Project Narrative

Title Page

Company Name: Particle Beam Lasers, Inc.
Address: 8800 Melissa Court
Waxahachie, TX 75167-7279

Principal Investigator: Ramesh Gupta, Ph.D.

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CONTENTS

1 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 (left) shows the layout of the entire complex, including the collider, other accelerators and the ion sources [6], whereas Fig. 1 (right) shows the Interaction Region (IR) between the electron and ion beams that will need new magnets.

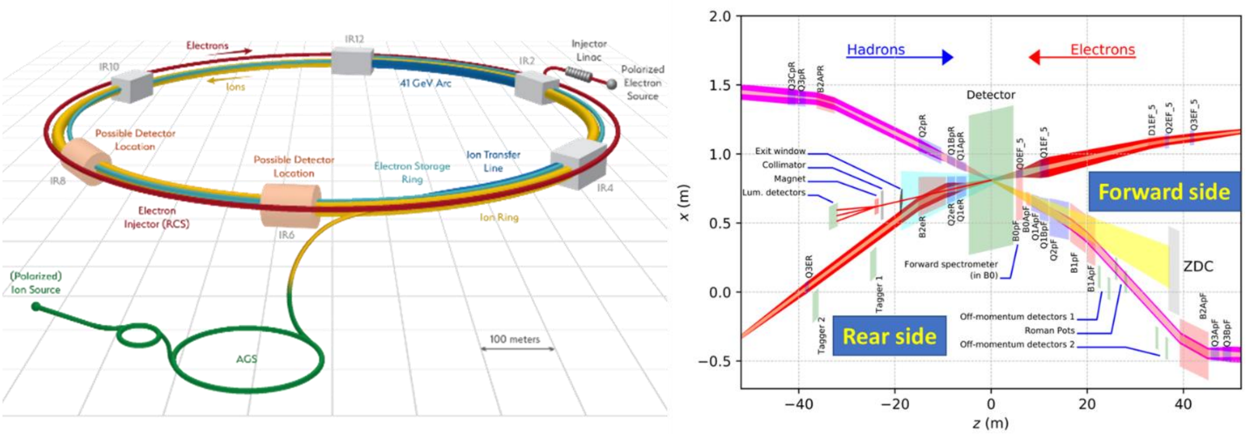


Figure 1: Layout of the proposed Electron Ion Collider (left) and of its Interaction Region (right).

1.2 IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

The Hadron ring on the forward side of the EIC IR needs seven superconducting magnets (see Table 1) and only one of each is needed. The cost of the engineering design and analysis together with the cost of various tooling becomes a significant factor in determining the cost of each magnet, particularly in the case of superconducting cosine n-theta magnets based on Rutherford cable. Section 1.2.1 describes an alternate “Direct Wind Technology” that has been demonstrated as a lower cost alternative for superconducting magnets. Direct Wind Technology is being currently considered for the EIC to reduce the cost of the magnets. Note that the EIC magnets will operate at a much higher field and coil aperture combination than what has been demonstrated so far.

Another noteworthy aspect of the magnets shown in Table 1 [6] is the ratio of the magnet length (given in meters) to the coil aperture (given in mm). The field created from the ends in the conventional design is significantly less than that in the body of the magnet. This loss is not of significant concern in most superconducting magnets where the length is well over an order of magnitude larger than the coil aperture. However, this is not the case for some EIC magnets, such as the IR dipole B0APF. This issue is discussed in more detail in section 1.2.2.

Although the EIC is a collider, EIC IR magnets operate in a DC mode during the experiment.

Table 1: Forward side hadron magnets for 275 GeV operation (from page 111 of EIC CDR [6]:

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 [cm]	-1.50	5.5	1.40	2.38	4.07	3.90	8.00
Angle w.r.t. to z-axis [mrad]	-25.0	0.0	-5.5	-10.0	-10.2	9.0	0.0
Inner radius [cm]	20.0	4.3	5.6	7.8	13.1	13.5	16.8
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	-66.180	40.737	0.0	0.0

1.2.1 Direct Wind Technology

Direct Wind Technology [7] is a process (Fig. 2) 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 using 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 complete, 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.

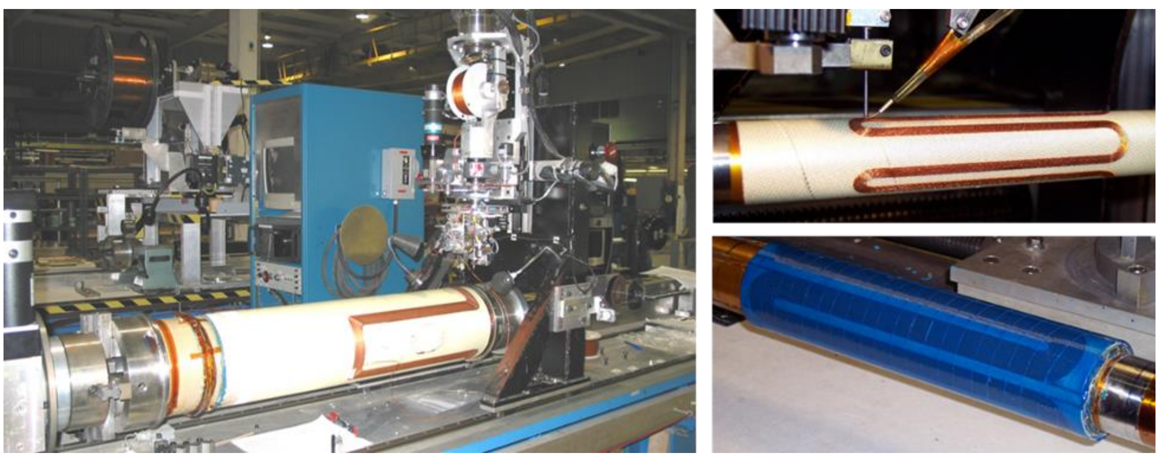


Figure 2: The Direct Wind Machine with its main components (left); superconducting wire directly being laid on the insulated tube and bonded with ultrasound heating (top-right); and final package after filler/epoxy addition (bottom-right).

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 have 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 become 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 the 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. 3 (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.

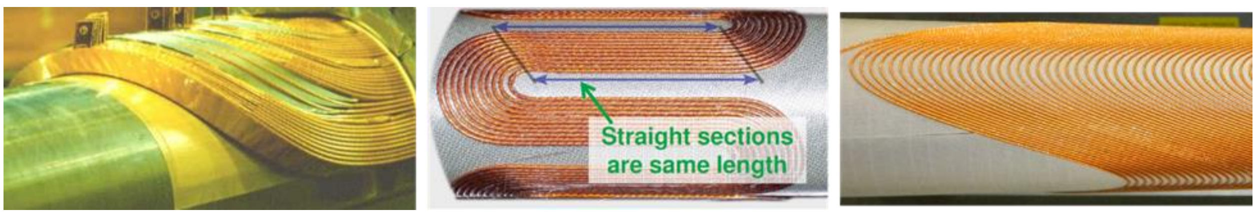


Figure 3: (a) Ends of the cosine theta design (left); (b) Straight section and ends of the serpentine design (middle); and (c) End region of the first layer of the double helix design (right).

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. 3 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. 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 the Advanced Magnet Lab [8] for various magnets. Fig. 3 (right) shows the end region of the first layer of the double helix design. Note that the end span of the second layer will be cutting halfway 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.

2 TECHNICAL APPROACH

The major component of our technical approach is (a) to develop an *Optimum Integral Design [12]*, that is more efficient than the traditional designs and (b) to demonstrate it for a superconducting EIC IR magnet using *Direct Wind Technology*. The immediate goal will be to apply this new design, if successfully demonstrated to meet the performance specifications, in certain magnets for the EIC. The long-term goal is to use the technology in other future magnets, where in some cases no other solution exists.

