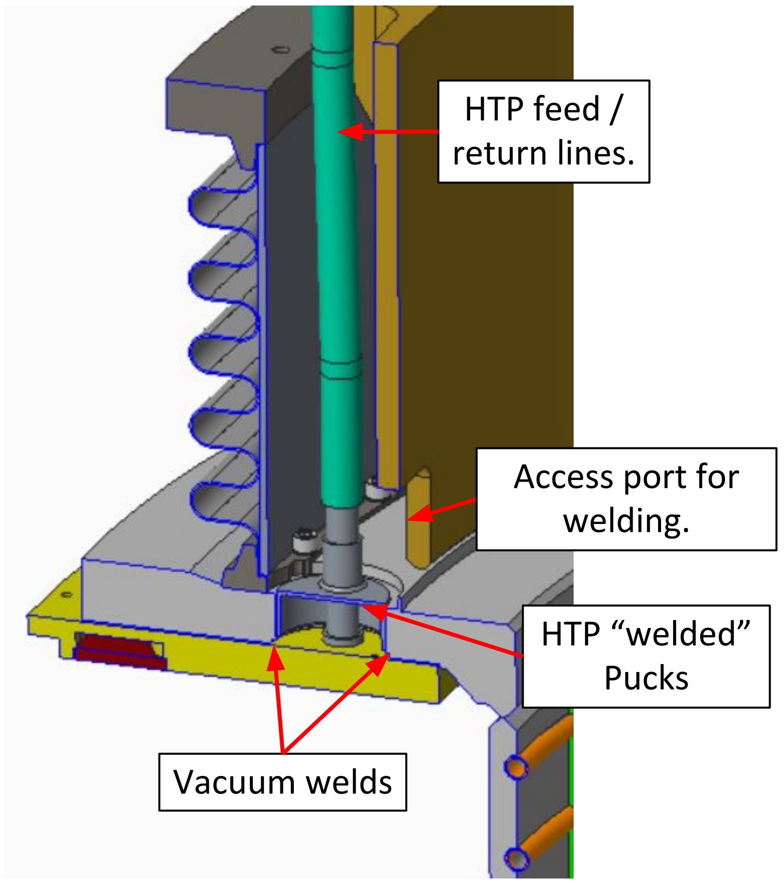




Cross Section View: PF1A&B Assembly

CenterStack Case Interfaces with Heat Transfer Plate and Heat Transfer Tube Fittings are Integrated into the Design

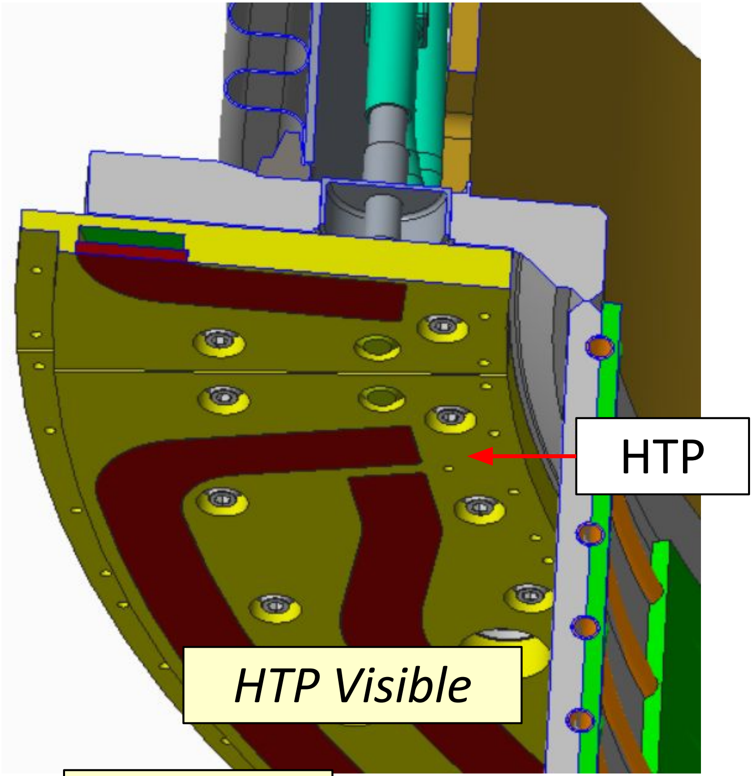


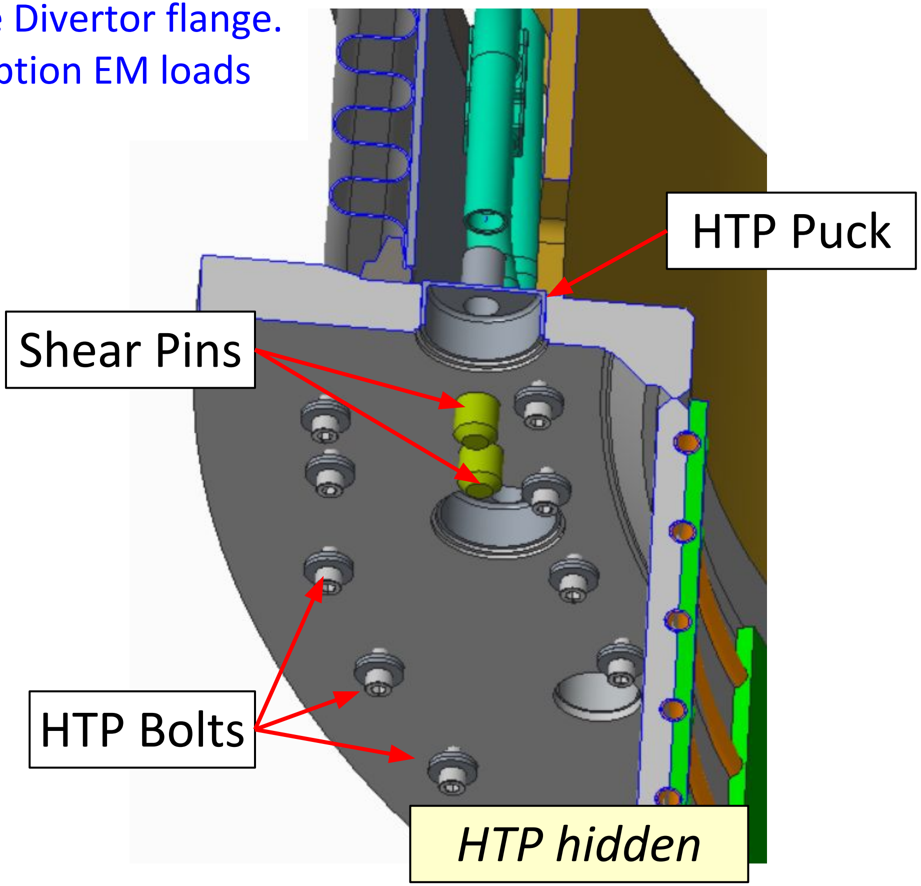


Clearance ensured between feed / return tubes and adjacent CSCA components.

