Project Narrative

Cover Page

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Contents

Introduction

1.1 Background Information

Following the recommendation of the Nuclear Science Advisory Committee (NSAC) [1] and of the Long Range Plan (LRP) for Nuclear Science [2] to make the proposed Electron Ion Collider (EIC) the highest priority for new construction, the Department of Energy (DoE) is now proceeding with the next phase of pursuing the EIC. The EIC will be the next major research facility in the United States, and it is expected to answer several basic questions such as “where does the proton mass come from?” Through its collisions, the EIC will also deepen our understanding of the internal structure of ordinary matter via the interactions of its elementary constituents, the quarks and gluons. By providing this better understanding, the EIC is expected to help us unlock the secrets of the strongest force in nature. Beyond sparking scientific discoveries, building the EIC is also expected to trigger broader benefits for society. The estimated cost of the proposed Electron Ion Collider is $1.6 billion to $2.6 billion [3]. The EIC will be built at the Brookhaven National Laboratory (BNL) [4] with active participation of the Thomas Jefferson National Accelerator Facility (TJNAF) [5].

The EIC will consist of two intersecting accelerators, one producing an intense beam of electrons, the other a high-energy beam of protons or heavier atomic nuclei. These two beams will then be steered into head-on collisions. Fig. 1 shows the layout of the entire complex, including the collider, other accelerators and the ion sources [6]. Whereas the electron ring will be a new ring constructed with new magnets and other hardware, the proton ring will use many of the existing superconducting magnets from the presently operating Relativistic Heavy Ion Collider (RHIC). The Interaction Region (IR) between the electron and ion beams will primarily consist of new hardware, including new detectors and new magnets.

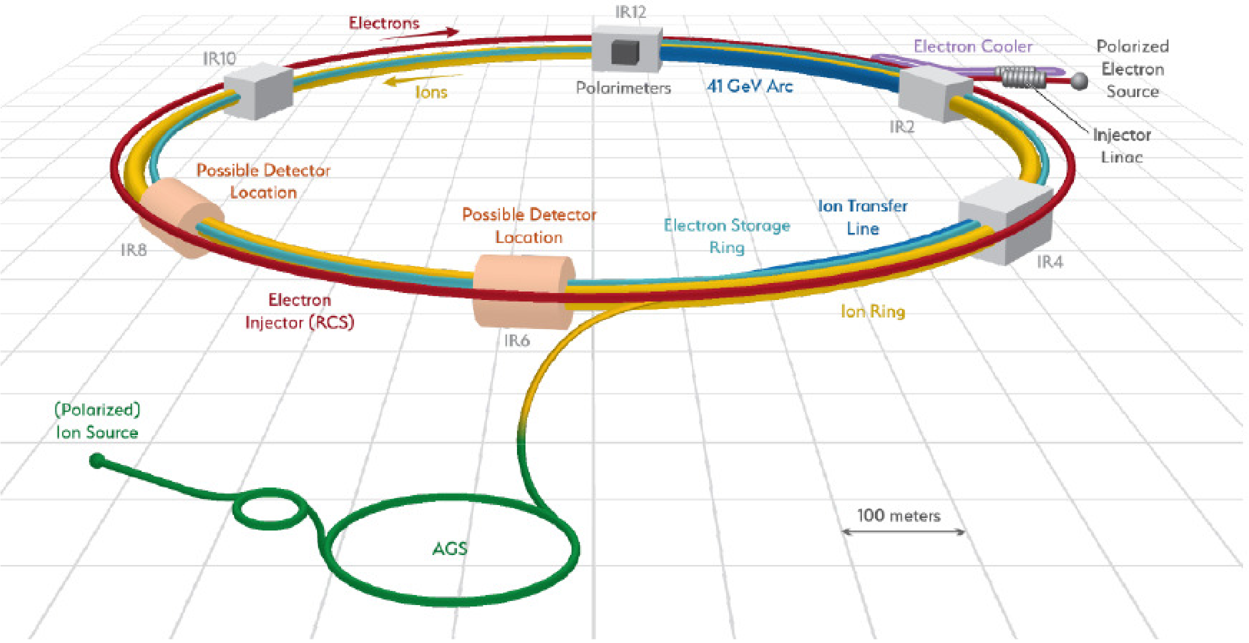

Figure 1: Layout of the proposed Electron Ion Collider (EIC).

1.2 Identification and Significance of the Problem

This proposal addresses the superconducting magnets in the Interaction Region (IR) of the EIC. Superconducting magnets are used only for the hadron (proton or ion) beams which require much higher magnetic fields than does the electron beam. (Room temperature copper-coil-based magnets will suffice for the electron beam because of the lower field requirements.) The current layout [Ref] of the EIC IR is shown in Fig. 2. The figure on the left shows the beamlines and important components both upstream (rear) and downstream (forward) from the ion beam perspective. The figure on the right shows the forward side. The basic parameters of the forward side magnets for the hardon beam are given in Table 1.

