Design Verification & Validation Review

Magnet Sytems

Existing Inner PF Coils
Issue & Gaps

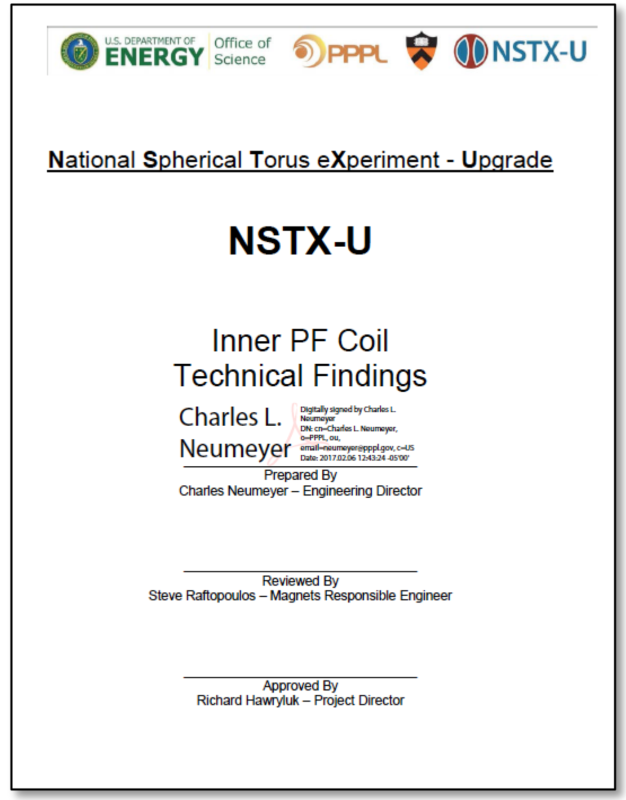
Charles Neumeyer

NSTX-U Recovery Project

Engineering Director

Outline

- Background facts
  - Design basis
  - Procurement + Fabrication
  - Commissioning and Operation
  - Coil failure
  - Forensic examination
- Issues
  - PF1A Issues
    - Insulation configuration
    - Vacuum Pressure Impregnation
    - Conductor
    - Surge Testing
  - PF1B + PF1C Issues
- PF1A Failure modes
  - Insulation properties
  - Electrical exposure of fault region
  - Partial dischage assessment
  - Failure hypotheses
- Discussion of suitability of existing Inner PF Coils for continued use



U.S. DEPARTMENT OF ENERGY | Office of Science | PPPL | NSTX-U

National Spherical Torus eXperiment - Upgrade

NSTX-U

Inner PF Coil
Technical Findings

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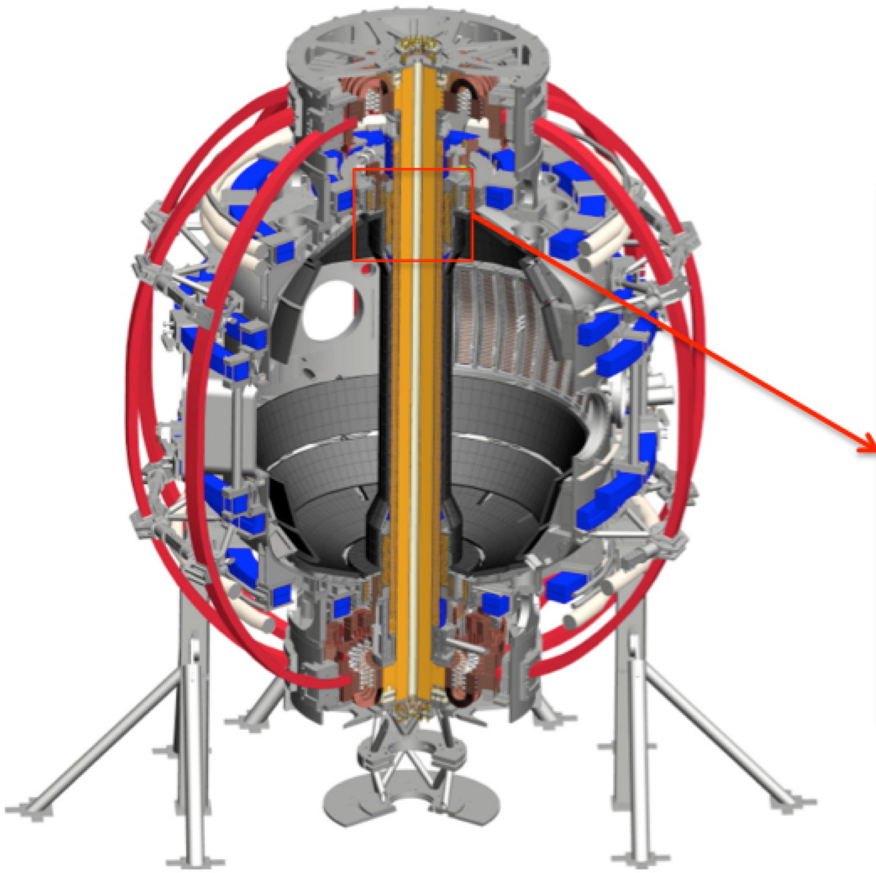
Reviewed By
Steve Raftopoulos – Magnets Responsible Engineer

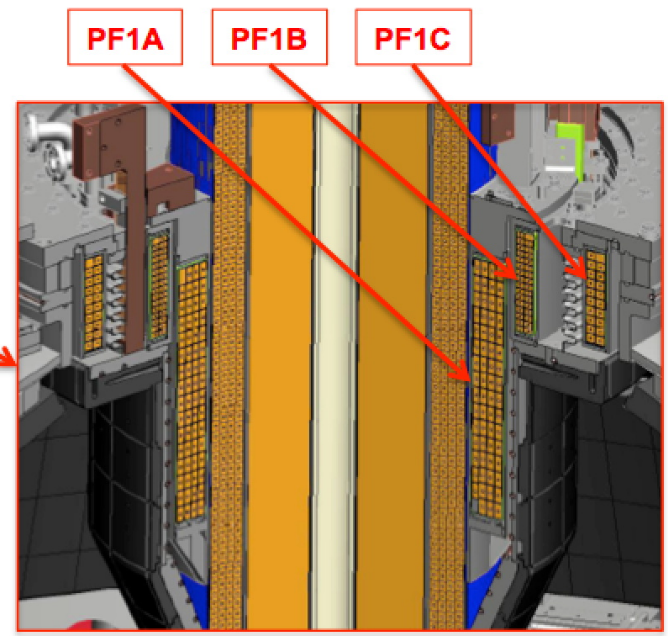
Approved By
Richard Hawryluk – Project Director

https://drive.google.com/file/d/0B5etK6OoFMi1a3dHMDVJZWlIQ00/view?usp=sharing

Design Basis

Function





- The Inner PF coils control the magnetic geometry of the divertor
  - X-point
  - outer divertor strike point
  - local flux expansions

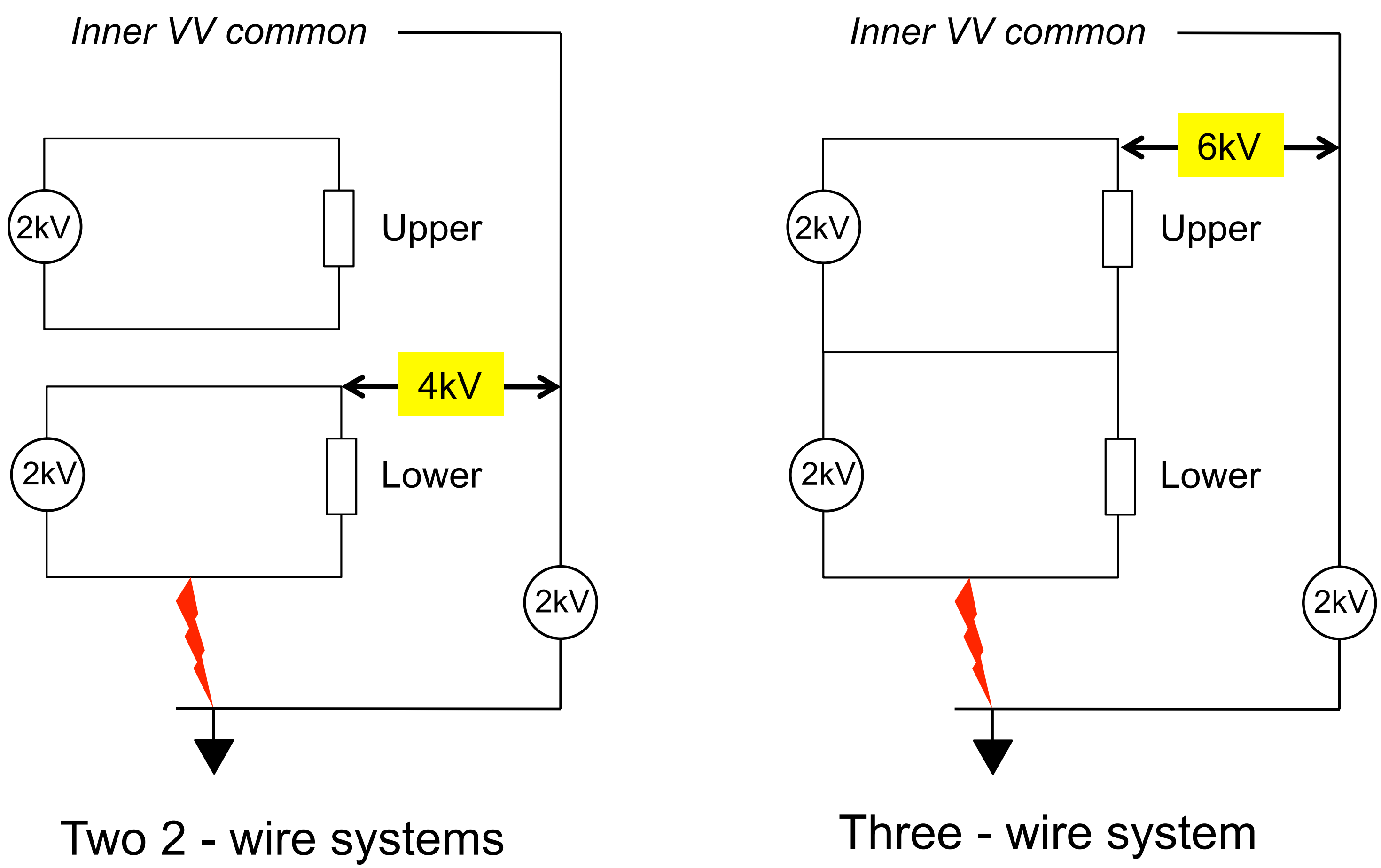
Design Point Spreadsheet Specs (1)

Parameter	Units	PF1A	PF1B	PF1C
Conductor width	mm	14.3	16.1	17.9
Conductor height	mm	27.6	10.0	15.3
Cooling hole diameter	mm	5.2	3.2	3.2
Corner radius	mm	1.0	1.0	1.0
Turn insulation	mm	0.7	0.7	0.7
Number of turns radially nr		4	2	2
Number of turns vertically nz		16	16	10
n	turns	64	32	20
Packing fraction		0.8244	0.7883	0.8495
Current per turn	amp	19000	13000	16000
ESW at Max Current	sec	5.5	2.1	4.3
T_max	deg_C	92	100	100
Max Power Supply Vdc (Vdo)	volt	2026	2026	2026
Voltage per turn	volt	31.7	63.3	101.3
Layer-layer voltage	volt	1013	2026	2026
Turn insulation maximum stress (layer-layer)	kv/mm	0.6	1.2	1.2
Ground insulation	m	0.0022	0.0028	0.0018
Ground & turn insulation	m	0.0029	0.0035	0.0026
Turn-ground stress	kV/mm	2.1	1.7	2.4
Hipot voltage	Volt	13103	13103	13103
Turn-ground stress (hipot)	kV/mm	4.5	3.7	5.1

Design Point Spreadsheet Specs (2)

Parameter	Units	PF1A	PF1B	PF1C
Turn insulation glass tape thickness	mm	0.127	0.127	0.127
Turn insulation glass tape compression		0.070	0.070	0.070
Turn insulation #half lapped glass tape layers		2	2	2
Turn insulation kapton tape thickness	mm	0.1	0.1	0.1
Turn insulation kapton adhesive thickness	mm	0.02	0.02	0.02
Turn insulation #half lapped kapton tape layers		2	2	2
Turn insulation build	mm	0.7	0.7	0.7
Ground insulation glass tape thickness	mm	0.2	0.3	0.3
Ground insulation glass tape compression		0.1	0.1	0.1
Ground insulation #half lapped glass tape layers		5	6	4
Ground insulation build	mm	2.2	2.8	1.8
Ground + Turn insulation build	mm	2.9	3.5	2.6
Terminal-terminal voltage	kV	2	2	2
Turn voltage stress factor		0.5	1.0	1.0
Max turn-to-turn voltage	kV	1	2	2
Max turn-turn stress	kV/mm	1	1	1
Turn insulation dielectric strength constant	$kV/mm^{0.5}$	50	50	50
Turn-turn dielectric strength	kV	61	61	61
Turn insulation safety factor		60	30	30
Max turn-ground voltage	kV	6	6	6
Hipot voltage	kV	13	13	13
Max turn-to-ground stress, nominal	kV/mm	2	2	2
Max turn-to-ground stress, hipot	kV/mm	4	4	5
Ground insulation dielectric strength constant	$kV/mm^{0.5}$	50.	50.	50.
Ground insulation dielectric strength	kV	85	94	80
Ground insulation safety factor		21	23	20
Ground insulation safety factor (hipot)		7	7	6

Voltage to Ground



- CHI adds another 2kV on common
- $V_g^{max} = 2+2+2 = 6kV$
- Hipot = 2*6+1 = 13kV

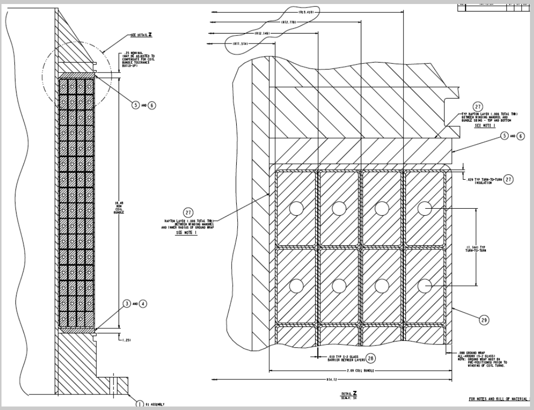
Assembly Drawings

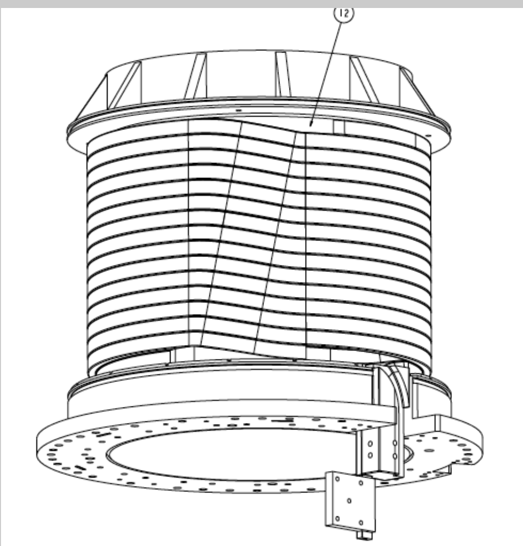
PF1A [1EDC1447]

PF1B [2EDC1452]

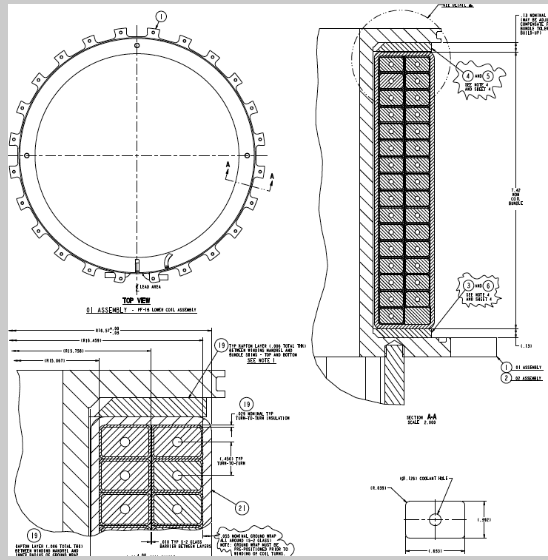
PF1C [1EDC1448]