2.1 CONVENTIONAL DESIGN

The conventional conductor-dominated design involves 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 over the entire coil length. Also, end spacers are needed to reduce the effective current density in the ends to minimize the integrated field harmonics.

2.2 <u>OPTIMUM INTEGRAL DESIGN</u>

The *Optimum Integral Design [12]* is a one step process where the length of the midplane turn is made essentially equal to the coil length (end-to-end) with the bend radius of the 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 the 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 (L_o is the 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).

2.3 <u>OPTIMUM INTEGRAL DESIGN FOR SHORT DIPOLE, QUADRUPOLE AND OTHER MULTIPOLE MAGNETS</u>

The *optimum integral design* opens a new window for building very short magnets. The design can be used in quadrupole and higher order multipole magnets. Examples of a dipole with a length shorter than the coil diameter, a quadrupole with a length shorter than the coil radius and a sextupole with a length shorter than one third of the coil diameter have been presented earlier [12].

The optimum integral design was used earlier in a very low field "direct wind" magnet (see Fig. 4) for the AGS corrector dipole [12]. The winding and the computed field profile along the axis are shown in Fig. 4. 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.

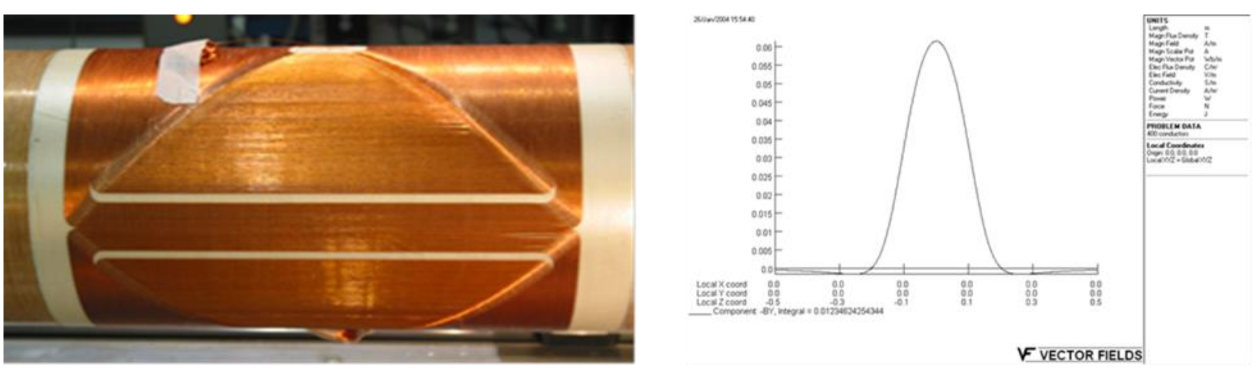


Figure 4: (a) AGS corrector dipole based on the Optimum Integral Design (left) and (b) the computed field profile at the design current of 38 A (maximum computed field 0.06 T).

2.4 OPTIMUM INTEGRAL DESIGN FOR EIC IR DIPOLE B0APF

The requirements of the field and field integral for EIC IR dipole B0APF are significantly higher than those of the AGS corrector dipole. The relative benefit of the *optimum integral design* over the base line double helix design were examined for EIC IR dipole B0ApF during Phase I of this program. Fig. 5 clearly shows that the *optimum integral design* succeeded in extending the effective magnetic length, and hence the field integral, over the current baseline design of this dipole.

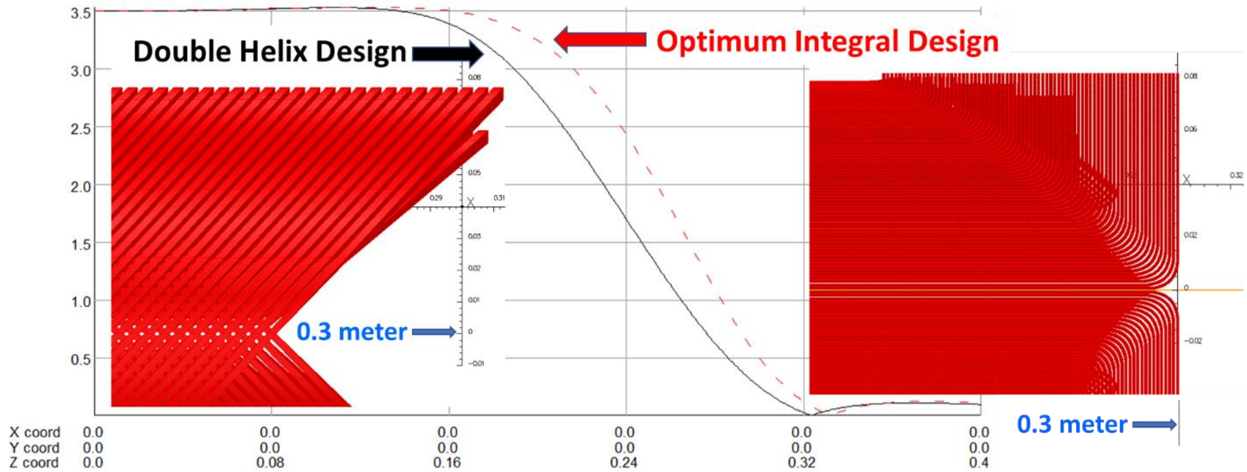


Figure 5: A comparison between the present design and the optimum design for EIC IR dipole B0ApF when the field is plotted along the axis from the magnet center. The optimum integral design clearly extends the effective length and increases the field integral for the same length.

3 ANTICIPATED PUBLIC BENEFITS

Development of a new and efficient design for medium field magnets, as well as 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 the EIC will be 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.

4 DEMONSTRATION OF TECHNICAL FEASIBILITY FOR A STRONG PHASE II PROPOSAL

All technical objectives outlined in the Phase I proposal were met, resulting in the demonstration of a proof-of-principle 1.7 T, 114 mm coil aperture superconducting dipole based on the *optimum integral design*. While carrying out the design of B0ApF for Phase II (which is 600 mm long) and comparing it with the one mentioned in the Phase I proposal (which was 150 mm long), significant technical differences were observed between the two (see Fig. 6). Therefore, the length of the Phase I proof-of-principle magnet was increased from 150 mm to 600 mm. Making the Phase I coils similar in length to the Phase II coils not only makes the Phase I coils more technically representative of EIC IR dipole B0Apf, but it also allows the Phase I coils to be used in the Phase II magnet. The additional cost of conductor didn't play a role since spare conductor was used and the labor associated with the increased length was small.

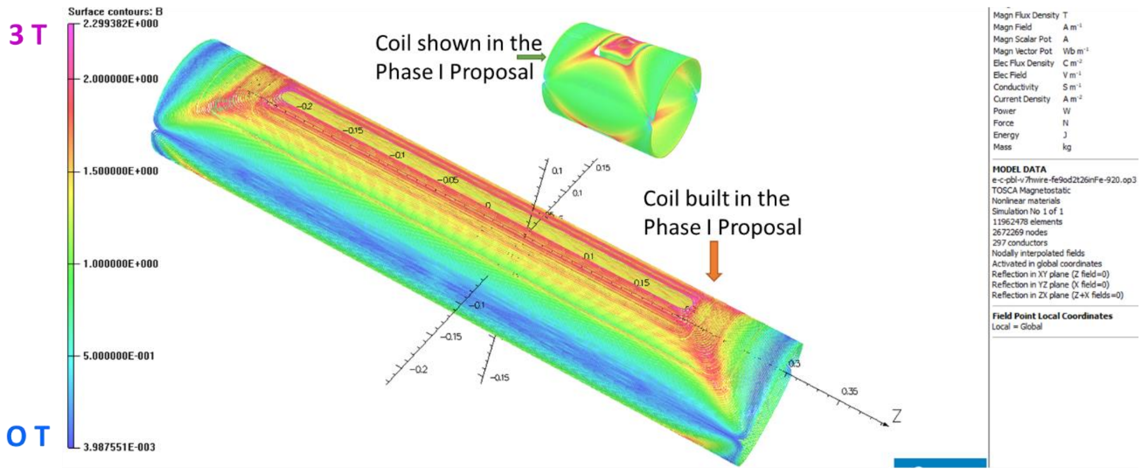


Figure 6: Models of two coils with field superimposed. (a) 150 mm long 2-layer coil design as mentioned in the Phase I proposal (upper coil); (b) 600 mm long design of the inner-most 2-layer coil of the B0ApF dipole as investigated for Phase II. Because of the major technical differences between the two coils, a shorter 150 mm long coil would not have been a good representation of the magnet to be built in Phase II (lower coil) and therefore the coil length of the Phase I coil was increased to 600 mm.

