Field Compensation in Electron-Ion Collider Magnets With a Passive Superconducting Shield

Ramesh Gupta, Shresht Joshi, Brett Parker, William Sampson, Shailendra Chouhan, Stephen Kahn, James Kolonko, Delbert Larson, Ron Scanlan, Robert J. Weggel, and Erich Willen

***Abstract*—This paper presents work under a Small Business Innovation Research Phase I grant to Particle Beam Lasers, Inc. and Brookhaven National Laboratory to develop a passive superconducting shield as an alternative to the present design of an active shield with superconducting coils. This shielding provides a nearly field-free region for the electron beam near the high-gradient quadrupole for the proton beam in the interaction region (IR) of the proposed electron ion collider. Several materials are being examined for this shielding—tubes of low- or high-temperature superconductors (LTS or HTS), LTS sheets, and HTS tapes. Supplementing this shielding is an iron ring between the superconducting shield and beam tube to counter any decay in shielding currents. If successfully developed, demonstrated, and shown to be compatible with the magnet designs of all the IR magnets, this technique will provide an economical and technically excellent solution that reduces the need to operate IR magnets at higher current. This paper will summarize the latest design studies and test results both at 77 K for the shielding by the bulk-HTS tube and at 4 K for the shielding by tubes of HTS or LTS.**

***Index Terms*—Superconductive passive shield, electron ion collider, interaction region magnets, HTS shield, LTS shield.**

I. INTRODUCTION

THE proposed Electron-Ion Collider (EIC) could solve mysteries of the atomic nucleus by colliding high energy electron beams with ion or proton beams [1]. Currently two sets of designs are being considered for the Electron Ion Collider, one proposed by Brookhaven National Laboratory (BNL) [2] and the other by Thomas Jefferson National Accelerator Facility (JLAB) [3]. The Interaction Region (IR) magnets must satisfy requirement that are unusual and challenging, in that the electron beams travel very close to the proton or ion beam [4] and must be shielded magnetically from the fringe fields of the beamline magnets that bend and focus that beam. A Phase I SBIR to PBL and BNL has been funded to develop a passive superconducting shield, as an alternate to the present design of an active shield with superconducting coils [5].

The basic principle of superconducting shielding is that currents induced in the conductor per Lenz's Law oppose the change in field. In superconductors, these opposing currents persist, in principle, forever. If the capability of the superconductors is adequate (critical current density decreases with field and temperature) and the geometry allows a path for the induced currents to oppose the change in field, the field inside the shielded region will not change.

Superconducting shielding has been applied in various applications, such as the g-2 experiment [6], a cloak experiment [7], and proposed for a high field septum magnet for the Future Hadron Collider [8]. The challenge for this application is to shield the field of a high-gradient quadrupole without appropriating much space. The method was considered [9], but never applied, for shielding the HERA electron beam from the dipole field of the HERA B detector. The benefit of demonstrating this technique will be significant, as it will lower the current required in the high field quadrupole and possibly increase the luminosity of the EIC. The geometric advantage for cold shielding is that it needs relatively little radial space.

II. MAGNET DESIGN

Shielding will benefit magnet designs in the EIC IR magnets of both BNL and JLAB proposals. Various superconductors suitable for this application will be discussed in the next section. To provide shielding against any transient or decay of shielding currents inside the superconductors, we propose to add a small ring of ferromagnetic material inside the superconducting shield.

The most critical quadrupole that needs shielding is closest to the interaction point for focusing the proton beam in the front end. Fig. 1 shows the cross-section of the BNL design Q1PF [5], with 96-mm-aperture Nb_3Sn superconducting coils providing a field gradient of 140 T/m, and a cutout in the iron yoke providing passage for the electron beam. The electron beam will be at an angle of 20-25 mrad with respect to the proton beam. The passive superconducting shield is within the cutout, along with an iron ring inside. The bottom picture shows the field contour inside the cutout region, with the passive superconducting shield simulated together with a passive magnetic shield 1 mm thick. The computed maximum field in the upper-left corner is about 0.72 T; in the shielding region, it is about half this. This can be shielded by a modest thickness of superconducting shield made of either LTS sheet or HTS tape, as per the initial preliminary

Manuscript received October 26, 2018; accepted January 30, 2019. Date of publication February 6, 2019; date of current version February 22, 2019. This work was supported in part by the Brookhaven Science Associates, LLC under Contract DE-SC0012704 and in part by the U.S. Department of Energy under SBIR Grant DE-SC0018614 to Particle Beam Lasers, Inc. *(Corresponding author: Ramesh Gupta.)*

R. Gupta, S. Joshi, B. Parker, and W. Sampson are with the Brookhaven National Laboratory, Upton, NY 11973 USA (e-mail: gupta@bnl.gov).