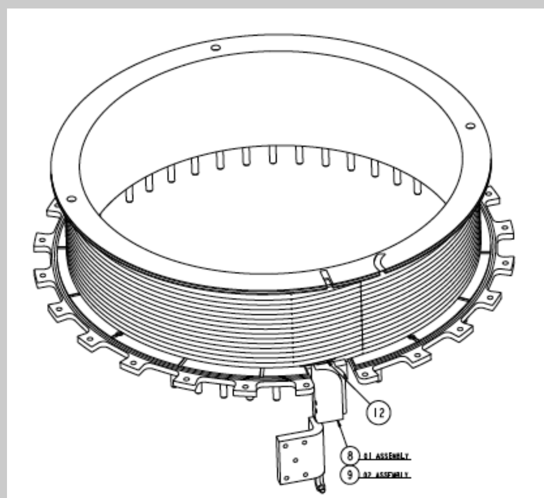
PF1A



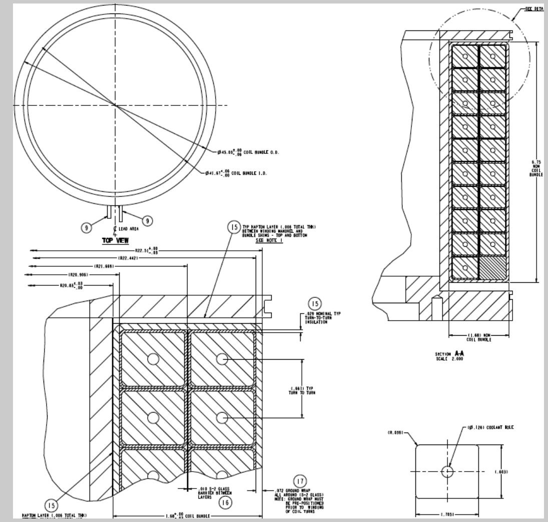


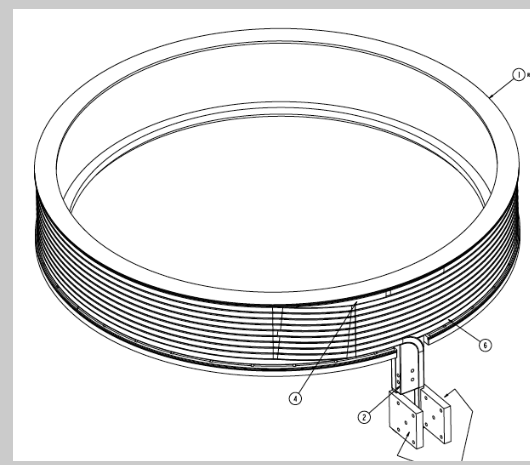
PF1B





PF1C

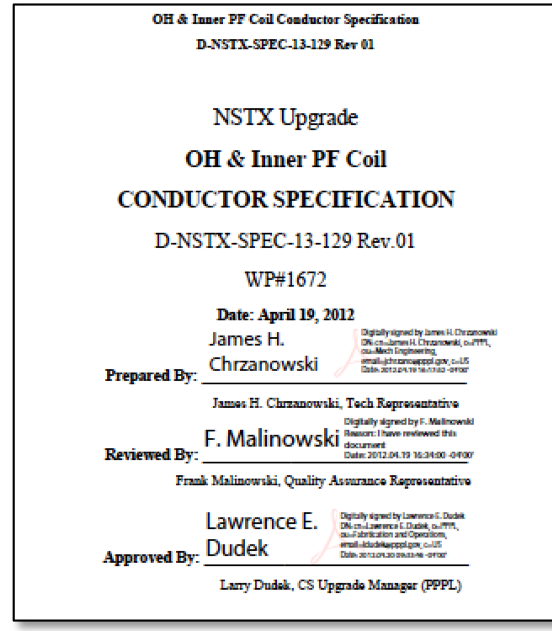




Procurement
+ Fabrication

Procurement

- A common specification was used to procure conductor or the Inner PF coils and Ohmic Heating (OH) coil. The specified range of yield strength was 29 ksi (200 MPa) min to 36 ksi (250 MPa) max, corresponding hardness range between half-hard and hard.



OH & Inner PF Coil Conductor Specification
D-NSTX-SPEC-13-129 Rev 01

NSTX Upgrade
OH & Inner PF Coil
CONDUCTOR SPECIFICATION
D-NSTX-SPEC-13-129 Rev.01
WP#1672
Date: April 19, 2012

Prepared By: James H. Chrzanowski
James H. Chrzanowski, Tech Representative

Reviewed By: F. Malinowski
Digitally signed by F. Malinowski
Reason: I have reviewed this document
Frank Malinowski, Quality Assurance Representative

Approved By: Lawrence E. Dudek
Larry Dudek, CS Upgrade Manager (PPPL)

- A common specification was used to procure all three coil pairs. Only one viable proposal was received and the contract was awarded to Everson-Tesla of Nazareth, Pennsylvania, USA under subcontract S012485.

NSTX-U

MANUFACTURING SPECIFICATION

Fabrication of Inner Poloidal Field (PF) Coils

D-NSTX-SPEC-134-137 Rev.00

November 16, 2012

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Steve Raftopoulos
Coil Engineer

Approved By: ______ Date: ______
Larry Dudek
NSTX-U Centerstack RLM

Fabrication

everson
tesla
incorporated

Inner PF Report Log

Blake Koop, Project Engineer, ETI
Prepared for: Princeton Plasma Physics Laboratory
Date of PO: March 12, 2013
PPPL PO#: S012485-G
ET#: 53156

Inner PF Report Log, B. Koop, Project Engineer, Everson-Tesla, Inc

Everson "Manufacturing Process Outline" (MPO) forms

Manufacturing Process Outline/Traveler
For the Inner PF-1A Coils
ETI Doc #: 53156-603

Coil Identification Number: PF-1A-UPPER

Everson Tesla Inc. # 53156

Work Order# 5789

Customer:	Princeton University Plasma Physics Laboratory PO Box 451 Princeton, NJ 08543
PPPL Purchase Order Number: S012485-G	Date: 3/14/13

Original Author(s): BLAKE KOOP	APPROVED BY (Signature & Date)
Date: 12/10/13	Project Engineer: BLAKE KOOP 2/11/14
Revised by:	Manufacturing Rep: 2/11/14
Revision Date:	Quality Assurance: Roger Brown 2/11/14
Revision:	PPPL Rep.: Steve Raftopoulos

The original completed Traveler and the Test Record Sheets shall be maintained in the Everson Tesla QA Department.

Revision Table

Revision	Description	Date
A	Initial Document Release	2/10/14

PF-1A-Lower-MPO-Complete.pdf

MPO Process History (in order of VPI completion)

VPI completion date-->	*12/19/13*	*1/27/14*	*4/28/14*	*5/9/14*	*6/3/14*	*6/16/14*
	PF1BL	**PF1BU**	**PF1AL**	**PF1CL**	**PF1AU**	**PF1CU**
4.8.1 Pre-VPI 1kV 1Min Megger (MOhms)	4000	23100	8000	2000	>2000	2250
4.11 Water Flow Test (GPM)	0.35	0.336	0.93	0.38	0.96	0.38
4.13.5 Mold Degas 0.5Torr/8Hr/120F 2min Leak Rate <0.35 (T/Min)	0.01	Vac Tank	0.23	0.28	0.34	0.14
4.14.3 Mixture Degas Weight (Lbs)	57.5	45	76	35	76	35
4.14.3 Mixture Degas mix time >30 (Minutes)	100	180	160	80	150	150
4.14.3 Mixture Degas temperature (C)	49	60	57	55	55	50
4.14.3 Mixture Degas vacuum 0.2 (Torr)	0.21	0.6	0.41	0.49	0.37	0.28
4.14.5 Impregnate Pressure (Torr)	NR (1.5-2.0 spec)	NR (1.5-2.0 spec)	2.7	NR (1.5-2.0 spec)	NR (1.5-2.0 spec)	NR (1.5-2.0 spec)
4.14.7 Unused Resin (Lbs)	35	15	41.3	14.6	35	19
Calculated Resin Used (Lbs)	22.5	30	34.7	20.4	41	16
4.14.9 Cure Ramp 50C to 100C >10 hrs/600 minutes time (Minutes)	615	600	810	855	1410	1740
4.14.9 Cure Hold 100C time 15 hrs/960 minutes (Minutes)	870	900	960	900	1020	900
4.14.9 Cure Ramp 100C to 170C >14hrs/840 minutes time (Minutes)	855	825	814	840	1260	840
4.14.9 Cure hold 170C for 24 hours/1440 minutes (Minutes)	585	615	626	600	600	585
4.14.9 Cure Ramp 170C to 25C for >13 hours/780 minutes (Minutes)	>1050	>600	660	>600	1440	>1170
4.17.1 Conductor Resistance (Corrected @20C) Ohms (but really mOhms)	8.88	8.93	5.85	4.24	5.34	4.22
4.17.3 9kV Megger spec'd - 10kV performed (Gohms)	128	161	89.4	62.3	32.2	51
4.17.4 9kV current leakage (uA)	<0.2	0.1	<0.1	0.1	<0.2	<0.2
4.20.2 Water Flow Test (GPM)	0.35	0.345	0.93	0.38	0.91	0.39

- Concerns
  - Outgassing did not reach spec pressure
  - Fill times were less than spec in some cases
  - Cure times were less than spec in some cases
  - Resin usage difference between upper and lower coils that should be the same

Surge Testing (1)

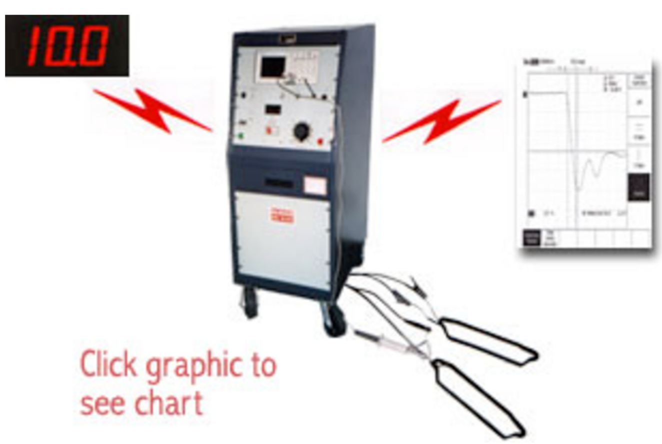
- Specification for final acceptance

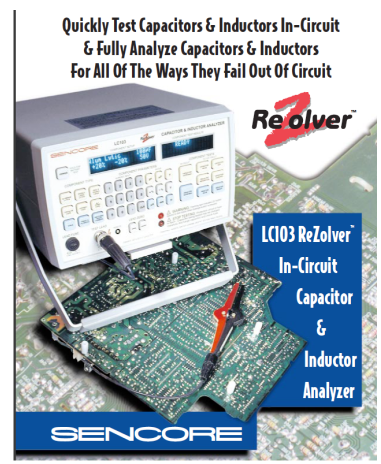
5.3.5 <u>Induced Test [turn to turn]:</u>

Performed to electrically stress the coil turn to turn insulation to check the insulation integrity and confirm its ability to withstand any voltage to which it will be subjected to in service. Record test data.

Test Terminal voltage: **5000 volts**

- Actual test was pre- and post-VPI surge test using PJ tester (model #?) followed by Sencore LC103 ring test

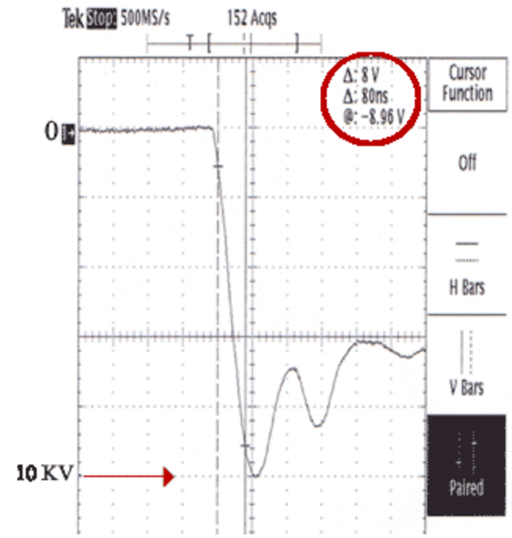




Surge Testing (2)

- PJ tester
  - Repetitive surge
    - 1 per cycle at 60Hz
    - 100 nanosecond rise time

http://www.pjelectronics.com/



- Sencore LC103 ring test

RINGING TEST:
- A dynamic test of inductor quality determined by applying an exciting pulse to the inductor and counting the number of cycles the inductor rings before reaching a preset damping point.
Inductor Range: 10 uH and larger, non-iron core
Accuracy: ±1 count on readings between 8 and 13 Rings Resolution: ±1 count
Exciting Pulse: 5 volts peak

Commissioning + Operation

Surge Testing

- In addition to DC hipot tests, surge testing was performed by PPPL on all coils at 2kV using a PJ Tester Model S12 per D-PTP-NSTX-CL-049

http://www.pjelectronics.com/

Operational History

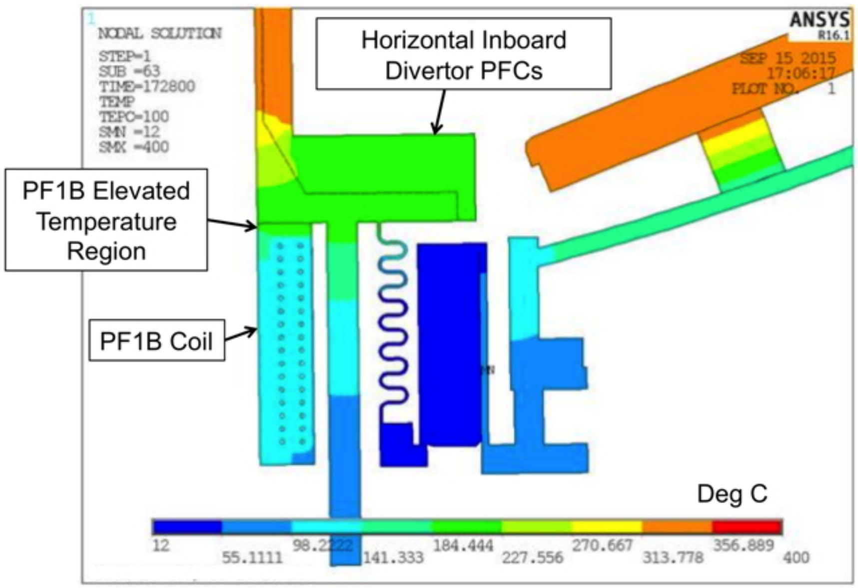
	PF1A-U	PF1A-L	PF1B-U	PF1B-L	PF1C-U	PF1C-L
Total No. Shots @ 1kV	1119	1122	0	0	37	26
Total No. Shots @ 2kV	4	4	0	0	2	2
Total No. Shots	1123	1126	0	0	39	28
Maximum Current	14.8	14.9	0	0	7.5	-7.5
Maximum Rated Current	19	19	13	13	16	16
Maximum Current (% rated)	78	78	0	0	47	47
Maximum I2T	252	219	0	0	53	67
Maximum Rated I2T	2000	2000	356	356	1100	1100
Maximum I2T (% rated)	13	11	0	0	5	6

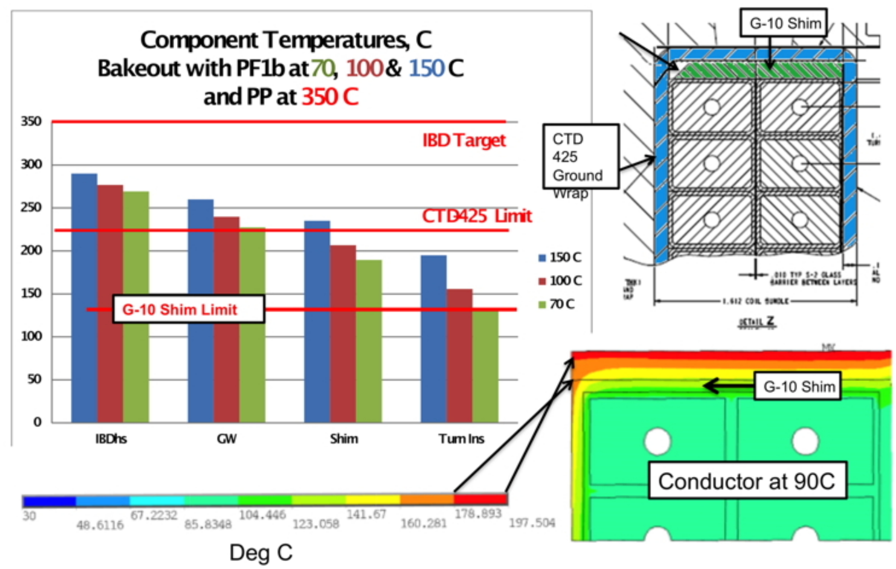
- Summary
  - Most pulsing with PF1A thus far but at low levels
  - No pulsing on PF1B
  - Limited number of pulses on PF1C

