

Design, Construction, and Test of R&D Dipole B0ApF for the EIC

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Abstract— The Department of Energy awarded Phase I and Phase II Small Business Technology Transfer grants to Particle Beam Lasers, Inc. (PBL) with Brookhaven National Laboratory (BNL) serving as a partner to demonstrate the Optimum Integral Design (OID) in a full-length R&D model. The chosen magnet B0ApF is one of several large-bore superconducting magnets in the Interaction Region (IR) of the proposed Electron Ion Collider (EIC), where the coil length to coil aperture ratio is relatively small compared to those in most accelerators. Conventional cosine n -theta cable magnet designs are not efficient for such short magnets as the ends dominate and dilute the integral field. The OID offers a novel solution to keep the maximum field in short length magnets low for the required integral field. After introducing the optimum integral design principle, design, construction, and a series of tests (later tests supported by BNL) of the magnet will be presented. Primarily because of this initiative, the optimum integral design is now being used in several other EIC IR magnets, including in the large aperture spectrometer dipole B0pF where it has significantly reduced the risks to EIC.

Index Terms—Accelerators, Colliders, Dipoles, Electron Ion Collider, Magnets, Superconducting Magnets.

I. INTRODUCTION

THIS paper summarizes the work performed on B0ApF, a modest field Interaction Region (IR) dipole magnet for the Electron Ion Collider (EIC) [1], now under construction at Brookhaven National Laboratory. Figure 1 shows the location of B0ApF and other magnets in the EIC IR. Because the IR is crowded, minimizing magnet length is crucial to the luminosity performance of EIC. The Optimum Integral Design (OID) [2], described in the next section, is particularly efficient for short magnets. Table I lists EIC IR magnets in which the ratio of coil length to aperture is small (compared to over 100 in most accelerator magnets). As a part of this STTR [3], the OID was examined for these magnets. Among them, B0ApF was the most economical to carry out a proof-of-principle demonstration. The design requirement of

B0ApF for an integral field of 1.98 T.m for a coil of length 600 mm, made its design parameters (coil ID = 114 mm, central field $B_0 = \sim 3.6$ T) even more challenging than that of the RHIC arc dipoles (coil ID = 80 mm, $B_0 = 3.45$ T). Such an ambitious task could be carried out in the limited budget of STTR because the direct wind technology [4] required no new tooling or detailed engineering.

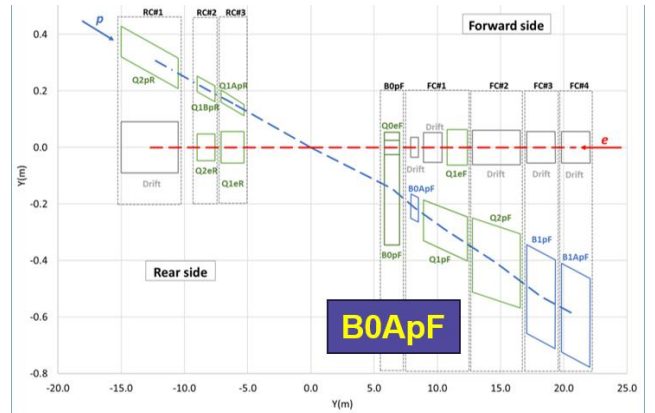


Fig. 1. Location of various magnets (including B0ApF) in the Interaction Region (IR) of the Electron Ion Collider (EIC).

TABLE I
GEOMETRIC PARAMETERS (COIL LENGTH, COIL ID AND LENGTH TO ID RATIO) OF A FEW SHORT EIC IR MAGNETS

Magnet	Length (mm)	ID (mm)	Ratio
B0pF	1240	656	1.9
B0ApF (original)	600	114	5.3
B0ApF (current)	500	105.3	4.7
B1pF/B1ApF	2036	356	5.7
Q3 Package	400	137.4	2.9

II. OPTIMUM INTEGRAL DESIGN

In Rutherford cable magnets, the length of the two ends of a dipole is generally between 3 to 4 times the diameter of the coil (3 to 4 times the coil radius in a quadrupole). The average field in the end region is only about half of that in the body of the magnet. Therefore, the conventional cosine n -theta designs are not efficient for short magnets such as B0ApF where ends become a significant fraction of the overall coil length and significantly dilute the integral field. The situation becomes somewhat better in direct wind magnets using a small diameter cable in designs such as the double-helix or the serpentine since the bending radius

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could be small. However, a relative loss in integral field from these ends remains large in the magnets listed in Table 1.

