INTERACTION REGION MAGNETS FOR FUTURE ELECTRON-ION COLLIDER AT JEFFERSON LAB

Renuka Rajput-Ghoshal†, Chuck Hutton, Fanglei Lin, Tim Michalski, Vasiliy Morozov and Mark Wiseman

Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA, 23606

Abstract

The Jefferson Lab Electron Ion Collider (JLEIC) is a proposed new machine for nuclear physics research. It uses the existing CEBAF accelerator as a full energy injector to deliver 3 to 12 GeV electrons into a new electron collider ring. An all new ion accelerator and collider complex will deliver up to 200 GeV protons. The machine has luminosity goals of 10^{34} cm^{-2} sec^{-1}. The whole detector region including forward detection covers about 80 meters of the JLEIC complex. The interaction region design has recently been optimized to accommodate 200 GeV proton energy using conventional NbTi superconducting magnet technology. This paper will describe the requirements and preliminary designs for both the ion and electron beam magnets in the most complex 34 m long interaction region (IR) around the interaction point (IP). The interaction region has over thirty-four superconducting magnets operating at 4.5K; these include dipoles, quadrupoles, skew-quadrupoles, solenoids, horizontal and vertical correctors and higher order multipole magnets. The paper will also discuss the electromagnetic interaction between these magnets.

Keywords – Superconducting magnet, quadrupole, interaction region, Electron-Ion Collider (EIC).

INTRODUCTION

The Jefferson Lab Electron Ion Collider (JLEIC) is a proposed new machine that uses the existing CEBAF (Continuous Electron Beam Accelerator Facility) as an electron injector, ion source linac, figure of eight low energy ion booster, figure of eight high energy ion booster and a unique figure of eight shape for the collider rings [1]. The machine design is updated recently in order to achieve higher energy and reduce the risk in superconducting magnets [2 - 3]. The original machine design was to deliver between 15 and 65 GeV center of mass energy collisions between electrons and nuclei. The updated design is to deliver up to 100 GeV center of mass energy collisions. The electron and ion rings intersect at the interaction point (IP) and the region around IP is called interaction region (IR). The interaction region contains a full acceptance detector built around a detector solenoid. This paper focuses only on the magnets in the IR (except the central solenoid and detector dipoles). The IR layout is shown in Figure 1. A preliminary design was done for all the IR magnets for the earlier machine design parameters [4]. Some of the quadrupoles in that design had high field in the coils, and coil design assumed Nb_3Sn conductor. The new improved machine design reduces the risk for IR magnets by bringing the peak field in the coils down to NbTi design limits.

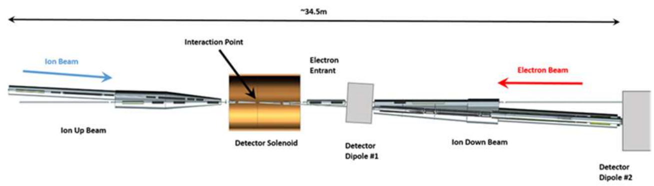

Figure 1: Interaction Region layout

MAGNET REQUIREMENT AND DESIGN

The IR magnet design specifications are given in Table 1. Preliminary designs have been completed to the first order for all the IR magnets. The main purpose of this initial design work is to optimize the coil geometry to calculate the peak field in the coils and to make sure all the magnets fit longitudinally. The magnet geometry is not yet optimized for higher order harmonics. Magnet-magnet interactions for the most challenging locations have been studied; this will be extended to all the magnets in the next phase of the project. The peak field in the coils is less than 7 T for all magnets, which is within the limit for the NbTi magnets operating at 4.5K. The design summary for all the magnets is also given in Table 1. The higher order multipole corrector magnets are not included in this table, as the requirements for these magnets are still being finalized. SIMULIA Opera FEA by Dassault Systemes [5] is used for all electromagnetic simulations, and the optimizer module is used for optimizing the coil geometry.

A. *Electron Beam IR Quadrupole*

The electron quadrupole and skew quadrupole have reduced field strength in new layout; therefore, the electron quadrupole design is kept same. All the electron quadrupole and skew quadrupole have same design as of now with main quadrupole strength of 45 T/m and 9.5 T/m for skew-quadrupole strength. The peak field in the electron quadrupole is approximately 3.5 T [4]. These quadrupoles can be optimized further to reduce space or reduce peak field in the coils.

