National Spherical Torus eXperiment Upgrade

PFC Diagnostics & I_P Rogowski

WBS 1.04.01.02 & 1.04.01.04

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

PFC Diagnostics - Brent Stratton

Last edit: 3/9/20

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 1.04.01.01 & 1.04.01.06

(CDE-3A Scope)

WBS Title	PFC Diagnostics	WBS #	1.04.01.01 & 1.04.01.06
Project Cog.	B. Stratton	Assoc. Proj. Man.	W. Gattoni
Design Scope	Design new PFC-mounted diagnostics: Mirnov coils, thermocouples, Langmuir probes, and halo current shunt sensors. Design new halo current Rogowski coils.		
Technical Impact of Scope	Sensors required for NSTX-U operation and research program		
Design Status	FDR completed on 3/28/2018: review link chits: link calculations: link drawings: link SoW/Tech Spec: N/A		
Fabrication Status	PFC diagnostics being fabricated at PPPL. Halo current Rogowski coils will be wound a by vendor with finish work by PPPL.		
Installation Status	PFC diagnostics will be installed in tiles prior to installation in NSTX-U. Halo current Rogowski coils will be installed during machine reassembly.		

Overview - WBS 1.04.01.04

(CDE-3A scope)

WBS Title	I_P Rogowski Replacement	WBS #	1.04.01.04
Project Cog.	B. Stratton	Assoc. Proj. Man.	W. Gattoni
Design Scope	Fabricate new I_P Rogowski sensor for NSTX-U		
Technical Impact of Scope	I_P Rogowski sensors are used to measure the plasma current		
Design Status	FDR completed on 3/28/2018: review link chits: link calculations: N/A drawings: link SoW/Tech Spec: link		
Fabrication Status	Ip Rogowskis being wound by a vendor with finish work by PPPL		
Installation Status	Ip Rogowskis will be installed on center stack during machine reassembly		

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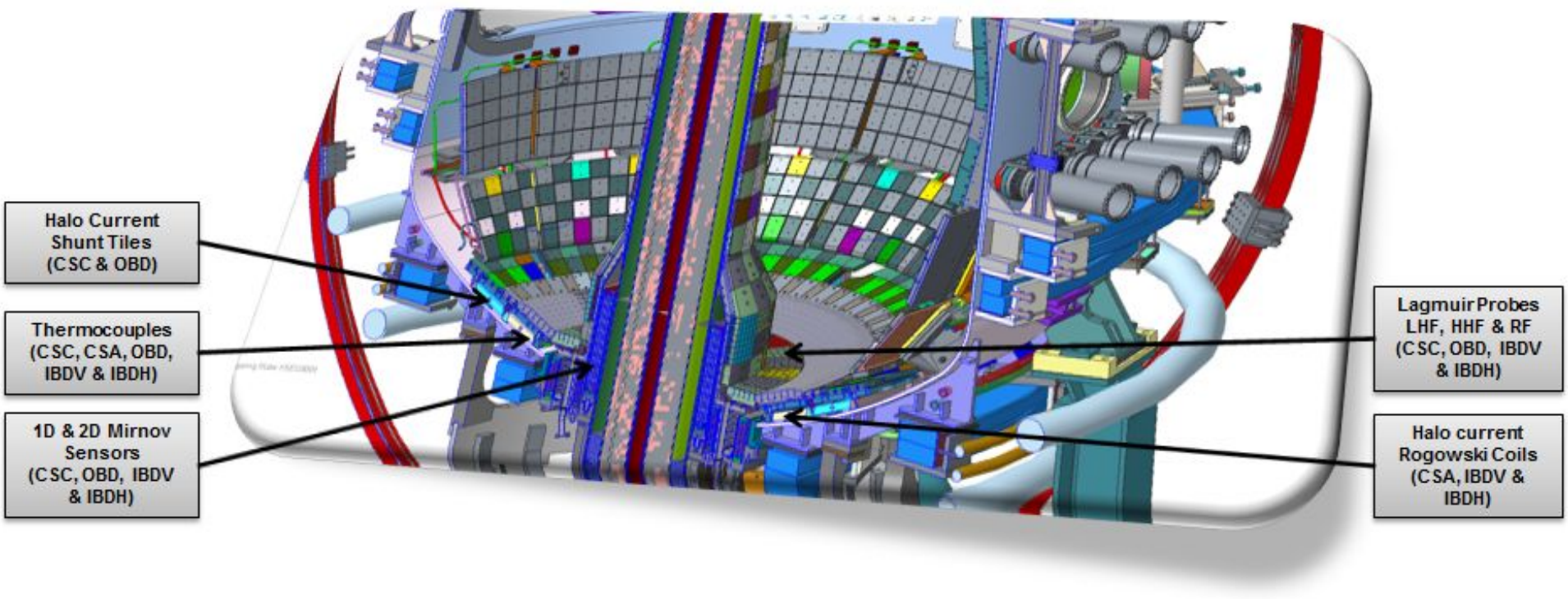
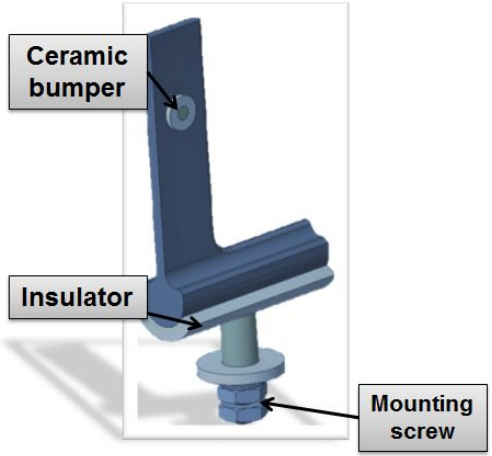
Plasma Facing Component Diagnostics - Scope

