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SOLDER JOINT CRYOGENIC FATIGUE OF THE RHIC 12x150A CURRENT LEADS AND MITIGATION FOR FUTURE OPERATION

F. Micolon†, E. Becker, D. Bruno, A. Drees, J. Escallier, R. Feder, W. Fischer, A. Marusic, C. Mi
R. Michnoff, M. Minty, J. Sandberg, P. Talty, R. Than, J. Tuozzolo
BNL, Upton, New York, USA

Abstract

A failure of the RHIC powering system occurred at the end of Run 23 and led to the discovery of ruptured conductors on the 12x150A current leads used to feed current to the superconducting (SC) magnet circuits. These ruptured conductors are thought to have caused an electrical breakdown, first within the solder joint, and then across adjacent conductors of the same current lead assembly. A fatigue experiment has been set up to study the behavior of Sn96Ag4 solder joints under cycling load at cryogenic temperature. Mitigation measures to minimize fatigue cycling have been implemented for the next RHIC run and will be discussed. This paper aims to describe our understanding of the solder joint cracking issue encountered and present the mitigation measures for future RHIC operation.

RHIC RUN 23 POWERING FAILURE

On August 1st 2023 at 12:31pm a magnet quench link interlock (QLI) occurred, and the beam was dumped. Shortly thereafter, a helium leak was observed from a cryogenic valvebox. It was later determined that the dipole and quadrupole superconducting circuits within a 12x150 A current lead had shorted together and to ground. Initial investigations revealed a ruptured bellow and sleeve from one of the 12x150 A superconducting lead insertion ports. The inside of the flange, bellow and vacuum feedthrough pipe were covered in copper residue and the lead was severely damaged from overheating. SC dipole (DX) electrical connections were damaged during the event and the magnet was replaced by its spare during the ensuing shutdown in winter 2023-2024.

Later analysis revealed that following the QLI, unusual current patterns were seen in the SC circuits. An abnormal current flow between two legs of the quadruple circuit was seen 11 ms after the QLI, the voltage difference between these legs prior to this connection was around 530 V. 50 ms after the QLI a large current to ground (over 500 A) was detected, and the DX quench heaters were nominally triggered 80 ms later to protect the magnet from a quench due to fast current variation. The initial cause of the QLI was due to an unrelated glitch in an electronic board.

The conclusion of the investigation was that an arc had initiated between quadrupole conductors within a 12x150A helium cooled lead. This arc then spread to a dipole conductor and to ground through the overheating of this 12x150 A lead and destruction of its electrical insulation.

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† fmicolon@bnl.gov

12X150 A LEAD DESIGN

The 12x150 A current leads are used to trim the current of the quadrupole magnets around the RHIC interaction regions. They are designed to route a series of 12x copper conductor from room temperature to the 4.5 K helium bath where they are soldered to SC conductors. A simplified sketch of their integration in the valvebox environment is depicted in Fig. 1. More details can be found in Ref. [1].

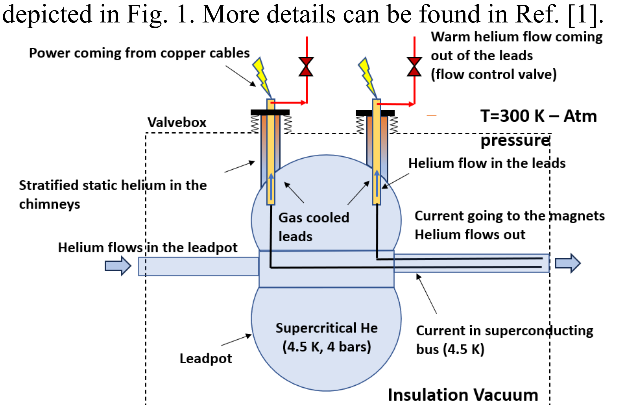

Figure 1: Sketch of the lead integration in the valvebox.

