National Spherical Torus eXperiment Upgrade

Bus Work
WBS 1.01.03.02

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

D. Cai - Cognizant Engineer

Last edit: 03/10/20

Outline

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

Overview - WBS 1.01.03.02

(CDE-3B Scope)

WBS Title	Bus Work	WBS #	1.01.03.02
Project Cog.	Danny Cai	Assoc. Proj. Man.	Gary Swider
Design Scope	Design hard bus for the inner PF coils and bakeout legs. Design additional supports for PF4 BUS. Design PF1B flex cable. Field fit for TF extension and OH Coax BUS		
Technical Impact of Scope	PF inner coil BUS carries current to coils which provide primary capability to form a magnetic divertor on NSTX-U		
Design Status	FDR1 completed on 02/07/2020: review link FDR2 completed on 02/19/2020: review link FDR3 completed on 03/06/2020: review link chits: link calculations: link drawings: link		
Fabrication Status	Fabrication pending 3B approval		
Installation Status	Bus and supports will be installed as part of the Magnet Scope		

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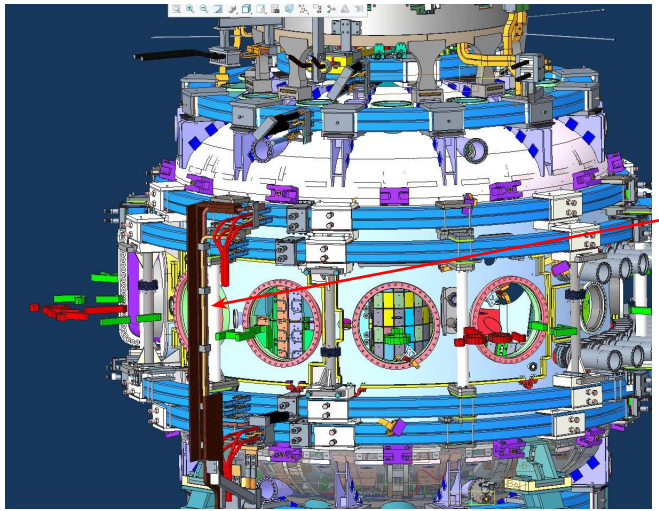
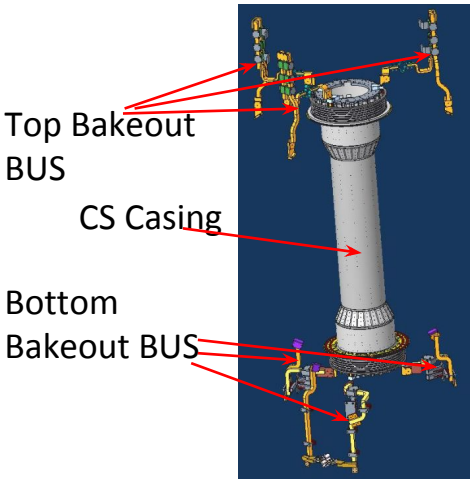
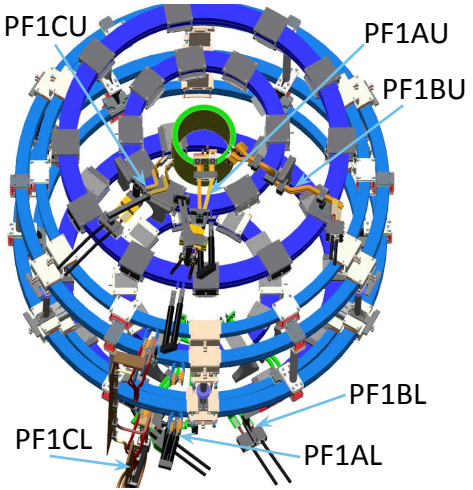
Scope[1]