Courtesy S. Gerhardt

PF1B Bakeout Issue

- Design issue related to ability to bake PFCs at 350ºC vs. limit on PF1B temperature
  - Insulating materials exposed to relatively high temperatures



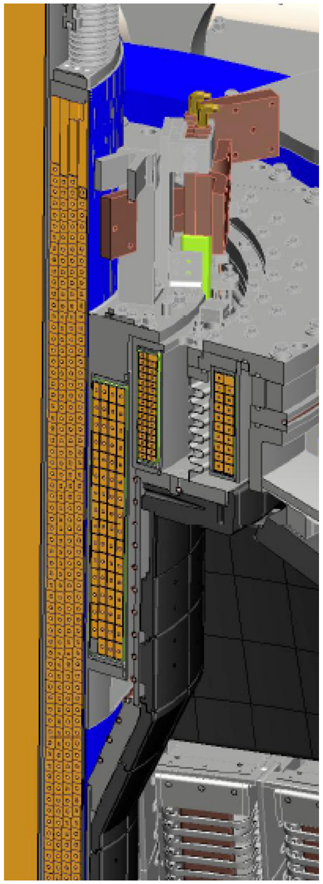


Temperature	G-10 Shims	CTD-425 Ground and Turn Insulation
Calculated maximum temperature	Between 160 - 179^{o}C	Between 179 - 198^{o}C
Rated service temperature (taken to be equal to glass transition temperature)	140^{o}C	185^{o}C

Exposure to Water after OH fault on April 24, 2015

- Water return lines (4 of 8) were breached and a significant quantity of water was released

- PF1CU sits in a can that forms a reservoir and was submerged
  - this did not cause any hipot problem until 10 months later



- After event ~ 1 month of drying with fans was required before the inner VV could pass 5kV hipot

- PF1AU coil got very wet, but whether or not the water pooled up such that the coil was submerged, is unclear

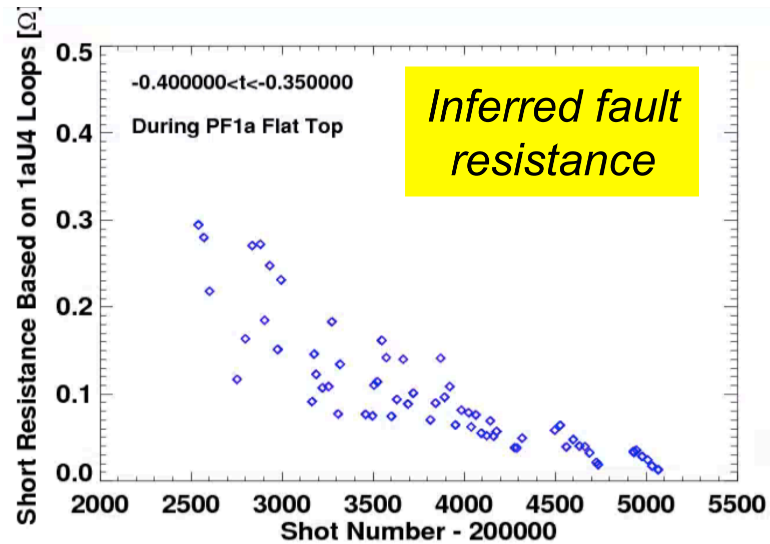
PF1AU Failure

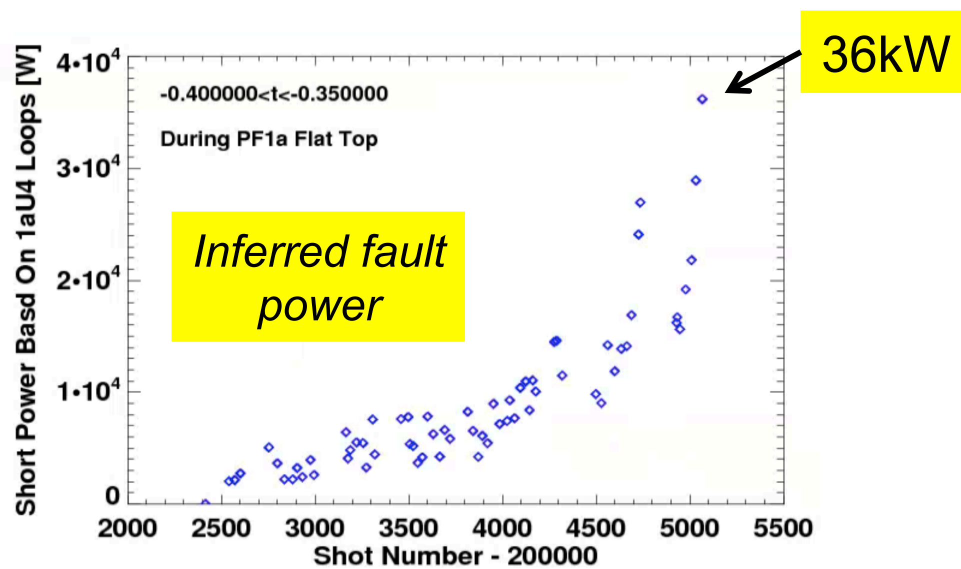
PF1AU Failure

- A water flow blockage occurred in PF1AU in June 2016, followed by a water leak
- These events, along with other observed electromagnetic anomalies led to the conclusion that a turn-to-turn short had occurred
- NSTX-U operations were ceased, the center stack was removed, and the PF1AU coil was removed for forensic examination

Morning Test Shots Show Degradation of the Coil Over Time

- Based on daily 100% test shots
  - Portion of shot w/steady PF1AU current
- Flux loops on the coil
  - showed a decrease in flux per unit current (inductance) over time
- Assume 18 turns shorted and fit the resistance of the short

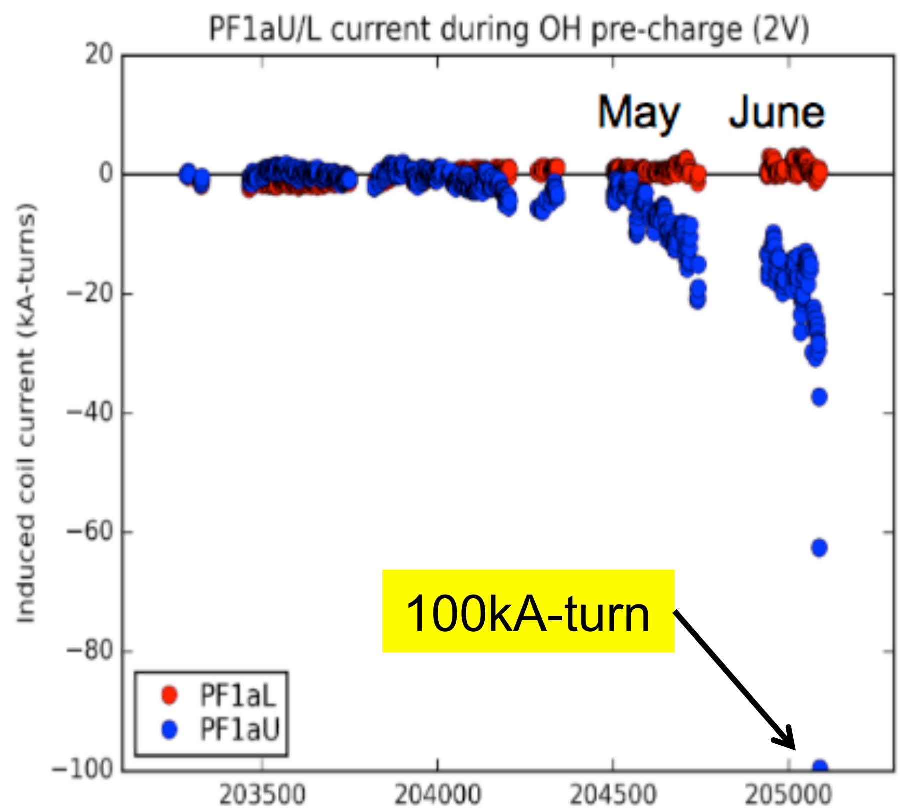




Courtesy S. Gerhardt

Induced Current Grew Rapidly on the Final Shots

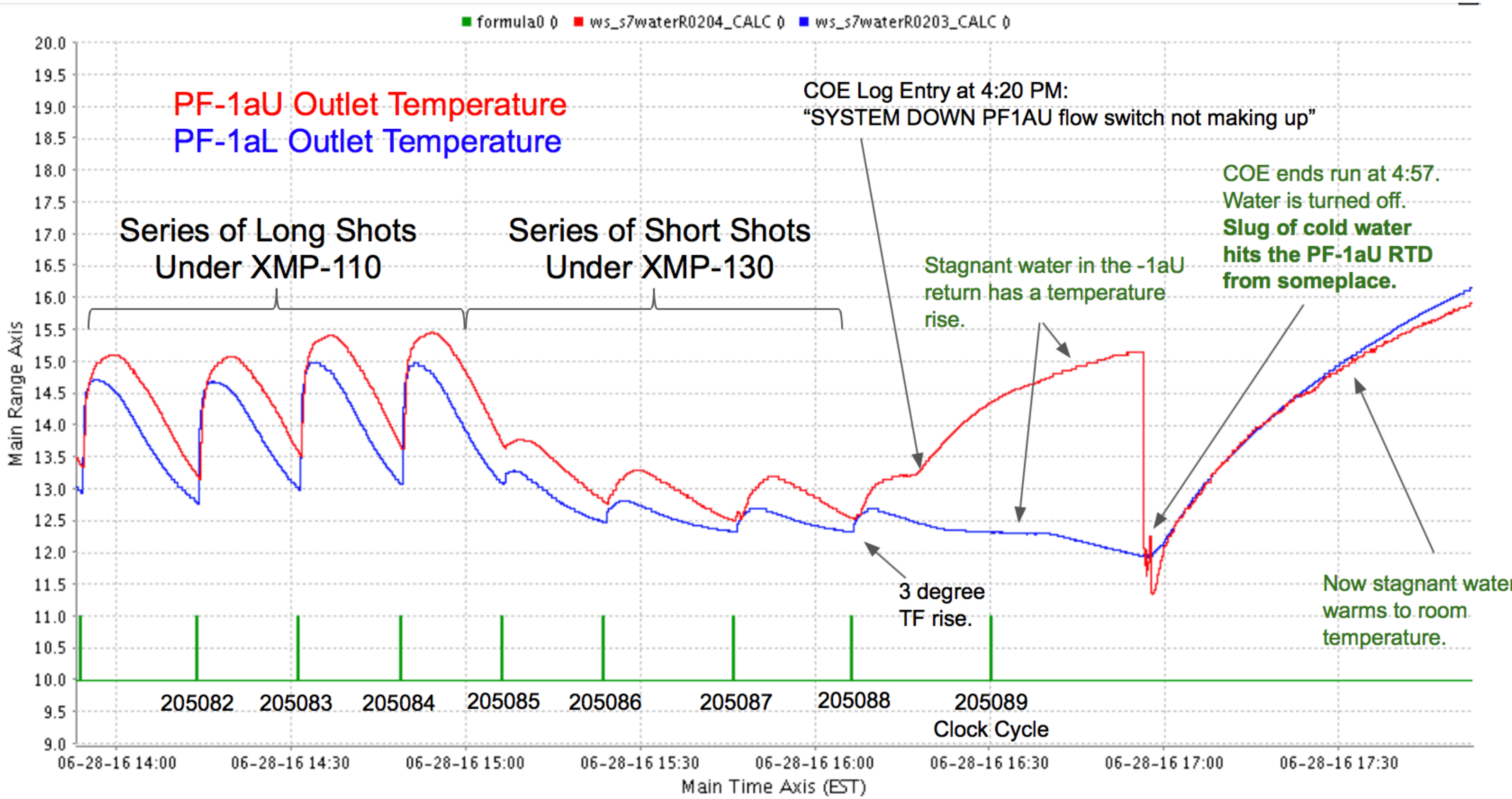
- Based on OH pre-charge phase of the discharge
  - PF-1aU rectifier controlled to zero during this time
- Infer current induced in shorted turns from flux loops
  - Reached 100kA-turns (6kA/turn assuming 18 turns)
- Rapid degradation of the coil in the final shots
  - Indicates substantially more power was dissipated on the final shots



Courtesy S. Gerhardt

Water Flow Was Only Plugged After Final Shot

Temperature on outlet side at the water manifolds, many meters from coil

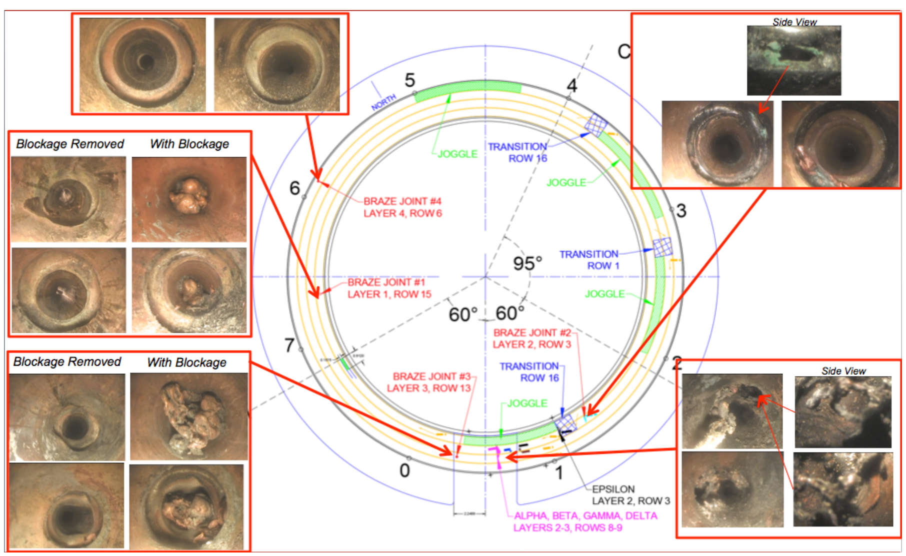


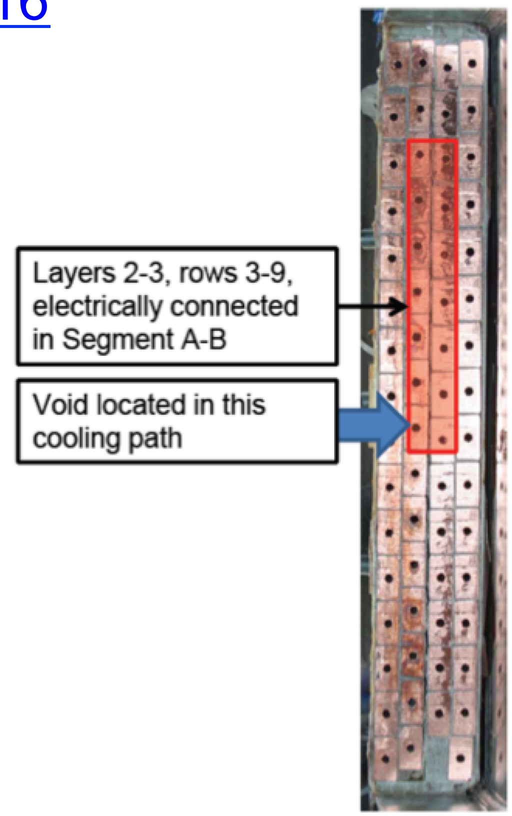
Courtesy S. Gerhardt

Forensic Examination

Forensic Examination

[Forensic Analysis of the NSTX-U PF1A-Upper Coil Failure, I. Zatz, J. Petrella, 11/18/16]





- Revealed poor quality
  - VPI
  - Braze joints
- Identifed fault zone

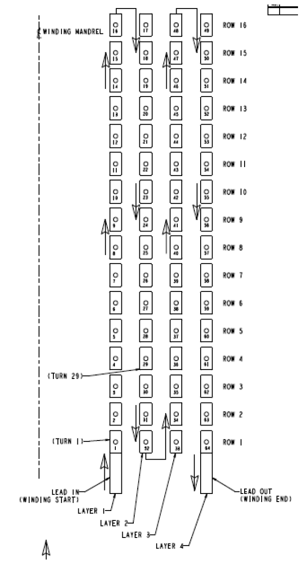
Courtesy J. Petrella

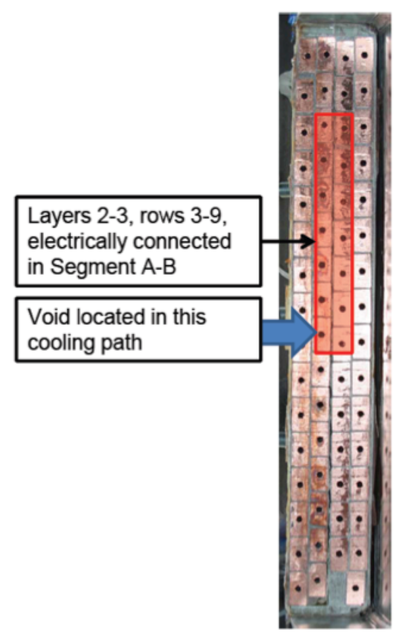
Winding Pattern - Effected Turns

C/L

2000	Volt					
31	V/turn					
Start Lead	V_L-L	Turn#	V_L-L	Turn#	V_L-L	Finish Lead
1	969	32	31	33	969	64
2	906	31	94	34	906	63
3	844	30	156	35	844	62
4	781	29	219	36	781	61
5	719	28	281	37	719	60
6	656	27	344	38	656	59
7	594	26	406	39	594	58
8	531	25	469	40	531	57
9	469	24	531	41	469	56
10	406	23	594	42	406	55
11	344	22	[illegible]	43	344	54
12	281	21	[illegible]	44	281	53
13	219	20	781	45	219	52
14	156	19	844	46	156	51
15	94	18	906	47	94	50
16	31	17	969	48	31	49