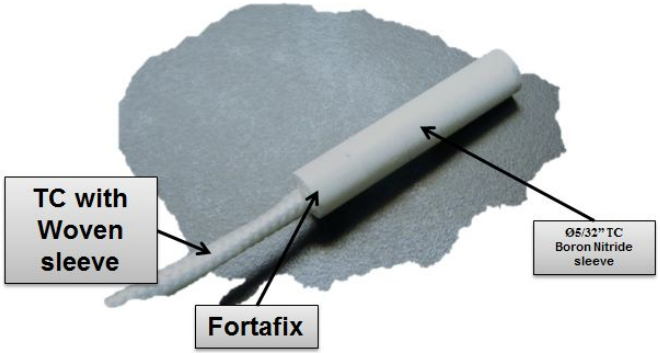


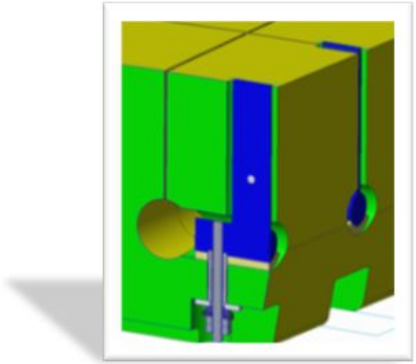
All sensors replicated on the machine top as well

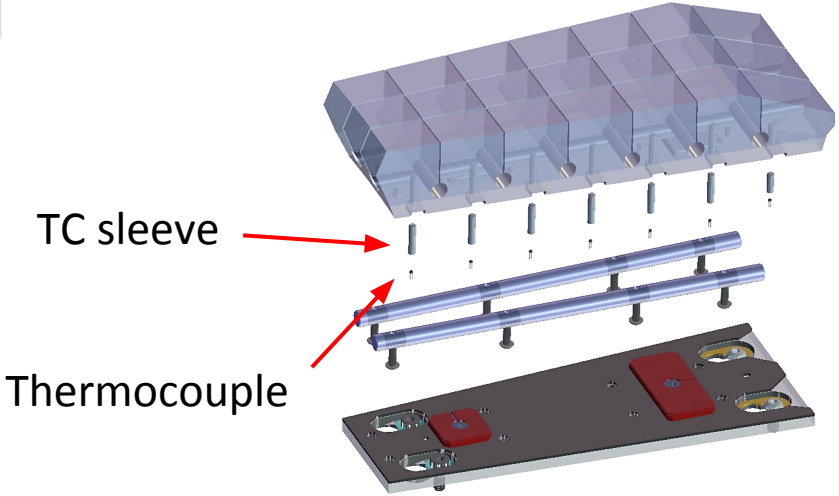
Langmuir probes and Thermocouples have been updated

- "Rail probe" design for Langmuir probes on high heat flux tiles. (OBD rows 1-2, Inboard Divertor)
- Thermocouples have increased (500V) standoff



