Executive Summary

On April 24th, 2015 during the execution of the coil power tests the NSTXU OH circuit suffered arc damage from a short created by the movement of a grounding conductor on the OH Ground Plane across energized OH water connections. The arc damaged the conductor water connections, caused a water leak and tripped off the power supplies. The cause was identified as a grounding conductor on the OH ground plane that was installed without the required electrical break. The resulting circulating currents in the conductor interacted with the OH field propelling it into the water connections. The lack of a proper ground on the OH compression ring to which the water connections were mounted was identified as a contributing cause. Subsequent inspection and investigation identified the cause as well as other areas of the design that can be improved to avoid a recurrence of the fault. These items include redesign of the grounding clamp on the OH ground plane, grounding of the OH compression ring, and redesign of the water connections on the OH coil. Disassembly and inspection of all of the TF and OH components in the upper and lower umbrella identified other areas that can be improved upon including TF finger supports, OH Coaxial connector, and Bussbar support grounding.

OH Coil Design

The OH coil and surrounding hardware at the top of the NSTXU is shown in Figure 1. The OH coil shown at the bottom is cooled by water cooling passages in each layer of the conductors. The cooling water exits through 8 ports near the top of the coil just below the OH compression ring. The OH compression ring provides a minimum 20,000 lbs. of downward force to the OH coil against the electromagnetic launching loads and thermal bakeout dimensional excursions. The OH compression ring was not grounded at the time of the event. The ground clamp and conductor (braid) shown several inches below the water connections provides a grounding path for the painted ground plane on the outside of the OH coil. Figure 2 shows an undamaged OH water connections supported by an insulating clamp to the OH compression ring.