18 turns





531 V across 18 turns @ V_{ps} = 2kV

Opinion of Magnet Expert – Possible Causes of Fault

- A foreign object (a metal chip, a screw, a paper clip, etc) in the winding pack that got in the winding pack before VPI, punctured the insulation to the extent that it was a weak short that developed a bad short, melting, massive short and so on. This may be possible to discover when PPPL team will take apart the winding portion with the short, and maybe find fragments of this foreign object. *[note: this was written before layers 2 + 3 were separated]*

- Initial micro crack in copper tube due to fabrication, which might have started during drawing, then opened during winding and was sealed by the VPI. After several cycles – opened up and initiated a leak. It is worth checking each conductor in the area which did not have a hole by hydraulic or gas pressure test to check if any of these conductors have a crack other than the one with the obvious hole... *[note: in fact, this was done, all paths were tested]*

- A pinhole because of corrosion. This is not very likely, but not impossible. The corrosion usually happens after years of operation with the regular water. In PPPL I presume it is de-ionized water that should have a low level of corrosion even at elevated temperatures and presence of strong electrical potentials

Continuing Forensic Work

- Coil was split open to reveal fault and extract samples (photos following)
- Conductor metallurgical examination (Test Plan)
  - Tests
    - Grain Size Exam
    - Micro-Hardness
    - Microstructure (Cuprous Oxide)
  - Samples
    - 2 straight sections from unused, spooled conductor
    - 3 from PF1AU coil, main conductor pack
    - 3 from PF1AU coil, joggles
- Insulation samples being sent to CTD (Insulation Samples)
  - Dynamic Mechanical Analysis (DMA)
  - Differential Scattering Calorimetry (DSC)
- Water absorbtion test at PPPL
  - ASTM D570 Standard Test Method for Water Absorption of Plastics
- Investigating neutron radiography as a void detection scheme
  - first results prove that voids can be seen but rules for interpretation unclear

Courtesy J. Petrella

Water Absorbtion Result (2/6/17)

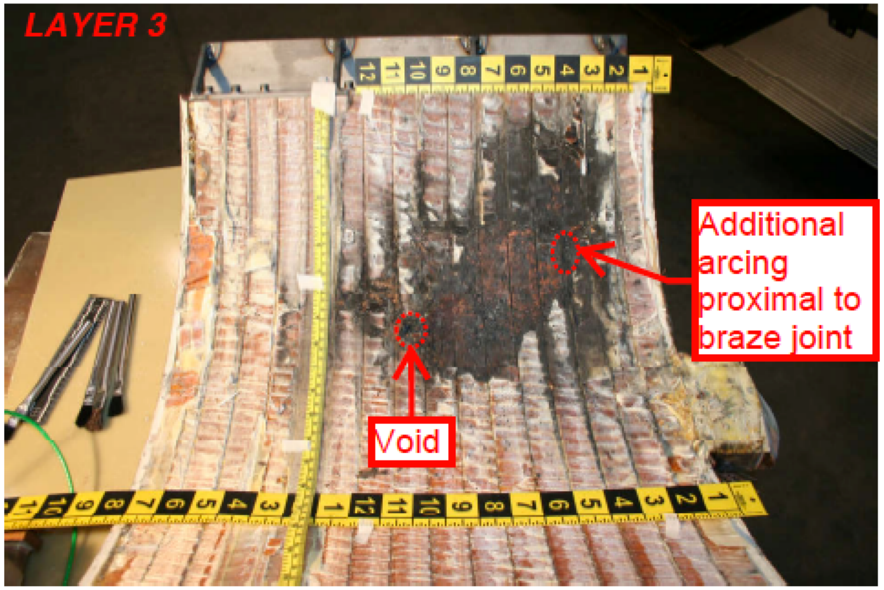
- We completed immersion testing of the PF1AU ground wrap samples in accordance with ASTM D570.

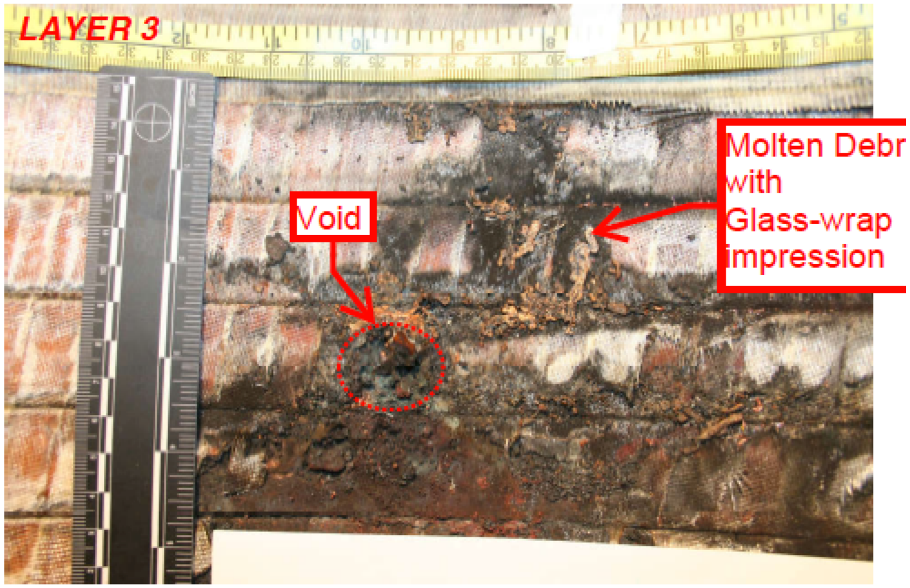
- The standard presents several options for the test parameters, and we chose to use a 2-hour boiling test to expedite the results and stress the samples.

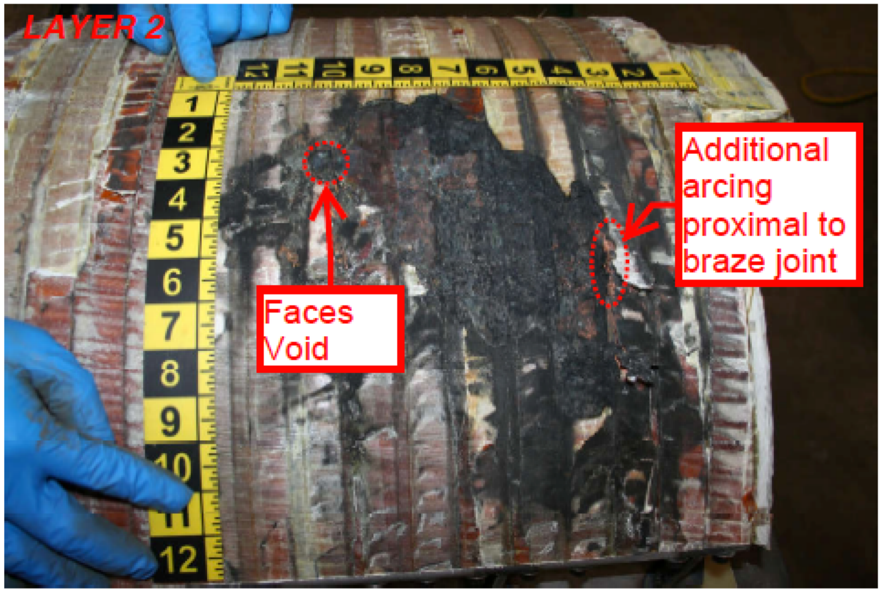
- The selected samples had minimal defects to avoid surface tension water retention. The results should be considered the 'best case' scenario for the VPI ground wrap quality.

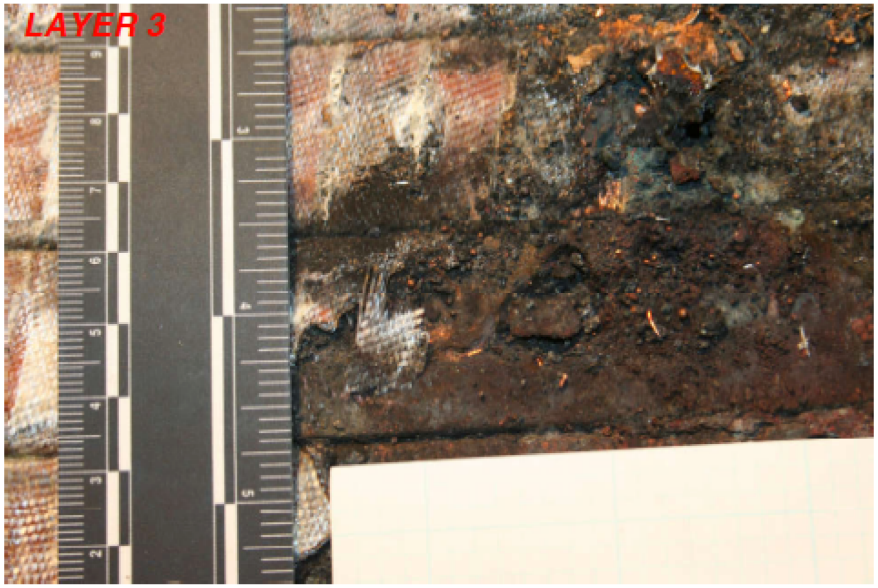
- The overall upshot is that the ground wrap samples did not electrically degrade after the immersion exposure at 1kV. Absorption was on average 0.24% by weight which is consistent with reviewed literature on glass/epoxy composites.

Photos of Fault (1)

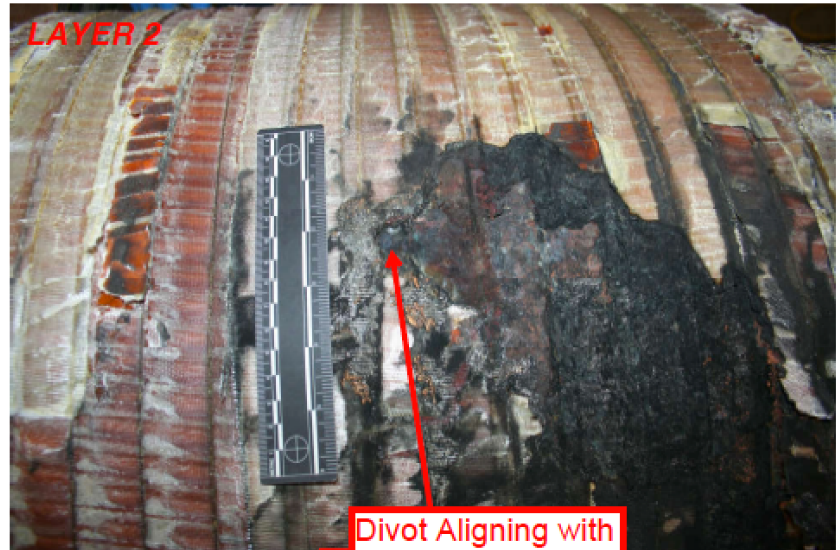


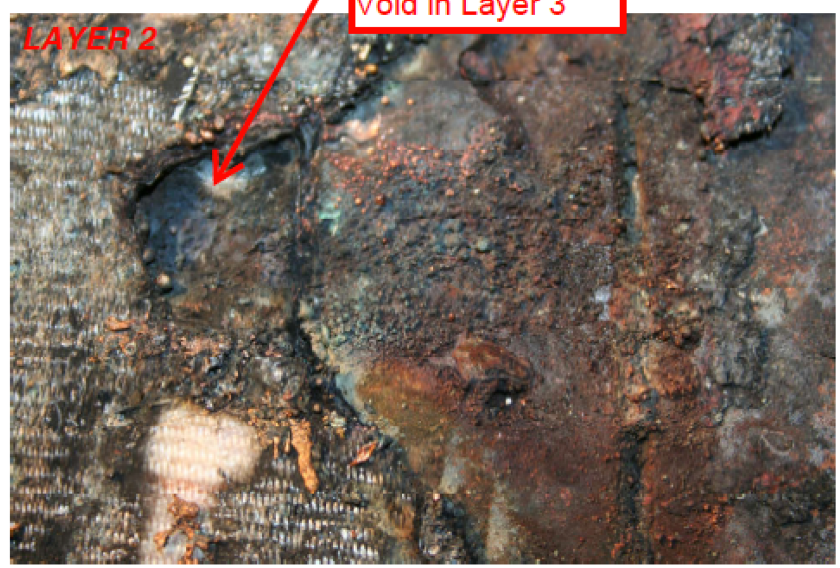




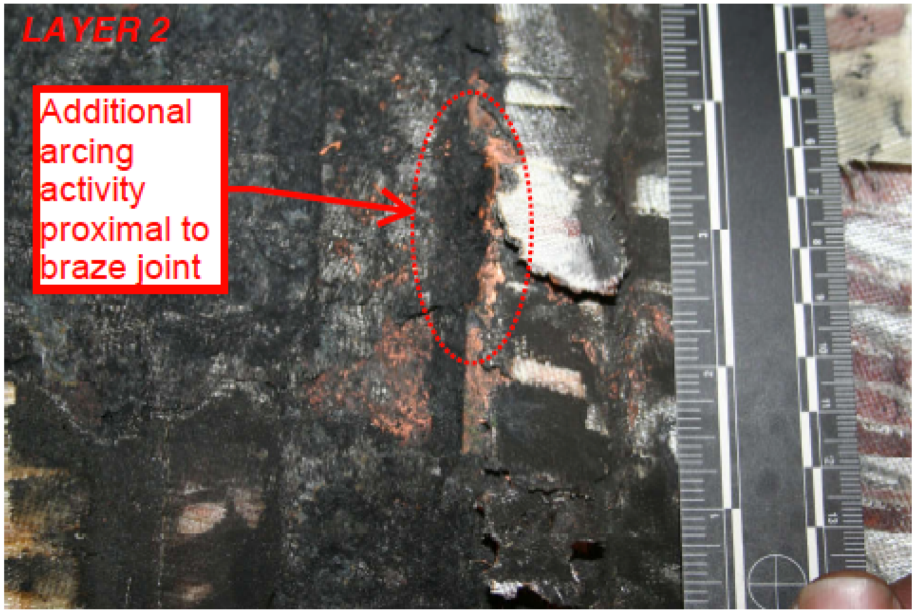


Photos of Fault (2)

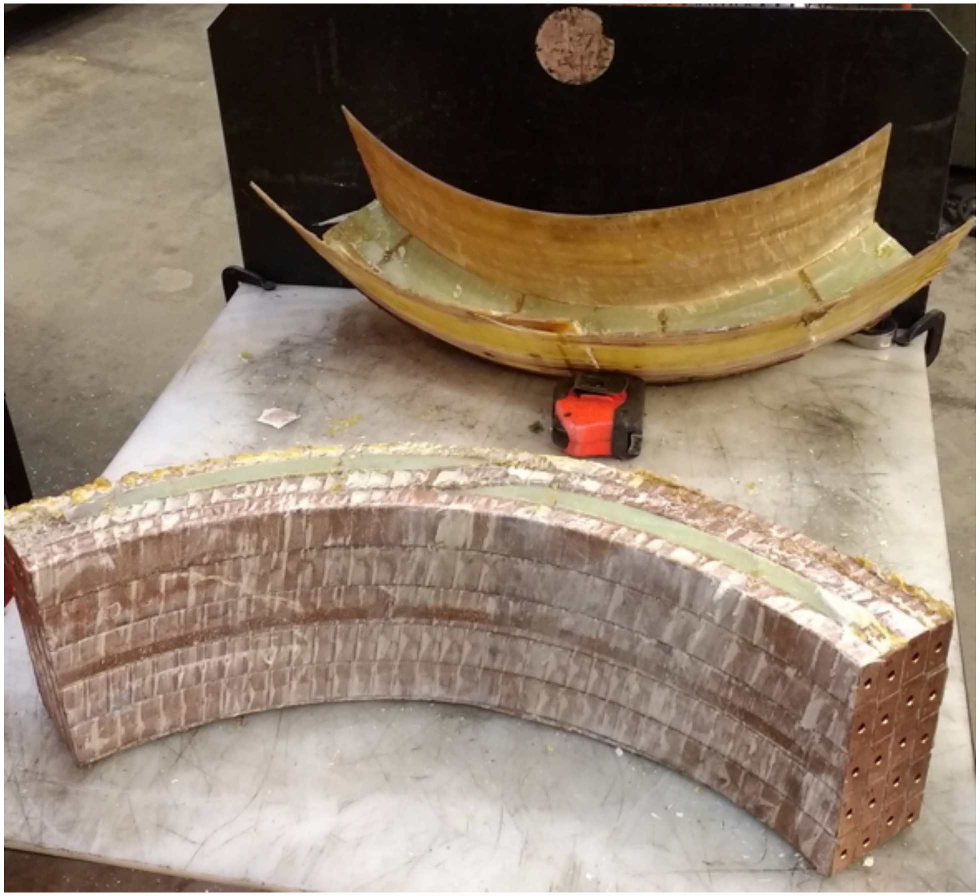




Photos of Fault (3)



