National Spherical Torus eXperiment Upgrade

Inner PF Coil Prototype Coil Notable Report

NSTX-U-REC-039-00

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Record of Changes

Rev.	Date	Description of Changes
0	07/12/28	Initial Release

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1 Executive Summary

This report summarizes the results of the following FY2018 Notable Outcome milestone:

"*For the NSTX-U recovery project, build at least one prototype PF1A inner poloidal magnetic field coil. Qualify the coil by operating it at both the maximum required current and at maximum joule heating. Verify the quality of the coil's insulation system through electrical testing followed by destructive sectioning and inspection. Submit a final report documenting the results by July 15, 2018. (Objective 2.2)* "

In support of achieving this milestone, a comprehensive suite of tests defined in an Inner PF Coil Prototype Technical Evaluation Procedure (PTEP) C/D-PTP-NSTX-CL-063 [1] was applied to two prototype coils that were delivered to PPPL. This suite involves physical inspections and tests of the delivered coil, low- and high-voltage testing, power testing, and ultimately sectioning for internal inspections and turn-to-turn insulation electrical testing.

Key findings include:

- Two PF-1a prototype coils (from ETI and PPPL) have been evaluated and passed basic dimensional inspections, mechanical evaluation before and after sectioning, as well as low power electrical tests (Section 4.1 and 4.2).
- The two (ETI and PPPL) prototype coils were then subjected to high power tests successfully completed on the Field Coil Power Conversion (FCPC) test stand. (Section 4.3).
- The low power electrical tests were repeated and no change in coil properties was observed - the electrical insulation properties unmodified by the high-power tests. (Section 4.3).
- The ETI and PPPL prototype coils have also been successfully sectioned, and visually examined to confirm the quality of the Vacuum Pressure Impregnation (VPI). (Section 4.4).
- The Everson Tesla Incorporated (ETI) coil evidenced 2-3 continuous voids along toroidal channels proximal to turn corners at section ends. The PPPL coil evidenced 4-6 small non-continuous voids (Section 4.4).
- Turn-to-turn and turn-to-ground insulation of both halves of the sectioned coils was successfully tested using insulation resistance and hi-pot tests (Section 4.5).
- Samples of the fully cured resin material properties were confirmed by a Differential Scanning Calorimetry (DSC) test. (Section 4.6).

These findings satisfy the Notable Outcome objectives. In addition, these results are key inputs to the process of vendor evaluation, for production inner-PF coils for NSTX-U and the issues identified provide guidance for process optimization. This effort, except high power test, will be continued to complete the tests on all four coils, and a full follow-on report will be written to complement this milestone summary.

The remainder of this report is organized as follows:

Section 1: Executive Summary - This section.

Section 2: Prototype Process Summary - This section briefly describes the process and philosophy behind use of prototype coils.

Section 3: Methodology - This section describes the tests that will be applied to prototype coils.

Section 4: Test Results - This section highlights results of these tests to date, including evidence of satisfying the laboratory milestone.

Section 5: Summary - This section concludes the report with a brief summary.

2 Prototype Process Summary

In order to ensure high quality production coils for operation on NSTX-U, PPPL embarked on the fabrication of prototype coils. These coils have geometric properties very similar to the production PF-1a coils, and therefore are referred to as the PF-1a prototype coil, or PF-1aP. PF-1a was chosen as the basis for prototyping because, amongst PF-1a, -1b, and -1c, it is the most difficult to manufacture. The PF-1aP and PF-1a production coil design are compared in *Table 1*.

Table 1: Comparison of properties between the prototype and production PF-1a coils

		PF-1aP	PF-1a
Coil Inner Diameter	m	0.5746	0.5850
Coil Outer Diameter	m	0.7219	0.7165
Coil Pack Height	m	0.5014	0.4940
Conductor Width	mm	14.33	12.22
Conductor Height	mm	27.58	24.89
Cooling Hole Diameter	mm	5.72	4.70
Conductor Length	m	124	142
# of Turns	---	60	61
Turn Insulation Thickness	mm	1.04	1.04
Layer Insulation Thickness	mm	0.30	0.30
Ground Wrap Thickness	mm	3.17	3.83

Following a Request For Proposal (RFP) process, four coil fabricators were selected to construct prototype coils in accordance with PPPL Specification NSTX-U-SPEC-MAG-004-R3 [2] hereinafter referred to as “the purchasing specification” and PF1A prototype Coil Assembly Drawing E-DC11053 [3] hereinafter referred to as “the coil drawing”:

- PPPL (USA, Princeton)
- Everson Tesla Incorporated (ETI) (USA, Pennsylvania)
- Tesla Engineering (UK)
- Sigma phi (France)

An Inner PF Coil Prototype Technical Evaluation Procedure (PTEP) was prepared to define various mechanical inspections and electrical tests to be performed on the prototype coils. The PTEP scope is to be performed on all prototype coils for purposes of vendor technical qualification, except that power testing is required only on one coil. The results of these tests, in concert with observations of vendor practices, considerations of project schedule, and other source-selection factors will be used to identify vendors for fabrication of production coils.

Note that in this context, the PPPL coil shop is being treated in a fashion identical to the external vendors.

3 Methodology

A high level summary of the testing methodology is described in the Sections below. Selected evaluation results related to the milestone are described in Section 4.

Note that these testing methods are distilled from the process described in the PTEP procedure, which in turn calls out several specific procedures to implement the mechanical and electrical tests.

3.1 Non-Destructive Mechanical Evaluation

The non-destructive mechanical evaluation including dimensional inspection of the complete coil is performed as described in the purchasing specification NSTX-U-SPEC-MAG-004-R3 [2] and is reflected in each coil fabricators manufacturing plans. Different inspection methods may be used by each coil supplier prior to shipping but an inspection report indicating all measured dimensions relative to their nominal per the coil drawing E-DC11053 is submitted to PPPL.

PPPL performs a general inspection of workmanship and dimensions of the delivered prototype, complementing and validating the analysis done at the factory. Inspection is performed on a table with a calibrated surface.

A calibrated ROMER Arm is used to take measurement points at 45 degree increments on the inside and outside surfaces at heights corresponding to 1” increments from datum per coil drawing E-DC11053. A gauge block is used to measure the two other smaller dimensions per coil drawing at terminal flags.

Any noticeable defects and non-conformances are noted, characterized, and recorded. Confirmation of dimensions is based on the coil drawing and the tolerances defined thereon. To ensure validity of comparison of prototypes, test equipment and methodology used for all evaluations are identical for each coil including make, model and serial number of test equipment wherever possible.

3.2 Low Power Electrical Evaluation

Low Power electrical evaluation of the prototype coils consists of the following steps:

DC conductor resistance measurement

The temperature-corrected DC resistance of the prototype coils is assessed relative to expectations based on Cu properties and the coil geometry such as conductor length and cross section area. A calibrated Low-Resistance Ohmmeter (Model DLRO10) is used to perform this measurement.

Inductance measurement at 1 kHz and rectifier harmonic frequencies

To benchmark the coils relative to each other, the inductance at a reference frequency of 1 kHz, and at the rectifier harmonic frequencies (10 Hz, 100 Hz, 360 Hz, 720 Hz, 840 Hz, 960 Hz and 1 kHz) is recorded and assessed relative to the expected target values. An L-C-R Meter (HIOKI IM3533-01) is used to perform this measurement.

Outer Ground Wall Insulation Resistance Test

Megger and high-pot testing of the ground wall insulation is performed. This instrument applies a DC high voltage to the conductors and measures the leakage current to an aluminum foil ground plane wrapped around the coil. This test provides a measure of the quality of the coil ground insulation. An Insulation Resistance Test Set (MIT1020 Megger PE7043-W) is used to perform this test.

Surge test

A specifically purchased and configured surge tester is utilized to confirm the dielectric strength of the turn-to-turn insulation of the coil. This system applies a short pulse of high voltage from a pre-charged capacitor, and measures the ringing LCR response of the system. Electrical faults between the turns or the layers would result in non-linear behavior in the waveform as the voltage is increased, or deviations in the waveforms between good and faulted coils. A surge tester (Elytt CDG 7000) is used for this test.

3.3 High Power testing on the FCPC test stand

Although required by the notable on only one prototype, both the ETI and PPPL coils were power tested after completion of the electrical testing described in Section 3.2 to ensure that at least one coil would successfully pass the full end-to-end evaluation procedure.

