ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW123

FULL ACCEPTANCE INTERACTION REGION DESIGN OF JLEIC*

V.S. Morozov†, R. Ent, Y. Furletova, F. Lin, T. Michalski, R. Rajput-Ghoshal, M. Wiseman, R. Yoshida, Y. Zhang, Jefferson Lab, Newport News, VA, USA
Y. Cai, Y. Nosochkov, M. Sullivan, SLAC, Menlo Park, CA, USA
G.-L. Sabbi, LBNL, Berkeley, CA, USA

Abstract

Nuclear physics experiments envisioned at a proposed future Electron-Ion Collider (EIC) require high luminosity of 10^{33}-10^{34} cm^{-2}s^{-1} and a full-acceptance detector capable of reconstruction of a whole electron-ion collision event. Due to a large asymmetry in the electron and ion momenta in an EIC, the particles associated with the initial ion tend to go at very small angles and have small rigidity offsets with respect to the initial ion beam. They are detected after they pass through the apertures of the final focusing quadrupoles. Therefore, the apertures must be sufficiently large to provide the acceptance required by experiments. In addition, to maximize the luminosity, the final focusing quadrupoles must be placed as close to the interaction point as possible. A combination of these requirements presents serious detection, optics and engineering design challenges. We present a design of a full-acceptance interaction region of Jefferson Lab Electron-Ion Collider (JLEIC). The paper presents how this design addresses the above requirements up to an ion momentum of 200 GeV/c. We summarize the magnet parameters, which are kept consistent with the Nb-Ti superconducting magnet technology.

INTRODUCTION

The basic process at the EIC, deep inelastic scattering, is illustrated in Fig. 1. An ion, composed of nucleons, in turn composed of partons (quarks and gluons), moves to the right and collides with an electron moving to the left. The electron interacts with a parton within the ion in a hard collision and excites the ion to a state with high invariant mass. We can, qualitatively, define three classes of particles in the final state:

1. The scattered electron,
2. Particles associated with the initial state ion, and
3. Particles associated with the struck parton.

All three classes of final-state particles carry information about the inner structure of the ions in the collisions and allow one to investigate the quark-gluon structure of the nucleons and nuclei.

We define the concept of a total acceptance detector as one that achieves close to 100% acceptance for all three classes of particles. The final state electron and the particles associated with the struck parton are scattered at relatively high angles with respect to be beam direction and can be detected in a conventional collider detector using a solenoidal field. The particles associated with the initial-state ion, however, tend to be nearly collinear with the ion-beam direction. Collider detectors in the past have had rather small acceptance for these particles.

The main requirements on an EIC interaction region (IR) design are:

1. Close to 100% acceptance for all three classes of particles,
2. High luminosity of 10^{33}-10^{34} cm^{-2}s^{-1}, in the entire center-of-mass energy range of 20 to 100 GeV,
3. Use of conventional technologies as much as possible.

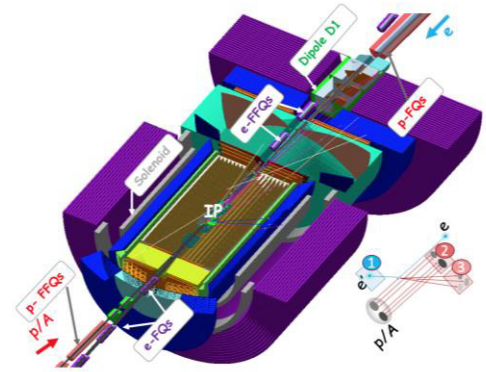

Figure 1: Classification of the final-state particles of a Deep Inelastic Scattering (DIS) process at the EIC: (1) scattered electron, (2) the particles associated with the initial state ion, and (3) the struck parton.

JLEIC FULL-ACCEPTANCE DETECTOR

Assuming constant chromatic contributions of the final focusing blocks, the luminosity at the interaction point (IP) is (to first order) inversely proportional to the distance between the last upstream and first downstream final focusing quads. However, the closer the beam elements are to the IP, the more they restrict the size of the detector and compromise the measurements. In Jefferson Lab Electron-Ion Collider (JLEIC) [1], the solution to achieve the necessary high luminosity while maintaining a full acceptance detector is twofold. We first introduce an angle between the colliding beams to separate the collision products moving along the ion beam from the incoming electron beam. We then let the small-angle particles pass through the apertures of the nearest machine elements, which perform the function of angle and momentum analyzer for those particles as illustrated in Fig. 2.