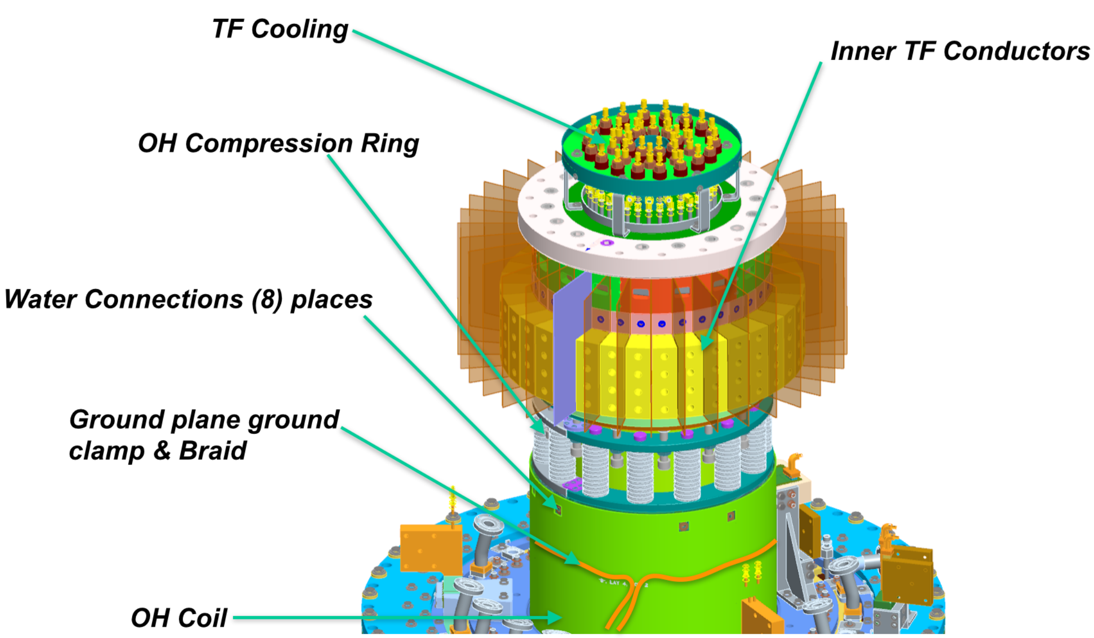

Figure 1 OH Coil, Water Connections, Ground Clamp and Compression ring

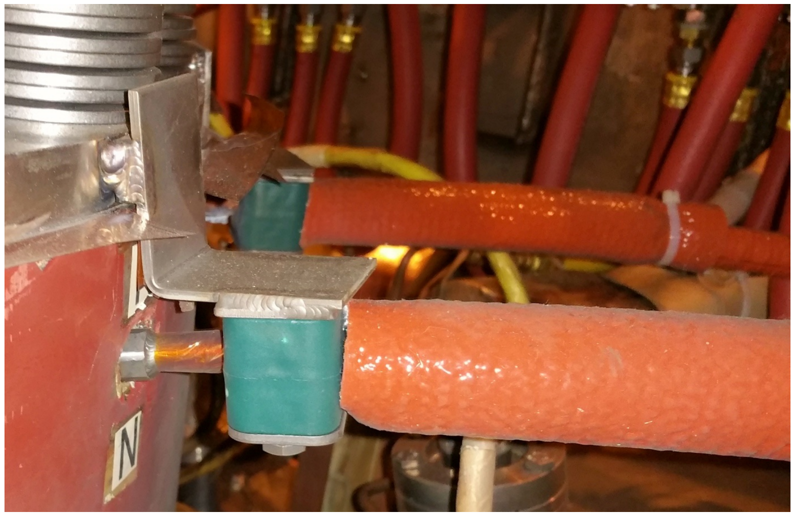

Figure 2 Photo of an undamaged hose connection to OH water passage

Shot Sequence Leading up to the Fault

The NSTX-U coils are qualified for use by the completion of ISTP-NSTX-001 “NSTX-U Coil Energization Tests”. This procedure executes single-coil “clean” shots and deliberate trips of key protection systems, followed by combined field test shots. The ISTP was executed between April 16, 2015 and April 21, 2015. The final shots were a series of 8%, 25%, 50%, 75%, and 100% combined field shots, where the fractions refer to the maximum currents allowed for the CD-4 run period (21 kA in the case of the OH coil).

Operations on 4/24/2015, intended to culminate in the NSTX-U test plasma, started with low-pots of the coil systems from the rectifier room (known as FCPC); these low-pots are 500 V insulations tests of the rectifiers and coils. These low-pots were followed by repeats of the previously successful 8%, 50%, and 100% coil-only test shots from April 21. While the 8% and 50% test shots ran through without incident, three attempts to repeat the 100% test shot failed on OH circuit ground fault trips. In particular the OH circuit is equipped with both industry standard “inverse time” ground fault relays and PPPL designed “instantaneous” relays, with the latter providing all three faults in this case. The three trip shots (200185, 200187, 200189) are shown in Figure 3, along with the waveforms for the successful 100% test shot on April 21.

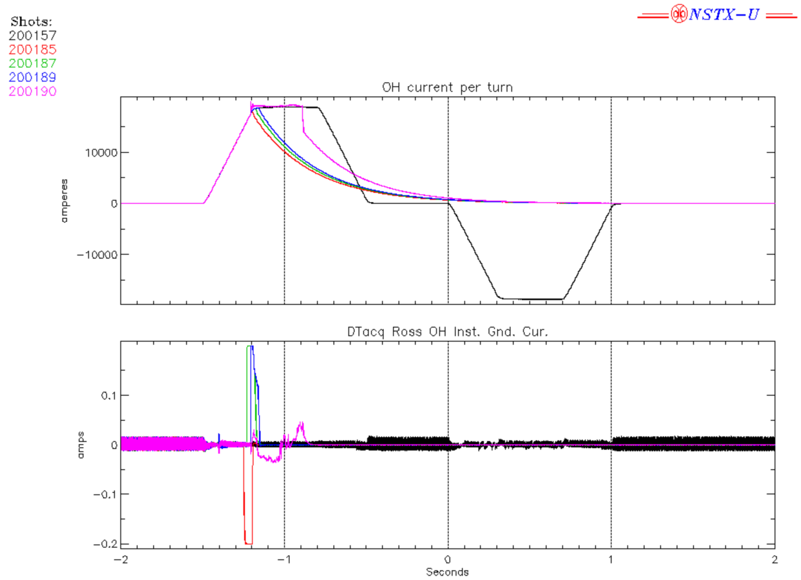

Figure 3 OH Coil Current (top) and ground current (bottom) for the final shot of the ISTP (200157), three shots with trips on 4/24/2014, and the shot with the damaging arc (200190)

Shot 200185 was the first attempt at the 100% test shot on April 24th, as well as the first ground fault trip, and was accompanied by an inner to outer vessel loop fault that developed during the shot. A controlled access to the NSTX-U test cell (NTC) was made, where the source of the loop fault was found to be the OH ground braid. This braid had been connected to the outer vessel (Cat. 4), while a higher impedance path from the ground plane to the PF-1aU coil mandrel was likely completing the circuit causing the loop. The braid was moved to an inner vessel (Cat. 3) connection, clearing the loop fault.