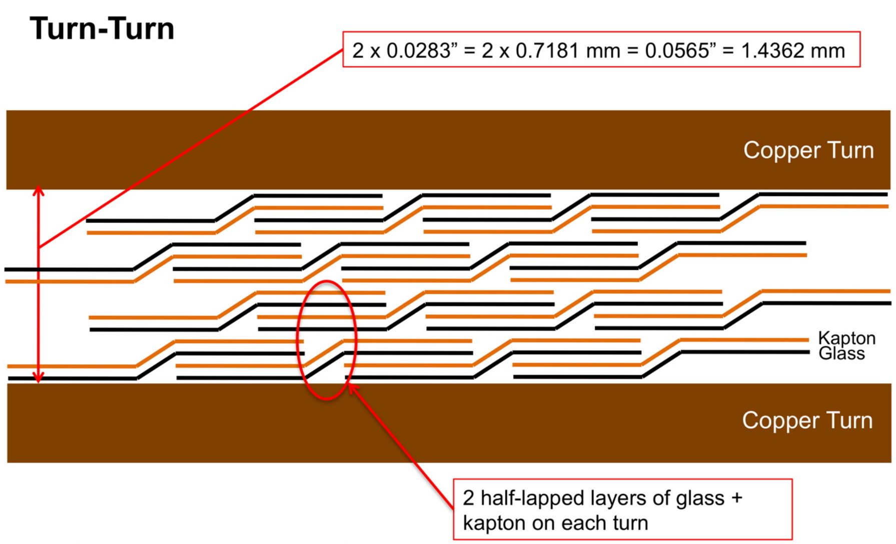
Removal of Groundwall to Access Conductor Samples

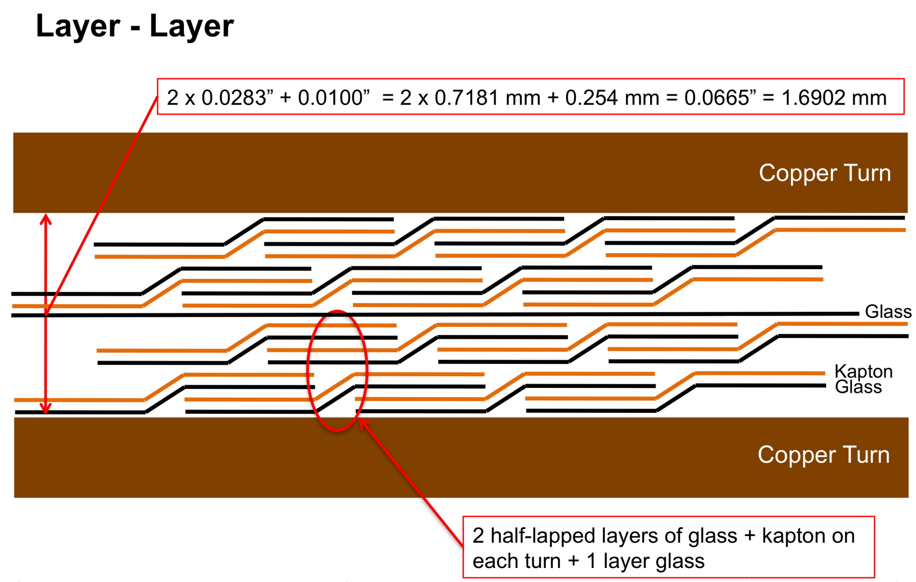


PF1A Issues

Insulation (1)

- Design point spreadsheet configuration
  - If glass facing conductor (favored for bonding insulation to conductor), then kapton-to-kapton interface exists midway between turns (undesirable)

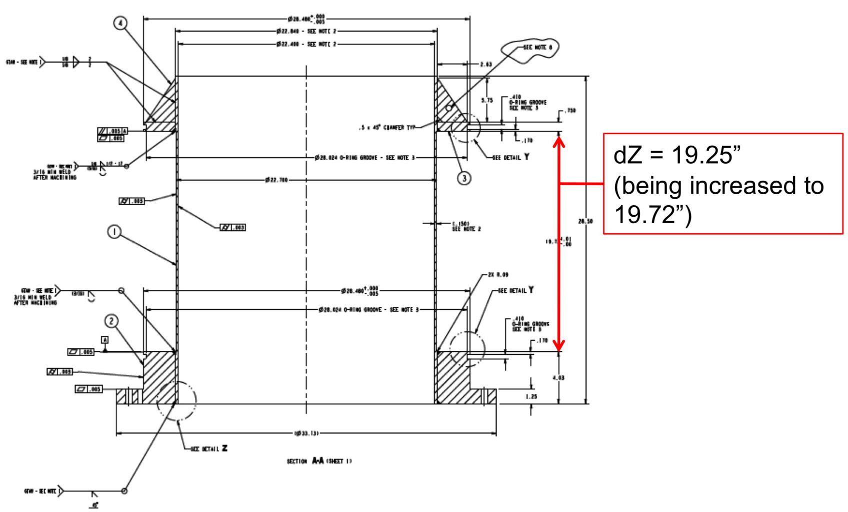


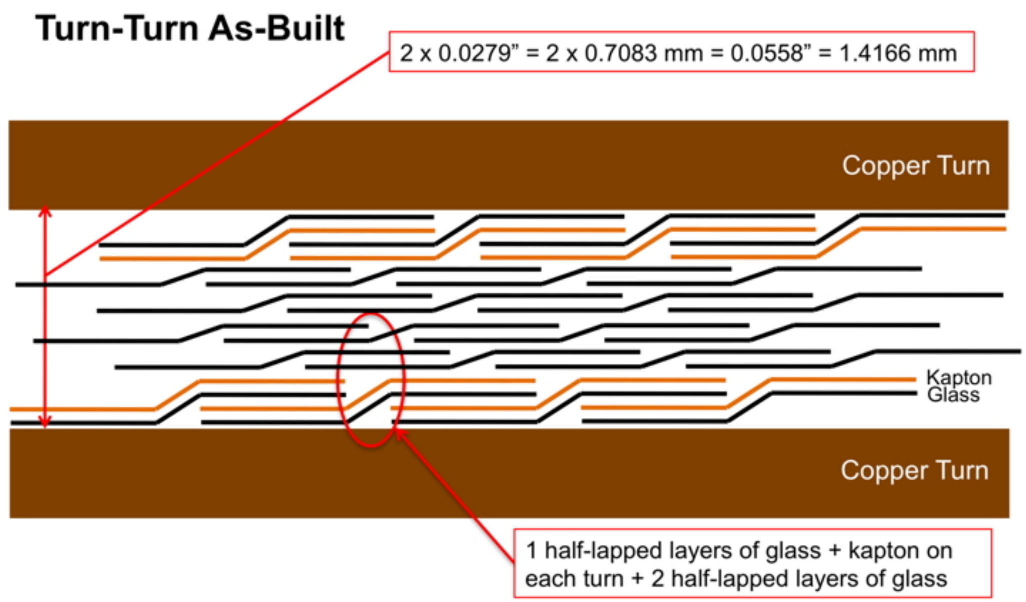


Insulation (2)

- To avoid kapton-to-kapton interfac (?) the spec called for the 2 co-wound layers of glass-kapton per the DPSS, then added 2 half-lapped layers of 0.004” glass.
  - would not fit in gap between the flanges on the mandrel

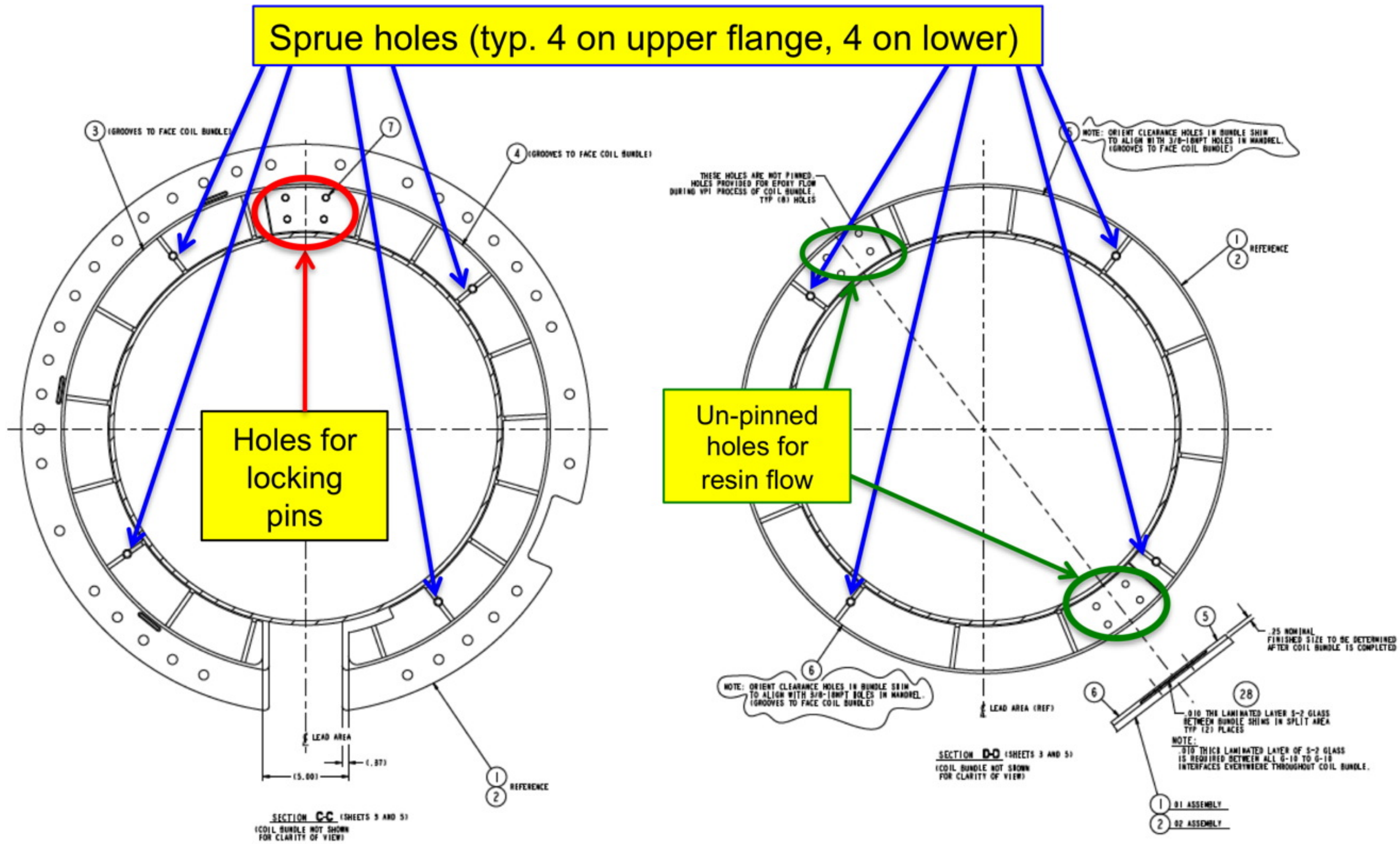
- One of the two layers of co-wound glass-kapton was eliminated





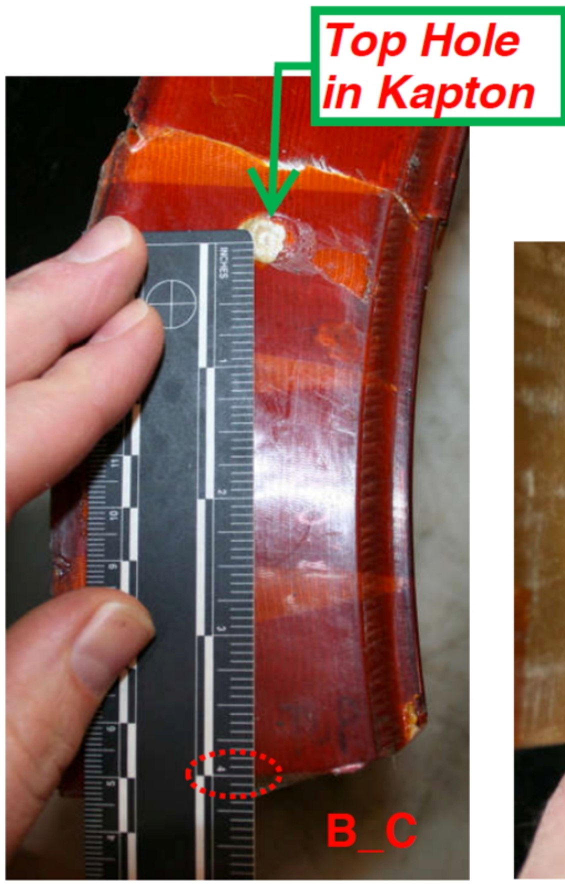
Vacuum Pressure Impregnation (1)

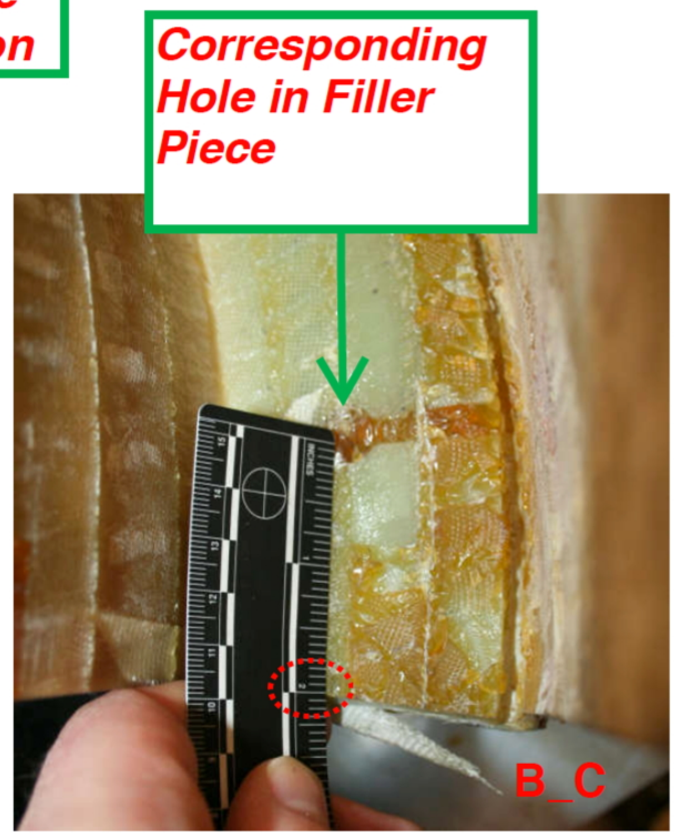
- Sprue holes on flanges for resin inlet and outlet
  - Requires that holes in G-10 align with holes in flanges



Vacuum Pressure Impregnation (2)

