A 2K Design for the Low Beta Quadrupoles Q1ApF/Q1BpF for the Interaction Region of the Electron-Ion Collider (EIC)

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A 2K Design for the Low Beta Quadrupoles Q1ApF/Q1BpF for the Interaction Region of the Electron-Ion Collider (EIC)

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***Abstract*—The forward hadron magnets of the planned electron-ion collider (EIC) at Brookhaven National Laboratory (BNL) present a set of unique challenges. In addition to the typical magnet requirements in terms of aperture, gradient, and field quality, the field leakage from the hadron magnets to the electron apertures must be negligible. Due to the close proximity of the two apertures the shielding solution for the electron beam can affect the field quality of the hadron magnets.**

In this paper, a design for the Q1ApF/Q1BpF low beta quadrupoles based on NbTi Rutherford cable operating at 2K is presented. In this design the electron beam shielding and the required field quality in the hadron magnets are achieved using a set of cutouts in the iron yoke solely without resorting to active shielding. The chosen layout along with the key parameters are presented and their effect on hadron magnets in term of field quality and operational margins are also discussed.

***Index Terms*— Accelerator magnets, superconducting magnets, interaction region, magnetic shielding, crosstalk.**

I. Introduction

THE electron-ion collider (EIC) is a newly planned facility at Brookhaven National Laboratory (BNL). The EIC is designed to reach a luminosity of 10^{34} cm^{-1} s^{-1}. The maximum luminosity is achieved at a center-of-mass energy of 105 GeV, colliding 10 GeV electrons and 275 GeV protons. While the EIC will leverage extensively the existing facilities from RHIC, several new infrastructures are needed to meet the physics requirements including a new interaction region. The layout of interaction region is shown in Fig. 1. Details about the general IR layout can be found in [1]. The chosen 25 mrad crossing angle means that close to the interaction point (IP) the beams are not very separated. This makes reducing magnetic crosstalk between the two apertures challenging particularly on the forward side where large apertures are required for the hadron magnets.

The low beta quadrupoles Q1ApF/Q1BpF are both vertically focusing and are split to minimize the aperture of the magnet closer to the IP (Q1ApF). Currently two possible designs for these magnets are being evaluated: first a tapered double helix [2] based on BNL Direct wind technology, where the two magnets can be recombined into one and the second is a cos-θ design. This paper presents the design the cos-θ design of Q1ApF and Q1BpF based on NbTi Rutherford cables operating at 2K.

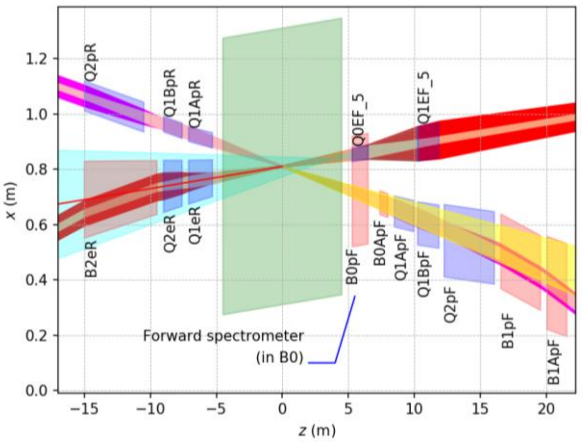

Fig.1. Layout of the inner interaction region of the EIC [3]. The green represents the central detector, dipole and quadrupole magnet apertures are shown in pink and blue, respectively.

II. Magnet requirements and design considerations

Due to the limited space, both Q1ApF and Q1BpF are twin-aperture magnets. For Q1BpF, there is an additional quadrupole, Q1eF, in the electron aperture. The baseline parameters of the magnets are shown in Table 1, although as mentioned previously, since the two hadron magnets are functionally the same it is possible to trade-off the gradient between the two as long as the integrated gradient of the pair meets the requirement of 207.8 T. A field quality of less than 10^{-4} is required for the both the hadron and electron quadrupoles. For Q1ApF, the field leakage in the electron aperture should be in the order of 10^{-5} T. Other mechanical and practical consideration such as using the

TABLE I
Baseline Magnet parameters

Magnet	Q1ApF	Q1BpF	Q1eF
Gradient [T/m]	72.6	66.2	8.1
Length [m]	1.46	1.61	1.61
Aperture diameter [mm]	56	78	63

The gradients of Q1ApF and Q1BpF can be changed as long as the sum of the integrated gradients achieves the baseline numbers.

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same cable geometry and enough spacing for the structure were considered.