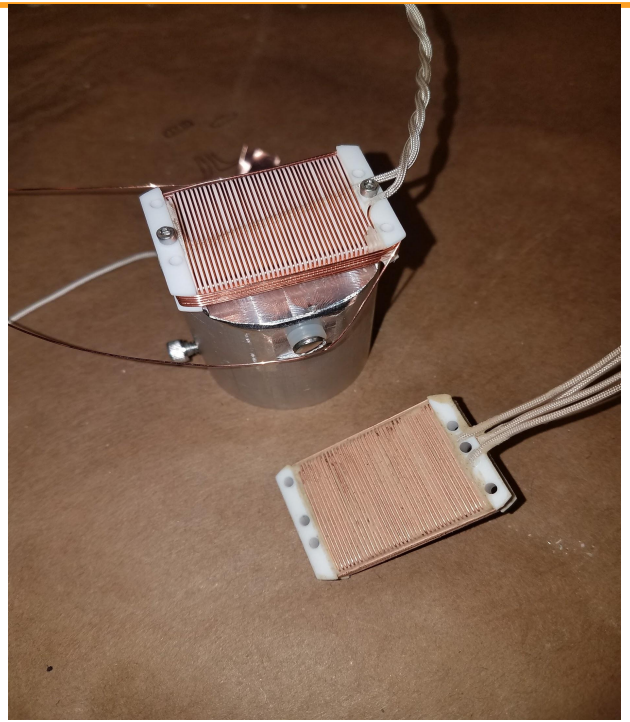




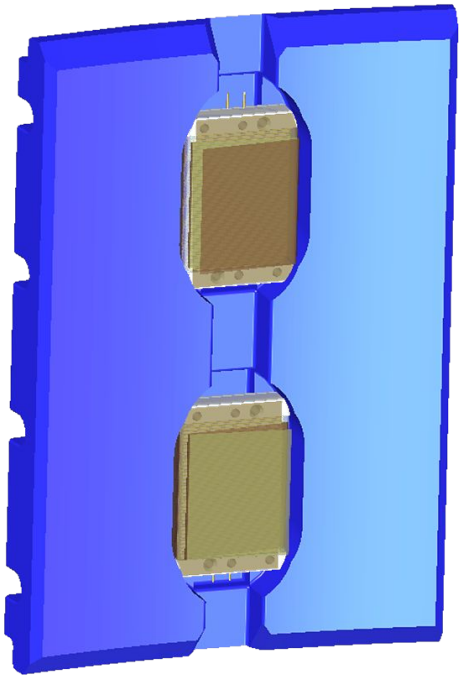


Mirnov sensors are updated

- Mirnov sensors have return wire under tangential windings.
  - Reduced height
- Grooves to center the windings
- Use of high temperature cement to prevent conductors from touching



2-D Mirnov Sensor Winding

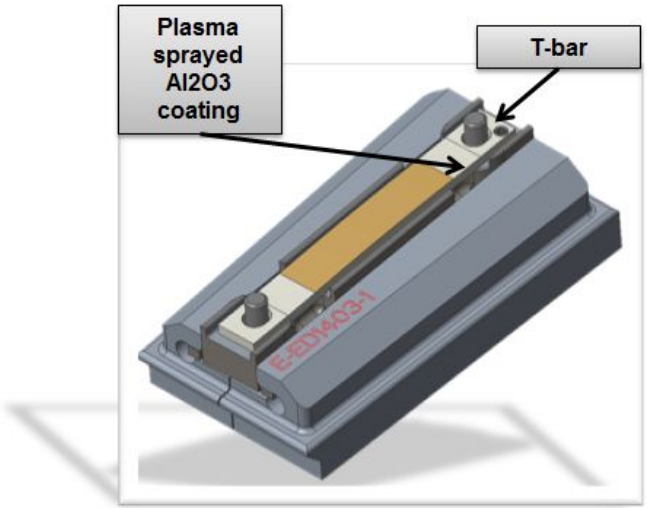


Tile with 2 Mirnov Sensors

Halo current shunts are updated

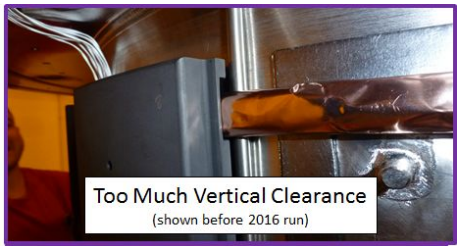
- Halo current shunts on the Center Stack First Wall tiles resemble previous version.
- New design required for OBD row 3-4 tiles.

CSFW Shunt

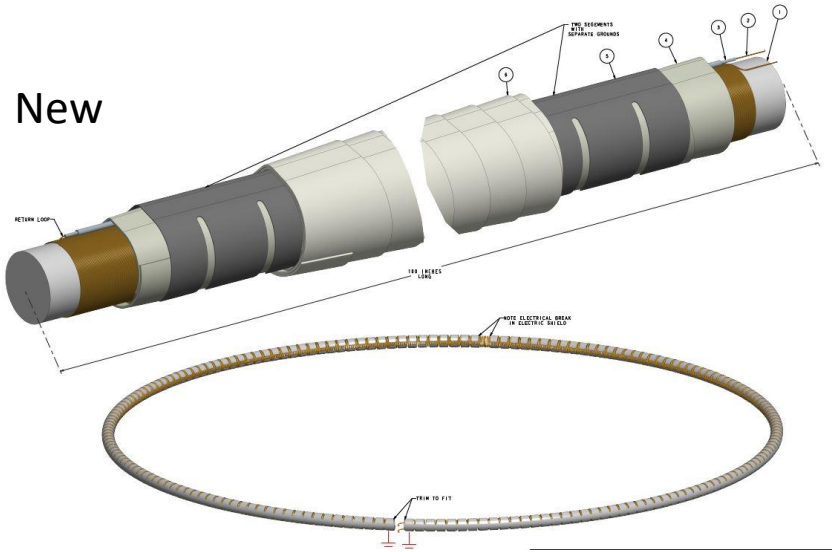


New design for center stack halo current Rogowski coils

- Addresses problems with previous version.
  - Double fiberglass sleeve on return wire minimizes risk of short circuit.
  - Stainless steel electrostatic shield reduces electromagnetic force by factor of ~50.
  - Electrostatic shield is sandwiched between two layers of fiberglass wrap.
  - Motion of coils is constrained.



