

A Novel Optimum Integral Design for EIC Spectrometer Magnet B0pF

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Abstract— B0pF is one of the most challenging magnets in the Interaction Region (IR) of the Electron Ion Collider (EIC), now under construction at Brookhaven National Laboratory (BNL). B0pF is a multifunction magnet with a set of coils. This paper focuses on the outermost coils. Original coil design was based on serpentine geometry with quadrupole layers in series with two dipole layers (total ten). That design faced a set of major technical challenges (including quench protection and mechanical), associated with the high peak field and large coil inner diameter needed in the design. A small inner diameter to length ratio rendered the conventional designs (including the serpentine design) inefficient. The Optimum Integral Design (OID) offered a set of significantly more efficient novel solutions. OID extends the midplane turns to the full length of the coil which minimizes the loss in field integral from the ends. OID simultaneously reduces the number of layers and the operating current, reducing both the cost and the technical risks. OID approach will be explained. An important part was the development and use of new software. This paper will present the overall design approach along with a set of options. Current B0pF is now based on OID, with coil the winding already started.

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

I. INTRODUCTION

B0pF is a multi-purpose magnet system for the Electron Ion Collider (EIC). It provides bending with focusing on the hadron beam and focusing with no bending on the electron beam, and field to the experimentalist to provide the spectrometer function. Overall functionality, along with the design of a set of coils in the B0pF magnet system, is presented elsewhere [1]. This paper focuses on the design of the high-field, larger-aperture outer coils which must be short. A small length (~ 1240 mm) to coil inner diameter (656 mm) ratio (~ 1.9) makes the conventional cosine (n -theta) cable design impractical. Present design is based on the direct wind technology [2-4] which, for the small diameter 6-around-1 cable, allows bending radius in the ends to be small (~ 15 mm). Original design was based on the serpentine geometry with eight layers of quadrupole winding in series with the two layers of dipole winding (total ten). Even though that offered a

working solution, a combination of high field and large aperture made that design B0pF a high-risk magnet.

Optimum Integral Design (OID) [5], which has been recently validated in another EIC R&D magnet [6], significantly reduces the technical challenges, risks and cost. OID geometry led to a set of solutions that resulted in many major improvements. These included (a) the number of layers reduced from 10 to up to 6, (b) operating current reduced from 1143 A up to 671 A, (c) load line fraction margin improved from 70% up to 50% at 1.92 K or opening the possibility of operating temperature increased to 4.5 K, (d) peak field on the conductor at design reduced from ~ 5.3 T to ~ 4 T, (e) Lorentz force density, local strain (proportional to “ $I \times B$ ”) and accumulated stress on the coil package reduced by $\sim 30\%$, (f) voltage to ground on the coil reduced during energy extraction to protect the magnet after quench reduced from 950 V up to 466 V, and (g) need for quench heaters to keep hot spot temperature low eliminated.

OID opened other options also, such as the combined function windings and replacing the central non-transposed superconducting wire in 6-around-1 cable by copper wire to aid quench protection.

After introducing the OID approach, a set of options will be discussed and compared with the original design. OID has eliminated the need for certain R&D and tests planned originally intended to address those risks. This paper focuses on the electro-magnetic design of the large coils and does not cover a wide range of parallel work on the mechanical design, quench protection, and support engineering which has led to OID now becoming the chosen design choice for B0pF [4].

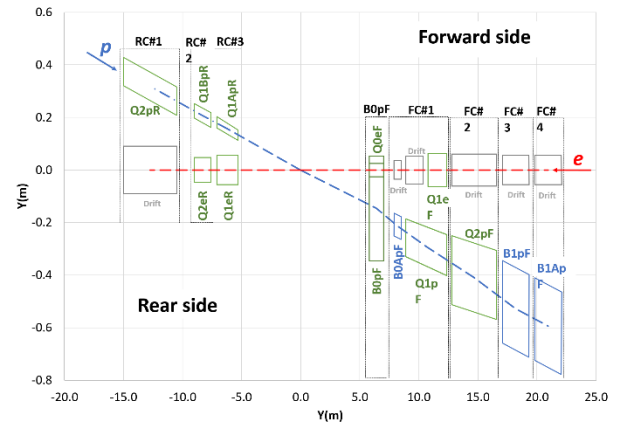


Fig. 1. Location of various magnets (including B0pF) in the Interaction Region (IR) of the Electron Ion Collider (EIC).

