8. Project Narrative

Cover Page

Company Name & Address:	Particle Beam Lasers, Inc. 18925 Dearborn Street Northridge, CA 91324-2807
Principal Investigator:	Dr. Shailendra Chouhan
Project Title:	Field Compensation in Electron-Ion Collider Magnets with Passive Superconducting Shield
Topic No 29:	Nuclear Physics Accelerator Technology
Subtopic (h):	Magnet Development for Proposed Future Electron-Ion Colliders (EIC)

Proprietary data legend: This narrative contains no proprietary data.

Identification and Significance of the Problem or Opportunity

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 external field generated by high field quadrupole and dipole magnets in the Interaction Region (IR). Currently two set 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 (JLAB) [4]. Fig. 1 shows the current IR region for the BNL design and Fig. 2 for the JLAB design [5]. To achieve high luminosity, both IR designs need a high field quadrupole (≥ 8 T pole tip field) for the heavier proton beams and an almost field free path (desired magnetic field within a few mT) for the electron beams which must travel very close to the quadrupole and dipole of proton beams.

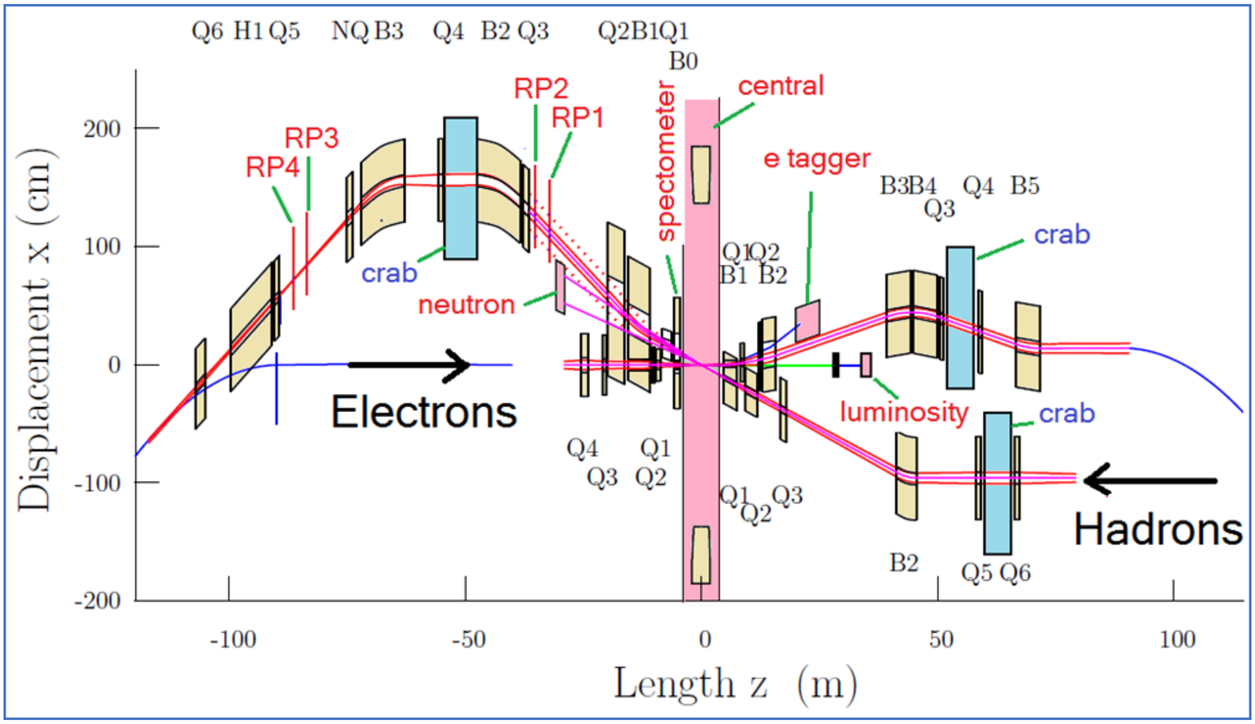

Fig. 1: Proposed layout of the Interaction Region for the BNL design of the EIC (courtesy R. Palmer).

The present design approach [6] is based on the active shielding (together with a thin magnetic shield) to obtain a field free region for the passage of the electron beam. The approach is shown in the Fig. 3 for the first high gradient quadrupole (Q1) for the proton or ion beam at the interaction point. Fig. 3 shows the main Nb_3Sn coils creating the high field gradient for the proton or ion beams and outer NbTi coils having an opposite polarity to the main coils to provide active cancellation of the field in a region outside it. The current in the active coil is proportional but in the opposite direction to that in the main coil. Therefore, the active coil reduces the field of the main coil which must now operate at even higher current to produce the required field gradient for the proton or ion beams. The challenges become greater when the desired gradient becomes higher and the space between the electron and proton beams becomes smaller.

Enough space must also be left for the support structure for the high gradient quadrupoles and for satisfying various spatial requirements around the beam pipe of the electron beams.

