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MULTIPOLE EFFECTS ON DYNAMIC APERTURE IN JLEIC ION COLLIDER RING*

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Abstract

In a collider, stronger focusing at the interaction point (IP) for low beta-star and high luminosity produces large beams at final focusing quadrupoles (FFQs). To achieve the high luminosity requirement in the Jefferson Lab Electron-Ion Collider (JLEIC), the interaction region (IR) beta functions peak at ~4.2 km in downstream FFQs. These large beta functions and FFQ multipoles reduce the dynamic aperture (DA) of the ring. A study of the multipole effects on the DA was performed to determine limits on multipoles, and to include a multipole compensation scheme to increase the DA and beam lifetime.

INTRODUCTION

The Jefferson Lab Electron-Ion Collider (JLEIC) [1] is a high-luminosity high-polarization facility based on the existing CEBAF facility. The JLEIC design was recently updated to have a center-of-mass energy of 100 GeV, with an ion collider ring (ICR) maximum energy of 200 GeV. An aggressive final focus for high luminosity of $10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ produces maximum IR beta functions of ~4.2 km in both planes. Beam parameters are $\varepsilon^{\mathrm{N}}_{\mathrm{x,y}} = 0.5/0.1$ µm, and rms $\Delta p/p = 3\times10^{-4}$.

JLEIC IR OPTICS

The JLEIC IR schematic layout is shown in Fig. 1 [2]. At small angles with respect to the beam directions, the detection regions extend 30 m to 40 m in either direction from the central detector. The central detector is designed around a 4 m solenoid with maximum field of 2 T extending 2.4 m on the outgoing ion side, and 1.6 m on the opposite side. The solenoid field is adjustable independent of the beam energies to optimize the detection for various processes. The electron beam is aligned with the detector solenoid axis to avoid local synchrotron radiation generation.

The IR optics must be flexible enough to support the β-squeeze and optimization of the luminosity and detection in different collider configurations, including different beam energies, ion species, and detector solenoid strengths. The ion IR optics designed to support these requirements is shown in Fig. 2. There are three physical quadrupoles on each side of the IP. Their lengths and apertures have been optimized to meet the conditions:

- Downstream angular acceptance of ±10 mrad,
- Integrated field gradients sufficient to provide focusing at the IP up to 200 GeV/c, and
- Maximum field less than 4.6 T at the aperture limit.

The parameters for the IR quadrupoles are shown in Table 1.

Table 1: JLEIC Ion Ring IR Quadrupoles

Name	length [m]	Aperture [cm]	Gradient [T/m]
iQUS2	2.1	4	94.07
iQUS1b	1.45	3	-97.88
iQUS1a	1.45	3	-97.88
iQDS1a	2.25	9.2	-37.23
iQDS1b	2.25	12.3	-37.23
iQDS2	4.5	17.7	25.96

Chromaticity Correction

With the upgrade to the 200 GeV proton ring, the ICR was optimized to attain the proper phase advance between sextupoles and IR which was necessary for local chromaticity correction.

The momentum acceptance for the optimized lattice is about $\Delta p/p = \pm3\times10^{-3}$ as shown in Fig. 3. With the design momentum spread of about 3×10^{-4}, this gives about $\pm10\sigma_p$ which is adequate for the ICR.

Fig. 4 shows the DA found for this momentum acceptance with a step size of ($2\sigma_{\mathrm{p}}$). The aperture size is about $\pm60\,\sigma$ (shown by the dotted black line) for the largest momentum offset. This sets the basis for the development of the EIC IR magnet requirements and tests of whether the demonstrated magnet parameters satisfy them.