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†*Corresponding author:* renuka@jlab.org

Table 1: Design specifications and design summary of IR magnets

Element Name	Type	Length [m]	Good field half-aperture [cm]	Inner Half-A [cm]	Outer Radius [cm]	Dipole field [T] Bx	Dipole field [T] By	Quadrupole field [T/m] Normal	Quadrupole field [T/m] Skew	Solenoid [T]	Coil Inner radius (cm)	Coil Outer Radius (cm)	Coil Width in Radial Direction (cm)	Peak Field in the coil (T)
		Specifications									Design			
Ion Upstream Elements														
iASUS	SOLENOID	1.6	3.0	4.0	12.0	0	0	0	0	2	6	6.7	0.7	2.0
iQUS3S	QUADRUPOLE	0.5	3.0	4.0	12.0	0	0	0	3.38	0	4.5	4.7	0.2	0.3
iQUS2	QUADRUPOLE	2.1	3.0	4.0	12.0	0	0	94.07	0	0	4.5	7.8	3.3	5.7
iQUS2S	QUADRUPOLE	0.5	2.0	3.0	10.0	0	0	0	-9.26	0	3.5	4	0.5	0.6
iQUS1b	QUADRUPOLE	1.45	2.0	3.0	10.0	0	0	-97.88	0	0	3.45	4.95	1.5	5.1
iQUS1S	QUADRUPOLE	0.5	2.0	3.0	10.0	0	0	0	16.42	0	3.5	4.4	0.9	0.9
iQUS1A	QUADRUPOLE	1.45	2.0	3.0	10.0	0	0	-97.88	-3.08	0	3.45	5.75	2.3	5.1
iCUS1	KICKER	0.3	2.0	3.0	10.0	-3.90	0.076	0	0	0	3.45	5.25	1.8	6.3
iCUS2	KICKER	0.3	2.0	3.0	10.0	4.50	-0.019	0	0	0				
Ion Downstream Elements														
iQDS1a	QUADRUPOLE	2.25	4.0	9.2	23.1	0.0	0	-37.23	-1.23	0	13.0	17.1	4.1	6.4
iQDS1S	QUADRUPOLE	0.5	4.0	9.9	24.8	0.0	0	0	14.85	0	13.0	14.2	1.2	3.9
iQDS1b	QUADRUPOLE	2.25	4.0	12.3	31.0	0.0	0	-37.23	0	0	13.0	16.3	3.3	6.4
iQDS2S	QUADRUPOLE	0.5	4.0	13.0	32.7	0.0	0	0	-7.83	0	13.6	14.5	0.9	2.3
iQDS2	QUADRUPOLE	4.5	4.0	17.7	44.4	0.0	0	25.96	0	0	18.2	21.5	3.3	7.0
iQDS3S	QUADRUPOLE	0.5	4.0	18.4	46.2	0.0	0	0	0.63	0	20.0	20.2	0.2	0.4
iASDS	SOLENOID	1.2	4.0	19.8	49.7	0.0	0	0	0	4	22.5	24.0	1.5	4.0
Electron Upstream Elements														
eASDS	SOLENOID	1.2	2.2	4.5	11.0	0	0	0	0	-4	6.5	8.0	1.5	4.0
eQDS3	QUADRUPOLE	0.6	2.4	4.5	10.0	0	0	-18.72	-2.71	0	4.95	6.5	1.55	3.6
eQDS2	QUADRUPOLE	0.6	2.8	4.5	8.5	0	0	36.22	5.25	0				
eQDS1	QUADRUPOLE	0.6	1.7	4.5	8.0	0	0	-33.75	-4.89	0				
Electron Downstream Elements														
eQUS1	QUADRUPOLE	0.6	2.0	4.5	10.0	0.0	0.00	-36.94	8.10	0	4.95	6.5	1.55	3.6
eQUS2	QUADRUPOLE	0.6	3.2	4.5	11.0	0.0	0.00	33.66	-7.38	0				
eQUS3	QUADRUPOLE	0.6	1.5	4.5	11.0	0.0	0	-20.80	4.56	0				
eASUS	SOLENOID	1.8	2.2	4.5	11.0	0.0	0	0	0	-4	6.5	8.0	1.5	4.0