S. Chouhan, S. Kahn, J. Kolonko, D. Larson, R. Scanlan, R. J. Weggel, and E. Willen are with Particle Beam Lasers, Inc., Northridge, CA 91324-2807 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2019.2897266

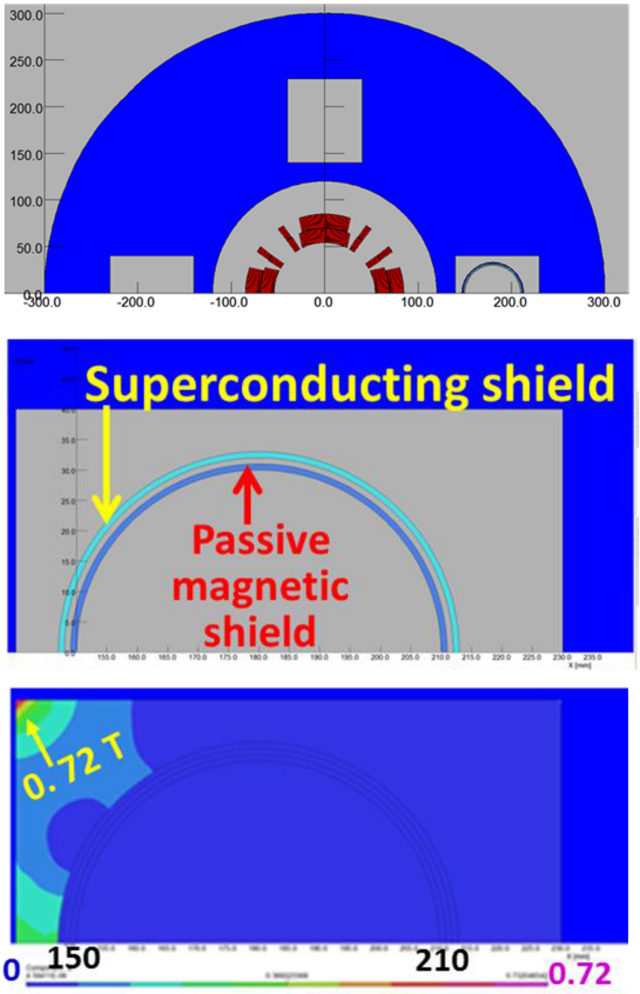

Fig. 1. Magnetic design of the quadrupole with iron yoke and superconducting shield. Top: Cross-section of the upper half of the magnet. Center: Details of the cutout, including passive superconducting shield and passive magnetic shield. Bottom: Field in the cutout region. Additional passive magnetic shielding will ensure that the residual field and field due decaying screening currents of the superconducting shield remain small.

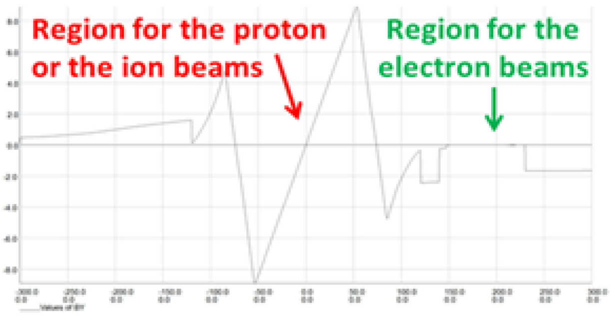

Fig. 2. Magnitude of the field on the horizontal axis at ~168 T/m in the Q1PF quadrupole with shielding, showing near-zero field in the region of interest.

magnetic simulations. The magnitude of the field on the horizontal axis is plotted in Fig. 2. The field becomes essentially zero inside the shielded region traversed by the electron beam.

Fig. 3. Bi2223 tube provided by CAN superconductor [10]. The tube and test holder will be inserted inside the bore of a coil providing background field.