PF4 Bus



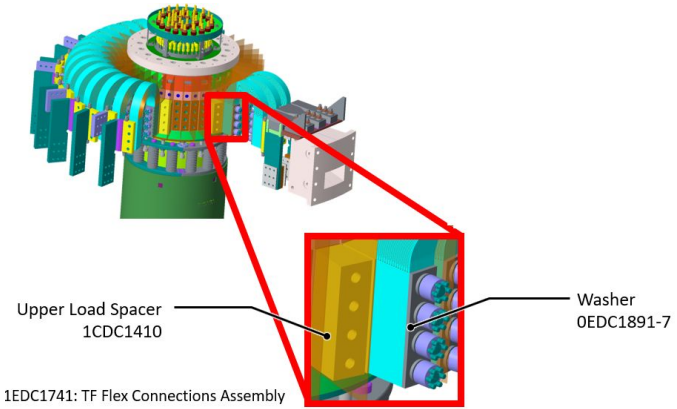
Bakeout Bus



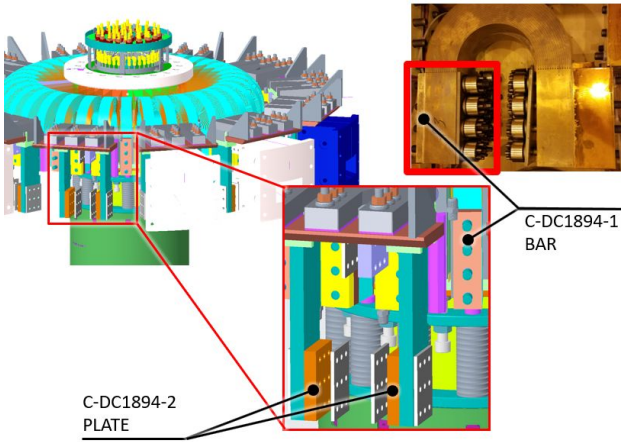
PF1 BUS

- The PF4 hard BUS and flexible cable supports
- The Inner PF1 coil support, hard BUS and hard/flex BUS support
- The center stack casing bakeout BUS and BUS support

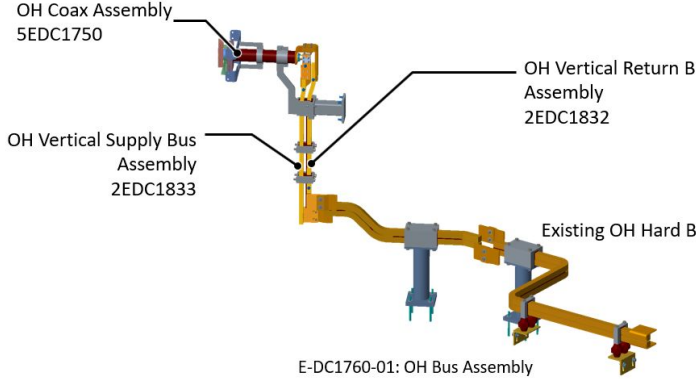
Scope[2]



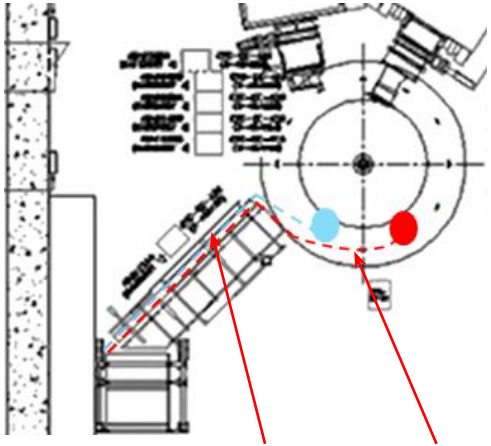
Inner TF bundle extension



Outer TF bundle extension



OH BUS Assembly



PF1B cable routing

- Inner and outer TF bundle extension field modification
- OH BUS assembly field modification
- PF1B water cooled flex power supply cable design and installation

