National Spherical Torus eXperiment Upgrade

Overview of NSTX-U Central Core and Recovery Design Process

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

Yuhu Zhai

NSTX-U Recovery Project Project Engineer

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

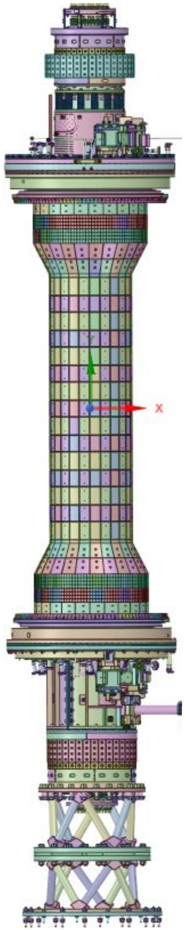
Outline

- Machine Core Overview
  - Inner PF magnets
  - Machine core structures
  - Center stack casing
  - Ceramic break assembly
  - Plasma facing components
- Machine Alignment
  - Precise dimensional control, alignment of core components
- Assembly Sequence
- Design Process
  - Project reviews & chit resolution
  - Design validation & assurance

More details can be found in talks by COGs at breakout sessions

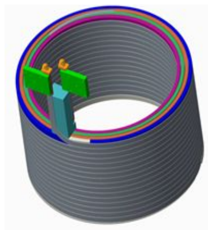
Machine Core Overview

- Project PEP defined central core system modification
  - Engineering parameters for key design requirements
    - 2x higher field, current, power & 4x heat flux, 5x pulse length
    - 4000 full performance pulses (1 T, 2 MA, 3-5 s duration)
- Metrics to demonstrate higher technical capabilities
  - KPPs -> stakeholder requirements -> high reliability operations
    - #1 Magnetic Alignment -> TF PF-5 shift, tilt
    - #2 Graphite Tile Bakeout -> T > 260 ^{0}C
    - #3 Magnet Performance -> 1.4 MA, 0.85 T, 4 s plasma with 2 s flat-top
    - #4 First Plasma -> 50 kA, 0.1 T
- New design meets requirements with improved reliability
  - Design driven by GRD, SRDs, RDs to achieve higher core capabilities
- Central core system design increased technical capabilities

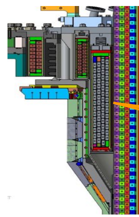


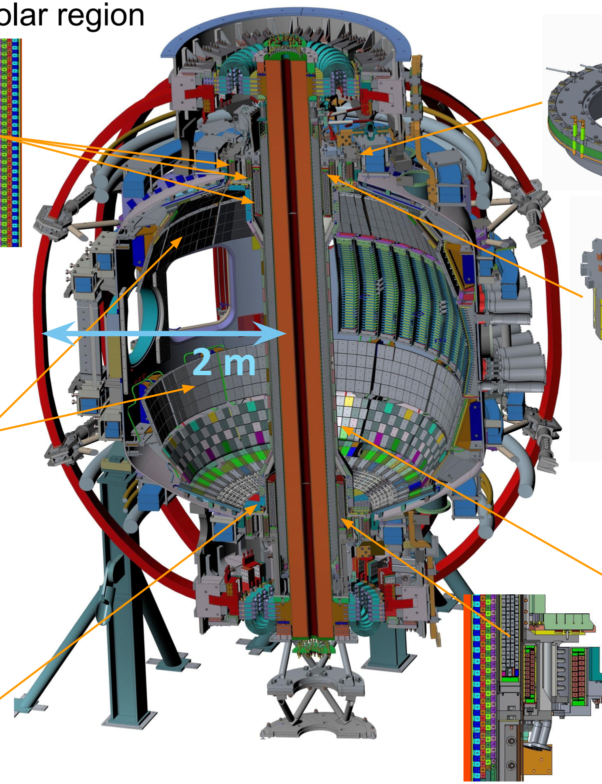
Machine Core Meets Requirements for High Reliability Ops.

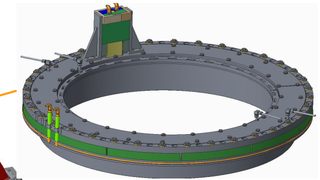
Six new inner-PF coils
WBS 1.01.02.01
CAM: Swider
See talk by Kalish

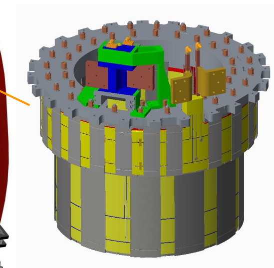


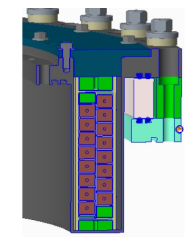
upper polar region





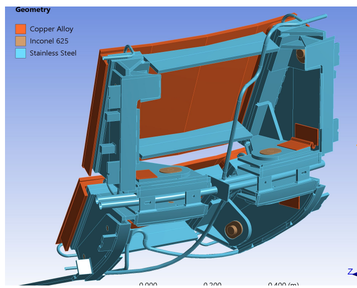




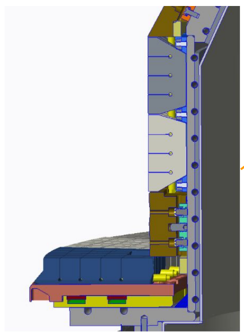


New PF-1a, -1b, -1c support structures
WBS 1.01.02.01
CAM: Swider
See talk by Smith

Repairs to passive plate bracketry
WBS 1.01.02.02
CAM: Gattoni
See talk by Jariwala



New graphite tiles
WBS 1.01.01
CAM: Gattoni
See talk by Klabacha



lower polar region

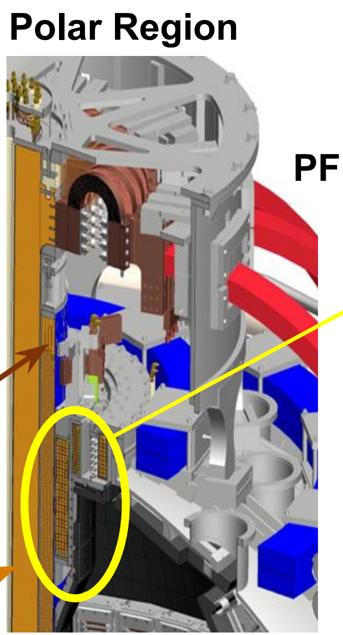
New Center Stack Casing
With **Improved Heating/Cooling Features**
WBS 1.01.02.06 and 1.01.02.04
CAM: Swider
See talks by Smith, Cai, Viola