III. SHIELDING MATERIAL

Several superconducting shielding materials are being considered for this application. Because the magnet itself is planned to be operated at ~4.2 K, the shield automatically can be at that temperature, allowing low temperature superconductors (LTS) to suffice, in the form of either sheets (as already used in many applications, for example g-2 [6]) or tube, as we have investigated as part of this program. HTS can be tapes or tube. HTS can be either Bi2223, a first-generation (1G) superconductor, or rare-earth barium copper oxide (ReBCO), a second-generation (2G) material. A practical advantage of HTS is that an experimental program in liquid nitrogen (LN_2) is simpler and more economical that in liquid helium.

IV. SHIELDING TESTS

This section presents superconducting shielding tests of HTS in liquid nitrogen at 77 K and tests of both HTS and LTS shielding in liquid helium at 4 K. For these investigations, HTS and LTS tubes were provided to BNL by our collaborators at no cost.

Fig. 3 shows a Bi2223 (HTS) tube 80 mm long, ~1.5 mm thick and 10 mm inner diameter, provided by CAN SUPERCONDUCTORS, s.r.o., a Czech company [10].

Fig. 4, left, shows a tube made from the NiTi rod provided by J. Parrell from Bruker [11], and (right) the NbTi rod provided by H. Kanithi from Luvata [12], each bored axially with a ½" (12.7 mm) drill. Both tubes were annealed at a temperature of 400 C for 4 hours in vacuum better than 10^{-5} torr by Qiang Li at BNL [13].

A. Shielding Tests at 77 K

A practical advantage of HTS shielding is that its basic configuration can be tested inexpensively at 77 K. For field-parallel (axial) measurements, a copper coil was wound directly on the Bi2223 tube [10] (see Fig. 5). Field-perpendicular (radial)

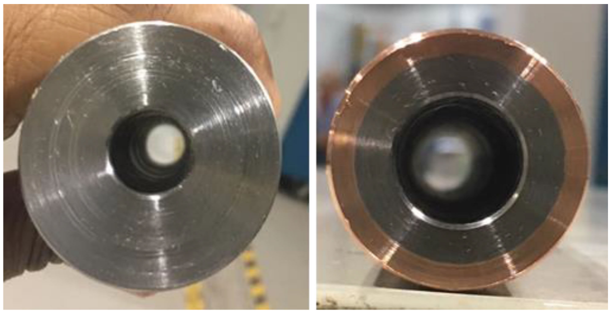

Fig. 4. LTS tubes made from the NbTi rods provided by Bruker [11] (left) and by Luvata [12] (right). The inner diameter of both tubes is 12.7 mm.

Fig. 5. Copper windings on the HTS tube to immerse it in a field that is primarily axial.

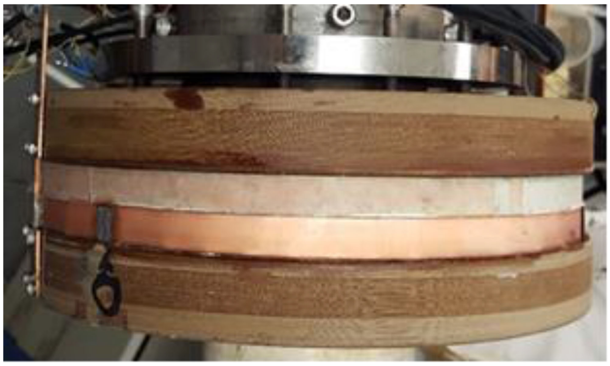

Fig. 6. HTS coil to generate a field with a large radial component over much of the volume of shielding tubes.

measurements utilized a short HTS coil of $\sim$100 mm bore (Fig. 6).

The field at the center of the shielding tube is measured with the tube in an ambient magnetic field. Fig. 7 shows the results with the coil of Fig. 5, which provides a field that is primarily axial, and with the coil of Fig. 6, whose field is primarily radial. The tube shields the axial field more than the radial field.

Fig. 7 shows the results of two hysteresis runs. The field inside the tube increases in step with the applied field once the field has reached the maximum that the tube can shield. When the applied field is decreased, the field inside the tube initially remains unchanged, because shielding currents oppose the change. Field inside the tube is trapped, leaving a residual field when the applied field has become zero. The whole cycle repeats itself for both cases.