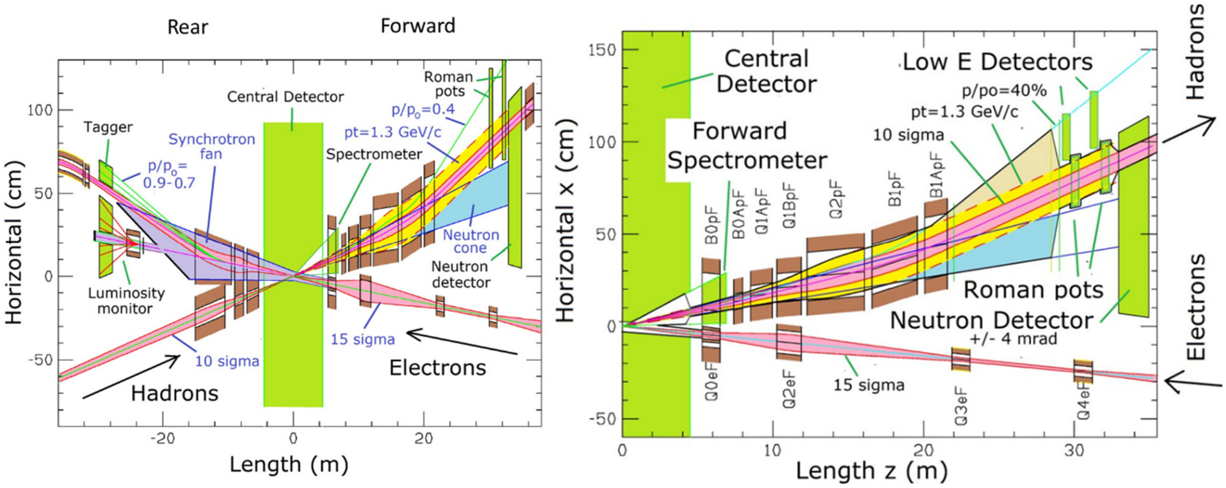

Figure 2: Schematic layout of the EIC interaction region (top view). The figure on the left shows the hadron and electron beamlines on both sides of the central detector. The figure on the right shows more details of hadron-downstream-side (the 'forward' side). The above figures incorporate the dipole and quadrupole magnets for both beams (electron and hadron), spectrometer magnets, and other major components of the IR.

Table 1: Forward hadron magnets for 275 GeV operation

FORWARD DIRECTION	Hadron Magnets						
	B0PF	B0APF	Q1APF	Q1BPF	Q2PF	B1PF	B1APF
Center position [m]	5.9	7.7	9.23	11.065	14.170	18.070	20.820
Length [m]	1.2	0.6	1.46	1.6	3.8	3.0	1.5
Center position w.r.t. to x-axis [mm]	-15	55	140	238	407	390	800
Angle w.r.t. to z-axis [mrad]	-25.0	0.0	-5.5	-10.0	-10.2	9.0	0.0
Beam tube radius [mm]	200	43	56	78	131	135	168
Coil inner diameter [mm]	----	120	142	186	330	300	370
Peak field [T]	-1.3	-3.3	0.0	0.0	0.0	-3.4	-2.7
Gradient [T/m]	0.0	0.0	-72.608	-66.18	40.737	0.0	0.0

The magnets listed in the Table 1 are superconducting magnets and only one of each is needed. In such cases the cost of engineering design and analysis together with the cost of various tooling becomes a significant factor in determining the cost of each magnet. To minimize such cost several magnets are being proposed to be built using "Direct Wind Technology" (see section 1.2.1).

Another noteworthy aspect of the magnets shown in Table 1 is the ratio of the coil length (given in meters) to the coil aperture (given in mm). This ratio in most superconducting magnets is well over an order of magnitude, but this is not the case for some EIC magnets, such as the dipole B0APF. This means that the ends will play a significant role in the magnet by increasing the required field in the body of the magnet (see section 1.2.2).

1.2.1 Direct Wind Technology

Direct Wind Technology [7] is a process where superconducting wire or small diameter round cable is directly bonded on an insulated beam tube coated with b-stage epoxy. The bonding is created with local heating created with ultra-sound, followed by rapid cooling. The wiring pattern is laid on the tube via a computer-controlled multi-axis winding machine with a winding head supported in a gantry which traverses along the length of the tube while the tube rotates on its axis. After the winding is completed, small gaps between conductors are filled with a matching thermal expansion epoxy or pieces of other custom-cut insulator (such as Nomax®), depending on the size of the gap. The coil is then wrapped with multiple layers of tensioned fiberglass roving, epoxied and cured. The amount of tension to be provided by the fiberglass depends on the amount of pre-stress needed on the coil. These steps make a package that can withstand a significant amount of Lorentz forces as has been demonstrated in the "Direct Wind" magnets made so far. If needed for future magnets with higher field and larger aperture, this structure can be placed in a stainless steel or high strength Aluminum tube which will provide an additional support.