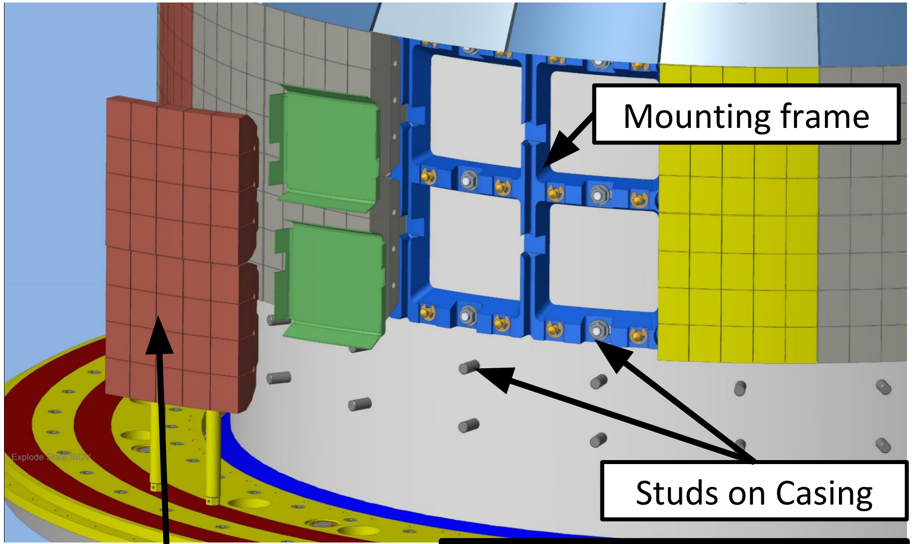
CenterStack Case Interfaces with Heat Transfer Plate and Heat Transfer Tube Fittings are Integrated into the Design

HTP bolt, shear pin, and puck holes machined into the Divertor flange.
Provide alignment capability, restraint against disruption EM loads



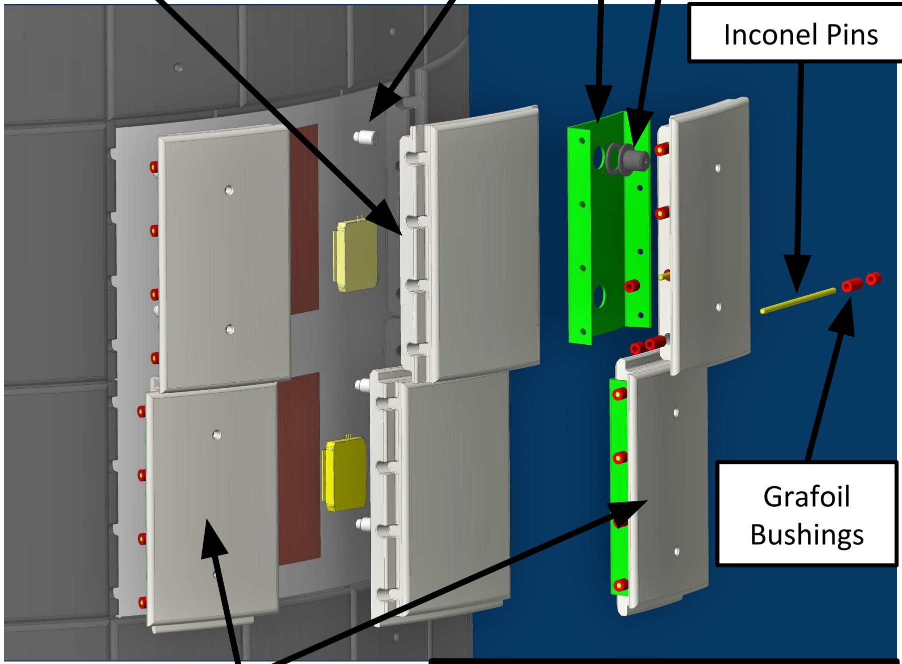


CenterStack Case Features Accommodate Interfaces with PFCs



Inboard Divertor Vertical

Interfaces accommodate required tile pre-loads, transfer halo and eddy current loads to casing.

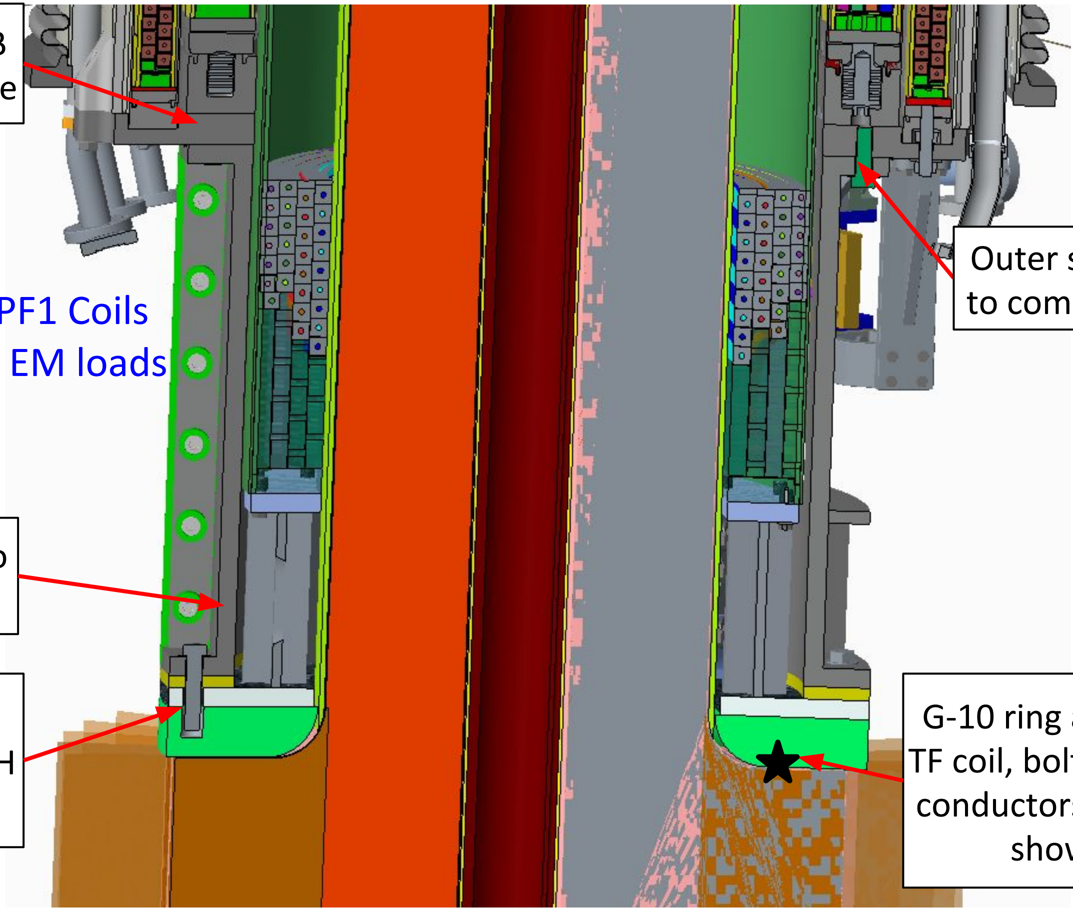


Inboard Divertor Vertical

Outer Skirt Interfaces to Common Flange and OH Skirt-TF Bundle are Defined

Interfaces support the CSC loads:

- Static vertical: PF coil interactions
- Static side loads: Error field effect PF1 Coils
- Dynamic vertical: Disruption / VDE EM loads
- Dynamic side loads: CS halo
- Dynamic Seismic loads



Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Center Stack Assembly	Magnets	link	Defines interfaces between the Center Stack Assembly, PF1 Support Structures, PF1a, 1b, and 1c coils, and TF/OH coils
Center Stack Assembly	Plasma Facing Components	link	Defines interfaces between the center stack assembly and Plasma Facing components
Center Stack Assembly	Vacuum Vessel	link	Defines interfaces between the Center Stack Assembly and Vessel Interface
Center Stack Assembly	Test Cell	link	Defines interfaces between the Center Stack Assembly and the Test Cell Floor
Center Stack Assembly	Coolant Systems	link	Defines interfaces between the Center Stack Assembly and the Water Coolant System
Center Stack Assembly	Bakeout System	link	Defines interfaces between Center Stack Assembly and the Bakeout Bus System