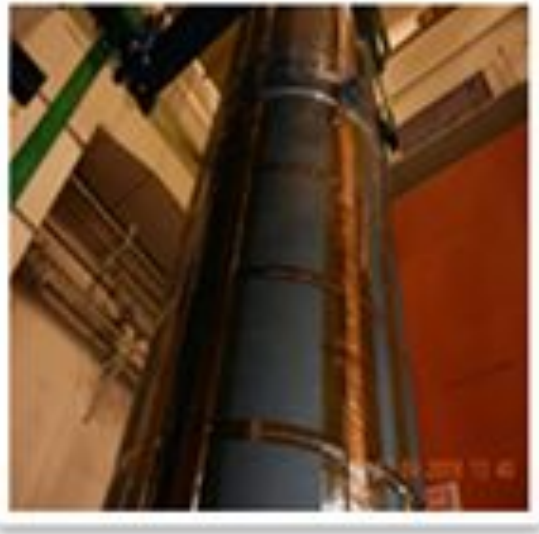
New



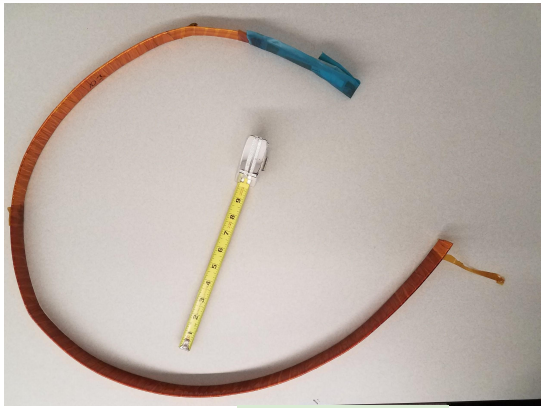
Plasma Current Rogowski Sensors Scope

- Build a replacement set of plasma current (Ip) Rogowski sensors
  - Old sensors were physically damaged during CS assembly.
  - Inadequate clearance between Center Stack bundle and CS casing.
  - Function was not impaired.
- Rebuild with identical design, ideally use the same vendor.
- New toroidal placement and larger inside diameter of CS casing minimize the risk of sensor damage.

Rogowski sensor installed on CS



Section of Rogowski sensor



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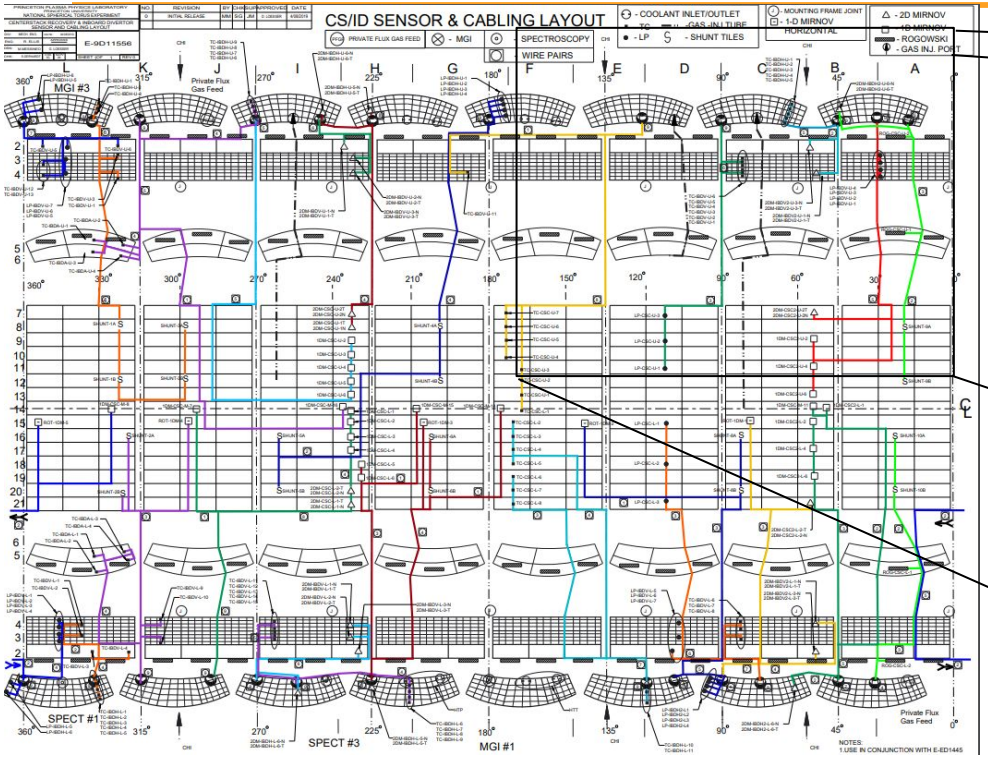
Requirements Defined and Met