We have chosen a crossing angle of 50 mrad between the electron and ion beams. It enables the necessary forward acceptance and provides sufficient space for placement of the electron and ion final focusing quadrupoles (FFQs).

* This material is based upon work supported by the U.S. DoE under Contracts No. DE-AC05-06OR23177, DE-AC02-76SF00515, and DE-AC03-76SF00098.
† morozov@jlab.org

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW123

The space constraints are particularly important for the FFQs in the forward ion direction, which must have large apertures and high field strengths consistent with the detector space of 10.5 m. With this design, the beam elements of the electron and ion beams are interleaved but independent, reducing engineering complexity. The crossing angle also eliminates parasitic collisions of closely-spaced bunches and reduces the detector background by shortening the section of the detector beam pipe common for both beams.

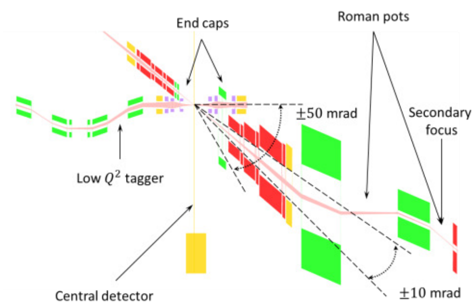

Figure 2: Layout of the JLEIC full-acceptance detector region.

The detection region extends about 50 m in the forward ion direction and about 30 m in the forward electron direction from the central detector [2, 3, 4]. Momentum analysis of the particles moving in the forward ion direction is first done by a 3 mrad spectrometer dipole. It has a round aperture with an opening angle of ± 50 mrad. There is a shielded region inside the dipole aperture for the electron beam to pass through.

Particles that are not detected after the first dipole travel through the round apertures of the forward ion FFQs with an opening angle of ± 10 mrad. This aperture size is chosen based on the requirement of detecting 100 GeV/c particles with transverse momentum of up to 1 GeV/c. After passing through the FFQs, the particles are momentum analyzed by the second 53 mrad spectrometer dipole. There is a long drift space after the second dipole to let the dispersion build up to about 1 m. The dispersion slope is compensated by the third 53 mrad spectrometer dipole. The ion beam is focused after the third dipole at a dispersive location to separate the particles with a relative magnetic rigidity offset of greater than 1% from the beam core.

IR MAGNET DESIGN

To minimize the technical risk associated with the interaction region magnet designs, all magnet parameters are chosen to be consistent with the Nb-Ti super-conducting magnet technology. For the ion FFQs, this requirement roughly translates into the maximum field at the aperture edge not exceeding about 4.6 T. The consistency of their conductor peak fields with the Nb-Ti technology was verified by 3D modeling of each magnet. The first spectrometer dipole has an aperture comparable to its length. It also integrates two relatively strong vertical orbit correctors. Its integrated central field is designed to be low enough not to exceed the Nb-Ti peak field limit. A 3D model of the first spectrometer dipole is shown in Fig. 3. We also completed preliminary analyses of the inter-magnet interactions and shielding requirements. We plan to include these results in beam tracking simulations.

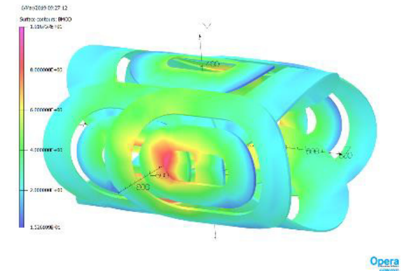

Figure 3: 3D model of the first spectrometer dipole.

ION IR OPTICS

Optics of the ion interaction region is based on the doublet FFQ configuration as shown in Fig. 4. There are three physical quadrupoles on each side of the IP. Their lengths and apertures have been optimized to meet the following conditions.

1. Downstream angular acceptance of ± 10 mrad,
2. Integrated field gradients sufficient to provide focusing at the IP up to 200 GeV,
3. Maximum aperture edge fields of less than 4.6 T.