Once personnel cleared the NTC, a low-pot of the OH coil was performed from the rectifier room. The leakage current was found to be the same during the morning low-pots. Shot 200187 was then a repeat of the 100% test shot attempt, and also succumbed to a trip due the OH ground currents. The trip level on the ground current on the instantaneous relays was then raised from the previous 50 mA to 100 mA. The 100% shot was then repeated as shot 200189; this shot again tripped the OH ground fault relays. At this point, the instantaneous ground fault relays were removed from the protection circuit; note that the inverse time relays were NOT disabled, and were still part of the rectifier/machine protection system. The next shot, 200190, was a fourth attempt at the 100% test shot; it is also shown in Figure 3. The damaging arc occurred on this shot. This arc was supported for approximately 300 ms, and the shot was tripped off by a TF ground current trip.

Fault Damage

Inspections during the hours and days immediately following the fault showed that the damage was restricted to an area at the top of the OH coil, within the upper structure; see Figure 4 and 5 for examples of this damage. Most clearly obvious was the damage to four of eight upper water feeds. In some cases, the stainless steel brackets that supported the water feeds off the Belleville spring stack were disintegrated by the arc. The water fittings on the coil were badly damaged in other cases. All four of these failures resulted in water flowing out of the coil and throughout the upper umbrella structure. Some other water-cooling hoses within the umbrella were also damaged, though none badly enough to result in water leaks. The arc also distributed soot over many components within the umbrella.

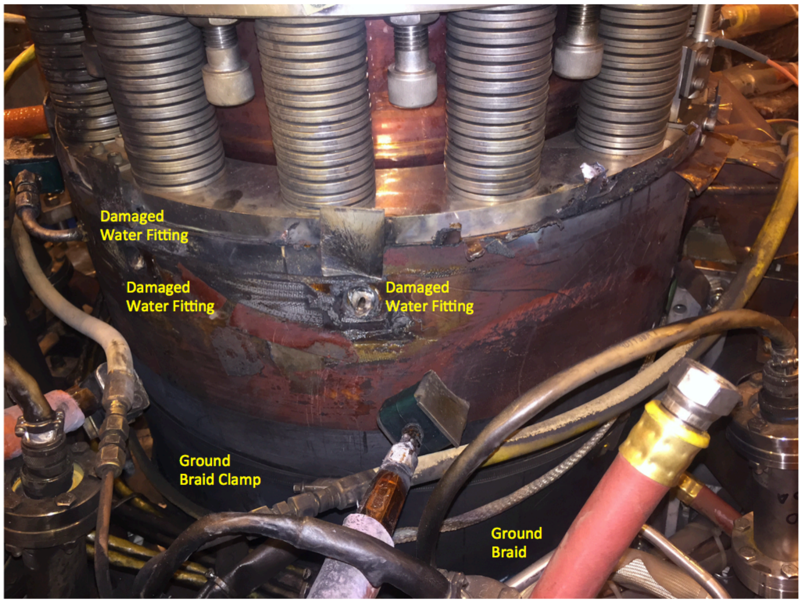

Figure 4 Image of the damaged area with labels on some key features

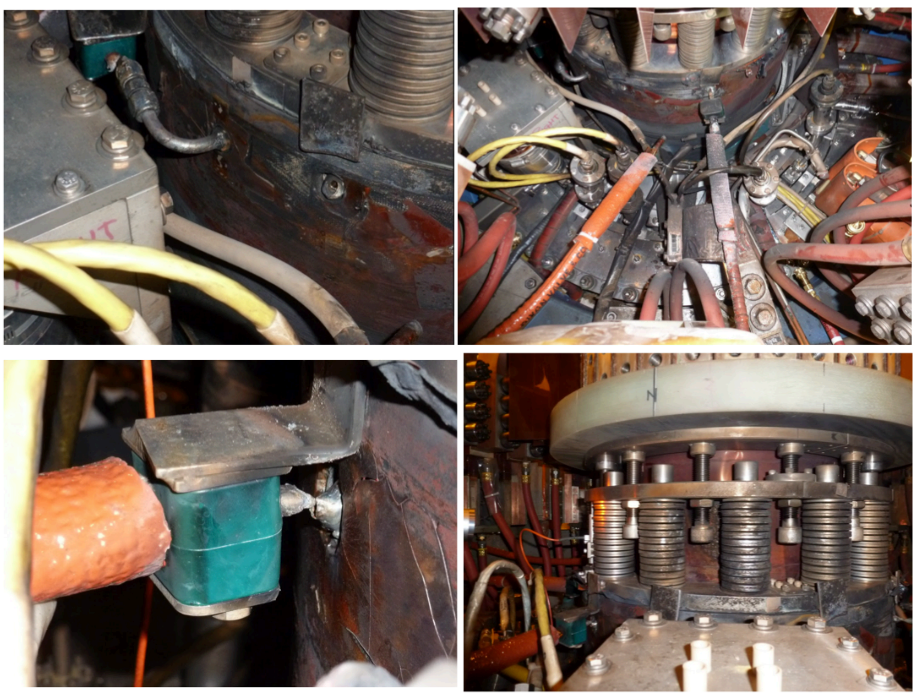

Figure 5 Additional images of the damaged areas

Testing from that time has shown positive results. All eight cooling channels of the OH coil are free of obstruction and have passed hydrostatic pressure tests. The OH and TF coils have passed 9 kV megger insulation tests. All magnetic diagnostic cabling within the umbrella, including the three plasma current rogowskis, appear to be intact and undamaged.

