Project Narrative

Cover Page

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Table of Contents

1.0 Introduction

1.1 Significance and Background Information

The Nuclear Science Advisory Committee (NSAC) [1] constituted by the Department of Energy (DOE) Office of Nuclear Physics (NP) recommended that the proposed Electron Ion Collider (EIC) be the highest priority for new construction in the 2015 Long Range Plan (LRP) for Nuclear Science [2]. The EIC requires development of several key technologies. This proposal concerns the development of alternate techniques for efficient compensation of the fringe field generated by high field quadrupole and dipole magnets in the Interaction Region (IR). Currently two sets of designs are being considered for the Electron Ion Collider, one proposed by the Brookhaven National Laboratory (BNL) [3] and the other by the Thomas Jefferson National Accelerator Facility (TJNAF) [4]. Fig 1 shows two designs [5, 6] of the IR region for the BNL eRHIC proposal and Fig. 2 for the TJNAF JLEIC proposal [6, 7]. Both IR designs need a high field gradient quadrupole for the heavier proton or ion beams and a near field free region (no more than a few mT) for the electron beams close to the proton or ion beams.

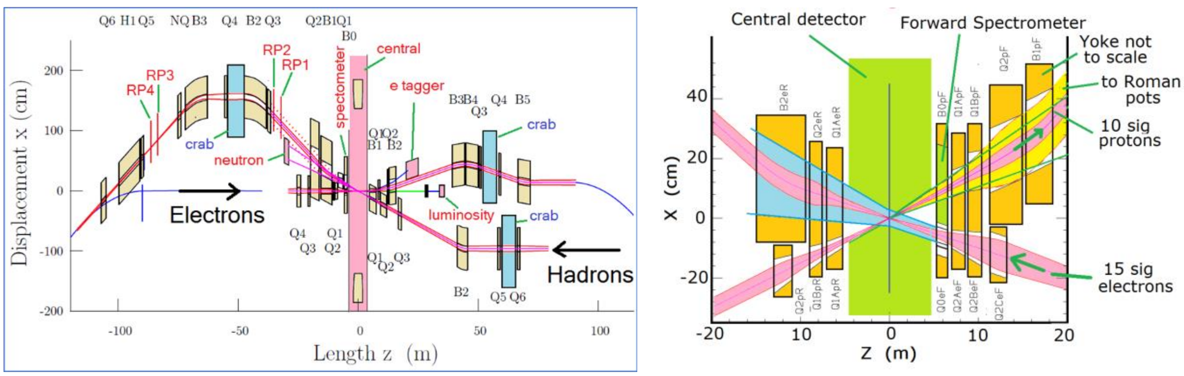

Fig. 1: Proposed layout of the Interaction Region (IR) for the BNL eRHIC design of the EIC (courtesy R. Palmer). Layout on the left is drawn from the collaboration meeting at BNL [5]; the layout on the right is from the collaboration meeting at the Thomas Jefferson National Accelerator Facility [6].

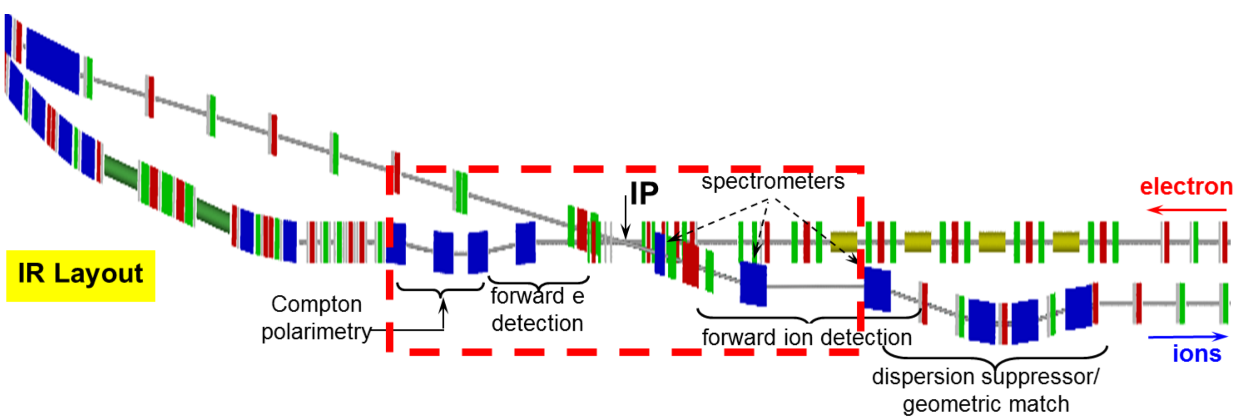

Fig. 2: Proposed layout of the Interaction Region for the JLAB design of the EIC.

The present design approach is based on active shielding [5] to obtain a field-free region for the passage of the electron beam. The approach is shown in Fig. 3 for the first high gradient quadrupole (Q1PF) for the proton or ion beam at the interaction point. Fig. 3 shows the main coils and active cancellation coils with the current in the active coils proportional to but in the opposite direction to that in the main coils. The main coils in the quadrupole, therefore, must now operate at higher current to produce the required field gradient for the proton or ion beams. Fig. 4 shows the basic design of spectrometer dipole B0 in the BNL proposal [6, 8]. The compensation dipole coil needs to be inside the magnet, with an appropriate field profile needed for both the electron beam and the proton or ion beam.

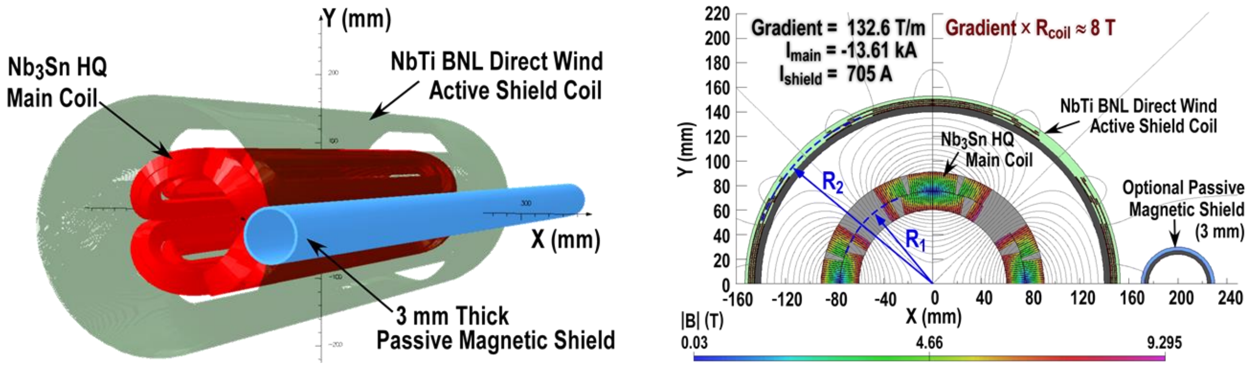

Fig. 3: 3-d and 2-d models of the current approach, in which the external field of the main high field Nb_3Sn quadrupole coils for the proton or ion beams is cancelled by the outer NbTi coils (providing active shielding) to obtain a nearly field-free region for passage of the electron beam. Also shown is thin passive magnetic shielding.