III. THE ELECTRON BEAM SHIELDING AND CROSSTALK

To shield the electron beam from the field generated by the hadron quadrupoles, a layered structure consisting of iron rings separated by thin air gaps was chosen. The number and thickness of the rings can be optimized for a given hadron magnet field to minimize the field leakage into the electron aperture and at the same time reduce the effect on the field quality in the hadron quadrupole since the electron aperture and its surrounding structure break the symmetry around the hadron quadrupole. However, this approach works only to a certain limit determined by the field in the hadron quadrupole and the size of that coil which will determine the usable space (amount of iron) between the two apertures. For this reason, operating at 2 K is critical to reach the highest possible gradient with the most compact coil cross-section. The width and gradient of each coil was optimized to maximize the gradient while also minimizing the flux leakage in the electron aperture and the effect on field quality. This resulted in Q1ApF (with the smaller aperture) being a two-layer coil and Q1BpF a single layer coil, both using the same 15 mm wide conductor. The optimization was performed using COMSOL Multiphysics [4]. For the yoke, a low carbon steel (JFE-EFE) was used for its high saturation value. The magnetization curves were provided by a commercial supplier and are available in [5]. The effect of the hysteresis was

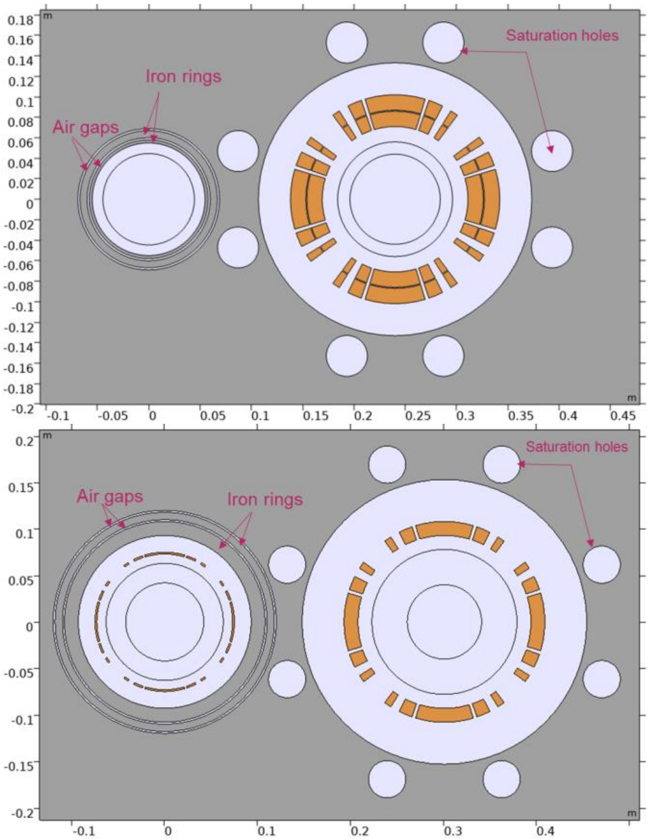

Fig. 2. 2D models of the magnets, top is Q1ApF, and bottom is Q1BpF. The superconductor is represented in orange, gray is the iron yoke, and the light purple represents the non-magnetic domains (air in this model).

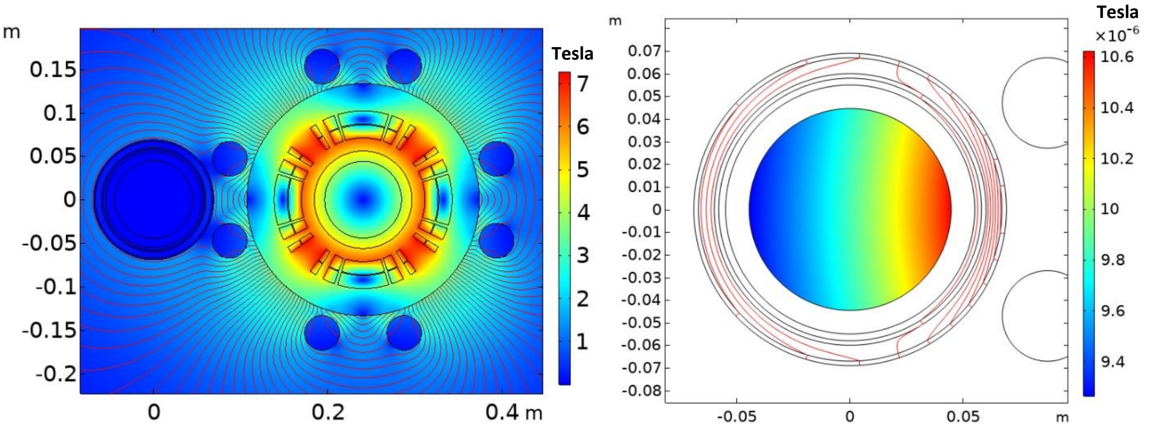

Fig. 3. Magnetic flux density in Q1ApF. For a 91 T/m gradient, the maximum field in the electron aperture is 10.6 μT and b_1 in the Q1ApF: 0.32 unit (higher order harmonics < 0.1 unit). The red contours show the field lines (omitted in the hadron magnet domain).