DA WITH MULTIPOLES

In a collider the dominant effect from multipoles comes from magnets located in areas with high beta function which occurs in the final focus quads. To better understand the limits imposed on the DA from multipoles we use multipole data from existing magnets by scaling them to JLEIC design parameters [3]. The relation for the magnetic field components containing the non linear elements is,

$$B_{\mathrm{y}} + iB_{\mathrm{x}} = 10^{-4} B_{\mathrm{Q}} \times \Sigma_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0}\right)^n, \quad (1)$$

where a_n and b_n are the relative values of skew and normal multipoles determined at a reference radius r_0 (typically

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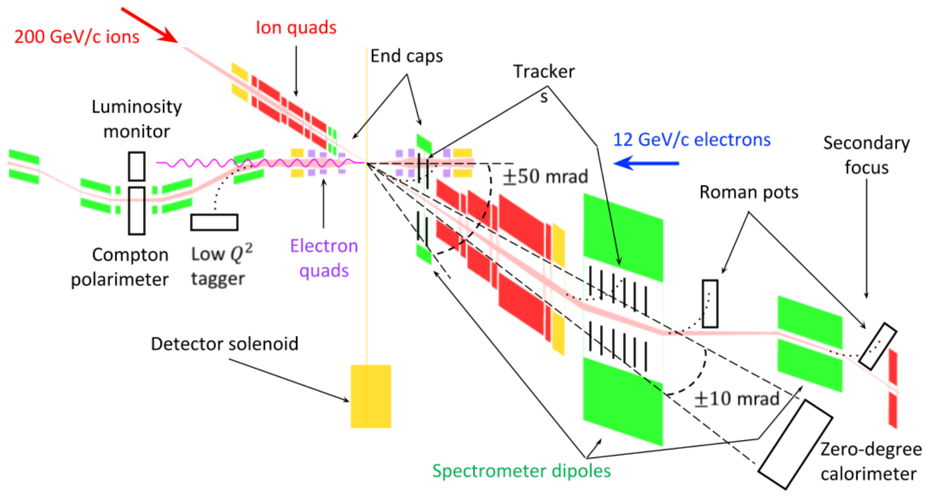

Figure 1: JLEIC detector region elements layout.

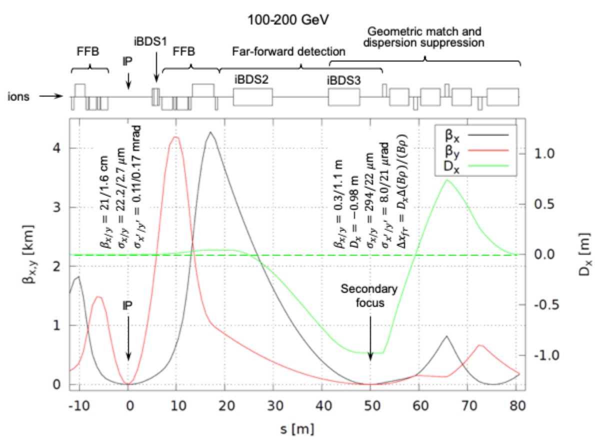

Figure 2: Beam optics of the ion detector region. Also shown are the positions of the IP and secondary focus, and the beam parameters at those locations.

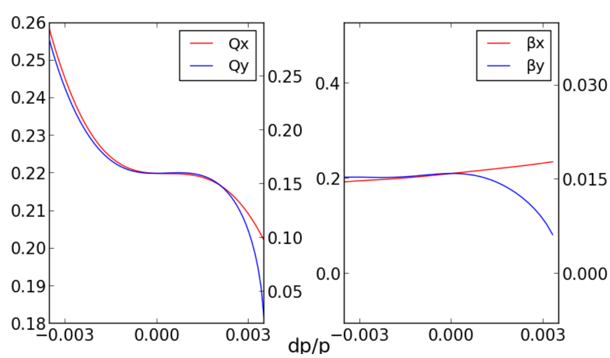

Figure 3: Chromatic dependence of the fractional betatron tunes (left) and β^* (right).

taken as 2/3 of the aperture) in units of 10^{-4}. B_Q is the main quadrupole field taken at r_0. Furthermore, the a_n and b_n values have systematic and random terms. For the consideration of this paper the systematic data from the sampling quadrupoles was taken as is while the random data was generated by using the *rms* value of the combined data sets to generate a gaussian distribution with a 2σ cutoff.