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II. OPTIMUM INTEGRAL DESIGN

Overall design approach is described here. It explains the rational and benefits of the OID approach.

In Rutherford cable magnets, mechanical length of the two ends of a dipole is generally between 3 to 4 times the diameter of the coil and in a quadrupole 3 to 4 times the radius. Ends reduces the length of body (or straight section). In addition, the field per unit length in the end region is also lower (about half of that in the body). The conventional cosine (n-theta) designs, therefore, are not efficient for short magnets such as B0pF where ends become a significant fraction of the overall length. The situation is somewhat better in direct wind magnets using small diameter cables in double-helix or serpentine designs as the bending radius in the ends could be small. However, a relative loss in integral field due to coil ends remained relatively large in the original serpentine design of B0pF.

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



Fig. 2. A highly filled winding pattern of an optimum integral direct wind coil with midplane turns extending full length.

Optimum Integral Design [5] is a one step process where the length of the midplane turn (Figure 2) is made essentially equal to the length of coil in direct wind coils. If there are no spacers in the ends and in the straight section, then the length of successive turns decreases linearly from the midplane to the pole. This distribution is then further modulated with the help of a few spacers in the body and a few in the ends so that the azimuthal current distribution becomes proportional to $\cos(n\theta)$ in an integral sense for any “2n” multipole. The modulation is optimized with the help of a computer program to effectively achieve an integral functional distribution varying azimuthally as:

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

Since 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 conventional Rutherford cable, or direct wind serpentine or direct wind double helix coil designs where the loss in effective magnetic length from L_0 is about a coil diameter/(n).

III. OPTIMUM INTEGRAL DESIGN SOFTWARE

Software 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:

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

Integral skew harmonics A_n 's are similarly obtained when the trigonometric function “cosine” replaced by “sine”.

Software based on above formulation can rapidly optimize a 3-d design in about a minute and create files for making models for OPERA3d [7] and RAT [8] and file for coil winding software. To minimize integral 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.

The original software *MINXEND* [9] was written for a VAX/VMS system. Software has been ported and used Personal Computers running with Ubuntu [10] in a terminal-based mode and named *IntegralOpt* [11]. Software allows up to 199 variables to optimize the body and ends together. Software was further enhanced to perform design of combined function magnets and to optimize harmonics simultaneously at multiple locations with different reference radii. This feature is particularly important in B0pF as the electron and proton travel off-axis and it is desirable to optimize harmonics along the path of these beams rather than at the center of the magnet. The software is now being upgraded to GUI based python code and named *MADEO* [12] with enhanced pre- and post-processing. New features include the calculations of the field components and field harmonics at a point and along the line, and peak field calculations on the conductor for a fixed permeability yoke. Immediate upgrade plans include the ability to modulate winding patterns of subsequent layers to correct for the measured harmonics in the previous layer.

IV. BASIC DESIGN PARAMETERS OF B0pF

Key parameters of the superconducting wire and 6-around-1 cable used in designing the B0pF are listed in Table I. Key design parameters are listed in Table II.

TABLE I
KEY PARAMETERS OF THE SUPERCONDUCTOR USED IN B0pF

Wire diameter	0.47 mm
Copper to Non-Copper ratio	1.7
Cable type	6-around-1
Cable diameter, bare	1.5 mm
Cable diameter, insulated	1.6 mm
Cable I_c @ 5 T, 1.92 K	2070 A

TABLE II
KEY PARAMETERS TO OPTIMIZE THE DESIGN OF B0pF

Nominal integral quadrupole gradient	9.75 T
Nominal integral dipole field	1.56 T.m
Coil inner diameter (id)	656 mm
Coil length	~1240 mm
Coil length/coil id ratio	~1.9