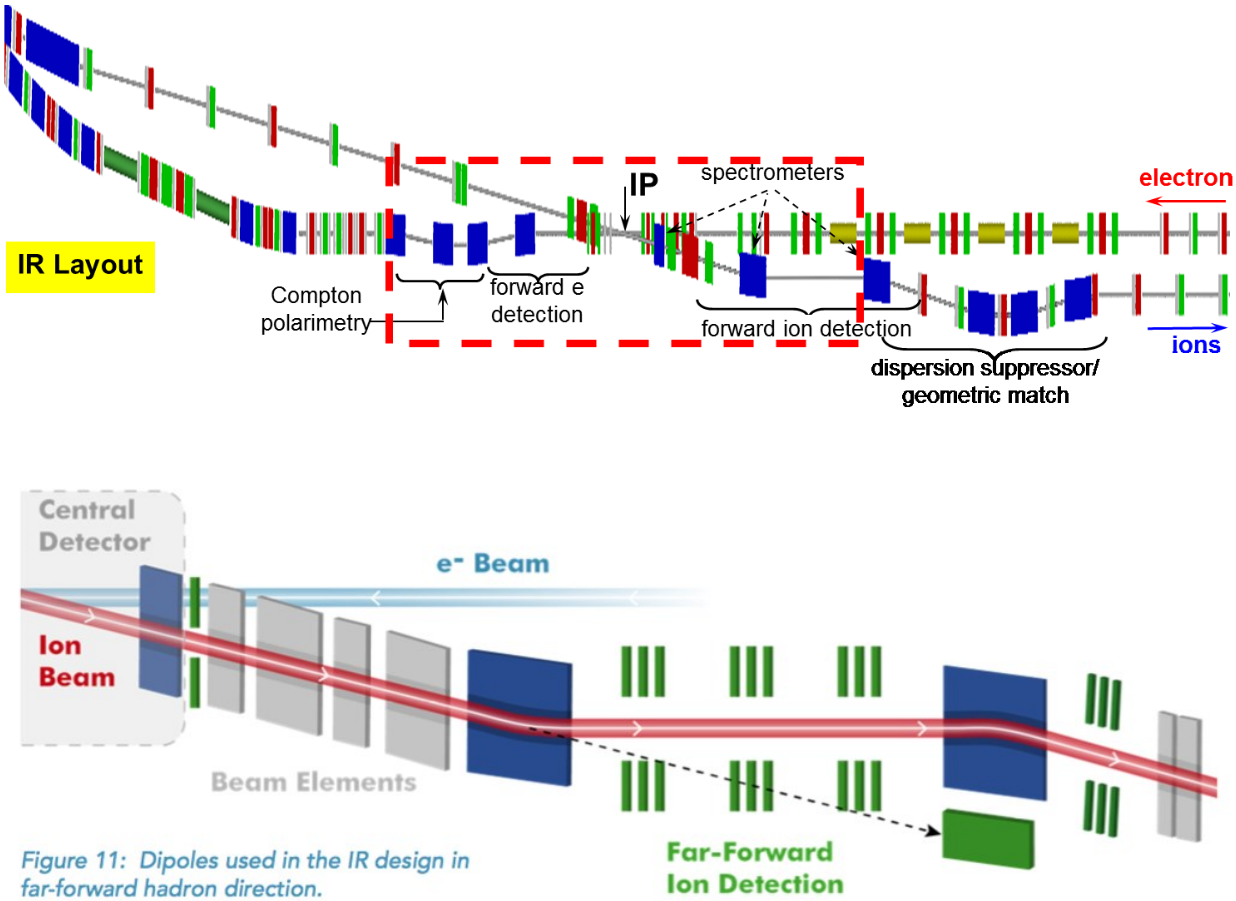

Fig. 2: Proposed layout of the Interaction Region for the JLAB design of the EIC (see top). The sketch at the bottom shows more detail of the critical region where the shielding is needed, showing the magnet elements and the path of the ion and electron beams on one side of the IR.

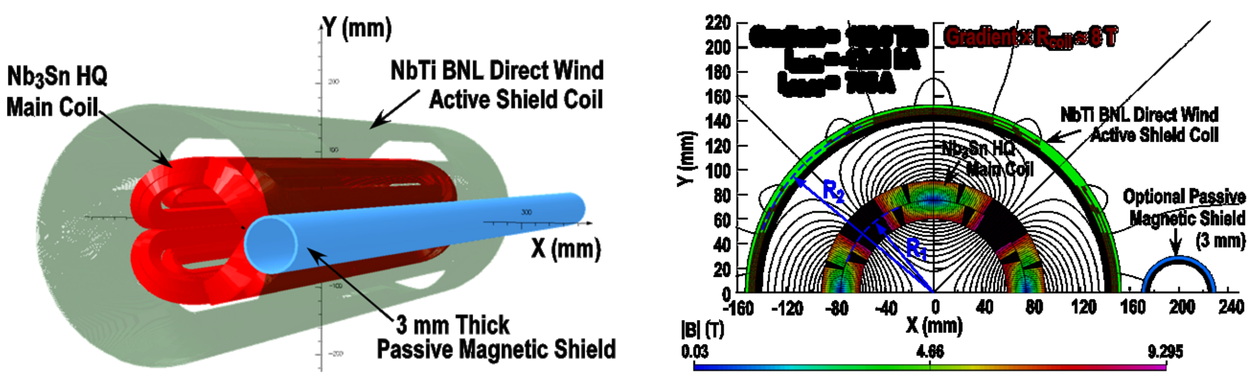

Fig. 3: 3-d and 2-d models of the current approach where the external field of the main high field Nb3Sn quadrupole coils for the proton or ion beams is cancelled by the outer NbTi coils (providing active shielding) to obtain a near field-free region for passage of the electron beam. A thin passive magnetic shielding is also shown.