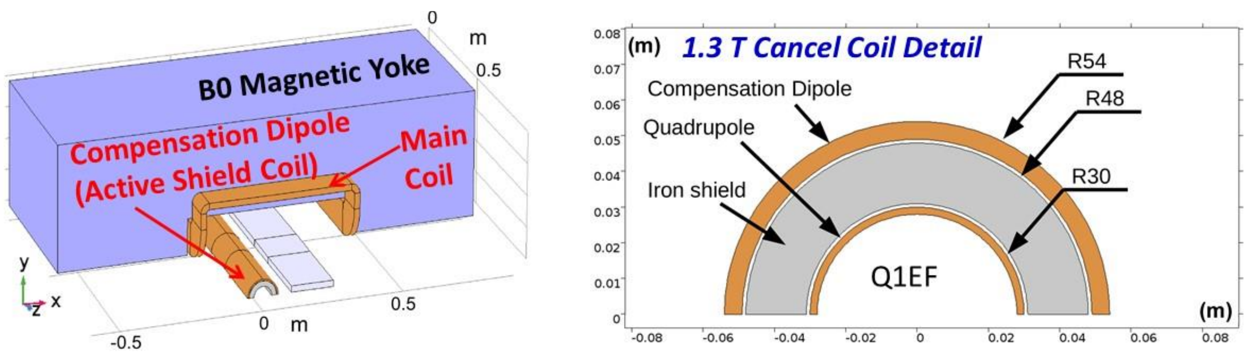

Fig. 4: Conceptual design of the spectrometer dipole B0 for eRHIC EIC proposal. Shown on the left are the main coil, yoke and compensation dipole coil (also referred to as the active shield coil). Shown in detail on the right are major elements of the quadrupole for the electron beam.

In this proposal we will develop and demonstrate an alternate technique for the EIC, whereby the field-free region for the electron beam is created by passive superconducting shielding, which opposes changes in the field. This technique has been applied earlier in various applications, such as a g-2 experiment [8] and a cloak experiment [9, 10], but never to combat such fields in accelerator or beam line magnets in such a limited space. The method was considered [11] for shielding the HERA electron beam from the dipole field of the HERA B detector but was never applied. The proposed shielding option for a high-field septum magnet for the Future Hadron Collider is based on multi-layer (NbTi/Nb/Cu) superconducting material [12]. High permeability ferromagnetic material shielding along with superconducting niobium cavities was demonstrated in the ReA-3 superconducting cryomodule [13] at Michigan State University (MSU).

The benefit of this approach was also pointed out in the "*Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics*" [14]. In fact, it specifically mentioned on page 43 that:

"An open question for a study, common to the dipole and quadrupole sweet spot work, is the use of mu metal or a 'Meissner shield' (superconducting shield) for passive magnetic shielding. The geometric advantage for cold shielding is much less radial space required. However, shield geometries can be tested inside existing BNL magnets."

The successful development and demonstration of the proposed techniques will play a key role in the design of the IR dipoles and quadrupoles, as well as the overall design of the interaction region. The EIC proposal is evolving, and changes in optics may change the requirements of the active shield coils for the quadrupole, however, it remains significant in the spectrometer dipole. There must be an appropriate field profile for the electron beam traversing the quadrupole magnet and for the proton or ion beam going through the dipole magnet despite the field of the other magnet. This also is the general motivation behind the cloak proposal [9,10] for the EIC.

1.2 Technical Approach

Our proposal is based on passive superconducting shielding supplemented with iron to shield field coming from the transient or decaying persistent or remnant field in the yoke iron. Shielding currents created in the passive superconducting shield will compensate the field created by the high field magnets in the region of interest, if properly designed, developed and implemented.

During Phase II, we will demonstrate superconducting shields made of conventional Low Temperature Superconductor (LTS) in sheet form and tubes, and High Temperature Superconductor (HTS) in tape form and tubes made with bulk material. This demonstration will be carried out with an appropriate magnet. The best choice may be different for different EIC magnets.

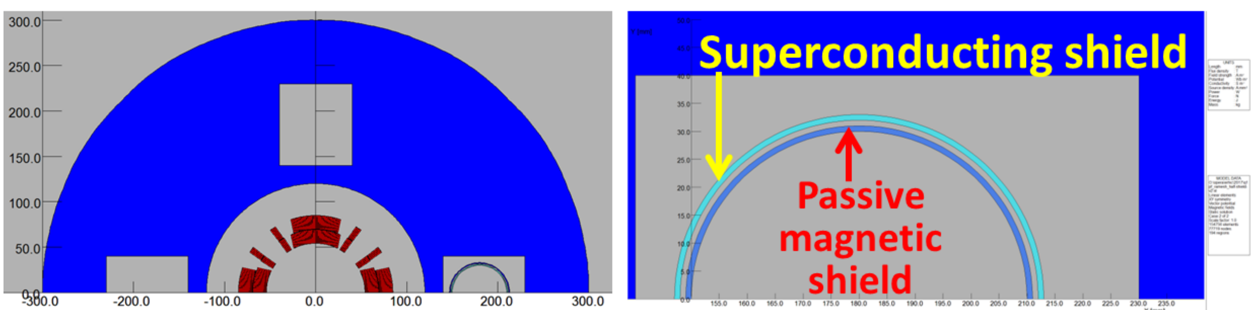

Fig. 5: Magnetic design with iron yoke and superconducting shield. Upper half of the magnet is shown on the left; details of the cutout, including a passive superconducting shield and passive magnetic shielding, is shown on the right. Additional passive magnetic shielding will ensure that the residual field or the field due decaying screening currents of the superconducting shield is kept small.

An equivalent magnetic design of the quadrupole shown in Fig. 3 with active shielding is the passive superconducting shield in Fig 5. The design uses the same main coils; however, the field-cancelling coils are replaced by an iron yoke having the same inner radius as the field cancelling coils, with a cutout for the electron beam. The electron beam runs at an angle, as shown in Fig. 1 and Fig. 2. The passive superconducting shield is placed within the cutout (shown more clearly on the right side of Fig. 5). Additional passive shield made of cryoperm or mu-metal (depending on the detailed design and temperature of the beam pipe) will also be included, as shown in Fig. 5.

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This shielding is expected to bring the small residual field or the field due to decaying screening currents to a low level in the region occupied by the electron beams.

The magnitude of the field on the horizontal axis is plotted in Fig. 6. The field becomes essentially zero inside the shielded region (see Fig. 6 right) where the electron beam traverses.

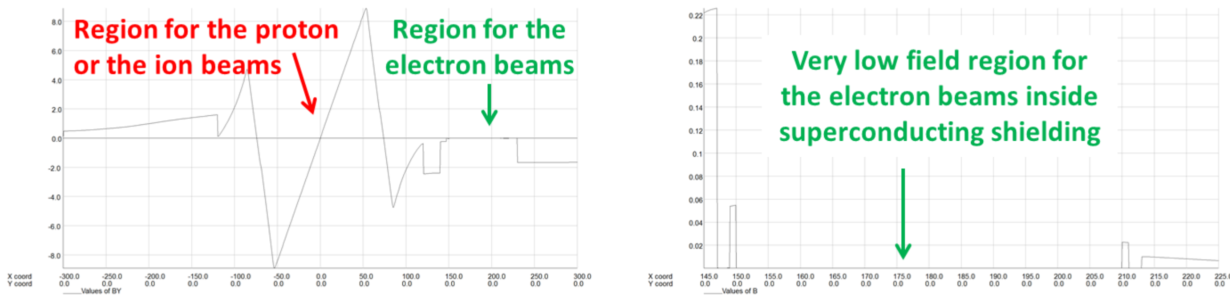

Fig. 6: Magnitude of the field on the horizontal axis (left) for the design in the quadrupole with an iron yoke. Field on the horizontal axis of the cutout region is shown on the right.

1.3 A Recent Invention for Shielding

This section describes a technique on which a provisional patent application has been filed [15]. The information presented here is proprietary and protected. This is a promising technique, with potentially wide applications in accelerator magnets (such as those for EIC) and other areas. The technique will be evaluated and developed as a part of the Phase II program, if funded.

