IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012134 doi:10.1088/1757-899X/1344/1/012134

Design of a new 12x150A helium-cooled current lead for EIC

F. Micolon[1*], H. Lovera[1]

[1]Brookhaven National Laboratory, Upton, New York, USA

*E-mail: fmicolon@bnl.gov

Abstract. Following the failure that ended the RHIC run 23, a review of the 12x150A RHIC current leads has uncovered a series of design issues that granted a complete redesign ahead of the EIC project. Taking advantage of the lessons learned from 24 years of operation, significant improvements to the old design have been studied. We have derived suitable materials and conductor geometry from thermal and electrical conductivity measurement. It became apparent that materials with a low RRR are preferable for helium-cooled leads. The new current lead design was optimized through thermal and CFD analysis, aiming at a greater reliability and improved efficiency through its lifecycle. Operational aspects such as helium-flow adjustment, terminal condensation and electrical breakdown are also discussed. This paper will describe the lesson learned from the original lead operation, the principles driving this new current lead design, the lifecycle design optimization and the expected operational performances of the proposed design.

1. Introduction

Current leads have the difficult task of transferring electrical current from room temperature to the cryogenically-cooled superconducting circuits (SC) while minimizing the cryogenic system load. The design of efficient current leads has been studied extensively in literature [1][2][3]. Indeed, they often represent the largest contributor to the cryogenic load for accelerators. For the Relativistic Heavy Ion Collider (RHIC), the leads represented 40% of the initial cryogenic load [4].

The 12x150A current lead is an assembly of 12x conductors sharing the same helium cooling circuit for compactness. They are cooled by a valve-regulated flow of 4.5 K supercritical helium from the pressurized RHIC magnet line. The initial design for RHIC operation is described in [5][6]. Operation of these leads has proven problematic with several issues over the years:

- Failures of some ceramic feedthroughs during cool-down/warm-up cycles,
- Frosting/condensation of the warm terminal producing electrical shorts (see [7])
- Quenching of the cold-end superconductors imposing higher-than-ideal helium flow [6]
- Solder joint failure leading to a catastrophic short-to-ground of the RHIC SC circuit [8]

In view of the Electron-Ion collider (EIC) project [9], these leads have been redesigned to solve these issues and improve their cryogenic efficiency.

2. Current leads design guidelines

Superconducting current lead are typically one of two types:
Self-cooled – where the heat conducted to the saturated boiling bath of cryogen will produce the vapor used to cool the conductor.

Forced-flow - where the pressurized cryogenic volume supplies a controlled vapor flow. The forced-flow leads offer more operational flexibility and can be operated with less heat dissipated on the cryogenic bath thanks to the control of vapor flow rate.

2.1 Lead design guidelines

Current leads are generally designed with the following requirements in mind:

- Keep the superconductor under its critical temperature to avoid a quench
- Minimize the cryogenic load (both liquefaction and refrigeration load)
- Avoid condensation/frosting of the warm terminal for good electrical insulation
- Provide enough thermal inertia to avoid a sudden thermal runaway and lead damage

The heat conservation equation describes the behaviour of the electrical conductors (equation 1):

$$\underbrace{k(T).A.\frac{d^2T(x)}{dx^2}}_{\text{Conducted heat}} - \underbrace{\frac{h.A_s.(T-T_h)}{L}}_{\text{Heat extracted by gas coolant}} + \underbrace{\frac{\rho(T)I^2}{A}}_{\text{Resistive heat generation}} = 0 \qquad \text{Eq. (1)}$$

With the helium flow temperature following equation 2 :

$$\dot{m}.c_p.\frac{dT_h(x)}{dx} = h.A_s.(T - T_h) \qquad \text{Eq. (2)}$$

All terms of the equations used in this paper follow the nomenclature detailed in [10].

The only material-dependent terms in Eq.(1) are the thermal conductivity $k(T)$ and the electrical resistivity $\rho(T)$. A simplified analytical resolution is possible under the assumption that the materials follow the Wiederman-Franz law (WFL) and with perfect coolant convection ($h = \infty$) [10]. The WFL states that for a given material: $\rho k = L_0 T$ and the factor L_0 has a constant value, the Lorentz number: $$L_0 = \frac{\rho k}{T} = 2.44 \times 10^{-8}\, V^2 K^{-2}$$

While this may be acceptable as a first approach for highly pure materials, significant deviations are seen for impure and alloyed materials (Figure 1). A desirable property of current lead material is a low electrical resistivity $\rho(T)$ and a low thermal conductivity $k(T)$ (i.e. a low Lorentz number) to minimize the lead heating (Eq. 1, 2). Unfortunately, these two properties tend to be closely related as suggested by the WFL.

