National Spherical Torus eXperiment Upgrade

Plasma Facing Components

WBS 1.01.01

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

J. Klabacha - Cognizant Engineer

Last edit: ?/?/??

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	Plasma Facing Components	WBS #	1.01.01
Project Cog.	Jonathan Klabacha	Assoc. Proj. Man.	W. Gattoni
Design Scope	Design and fabricate new graphite plasma facing components for casing and divertors		
Technical Impact of Scope	PFCs provide primary armor for vessel metal components, prevent metal impurities from entering plasma		
Design Status	FDR completed on 09/28/2018: review link chits: link calculations: link drawings: link SoW/Tech Spec: link		
Fabrication Status	Graphite material procurements complete, metal component and graphite machining to follow ESAAB approval		
Installation Status	Tiles will be installed in NSTX-U under the reassembly control account		

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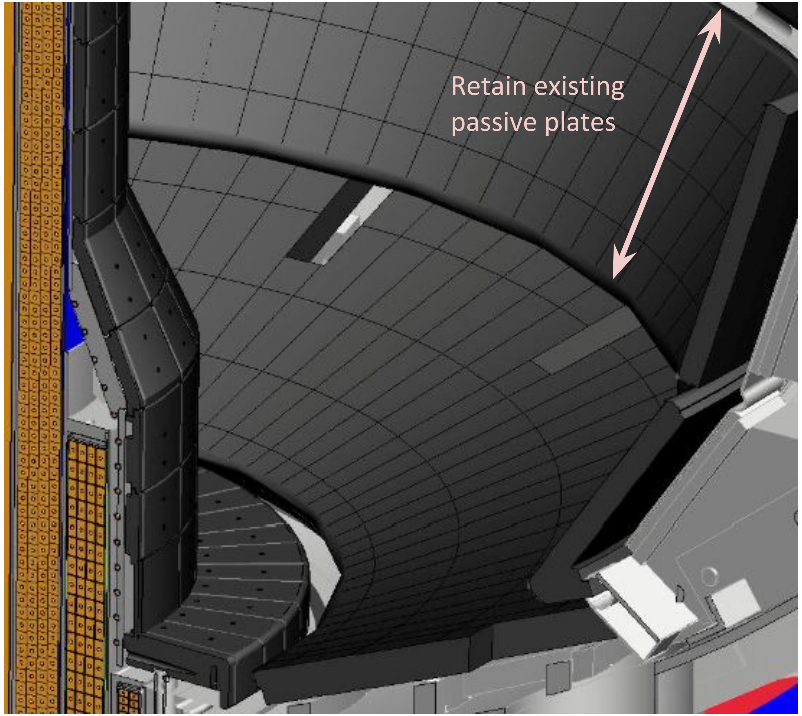
PFC Project Scope Summary

- Emphasis on reliable operation resulted in Recovery Project PFC effort:
  - Updated EM and thermal loads
  - More conservative approach to heat-removal solutions requiring improved PFC performance
  - New PFCs to be qualified for full-power and full-disruption load operations on day 1

NSTX-U



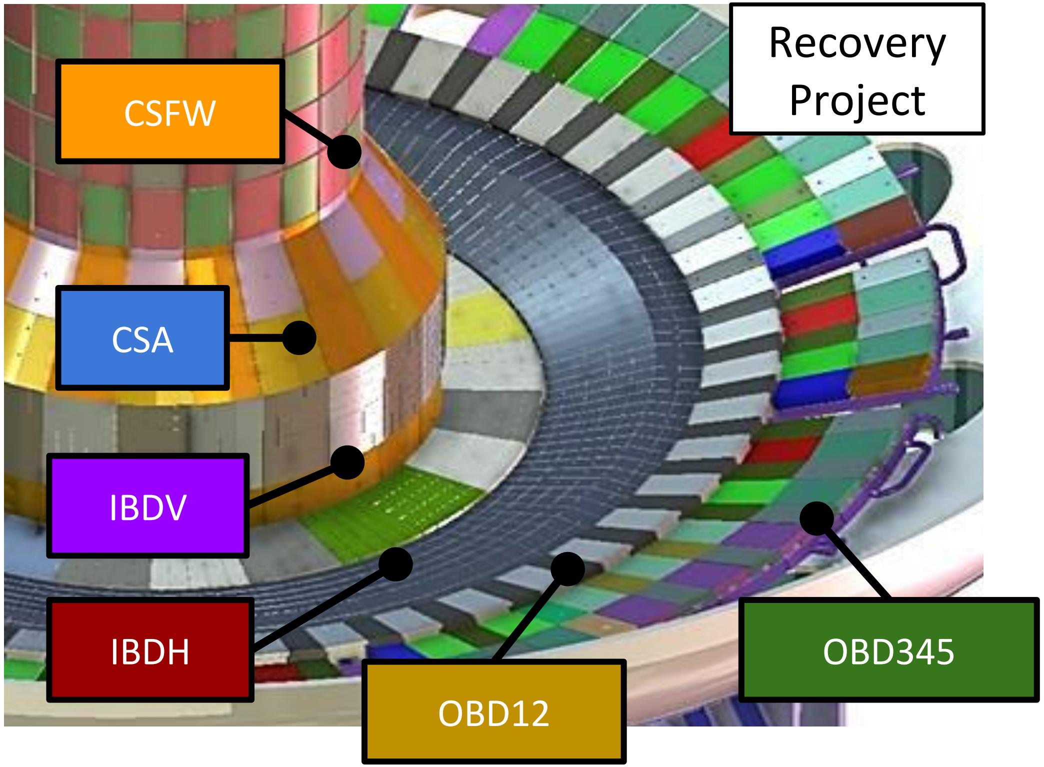
PFC Project Scope Summary

- Six Tile Regions:

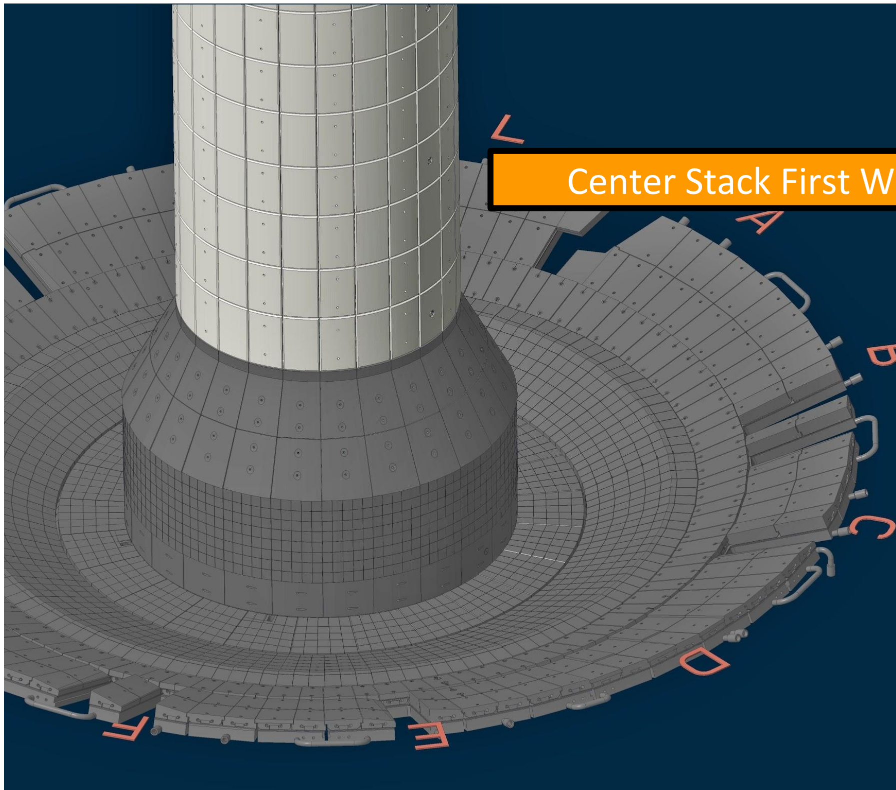
  Low Heat Flux (LHF):
  - Center Stack First Wall (CSFW)
  - Center Stack Angled (CSA)
  - Outboard Divertor-345 (OBD345)

  High Heat Flux (HHF):
  - Inboard Divertor-Vertical (IBDV)
  - Inboard Divertor-Horizontal (IBDH)
  - Outboard Divertor-12 (OBD12)

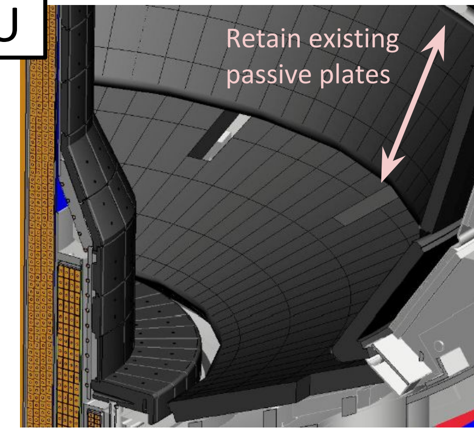
- Two Control Accounts:
  - Team Integration [PFC6]
  - Procurement and Manufacturing [PFC8]

