CHI Resistor Assembly Spark Event

**The Incident**

On April 20 2015, while conducting dummy load testing of the CHI Cap Bank, a spark was observed.

Three successful dummy load shots had been completed at 500 Volts. The spark was noted on the first dummy load attempt at 1000 Volts. Waveforms generated during the discharge indicate normal operation except for the spark, with Cap Bank 1 firing at T = 0, Bank 2 at T = 3 ms, and Bank 3 at T = 7 ms. (See W20150420c)

Here follows an analysis of the spark incident and its likely causes, an assessment of the current status of affected Cap Bank components, and a proposed plan to complete remediation and resume dummy load testing in preparation for a return to operational status.

A number of drawings, photos, and other files pertaining to this system, including this document, can be found on my PPPL Google Drive; please inquire if you would like an access invitation. Drawing 1B4FD1221 is an overview of the CHI system, and drawing 1D4FD107 shows details of the Resistor Assembly.

**Analysis and Assessment**

The Coaxial Helicity Injector system hardware was initially assembled roughly ten years ago, and has a record of reliable performance. Logs indicate that the last Run Day was October 20, 2010, since which time the system has been idle during the NSTX-U upgrade.

In the current configuration, Cap Bank 1 consists of Capacitor and Resistor Assemblies 1, 2 and 3, discharging through Ignitron VFWD-1; Cap Bank 2 is comprised of Capacitor and Resistor Assemblies 3, 4 and 5 with Ignitron VFWD-2; Cap bank 3 now contains only Capacitor and Resistor Assemblies 8 and 10, controlled by means of Ignitron VFWD-3. Capacitors 7 and 9 are currently located at The University of Washington, and are not expected to be used here at PPPL during the upcoming run period.

Inspection revealed evidence of sparking on Resistor Assembly #8. All ten Resistor Assemblies were electrically isolated and their resistance measured with an AEMC 6240 Micro-ohmmeter. RA8’s post-failure resistance was found to be the highest of the ten, at 56.6 milliohms; others ranged from 53.4 to 55.7 milliohms. RA8 was removed and disassembled for examination.

The five threaded rods holding the assembly together were checked for torque prior to removal. The four ½” rods had torque values of 2, 5, 8, and 9 ft-lb, while the center 1” rod was quite difficult to remove, with a torque estimated at more than 200 ft-lb, and requiring the use of a power impact driver.

As can be seen in the various photos, arcing occurred between one of the ceramic resistors and the positively charged Pressure Plate, and also between the adjacent resistor and the negatively charged Pressure Plate. It is believed that inadequate and uneven contact pressure combined with surface oxidation over time resulted in a small resistor-to-plate contact area and resistance high enough to generate a spark, with the subsequent jet of ionized metal and other materials providing a plate-to-plate current path. The oxidation pattern on one of the sparked Contact Plates can be seen in P1000427; areas with poor contact appear to show more oxidation.

As all ten of these Resistor Assemblies share the same design and environmental history, there was concern that other assemblies may be nearing failure as well, so the Resistor Assembly with the next highest measured resistance, RA7 at 55.7 milliohms, was also disassembled for inspection. While this assembly shared some of the same poor torqueing characteristics as RA8, with values of 4, 7, 8, 10, and >200 ft-lb, the silver-plated copper Contact Plate showed considerably less oxidation, as seen in P1000469.

There are a number of aspects of this mounting design which are less than ideal. In addition, there are several errors on the design drawing, and, further, the construction of all ten of the assemblies deviates from the parts specified in the Bill of Materials.

Sandwiching four of these disc-shaped resistors between two pressure plates creates a situation where consistent pressure applied across all surfaces is difficult. Even 5/16” thick steel Backing Plates such as used here deform a bit under load, and the 3/8” thick copper Contact Plates are not soft enough to conform to the resistor surfaces.

If the safety of personnel or valuable equipment were at stake, this would be enough to warrant consideration of a redesign of the Resistor Assembly. However, in this case, the equipment is safely located in the CHI High Voltage Cage, extensive equipment damage is not foreseen as a possible result of this type of failure, and importantly, we know that this equipment functioned successfully for several years.

The brass-coated contact area on each side of these resistors is nearly 5 square inches, for a total of 20 square inches of contact surface on each Contact Plate. Compared to the roughly 2 square inch contact area of the electrical crimp connectors used elsewhere to carry the same or greater current, this is a huge conducting surface area.