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Center Stack Assembly	Integrated Machine Operations	link	Defines interfaces between the Center Stack Assembly and Instrumentation
Center Stack Assembly	Diagnostics	link	Defines interfaces between the Center Stack Assembly and Flux Loops and Halo/Plasma Current Rogowski Coils
Center Stack Assembly	Vacuum Pumping System	link	Defines interfaces between the Center Stack Assembly and Interspace Pumping System
Center Stack Assembly	Gas Delivery System	link	Defines interfaces between center stack assembly and the Private Flux injectors, Massive Gas Injection and High Field Injectors

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MCS Analyses Loads, Load Cases, & Workflow

<u>Analyses of complex load environment.</u>

Based on 96 static plasma equilibria

Disruption & Vertical Displacements events

Dynamic & static loads.

Electromagnetic loads: Vertical, lateral loads, & moment loads.

Electromagnetic Error field loads.

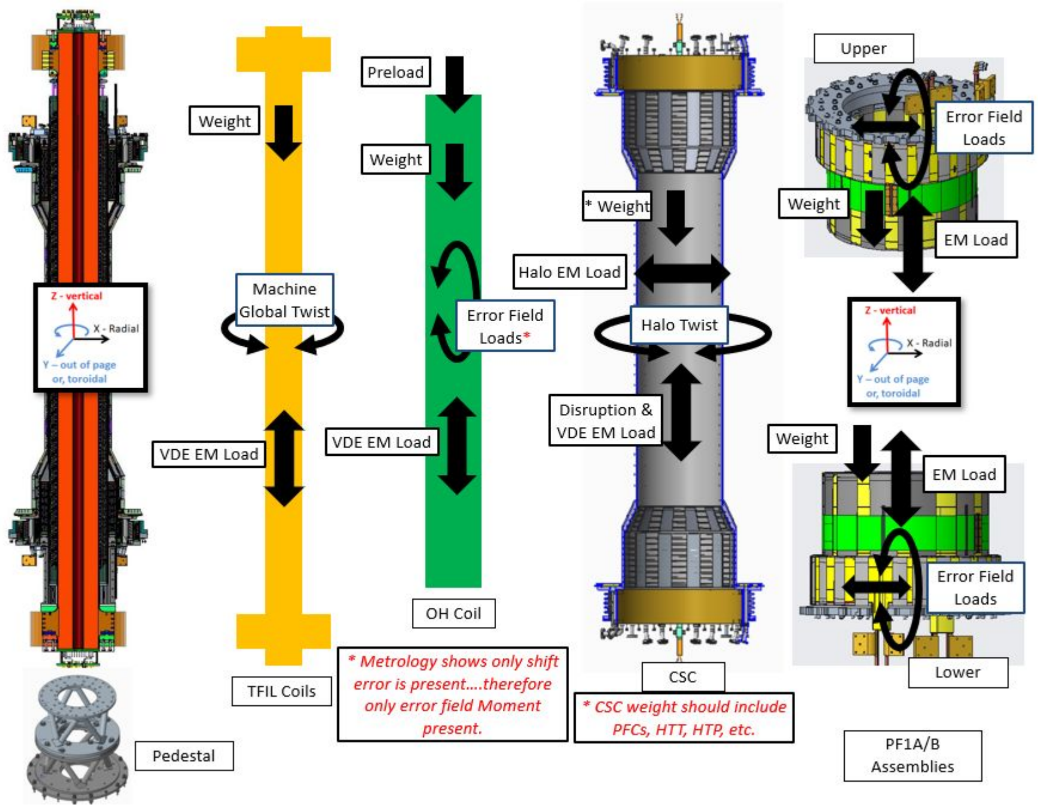
Thermal Loads during Bakeout

Thermal loads from 5 operating scenarios.

Seismic events

Interface & interaction loads.

Up to 8-12 finite element simulations required for each component / assembly.



MCS Analyses Loads, Load Cases, & Workflow

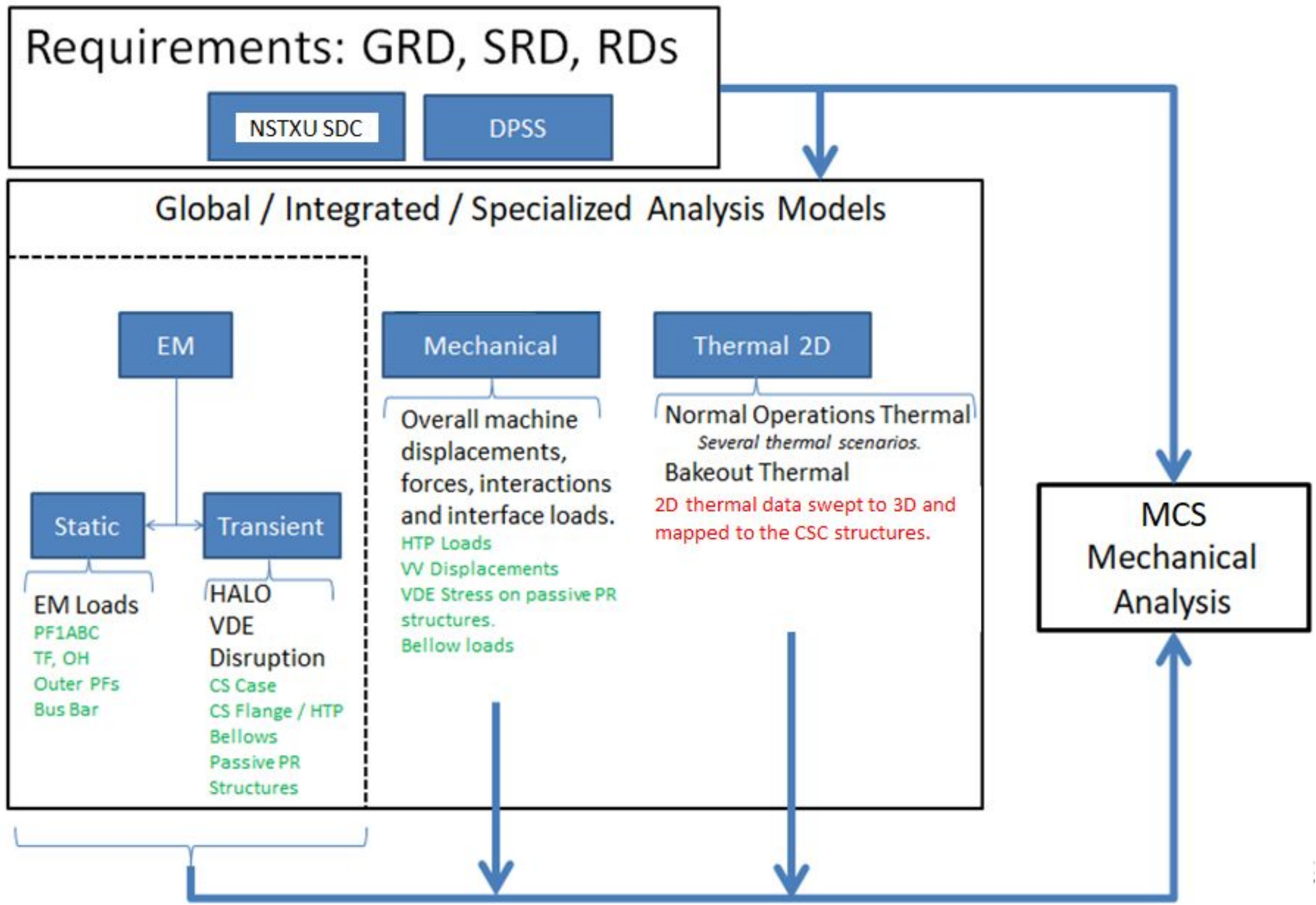
<u>MCS Analysis workflow:</u>

GRD, SRDs, RDs, ICDs, drive the design & analyses.