HTS tapes are available in a relatively small width. Narrow widths limit the volume that can be efficiently shielded. The technique described here overcomes this limitation

Our proposal is to cut most of the tape in two parts along the length, as in Fig. 7 (leaving the two ends uncut), and then placing it around the tube along the beam direction (see Fig. 8). Keeping the two ends intact allows a complete path for circulating currents to provide shielding against the dipole field (see Fig. 7 and Fig. 8). The configuration in Fig. 7, left, is a simple one for performing initial proof-of-principle testing. On the right of Fig. 8, the tape is folded in a special way to clear the path for particle beams. In general, the two sides of the tapes will be apart at different angles, not just 180 degrees. A series of such split tapes will be placed across the azimuth to provide complete shielding. The actual pattern or distribution of the tape across the azimuth will be optimized for the pattern of the field to be shielded in the region of interest. Properly placed tapes will cover an area or volume for magnetic shield region that will be much larger and wider than was possible by the width of a tape in a conventional approach.

The basic concept will require further development and testing along with proper engineering to support a series of such tapes in a magnetic field in a proper mechanical structure. We plan to carry that out in Phase II.

Figure 7: A superconducting tape cut along the length while keeping the two ends intact. A possible path of circulating current to provide shielding is shown.

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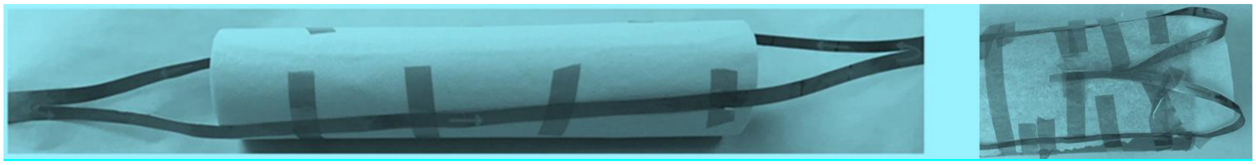


Figure 8: Two sides of the middle part of the superconducting tape are separated and placed on either side of the tube, while the ends are kept intact (see left). The ends are folded in the picture on the right to clear the path for electron beam through the beam tube. Several such split tapes will be used across the azimuth to provide the magnetic shielding inside the tube.

2.0 Anticipated Public Benefits

The passive superconducting field shielding to be investigated in this project is expected to provide a lower cost and technically attractive solution for the shielding problem facing the Interaction Region (IR) magnets in the proposed Electron Ion Collider (EIC). Lower costs are expected because of (a) the simpler, passive implementation and (b) the elimination of power supplies, cabling and associated equipment needed for an active shielding solution.

Development of such a shielding method is valuable in many diverse areas of significant research, such as the g-2 experiment [8] and the magnetic cloak experiment [9, 10]. Development of such shielding technology may also play a role in major commercial applications such as Magnetic Resonance Imaging (MRI). At present, commercial MRI uses two approaches for magnetic field shielding--active (superconducting outer magnet), and passive (massive iron yoke). The technology developed in this SBIR may provide an additional option for magnetic field shielding based on superconducting sheets.

Moreover, since the proposed project aims to benefit the science of building colliding beam accelerators for nuclear physics research, the most immediate beneficiaries are researchers working in nuclear physics around the world. The market for colliding beam accelerators is small when measured in number of units – typically only one or two such devices are constructed every 10 to 20 years. However, the market as measured in dollars can be significant, with project costs in the range of hundreds of millions of dollars. Enabling supporting technology for such significant investments is important for the eventual success of the project, assisting to get the most scientific output possible for the money spent.

PBL has focused its business plan on advancing the state of the art of high field magnets, and the project proposed herein is envisioned to contribute to the Intellectual Property (IP) portfolio of PBL. As discussed more fully in the Commercialization Plan attached as part of this proposal, the MRI and SMES markets are in the billion-dollar range, which is indicative of a significant public market.

3.0 Technical Feasibility as Demonstrated by the Phase I Tasks and Additional Experiments

This section summarizes the Phase I experimental test results of several options involving superconducting shielding. These include 77 K tests of (a) two configurations of High Temperature Superconducting (HTS) ReBCO tape and (b) two orientations of tube made with the HTS bulk material. A practical advantage of HTS for Phase I was that its basic configuration could be tested at a relatively low cost at 77 K. Existing HTS coils were used by themselves and in making a C-shaped dipole magnet (see Fig. 9) to perform these tests (see Fig. 10 and Fig. 11).

The PBL/BNL team collaborated with conductor manufacturers and was able to obtain conductor free of cost in return for sharing data and acknowledging their contributions. CAN SUPERCONDUCTORS, s.r.o., a Czech company [16] provided the HTS (Bi2223) tube made of bulk material (see Fig. 11). Oxford [17] and Luvata [18] donated NbTi tubes (see Fig. 12).

In addition, limited shielding tests for both an HTS tube and an LTS tube were performed at ~4 K, which was beyond what was promised by the Phase I proposal. This was possible thanks to the synergy with another ongoing magnet test at BNL which could accommodate such shielding tests. The ~4 K tests are valuable to EIC, because the magnets will operate at ~4 K. As expected, 4 K provided shielding to much higher fields.

The additional activities and tests demonstrate the interest and commitment of the PBL/BNL team towards developing the shielding technology for EIC magnets and other applications. It has allowed us to make a strong Phase II proposal to demonstrate this shielding development alongside a real superconducting quadrupole.

3.1 Shielding Tests with HTS Tape at 77 K

The first configuration is a spirally wound HTS tape. We used 12 mm tape from SuperPower wound on a stainless-steel tube, as shown in Fig. 9 (a). Each spiral creates a small dipole with shielding current running parallel to the tube and in the opposite direction on two sides with the circuit completed with current running along the spiral using a partial width of the tape. The direction of current in two nearby spirals is opposite to each other and thus the axial field created by them essentially cancels out. Many small dipoles add together to provide complete shielding until the induced current in the tape reaches its critical value. Fig. 9 (b) shows an insulation wrap, which also holds the tape together. Fig. 9 (c) shows a C-shape dipole built specifically for this experiment with the leftover HTS coils from another project. Fig. 9 (d) demonstrates the shielding at the center of the tube against the applied field. A single wrap of ~12 mm wide HTS tape from SuperPower was able to shield a field of ~20 mT at 77 K.

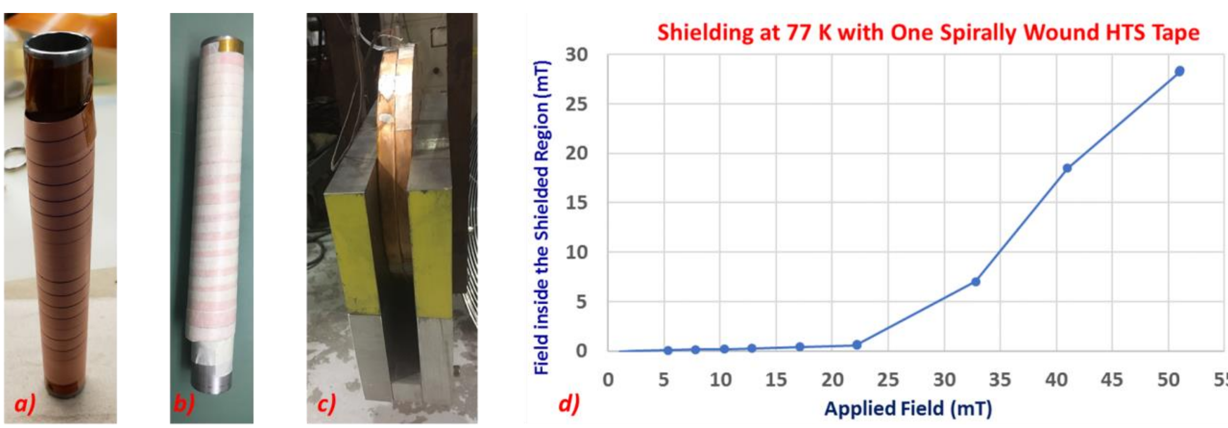


Fig. 9: (a) 12 mm wide HTS tape spirally wrapped around a tube, (b) HTS tape further wrapped with insulation to hold it securely, (c) a C-shaped dipole built with HTS coils for applying field primarily perpendicular to the tube for testing the shielding, and (d) test results showing the field inside the tube as a function of the applied field.