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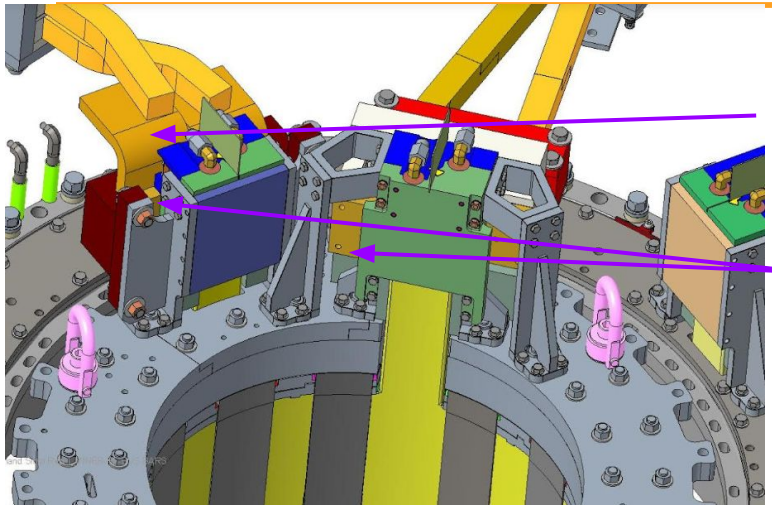
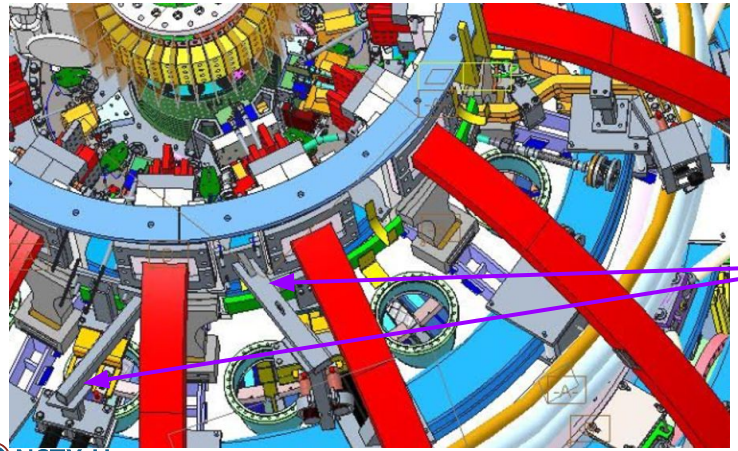
Requirements Defined and Met

Source	Requirements	Comment	met
NSTX-U-RQMT-GRD-001	Highest level machine parameters	Defines 2 MA, 1 T, 5 second, 10 MW operating point.	✓
NSTX-U-RQMT-GRD-001	Field/current directions	Requires design to be compatible with either direction of the toroidal field or plasma current	✓
NSTX-CRIT-0001	Design Criteria	Provides the project definition of margin for loads vs. allowables	✓
NSTX-U-RQMT-SRD-02	Coil voltages	Provides working and high-pot voltages for each coil system, for use in insulation design	✓
NSTX-U-RQMT-SRD-02	ESW current and duration	Defines the Ohmic heating the PF bus work must accommodate	✓
NSTX-U-RQMT-SRD-06	Power supply currents	Provides power supply currents for the PF bus bars	✓
NSTX-U-RQMT-RD-003	Disruption requirements	Provides specification of halo currents for computing the bakeout bus bar loads	✓
NSTX-U-RQMT-RD-15	Bakeout bus work amperage	Requires that each bakeout busbar be qualified for 5.3 kA during bakeout	✓
Design Point Spreadsheet	Background fields	Provides the plasma scenarios for which the backgound fields are computed	✓

Complete RVTM maintained by Project Systems Engineering

Interfaces





- Coil and BUS are bolted together through coil flag and BUS flag
- BUS routine is based on the space available inside umbrella
- Hard BUS is supported by stainless steel brackets that are attached to umbrella or PF3 supporting structure

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Magnets	Vacuum Vessel Structure	link	Defines interfaces between the Magnet Bus Bars and the vacuum vessel structures (e.g., umbrella, structural supports)
Magnets	Power Systems	link	Defines interfaces between the Magnet Bus Bars and the power system interconnection
Magnets	Cooling Systems	link	Defines interfaces between the Magnet Bus Bars and the Cooling System.
Bakeout	Vacuum Vessel Structure	link	Defines interfaces between the Bakeout Bus Bars and the vacuum vessel structures (e.g., umbrella, structural supports)

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Comprehensive Calculations Used to Verify Design will Meet Requirements

Physical Quantity	Calculation #	Comment
Stresses on PF-1aL and -1bL bus bars and flex leads	NSTXU_1-1-3-4_CALC_101	Demonstrates the supports provided in the bus work design produce acceptable stresses in the coil leads, bus bars, and supports, for the PF-1aL and PF-1bL coils
Stresses in the PF-4 leads and bus bars	NSTXU_1-1-3-4_CALC_104	Demonstrates the supports provided in the bus work design produce acceptable stresses in the coil leads, bus bars, and supports, for the PF-4 upper and lower coils
Stresses in the PF-1cU leads and bus bars	NSTXU_1-1-3-4_CALC_102	Demonstrates the supports provided in the bus work design produce acceptable stresses in the coil leads, bus bars, and supports, for the PF-1cU coil
Stresses in the PF-1cL leads and bus bars	NSTXU_1-1-3-4_CALC_103	Demonstrates the supports provided in the bus work design produce acceptable stresses in the coil leads, bus bars, and supports, for the PF-1cL coil
Stresses in the PF-1aU and -1bU leads and bus bars	NSTXU_1-1-3-4_CALC_100	Demonstrates the supports provided in the bus work design produce acceptable stresses in the coil leads, bus bars, and supports, for the PF-1aU and PF-1bU coils