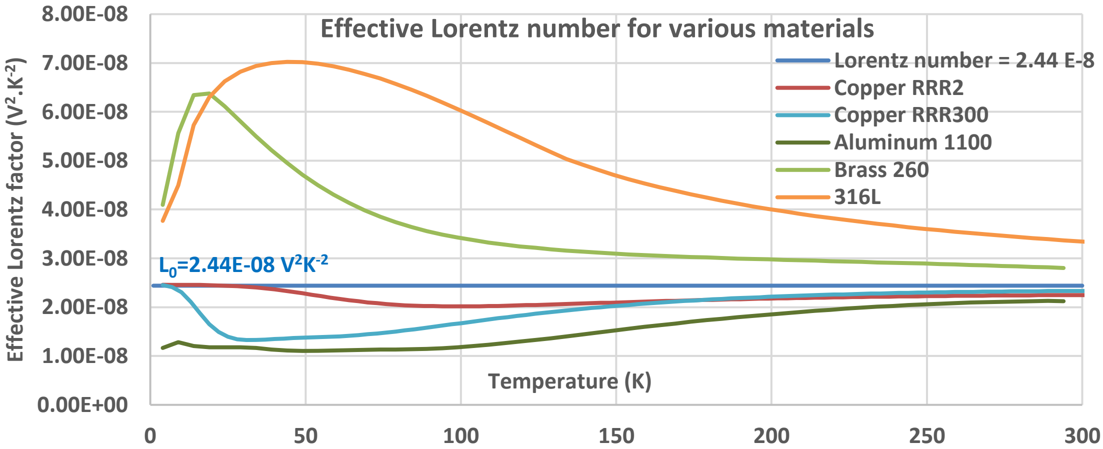

Figure 1. Expected Lorentz number for various candidate materials. Material properties from [11]

Figure 1 shows that highly alloyed materials generally have a high Lorentz number and as such are unsuitable. Pure copper and aluminium perform better than the Lorentz number.

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012134 doi:10.1088/1757-899X/1344/1/012134

Pure aluminium (1100-O) is the best material considered, but it is notoriously difficult to solder without aggressive flux. Nickel has been mentioned as having even better performance [3], but limited material properties are available. Testing has been done to cross check this number and is reported in section 2.2.2.

2.2 Optimal aspect ratio for forced flow helium-cooled leads

For self-cooled leads, the heat incident on the cryogenic bath is often used to reflect the lead overall thermodynamic efficiency. For a forced-flow lead however, a combination of liquefaction and refrigeration load need to be considered. Following the same logic as in [5][10] we chose to evaluate the equivalent cryogenic heating power as follows:

$$P_{eq\ 4.5\ K}(W) = \underbrace{\dot{m_{He}}\left(\frac{g}{s}\right).100(W/(\frac{g}{s}))}_{\textbf{Liquefaction}} + \underbrace{P_{4.5\ K}(W)}_{\textbf{Refrigeration load}}$$

The refrigeration load represents the heat extracted by the 4.5 K helium bath. The liquefaction load is representative of the ideal Carnot work needed to cool helium from 300 K gas to 4.5 supercritical, it is the enthalpy difference compounded by the effective cryoplant efficiency and made equivalent to a 4.5 K refrigeration load. The lead optimization can be made for a given material by finding an optimal aspect ratio $\frac{LI}{A}$ $[\frac{A}{m}]$ which depends on material properties only [2][10]. Under the assumption of perfect convection, a numerical analysis was done to get the optimal lead aspect ratio for various materials as seen on Figure 2.