Conventional cosine theta design optimization is a two-step process of the magnet body and of magnet ends. The packing of turns in both body and ends of the magnets gets diluted to reduce the peak field and meet the field quality requirements.

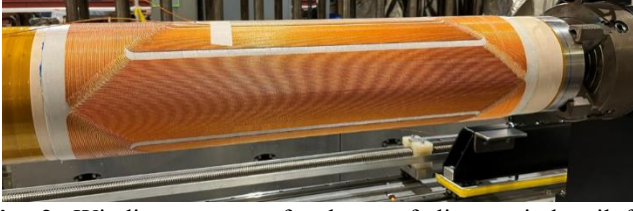


Fig. 2. Winding pattern of a layer of direct wind coil for B0ApF, based on the optimum integral design.

OID [2] is a one-step process in which the length of the midplane turn is made essentially equal to the coil length (Figure 2) with the bend radius of the turns at 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. In practice, 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 that distributes the number of turns from each layer in a few end blocks and in a few cross-section blocks. The size of the spacers between the blocks is optimized to achieve an integral distribution varying azimuthally as:

$$I(\theta) \cdot L(\theta) = I_0 \cdot L_0 \cdot \cos(n\theta) \quad (1)$$

Because the cosine theta modulation is normalized to the current I_0 times the length L_0 (L_0 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_0). This is a significant improvement over the designs discussed in the previous section, where the loss in effective magnetic length from L_0 was about a coil diameter/ (n) .

III. OPTIMUM INTEGRAL DESIGN CODE *INTEGRALOPT*

The original software *MINXEND* [5] was written for a VAX/VMS system. It has been ported and enhanced for modern Personal Computers and named *IntegralOpt* [3]. It is based on the formula that the integral harmonics B_n ($n=0$ for dipole) at a reference radius R_0 for a wire of length L located at a radius of a and at an angle of ϕ are given by:

$$B_n = 10^4 \left(\frac{R_0}{a} \right)^n \cdot L \cdot \cos[(n+1)\phi] \quad (2)$$

Software rapidly optimizes a 3-d design for maximizing the integral field while minimizing the unwanted field harmonics. The program adjusts the number of turns per block (independently for the straight section and ends), spacing between the blocks and inter-turn spacing within each block.

IV. MAGNETIC DESIGN

Key parameters of the conductor used in B0ApF are listed in Table II. It is a 12-layer design with a coil inner radius of 114 mm and coil length of 600 mm. Key design parameters are given in Table III and OPERA3d [6] model in Figure 3.

TABLE II

KEY PARAMETERS OF THE SUPERCONDUCTOR USED IN B0ApF

Filament diameter	10 microns
Wire diameter	0.33 mm
Cu to Non-Cu ratio	2.51
Cable type	6-around-1
Cable diameter, bare	1 mm
Cable diameter, insulated	1.1 mm
Cable I_c @ 5 T, 4.2 K	420 A

TABLE III

KEY PARAMETERS OF THE PBL/BNL DIPOLE B0ApF

Coil inner diameter	114 mm
Coil outer diameter	183 mm
Design integral field	1.98 T.m
Design current	470 A
Field at center of the magnet design	3.9 T
Peak field at the design current	4.3 T
Computed quench current at 4.2 K	480 A
Coil length	600 mm
Magnetic length	0.51 m
Stored energy (design)	70 kJ
Inductance	0.7 henry
Number of layers (inner + outer)	12 (6 + 6)
Number of turns per quadrant	762
Inner tube inner diameter	102.3 mm
Inner tube outer diameter	113.5 mm
Intermediate support tube inner diameter	145.1 mm
Intermediate support tube outer diameter	158.0 mm
Yoke inner diameter	200 mm
Yoke outer diameter	317.6 mm
Yoke length	667 mm

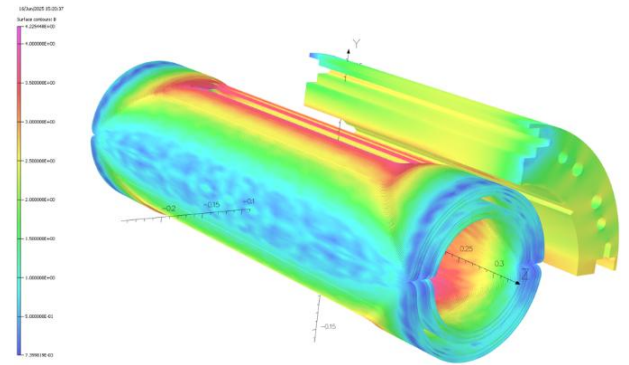


Fig. 3. OPERA3D model of the 12-layer (6 double-layer) optimum integral dipole with the magnetic field superimposed over the coils and iron at the design current of 470 A.