V. OPTIMUM INTEGRAL DESIGN OPTIONS

Optimum integral design opened a wide range of possibilities, with all reducing the number of layers and operating current for the design requirements mentioned here. The coil must have an inner diameter of 656 mm and a length of 1240 mm. All designs were optimized for (a) an integral field along the hadron beam path of 1.56 T.m, (b) a maximum integral field gradient of 9.75 T (actual value depends on the beam energy and the gradient in the quadrupole Q0eF inside), (c) a net zero integral field along the electron beam path with a variation below 0.02 T, (d) harmonics along the path of hadron and electron beams meet the field quality requirements, and (e) providing sufficient margin (<65% on load line).

The designs are grouped in two categories (a) separated function designs (quadrupole or dipole for each layer), and (b) combined function designs. All layers are connected in series.

A. Separated Function Design with Seven Layers

The preferred option for the separated function design for the optimum integral designs is based on six quadrupole layers and one dipole layer (total seven), as compared to the ten in the serpentine. Even though all layers will run in series, they are all individually optimized. First layer of the quadrupole coil is shown in Figure 3(left) and the single layer of dipole coil in Figure 3(right). A single dipole layer was sufficient and allowed in OID (another benefit of OID over the serpentine or double helix which must have two layers of each multipole).

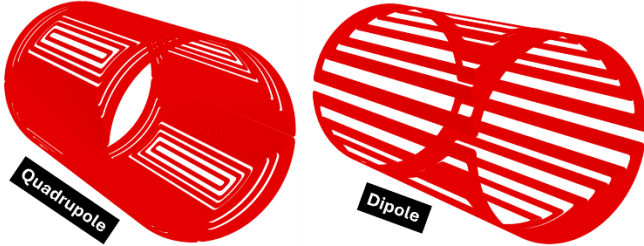


Fig. 3. A highly filled winding pattern of optimum integral direct wind coils with midplane turns extending full length.

Optimized harmonics at low field are given in Table III for the 1st quadrupole layer (the most critical layer) and for the dipole layer. Field harmonics are given at a reference radius of 220 mm at the center of the magnet and at a reference radius of 50 mm at the center of hadron beam and at the center electron beam. Hadron beam is at an angle of 25 micro radian.

Turns are tightly packed in the body and sparsely distributed at the ends in the quadrupole layer, opposite to that in the dipole layer (see Figure 3 for one layer each and Figure 4 for model of all seven layers and upper half of the yoke with field contour superimposed). The design provided the required integral fields at 864 A for hadron and electron, while minimizing the variation in the field along the path electron (see Figure 5). Peak field on the conductor at design is ~4 T.

Computed short samples are 1480 A at 1.92 K and 1110 A at 4.2 K (Figure 6). This provides a load line margin of 58% (required < 65%) and allows testing at 4.5 K, if desired.

TABLE III

HARMONICS IN THE FIRST QUADRUPOLE LAYER AND IN THE DIPOLE LAYER (A) AT CENTER OF MAGNET AT A REFERENCE RADIUS OF 220 MM AND (B) AT CENTERS OF THE HADRON AND (C) ELECTRON BEAMS AT A REFERENCE RADIUS OF 50 MM

	Quadrupole Layer #1			Dipole Layer		
(x,y)	center (0,0)	h (-126,0)	e (34,0)	center (0,0)	h (-126,0)	e (34,0)
n=	bn@220mm	bn@50mm	bn@50mm	bn@220mm	bn@50mm	bn@50mm
1	0	-3181	1393	10000	10000	10000
2	10000	10000	10000	0.00	-0.04	0.00
3	0.00	0.05	0.00	0.19	0.13	0.10
4	0.00	-0.03	0.00	0.00	-0.05	0.00
5	0.00	0.02	0.00	-0.13	-0.01	-0.06
6	0.01	-0.01	0.01	0.00	-0.01	0.00
7	0.00	0.01	0.00	0.40	0.14	0.20
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	1.00	0.33	0.50
10	-0.03	-0.02	-0.02	0.00	0.00	0.00