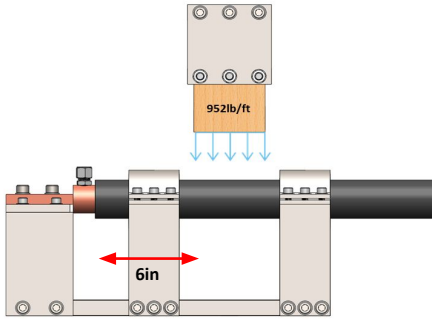
Prototype

- PF1B Power Cable Electrical Requirements:

Cable Size	Operating Current kA	Operating Voltage kV	Hi-pot Voltage	Frequency	Duty Cycle	Water Cooling	Terminal	Carrier
1000MCM	DC & AC +21 / -10	2	9.1	DC – 60	2 sec ON/ 20 min OFF	Deionized Water Up to 300 psig 2-2.5GPM	4" x .625" x 1.625" Silver Plated Copper	Cable Tray Open to Air

- Life Cycle Testing Parameters:
  - Cable Pressurized to 120 PSIG
    - Survive without Leak
  - 952 lb/ft Load
  - Time/Cycle: 2sec
  - Frequency: 0.5Hz
  - 100,000 Total Cycles (NSTX-U Pulse Spec: 20,000)
- Testing Results

Cable	Young's Modulus	Shear Modulus	100,000 Cycles	120PSIG	Untested Resistance	Tested Resistance
PF1-A/C	12.5ksi	4.4ksi	Survived 50,000 Half load / 50,000 Full Load	No Pressure Loss	162μΩ	162μΩ
PF1B	7.21ksi	2.5ksi	Survived 50,000 Half load / 50,000 Full Load	No Pressure Loss	24μΩ	24μΩ



Fixture on the 10kip MTS Machine with 4.25in Wood Saddle applying distributed load.

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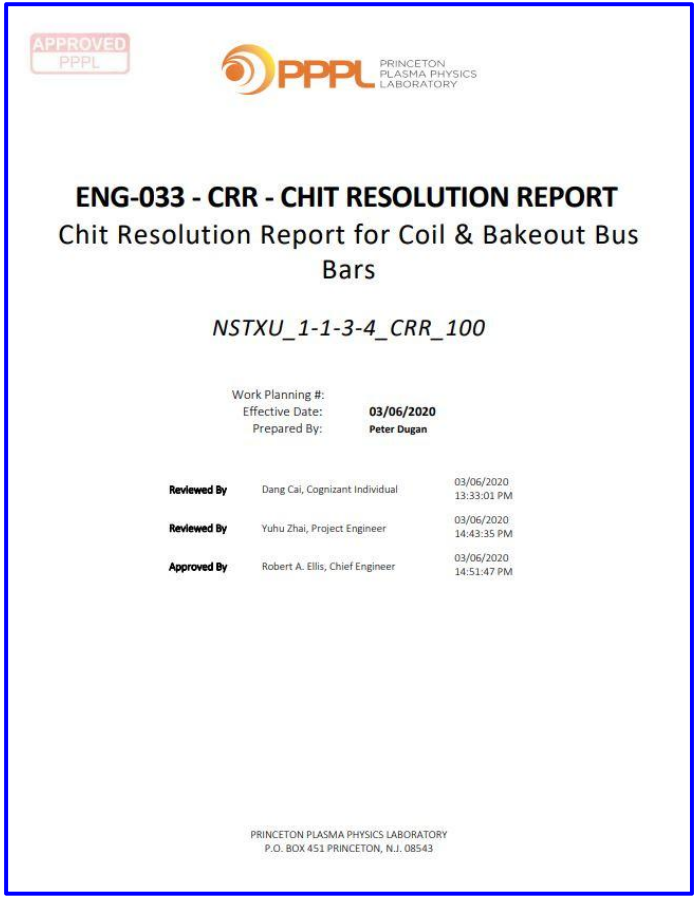
All Chits have been Closed

Chits from DVVR, CDR and PDR have been closed at FDR LINK

Chits collected during FDRs (FDR1- 02/07/20, FDR2-02/19/20, FDR3-03/06/20) are being actively worked on. These chits are mostly regarding manufacturing and installation.


