EVALUATION AND COMPENSATION OF DETECTOR SOLENOID EFFECTS IN THE JLEIC*

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Abstract

The JLEIC detector solenoid has a strong 3 T field in the Interaction Region (IR) area with a big crossing angle of 50 mrad. One of the main effects of the solenoid field is coupling of the horizontal and vertical betatron motions which must be corrected in order to preserve the dynamical stability and beam spot size match at the Interaction Point (IP). Additional effects include influence on the closed orbit and dispersion caused by the crossing angle between the solenoid axis and the ion beam orbit. Another important aspect of the solenoid is that it affects ion polarization breaking the figure-8 spin symmetry. Crab dynamics further complicates the picture. All of these effects have to be compensated or accounted for. The proposed correction system is equivalent to the Rotating Frame Method. However, it does not involve physical rotation of elements. It provides local compensation of the solenoid effects independently for each side of the IR. It includes skew quadrupoles, dipole correctors and anti-solenoids to cancel perturbations to the orbit and linear optics. The skew quadrupoles and final focus quadrupoles together generate an effect equivalent to adjustable rotation angle to do the decoupling task. Details of all of the correction systems are presented.

INTRODUCTION

The Interaction Region (IR) of the JLEIC (Jefferson Lab Electron Ion Collider) [1] includes a strong 3 T detector solenoid field. The solenoid creates coupling of the horizontal and vertical betatron motion which must be corrected in order to preserve the design ultra-small beam size at the IP. The solenoid breaks the figure-8 spin symmetry as well [2]. This should also be compensated. Additional complications are that the solenoid is not parallel to the ion beam in order to make a full-acceptance detector [3]. This leads to orbit and dispersion perturbations and additional coupling effects. The proposed correction system will provide local compensation of the solenoid linear effects independently for each side of the IR.

DETECTOR SOLENOID IN THE INTERACTION REGION OF THE JLEIC

The JLEIC ion collider ring accelerates protons from 9 to up to 100 GeV/c or ions in the equivalent momentum range and is designed to include a full-acceptance detector [2, 3]. This brings new challenges to the design of the interaction region, including asymmetric lattice and large crossing angle. An overall layout of the detector region is shown in Fig 1.

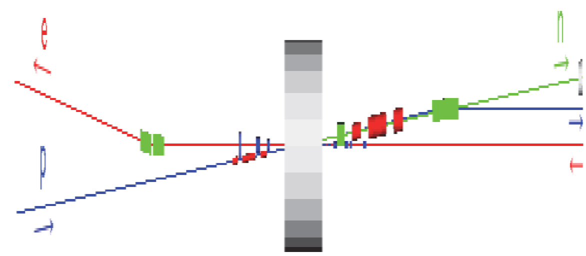

Figure 1: Interaction Region (IR) layout of the JLEIC (Jefferson Lab Electron Ion Collider).

The detector solenoid is parallel to the electron beam, but makes a 50 mrad angle with the ion beam. A 6 mrad horizontal spectrometer dipole is placed downstream of the detector solenoid to meet the requirements of the full-acceptance detector. The longitudinal center of the detector solenoid has an offset of 0.4 m from the IP (Interaction Point). For the ion beam line, it is on the downstream side. A hard edge model of the detector solenoid is used in the simulation to represent a real main field of the detector solenoid, which is shown in Fig. 2. Also for the ion beam line, about 1.6 m of the solenoid is upstream of the IP, and 2.4 m are downstream of it.

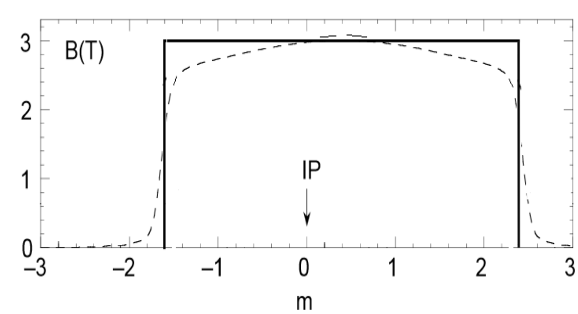

Figure 2: Hard edge model of the detector solenoid.

DETECTOR SOLENOID EFFECTS

Similar to Super B [4], the JLEIC detector solenoid creates the following effects:

- Coherent orbit distortion in the ion ring. The vertical orbit distortion is due to the solenoid angle relative to the beam trajectory (50 mrad). The horizontal orbit distortion arises due to the vertical orbit and coupling.

