HIC SUPERCONDUCTING CIRCUIT FAILURE DURING RUN 23*

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Abstract

A failure of the RHIC superconducting circuit occurred at the end of Run 23 and led to an unplanned shutdown and extensive work to replace a damaged superconducting dipole magnet. After an in-depth investigation, the failure was found to originate from an electrical arc within a superconducting current lead. The arc led to large spilling of current through auxiliary superconducting circuits with limited quench stabilization, which resulted in a superconducting splice burning out. This paper will summarize our understanding of the series of events leading to the superconducting circuit damage, describe the repair work undertaken for the remaining RHIC runs and discuss some lessons learned in view of EIC operation.

FAILURE SYMPTOMS

On August 1st 2023 at 12:31pm a magnet quench link interlock (QLI) occurred during high-energy collision operation at 200 GeV with Au ions [1]. The beam was nominally dumped, but shortly after all 12x blue ring DX magnet quench heater were unexpectedly triggered. A few minutes later, a large helium release was observed outside of the Interaction Region 4 (IR4) cryogenic valvebox (Fig. 1), both from the pressure release duct and the vacuum seal at the valvebox bottom flange which gives access to the leadpot, the helium-filled vessel where superconducting current leads are located.

Figure 1: Aug 1st 2023 - Helium release through (left) the blue IR4 valvebox (right) the service building exhaust.

Subsequent electrical diagnostics revealed that the main dipole and quadrupole superconducting (SC) buses were shorted together and to ground, making the collider SC circuits unusable. This concluded the physics Run 23 and led to an early shutdown seven weeks ahead of schedule.

RHIC SUPERCONDUCTING CIRCUITS

RHIC has two parallel counter-rotating storage rings, the "blue" and "yellow" rings. For each ring, the RHIC SC system is composed of two independent SC circuits, the quadrupole and dipole circuits. The quadrupole circuit is wired symmetrically around the ring from the power supply (PS) located at IR4 and it loops back at IR10 to feed all the SC quadrupole in series (Fig. 2).

On Fig. 2, the outer legs feed all the vertically focusing quadrupoles (Qv) from IR4, the circuits loop back at IR10 and the inner legs feed the horizontally focusing quadrupoles (Qh) with an auxiliary shunt circuit used to trim the Qv/Qh current to adjust the accelerator optics. Two dump resistors are located at IR4.

Both the dipole and quadrupole circuits have a variety of so-called "shunts" auxiliary SC circuits to adjust current locally around each of the six IRs. For example, the final focusing quadrupoles are principally powered through the main Qv/Qh circuits, but adjustment of the magnet current can be done by a "shunt" circuit connected in-parallel at the SC magnet leads inside the helium vessel.

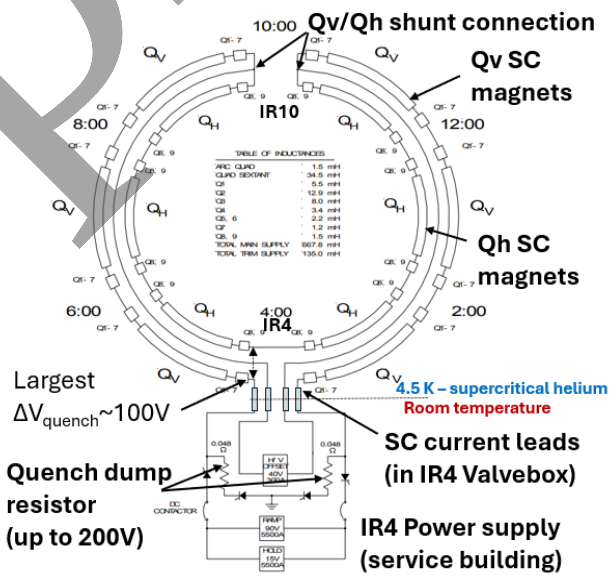

TABLE OF INDUCTANCES	
ARC QUAD	1.5 mH
QUAD SEXTANT	34.5 mH
Q1	5.5 mH
Q2	12.9 mH
Q3	8.0 mH
Q4	3.4 mH
Q5, 6	2.2 mH
Q7	1.2 mH
Q8, 9	1.5 mH
TOTAL MAIN SUPPLY	667.8 mH
TOTAL TRIM SUPPLY	135.0 mH

Figure 2: Sketch of the RHIC quadrupole SC circuit [2].

