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A BEAM SCREEN TO PREPARE THE RHIC VACUUM CHAMBER FOR EIC HADRON BEAMS: CONCEPTUAL DESIGN AND REQUIREMENTS*

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Abstract

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) will use the existing Relativistic Heavy Ion Collider storage rings, including the superconducting magnet arcs [1]. The vacuum chambers in the superconducting magnets and the cold mass interconnects were not designed for EIC beams and so must be updated to reduce resistive-wall heating and to suppress e-clouds. To do so without compromising the EIC luminosity goal, a stainless steel beam screen with co-laminated copper and a thin layer of amorphous carbon will be installed. This paper describes the main requirements that our solution for the hadron ring vacuum chamber needs to satisfy, including impedance, aperture limitations, vacuum, thermal and structural stability, mechanical design, installation and operation. The conceptual design of the beam screen currently under development is introduced.

INTRODUCTION

The Electron-Ion Collider at Brookhaven National Laboratory (BNL) is a high-luminosity machine designed to advance our understanding of matter [1]. The EIC uses part of the existing Relativisitic Heavy Ion Collider (RHIC) at BNL, including the superconducting (SC) magnet from the arcs and some others from the straight sections for the EIC hadron storage ring. Reusing these SC magnets is a cost-effective solution although it makes necessary to update the vacuum chambers of the SC magnets, currently stainless steel 316LN pipes as in Fig. 1, and their cold mass interconnects. These vacuum chambers were not designed to host the EIC hadron beams, which feature higher intensity, shorter bunches than the RHIC beams and in some instances circulate around the HSR with a large radial shift [2]. The update needs to address two main concerns: resistive-wall heating and e-cloud build-up. Previous work inspected the possibilities of in-situ coating the beam pipes of the RHIC superconducting magnets [3,4], an option that is no longer pursued. Our baseline solution is now to use beam screens. The next sections will introduce the conceptual design of the HSR beam screen and review the main requirements.

CONCEPTUAL DESIGN

The EIC screen design is based on the CERN's Large Hadron Collider (LHC) and the HL-LHC beam screens, which are made from copper-clad stainless steel sheets and feature a thin film of amorphous carbon (a-C) applied to the inner surface of the screen [5,6]. Copper has a superior electrical conductivity, especially at cryo temperatures, that reduces resistive-wall heating while the thin a-C layer shows a low secondary electron emission necessary to mitigate e-clouds. There are however major differences between the LHC and EIC designs. The LHC screen design includes an integrated 4.5 K supply (20 K return) cooling system mounted on the screen itself. The HSR screens will instead have contact cooling with the RHIC magnet cold bore pipe at 4.5 K. Several reasons drive this choice: smaller dynamic heat load expected for the HSR cold bore than for LHC, cold bore operated at 4.5 K instead of the more costly 1.8 K, and increased difficulty to add the cryogenic distribution system once the cold masses are already installed in the tunnel.

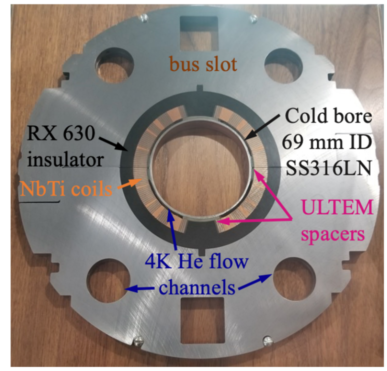

Figure 1: Cross section of RHIC SC dipole magnet.

REQUIREMENTS

To reach nominal EIC luminosity under reliable operation, the EIC HSR beam screen must ensure:

- Low impedance to limit the dynamic heat load to the cryogenic system and to avoid impedance-driven instabilities.
- Adequate vacuum level and stability, which also involves the control of e-clouds.
- Compliance with beam optics requirements like aperture.
- Mechanical resistance to eddy-current forces resulting from magnet quenches.
- Clean, feasible installation and the possibility for removal.

The next sections discuss some of these requirements and their impact on the design of the HSR beam screen.

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Limited Dynamic Heat Load

The highest center-of-mass energy E_{CM} scenario, featuring a 275 GeV proton beam with 290, 6 cm-long bunches, 1.98×10^{11} protons per bunch and 18 mm maximum offset (see Table 1), provides the largest resistive-wall heating in the HSR. For the nominal 69 mm-diameter, stainless steel 316LN ($\rho_{dc} = 5.07\times10^{-7}\,\Omega\cdot$m at 10 K [7]), round beam pipe, the expected resistive-wall heating is about 8 W/m [1], well above the dynamic heat load budget of about 0.5 W/m [8].