APPROVED
PPPL

PPPL PRINCETON PLASMA PHYSICS LABORATORY

ENG-033 - CRR - CHIT RESOLUTION REPORT

Chit Resolution Report for Coil & Bakeout Bus Bars

NSTXU_1-1-3-4_CRR_100

Work Planning #:
Effective Date: **03/06/2020**
Prepared By: **Peter Dugan**

Reviewed By	Dang Cai, Cognizant Individual	03/06/2020 13:33:01 PM
Reviewed By	Yuhu Zhai, Project Engineer	03/06/2020 14:43:35 PM
Approved By	Robert A. Ellis, Chief Engineer	03/06/2020 14:51:47 PM

PRINCETON PLASMA PHYSICS LABORATORY
P.O. BOX 451 PRINCETON, N.J. 08543

Chit Resolution Report: link

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Procurement, Fabrication, Installation, and Test

- Raw materials will be purchased through qualified vendor with material certs
- For hard BUS run, wooden mockup will be built in the field before final drawing release for fabrication
- Field fit is expected during installation for coil flag tower assembly
- Electrical joint resistance (<5MicroOhm) will be tested as well as hipot test (2E+1KV)

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Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Closed	Risk Retirement Event
If the bakeout DC power supply buss connections at the upper flange does not meet the newly revised current requirements	12	RETIRED	FDR

FMECA - Bakeout Bus (I)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Bakeout Bus Work	Loss of water flow to hard bus	flow blockage; pumps turn off	overheating of bakeout bus; potential failure at interface to vessel	9	CWS Flow and Temperature Instrumentation	None	None	2
Bakeout Bus Work	Bus work moves under EM load	Excessive halo currents in any single bar of the bakeout bus.	bending of bus bar, including failure at joints and potential ground fault	9	DCPS Software	Tile and Rogowski Halo Current Measurements	None	6
Bakeout Bus Work	Failure of connection between two pieces of hard bus within umbrella	improper torques at installation; contamination on joint surfaces at installation	charing; must repair electrical faces on either side of connection	6	None	None	None	6
Bakeout Bus Work	water leak in water cooled flex bus	Leak through jacket of water cooled flex	potential ground fault, potential damage to nearby items due to water ingress	6	Low-Pressure NTC Cooling Water Distribution	FCPC Ground Fault Detection	None	2
Bakeout Bus Work	Hose complete detachment at interface to bakeout bus	overpressure transient	Water leak within umbrella; overheating of bus work	4	CWS Flow and Temperature Instrumentation	None	None	2
Bakeout Bus Work	Lower bakeout jumper disconnected (note: jumper connects the inner and outer vessel hard bus legs)	Loosen of joint over multiple cycles	Bellows absorbs halo current. Bellows are damaged.	4	DCPS Software	None	None	3

FMECA - Bakeout Bus (II)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Bakeout Bus Work	Cooling water leaks out of bakeout BusBar(s)	Repeated flexing of water cooled Busbar from Excessive halo current causes fatigue failure, and cracking of Busbar, allowing water to escape.	Water leaks into various places, causing shorts	3	None	None	None	3
Bakeout Bus Work	Failure at electrical joint between hard bus and flexible cabling	improper torques at installation; contamination on joint surfaces at installation	charing; must repair electrical faces on either side of connection	2	None	None	None	2
Bakeout Bus Work	Development of ground fault on DC bus work bus work and cabling	metal object touch (fall on) exposed bus work; insulation appraisal	single ground has minimal consequence; 2nd ground can divert bakeout current	2	None	None	None	2
Bakeout Bus Work	Individual touches DC supply outputs or bus work	work near energized conductors	negligible; supplies are 8 V supplies	2	None	None	None	2