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- Coupling of the X and Y betatron motions, which, in the absence of other magnets, creates a beam rotation around the S-axis by an angle BsL/(2Bρ), where Bs and L are the solenoid field and length. In a collision mode of 5 GeV electron beam and 100 GeV proton beam, the corresponding rotation angles are 359.7 mrad for electrons and 17.8 mrad for protons.
- Vertical and horizontal dispersion due to the Y and X orbit bends.
- Perturbation of the β functions, tune, linear chromaticity and W function due to the solenoid focusing effects.
- Breaking of the figure-8 spin symmetry for ion polarization.

MECHANISM OF DECOUPLING IN A COMPENSATION SYSTEM

A solenoid is often a source of coupling in a ring, for example, a detector solenoid or solenoids used in electron cooling and spin rotators. A matrix, which can represent a solenoid in an accelerator physics calculation, can be written as [5].

$$\mathrm{M}_{sol} = \begin{bmatrix} C^2 & SC/K & SC & S^2/K \\ -KSC & C^2 & -KS^2 & SC \\ -SC & -S^2/K & C^2 & SC/K \\ KS^2 & -SC & -KSC & C^2 \end{bmatrix} \quad (1)$$

where, $\mathrm{C} = \cos(KL)$, $\mathrm{S} = \sin(KL)$,

$$\mathrm{K} = B_{sol}/(2B\rho) \quad (2)$$

It can be presented as a multiplication of a focusing part and a rotation part.

$$\mathrm{M}_{sol} = \begin{bmatrix} C & S/K & 0 & 0 \\ -KS & C & 0 & 0 \\ 0 & 0 & C & S/K \\ 0 & 0 & -KS & C \end{bmatrix} R[KL] \quad (3)$$

$$= M_{sol}^{focus} R$$

where,

$$\mathrm{R}(\alpha) = \begin{bmatrix} I\cos\alpha & I\sin\alpha \\ -I\sin\alpha & I\cos\alpha \end{bmatrix}, I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (4)$$

Although the simplest way to compensate coupling of a solenoid is to put an anti-solenoid (a solenoid with a field integral equal in magnitude and opposite in sign) next to it, sometimes focusing quadrupoles need to be inserted between the two solenoids to keep transverse focusing. Then the compensation will not work as before.

$$\begin{aligned} &M_{a.sol}[-KL]M_{ins}M_{sol}[KL] \\ &= M_{a.sol}^{focus}R[-KL]M_{ins}R[KL]M_{sol}^{focus} \end{aligned} \quad (5)$$

Eq. (5) above can be decoupled if the quadrupole is tilted by the solenoid rotation angle, also called a Rotating Frame Method [6], as shown in Eqs. (6) and (7):

$$M_{ins}^{tilt} = R[KL]M_{ins}R[-KL] \quad (6)$$

$$M_{a.sol}[-KL]M_{ins}^{tilt}M_{sol}[KL] = M_{a.sol}^{focus}M_{ins}M_{sol}^{focus} \quad (7)$$

In JLEIC case, nuclear physics studies are planned not only for collisions at a single energy and with a proton/electron beam, but also at other energies and many other particle species. For different energies and different particle species, the tilt angle should be adjusted according to the rotation angle of the solenoid. In this case, an effect analogous to quadrupole rotation can be effectively produced by appropriately combining a normal quadrupole component (strength: kn) and a skew component (strength: ks) as shown in Eq. (8).

$$\alpha = \frac{1}{2}arc\tan\frac{ks}{kn} = \frac{B_{sol}L}{2B\rho}. \quad (8)$$

SIMULATION RESULTS OF A COMPENSATION SYSTEM

For the JLEIC, a proposed correction system provides local compensation of the solenoid effects independently for each side of the IR. It includes 2 IR triplets with skew quadrupole components or skew quadrupoles, dipole correctors and anti-solenoids to cancel perturbations of the optics and spin symmetry.

Local Correction of Coherent Orbit Distortion

The correction of the beam orbit in the solenoid uses two dipole correctors on each side of the IP. The resultant orbit after correction is shown in Fig. 3 for 60 GeV proton with 3 T solenoid. Here not only the orbit offset but the orbit slope is corrected at the IP as required for crabbing. The maximum offset is -3 mm at the 3rd corrector in vertical. And the strength of the 3rd correctors vertically is large as 1.6 mrad.

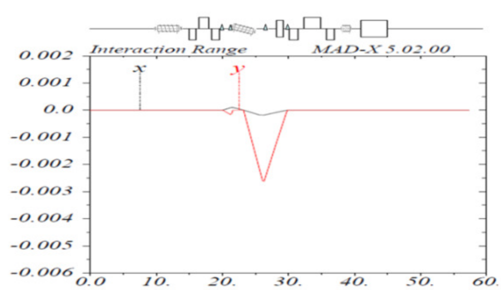

Figure 3: Closed orbit in the IR of the JLEIC ion ring.

Local Compensation of Coupling Effect

With the effective rotation angle produced in the IR triplets by skew field components or nearby skew quadrupoles, the coupling effects can be controlled locally between the detector solenoid and anti-solenoid.