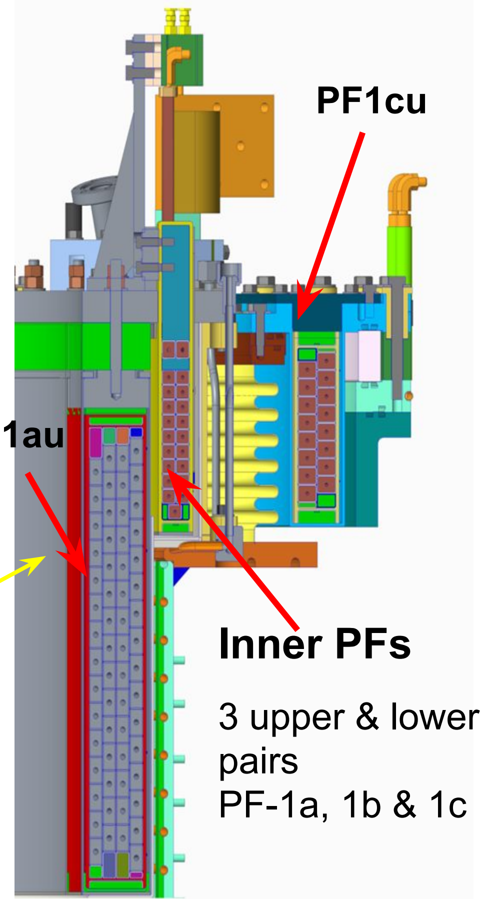
Meet machine core integration challenges to achieve project goals

New Inner PF Coils with Improved Testability, Manufacturability and Operation Reliability

- Difficult to access and requires high reliability
- Part of center stack assembly in tight space & tolerances
- New design meets space and performance requirements
  - *Minimum ampacity and ESW durations*
  - *Repetition period of all inner PFs is 1200 seconds*
  - *Configuration requirement: 1 cm coil center dev.*
  - *Required a significant margin on insulation*
- New design features *see talk by Kalish*
  - Continuous spiral wound (no joint braze)
  - No integral mandrel
  - No joggles and thicker insulation

Inner PFs are conventional copper coils but require high precision/craftsmanship on coil fabrication for reliability and design assurance!

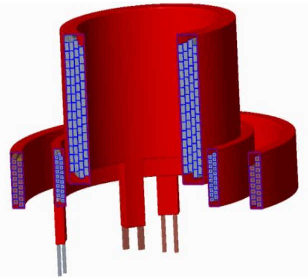




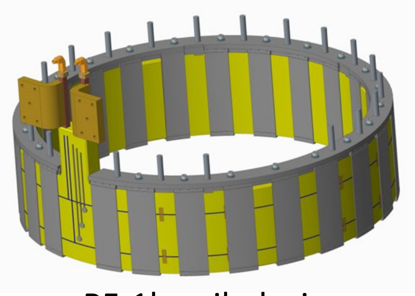
Production coil Fabrication Is on Track for Testing

- New design meets requirements & NSTX structural design criteria
  - Design is largely driven by temperature limit and cool down time
  - *A pre-load (PF1a & 1b) is chosen to limit insulation thermal strain*
- Prototype evaluated vendor quality and validated design
  - A series of electrical tests and mechanical inspections (final report)
  - Electrical endurance test demonstrated required margin on insulation
- Production coils to be assembled with supports & power tested