The widest tape available from most HTS manufacturers (such as SuperPower, Inc. [19]) is 12 mm width, but American Superconductor Corporation [20] can provide it in ~40 mm width as a special order. Fig. 10 (left) shows the configuration when this 40 mm wide tape is placed on the tube with the length parallel to the tube. Using this, we create a long dipole with the shielding current running along the length of the tape if it rolls over the top to accommodate currents in the opposite direction on the other side. For shielding to work properly, the minimum width of the tape should be ½ the circumference to shield a dipole field; ¼ the circumference to shield a quadrupole field. Therefore, the maximum tube cross-section that can be shielded with this geometry is limited by the width of the tape.

Fig. 10 (right) shows the results of the shielding experiment. It must be mentioned that the tape was folded in a tight radius (<10 mm) which might have degraded its performance, possibly reducing the shielding current it could generate and the magnitude of shielding it could provide. Unlike the case shown in Fig. 9 (right), the field inside the shield region in this case as shown in Fig. 10 (right) is non-zero at the start. That is because the iron was already magnetized from the previous run and the field applied from powering the coil was in addition to the previous field. Superconducting shielding simply resist the change in field (retaining the trapped field) whether it is from zero or non-zero, provided it can tolerate enough shielding currents. Fig. 10 (right) shows several cases of different starting conditions.

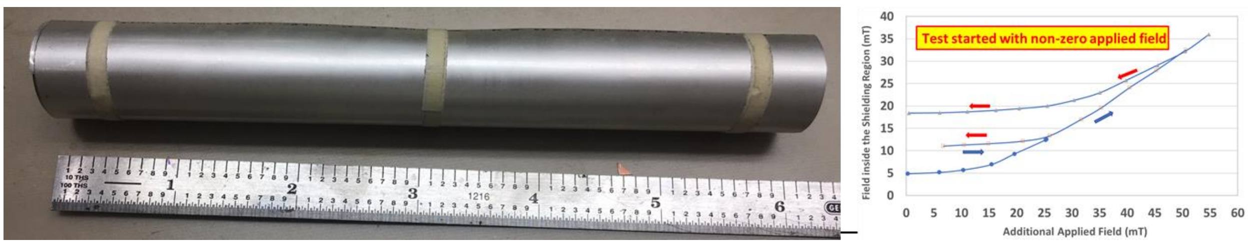


Fig. 10: HTS tape placed on a tube to shield a primarily dipole field along the axis is shown on the left and the test results of the shielding experiment on the right. This test demonstrates that the superconducting shield can resist the change in field.

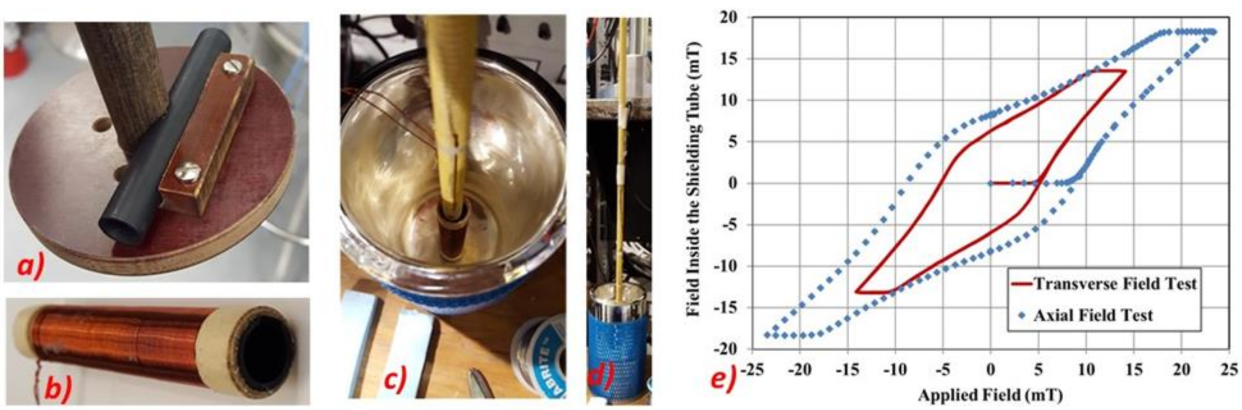


Fig. 11: (a) *Bi2223 tube provided by CAN superconductor. The tube and test holder will be inserted inside the bore of a coil providing background field, (b) copper windings on the HTS tube to apply a field that is primarily along the axis, (c) placed in the dewar, (d) filled with liquid nitrogen with Hall probe placed at the center of the tube and (e) measured field at the center of the Bi2223 tube at 77 K with an ambient field primarily axial (blue) or primarily radial (red).*

3.2 Shielding Tests with an HTS Tube at 77 K

Fig. 11(a) shows a Bi2223 (HTS) tube (80 mm long, ~1.5 mm thick and 10 mm inner diameter) in a holder. For field-parallel measurements, a copper coil was wound directly on the Bi2223 tube (see Fig. 11b). Fig 11 (c) and Fig 11 (d) show the tube (with a Hall probe installed at the center of the tube) in a dewar into which liquid nitrogen can be poured. Field-perpendicular measurements utilized a short HTS coil of ~100 mm bore (shown later in Fig. 15a). Fig. 11 (e) shows the results of two hysteresis runs (1) with an ambient field primarily axial (blue) simulating the case of a primarily parallel field and (2) with an ambient field primarily radial (red) simulating the case of a primarily perpendicular field. 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. The field inside the tube is trapped, leaving a residual field when the applied field returns to zero.

3.3 Shielding Tests with HTS and LTS Tubes at 4 K

Fig. 12(a) shows the NiTi rods donated by Luvata [18] and Bruker [17], each bored axially with a ½" (12.7 mm) drill as shown in Fig. 12(b) and Fig. 12(c). Both tubes were annealed at a temperature of 400 C for 4 hours in a vacuum better than 10^{-5} torr. The NbTi tube used in this shielding experiment was made from the ~20 mm diameter NbTi rod sent by Luvata [18]. It was clad with ~3 mm of copper and included a thin (<< 1 mm) Nb barrier. Fig. 12(d) and Fig. 12(e) shows tubes of HTS (black) and LTS (copper clad) on a disc. 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.

