National Spherical Torus eXperiment Upgrade

# Inner-PF Magnet Replacement

## WBS 1.01.03.01 & 1.01.03.01a

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

Mike Kalish - Cognizant Engineer

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 1.01.03.01 &.01A
(CDE-3A Scope)

| | | | |
|---|---|---|---|
| WBS Title | Inner PF Replacement | WBS # | 1.01.03.01 & .01A |
| Project Cog. | Mike Kalish | Assoc. Proj. Man. | Gary Swider |
| Design Scope | Design new inner-PF coils for NSTX-U | | |
| Technical Impact of Scope | Coils provide primary capability to form a magnetic divertor on NSTX-U | | |
| Design Status | FDR completed on 3/30/2018: review link<br>chits: link<br>calculations: link<br>drawings: link<br>SoW/Tech Spec: link | | |
| Fabrication Status | Six solenoid coils of three types being fabricated at Sigmaphi in France; Of the six two have been wound and are awaiting epoxy impregnation (VPI). Two more are in the process of winding | | |
| Installation Status | Coils will be installed in slings as part of the Machine Core Structures Scope | | |

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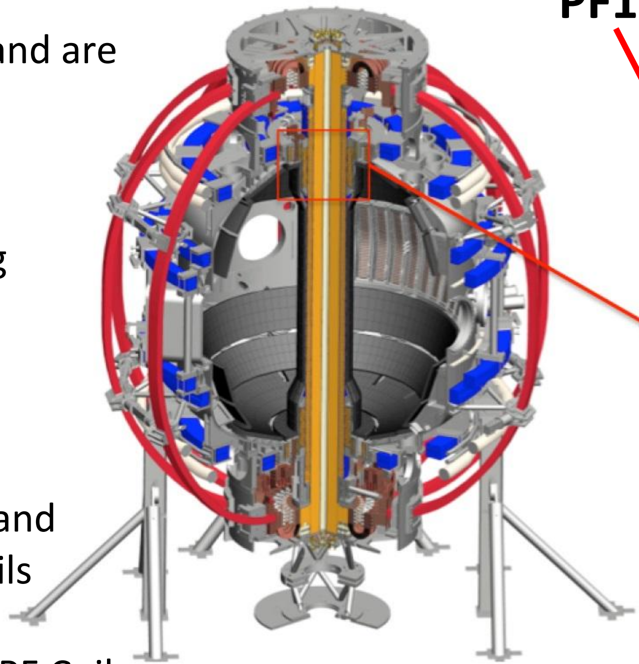
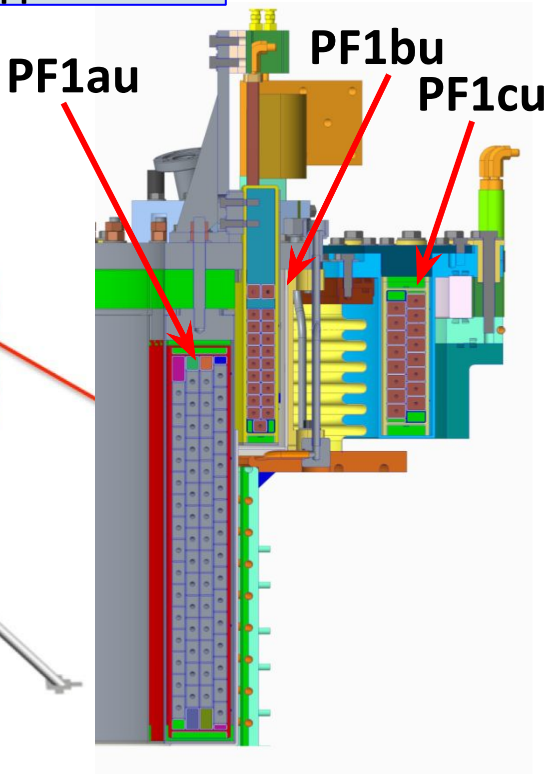
# Inner PF Coils - Scope

- There are six Inner PF Coils, a pair each of PF1a, PF1b and PF1c at the top and bottom of the center stack.
- All Inner PF Coils have been redesigned, and are being fabricated, tested and replaced
- Completed scope (sunk cost) includes
  - designing a prototype PF1a coil
  - fabricating, testing and evaluating four PF1a prototypes (3 at vendors, 1 at PPPL).
  - designing new Inner PF production coils
  - fabricating conductor, insulation and other materials for production coils
- Remaining scope includes
  - completing fabrication of 6 Inner PF Coils
  - testing those six coils

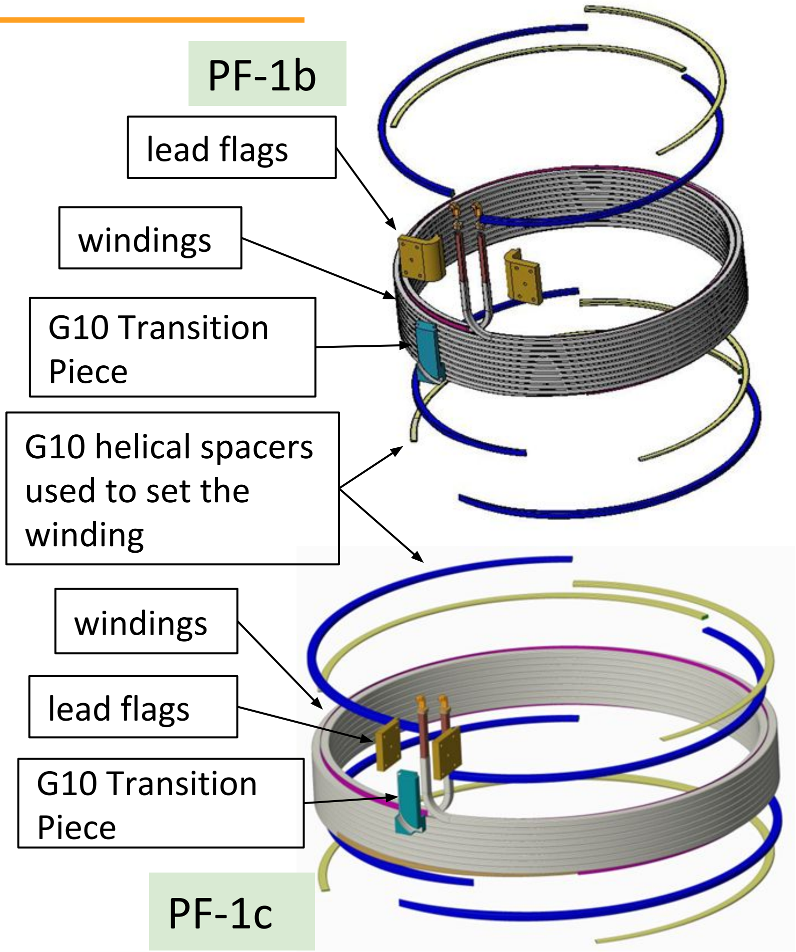
**Cross-Section showing three Upper Coils.**