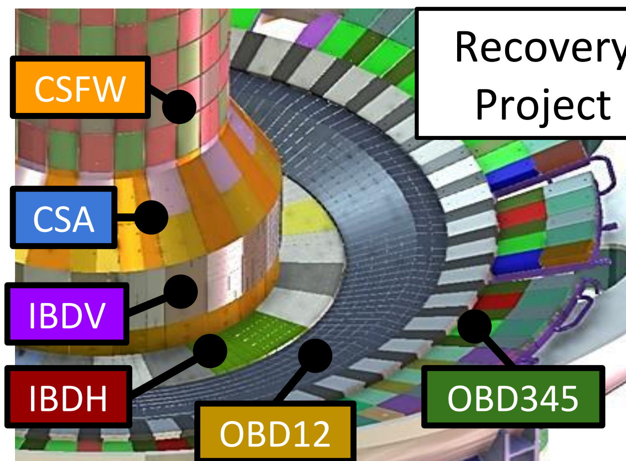


Center Stack First Wall tiles accommodate challenging EM loads



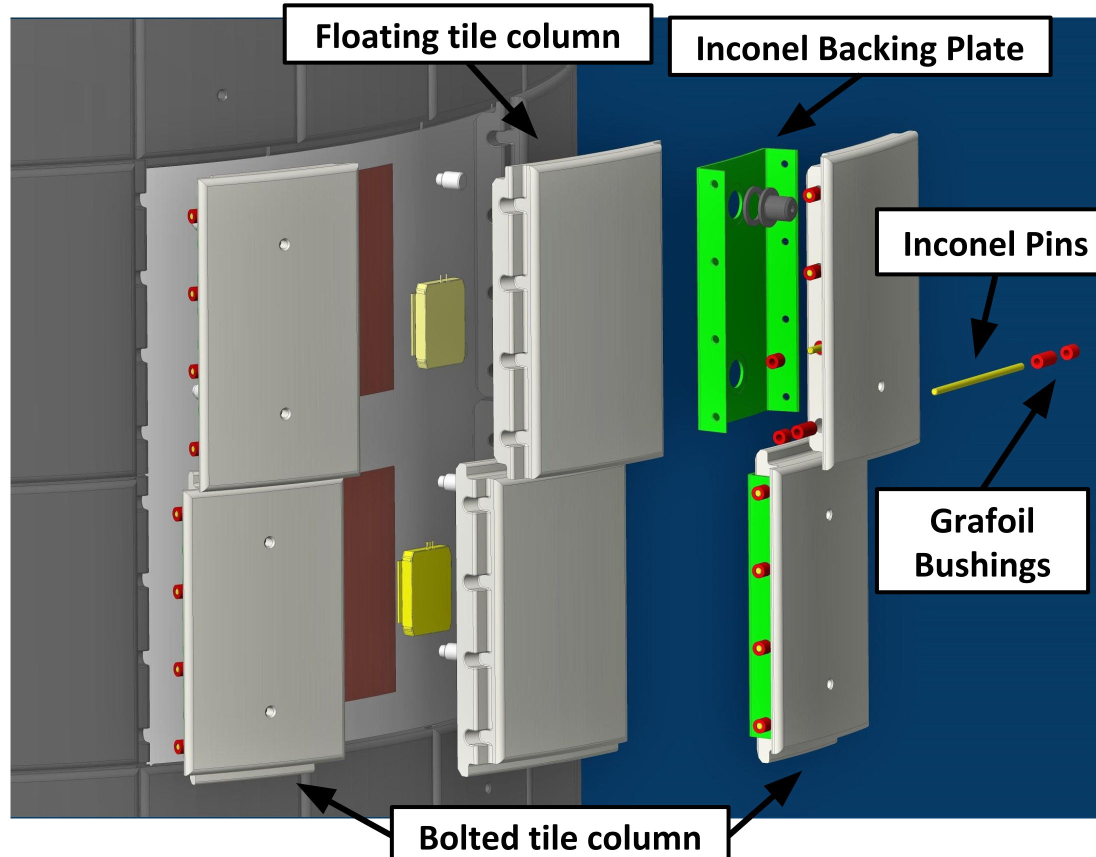
NSTX-U



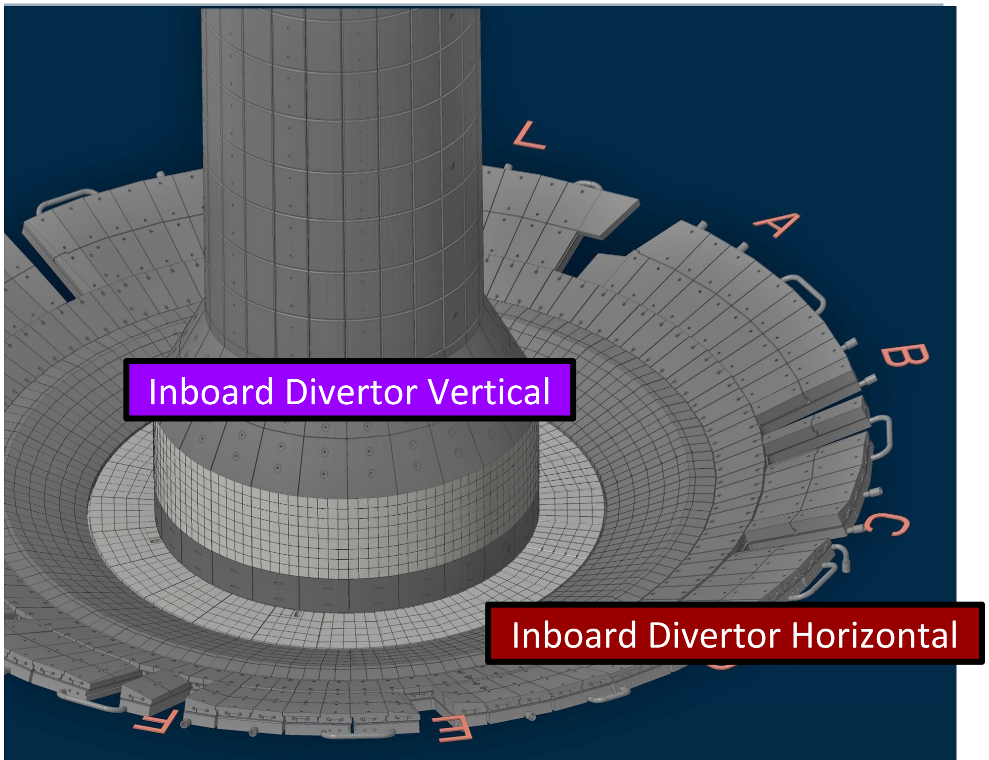


Center Stack First Wall Tiles Accommodate Challenging EM Loads

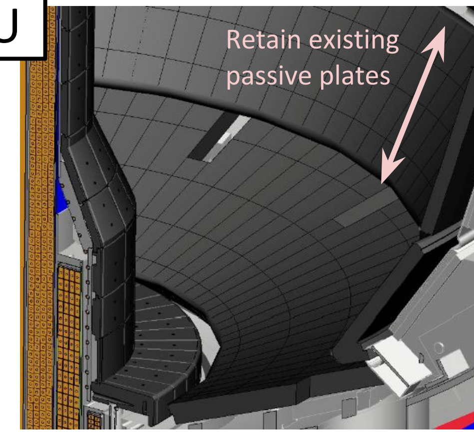
- Use of a two-tile method using stud attachment to the Center Stack Casing
- Floating tile supported between two bolted tiles through inconel pins
- Floating tile used for diagnostics
- Grafoil bushings used to alleviate excessive contact stresses on pins



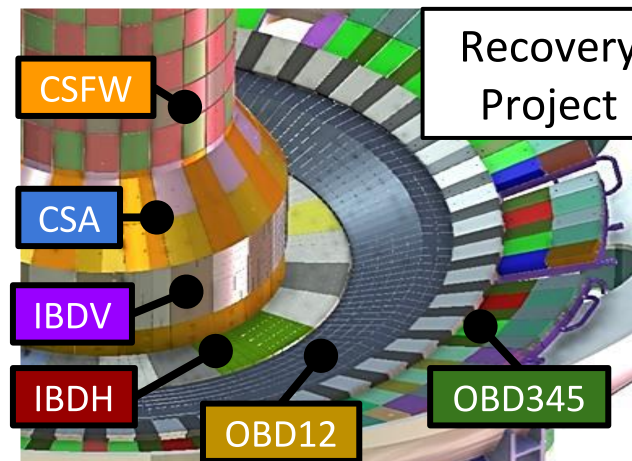
Inboard Divertor Tiles Designed to Handle Extreme Heat Fluxes



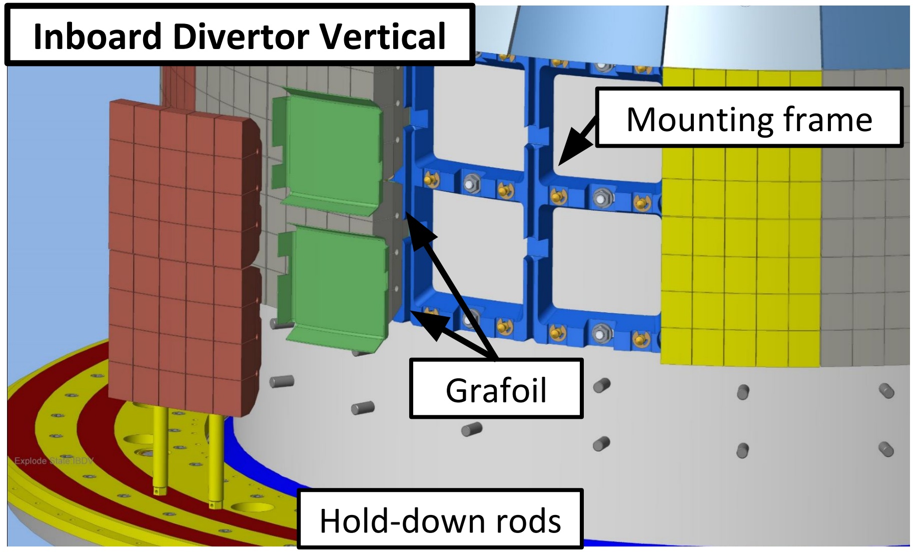
NSTX-U



Recovery Project



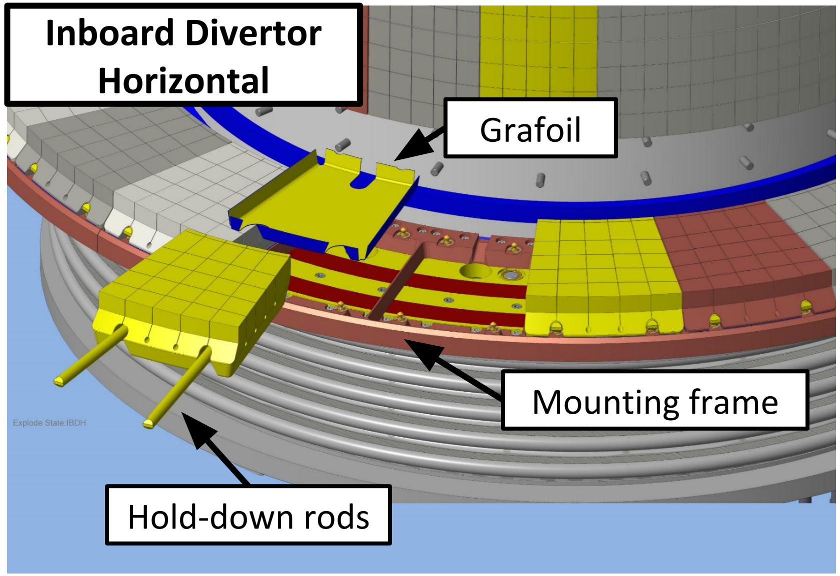
Inboard Divertor Tiles Designed to Handle Very High Heat Fluxes



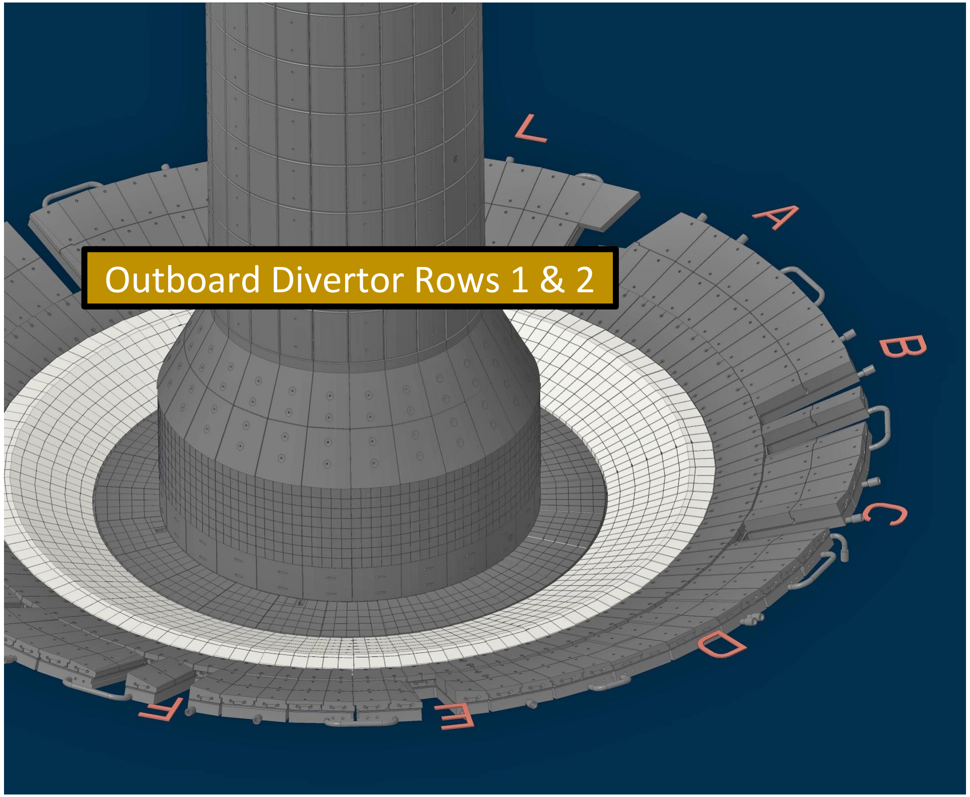
- Tile fixture guarantees single reference surface
  - Grafoil interface between substrate and tile to improve heat transfer
  - Preload controlled with lock-bar system (hold-down rods)
  - EM forces resisted with grid walls

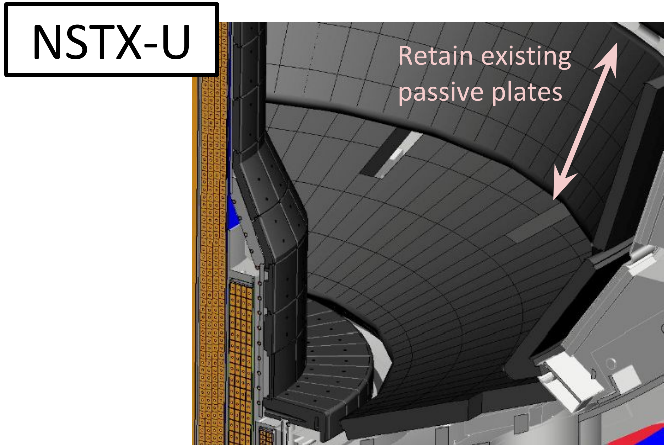
<u>Engineering Choices to Accommodate High Heat Fluxes</u>