The 12x150 A leads are a forced-flow type, cooled by 4.5 K supercritical helium at 4 bars. The helium flow is controlled by a warm flow control valve. The 12 square copper conductors are guided in slots in the Noryl core. The helium flows around the conductors and up a helical channel machined in the Noryl core (Fig. 2). At the warm end, the square conductors are inserted in a round conductor inside a bore hole and soldered with Sn96Ag4.

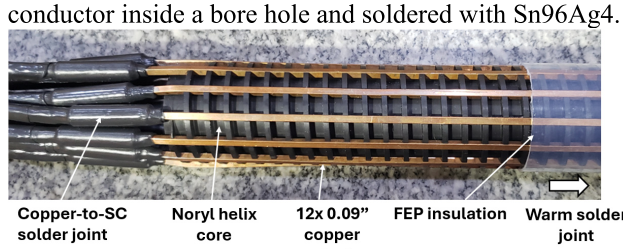

Figure 2: Cold end of the lead.

LOADS FROM THERMAL CYCLING

Initial commissioning of these leads has shown the need for high helium flow to keep the cold end superconducting due to higher-than-expected conducted heat [2]. Warm terminal frosting was also an issue until heaters were implemented [3] and the idle helium flow through the lead was initially set lower than the thermodynamic ideal.

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Due to varying current passing in the conductors of the same 12x150 A bundle, setting the right helium flow is not straightforward. A high current in a single conductor can pose a serious risk of overheating if the helium flow is not increased accordingly. To cope with this, the previous helium flow logic was supplying large amounts of helium when a conductor current was reaching 80 A, overcooling the entire lead bundle in the process.

In summary the leads were under-cooled at low current to avoid frosting the terminal and largely overcooled when at high current to avoid thermal runaway, creating large temperature profile variations.

Another contributing factor is the control system latency, the helium flow ramp started a few minutes after the current ramp. This created a situation where some conductors with high current were gradually heating up until a surge of helium cooled all conductors abruptly. This fast transient temperature difference led to significant thermal expansion variations between conductors of the same 12x conductor bundle during each current ramp.

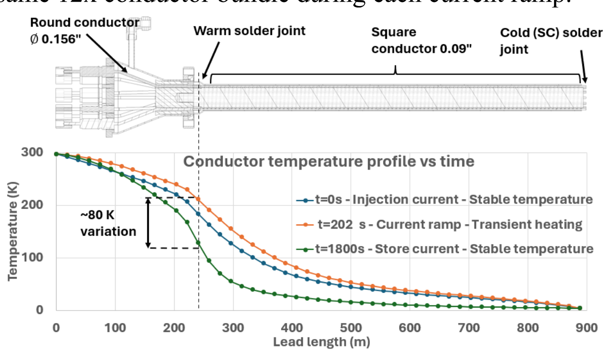

Figure 3: Temperature profile along the lead conductor at different point of the current ramp for B4Q2 (2023).

As seen in Fig. 2 the 12 square conductors are inserted in square slots in the Noryl core. A tight fit has led to conductor assembly issues, with plastic fins being broken during the initial conductor insertion. At cryogenic temperature, this tight-fit will close further and pinch the conductor due to Noryl's greater thermal contraction (measured Noryl contraction -1.1% at 77 K – copper -0.3% at 77 K). The Noryl elastic modulus was measured as 2.5 GPa (293 K) and 3.5 GPa (77 K) with a vibrating rod test. With these values, a simulation with a perfectly tight conductor/groove fit estimated a frictional force of 600-900 N at cryogenic temperature with assumptions on the friction coefficient μ=0.1 – 0.15 from [4]. Later measurement on the damaged lead confirmed this and showed friction force up to 700 N at 77 K.

During the temperature variation event, significant variation of conductor thermal expansion will occur. With the conductors pinched in the Noryl core at the cold end and fixed by the ceramic feedthrough at the warm end, high thermomechanical forces are developed in the assembly. With a single conductor expanding, sliding of the conductor in the core will only occur when the friction force is overcome (600 – 900 N). The other conductors of the bundle, expanding less, will act to resist this expansion. This will result in a compression of the solder joint with the expanding conductor sliding down the slot when heated, followed by tension when the conductor is pulled up when contracting. The Noryl core will also contract longitudinally around the conductors and press/pull them toward an indeterminate fixed point (the core is free-floating and held only by the conductor bundle and the FEP insulation). This cycling will occur each time the current and helium are ramped up and down. For 23 years of RHIC operation, this gives an estimate between 10000 and 20000 cycles.