CAD models are used to create finite element models.

Various types finite element analysis simulations used to create input data for the mechanical simulations.

All MCS components are assessed for structural integrity per the NSTXU Structural Design Criteria.



Calculations Verify Design Meets Requirements - CS Casing

Physical Quantity	Calculation #	Comment
Global heat balance	NSTX-U-CALC-10-6	Describes energy flows and temperatures of PFCs and vessel components, during operations and bakeout
Bellows Loads	NSTX-U-CALC-12-29	Provides all thermal & EM (static and disruption) loads on the bellows, in support of structural qualifications (CALC-12-19)
Upper and Lower Bellows Analysis	NSTX-U-CALC-12-19	Demonstrates that the casing bellows satisfy all static and fatigue requirements
Global Disruption Simulations	NSTX-U-CALC-10-07	Provides loads on numerous components (casing, slings, passive plates) from the global model.
Disruption Loads on CS Casing	NSTX-U-CALC-12-20	Computes halo and eddy current for midplane (P2) and displaced (P6) disruption scenarios
Load Combinations and Material Properties	NSTX-U-CALC-12-28	Summarizes loads, static loads, disruption scenarios and thermal scenarios (bakeout, ops) for the CS casing. Provides In625 material properties to use.
Structural Analysis of the Casing under P2 Disruption Scenario	NSTX-U-CALC-12-23	Shows significant structural margins for all components under the CS-limited midplane disruption scenario (P2) (from -CALC-12-20, -CALC-10-6)
Structural Analysis of the Casing under P6 Disruption Scenario	NSTX-U-CALC-12-32	Demonstrates adequate structural response of the casing due to P6 load cases (from -CALC-12-20, -CALC-10-6)
Structural Analysis of the Casing under Aux3 Disruption Scenario	NSTX-U-CALC-12-33	Demonstrates adequate structural response of the casing due to Aux3 load cases (from -CALC-12-20, -CALC-10-6)
Tolerances	NSTX-U-CALC-133-37	Describes how the tolerances in the drawings will result in meeting all physics and engineering requirements

Calculations Verify Design Meets Requirements - Coil Supports, Ceramic Break, Outer Skirt & Pedestal

Physical Quantity	Calculation #	Comment
MCS Mechanical Analyses	NSTXU_1-1-3-3_CALC_115	Provides structural calculations for all slings and coil supports, the pedestal, the outer skirt, etc. Several section superseded by calculations listed below.
PF1A and PF1B Components	NSTXU_1-1-3-3_CALC_111	Provides assessment per NSTXU structural design criteria for the PF1 A/B coil support structures.
Upper PF1C components	NSTXU_1-1-3-3_CALC_117	Provides assessment per NSTXU structural design criteria for the PF1C coil supports.
Upper and Lower Bellows	NSTXU_1-1-3-3-6_CALC_100	Provides structural assessment of the Upper/Lower Bellows.
Machine Core Structure Ceramic Break Structural Analysis.	NSTXU_1-1-3-3_CALC_109	Provides assessment per NSTXU structural design criteria for the Ceramic Break.
Upper Bellows Flange Joint	NSTXU-1-1-3-3_CALC_119	Provides assessment per NSTXU structural design criteria for the upper bellows flange.
Global Core FEA	NSTXU_1-1-3-3_CALC_113	Provides description, assessments, buckling evaluation using the Global Machine FEM.
Pedestal	NSTXU_1-1-3-3_CALC_114 (draft in checking)	Provides assessment per NSTXU structural design criteria for the Pedestal.

Calculations Verify Design Meets Requirements - Coil Supports, Ceramic Break, Outer Skirt & Pedestal

Physical Quantity	Calculation #	Comment
MCS Vacuum Calculations	NSTXU_1-1-3-3_CALC_103	Calculation of vacuum performance of the double O-ring seal design.
MCS EM Analyses	NSTXU_1-1-3-3_CALC_102	Documents the EM simulations included in the MCS efforts.
Alignment & Tolerance Stack Assessment	NSTXU_1-1-3-3_CALC-101	Documents all the tolerances of the design relative to the physics and assembly requirements.
GLOBAL HEAT BALANCE ANALYSIS.	NSTXU_1-3-3_CALC_100	Documents the thermal global machine simulations included in the MCS efforts.
NSTXU Recovery Global Heat Balance Calculations	NSTXU_1-1_CALC_101	Documents the thermal global machine simulations included in the MCS efforts.
Disruption Simulations and Lorentz Force Cloud Data Generation	NSTXU-CALC-10-07-2	Documents the EM simulations included in the MCS efforts.
PF1A COIL: Temperature Effects from Coil Support Slings.	NSTXU-1-1-3-100	Documents the mechanical effects on the coils due to coil support slings thermal gradients.
Outer Skirt	Refer to NSTXU_1-1-3-3_CALC_115	Detailed submodel and analyses being evaluated.
Nonuniform Preload On Coils	NSTXU_1-1-3-3_CALC_116	Documents the effects of nonuniform preload on the Coils.

Calculations Verify Design Meets Requirements - Coil Supports, Ceramic Break, Outer Skirt & Pedestal

Physical Quantity	Calculation #	Comment
PF1A Sling Eddy Current Load Support System	NSTXU_1-1-3-3-11_CALC_102	Mechanical analyses calculation report for the PF1A Belt Peer Review.
PF1A Single Sling Modal, Transient, Static FEAs.	NSTXU_1-1-3-3-11_CALC_101	Mechanical analyses calculation report for the PF1A Belt Peer Review.
PF1A Sling-Belt Miscellaneous Computations	NSTXU_1-1-3-3-11_CALC_100	Calculation report for the PF1A Belt Peer Review.
PF 1A Sling Thermal Calculation	NSTXU-1-1-3-3_CALC_106	Thermal analyses calculation report for the PF1A Belt Peer Review.
Calculation Radiation Effects on Plastic Belt	NSTXU_1-1-3-3-3_CALC_100	Calculation / memo. Explains the effects of radiation damage on the polymer materials (ie, belt).
UPPER_DIVERTER_FLANGE_MODIFICAITON	VVIH_200122_TJR_2	Memo for the Divertor Flange Peer review.
PF1A Belt Analyses	NSTXU_1-1-3-3-11_CALC_107	Calculation documenting the analyses of using a 6" belt made from KT-880-GF30.