Fault Scenario

Over a few weeks of inspection and analysis by many members of the NSTX-U physics and engineering teams, the following three items were identified as contributing to the fault: i) the ground braid on the OH coil was installed to be toroidally continuous, ii) the Belleville washer stack was not properly grounded or otherwise electrically referenced, iii) though not a direct cause, the brackets that hold the OH coil water fittings were not of a robust design. These observations will be described below. Key to these conclusions were the observations of ground currents and line-to-ground voltages during this forensic analysis; these signals were not, however, inspected in the control room during the shot sequence leading up to 200190.

As noted above, the first three trips were due to the OH ground circuit interlock, and are almost certainly related to the mobile braid. This ground braid was installed around the coil without a conductive break. As a consequence, large currents lowed in the braid during the OH current swing. These currents, immersed in the large radial field of the solenoid, cause a larger vertical force on the braid. Over time, this braid appears to have worked itself free of its clamp (this was likely occurring during the OH shots of the ISTP). Inspection of the machine following the fault shows that the ground braid was laying loose on the coil, largely free of its clamp, and could move vertically far enough to touch the water fittings (see Figure 2). The only restraint point for the braid was on the side of the OH coil opposite where the damage occurred.

Once the braid had worked sufficiently free of its clamps, it was able to come in contact with different water fittings. As can be seen in Figure 6, both the +2.25 and the -2.25 kV water fittings are in near proximity to each other, such that small variations in the vertical travel could result in different fitting coming in contact with the braid. This can explain the observed changes in the sign of the measured ground current between 200185 and 200187 in Figures 3 and 6, when the braid comes in contact with fittings at different voltages, causing different ground current signatures.

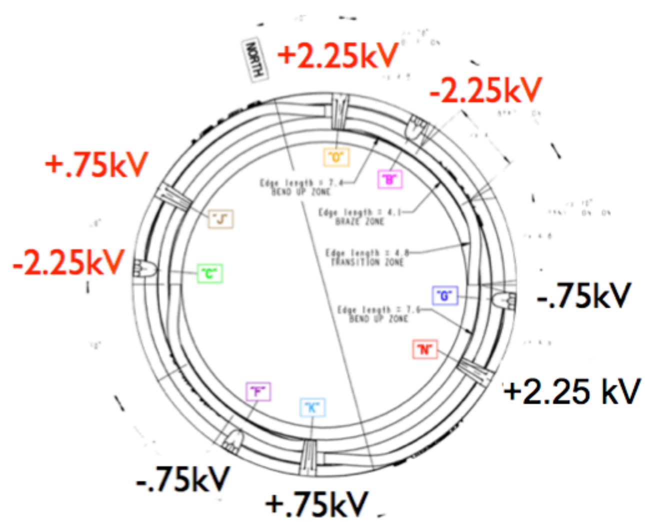

Figure 6 Potentials on the various water feeds at the top of the NSTX-U coil. The red labels indicate the four feeds with damage during the arc on shot 200190

Shot 200190, however, had a quite different ground current signature, as can be seen in the expanded plot in Figure 7. The ground currents were much smaller, and thus the decision to remove the "instantaneous" ground current relays did not impact the ultimate fault (recall also that the inverse-time OH ground current relays were still present in any case).

In this case, it appears that the mobile ground braid likely interacted with two of the water feeds at the same time. In doing so, the net reference of the OH circuit was not dramatically changed, and so the ground currents were minimized. On the other hand, this interaction apparently resulted in an arc across the insulating clamp on the OH water feed. Once this happened, the Belleville stack was at high voltage with respect to the other water feeds and could easily arc to those other feeds. The net result was an electrical path from one water feed to its bracket via an arc, to the bottom of the Belleville stack, to the bracket of another water feed, and finally to the water feed by an arc. This is consistent with the observed line-to-ground voltages, and the OH current waveform can be reproduced by simple models involving an arc that shorts out ¾ of the turns of the coil. This fault then evolved to include two additional water feeds. Note that if the Belleville washer stack had been properly grounded, it is possible that the inverse time ground current relays would have tripped more rapidly, reducing the damage; the floating washer stack rendered the FCPC ground current interlock ineffective for this style of arc. Additionally, any high-pots would not have been capable of determining any compromised insulation between the OH coil and the Belleville stack.