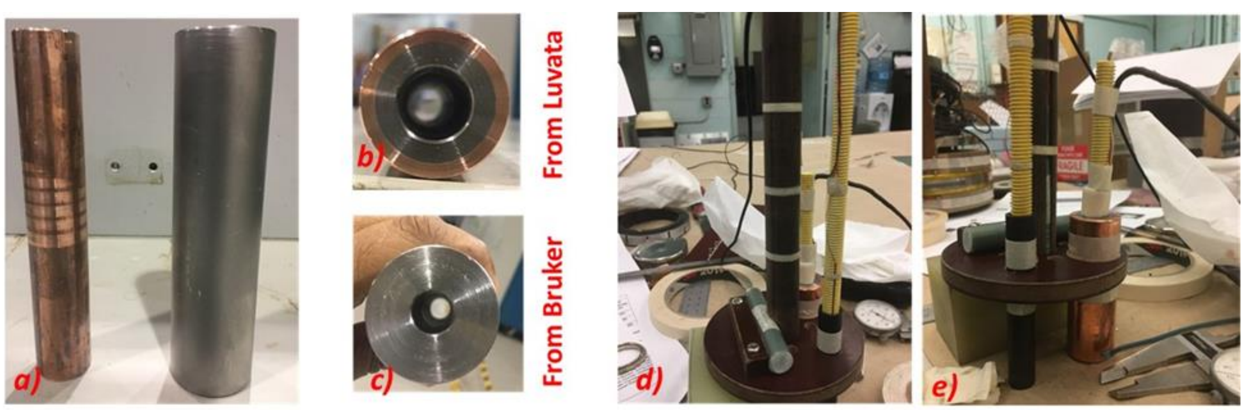


Fig. 12: (a), (b) and (c) show the *LTS tubes made from the NbTi rods provided by Luvata and Bruker.* (d) and (e) show *the disc with tubes of HTS (black) and LTS (copper-clad NbTi), and a center tube holding a Hall probe on the axis of the disc.*

Fig. 13 (left) shows the HTS and LTS tubes inserted inside the field-applying HTS coil. Fig 13 (middle) shows the field at the center of the NbTi tube as a function of the applied field; the NbTi tube shields completely to about ~1.5 T. Beyond that, the current density needed to fully negate the applied field exceeds the superconducting capacity 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 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. 13 (right) 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.

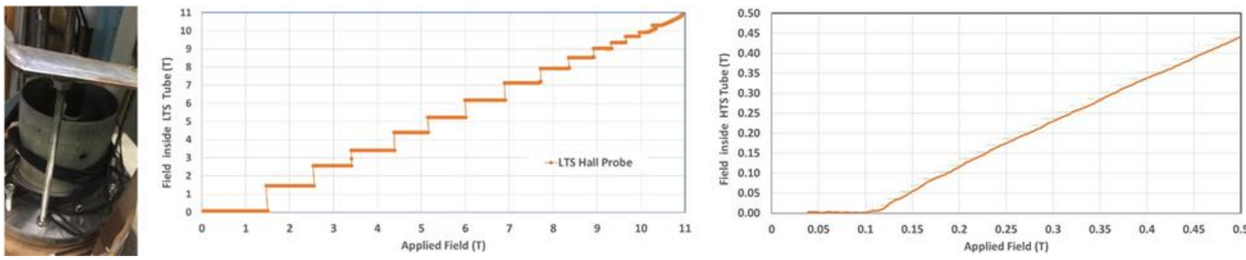


Fig. 13: Picture on the left shows HTS and LTS shielding tubes inside an HTS coil with several Hall probes. The plot in the middle shows the field inside the NbTi tube as a function of applied field (the shielding is complete up to ~1.5 T, thereafter trapping field). The plot on the right shows the field inside the Bi2223 (HTS) tube as a function of the applied field.

4.0 The Phase II Project

4.1 Technical Objectives

Taking advantage of the substantial progress made during Phase I (including carrying out initial 4 K tests that were not part of the Phase I proposal), we are able to propose a strong Phase II with more ambitious technical objectives. The expanded technical objectives include testing of four shielding techniques at ~4 K (rather than just one) and evaluating a novel shielding technique with HTS tape that overcomes the limitation that stems from its relatively smaller width.

The following technical objectives should result in an outcome that should impact the design of the Interaction Region (IR) of the EIC and can have applications of the superconducting shielding technology beyond the EIC:

1. **Evaluate the novel shielding technique presented above at 77 K (in liquid nitrogen).**
2. **Prepare a superconducting magnet and 4 K superconducting shielding system for simulating an EIC type environment as practical as possible.**
3. **Perform four 4 K tests of four different shielding techniques (two based on HTS and two based on LTS) for a fringe field exterior to the superconducting coils.**
4. **Perform one 4 K shielding test inside the magnet for applicability of such shielding over an EIC quadrupole inside the field of another magnet.**
5. **Perform model shielding calculations with commercially available codes.**
6. **Perform evaluation of the shielding techniques for all EIC IR magnets in both the BNL and Jefferson Lab EIC proposals.**
7. **Develop a detailed engineering design for applying passive superconducting shielding technology in at least one EIC magnet where it is most beneficial.**
8. **Explore the potential of superconducting shielding technology beyond Phase II.**

4.2 Phase II Work Plan

To achieve the technical objectives mentioned in the previous section in a period of 24 months, the Phase II Work Plan will consist of several specific tasks as listed below. We also list the roles of the teams. The project benefits from the fact that PBL PI (Dr. Kahn) is local and has a guest appointment and an office at BNL.

Task 1: Evaluation of the novel shielding technique and extended shielding tests at ~77 K

The Phase II effort will start with the development and 77 K testing of the new concept proposed in section 1.3 (A Recent Invention for Shielding). Future work on this approach will depend on the initial successful demonstration of the proof-of-principle test. We will start out with a pair of tapes in a simpler configuration as shown in Fig. 8 (left). Then we will carry this out with more tapes before moving to a more complicated geometry to clear the beam tube as shown in Fig. 8 (right). If successful (which from first principle we believe it will be), we will procced with more detailed work. If not, we will revert to the tape geometry that was demonstrated to in Phase I. We will also perform extended shielding tests for several days at 77 K to demonstrate that a field-free region is maintained for a long term with the iron tube placed inside the superconducting shield. This task will be led by the BNL team with participation by the PBL team.

Task 2: Preparation of a superconducting magnet and 4 K superconducting shielding system

This is a major task. The overriding technical objective of Phase II is to demonstrate passive shielding technology at 4 K with a sufficiently long magnet creating conditions similar to those in EIC magnets. A ~95 mm aperture, ~470 mm long quadrupole magnet (see Fig. 14) is available to provide sufficient fringe field. The superconducting shielding should extend beyond the magnet ends. We will do that for one HTS shielding test and for one LTS shielding test. The assembly shown in Fig. 14 has both quadrupole and sextupole windings; however, only the quadrupole windings will be energized. The picture on the left shows the two windings before the insulating wrap; the picture on the right shows the completed magnet with wrap, which also serves as the outer support structure to contain the Lorentz forces.

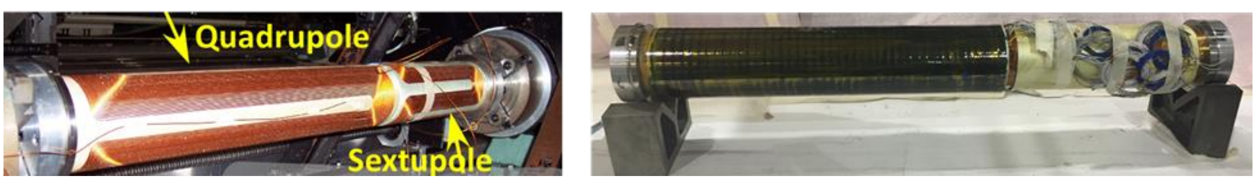


Fig. 14: Superconducting coil windings before (left) and after insulating and structural wrap (right) that will be used in providing the test field in Phase II.