The following sections summarize several tasks performed during Phase I. More details can be found in the separate Phase I report submitted along with this proposal.

4.1 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 a 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 was to fully port this software to CYGWIN and a LINUX platform. The software (now called *IntegralOpt*) was upgraded to include more features for optimization. These included different turn-to-turn spacing between the ends and body of the magnet. These were required for laying out the turns more robustly while using the direct wind technology and this provides an additional feature in optimizing the field harmonics. A new feature was added where the turn-to-turn spacing could be changed between the blocks of conductor of the same layer both in the body and end of the magnet. These are features which are easy to implement in a coil wound with direct wind technology and they play a significant role in reducing the peak-fields on the conductor, as well as reducing the field harmonics. Finally, output functions to create an OPERA3D file and for direct wind software were enhanced. Preparing a user manual is the part of Phase II proposal.

4.2 SELECTION OF THE CONDUCTOR

The conductor used in winding two layers of coil was similar to that was used in building a helical magnet for AGS at BNL. The key conductor parameters are given in Table 2.

Table 2: Key parameters of the superconductor used in the proof-of-principle dipole in Phase I.

Filament diameter	10 microns
Wire diameter	0.33 mm
Cu to Non-Cu ratio	2.5:1
Cable type	6-around-1
Cable diameter, bare	1 mm
Cable diameter, insulated	1.1 mm
Cable I_c @ 5 T, 4.2 K	490 A

Phase II will use a similar conductor since the outer 8 layers of Phase II will be connected in series with the inner two layers of Phase I.

4.3 DESIGN OPTIMIZATION OF THE PROOF-OF-PRINCIPLE DIPOLE

The design of the proof-of-principle dipole used in the Phase I proposal was significantly upgraded by increasing the length of the coils from 150 mm to 600 mm. The emphasis of the proof-of-principle dipole was to optimize the maximum achievable field integral (rather than the field quality) with representative spacers in the body of the magnet and representative spacers in the ends of the magnet in each of the two layers of windings. The integrated field harmonics were kept within 10 units (computed at a 38 mm reference radius for a coil inner radius of 57 mm). The total integrated field harmonics will be made small by optimizing the remaining 8 layers in Phase II. The magnet also had an iron yoke over the coil. The inner radius of the yoke was 63.5 mm (2.5”) and the outer radius was 114.3 mm (4.5”).

The coil winding was optimized with the code ported and developed as part of Phase I. We varied the number of turns in each layer along with the number of coil blocks in the body and in the end of the magnet. The final choice was to have three blocks in the body and three in the ends in each of two layers. Apart from the maximum integral field and field harmonics, an attempt was made to minimize the peak field in the body and in the end of the magnet. The program also creates a conductor file that can be imported into OPERA3d for further analysis. Fig. 7 shows the OPERA3d model with a coil (red) and an iron yoke (transparent green) on the left; field superimposed over the coil and iron in the middle, and over only half of the coil on right.

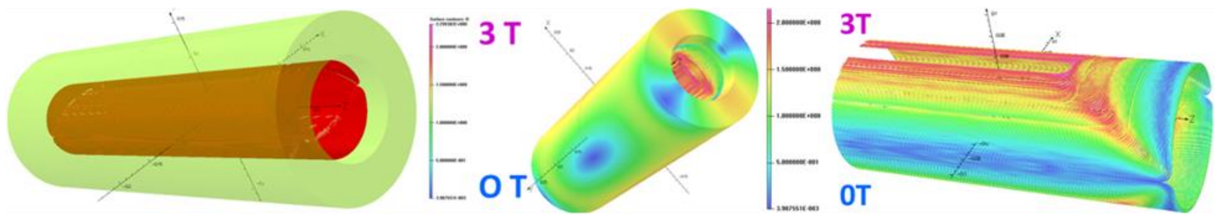


Figure 7: Left: OPERA3D model of the optimum integral dipole as built (the coil is red and the iron is green); middle: field superimposed over the coil and the iron yoke at 920 A; right: field superimposed over half of the coil (iron yoke and the rest of the coil is hidden).

The key parameters of the optimum integral dipole as designed for Phase I are given in Table 3.

Table 3: Key Parameters of the Phase I proof-of-principle optimum integral dipole

Coil Aperture	114 mm
Quench Field	1.7 T
Peak Field	2.2 T
Coil Length	0.6 m
Number of Layers	2
Number of turns	99
Stored Energy	7.5 kJ

4.4 WINDING OF THE PROOF-OF-PRINCIPLE OPTIMUM INTEGRAL DIPOLE COIL

Winding of the proof-of-principle optimum integral dipole coil was the most expensive, time consuming, and critical task of Phase I. Several practice coils were wound to optimize various parameters before winding the coil for the proof-of-principle demonstration magnet. The key components of the steps involved in building a *direct wind magnet* will now be described with the aid of a series of pictures.

Fig. 8(left) shows the Kapton wrap on the stainless-steel tube and Fig. 8(right) shows the Fiberglass wrap on the Kapton in preparation for winding of the Phase I coil.

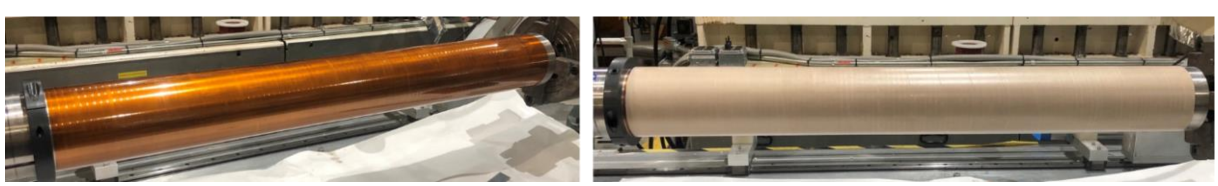


Figure 8: Left: Kapton wrap on the stainless-steel tube in preparation for winding of the Phase I coil; Right: Fiberglass wrap on the Kapton in preparation for winding of the Phase I coil.

Figure 9 shows the winding of the first layer of the proof-of-principle coil of the *optimum integral design*. The picture on the left clearly shows the midplane turns extending for the full length: this is the reason why the optimum integral design creates a larger effective length than the conventional designs for the same coil length. The picture in the middle shows one half of the full coil length. The picture on the right shows the right end. One can see two spacers between the groups of turns in the straight section and the two in the end. The winding for each layer starts from the pole turn of one-half of the coil, proceeds to the midplane, and then to the pole of the other half of the coil. This avoids a splice between the two coil halves.