A simulation result for 60 GeV proton beam with 3 T detector solenoid is shown in Fig. 4. The coupling betas without compensation can be seen in the upper sub-figure. Coupling betas (beta12 and beta21) [7] are about 5 % of

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the values of beta11 and beta22, which turn into the usual beta x and beta y without coupling. With the anti-solenoid on and the effective rotation angle set to be the same as the rotation angle produced by the detector solenoid, the coupling betas (beta12 and beta21) can be controlled locally in the interaction region and compensated at the IP.

Decoupling schemes for electron ring and other species are similar. Due to the requirement of different detector solenoid strengths for nuclear physics studies, field integral of the anti-solenoid should be a minus value of the field integral of the detector solenoid on each side of the IP, and the effective rotation angle of the triplet the same as the rotation angle in the detector solenoid on each side of the IP.

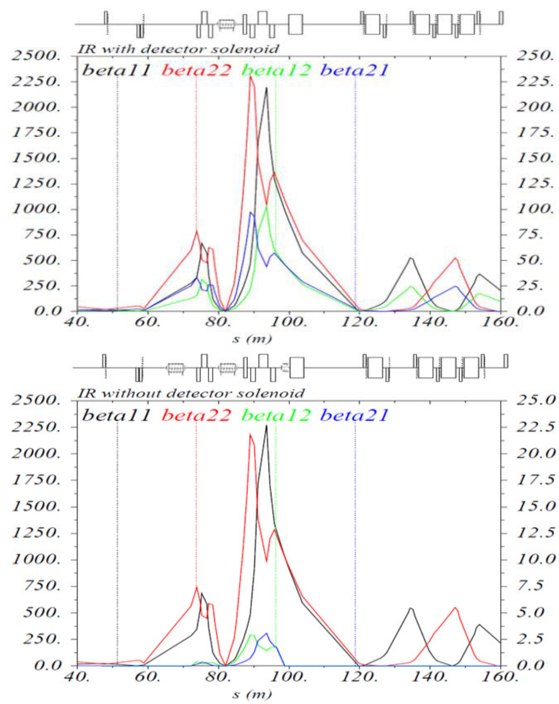

Figure 4: Local compensation of the coupling effect caused by the detector solenoid in the JLEIC ion collider ring (top: without compensation, bottom: with compensation).

Correction of Other Effects

Although with effective rotation angles of the IR triplets, 3 independent values can be used for matching in the IR, for complete compensation, nearby quadrupoles are needed to do matching to compensate effects on the tune, beta function, dispersion, and linear chromaticity. Adjustments to chromatic sextupoles and their phase advances are also needed to restore the linear chromaticity compensation and W function. A result for 60 GeV case is shown in Fig. 5. In this figure, the vertical dispersion is not 0 but it is less than 0.5 m around the ring, which seems acceptable.

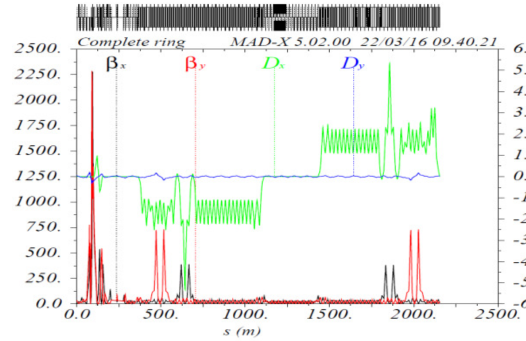

Figure 5: Beta and dispersion functions around the JLEIC ion collider ring after correction.

Opposite integrated fields of the detector solenoid and anti-solenoids can make the net longitudinal field integral zero to compensate their effect on the ion spin.

CONCLUSION

A correction system for the JLEIC detector solenoid is designed based on a hard edge solenoid field model. It includes two anti-solenoids, skew quadrupole components in the IR triplets, and orbit correctors for complete compensation of linear coupling and coherent orbit distortion on each side of the IR. β function, dispersion, linear chromaticity and W function are also re-matched by adjusting quadrupole and sextupole settings. The detector solenoid and two anti-solenoids can cancel their effects on the spin.

With dipole correctors between the two IR triplets, the closed orbit can be controlled with only a small offset, but the strengths of some of the vertical correctors reach 1.6 mrad. Correctors located further away are considered to make a comparison. For different collider energies and ion species, beta squeeze may be needed after injection in a special injection mode. The detector solenoid may be set to 3 T at injection because ramping it may be impractical. However, compensation requirements are different, including the fact that the beam orbit and W function do not need to be 0 at the IP, etc. These should be studied as a next step. Further studies are also needed to evaluate the non-linear effect of the solenoid and dynamic aperture.

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