B. *Ion Beam IR Quadrupole*

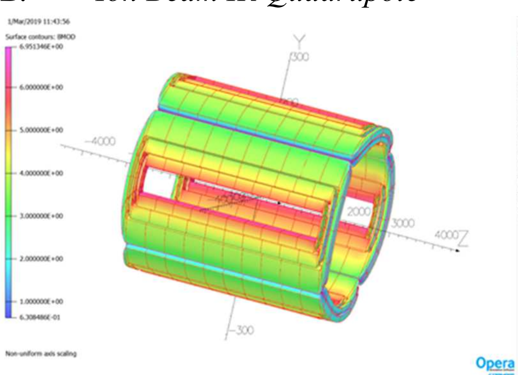

Figure 2: The peak field in iQDS2

There are 6 main quadrupoles in the ion beam line, three up-stream and three down-stream. All the up-stream quadrupoles are smaller bore and all the down-stream quadrupoles have larger bore. The first quadrupole in the downstream side iQDS1a needs the gradient of 37.23 T/m and the required beam aperture is 92 mm radius, the next quadrupole iQDS1b also needs the gradient of 37.23 T/m and has a beam aperture requirement of 123 mm radius. The first quadrupole had a skew component as well. For now, both these main quadrupoles are of the same design. This coil design is optimized to the first order but not fully optimized yet. The peak field in this coil is approximately 6.38 T. The last down-stream quadrupole (iQDS2) has the largest bore requirement. The peak field in this quadrupole is approximately 6.9 T, with further optimization the peak field in the coils is likely to reduce. The peak field in iQDS2 is shown in Figure 2.

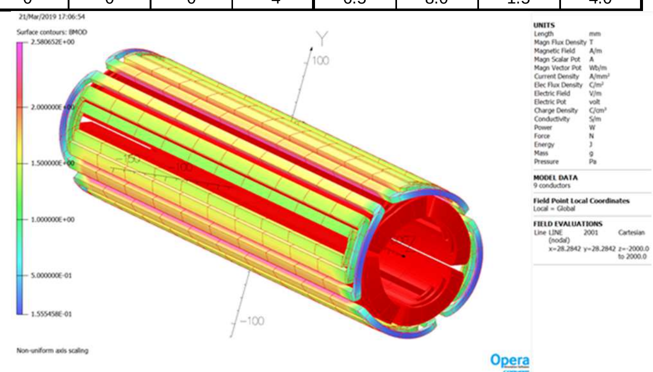

Figure 3: The coil field in skew quadrupole ion beam up-stream middle quadrupole

C. *Skew Quadrupoles*

Electron ring skew-quadrupoles are combined with the main quadrupole. In the ion ring, skew quadrupoles will be independent except the two skew quadrupoles on the first up-stream and downstream quadrupoles. The coil field in the skew quadrupole nested over the main ion beam upstream quadrupole (iQUS1a) in the presence of the main quadrupole field is shown in Figure 3. The coil field in all the skew quadrupoles is relatively low to moderate. The conductor is not fully designed for these magnets, but it will either be standard MRI rectangular conductor or standard round conductor.

D. *Solenoid Magnets*

There are four solenoid magnets in the IR. The downstream ion beam solenoid has a larger bore (198 mm radius) and it is a 4 T solenoid. The small bore solenoids have a central field of 4T (2 T for one); the coil inner radius is 60 mm. The larger bore solenoid has a central field of 4 T and the coil inner radius is 225 mm. All the solenoids will be wound with NbTi conductor. The detail conductor design will be done after further optimization and after looking into the shielding requirements

MAGNET-MAGNET INTERACTION

There are more than 34 individually powered magnets in the IR; these magnets are very close to each other. These magnets will have some electromagnetic interaction with each other. In order to study the magnet-magnet interaction, the following sections are considered for the initial study:

1. eQUS1 with Ion beam line

The effect of this magnet on the ion beam and shielding options were presented earlier [4].

