ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB381

THERMAL ANALYSIS OF THE RHIC ARC DIPOLE MAGNET COLD MASS WITH THE EIC BEAM SCREEN*

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Abstract

The EIC will make use of the existing RHIC storage rings with their superconducting (SC) magnet arcs. A stainless-steel beam screen with co-laminated copper and a thin amorphous carbon (aC) film on the inner surface will be installed in the beam pipe of the SC magnets. The copper will reduce the beam-induced resistive-wall (RW) heating from operation with the higher intensity EIC beams, that if not addressed would make the magnets quench. Limiting the RW heating is also important to achieve an adequately low vacuum level. The aC coating will reduce secondary electron yield which could also cause heating and limit intensity. Among all the RHIC SC magnets, the arc dipoles present the biggest challenge to the design and installation of beam screens. The arc dipoles, which make up for 78% (2.5 km) length of all SC magnets in RHIC, expect the largest RW heating due to their smallest aperture. These magnets are also the longest (9.45 m each), thus experiencing the largest temperature rise over their length, and have a large sagitta (48.5 mm) that increases the difficulty to install the beam screen in place. This paper presents a detailed thermal analysis of the magnet-screen system.

INTRODUCTION

An Electron Ion Collider (EIC) will be built at Brookhaven National Laboratory in the coming years. The EIC hadron storage ring will make use of the existing RHIC storage rings including their SC magnet arcs. This design choice will spare the project from building new, expensive SC magnets. Since the RHIC SC magnets were not designed for the EIC beams, an upgrade of their vacuum chamber is projected to enable reliable operation without compromising the EIC luminosity goal. The upgrade consists in installing a beam screen in the vacuum chamber of the RHIC SC magnets and cold mass interconnects [1].

Detailed thermal analyses have been carried out for a RHIC dipole magnet cold mass equipped with the EIC beam screen. The peak coil temperature and peak screen temperature for different beam screen designs and heat load cases are presented and discussed.

THE RHIC ARC DIPOLE COLD MASS

The cross-section of a RHIC arc dipole magnet cold mass is shown in Fig. 1. Each dipole magnet is about 10 m long and has 243 m bending radius with 45 mm sagitta. There are four ULTEM6200 spacers, two in horizontal plane and two in vertical plane [2]. The 2 mm-thick SS316LN beam tube is wrapped with Kapton. Four kelvin He flows through four channels formed between the spacers, beam tube and coils. The coils are keyed to the ultra-low carbon steel yoke laminations through precision-molded glass-filled phenolic (RX630) insulator spacers. The 4K He also flows through four round holes opened in the yoke laminations for the passage of the coolant and through the two square slots that host the electrical buses.

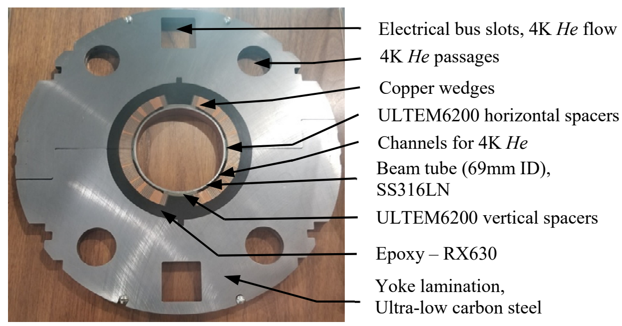

Figure 1: Cross-section image of RHIC dipole magnet cold mass.

Each half of magnet coil consists of a single layer of 32 turns arranged in four blocks with intervening copper wedges. The SC cable is made from 30-strand wire. Each wire consists of 3510 NbTi filaments arranged in an OFHC copper matrix which is surrounded by an OFHC copper casing [2].

BEAM SCREEN

With the current stainless-steel RHIC beam pipe, the EIC hadron ring will be vulnerable to electron cloud instabilities and high resistive losses from beam-induced currents [3]. The vacuum chamber of the EIC hadron ring will be updated with a beam screen designed to present sufficiently low impedance and low secondary electron-emission yield (SEY). The beam screen is a sleeve of stainless-steel (SS) co-laminated with copper and coated with a thin film of amorphous carbon [4]. The copper reduces the RW heating and conducts the heat well, the SS reduces the eddy current force arising from the magnetic field decay expected after quenches and the aC helps to mitigate electron cloud thanks to its low secondary electron emission. The aC carbon surface is the closest to the beam and only 100 nm thick, followed by the 75 µm thick copper and 0.5 mm-thick SS layers. The beam-induced currents are fully attenuated before reaching the SS layer.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. DOE.
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The heat in the beam screen will be mainly extracted by conduction through direct contact with the beam pipe. The beam screen (Fig. 2) has a circular contour in the horizontal plane that conforms well to the beam tube inner radius to ensure good thermal contact with the beam tube. Its top and bottom sections are ridge-shaped to exert spring action when compressed and undersized to enable the screen to collapse inward and facilitate the insertion through the 10-m long beam tube. Once inserted, wedges are installed to push the ridges towards the centre, which in turn forces the screen to hold in position and to maintain good thermal contact with the beam pipe.