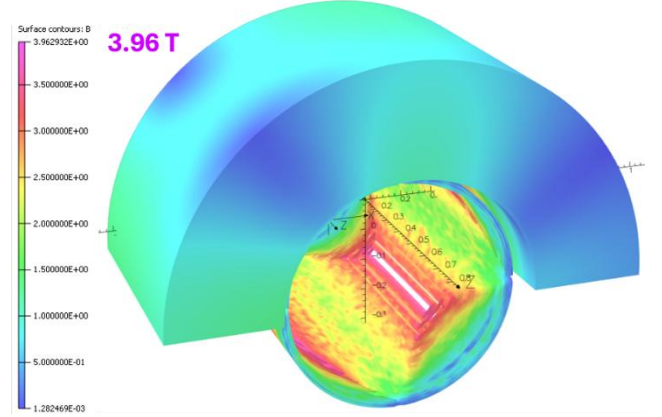


Fig. 4. Electro-magnetic model of the separated function B0pF with field contours superimposed over coil and yoke at 860A.

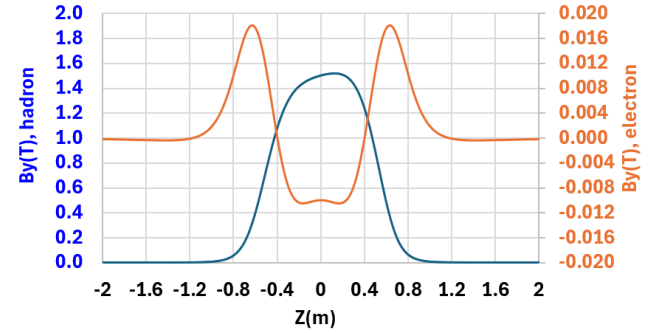


Fig. 5. Vertical component of the field along the path of hadron (integral field 1.56 T.m) and electron in B0pF.

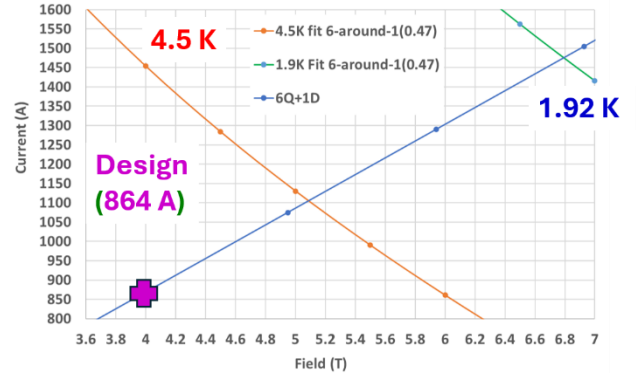


Fig. 6. Computation of short sample with the expected performance of the cable at 1.92 K and 4.5 KA and computed integral field and field gradient as a function of current.

B. Combined Function Designs with Six and Eight Layers

OID offers an opportunity for B0pF that was not possible in serpentine design. OID allows each layer to be a combined function layer, having the required ratio of the gradient and the field. This produces many efficient design options. In one option a four-layer design reached the required performance at 1220 A with 82% on load line as compared to 1143 A in the original ten-layer serpentine design. In another option, an 8-layer design at 671 A allowed a 4.5 K operation with 70% on load line. An advantage of the combined function design is that a non-working or a poorly working coil set can be bypassed without impacting gradient to field ratio.

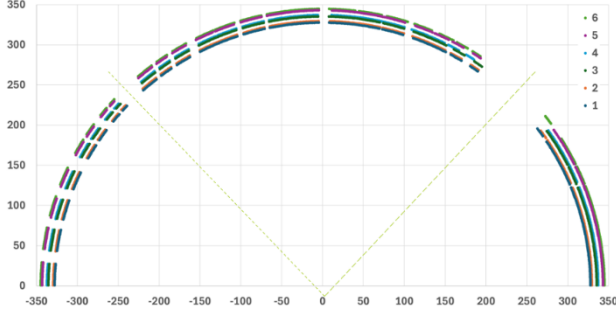


Fig. 7. Cross-section of a six-layer (three coil set) combined function coil design. Each layer has an up-down symmetry, however, not a left-right, which shifts the quadrupole center.