As in indirect contributor to the failure, the design of the OH water feed clamps and insulators can be improved. Improvements would include providing larger gaps between the coil conductor and the grounded parts of the bracket, and an elimination of any points and sharper corners.

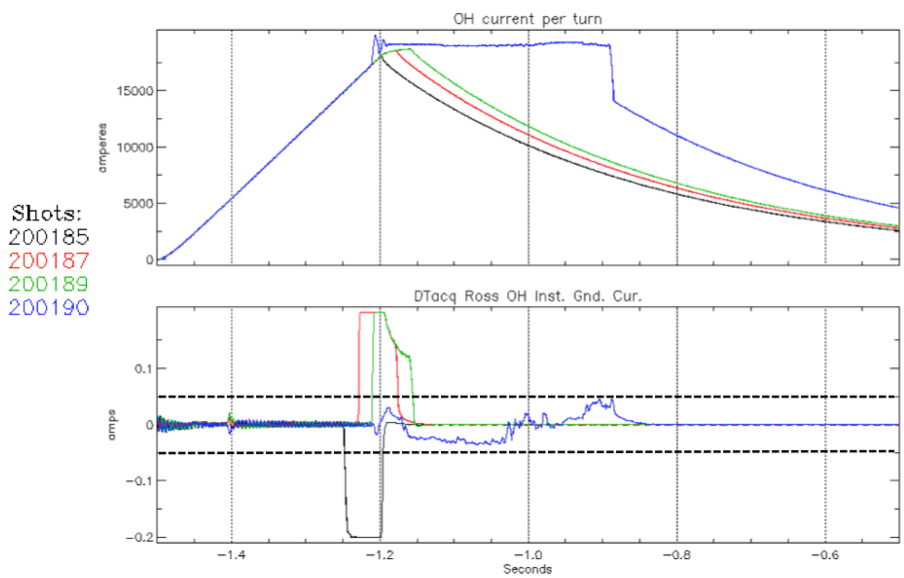

Figure 7 Zoom in on the OH coil current and OH ground currents for the four attempts at the 100% test shots on 4/24/2015

Causes of the Fault

After studying the parts involved in the arc, the timeline of the events leading up to the arc and the shot data in the previous section it was determined the most likely technical causes of the arc were as follows:

1. Ground Plane Grounding clamp was not properly installed creating a loop (launching force)
2. OH Compression ring was floating - prevented Ground Fault Monitor, and potentially a high-potter, from detecting a short to the assembly

A review of the design documentation regarding the ground braid was conducted. The review found the documentation package was fairly comprehensive, but technical details needed improvement. No details associated with the OH Ground Plane Braid were depicted in system engineering drawings and the ground plane braid wasn't shown on Center Stack drawings. While detailed mechanical drawings exist, there is only an old drawing (from the first center stack) to show the electrical grounding in the centerstack. The installation procedure D-NSTX-IP-3572 Rev 2, section 4.1.8 has a sign-off by the test director confirming that the electrical grounding connections between the OH ground plane and Center Stack casing were in place. The procedural causes of the event were identified as:

1. Lack of policy regarding referencing (grounding) and insulation of machine structures

2. Lack of design drawing showing machine structure referencing (grounding) and insulation
3. Lack of detailed engineering design for OH ground plane clamp and ground strap
4. Testing proceeded without identifying the cause of the OH Trips

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Redesigned Components and Recommissioning

To address the technical causes the OH Ground Clamp loop, and ungrounded OH compression ring the parts are being redesigned. In addition the cooling water connections and insulating supports are being upgraded to improve their electrical insulation.

Ground Clamp

The OH ground plane, which is composed of low resistance paint applied to the OH coil's outer surface, shall be grounded to the inner vacuum vessel, with a single point connection, through a 10Ω resistor. The revised hose clamp employs a spring-loaded tightening system, which allows the hose clamp to maintain tension on the braid during typical OH coil thermal cycling. The hose clamp is modified to incorporate an electric break, approximately four inches in length, which prevents a current loop from forming in the clamp. The conductive braid, which is a flattened tube, will be opened and slipped over the hose clamp, ensuring that it cannot separate from the hose clamp even if the hose clamp loses spring tension. The braid will be arranged so that it cannot slide over the hose clamp's electric break, which would compromise its benefit.

