ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB003

OVERVIEW OF THE MAGNETS REQUIRED FOR THE INTERACTION REGION OF THE ELECTRON-ION COLLIDER (EIC)*

H. Witte†, K. Amm, M. Anerella, J. P. Cozzolino,
R. C. Gupta, H. Hocker, P. Kovach, G. Mahler, A. Marone, R. B. Palmer,
B. Parker, S. R. Plate, J. Schmalzle, C. Runyan, J. Avronsart, A. B. Yahia
Brookhaven National Laboratory, Upton, NY, USA

Abstract

The planned electron-ion collider (EIC) at Brookhaven National Laboratory (BNL) is designed to deliver a peak luminosity of 1×10^{34} cm^{-2}sec^{-1}. This paper presents an overview of the magnets required for the interaction region of the BNL EIC.

To reduce risk and cost the IR is designed to employ conventional NbTi superconducting magnets. In the forward direction the magnets for the hadrons are required to pass a large neutron cone and particles with a transverse momentum of up to 1.3 GeV/c, which leads to large aperture requirements. In the rear direction the synchrotron radiation fan produced by the electron beam must not hit the magnet apertures, which determines their aperture. For the forward direction a mostly interleaved scheme is used for the optics, whereas for the rear side 2-in-1 magnets are employed. We present an overview of the EIC IR magnet design including the forward spectrometer magnet B0.

INTRODUCTION

The Electron Ion Collider is a planned new facility at Brookhaven National Laboratory, which is based on the existing RHIC (Relativistic Heavy Ion Collider) facility. The EIC facility is discussed in more detail in [1]; more information on the general IR design can be found in [2].

An overview of the inner IR is shown in Fig. 1. For the interaction region a crossing angle of 25 mrad was chosen, which is challenging in terms of the magnets as the beams in particular for the magnets close to the IP are not very separated. The challenges here lie in the combination of restricted space, required magnet performance (field/gradient and field quality) and magnet apertures.

The forward hadron magnets represent a particular challenge as they require large apertures. The size of the apertures is determined by scattered protons with a maximum transverse momentum of 1.3 GeV and the ±4 mrad neutron cone. This is shown in Fig. 2, which shows the required minimum magnet apertures of the magnets.

In order to keep the magnet apertures at a minimum, magnets on the forward side are rotated and shifted. In addition, certain magnets are split into two, which allows smaller apertures for magnets closer to the IP (both the neutron cone as well as particle orbits with a transverse momentum are diverging). This is the case for Q1ApF and Q1BpF, which

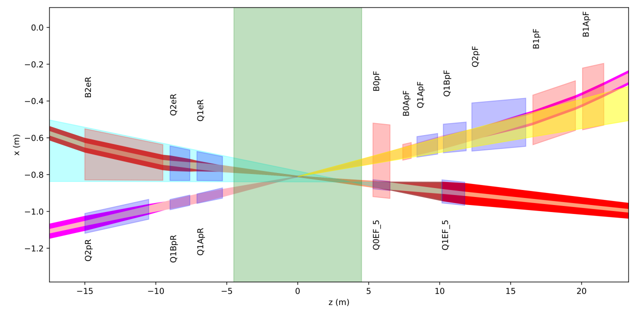

Figure 1: Layout of the inner interaction region of the EIC. In this figure the hadrons go from left to right. Shown in green is the central detector. Dipole and quadrupole magnet apertures are shown in pink and blue, respectively.

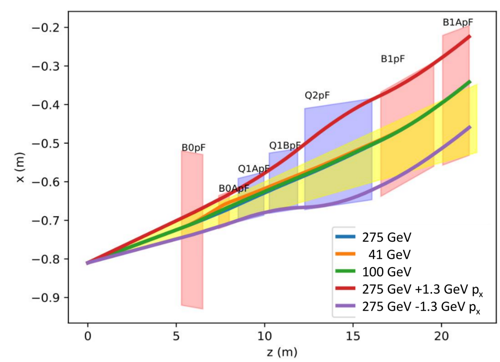

Figure 2: Magnet apertures of the forward hadron magnets.

are both vertically focusing. Similarly, B1pF and B1ApF bend in the same direction.