Source	Requirements	Comment	met
NSTX-U-RQMT-SRD-011	Mirnov sensors	Materials & design guidance, general location guidance, etc	✓
NSTX-U-RQMT-SRD-011	Langmuir probes	Materials & design guidance, general location guidance, etc	✓
NSTX-U-RQMT-SRD-011	Tile thermocouples	Sensitivity (magnitude and time, general location guidance, etc.	✓
NSTX-U-RQMT-SRD-011	Plasma current rogowski	Design guidance, routing guidance, redundancy	✓
NSTX-U-RQMT-RD-004	Horizontal target sensor counts	Nature of measurements, spatial distribution, interface with PFCs, operational requirements	✓
NSTX-U-RQMT-RD-004	Vertical target tile sensor counts	Specific guidance on poloidal and toroidal distribution of sensors (Mirnovs, Langmuir probes, thermocouples, etc) in each region	✓
NSTX-U-RQMT-RD-004	Horizontal target tile sensor counts		✓
NSTX-U-RQMT-RD-004	CS angles section tile sensor count		✓
NSTX-U-RQMT-RD-004	CS first wall tile sensor count		✓
NSTX-U-RQMT-RD-004	Plasma current Rogowski	Specific routing details within the CS assembly	✓

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
PFC Diagnostics	Center Stack Structures	link	The PFC Diagnostics and Ip (Plasma Current) Rogowski interface with the organ pipes and PF-Support structures
PFC Diagnostics	Plasma Facing Components	link	The PFC Diagnostics and Halo Current Rogowski interface with CSC PFCs and OBD PFCs
PFC Diagnostics	Magnets	link	The Ip Rogowski interfaces with the OH and PF1 coils
PFC Diagnostics	In Vessel Structures	link	The PFC Diagnostics and Ip Rogowski interface with the In Vessel Structures (i.e., Passive Plates & OBDs)
PFC	Test Cell	link	The PFC thermocouples interface with the test cell cable trays, and racks
PFC	CI&C	link	The PFC thermocouples interface with the CI&C

Sensor Wire Routing is Integrated into PFC Design



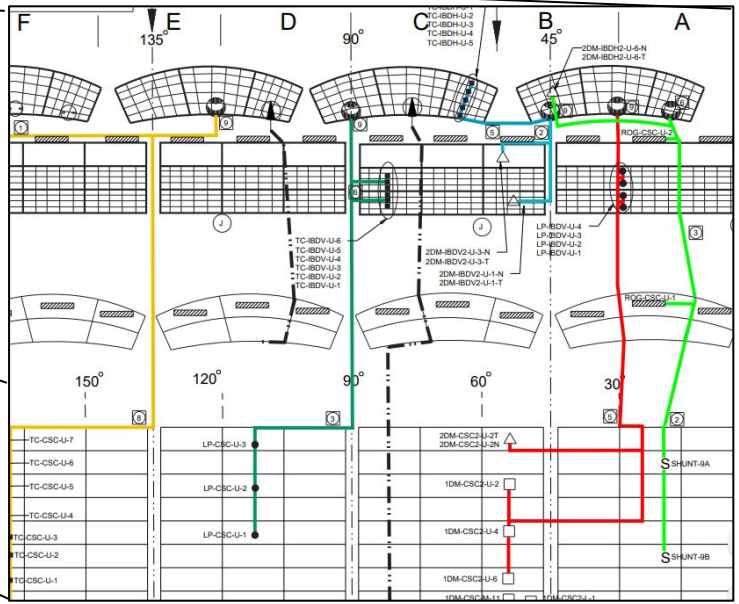
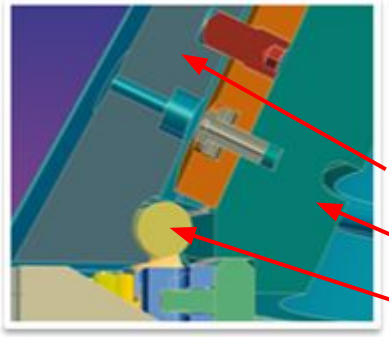


Image of previous wire installation

- 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 J. Klabacka (this session)

Structural/Spatial Interfaces Between Sensors and PFCs are Well Defined



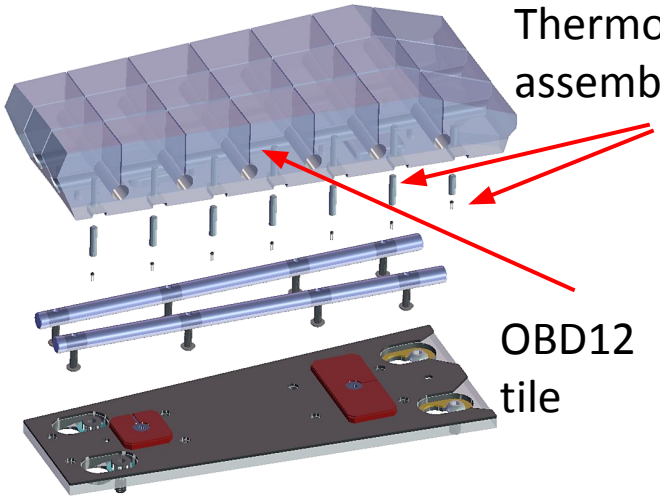
Halo Current Rogowski Coil Interfaces to CSAS