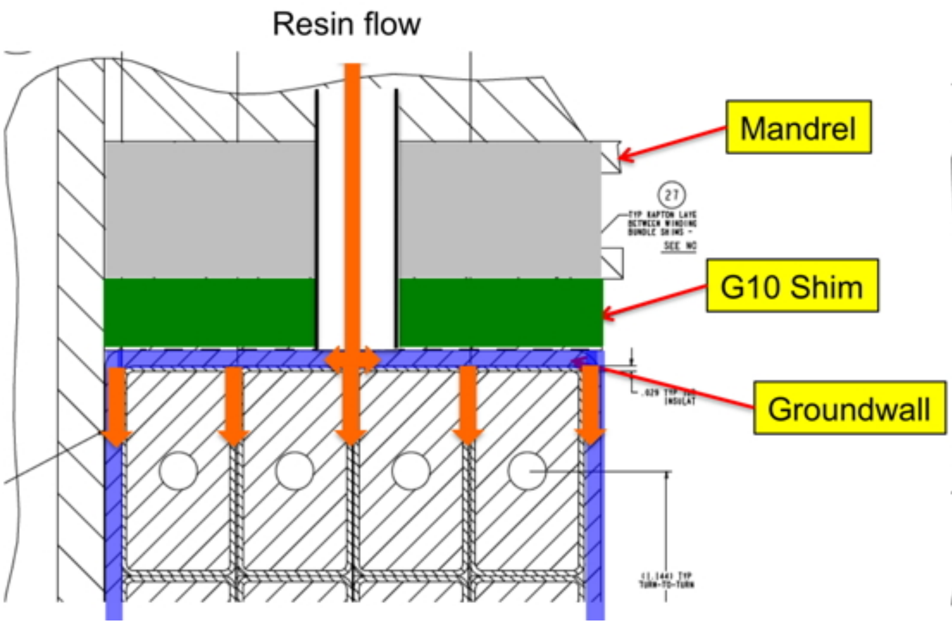
- Holes misaligned by 1.75” inches on PF1AU top flange, 0.625” on bottom flange



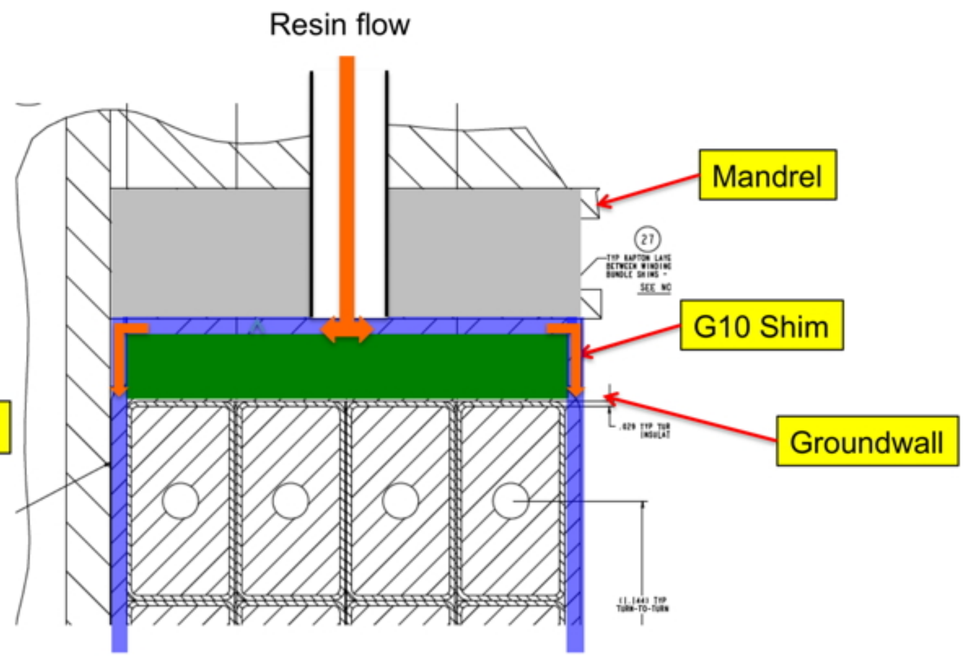


Vacuum Pressure Impregnation (3)

- Sprue hole misalignment increased impedance to resin flow but there was still a path



Specified arrangement of mandrel, G-10 shim and groundwall



As-built configuration and resin flow path

Conductor Hardness

- Hard copper was not necessary for the Inner PF coils and created manufacturing issues

- Specified that way out of convenience (?) since the a common procurement specification was used for the OH and Inner PF coil conductors and the hardness requirement was specified in a single section

- Stress calculations for PF1A without joggles indicate peak stress below 20 MPa and 60 MPa with joggles

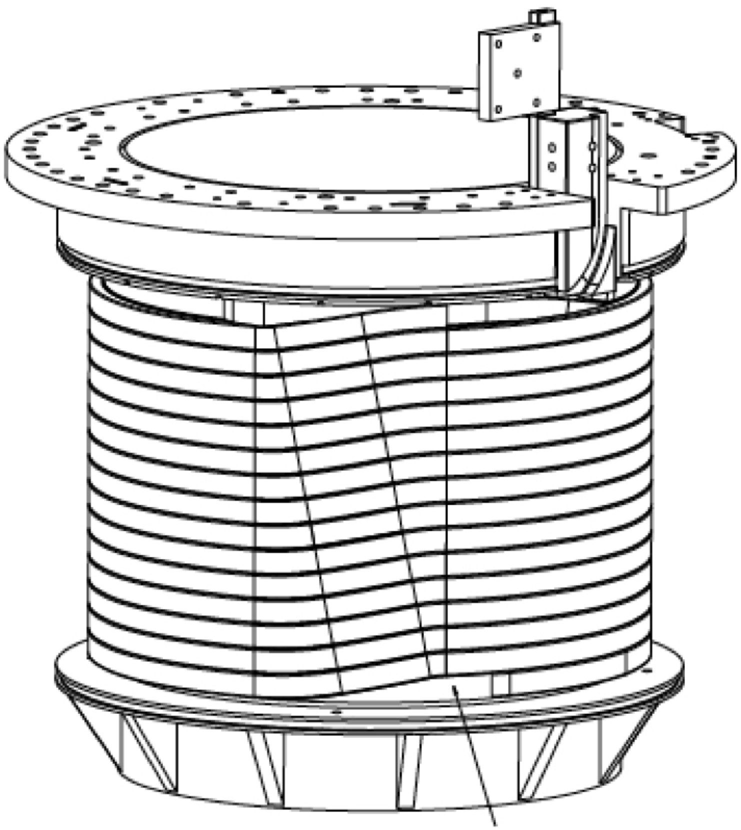
- Assuming an allowable stress of 2/3 yield, a yield strength of 3/2 x 60 MPa = 90 MPa would have been adequate.

- This yield strength (90 MPa = 13ksi) is in the soft copper hardness range and would have been much easier to wind and form into joggles.

Braze Joints

- PF1A conductor could not be supplied in the full length at the specified hardness
  - Winding was fabricated using five sections with four braze joints located at various toroidal angles
  - Note: two vendors have recently supplied the same conductor size in full required length at reduced hardness appropriate for PF1A re-build
- The braze joint process qualification exercise did not meet the PPPL specification criteria, namely that the tensile test failure should occur away from the joint, not at the joint
  - However, the braze joint qualification tests exhibited tensile failure at 22 ksi which does exceed the peak calculated stress and was deemed acceptable
- Everson-Tesla noted on their NCR that "future joints will be heated for a longer period of time"
  - Statement may be accurate but the failure at the braze joint and the comment about heating time raise a flag as to the control of the process
- Note: PF1AU failure did not occur at a braze joint

Joggles (1)



- Joggles were introduced to maximize the number of turns in the winding pack dr x dz
  - DPSS assumed 16 x 4=64
  - Spiral winding achieves 15 x 4 = 60
  - Joggle scheme achieves 63
- 60 turns, compared 64 turns, is within 1.1 headroom multiplier over physics requirement that is used to set current rating
  - Additional margin from round-up to nearest kA used by DPSS in setting current rating

Joggles (2)

- Difficult to wind
  - the position of the joggle had to be precisely anticipated, then the (hard) conductor had to be bent with a heavy hydraulic fixture

- Cross-section becomes distorted
  - conductor had to be shaved and ground down to avoid a bulge in the winding
  - removed copper material (dust, particles, etc.) puts the integrity of the coil at risk

- Temper of the copper is altered and does not yield during winding bending while winding under tension) in the same way as the non-joggled conductor, leading to bulges and points of high pressure on the turn insulation

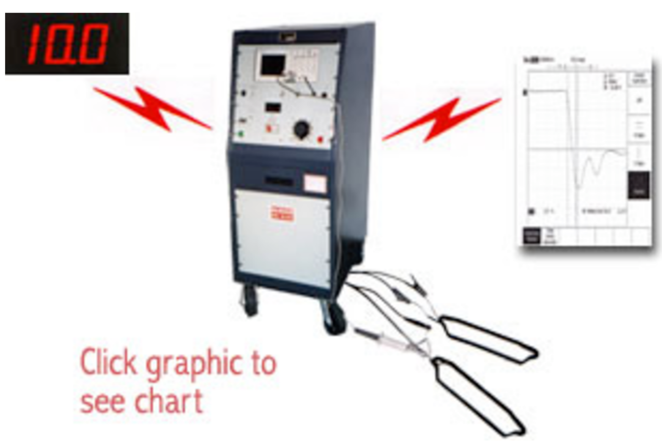
- Insulation over joggle cannot be applied using a taping machine, has to be applied manually in the joggle region, and is subject to rough handling as the joggle section is forced into position

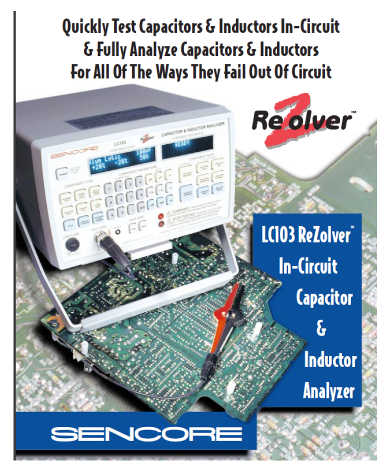
- Joggles cause local electrical and mechanical stress concentration ~ 3x and produce unusual non-axisymmetric field errors and forces

Surge Testing at Factory

- 5kV test was pre- and post-VPI surge test using PJ tester (model #?)
  - Repetitive surge
    - 1 per cycle at 60Hz
    - 100 nanosecond rise time

- Followed by Sencore LC103 ring test





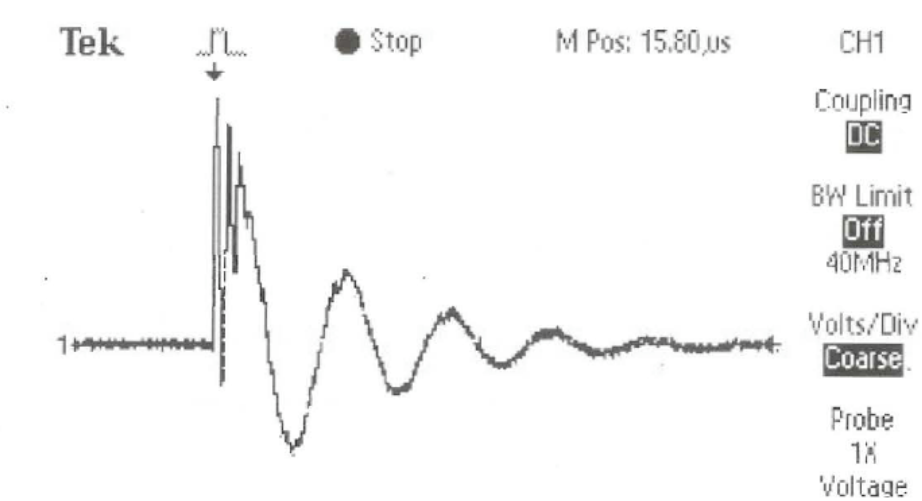
Ring Test - PF1AL

COIL # PF-1A-LOWER

VOLTAGE 5000 V

SIGNATURE [illegible] 4/17/14

BEFORE / AFTER VPI (CIRCLE ONE)

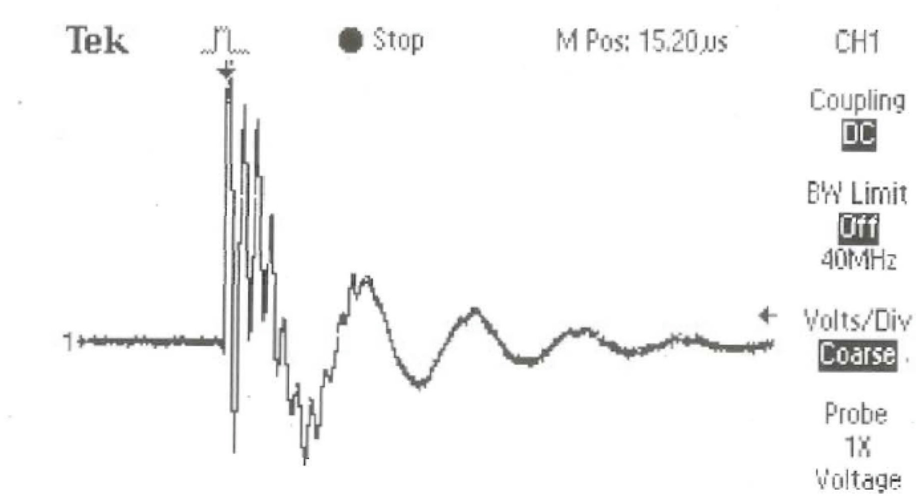


COIL # PF-1A-LOWER

VOLTAGE 5000V

SIGNATURE [illegible] 4/28/14

BEFORE / AFTER VPI (CIRCLE ONE)



Reported as 8 rings

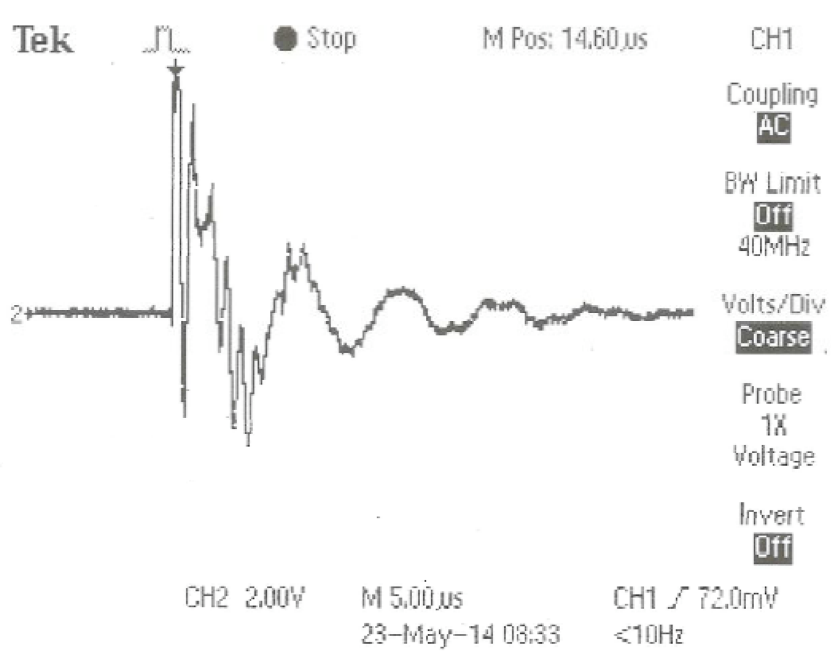
Ring Test - PF1AU

COIL # PF-1A-UPPER

VOLTAGE 5000 V

SIGNATURE 5/23/14

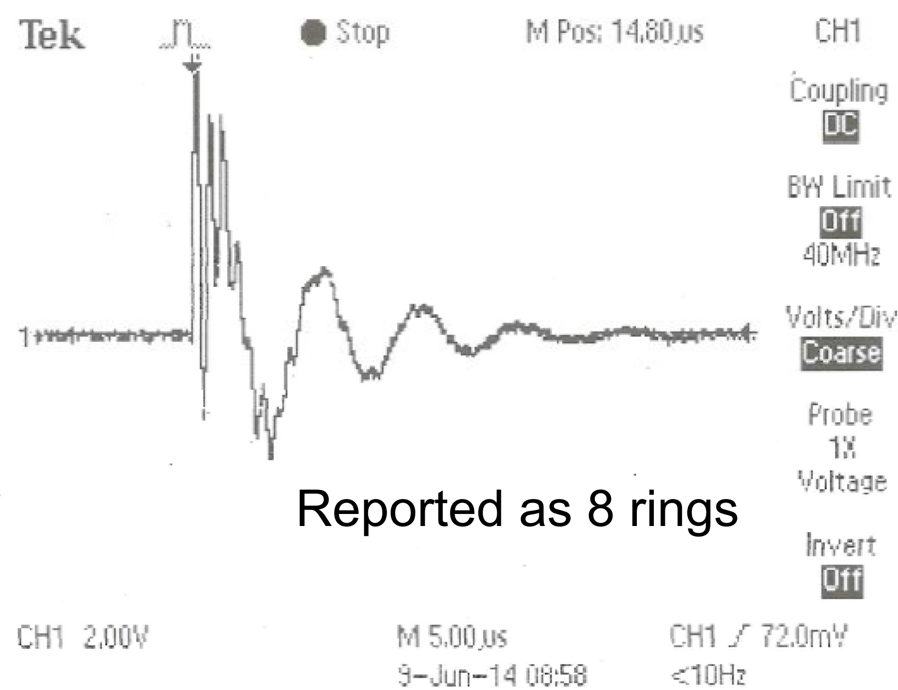
BEFORE / AFTER VPI (CIRCLE ONE)