In this proposal we propose an alternate technique for the high gradient quadrupoles where the field free region for the electron beam is created by passive superconducting shielding which naturally excludes the field lines due to the "Meissner effect". This technique has been applied earlier in various applications such as a g-2 experiment [7], a cloak experiment [8], etc., but never to shield the field of such a high gradient quadrupole in such a limited space. The method was considered [9] for shielding HERA electron beam from the dipole field of HERA B detector but was never applied. The benefit of demonstrating this technique will be significant as among other it will lower the current in the required high field quadrupole and possibly increase the luminosity of the EIC. Such a passive superconducting shield will not only be useful for the quadrupole, but also can be used in the dipole magnet near the interaction point.

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,*" as recently as in February 2017 [10]. 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."

This proposal is based on 'Meissner shield' and mu metal. 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 superconducting shield will be used together with the iron yoke and "mu metal" or "cryoperm". We will explore superconducting shields made of conventional Low Temperature Superconductor (LTS) in sheet form. LTS sputtered niobium film, and High Temperature Superconductor (HTS) in tape form. The basic Proof-of-Principle HTS shielding can be tested at 77 K in the limited budget of Phase I.

Technical Approach

The current design of the Q1PF quadrupole with the main Nb_3Sn coils and NbTi active shield coils is shown in Fig. 4 [6].

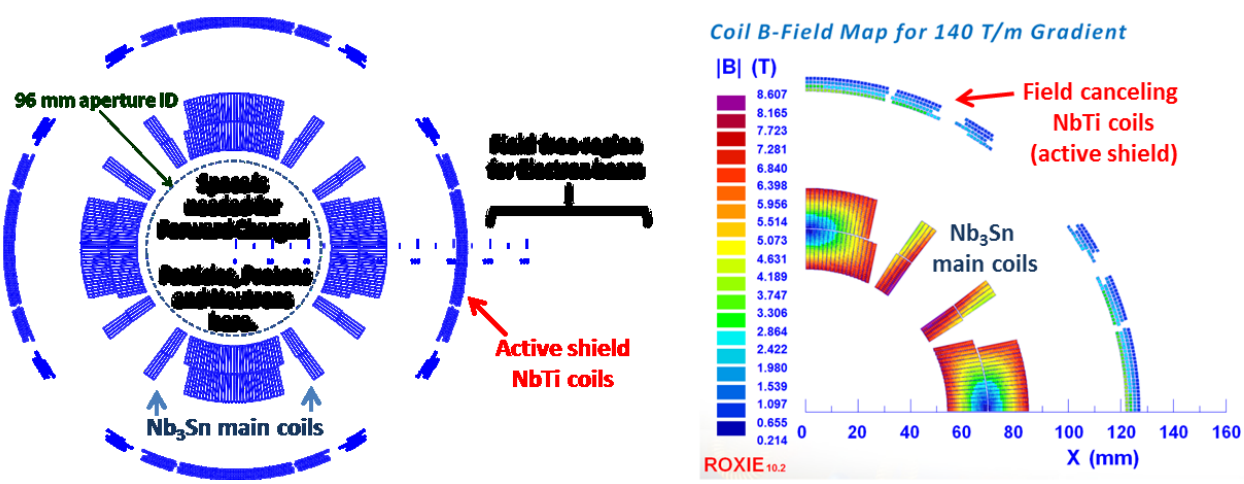

Fig. 4: Current design of Q1PF quadrupole for the BNL design of the EIC (eRHIC) showing the main Nb_3Sn coils and the field-cancelling NbTi coils. One can see the full cross-section on the left and a quadrant on the right.

The field-free region for the electron beam is outside the field-cancelling NbTi coils. The gradient for the proton or ion beams in the present design is 140 T/m for a 96 mm aperture. Nb_3Sn technology for the main coil is chosen to provide sufficient margin as needed in the IR magnets. Although the Nb_3Sn technology can in principle provide an even higher field gradient for better optics with higher luminosity, the magnet design is currently limited by the space available for the support structure between the Nb_3Sn coils and the field cancelling NbTi coils.