Two adjacent conductors have a minimum spacing of 3.5 mm with an FEP insulation cover at the solder joint. Rupture of the conductor/solder joint may have reduced this clearance further and compromised the insulation. Analysis of the helium Paschen curve shows that at 1 mm gap a voltage difference of 600 V can start an arc [5].

STUDY OF SOLDER FATIGUE

The square conductor has a width/thickness of 0.09" (2.3 mm) giving a cross section of 5.22 mm^2. At the solder joint location, the conductor's edges were sanded to allow insertion in the bore hole (see Fig.4). Necking down to 4.1 mm^2 of conductor cross section (Ø0.09) is possible. With a 700 N frictional force, the stress at the onset of friction would then be 170 MPa. Annealed copper tensile strength at 200 K is estimated to be 267 MPa while the yield strength is 80 MPa [6]. The estimated fatigue lifetime of annealed copper at 200 K and 170 MPa is between 10 000 and 100 000 cycles [6]. It is considered that the Sn96Ag4 soldering operation (220°C) will have annealed the copper. Thus, with an estimate of 20000 cycles for RHIC, rupture of the conductor through fatigue is possible, especially in the necked down region close to the solder joint.

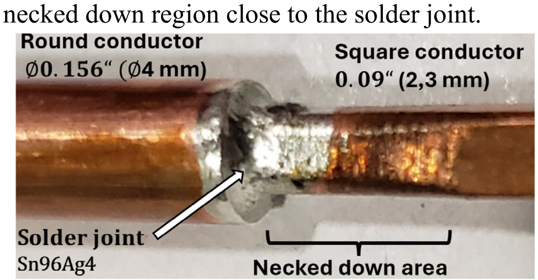

Figure 4: Warm solder joint geometry.

The solder shear area for a perfect filling is 91 mm^2. Through cuts of solder joints from the damaged lead were analyzed and a limited filling ratio was estimated to be around 30%. This would result in an effective shear area of 27 mm^2. The shear stress at 700 N friction force would then be 26 MPa. Shear strength of Sn96Ag4 solder was reported in [7]. Averaging 298 K and 77 K data, the shear strength of Sn96Ag4 would be 28.5 MPa. An unusual decrease of strength at cryogenic temperature is noted in [7] as well as a tendency to crack due to a phase change of the solder material called "tin pest" which is known to stress the solder joint (volume expansion) and make them brittle. It was noted that original solder samples RHIC looked duller than new Sn96Ag4 samples and some cracks were also visible (pre-loading) but no "powdering" was witnessed.

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The Ductile-to-Brittle Temperature (DBTT) of Sn96Ag4 is reported around 215 K [8].

A fatigue testing campaign at cryogenic temperature was undertaken to replicate the loading pattern, validate the conductor/solder fatigue rupture theory and study possible replacement solder alloys. The temperature was kept between 170-200 K to replicate the expected joint temperature (see Fig.3) and below the Sn96Ag4 DBTT. Some initial RHIC samples were available for this study and other samples were made with the same soldering technique as original RHIC joints. When cycled at +/- 600 N two RHIC sample broke after 17300 cycles and 22800 cycles respectively (Fig.4). When cycled at +/-800 N a new (RHIC-like) sample broke after 430 cycles. In every case the entire conductor broke off in the necked-down region close to the solder joint (Fig.5). Another RHIC sample buckled at 800 N compression. This suggests that fatigue due to repeated bending through small-displacement buckling is also possible if the conductor friction force is 800 N or above. It is noted that possible creep of the solder joint was not evaluated during the test due to fast cycling. Although solder creep rate at high stress is considerably slowed by low temperatures [9].