# Inner PF Coils - Design Parameters

| | | PF-1a | PF-1b | PF-1c |
|---|---|---|---|---|
| Coil Terminal to Terminal Voltage | kV | 2.03 | 2.03 | 2.03 |
| Current | kA | 19.7 | 20.0 | 20.2 |
| # of Layers | | 4 | 2 | 2 |
| # of Turns | | 61 | 20 | 16 |
| Turn-to-Turn Voltage | V | 33 | 101 | 127 |
| Turn-to-Turn Safety Factor | | 2168 | 709 | 567 |
| Layer-to-Layer Voltage | V | 1013 | 2026 | 2026 |
| Layer-to-Layer Safety Factor | | 76 | 38 | 38 |
| Max Turn-to-Ground Voltage | V | 2026 | 4052 | 4052 |
| Turn-to-Ground Safety Factor | | 54 | 27 | 27 |



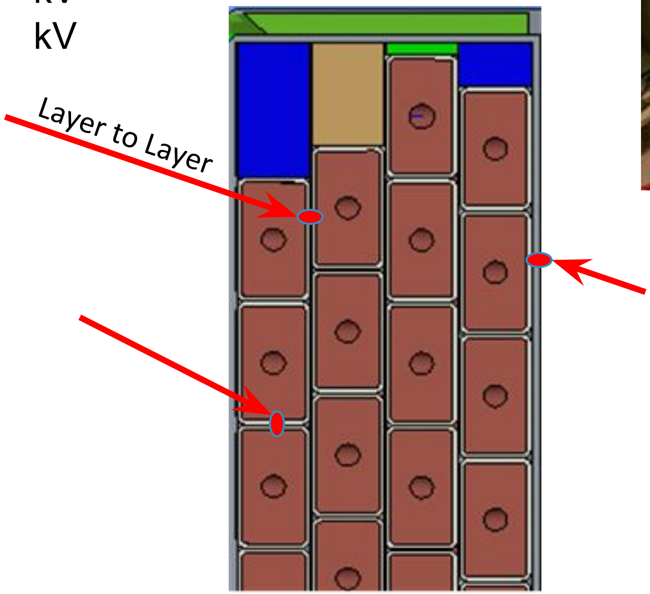

Temperature limit and pre-load chosen to limit thermal strains to acceptable values

# Insulation Design Has High Dielectric Standoff

**Could not induce failure in any coil at max limit of test equipment:**
**= 20kV for layer to layer testing**
**= 55kV for conductor to gnd testing**

## Layer to Layer Voltage Standoff

| | | |
|---|---|---|
| Maximum Layer to Layer voltage PF1b and PF1c | 2.03 | kV |
| Dielectric strength | 77 | kV |
| **Safety factor PF1a** | **76** | |
| **Safety Factor PF1b** | **38** | |
| **Safety Factor PF1c** | **38** | |




## Turn to Turn Voltage Standoff

**Safety Factor is 2168 for PF1a**

**Safety Factor is 709 for PF1b**

**Safety Factor is 567 for PF1c**

## Turn to Ground Voltage Standoff

| | | |
|---|---|---|
| Maximum Turn to Ground voltage PF1b and PF1c | 4.05 | kV |
| Dielectric strength | 110 | kV |
| **Safety Factor PF1a** | **54** | |
| **Safety Factor PF1b** | **27** | |
| **Safety Factor PF1c** | **27** | |

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# Requirements Defined and Met