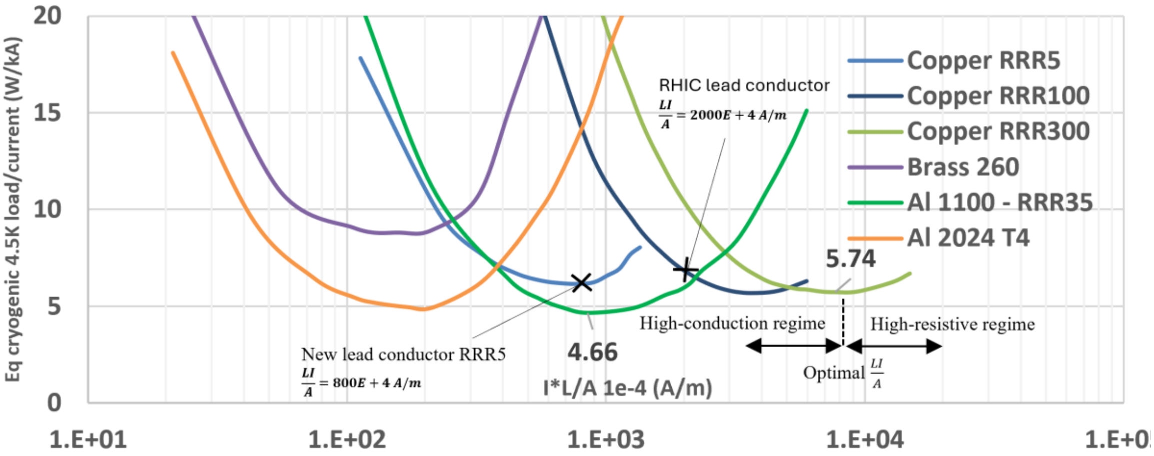

Figure 2. Forced-flow lead efficiency for various materials – properties from [11]

From Figure 2, we see that each material has an optimal aspect ratio $\frac{LI}{A}$ for best efficiency. Aspect ratio lower than the optimum corresponds to a conduction-dominated regime where the conductor is "too large" for the current and higher-than-optimal heat conduction occurs along the conductor. Aspect ratio higher than the optimum corresponds to a resistive-heat-dominated regime where the conductor is "too small" for the current and higher-than-optimal resistive heat gets generated along the conductor. Note that this analysis assumes a perfect thermal convection ($h \propto \infty$), so this is an ideal case. Self-cooled leads have different optimal aspect ratio [2].

2.2.1. The downside of high-purity metals

From Figure 2, selecting a highly pure copper (high RRR) seems a slightly more efficient choice than a low purity copper (low RRR). However, aiming for a high RRR has a significant downside.

The high purity copper has a resistive heating concentrated on a small portion of its length, close to the warm end (blue dashed line on Figure 3). This makes the conductor much more susceptible to thermal runaway instability and makes it hard to get enough local convection heat exchange with helium to avoid this runaway [1]. On the other hand low purity copper has a smoothly distributed resistive heating, this results in a longer useful length for convection heat exchange and better thermal stability against thermal runaway (see Figure 3).

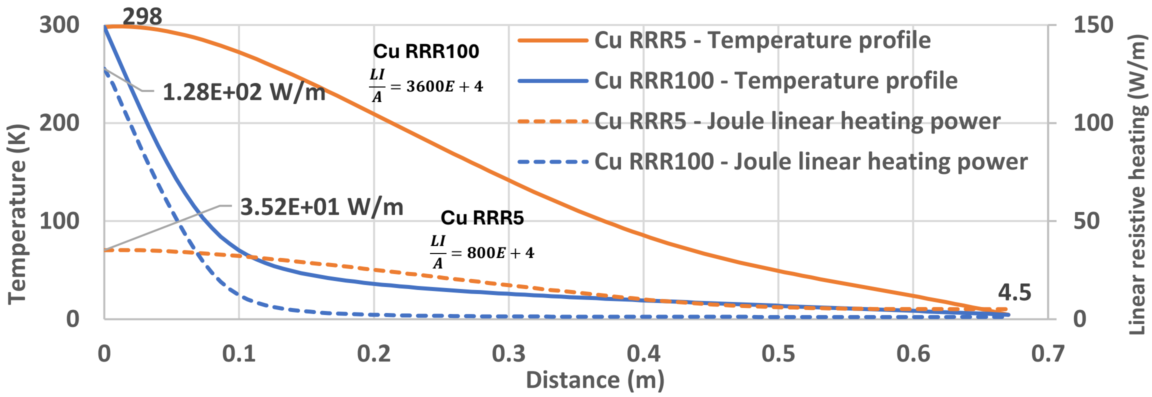

Figure 3. Simulated temperature and resistive heating profile at optimum $\frac{LI}{A}$ for a L=0.67m lead

2.2.2.RRR and thermal conductivity testing

Electrical resistivity and thermal conductivity testing have been performed at BNL to qualify commercially available material grades for current leads design (See table 1).