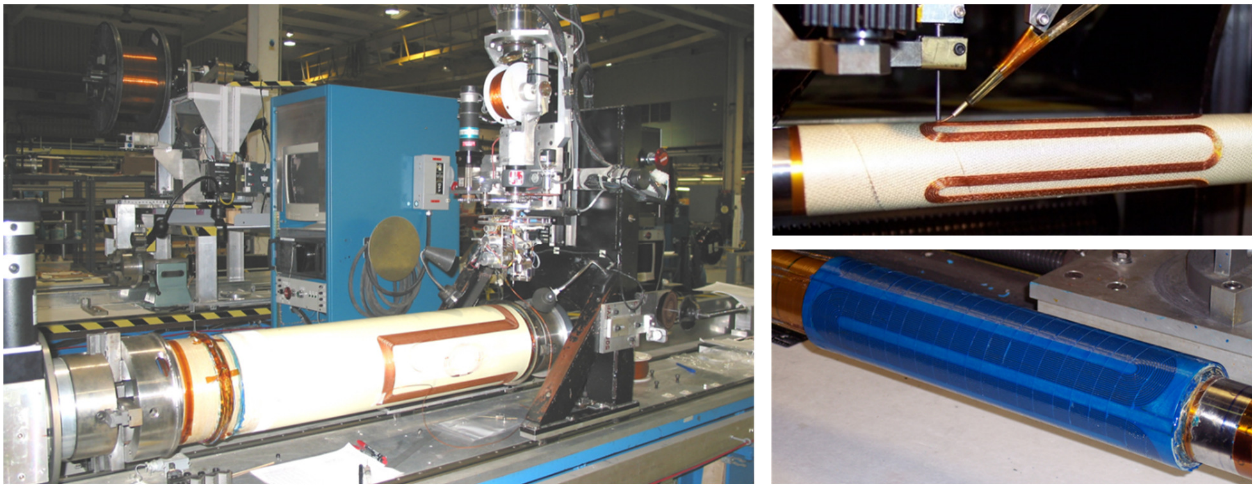

Figure 3: The Direct Wind Machine with its main components (left); superconducting wire directly being laid on the insulated tube and bonded with ultrasound heating (top-right); and final package after filler/epoxy addition (bottom-right).

The winding pattern and gaps determine the type of magnet (dipole, quadrupole, sextupole, octupole, etc.) and field quality. These are pre-computed via a separate computer program for each layer. In fact, by measuring the field quality in between the layers, subsequent layers can correct the residual errors of the previous layer and thus create a highly accurate magnetic field. Earlier magnets of this type with lower self-field or smaller aperture than the EIC magnets had reached the short sample field with almost no quenches.

A similar technology is being used at the Advanced Magnet Lab [8].

The major cost and schedule benefit of the direct wind technology is that it avoids the need for detailed engineering as well as the cost of various tooling and support structures that are required for conventional superconducting magnets made with Rutherford cable. These up-front costs are relatively small if the number of magnets based on each design is large but becomes a major portion of budget and schedule for single magnet production. Therefore, extending and demonstrating the "Direct Wind" technology to the higher fields and larger apertures required for many EIC magnets will provide major cost and schedule savings and retire significant risk. The demonstration of a design that helps achieve this task could be a game changer, not only for the EIC, but for similar applications in the future.

1.2.2 Coil End Designs

A magnet coil is described by two parts: (a) the 'body' portion of the magnet where the coil pattern remains similar as the conductor in each turn moves along the length and b) the two 'end' portions on either side of the coil where the winding wraps from one side to the other so that the direction of current can be changed. In most magnets the length of the body of the magnet is over an order of magnitude greater than an individual end. In cosine theta dipoles, the length of each end is 1.5 to 2 times the coil diameter as shown in Fig. 4 (left) [9]. For the RHIC arc dipoles made with Rutherford cable a similar ratio is seen in "Direct Wind" magnets as well. Moreover, the average field in the end sections is smaller than the field in the same length of the straight section. The integral field is about 2/3 (or even less in many cases) of that for the same length of straight section. The effective magnetic length, defined as the field integrated over the length of the magnet divided by the body field, is therefore smaller than the coil length. The typical loss in the effective magnetic length over the coil length due to ends in cosine theta magnets is of the order of a coil diameter for dipoles, a coil radius for quadrupoles, etc.

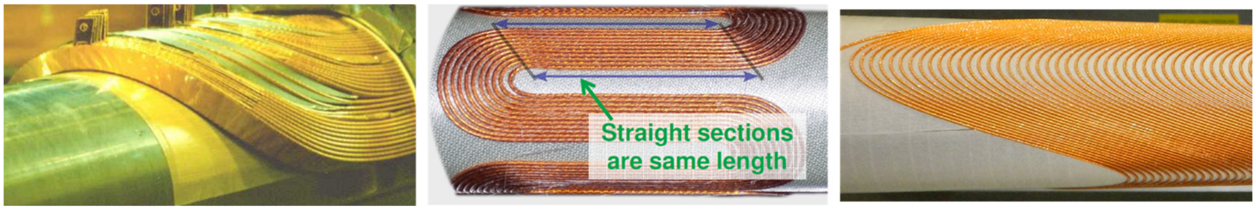

Figure 4: (a) Ends of the cosine theta design (left); (b) Straight section and ends of the serpentine design (middle); and (c) End region of the first layer of the double helix design (right).

The *Serpentine* design [10] is being used in most "direct wind" magnets at BNL as it offers several advantages. In the Serpentine design (see Fig. 4 center), a coil of any number of poles is continuously wound with the end-turns for each layer of turns located only on one end azimuthally, with the return end being located in the next azimuthal turn. Since each turn is successively moved axially by a similar (~wire diameter) length, the length of every turn remains the same. In the limiting case where the bend radius of each turn in the end approaches zero, the integral field and the field harmonics in the entire coil will be the same as those in the 2D section, even when no end-spacers are used [12]. Therefore, to a good approximation, the integral field will be given by the "2D field" multiplied by the "coil length minus the space taken by the end turns". Therefore, the loss in effective magnetic length is still about a coil diameter for dipoles and a coil radius for quadrupoles.

The third geometry used for Direct wind magnets is the Double helix coil. This geometry has been used recently at BNL for the "tapered quad" [11] and at Advanced Magnet Lab [8] for various magnets. Fig. 4 (right) shows the end region of the first layer of the double helix design. Note that end span of the second layer will be cutting half way through the end span of the first layer. The loss in the magnetic length of the double helix design remains at least as much as in the other designs and is often even more.