We propose a passive superconducting shield over the electron beam pipe rather than the active superconducting shield coil over the high field quadrupole magnets to obtain the field free region for the passage of the electron beams. *Shielding currents created in the passive superconducting shield will compensate the fringe field created by the high field magnets in the region of interest, if properly designed, developed and implemented.*

A preliminary magnetic design for the same Q1PF quadrupole with the proposed passive superconducting shield is shown in Fig 5. The design uses the same Nb_3Sn coils; however, the NbTi field-cancelling coils are replaced by an iron yoke having the same inner radius as the NbTi coils. The iron yoke has a cutout for the electron beams. In reality the electron beams will be running at an angle along the beam as shown in Fig. 1. 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 detail design and temperature of the beam pipe) will also be included as shown in Fig. 5. This shielding is expected to bring the small residual field or field due to decaying screening currents to a low level at the electron beams which have a relatively high energy in the proposed Electron Ion Collider. This will be examined in more detail in the early part of Phase I.

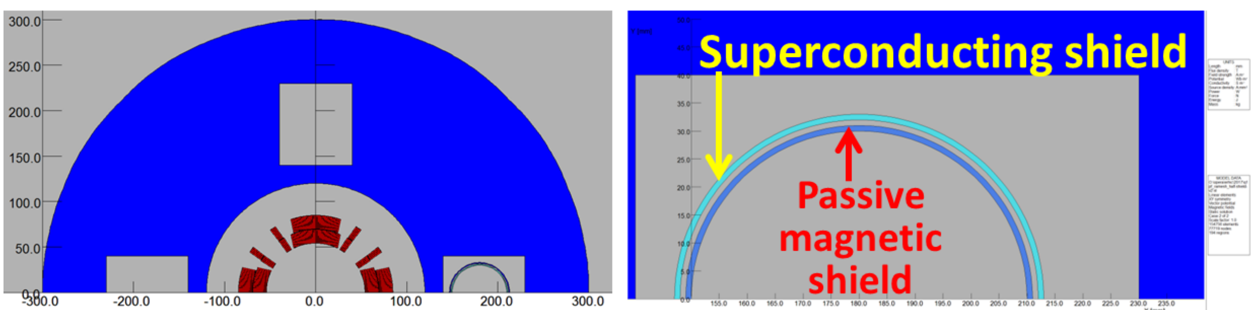

Fig. 5: Proposed magnetic design with iron yoke and superconducting shield. Upper half of the magnet is shown on the left and details of the cutout including passive superconducting shield and passive magnetic shield is shown on the right. Additional passive magnetic shielding will ensure that the residual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

Fig. 6 (left) shows the field contour and field lines at ~168 T/m. The field inside the cutout region with the simulative passive superconducting shield together with a passive 1 mm thick magnetic shield is shown on Fig. 6 (right). The computed maximum field in the upper-left corner is about 0.72 T and in the shielding region is about half of this. This can be easily shielded by a modest thickness of superconducting shield made of either LTS sheet or HTS tape as per the initial preliminary magnetic simulations. The magnitude of the field on the horizontal axis is plotted in Fig. 7. The field becomes essentially zero inside the shielded region (see Fig. 7 right) where the electron beam traverses. More optimization and better modelling (including 3-d modelling) will be carried out as part of the Phase I project.

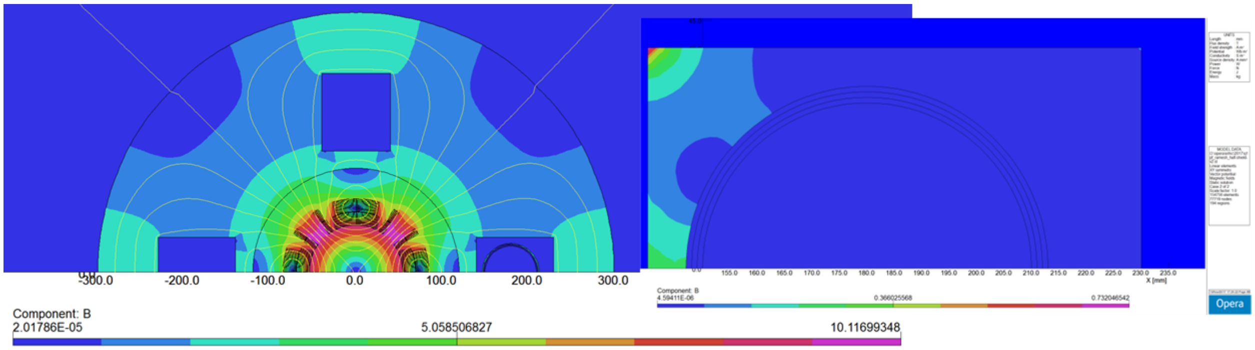

Fig. 6: Field contour and field lines (left) at ~168 T/m in the proposed design of quadrupole Q1PF with iron yoke. Field contour inside the cutout region with passive shields is shown in more detail on right.