A series of current pulses were applied, with increasing current and heating up to the rated current and maximum temperature. These pulses are designed to result in three equal increments of hoop stress ($\propto I^2$) at short pulse, followed by three equal increments of total heating ($\propto I^2 t$). The final pulse has the full field and heating applied.

Examples of these pulses are provided in *Figure 1*. The pulse waveform breakpoints are defined in *Figure 2*. The pulse waveform specifications are given in *Table 2*.

The details of the coil test facility dictate some details of the test. Cooling water in the Field Coil Power Conversion (FCPC) building is provided at a maximum of 25 ^{0}C whereas the NSTX Test Cell cooling water is 12 ^{0}C. Given the desire to limit the final temperature to that which the coil has been qualified for and which production coils will experience in the field, the temperature rise during these tests is less than in service by 25-12 = 13 ^{0}C. To this end, sufficient joule heating is applied for the coil to reach the maximum temperature anticipated during full power operation.

The inlet water temperature in FCPC is typically lower than 25 ^{0}C, and it varies depending on the outside weather conditions. Therefore, it becomes necessary based on the day of the test to pulse the coil with a higher total heating level than was calculated based on the 25 ^{0}C estimate. To this end, the actual waveforms and set-points are adjusted based on operating conditions on the day of the test (water inlet temperature, power supply control precision, etc.)

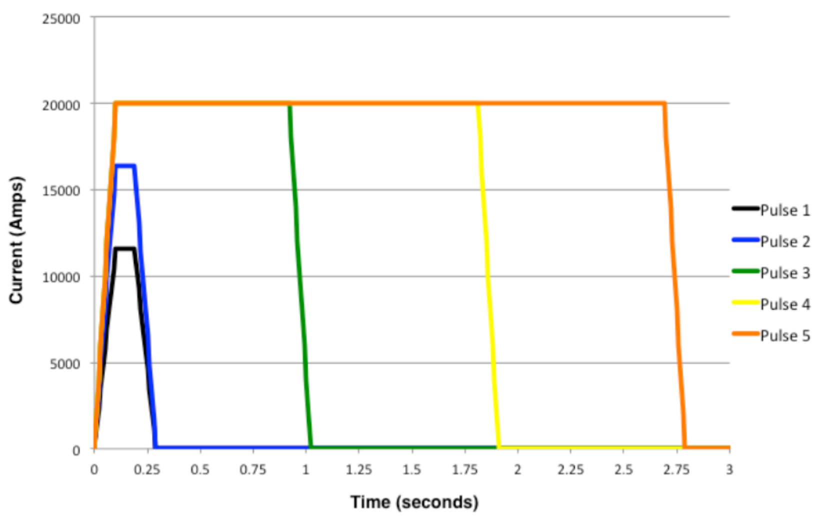

Figure 1: Model pulse waveforms for the FCPC tests of the PF-1aP coil

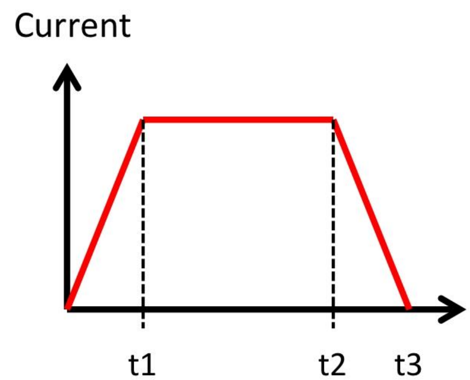

Figure 2: Pulse waveform breakpoint definitions

Table 2: Pulse Waveform Specifications

Pulse No.	**1**	**2**	**3**	**4**	**5 (ETI)**	**5 (PPPL)**
I_ft (amp)	11547	16330	20000	20000	20000	20000
t_ft (sec)	0.100	0.100	0.845	1.756	2.633	2.431
ESW (sec)	0.167	0.167	0.911	1.823	2.734	2.734
t1 (sec)	0.100	0.100	0.100	0.100	0.100	0.100
t2 (sec)	0.200	0.200	0.945	1.856	2.733	2.531
t3 (sec)	0.300	0.300	1.045	1.956	2.833	2.631
I^2t	2.22E7	4.44E7	3.65E8	7.29E8	1.07E9	9.86E8
T_max (^{o}C)	18	19	31	45	60	60

Note that the low power electrical tests described in Section 3.2 were performed before and after the high power tests to confirm that no measurable coil parameters were degraded by the high power testing.

3.4 Sectioning

Each of the prototype coils is cut into two sections for further inspection. The cuts are made as shown in *Figure 3* unless the visual inspections described in Section 3.1 indicate that an alternate approach may be more revealing. Multiple smaller sections may be subsequently extracted from the halves for detailed inspection. Care is taken to minimally damage the surfaces, and a skimming cut (small depth, slow tool feed) is taken to fully polish the surface.

The sectioning of the prototype coil required the fabrication of a base plate fixture to mount the coil to a rotary table and the mounting of the rotary table on the horizontal mill. The sectioning of each prototype coil is thus divided into the following steps:

- Lift the coil onto the Horizontal end mill in the C-MG building.
- Fixture the coil in accordance with the tooling
- Mill the coil into sections with plunge cut and finish cut in accordance with the sectioning procedure without re-mounting by using the rotary table
- Dismount the newly portioned coil pack sections from the tooling for further testing

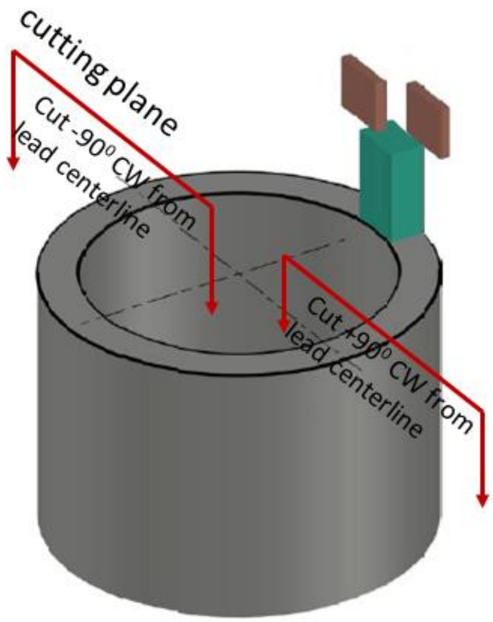

Figure 3: Planes for sectioning the PF-1aP coil

3.5 Mechanical Evaluation of Sectioned Coils

After sectioning, coil section ends are visually examined under magnification. The accuracy of the conductor positioning and insulation thickness within the winding pack array are evaluated with a Go/No-Go Gauge. Any voids evident in the turn or ground insulation are noted including void size and location. In particular, the sectioned coil is examined for voids, cracks, crazing such as surface cracks, de-laminations and dry spots within the insulation. Special attention is paid to the potential resin-rich areas during the examination. Surface examination is undertaken using magnification as necessary with photographs taken to aid further analysis of any potential defects. Any dry spots, cracks, ruptures or de-bonds between conductor and insulation within the coil winding pack identified are recorded so that logging flaws can be compared among vendors to determine the quality of the prototype coils.

3.6 Electrical Testing of Sectioned Coils

After visual examination the section ends are immersed in a dielectric fluid to increase the flashover voltage between the ends of the cut turns. Electrical evaluation of the sectioned prototype coils at PPPL consists of the following steps:

- Megger test of turn-to-turn insulation resistance at 500 V DC, performed between adjacent turns
- DC breakdown test of turn-to-turn insulation, performed between adjacent turns, unless flashover occurs first
- DC breakdown test of turn-to-ground insulation, performed with all turns connected together, with respect to a ground plane, unless flashover occurs first

The breakdown tests confirm the ultimate capability of the electrical insulation system, at least up the level where flash-over at the end of the sectioned coil limits the applied voltage.

3.7 VPI Cured Resin Test

A small piece of the cured epoxy sample after the VPI process is obtained from each vendor for PPPL to examine the quality of vendor VPI process. The material property measurements are performed via Differential Scanning Calorimetry (DSC) per ASTM E1356 to confirm the second order glass transition temperature (T_g). The resultant T_g shall be within a band of 7 ^{0}C of the target T_g (i.e., either that specified by the resin supplier or a benchmark value determined from laboratory samples that have undergone the same cure cycles as the coil in terms of times and temperatures). Should a sample record a low T_g (outside benchmark value minus 7 ^{0}C), post-cure that sample and re-measure. If T_g rises to the desired value, the sample was under-cured. If T_g fails to rise, it suggests an incorrect mix ratio.