During a quench, the quadrupole circuit voltage goes up to ~200V at the dump resistor, driven by the inductance of the large number of SC magnet wired in series during the current decay.

Any two points of the circuit will see a different voltage-to-ground depending on how many SC magnets separate them. The highest wire-to-wire voltage difference will reach ~100V (~50% of the total dump resistor voltage) at IR4 between the Qh/Qv legs. (see Fig. 2).

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* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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FAILURE DATA ANALYSIS

Analysis of the high-frequency signal acquisition after the QLI (t=0 ms), showed the first abnormal signal was a drift of the shunt circuits B4Q9 (Qh) and B4Q1(Qv) current of opposite sign (t+11 ms), suggesting that the two circuit were shorted together and current was spilling over between the Qv and Qh quadrupole legs (Fig. 3).

At (t+26 ms) abnormal signal readout also appeared on the dipole shunt circuit B4DX, part of the dipole bus.

At (t+61 ms) after the QLI, a large ground current started to appear both on the quadrupole and dipole circuits and as a result, the magnet string current decay was much faster than usual (Fig. 4). This produced a large and sudden current variations in the SC circuit (up to 5000 A/s) which quenched many SC magnets all around the blue ring.

The large separator dipoles DX, located at each IR, are the only RHIC SC magnet that are not self-protecting and are equipped with coil quench heaters. These quench heaters triggered at (t+132 ms) on all blue DX magnet at once.

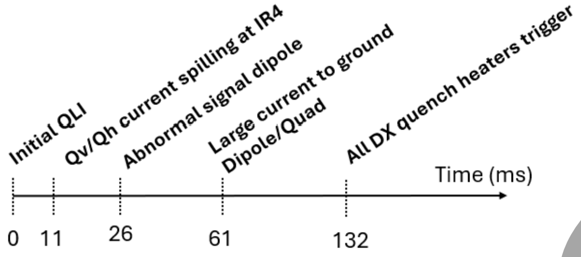

Figure 3: Timeline of failures during the QLI event.

HARDWARE DAMAGE

After the QLI a large helium release was witnessed at IR4 inside and outside of the service building housing the PS and the cryogenic valveboxes (Fig. 1). The release in the blue circuit valvebox bottom flange was through a volume normally under insulation-vacuum, indicating an internal rupture in the valvebox piping. Indeed, one of the 12x150 A current lead was found severely burned (Fig. 5) and a hole was burned through the stainless-steel pipe housing the current lead, indicating the location of the electrical arc. The dipole and Qv/Qh circuit short-to-ground were located at the B4DX magnet splice box connections.

POSTMORTEM INVESTIGATION

12x150A Current Lead

The 12x150A current leads are primarily used to shunt the quadrupole current locally around each of the six IRs. It is a bundle of 12x copper conductors held in close proximity and cooled by helium vapor circulating around a helix channel (see [3, 4] for design details).

The autopsy of the 12x150A current lead showed a severely burned FEP insulation sleeve along one of the 12x vertical copper conductors (Fig. 5), the copper conductor was entirely missing on a ~150 mm length (Fig. 5). Upon removal, copper dust/droplets were found covering the surrounding structures.

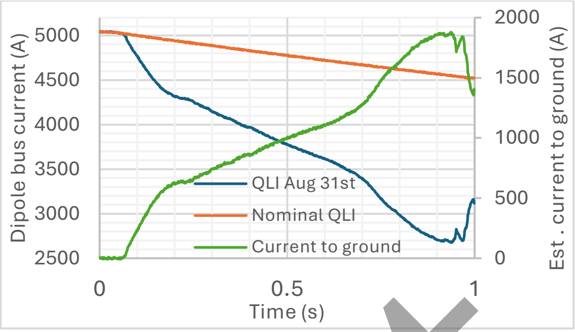

Figure 4: Failure - main dipole circuit current during QLI.