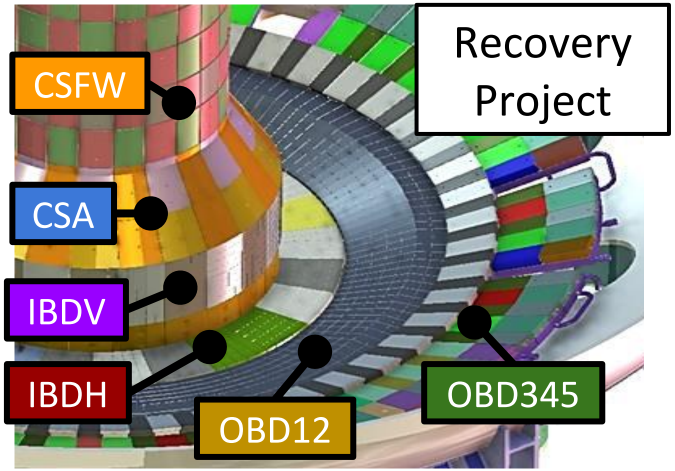
- Designed with castellated surfaces
  - Relieves surface compressive stresses
  - Design reaches surface temperature limits before stress allowables
- Fishscaling avoids leading edges
- No front surface access holes



Outboard Divertor Rows 1 & 2 Merged to Single Tile to Handle Extreme Heat Flux

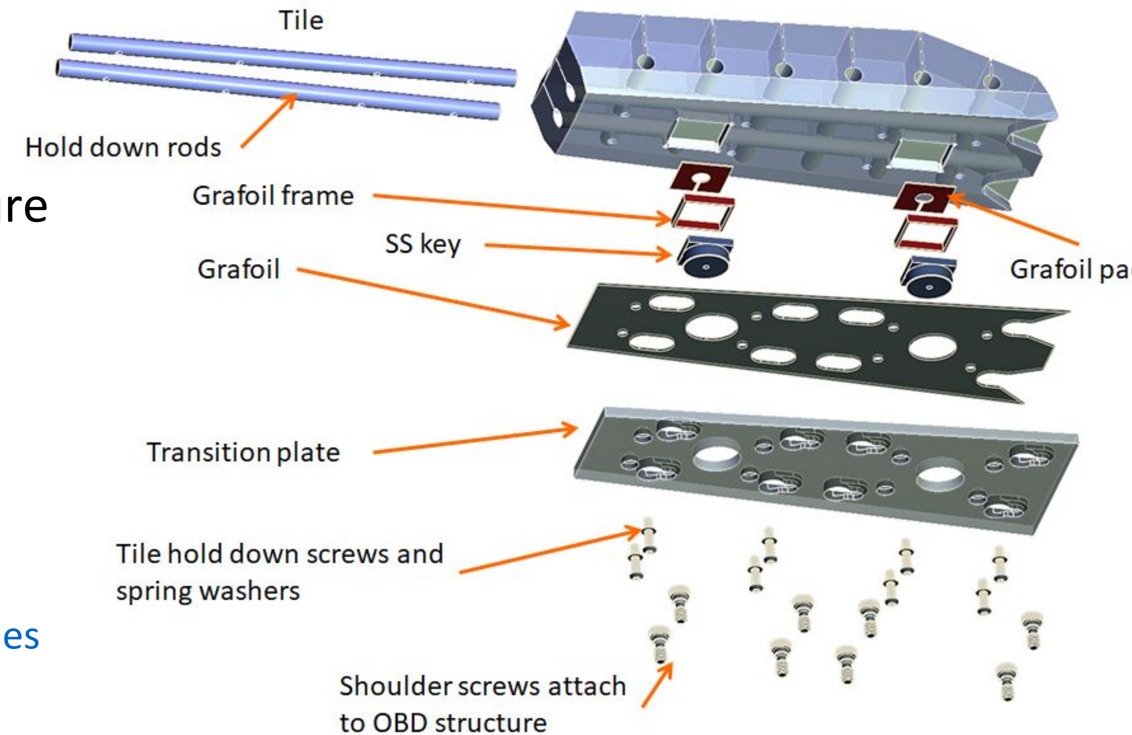




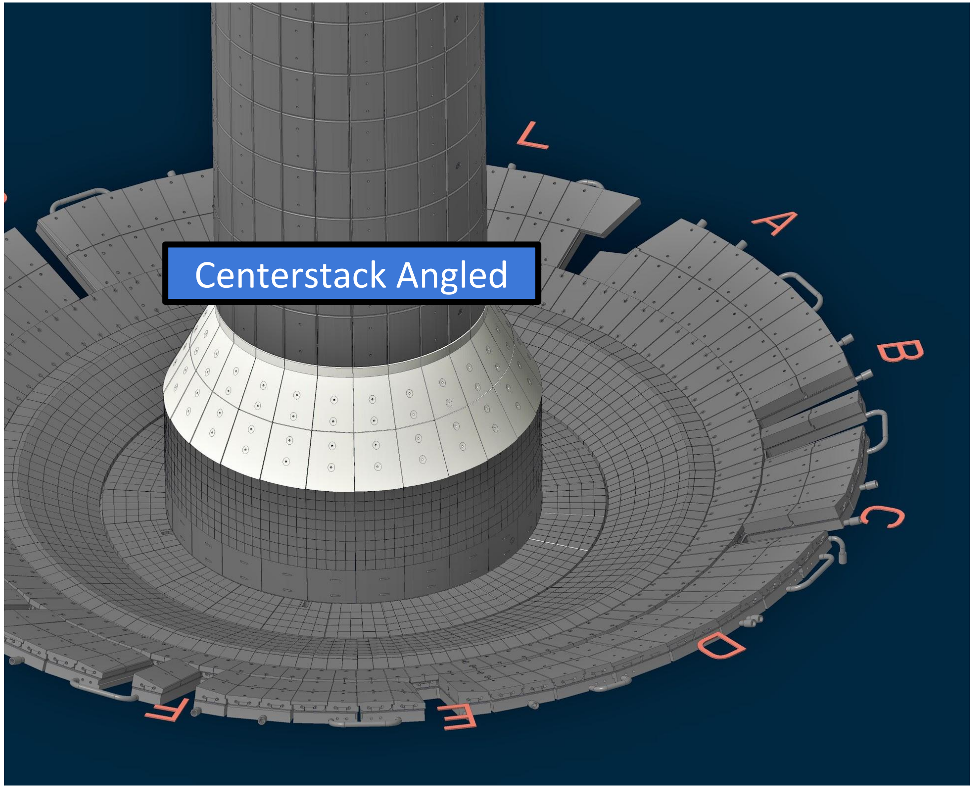


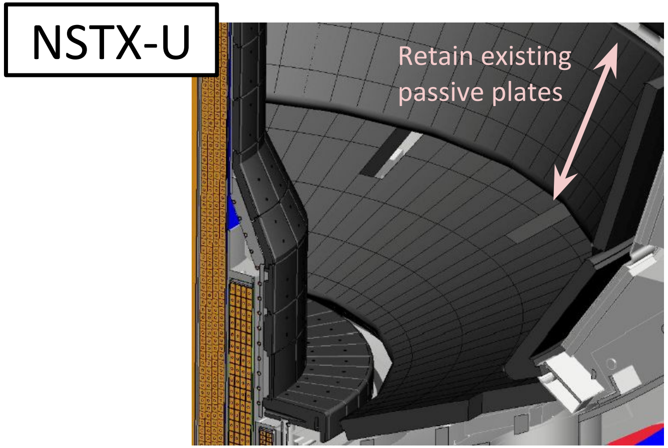
Outboard Divertor Rows 1 & 2 Merged to Single Tile to Handle Very High Heat Flux

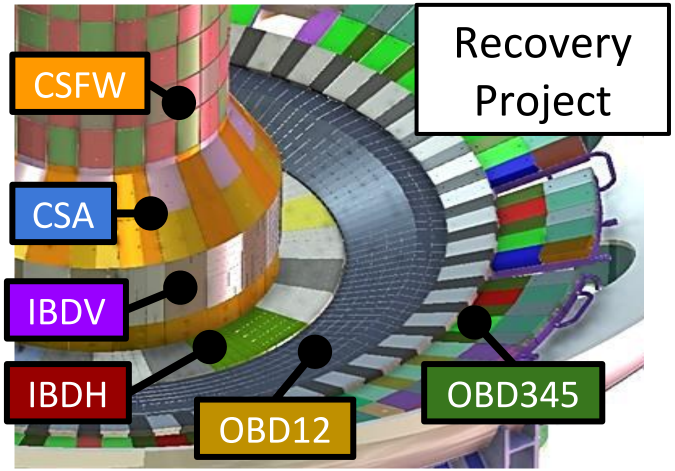
- Hold-down rods resist pull forces
- Stainless Steel (SS) key feature resists sliding motion
- Uneven outboard divertor structure corrected by individualized transition plates
  - structure metrology determines unique transition plate geometry
  - Identical graphite components



Center Stack Angle Tiles are the Transition Between High and Low Heat Flux

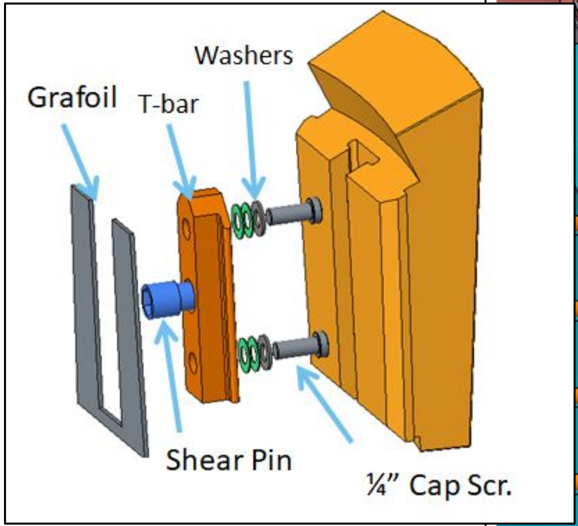


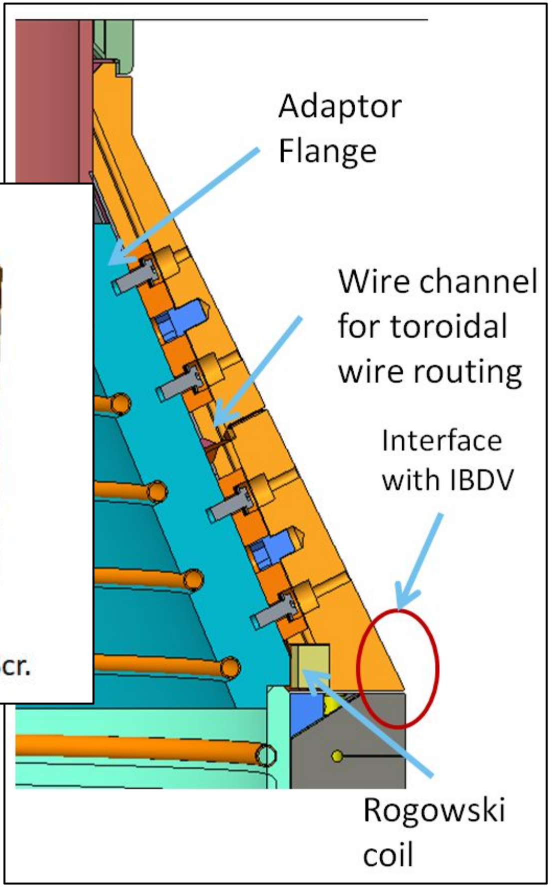




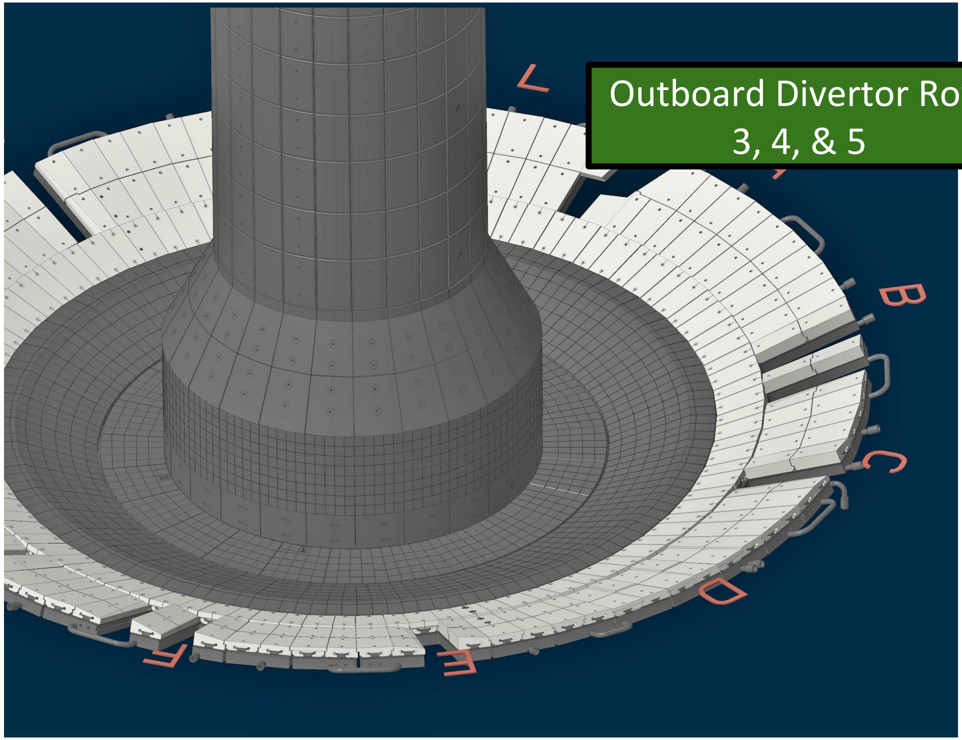
Center Stack Angle Tiles are the Transition Between High and Low Heat Flux

