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DESIGN OF DIPOLE MAGNETS FOR LUMINOSITY PAIR SPECTROMETER SUBSYSTEM AT THE DETECTORS OF ELECTRON ION COLLIDER*

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Abstract

The electron ion collider (EIC) will collide high energy and highly polarized hadron and electron beams with luminosities up to 10^{34} cm^{-2}s^{-1}. Bremsstrahlung photons from the Bethe-Heitler process at the interaction point (IP) need to be counted to determine the delivered luminosities. The pair spectrometer luminosity detector utilizes photon conversions (e+ and e- pairs) in the far-backward region. A sweeper dipole magnet was designed to sweep away the photon conversions that occur at the thick exit window. An analyzer dipole magnet was designed with an integrated field of 1.13 Tm to deflect the electrons and positrons that will be analyzed by the tracker and calorimeter detectors. Both magnets were designed and simulated using the 3-dimensional (3D) finite element method (FEM). The effects of notch size and locations on the iron yoke to the magnetic field quality were studied. The tracker performance, including tracker position resolutions and tracker energy resolutions, were analysed based on the field map of the designed dipole magnets.

INTRODUCTION

The luminosity of a collider is usually determined by direct detection of bremsstrahlung photons or by using a pair spectrometer (PS) which utilizes photon conversions of the bremsstrahlung photons [1]. In principle, one can perform the direct bremsstrahlung photons measurement by simply counting photons above some energy cutoff. However, it is only possible at low luminosities [2]. With high luminosities up to 10^{34} cm^{-2}s^{-1} for EIC [3] and target absolute uncertainty of less than 1% (exceeding 10^{-4} in precision), the PS is used in the detector. A novel PS design includes a thin converter foil, a sweeper and an analyzer dipole magnet, a helium/vacuum chamber, tracking layers, and modern electromagnetic (EM) calorimeters. A schematic of the luminosity pair spectrometer is shown in Fig. 1.

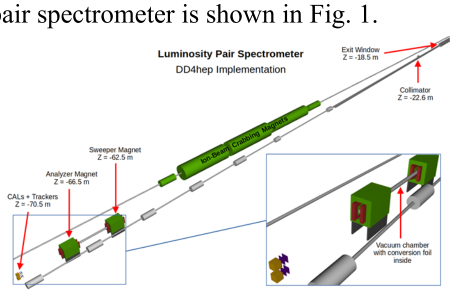

Figure 1: Layout of luminosity pair spectrometer at the detector of EIC.

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MODELING

Magnet Requirement

The requirements for both the sweeper magnet and analyzer magnet are similar, where the analyzer dipole magnet requires larger gap, higher integrated field, and more uniform field distribution compared with the sweeper magnet. Thus, only the important requirements of the normal conducting analyzer magnet are listed below:

- Integrated main field at least 0.1 to 0.4 Tm, a wider range and larger mean would be highly beneficial.
- Square bore of at least 12 cm in total width.
- Field should be as uniform as possible, ~10^{-3} at least.
- Fringe fields need to be smaller than 10 Gauss at a horizontal distance of 84 cm from the magnet's longitudinal axis, to ensure negligible impact on the electron beam.

Table 1 shows the designed magnet parameters.

Table 1: Magnet Parameters

Parameters	Value
Magnet length	1.2 m
Magnet gap	15 cm
Dipole field, min	6 Gauss
Dipole field	0.863 T
Designed field quality	0.0004
Current density	3.5 A/mm^2

Model Description

The magnet was first designed in 2D by optimizing the field quality in the pole, then the 3D model was built based on the optimized 2D geometry. The field quality of the 3D design was optimized by adding a notch at the end of the iron yoke with parametric analysis on the notch dimension, including the length, height, and width.

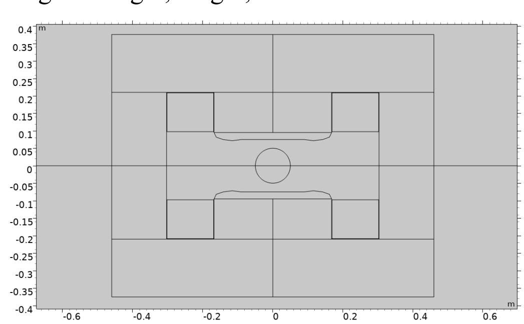

Figure 2: 2D geometry of the analyzer dipole.

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RESULTS AND DISCUSSION

2D Model

The 2D simulation was performed using COMSOL Multiphysics [4]. Since the coil and the pole edges provide imperfect boundary conditions for a uniform dipole field, design work is required to improve the size of the aperture in which the field is uniform [5]. An optimized pole contour is one with bumps near the pole edge to shape the field and increase the width of the uniform field region at the transverse center of the magnet.