For thermal analysis, the nominal thickness of the SS and copper are taken as 1 mm and 75 µm respectively. The amorphous carbon layer is only about 100 nm and not considered in the thermal model.

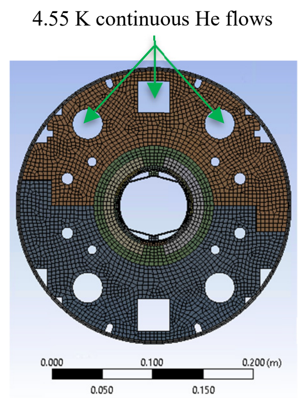
THERMAL ANALYSIS

A thermal simulation of the entire RHIC arc dipole magnet would be computationally expensive. Our analysis utilizes the transverse cross section of the magnet, which is basically uniform along the magnet's length except at both ends. A 2-D steady-state thermal analysis has been carried out in ANSYS 2020. The purpose of this analysis is to evaluate the maximum temperature reached at the coil and at the beam screen. First, the temperature at the coil determines the maximum operational current and thus magnetic field that the magnet can provide before it quenches. The effective surface resistance seen by the beam-induced currents depends in turn on the temperature reached by the beam screen and ultimately determines the resistive-wall heat load to the beam screen. The vacuum conditions in the vacuum chamber will also depend on the temperature of the beam screen.

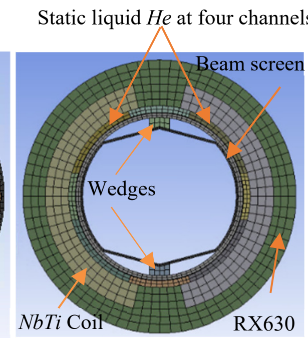
The finite element model of the cross-section of RHIC dipole magnet cold mass with beam screen is shown in Fig. 2. Here, the entire coil is modelled as a homogenous material and copper wedges are not part of the model.

Temperature-dependent thermal conductivity (K) values at cryogenic temperatures [5] are used for all the materials. As depicted in Fig. 1, the coil is not a homogenous material. To reduce computational time and make the model simpler, suitable engineering assumptions were made to model the coil as a homogenized material and applied with an effective thermal conductivity calculated manually in radial direction.

Perfect thermal contacts are considered between all insulators, and between insulators and metals. A thermal contact conductance (TCC) of 5 W/m^2-K is applied between all metal contact surfaces. The TCC depends upon the type of materials in contact, surface finish of the contacting faces, contact pressure, contact temperature and operating pressure. TCC between SS materials at room temperature and at 1-10 atm contact pressure is 2000-3700 W/m^2-K [5]. In vacuum it drops to 400-1667 W/m^2-K [6]. Limited TCC data are available for low contact pressure (below 1 atm) which is expected in our design. The TCC between SS at 1/8 atm contact pressure, in vacuum and at about 65 K is about 100 W/m^2-K [7]. As a conservative approach, a low TCC (5 W/m^2-K) is considered in this study.



(a)



(b)

Figure 2: (a) FEA model of transverse cross-section of RHIC arc dipole, (b) Close-up view without yoke and containment vessel.

The aim is to maximize the area of contact between the beam screen and the beam tube. However, gaps may appear in some part of intended contact area due to geometric imperfections of beam tube and the screen. Our study evaluates the impact of different contact area percentages.

Boundary Condition

Supercritical He flows at 4 bar pressure through the two square electrical bus slots and four round holes in the yoke, where a temperature boundary condition of 4.55 K is applied. The temperature rise of the coolant as it extracts heat on its way from one end of the magnet to the other is expected not to exceed 150 mK.

The four He flow channels around the beam pipe keep a 2.7 mm radial spacing with the magnet coils. The straight dipole assembly was pressed into a curved shape during fabrication, and in consequence, the dimensions of the annular channel around the beam pipe are uncertain. The spacers between beam pipe and coils are found every 0.3 meters over the full length of the magnet. We assume the worst-case scenario, that is, the He flow through the annular channel is minimal or even null, hence no temperature boundary conditions are applied here. The coolant is modelled to transfer the heat through conduction.