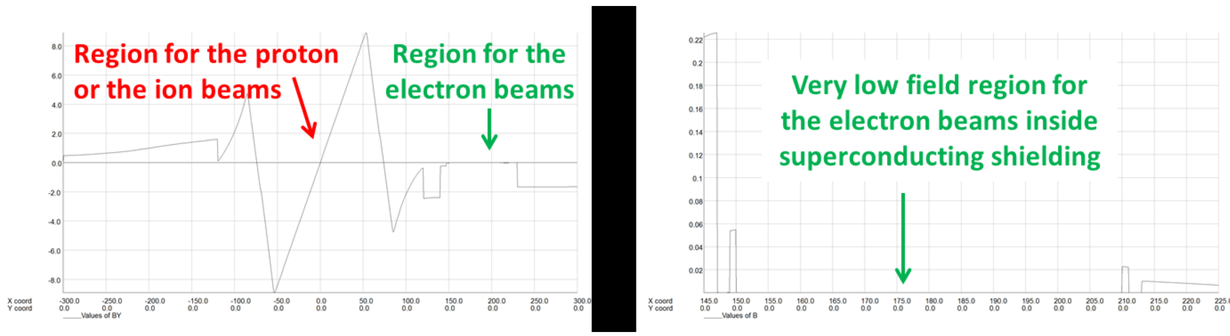

Fig. 7: Magnitude of the field on the horizontal axis (left) at ~168 T/m in the proposed design of quadrupole Q1PF with iron yoke. Field on the horizontal axis of the cutout region is shown on right.

Anticipated Public Benefits

The passive magnetic 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 proposed Electron Ion Collider. 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 shielding method is valuable in many diverse areas of significant research, such as g-2 experiment [7] and magnetic cloak experiment [8]. Development of such shielding technology may also play a role in major commercial application 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 on 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 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.

Technical Objectives

The primary technical objective of this proposal is to develop the design and technology of passive superconducting shielding to a level that it can be used in EIC magnets to create a field -free region within a radius of 3 cm or more. This is an alternative approach to the active superconducting shield which requires extra superconducting coils, extra power supplies, reduces the field gradient generated by the main coils, and limits the capability of Nb_3Sn technology in designing the high gradient IR quadrupoles needed for higher luminosity. The work performed in Phase I will show that passive shielding is a viable technology for providing the required shielding to create a near field-free region for the electron beams in the presence of the strong field magnets that are needed for the proton or ion beams. The specific technical objectives of Phase I of this proposal are (a) develop a specific design for the most critical quadrupole that is closest to the interaction point (Q1PF for BNL), (b) examine all options for passive superconducting shielding (LTS and HTS) along with the passive magnetic shield for all EIC interaction region magnets, where needed, (c) demonstrate HTS shielding at 77 K within the limited budget of Phase I, (d) develop the design and technology of this technique to a level that it can be used to create a field-free region of a radius of 3 cm or more, and (e) make detailed plans for the Phase II proposal where the passive superconducting shielding can be demonstrated at 4 K and the technology developed to a level that it can be used in EIC magnets.

Work Plan

The Phase I Work Plan will consist of the following specific tasks:

Task 1: Perform a detailed magnetic design of the iron yoke with a cutout for the electron beam with superconducting shielding

We will start Phase I with a more detailed magnetic design of the iron yoke with an adequate size cutout in the quadrupole Q1PF. The most critical quadrupole in the EIC interaction region design is the one closest to the interaction point (Q1PF for BNL). We will optimize the magnetic design of the Q1PF quadrupole which will involve providing adequate space for the electron beam with shielding while minimizing the saturation-induced harmonics. It should be pointed out that non-allowed harmonics may be generated at higher fields due to missing 4-fold symmetry in the iron yoke (see Fig. 5). The cutout is made in one quadrant only (not in all four) to minimize the size of the iron yoke. This task will be carried out jointly by the PBL and BNL teams.

Task 2: Examine HTS and LTS for superconducting shielding

We will evaluate the prospects for the superconducting shield made of both NbTi and HTS. This will include availability of the material (for example NbTi sheet) that will satisfy the requirements. The superconductor should be able to carry enough shielding current to fully compensate for the field of the high field quadrupole coils and iron yoke. This task will be carried out jointly by the PBL and BNL teams.

Task 3: Examine various geometries for superconducting shielding

HTS tape is available only in certain widths. Since HTS may not be available in sufficient width to cover the entire circumference of the whole tube (or at least ¼ of the circumference), we will examine the prospects of several geometries including helically wound tape in addition to the tape being wound parallel to the beam tube. We will also examine the bulk material and survey additional possibilities. This task will be carried out jointly by the PBL and BNL teams.

Task 4: Procure HTS tapes

HTS tape will be procured. The available widths are 12 mm and also 46 mm (on special order from American Superconductor Corporation). Bulk HTS tubes, if found attractive and available, will also be purchased. (Note that only small quantities are needed for the Phase I work.)

Task 5: Experimentally demonstrate the superconducting shielding with HTS tape at 77 K

A key part of the Phase I proposal is the experimental demonstration of the applicability of HTS shielding at 77 K in liquid nitrogen in the presence of the magnetic field. An existing magnet will be used to carry out this experiment at the maximum magnetic field expected in the cutout region of the iron yoke of the first quadrupole (Q1PF in BNL design). This will be carried out over a tube of 3 cm radius (as mentioned in the FOA or funding opportunity announcement) or more. This task will be primarily carried out by BNL with an active participation of the PBL team.

Task 6: Perform a preliminary engineering design of installation of superconducting shielding

We will also perform a preliminary engineering design of how this shielding will be integrated into the design of the Q1PF magnet. All aspects of placing this shielding inside the actual magnet will be examined including the mechanical placement and satisfying the cryogenic requirements. This task will be primarily carried out by BNL with active participation of the PBL team.