see talk by Kalish

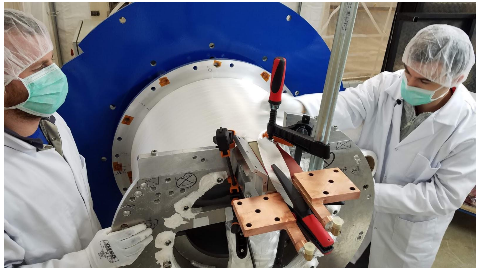


New design



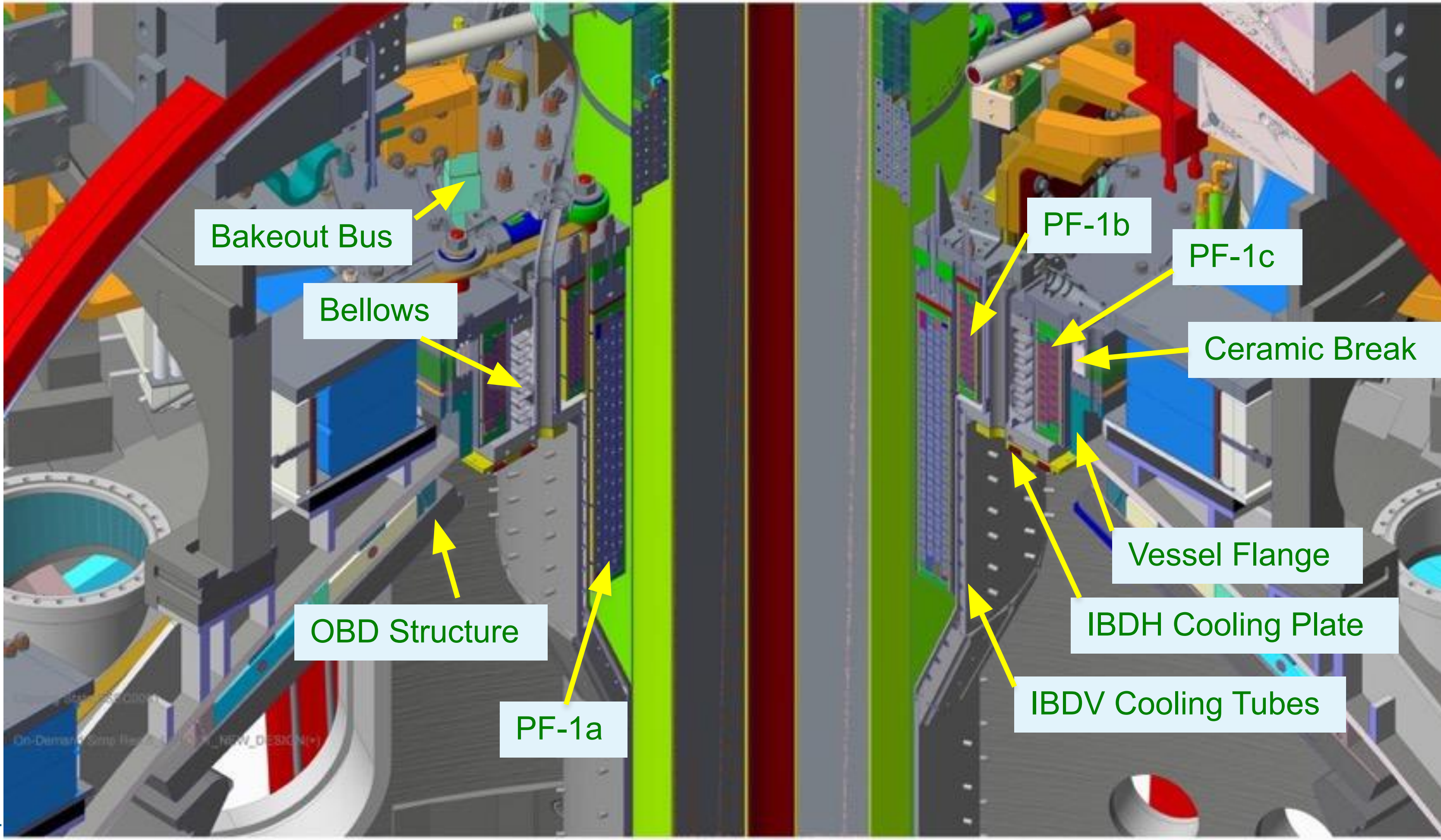
PF-1b coil, design installed in slings

Sectioned Pro1a coil test



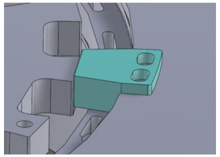
Production coils fabricated

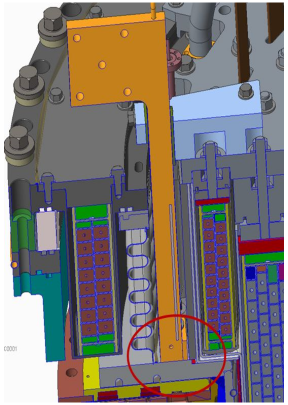
Polar Region Machine Core



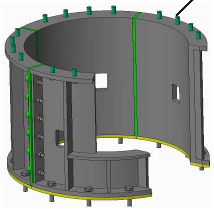
Machine Core Structure Components in Fabrication

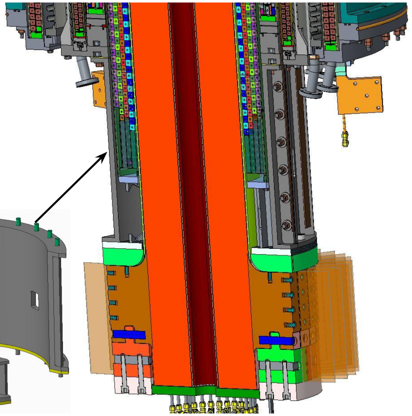
- Polar region core structure supports required
  - PF1a & 1b sling upper assembly, PF1c upper with ceramic break
  - Ceramic break provides electrical isolation
  - Upper lateral support "shims"
  - PF1a & 1b sling lower assembly, PF1c lower support assembly
  - Outer skirt – support center stack casing assembly *see talk by Smith*





- Design meets requirements & NSTX structural design criteria
  - Static and fatigue evaluation meets GRD shot spectrum
- Machine core structure integration
  - Structural integrity validated by component and integrated analysis
  - TF/OH bundle, skirt, test cell floor, lid, torque plate etc.
  - Critical loads and load transfer paths
    - Tiles -> casing -> core structures -> floor via pedestal

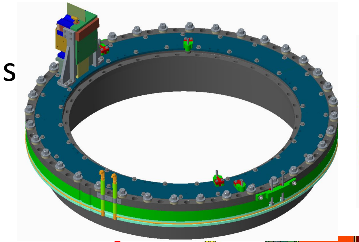




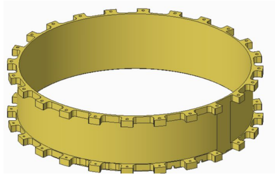
MCS Robustly Support Coils & Provide Reliable Vacuum Boundary

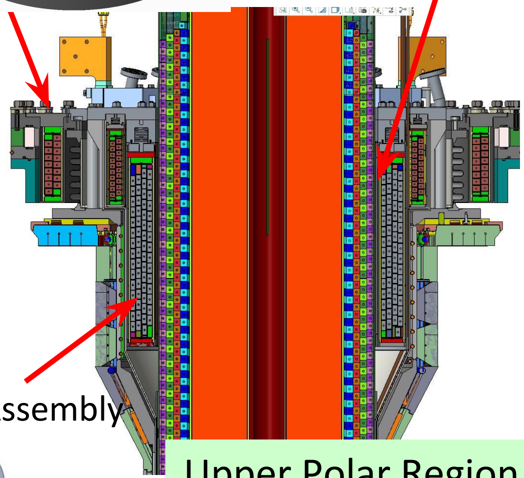
- Design features meet MCS requirements
  - PF1a&b sling supports mandrel-free coils against full EM loads
  - Sling supports provide pre-load (1a&1b coils)
  - PF1a&1b bolted assembly then bolted onto common flange
  - Isolates coils from hot regions during bakeout
- PF1c supports meet all requirements
  - Single machined forging for improving vacuum reliability
  - Provides robust elements of vacuum boundary
  - Double O-ring seals with pumped interspace

PF-1c and Ceramic Break



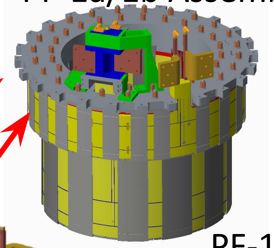
Collar



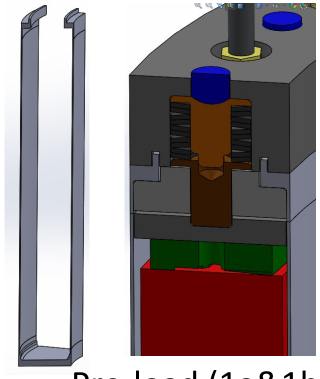


Upper Polar Region

PF-1a/1b Assembly



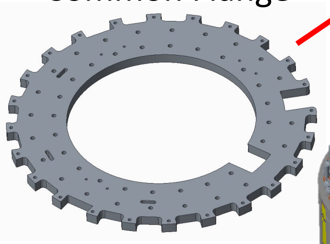
prototyping slings



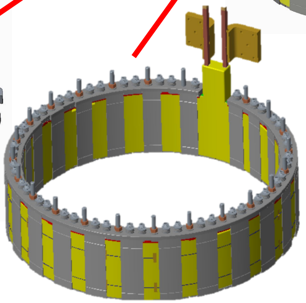
Pre-load (1a&1b)