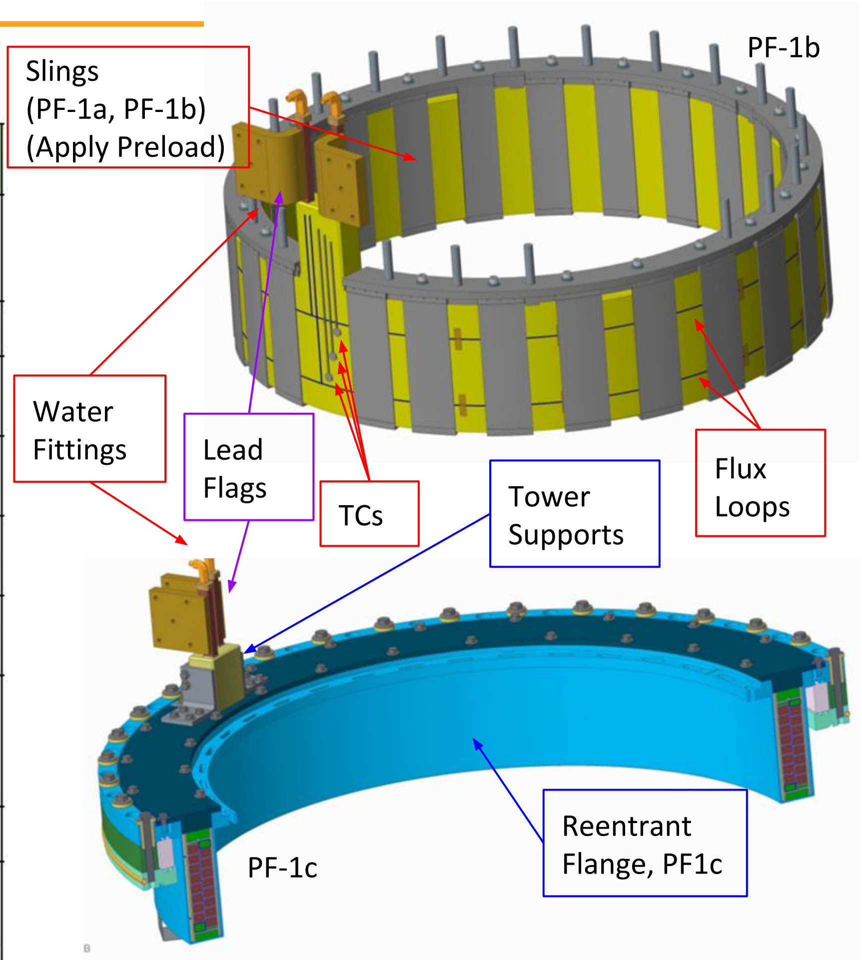
| Source | Requirements | Comment | met |
|---|---|---|---|
| NSTX-U-RQMT-GRD-001 | Waveform Specifications, Duty Cycle | Provides highest level requirements for 2 MA, 1 T, 10 MW, 5 second operation | ✓ |
| NSTX-CRIT-0001 | Design Criteria | Provides the project definition of margin for loads vs. allowables | ✓ |
| NSTX-U-RQMT-SRD-002 | Amp-Turn Capability For Each Coil | Requirements determined by physics goals for flexibility in shaping | ✓ |
| NSTX-U-RQMT-SRD-002 | $I^2t$ Limit For Each Coil | Constrained by physics needs and thermal stress limits | ✓ |
| NSTX-U-RQMT-SRD-002 | Coil Centroids | Determined by required plasma shaping capability | ✓ |
| NSTX-U-RQMT-SRD-002 | Design to facilitate turn-to-turn testing | Will utilize a mandrel-free construction method | ✓ |
| NSTX-U-RQMT-SRD-002 | Diagnostic on Coils | Thermocouples and flux loops required | ✓ |
| NSTX-U-RQMT-SRD-002 | High-pot requirements | 2E+1 defined as the high pot voltage, including fault case | ✓ |
| NSTX-U-RQMT-SRD-002 | Insulation Requirement | Safety factor of >10 required for ground and turn insulation | ✓ |

# Interfaces Defined in the SRD and Accommodated by Design

Interface Table from NSTX-U-RQMT-SRD-002

*Table 7.6-1: Interfaces for the PF-1a coils (WBS 1.1.3.3.3)*

| Interfacing WBS | Interfacing System | Nature of Interface | Interface Boundary | Interface Description | Required Interface Documentation |
|---|---|---|---|---|---|
| 1.3.2.1.2 | High-Pressure NTC Cooling Water Distribution | Fluid | connection between i) hose w/ fitting and ii) and fitting on the coil | Hose connections at coil leads; cold water cools outer layers first | P&ID, Mechanical Design Drawing |
| 1.7.3.4.2 | Center stack coil thermocouples | Diagnostic | Surface of ground insulation | thermocouples applied to surface of coil | Mechanical Drawing |
| 1.1.3.4 | Bus Bar Systems and Bus Tower | Electrical Power | Flat surface of the coil flags. | Solid bus bars connect to the coil terminal | Calculation, Mechanical Design Drawing |
| 1.1.3.4 | Bus Bar Systems and Bus Tower | Structural | Flat surface of the coil flags. | Solid bus bars connect to the coil terminals, supporting part of bus bar run | Calculation, Mechanical Design Drawing |
| 1.1.3.3.6 | Center Stack Casing | thermal | At surface of coil | microtherm blanket provides thermal isolation between coils and casing | Mechanical drawing, Calculation |
| 1.1.3.3.11 | PF-1a Support Structure | Structural | At surface of coil support structures | Coil leads are supported as they extend from the winding pack | Mechanical drawing, Calculation |
| 1.1.3.3.11 | PF-1a Support Structure | Structural | Surface of ground wall insulation | Inner-PF coils are supported against all loads by the CS assembly. Pre-load is applied to the coils by the coil supports. | Calculation, Mechanical Design Drawing |
| 1.4.1.2.2 | Mirnov and Flux Loop System | Diagnostic | Inner Poloidal Field Coil Ground Insulation Surface | Poloidal Flux Loops mounted on Inner Poloidal Field Coils | Mechanical Drawing |
| 1.1.3.3.10 | Vertical Target Cooling System | spatial | at the surface of the heat transfer tubes | heat transfer tubes need to allow the PF-1a coil to fit through with sufficient clearance for alignment. | Mechanical Drawing |



# Details of Interfaces Defined in Interface Control Documents

| System 1 | System 2 | ICD Link | Exposition |
|---|---|---|---|
| Magnets | Center Stack Assembly | link | Defines interfaces between the inner-PF coils and the center stack assembly |
| Magnets | Diagnostics | link | Defines interfaces between the inner-PF magnets and diagnostics such as flux loops and thermocouples |
| Magnets | Cooling Systems | link | Defines interfaces between the inner-PF magnets and the cooling water systems |
| Magnets | Power Systems | link | Defines interfaces between the inner-PF magnets and the Power Systems |
| Magnets | Operations and Systems Safety | link | Defines interfaces between the magnets and the Power Systems via a light curtain |