In contrast to this the hadron magnets on the rear side are designed to be large enough for a 10σ beam, which includes sufficient space for orbit shifts and mechanical tolerances. The size of the electron rear magnets is determined by the synchrotron radiation fan, which predominantly originates in the low-β quadrupole magnets Q0eF and Q1eF on the forward side.

MAGNET REQUIREMENTS

The basic parameters of the forward and rear magnets are shown in Tables 1, 2 and 3. In the tables gradients and dipole fields are for the highest energies; some of the rear magnets are tapered, so the apertures are specified for the IP and non-IP side of the magnets separately. Due to the smaller beam rigidity the gradients and dipole fields required for the

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† hwitte@bnl.gov

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB003

electron beam are usually much lower. Several of the rear magnets are envisaged to be tapered, that is the IP side of the magnet has a smaller aperture in comparison to the non-IP side. To facilitate this, a novel winding scheme based on the double-helix or canted cosine theta (CCT) technique is used, which will be described in more detail later on.

Table 1: Forward Quadrupole Magnet Parameters

	Hadron Magnets			Electron Magnets	
	Q1APF	Q1BPF	Q2PF	Q0eF	Q1eF
Length [m]	1.46	1.6	3.8	1.2	1.61
Inner radius [cm]	5.6	7.8	13.1	2.5	6.3
Gradient [T/m]	-72.6	-66.2	40.7	-14.05	6.3

Table 2: Forward Dipole Magnet Parameters

	Hadron Magnets			
	B0PF	B0APF	B1PF	B1APF
Length [m]	1.2	0.6	3.0	1.5
Inner radius [cm]	20.0	4.3	13.5	16.8
Dipole field [T]	-1.3	-3.3	-3.4	-2.7

Table 3: Rear Hadron and Electron Quadrupoles

REARWARD DIRECTION	Hadron Magnets			Electron Magnets		
	Q1APR	Q1BPR	Q2PR	Q1eR	Q2eR	B2ER
Length [m]	1.80	1.40	4.50	1.80	1.4	5.50
Entrance radius [cm]	2.60	2.80	5.40	6.60	8.30	9.70
Exit radius [cm]	2.8	2.80	5.40	7.90	9.40	13.9
Dipole field [T]	NA	NA	NA	NA	NA	-0.198
Gradient [T/m]	-78.375	-78.375	33.843	-13.980	14.100	NA

The hadron forward quadrupole magnets, B1pF and B1ApF are envisaged to be standard collared magnets based on a Rutherford cable. All other magnets use the BNL direct wind technique [3]. The forward spectrometer magnet B0pF is special as it is a combined function magnet as described below. In difference to all other magnets the field strength is not varied with energy of the particles. To ensure that particles end on the reference orbit the corrector dipole B0ApF and the dipole B1pF are used.

While the magnets on the rear side of the IR are 2-in-1 magnets, the forward side magnets have mostly field free regions for the electron beam. Q1BpF is a 2-in-1 magnet with Q1eF. In the following section we discuss representative examples of the magnets: B0pF, Q2pF and Q1ApR/Q1BpR.

MAGNETS

Forward Spectrometer B0pF

The purpose of the B0pF magnet is to provide a 1.3 T dipole field to the hadron beam. To allow sufficient space for detectors the inner clear aperture of the magnet is 40 cm. Due to the geometry of the magnet the electron beam passes through the same aperture.

In practise the B0pF magnet is realized as a combined function magnet (dipole and quadrupole), as shown in Fig. 3, with the zero-field axis at the location of the electrons (the magnet is aligned with the electron beam). A small additional quadrupole magnet for the electron beam allows the gradient to be varied for different energies.

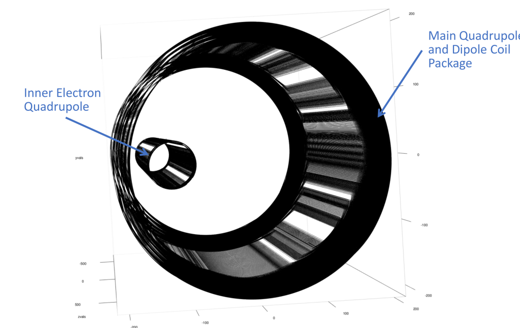

Figure 3: B0pF Concept.