See talk by Smith

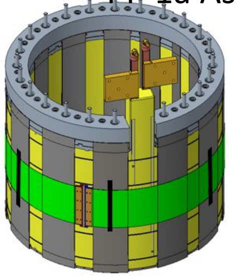
Common Flange



PF-1b Assembly



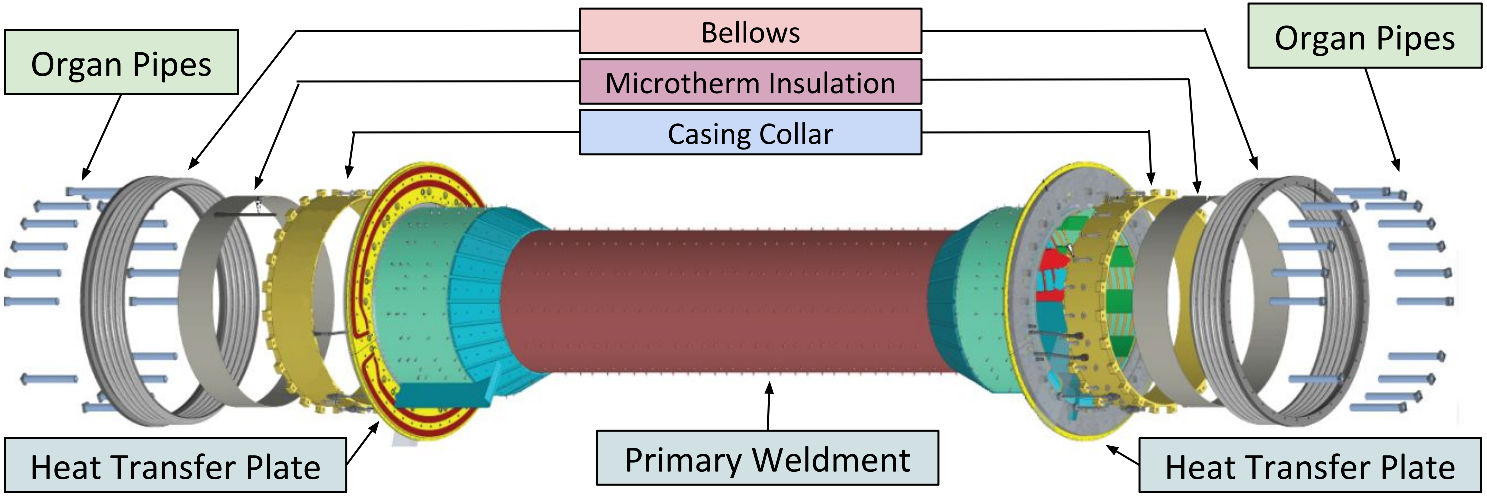
PF-1a Assembly

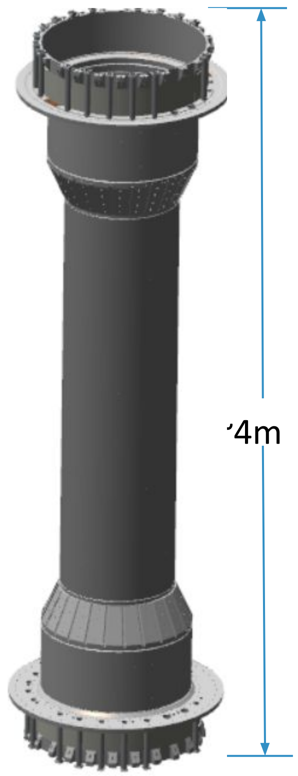


Status: FDR completed on 12/28/18 (Casing) & 8/5-6/19 (MCS)
Comp. Fab. started, casing related parts fabricated

New CS Casing Designed to Take Full Loads

- Casing is integration of full penetration welded components
  - First wall, angled section, vertical & horizontal divertor
  - Organ pipes, integrate casing collar and bellows
  - Heat Transfer Plates and Heat Transfer Tubes (heating & cooling)
  - Maintain vacuum, accommodate thermal growth & coil supports
- Casing assembly – CSFWS, CSASA, CSVS forged, pre-machined, weld





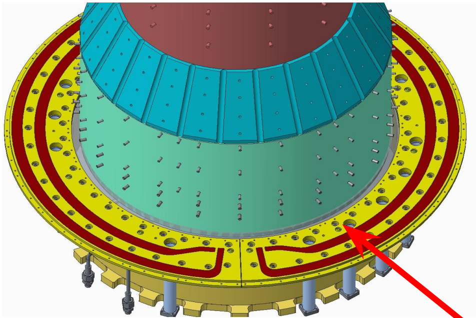
See talks by Smith, Viola

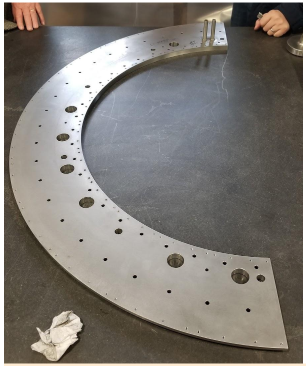
New Casing Features Support Bakeout Heating and Operations Cooling Functions

Requirements:

- Remove heat from tiles during normal operation, support 20 minute repetition rate
- Add heat to tiles during bakeout, supporting > 300 C bakeout for all tiles.
- No use of water in the vacuum boundary

2: Inconel 625 Heat Transfer Plate- vacuum side cooling channels for hot or cold He