Table 1. Summary of electrical/thermal test results for selected materials [12]

Material	Resistivity at 293K (ohm.m)	RRR measured (at 20K)	Average thermal conductivity from 273K to 77K (W/m.K)	Average Lorentz number from 273K to 77K (V^2K^{-2})
Copper 122-H02	2.00E-8	5.3	277	1.95E-8
Copper 110-0	1.72E-8	273	430	2.03E-8
AL 1100-O	2.92E-8	24	191	1.54E-8
Nickel 200	9.64E-8	3.7	75	2.49E-8

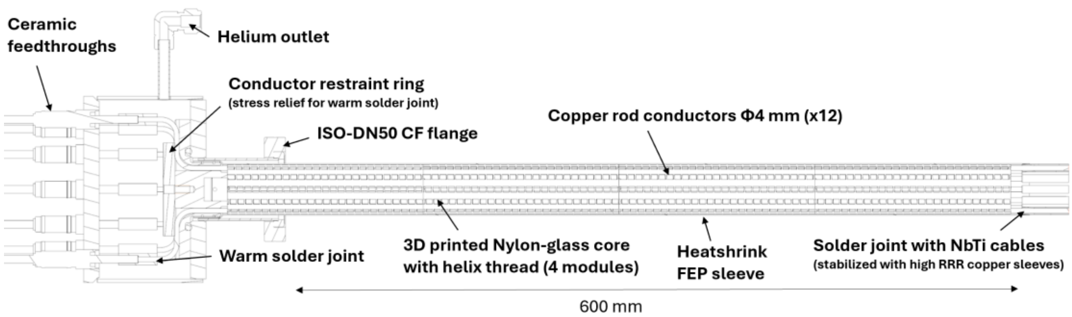

Figure 4. Cross section of the new 12x150 A lead design

3. Lifecycle optimisation of the 12x150A lead

A particle accelerator is not always running at full energy. In fact, a significant portion of a run is spent at beam injection energy where the lower beam rigidity requires lower magnet currents. An analysis of the RHIC runs from 2012 to 2024 shows that, on average, the superconducting system usage is 52% at high current (store), 29% at low current (injection) and 19% not powered (standby).

Besides, RHIC has proven a very versatile collider with a wide variety of particles and energies during its physics program, and only a few of its runs were made at top beam energy and high current. Likewise, for the EIC project, the physics program will also require a sweep of beam energies. Furthermore, the 12x150A current leads contain 12x conductors operated at various current. Even for a high-energy beam (100 GeV/u Au ions), the average RMS current per conductor was only 61 A.

So, optimizing the lead for its top current exclusively (150 A) results in sub-optimal operation for most of the lead lifecycle. Thus for the new design, an emphasis was placed on cryogenic efficiency through the lower current range while still allowing safe operation up to 150 A.

4. EIC 12x150A lead design

4.1. Maximizing helium convection

The new current lead (see Figure 4) must interface with an existing feed-box through a ISO-DN50CF flange and insert in a Ø47.5 mm sleeve down to the helium vessel where the conductors are soldered to the NbTi superconducting wires (more details in [5][8]). The feedthrough separating the helium volume to air are alumina brazed. These feedthroughs are soldered to the lead conductors running down an insulative plastic mandrel which purpose is to keep the conductors apart and to guide the helium flow spiralling up and around the conductors. This lead is not designed with a High Temperature Superconductor (HTS) stage, such stage would greatly benefit efficiency at lower currents [5], but space integration constraints prevented their use.