- LHF CSA tiles accommodates heat flux and electromagnetic loads
- Use of bolt and T-bar to mount to Center Stack Casing
- Analysis verifies design through multiple operational loads
  - sliding along T-bar due to EM loads mitigated with bolt preload
- Plasma facing surface of tile expands more than the time mounting surface due to heat loads
  - Specialized T-bar, shear pin clearance, grafoil and specialized tile geometry mitigate stresses

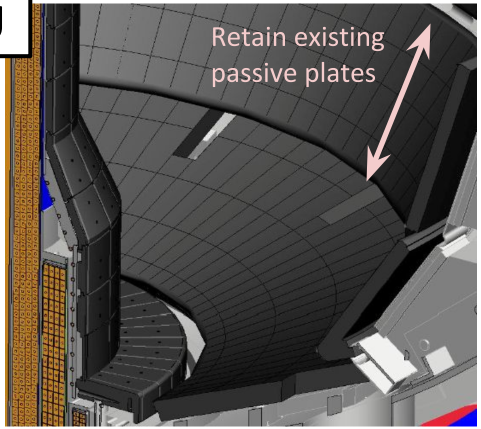


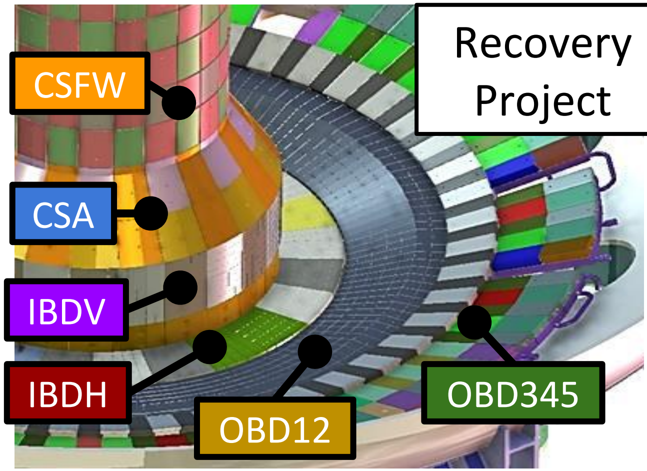


Outboard Divertor Rows 3, 4, & 5 Support the Largest Number of Tile Variants



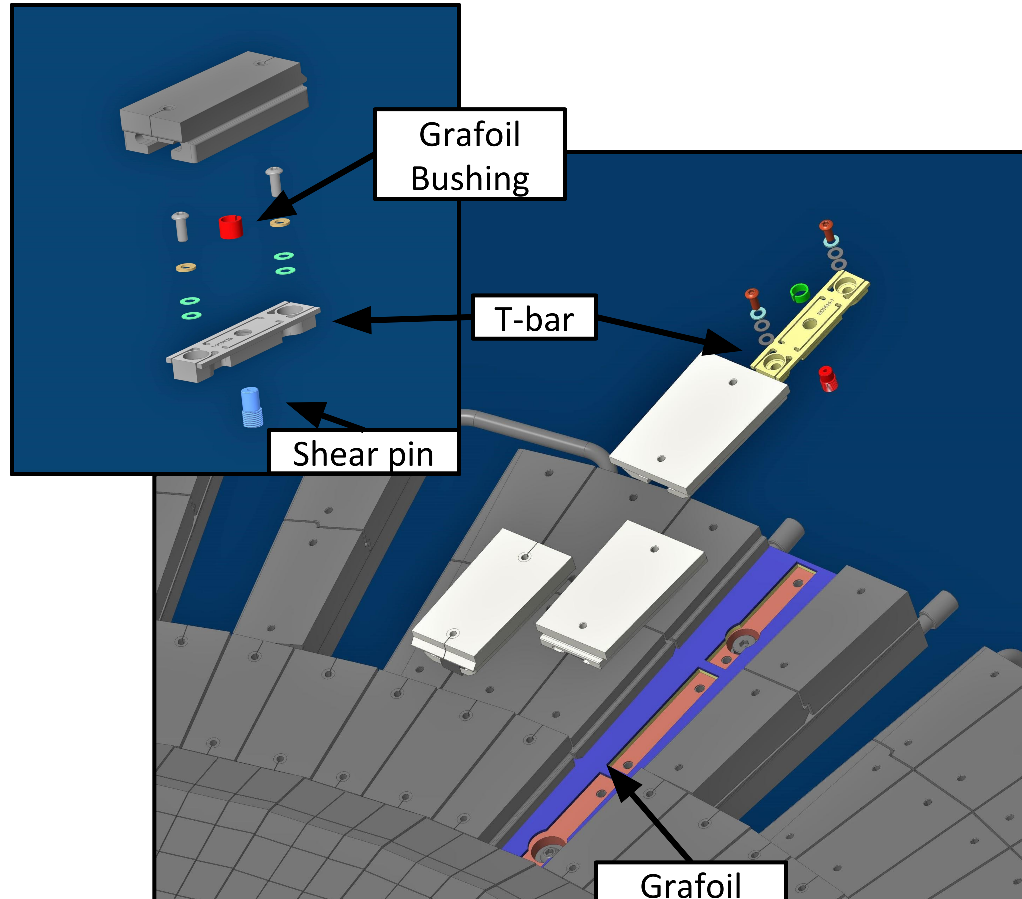
NSTX-U





Outboard Divertor Rows 3, 4, & 5 Support the Largest Number of Tile Variants

- OBD345 tiles subject to heat flux and electromagnetic loads
- Use of bolt and T-bar to mount to Cu baseplate
- Specialized T-bar design to mitigate stress concentrations
- Specialized grafoil shear-pin bushing to distribute loads
- Largest number of variants (55)
    - Diagnostics and diagnostic access drive large number of variants
- Unique gap and diagnostic tiles use Carbon Fiber Composite (CFC)
    - 71 CFC tiles out of 592 tiles



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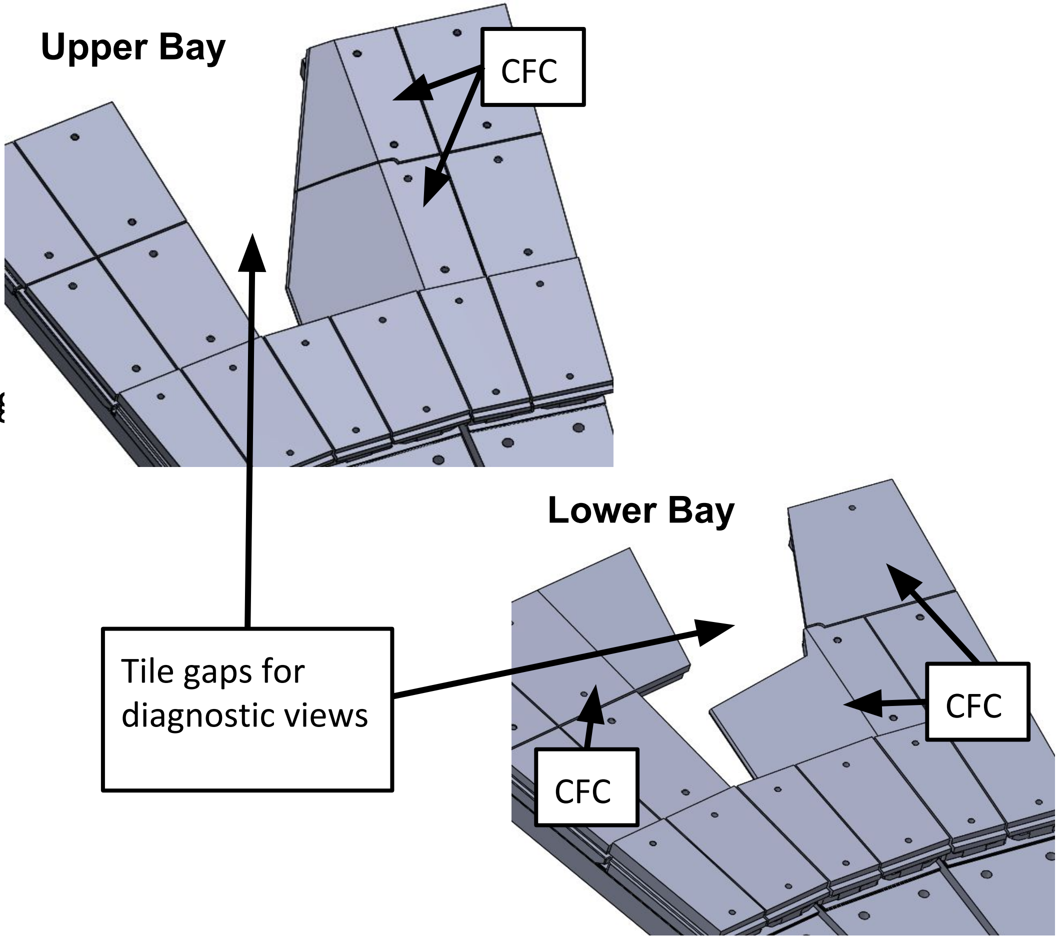

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Requirements Defined and Met - I

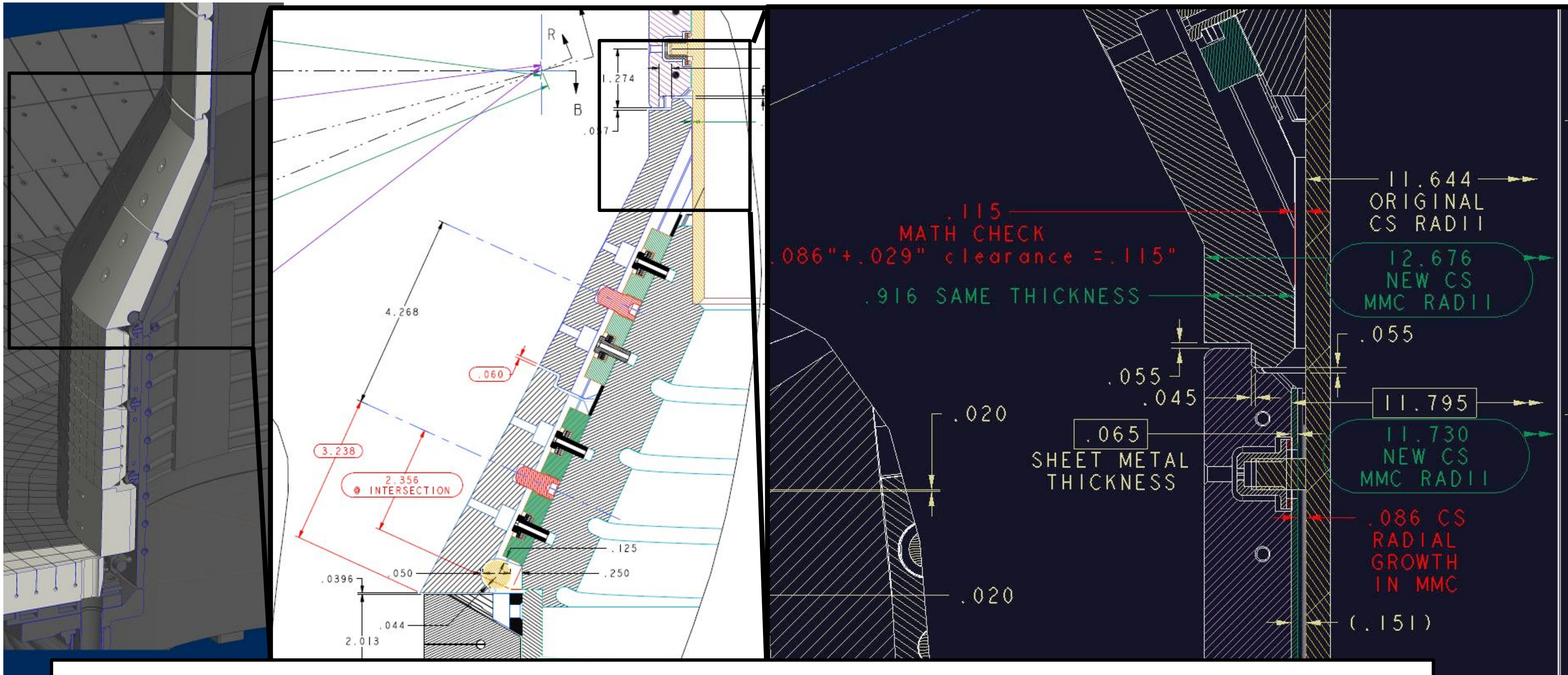
The General Requirements Document details out the highest level machine parameters of 2 MA, 1 T, 5 s, and 10 MW operating points