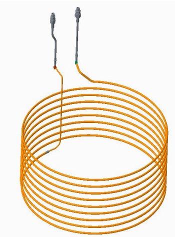




Heat Transfer Plate fabricated

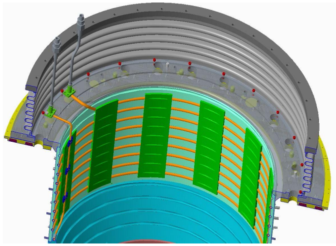
1: Heat Transfer Tubing – air side

See talk by D. Cai

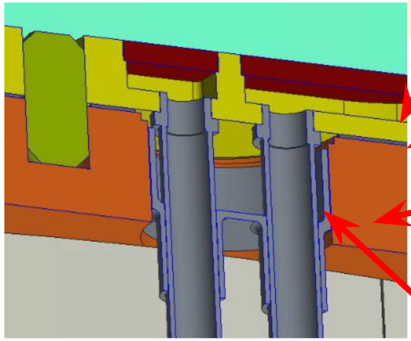


Formed Tube

Completed HTT at vendor



Installed in Casing



Grafoil

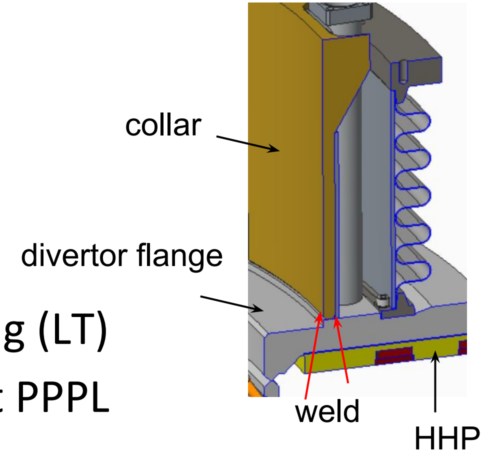
Casing Flange

Feedthrough Puck

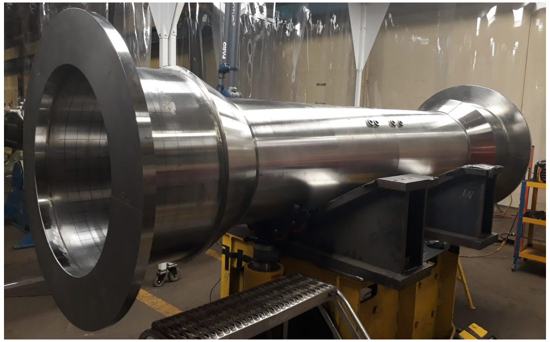
Status: FDR completed on 11/1/18 & 12/17/19
Fab. contracts placed on 3/31/19, casing related parts fabricated

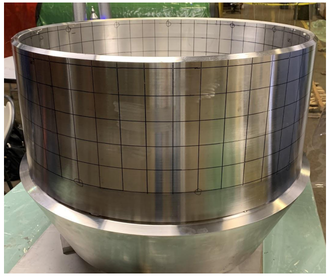
New Center Stack Casing in Fabrication

- Casing fabricated with great attention on quality
  - Main parts forged & all parts tacked with precision
- Design assurance
  - Post machine welded assembly & final metrology
  - Ultrasonic Weld Inspection (UT) and Vacuum Leak Testing (LT)
  - Tech Spec, Oversight Plan, QA Plan, MIT Plan approval at PPPL
    - Oversight on fabrication process & forging UT inspections
    - All NCRs generated by vendor reviewed through PPPL design process



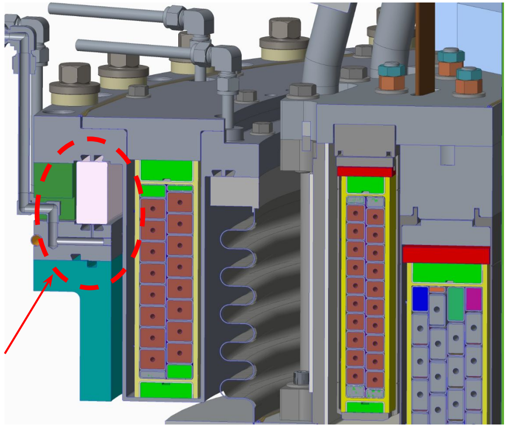
See talk by Viola

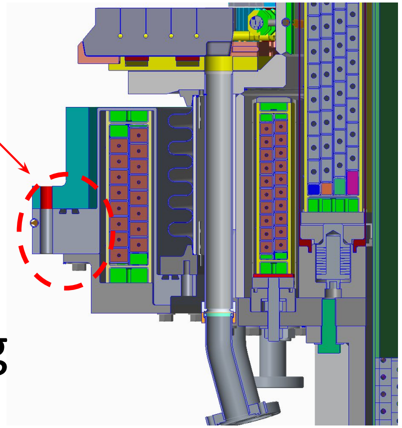




PF-1c Supports and Ceramic Break Assembly

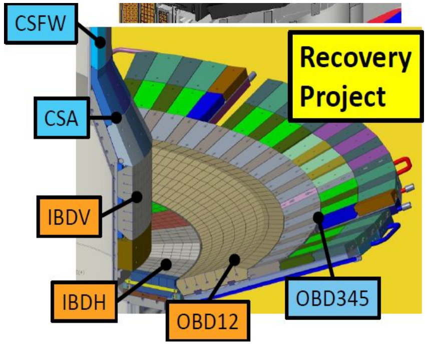
- Polar Region vacuum boundary
  - PF1c upper support integrated with ceramic break
  - Ceramic break assembly enables reliable high vacuum
  - PF1c lower region support assembly
- Double O-rings
  - Design assurance for high vacuum interfaces
- Integration at interfaces
  - PF-1c support integrated with outer VV
  - Bellows integrated with PF-1c support via flange
- Design validation – integrated analysis
- Design assurance – component prototyping & testing

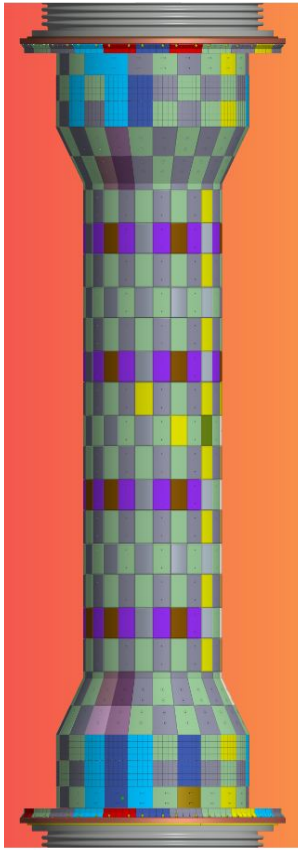




Plasma Facing Components Designed for High Reliable Operations

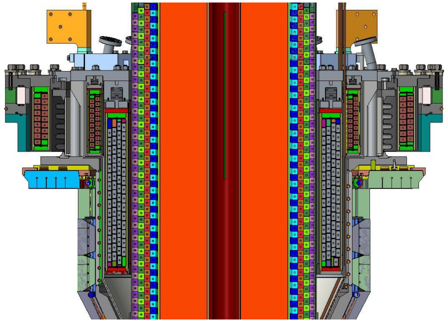
- New PFCs to enhance handling of heat flux, disruption loads
  - Updated EM and thermal loads
  - Qualify six regions new tiles for full power full EM loads
  - CSFW tiles challenging EM loads
    - Floating tile supported between two bolted tiles through inconel pins
    - Grafoil bushings used to alleviate excessive contact stress on pins
  - Inboard divertor tiles designed to handle extreme heat fluxes
    - Castellated surfaces – relieves surface compressive stress
    - Design driven by Temperature not stress limit
- Tile surface shaping & alignment
  - Fixture guarantees single reference
  - Preload controlled with lock-bar (hold-down)
- Fish-scale angle via Installation
  - Avoid leading edges with localized heating
  - Set by tolerance analysis but defined via manufacturing part