4.1. Maximizing helium convection

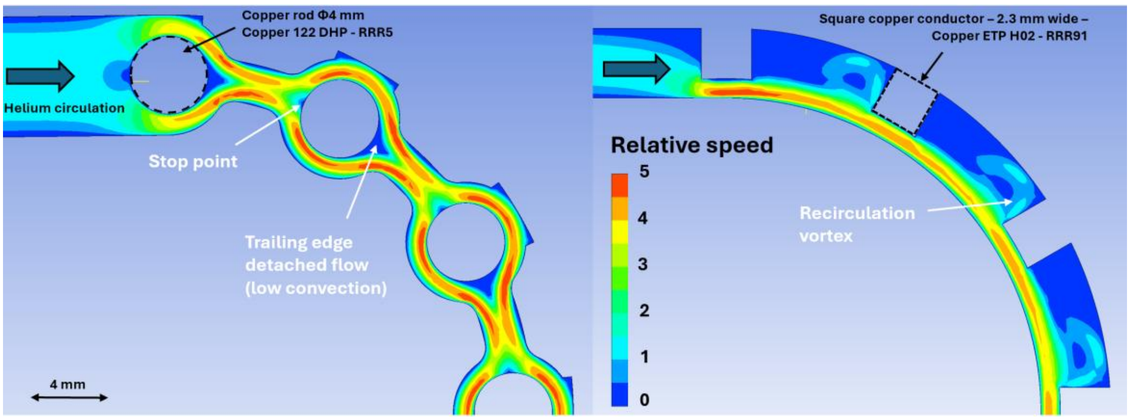

Figure 5. 2D CFD simulation – Helium flow at Re3200 - comparison of the new round conductor layout (left) and the previous RHIC square conductor arrangement (right)

As discussed in section 3, large current differences will be seen between conductors. So, an efficient convective heat exchange is critical to a good lead efficiency. And a limited convection would impose a higher-than-optimal helium flow to avoid thermal runaway of a single conductor.

So, steps were taken to improve the helium convection in the new design:

1. A low-purity copper conductor was chosen to better spread the effective length of resistive heating along the conductor length (Figure 3).
2. The cooling channel geometry was optimized through a series of parametric 2D CFD simulations for best convection cooling while satisfying the pressure drop budget (Figure 5). The k-ω SST and k-ε turbulence models tested gave very similar results.

The complex helical channel geometry is made possible by 3D printing the conductor mandrel with Selective Laser Sintering (SLS), which does not require support during printing. Nylon filled with 40% glass was selected to provide a good shape stability and limited thermal contraction around the copper conductors. This helps in minimizing the required radial clearance between the mandrel holes and the conductors, needed for insertion but detrimental to heat convection. To evaluate the effective convection and assess the impact of the radial clearance around the conductor diameter, experimental convection testing was made in air on a short 11" sample. Convection coefficient and pressure drop were measured and are reported on Figure 6.

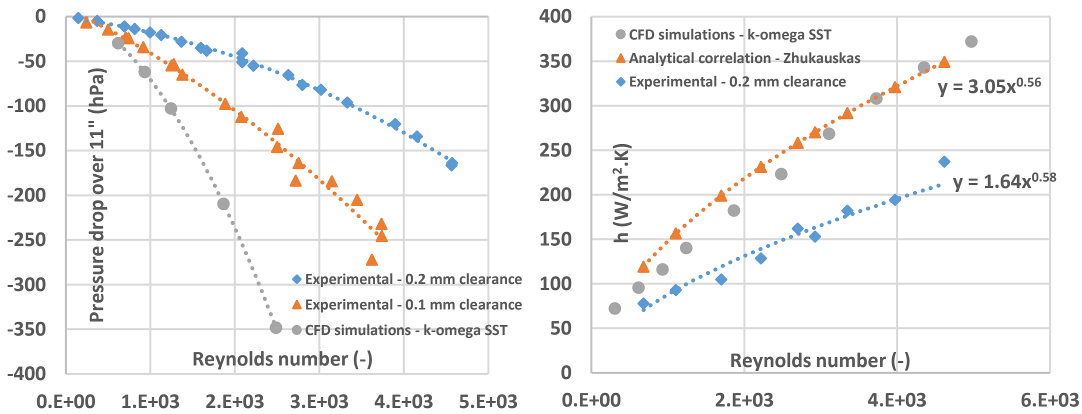

Figure 6. Comparison of experimental and analytical/simulation (left) convection coefficient (right) pressure drop

On Figure 6 the effect of the radial gap between conductor and core, and the associated bypass of coolant flow, is clearly visible on pressure drop. This also reduces the convection coefficient. The results of this experimental campaign have been reused in thermal simulations to evaluate the lead thermal behaviour in helium, with a correction of the difference between air and helium properties based on Zhukauskas analytical correlation [13]. While the helium and air Prandtl numbers differ only slightly, helium has a much higher thermal conductivity which will drive the convection coefficient up in the same proportions.