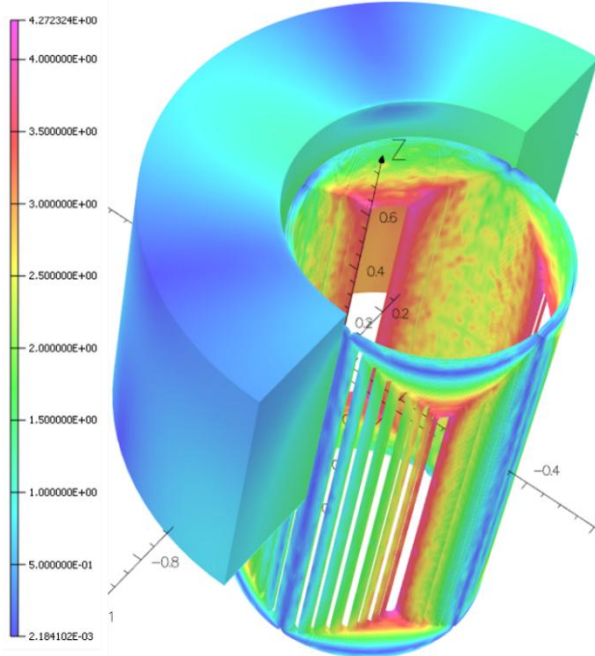


Fig. 8. Electro-magnetic model of the combined function B0pF with field contours superimposed over coil and yoke.

A six-layer (3 coil set) design operating at 889 A, with 58% on load line margin at 1.92 K was the most preferable. It kept the required margin of 65% on load even if the central superconducting wire in the six-around-1 cable is replaced by a copper wire to aid quench protection. The cross-section of the chosen 6-layer design is shown in Figure 7. Figure 8 shows the 3-d electro-magnetic model with field contours

superimposed over the six coils and upper half of iron yoke. Computed short samples are ~ 1520 A at 1.92 K and ~ 1160 A at 4.2 K.

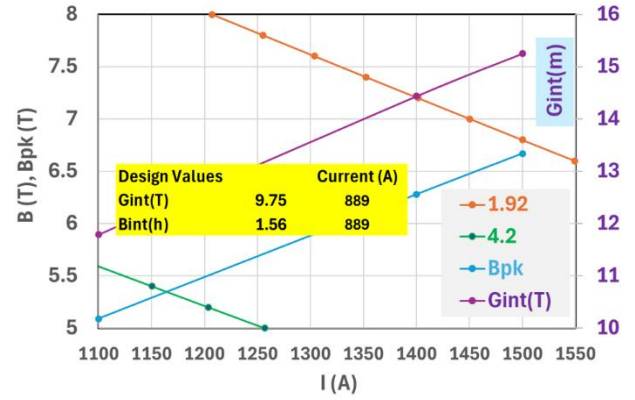


Fig. 8. Computation of short sample with the expected performance of the cable at 1.92 K and 4.2 K and computed integral field and field gradient as a function of current.

VI. COIL WINDING

Winding of B0pF based on the optimum integral design has started. Figure 9 shows a quadrant of the quadrupole layer.



Fig. 9. First quadrant of the first layer of B0pF winding based on the separated function optimum integral design.

VI. DISCUSSION AND CONCLUSION

The efficiency of optimum integral design in short B0pF (coil length to coil aperture ratio only ~ 1.9) has reduced the number of layers to seven from the ten in the original serpentine design. This reduces the cost. In addition, it has reduced operating current from 1143 A to 864 A which, in addition, improves the technical performance with reduced strain from the lower local and accumulated " $I \times B$ " Lorentz forces. This also reduces risk during energy extraction with voltage on coils reduced significantly during energy extraction after quench. One of several general options examined and is now in use in the current design of B0pF. OID was earlier validated in an R&D dipole [6].

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