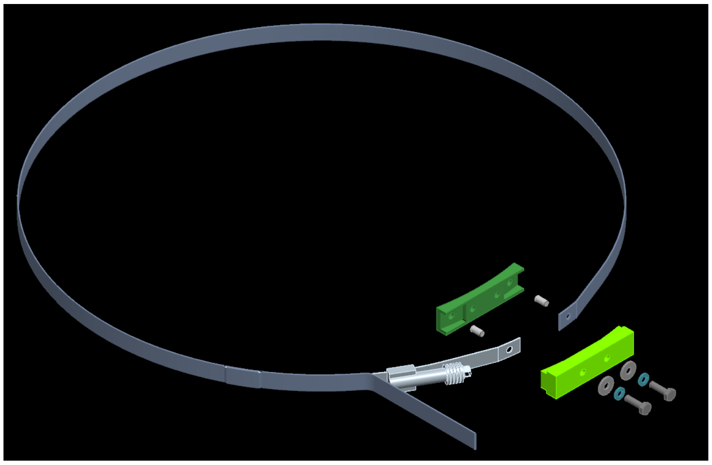

Figure 8 Redesigned OH ground clamp with G10 insulator

OH Compression Ring

The OH compression ring is an assembly of three stainless steel rings with welded posts that hold belleville spring washers and jacking screws. The compression ring assembly maintains a preload on the OH coil, keeping it seated during operations. This metallic structure is located approximately 1.5 inches above the eight OH cooling tubes, which are at high voltage potentials. To ensure proper grounding of this metallic structure, jumper cables are being installed between the mechanically bolted sections of the assembly. An AWG #6 cable will ground the assembly to the inner vacuum vessel at a single point.

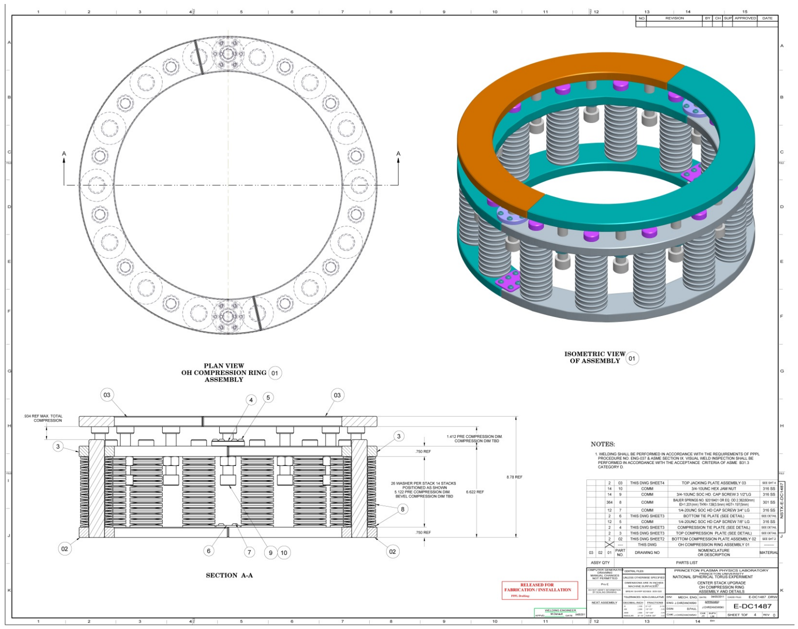

Figure 9 OH Compression Ring

OH Cooling Tube Support Brackets

The OH cooling tube support brackets provide support and strain relief for the OH cooling tubes and the OH cooling hoses. The design, shown in Figure 10, includes an "L"-shaped stainless bracket that attaches to the OH compression ring (top) and the PF-1A coil support structure (bottom). A G-10, electrically isolating block, bridges the L-shaped bracket and the cooling tube. The support bracket is being redesigned so that the metallic L-shaped component has at least one inch of air gap and/or tracking length to any electrically energized component (the cooling tubes). The design of the new bracket is based on input from an electrical engineer experienced in high voltage design, and validated with electrostatic finite element analysis. A prototype shall be built and bench hi-pot tested to 26 kV to validate the analysis. All production support pieces shall be bench hi-pot tested to 13 kV prior to installation. All installed components shall be in-situ hi-pot tested to 9 kV to validate installation.