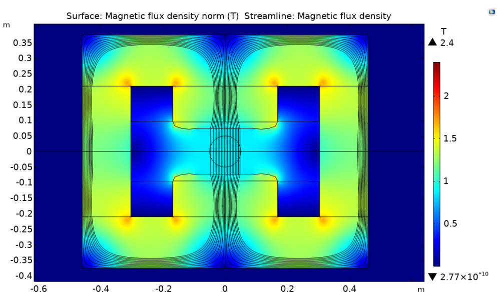

Figure 3: Magnetic flux density distribution of the designed analyzer dipole with optimized pole shape.

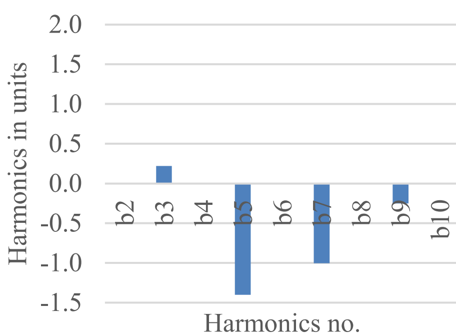

Figure 4: Harmonics of the 2D dipole magnet.

The magnetic flux density is shown in Fig. 3, where the majority of the magnetic field at the iron yoke is less than 1.5 T, the field at the center of the aperture is 0.863 T, with the field quality 0.00027. The harmonics are estimated at the 2/3 circle of the aperture, where the harmonics are defined as the multipole components divided by the main field and then times 10,000. For example, b1 is the dipole field (0.863 T) divided by the main field (0.863 T) and then multiplied by 10,000, which is 10,000 units. For a dipole magnet, the allowed harmonics are b3, b5, b7, b9 etc., [6]. The harmonics of the optimized 2D dipole design are shown in Fig. 4.

3D Model Verification

A comparison between the COMSOL simulation and the Opera 3D [7] simulation was made in 3D geometry, shown in Fig. 5, for verification. The integration method was used to calculate the magnetic field in Opera 3D. The comparison of the harmonics is shown in Fig. 6, with good agreement. Since Opera 3D used the Biot-Savart law in the conductor, which was not required to mesh the conductor, it runs much faster than the COMSOL simulation as the latter requires mesh in the conductors. In the following results, the Opera 3D model was used.

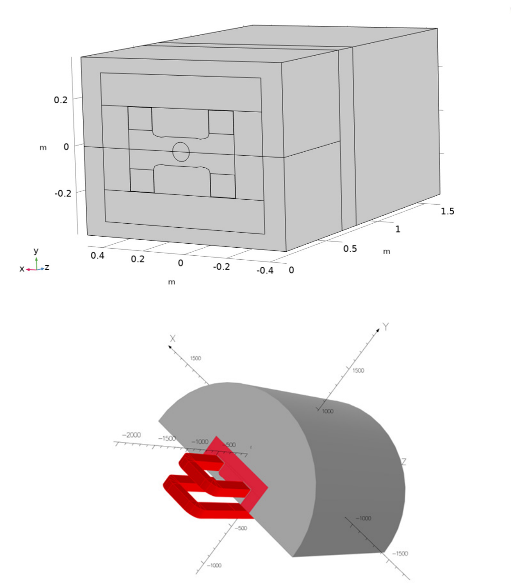

Figure 5: 3D geometry in COMSOL (upper) and in Opera 3D (lower).

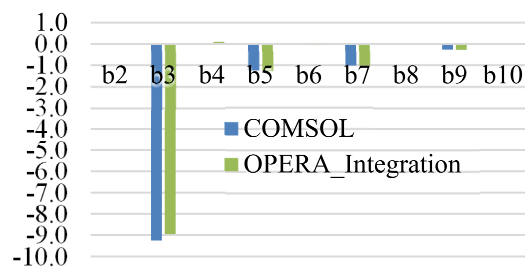

Figure 6: Harmonics comparison between the 3D COMSOL simulation and the Opera 3D simulation.

3D Field Quality Optimization

The coil ends have proven to be a difficult part of magnet design and are a critical factor in magnet performance and reliability [8]. A notch can be added to the yoke end to reduce the field thus reduce the saturation of the iron [9] to improve the field quality. The magnetic flux density distributions with and without notch are shown in Fig. 7 and Fig. 8, respectively.

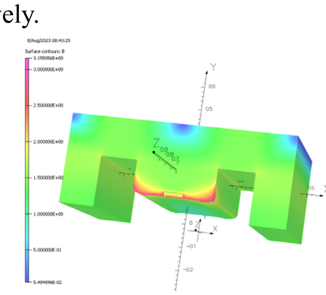

Figure 7: 3D yoke geometry with notch, peak field 3.16 T, notch size 0.08x0.02x0.01 m^3 (rectangle).

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The harmonics comparison with and without notch are shown in Fig. 9. The sextupole component (b3) has improved a lot by adding the notch, although the decapole component (b5) was degraded a little.

The optimization of the harmonics with depth and height are shown in Fig. 9 and Fig. 10, respectively. The optimized notch is 0.08x0.015x0.01 m^3. More optimizations may be needed based on the particle tracking results.