1.2.3 EIC Interaction Region B0APF Dipole

B0APF is a 120 mm coil aperture dipole in the Interaction Region of the proposed electron ion collider. A 3.3 T bore field requirement makes it a relatively high field dipole for the direct wind technology at such a large aperture. The current design is based on Rutherford cable. Major parameters of the B0APF dipole are given in Table 2 and the superconducting coil with field contour superimposed over the coil body and coil ends is shown in Fig. 5. The allocated space for the superconducting coils of this magnet is only about five times the coil aperture. As mentioned earlier, coil ends typical reduce the effective magnetic length of the dipole by about a coil aperture. In the case of the B0APF dipole this is a significant loss (approximately 20%). To compensate for this loss the field in the body would have to be increased, which is a significant penalty.

Table 2: Parameters of the B0APF magnet

Parameter	Value
Maximum dipole field [T]	3.3
Coil Aperture [mm]	120
Magnet Bore [mm]	90
Required field quality	1×10^{-4}
Physical length [m]	0.6
Physical width [m]	0.16
Physical height [m]	0.16
Superconductor type	NbTi
Conductor [mm^2]	RHIC cable,9.73 ×1.2679
Current density [A/mm^2]	421
Cu:Sc ratio	2
Temperature [K]	4.2
Peak field wire [T]	4.36
Magnetic energy [J]	264000
Ampere turns [A·t]	343200
Number of turns	78
Current [A]	4400
Inductance [H]	0.027273
Margin loadline [%]	30

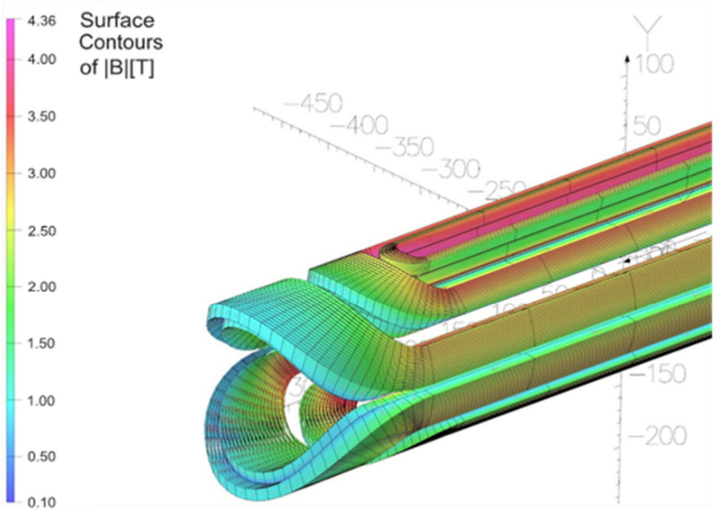

***Figure 5**: B0APF coil with field contour superimposed on the body and ends.*

1.3 Technical Approach

Our atypical conductor-dominated design is a two-step process. First the coil cross section is optimized for the body of the magnet to create a cosine $(n\theta)$ type azimuthal current distribution:

$$I(\theta) = I_o\, COS(n\theta)$$

Then, in the second step, the ends are optimized to minimize the field harmonics to practically create an integrated cosine theta current distribution in the end section with a peak field on the conductor. This 2-step optimization creates a magnet with low integral harmonics but, unfortunately, also one that has a magnetic length that is smaller than the coil length, typically by a coil diameter/(n). For the typical magnet, the main issue is that the field is primarily determined by the turns at the midplane which do not extend to the entire coil length. Also, end spacers are needed to reduce the effective current density in the ends to minimize the integrated field harmonics.

In the *Optimum Integral Design [12]*, the length of the midplane turn is made essentially equal to the coil length (end-to-end) with the bend radius of turns in the ends approaching zero. If there are no spacers in the ends or in the straight section, and if all turns are spaced equally, then the length of successive turns decreases linearly from the midplane to the pole. However, the length and distribution of turns is modulated with the help of a few spacers in the body and the ends so that the current distribution (in the integral sense) becomes proportional to *cosine* $(n\theta)$. The desired integral modulation is obtained with the help of a computer program after distributing a total of “N” turns in a few end blocks and/or in a few cross-section blocks. The size of spacers between the blocks is optimized to achieve an integral distribution varying azimuthally as:

$$I(\theta)\ L(\theta)\ =\ I_o \sum_{i}^{N} L_i\,(\theta)\ \propto\ I_o\ L_o\ .\ cos(n\theta)$$

Since the cosine theta modulation is normalized to the current I_o times the length L_o (end-to-end coil length), this equation suggests that the integral field of the magnet may be closer to a typical 2D field times the mechanical length of the coil (L_o). This is a significant improvement over the designs discussed in the previous section where the loss in effective magnetic length from L_o was about a coil diameter/(n).

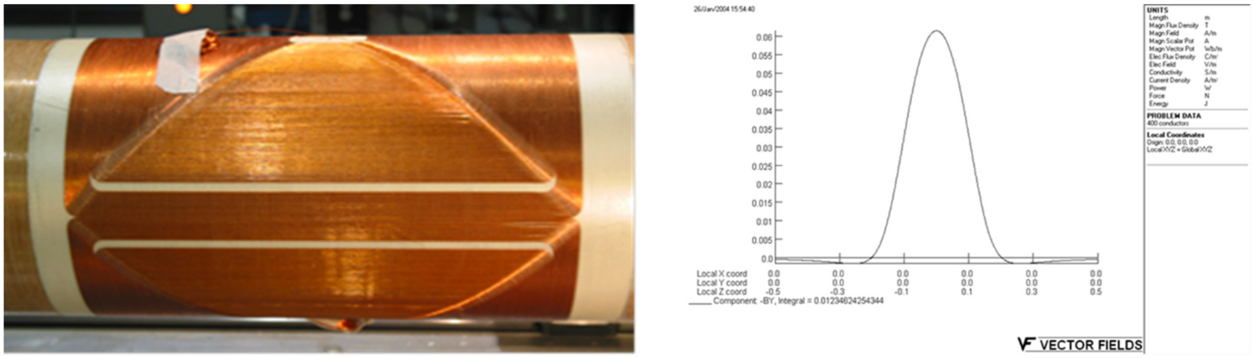

Figure 6: (a) AGS corrector dipole based on Optimum Integral Design (left) and (b) the computed field profile at the design current of 38 A (maximum computed field 0.06 T).