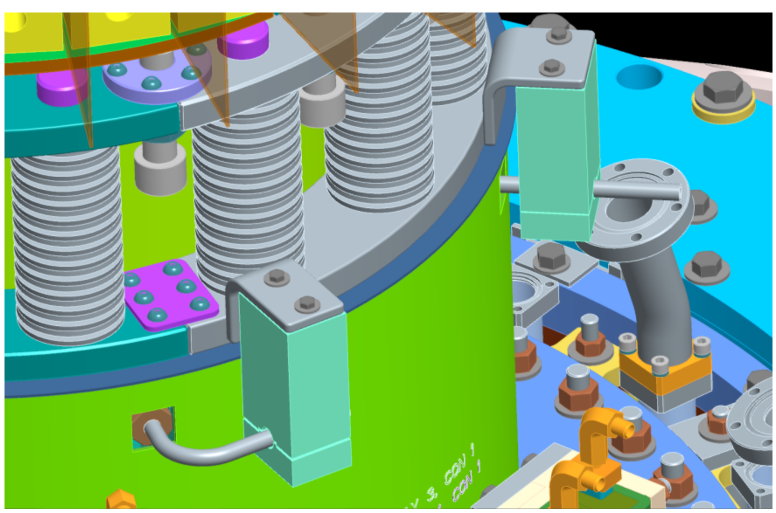

Figure 10 Redesigned OH Water tube support and insulator

Determination of the Extent of Condition

All of the OH and TF electrical connections and their related mechanical support structure in the upper and lower umbrella were disassembled so a visual inspection of the parts could be performed to determine if there were any other areas that could be improved upon.

TF Electrical Contact surfaces

Disassembly of the electrical connections between the TF bundle and the TF Outer Legs (TFOL) revealed discoloration on the silver-plated electrical contact faces as shown in Figure 11. This discoloration was present on the electrical faces between the TF connectors and TFOL mating flags and may be due to water during the incident. Flatness and surface finish measurements of the contact are being taken. Electrical resistance measurements of the joints indicate an acceptable value (~.020 micro-ohms).

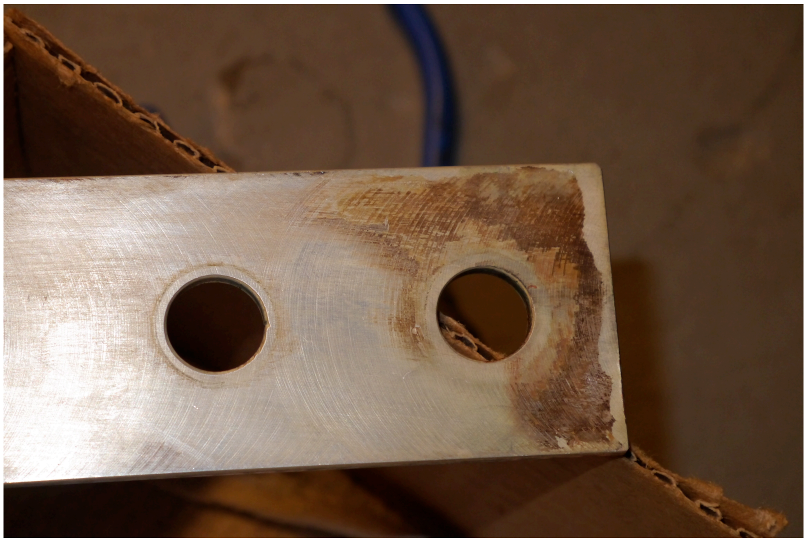

Figure 11 Example of staining found on TF connections

TF Connector Support Brackets

The TF connector support brackets (see Figure 12) are structures that prevent the mechanical forces, induced from electromagnetic interaction between the TF flex strap and the vertical magnetic fields, from being transmitted to the TF outer leg (TFOL) flag's braze joint. At the time of initial assembly, the specified structural adhesive/gap filler was not available, and in order to meet the design intent the installation crew used shimming to eliminate gaps between the TF connector, G-10 electrical isolator and the Inconel support bracket. Inspection indicated that the shimming effort was effective. However the structural filler has become available and shall be applied during reassembly of the TF flex strap/connectors/ bracket system.

At disassembly, four of the thirty-six G-10 isolators were found to have cracks along the plane of the G-10's laminations. It is difficult to ascertain whether the cracking is due to assembly technique, excessive play (improper shimming or shifting during coil pulsing), or stack up of tolerances that caused unanticipated loads in sections of the G-10. Application of the structural filler will alleviate these conditions.