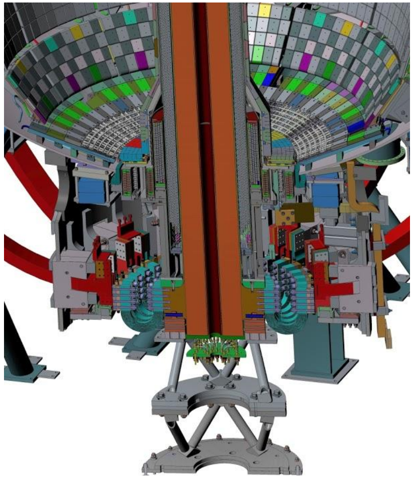


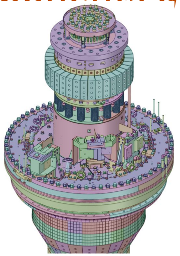


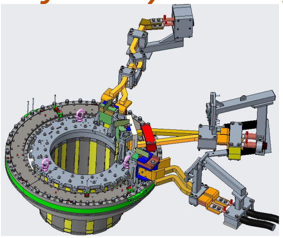
Machine Core Integration Meets Design Challenges

- Central core Integration is an engineering challenge
  - Machine core design driven by CS casing loads – *quantified*
  - Coil support design driven by coil loads – *pre-load defined*
  - Casing worst EM and thermal loads – *identified for design*
    - Bellows - CS casing and polar region metal core structures
    - Upper bellow reacts casing thermal growth, halo side loads
    - Lower bellow protected by collar from halo over currents
- Skirt interfaces to casing and TF/OH bundle
  - Lower 1a & 1b common flange – integrated analysis
  - Inner TF bundle – *interface components qualified by testing*
- Casing interface with BUS
  - Inner PF BUS & Support
  - Bakeout BUS – halo, thermal









Machine Alignment Requirements

- Alignment Requirements are driven by plasma physics
  - TF, PF-5s & 4s misalignments -> B field perturbations -> torque on plasma -> slow/stop plasma rotation -> loss of confinement (global MHS stability)
- Alignment tolerances can be met, accuracy verified via metrology
  - Dimensional control & tolerances between coils and V divertor targets
  - Non-axisymmetric fields from TF/PF1 misalignment
  - Heat flux enhancements on PFCs
  - Local field perturbations
    - heat flux enhancement factor change
    - Define tile tolerances and fishscale angles
- PF-4/5 realignment & vessel metrology
  - Measure coil position in an established VV global coordinate system
  - Repositioning of PF-4/5 coils to meet KPP requirements
- TF alignment met during assembly, CS install via CS casing coordinate system

Coil Positional Tolerances ***Relative to Global Coordinate System***
→ NSTX-U-RQMT-RD-11

Tolerance	Symbol	units	Tolerance
PF-4U, Shifts, Coil	$\sigma_{-4U,\ shift,\ coil}$	mm	2
PF-4L, Shifts, Coil	$\sigma_{-4L,\ shift,\ coil}$	mm	2
PF-5U, Shifts, Coil	$\sigma_{-5U,\ shift,\ coil}$	mm	2
PF-5L, Shifts, Coil	$\sigma_{-5L,\ shift,\ coil}$	mm	2
PF-4U, tilt	$\sigma_{-4U,\ tilt}$	mrad	0.9
PF-4L, tilt	$\sigma_{-4L,\ tilt}$	mrad	0.9
PF-5U, tilt	$\sigma_{-5U,\ tilt}$	mrad	1.1
PF-5L, tilt	$\sigma_{-5L,\ tilt}$	mrad	1.1
TF, shift	$\sigma_{TF,\ shift}$	mm	0.8
TF, tilt	$\sigma_{TF,\ tilt}$	mrad	0.6

Alignment based on a Global Machine Coordinate

- Dimensional control and alignment of CS components
  - Facilitate assembly, optimize plasma runs (TF vs. outer PFs)
  - Avoid uneven heat flux on PFCs (TF and inner PF alignment)
- Alignment chain defined and augmented with tolerances
  - TF/OH trial fit-up, alignment affects performance (most likely shifts/tilts)
- Tolerances defined from Global MHD simulations
  - Alignment of TF vs. outer PFs – TF bundle tilting in Casing
  - Improve TF-to-CSC alignment and CSC-to-vessel alignment
    - Casing shifted relative to VV (1.8 mm)
    - Bundle tilted (1.2 mrad ~ 6 mm) and shifted (4.9 mm) within Casing
- New clamps to maintain relative position of PF-4/5 Pancakes
  - PF-4/5 coils realignment to achieve KPP goals
  - PF-4U/L Radial constraining pins – align & maintain coil center

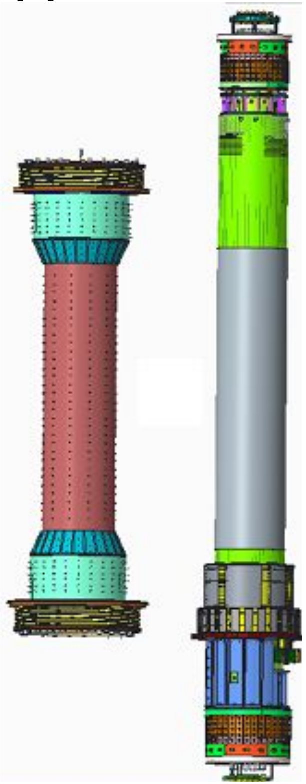
Machine Assembly

- Assembly sequence
  - Clear defined scope for reassembly as machine was assembled once
  - No change on OH, TF, pedestal and outer vessel
  - Significant design change on tiles and inner PF assembly
- Assembly challenge – component alignment
  - New focus on alignment to meet KPPs
  - Space constraint and tight tolerances
- Assembly verification
  - Metrology verification in assembly procedures
  - Position of bundle in casing, casing in machine core

Assemble the Machine

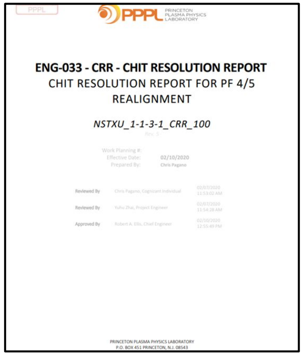
Machine Assembly

- Assembly sequence
  - New tile on outboard divertor and casing, lower PF-1c coil on VV
  - CS casing welded assembly
    - Gas injection tubing, tile frames, CSFW, CSAS tiles, Rogowski, HHF tiles
  - TF/OH bundle – fit up skirt
    - Install PF-1a/b, CS diagnostics (flux loops, thermal couples, IP Rogowski
    - Install microtherm
  - Lower casing onto TF/OH bundle assembled
    - CS skirt supports the rest of CS casing assembly as foundation
    - Skirt will be aligned using metrology
  - Upper PF-1a/1b & 1c installed as an assembly
- Verification of requirements
  - Alignment adjusted at the skirt/TF/OH interface