The optimum integral design was used earlier in a very low field "direct wind" magnet (see Fig. 6) for the AGS corrector dipole [12]. The winding and the computed field profile along the axis are shown in Fig. 6. The required integral field was reached with only a single layer of 0.33 mm wire and the maximum computed field of 0.06 T at the center was achieved with 38 A.

For the EIC B0APF, we need a significantly higher field. We envision using intermediate tubes between the layers for the support structure. The increase in the effective length provided by the optimum integral design should significantly reduce the technical challenge for construction of a direct wind magnet. This is especially important for magnets designed with a combination of high fields and large apertures which are beyond what has been built with the technology up to now.

1.4 Anticipated Public Benefits

Development of new and efficient design for medium field magnets, as well as the construction of the EIC, will maintain and continue to expand U.S. leadership in nuclear physics and accelerator science. The most immediate beneficiaries of building EIC will be the researchers working in Nuclear Physics in the United States and around the world. The public benefit may also prove to be great, but it is hard to specify in advance. It is the nature of the enterprise that advances cannot be predicted; one can only speculate. Greater knowledge over the particles and forces that make up our world may be used to enable devices that are unforeseen at present. Past experimentation led to understanding and control of the electromagnetic force, with revolutionary benefits accruing to mankind. Future experimentation may lead to understanding and control of other forces, such as the nuclear forces, and such gains could be revolutionary as well. One thing is certain – if we stop experimenting, progress in these areas will stagnate.

The specific benefit of this application applies where space is limited and very short length medium field superconducting dipoles, quadrupoles, sextupoles, octupoles, etc. are needed. Apart from research accelerators, such requirements of compact superconducting magnet technology are often faced in medical physics, including proton and ion therapy accelerators, and in national security applications. The advances in superconducting technology gained during the project may prove very important for superconducting magnet technology in general.

The Phase I Project

1.5 Phase I Technical Objectives

The three main technical objectives of Phase I are (a) development of an optimum integral design with the direct wind technology of a medium field, large aperture dipole (taking the latest specifications of EIC IR dipole B0APF as an example), (b) development of a proof-of-principle design of a demonstration magnet, and (c) demonstration of the proof-of-principle magnet with a 4 K test. This is an ambitious plan for Phase I, but one that can be achieved thanks to the benefit of the direct wind approach as discussed above.

1.5.1 Optimum Integral Design of EIC IR Dipole B0APF

The initial design concept of the optimum integral design of the EIC IR B0APF is shown in Fig. 7. Fig 7(a) shows the magnetic field superimposed on the coil and on the upper half of the yoke. Fig. 7(b) shows midplane turns in the ends of the optimum integral design extending the full coil length (except for a small bend radius) to increase the effective length. Fig 7(c) shows the vertical component of the field on the axis. Note these calculations are performed at ~4 T field rather than the specified design field of 3.3 T to allow for some operating margin.

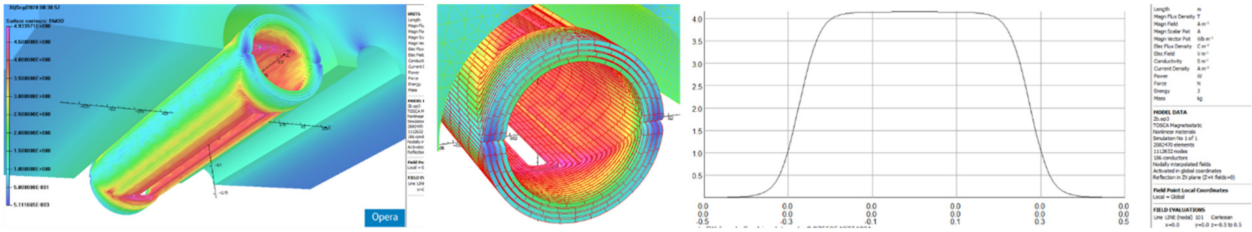

Figure 7: (a) Coil and upper half of the yoke with field superimposed; (b) Ends of the optimum integral design with the midplane turns extending to nearly the full coil length; and (c) Vertical component of the field along the axis.

A major technical objective of Phase I will be to develop a good field quality design for B0APF along with an appropriate support structure. We will also perform an estimate of cost of building such a magnet with some margin. The support structure is likely to have one or more tubes made of stainless steel to intercept the Lorentz forces. The size of spacers in the body and ends will be used to optimize field quality and to reduce the peak field (particularly in the ends). It has been shown that the optimum integral design can produce good field quality even in short dipoles [12]. Fig. 8 and Table 3 show such a design for a dipole with a coil diameter of 200 mm and a length of ~175 mm (coil length less than a coil diameter).