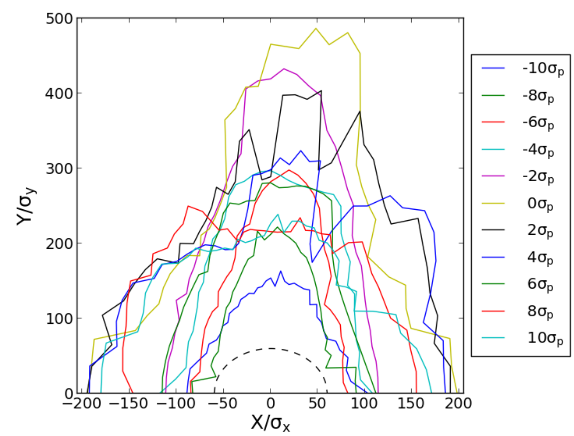

Figure 4: DA of the bare ion collider lattice at different relative momentum offsets. DA $\simeq 60\,\sigma$.

SuperKEKB Multipole Data

We statistically analyzed the multipole values of the eight superconducting quadrupoles in the SuperKEKB IR [4] to produce a set of random and systematic multipoles. The values scaled to a reference radius of 2/3 of the inner coil radius of a quadrupole are listed in Table 2. A few sets of the multipoles values randomly generated according to the parameters in Table 1 were applied to all six IR quadrupoles. The DA for the on-momentum particle is shown in Fig. 5 for 10 random seeds. As expected, the DA reduced significantly in comparison to the bare lattice. As one can see the DAs are similar for different random seeds and have acceptable sizes of at least 12.7σ even without any multipole correction.

JLEIC Electron IR Quadrupole Data

Another set of multipole data was obtained from the electron quad design [5]. For this case the systematic terms considered were the allowed terms b_6 and b_{10}, together with the random multipoles on all harmonics up to 10. The resulting DA is shown in Fig. 6.

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Table 2: Multipole Data Generated from SuperKEKB FFQs

n	Avg.		rms	
	a_n	b_n	a_n	b_n
3	0.84	0.42	2.27	2.03
4	0.43	-0.22	1.36	0.68
5	-0.38	-0.18	0.84	0.91
6	-0.18	4.44	1.36	3.49
7	0.27	-0.04	0.24	0.39
8	0.04	-0.41	0.72	0.35
9	0.48	1.48	1.8	2.88
10	-0.55	-7.2	1.28	3.66

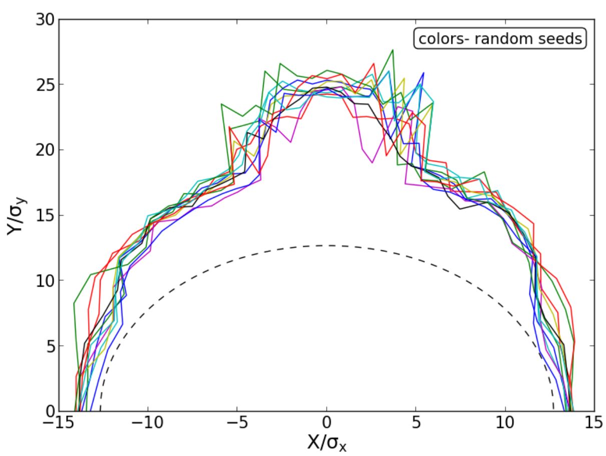

Figure 5: DA with multipole errors from Table 2. DA $\simeq 12.7\sigma$.

MULTIPOLE CORRECTION

As seen in Figs. 1 and 2 there is space reserved for multipole correctors to be introduced. Future work involves optmizing these corrector packages to minmize the effect from multipoles and increase the DA. An initial pass on the corrector compensating only the systematic b_6 body multipole, is shown in Fig. 7. Note that only the upstream quad closest to the IP is considered because that quadrupole has the smallest aperture and may set a limit on the DA.