4 Test Results

As of the writing of this report, coils manufactured by PPPL and ETI have completed the evaluation process, including the high power testing. Coils from the other two vendors will be subjected to the same tests, except for the high power tests, after they arrive at PPPL.

4.1 Mechanical Inspection

Mechanical inspections of the ETI and PPPL prototype coils have been completed. Photographs of the coils are shown in *Figure 4* and *Figure 5*.

The ETI coil arrived at PPPL on June 8, 2018. The coil was wrapped in a plastic protective cover and secured in a wood crate with no evidence of damage during shipping. The coil was uncrated and observed to be in good condition with no damage except that, around the lead area, it was observed that the cooling tube was misaligned on the right hand terminal flag. This was noted as the as-built condition by QA at the factory, it is not shipping damage. In addition, some local resin rich areas around lead terminal support tower were noted.

Figure 4: Photograph of the ETI PF-1aP as received by PPPL

Figure 5: Photograph of the PPPL PF-1aP coil in the coil shop

The PPPL coil was delivered to the test team on June 20, 2018. The coil was secured in the wood cribbing with no damage evident. The coil was then rotated by 90 degree to the vertical position and was observed in good condition with no damage. Some local resin-rich areas around lead terminal support tower were observed. It was noted that one broken bolt was present in the left terminal flag but no request was made to remove it as it would not affect the coil testing.

The final dimensions of the two coils were measured with a portable coordinate measuring machine such as a calibrated ROMER Arm with hundreds of measurement points. These dimensions, as well as the design objectives, are shown in *Table 3*.

Critical dimensions include the inner radius and thickness of the coil pack, which are assigned tolerances of 0.03" (0.762 mm) and 0.02" (0.508 mm) respectively. Both the ETI and PPPL coils were within tolerance on the inner radius. Only a few points measured on the ETI coil indicate slightly higher than required tolerance on the outer radius, mainly the result of resin roughness on outer surface due to overlapping of the ground wrap layers that could be corrected by smoothing (e.g., sanding or machining). The ETI coil was also out of tolerance on height. However, this is not a critical dimension since, on the production coils, machining of the upper and lower coil surfaces is planned to establish a precise interface with the coil support slings.

The additional dimensions around the terminal flags per coil drawing also passed the dimensional / tolerance inspection with gauge blocks.

Despite the minor deviations noted, both coils are judged to have passed their dimensional inspection.

Table 3: Dimensions of prototype drawings and prototype coils

		Nominal		Tolerance		Measured deviation	OK
		Inch	meter	Inch	mm	mm	
Inner Radius	PPPL	11.311"	0.2873	0.03"	0.762	+0.5/-0.2	Yes
Outer Radius		14.211"	0.3610	0.05"	1.270	+1.2/-1.7	Yes
Height		19.74"	0.5014	0.06"	1.524	+0.2/-0.7	Yes
Inner Radius	ETI	11.311"	0.2873	0.03"	0.762	+0.3/-0.4	Yes
Outer Radius		14.211"	0.3610	0.05"	1.270	+1.5/-1.8	Yes
Height		19.74"	0.5014	0.06"	1.524	+2.5/-0.4	No

4.2 Electrical Evaluations

Coil Resistance

The coil resistances as measured after delivery to PPPL are shown in *Table 4* corrected to 20 ^{0}C. The values are the averaged over three time measurements.

Table 4: Coil Resistances

		Value	OK
Nominal	mΩ	5.80	+/-5%
PPPL	mΩ	5.66	Yes
ETI	mΩ	5.67	Yes

Coil Inductance

For low frequency (near DC) inductance characterization of the prototype coil, the Hioki L-C-R meter was used. *Table 5* shows the inductance measured at 10 Hz.

Table 5: Coil Inductances

		Value	OK
Nominal (calculated)	mH	1.97	+/-10%
PPPL (measured)	mH	1.79	Yes
ETI (measured)	mH	1.80	Yes

AC Impedance Sweep

The Hioki IM3533-01 L-C-R meter was used for a low frequency AC impedance sweep from 10 Hz (~DC) to 2 kHz to cover the range of power supply rectifier harmonics, and a 1 kHz to 200 kHz sweep to identify the resonance frequencies where the equivalent capacitive impedance of the coil insulation matches the inductive impedance of the coil winding. *Figure 6* presents results of the impedance sweeps for electrical characterization of the PPPL coil with detailed comparison between testing at coil shop vs. testing at the FCPC on the test stand before and after power testing. The coil shop measurement is made with no nearby metallic objects and is representative of conditions during measurement of the remaining two prototypes as well as measurement of future production PF1a coils in the factory. The FCPC measurement is influenced by nearby metallic objects (e.g., the coil stand, the walls of the test enclosure, etc.) and differs slightly from the coil shop measurement. To ensure comparison of measurements under identical conditions, the before and after power test measurements were both made with the coil mounted on the FCPC test stand. Results for the ETI coil were similar to those measured for the PPPL coil.

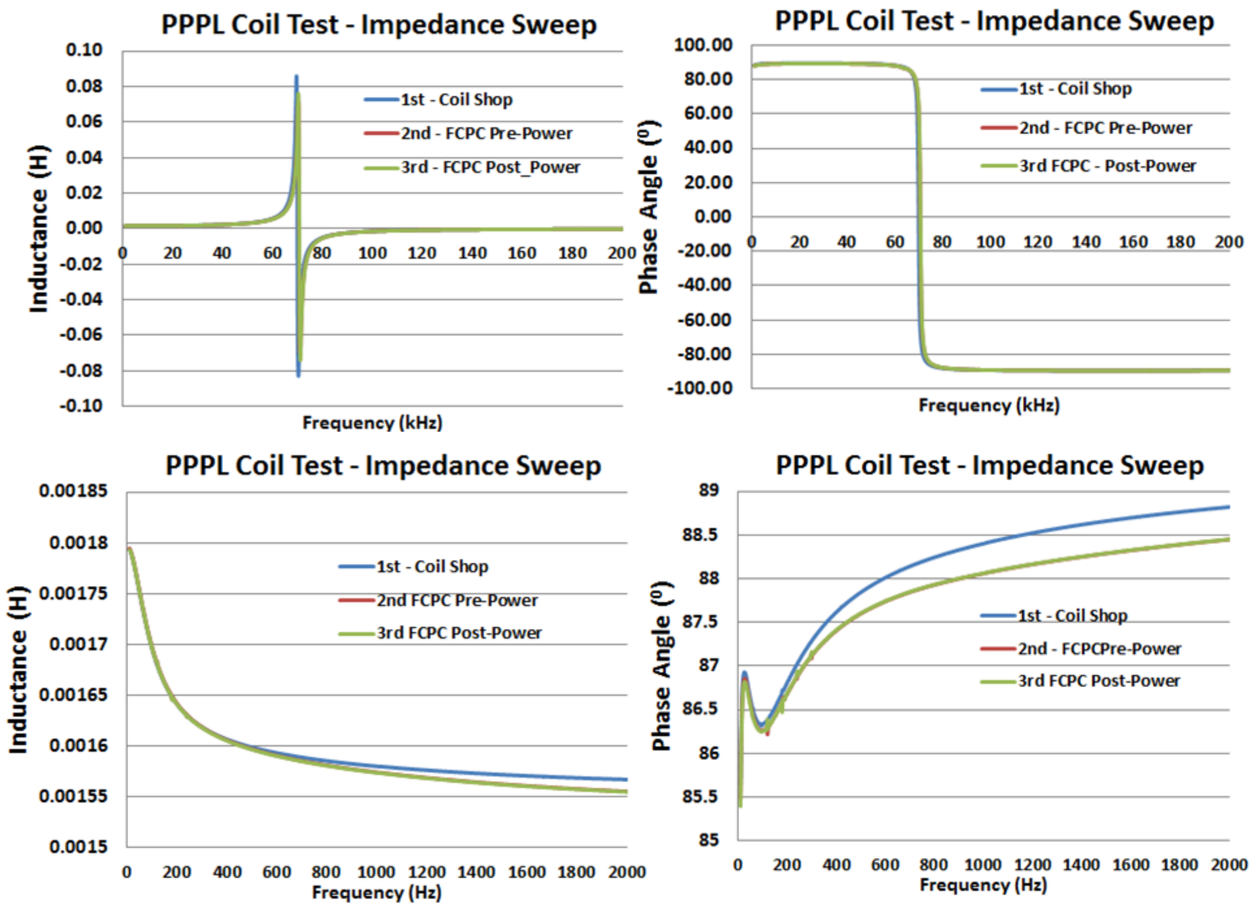

Figure 6: Impedance Sweep for electrical characterization of the PPPL coil (comparison between testing at coil shop vs testing at FCPC)

Outer Ground Wall Insulation Resistance Test

The ground wall insulation resistance of each coil was measured after delivery to the PPPL coil shop, at FCPC prior to power testing and at FCPC after power testing. Typical test setup is shown in *Figure 7*. A ground plane was formed using aluminum foil that was pressed against the ground wall using an inflated plastic membrane. *Insulation resistance measurements for both coils were all well above the 1 GΩ minimum requirement.* Typical results are given in *Table 6*.