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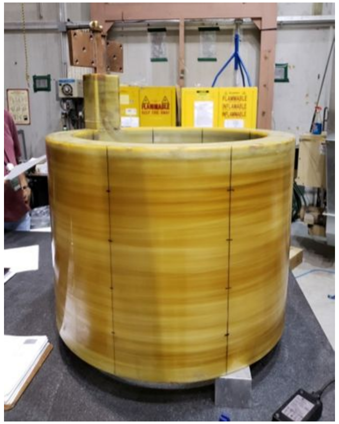
# Comprehensive Calculations Verify Design will Meet Requirements

| Physical Quantity | Calculation # | Content |
| --- | --- | --- |
| Forces on Coil lead from Bus Bars | NSTX-U-CALC-55-04 | Inner PF Coil Leads and Bus Bar Analysis: Verifies coil lead design with Bus Bar interface loads |
| PF-1cL Coil, Leads and Busbar | NSTX-U-CALC-131-001 | Calculation of PF1c Lower Coil: Verifies design of the PF-1cL Coil Leads and Bus bar |
| PF-1cU Leads and Busbars | NSTX-U-CALC-131-002 | Calculation of PF1c Upper Leads and Busbar: Verifies design of the PF-1c Upper lead tower |
| Loads on coils due to Electro-Magnetic forces | NSTX-U-CALC-133-23 | Inner PF Coil Electromagnetic Analysis: Provides EM loads on the conductors, for the full range of operating conditions. |
| Fatigue Stress and Crack Propagation | NSTX-U-CALC-133-24 | Inner PF Fatigue and Fracture Mechanics: Verification of design with respect to number of required pulses with worst case assumptions for flaws |
| Insulation Physical Properties | NSTX-U-CALC-133-25 | Calculation of Insulation and Coil Winding Pack Orthotropic Properties for Analysis: Determination of insulation properties to to be used for inputs in analysis |
| Thermal Strains and Stress | NSTX-U-CALC-133-27 | Inner PF Coil Thermal Analysis: Evaluates the thermal stresses and strains associated with thermal excursions due to the resistive heating and the differential layer to layer cooling |
| PF1 Loads on Leads due to Electro-Magnetic forces | NSTX-U-CALC-133-28 | Summary of Loads for PF1 Leads and Busbar: Evaluates the loads on the PF1 busbar connections and provides interface loads for evaluation of coils stresses |

# Prototype Coils Evaluated Vendors and Validated Design



- The four prototypes provided a basis to evaluate vendor quality, both the process and final product.
- The coil prototyping and testing effort was designed to validate improvements made in design and manufacturing that were based on lessons learned.
- The prototype evaluation demonstrated that the new design has generous margins with respect to preventing a repeat of the initial layer to layer electrical coil failure. The evaluation included:
  - Mechanical Inspection, metrology and hydrostatic testing
  - Low power, high voltage, and high power tests
  - Coil sectioning for visually examined
  - Turn-to-turn and turn-to-ground insulation of sectioned coils successfully tested

# Extensive Electrical Testing Program For Prototype

- Low power electrical testing (high pot, megger, surge testing, impedance)
- High power tests (2 coils) simulating NSTX-U operation, successfully completed
- Low power electrical tests repeated and no change observed in coil properties after high power testing
- Coils sectioned, visually examined to confirm good VPI
- High voltage testing performed on turn-to-turn and turn-to-ground insulation of both halves of sectioned coil demonstrated high Safety Factor, SF=150 min Turn to Turn, SF=20 min Layer to Layer with no breakdown
- High voltage testing was successfully repeated after Corona testing to validate long term durability of insulation

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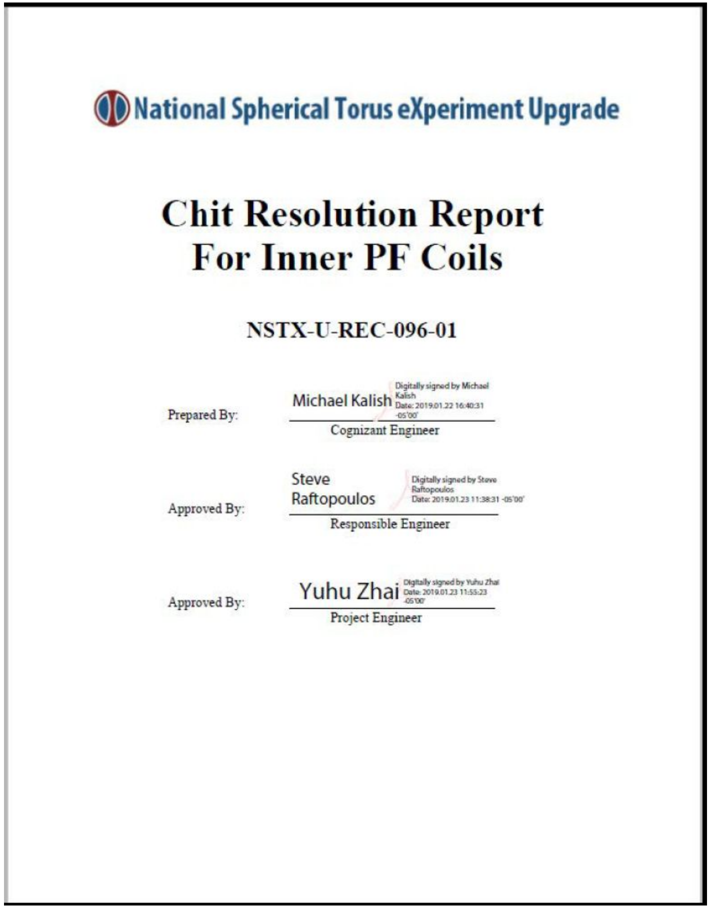
# All Chits Have Been Closed

Chits closed following FDR


National Spherical Torus eXperiment Upgrade

**Chit Resolution Report**
**For Inner PF Coils**

NSTX-U-REC-096-01

Prepared By: Michael Kalish Digitally signed by Michael Kalish Date: 2019.01.22 16:40:31 -05'00'
Cognizant Engineer

Approved By: Steve Raftopoulos Digitally signed by Steve Raftopoulos Date: 2019.01.23 11:38:31 -05'00'
Responsible Engineer

Approved By: Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2019.01.23 11:55:23 -05'00'
Project Engineer

Chit Resolution Report: [Report Link]