Table 1: Beam parameters for the EIC operational scenarios leading to the largest resistive-wall heating (highest E_{CM}) and to the lowest SEY threshold (highest $\mathscr{L}$) in the HSR.

Beam scenario	**Highest E_{CM}**	**Highest $\mathscr{L}$**
Proton energy, E_p (GeV)	275	275
Number of bunches, N_b	290	1160
Bunch charge, Q_b (ppb)	1.98×10^{11}	0.69×10^{11}
Bunch length, σ_s (cm)	6	6

Using a high-conductivity copper-clad stainless steel screen can significantly reduce the heating. Figure 2 shows the resistive-wall heating expected when using a beam screen that has a 0.5 mm layer of 316LN stainless steel under a 75 µm layer of copper covered with 150 nm of a-C. That thickness of copper is sufficient for the beam-induced currents to sufficiently attenuate before reaching the stainless steel. The calculation includes the magneto-resistance effect suffered by copper [9] when exposed to the 3.78 T in the arc dipoles, the impact of operating with a 20 mm beam offset (18 mm max. + 2 mm for orbit errors) [10], the contribution from the a-C layer [11] and a 20% margin to accommodate for the eventual case in which the screen shape, not yet defined, deviates from the round shape, which provides the lowest heating. For simplicity, copper is treated as a normal skin effect conductor. Specifying a beam screen with the residual resistivity ratio RRR ≥ 100 copper operating below 20 K provides a safety margin of 35%.

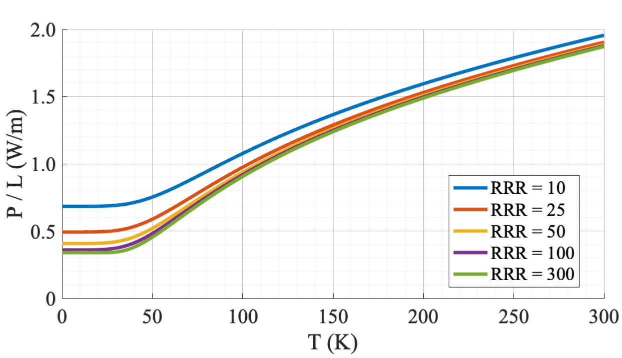

Figure 2: Resistive-wall heating per unit of length (P/L) in function of temperature and copper RRR for HSR beam screen with 150 nm of a-C ($\rho_{dc} = 1.5\times10^{-5}\,\Omega\cdot$m) and 75 µm of copper, including impact of magneto-resistance, beam offset and screen shape.

These estimates assume that e-cloud will be fully suppressed after the commissioning period, thus the only contribution to the dynamic heat load is from resistive-wall heating. The contribution of synchrotron radiation to the dynamic heat load is negligible due to the relatively low energy of the EIC hadron beams. The necessary conditions to suppress e-cloud are described next.

Suppression of Electron Clouds

E-cloud is an undesired electron multiplication mechanism in the beam vacuum chambers of particle accelerators that can generate sudden, large vacuum pressure rises, beam instabilities, emittance growth, contribute to the dynamic heat load, interfere with diagnostics, *et cetera*. RHIC experienced first e-cloud effects in 2001 [12]. Different mitigation countermeasures were implemented and e-cloud was successfully suppressed [13].

PyECLOUD [14] simulations predict the return of e-clouds to the RHIC beamlines with the passage of the EIC beams. The lowest Secondary Electron Yield (SEY) threshold requirement for the vacuum chambers of the HSR arcs is found in the arc sextupoles for the highest luminosity $\mathscr{L}$ scenario, when 275 GeV proton beams with 1160, 6 cm-long bunches, 6.9×10^{10} protons per bunch circulates with a 18 mm offset (see Table 1). Figure 3 shows the expected heat load from e-cloud formed with the passage of this beam through different magnets of the HSR arc in function of the SEY exhibited by the surface of their vacuum chambers. The current RHIC beam pipes have conditioned over many years of operation but the SEY of scrubbed stainless steel surfaces could still be too high, about 1.48 – 1.55 [15], to suppress the e-cloud expected in the EIC. Copper also exhibits an SEY well above 1 [16]. Thus the update of the HSR vacuum chambers with screens covered with a-C, which can have an SEY below 1 [17].