The B0pF quadrupole magnet will have four layers and the dipole magnet six layers with an operating current of about 1300 A. The electron quad will consist of four layers. The peak field on the wire is 4.85 T. The B0pF magnet is expected to be housed in its own cryostat as shown in Fig. 4.

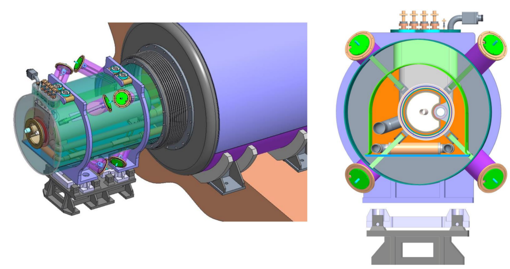

Figure 4: B0pF Cryostat Concept.

Collared Magnet Q2pF

Q2pF is a large aperture 3.8 m long quadrupole magnet in the hadron forward direction. The magnet is a collared magnet, based on a Rutherford cable with 36 strands. The strand diameter is 1.065 mm; the cable width is 19.4 mm and the thickness 1.788/2.012 mm. The Cu:Sc ratio is 1.6. To allow operation at 4.2 K a two layer structure is chosen.

The inner coil radius is 140 mm, which leaves enough space for the cold bore tube. The calculated temperature margin is shown in Fig. 5. In 3D the margin is slightly reduced due to the space constraints in longitudinal direction (21%, assuming 20% cable degradation). Higher order harmonics were reduced to less than one unit at a reference radius of 83 mm.

Tapered Double-Helix Q1ApR/Q1eR Magnet

The distance between the two beams is 132.5 mm; due to the required clear apertures for the beams and the synchrotron radiation and the need to leave sufficient space for the support structures, only 8 mm of space is available for

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB003

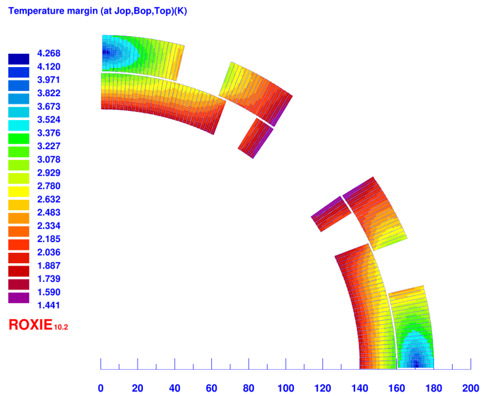

Figure 5: Temperature margin Q2pF at 36 T/m at 4.6 K.

iron in-between the two magnets on the IP side. This amount of iron however is sufficient to provide adeuqate shielding against cross-talk.

For this magnet the double-helix, or canted cosine theta, winding pattern is employed. The coil concept has been known since the 1960s [4] and has been shown to be able to create arbitrary multipole fields, combined function magnets [5, 6] and is under consideration for future high field magnets [7, 8].

The conductor path in three dimensions is described by the following equations:

$$x(\theta) = R \cdot \cos\theta \tag{1}$$

$$y(\theta) = R \cdot \sin\theta \tag{2}$$

$$z(\theta) = \frac{h\theta}{2\pi} + \frac{R}{\tan(\alpha)} \sum_n \varepsilon_n \sin(n\theta) \quad . \tag{3}$$

In the Eqs. (1) to (3) θ is the azimuthal angle, R the coil radius, h the winding pitch, α the tilt angle of a single turn with respect to the central axis and n the multipole order. ε_n is an additional parameter for combined function magnets, which allows to adjust the individual multipole components. For tapered magnets multipole field components can be kept constant along the length of the magnet by changing ε_n for each turn [9].

Q1ApR will be made of eight layers of a 0.75 mm cable (non-insulated); the calculated margin on the load-line is 37% assuming a copper to superconductor ratio of 2:1 at 4.2 K (peak field on the wire 3.3 T). Q1eR will consist of four layers using a 0.33 mm conductor (1.5 T). Figure 6 shows the two magnets in the iron yoke.

The integrated field harmonics for the electron quadrupole magnet are shown in Table 4. The normal (B_n) and skew (A_n) harmonics are defined as:

$$B = \sum_{n=1}^{\infty} [B_\mathrm{n} + iA_\mathrm{n}] \left(\frac{z}{R_\mathrm{ref}}\right)^{n-1} .$$

The harmonics are evaluated for a radius of 25 mm (harmonics for n>7 are zero and not shown).