4.2. Conductor aspect ratio and achievable performance

We chose a low RRR copper for the reasons mentioned earlier. At 150 A, the optimal aspect ratio for copper 122 (RRR5) is $\frac{LI}{A} = 800\text{E} + 4\ \text{A/m}$ (Figure 2). The cooled conductor's length is *670 mm.* So the nearest available round cross section is a Ø4 mm copper 122 rod.

The previous RHIC 12x150A lead design has two main design limitations:

- An aspect ratio ~2x larger than optimal producing excessive heat conduction (Figure 2)
- An uncooled conductor length on the warm end which promoted early thermal runaway.

By ensuring a limited resistive power dissipation of the uncooled length, adopting a correctly sized cooled conductor and improving the helium convection as much as possible, the new lead is expected to achieve greater efficiency through the entire operating range of current (Figure 7).

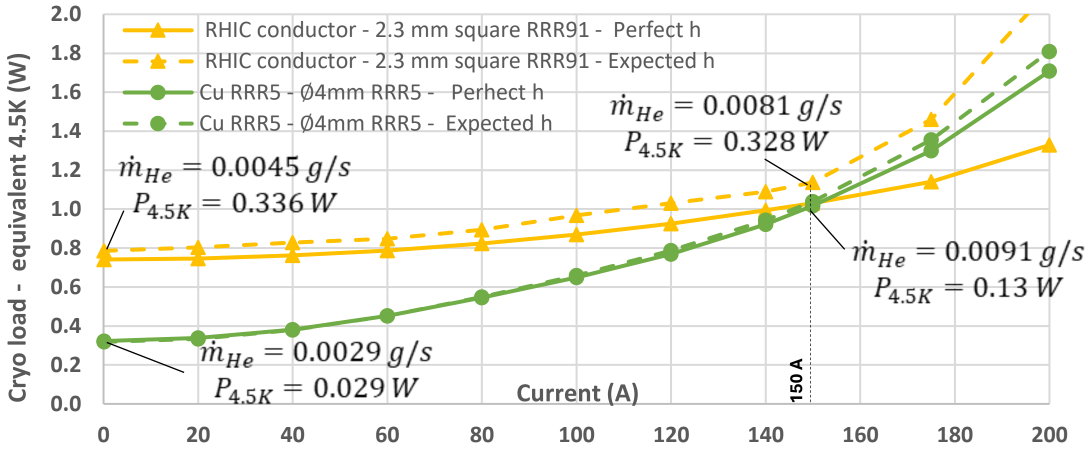

Figure 7. Cryogenic 4.5K equivalent load for the RHIC initial design and the new lead design

Condensation or frosting of the conductors in air is a significant operational concern, as it can lead to short-to-ground in humid weather. To avoid condensation, heaters are placed close to the ceramic feedthrough to keep their temperature above the air dew point. In addition, a top box covers the ceramic feedthroughs on the air-side and dry air circulation in the box reduces condensation further. At the cold end, too much conducted heat can lead to a quench of the superconductor, this was a concern for the RHIC design due to a too low conductor aspect ratio [6], in the conduction-dominated regime (Figure 2). This new lead design is expected to both, conduct significantly less heat to the superconducting end, and minimize condensation of the ceramic feedthroughs, thanks to better sized conductors (Figure 2).

4.3. Electrical breakdown between conductors

In this lead bundle design, conductors feeding different parts of the collider are held in close-proximity. During a quench of a SC circuit, high voltage difference can be generated as the inductive magnet current gets dumped in resistors. It is critical to ensure no electrical breakdown occurs between conductors as was the case during the RHIC 2023 catastrophic event [8] due to solder joint failure. This new design has the same inter-conductor spacing as the previous design, and without sharp edges. From the Paschen curve in air, the breakdown was expected around 15 kV. It was measured around 7.5 kV. For pressurized helium around 3.5 bars, the Paschen breakdown is expected at 3 kV. Following the air test results this could result in around 1.5 kV of effective breakdown strength in helium. The maximum voltage difference between conductors is 800 V. The effective breakdown strength will be measured in helium on the first prototype for confirmation.

5. Operational aspects

5.1. Target helium flow for various conductors

The bundle of conductors is often operated with large current variations between conductors. For a high-energy RHIC run, peak currents reach 149A at beam store energy on some conductors while the average RMS current is only 61 A. This large difference, and the limited convection efficiency, imposed a high helium flow to avoid thermal runaway of a single conductor in RHIC.