Task 7: Evaluate the prospects of superconducting shielding in all EIC magnets

In addition to the critical first IR quadrupole, we will examine the prospects of superconducting shielding in the interaction region magnets of the Electron Ion Collider (EIC), where needed. This preliminary exercise will be performed for the current designs of all IR magnets (dipoles and quadrupoles) for both the BNL and JLAB proposals for the EIC. Of particular additional interest is the forward spectrometer magnet that requires a shield around the electrons that pass through the active dipole field [11]. This task will be carried out jointly by the PBL and BNL teams.

Task 8: Write the project final report and prepare the Phase II proposal

Both the PBL and BNL teams will participate in identifying the key components for a Phase II proposal and for writing the Phase I final report. The key component of the Phase II proposal will include making the detailed plans for the work to be carried out in Phase II where the passive superconducting shielding will be demonstrated at 4 K.

Performance Schedule

Task 1: Perform the detailed magnetic design of an iron yoke with cutout for the electron beam with superconducting shielding – Weeks 1-16.
Task 2: Examine HTS and LTS options for superconducting shielding – Weeks 1-24.
Task 3: Examine various geometries for superconducting shielding – Weeks 1-24.
Task 4: Procure HTS tape – Weeks 1-20.

Task 5: Experimentally demonstrate the superconducting shielding with HTS tape at 77 K – Weeks 21-32.
Task 6: Perform a preliminary engineering design of installation of superconducting shielding – Weeks 26-34.
Task 7: Evaluate the prospects of superconducting shielding in all EIC magnets – Weeks 11-34.
Task 8: Write project final report and prepare the Phase II proposal – Weeks 35-39.

Related Research and R&D

Past Experience with Superconducting Shielding

A simple demonstration at BNL for the general public is shown in Fig. 8. This simple apparatus demonstrates the disappearance of the magnetic shielding effect as the liquid nitrogen is allowed to evaporate and the HTS tape (46 mm wide from American Superconductor Corporation) warms up.

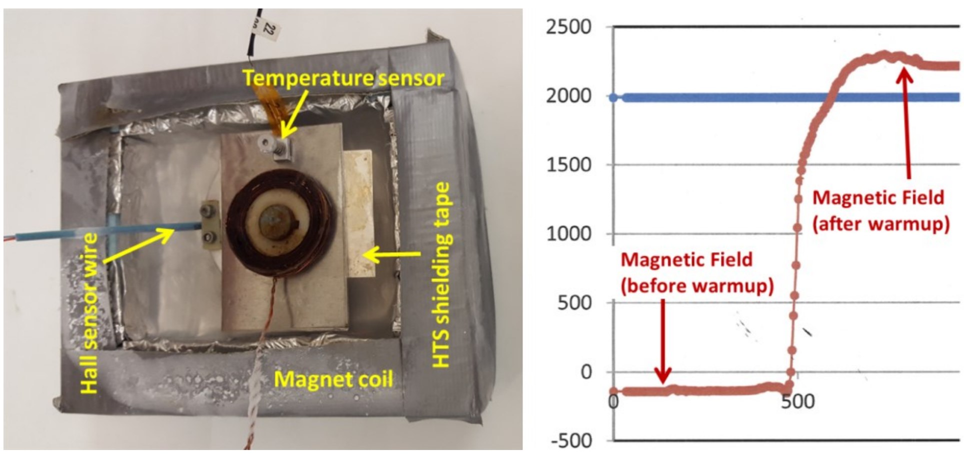

Fig. 8: A simple demonstration of the passive superconducting shielding against the magnetic field provided by the HTS tape. Picture on the left shows a simple apparatus; On the right a zero magnetic field is shown (plotted in arbitrary units, ignore the small offset) when the tape was cold; appearance of the magnetic field (disappearance of shielding) appears as the nitrogen evaporates and the HTS tape warms up and reverts to the normal state.

Superconducting shielding has been used earlier in several scientific experiments. For example, a successful use of low temperature shields was demonstrated at BNL in the g-2 experiment [7]. Also, a high temperature shield was examined by the Stony Brook University (SBU) group in consultation with BNL for a magnetic cloak proposal for the Electron Ion Collider [8]. Whereas the g-2 experiment used a special superconducting sheet made of NbTi, the initial magnetic cloak proposal tests were carried out using HTS tape in liquid nitrogen at ~77 K. Fig. 9 shows two version of the experiment. The picture on the right shows two wider 46 mm tapes wrapped around the tube, [8] one above the midplane and another below. The picture on the right side shows a helically wound tape using 12 mm wide HTS tape [12]. The first option is more efficient but it requires wider HTS tape each covering about 1/4 of the tube circumference. The widest tape available from American Superconductor (without copper) on special order is 46 mm. This width is about 10% less than desired but may still do the job when several are placed appropriately. Bulk HTS superconducting tube, though attractive in principle, does not seem to provide sufficient shielding for an acceptable thickness. However, we will re-examine this option taking into account the latest developments.