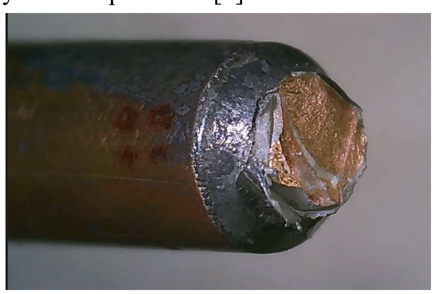

Figure 5: Ruptured solder joint - 22800 cycles at ±600 N.

Other solder alloys have been considered to mitigate the possible solder cracking of Sn96Ag4. Aside from the conventional 63SnPb37 we considered 93Pb-5Sn-2Ag and In80Pb15Ag5 which are both known to remain ductile at cryogenic temperatures.

FATIGUE MITIGATION MEASURES

We determined that the root cause of this fatigue issue is the interference fit of the Noryl core/conductor interface that develops high frictional stress when there is a thermal contraction mismatch between conductors. A looser conductor fit, ensuring unimpeded sliding, will suppress structural fatigue of the solder/conductor. However, for the remaining RHIC runs replacing all 60 leads in the 12 leadpots is out of reach. Instead, we have aimed to limit the fatigue loading by minimizing the temperature variations of the lead conductors. First the latency of the control system has been reduced to a few seconds. Then the undercooling at low current has been reduced by increasing the flow of helium. This was made possible because initial frosting issues have been solved with the warm heaters [3].

A series of thermal simulations were done to devise a new high-current helium flow logic operating with less overcooling. However, this also implies operating with less margin to thermal runaway [1]. The main challenge is the large difference in operating current between conductors of the same 12x conductor bundle. The helium will help keep a relatively consistent temperature profile between adjacent conductors. However, the convection heat transfer being non-ideal, some temperature – and thermal expansion - difference between conductors cannot be avoided with the current lead design.

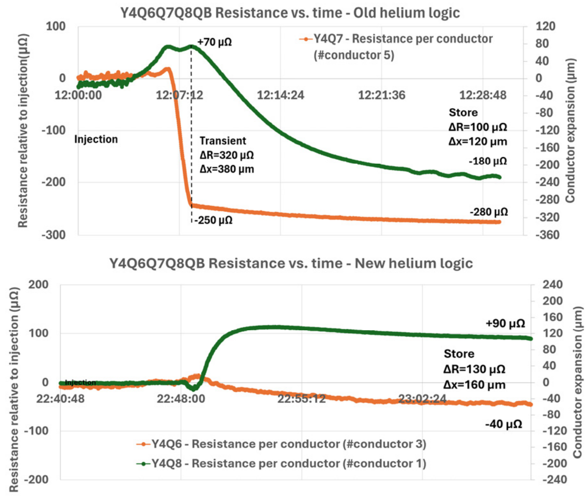

Figure 6: Conductor resistance variation with (top) the old helium logic (bottom) new helium logic.

From Fig. 6, the resistance variation and thus the thermal expansion mismatch between conductors has been greatly reduced from an estimated 0.38 mm to 0.16 mm. Each bundle is composed of 4x straight conductors and 8x bent conductors. The stiffness of the straight conductors is estimated around 1700 N/mm. The estimated pulling force has then been reduced from 610 N to 270 N. No fatigue is expected at 270 N (~ 66 MPa) conductor pulling force [6].

A beneficial side effect of reducing the lead overcooling is an improvement in their thermodynamic efficiency, estimated to be up to 6% for high-energy operation [1]. This is expected to save up to 80 MWh per high energy run.

CONCLUSION

After investigation of the 2023 lead failure event, we consider the scenario of a solder joint or copper conductor rupture due to structural fatigue to be very probable. A dedicated fatigue test confirmed this hypothesis. The root cause is the interference fit between the Noryl and the 12x conductors at cryogenic temperature. Poor solder filling and necking of the conductor close to the joint are both contributing factors. To mitigate this for the next RHIC runs, a new helium flow control logic has been implemented and the pulling force on the conductor has been reduced to a point where no further fatigue is expected.

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