2. eQUS3, eASUS, iQDS1a and iQDS1b

The iQDS1a and iQDS1b magnets are close to the upstream electron quadrupole (eQUS3) and anti-solenoid (eASUS) of the electron beam line. The skew quadrupole between iQDS1a and iQDS1b is not included in this simulation. Figure 4 shows the lattice layout for these magnets and Figure 5 shows the coil layout in SIMULIA Opera of the coils. Figure 6 shows the field at the electron beam line due to ion line magnets.

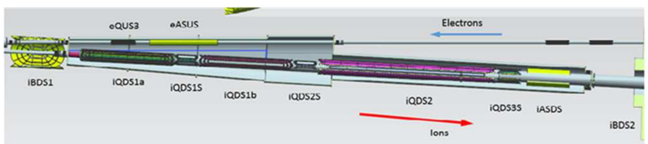

Figure 4: eQUS3, eASUS, iQDS1a and iQDS1b in the lattice layout

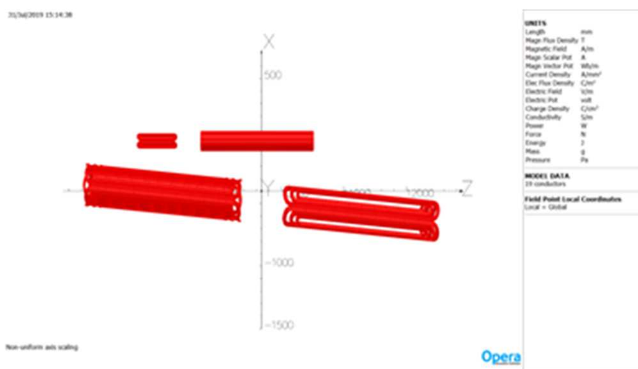

Figure 5: eQUS3, eASUS, iQDS1a and iQDS1b in SIMULIA Opera

The electron beam line quadrupole eQUS3 and electron beam solenoid are centered at z= 8010 mm and z=9610 mm respectively. These two magnets are in a straight line. The ion beam quadrupole iQDS1a is centered at z=8114.48 mm and iQDS1b is centered at z=11260.06 mm, but the ion beam quadrupoles are inclined; therefore, the effect of this one on the eQUS3 field varies along the beam axis. It is clear from the above plots that these magnets interact significantly and the effect varies along the axial position. The maximum field from the ion line magnets on the electron line in this region is approximately 0.31 T. These effects must be reduced further by either using active or passive shield around all the magnets.

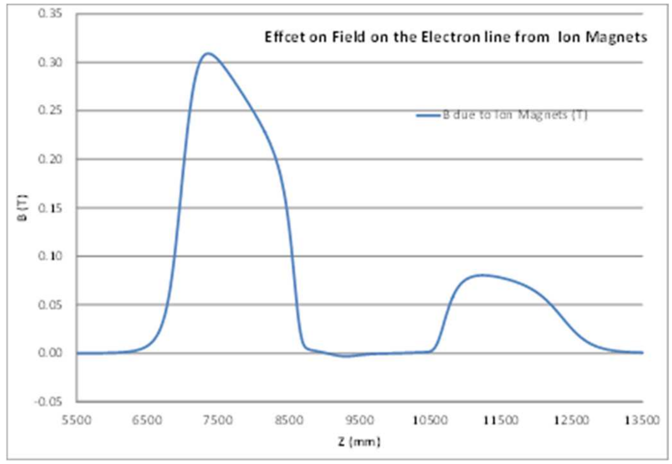

Figure 6: Field at the electron beam line due to ion line magnets

DESIGN SUMMARY

All of these magnets have only had preliminary optimization for the coil peak field for the required gradient and magnetic length. The maximum peak field in the coils is less than 7 T. The magnets for both ion and electron beam lines are all based on cold bore designs. This is primarily to lower the peak field in the coils. The cold bore designs reduce the radial space required, and this is an additional advantage, especially for the magnets which are closer to the IP. The conceptual cryostat design for all these magnets is in progress [6].

CONCLUSION AND OUTLOOK

Preliminary designs for all the IR magnets in the interaction region are complete. Some of the magnets in the interaction region are very close to each other and influence the field and gradient of other magnets. Magnet-magnet interaction is studied for two locations; this study shows that the effect of one magnet on another magnet or other beam line can be shielded.

The interaction between the detector magnets (main detector solenoid, and two dipoles), and the transport magnets remain to be studied.

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