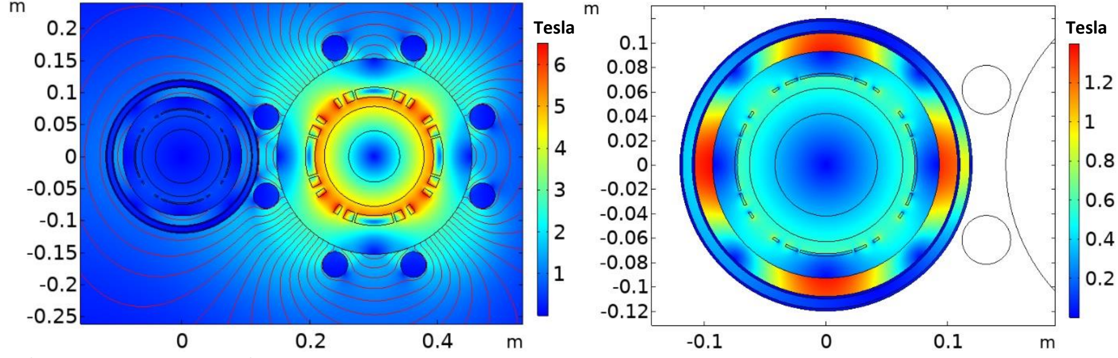

Fig. 4. Magnetic flux density in Q1BpF (left), the electron aperture and shielding structure (right). For Q1BpF, there is an 8.1 T/m quadrupole (Q1eF) in the electron aperture. For Q1BpF operating at 58 T/m, the field quality in Q1eF remains good (b_1 : 0.67 unit). For Q1BpF b_1 : 1.1 unit and b_3 : 0.2 unit (higher order harmonics < 0.1 unit). The red contours show the field lines (omitted in the hadron magnet domain).

not taken into account at this stage but it will be studied and be in the future. A three-wedge coil is used to speed up the calculations, since the focus here is on the non-allowed harmonics. Fig. 2 shows the geometry of the model used. The saturation holes shown do improve the shielding, but their primary purpose is to minimize the saturation effect on field quality. In both case, two iron rings with 2 mm air gap were found to provide the desired shielding.

Fig. 3 shows the magnetic flux density in Q1ApF. For a 91 T/m gradient, with two rings 3 and 7 mm thick separated by a 2 mm air gap, the maximum field in the electron aperture was 10.6 µT. As for the field quality in the hadron quadrupole, the electron beam shielding structure creates only 0.32 unit of dipole and all higher order harmonics are below 0.1 unit. For Q1BpF, shown in Fig. 4, the inner and outer rings around Q1eF are, respectively 15 and 8 mm thick. In this configuration, for a gradient of 58 T/m, the cross-talk between the two magnets resulted in 0.67 unit of dipole in Q1eF and in 1.1 unit in Q1BpF. It should be noted that the aforementioned results were first obtained based on the spacing on the IP side where the beams are closer, than validated for the non-IP side and the results remains valid.

IV. HADRON MAGNETS CROSS-SECTIONS

Based on the results obtained in the previous section, a 28-strand, 15.1 mm wide with a copper to superconductor ratio of 1.6 cable was selected. The thickness of the cable is 1.79 mm on the inner edge and 2.01mm on the outer. The insulation thickness is 0.15 mm. The strand diameter is 1.065 mm. The coil cross-sections were optimized using the ROXIE package [6]. For the cross-section, optimization, a round yoke with 1.2 m diameter was used. The gap between the coil and the yoke is 30 mm for Q1ApF and 45 mm for Q1BpF.