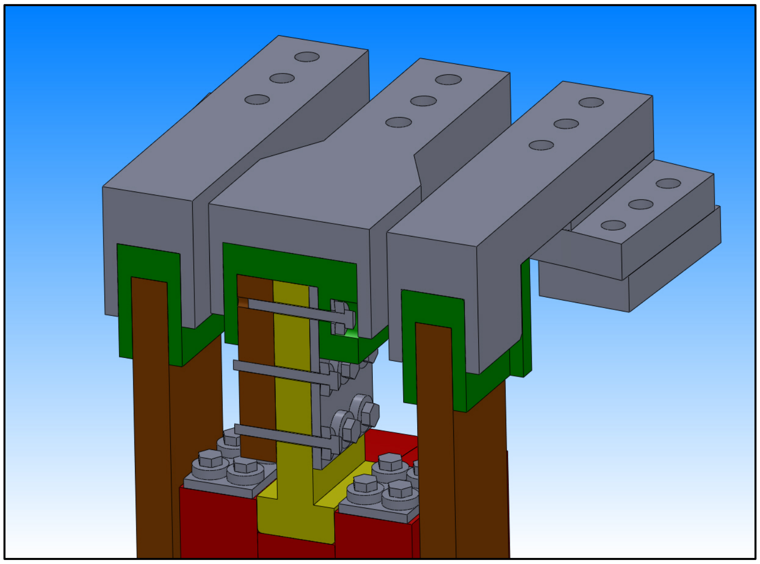

Figure 12 OTF Finger Supports cross section

OH Coaxial Bus

The OH coaxial electrical buss (see Figure 13) will be removed as part of the lower umbrella disassembly. While the coaxial bus is removed, it shall be disassembled and holes shall be drilled into the external conductor to allow injection of epoxy filler after it is reinstalled. The epoxy filler shall eliminate any deflection of the conductors which in turn minimizes loads on the OH electrical contact faces.

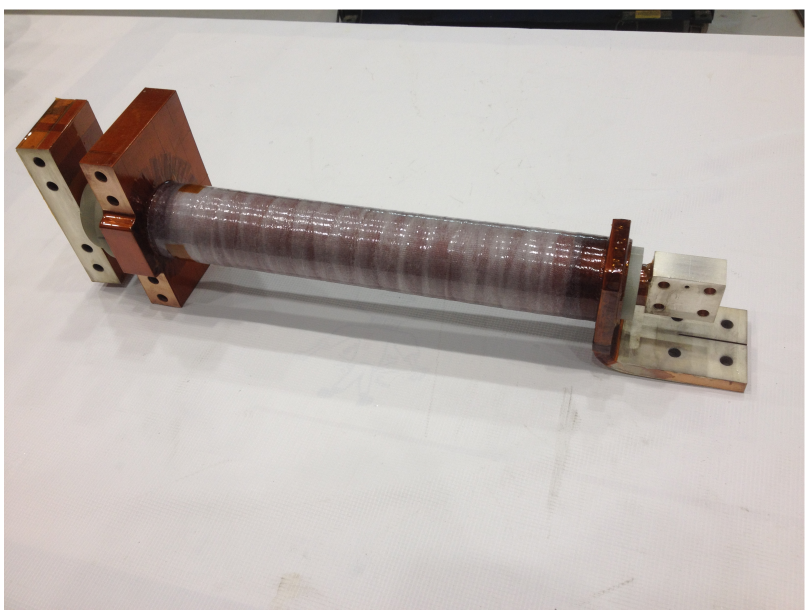

Figure 13 OH Coax connection

Ungrounded Structures

Field inspections have revealed that the brackets that support the TF, OH and CHI bus are not properly grounded. They are mechanically fastened to the NSTX test Cell concrete floor, which provides a weak electrical connection to building ground. These structures (see Figure 14) will be bonded with cables to copper plates that will reference them directly to the building steel.

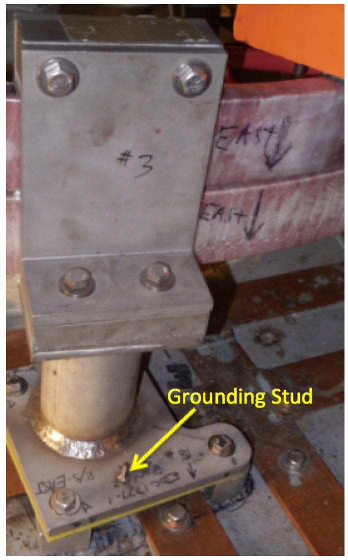

Figure 14 Bussbar floor support missing grounding jumper

Hipotting of the Inner Vacuum Vessel (Centerstack Casing)

The inner vacuum vessel is normally hipotted to demonstrate its isolation. Since the arc event the inner vessel has not been able to be hipotted due low resistance between the inner and outer vessels. Evidence indicates this is residual water from the ruptured water tubes during the event. It is believed this will return to normal after the water has dried out, but this remains to be verified.

Recommissioning the Coil System

After all repairs and changes are incorporated, the affected coils will undergo Pre-Operational tests under PTP-CL-026. This procedure validates that the coil system is capable of handling the voltages applied during NSTX-U operations. The NSTXU will then be ready to resume ISTP testing.