IV. MECHANICAL ANALYSIS

The mechanical structure consists of tension roving over a pair of layers, stainless-steel tubes and the iron yoke. The initial design had three tubes (inner, middle and outer); as-built, the outer tube was not installed, and there was a gap between the outer surface of machined coil and yoke. The analysis employed the software COMSOL [7] and ANSYS [8]. Figure 4 shows the key structural components in a 2-D ANSYS model of the magnet.

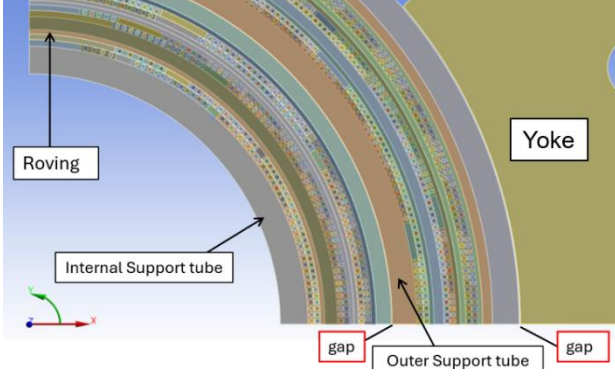


Fig. 4. ANSYS model with the key structural components.

IV. MAGNET CONSTRUCTION

The coil is wound using Direct Wind Technology [4] with cable directly bonded on an insulated beam tube coated with B-stage epoxy (see Figure 2). The wiring pattern is laid on the tube via a computer-controlled multi-axis winding machine. After the winding is completed, small gaps between conductors are filled with insulation of matching thermal expansion coefficient, either epoxy or a custom-cut insulator, depending on the size of the gap. The coil is then wrapped with multiple layers of tensioned fiberglass roving, epoxied and cured. Machining generates a smooth cylindrical surface after each two layers of coil. Six layers were wound on each of the two tubes, inner and outer. The two tubes were pinned and installed in the yoke. Tension roving, stainless-steel tubes and the yoke are the key components of the structure of the magnet.

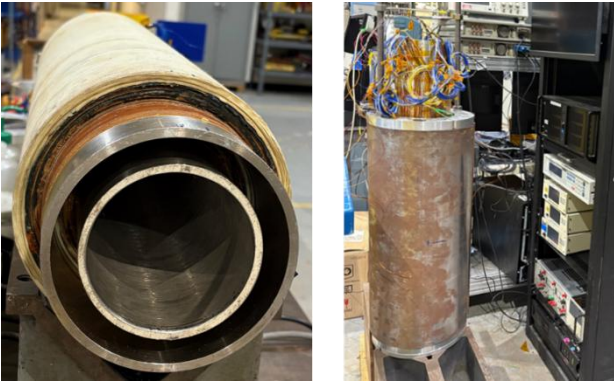


Fig. 5. Left: Inner and outer tubes together with six layers each; Right: 12-layer coil in yoke iron, ready for testing.

IV. TEST RESULTS

The primary purpose of this STTR and hence of the test program was to validate all major components of the optimum

integral design to a level that it can be used in the EIC. The main premises of the optimum integral design in enhancing magnetic length and integral field were validated during Phase I of the STTR. Figure 6 shows good agreement between the calculations and measurements in a 2-layer coil measured at room temperature.