Figure 7: ETI (left at FCPC) coil and PPPL coil (right at coil shop) being high-pot tested relative to an applied ground plane

Table 6: Ground insulation values for the two PF-1aP coils (Coil Shop at 5 kV).

		Value	OK
Target	GΩ	>1	
PPPL	GΩ	115	Yes
ETI	GΩ	129	Yes

Surge Testing

As noted in Section 3.2, the sign of a successful surges test is the similarity of normalized waveforms as the voltage is increased and / or comparison between results on identical coils. With the rated coil voltage of ~2 kV, the 2E+1 rule is applied to set the maximum surge test voltage at 5 kV.

Figure 8 shows the setup at FCPC for the post-power surge test. The surge test results for the ETI PF-1aP coil are shown in *Figure 9*, with the time scale set to cover the full waveform decay. Data is shown for tests at increasing voltage levels up to 5 kV, and for the 10^{th} of a sequence of pulses at 5 kV. The same data are shown in *Figure 10* with the time scale zoomed in on the first 6 cycles; and in *Figure 11* with the data normalized to 5 kV.

Figure 8: Surge test results at increasing voltage levels up to 2E+1 = 5 kV, for the ETI PF-1aP coil

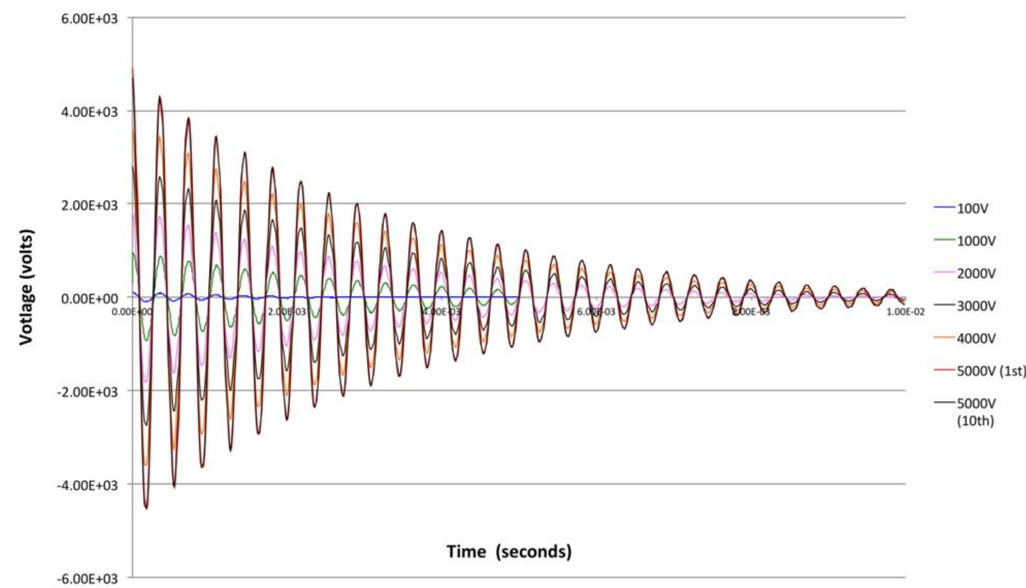

Figure 9: Surge test results at increasing voltage levels, for the ETI PF-1aP coil

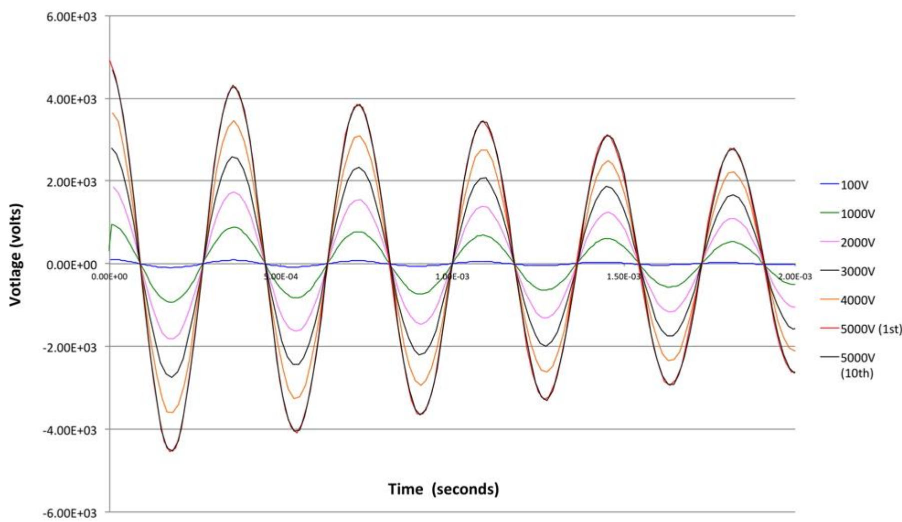

Figure 10: Surge test results at increasing voltage levels for ETI PF-1aP coil, zoom view

The surge test results at 5 kV indicate slightly different behavior in FCPC as compared to the test performed at the coil shop as shown in *Figure 12*. This may imply that the surge tester is quite sensitive to the environment.

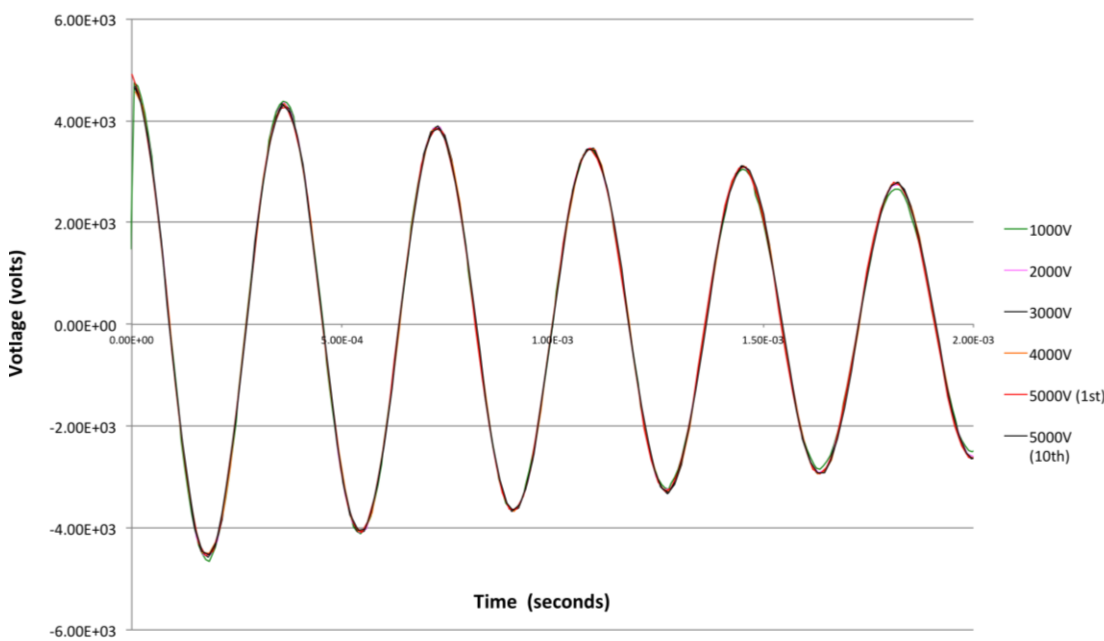

Figure 11: Surge test results at increasing voltage levels, for the ETI PF-1aP coil, zoom view, normalized to 5 kV

The results of Figure 11 confirm the integrity of the turn-to-turn insulation of the coil. If the coil was faulty, the waveform would degrade as the voltage is increased, or as the sequence of 10 pulses was applied.