Dynamic Heat Load

Assuming that the electron cloud is suppressed by the low SEY of the aC film, the main source of dynamic heat load is the resistive-wall heat from the beam-induced currents. The electrical resistivity of copper increases with temperature [8-10]. Expected power dissipation for the most demanding operating scenario is 0.37 W/m when the screen is at 10 K and copper has a RRR $\geq$ 100 [1]. This estimate includes the effect of the 275 GeV beams circulating with a 20 mm offset, the impact of magneto-resistance on the resistivity of copper exposed to a field of 3.78 T necessary to steer the 275 GeV in the arc dipoles, the contribution of the thin a-C film, and screen

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB381

geometry [1]. The RW heat will still be lower than 0.5 W/m with less tight conditions, if the screen can be kept below 50 K and the copper has a RRR > 25. Thus our baseline simulations assume a heat load of 0.5 W/m, which offers a 35% safety factor with respect to the 0. W/m.

For a centred beam, a uniform heat load is applied across the screen perimeter, although in reality the straight sections of the polygonal screen get more heat due to its proximity to the beam. For an offset beam, the total power dissipation increases by a factor F (see Eq. (1) [11]), with the power distribution profile for a round beam screen following Eq. (2) [12]. The heat load profile on the polygonal beam screen is calculated in CST Microwave Studio (Fig. 3) and the temperature distribution is presented in Fig. 4 for the 0.5 W/m case.

$$F = \left[\frac{b^2 + x^2}{b^2 - x^2}\right] = 2.1 \;\text{ for }\; x = 20\,mm \tag{1}$$

$$\frac{dF(\theta)}{d\theta} = \left[\frac{b^2 - x^2}{b^2 + x^2 - 2bx\cos\theta}\right]^2 \tag{2}$$

where b is the beam screen radius (33.55 mm) and x is the beam offset. Since most of the power is dissipated in the skin of the screen's surface, the heat load is applied in the form of heat flux to the copper surface.

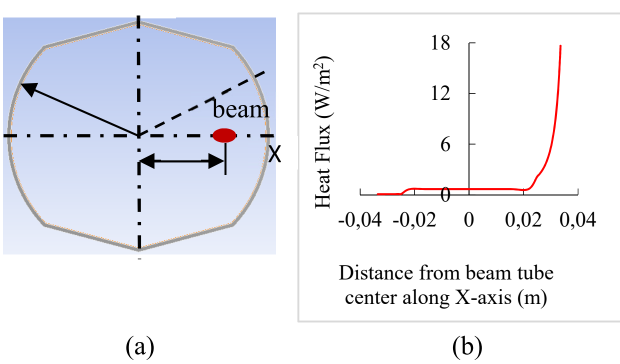


Figure 3: (a) Beam offset and screen radius, (b) Heat load profile for 20 mm offset beam and 0.5 W/m total heat.

Results

For 0.5 W/m offset-beam load case (Fig. 4), the peak temperatures at coil and screen are 4.9 K and 6.2 K respectively. Due to the high conductivity copper layer, the temperature gradient in the beam screen is negligible and, for the same total power dissipated, the position of the beam barely changes the temperatures at coil and screen (for 0.5 W/m centered beam case, the peak coil and screen temperature are 4.9 K and 6.1 K respectively). The location of coil peak temperature is always in the mid-plane due to good thermal contact of beam screen with beam tube in that plane.

Increasing copper plating thickness makes insignificant improvement on peak screen temperature and almost no effect on coil temperature. Adding copper layer on the outer face of screen or decreasing the beam screen thickness from 1 mm to 0.5 mm has very little effect on results.

Decreasing the area of contact between beam screen and the tube increases the screen temperature but has very little effect on coil peak temperature. If the contact area is reduced to 24% of intended contact area, the beam screen temperature goes up to 9.7 K for 0.5 W/m offset load case.

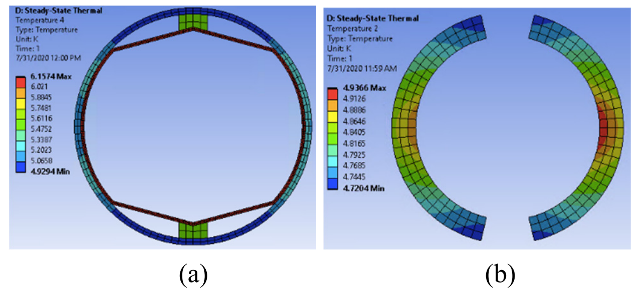


Figure 4: Temperature plots for 0.5 W/m, 20 mm offset beam (a) beam tube with beam screen and (b) SC coil.