Table 4: Normalized Harmonics of the Q1eR Magnet

	Q1eR	
n	**a_n**	**b_n**
2	-0.1	10000
3	0.0	0.07
4	0.0	0.19
5	0.0	0.07
6	0.0	0.01
7	0.0	0.01

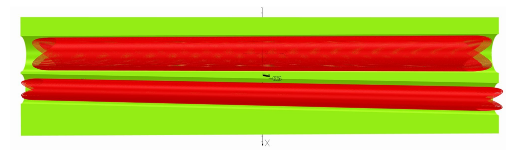

Figure 6: The Q1ApR/Q1eR 2-in-1 magnet.

CRYOSTATS

All forward magnets apart from the B0pF magnet will be housed in one cold mass (helium vessel) and one cryostat. This is necessary due to the limited space in-between the forward magnets. Figure 7 shows a top and front view of the forward cryostat.

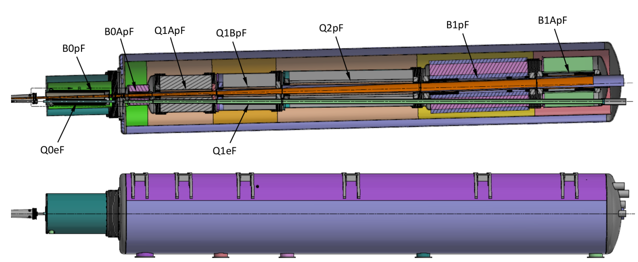

Figure 7: Cryostat for the forward magnets. As shown in the figure, all forward magnets except the B0pF spectrometer magnet share the same cryostat.

The rear side magnets are all direct wind magnets and do not require thick end plates. This provides sufficient space between magnets such that it is possible to locate every 2-in-1 magnet in its own cold mass (helium vessel) and cryostat.

CONCLUSION

The magnet design for the EIC has sufficiently advanced; solutions for all magnets have been found. Particular emphasis in the design process was on field quality, reducing crosstalk as much as possible and risk reduction.

A key technology is tapered double-helix magnets, which allows to place magnets closer to the IP than otherwise possible. These magnets can be wound using the direct wind technology at BNL, which was recently demonstrated in a lab-funded R&D project. A 400 mm long tapered (IR 30 to 40 mm) prototype quadrupole magnet was recently constructed and tested successfully up to 40 T/m.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB003

REFERENCES

[1] C. Montag *et al.*, "Design Status Update of the Electron-Ion Collider", presented at IPAC'21, Campinas, Brazil, May 2021, paper WEPAB005, this conference.

[2] H. Witte *et al.*, "The Interaction Region of the Electron-Ion Collider EIC", presented at IPAC'21, Campinas, Brazil, May 2021, paper WEPAB002, this conference.

[3] B. Parker *et al.*, "BNL Direct Wind Superconducting Magnets", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4101604, Jun. 2012. doi:10.1109/tasc.2011.2175693

[4] D. Meyer and R. Flasck, "A new configuration for a dipole magnet for use in high energy physics applications", *Nucl. Instrum. Methods*, vol. 80, no. 2, pp. 339–341, Apr. 1970. doi:10.1016/0029-554x(70)90784-6

[5] R. Meinke, C. Goodzeit, and M. Ball, "Modulated double-helix quadrupole magnets", *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1369–1372, Jun. 2003. doi:10.1109/tasc.2003.812674

[6] H. Witte *et al.*, "The Advantages and Challenges of Helical Coils for Small Accelerators—A Case Study", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 2, p. 4100110, Apr. 2012. doi:10.1109/tasc.2012.2186135

[7] B. Auchmann *et al.*, "Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, pp. 1–5, Apr. 2018. doi:10.1109/tasc.2017.2772898

[8] S. Caspi *et al.*, "Design of a Canted-Cosine-Theta Superconducting Dipole Magnet for Future Colliders", *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017. doi:10.1109/tasc.2016.2638458

[9] H. Witte, B. Parker, and R. Palmer, "Design of a Tapered Final Focusing Magnet for eRHIC", *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019. doi:10.1109/tasc.2019.2902982