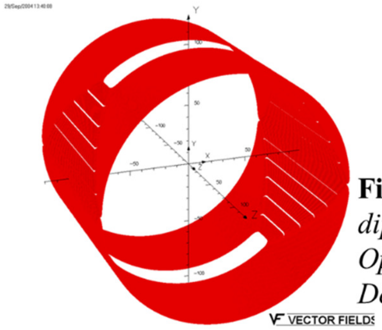

Figure 8: *A short dipole based on the Optimum Integral Design.*

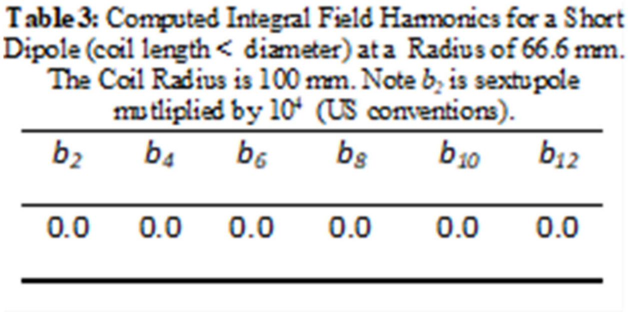

Table 3: Computed Integral Field Harmonics for a Short Dipole (coil length < diameter) at a Radius of 66.6 mm. The Coil Radius is 100 mm. Note b_2 is sextupole mutliplied by 10^4 (US conventions).

b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0	0.0	0.0	0.0	0.0	0.0

1.5.2 Proof-of-Principle Optimum Integral Design for B0APF

We will develop a design for a proof-of-principle optimum integral dipole that will achieve nearly the highest possible integral field at a reasonable length so that it can be built and tested within the budget of Phase I: 1) it will be a 2-layer design; 2) it will have the same coil diameter as that of B0APF (120 mm); 3) it will have as many turns as possible to maximize the field while having a typical pole; and 4) it will have representative spacers both in the body and in the ends of the magnet. The coil will have a length of 150 mm, as compared to the 500 mm specified for B0APF. An initial design of such a dipole is shown in Fig. 9. It is based on 1 mm cable, enough quantity of which is in stock. A maximum field of 2.6 T on the superconductor and 1.6 T at 850 Amperes in the bore is expected based on the computed short sample.

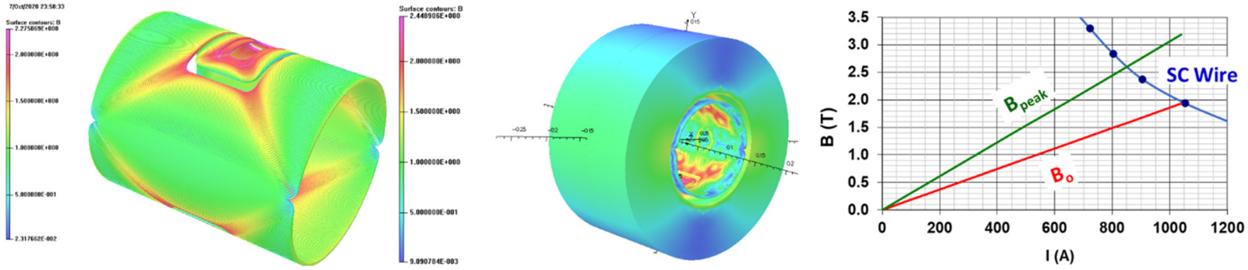

Figure 9: (a) Initial 2-layer coil design of the proof-of-principle optimum integral dipole design with the field contour superimposed on the coil at 800 A; (b) Initial design with additional field from the iron yoke; and (c) Load line for the peak field and field at the center of the dipole with an expected short sample current of 850 A.

1.5.3 4 K Test of the Proof-of-Principle Optimum Integral Dipole

An important task of Phase I is the construction and quench test of the proof-of-principle optimum integral dipole design. The above-mentioned initial design will be further iterated, superconducting coil based on that design will be wound on the BNL direct wind machine, and the magnet will be tested in the iron yoke to the quench field at 4 K.

1.6 Phase II Technical Objectives

The major technical objective of Phase II will be the detailed design, construction and test of a medium field dipole using direct wind technology. The length of this dipole will be the same as the specifications of the EIC dipole B0APF at that time. However, the maximum reachable field will depend on the budget the budget limitations of Phase II. We will review the specifications again along with the capability of the direct wind technology at the beginning of Phase II. A large diameter cable will reduce the number of turns and the number of layers which in turn will reduce the cost. Our expectation is that we will be able to build the Phase II dipole to the specifications even if it doesn't have any margin. The support structure is likely to have one intermediate tube. Quench protection will also be examined though even higher stored energy magnets built with the direct wind technology have tolerated energy safely dumped into the coils after a quench. Another important part of Phase II will be the measurement of field harmonics to ensure that the optimum integral design meets the field quality requirements.

We will also perform design studies to examine whether the optimum integral design with direct wind technology can be applied to other EIC IR magnets that are currently based on the cable magnet technology. That should reduce the cost and the time needed to build those magnets since cable magnets require significant engineering design and analysis, as well as the costs and time required to build both expensive tooling and the magnet itself. These factors become the cost and schedule driver of the cable magnets if just one of each designed magnet is required in the machine. Finally, the unique feature of this superconducting magnet design (a dipole with a coil length less than a coil diameter, a quadrupole with length less than a coil radius, an octupole with length less than ½ the coil radius, etc.) will be examined for other accelerator magnets and magnets for other fields like medical applications. The optimum integral design, once demonstrated and proven for medium field magnets, can also be used by others needing similar capabilities, likely under a licensing agreement.