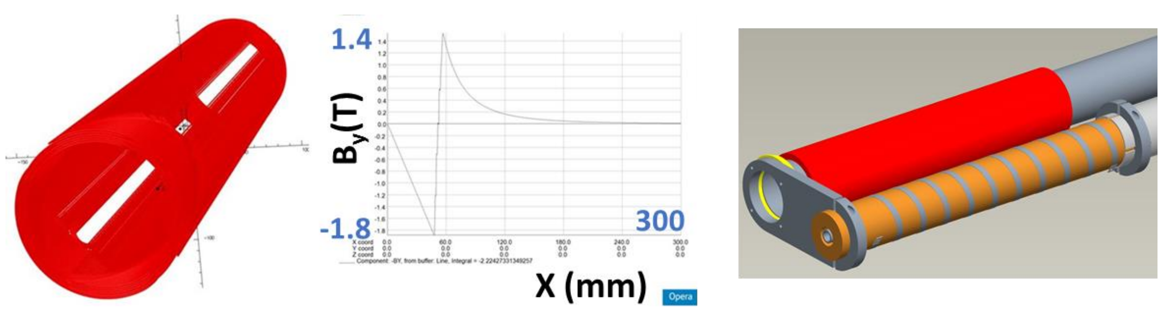


Fig. 15: 3-D model of the quadrupole magnet (left) chosen for the shielding experiment in Phase II, vertical component of the field at the midplane as a function of distance (center) and (right) a CAD model of the quadrupole, and a superconducting shield with heaters to quench it during the experiment.

The magnet does not have any yoke iron over the coil. A 3-D model of this magnet is shown in Fig. 15 (left); and the field profile at the midplane as a function of distance with the superconducting coils energized at 700 A is shown in Fig. 15 (center). Fig. 15 (right) shows the CAD model of the quadrupole, superconducting shield (with heaters shown over the superconducting shield to quench it during the experiment) and inside iron or low-retentivity material tube as mentioned in the proposal. Proper support structure will be designed and placed to deal with the Lorentz forces between the superconducting coils and the superconducting shield.

The CAD model in Fig. 16 (right) shows a separation of 180 mm between the magnet center and shielding tube system center. This separation can be changed from ~160 to 200 mm or more.

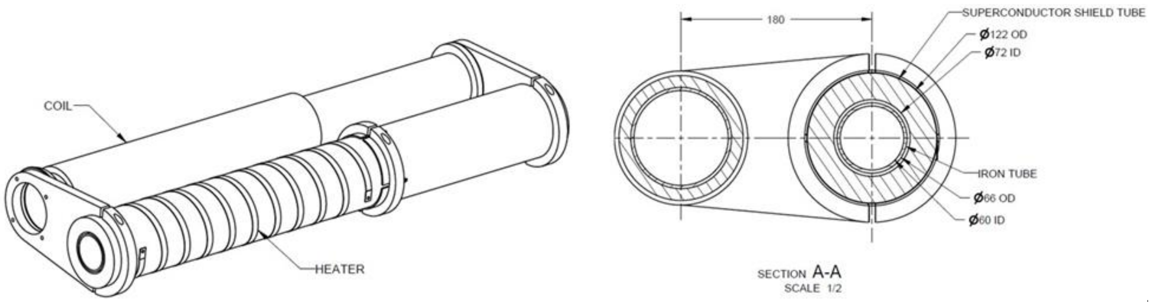


Fig. 16: Sketches and different views of the quadrupole, superconducting shield with heaters over the superconducting shield, and inside iron tube with the adapter plate. Heaters will quench the superconducting shield to remove the trap field from the previous run and inside iron tube will take care of the transient effects or decaying current of the superconducting shield. The separation between the quadrupole and the shield can be adjusted by using different adapter plates.

This task will be primarily carried out by the BNL team with a guidance from the PBL team.

Task 3: Procurement of material for the superconducting shielding test

Four different types of superconducting shielding material (two HTS and two LTS) will be procured for making 4 K shielding tube systems. In addition, material for what is called here as iron tube will also be purchased. Superconducting shielding to be procured are (a) HTS (Bi2223) tubes, (b) HTS (ReBCO) tapes, (c) LTS (NbTi) rods for making LTS tubes, and (d) LTS (NbTi) Sheets. The HTS shielding tube package for (a) will consist of several co-centric and interleaving HTS tubes. HTS tapes for (b) are readily available. NbTi rods will be purchased for (c) and holes will be drilled to make a set of tubes. NbTi sheets will use leftover material from a previous experiment. This task will be predominantly done by the PBL team with input from the BNL team.

Task 4: Perform 4 K shielding demonstration with HTS tubes

This task will be carried out after completion of task 2 and task 3. Since the thickness and length of a single HTS tube is not enough to provide adequate shielding, several co-centric tubes will be placed. They will be staggered to limit the impact of reduced shielding at the end of the tubes. The performance will be tested first at 77 K before testing at 4 K in the background field of the quadrupole. In all shielding tests, a set of Hall probes will be placed inside and outside the shielded region. The heating strip wrap (see Fig. 16) will be used to quench the shield to remove the trapped field. This task will be primarily carried out by BNL with participation by the PBL team.

Task 5: Perform 4 K shielding demonstration with HTS tapes

This task will be carried out after the completion of tasks 1-3. The experience from and the results of task 1 will determine whether to proceed with the novel configuration or with the one demonstrated in Phase I. This task will be primarily carried out by BNL with participation by the PBL team.

Task 6: Perform 4 K shielding demonstration with LTS sheets

A cylindrical shield of several wraps of NbTi/Nb/Cu multilayers will be wound over a tube. We plan to use the same material which was used earlier for the construction of the inflector magnet for the BNL g-2 experiment [8]. This material has been used recently at CERN in investigation for a septum magnet [12]. The sheets will be well secured. This task will be primarily carried out by BNL with participation by the PBL team.

Task 7: Perform 4 K shielding demonstration with LTS tubes

NbTi rods will be procured either from Luvata or from Bruker or both, depending on the availability. Tubes will be made from these rods and annealed as we did in Phase I. It is likely that we will use a set of tubes. This task will be primarily carried out by BNL with the active participation by the PBL team.

Task 8: Perform 4 K shielding demonstration inside the superconducting magnet

One of the techniques will also be tested inside the magnet to demonstrate the use of this shielding for the electron beam traversing through a field inside the magnet (as in the spectrometer dipole). Since the field to be shielded is inside the magnet, it will be significantly higher than in any of tests performed in the other four tasks, and the most efficient shielding technique will be used. This task will be primarily carried out by BNL with the active participation by the PBL team.

Task 9: Perform shielding model calculations

We will perform model shielding calculations for the above cases and in various magnet designs of EIC magnets using codes such as COMSOL [21], OPERA [22] and ROXIE [23]. Since these codes have limited capability of such modelling, we will try to develop methods to best fit the experimental data and use that information in modelling the EIC magnets. This task will be predominantly done by the PBL team with participation from the BNL team.

Task 10: Evaluate the prospects of superconducting shielding in all EIC IR magnets

We will examine the prospects of superconducting shielding in the interaction region magnets of all EIC magnets in both the BNL and Jefferson Lab proposals. It is possible that different techniques are more optimum in different magnets (we are developing four techniques) and some may not need superconducting shielding at all. This exercise will be performed for the designs of all IR magnets (dipoles and quadrupoles) for the latest designs of the IR magnets. This task will be primarily carried out by the PBL team with active participation by the BNL team.

Task 11: Develop a detailed engineering design for an EIC magnet

A detailed engineering design of integrating the complete superconducting shielding system for at least one EIC magnet will be performed. This task will be primarily performed by the BNL team with the magnetic and mechanical structure analysis performed by both the PBL and BNL teams.