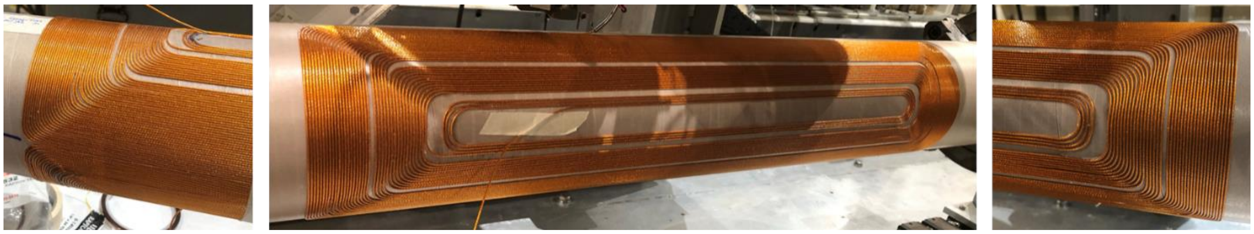


Figure 9: Views of the first layer of the proof-of-principle coil during the winding. The picture on the left shows the left end (where one can also see the midplane turn extending for the full coil length); The picture in the middle shows one half of the full coil and the picture on the right shows the right end.

Fig. 10 (left) shows the voltage tap install at the pole exit from the first layer of the proof-of-principle coil and Fig. 10 (right) shows a coat of the blue epoxy after filling the gaps in the coil winding that were left for the body and end spacers.

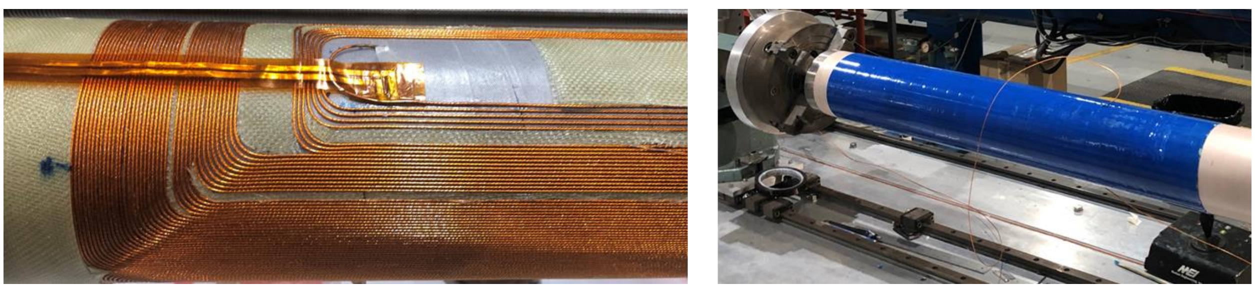


Figure 10: Left: Voltage tap install at the pole exit from the first layer of the proof-of-principle coil; Right: A coat of the blue epoxy after filling the gaps in the coil winding that were left for the body and end spacers.

Fig. 11 shows a snapshot taken during the winding of the second layer of the coil. One can again appreciate from this picture how far the midplane turns are extended which is the key to creating a larger integrated field in the optimum integral design over the conventional end design for the same coil length. Fig. 11 (left) is the photo taken during the winding and Fig. 11 (right) was taken after all windings for the proof-of-principle dipole were completed and the voltage-taps and quench testing heater installed.

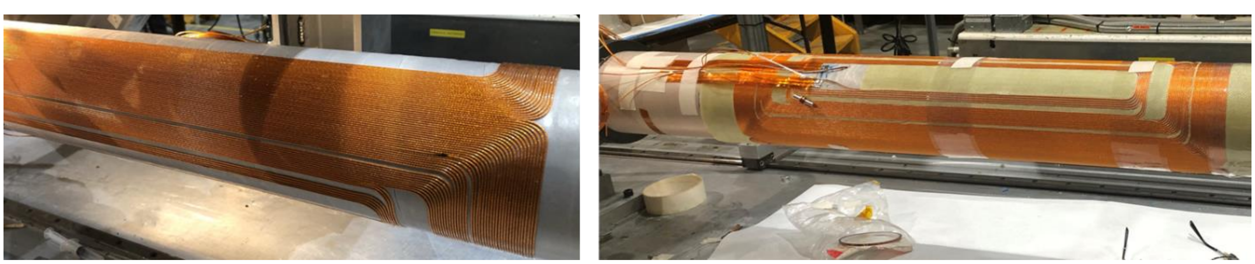


Figure 11: Left: Second layer of the optimum integral design being wound; Right: Second layer wound and voltage-tap wires at the leads installed.

Figure 12: Left: Optimum integral proof-of-principle dipole coil with Fiberglass roving providing necessary pre-tension after the final cure; Right: Optimum integral proof-of-principle coil inside the iron yoke completed as a part of a key Phase I deliverable.

Fig. 12 (left) shows the optimum integral coil for the proof-of-principle dipole with multiple layers of Fiberglass roving providing the necessary pre-tension after the final cure and Fig. 12 (right) shows the optimum integral coil placed inside the iron yoke ready for test. The magnet has a simple cylindrical yoke with an inner diameter of 5 inches (127 mm) and outer diameter of 9 inches (228.6 mm) and a length of 26” (660.4 mm).

The construction of the magnet with two layers of coil wound and placed inside the iron yoke was a key Phase I deliverable.

4.5 Preparation and Test of the proof-of-principle dipole for a 4 K test

The magnet was high-potted and various QA tests on the coil were performed as a part of the preparation for the 4 K test. Pictures in Fig. 13 (left and middle) show the magnet getting prepared with all electrical and instrumentation connections within the top-hat, and the picture in Fig 13 (right) shows the proof-of-principle optimum integral dipole placed in the Dewar for the 4K test.

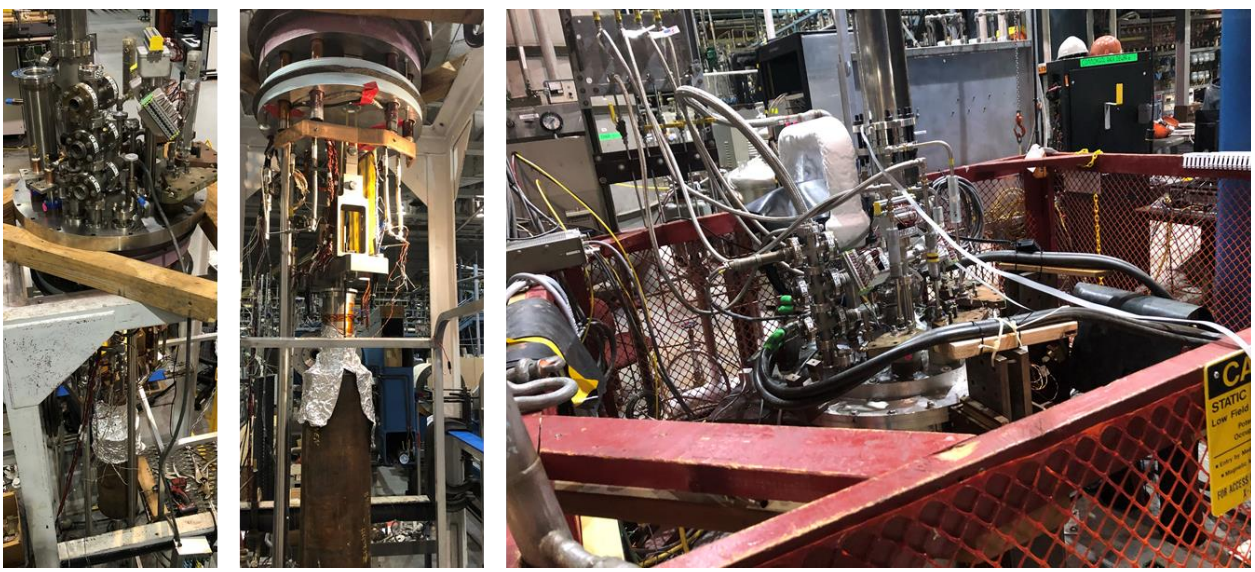


Figure 13: Optimum integral dipole getting ready with all electrical and instrumentation connections within the top-hat (left and middle) and in Dewar for the 4K test (right).