B. Shielding Tests at 4 K

The left side of Fig. 8 shows tubes of HTS (black) and LTS (copper clad) on a disc; the right side shows the two tubes inserted inside the field-applying HTS coil. The two superconducting shielding tubes are off-axis, with the center of each tube located at $r = 20$ mm to 30 mm. Three Hall probes are installed, two at the center of each tube and one at the center of the HTS coil applying the background field. The shielding tube measurements were performed at several temperatures ranging from 4.2 K to 77 K; reported here are only the measurements at 4 K.

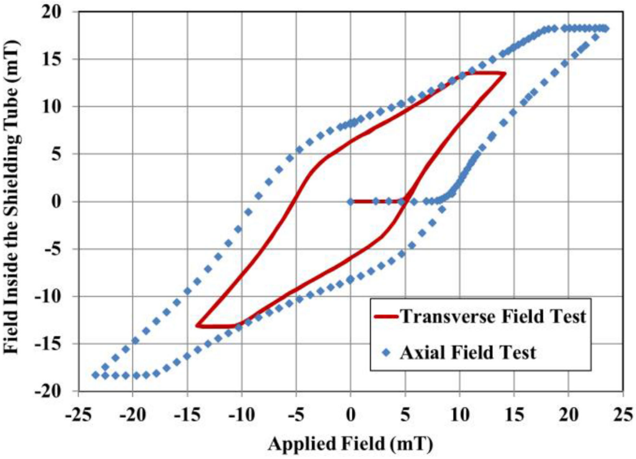

Fig. 7. Field at the center of the Bi2223 tube at 77 K with an ambient field from coil 5 (primarily axial) and from coil 6 (primarily radial).

Fig. 8. Left: Disc with tubes of HTS (black) and LTS (copper-clad NbTi), and a center tube holding a Hall probe on the axis of the disc. Right: The disc, with three Hall probes, inside the superconducting coil for testing at 4 K.

The NbTi tube used in this shielding experiment was made from the $\sim$20 mm diameter NbTi rod sent by Luvata [12]. It was clad with $\sim$3 mm of copper and included a thin ($<<$ 1 mm) Nb barrier.

The 76 mm (3”) long tube was centered at the midplane of the coil. The applied field across the volume of the tube was far from uniform, varying across the radius and falling to nearly zero at the ends of the tube. We define the applied field as its maximum value.

Fig. 9 shows the field in the middle of this NbTi tube as a function of the applied field; the NbTi tube shields completely

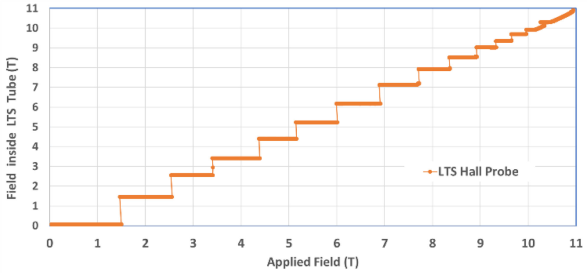

Fig. 9. Field inside the NbTi tube as a function of applied field. The shielding is complete up to ∼1.5 T, thereafter trapping field. Steps are due to quenches in the NbTi tube, temporarily removing the trapped field trapped.

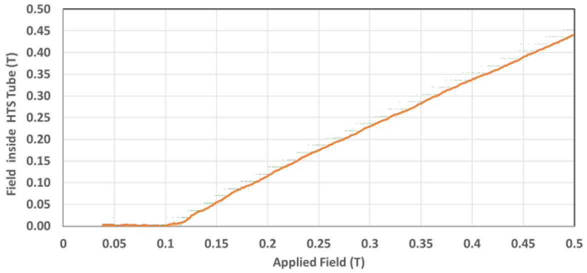

Fig. 10. Field inside the Bi2223 (HTS) tube as a function of the applied field. The shielding is complete up to ∼0.12 T.

to about ∼1.5 T. Beyond that, the current density needed to fully negate the applied field exceeds the superconducting properties of NbTi, and the tube quenches. However, the NbTi tube recovers and becomes superconducting again, resisting changes in field from 1.5 T; the tube traps field, as with the Bi2223 coil of Fig. 7, even if the applied field is turned off. The tube also resists further increases in field until the required current density exceeds the critical current density at a field that is higher by ∼2.6 T – 1.5 T = 1.1 T. The second field increment is smaller than the first because the critical current density decreases with increasing field. The thicker the tube, the greater its ability to shield fields, because the required current density decreases. Of course, at fields exceeding the critical field of NbTi, the tube is not able to provide any shielding at all, whatever its thickness. The IR magnets of EIC need not shield a field as high as 1.5 T, so a thinner shield should suffice.