CONCLUSION

Two-dimensional steady-state thermal simulations of the RHIC dipole magnet cold mass with a copper-coated stainless-steel beam screen find that, for screen below 10 K and copper RRR ≥ 100 and worst-case beam scenario including a 20 mm beam offset and a comfortable safety margin of 35% over the maximum expected heat load (0.37 W/m), the NbTi coil peak temperature (4.9 K) is less than half a degree above the He temperature and does not exceed 5.3 K, the temperature at which RHIC arc dipoles will quench while providing the 3.783 T necessary to keep the 275 GeV proton beams in their design orbit. The corresponding beam-screen peak temperature is 6.2 K, low enough to achieve ultra-high-vacuum to meet beam lifetime and emittance growth requirements [13].

Increasing the thickness of the copper layer in the inner surface of the screen does not significantly reduce the peak temperatures, so a 75 µm copper thickness is deemed sufficient. The addition of an outer copper layer hardly reduces the peak temperatures, but it can still be useful to improve the TCC between screen and beam tube. Reducing the thickness of the stainless-steel layer does not affect the result since copper dominates the heat conduction. By decreasing the area of contact between the beam screen and the beam tube, the peak beam screen temperature increases; however, the coil peak temperature remains the same. Calculations show that a minimum 24% contact area is necessary to keep the beam screen peak temperature below 10 K.

In this study, a conservative TCC (5 W/m^2-K) is used. Further studies and experiments are planned to assess the value of TCC which is critical to understand the peak temperatures we should expect at the beam screen and the RHIC arc dipole coils.

REFERENCES

[1] S. Verdú-Andrés *et al.*, "A beam screen to prepare the RHIC vacuum chamber for EIC hadron beams: requirements and conceptual design", presented at IPAC'21, Campinas, Brazil, May 2021, paper TUPAB260, this conference.

[2] *Configuration Manual*, RHIC https://www.bnl.gov/cad/accelerator/docs/pdf/RHICConfManual.pdf

[3] A. W. Chao, “Physics of collective beam instabilities in high-energy accelerators”, Weinheim, Germany, Wiley VCH, Jun.1993.

[4] G. P. Cruikshank *et al.*, “Mechanical Design Aspects of the LHC Beam Screen”, CERN, Geneva, Switzerland, Rep. LHC-Project-Report-128, CERN-LHC-Project-Report-128, July 1997.

[5] NIST – National Institute of Standards and Technology, https://trc.nist.gov/cryogenics/materials/materialproperties.htm

[6] Dassault Systèmes, http://help.solidworks.com/2012/English/SolidWorks/cworks/Thermal_Contact_Resistance.htm

[7] S. S. Kumar and K. Ramamurthi, “Thermal contact conductance of pressed contacts at low temperatures”, *Cryogenics*, vol. 44, pp. 727–734, 2004 doi:10.1016/j.cryogenics.2004.04.004

[8] F. Bloch, “Zum elektrischen Widerstandsgesetz bei tiefen Temperaturen” [Electrical resistance law for low temperatures]. *Zeitschrift fur Physik*, vol. 59, pp. 208-214, Mar. 1930. doi:10.1007/bf01341426

[9] E. Gruneisen, “Die Abhangigkeit des elektrische Widerstandes reiner Metalle von der Temperatur” [The temperature dependence of electrical resistance in pure metals]. *Annalen der Physi*k, vol. 408, pp. 530-540, 1933. doi:10.1002/andp.19334080504

[10] M. Deutsch, “An accurate analytic representation for the Bloch-Gruneisen integral”, *Journal of Physics A: Mathematical and General*, vol. 20, pp. L811-L813, Sep. 1987. doi:10.1088/0305-4470/20/13/001

[11] A. Piwinski, “Wakefields and ohmic losses in round vacuum chambers”, Desy, Hamburg, Germany, Rep. DESY-HERA -92-11, 1992.

[12] R. T. Avery, A. Faltens, and E. C. Hartwig, “Non-Intercepting Monitor of Beam Current and Position”, *IEEE Trans. Nucl. Sci.*, vol. 18, pp. 920-922, 1971. doi:10.1109/TNS.1971.4326231

[13] D. Weiss, S. Verdú-Andrés, M. Mapes, and J. Tuozzolo, “EIC hardon beamline vacuum studies”, presented at IPAC’21, Campinas, Brazil, May 2021, paper WEPAB189, this conference.