VOLTAGE 5000 V

SIGNATURE 6/9/14

BEFORE / AFTER VPI (CIRCLE ONE)



Reported as 8 rings

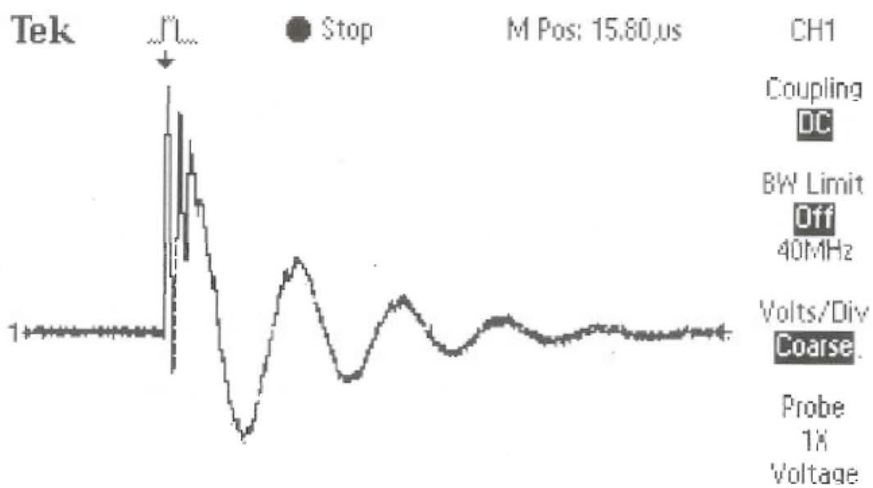
Ring Test - PF1AL v. U Pre-VPI

COIL # PF-1A-LOWER

VOLTAGE 5000 V

SIGNATURE [illegible] KP Jr 4/17/14

BEFORE / AFTER VPI (CIRCLE ONE)

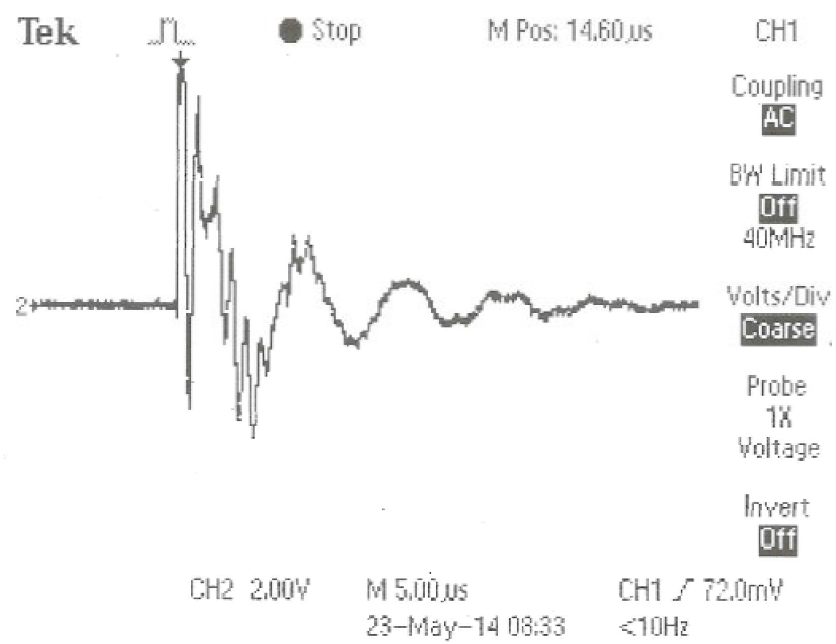


COIL # PF-1A-UPPER

VOLTAGE 5000 V

SIGNATURE [illegible] KPD Jr 5/23/14

BEFORE / AFTER VPI (CIRCLE ONE)



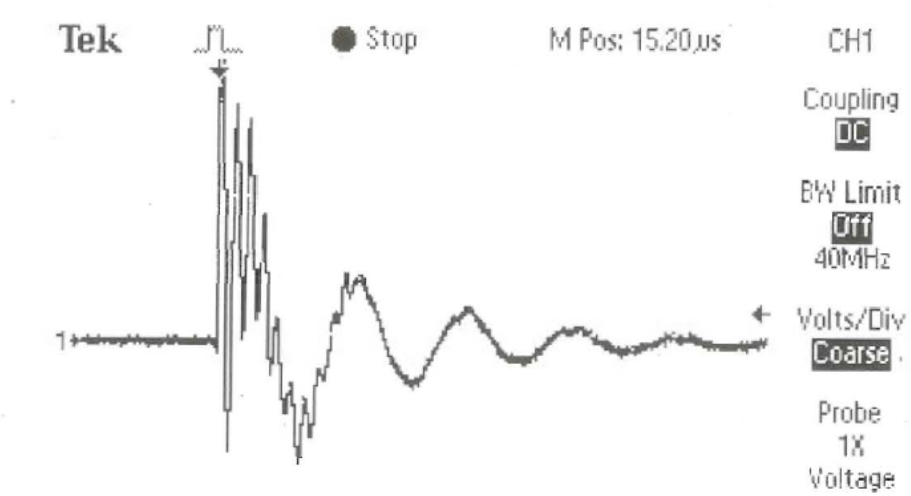
Ring Test - PF1AL v. U Post-VPI

COIL # PF-1A-Lower

VOLTAGE 5000V

SIGNATURE 4/28/14

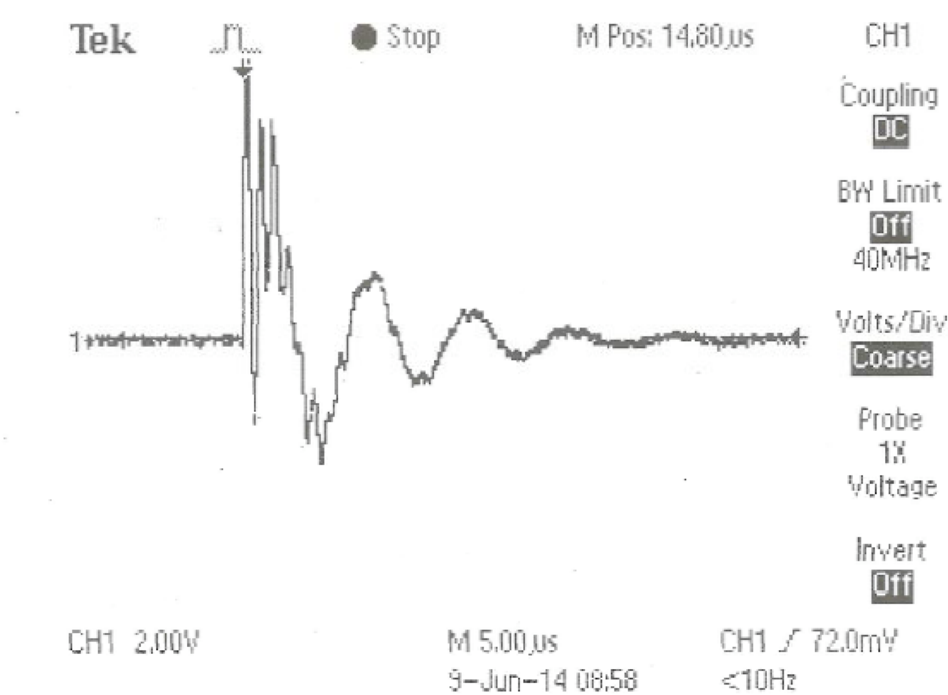
BEFORE / AFTER VPI (CIRCLE ONE)



VOLTAGE 5000 V

SIGNATURE 6/9/14

BEFORE / AFTER VPI (CIRCLE ONE)



Ring Test Summary

- Examination of the ring test waveforms leads to the following observations:
  - During the first ½ ~ 1 cycle, all waveforms exhibit a high-frequency component;
  - The high frequency component increases from pre-VPI to post-VPI on PF1A-L but is similar on PF1A-U;
  - The pre-VPI high frequency component is more prominent on PF1A-U than PF1A-L;
  - The post-VPI waveforms are similar but not identical;
  - Ignoring the high frequency component, both coils exhibited the same basic oscillatory behavior;
  - It is not clear what rule was used to determine the number of "rings" since the number of oscillatory cycles at various frequencies clearly exceeds the number of rings reported in the test documents.

- It is difficult to draw any definitive conclusions from these results but it is clear that:
  - There are differences between the PF1A-L and PF1A-U coils that should not exist if the coils are identical;
  - The high frequency components are unexpected;
  - The coils did not undergo a hard failure that this test could reveal.

PF1B + PF1C Issues

Issue	PF1AL	PF1B	PF1C
Insulation configuration	One co-wound glass/ kapton half-lapped layer omitted	One half-lapped layer of glass was omitted	Same as PF1A
VPI	1. Various process deviations 2. Sprue hole misalignment?	1. Various process deviations 2. Sprue hole misalignment?	1. Various process deviations 2. Sprue hole misalignment?
Conductor	Hard conductor with joggles	Same as PF1A	Same as PF1A
Surge testing	5kV pre-VPI & post-VPI	Same as PF1A	Same as PF1A

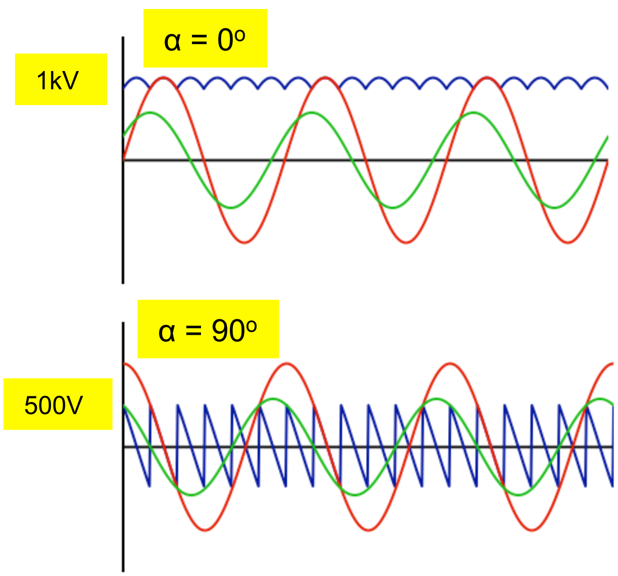
PF1A
Failure modes

Insulation Properties

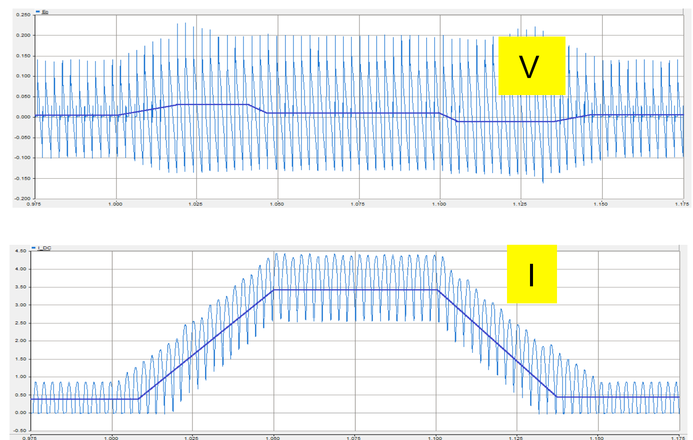
Configuration	Dielectric Strength	Comment
Nominal turn-to-turn @ 1.4mm, properly impregnated	60kV (42kV/mm)	Very large safety factor over any applied voltage
Nominal layer-to-layer @ 1.7mm, properly impregnated	65kV (39kV/mm)	“
1 layer kapton @ 0.05mm	12.2kV (240kV/mm)	Single layer kapton strength greater than any applied voltage
Air at atmospheric pressure (would exist pre-VPI)	3100V/mm	Partial discharges will occur above this level
Air at Paschen minimum (could exist post-VPI	330V/mm	Could exist in voids

Electrical exposure of fault region (1)

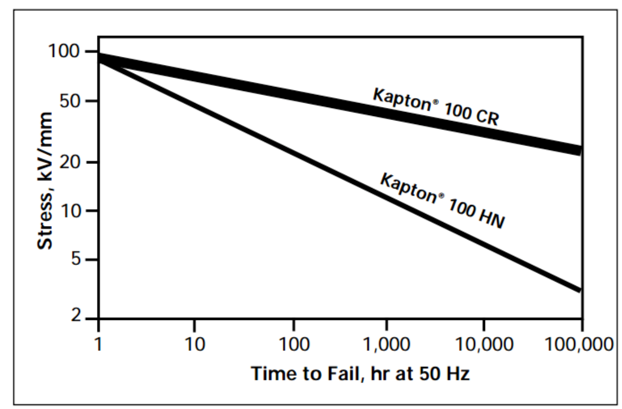
- Power Supply mode
  - 4 shots with w/2kV power supply, 12-pulse, 720Hz, 531V across 18 turns
  - Approx. 1000 shots with w/1kV power supply, 6-pulse, 360Hz
    - 1000 x 5 sec x 360Hz = 1.8M cycles
    - 1.8M / 60Hz / 60 / 60 = 8.3 hours equiv. AC