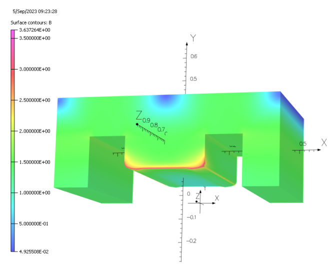

Figure 8: 3D yoke geometry without notch, peak field 3.64 T (a quarter geometry is shown due to symmetry).

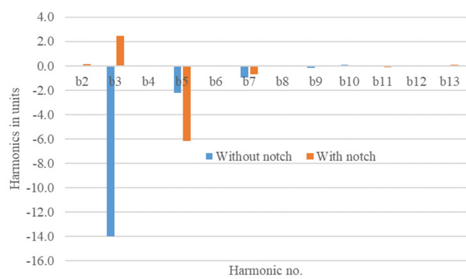

Figure 9: Harmonics comparison with and without notch.

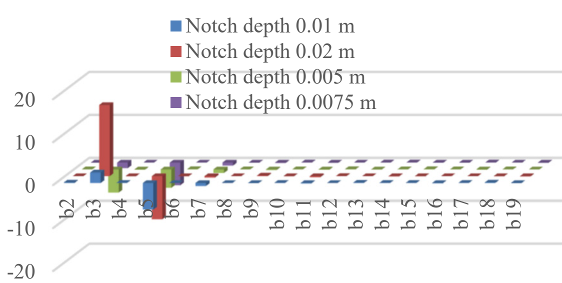

Figure 10: Notch depth optimization for the harmonics, where the width is 0.08 m, the height is 0.015 m.

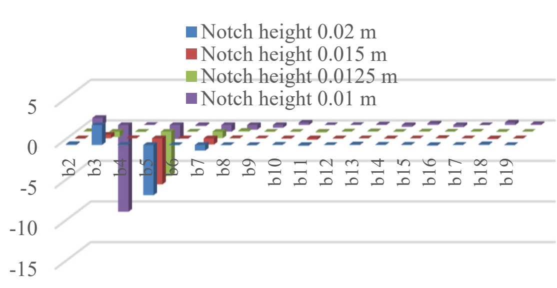

Figure 11: Notch height optimization for the harmonics, where the width is 0.08 m, the depth is 0.01 m.

Particle Tracking Results

The integrated field distribution is shown in Fig. 12 with 7.5 cm radius 5-sigma aperture. The average integrated field is -1.1395 Tm with standard deviation 0.0015 Tm.

The tracker position resolutions and tracker energy resolutions are shown in Fig. 13 and Fig. 14, respectively. The phonon X & Y resolutions are about 2 mm after cuts. The energy resolution is about 1-2% and it is better at low energy, where it has larger slope in the trackers.

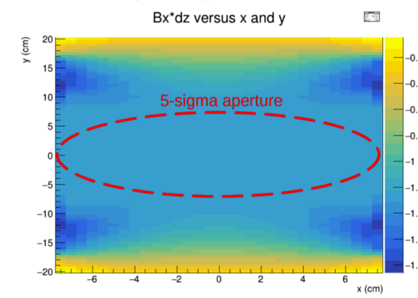

Figure 12: Integrated main field (Bx) distribution.

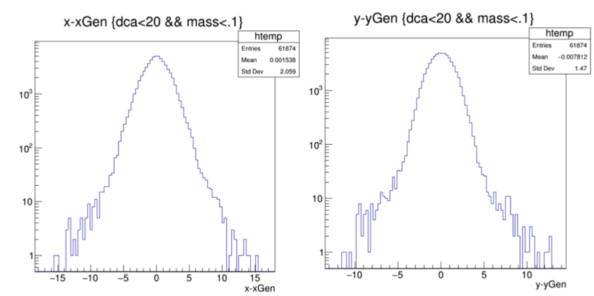

Figure 13: Tracker position resolutions.

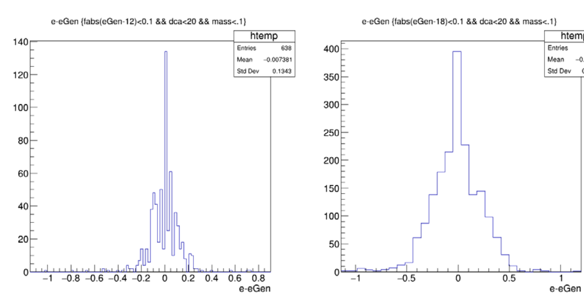

Figure 14: Tracker energy resolutions.

CONCLUSION

The dipole magnets were designed using FEA for the luminosity pair spectrometer detector at EIC with the field quality meeting the requirements. A notch was added to the end of the iron yoke to improve the field quality. The depth, height, and the width of the notch have been parameterized to optimize the field quality. Particle tracking simulations were performed based on the mapped dipole magnetic field with good position and energy resolutions.

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