1.7 Phase I Work Plan

To achieve the technical objectives mentioned in the previous section, the Phase I 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: Software upgrades to optimize the design

The software to do initial optimization of the optimum integral design was developed primarily on a VAX/VMS computer and ported to a PC over a decade ago using the DEC FORTRAN compiler. It also uses several CERN software libraries [13] to optimize the design. The software was partly ported to CYGWIN [14] to initialize optimization. The first task of this proposal is to fully port this software to CYGWIN and LINUX platform. The software in its current form computes the bore field and integral transfer function and harmonics, but it doesn't compute the maximum field on the superconductor. The software will be upgraded to compute the maximum field on the conductor as well. This task will be primarily carried out by the PBL team with guidance from the BNL team.

Task 2: Design optimization of the proof-of-principle dipole

The initial design of the proof-of-principle dipole used in this proposal will be iterated to reduce the maximum field (peak field) on the conductor and to meet various winding pattern requirements and restrictions of the direct wind machine. The emphasis of the proof-of-principle dipole will be to optimize the maximum achievable field with a pole spacer, a representative spacer in each quadrant of the body of the magnet and one representative spacer in each end of the magnet. The current choice of ~1 mm diameter 6-around-1 cable made with ~0.3 mm wire will be retained, as it is already in stock. This task will be primarily carried out by the BNL team with active participation of the PBL team.

Task 3: Selection of conductor for the Phase II magnet

As the field, length and aperture of the magnet increases, the stored energy, inductance, number of turns, number of layers and time required to wind the coil increases. Therefore, the use of a larger diameter cable is desired if the winding machine and various processes involved can accommodate that. The direct wind machine is getting upgraded from another source of funding to allow a larger diameter cable. It is likely that the use of 1.7-2.0 mm will be possible. The selection of the conductor will be jointly made by the PBL and BNL teams.

Task 4: Winding of the proof-of-principle optimum integral dipole coil

Winding of the proof-of-principle dipole coil is the major task. A Two-layer design has been chosen to meet the budget restrictions. The coil will be wound from one pole to another pole to avoid any splice within the layer. Body and end spacers will be installed and gaps between the turns will be filled with blue-epoxy. There will be three voltage taps, two at the two poles and one in the middle at the midplane to aid in quench protection. Once the first layer is wound it will be wrapped with multiple layers of tensioned fiberglass roving and cured. The same procedure will be followed for the second layer and a splice between the two layers will be made. This task will be primarily carried out by the BNL team in discussion with the PBL team.

Task 5: Preparation of the proof-of-principle dipole for a 4 K test

The coil will have a simple cylindrical yoke with an outer diameter of 140 mm and a length of 150 mm (same as the coil length). The magnet will be high-potted and various QA tests on the coil will be performed. The magnet will be installed on the test stand with all v-taps wires and electrical connections made. Cryogenic and final preparation will be performed prior to the 4 K test. This task will be primarily carried out by BNL; however, planning of the test will involve discussions with the PBL team.

Task 6: Magnetic, mechanical and winding design optimization for the Phase II magnet

The coil length of the Phase II coil will be 500 mm rather than the 150 mm in Phase I. The Phase II magnet will be designed to provide a good field quality with all harmonics meeting the specifications at that time. The pre-stress on the coil, which is provided by the tension in the Fibergalss, will be adjusted to the higher pre-stress requirements. In addition, it is likely that one or more stainless steel tubes will be used as the radial support structure. To reduce the number of turns, the number of layers and the inductance, a larger diameter (1.7 mm to 2 mm) cable is likely to be used in Phase II. (Phase I will use an ~1 mm diameter cable.) This task will be primarily carried out by BNL with participation of the PBL team.

Task 7: Proof-of-principle dipole test at 4 K

One of the important highlights of this proposal is the demonstration of the proof-of-principle optimum integral dipole with a 4 K test. Because of the rather small size of the magnet, it can be tested in a relatively small experimental dewar using a small amount of Helium. We plan to do two to four quenches. Because of the small stored energy, the loss of helium after each quench will be small and the magnet will be self-protecting. This task will be primarily carried out by BNL with active participation by the PBL team.

Task 8: Prepare the Phase I 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 in the writing of the Phase I final report.

Performance Schedule

Task 1: Software upgrades to optimize the design: Weeks 1-20.
Task 2: Design optimization of the proof-of-principle dipole: Weeks 9-22.
Task 3: Selection of conductor for the Phase II magnet: Weeks 20-24.
Task 4. Winding of the proof-of-principle optimum integral dipole coil: Weeks 23-28.
Task 5. Preparation of the proof-of-principle dipole for a 4 K test: Weeks 29-31.
Task 6: Magnetic, mechanical and winding design optimization for the Phase II magnet: Weeks 23-36.
Task 7. Proof-of-principle dipole test at 4 K: Weeks 32-34.
Task 8. Prepare the Phase I Final Report and prepare the Phase II proposal: Weeks 35-38.

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 a staff of about 35, including scientists, engineers, technicians and administrative staff. It has a 55,000 ft^2 multipurpose R&D complex with a variety tooling and machines. 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. Of interest for this project are two direct wind machines, as discussed in section 1.2.1 (direct wind technology), where the Phase I coil will be wound. It is expected that the winding machine will be upgraded in a year or two to allow a larger diameter cable to be wound at an increased winding speed. The superconducting magnet division has access to a variety of simulation and engineering software tools that will aid in the design of coils and magnets. The design software available includes ROXIE, OPERA, COMSOL and in-house software for magnetic design, ANSYS for mechanical design, and CREO and AutoCAD for engineering design. The magnet division has also developed an array of magnet design software. A prominent asset of the complex is an active cryogenic test facility, complete with high-current, high-resolution and high-stability power supplies. BNL also has several dewars with a variety of sizes. The 4 K test of the proposed Phase I and Phase II magnet will be carried out in one of the smaller dewars. The facility allows testing of a variety of coils and magnets from ~2 K to ~80 K. The building has several large-capacity (>15 ton) overhead cranes. Within the building complex are two machine shops with capacity to manufacture many components needed for the R&D tasks. BNL also has a central machine shop and a procurement group to handle orders with private companies.