CSAS tile

CSAS Structure

Rogowski Sensor

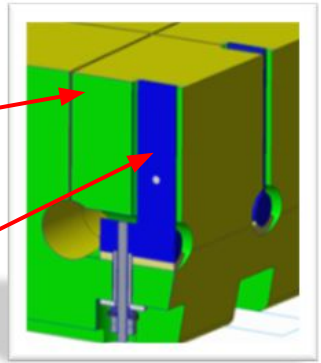
Thermocouple to Tile



Thermocouple assemblies

OBD12 tile

Langmuir Probe to Tile

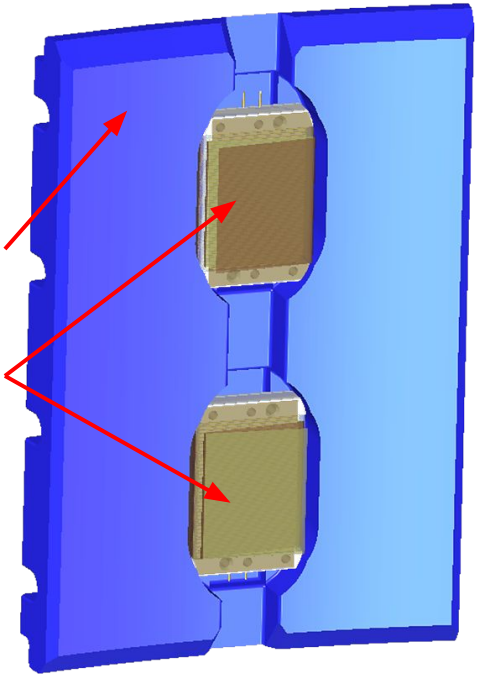


tile castellation

probe assembly

CSFW tile

Mirnov Sensor



Mirnov Sensor to Tile

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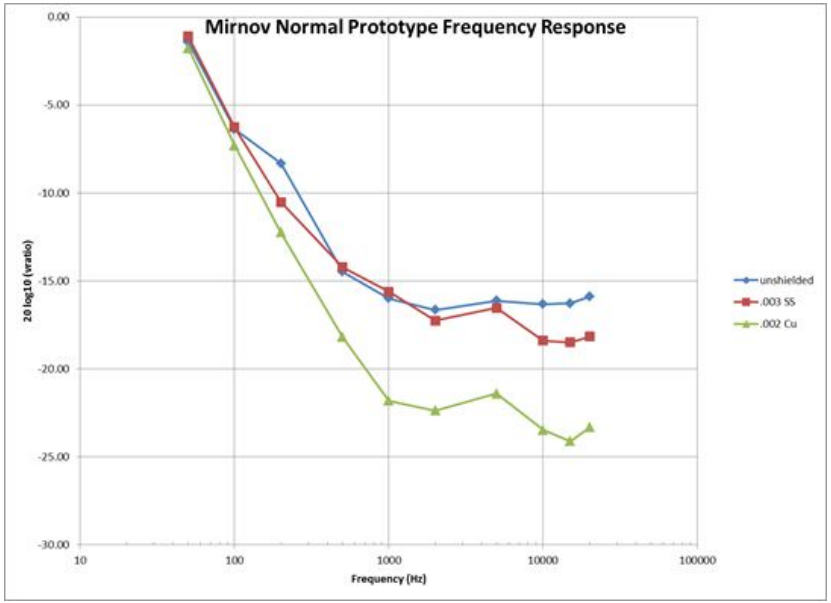
Calculations and Prototypes Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Thermal and stress analysis of High Heat Flux Langmuir probe	NSTXU-CALC-11-25-00	Simplified model of a high heat flux Langmuir probe in an OBD12 tile.
Halo current shunt performance	NSTXU 1.4.1 CALC 012	Analyzed temperatures and stresses in the new halo current shunt.
Eddy Current Loads on Electrostatic Shield for Center Stack Halo Current Rogowski Coil	NSTXU 1.4.1 CALC 015	Demonstrates that currents induced in the electrostatic shield will not result in any significant motion of the rogowski sensor

Calculation Archive:
https://drive.google.com/open?id=1qOkldoi7ClZvUy8P0-eMXhq5EaYnwOAl

Design Assurance: Mirnov sensor prototype tests

- Tested at varying frequencies, with a variety of electrostatic shields, in Helmholtz coil.
- Checked for short circuits between tangential and normal windings.



Design Assurance: Thermocouple Prototype Results

- Thermocouple assemblies with new geometry were bonded into graphite, then tested with megger and high pot.
  - Passed beyond 2kV; 0.5 kV requirement.

MEGGER TEST: 275 V (ups) - (5 GΩ) PASS

HI-POT TEST: 2000 V (no reading) PASS

Megger test measures the insulation resistance while the **Hi-pot** measures the current leakage.