Fig. 9: HTS tape wound around the tube to demonstrate passive superconducting shielding at 77 K. Picture on the left shows two 46 mm wide HTS tapes placed parallel to the tube, and picture on the right shows a 12 mm wide tape wound helically on the tube.

Experience of PBL/BNL Team with the HTS technology

The PBL/BNL team has established a strong R&D position in HTS superconducting magnet technology [13, 14]. One of the outstanding accomplishments of this effort is the achievement of world record fields in HTS solenoids. 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% as the proposal was for 12 T [13]. Another major achievement of this team is the recent demonstration of a significant HTS/LTS dipole magnet [14] with a field which is still a record at this time for a hybrid HTS/LTS dipole.

Experience with Shielding at FRIB

Low temperature Type-II superconductor alone or a combination of low temperature superconducting material (such as niobium) and high relative magnetic permeability material (such as iron/Mu-Metal/Cryoperm/Permalloy/Co-Netic) have been used earlier in several scientific experiments. Low temperature Type-II superconductor such as niobium cooled below critical temperature, Tc, expels magnetic flux from the material and acts as a diamagnetic material, whereas as a high permeability material due to low reluctance helps to contain the magnetic flux within the material. For ferromagnetic shields, the geometry of the shield, location and material choice and thickness play significant roles. For example, a successful use of high relative magnetic permeability ferromagnetic material shields along with superconducting niobium cavities was demonstrated in ReA-3 superconducting cryomodule [15]. The same shielding concept is used for the fabrication of superconducting cryomodules under construction for the accelerator Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Principal Investigator and Other Key Personnel

Shailendra Chouhan will serve as Principal Investigator for the proposed project. In addition, Dr. R. Scanlan, Mr. R. Weggel, Dr. E. Willen, Dr. D. Larson and Mr. J. Kolonko will play key roles for Particle Beam Lasers, Inc. (PBL). Ramesh Gupta will be sub-grant PI for Brookhaven National Laboratory (BNL). Other key players at BNL include Dr. B. Parker, Dr. W. Sampson and Mr. K. Capobianco-Hogan.

Dr. Chouhan has 15 years of experience in the field of superconducting magnets. Dr. Chouhan is a physics graduate of Devi Ahilya University, Indore, India, where he received a Ph.D. in physics. His thesis was entitled "Undulator radiation and gain studies in free electron laser". After graduation in 2002, Dr. Chouhan joined ANKA, Forschungszentrum Karlsruhe GmbH, Karlsruhe, Germany as a postdoctoral fellow where he worked in the field of superconducting undulator magnets (an insertion device) for a synchrotron light source. He worked there for two years and participated in the design and development of short period SC undulators. In 2004, he joined the National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NewYork as a research associate. During his two-year tenure at NSLS, he worked on the design, development and testing of a short period SC undulator prototype and a permanent magnet undulator. He also proposed a new concept for a variable polarized superconducting undulator. He presented this new concept as an oral talk at the Particle Accelerator Conference on the 16th of May 2005, in Knoxville, TN. Soon afterwards, in 2006, he joined the National Superconducting Cyclotron Laboratory. The cyclotron gas-stopper magnet design was his first assignment along with other room-temperature magnet design and development for the reaccelerator project. Over the last 11 years at Michigan State University, he is involved in many projects such as the hall "C" horizontal bend (HB) superconducting magnet for Jefferson Lab's 12 GeV upgrade project, magnets for the existing coupled cyclotron facility at MSU and Texas AMU, high field, large gap magnets for the High Rigidity Spectrometer (HRS) and the Isochronous Separator with Large Acceptances Recoil Separator (ISLA) design for experiments with reaccelerated rare isotope beams and hundreds of new magnet design and development (including both room-temperature and superconducting) for the Facility for Rare Isotope Beams (FRIB). At present, fabrication of the magnets for FRIB is in an advanced state.

Dr. 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, during which time a world-record 13 T Nb_3Sn dipole magnet was built and tested. 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 this Phase I 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. Recently, 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.

Dr. Ramesh Gupta will be sub-grant Principle Investigator (PI) for the work performed in the Superconducting Magnet Division (SMD) at the Brookhaven National Laboratory (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 beam lines.

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. Four times during the course of the project the technical staff will meet to ensure that important milestones are being met in a timely way. In the final meeting, PBL senior management will also travel to participate. At the final meeting, held approximately six weeks prior to project completion, the team will identify any problems as well as ensure ways to solve them. We will also plan for the Phase I final report and Phase II proposal at that final face to face meeting.

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

eRHIC Design and R&D Directorate

BROOKHAVEN
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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.