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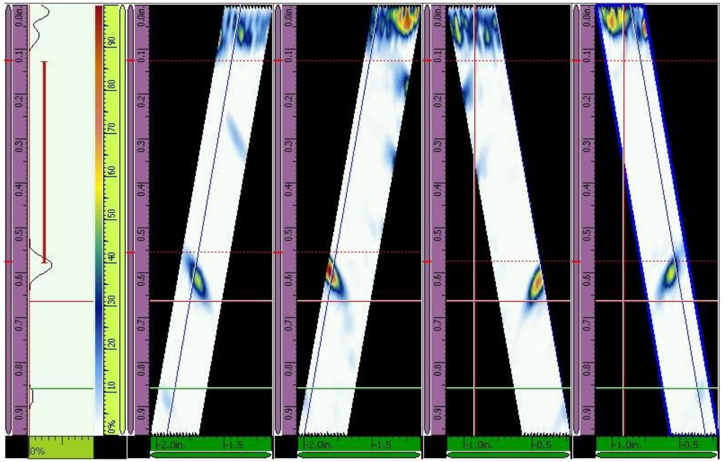
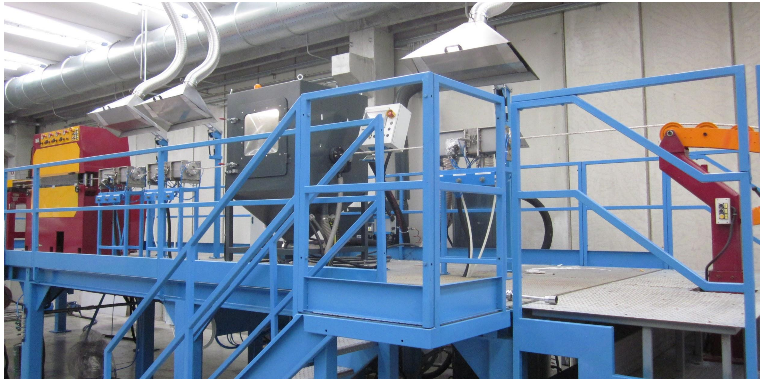
# Fabrication

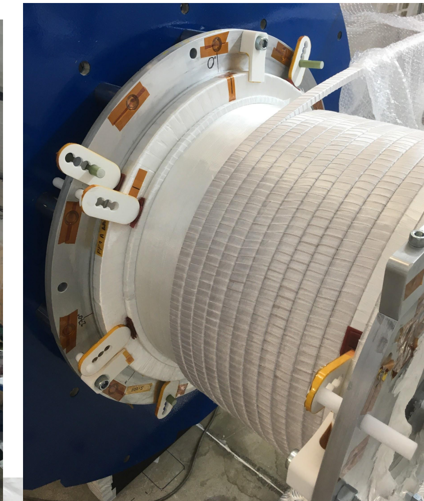
- Long lead items fabricated in advance and provided at award of contract
    - G11 Filler Pieces provided
    - Conductor purchased from Luvata in Finland 100% UT Inspection
    - Conductor sand blasted and primed by ICAS / Tratos in Italy
    - Co-wound glass / Kapton tape assembled and fully inspected at PPPL

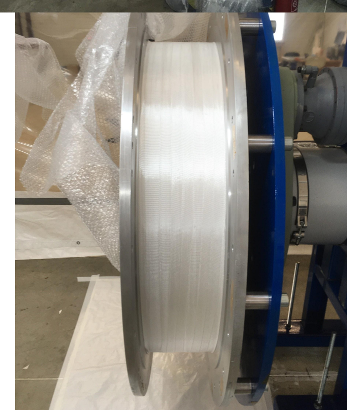


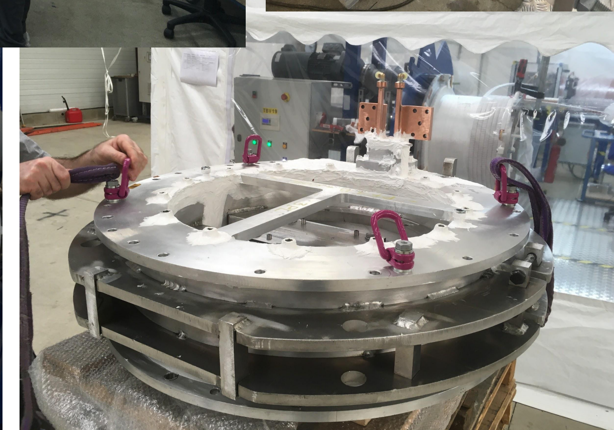


# Fabrication

- Fabrication proceeding at Sigmaphi
- Sigmaphi rented a dedicated building for our project
- Two clean rooms established for two winding lines
- Contract requires team of 2 technicians per winding line along with dedicated supervising engineer

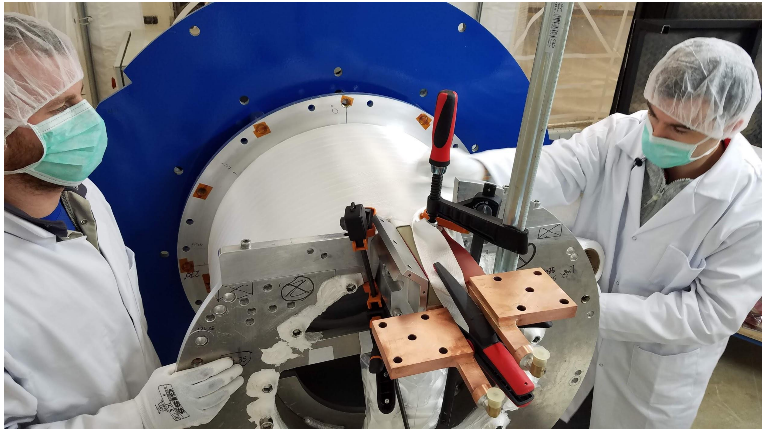




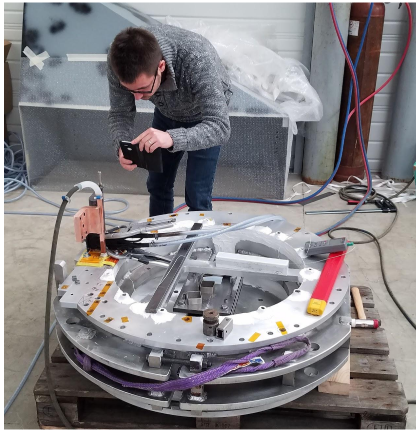


# Fabrication

- Of six coils two are wound and in their molds preparing for Vacuum Impregnation
- Two more coils are in the process of being wound
- Sigmaphi bought new equipment dedicated to our project including a new oven, mixing tank and electrical testing equipment
- There have been schedule delays due to issues with Sigmaphi subcontractors but quality has been maintained