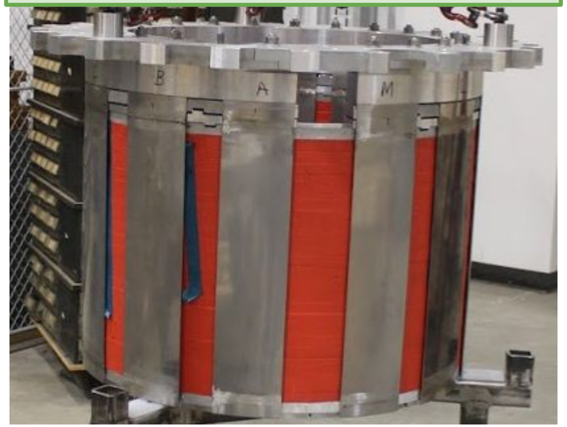
Prototyping Key Components of the MCS Design Activity

<u>Prototyping activities for MCS:</u>

- Fatigue testing welded 718 dogbones - Completed
- Prototypes of slings
  - Welding, machining, distortion control - Completed.
- Full size -1a mockup w/ flanges (in process)
  - Developing assembly procedures
  - Assess tolerances
- Pre-load monitoring instrumentation
  - Developing methods to control preload during assembly
- Ceramic break mockup (in process)
  - Confirm tolerances
  - Confirm electrical standoff and waterproofing techniques
- Belleville stack mockup
  - Confirm washer & pin fatigue - Completed

Prototype Sling

Mockup with Aluminum Flanges and Stainless Steel Slings



Distortion Control Weld Fixture for Slings

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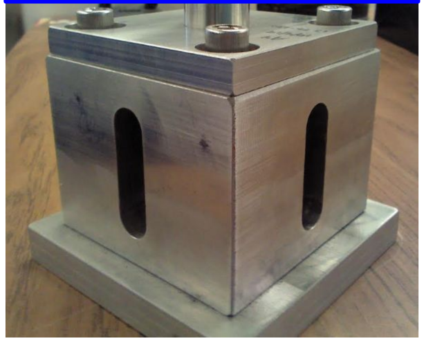
- Belleville stack mockup
  - Confirm washer & pin fatigue -

Ceramic Break Mockup

Belleville Stack Mockup (PF-1a shown)



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Chit Closure Is Nearly Done

APPROVED
PPPL

PPPL PRINCETON PLASMA PHYSICS LABORATORY

CRR_CHITID - CHIT RESOLUTION REPORT
CHIT RESOLUTION REPORT FOR THE CENTER STACK CASING FABRICATION

NSTXU_1-1-3-3-6_CRR_100
Rev. 3

Work Planning #:
Effective Date: **02/19/2020**
Prepared By: **Mark Smith**

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ENG-033 - CRR - CHIT RESOLUTION REPORT
CHIT RESOLUTION REPORT FOR THE MACHINE CORE STRUCTURES

NSTXU_1-1-3-3_CRR_100

Work Planning #:
Effective Date: **03/09/2020**
Prepared By: **James Sturges**

Approved By | Kathleen Lukazik, Preparer | 03/09/2020 16:03:45 PM

Chit Resolution Report for PF1A Sling Belt Peer Review

NSTXU_1.1.3.3.11_CR

Prepared By: M. Smith, Co ... er
Reviewed By: Doug ... ponsible Engineer
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Approved B ... is, Chief Engineer

WORK In Progress

Chit Resolution Reports: link

Outline

NCRs & ECNs MCS Parts Fabrication To Date

NCR Item	NCR Number	Description of the Issue
PF1A Sling Parts	4097	Plate thickness and radius out tolerance.

Drawing Number	ECN Number	Description of the Change
EDC11298	8305	Ceramic Break hardware under A1 cat.
EDC11251 EDC11256	8312	PF1C Cap Flange for Coating revisions and Keyway change.
EDC111250 EDC111255	8285	Coating note and tapped hole depth revisions.
EDC1428	8231	Update Bellows drawing: Match Vendor, add new PPPL tolerances.
EDC11210	8265	Modification to the Upper Divertor Flange.

NCRs & ECNs MCS Parts Fabrication To Date

Drawing Number	ECN Number	Description of the Change
EDC11139	8259	Revise coating callout. Tighten hole tolerance to match mating part.
EDC11138	8289	Add additional holes.
EDC11120	8302	Tighten holes tolerance to match with mating part.
EDC11141	8281	B sling ECN (loosen tilt requirements). Adjust dimensions/tolerances of PF1B slings for desired weld gap\
EDC11140 EDC11141	8280	Add edge break to greater portion of PF-1A slings. A sling ECN (round edges, loosen tilt requirements, change part marking, etc.) B sling ECN (change part marking). Update Part Marking Note on Pf1A and PF1B Slings.
EDC11140 EDC11141	8317	Update sling drawings to reflect title 3 requests.

Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
5. Chit Closure
6. Procurement, Fabrication, Installation, and Test
7. Risk - Project Risks and Design FMECA
8. Quality, Environmental, Safety, and Health
9. Summary

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If PF1AB slings cannot be fabricated within tolerance specs	49	RETIRED	Moved to project risk.
If the analysis of the CSC Bellows weld to flange shows insufficient design margin.	35	RETIRED	FDR for CSC
If the pedestal fails the structural design criteria	30	OPEN	After Calculation is signed.
If any component fails the structural design criteria during analysis	25	RETIRED	FDR for MCS

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If the VV main flanges as built conditions do not support assembly within various requirements (i.e. PF1C alignment, bellows stress, etc.)	25	RETIRED	FDR for Machine Core Structures
If interference with existing interfaces (bus work, etc.) is discovered during installation	25	OPEN	Post assembly
If initial error field calculations show the need for more elaborate calculations or tighter assembly tolerances.	25	RETIRED	FDR for Machine Core Structures

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If the sling fabrication has difficulty meeting dimensional tolerances	20	OPEN	End of fabrication
If material costs (Inconel) fluctuate higher than expected	20	RETIRED	receipt of goods
If fatigue specimens provide anomalous results	20	RETIRED	MCS FDR/PROTOTYPING
If tooling and fixtures required to perform fabrication/installation were overlooked	16	OPEN	Assembly

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If derived / assumed coil pack material properties do not match test data	15	RETIRED	FDR for MCS
If simulations of sliding joints reveal some unexpected sensitivity to misalignment or frictional variations	15	RETIRED	FDR for MCS
Coil dimensions change after prototype supports fabricated	4	RETIRED	Prototypes completed.

FMECA - PF-1a Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1a Support Structure	PEEK belt pulls out from In718 buckles	excessive tension relative to material strength	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requiring replacement.	12	DCPS Software	None	None	4
PF-1a Support Structure	PEEK belt tears/rips/fractures	damage during installation, excessive tension relative to material strength	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requiring replacement.	12	DCPS Software	None	None	4
PF-1a Support Structure	Bolts in belt buckle fail	excessive tension; manufacturing error; thread failure in bolt or buckle	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requiring replacement.	12	DCPS Software	None	None	4
PF-1a Support Structure	Adhesive fails at bond of sling to silicone sheet	Excessive temperature at adhesive; excessive shear on bond	Sheet comes loose; Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requiring replacement.	12	DCPS Software	None	None	4
PF-1a Support Structure	Welds attaching studs to buckle fracture	excessive belt tension	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requiring replacement.	12	DCPS Software	None	None	4

One item with high residual risk expected to be resolved by ongoing adhesive testing