Notes 1 and 2 on the Resistor Assembly drawing, D-4FD107, contain multiple errors. Note 1 states that Item 13, the 1” nut on the central threaded rod should be torqued to 1,977 lb. It would be clearer to say that the nut should be tightened to the specified tension, not torqued, but beyond the lack of clarity, 1,977 lb is the Flat Load of the ½” Belleville Washers, not the 1” size. The Flat Load of a 1” Belleville Spring Washer as listed in the McMaster catalog (See McMaster Belleville) is 9,362 lb, but the Flat Load would be too tight to accommodate thermal expansion, and it would be appropriate to tighten only to the Working Load of 6,270 lb. In Note 2, the correct value for Item 12 would be the ½” Belleville Working Load of 1,370 lb, not the 1” Flat Load of 9,362 lb, nor the ½” Flat Load of 1,977 lb.

It is not clear how these tension figures were arrived at in the original design. Ideally, the center 1” rod should carry half of the tension, and each of the ½” rods should exert an eighth of the total force. Both the numbers called for on the drawing and the actual tensions found are quite far from this balance.

The specification sheet for these Kanthal Globar 915WS resistors (See ‘1A D&W Technical DataR3’) calls for a minimum pressure of 25 psi, with 50-100 psi preferred; I’m told that some users apply a pressure of 150 psi or more. The tension specified on the drawing would result in a pressure of 17,270 pounds applied over an area of 20 square inches, or about 860 psi. Using the lower Working Load figures would yield a pressure of 11,750 lb, roughly 585 psi.

As long as the Belleville Spring Washers are not squeezed flat they should provide plenty of elasticity to accommodate expected thermal expansion. The extent of Resistor Assembly heating during operation has not been measured, but the duty cycle is quite low, and calculations indicate that even if the assembly warmed considerably from 20 degrees Celsius to 100 degrees, the expansion expected would be only 2.8 mils. (See ‘Resistor Assembly Thermal Expansion 20150515’)

Tension is best determined with a strain gauge or by calculating the number of thread turns, but in this case, torque specs should be adequate. Using the established formula P = 12KT/KD, where P = Desired Clamp Load Tension in pounds, T = Torque in ft-lb, D = Nominal Thread Diameter in inches, and K = Torque Coefficient, assumed to be a moderate value of 2.0, we find that 11 ft-lb would be a reasonable torque value for the 1/2” nuts, and 104 ft-lb for the 1” nuts. (See ‘Torque to Tension 20150513’)

I would not advise attempting to loosen the central 1” nut unless the assembly is to be rebuilt, but they should all be checked to ensure that none are below torque specifications. Tightening the ½” bolts to the Working Load specification is not enough to reach the ideal balance with the inner rod tension, but it would be better than what we have found on the units examined to date, and probably would not increase the risk of cracked resistors significantly.

A close examination of the Resistor Assemblies reveals other problems. In every case, Item #9, steel backing washers specified as ½” ID x 1-1/4” OD x 1/8” thick were replaced by thinner stainless steel washers. Far worse, on the failed RA8, there were no Belleville Spring Washers at all, cupped stainless steel washers having been mistakenly substituted.

Thus far, it appears that the condition of RA8 was significantly worse than that of any of the other Resistor Assemblies. I think that the chances are quite good that cleaning and torque adjustment will be sufficient to maintain good operating performance of the eight assemblies which have not been disassembled.

All four of the resistors removed from RA7 appear to be in re-usable condition. Of those from RA8, one looks good, one is clearly not usable, and two have some damage, but could possibly be used if need be. A couple of the resistors have edge cracks as shown in P1000438, P1000439, and P1000472. We are also in possession of two additional 915WS resistors found in a smaller resistor assembly near the CHI.

The Sandvik resistor product engineer recommends cleaning the brass contact surfaces when needed with a soft pencil eraser followed by a brush.

**Plan Of Action**

I propose the following steps moving forward:

1. Check and record the torque of each 1” central nut on the remaining eight units to ensure that each is at least 104 ft-lb.
2. Document the existing torque found on each of the ½” nuts.
3. Without removing the resistors or shifting their position, replace the Belleville Washers on the ½” rods with new ones, replace the backing washers with correct new ones as listed on the Bill of Materials, replace the nuts with Nylon insert lock nuts to prevent loosening, and torque to 11 ft-lb.
4. Thoroughly wipe down resistor surfaces with lint-free cloths, saturated in ethanol and wrung out to prevent liquid being drawn into cracks by capillary action.
5. Re-check resistances and return Resistor Assemblies to service.
6. Initially make use of the eight units which have not been fully disassembled and rebuilt, in order to subject each of these to the most extensive testing prior to the resumption of operations.
7. Rebuild the disassembled units, test fire them to verify satisfactory operation, then place them in the unused capacitor locations as spares for the upcoming run.
8. Update documentation as needed.

The four disassembled copper Contact Plates have been cleaned, refinished, and have had their silver plating refreshed.

We have procured the necessary parts to begin reassembling as soon as tension specifications and course of action are agreed upon.

I recommend that we maintain an inventory of four or more spare resistors in addition to what may be needed for these repairs. Their cost is approximately $140 each. A few may be available on short notice, but a large order could take as long as 4 months.

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