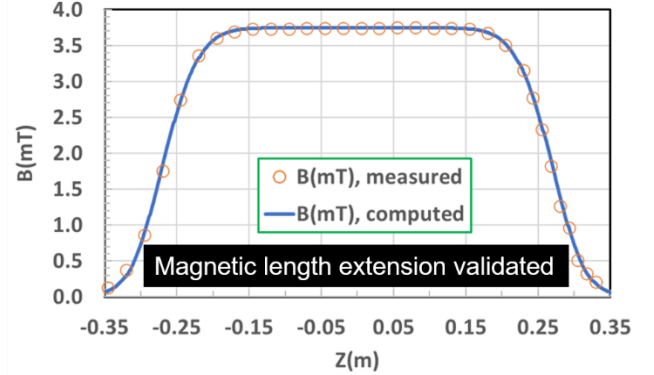


Fig. 6. Good agreement between the calculations and measurements in the 2-layer optimum integral design at room temperature validates the extension of magnetic length.

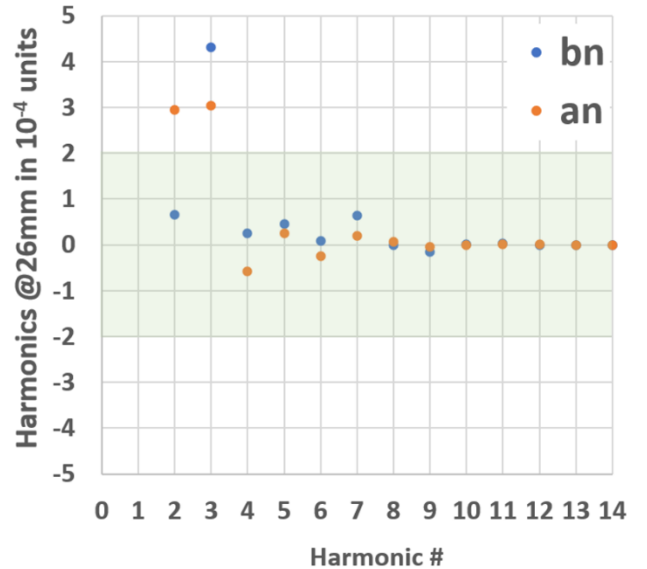


Fig. 7. Measured harmonics at a reference radius of 26 mm in a 6-layer coil designed and built with the optimum integral design. This validates the design principle and the software.

Measurement of the harmonics in the inner six-layer coil validated the optimum integral design principal and the new software (see Section III). The normal and skew harmonics (b_n and a_n) are defined in the following expression:

$$B_y + iB_x = 10^{-4} \times B_{R0} \sum_{n=1}^{\infty} (b_n + ia_n) [(x + iy)/R]^{n-1}, \quad (3)$$

where B_x and B_y are the components of the field at (x,y) , and B_{R0} is the magnitude of the field due to the most dominant harmonic at a “reference radius” R (26 mm). All harmonics met the specification of ± 2 units (see Figure 7), except for the lower order harmonics that may be coming from the leads. As such, the non-zero harmonics can be compensated in the subsequent layers of a direct wind magnet.

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The final validation of the optimum integral design came from the 4.2 K quench performance of the 12-layer coil and yoke. As shown in Figure 8, all quenches were over 367 A ($B_o = 3.2$ T, $B_{pk}=3.6$ T), which is 76% of the computed short sample, with the best reaching 426 A ($B_o = 3.6$ T, $B_{pk}=4.0$ T), which is $\sim 89\%$ of the short sample). The magnet retained the memory after a thermal cycle. The last data point (TRIP) was from a power supply trip and was not a real quench.

Overall, this (all quenches between 76% to 89% of the computed short sample) is an impressive performance in such a magnet built with a limited budget and engineering. Outer stainless-steel tube, included in the original design, was not installed due to budget and schedule. A small gap between the coil and the yoke, particularly after cool-down, prevented yoke from providing additional support. Movement of coil to the yoke because of the gap in between may be causing quench. Thus, there is room for even better performance.

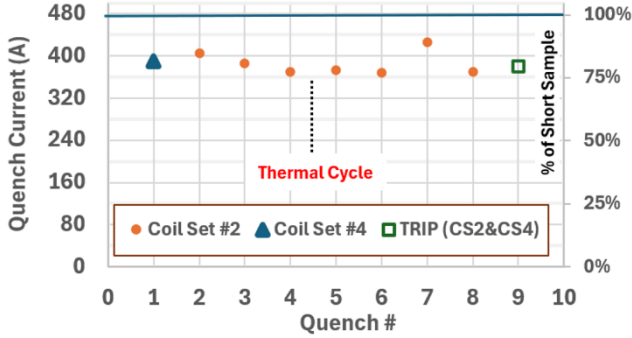


Fig. 8. Quench performance of the 12-layer PBL/BNL optimum integral dipole. The performance validates the basic design and construction.