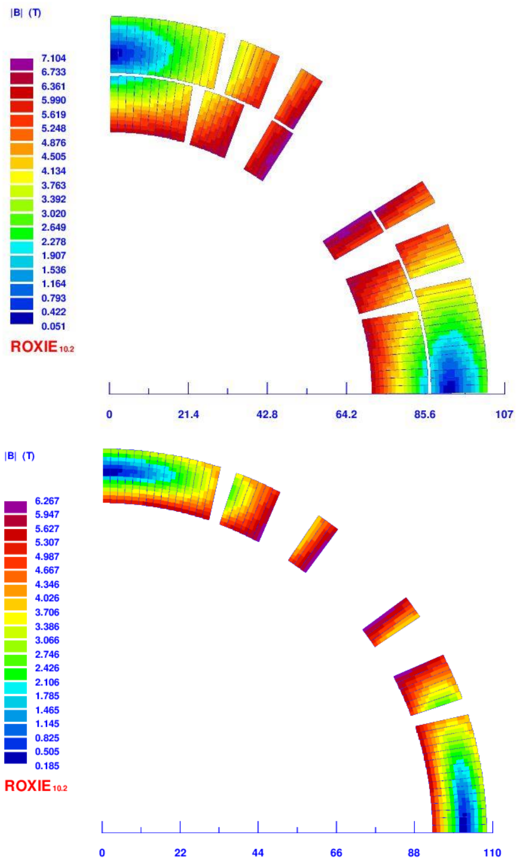

Fig. 5. Coil cross-section and magnetic field density in Q1ApF (top) and Q1BpF (bottom).

TABLE II
HADRON MAGNETS 2D PARAMETERS

Magnet Name	Units	Q1Apf	Q1BpF
Coil inner radius	mm	71	93
Reference Radius	mm	42.4	54
Number of layers	mm	2	1
Yoke inner radius	mm	133	154
Yoke outer radius	mm	600	600
Op. Temperature	K	2	2
Op. Current	kA	11	16
Load line margin	%	28.85	27.35
Temp. margin	K	2.74	2.59
Gradient	T/m	88.25	56.56
Cond. peak field	T	7.1	6.27
Geometric field errors			
b_6	units	0.08	0.01
b_{10}	units	0	-0.01
b_{14}	units	-0.03	-0.24
b_{18}	units	-0.01	0.02

To accommodate the bore tube, the inner coil radius for Q1ApF is 71 mm and 93 mm for Q1BpF. The layer layout, shown in Fig. 5, operating at 11 kA, provides a gradient of 88.25 T/m. The resulting peaking field on the conductor is 7.1 T, providing a load line margin of 28.8 % and temperature margin of 2.7 K. For Q1BpF, an operating current of 16 kA is needed to achieve the desired gradient of 56.56 T/m in a single layer configuration. The conductor peak field was 6.27 T at this operating current, giving a 27.35 % margin at 2 K. The coils cross-sections along with the field on the conductors are shown in Fig. 5 and key parameters are summarized in Table II.

V. 3D MODELS

The coil ends were generated using ROXIE. The primary focus was on minimizing peak field enhancement at the ends and on field quality. With the geometry shown in Fig. 6, the peak field in 3D was 7.2 T for Q1ApF and 6.28 T for Q1BpF. In order for the shielding to work, the coil have to be slightly smaller than the iron yoke. The integrated gradient, field quality and crosstalk in 3D were calculated used the finite element software

TABLE III
MAGNET PARAMETERS USED IN THE 3D MODELS

Magnet Name	Units	Q1Apf	Q1BpF
Yoke length	m	1.57	1.604
Coil length	m	1.494	1.528
Central gradient	T/m	87.19	56.07
Integrated Gradient	T	122.45	79.63
Peak field	T	7.2	6.28
Yoke inner radius	mm	133	154
Yoke outer radius	mm	600	600
Center of electron aperture	IP	240.11	300.76
	Non-IP	268.58	324.92

OPERA 3D [7]. Given the angle between the apertures, only top-bottom symmetry can be used in the 3D models shown in Fig. 7. In each model, in addition to the shielding structure around the electron beam, the saturation holes along with the hole for the 2 K heat exchanger were included. For Q1eF, to check the crosstalk a cos-θ coil with a gradient of 8.1 T/m was used. It should be noted that the actual Q1eF magnet will be either a double helix or serpentine magnet built using direct wind technology [8]. The obtained integrated gradient was 122.45 T for Q1ApF and 79.63 T for Q1BpF. The field quality of the magnets is summarized in Table IV. The integrated field harmonics were less than one unit of the main field. The Magnetic flux density in the electron aperture on the IP side is shown in Fig. 8. The field leakage from the hadron magnet was found to be in the range of 20-85 µT at 44.6 mm radius.