Principal Investigator and Other Key Personnel

Dr. Ramesh Gupta, inventor of the "*optimum integral design*," will be Principle Investigator (PI) for this grant and will supervise the work performed at BNL. Dr. Gupta currently leads the magnet science 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 new magnet designs and technologies, including magnets built with High Temperature Superconductors (HTS) for particle accelerators and other applications. Over the last decade he has developed several new innovative designs such as the optimum integral design, 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 Phase I STTR with PBL, namely "Overpass/Underpass coil design for high field dipoles". 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.

Other key BNL staff members who will work on this proposal will be Brett Parker (who invented the "serpentine design" for direct wind technology and has a decade of experience with it), Holger Witte (who is leading the EIC superconducting magnet program at BNL), Michael Anerella (group leader of the mechanical engineering group at the SMD), Piyush Joshi (group leader of the electrical engineering group at the SMD), John Escalier (who is an engineering expert and has played a major role in developing direct wind technology), Andrew Maron (who has supervised constriction of many direct wind coils), Thomas Van Winckel (lead technician with over two decades of experience with direct wind technology), and other staff as needed. Anis Ben Yahia, Post Doc, will play a lead role in magnet testing. Overall managerial supervision will be provided by Dr. Kathleen Amm, Head of the superconducting magnet division at BNL.

Dr. Stephan Kahn will be the lead investigator for PBL. Dr. Kahn has 35 years of experience with superconducting accelerator magnets. He ported the earlier version of the optimum integral design magnet to a modern platform to facilitate calculations for the current proposal. He has worked as PI on five 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 OPERA 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 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. Dr. Willen supervised the AGS helical magnet project where a low field precursor to the optimum integral design was previously used.

Dr. Al Zeller will contribute in the areas of magnet design and construction. Dr. Zeller has over 35 years of experience in magnet physics, predominantly at facilities associated with Michigan State University. Dr. Zeller served as Associate Project Manager at the Facility for Rare Isotope Beams until his retirement at the end of 2016. He is now a visiting scientist at the National High Magnetic Field Lab at Florida State University working on high-field solenoids and he will join PBL as an employee at the time of the award.

Letter of Support from Dr. Ferdinand Willeke, Technical Director EIC

Electron-Ion Collider Directorate

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October 17, 2020

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

Dear Dr. Kolonko,

This letter is to express our strong interest in your proposed work which is highly relevant for the EIC interaction region magnets.

I learned that you are proposing to study superconducting magnets in direct wind technology. Direct wind technology which was in the present form developed by the end of the 90-ties has enabled us to build accelerator magnets for a number of colliders.
Direct wind magnets are superior in achieving very high field quality and need only a minimum of physical space which makes them ideal for final focus magnets for accelerator applications.

Direct wind magnets techniques allow to implement complicated coil geometry quite easily and the technique has been used to demonstrate novel coil geometries such as serpentine winding or double helix geometries.

Direct wind magnets are known to reach their design fields in contrast to collared superconducting magnets without training which is also a remarkable feature of great practical interest.

What is not yet known, is are what the maximum achievable field levels using this technology. According to my information, fields of up to 3.5 T in the coil has been demonstrated. However, the absolute limit of this magnet technology has not yet been tested to my knowledge.

Expanding this technology to magnets of higher fields and learning what maximum achievable fields are is of great important for accelerator magnet technology and high field magnet in direct wind technology may open to door to a wide range of applications in other fields.

For this reason, I do not hesitate to support your STTR proposal.

Sincerely,

Ferdinand Willeke

Ferdinand Willeke
Deputy Project Director/Technical Director

How the Research Effort Could Lead to a Product if Funded Beyond Phase I

A successful demonstration of the proof-of-principle 150 mm long optimum integral dipole and a good design for a Phase II upgrade is expected to secure Phase II funding for the full length 500 mm dipole. The optimum integral design is a new design and is currently not a part of any magnet program. Such a design can't be considered in a high cost one-off magnet without a prior proof-of-principle demonstration. Therefore, the success of research including the demonstration of a proof-of-principle dipole in Phase I, followed by a more complete demonstration in Phase II is a crucial step in the development of the optimum integral design. Once Phase II is successfully completed, is likely that the optimum integral design will be used in other EIC magnets as well. The optimum integral design is unique in that it makes very short length superconducting magnets possible, such as dipoles with a coil length less than their coil diameter, quadrupoles with a coil length less than their coil radius, sextupoles with a coil length less than 2/3 of their coil radius, etc. Such a development has a potential for making significant advances in magnet technology and in the applications those magnets are intended for. PBL will be on the lookout for IP developed during Phase I that could then be patented and licensed for other applications in the medical, accelerator and defense market sectors. For a more complete description of the commercialization potential that this project has, please consult the commercialization plan that is attached to this proposal.

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 lead Dr. Kahn has an office at the 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 and STTR programs, having completed several SBIR and STTR 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.

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:
Ivar Strand
Manager, Research Partnerships
(631) 344-7549
istrand@bnl.gov

Total dollar amount of the subcontract: $114,000

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