Up to 100 GeV ion energy, the maximum integrated field gradients of the two quadrupoles adjacent on each side to the IP are sufficient to focus the beam at the IP by running them with opposite polarities as doublets as shown in Fig. 4 (bottom). In the 100 to 200 GeV energy range, the integrated gradient requirements exceed what the first two quadrupoles only can provide. They are then configured to run with the same polarities thus together forming the first quadrupole of an effective doublet. The third physical quadrupole is switched on as the second quadrupole of the effective doublet as shown in Fig. 4 (top). Thus, the doublet's focal parameter and therefore the β^* values can be adjusted in the two energy ranges while keeping the same maximum β values in the IR. We limit the maximum values of both β_x and β_y to about 4.2 km. This limit is set by the expected multipole components of the FFQs, which were obtained by scaling the measured HL-LHC FFQ multipoles to JLEIC parameters [5]. The $\beta^*_{x/y}$ values under this limitation are 8/1.3 cm and 21/1.6 cm in the 30-100 GeV and 100-200 GeV energy ranges, respectively. Such an optimization enhances the luminosity in the lower half of the complete energy range where it tends to suffer more from collective effects.

The beam is focused again about 50 m downstream of the interaction point at a location with about 1 m dispersion. The dispersion has a nearly zero slope at the focal point. The dispersion brings small-rigidity-offset particles out of the beam stay clear region, which has been minimized by focusing. The nearly zero dispersion slope ensures that the particles being detected are moving inside the detector parallel to the beam and the detector's edge. The secondary focus is followed by a section of dipole and quadrupoles that suppresses the dispersion localizing it to

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW123

the IR and adjusts the geometry of the ion beam line making it parallel to the electron one and setting a separation between them of 1.5 m.

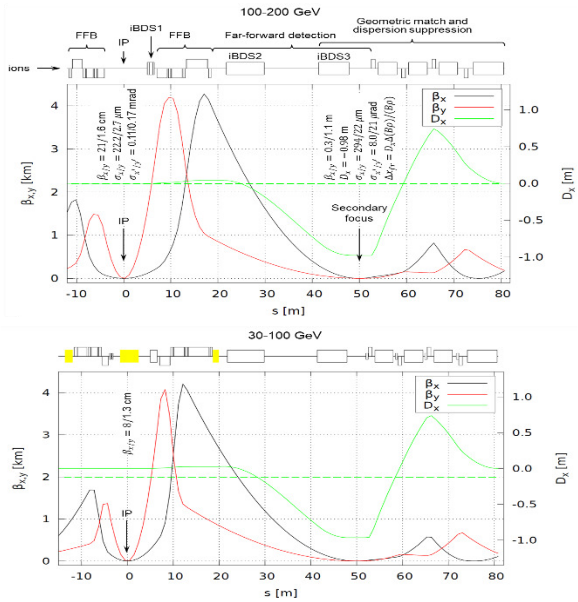

Figure 4: Ion IR optics in the 30-100 GeV (bottom) and 100-200 GeV (top) energy ranges.

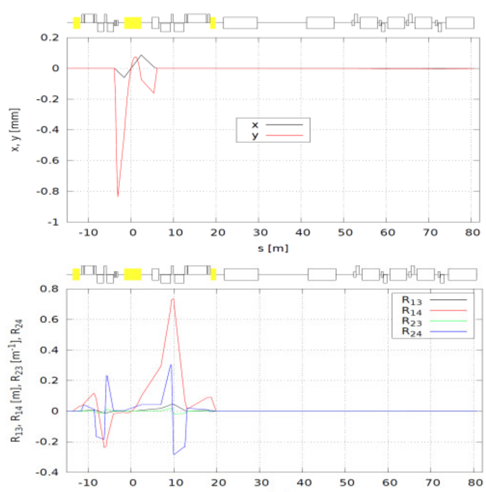

Figure 5: Ion closed orbit (top) and coupling elements of the beam transfer matrix (bottom) in the IR.

Since the ion beam goes through the detector solenoid at a 50 mrad crossing angle, the solenoid causes both obit excursion and betatron coupling. As illustrated in Fig. 5 (top), the orbit is corrected using two x/y kickers upstream of the IP and two y kickers integrated into the first spectrometer dipole. The dipole itself provides small horizontal steering. To bring the required corrector strength to within the Nb-Ti peak field limit, the orbit is tilted vertically at the IP by 0.15 mrad. The crabbing plane is adjusted to account for the vertical orbit tilt by rotating the beam's transverse plane about the longitudinal direction. The rotation is done by appropriately adjusting coupling at the IP.