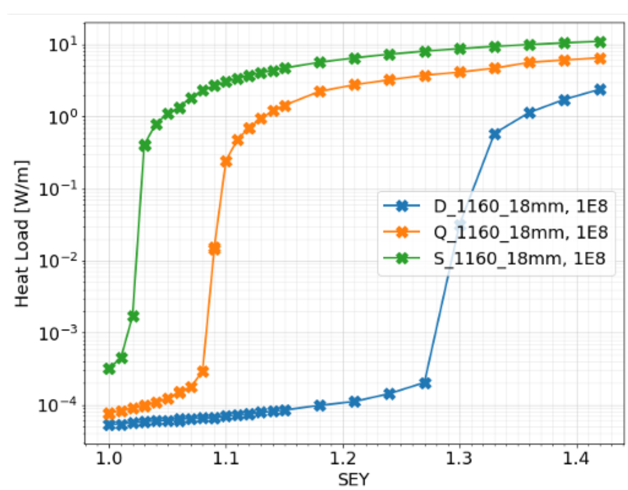

Figure 3: Dependency of the expected head load from e-cloud formed in different HSR arc magnets (D - dipole, Q - quadrupole, S - sextupole) on the SEY of their vacuum chamber surface for 275 GeV proton beam with 1160 bunches, 6.9×10^{10} ppb and 18 mm offset.

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Mechanical Constraints

Several mechanical constraints need to be respected by the beam screen design. The smallest beam pipe diameter across all the SC magnets and cold mass interconnects of the HSR will be 69 mm. This is the nominal beam pipe size in all the RHIC arc magnets [18]. Other SC magnets have slightly larger diameters. The dispersion suppression section in the Q4–Q5 region defines what will be the minimum vertical space that the screen must leave clear for the beams, ±29.5 mm.

The insertion of the screens through the beam pipe of the RHIC arc dipoles is challenging, given their significantly large sagitta (48.5 mm over 10 m length) compared to that of the LHC ones (9 mm over 15 m).

Structural Stability

Reducing the eddy-current forces acting on the beam screen after a magnet quench is the reason behind the introduction of the stainless steel layer. When the RHIC arc dipoles provide 3.78 T, the magnetic field variation with time [B(t)× dB(t)/dt] after quench can be as high as -30 T^2/s. For an all-copper screen with 1 mm-thick walls and RRR~300 copper, the net pressure exerted by the quench-induced eddy-currents against the screen walls would be about 1300 psi [19]. Reducing the copper thickness to 75 µm diminishes the quench-induced forces to 100 psi, as shown in Fig. 4.

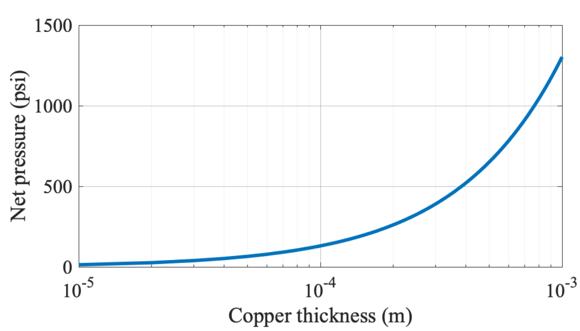

Figure 4: Variation of quench-induced eddy-current pressure as function of the copper layer thickness.

Structural simulations will follow to evaluate the impact of this pressure on the structural stability of the magnet components and its operation. Prototyping and testing will be key to ensure that the developed solution can be inserted, establishes good thermal contact with the beam pipe, remains locked in place during thermal cycles and magnet quenches, and can be removed.

Vacuum Level and Stability

Beam interactions with the residual gas in the vacuum chamber cause beam loss and emittance growth. The cold bore beamlines of the HSR need to show a vacuum level below 1×10^{-11} torr of H_2 in order to guarantee at least a few hundred hours of beam lifetime and acceptable emittance growth rates [20]. Preliminary studies evaluate the propagation of a H_2 gas wave through the cold bore of a RHIC arc dipole equipped with the beam screen, finding that in order to prevent the vacuum level going above the threshold, the maximum temperature for the beam screen has to be less than 10 K. These results will be reviewed after characterizing the vacuum properties of the beam screen at room and cryogenic temperatures.

OVERVIEW

This paper introduced the conceptual design of the EIC HSR beam screen and discussed the main requirements that the design must satisfy. The efforts are now focused on developing a beam screen design with low impedance that can be inserted in the beam pipes of the RHIC arc dipoless and enables cooling via direct contact with the cold bore. Our R&D program includes the development of a time-efficient coating recipe that allows to produce a film with good adhesion, low SEY and low outgassing rates, as well studies and tests intended to validate the structural, thermal, and vacuum stability of our design.

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