The short sample (quench current) calculations are shown in Fig. 14 (left) and the test results in Fig. 14 (right). The magnet reached the plateau at a current of ~868 A after the first quench at 860 A. A couple of quenches were also performed to study the ramp rate effects on the quench performance that was anticipated for the 6-around-1 cable. The magnet will not be ramped in the EIC at such high ramp rates and was merely an academic exercise for this purpose.

This was a significant demonstration of the *direct wind technology* for a Phase I. Phase I demonstrated that a 114 mm aperture magnet produced a bore field of ~1.7 T field (peak field on conductor ~2.2 T), only after one quench; the first quench itself was very close to the plateau. The exact cable performance is not known since it was a leftover (spare) conductor. The computed quench field was essentially the same as that predicted for a similar conductor.

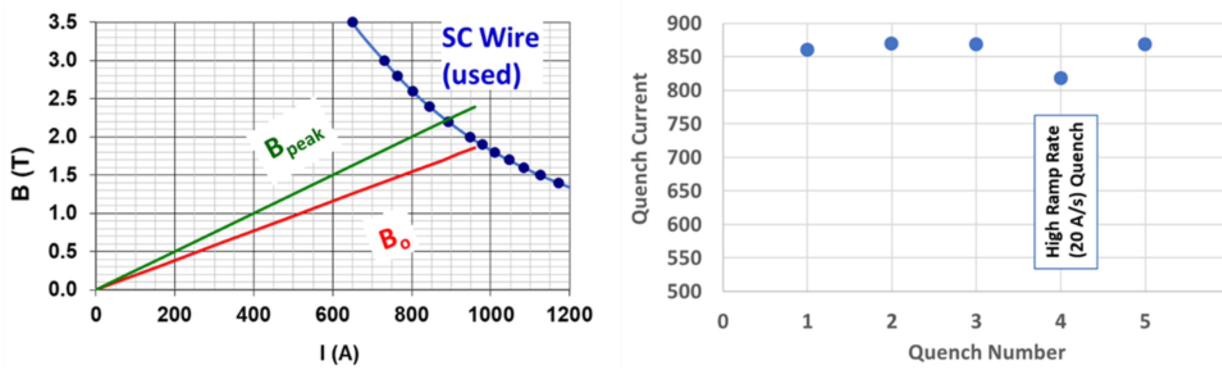


Figure 14: Left: Computation of the quench current, peak field on the conductor and the field at the center of the magnet for a conductor similar to the one used in the Phase I dipole. Right: Quench current for the first five quenches. Magnet reached the quench current of ~868 A after the first quench at 860 A. Ramp rate dependence can be seen at a high ramp rate (higher than that required in the EIC) as the magnet quenched at 818 A when the ramp rate was 20 A/s.

4.6 Comparison Between calculations and measurements in the Proof-of-principle dipole

We compare the measurement of the field along the axis with the calculations. This is an important evaluation of the claim that the optimum integral coil design can extend the high field region in the magnet. It was not a part of the test scheduled in Phase I but was carried out at room temperature (a low-cost test) given its importance. Fig. 15 compares the measurements and calculations at a current of 2 A. The calculations are shown with a solid blue line and the measurements are shown with an open red circle. A good agreement between the two shows the promise of the optimum integral design.

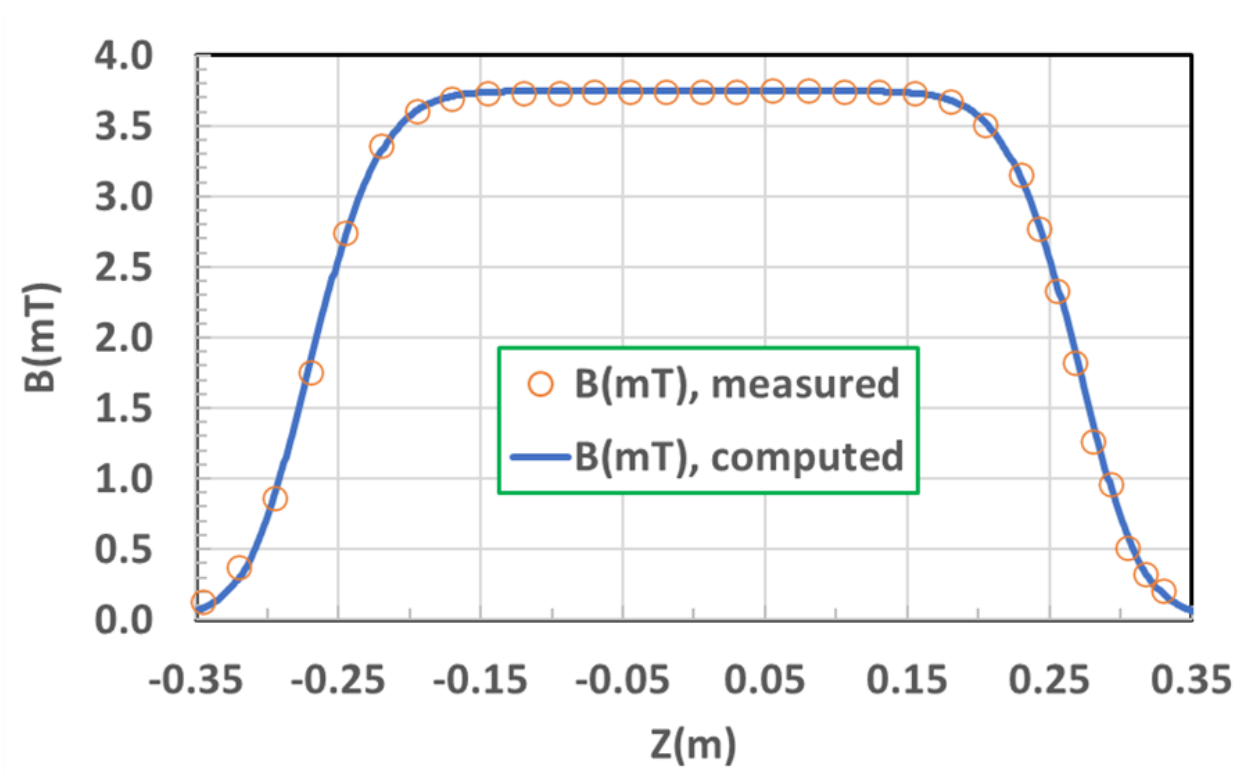


Figure 15: A comparison between the calculations (solid blue line) and measurements (open red circle) at a current of 2 A. A good agreement between the two shows the promise of the optimum integral design.

4.7 MAGNETIC, MECHANICAL AND WINDING OPTIMIZATION FOR THE PHASE II MAGNET

The initial overall design of the magnet that is being proposed to be built in Phase II has been developed. This includes the winding optimization, magnetic analysis, and mechanical structure concept and analysis sufficient to assure that Phase II will be successful. Detailed analysis and optimization will continue during the early part of Phase II. This work is discussed in more detail in the next section.

5 THE PHASE II PROJECT

5.1 TECHNICAL OBJECTIVES

The overall technical objective or goal of Phase II is to demonstrate that the *optimum integral design* can produce an accelerator quality dipole with significant field and aperture that can be used in an accelerator like the EIC. We are using the EIC IR dipole, with a central field of 3.8 T, an aperture of 114 mm and a length of 600 mm to produce an integral field of 1.98 T-meter, as an example. Giving the 2-year schedule and budget of the SBIR/STTR program, this is an ambitious goal that we believe can be achieved with the advantages of *direct wind technology*, as outlined earlier and demonstrated during Phase I.