Similar to the situation with the AC impedance scan, the presence of nearby metallic objects can influence the surge test waveform. In order to ensure valid comparisons before and after power testing, the surge tests were performed in the coil shop, at FCPC prior to power testing, and at FCPC after power testing. The small differences between the coil shop waveforms and FCPC waveforms are evident in *Figure 12*.

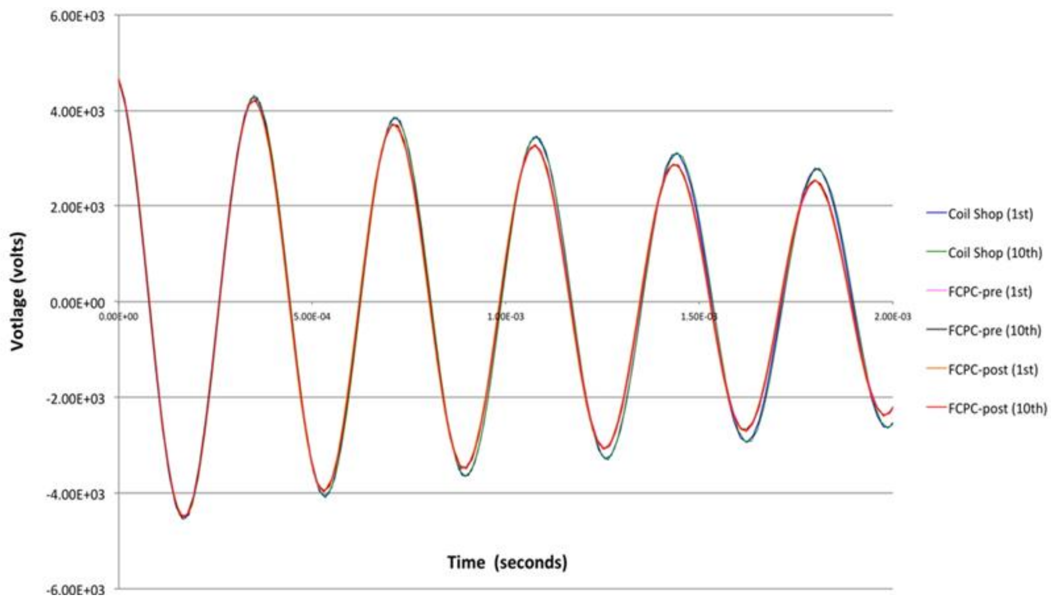

Figure 12: Surge test results at 5 kV indicating slightly different behavior in FCPC, for the ETI PF-1aP coil

4.3 Power Testing

The next step in the testing regime was to power test at least one coil in FCPC, using the same rectifier type as the coils will see in service. The ETI and PPPL coils were selected for this assessment. An image of the PF-1aP coil from ETI and PPPL on the FCPC test stand is shown in *Figure 13*.

Figure 13: ETI (top) and PPPL (bottom) prototype coils on the FCPC test stand for power testing

Five pulses were applied to the coil, as described in Section 3.3. The measured current waveforms are shown in *Figure 14* and *Figure 15*. The parameters of the waveforms are shown in *Table 7*. *The table shows that the target current and* $\int I^2 dt$ *values for both ETI and PPPL coils were achieved.*

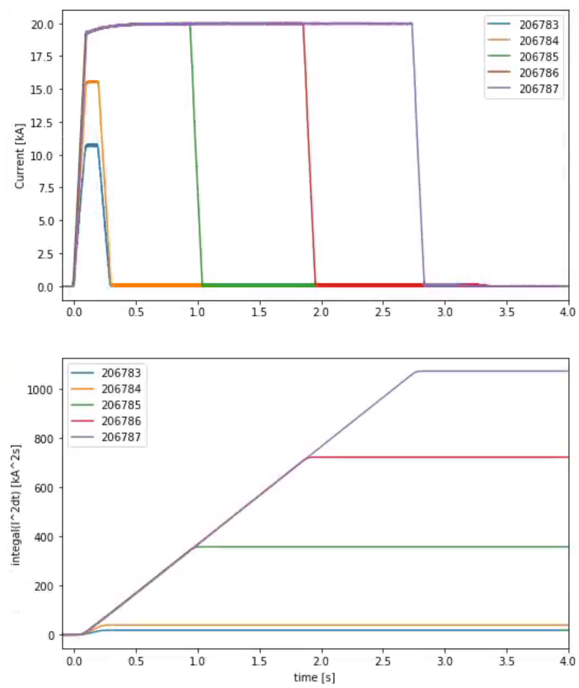

Figure 14: Actual current pulse waveforms (top) and Actual integral (bottom) for the FCPC tests of the ETI PF-1aP coil

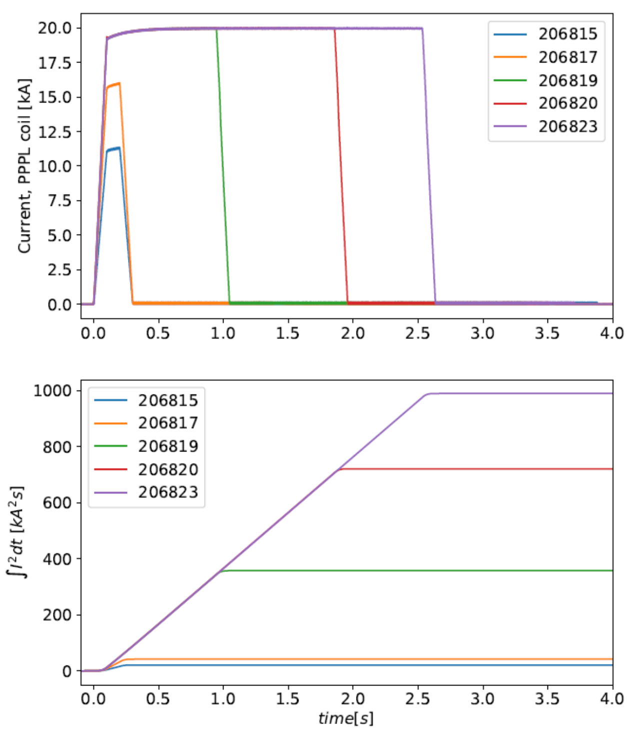

Figure 15: Actual current pulse waveforms (top) and Actual integral (bottom) for the FCPC tests of the PPPL PF-1aP coil

Table 7: Properties of target and achieved waveforms used on the PF-1aP coil

Pulse	Target Flat-Top Current	Achieved Flat-Top Current	Target $\int I^2 dt$	Achieved $\int I^2 dt$
	kA	kA	kA^2s	kA^2s
1	11.547	11.547	22.2	22.2
2	16.330	16.330	44.4	44.4
3	20.000	20.000	365	365
4	20.000	20.000	729	729
5 (ETI)	20.000	20.000	1070	1070
5 (PPPL)	20.000	20.000	986	986

As described previously the difference in $\int I^2 dt$ was necessary to drive the coil to a peak conductor temperature of 60 ^{0}C with slightly different inlet water temperatures.

For both the ETI and PPPL coils, following the power testing the surge test was repeated. *As shown in Figure 16 for the ETI coil, the 5 kV surge test data, 1st and 10th in a sequence, before and after power testing, precisely overlay one another, confirming that no coil degradation occurred.*

A diagnostic method called Error Area Ratio (EAR) is used to quantify the waveform comparison to a base case using the following algorithm. The calculation is performed over the first 6 cycles of the waveform.

$$EAR = \frac{\sum_n ABS(V_{no-fault}(n) - V_{fault}(n))}{\sum_n ABS(V_{no-fault}(n))}$$

Table 8 shows that the EARs of the surge response waveforms were within 1% the 1st pre-power test waveform serving as the base case. Simulations of the PF-1a coil with various types of faults suggest that EAR values ~20% can be expected with a hard fault across a single turn and much more for a layer-to-layer fault. PPPL will continue to develop the EAR tool and apply it as acceptance criteria for future production coil testing.