FMECA - PF-1a Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1a Support Structure	Crack develop in PF-1a sling	Excessive EM load, including disruption loads and side loads from error fields and misalignments	Excessive motion of PF-1A coil damages leads; coil conductor delamination	12	DCPS Software	None	Fiber Optic Strain, Temp., Disp. Meas.	4
PF-1a Support Structure	Failure of bolted connection of -1a coil to common flange	differential temperature, due to differential cooling/flow rates, leads to the pancake clamp "digging in" to coil surface	Coil may move, damaging lead tower and bus bar, or compressing microtherm	12	DCPS Software	None	None	4
PF-1a Support Structure	Crack developed in one of the hangar, capture, or compression flange	Excessive EM load, including disruption loads and side loads from error fields and misalignments	Coil may move, damaging lead tower and bus bar, or compressing microtherm	12	DCPS Software	None	None	4
PF-1a Support Structure	PEEK belt stretches	Creep at elevated temperature, for instance, during bakeout	None - no significant preload assumed	4	None	None	None	4
PF-1a Support Structure	"Belt Loops" on PF-1a belts come loose	fracture of weld of "belt loop" at the interface of the shim stock to the sling panel, presumably due to vibration or improper spot weld	Belt falls away from midplane, resulting in loss of function -->Potential microtherrm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requireing replacement.	4	None	None	None	4

FMECA - PF-1a Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1a Support Structure	RTV Silicone rubber bond fails	Excessive temperature; excessive shear or tension	Inner sling may twist, resulting in enhanced loads, sling fracture, and utlimately coil damage, requiring replacement	4	None	None	None	4
PF-1a Support Structure	Silicone sheet takes a severe "set", no longer in compression	excessive belt tension overly compresses the silicone	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requireing replacement.	4	None	None	None	4
PF-1a Support Structure	Nuts which secure belt come loose	Viibration and various cyclic stress	Belt no longer restrains outer sling twist --> Potential microtherm damage, enhanced disruption sling loads, sling fracture, and ultimately coil damage requireing replacement. . Also, loose nuts within CS assembly may create electrical issues	4	None	None	None	4
PF-1a Support Structure	Crack develop in PF-1a sling	Excessive motion of PF-1A coil after initial sling failure induces increased inertial loading into slings	Excessive motion of PF-1A coil damages leads; coil conductor delamination	4	Fiber Optic Strain, Temp., Disp. Meas.	None	None	4
PF-1a Support Structure	PF1a magnet sticks on one of the centering keys, during radial expansion	A burr, or machining ridge, on the mounting flange digs into the PF1a magnet	Induces abnormal radial stresses into the PF1a magnet	4	None	None	None	4

FMECA - PF-1a Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1a Support Structure	Modest loss of preload	Relaxation of belleville washers due to extended time under preload	Small increases in insulation strain won't impact coil	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
PF-1a Support Structure	Modest loss of preload	Sling Stretch due to extended time under preload	Small increases in insulation strain won't impact coil	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
PF-1a Support Structure	Modest loss of preload	Creep of coil insulation system under load	Small increases in insulation strain won't impact coil	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
PF-1a Support Structure	Modest loss of preload	Set screws that compress bellevilles back out over time, potentially due to vibration	Small increases in insulation strain won't impact coil	1	Fiber Optic Strain, Temp., Disp. Meas.	None	None	1

Summary → ***<u>PF-1a Supports</u>***

- 19 Identified Failure Modes
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis
  - Fiberoptic strain, temperature, and displacement measurements

FMECA - PF-1b Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1b Support Structure	Crack develop in PF-1b sling	Excessive EM load, including disruption loads and side loads from error fields and misalignments	Excessive motion of PF-1B coil damages leads; coil conductor delamination	12	DCPS Software	None	Fiber Optic Strain, Temp., Disp. Meas.	4
PF-1b Support Structure	Failure of bolted connection of -1b coil to common flange	Excessive EM load, including disruption loads and side loads from error fields and misalignments	Coil may move, damaging lead tower and bus bar, or compressing microtherm	12	DCPS Software	None	None	4
PF-1b Support Structure	Crack developed in one of the hangar, capture, or compression flange	Excessive EM load, including disruption loads and side loads from error fields and misalignments	Coil may move, damaging lead tower and bus bar, or compressing microtherm	12	DCPS Software	None	None	4
PF-1b Support Structure	Crack develop in PF-1b sling	Excessive motion of PF-1B coil after an initial sling failure induces increased inertial loading into slings	Excessive motion of PF-1B coil damages leads; coil conductor delamination	4	Fiber Optic Strain, Temp., Disp. Meas.	None	None	4
PF-1b Support Structure	PF1b magnet sticks on one of the centering keys, during radial expansion	A burr, or machining ridge, on the mounting flange digs into the PF1b magnet	Induces abnormal radial stresses into the PF1b magnet	4	None	None	None	4
PF-1b Support Structure	Modest loss of preload	Relaxation of belleville washers due to extended time under preload		2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2

FMECA - PF-1b Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PF-1b Support Structure	Modest loss of preload	Sling Stretch due to extended time under preload		2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
PF-1b Support Structure	Modest loss of preload	Creep of coil insulation system under load		2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
PF-1b Support Structure	Modest loss of preload	Set screws that compress bellevilles back out over time, potentially due to vibration		0	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2

Summary → ***<u>PF-1b Supports</u>***

- 9 Identified Failure Modes (fewer than the -1a due to their not being a “belt”)
- All mitigated to acceptable risk
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis
  - Fiberoptic strain, temperature, and displacement measurements

FMECA - Lateral Supports

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Lateral Support Structures	Lateral support cracks, and breaks, and falls out	fatigue	Loads no longer restrained by lateral supports cause failure of the G10 ring at the bottom of the TF coil	12	DCPS Software	DCPS Software	Fiber Optic Strain, Temp., Disp. Meas.	4
Lateral Support Structures	Mounting bolts come loose, allowing the lateral support to vibrate out of position.	vibration	Excessive bending moments in the lower CSC mounts.	4	Fiber Optic Strain, Temp., Disp. Meas.	None	None	4

Summary → ***Lateral Supports***

- 2 Identified Failure Modes
- All mitigated to acceptable risk
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis
  - Fiberoptic strain, temperature, and displacement measurements

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Weld of collar to casing fails	Excessive static and dynamic EM loads, or excessive thermal gradients	loss of load path, excessive motion of upper coil leads, loss of vacuum.	12	DCPS Software	None	None	4
Center Stack Casing	Plastic deformation of structural materials on the body of the casing	Excessive static and dynamic EM loads	Tile heat fluxes develop asymmetries,	12	DCPS Software	Plasma TV	None	4
Center Stack Casing	Plastic deformation of structural materials on the body of the casing	Excessive static and dynamic EM loads	distorted surface beyond what vacuum o-rings can seal	12	DCPS Software	Vacuum Gauges and Residual Gas Analyzers	None	4
Center Stack Casing	Plastic deformation of structural materials on the body of the casing	Excessive static and dynamic EM loads	Bellows are stressed. Bellows will have premature fatigue failure	12	DCPS Software	Vacuum Gauges and Residual Gas Analyzers	None	4
Center Stack Casing	Bellows welds (to casing or bellows flange) fail	Excessive halo current side load; misalignment of bellows	Vacuum leak disrupts plasma operations	12	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	4
Center Stack Casing	Failure of bolted connection at base of G10 ring (casing skirt to G10 ring)	Excessive vertical and side loads (static+disruptions)	Casing becomes mobile, coil lead failures	12	DCPS Software	Lateral Support Structures	None	4
Center Stack Casing	Outer Skirt bolt or flange insulators mechanically fail	Static or dynamic EM loads result in G7 material failing	local (bolt) or component-scale (flange) structural failure, may result in movement of the casing with resulting damage to bus towers, bellows, etc.	12	DCPS Software	None	None	4