The technical objectives listed below are meant to ensure that the goals of Phase II are ensured:

- Enhancement of Code to Optimize the Phase II Design
- Magnetic Design and Analysis of the Phase II EIC IR Dipole B0Apf
- Mechanical Structure Design and Analysis of the Phase II Dipole
- Winding of Phase II Coils and Construction of the Dipole
- Quench Protection and Analysis of the Phase II Dipole
- Phase II Dipole Field Quality and Quench Tests
- Ensuring Field Quality in the Phase II Dipole

5.2 PHASE II WORK PLAN

To achieve the above-mentioned technical objectives, satisfy various requirements of Phase II, and to apply the optimum integral design in other future potential applications, we have divided the Phase II work plan into the following tasks:

Task 1: Enhancement of Code to Optimize the Phase II Design: The code *IntegralOpt* developed and ported in Phase I will go through a significant upgrade in Phase II and a user manual will be written. The upgrade will include (1) a change in the structure of the program to optimize all ten layers (and more) of the coil together. The limitation comes from the external optimization routines that forced the initial Phase II design to be carried out in two parts; (2) *IntegralOpt* will be upgraded to compute the quench field (short sample) and OPERA3D files; (3) *IntegralOpt* will be upgraded to create "BRIC20" elements of OPERA3D as well, where a number of wires in the blocks can be combined. Currently it creates output for each turn separately which requires a large computer time. This task will be primarily carried out by the PBL team with active participation of the BNL team.

Task 2: Magnetic Design and Analysis of the Phase II EIC IR Dipole B0Apf: The initial optimum integral magnetic design developed for the EIC IR dipole B0Apf in Phase I (see Table 4) will be further optimized to create the highest possible integral field while iterating with the structural design. The optimization will involve further reduction in field harmonics, reduction in peak field on the conductor and maximization of the transfer function to produce the highest possible quench (short sample) field in ten layers.

Fig. 16. shows the initial magnetic design of the Phase II B0ApF optimum integral dipole with the OPERA3d model with coil (red) and iron yoke (transparent green) on the left; a zoomed in view of the model with field superimposed over the coil and iron in the middle at a current of 500 A, and another view of the coil with field superimposed on right (iron present in the model calculation but hidden in this view for clarity). This task will be performed jointly by the PBL and BNL teams.

Table 4: Key parameters of the initial Phase II *optimum integral design* for EIC dipole B0ApF

Coil Aperture	114 mm
Design Field	3.8 T
Peak Field	4.2 T
Coil Length	0.6 m
Number of Layers	*10*
Number of turns	*499*
Stored Energy	58 kj

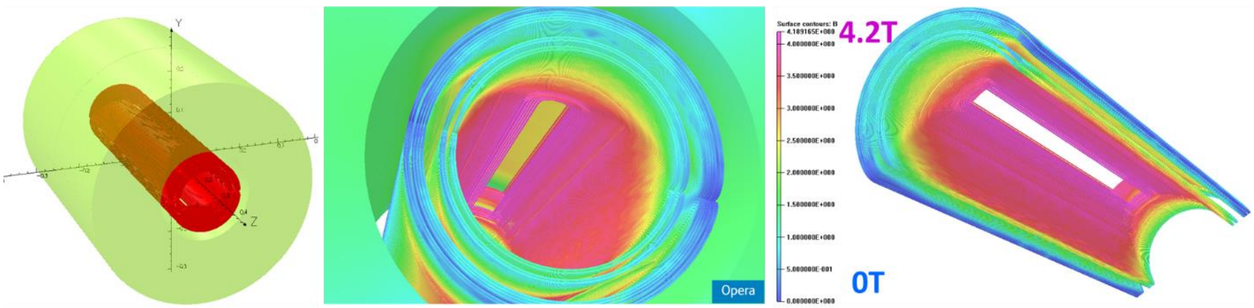


Figure 16: Left: OPERA3D model of the initial optimum integral dipole for Phase II (coil is red and the iron is green); middle: a zoomed in view of the field superimposed over the coil and the iron yoke at 500 A; right: another view of *field superimposed on the coil (iron yoke hidden).*

Task 3: Mechanical Structure Design and Analysis of the Phase II Dipole: An appropriate mechanical structure design and analysis is a key task of this proposal. The initial design concept is an iterated version of the current baseline double helix design of B0Apf. The overall concept is shown in Fig. 17. It will be further developed to deal with the Lorentz forces when the magnet is energized to the design field. The pre-stress on the coil will be provided with pre-tension in the Fiberglass, which is efficient against the radial Lorentz forces but not against bending. To provide appropriate support against bending, three tubes will be employed. Two stainless-steel tubes will be used on which the two coils will be wound, and one outer-most either made of stainless-steel or high strength Aluminum tube (choice to be made after further analysis during the first year) will go over the entire 10-layer coil set. The outer tube will be designed as interference fits for preload and heated at assembly to provide clearance for ease of installation. A gap of 3 mm is left between the outside surface of the inner coil with Fiberglass roving and the inside of the stainless-steel tube of outer coil to allow for Helium refrigerant flow, except for a pad at the midplane. The pads between the inner coil and outer coil, in the space left for the Helium cooling, will provide contact to transfer Lorentz forces from the inner to outer components at the midplane at high fields. End plates will play a role in locating the stainless-steel tubes and iron, as well as dealing with the end Lorentz forces, as needed.

Initial mechanical analysis of the initial structure is performed with the codes ANSYS and COMSOL. This analysis will continue in more details in Phase II. The analysis includes the stainless-steel tubes and wrapping of layers fiberglass applying tension on the coil. The tension provides partial support against the Lorentz forces. This tension is represented as a radial pressure on the outer surface. Fig. 18 (right) shows the maximum displacement in microns as a function of applied radial pressure, P. The red curve shows the maximum displacement in the coils and the blue curve shows the maximum displacement anywhere. The maximum displacement is generally in the coils however it will move away from the midplane with larger radial pressure. As the radial pressure becomes larger the maximum displacement moves from the coils to the stainless-steel support. Fig. 18 (middle) shows the displacements as computed by ANSYS in meters at P=1 N/mm^2 and at Fig. 18 (right) at P=25 N/mm^2. The maximum displacements are near the pole where the Lorentz force is not well matched to the radial tensile force and at the mid-plane where the Lorentz forces are large. As the tension increases the maximum displacement moves to the center. Such analysis and structure design will be further refined and optimized during the initial part of Phase II.

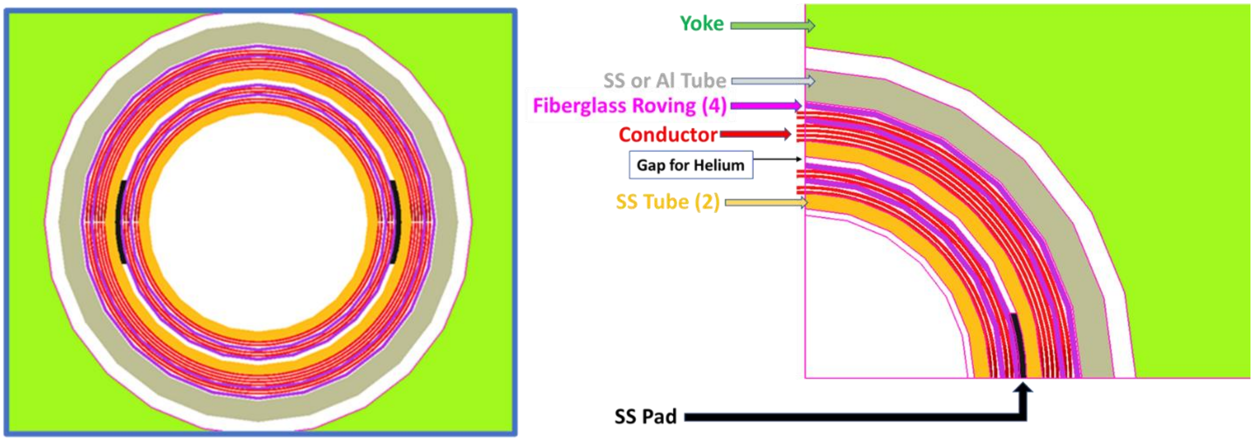


Figure 17: Initial structure design concept of the Phase II dipole, an iterated version of the baseline double helix design. The model on left shows the full model of coils and key structural components, and the picture on the right have the key components labeled in ¼ of the model.