6-pulse bridge



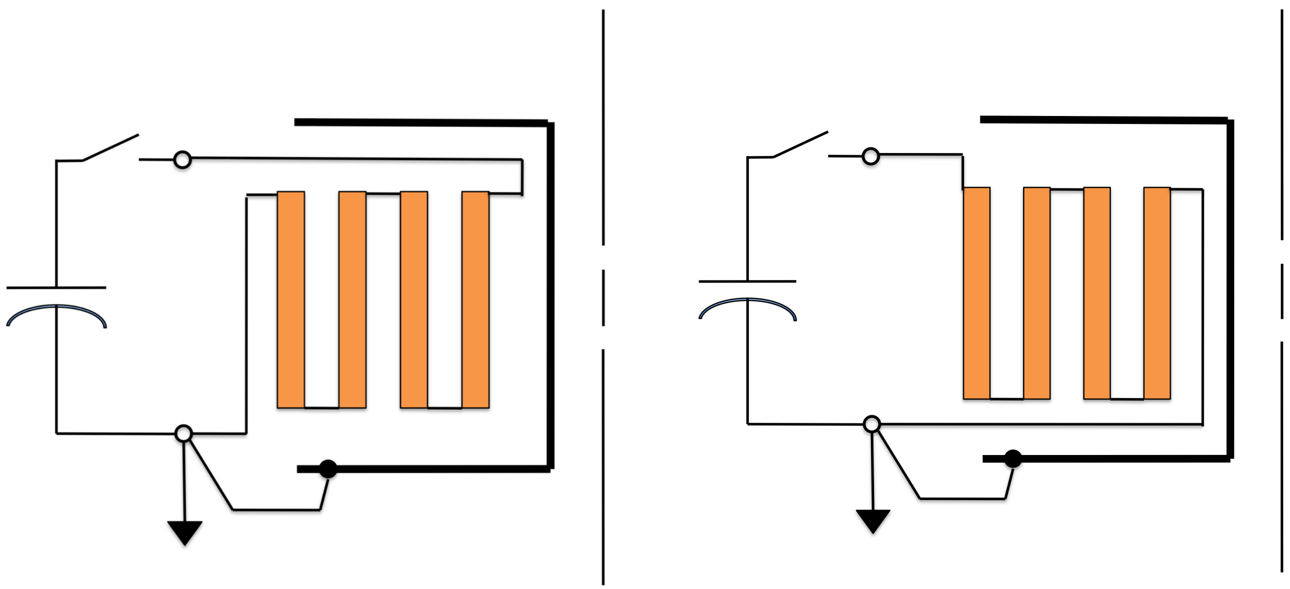
Typical pulse waveforms



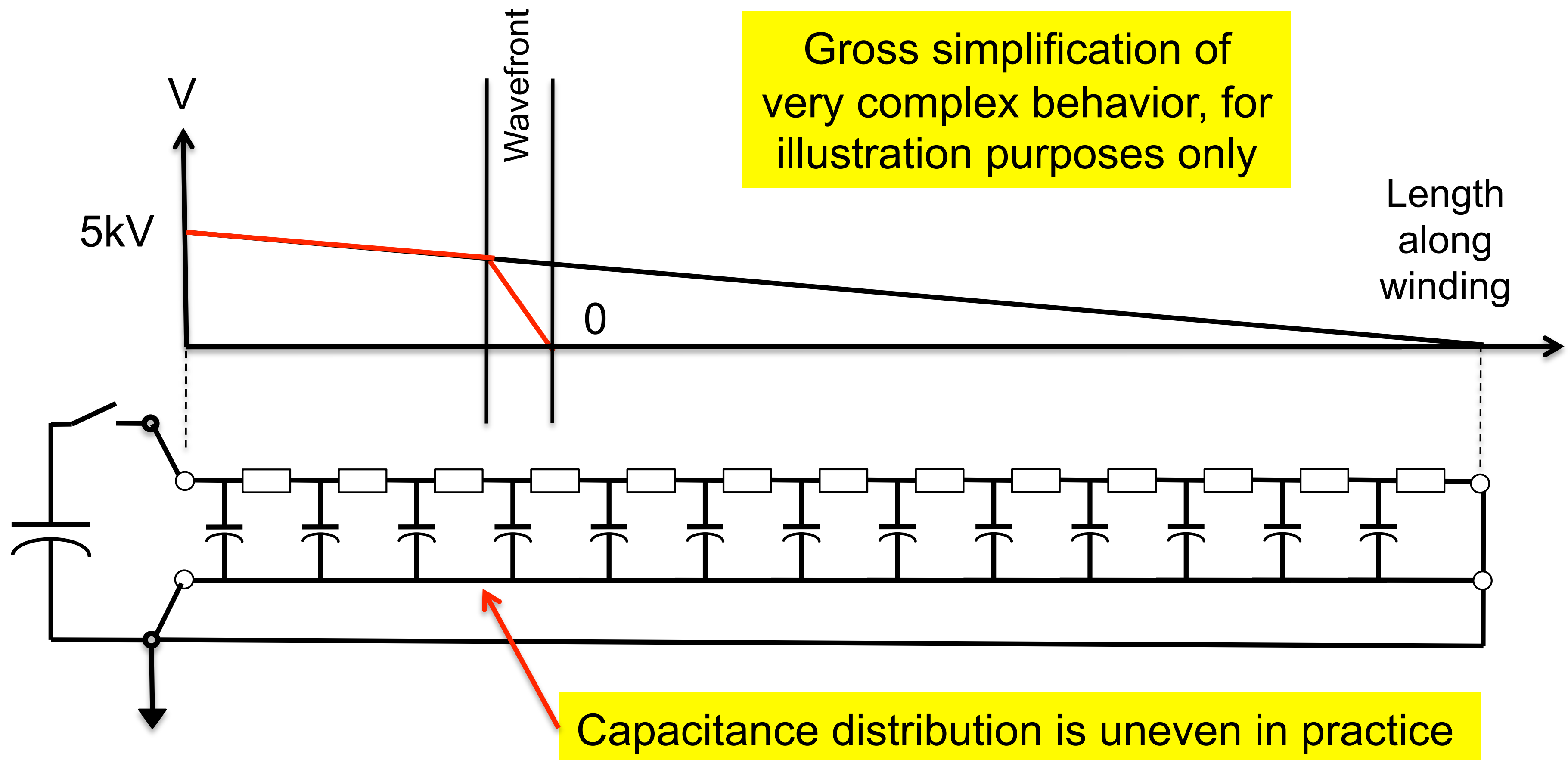
Kapton corona resistance

Electrical exposure of fault region (2)

- Surge test mode (1)
  - Since capacitance of inside layer to ground (mandrel) >> capacitance to ground of other layers, surge propogation inside winding will depend very much on connection scheme

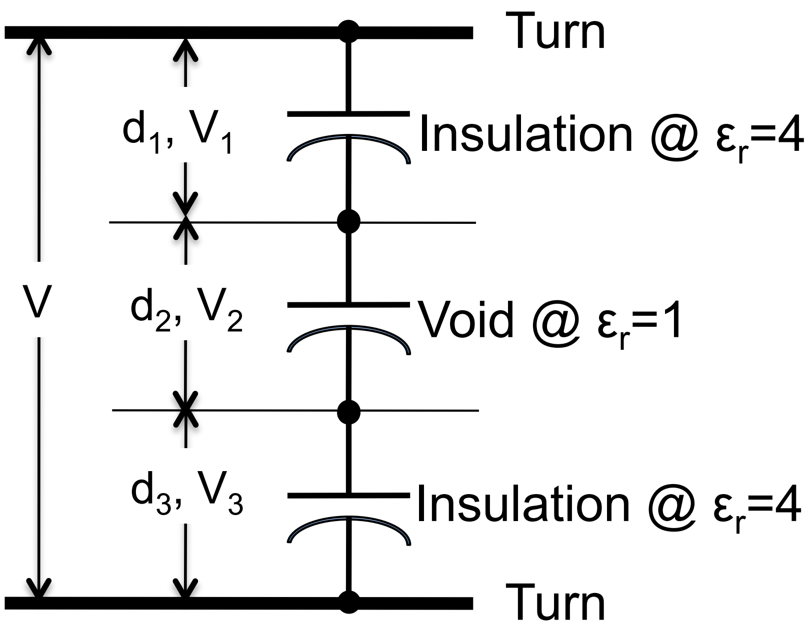


Electrical exposure of fault region (3)



- Depending on circuit parameters and rise time of applied voltage, voltage between turns can be >> average applied voltage divided by number of turns
  - In the limit, full voltage could appear across adjacent turns (or maybe more with repetitive surge, reflections, etc.)

Voltage Stress (1)



$$E_2 = V\frac{4}{2d_1 + 4d_2}$$

- Estimate electric field in void space
- Assume voltage transient distribution dominated by capacitance
- Assume void in middle of space between turns or layers (d_1=d_3)
- Case 1, equal voltage per turn

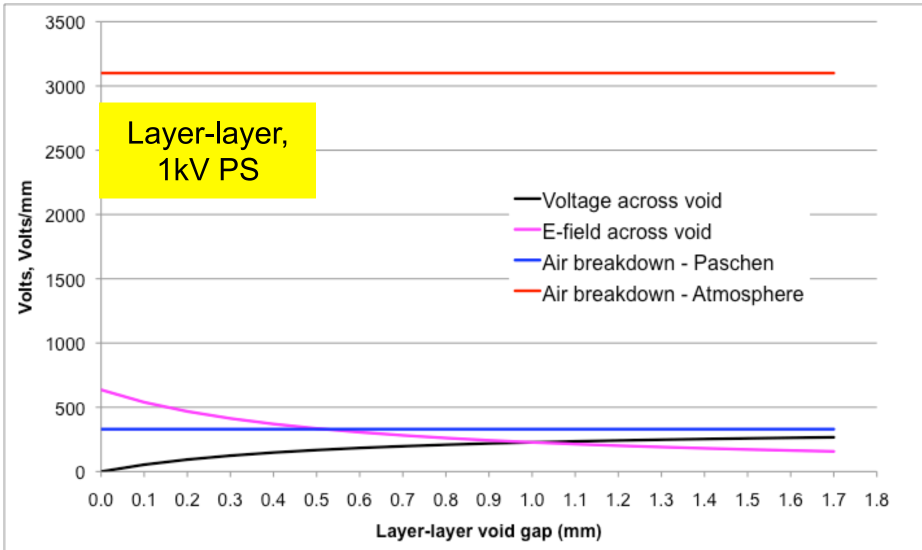
$$V = V_{applied}\frac{41-24}{64}$$

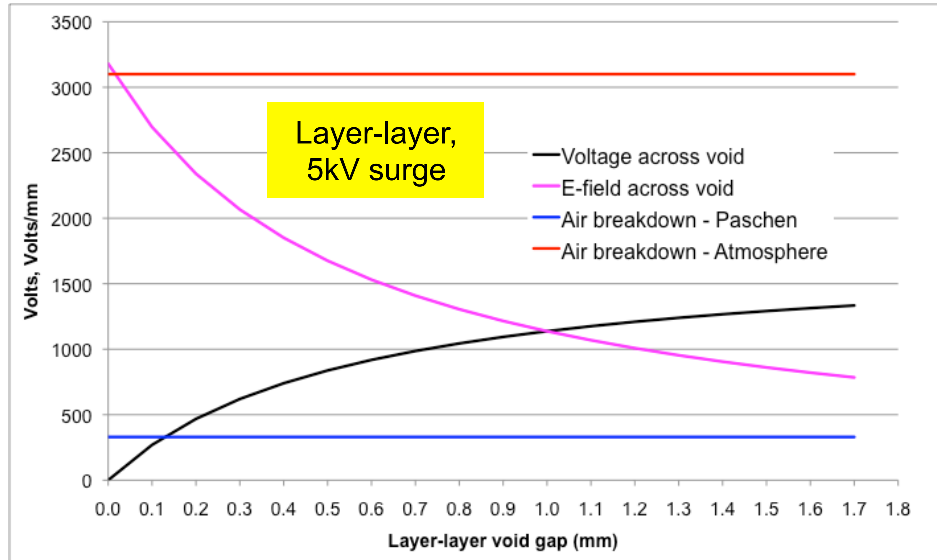
- Case 2, full voltage between adjacent turns

$$V = V_{applied}$$

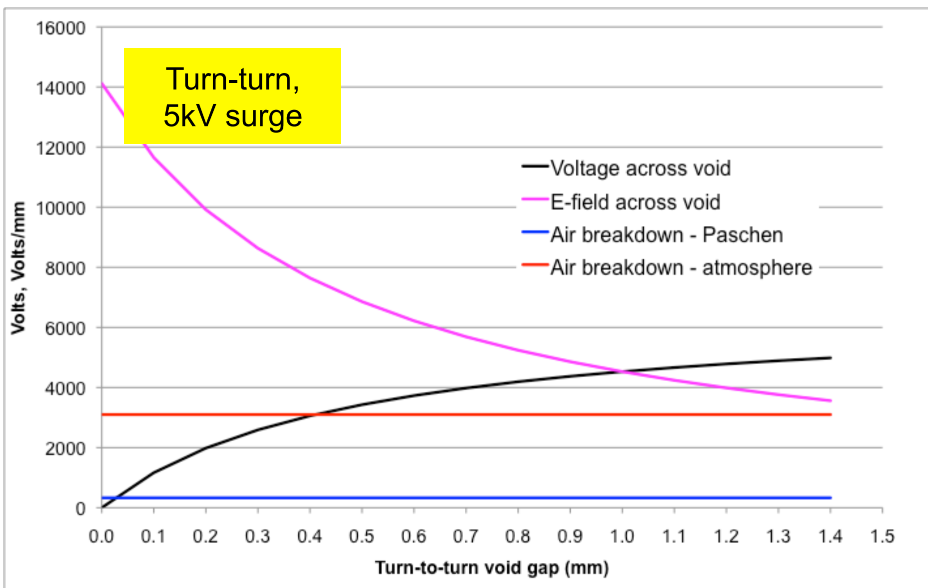
Voltage Stress (2)

Case 1



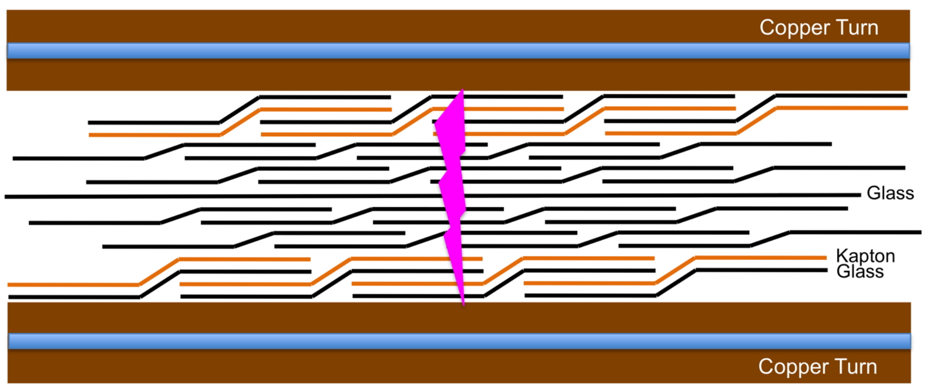


Case 2

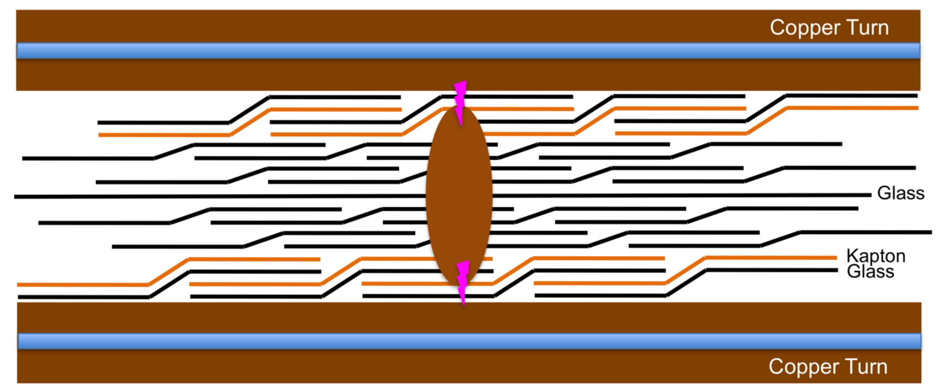


- Power supply mode
  - Low probability of partial discharges
- Surge test mode
  - Some probability of partial discharges, but low number of cycles
  - Applied < breakdown voltage
    - Through kapton
    - Creepage across kapton

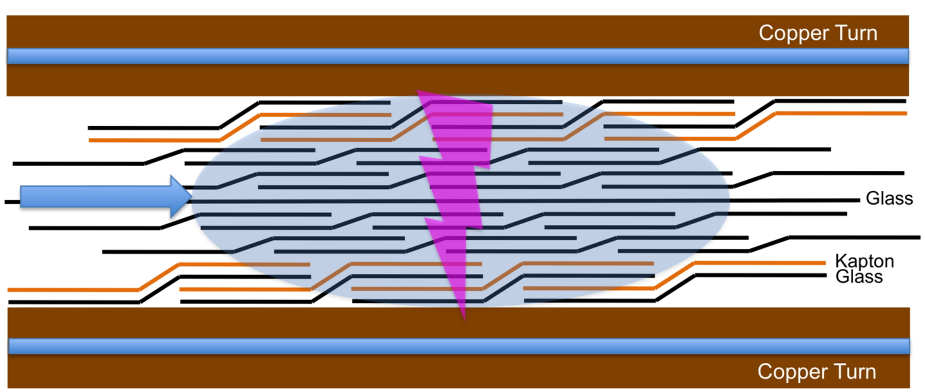
Hypothetical failure scenarios (1)



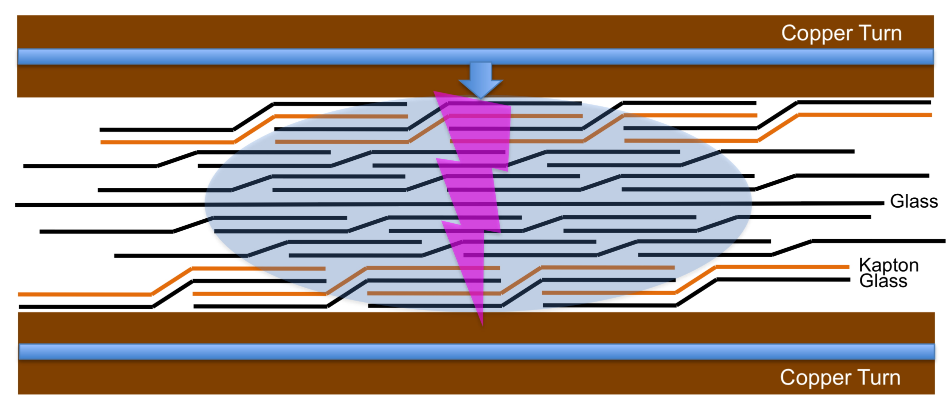
Simple insulation breakdown



Conductive impurity in insulation



Contaminated water entered conductor pack from outside



De-ionized water entered conductor pack from inside

Hypothetical failure scenarios (2)

	Poor VPI	Defective insulation	Surge testing	Mechanically damaged insul.	Electrically damaged insul.	Crack in conductor	Water deluge	(+)	(-)
Simple insulation breakdown	x	x	x	x	x				1. Gap between turns should withstand voltage even without any insulation 2. Carbonized insulation from partialy discharges unlikely 3. Would be a big bang, not gradual degradation
Conductive impurity in insulation	x	x	x	x	x				1. 4 layers of kapton would have to be compromised 2. Carbonized insulation from partialy discharges unlikely 3. Would be a big bang, not gradual degradation
De-ionized water entered conductor pack from inside	x	x	x	x	x	x		Consistent with gradual degradation	1. Low probabilitiy of conductor crack/breach 2. Would chemical reactions lead to increase in conductivity of water or resin?
Contaminated water entered conductor pack from outside	x	x	x	x	x		x	1. Consistent with gradual degradation 2. Consistent with water deluge	1. Is there a water pathway inwards through the leads and through the bad VPI? 2. High pressure cooling path purging did not exhaust outwards

Discussion of suitability of existing Inner PF Coils for continued use