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Failure of bolted connection of collar to common flange (upper or lower)	Excessive EM loading (static or transient)	May result in a progressive failure; upper coils shift radially (upper failure), full casing can shift (lower failure)	12	DCPS Software	None	None	4
Center Stack Casing	Crack developing in common flange (upper or lower)	Excessive EM loading (static or transient)	If upper, could result in excessive motion of the casing, damaging bus bars or bellows, or possibly leading to tile collision at upper gap	12	DCPS Software	None	None	4
Center Stack Casing	Structural weld on casing proper fails completely	Excessive static and dynamic EM loads, or excessive thermal gradients	loss of load path, excessive motion of upper coil leads, loss of vacuum.	9	Vacuum Gauges and Residual Gas Analyzers	DCPS Software	None	3
Center Stack Casing	Structural weld on casing proper develops vacuum leak	Excessive static and dynamic EM loads, or excessive thermal gradients	Vacuum leak disrupts plasma operations	9	Vacuum Gauges and Residual Gas Analyzers	DCPS Software	None	3
Center Stack Casing	CSFW stud breaks off casing	Excessive interface loads from PFCs due to combination of preload and disruption load	Tile becomes loose, requires vessel entry to repair	9	Plasma TV	DCPS Software	None	3
Center Stack Casing	IBDV stud breaks off casing	Excessive interface loads from PFCs due to combination of preload and disruption load	Ice-cube tray becomes loose	9	Plasma TV	DCPS Software	None	3

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Outer skirt vertical flange bolts fail	Excessive side load on the casing due to halo currents.	skirt no longer strong in torsion	9	DCPS Software	None	None	3
Center Stack Casing	Outer skirt lower flanges or flange bolts fail	Excessive side load on the casing due to halo currents, potentially with excessive vertical loads	shift the casing relative to the TF, stress to the PF-1a & PF-1b bus bars, interference with the OH lead block.	9	DCPS Software	None	None	3
Center Stack Casing	Outer skirt upper flanges or flange bolts fail	Excessive side load on the casing due to halo currents, potentially with excessive vertical loads	shift the casing relative to the TF, stress to the PF-1a & PF-1b bus bars	9	DCPS Software	None	None	3
Center Stack Casing	Outer skirt welds fail	Excessive side load on the casing due to halo currents, potentially with excessive vertical loads	shift the casing relative to the TF, stress to the PF-1a & PF-1b bus bars	9	DCPS Software	None	None	3
Center Stack Casing	Bellows overheat	Inadequate current shunted from bellows by bus bar	vacuum leak	8	None	None	None	8
Center Stack Casing	Leak in base of organ pipe	Mechanical impact (likely individual stepping)	Vacuum leak disrupts plasma operations	6	Vacuum Gauges and Residual Gas Analyzers	None	None	6
Center Stack Casing	O-ring on organ pipe leaks	Contamination on O-ring; small nick on O-ring	Vacuum leak disrupts plasma operations	6	Vacuum Gauges and Residual Gas Analyzers	None	None	6

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Failure at gas feedthrough connection on organ pipe	mishandling or installation error	vacuum leak	6	Vacuum Gauges and Residual Gas Analyzers	None	None	6
Center Stack Casing	Lower bake out busbar interface on casing damaged	Poor electrical contact due to insufficient contact pressure	Electrical connection disrupted between CSC and bakeout bus bar. Damage to lower bellows due to excessive halo current loads	6	Tile and Rogowski Halo Current Measurements	None	None	6
Center Stack Casing	Lower bake out busbar interface on casing damaged	Halo current loads lead to interface damage	Electrical connection disrupted between CSC and bakeout bus bar. Damage to lower bellows due to excessive halo current loads	6	Tile and Rogowski Halo Current Measurements	None	None	6
Center Stack Casing	Lower bake out busbar interface on casing damaged	Poor electrical contact due to insufficient contact pressure	Electrical connection disrupted between CSC and bakeout bus bar. Damage to lower bellows due to excessive bakeout current flowing in bellows	6	Bakeout DC Power Supplies	None	None	6
Center Stack Casing	Lower bake out busbar interface on casing damaged	Halo current loads lead to interface damage	Electrical connection disrupted between CSC and bakeout bus bar. Damage to lower bellows due to excessive bakeout current flowing in bellows	6	Bakeout DC Power Supplies	None	None	6

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Upper bake out busbar interface on casing damaged	Poor electrical contact due to insufficient contact pressure	Electrical connection disrupted between CSC and bakeout bus bar. Inability to provide bakeout current	6	Bakeout DC Power Supplies	None	None	6
Center Stack Casing	Thermal growth of casing results in collision between PF-1cU can and Horizontal Divertor Flange	Not enough space for CSC to thermally grow in the axial direction	Produces elastic bending in the CSC, and may result in damage to the welds at the interface of the horizontal target to the vertical target	4	Machine Instrumentation	None	None	4
Center Stack Casing	Bellows proper damaged	Excessive halo current side load; misalignment of bellows; fatigue	Vacuum leak disrupts plasma operations	4	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	4
Center Stack Casing	Bellows overheat	imbalance of bakeout currents among the three bus bars	vacuum leak	4	None	None	None	4
Center Stack Casing	microtherm insulation fails	abrasion caused when magnets and other components rub against it during heating/ or EM induced movement.	Overheating of ground insulation, and temperature induced failure of magnets, and other 'protected' components	4	None	None	None	4
Center Stack Casing	Outer skirt vertical flange insulators are bridge by water	water leak from various water fittings and connections on the CS assembly	Induced eddy currents on the outer skirt	4	None	None	None	4

FMECA - CS Casing

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack Casing	Screws come loose at bolted connection of collar to common flange (upper or lower)	vibration	May result in a progressive failure; upper coils shift radially (upper failure), full casing can shift (lower failure)	4	None	None	None	4
Center Stack Casing	Failure of electrical feedthrough on the organ pipe	quality or mishandling issue with component	Vacuum leak	3	Vacuum Gauges and Residual Gas Analyzers	None	None	3

Summary → ***<u>CS Casing</u>***

- 33 Identified Failure Modes
- All mitigated to acceptable risk
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis
  - Vacuum sensors

FMECA - Pedestal

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Pedestal	Bolts of the pedestal interface break	vibration	The TF/OH, CSC shifts out of alignment; vertical load path compromised	12	DCPS Software	None	None	4
Pedestal	Strut on one of the halves buckles	Vibration, Excessive loading	The pedestal, with CSC, TF/OH, etc would collapse	12	DCPS Software	None	None	4
Pedestal	Weld on the pedestal breaks	Vibration, Excessive loading	The pedestal, with CSC, TF/OH, etc would collapse	12	DCPS Software	None	None	4
Pedestal	Crack develops in one of the pedestal flanges	EM loadsing	the "trajectory" of the full CS becomes less constrained, including potentially damaging bus work and bellows.	9	DCPS Software	None	None	3
Pedestal	Nut falls off from the joint where the top half, and the bottom half meet	Vibration	There are fewer nuts to hold the pedestal together. Less margin of safety.	6	None	None	None	6
Pedestal	A floor anchor breaks	Seismic overloading	The alignment of the CSC changes	3	None	None	None	3

Summary → ***Pedestal***

- 6 Identified Failure Modes
- All mitigated to acceptable risk
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis

FMECA - PF-1c Support and Ceramic Break Assembly

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Ceramic Break Assembly & PF-1c Support	Screws holding captive flange fail	excessive vertical EM load on coil	coil leads fail	12	DCPS Software	None	None	4
Ceramic Break Assembly & PF-1c Support	Cracks in the PF1c Ceramic Break	Excessive static and dynamic EM loads on supporting flanges results in break coming on contact with metal.	vacuum leak requiring break replacement	9	DCPS Software	None	Vacuum Gauges and Residual Gas Analyzers	3
Ceramic Break Assembly & PF-1c Support	water leaks past the elastomer (EPDM) lining on the ceramic break assembly isolator nuts	elastomer (EPDM) over-molded liner on the isolator nut does not provide a sufficient seal	Water gets trapped inside the ceramic break sub-assembly, resulting electrical path and inability to bakeout.	6	None	None	None	6
Ceramic Break Assembly & PF-1c Support	Vacuum O-ring of the double o-rings, fails	fatigue/aging cracks develop within o-ring	increased stress on the outer o-ring, machine pressure rise	6	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	6
Ceramic Break Assembly & PF-1c Support	Vacuum O-ring of the double o-rings, fails	o-ring twisted, allowing a vacuum path	increased stress on the outer o-ring, machine pressure rise	6	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	6
Ceramic Break Assembly & PF-1c Support	Outside O-ring of the double o-rings, fails	fatigue/aging cracks develop within o-ring	Increased loading on the interspace vacuuming pump, marginal increase in machine pressure	6	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	6

FMECA - PF-1c Support and Ceramic Break Assembly

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Ceramic Break Assembly & PF-1c Support	Outside O-ring of the double o-rings, fails	o-ring twisted, allowing a vacuum path	Increased loading on the interspace vacuuming pump, marginal increase in machine pressure	6	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	6
Ceramic Break Assembly & PF-1c Support	Water fails to flow through cooling line on the OD of the ceramic break mounting flange	Flow blockackage; DI pump failure	Excess thermal gradients that cause warpage of the said mounting flange	6	Low-Pressure NTC Cooling Water Distribution	None	None	2
Ceramic Break Assembly & PF-1c Support	Water fails to flow through cooling line on the OD of the ceramic break mounting flange	Flow blockackage; DI pump failure	O-rings take a permanent set (lose compliance)	6	Low-Pressure NTC Cooling Water Distribution	None	None	2
Ceramic Break Assembly & PF-1c Support	Screws holding the captive flange (the flange that holds the PF-1c inside the reentrant forging) to the other parts come loose	vibration	The other screws take more load, and become more susceptible to also back-out; ultimately coil leads overloaded	4	None	None	None	4
Ceramic Break Assembly & PF-1c Support	The garolite (G7/10/11) insulating spacer delaminate/ decomposes	Garolite mechanical failure due to cooling line around the ceramic break flange failing	The ceramic break assembly loses radial stiffness, which can cause mechanical failure at the base of the CS.	4	None	None	None	4

FMECA - PF-1c Support and Ceramic Break Assembly

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Ceramic Break Assembly & PF-1c Support	Mechanical damage to PF-1c reentrant housing	PF-1c housing comes in contact with the casing flange during cooldown from bakeout, damaging the can	damage to coil inside the can; loss of vacuum integrity, requiring replacement of	4	None	Vacuum Gauges and Residual Gas Analyzers	None	4
Ceramic Break Assembly & PF-1c Support	Cracked isolator washer on ceramic break assembly, underneath isolator nut	Excessive torque during tightening	clamping force on the ceramic break has more toroidal variation. Greater chance for vacuum leak	3	None	None	None	3
Ceramic Break Assembly & PF-1c Support	Vacuum O-ring of the double o-rings, fails	Inadequate groove preparation,	increased stress on the outer o-ring, machine pressure rise	3	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	3
Ceramic Break Assembly & PF-1c Support	Outside O-ring of the double o-rings, fails	Inadequate groove preparation,	Increased loading on the interspace vacuuming pump, marginal increase in machine pressure	3	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	3
Ceramic Break Assembly & PF-1c Support	Outside O-ring of the double o-rings, fails	Outer o-ring extrudes into the interspace region	Increased loading on the interspace vacuuming pump	3	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	3
Ceramic Break Assembly & PF-1c Support	Both of the double O-rings fail	Warpage in the underlying structure, potentially due to disruption load	Increased loading on the interspace vacuuming pump; machine vacuum compromised	3	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	3

FMECA - PF-1c Support and Ceramic Break Assembly

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Ceramic Break Assembly & PF-1c Support	The PF-1c reentrant house develops leaks	fatigue from vibration and/or repeated shots	loss of vacuum	3	Vacuum Gauges and Residual Gas Analyzers	None	None	3
Ceramic Break Assembly & PF-1c Support	The garolite (G7/10/11) insulating spacer delaminate/ decomposes	Garolite mechanical failure due to cooling line around the ceramic break flange failing	Water ingression past the garolite segments, compromises the bakeout capability	3	Low-Pressure NTC Cooling Water Distribution	None	None	3
Ceramic Break Assembly & PF-1c Support	The garolite (G7/10/11) insulating spacer delaminate/ decomposes	Garolite mechanical failure due to cooling line around the ceramic break flange failing	The ceramic break assembly loses radial stiffness, which can cause vacuum leaks past the actual ceramic break	3	Vacuum Gauges and Residual Gas Analyzers	None	None	3
Ceramic Break Assembly & PF-1c Support	The interspace at the ceramic break flange and the vacuum vessel flange goes past the opposite o-ring groove	PF1c assembly is misaligned with respect to the vacuum vessel	vacuum leak	3	Interspace Vacuum Pumping System	Vacuum Gauges and Residual Gas Analyzers	None	3
Ceramic Break Assembly & PF-1c Support	Vacuum leak at O-rings on ceramic break	PF-1c can comes in contact with the casing flange during cooldown from bakeout, leading to a prying action about the ceramic break assembly.	vacuum leak, potential fracture of ceramic break if the breaks bottom out on stainless steel	3	None	Vacuum Gauges and Residual Gas Analyzers	None	3

FMECA - PF-1c Support and Ceramic Break Assembly

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Ceramic Break Assembly & PF-1c Support	PF1c magnet sticks on one of the centering keys, during radial expansion	A burr, or machining ridge, on the mounting flange digs into the PF1c magnet	Induces abnormal radial stresses into the PF1c magnet	0	None	None	None	0

Summary → ***<u>PF-1c and Ceramic Break Assembly</u>***

- 23 Identified Failure Modes
- All mitigated to acceptable risk
- Key mitigations:
  - Design to the NSTX-U/PPPL Structural Design Criteria
  - DCPS to limit loads to design basis
  - Double O-ring differential pumping

Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
5. Chit Closure
6. Procurement, Fabrication, Installation, and Test
7. Risk - Project Risks and Design FMECA
8. Quality, Environmental, Safety, and Health
9. Summary

Quality, Environmental, Safety, & Health

- MCS scope is category A-1.
- All fabrication within PPPL will use a travelers.
- Procurements only qualified vendors.
- Fabrictions from outside vendors have a PPPL-approve MIT Plan.
- Slings inspected by NDE before installation in coil sub-assemblies. Safety protocols for radiographic inspection to be followed.
- Installation of coils into slings, including preload application will have a dedicated traveler & QIP.
- Lift and assembly fixture designs with ergonomic and human factors considered.
- Hazards mitigated via the PPPL safety programs:
  - Hoisting and rigging, Appropriate PPE, Use of JHAs and pre-job briefs.

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Summary

- All Requirements have been satisfied through analyses and/or testing, mockup and prototyping .
- 10 ICDS are related to the MCS scope. These ICDs are controlled and used to manage the MCS interfaces.
- Most all MCS chits have been addressed. The remaining few are actively being resolved and present low risk.
- Risks are being managed and mitigated using the Risk Registry.
- Industrial safety has been accounted for in this work scope.