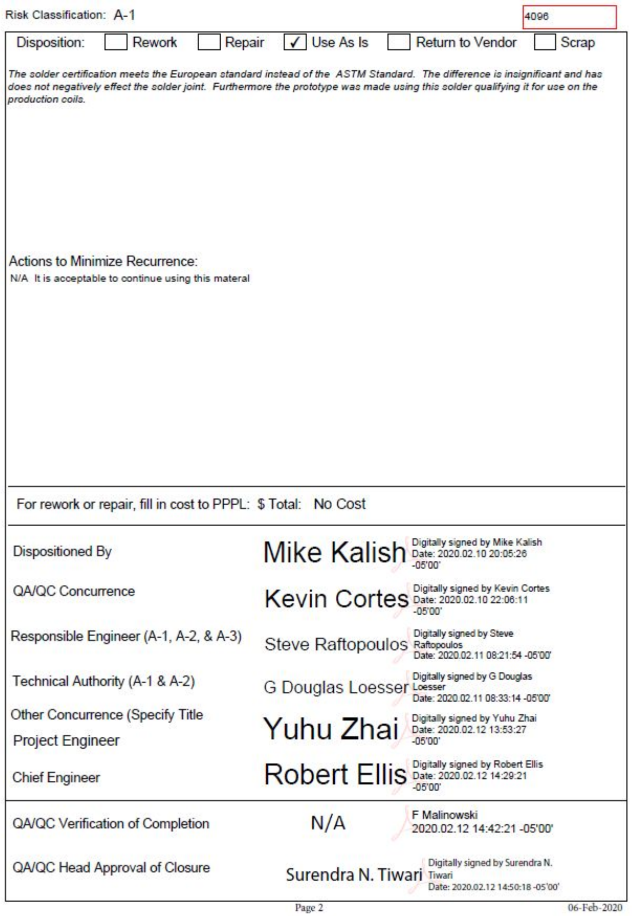
Video Winding PF1A Coil [LINK]



# NCRs and ECNs During Coil Fabrication To Date

- **NCRs**
  - 4096: Solder for water fitting met European chemistry standard instead of ASTM standard,
    no impact, accept as is
  - 4077: Small deviations in sizes of G11 filler pieces,
    no impact, accept as is

- **ECNs**
  - 8298: Change in reference dimensions on G11 Filler pieces to allow for fabrication from 3D models, fix dimension to center flag hole, rotate one water fitting on PF1b
  - 8321: Change in measurement requirement while winding for sigmaphi to determine where the center turn is to more accurately locate the flag


Risk Classification: A-1 4096

Disposition: ☐ Rework ☐ Repair ☑ Use As Is ☐ Return to Vendor ☐ Scrap

*The solder certification meets the European standard instead of the ASTM Standard. The difference is insignificant and has does not negatively effect the solder joint. Furthermore the prototype was made using this solder qualifying it for use on the production coils.*

Actions to Minimize Recurrence:
N/A It is acceptable to continue using this materal

For rework or repair, fill in cost to PPPL: $ Total: No Cost

| | | |
|---|---|---|
| Dispositioned By | Mike Kalish | Digitally signed by Mike Kalish Date: 2020.02.10 20:05:26 -05'00' |
| QA/QC Concurrence | Kevin Cortes | Digitally signed by Kevin Cortes Date: 2020.02.10 22:06:11 -05'00' |
| Responsible Engineer (A-1, A-2, & A-3) | Steve Raftopoulos | Digitally signed by Steve Raftopoulos Date: 2020.02.11 08:21:54 -05'00' |
| Technical Authority (A-1 & A-2) | G Douglas Loesser | Digitally signed by G Douglas Loesser Date: 2020.02.11 08:33:14 -05'00' |
| Other Concurrence (Specify Title Project Engineer | Yuhu Zhai | Digitally signed by Yuhu Zhai Date: 2020.02.12 13:53:27 -05'00' |
| Chief Engineer | Robert Ellis | Digitally signed by Robert Ellis Date: 2020.02.12 14:29:21 -05'00' |
| QA/QC Verification of Completion | N/A | F Malinowski 2020.02.12 14:42:21 -05'00' |
| QA/QC Head Approval of Closure | Surendra N. Tiwari | Digitally signed by Surendra N. Tiwari Date: 2020.02.12 14:50:18 -05'00' |

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# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If vendors cannot perform in the fabrication of PF1B and PF1C | 28 | RETIRED | |
| If the vendor quotes for production coils are higher due to their prototyping experience then the current basis of estimate will be low | 25 | RETIRED | Production coil contract award |
| If fabricated coils are damaged or lost in transit | 21 | OPEN | end of assembly |
| If a coil has an extreme exothermic reaction during fabrication | 21 | OPEN | Completion of Fabrication |
| If vendor(s) bid quotes for winding coil cannot meet currently assumed schedule | 20 | RETIRED | Award of coil contract |
| If vendors have performance issues that threatens either product quality or schedule in the fabrication of PF coils | 20 | OPEN | End of coil fabrication |

# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If production coil fails pre- or post-vpi electrical acceptance tests | 20 | OPEN | Successful coil test |
| If the new Inner PF coils' terminals are in different locations than the original coils' terminals as determined by field fit | 20 | RETIRED | Completion of machine assembly |
| If the method to separate the prototype coils from their temporary winding mandrels causes damage to a coil | 18 | RETIRED | |
| If a coil is damaged during finished machining | 18 | RETIRED | Completion of Fabrication |
| If the production coil fails pre-vpi electrical tests | 16 | RETIRED | Coil install |
| If there is a failure in existing power system component(s) to support coil testing | 16 | OPEN | End of coil testing |

# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If there are delays in awarding/completing conductor grit blast/prime | 16 | RETIRED | Award Completion |
| Evaluation of prototype coils delays | 16 | RETIRED | Evaluation Completion |
| If there is a PF Coil Shipping Delay | 16 | RETIRED | Receipt of coils |
| If foreign vendor surveillance is more challenging (multiple shifts, time-away limits,...), the lack of support may result in schedule delays. | 16 | RETIRED | Receipt of coils at PPPL |
| If less than three coil manufacturing facilities are available then we will not have parallel winding lines | 15 | RETIRED | Completion of procurement |
| If vendor quality decreases during production coils relative to prototype phase | 15 | RETIRED | Receipt of coils at PPPL |

# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If coil is damaged during finished machining or assembly | 15 | OPEN | end of assembly |
| If all the prototype testing failed then we have to re-evaluate the design and the process | 15 | RETIRED | |
| M8-1 & M8-2, If a flaw in the design/analysis/fabrication of magnet system component is found. | 15 | OPEN | Completion of component testing |
| if the schedule does not account for cultural differences (international holidays, work week differences,...), then the schedule may be overly optimistic | 15 | RETIRED | Award Completion |
| Two prototype coils fail post-acceptance destructive tests | 12 | RETIRED | Coil install |

# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If a vendor can not deliver due to unforeseen event in the middle of production then we will move production to another vendor and schedule will be increased | 12 | RETIRED | Receipt of coils at PPPL |
| If additional design risks to coils (CTD results etc.) | 12 | RETIRED | FDR |
| If problems occur with PF test stand during PF coil testing | 12 | OPEN | Completion of testing |
| If materials are damaged or lost in transit and we have to order more | 12 | RETIRED | receipt of coils |
| If the Polar Region structures design reviews reveal a problem for the coils | 9 | RETIRED | FDR for Machine Core Structures |
| PF-1A Proto tooling delayed | 5 | RETIRED | RETIRED |

# Project Risks are Actively Being Managed

| Risk | Score (1-81) | Open/Retired | Risk Retirement Event |
|---|---|---|---|
| If vendor or several vendors can fabricate PF1A coil in addition to PF1b and PF1C | 5 | RETIRED | completion of fabrication |
| If we start the early grit/blast/prime effort | 4 | RETIRED | Award Completion |
| If PPPL consolidates coil winding vendors | 3 | RETIRED | Award Completion |
| | | | |
| | | | |
| | | | |
| | | | |

# FMECA - Inner PF Coils (I)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1a Coils | Water leak at inlet | Fitting or hose failure | Potential loss of cooling; coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 6 |
| PF-1a Coils | Water leak at outlet | Fitting or hose failure | coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 6 |
| PF-1a Coils | Bending of coil lead flags | Excessive load on the leads | Failure of lead flags | 12 | DCPS Software | None | None | 4 |
| PF-1a Coils | Leads Bend | Excessive load away from the midplane is larger than preload | Damage to leads; may be severe up to a requiring replacement | 12 | DCPS Software | None | None | 4 |
| PF-1b Coils | Arc to ground at coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be severe up to a requiring replacement | 12 | FCPC Ground Fault Detection | None | None | 2 |
| PF-1b Coils | Water leak at inlet | Fitting or hose failure | Potential loss of cooling; coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 6 |

# FMECA - Inner PF Coils (II)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1b Coils | Water leak at outlet | Fitting or hose failure | coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 6 |
| PF-1b Coils | Excessive resistive heating of connection at coil/bus work interface | Loss of preload of bolted connections | Damage to electrical faces of coil | 12 | None | None | None | 4 |
| PF-1b Coils | Bending of coil lead flags | Excessive load on the leads | Failure of lead flags | 12 | DCPS Software | None | None | 4 |
| PF-1b Coils | Leads Bend | Excessive load away from the midplane is larger than preload | Damage to leads; may be severe up to a requiring replacement | 12 | DCPS Software | None | None | 4 |
| PF-1c Coils | Blockage of coil cooling channel | debris | coil temperature ratchets, damaging insulation | 12 | CWS Flow and Temperature Instrumentation | None | None | 2 |
| PF-1c Coils | Water leak at inlet | Fitting or hose failure | Potential loss of cooling; coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 4 |
| PF-1c Coils | Water leak at outlet | Fitting or hose failure | coil grounded; damage to coil leads or nearby components | 12 | FCPC Ground Fault Detection | CWS Flow and Temperature Instrumentation | Vessel and Diagnostic Grounds | 4 |

# FMECA - Inner PF Coils (III)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1c Coils | Bending of coil lead flags | Excessive load on the leads | Failure of lead flags | 12 | DCPS Software | None | None | 4 |
| PF-1a Coils | Arc to ground at coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be severe up to a requiring replacement | 8 | FCPC Ground Fault Detection | None | None | 2 |
| PF-1a Coils | Arc across coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be sufficiently severe to require replacement | 8 | Shorted Turn Protection System | None | None | 2 |
| PF-1a Coils | Excessive resistive heating of connection at coil/bus work interface | Loss of preload of bolted connections | Damage to electrical faces of coil | 8 | None | None | None | 4 |
| PF-1a Coils | Internal coil turn-to-turn failure | Insulation failure due to manufacturing error; transient over-voltage condition | Coil is inoperative, coil must be replaced | 8 | None | None | None | 8 |
| PF-1b Coils | Arc across coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be sufficiently severe to require replacement | 8 | Shorted Turn Protection System | None | None | 2 |

# FMECA - Inner PF Coils (IV)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1b Coils | Internal coil turn-to-turn failure | Insulation failure due to manufacturing error; transient over-voltage condition | Coil is inoperative, coil must be replaced | 8 | None | None | None | 8 |
| PF-1c Coils | Arc to ground at coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be severe up to a requiring replacement | 8 | FCPC Ground Fault Detection | None | None | 2 |
| PF-1c Coils | Arc across coil terminals | Water leak or item falling across leads; transient over-voltage condition | Damage to leads; may be sufficiently severe to require replacement | 8 | Shorted Turn Protection System | None | None | 2 |
| PF-1c Coils | Excessive resistive heating of connection at coil/bus work interface | Loss of preload of bolted connections | Damage to electrical faces of coil | 8 | None | None | None | 4 |
| PF-1c Coils | Internal coil turn-to-turn failure | Insulation failure due to manufacturing error; transient over-voltage condition | Coil is inoperative, coil must be replaced | 8 | Shorted Turn Protection System | None | None | 8 |