Task 12: Explore the potential of superconducting shielding technology beyond Phase II

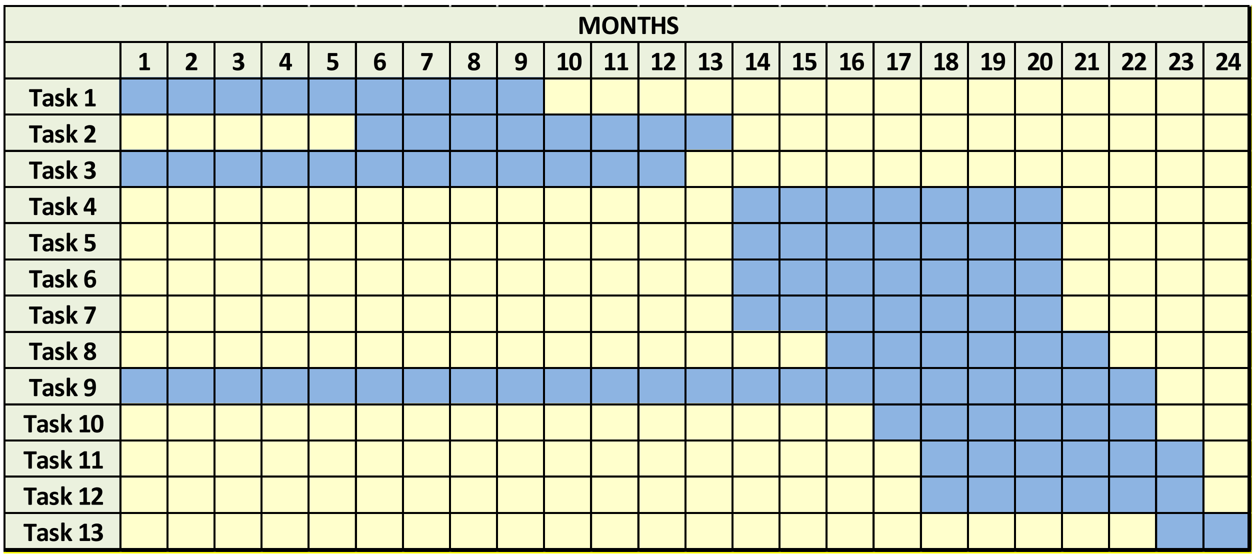
Both the PBL and BNL teams will participate in identifying the key components of this technology that could be useful for a Phase III proposal. The engineering development of the design and integration with the magnet application will not only be useful for a potential Phase III in the EIC but also for transferring this technology to other future applications. A list of potential applications of shielding has already been mentioned earlier in this proposal. A complete development of this can become a source of revenue for PBL. In addition, the invention discussed in this Phase II proposal is promising and if successfully demonstrated, it could also be a good source of revenue for PBL.

Task 13: Write the Phase II Final Report

Both the PBL and BNL teams will participate in writing the Phase II final report.

5.0 Performance Schedule

The project duration will be 104 weeks (24 months). The following is the schedule of Tasks corresponding to the Objectives listed in the work plan:



6.0 Related High Field Magnet R&D Done by the PBL/BNL Team

Over the years, the PBL/BNL team has been involved in various high field magnet SBIR/STTR R&D projects for high energy physics. The R&D proposed herein directly benefits from the technology generated and the experience gained in those earlier SBIR/STTRs. This experience also helps in developing high field magnet technology for wider use. This point has been well recognized by professionals in the field as well as in the comments of various SBIR/STTR reviewers on previous submissions. This section will now highlight some of the important contributions made by the PBL/BNL team.

The PBL/BNL team has established a strong R&D position [24-26]in HTS superconducting magnet technology with several outstanding accomplishments. One HTS solenoid designed and built through a PBL/BNL SBIR produced a field of ~16 T (a record field at that time), exceeding its nominal field by more than 30% [25]. Another major achievement of this team is the recent demonstration of a significant HTS/LTS dipole magnet [26], whose field remains a record at this time for a hybrid HTS/LTS dipole.

7.0 Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL has been a major force in the development of accelerator magnets for many decades. The Superconducting Magnet Division has extensive facilities for winding demonstration coils and for testing these coils. It also has access to simulation and engineering software tools that will aid in the design of coils and magnets. The design software available includes ROXIE, OPERA2d, OPERA3d and in-house software for magnetic design, ANSYS for mechanical design, and Pro/ENGINEER and AutoCAD for engineering design.

The superconducting magnet division has a staff of about 30, including scientists, engineers, technicians and administrative staff. Construction and testing of the pole coils will be carried out in a 55,000 ft^2 multipurpose R&D complex at the SMD. A prominent asset of the complex is an active cryogenic test facility, complete with high-current, high-resolution and high-stability power supplies.

The facility allows testing of a variety of superconductors, coils and magnets from ~2 K to ~80 K. Among the elements of the dedicated equipment in the facility are several computer-controlled, automated coil-winding machines, automated-cycle curing and soldering stations, centralized exhaust-vent systems, and hydraulic presses. The building has several large-capacity (>15 ton) overhead cranes. Within the building complex are two machine shops with capacity to manufacture the majority of components needed for the R&D task. BNL also has a central machine shop and a procurement group to handle orders with private companies.

8.0 Principal Investigator and Other Key Personnel

Dr. Ramesh Gupta will be Principle Investigator (PI) for this grant and will supervise the work performed at BNL. Dr. Gupta currently leads the HTS magnet R&D group in the Superconducting Magnet Division (SMD) at BNL. Dr. Gupta has more than three decades of experience in the design of superconducting accelerator magnets for various applications. His current interests include developing and demonstrating HTS magnet designs and technology for particle accelerators and other applications. Over the last decade he has developed several new innovative designs such as the common-coil dipole, the modular design and modular program for high gradient quadrupoles, the HTS quadrupole for RIA and FRIB, and a low-cost medium-field HTS dipole. He has developed a cost-effective, rapid-turnaround and systematic magnet R&D approach. Dr. Gupta is the PI or sub-grant PI of several grants, including a 25 T HTS solenoid for Axion search experiment and a high field HTS solenoid for a Superconducting Magnetic Energy Storage system (SMES). Dr. Gupta has also worked on conventional Low Temperature Superconductor cosine-theta magnet designs for RHIC and the SSC. Dr. Gupta has taught several courses on superconducting magnets at U.S. Particle Accelerator Schools.

Dr. William Sampson, who will lead the experimental demonstration at BNL, has over five decades of experience in superconducting magnets and has received the prestigious IEEE Council on Superconductivity award for "Continuing and Significant Contributions in the Field of Applied Superconductivity". Michael Anerella, head of the mechanical engineering group at the Superconducting Magnet Division and Piyush Joshi, head of the electrical engineering group at the Superconducting Magnet Division will lead the engineering work at BNL.

Dr. Stephan Kahn will be the Principle Investigator principle investigator for PBL. Dr. Kahn has 25 years of experience with superconducting accelerator magnets. He has worked as a PI on four previous SBIR grants. He has worked at the Advanced Accelerator Group at BNL on neutrino factory and muon collider R&D. His previous experience at Brookhaven has been broad, including work on high energy physics experiments (neutrino bubble chamber experiments and the D0 experiment) and superconducting accelerator magnets (for ISABELLE, RHIC, the SSC and the APT). His design work on superconducting magnets included 2D and 3D finite-element field calculations using the Opera2d and Tosca electro-magnetic design programs along with structural finite-element calculations with ANSYS.

Dr. Ronald Scanlan has had 35 years of experience in the field of superconducting magnets and materials at General Electric R&D Laboratory, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory. From 1995 to 1999, he was Program Head for Superconducting Magnet Development at LBNL. In 1991, he shared the IEEE Particle Accelerator Conference Award with Dr. David Larbalestier for "the development of NbTi superconducting material for high current density application in high field superconducting magnets", and in 2011 he received the IEEE Council on Superconductivity award for "Continuing and Significant Contributions in the Field of Applied Superconductivity".