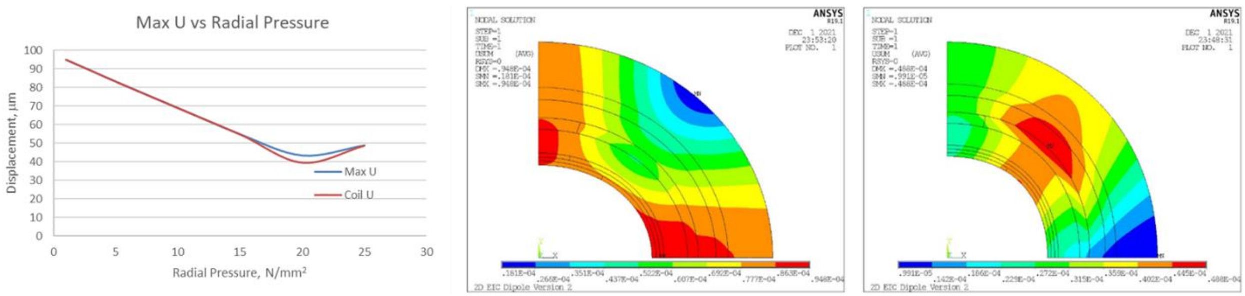


Figure 18: Left: Maximum displacement (in microns) as a function of applied radial pressure; Center: Displacements in meters from ANSYS model for a radial pressure of 1 N/mm^2; Right: for a radial pressure of 25 N/mm^2.

Study of other structure options with corresponding mechanical analysis, including optimizing the thickness of various tubes will continue in Phase II. This task will be performed jointly by the PBL and BNL teams. The BNL team will lead the overall structural design and PBL will lead the analysis using the codes ANSYS and COMSOL.

Task 4: Winding of Phase II Coils and Construction of the Dipole: The Phase II dipole will have 10 layers in two coils (an inner coil with 4 layers and an outer with 6) wound on two separate stainless-steel tubes.

> **Task 4a:** Winding of the inner layer will be performed during the first year of the project. For the inner coil, two more layers will be wound on the existing two layers of the Phase I coil which underwent short sample testing during Phase I. Fiberglass roving will provide the required pre-tenson. The preliminary engineering and detailed plan for the construction of the magnet will also be completed during the first year of the project.
>
> **Task 4b:** Six layers will be wound on a separate stainless-steel tube for the outer coils, with an intermediate Fiberglass roving after four layers. Voltage taps and quench heaters will be installed. Both coils will be assembled with stainless-steel pads. Stainless-steel or high strength Aluminum tube will go over the outer coil, and end plates and an iron yoke will be installed. The two stainless-steel tubes will be located inside the iron yoke with the end plates.

Winding of coils and construction of the magnet is the task that will require the most labor in this project. This task will be primarily performed by the BNL team with guidance and supervision from the PBL team.

Task 5: Quench Protection and Analysis of the Phase II Dipole: Calculations will be performed to ensure that the maximum temperature rise remains below an acceptable limit in the event of a quench. An external dump resistor will be used, and the 10 layers of coils may have to be divided into a few sections with internal cold diodes between the layers. This task will be performed jointly by the PBL and BNL teams.

Task 6: Phase II Dipole Field Quality and Quench Tests: Field quality will be measured warm (see more in Task 7) and cold using the existing measuring coil at BNL. The magnet will be instrumented, high-potted and prepared for quench the test with external dump resistors. Results of Task 5 will be incorporated in planning of the appropriate quench protection. A 4 K test will be performed in the main test area of the magnet division and successful completion of this will be the major demonstration of the *optimum integral design* and the *direct wind technology* at high field (3.8 T) and with a large aperture (114 mm). This task will be primarily performed by the BNL team with guidance and supervision from the PBL team.

Task 7: Ensuring Field Quality in the Phase II Dipole: Several field quality measurements will be performed at room temperature during the construction of the magnet. The first measurement will be performed after the inner coil with four layers has been wound. Any non-zero harmonics will be compensated for by iterating the winding pattern of the outer layers. Such a method, which requires only a small adjustment in the original winding pattern, has been used successfully earlier in other direct wind magnets in producing high field quality magnets. The second warm measurement will be performed after four layers of the outer coils are wound. The final adjustment/correction will be performed in the last two layers of the coil. Controlling yoke saturation is not part of the present proposal for the budget reasons. Such optimization has been carried out earlier with holes and other saturation control techniques at BNL and could be part of a proposal beyond Phase II. This task will be primarily performed by the BNL team with guidance and supervision from the PBL team.

Task 8: Evaluation of the *Optimum Integral Design* for Other Applications: The *optimum integral design*, once demonstrated for EIC IR dipole B0Apf can be applied to other EIC magnets (dipoles and quadrupoles) to reduce the maximum field required for the same integral field in the allocated length of the magnet.

The *optimum integral design* can be used in other accelerator, medical and fusion energy magnet application magnets as well. The *optimum integral design* provides a unique solution for building short magnets, with dipole coil lengths less than their coil diameter, quadrupole coil length less than their coil radius and sextupole coil length 2/3 of their coil radius, etc. [12]. Such short superconducting magnets are otherwise not possible with a comparable integral field for the same coil length and coil thickness. Examples of short quadrupole, sextupole, and octupole coils are given in Fig. 19.

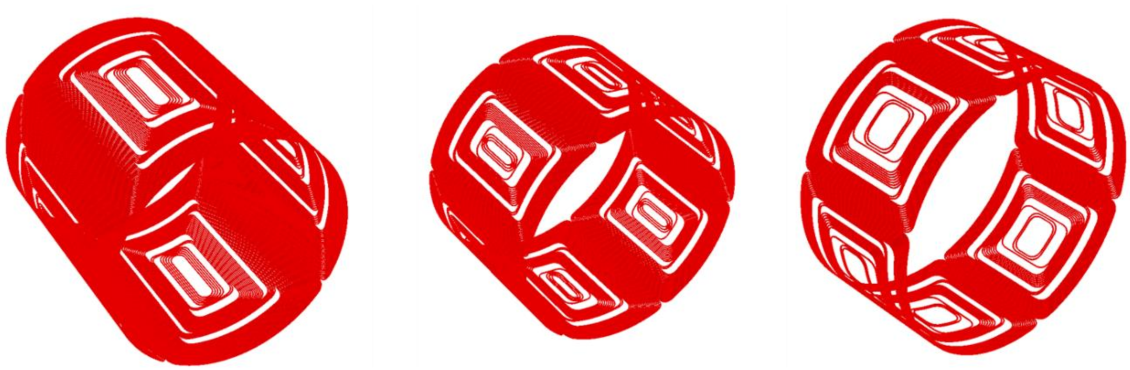


Figure 19: Examples of short quadrupole, sextupole, and octupole coils based on the optimum integral design.

This task will be performed jointly by the PBL and BNL teams.

Task 9: Preparation of Phase II Report and Plans beyond Phase II: The PBL and BNL teams will jointly prepare the Phase II report. The PBL team, with support from BNL, will take the lead in making plans beyond Phase II. The coil for EIC IR dipole B0Apf is expected to be optimized for geometric field quality and for producing low field harmonics from injection to medium field. However, since the yoke is not optimized, the saturation induced harmonics may be large. The yoke can be optimized and demonstrated to produce low saturation-induced harmonics in a program beyond Phase II.