# FMECA - Inner PF Coils (V)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1a Coils | Blockage of coil cooling channel | debris | coil temperature ratchets, damaging insulation | 4 | CWS Flow and Temperature Instrumentation | None | None | 2 |
| PF-1a Coils | Ground Wall insulation failure | Mechanical damage during maintenance or operations; inadvertent over-voltage condition during operations or testing | Excessive current to ground, or arcing, during operations; may degrade over time; may mandate replacement | 4 | FCPC Ground Fault Detection | None | None | 4 |
| PF-1a Coils | Magnet ground insulation failure | slings develop resonance or large displacement with EM forces, and start slapping against the magnet insulation | leakage through ground insulation, may mandate major repair or replacement | 4 | FCPC Ground Fault Detection | None | None | 4 |
| PF-1a Coils | Ground insulation degradation | Excessive heat from bakeout due to issue with manufacture or installation of the microtherm insulation | Coil cannot pass high pot testing, excessive leakage current, coil may need to be replaced | 4 | Center Stack Coil Thermocouples | None | None | 4 |

# FMECA - Inner PF Coils (VI)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1b Coils | Blockage of coil cooling channel | debris | coil temperature ratchets, damaging insulation | 4 | CWS Flow and Temperature Instrumentation | None | None | 2 |
| PF-1b Coils | Ground Wall insulation failure | Mechanical damage during maintenance or operations; inadvertent over-voltage condition during operations or testing | Excessive current to ground, or arcing, during operations; may degrade over time; may mandate replacement | 4 | FCPC Ground Fault Detection | None | None | 4 |
| PF-1b Coils | Magnet ground insulation failure | slings develop resonance or large displacement with EM forces, and start slapping against the magnet insulation | leakage through ground insulation, may mandate major repair or replacement | 4 | FCPC Ground Fault Detection | None | None | 4 |
| PF-1b Coils | Ground insulation degradation | Excessive heat from bakeout due to issue with manufacture or installation of the microtherm insulation | Coil cannot pass high pot testing, excessive leakage current, coil may need to be replaced | 4 | Center Stack Coil Thermocouples | None | None | 4 |

# FMECA - Inner PF Coils (VII)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1c Coils | Ground Wall insulation failure | Mechanical damage during maintenance or operations; inadvertent over-voltage condition during operations or testing | Excessive current to ground, or arcing, during operations; may degrade over time; may mandate replacement | 4 | FCPC Ground Fault Detection | None | None | 4 |
| PF-1c Coils | Ground insulation degradation | Excessive heat from bakeout transferred through the PF-1c can | Coil cannot pass high pot testing, excessive leakage current, coil may need to be replaced | 4 | Center Stack Coil Thermocouples | None | None | 4 |
| PF-1a Coils | Delamination of turn to turn insulation | gradual loss of sling preload | Motion of conductors in the matrix of the insulation | 0 | None | None | None | 0 |
| PF-1a Coils | A gouge develops in the magnet's top surface | A burr, or machining ridge, digs into the top surface of the magnet during magnet radial expansion | produces weakened thermal/electrical insulation in one spot | 0 | None | None | None | 0 |
| PF-1b Coils | Delamination of turn to turn insulation | Mechanical (thermal, EM) during operations | Motion of conductors in the matrix of the insulation | 0 | None | None | None | 0 |

# FMECA - Inner PF Coils (VIII)

| System | Failure Mode | Failure Cause | Failure Effect | R | Detection/ Mitigation System (1) | Detection/ Mitigation System (2) | Detection/ Mitigation System (3) | R_R |
|---|---|---|---|---|---|---|---|---|
| PF-1b Coils | A gouge develops in the magnet's top surface | A burr, or machining ridge, digs into the top surface of the magnet during radial expansion | produces weakened thermal/electrical insulation in one spot | 0 | None | None | None | 0 |
| PF-1c Coils | Delamination of turn to turn insulation | Mechanical (thermal, EM) during operations | Motion of conductors in the matrix of the insulation | 0 | None | None | None | 0 |
| PF-1c Coils | During radial expansion of the PF1c magnet, a gouge develops in the magnet's top surface | A burr, or machining ridge, on the mounting flange digs into the PF1c magnet | produces weakened thermal/electrical insulation in one spot | 0 | None | None | None | 0 |

40 FMs, all but three mitigated to acceptable level.
Key mitigations

- DCPS to limit loads to the design basis
- FCPC ground fault monitors
- Shorted turn protection system
- Cooling water interlocks

Internal turn-to-turn faults challenging to defend as “extremely unlikely” (<$10^{-4}$/yr) given history of fusion program with magnets. Flagged as “unlikely”

# 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

# QA & Fabrication Oversight / ES&H

- Extensive prototyping effort qualified vendors and provided trial run for QA oversight
- PPPL QA & PPPL Engineering attend on-site Manufacturing Readiness Review
- Resident PPPL Engineering is on site for coil manufacturing
- Local subcontracted QA Engineers assure on-site PPPL QA presence.
- Resident Engineering representative is supplemented by visits from cognizant engineer
- The oversight plan for the production coils is a dramatic increase in PPPL presence compared to the oversight provided during the original PF1 fabrication
- PPPL representatives may stop work when required to resolve quality or safety issues
- Steps are taken to ensure coil fabrication does not subject employees to hazards at Sigmaphi
    - Work hazards at External Vendors mitigated with vendor oversight training and use of Job Hazard Analysis
    - Subcontract requires site-specific safety plans for PPPL workers.
    - During Prototype production PPPL stopped work at a vendor and removed personnel in response to potential safety issues returning only after confirmation issues were resolved

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# Summary

- Requirements have been met through design and analysis and then verified with prototyping and testing
- Interfaces are considered in the design and documented in the ICDs.
- All chits related to the inner-PF replacement job are closed
- Risks are mitigated through:
  - Inner-PF prototype program to prove and refine manufacturing techniques and down select the highest quality manufacturer
  - Prototype testing and inspection
  - On-site presence during manufacturing
  - Extensive testing of final coils
- Safety practices such as JHA extended to work at external vendors