Design Process and Project Chits

- Chits from design reviews recorded on the master chit log (here)
  - Total chits from 137+ reviews – closure & resolution updated
  - Resolved at FDR – chit resolution report reviewed and signed (here)
  - Chits involving higher integration across WBS addressed at project level
- Project chits are closed at individual WBS FDRs
  - Revision submitted to include closure of FDR chits
  - 50+ chit reports uploaded onto DMS
- Project integration chit reports (here)
  - Signed & filed – initial release prior FDR
  - Post FDR Revision



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ENG-033 - CRR - CHIT RESOLUTION REPORT
CHIT RESOLUTION REPORT FOR PF 4/5 REALIGNMENT

NSTXU_1-1-3-1_CRR_100
Rev. 5

Work Planning #:
Effective Date: 02/10/2020
Prepared By: Chris Pagano

Reviewed By	Chris Pagano, Cognizant Individual	02/07/2020 11:53:02 AM
Reviewed By	Yuhu Zhai, Project Engineer	02/07/2020 11:54:28 AM
Approved By	Robert A. Ellis, Chief Engineer	02/10/2020 12:55:49 PM

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National Spherical Torus eXperiment Upgrade

CHIT RESOLUTION REPORT
FOR
CENTER STACK CASING
FABRICATION

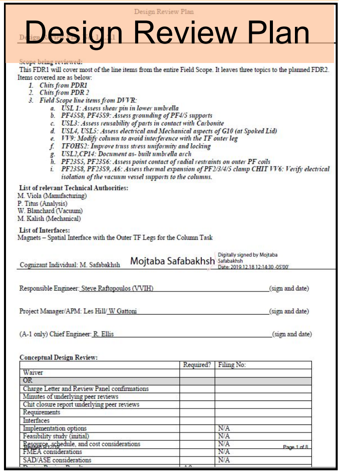
NSTX-U-REC-111-02

Reviewed By: M. Smith, Cognizant Individual
Reviewed By: D. Loesser, Responsible Engineer
Approved By: Y. Zhai, Project Engineer

Design Validation and Assurance

- Design validation
  - PPPL ENG33 procedure – Design Review Plan
  - CDR – development design concept
  - PDR – select design from CDR options
  - FDR – Finalize PDR design and close chit report
  - Design is largely validated by Analysis
- Design review process – 137+ reviews completed
  - PE issues design review charge letter
  - CE approves DRC and committee
  - External reviewers (participation) – central core component
    - MCS and Passive Plate FDRs, PSS and CCS PDR and FDRs
    - TF Bundle Expert Reviews
    - Project CDR, PDR and FDR

Design Review Plan



Design Review Plan

Scope being reviewed:
This FDR1 will cover most of the line items from the entire Field Scope. It leaves three topics to the planned FDR2. Items covered are as below:

1. *Chits from PDR1*
2. *Chits from PDR 2*
3. *Field Scope line items from DVVR:*
   a. *USL 1: Assess shear pin in lower umbrella*
   b. *PF45S8, PF45S9: Assess grounding of PF4/5 supports*
   c. *USL3: Assess reusability of parts in contact with Carbonite*
   d. *USL4, USL5: Assess electrical and Mechanical aspects of G10 (at Spoked Lid)*
   e. *VV9: Modify column to avoid interference with the TF outer leg*
   f. *TFOHS2: Improve truss stress uniformity and locking*
   g. *USL2,CP14: Document as- built umbrella arch*
   h. *PF23S5, PF23S6: Assess point contact of radial restraints on outer PF coils*
   i. *PF23S8, PF23S9, A6: Assess thermal expansion of PF2/3/4/5 clamp CHIT VV6: Verify electrical isolation of the vacuum vessel supports to the columns.*

List of relevant Technical Authorities:
M. Viola (Manufacturing)
P. Titus (Analysis)
W. Blanchard (Vacuum)
M. Kalish (Mechanical)

List of Interfaces:
Magnets – Spatial Interface with the Outer TF Legs for the Column Task

Cognizant Individual: M. Safabakhsh Mojtaba Safabakhsh Digitally signed by Mojtaba Safabakhsh Date: 2019.12.18 12:14:30 -05'00'

Responsible Engineer: Steve Raftopoulos (VVIH) ______ (sign and date)

Project Manager/APM: Les Hill/ W Gattoni ______ (sign and date)

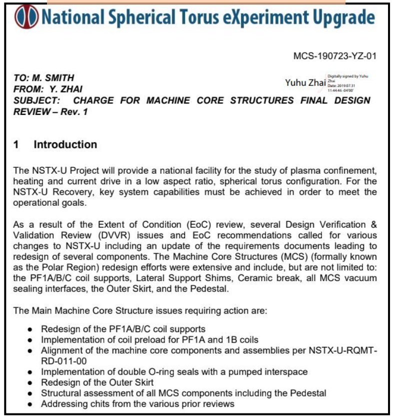
(A-1 only) Chief Engineer: R. Ellis ______ (sign and date)

Conceptual Design Review:

	Required?	Filing No:
Waiver		
OR		
Charge Letter and Review Panel confirmations		
Minutes of underlying peer reviews		
Chit closure report underlying peer reviews		
Requirements		
Interfaces		
Implementation options		N/A
Feasibility study (initial)		N/A
Resource, schedule, and cost considerations		N/A
FMEA considerations		N/A
SAD/ASE considerations		N/A

Page 1 of 8

DR Charge Letter



National Spherical Torus eXperiment Upgrade

MCS-190723-YZ-01

TO: M. SMITH
FROM: Y. ZHAI
SUBJECT: CHARGE FOR MACHINE CORE STRUCTURES FINAL DESIGN REVIEW – Rev. 1

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2019.07.31 11:44:46 -04'00'

1 Introduction

The NSTX-U Project will provide a national facility for the study of plasma confinement, heating and current drive in a low aspect ratio, spherical torus configuration. For the NSTX-U Recovery, key system capabilities must be achieved in order to meet the operational goals.