The *optimum integral design* can be used to increase the margin and reliability or to reduce the cost of other EIC IR magnets as well. This becomes important as there is a desire to use the *direct wind technology* for EIC high field magnets to reduce cost, as emphasized by Dr. Ferdinand Willeke, Deputy Project Director/Technical Director of the EIC in the attached letter of support in section 8.

General Atomics GA is participating in this proposal at their own cost, as mentioned in their letter of support attached to this proposal. They are interested in taking the magnet design and program for the EIC magnets to markets for other applications beyond what is planned in Phase II.

Managerial Controls for a Successful Project

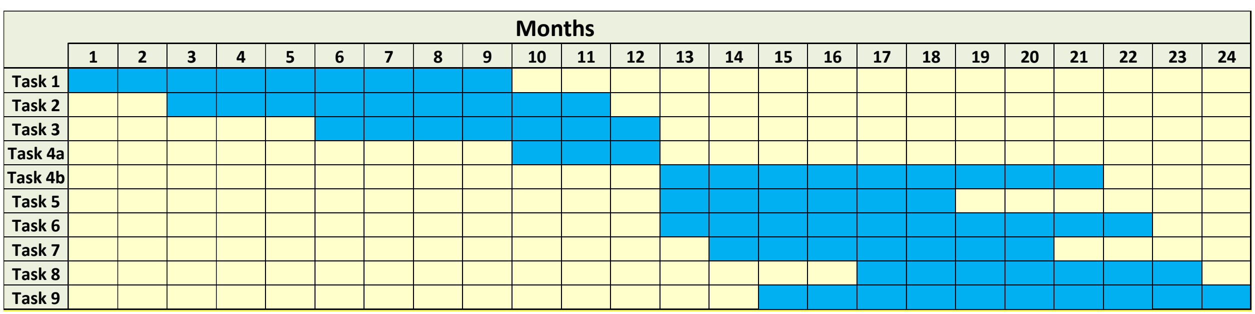
To ensure a successful project, PBL will hold regular technical meetings and compare progress made against the performance schedule below. The technical staff will meet to ensure that important milestones are being met in a timely way. PBL PI Dr. Kahn has an office at the BNL campus. PBL senior management 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 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.

6 Performance Schedule

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

- Task 1: Enhancement of Code to Optimize the Phase II Design
- Task 2: Magnetic Design and Analysis of the Phase II EIC IR Dipole B0Apf
- Task 3: Mechanical Structure Design and Analysis of the Phase II Dipole
- Task 4a: Winding of Phase II Inner Coils
- Task 4b: Winding of Phase II Outer Coils and Construction of the Dipole
- Task 5: Quench Protection and Analysis of the Phase II Dipole
- Task 6: Phase II Dipole Field Quality and Quench Tests
- Task 7: Ensuring Field Quality in the Phase II Dipole
- Task 8: Evaluation of the *Optimum Integral Design* for Other Applications
- Task 9: Preparation of Phase II Report and Plans beyond Phase II



7 Related Magnet R&D Done by the PBL/BNL Team

Over the years, the PBL/BNL team has been involved in various magnet SBIR/STTR R&D projects for high energy and nuclear physics. This experience helps in developing magnet technology for wider use. The PBL/BNL team has established a strong R&D position in 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%. Another major achievement of this team is the demonstration of a significant field HTS/LTS dipole magnet. In an earlier SBIR, PBL/BNL has demonstrated the promise of superconducting shielding in EIC magnets and in another SBIR, developed a novel preliminary Nb_3Sn quadrupole design for high field EIC IR magnets.

8 LETTER OF SUPPORT FROM DR. FERDINAND WILLEKE, TECHNICAL DIRECTOR EIC

Electron-Ion Collider Directorate

BROOKHAVEN NATIONAL LABORATORY

Electron-Ion Collider

Building 911
P.O. Box 5000
Upton, NY 11973-5000
Phone (631) 344-2216
willeke@bnl.gov

November 30, 2021

Mr. James Kolonko
Particle Beam Lasers, Inc.
8800 Melissa Court
Waxahachie TX 75167-7279

Dear Mr. Kolonko,

This letter is to express our strong interest in your proposed work which is highly relevant for the EIC interaction region magnets. The EIC, the electron ion collider is a new collider project underway a Brookhaven National laboratory. In its interaction region, high energy electron and ion beams will be brought into collisions using superconducting magnet technology.

I learned that based on the Phase I study of superconducting magnets in direct wind technology, you plan to build a prototype.

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 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 has not yet been demonstrated, are high magnetic fields in the range of 2 Tesla using the proposed methods.

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.

The study carried out in the first phase of this STTR is quite promising and is an excellent base for phase II prototyping. This is the next logical steps. An earlier prototype of a direct wind magnet based on the double helix coil pattern was quite successful. With the latest design work in the frame of the Phase I STTR, the prototype promises to meet the challenging parameters of large aperture superconducting dipole such as the B0PFspectrometer magnet in the EIC interaction region.

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

Sincerely,

Ferdinand Willeke

Ferdinand Willeke
Electron Ion Collider Deputy Project Director/Technical Director

9 FACILITIES/EQUIPMENT

The Superconducting Magnet Division (SMD) at BNL, working in collaboration with PBL, will have primary responsibility for winding the coils, and building and testing of the magnet. SMD at BNL has been a major force in the development of accelerator magnets for many decades. It has a staff of over 35, including scientists, engineers, technicians, and administrative staff. It has a 55,000 ft^2 multipurpose R&D complex with a variety of 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* that were used during Phase I (one for winding the practice coil and another for the proof-of-principle coil). These machines will be used for winding the Phase II coils. SMD has access to a variety of simulation and engineering software tools which includes ROXIE, OPERA2d, OPERA3d and in-house software for magnetic design, ANSYS and COMSOL for mechanical design, and CREO and AutoCAD for engineering design. The magnet division has also developed an array of magnet design software, such *IntegralOpt*, which is being used and further developed for the *optimum integral design*. 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. Within the building complex are two machine shops with capacity to manufacture many components needed for the R&D tasks. The infrastructure (space, tools, test equipment, etc.) that are part of the Division will be made available for the Phase II work. The value of the infrastructure at BNL is well over $40 million, use of which is an "in-kind" contribution crucial to the project.

10 PRINCIPAL INVESTIGATOR AND OTHER KEY PERSONNEL

Dr. Ramesh Gupta, inventor of the "optimum integral design," will be Principal 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. 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), 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 who has played a major role in developing the direct wind technology), Jason Becker (who is involved in upgrading the direct wind software and hardware), 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 magnet division at BNL.

Dr. Stephan Kahn (senior scientist) will be the principal investigator for PBL. Other key members of PBL team are Dr. Ronald M. Scanlan (senior scientist), Dr. Erich Willen (senior scientist), Mr. Robert J. Weggel (senior engineer), Mr. Carl Weggel (senior engineer), Dr. Erich Willen (senior scientist), Dr. Al Zeller (senior scientist and consultant), Mr. Roger London (Commercialization Assistance Provider and consultant), Dr. Delbert Larson (senior scientist and Vice President), and Mr. James Kolonko (President).

More information about our team members, including their brief bios, can be found in the form "Research and Related Senior/Key Person Profile" which is uploaded as a part of this proposal.

11 Consultants and Subcontractors

11.1 Brookhaven National Laboratory (Research Institution)

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

Name, phone number, and email address of the certifying official from the RI:

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

Total dollar amount of the subcontract: $590,000

11.2 Consultants

Dr. Al Zeller will serve as senior physicist consultant for the Phase II work. Dr. Zeller will assist the project by providing his technical services on superconducting magnets, PBL has a budget of in $4,800 of consultant payments for each year during this Phase II. PBL will also be using Roger London as our CAP provider. Mr. London will assist PBL in all phases of business development and marketing during the Phase II. PBL has a total budget of $25,000 for his services in each year.

12 References

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