FMECA - Coil Bus (I)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Bus Bar Systems and Bus Tower	Hard bus displaced under EM load	Large EM loads, potentially beyond design basis	Damage to coil terminals, including water leaks and cracks in conductors	12	DCPS Software	None	None	4
Bus Bar Systems and Bus Tower	Individual touches exposed busbar conductor when energized	work near energized conductors	exposure to high voltage (~1-6 kV)	12	Bus Work Guards & Exposed Conductors >50V Guards	Trapped Key System	Personnel Safety System (SIS)	0
Bus Bar Systems and Bus Tower	Hard or flex bus cooling flow stopped	debris in line; valve misalignment, pump failure	bus bar overheats	9	Low-Pressure NTC Cooling Water Distribution	None	None	4
Bus Bar Systems and Bus Tower	Insulation failure	Excessive time-average current; exceeds the RMS current rating for the circuit which failed resulting in excessive temperatures	Single or double ground of bus work	9	PDP Timer	None	None	6
Bus Bar Systems and Bus Tower	Flex Bus work displaced under EM load	Large EM loads, potentially beyond design basis	Damage to Hard bus and Flex Bus terminals, including water leaks and cracks in conductors	9	DCPS Software	None	None	4
Bus Bar Systems and Bus Tower	water leak in water cooled flex bus	Leak through jacket of water cooled flex	potential ground fault, potential damage to nearby items due to water ingress	6	Low-Pressure NTC Cooling Water Distribution	FCPC Ground Fault Detection	None	2

FMECA - Coil Bus (II)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Bus Bar Systems and Bus Tower	water leak in bus (hard or flex bus)	Hose comes detached from water cooled bus or flex cable	large water leak, potential ground fault, damage to nearby items due to water ingress	6	Low-Pressure NTC Cooling Water Distribution	None	None	2
Bus Bar Systems and Bus Tower	Flex bus ground fault	Inadvertent over-voltage condition; abraisan of ground insulation	high ground current, damage to nearby components in ground fault	6	FCPC Ground Fault Detection	None	None	4
Bus Bar Systems and Bus Tower	Hard bus ground fault	Inadvertent over-voltage condition; abraisan of ground insulation	high ground current, damage to nearby components in ground fault	6	FCPC Ground Fault Detection	None	None	4
Bus Bar Systems and Bus Tower	Flex bus short between conductors	fatigue damage of insulation due to motion	large current through the short; local explosion and debris	6	Shorted Turn Protection System	FCPC Ground Fault Detection	None	6
Bus Bar Systems and Bus Tower	Hard bus short between conductors	over voltage condition, fatigue damage due to small amounts of motion, water leak	large current through the short; local explosion and debris	6	Shorted Turn Protection System	FCPC Ground Fault Detection	None	6
Bus Bar Systems and Bus Tower	Failure of connection between two pieces of hard bus within umbrella	Joint becomes loose, due to the loads experienced	Joint overheats, melts coil flag or bus flag and creates an open circuit	6	Shorted Turn Protection System	None	None	6

FMECA - Coil Bus (III)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Bus Bar Systems and Bus Tower	Failure of connection between hard bus and flex-bus	Joint becomes loose, due to the loads experienced	Joint overheats, melts and creates an open circuit	6	Shorted Turn Protection System	None	None	6
Bus Bar Systems and Bus Tower	Failure of PF-4 hard bus / lead flags	PF-4 Pin failure can allow the coil to move leading to high stress in the hard bus leads	Hard bus lead flag are damaged	6	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Bus Bar Systems and Bus Tower	Failure of PF-5 hard bus / lead flags	PF-5 Pin failure can allow the coil to move leading to high stress in the hard bus leads	Hard bus lead flag are damaged	6	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2

25 failure modes identified - all mitigate to acceptable risk

Key mitiations -
Digital coil protection system to limit loads
Cooling water interlocks to ensure cooling is present

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Quality, Environment, Safety and Health

- Travelers required for all machining components
- Approved installation procedures required for all mechanical and electrical work
- Joint resistance test and hipot test shall be performed to validate the BUS assembly functionality

Assemblies	Vendor	QA LEAD	QA BACK-UP	QC
All mechanical and electrical assemblies	PPPL fabrication Shops	Ramos	Malinowski	Ramos

- Potential ES&H concerns:
  - Design: none
  - Fabrication: mitigated by standard PPPL ES&H program
  - Installation: mitigated by standard PPPL ES&H program
  - Operation: mitigated by standard PPPL ES&H program

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- Requirements for BUS work have been met via a combination of analysis and test
- Interfaces are considered in the design and documented in the ICDs
- All DVVR, CDR and FDR chits related to the BUS work job are closed at FDRs. All the chits collected from FDRs are being actively worked on
- Risks are mitigated through:
  - Flex cable cyclic testing
  - Field mockup fabrication before final drawing release
  - Electrical joint and hipot tests
- No potential hazard of item/activity to people/environment