SUMMARY

The dynamic aperture of the bare lattice is about $\pm 60\,\sigma$ for $\Delta p/p = \pm 10\sigma_p$, which is quite large for the ion collider ring. With multipole fields introduced in all IR quadrupoles, the DA was reduced to about $\pm 10\,\sigma$ at a minimum (Fig. 6). An initial pass on the multipole correction (without optimization) for a single quad shows a reasonable improvement of the DA. Future work includes adding multipole effects in all the magnets in the ring and taking in to account the closed-orbit excursion and beam-beam effects and optimizing the corrector package to maximize the final dynamic aperture of the JLEIC ion collider ring.

Table 3: Multipole (random) Data from JLEIC Electron IR Quadrupole Preliminary Analysis

n	a_n	b_n
3	4.68	4.27
4	3.54	8
5	2.54	2.54
6	1.75	1.99
7	1.41	1.11
8	0.83	0.81
9	0.48	0.49
10	0.34	0.34

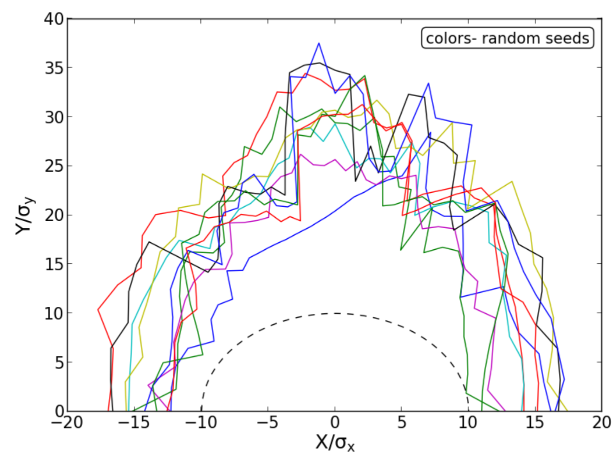

Figure 6: DA with multipole errors from Table 3. DA $\simeq 10\sigma$.

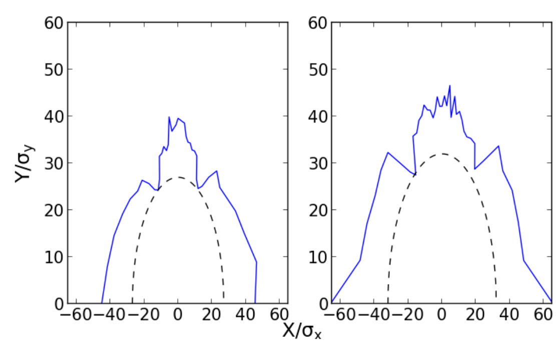

Figure 7: DA with b_6 multipole component 27σ (left) and with correction 32σ (right).

REFERENCES

[1] T. Satogata and Y. Zhang, "JLEIC - A Polarized Electron-Ion Collider at Jefferson Lab", *ICFA Beam Dynamics Newsletter*, vol. 74, pp. 92-182, Aug. 2018.

[2] V.S. Morozov *et al.*, "Full Acceptance Interaction Region Design of JLEIC", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2787–2790.

[3] E. Todesco, B. Bellesia, and J.-P. Koutchouk, "Field Quality in Low-Beta Superconducting Quadrupoles and Impact on the Beam Dynamics for the Large Hadron Collider Upgrade", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 10, no. 6, p. 062401, Jun. 2007. doi:10.1103/PhysRevSTAB.10.062401

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[4] N. Ohuchi *et al.*, "Final-focus Superconducting Magnets for SuperKEKB", in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr. 4, pp. 1215–1219.

[5] G. L. Sabbi *et al.*, "Field Quality Analysis of Interaction Region Quadrupoles for JLEIC", presented at the NAPAC'19, Lansing, MI, USA, Sep. 2019, paper MOPLO13, this conference.