The coupling is compensated locally using the rotating frame method [6]. Separate skew quadrupoles placed next to the FFQs provide effective rotation of the whole final focusing block. Coupling induced by the detector solenoid from the IP out is then compensated on both sides by anti-solenoids with matching field integrals. The skew quads are also used to control coupling at the IP for the reasons discussed above. Figure 5 (bottom) shows the coupling elements of the beam transfer matrix in the IR.

ELECTRON IR OPTICS

Since forward collision products move in a relatively small cone around the ion beam, the 50 mrad crossing angle allows us to reduce the distance between the electron FFQs to about 5.2 m. The optics of the electron IR is shown in Fig. 6 (top). The downstream electron final focusing block is followed by a 4-dipole chicane housing a low-Q^2 tagger and a Compton polarimeter and creating space for a luminosity monitor. Since the electron beam moves along the detector solenoid axis, the solenoid has no impact on the electron closed orbit. Compensation of betatron coupling induced by the detector solenoid is done for electrons similarly as for ions. Since the required FFQ gradients are lower for electrons than for ions, the electron skew quads are nested inside the electron FFQs. As illustrated in Fig. 6 (bottom), electron betatron coupling is localized to the IR and is locally compensated at the IP. Coupling compensation at the IP is needed for proper alignment of the crab tilt planes.

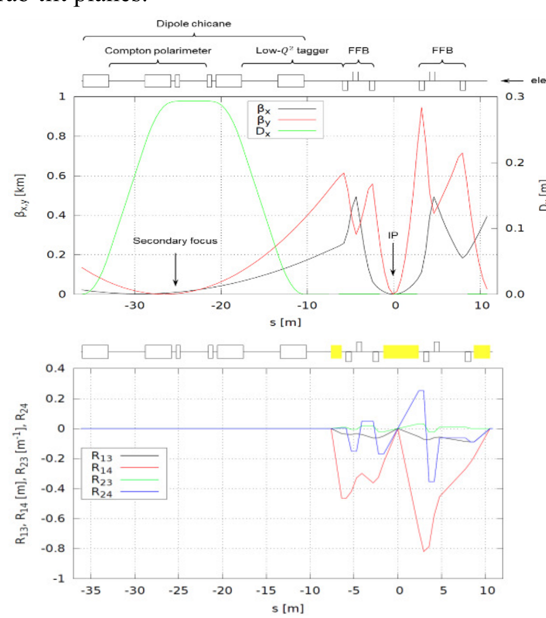

Figure 6: Electron IR optics (top) and coupling elements of the beam transfer matrix (bottom).

CONCLUSION

The JLEIC interaction region design integrates a full-acceptance detector, provides large forward acceptance and enables momentum analysis of the forward particles. It is integrated into the collider rings optically and geometrically. The parameters of all interaction region elements are consistent with the conventional Nb-Ti superconducting magnet technology.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW123

REFERENCES

[1] T. Satogata and Y. Zhang, "JLEIC – A Polarized Electron-Ion Collider at Jefferson Lab", ICFA Beam Dynamics Newsletter 74 (2018), p. 92.

[2] V.S. Morozov *et al.*, "Integration of Detector into Interaction Region at MEIC", Conf. Proc. C 1205201, 2011 (2012).

[3] F. Lin *et al.*, "Interaction region design and detector integration at JLab's MEIC", in *Proc. 2013 North American Particle Accelerator Conf. (NA-PAC'13)*, Pasadena, CA, USA, September 2013, pp. 508-510.

[4] V.S. Morozov *et al.*, "Progress on the interaction region design and detector integration at JLab's MEIC", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, June 2014, pp. 71-73. doi:10.18429/JACoW-IPAC2014-MOPRO005

[5] G.H. Wei *et al.*, "Influence of magnet multipole field components on beam dynamics in JLEIC ion collider ring", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 16, pp. 3525-3527. doi: 10.18429/JACoW-IPAC2016-THPMR053

[6] M.Bassetti *et al.*, "Solenoidal field compensation", Frascati Phys. Ser. 10, 209 (1998).