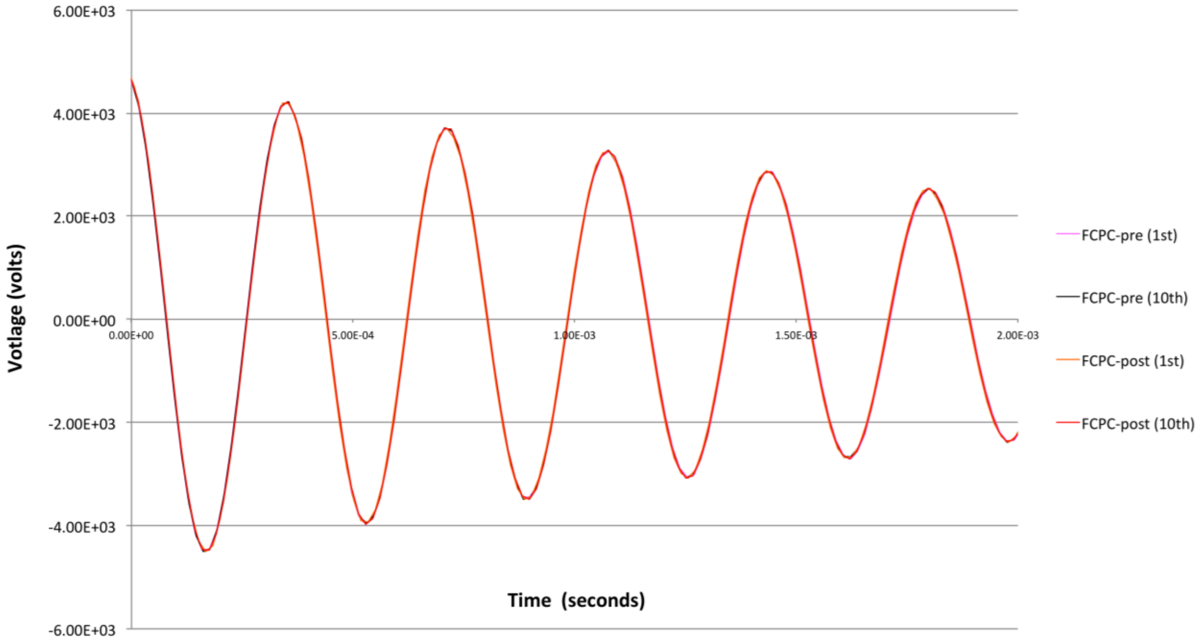

Figure 16: Overlay of the 5 kV surge test waveform, for the ETI coil, before and after power testing

Table 8: Error Area Ratio of the ETI coil integrated over 6 cycles

	EAR (%)
Pre-power test (1st surge) – base waveform	0.00
Pre-power test (10th surge)	0.34
Post-power test (1st surge)	0.48
Post-power test (10th surge)	0.24

4.4 Sectioning and Inspections

The coils were sectioned on a horizontal milling machine for further inspection and Hi-pot testing of turn-to-turn insulation in the coil pack following the preceding electrical tests. The ETI coil and PPPL coil are shown on the horizontal milling machine in *Figure 17* and *Figure 18*.

Figure 17: ETI and PPPL coils being sectioned on the Lucas milling machine

Figure 18: ETI (left) and PPPL coil (right) being sectioned on Lucas milling machine

Figure 19 and *Figure 20* illustrate the sectioned ETI coil and PPPL coil, respectively prior to further inspection and testing.

Figure 19: Sectioned ETI coil – No-lead section

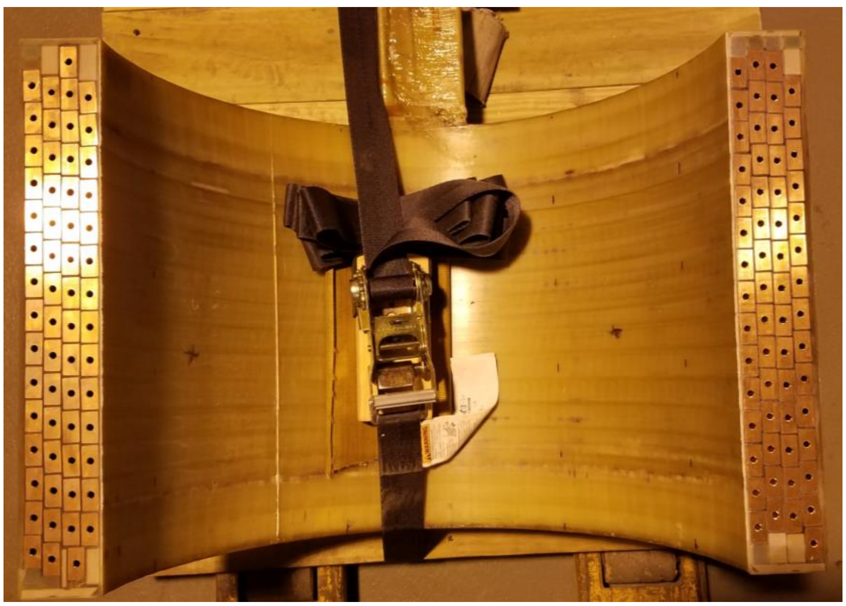

Figure 20: Sectioned PPPL coil – Lead section

Visual inspections of the sectioned ETI coil revealed significant void regions close to the lead-end of the inner turns as shown in *Figure 21*. Voids were substantial enough that there was communication through the matrix to the other side along toroidal channel through multiple turn corners as shown in *Figure* 19 (circled).

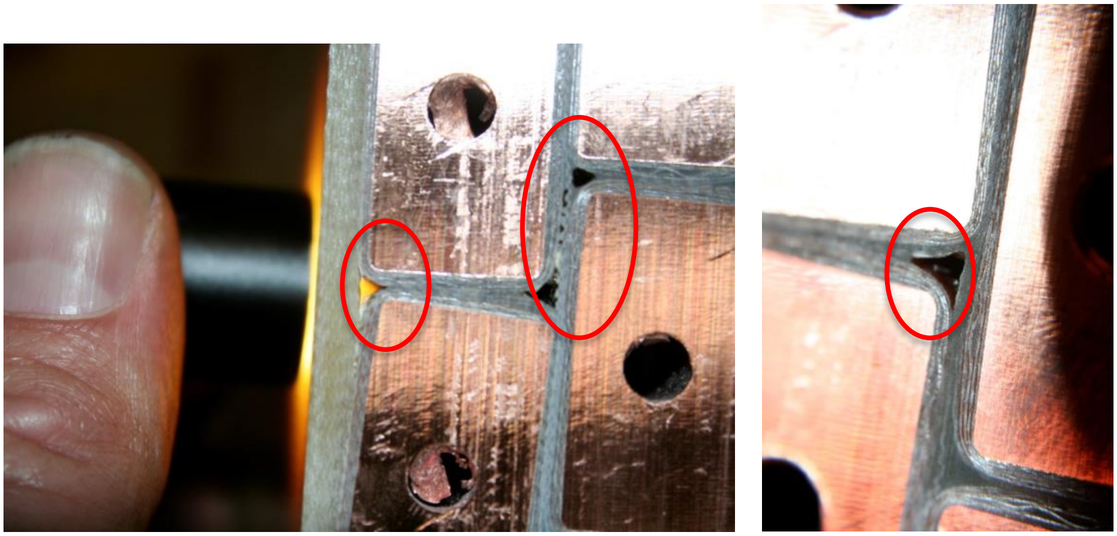

Figure 21: Toroidally Continuous voids found from the sectioned ETI coil (circled)

Visual inspection of the sectioned PPPL coil revealed some small local voids as shown in *Figure 22*. Such voids were noted at 6 conductor corner locations for the lead section, and 4 conductor turn corner locations for the non-lead section were evident at the ends of the sections. Similar voids likely exist in the insulation within the body of the sections. These small local voids appear mostly close to the end turns (more at the bottom turns away from the leads) with a maximum size of 1/32" (~0.8 mm at the section end surface). The maximum length or depth of the voids is less than 3 mm when a small diameter wire probe is used as shown in *Figure 23*.