Source	Requirements	Comment/Elaboration/Impact	met
NSTX-CRIT-0001	Design criteria	Provides allowable of ½ ultimate compressive and tensile for critical brittle materials	✓
NSTX-U-RQMT-SRD-003	Materials and environmental conditions	Use of graphite: compatibility with boronization, lithium, GDC	✓
NSTX-U-RQMT-SRD-003	Field line directions and angles	Determines the direction of the tile offset, ramping, and fishscaling	✓
NSTX-U-RQMT-SRD-003	Surface and edge temperatures	1600 °C top surface, 2000 °C edges. Extra allowance for erosion when defining angles	✓
NSTX-U-RQMT-SRD-003	PFC boundary outline	Provides volume in which the PFC design must reside	✓
NSTX-U-RQMT-SRD-003	Installation and maintenance	Weight limits, ability to replace individual broken tiles if necessary, ability to bear technician weight	✓

Requirements Defined and Met - II

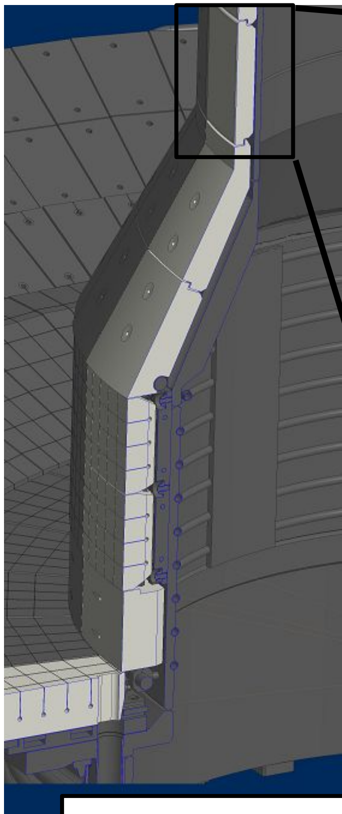
Source	Requirements	Comment/Elaboration/Impact	met
NSTX-U-RQMT-SRD-003	Gas delivery	Provision to accommodate required gas delivery lines	✓
NSTX-U-RQMT-SRD-003	Heat Fluxes	Heat fluxes at high and low angles of attack for field lines for each region of interest; determines the material and fishscale angle	✓
NSTX-U-RQMT-SRD-003	Bakeout	PFC tiles shall be subjected to a high temperature bake before diagnostic and tile installation	scheduled
NSTX-U-RQMT-SRD-003	Diagnostic allowance	Diagnostic gaps, cut-out, and feed-throughs in tiles defined and specified	✓
NSTX-U-RQMT-RD-003	Disruptions Physics	Provides input to analysis on halo and eddy currents, including fatigue considerations	✓
NSTX-U-RQMT-RD-004	PFC Diagnostics	Provides requirements on PFC diagnostic designs (Mirnov sensor, Thermocouples, Langmuir Probes), including design guidance and sensor distributions	✓

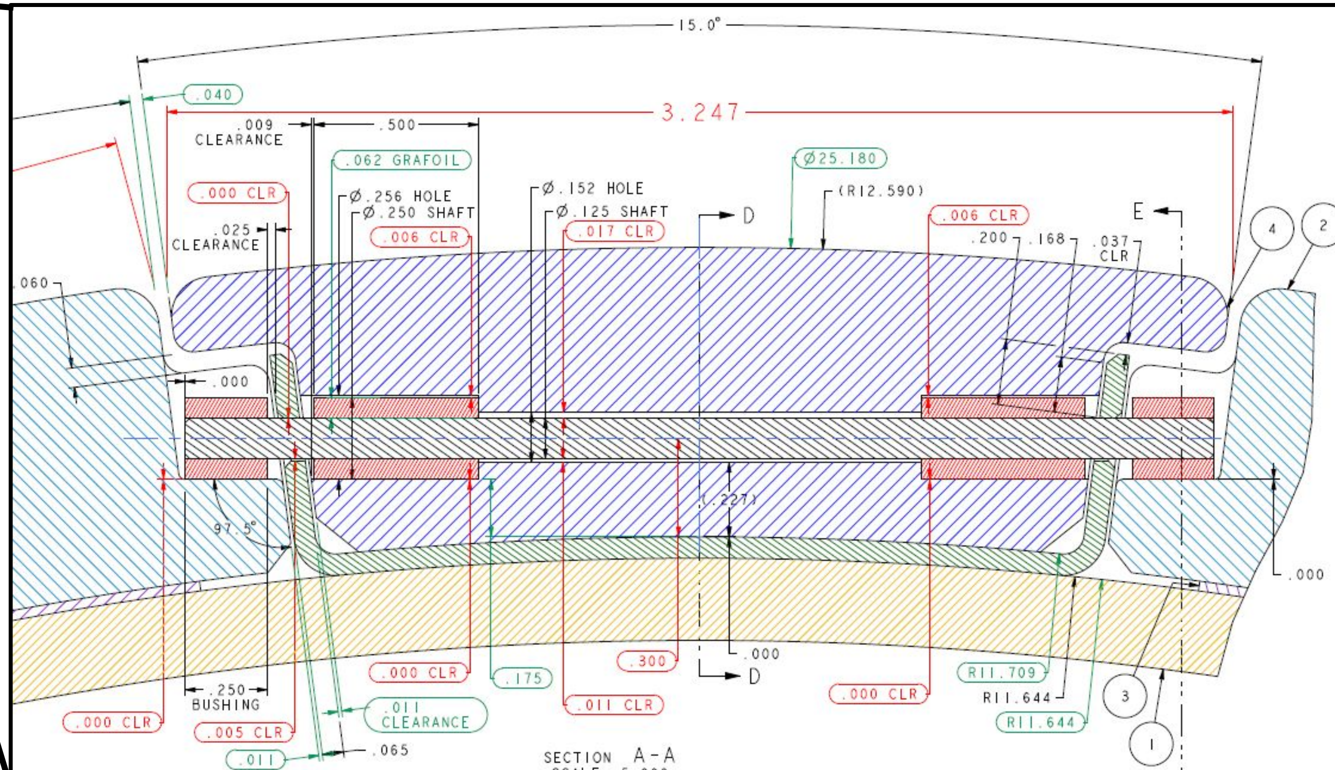
Center Stack Casing Interfaces Defined in the SRD and Accommodated by Design