Megger Test:

- All tests will use a Megger (275V) first, and follow up with a Hi-pot if the megger test is successful.

Hi-pot Test:

- The graphite block can be connected electrically by either clamping it to a conducting plate or clamping an electrode directly to it.
- The test should then be performed on an insulating surface.
- The test voltage is applied between the wire and the graphite block.

Design Assurance: New CS halo current Rogowski coil

- A prototype has demonstrated feasibility of assembling and winding the coil, and fabricating the shield.
- Torsional stiffness was measured.
- Influenced decision to use stainless steel shield.
- Over wrapping of the shield, along with reduced force and constrained installation, will prevent the failure exhibited earlier.

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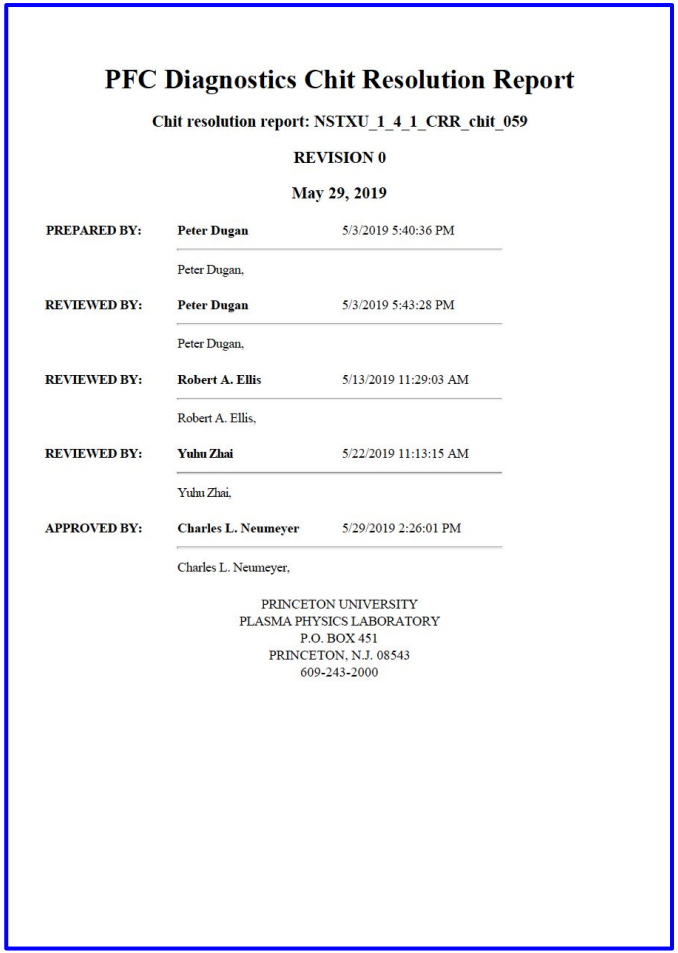
All Chits have been Closed

Chit Resolution Reports: link



PFC Diagnostics Chit Resolution Report

Chit resolution report: NSTXU_1_4_1_CRR_chit_059

REVISION 0

May 29, 2019

PREPARED BY:	**Peter Dugan**	5/3/2019 5:40:36 PM
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Fabrication Status

- General:
  - Fabrication procedure covering Mirnov coils, Langmuir probes, and thermocouples written and approved.
- Mirnov Coil Status:
  - Being fabricated at PPPL - prioritized because fabrication is time consuming
  - Prototypes successfully fabricated
  - Requisitions submitted for all material
  - Most items delivered
  - Mirnov coil mandrels in fabrication in PPPL shop with first batch to be completed mid-March
  - Technicians ready to wind coils when mandrels are available

Fabrication Status - continued

- Thermocouples and Langmuir Probes
  - Requisitions submitted for all material
  - Majority of POs issued
  - Some items delivered
- Ip Rogowski Coils
  - Being wound by vendor with finish work by PPPL
  - SOW for winding written and approved
  - Requisitions for winding and material to be provided by PPPL submitted
- Halo Current Rogowski Coils
  - Being wound by vendor with finish work by PPPL
  - Requisitions for material to be provided by PPPL submitted
  - SOW for winding written and in approval process
  - Requisition for winding will be submitted when SOW is approved

NCRs and ECNs During PFC Diagnostics Fabrication/Installation Activities to Date

Drawing Number	ECN Number	Description of the Change
E-9D11170 E-9D11171	8195	Minor updates to dimensions and tolerances for some tile-mounted components
E-ED1395	8196	Add sensors to assemblies for some inboard divertor vertical tiles
B-9D1095	8202	Update control wiring diagrams for various sensors to match currently planned configuration
E-9D11551	8288	Update corner radii of Mirnov coil mandrel block to match prototype built for FDR
E-9D11552	8293	Change copper grade used for Mirnov coil shielding

- No NCRs to date

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Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
If the PFC diagnostic designs are not finalized by mid-August	20	RETIRED	RETIRED
Difficulty in attaching sensors	20	RETIRED	
If the typical Rogowski winding vendor is unable to perform work	15	OPEN	Receipt of Rogowskis
If the design of tile diagnostic sensors is incompatible with new tiles.	12	RETIRED	FDR