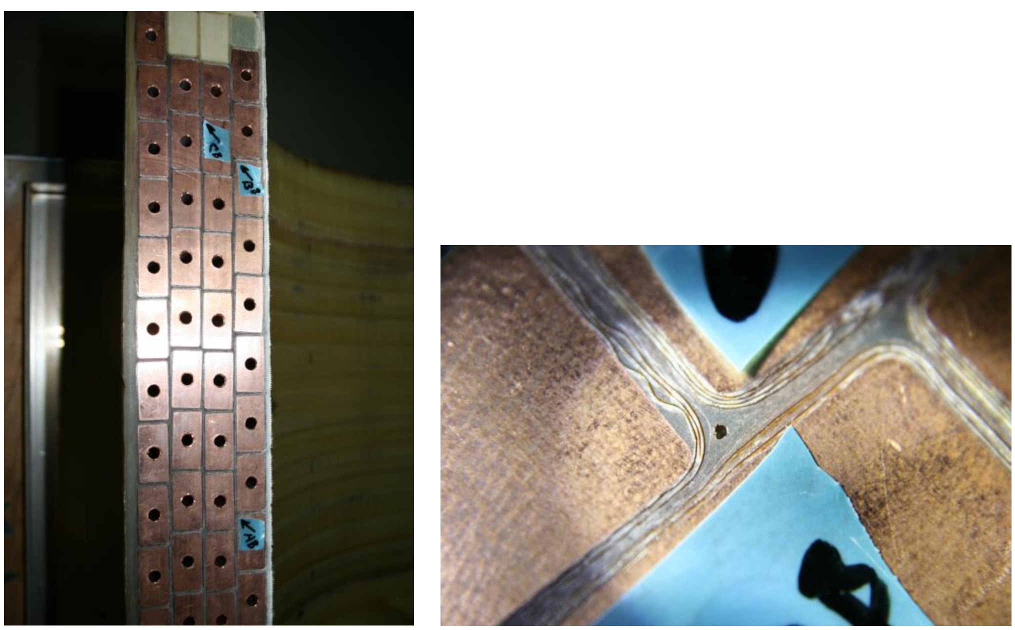

Figure 22: Non-toroidally-continuous local voids found from the sectioned PPPL coil

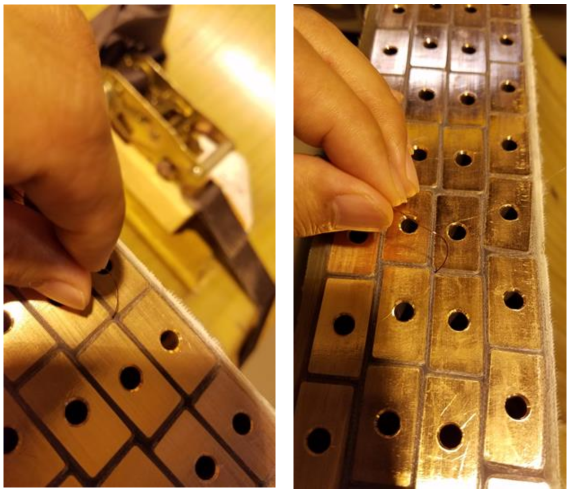

Figure 23: Local voids found from the sectioned PPPL coil

Although a perfect, void-free insulation is desirable, the relatively low operating voltage of the inner PF coils is such that partial discharge activity in voids is unlikely. Moreover, the relatively short integrated time that voltage is applied to the coils over their operating lifetime is such that damage due to partial discharges, if they occur, is unlikely. Based on their small size and extent, the voids in the PPPL coil are judged to be acceptable but the more extensive voids in the ETI coil are a cause for concern. Experience with the remaining two prototypes will reveal whether or not a completely void-free insulation is realizable.

Visual inspections of the sectioned ETI and PPPL coils also indicate difference in the conductor straightness layout in the coil winding pack as shown in *Figure 24* and *Figure 25*. A maximum conductor twisting of +/- 3 degrees was found for multiple turns in the sectioned PPPL coil winding pack. Two turns were found twisted up to 3 degrees in the sectioned ETI coil winding pack.

It is noted that the specifications to procure conductor for the production coils have a special tolerance on twist, and the fabrication results are very favorable so the deviations evident in the prototype coils will be much less in the production coils.

A Go/No-Go gauge was also used to inspect turn to turn insulation thickness. Although all turns for both the no-lead and lead sections of the sectioned ETI and PPPL coils passed the 0.070” minimum turn insulation thickness acceptance criteria, 3-5 turns in the PPPL coil were marginal. One turn was noted to be marginal for the sectioned ETI coil. It is suggested that optical measurements be performed to confirm conductor spacing and turn insulation thickness in the coil winding pack for future analysis.

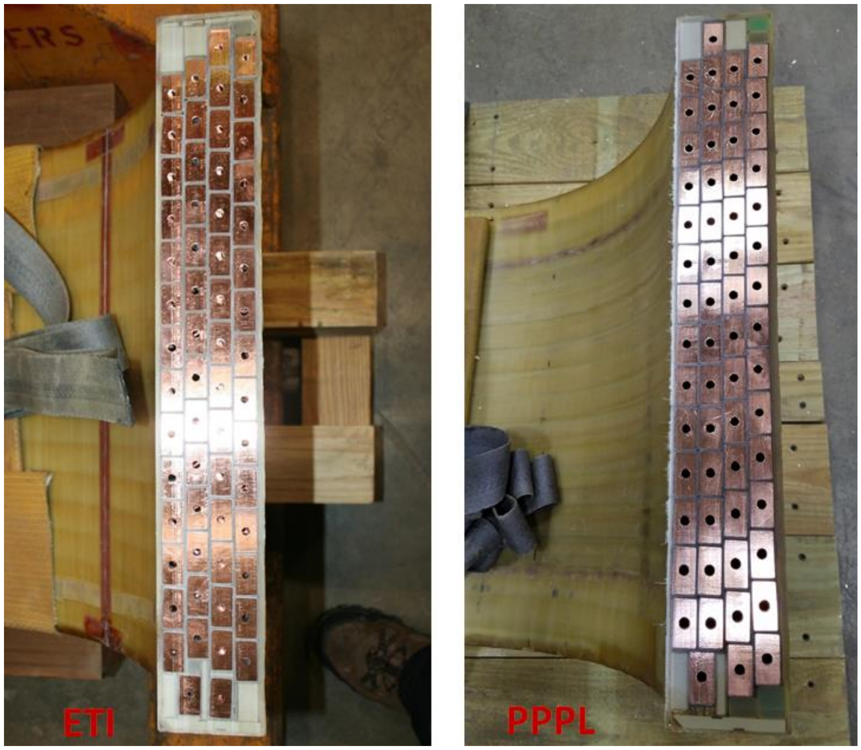

Figure 24: Conductor layout in coil winding pack from the sectioned PF-1aP coil

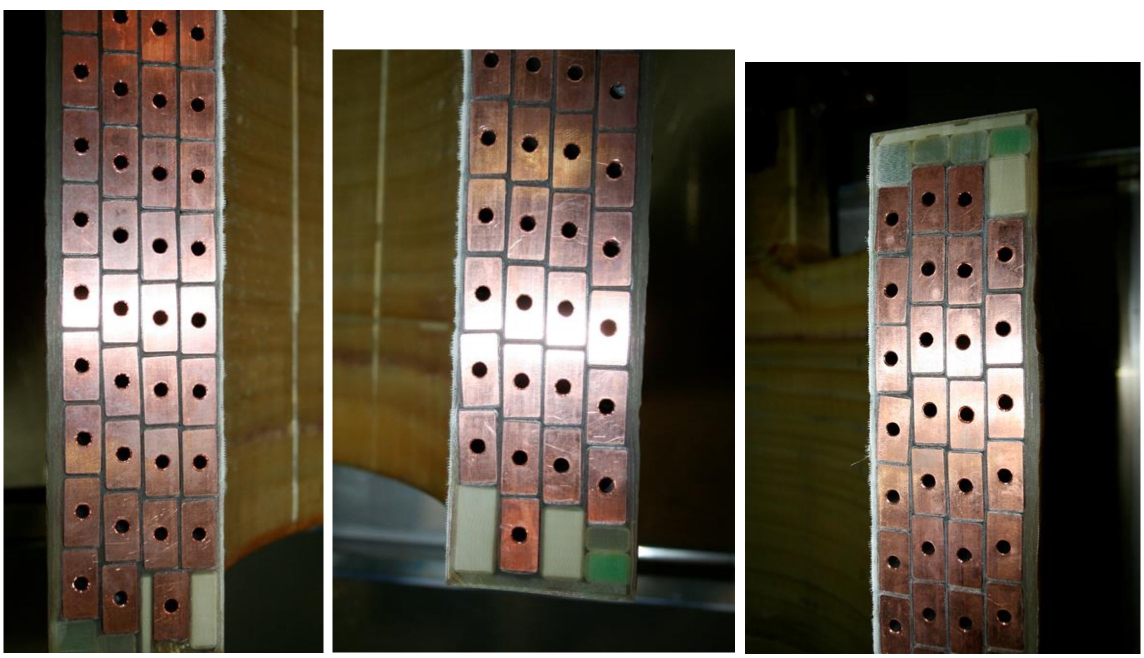

Figure 25: Conductor layout in coil winding pack from the sectioned PPPL PF-1aP coil

4.5 Post-Sectioning Testing

The objective of the electrical testing of the sectioned coil is to qualify the turn-to-turn insulation system of the sectioned coil to at least 10 kV, and to qualify the turn-to-ground insulation to at least 20 kV.