So, a robust indicator must be found to drive the helium flow adjustment for best cryogenic efficiency while avoiding thermal runaway of a single conductor.

5.2. Resistance control and interlock for lead protection

It is shown in [1] that voltage correlates closely with maximum lead temperature at design current. However, as voltage depends also on current, it is not a very robust interlock criterion in case of runaway at low current. Instead, we chose to use the resistance of each lead conductor, which is linearly dependent on conductor temperature. This will be used in a control feedback loop to adjust the helium flow rate for operation. The voltage time constant of the new lead design is simulated around 70 s which provides ample time for a control system adjustment and safe shutdown if overheating occurs.

5.3. Estimated savings compared to RHIC leads

EIC will reuse the RHIC yellow ring which comprises 30x of such 12x150 A lead. Taking the currents used for RHIC operation at high-energy operation during 100 GeV Au RHIC run 2024, we estimate a gain of 57 % (-154 W $P_{eq\ 4.5\ K}$) at standby/injection and 52 % at store (-158 W $P_{eq\ 4.5\ K}$). An average gain of 150 W at 4.5 K leads to estimated savings of 4 530 MWh through EIC operation [13]. With a conservative estimated energy cost of $0.1/kWh, the operation cost saving associated with the implementation of these new leads will be in the order of $453,000 through their lifetime.

6. Conclusion and outlook

Leveraging 24 years of operational experience with the RHIC 12x150 A current leads, we have identified and investigated the main shortcomings of the original lead design. Starting from material testing data and basic lead design principles, an alternative design has been proposed, aiming to solve the past operational issues and improve their overall thermodynamic efficiency. Prototyping will now take place to validate the lead construction and operation in a dedicated test cryostat, ahead of series production for early installation after RHIC final shutdown.

References

[1] M. Wilson, Superconducting Magnets (Clarendon Press, Oxford, 1983), pp. 256–278.
[2] A. Ballarino "Current Leads, Links and Buses" CAS-CERN accelerator school DOI 10.5170/CERN-2014-005.547
[3] Y. Buyanov,A.B. Fradkov, I.Y. Shebalin. (1975). "A review of current leads for cryogenic devices" Cryogenics (1975) https://doi.org/10.1016/0011-2275(75)90033-8
[4] The RHIC team 2006 Relativisitic Heavy Ion Collider Configuration Manual (unpublished)
[5] F Micolon et al 2024 IOP Conf. Ser.: Mater. Sci. Eng. 1301 012155
[6] Nicoletti, A., Rehak, M.L.F. (1998). Performance of Magnet Leads for RHIC. Advances in Cryogenic Engineering, vol 43. Springer, Boston, MA. https://doi.org/10.1007/978-1-4757-9047-4_30
[7] C. Mi *et al.*, "RHIC 12x150A Current Lead Temperature Controller: Design and Implementation", in *Proc. PAC'11*, New York, NY, USA, Mar.-Apr. 2011, paper THP060, pp. 2238-2240.
[8] F. Micolon et al., "Solder joint cryogenic fatigue of the RHIC 12x150A current leads and mitigation for future operation", in Proc. IPAC'24, doi:10.18429/JACoW-IPAC2024-TUPR56
[9] F.Micolon et al., "From RHIC to EIC hadron storage ring – overview of the engineering challenges" in Proc. IPAC'24, paper TUBD1, DOI: 10.18429/JACoW-IPAC2024-TUBD1
[10] M.L.F. Rehak 1998 A simplified theory of current leads Adv. Cryo. Eng. 43 [https://doi.org/10.1007/978-1-4757-9047-4_167]
[11] Hust, J. and Lankford, A. (1984), Thermal conductivity of aluminum, copper, iron, and tungsten for temperatures from 1 K to the melting point:, , NIST, doi.org/10.6028/NBS.IR.84-3007
[12] F.Micolon "Electrical resistivity testing from 300K to 20K of some commercially available copper, aluminum and nickel" BNL report EIC-ADD-TN-122 (May 2025)
[13] Incropera and D. DeWitt, "Fundamentals of Heat and Mass Transfer," 6th Edition, J. Wiley & Sons, 2007
[14] F.Micolon et al. "Estimate of the cost of incident heat on the cryogenic circuits for EIC" BNL EIC-ADD-TN-042