Other risks (generic component delay, fitup issues) held at the Project level

FMECA - Rogowski

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Plasma Current Rogowski System	Open circuit failure on rogowski	temperature excursion during bakeout, or failure at high stress location	Rogowski cannot be used	4	Plasma Current Rogowski System	None	None	4
Plasma Current Rogowski System	Rogowski insulation failure to OH ground plane	abrasion, or possibly high temperature excursion	Common mode voltage electrically coupled into integrator circuit	4	Plasma Current Rogowski System	None	None	4
Plasma Current Rogowski System	Rogowski insulation failure to inner vessel components (common flange, PF-1c capping flange)	mechanical damage to insulation, possible coupled to something conducting bridging to the flange components	Large circulating current renders signal unusable	4	Plasma Current Rogowski System	Vessel and Diagnostic Grounds	None	4
Plasma Current Rogowski System	Rogowski insulation failure to outer vessel	mechanical damage to insulation, possible coupled to something conducting bridging to the vessel	Large circulating current renders signal unusable	4	Plasma Current Rogowski System	Vessel and Diagnostic Grounds	None	4

All Rogowski failure modes mitigated by presence of spare rogowski; need 2 oo 3

FMECA - PFC Diagnostics

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
PFC Thermocouples	TC loses thermal contact with tile	Manufacturing or installation error	TC renders inaccurate reading of the local tile temperature	3	PFC Thermocouples	None	None	3
PFC Thermocouples	TC develops open circuit in cabling	Manufacturing or installation error	TC reading is off-scale high/low	3	None	None	None	3
PFC Thermocouples	TC becomes electrically grounded to tile or wire becomes grounded to vessel	Manufacturing or installation error	TC signal becomes noisy	3	None	None	None	3
PFC Thermocouples	TC junction becomes open	Excessive tile heating during operations	TC reading is off-scale high/low	3	None	None	None	3
Langmuir Probes	Cable becomes disconnected at Langmuir probe itself inside the vessel	improper installation	sensor produced no useful data	3	None	None	None	3
Langmuir Probes	Langmuir probe surface overheats	excessive heat from plasma	no useful data, carbon contamination of the plasma	3	None	None	None	3

FMECA - PFC Diagnostics

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Langmuir Probes	Langmuir probe tip fractures	excessive heat from plasma	sensor produced no useful data; may expose a leading edge	3	None	None	None	3
Langmuir Probes	Langmuir probe develops short to tile	lithium accumulation, other material that bridges insulators	probe produces no useful data	3	None	None	None	3
Mirnov and Flux Loop System	Mirnov coil fail open in vessel	conductor failing on mandrel, connection at feedthrough fails	Sensor cannot be used; abandon in place and rely on redundant sensors; repair at next opening	4	Mirnov and Flux Loop System	Digitizers and Integrators	None	4
Mirnov and Flux Loop System	Mirnov coil fail short to vessel inside the vessel	failure of fiberglass insulation	Sensor cannot be used; abandon in place and rely on redundant sensors; repair at next opening	4	Mirnov and Flux Loop System	Digitizers and Integrators	None	4
Mirnov and Flux Loop System	Flux loop single conductor fail open	thermal expansion in bakeout, wear due to manipulation over time	Switch to alternate conductor in the loop; if that does not work, abandon and repair at next outage	4	Mirnov and Flux Loop System	Digitizers and Integrators	None	4

FMECA - PFC Diagnostics

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Mirnov and Flux Loop System	Flux loop both conductors fail	thermal expansion in bakeout	abandon and repair at next outage	4	Mirnov and Flux Loop System	Digitizers and Integrators	None	4
Mirnov and Flux Loop System	Flux loop conductors short to ground	insulation failure	Switch to alternate conductor in the loop; if that does not work, abandon and repair at next outage	4	Mirnov and Flux Loop System	Digitizers and Integrators	None	4

All 13 diagnostics failure modes identified; mitigated by high redundancy

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QA & Fabrication Oversight, ES&H

- Follow PPPL's QAPD as appropriate for an A-1 system
  - PPPL QA supplier qualification audits
  - Vendors will provide material certifications
  - Vendor surveillance to be determined as part of MIT plan with vendors
  - PPPL fabrication to follow a reviewed and approved procedure
  - Travellers used for Mirnov coil mandrel fabrication
  - Serial number scheme to be employed for Mirnov coil fabrication

- ES&H issues are covered by PPPL's standard work practices
  - Job Hazard Analysis
  - Appropriate PPE, e.g., safety glasses and gloves when needed

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Summary

- Requirements have been met via a combination of analysis and testing.
- Interfaces are considered in the design and documented in the ICDs
- All chits related to the PFC Diagnostics job are closed
- Risks are mitigated through:
  - Prototyping
  - Testing of fabricated diagnostics
  - High redundancy of sensors
- Standard PPPL safety practices are followed during all work