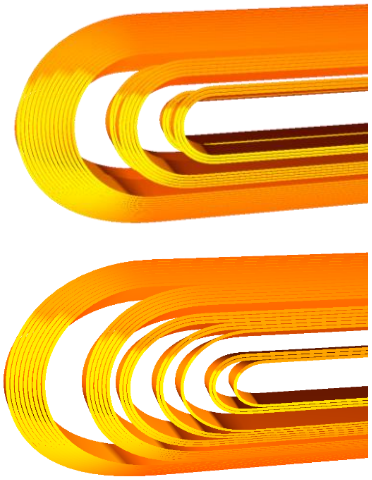

Fig.6. Coil ends geometry for Q1ApF (top) and Q1BpF (bottom).

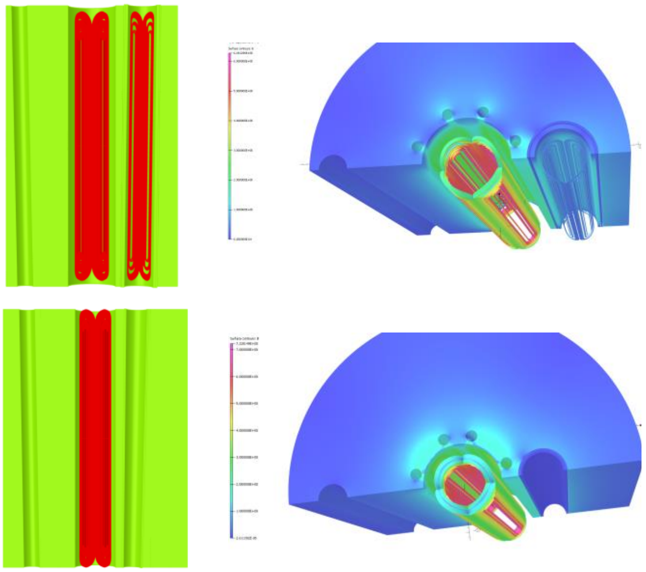

Fig. 7. 3D model of the two magnets of Q1BpF/Q1eF (top) and Q1ApF (bottom). At the center is the hadron quadrupoles, on the right the electron aperture, and on the left is hole for the 2 K heat exchanger.

TABLE IV
INTEGRATED FIELD HARMONICS

harmonic	Q1ApF	Q1BpF	Q1eF
b_1	0.2	-0.4	-0.2
b_2	10000.0	10000.0	10000
b_3	0.1	-0.1	0.3
b_4	-0.1	-0.1	-0.5
b_5	0.0	0.0	-0.3
b_6	-0.1	-0.1	-0.5
b_7	0.0	0.0	-0.3
b_8	0.0	0.0	-0.2
b_9	0.0	0.0	-0.1
b_{10}	-0.4	-0.6	-0.9
b_{11}	0.0	0.0	-0.1
b_{12}	0.0	0.0	0.0
b_{13}	0.0	0.0	0.0
b_{14}	-0.1	-0.2	-0.1

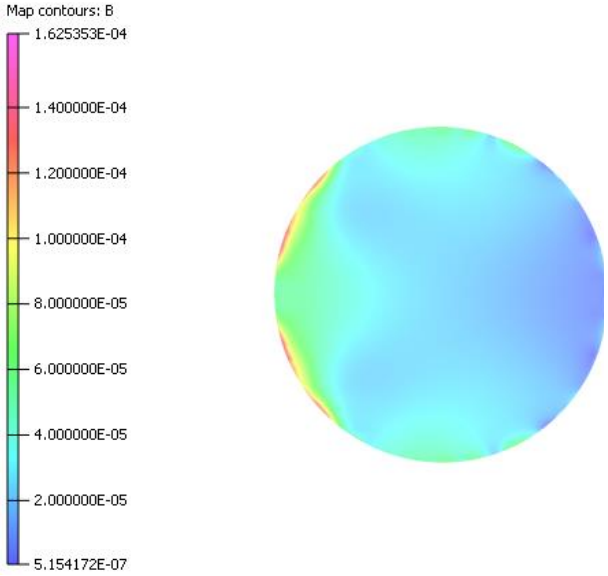

Fig. 8. Magnetic flux density in the electron aperture at z = -0.7 m (the IP side). This is a cut view from the results shown in Fig. 8. The shown region has a radius of 44.6 mm.

VI. CONCLUSION

In this paper, a potential design for the Q1ApF/Q1BpF low beta quadrupoles of the interaction region for the EIC is presented. A simple layered structure consisting of iron rings separated by thin air gaps can provide sufficient shielding for the electron beam by optimizing the coils width and trading off gradients between the two magnets. The initial 3D models shows that the chosen layout can provide sufficient shielding for the electron beam with minimal impact on the field quality in the hadron magnets.

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