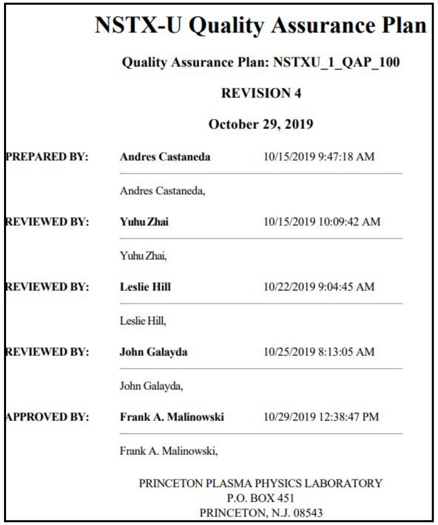
As a result of the Extent of Condition (EoC) review, several Design Verification & Validation Review (DVVR) issues and EoC recommendations called for various changes to NSTX-U including an update of the requirements documents leading to redesign of several components. The Machine Core Structures (MCS) (formally known as the Polar Region) redesign efforts were extensive and include, but are not limited to: the PF1A/B/C coil supports, Lateral Support Shims, Ceramic break, all MCS vacuum sealing interfaces, the Outer Skirt, and the Pedestal.

The Main Machine Core Structure issues requiring action are:

- Redesign of the PF1A/B/C coil supports
- Implementation of coil preload for PF1A and 1B coils
- Alignment of the machine core components and assemblies per NSTX-U-RQMT-RD-011-00
- Implementation of double O-ring seals with a pumped interspace
- Redesign of the Outer Skirt
- Structural assessment of all MCS components including the Pedestal
- Addressing chits from the various prior reviews

Design Validation and Assurance

- Design validation
  - Follow PPPL lab-wide QAPD and ENG33 procedure
  - Design is largely validated by extensive Analysis
  - Validation by Experiment – prototyping & testing
  - Validation by working comparison of existing systems
- Design assurance
  - Quality Assurance Plan – NSTX-U QAP
    - Application of PPPL Quality Assurance Program (QAPD)
    - PPPL procedures requirements & supplemental QA
    - Project Engineer (PE) & associate project manager
  - PE responsible for design review and assurance processes
  - Trial-fit, prototyping and in-vessel inspection



NSTX-U Quality Assurance Plan

Quality Assurance Plan: NSTXU_1_QAP_100

REVISION 4

October 29, 2019

PREPARED BY:	**Andres Castaneda**	10/15/2019 9:47:18 AM
	Andres Castaneda,	
REVIEWED BY:	**Yuhu Zhai**	10/15/2019 10:09:42 AM
	Yuhu Zhai,	
REVIEWED BY:	**Leslie Hill**	10/22/2019 9:04:45 AM
	Leslie Hill,	
REVIEWED BY:	**John Galayda**	10/25/2019 8:13:05 AM
	John Galayda,	
APPROVED BY:	**Frank A. Malinowski**	10/29/2019 12:38:47 PM
	Frank A. Malinowski,	

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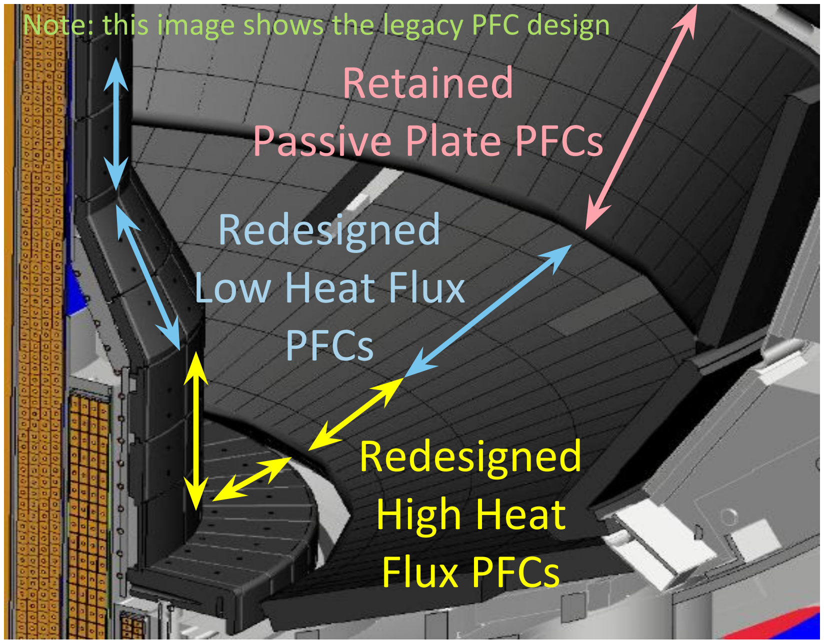
P.O. BOX 451
PRINCETON, N.J. 08543

Summary

- NSTX-U is a low aspect ratio Spherical Torus
  - Recovery scopes are project PEP defined system modifications
- Project component final design is complete
  - 137+ design reviews completed (here) – CDRs, PDRs, FDRs and PRs
- Integration challenges across WBS elements of core addressed
  - Inner PF coils & coil supports including upper ceramic break assembly
  - Machine core structures including new center stack casing
  - Plasma facing components
- Assembly sequence and alignment for machine core developed
- Final design analysis complete & chit resolutions reported (here)
- Design validated per ENG process and assured per QAP
  - 100+ FDR calculation reports (here) checked, signed and filed

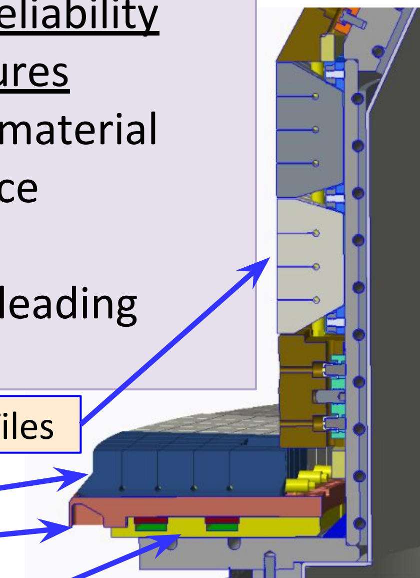
BACKUP

Plasma Facing Components Meet Full Performance Thermal and EM Loads with High Reliability



<u>High Heat Flux Region Reliability Enhancement Features</u>

- ➔ Castellations minimize material stresses for given surface temperature
- ➔ Fishscaling protects all leading edges



See talk by J. Klabacha

Status: FDR done on 9/28/18
Graphite materials purchased, metal manufacturing awarded on 3/6/20 graphite machining awarded on 2/xx/20

High Heat Flux- Full EM loads, with aggressive heat flux requirements: ~5.5 MW/m^2, 5 seconds @ 5 degrees incident angle, no leading edges

Low Heat Flux Region- Full EM loads, but modest heat flux requirements: ~3 MW/m^2, 5 seconds @ 8 degrees incident angle, leading edges allowed