Center Stack interfaces are well defined to maintain machine requirements

Center Stack Casing Interfaces Defined in the SRD and Accommodated by Design

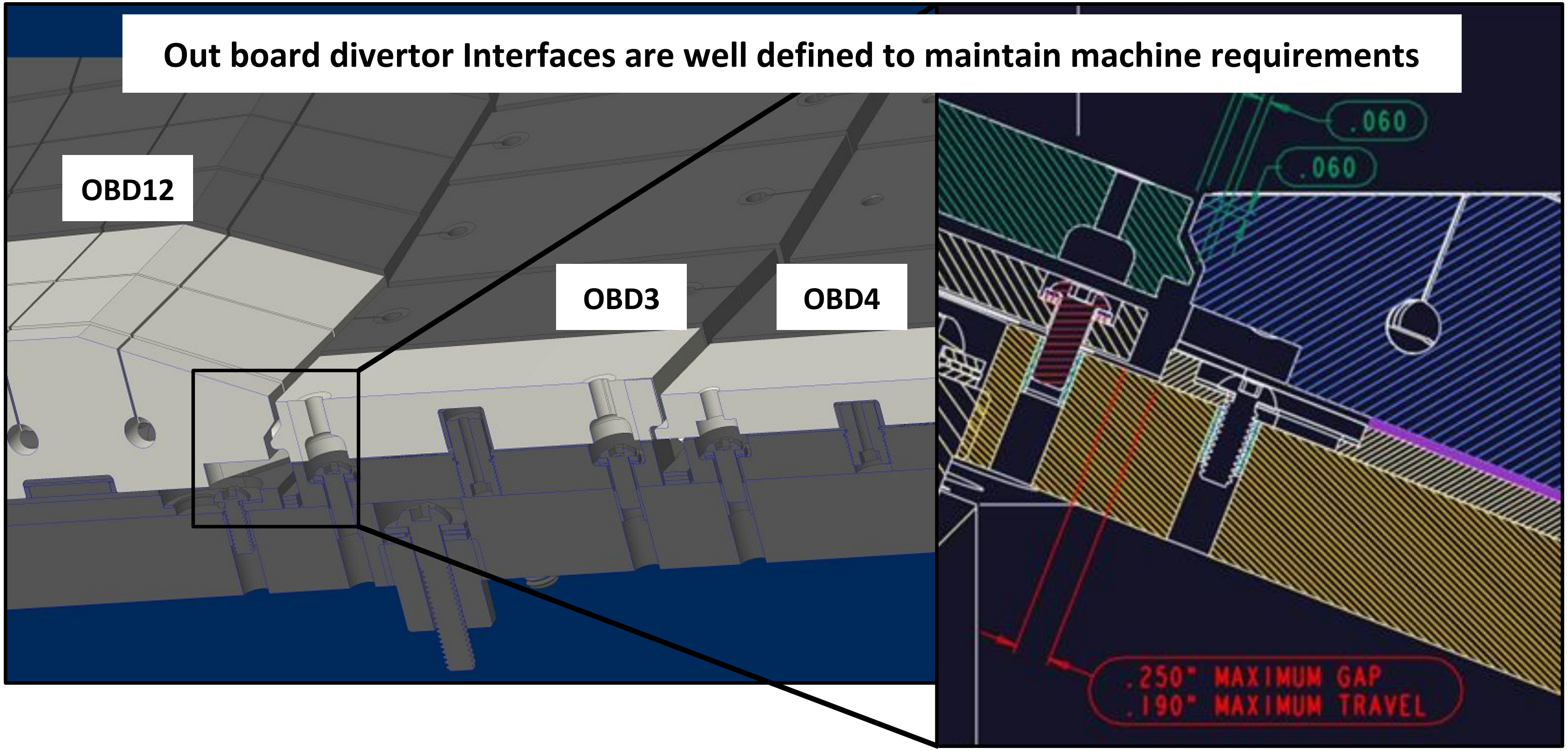




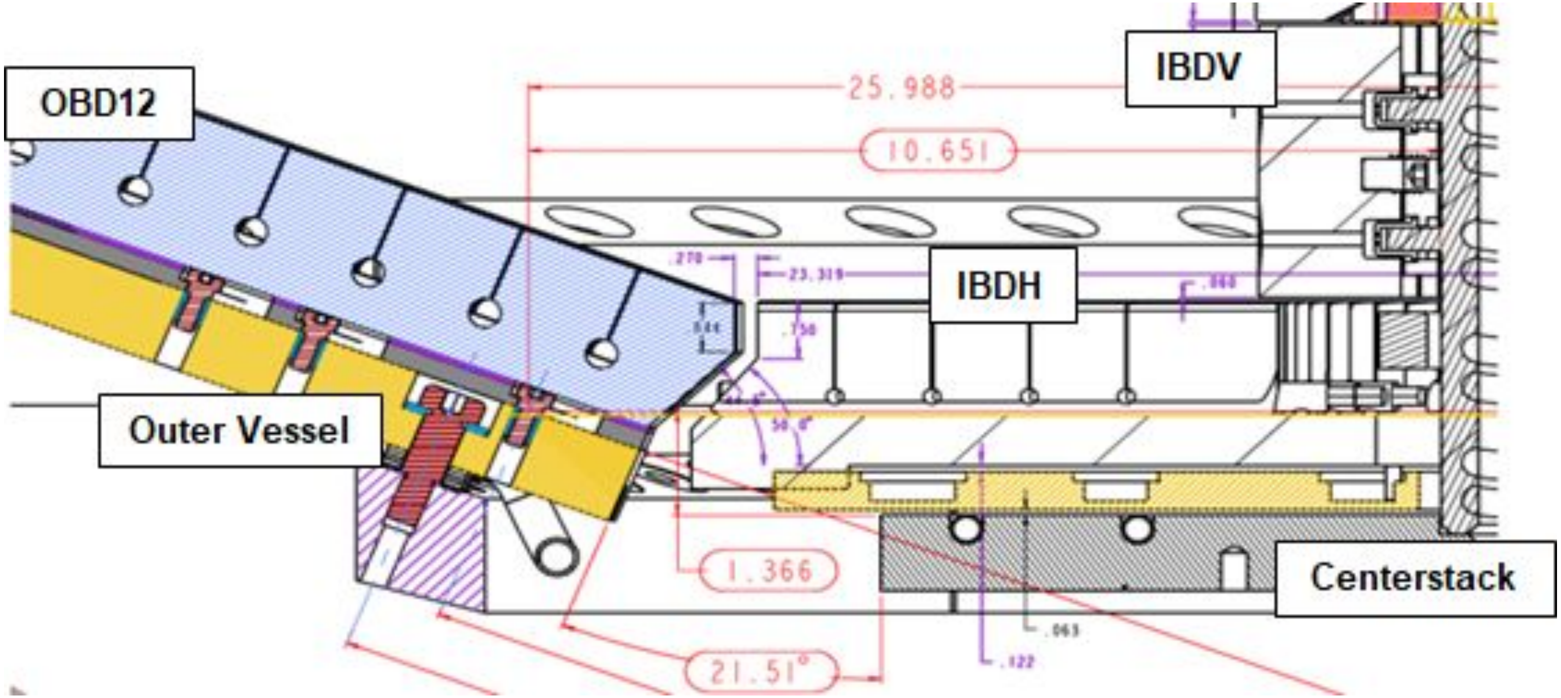
Center Stack interfaces are well defined to maintain machine requirements

Outboard Divertor Interfaces Defined in the SRD and Accommodated by Design

Out board divertor Interfaces are well defined to maintain machine requirements

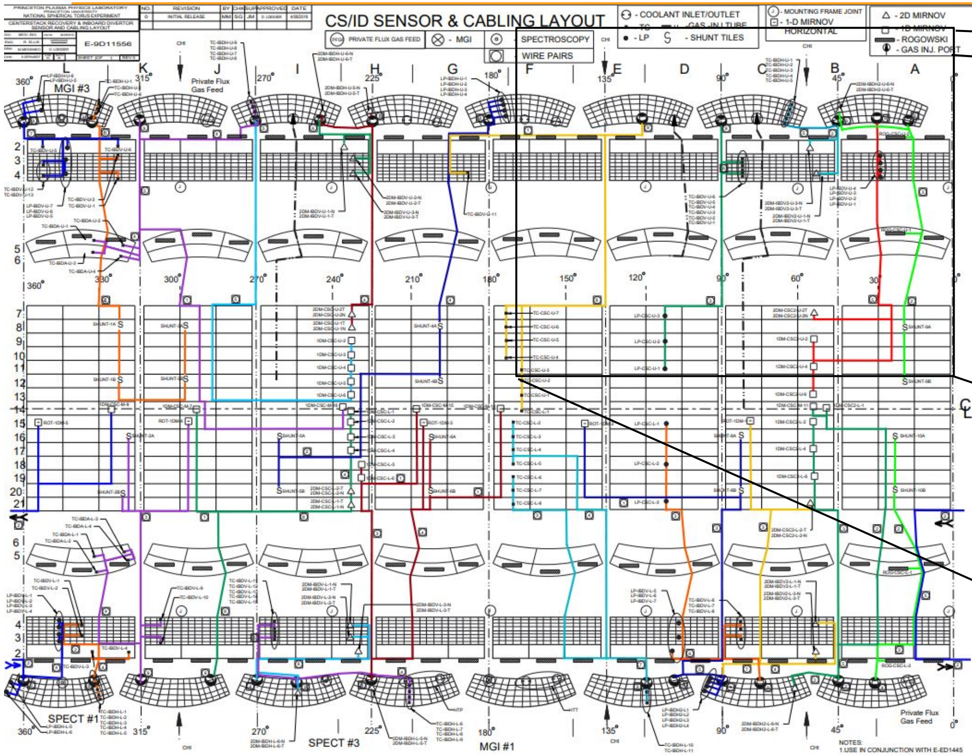


Outboard Divertor to Center Stack Casing Interfaces Defined in the SRD and Accommodated by Design



- Interface Drivers for the OBD12/IBDH/Outer Vessel/Centerstack Labyrinth
  - Prevents plasma impingement on the Polodial Field 1c reentrant flange and on the diverter metallic components.
  - Protects the upper insulator from lithium
  - Is designed to accommodate thermal expansion of the casing

Sensor Wire Routing is Integrated into PFC Design



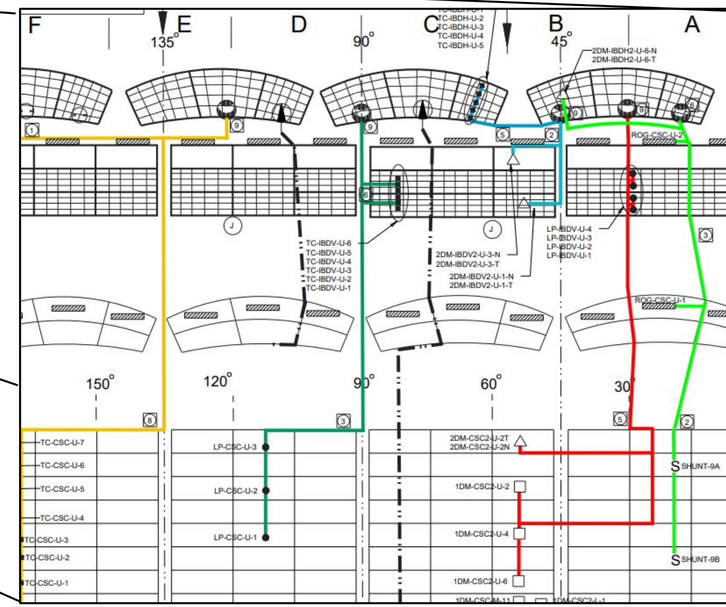


Image of previous wire installation

- Image shows unwrapped image of CS tiles, with sensors as small symbols and wires in different coils
- All necessary wire routes are accommodated by PFC design
- Similar drawing made for outboard divertor

For addition PFC Diagnostic interfaces, see talk by B. Stratton

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Plasma Facing Components	Center Stack Assembly	link	Defines interfaces between the Plasma Facing Components and the center stack assembly First Wall, Angled Section, IBDV and IBDH
Plasma Facing Components	Diagnostics	link	Defines interfaces between the Plasma Facing Components and diagnostics such as Mirnov Sensors, Langmuir Probes, Shunts, and associated wiring including thermocouples
Plasma Facing Components	In-Vessel Structures	link	Defines interfaces between the Plasma Facing Components and the OBD
Plasma Facing Components	Wall Conditioning System	link	Defines interfaces between the Plasma Facing Components and the clearance for LITER
Plasma Facing Components	Gas Delivery System	link	Defines interfaces between the Plasma Facing Components and the clearance for Mass Gas Delivery, High Field and PRivate Flux

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Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Electromagnetic Loads on CSA Tiles	NSTXU-CALC-11-11-00	Provides all EM loads on the Center Stack Angled tiles
CSA Structural Analysis	NSTXU-CALC-11-21-00	Validates the design of CSA tiles
Heat Flux Enhancement and Fish Scale Angles for CSA Tiles	NSTXU-CALC-11-28 -00	Calculates heat flux enhancement of CSA tiles and determines fish-scale angle which minimizes tile heating.
Electromagnetic Loading and Structural Analysis of CSFW PFCs	NSTXU-CALC-11-10-00	Determines EM Loading and verifies the design of CSFW tiles
Eddy Currents in OB12 PFCs	NSTXU-CALC-11-24-00	Determines EM Loading for OBD12 tiles
OBD12 Halo Force Restraints	NSTXU-CALC-11-23-00	Verifies OBD12 tile assembly properly restrained against inplane halo current forces

Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Fish Scale Directionality of OBD12 Tiles	NSTXU-CALC-11-22-00	Determines angles required for OBD12 tile ramping and castellations
Analysis of OBD12 Langmuir Probe Sensors	NSTXU-CALC-11-25-00	Validates performance of OBD12 Langmuir probes
Analysis of OBD12 Thermocouple Sensors	NSTXU-CALC-11-26-00	Validates performance of OBD12 thermocouples
Analysis of OBD12 Hold-Down Assembly	NSTXU-CALC-11-29-00	Verifies acceptable contact stresses between OBD12 tiles and hold-down assembly
Thermal and Structural Analysis of OBD12 Tiles	NSTXU-CALC-11-27-00	Verifies design of OBD12 tiles
Tile Shaping of IBDH High Heat Flux Tiles	NSTXU-CALC-11-31-00	Determines IBDH tile-tile and castellation-castellation gaps required to eliminate direct heating
Tile Shaping of IBDV Tiles	NSTXU-CALC-11-32-00	Determines IBDV tile-tile and castellation-castellation gaps required to eliminate direct heating

Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Thermal and Structural Analysis of IBDH Row 1 Tiles	NSTXU-CALC-11-18-00	Verifies design of IBDH Row 1 tiles
Stresses in IBDH and IBDV Pin-Lockbar Assembly	NSTXU-CALC-11-30-00	Verifies design of pin and locking bar used in IBDH/IBDV support structure
PFC Fields and dBdts	NSTXU-CALC-11-08-00	Determines the B and dB/dt values for PFC tiles for machine operating and disruption scenarios
Thermal and Structural Analysis of IBDV High Heat Flux Tiles (Rows 3-4)	NSTXU-CALC-11-19-00	Verifies design of IBDV Row 3-4 tiles
Thermal and Structural Analysis of IBDV Low Heat Flux Tiles (Row 2)	NSTXU-CALC-11-20-00	Verifies design of IBDV Row 2 tiles
Electromagnetic Loads for OBD4-5 PCHERs Tiles	NSTXU-CALC-11-12-00	Determines EM Loading for OBD PCHERs tiles

Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Thermal and Structural Analysis of OBD Row 3 Tiles	NSTXU-CALC-11-14-00	Verifies design of OBD Row 3 tiles and support structure
Thermal and Structural Analysis of OBD Row 4 Tiles	NSTXU-CALC-11-15-00	Verifies design of OBD Row 4 tiles and support structure
Thermal and Structural Analysis of OBD Row 5 Tiles	NSTXU-CALC-11-16-00	Verifies design of OBD Row 5 tiles and support structure
Structural Analysis of Passive Plate Tiles Subjected to Preload, Plate Deformation and Halo Forces	NSTXU_1-1-1-1-6_CALC_100	Verifies the Passive Plate tiles able to withstand anticipated loading without design modification
Thermal, Halo & Structural Analysis of Center Stack First Wall (CSFW) Tiles Updated to Incorporate Center Stack Casing Diameter Change NSTXU_1_1_1_1_CALC_036	NSTXU_1-1-1-1_CALC_103	Validates the CSA tile design (including preload)

Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Thermal, Halo & Structural Analysis of Center Stack Angular Section (CSA) Tiles Updated to Incorporate Center Stack Casing Diameter Change NSTXU_1_1_1_1_CALC_034	NSTXU_1-1-1-1_CALC_102	Validates the CSFW tile design

Material Performance Qualified Through Testing

- Material certification carried out by Precision Measurements and Instruments Corporation to verify properties **(June 2018)**
  - No industrial standards for graphite grades
  - Vendors unwilling to guarantee material properties
  - All material purchased will be independently tested through ASTM standards
  - Material certification through PMIC - benchmarked testing process

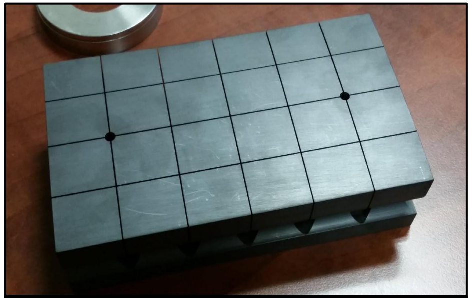
Material	Tested Peak Stress [MPa]	+/-	Vendor Data Sheet Value	Percent Diff
ET10	34.96			
	38.66			
	31.83			
	33.64			
	35.07			
Average	34.83	1.12	34.3	1.54%
St. Dev.	2.51	0.50		
T953	43.31		There was no given tensile strength for T953, data sheet value is calculated as 65% of flexural	
	42.46			
	41.40			
	39.24			
Average	41.60	0.88	32.5	24.57%
St. Dev.	1.76	0.44		
6510	39.09			
	41.40			
	38.72			
	39.07			
	43.59			
Average	40.38	0.93	38	6.06%
St. Dev.	2.09	0.42		

Figure 5, Tested UTS specimens.