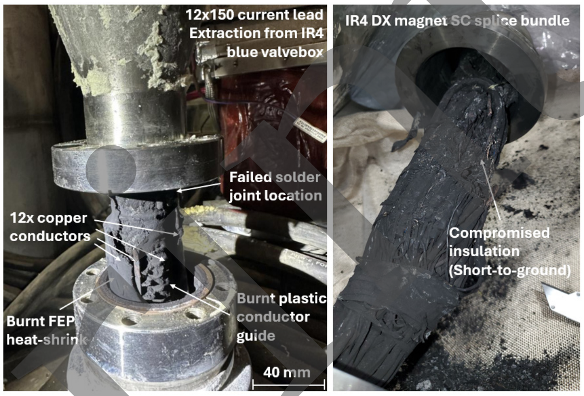

Figure 5: Hardware damage (left) 12x150 current lead (right) DX magnet splice bundle.

The copper-copper solder joints of the 12x150A lead were examined and showed obvious defects [5, 6] such as what appears to be fatigue cracks in the solder fillet, poor solder joint geometry (blind hole) leading to limited solder penetration and voids generated by trapped soldering flux. By reviewing data from previous run, it was found that the leads were routinely undergoing significant temperature cycling at each ramp, would have compromised the lead solder joints further and eventually led to the rupture of a conductor. Fatigue testing of spare conductors has confirmed this to be a credible explanation [7].

As the QLI took place, the nominal voltage gradient (~100V) developed between the Qv and Qh legs quadrupole circuit which are running through adjacent bare conductors in the 12x150A bundle. And a ruptured solder joint has led to an electrical breakdown between the Qv/Qh conductors. One of the 12x conductors also include an auxiliary shunt circuit connected to the main dipole circuit (D6 shunt). Once the lead insulation layer was compromised by the initial arc from the Qv/Qh circuit, it spread to the dipole circuit (t+26ms) and eventually to ground (t+61 ms) before the high current-to-ground drawn though the arc burned a hole in the stainless-steel pipe housing the lead. This led to a large helium release, first in the valvebox insulation vacuum and then through the bottom flange when the Viton™ o-ring became compromised by the low temperature.

DX Magnet Damage

The DX dipole SC magnet are the large aperture separator dipole magnets located across each RHIC IR (colliding and non-colliding).

Additional damage was found in the splice connections adjacent to the DX magnet (Fig. 5). Splice connections were severely burned and short-circuited, soot has been generated that polluted the DX magnet itself and so it was later replaced it by a spare DX magnet.

As discussed previously, the electrical arc in the 12x150A lead had spread to the dipole circuit through the D6 shunt circuit. This shunt circuit was designed to handle 150A only and the current-to-ground drawn through the D6 circuit was much higher. The current variation of the main dipole circuit is represented on Fig. 4 for a nominal quench (orange) and on the day of the failure (blue).

The estimated current-to-ground reached up to ~1850 A (Fig. 4) while running through the D6 shunt circuit designed for 150 A. The D6 circuit uses two types of SC cables in series, at different locations: in the so-called *cold-crossing bus* it consists of a heavily stabilized cable with a large copper content and a MIITS rating of 1.5E+6 A^2.s [8]. However, through the RHIC SC *magnet bus*, it uses a much less-stabilized conductor, the so-called *trim cable* consisting of 3x cables each with 3x strand of Cu-NbTi wire with a 1.75:1 Cu ratio and a MITTS rating of 0.106E+6 A^2.s only [2][8]. The MIITS accumulated by the current-to-ground in Fig. 4 reaches 1.3E+6 A^2.s. So, it is unsurprising that the *trim-cable* burned in the magnet splice while the *test cable* looks undamaged (Fig. 6).