V. QUENCH PROTECTION

As in any superconducting magnet, quench protection becomes a significant issue when the stored energy and inductance are large (see Table III). Quench protection for this test was based on the external energy extraction system with a dump resistor of 2.1Ω (see Figure 9). Figure 10 shows the quench transient for 426 A spontaneous quench. The experimental results are compared with the predictions of the SQUID quench simulation software [13, 14]. SQUID has been developed specifically for direct wind magnets. Good agreement between simulation and experiment validates the SQUID software.

The computed hot spot temperature was 206 K.

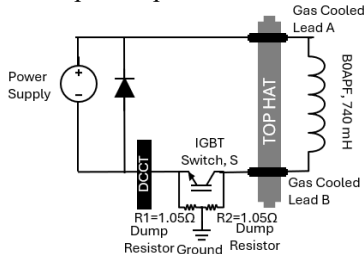


Fig. 9. Powering and quench protection circuit based on External Energy extraction at dump resistors.

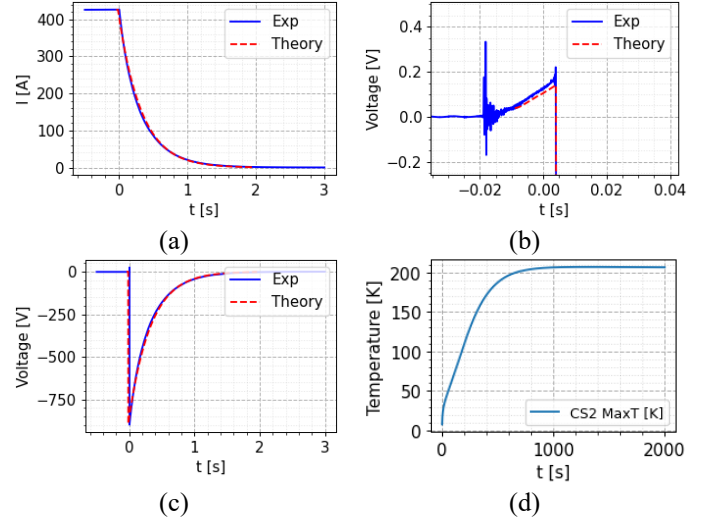


Fig. 10. Spontaneous quench at 426 A. (a) Magnet Current discharge, (b) Resistive voltage rise, (c) voltage at external dump resistor, (d) computed hotspot temperature.

VI. APPLICATION OF OID TO OTHER MAGNETS IN EIC IR

After proving the basic design, an important task of the STTR was to examine the benefit of OID to other magnets in EIC [9]. Apart from using it in the new design of B0ApF [9] and in the corrector magnets within the same package, it was earlier examined for B1pF and B1ApF [10] and is being currently used in the design of other EIC magnets. In particular, the optimum integral design (now in use) had a major impact on the design of spectrometer magnet B0pF [11] (the most challenging magnet in EIC). B0pF has a coil inner diameter of 656 mm and a coil length of ~ 1250 mm, making the diameter/length ratio only ~ 1.9 . Compared to the original serpentine design of B0pF [15], OID has been able to:

- Reduce the number of layers from 10 to 7
- Reduce the operating current from 1143 A to ~ 890 A
- Reduce the peak field on the conductor from 5.3 T to 4.2 T
- Reduce local strain and accumulated stress on the conductor and coil package due to Lorentz forces
- Improve load line fraction margin from 70% to $\sim 60\%$
- Reduce demand on quench protection (voltage to ground 950 V to 535 V)
- Eliminate the absolute need of the quench heaters
- Reduce cost

V. CONCLUSION

Optimum Integral Design essentially eliminates the dilution of integral field due to magnet ends. The design is most beneficial for short magnets. All aspects of the OID have been validated in the PBL/BNL B0ApF R&D magnet built under the STTR program, namely (a) enhancement in integral field, (b) small geometric field harmonics, and (c) good quench performance of 3.6 T in 114 mm aperture magnet. Optimum integral design is now being used in the new design of B0ApF and in several other short direct wind magnets in EIC, including the large aperture spectrometer magnet B0pF.

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