Fig. 10 shows the shielding properties of the Bi2223 HTS tube. Because the tube is much thinner (∼1.5 mm), it shields much less (∼0.12 T). However, because the current density of HTS at 4 K decreases very little with field, an HTS shield of sufficient thickness could, in principle, shield fields even higher than LTS.

V. FUTURE WORK

Having evaluated the shielding options provided by HTS and LTS tubes, the next step will be to evaluate the shielding capabilities of HTS tapes, which are more readily available. A more extensive program will be carried out in Phase II, if funded. This will include designing and testing the complete shielding system (including the iron ring inside) in a magnet which simulates more closely the expected EIC IR configuration (there is no EIC IR model magnet available yet). We will evaluate numerous options, including both HTS and LTS tubes and HTS tapes and LTS sheets. We also will examine the long-term stability of superconducting shielding and verify that decay or transient effects, if any, can be remediated with iron. We will also examine the ends of the magnet and superconducting shielding, ensuring that the overall solution is viable. The goal of the Phase II program will be to demonstrate a fully developed solution that can be used in the EIC and similar applications.

VI. DISCUSSION AND CONCLUSION

A first round of shielding experiments has been completed with superconducting tubes as a part of an SBIR Phase I. Tubes likely can shield a wide range of field shapes or distributions anticipated in the region of interest in an EIC, including the end region of the IR magnets. These tubes are very robust: NbTi is robust inherently, and Bi2223 or ReBCO can be made so, by the addition of a simple support tube; incorporating them in a magnet should not pose any challenge. The experimental test setup with single tube was simple. One can incorporate many such tubes (multiple layers across the radius and/or length, or perhaps staggered together) across the length.

The test results point to a promising solution for shielding the electron beam from the fringe field of nearby high field magnets, both quadrupoles and dipoles, in the EIC IR magnets. The benefit of a passive shielding system (superconducting shield with added iron ring inside) over an active superconductive coil shield is that it should be simpler and cheaper and does not require any increase in magnet current to overcome the opposing field created by the active shielding coils.

REFERENCES

[1] The 2015 Long Range Plan for Nuclear Science “Reaching for the Horizon.” Nuclear Science Advisory Committee, Oct. 20, 2015. [Online]. Available: https://science.energy.gov/∼/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

[2] RHIC Electron–Ion Collider. Brookhaven National Laboratory, [Online]. Available: https://www.bnl.gov/rhic/eic.asp

[3] JLEIC Design—Electron Ion Collider Wiki. [Online]. Available: https://eic.jlab.org/wiki/index.php/Main_Page

[4] EIC Collaboration Meeting at BNL. (2017). [Online]. Available: https://indico.bnl.gov/conferenceDisplay.py?confId=3492

[5] B. Parker, “Fast track actively shielded Nb_3Sn IR quadrupole R&D,” Oct. 11, 2017. [Online]. Available: https://indico.bnl.gov/getFile.py/access?contribId=28&sessionId=5&resId=1&materialId=slides&confId=3492

[6] A. Yamamoto *et al.*, “The superconducting inflector for the BNL g-2 experiment,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 491, pp. 23–40, 2002.

[7] K. G. Capobianco-Hogan *et al.*, “A magnetic field cloak for charged particle beams,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 877, pp. 149–156, 2018.

[8] D. Barna, “High field septum magnet using a superconducting shield for the Future Circular Collider,” *Phys. Rev. Accel. Beams*, vol. 20, no. 4, 2017, Art. no. 041002. [Online]. Available: http://link.aps.org/doi/10.1103/PhysRevAccelBeams.20.041002

[9] A. Koski and S. L. Wipf, “Magnetic shielding of an accelerator beam using passive ferromagnetic material,” *IEEE Trans. Magn.*, vol. 32, no. 4, pp. 2663–2666, Jul. 1996.

[10] J. Plecháček, private communication. (2018). [Online]. Available: https://www.can-superconductors.com

[11] J. Parrell, private communication. (2018). [Online]. Available: https://www.bruker.com

[12] H. Kanithi, private communication. (2018). [Online]. Available: http://www.luvata.com/waterbury

[13] Q. Li, private communication. (2018). [Online]. Available: https://www.bnl.gov/cmpmsd/aem/people/profiles/liQiang.php