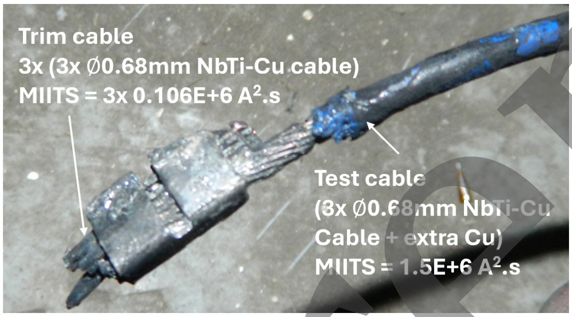

Figure 4: Failed D6 splice connection in the DX magnet.

The NbTi critical current for both these cables is high. From [9] a single Ø0.68 mm strand of a trim cable cable can sustain 270 A under 5T magnetic field. So using the SC critical surface fit from [10], at 0T and 4.2K the same strand could sustain 1350 A and so the entire trim cable (3x strands) could sustain 4050 A (at 0T) if the current is shared equally. So, the maximum ground current seen on Fig. 4 may not have sufficed to quench the entire SC cables. However, the proximity to the splice solder joint, with limited Cu stabilization and a non-ideal side-by-side conductor arrangement (Fig. 6) is likely to have generated significant resistive heat at 1850 A, enough to raise the local temperature past the cable quench limit.

Another contributing factor is the proximity of the quenched DX magnet which stores significant inductive energy at 5050 A operating current (630 kJ). During the quench, this inductive energy is transferred to the coils and the surrounding helium. At low temperature, the specific heat of the coils being very low, most of the energy dissipation will have been absorbed by the helium. The "warm" helium in contact with the coil will have expanded and rushed out of the magnet through the splice cans. This rush of "warmer" helium past the splice joint may also have contributed to heating up the splice joints past the point of quenching. And this explains why the damage was limited to the DX splice and similar splice joints in other magnet connections downstream were not damaged.

REPAIRS AND MITIGATION FOR RHIC RUN 24&25

The DX magnet with failed splices has been replaced by the spare DX magnet. This represented a large effort to finalize the magnet lead connections and end volume internals [11] and carry out warm magnetic testing needed to fiducialize the dipole field orientation.

The spare 12x150A current lead was also tested and installed in place of the failed lead. The root cause of the initial failure of the 12x150A lead has been investigated and described in [7]. It was found that the design improperly applies thermomechanical loads to the conductor and their solder joints. In order to mitigate the structural fatigue issue for the remaining RHIC run, a new helium-cooling algorithm has been implemented to minimize temperature cycling and extend the solder joint lifetime [7] until the end of the RHIC experimental program in 2025.

LESSON LEARNED FOR EIC

The RHIC yellow ring is poised to become the EIC HSR magnet system [12].

For EIC a new design of 12x150 A current lead has been proposed to remove all the risk identified and improve their cryogenic efficiency [13].

As visible on Fig. 6 the SC splice had a limited Cu stabilization and a cable arrangement not conducive to good current-sharing between cables (*trim cables* are arranged side-by-side when they should ideally be around the *test cable* to favor current-sharing and limit the splice resistance). A review of the SC splice design should aim to minimize splice resistance and maximize quench stabilization. Especially in areas that are hard to access and can foreseeably impose a long shutdown for future damage repair. Instead, easier to access areas could be purposefully equipped with lower-stabilization splices, acting as fuses, and potentially be equipped with local electrical diagnostic probes to simplify the fault location and the SC system recovery effort in the future.

CONCLUSION

The RHIC run 23 suffered a superconducting circuit failure, originating from an electrical breakdown within a 12x150A current lead. This was determined to come from thermomechanical fatigue and rupture of a solder joint within the current lead. The intense current-to-ground drawn by the electrical arc - through an auxiliary dipole shunt circuit - destroyed the lead, its containing stainless-steel pipe and two magnet splice connections downstream. This resulted in a months-long unplanned shutdown to resume collider operation in spring 2024.

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