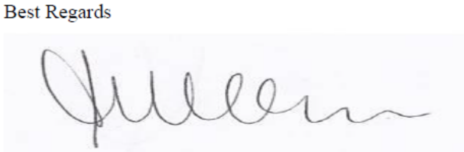
One idea of mitigating this problem is to shield the electron beam from residual field from the strong, superconducting hadron low-beta quadrupoles by a passive superconducting shielding. This idea is not new and the method has been considered on several occasions (for example: shielding the HERA electron 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

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,

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.*

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Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL working in collaboration with the PBL Principal Investigator and other personal will jointly perform the HTS shielding test with liquid nitrogen at ~77 K and perform magnetic and mechanical design tasks within the scope of the Phase I proposal. In addition to a variety of cryogenic facilities, SMD 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 BNL Magnet Division has been a major player in the development of conventional superconducting magnets over the last four decades and of HTS magnets for over a decade. It has dedicated coil winding machines, cryo-coolers and other equipment. The Division has a staff of about 35 scientists, engineers, technicians, administrative staff and others. Construction and testing of the HTS superconducting shield in the presence of magnetic field will be carried out in a 55,000 ft^2 multipurpose complex at the Division. Utilizing BNL facilities, the superconducting shieling test in the presence of magnetic field will be carried out with liquid nitrogen at ~77 K in Phase I, and in addition with liquid helium at ~4 K in Phase II. The infrastructure (space, tools, test equipment, etc.) that are part of the Division will be made available for the Phase I and Phase II work. The value of the infrastructure at BNL is well over $1 million; this infrastructure is a very valuable "in-kind" contribution crucial to the project.

American-Made

To the extent possible in keeping with the overall purposes of the program, PBL and BNL will work to ensure that only American-made equipment and products will be purchased with the funds provided by the financial assistance under DOE Phase I grants.

Research Institution (RI)

This grant application involves a formal collaboration between Particle Beam Lasers, Inc. and a research institution, Brookhaven National Laboratory (BNL). 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
Phone: (631) 344-2103

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: $45,000

Other Consultants and Subcontractors

BNL will be a subcontractor for the Phase I effort. There will be no other consultants or subcontractors on the Phase I effort.

Bibliography & References Cited

1. Nuclear Science Advisory Committee (NSAC) is an advisory committee that provides official advice to the Department of Energy (DOE) and the National Science Foundation (NSF) on the national program for basic nuclear science research. https://science.energy.gov/np/nsac/
2. 2015 NSAC Long Range Plan "*Reaching for the Horizon*", October 20, 2015. https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf
3. RHIC | Electron-Ion Collider - Brookhaven National Laboratory https://www.bnl.gov/rhic/eic.asp
4. JLEIC Design - Electron Ion Collider Wiki https://eic.jlab.org/wiki/index.php/Main_Page
5. EIC Collaboration Meeting 2017 at Brookhaven National Laboratory Oct. 10-12, 2017. https://indico.bnl.gov/conferenceDisplay.py?confId=3492
6. B. Parker "*Fast Track Actively Shielded Nb_3Sn IR Quadrupole R&D*", Oct 11, 2017 https://indico.bnl.gov/getFile.py/access?contribId=28&sessionId=5&resId=1&materialId=slides&confId=3492
7. A. Yamamoto, et al. "*The superconducting inflector for the BNL g-2 experiment*", Nuclear Instruments and Methods in Physics Research A 491 (2002) 23–40.
8. K.G. Capobianco-Hogan, et al. "*magnetic field cloak for charged particle beams*", Nuclear Inst. and Methods in Physics Research, A 877 (2018) 149–156.
9. A. Koski and S. L. Wipf, "*Magnetic shielding of an accelerator beam using passive ferromagnetic material*," IEEE Trans.Magnetics, vol. 32, pp. 2663–2666, 1996.
10. NP Community Panel Report on Electron Ion Collider (EIC) Accelerator R&D, Feb 2017 https://science.energy.gov/~/media/np/pdf/Reports/Report_of_the_Community_Review_of_EIC_Accelerator_RD_for_the_Office_of_Nuclear_Physics_20170214.pdf
11. R. Palmer, "Private Communication".
12. A. Deshpande, N. Feege, R. Gupta, "*A Magnetic Field Cloaking Device For Applications With Strong Magnetic Fields*" SBU/BNL See Grant Proposal (unpublished), April, 2015.
13. Gupta, R., Anerella, M., Ghosh, A., Joshi, P., Kirk, H., Lalitha, S.L., Palmer, R., Sampson, W., Wanderer, P., Witte, H., Shiroyanagi, Y., Cline, D., Garren, A., Kolonko, J., Scanlan, R., Weggel, R., "*High Field HTS Solenoid for a Muon Collider – Demonstrations, Challenges and Strategies*," Proc. 23rd International Conference on Magnet Technology (MT23), Boston, MA, July 14-19, 2013, IEEE Transactions on Applied Superconductivity 24, Article#: 4301705 (2014).
14. R. Gupta, M. Anerella, J. Cozzolino, P. Joshi, W. Sampson, P. Wanderer, J. Kolonko, D. Larson, R. Scanlan, R. Weggel, and E. Willen, "*Design, Construction and Test of HTS/LTS Hybrid Dipole,*" International Conference on Magnet Technology (MT-25), Amsterdam, August 27 – September 1, 2017
15. S. S. Chouhan, et al., "*Design and Fabrication of Iron-Dominated Magnets and Cryomodule Magnetic Shielding for the Re-Accelerator Project at MSU*", IEEE Trans. On Applied Superconductivity, Vol. 24, No. 3, June 2014.