Tensile test results showing comparison from results to the vendor provided material property - tests show **Higher** results than Vendor Provided Data

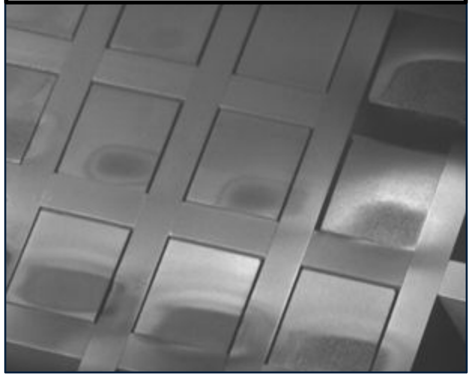
Castellation Design Principles were Tested at NSTX-U Relevant Heat Fluxes with no Castellation Failures

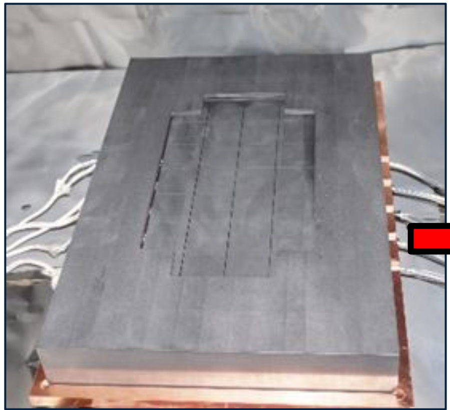
- High heat flux testing conducted at Applied Research Lab (Penn State)
  - Material survey experiments with ORNL collaborators **(Nov. 2017)**
    - Ablation of graphite samples with no observable fractures
  - ORNL castellated tile test sample and TC calorimeter testing **(Feb. 2018)**
    - Tile had intentionally deoptimized castellations to test performance limits
    - Surface damage, but survival of castellations, under extreme heat fluxes
- No observable mechanical fracturing or cracking under these conditions
  - Graphite subjected to thermal load comparable to system requirements



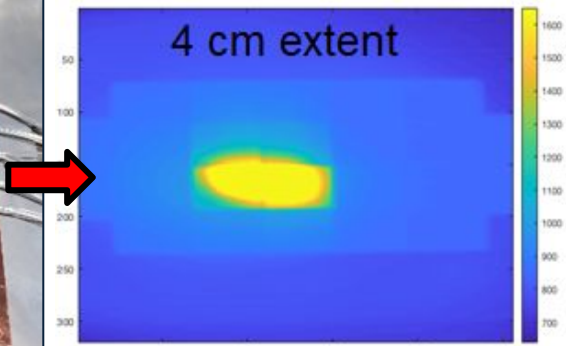
Castellated Manufacturing Prototype

Material Survey Thermal Shock Testing (Nov. 2017)





ORNL Castellated Testing Sample (Feb. 2018)



7 MW/m^2 E-Beam Heating (Feb 2018)

Thanks to analysis and testing support from Oak Ridge Laboratory and Penn State, we had the successful FDR on 9/28/18

Charge question: 1

Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
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9. Summary

All Pre and Post FDR Chits Have Been Closed

Link to Chit Report: link

Chits from peer-reviews in final process of closure

Chit Resolution Report: NSTXU_1-1-1-1_CRR_chit_100

List of chits closed in this report on the cover, details inside the report

CHITS closed in this report are indicated in the Table of Contents. Each CHIT begins a new page.

Attach total log of chits, including all those previously closed and those not yet closed.

Attached

Cognizant Individual: Jonathan Klabacha Digitally signed by Jonathan Klabacha Date: 2019.08.15 18:47:46 -04'00' (sign and date)

Approver (*): Valeria Riccardo Digitally signed by Valeria Riccardo Date: 2019.08.16 10:57:15 -04'00' (sign and date)

(*) For CDR and PDR the DRC, for FDR and after FDR the Main Approver (A-1: Chief Engineer, A-2 and A-3: DRC) DRC =Design Review Chairperson

Chit Resolution Report: link

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Procurement/Manufacturing Status

- Graphite Tiles Manufacturing:
  - Awarded to MWI Industries Inc. - 03/03/20
    - MIT Plan and Setups in Process
  - Graphite Tiles shipped from PPPL to MWI - 03/09/20
- Metal Manufacturing:
  - Awarded to Stillwater - 03/06/20
    - MIT Plan and Setups in Process
  - Inboard divertor inconel frames manufactured in-house
    - material is delivered and estimated completion is
- Graphite Testing Procurement:
  - Working with PMIC for thermal capacity testing
    - In-house adjustment to testing samples underway
  - In-house testing coming to completion - 03/27/20

Procurement/Manufacturing Status

- Hardware Procurement:
  - Split into multiple procurements
    - Hardware (standard & custom) / bellevilles
  - Standard hardware awarded to Extreme Bolt and Fastener - 02/12/20
    - Estimated delivery 04/30/20
  - Custom hardware awarded to Extreme Bolt and Fastener - 03/02/20
    - Estimated delivery 05/08/20
  - Bellevilles requisition moving towards approval with Belleflex
- Bakeout and XPS:
  - Collected bakeout and XPS vendors
  - Working with procurement to validate capabilities
    - match PPPL graphite manufacturing schedule requirements

NCRs and ECNs During PFC Fabrication Activities to Date

NCR Item	NCR Number	Description of the Issue
	4081	14 graphite blocks when delivered were chipped. All blocks were acceptable for manufacturing. Resolution was completed with proper packaging written within graphite manufacturing SOW.
	1430	Aluminum prototype frame was out of tolerance in three areas. Revisited GD&T with input from in-house manufacturing and PFC engineering team.

Drawing Number	ECN Number	Description of the Change

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Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If overloading of experienced PFC manufacturers	36	RETIRED	End of fabrication of PFCs
If the preload on the passive plate tiles causes stresses that exceed allowables	36	RETIRED	Retired
PP flex cracking tiles found during analysis	27	RETIRED	Retired
If PFC prototypes fail testing	27	RETIRED	FDR
If the base PFC material is not available by CDE3a through USA vendors	25	RETIRED	Post fabrication of PFCs
If metrology of existing CS or OBD indicates worse than expected condition	25	Open	Completion of subcomponent assembly
If the physics requirements drive excessive fabrication tolerances	21	RETIRED	FDR

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If voids are formed between the studs and casing when the studs are attached to the casing	21	OPEN	Machine reassembly
If analysis reveals tile issues	20	RETIRED	RETIRED
If parallel activities in-vessel spacial or resource limitations occur	20	RETIRED	Post assembly
If the inboard divertor mounting features are not aligned	20	RETIRED	Completion of subcomponent assembly
If Center Stack Casing studs threads are deformed due to installation and removal of spiralock nut caps	20	OPEN	Machine reassembly
If during procurement the testing of the PFC material shows inadequate properties for a large portion of purchased material	18	OPEN	end of material testing

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If PFC bake out vendors do not adhere to the vacuum quality preparation specs	16	RETIRED	Receipt of PFC
If analysis results show need to augment outboard limiter	15	RETIRED	FDR
If there are not enough spares of the passive plate tiles to accommodate the required replacements	15	OPEN	Machine reassembly
If the fabrication of high-precision PFC graphite or metal parts results in vendor failures to meet tolerances	12	OPEN	Completion of fabrication
If ORNL cannot maintain FEA support schedule	12	RETIRED	
If during installation a tile is damaged AND there are not sufficient spares	12	OPEN	completion of assembly

Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If the PFC fatigue life requirements are revised	12	RETIRED	
If machining of fishscaling redefines interfaces or produces leading edges	9	RETIRED	
Delay in down selection of PDR developed concept (IBDH/IBDV)	4	RETIRED	
insufficient thermal conductance for intershot cooldown	4	RETIRED	
Uncertainty in new requirement for plasma "locked-modes" heat flux	4	RETIRED	
Permanent deformation of machine (loads) effects PFC alignment	1	RETIRED	

FMECA - Vertical Target PFCs

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Vertical Target PFCs	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	None	Plasma TV	6
Vertical Target PFCs	Failure of rods and other hardware in individual tile hold-down mechanism	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	None	Plasma TV	0
Vertical Target PFCs	Castellation failing at root	Excessive thermal stress due to localized overheating	Inability to place strikepoint on that surface due to large non-axisymmetry in tile surface	6	None	Physics Imaging Systems	Plasma TV	6
Vertical Target PFCs	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	6	Real Time Control Software (PCS, FPDP)	None	None	0

Top 4 of 6 total FMs, all mitigated to acceptable risk

FMECA - Outboard Target PFCs

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Outboard Divertor PFCs	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	6
Outboard Divertor PFCs	Failure of T-bar or bolts attaching OBDR3-5 tiles to the outer divertor	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	3
Outboard Divertor PFCs	Failure of hardware attaching OBDR1/2 tiles to the outer divertor	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	3
Outboard Divertor PFCs	tile fracture	loss of heating capability during bakeout results in CS contracting faster than outer vessel, with subsequent collision of tiles	cannot run plasmas of interest; need to vent to repair	6	Machine Instrumentation	Physics Imaging Systems	Plasma TV	6

Top 4 of 6 total FMs, all mitigated to acceptable risk

FMECA - Horizontal Target PFCs

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Horizontal Target PFCs	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	6
Horizontal Target PFCs	Failure of rods and other hardware in individual tile hold-down mechanism	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	3
Horizontal Target PFCs	Castellation failing at root	Excessive thermal stress due to localized overheating	Inability to place strikepoint on that surface due to large non-axisymmetry in tile surface	6	Real Time Control Software (PCS, FPDP)	Physics Imaging Systems	Plasma TV	6
Horizontal Target PFCs	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	6	Real Time Control Software (PCS, FPDP)	Physics Imaging Systems	Plasma TV	6

Top 4 of 7 total FMs, all mitigated to acceptable risk

FMECA - CSAS PFCs

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
CSAS PFCs	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	6
CSAS PFCs	Failure of T-bar or bolts attaching tiles to angled portion of casing	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	3
CSAS PFCs	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	6	Real Time Control Software (PCS, FPDP)	Physics Imaging Systems	Plasma TV	6

FMECA - CSFW PFCs

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Center Stack First Wall PFCs	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	6
Center Stack First Wall PFCs	Failure of pins and other metal parts results in tile breaking loose	Excessive thermal stress	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	9	DCPS Software	Physics Imaging Systems	Plasma TV	6
Center Stack First Wall PFCs	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	6	Real Time Control Software (PCS, FPDP)	Physics Imaging Systems	Plasma TV	6

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ES&H and QA

- Minimal Environmental Safety and Health impacts to new designs
  - Isotropic graphites used similar to legacy NSTX material
  - Mounting hardware has been kept to below 30 lb. to aid in installation
  - Hazards during installation managed by the PPPL worker safety program (JHAs, pre-job briefs, proper PPE training and use)

- Fabrication and Oversight Plans along with Quality Inspection Plans
  - External fabrication processes not defined by PPPL
    - Guide subcontractor through statements of work
    - Subcontractor oversight and on site inspections
  - First off the line quality inspections
  - Random sampling inspection throughout manufacturing

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Summary

- Requirements have been met through rigorous analysis and testing
  - Iteration with the project has converged on acceptable requirements through analysis and testing
  - Within project progression, communication between the PFCs and other NSTX-U components along with detailed analysis has created achievable PFC requirements
- Interfaces have been managed and defined within the ICDs with close input from NSTX-U components that affect PFCs
- All pre and post FDR chits related to the PFCs have been resolved and are available within the PFC Chit report
- Risk are reviewed, identified, and adjusted on a monthly basis
  - Analysis and design risks are minimal
  - Manufacturing risks have been identified and a rigorous manufacturing oversight and QA process has been identified
- Minimal ES&H impacts to new designs

BACKUP

Vast Majority of Chits Have Been Closed

- POLARPEER31
  - Regarding the “small tile” option with a single bolt on each tile, it is important to build in a keyway groove or equivalent structure in the back plate that engages with the tiles to keep the tiles from rotating about the bolt – lesson learned from C-Mod inner wall tiles.
    - Tile down selection review was completed and the small tile option was not selected. Castellated tile geometry was selected.
- POLARPEER34
  - Regarding the “small tile” option: Consider castellated design of smallish tiles instead of a full array of separate very small tiles.
    - Tile down selection review was completed and the small tile option was not selected. Castellated tile geometry was selected.