Robert J. Weggel will be the PBL magnet designer for the Phase II project. He has been PI for PBL on several recent SBIR/STTR projects (see related research section). Mr. Weggel has had over 50 years of experience as a magnet engineer and designer at the Francis Bitter National Magnet Laboratory at MIT and Brookhaven National Laboratory and as a consultant in magnet design. In the course of his career he has authored over 100 peer-reviewed articles concerning resistive and superconducting magnets as well as hybrid high-field versions.

Dr. Erich Willen, a PBL employee, will contribute his expertise in the areas of magnet design and magnetic field quality. Previously, he served as PI on a related SBIR entitled "Magnet Coil Designs Using YBCO High Temperature Superconductor." Dr. Willen became the head of the Magnet Division at BNL in 1984 and led the development of the SSC and RHIC superconducting magnets.

9.0 Managerial Controls for a Successful Project

To ensure a successful project, PBL will hold regular technical meetings and compare progress made against the performance schedule above. The technical staff will meet to ensure that important milestones are being met in a timely way. PBL PI Dr. Kahn has an office at BNL campus. PBL senior management will also travel to supervise and participate in various activities at BNL. During each meeting, the team will identify any problems as well as ensure ways to solve them. PBL has extensive experience with the DOE SBIR program, having completed several SBIR research efforts over the years. As such, PBL personnel are well versed in the reporting and administrative needs that will be an important part of the project proposed herein.

10.0 Consultants and Subcontractors (Including Research Institution)

This grant application involves a formal collaboration between Particle Beam Lasers, Inc. and a research institution, Brookhaven National Laboratory. As can be found in more detail in the attachments found in block 12, what follows is the requested identifying information for this collaboration:

Name and address of the institution:
Brookhaven National Laboratory
Building 460
P.O. Box 5000
Upton, NY 11973-5000

Name, phone number, and email address of the certifying official from the RI:
Erick Hunt
Manager, Research Partnership
(631) 344-2103
ehunt@bnl.gov

Total dollar amount of the subcontract: $550,000

11.0 Letter of Support from Dr. Ferdinand Willeke, Director eRHIC Design and R&D at BNL

eRHIC Design and R&D Directorate

BROOKHAVEN NATIONAL LABORATORY

Building 911B
P.O. Box 5000
Upton, NY 11973-5000
Phone 631 344-7159
Fax 631 344-2646
Alyssa Petrone

managed by Brookhaven Science Associates for the U.S. Department of Energy

Memo

Date: November 30, 2017

To: To Whom It May Concern

From: F. Willeke

Topic: Letter of Support for SBIR Proposal on passive superconducting magnetic shielding

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Dear reviewer,

This letter is to express the relevance for developing passive magnetic shielding using superconducting materials for Electron Ion Colliders. I am a staff scientist at Brookhaven National Laboratory and I am assuming responsibility for eRHIC design and R&D.

A common problem of any particle collider for beams with non-equal species of particles which have different magnetic rigidity is that the fields of focusing magnets for one beam which need to be placed as close as possible to the collision point, might have a detrimental impact on the other beam which is in close proximity.

This applies in particular to the designs of Electron Ion Colliders in which hadrons and electrons of very different beam energies will be colliding. Stray-fields from the hadron low beta quadrupoles may not only impact the electron dynamic aperture but might cause the electrons to generate unwanted synchrotron radiation in the detector region.

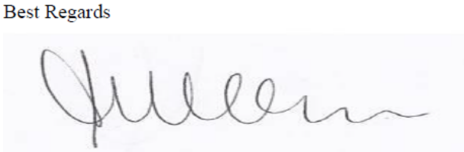
One idea of mitigating this problem is to shield the electron beam from residual field from the strong, superconducting hadron low-beta quadrupoles by a passive superconducting shielding. This idea is not new and the method has been considered on several occasions (for example: shielding the HERA electron beam from the dipole field of the HERA B detector, Stefan Wipf, 1996, IEEE Trans.Magnetics 32 (1996) 2663-2666v). But the lack of control of the compensation, considerations of magnetic stability, and the complication of low temperature cryostats in an environment with confined space were the reason for choosing more conventional solutions (e.g. active shielding).

However, in view of the development of thin film high temperature superconductors in recent years, one can see the potential that HTS based passive magnetic shielding become a superior solution to such problems. The relatively high temperature of the cryogenic coolant and corresponding simplifications of the cryostat and generation of coolants, a large critical current density and the fact that the critical current density in HTS materials is fairly independent of the magnetic field it is exposed to are reasons for the attractiveness of this approach. The fact that the geometry of the required shielding is usually quite simple support the choice of thin film material.

Thus in summary, the choice of HTS thin film material for passive magnetic shielding of magnetic fields in interaction region magnets of an EIC appears to be an interesting option which has good potential to becoming the winning scheme in comparison with active shielding. One advantage is that the technology would be applied in an already cold environment into which the passive cooling could be integrated. So there is probably no or little extra expense for cryostating and for providing cryogenic coolants.

This is the reason why I believe that this intended SBIR could make a relevant and novel contribution to EIC magnet design.

Best Regards



Ferdinand Willeke

Director, eRHIC Design and R&D

12.0 Letter of Support from Mr. J.L. Scarcello, CFO & Business Operation Manager at Jefferson Lab

Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

November 30, 2017

Dr. James J. Kolonko
Particle Beam Lasers. Inc.
18925 Dearborn Street
Northridge, CA 91324-2807

Subject: Support Letter for Particle Beam Lasers. Inc. SBIR Phase I proposal titled:

"Field Compensation in Electron-Ion Collider Magnets with Passive Superconducting Shield "

Dear Dr. Kolonko,

Thomas Jefferson National Accelerator Facility (Jefferson Lab) is pleased to support your Phase I SBIR proposal to the Department of Energy entitled: "*Field Compensation in Electron-Ion Collider Magnets with Passive Superconducting Shield* "

In the proposed Electron-Ion Collider, the electron beam must travel very close to the proton or ion-beam in the interaction regions (IR). Whereas the ion or proton beams need high field magnets, beams of lighter electrons must be magnetically shielded from the fringe fields of the ion beamline magnets and the limited space between the electron beam and the ion beam poses a significant design challenge. This proposal is for the passive superconducting shielding. Shielding made of Low Temperature Superconductor (LTS) sheets and High Temperature Superconductor (HTS) tapes will be considered. In addition, a thin sheet of high permeability magnetic material such as mu-metal or Cryoperm will also be used. The design studies will be performed for providing and integrating this shielding with the magnets. In addition, proof-of-principle shielding made with HTS tape will be demonstrated at 77 K in liquid nitrogen. Jeffeson Lab is interested in this since the JLEIC interaction region magnet will require similar shielding for the IR magnets and therefore this shield design and development could benefit the magnet shielding design for the JLEIC IR magnet.

We look forward to working with Particle Beam Lasers, Inc. when your SBIR is awarded. By our contract with the DOE, a Cooperative Research and Development Agreement (CRADA) or a Strategic Partnership Project (SPP) agreement would be the appropriate mechanism under which the work can proceed. Jefferson Lab's participation in the proposed project is subject to review and approval by JSA/Jefferson Lab management and the Department of Energy.[1]

Sincerely,

J.L. Scarcello

Joseph L. Scarcello
Chief Financial Officer
& Business Operations
Manager

cc: R. Rajput-Ghoshal, M. Spata

[1]All work performed by Jefferson Lab is subject to the terms and conditions of Contract No. DE-AC05-06OR23177 between DOE and Jefferson Science Associates and is subject to the approval of the Department of Energy. A fully executed CRADA or SPP Agreement constitutes authorization for Jefferson Lab to work on the effort so specified.

12000 Jefferson Avenue, Newport News, VA 23606 • phone 757.269.7100 • fax 757.269.7363 • www.jlab.org

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