The 10 kV acceptance criteria selected was based on a safety factor of 10 on the 1 kV nominal maximum layer-to-layer voltage for PF1aP. Since the coil is rated for 2 kV across the terminals, with four layers the approximate maximum value of voltage appearing between turns is 1 kV. Therefore, using a rule of thumb for electrical insulation design, the ratio of insulation strength to service voltage should be at least 10 [4]. In fact, the theoretical safety factor is >>10.

To qualify the insulation a pass/fail criteria of 10 kV turn-to-turn and 20 kV to ground was chosen based on the aforementioned safety factor of 10. To stress the insulation as much as possible during the tests a target voltage of 20 kV during the turn-to-turn tests was selected based on the anticipated flashover voltage between the ends of the sectioned turns when immersed in the dielectric fluid (Fluorinert). Considering the very high theoretical insulation strength, any insulation breakdown in the solid insulation between turns would suggest a significant quality defect.

Figure 26 shows the setup for the electrical testing of the sectioned coil. *Figure 27* shows testing of the sectioned ETI coil. *Figure 28* and *Figure 29* show the flashover at ends observed during Hi-pot testing of sectioned ETI coil and PPPL coil respectively.

Both halves of the sectioned coils have been tested. *On the ETI coil, all turn-to-turn tests passed the 10-kV acceptance criteria and most turns achieved the 20 kV goal. No internal breakdowns occurred in the solid insulation between turns. The ground wrap insulation for both halves passed the 20-kV acceptance criteria.* The non-lead halves achieved better than 60-kV ground and the lead halves achieved 55-kV, with the ultimate breakdown occurring along the creepage path from one of the connection flags to the foil ground added for the test.

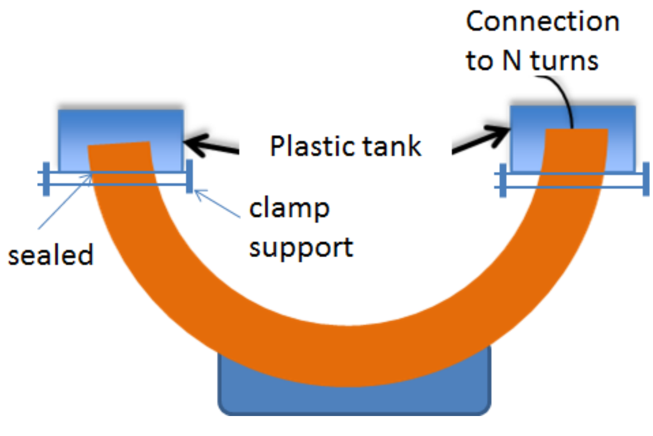

Figure 26: Setup for turn-to-turn Hi-pot test of the sectioned PF-1aP coil

Figure 27: Turn-to-turn insulation resistance and hi-pot test of sectioned ETI PF-1aP coil

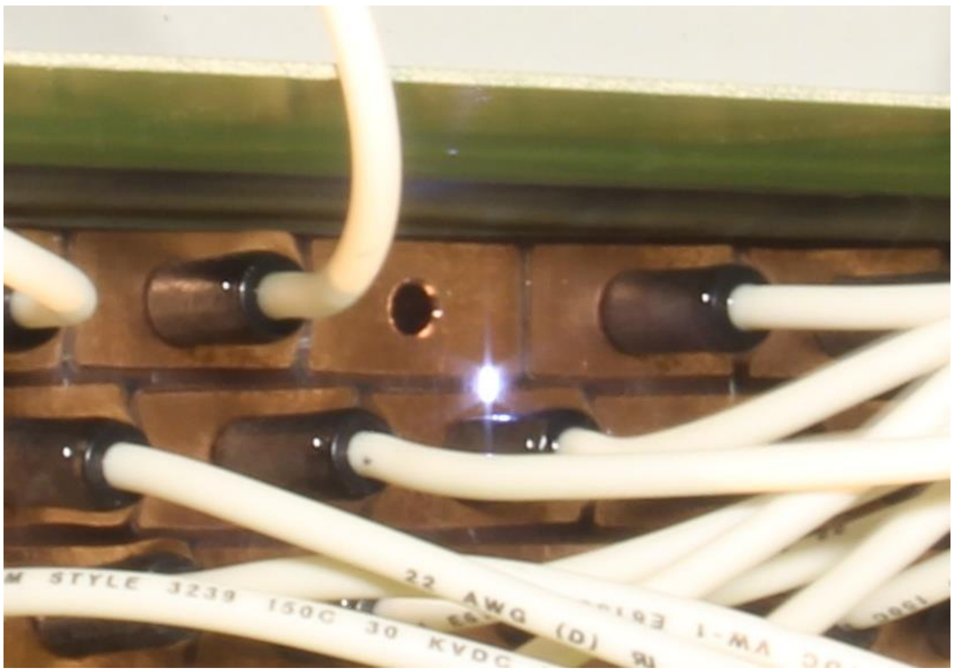

Figure 28: Flashover at ends observed during Hi-pot test of sectioned ETI PF-1aP coil (2^{nd} half, turn #10)

Figure 29: Flashover at ends observed during Hi-pot test (at 20 kV) of sectioned PPPL PF-1aP (1st half, turn #22)

Electrical testing of the no-lead and lead-halves of the sectioned PPPL coil was completed and all turns successfully passed the 10 kV turn-to-turn acceptance criteria without internal insulation breakdown. All turns were also tested up to 15-20 kV and passed with no internal insulation breakdown occurring. The outer ground wrap passed its 20 kV acceptance criteria, and was then tested up to 60 kV for the no-lead halves, and 54 kV for the lead-halves without failure.

4.6 VPI cured resin test

Cured resin samples from both ETI and PPPL coil VPI processes were tested with Differential Scanning Calorimetry (DSC) method by Composite Technology Development, Inc., the resin supplier.

In the DSC test, the difference in the amount of heat required to increase the temperature of a sample and a reference is measured as a function of temperature. When the sample undergoes a physical transformation such as phase transitions, more or less heat will need to flow to it than the reference to maintain both at the same temperature. By observing the difference in heat flow between the sample and reference, differential scanning calorimeters are able to measure the amount of heat absorbed or released during such transitions.

Table 9 shows the DSC data summary. The results confirm that for all intents and purposes, the material was fully cured in the coils from both suppliers.

Table 9: DSC Data Summary for CTD Standard reference sample and the ETI and PPPL coil resins

Specimen #	Weight (mg)	ΔH (J/g)	Tg (^{0}C)	% Cure
CTD Standard	5.500	30.09	Not evaluated	96.58
CTD-425 ETI Coil Resin	9.80	37.37	178.87	95.76
CTD-425 PPPL Coil Resin	10.4	36.25	171.63	95.88

5 Summary

The NSTX-U Recovery project has obtained and evaluated two prototype inner PF coils, one supplied by ETI and another supplied by PPPL.

The two coils successfully passed all tests, although neither coil was entirely void-free. It is concluded that, based on the findings reported herein, the Notable Outcome requirements have been met.

The NSTX-U Recovery project is obtaining prototype inner PF coils from four suppliers (expecting two more suppliers) per a common specification. The technical evaluation of the remaining two prototypes will begin as soon as they are received by the coil test team. The information obtained in the technical evaluation process, along with other factors, will be considered as part of the Source Selection Procedure for suppliers of production coils.

6 References

[1] C/D-PTP-NSTX-CL-063 Inner PF Coil Prototype Technical Evaluation Procedure (PTEP)

[2] NSTX-U-SPEC-MAG-004-R3 Specification for Prototype – Phase 1 Inner PF Coils

[3] PF1A Prototype Coil Assembly, E-DC11053

[4] PF1a Prototype FDR, June 7, 2017.