Chit Resolution Report: [link]

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR01
  - Please ensure that the high vacuum outgassing test of the purchased graphite will be also included in the test plan.
    - High vacuum outgas testing requirements are specified in the Statement of Work for Bakeout of NSYX-U Recovery Tiles (NSTX-U-SOW-PFC-003-00).
- PFCPEMPFDR02
  - Review the numerous procurements and determine which ones require Statements of Work to ensure that suppliers understand and agree to all technical and QA requirements, and that all steps are taken during the manufacturing and delivery process are compliant with project needs.
    - PFC related procurements will be carried out following the Statement of Works (SOWs)

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR03
  - Calculation 11-10 section 3.1 mentions a "PPPL material database." No reference is provided for this information. What properties were used in this analysis? This comment applies to other calculations as well: PFC calculation reports generally specify the types of materials used but do not provide explicit material property information.
    - ANSYS material properties used in calculations are included in the digital archive. Link has been made through the FDR dashboard. This is the analysis group database used within the PFC group. Link to the FDR dashboard:
    - https://sites.google.com/pppl.gov/20180926pfcs-pempfdr/home

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR04
  - The CSA tiles nearest to the center-tube have a sharp internal angle of about 140 degrees, at the thinnest point of these "not quite L-shaped" tiles. Wouldn't it be a good idea to radius that internal corner by a few cm, to improve its margin against unforeseen extreme loads, achievable at negligible cost?
    - The CSA Row 6 tile drawing (E-ED1423) has a 0.020" radius for the edge in question. Internal discussions with the fabrication shop has shown this is not a problem to manufacturer. All other sharp edges have a standard "break sharp edges 0.005/0.020" definition. No sharp edges will be present, unless otherwise noted. The SOW for graphite manufacturing will have a machining definition that will also detail edge requirements for any direct from CAD manufacturing.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR06
  - As the pre-load is the most significant source of stress on the tiles (quoting the presenter - mechanical stresses at the fixtures decrease when tiles are heated), consider carry out pre-load tests to support analysis result.
    - The confidence in the analysis done on the tiles is high and the software that was used was qualified through our Software Quality Assurance following QA-028. Prototypes do not add validity to the final design, but prototypes are being manufactured as a project risk mitigation strategy.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR07
  - Calculations make reference to PFC-180613-AK-01. This appears to be a procedure for doing some of the PFC FEA. (1) I could not find this reference in the dashboard. (2) Has this procedure been vetted / checked?
    - PFC-180613-AK-01 has been filed in the NSTX-U document management system with the appropriate reviews and signatures.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR08
  - We witnessed in testing that the rod(pin) bends and could potentially crack the tile. The solution of adding the grafoil bushing is a good option; but it helps to be tested to see if it sets.
    - Repeat testing (static and fatigue) was performed for tile subjected to shear pin loading. The tests incorporated the grafoil inserts presented at the FDR. Deformation of the grafoil bushings was observed and determined to be acceptable for achieving the design function; no significant damage to the tile was observed in any test. The memo documenting this testing is NSTX-U-REC-171-00.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR10
  - Slide 12 of Bob's presentation on the OBD-R12 tile assemblies shows four shoulder screws to attach the transition plate to the OBD structure, only two of which (at the end) have marginal access for a modified hex-key to tighten them. The other two are intended to have welded-on Belleville washers to provide inhibition of rattling when the heads were slid along the key-hole slots. Use a wedge plus a spring washer of some different type with a threaded hole so it is trapped on the screw without welding?.
    - Testing was done to assess OBD12 assembly installation using a prototype transition plate. The results of the prototype testing demonstrated that the OBD12 design is viable and indicated that use of a simple fixture as well as jacking screws would be helpful for installation. The prototype testing results were documented and filed in NSTX-U-REC-171-00.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR12
  - NSTXU-CALC-11-31-00 assumes the HTP can be shimmed to within 0.003-0.005". Calculation thus indicates that one of three things is required: A) The tile fish scale should be redone to the expected HTP value, or B) the HTP COG should concur that the required surface flatness can be delivered, or C) the reassembly WAF should be revisited to ensure shimming in the IP is consistent with this requirement.
    - The inter-castellation step size will be 0.009" and the inter-tile step size will be 0.036". These assume the HTP will retain a surface profile tolerance of 0.010" per plate. The IBDH drawing has been adjusted to reflect the GD&T of the front surface as 0.004" surface profile tolerance and provide *reference* thicknesses (i.e. since the surface profile is defined with 3 datum features, allowing the control required). The forward helicity case is covered with this adjustment and the physics program will prioritize forward-helicity performance.

Chit Resolution Report: [link]

Vast Majority of Chits Have Been Closed

- PROJPDR26
  - How the Grafoil under the HHF tiles will react to pre-loads + heating is not understood. Testing should be done to make sure the tiles will maintain the proper pre-loads and positioning.
    - We have experience using this grafoil in several NSTX and NSTX-U PFC designs. No issues have been reported with its performance or degradation (relaxation, cracking, flaking or otherwise). Analysis of the grafoil used in HHF designs (Calculation Reports NSTXU-CALC-11-17-00, NSTXU-CALC-11-18-00 and NSTXU-CALC-11-19-00) did not raise any concerns about the ability of the grafoil to withstand design loads. Testing will not be pursued based on the HHF analysis and the materials prior use in the machine.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PFCPEMPFDR13
  - In slide 11 of Andrei's talk on IBDH, the 90 degree rotated tie-bar design is shown (similar to an IKEA furniture locking cam ring). Depending on the preload applied by the Belleville stacks, this might need a large torque to make the initial rotation - but once vacuum tribology and the occasional halo current has gone through the pull-down pins, they might get welded to the tie-rods. What would then be the recovery method to disassemble these components? Can you use some mismatch of alloys (maybe Monel against Inconel?) to avoid the welding effect?
    - PFC team is utilizing silver coating per ASTM B700-08 (min. 5.0 um) on all hardware to avoid galling.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- CSCFDR29
  - Suggest assessment of center stack first wall under worst deformation cases and making sure internal and external (PFC) components are not damaged, or stressed more than expected.
    - The deformation of CSFW and CSA tiles under PFC design loads was analyzed and reported in calculations NSTXU_1_1_1_1_CALC_036 and NSTXU_1_1_1_1_CALC_034. Additional analysis was done to assess deformation of the CS PFCs
- LHFPDR3
  - PFC performance & requirements must consider/asses tile to field alignment as well as tile to tile alignment.
    - The SRD for plasma facing components, NSTX-U-RQMT-SRD-003-02, specifies performance requirements considering field alignment and tile-tile misalignment. All PFC designs meet their respective requirements.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- PROJPDR33
  - PFC Supplier of graphite is unwilling to guarantee material properties. However, they will supply test data with each provided piece of material. If they are willing to share historical data on these values with us (e.g. ~35+ most recent reports), we can construct statistically significant confidence intervals for the true mean & std dev of each of the measured properties. Though short of a guarantee, it will be sufficiently reliable and should ameliorate the uncertainty which is complicating our design process.
    - To guarantee the material properties, the vendor provided data will not be used. Testing will be carried out on each billet of graphite as received, and the material that reaches the requirements will be designated for use in PFC tiles. See NSTX_1_1_1_1_SOW_104

Chit Resolution Report: link

Charge question: 3

Vast Majority of Chits Have Been Closed

- CSCFDR14
  - Add thermocouples where the casing bakeout thermal analysis shows critical strains and or temperature limits.
    - Thermocouple location requirements are defined in the PFC diagnostic requirements document (NSTX-U-RQMT-RD-004). Between the PFC FDR and the PFC diagnostics FDR, extensive work was done on sensor location and cabling. After the final set of sensor locations was decided, we updated the requirements document to reflect that. Rev. 1 of the PFC Diagnostics and Fueling RD was signed in February 2019. Sensor locations were discussed at the PFC Diagnostics FDR.
    - https://sites.google.com/pppl.gov/20190305pfcsdiagnosticsfdr/requirements-project-documents

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- CSCFDR16
  - Consider adding thermocouples where the thermal analysis shows critical strain differentials or temperature limits.
    - Thermocouple location requirements are defined in the PFC diagnostic requirements document (NSTX-U-RQMT-RD-004). Between the PFC FDR and the PFC diagnostics FDR, extensive work was done on sensor location and cabling. After the final set of sensor locations was decided, we updated the requirements document to reflect that. Rev. 1 of the PFC Diagnostics and Fueling RD was signed in February 2019. Sensor locations were discussed at the PFC Diagnostics FDR.
    - https://sites.google.com/pppl.gov/20190305pfcsdiagnosticsfdr/requirements-project-documents

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- HHFPDR42
  - Look into terminal strips or connections with feeds to the other side built into IBDV frames that can be built into frames to allow for easy in vessel connection/repair.
    - The finalized IBDV frame design is one solid piece and does not include terminal connections
- HHFPDR50
  - The cooling plate and other components (that require cooling/heating fluids) design shall comply with Mech-015 to ensure their safety as pressurized components.
    - The final design does not include fluid driven cooling/heating plates.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- HHFPDR51
  - Procedure shall be developed to explain technical and configuration priorities for assembly, installation and testing.
    - Procedures for assembly and installation of PFCs have been developed and integrated with the project management in close consultation with machine technicians. The centerstack procedure is documented under D-NSTXU-IP-TOK-4046 and the Outboard Divertor procedure is documented under D-NSTXU-IP-TOK-4047.
- CSFWATILEPR01
  - Update the SRD to be consistent w/ regard to the new nominal radius of the tile surface given the growth of the casing FW radius.
    - The revised FW radius has been incorporated into the working version of the SRD (rev3).

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- CSFWATILEPR02
  - Revisit tolerances: Some of the non-critical tolerances appear to be too tight. Revisit the tolerances.
    - Tolerances of CSFW PFCs and associated components were revised with input from the manufacturing experts and the PPPL machine shop. The updated tolerances were determined to support the design while not adversely impacting production cost.
- CSFWATILEPR03
  - List of all relevant calculations to be included on Design Approval Form, and all calculation checking to be complete prior to submittal of Design Approval Form.
    - An updated DAF has been filed (NSTXU_1-1-1-1_DAF_100) which captures the CSFW calculation filed post FDR.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- CSFWATILEPR04
  - Verify the mounting surface of the angled sections accommodates the 0.030" offset requirement.
    - The CSFW assembly tolerances (E-ED1391, E-ED1356) were reviewed to ensure the 0.030" tile-tile offset was maintained under all LMC/MMC conditions.
- CSFWATILEPR05
  - Two belleville washers stacked for 360lb preload might not be necessary. Please find out if one washer can give you the 360 lb preload.
    - The CSFW design was qualified to preload per NSTXU-1-1-1-1_CALC-036. The Belleville washer design selected is currently being reviewed by BelleFlex Technologies; they will propose an alternative Belleville washer for our application should their analysis show that the selected washers are overstressed.

Chit Resolution Report: link

Vast Majority of Chits Have Been Closed

- CSFWATILEPR06
  - On the calculation of Tile shear pin hole slide, the peak stress from FEA exceeds allowable, Please check using analytical approach to extract local peak stress to resolve this issue (i.e., the Peterson's stress concentration factor).
    - A refined mesh was used in the revised calculation qualifying CSA PFC design (NSTXU-1-1-1-1_CALC-034) such that the peak tile stress in the shear pin hole was fully resolved and shown to be within material allowables.

Chit Resolution Report: link