TOWARDS A SMALL EMITTANCE DESIGN OF THE JLEIC ELECTRON COLLIDER RING*

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Abstract

The electron collider ring of the Jefferson Lab Electron-Ion Collider (JLEIC) is designed to provide an electron beam with a small beam size at the IP for collisions with an ion beam in order to reach a desired high luminosity. For a chosen beta-star at the IP, electron beam size is determined by the equilibrium emittance that can be obtained through a linear optics design. This paper briefly describes the baseline design of the electron collider ring reusing PEP-II components and considering their parameters (such as dipole sagitta, magnet field strengths and acceptable synchrotron radiation power) and reports a few approaches to reducing the equilibrium emittance in the electron collider ring.

INTRODUCTION

The electron complex of JLEIC consists of the existing CEBAF serving as a full energy injector and the electron collider ring. The baseline optics of the electron collider ring is designed reusing major PEP-II High Energy Ring (HER) magnets within their magnet specification in both arcs and straights and new dipoles and quadrupoles in particular machine blocks, such as spin rotators, interaction regions, etc [1]. The required arc dipole field for a 10 GeV electron beam is 0.3 T, well within the 0.363 T field that a PEP-II dipole can provide [2]. For the JLEIC application, each dipole has a bending angle of 2.8o, resulting a 3.3 cm sagitta. This sagitta is about 1 cm larger than the PEP-II dipole sagitta of 2.2 cm, but it is still within the dipole good field region of 5 cm. Optics was designed to keep the reused PEP-II quadrupole strengths within their specifications below 17 T/m [2] and new dipoles and quadrupoles at low fields.

Due to the natural synchrotron radiation effect, the electron beam in the collider ring reaches an equilibrium emittance that is primarily determined by the linear optics design. The two arcs, consisting of regular FODO cells, spin rotators and matching sections between them, contribute up to 92% of the natural horizontal emittance. The phase advance of a regular arc FODO cell was chosen to be 108o, close to 138o that gives the minimum emittance for FODO cell optics [3]. In addition, such a phase advance allows one to have a 3π phase advance between sextupoles so that the sextupole induced geometric resonance driving terms can be cancelled every 5 cells. The spin rotators were designed with interleaved

solenoids, dipoles and quadrupoles, mainly considering the spin rotation between the vertical (in the arcs) and longitudinal (at the IP) directions. Matching sections match the optics between the regular FODO cells and spin rotators.

For a given optics design, the normalized and un-normalized (or geometric) emittances are proportional to the 3rd and 2nd power of the beam energy, respectively. Table 1 lists the normalized emittances at various energies in the JLEIC electron ring baseline design. At low energies (< 5 GeV), small electron beam sizes due to very small emittances require strong cooling of the ion beams. A proper approach can be introduced to expand the electron beam emittances. For example, one can simply adjust the phase advance in the regular arc FODO cell from 108o down to 90o, away from 138o. At high energies (> 5 GeV), large emittances result in large colliding beam sizes at the IP and lead to a reduction of the luminosity. This requires to reduce the emittances, accordingly. This paper reports a few approaches to reduce the equilibrium emittances at high energies, in particularly.

Table 1: Normalized Emittances at Various Energies in the JLEIC Electron Ring Baseline Design

Energy (GeV)	Normalized Emittance (μm)
3	30
5	137
6.95	425
9.3	797
10	1093

APPROACHES TO EMITTANCE REDUCTION

Optimizing Ring Optics

Since the emittance contribution of the local chromaticity compensation block and chicane in the detector region in the straight has been minimized to only about 8%, optimization of the ring optics is performed in the two arcs to further reduce the emittance. The regular arc FODO cell design, in terms of the dipole bending angle, bending radius and phase advance, has been chosen considering the ring geometry, PEP-II magnet field specification, synchrotron radiation power and nonlinear beam dynamics. There is no further optimization that can be applied to the FODO cell optics if reusing the PEP-II magnets. However, the spin rotator and matching section optics can be adjusted to reduce their emittance contribution. Figure 1 shows the spin rotator (left) and

matching section (right) optics in the baseline design of the electron collider ring. The beta functions and dispersion in the dipoles in these sections are not low. This results in a large average value of the *H*-function in the dipoles that determines the natural horizontal emittance in an electron storage ring [3].
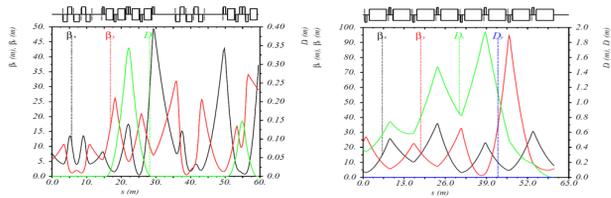
Figure 1: Optics of the spin rotator (left) and matching section (right) in the baseline design of the electron collider ring.

Optimization of the optical functions in these two sections has been performed to reduce the emittance. In the spin rotator section, a double-bend-achromat (DBA)-like lattice is implemented in the areas of the dipole sets so that both the horizontal beta function and dispersion are suppressed in the dipoles. Consequently, the average of the *H*-function is small along with the emittance. In the matching section, a "missing magnet"-like approach is adopted to suppress the dispersion down to zero, while not introducing an emittance growth. Optical functions between the two sections are matched by simply using four quadrupoles. Because the phase advance in a regular FODO cell is 108° (not 60°), instead of a missing dipole, the dipoles in the matching section have different bending angles. They are calculated using the regular FODO cell dipole bending angle and phase advance [4]. Optimized lattice functions in the spin rotator (left) and matching section (right) are shown in Fig. 2. By doing this, the total emittance of the electron collider ring is reduced by 30%.
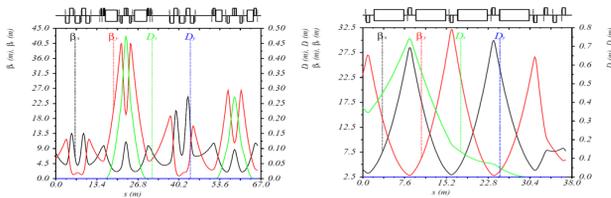
Figure 2: Optics of the spin rotator (left) and matching section (right) optimized for reducing the emittance in the electron collider ring.

Introducing Damping Wigglers

Introducing damping wigglers is another effective way to control the electron emittance in a storage ring. Damping wigglers can be placed between the quadrupoles in the straight section and require only a local optics adjustment. Depending on the requirement of the emittance reduction, one can easily insert or remove the damping wigglers, leaving the rest of the ring design intact. Figure 3 shows examples of the optics of one dipole damping wiggler (left) and 6 dipole damping wigglers (right) located between the quadrupoles in the straight of the electron collider ring. Each damping

wiggler consists of nine 0.1m-long and two 0.05m-long 1.6 T dipoles. The dipoles in each wiggler are arranged so that the dispersion is excited only inside the wiggler. At 5 GeV electron beam energy, 6 damping wigglers in the straight reduce the emittance by a factor of 2.
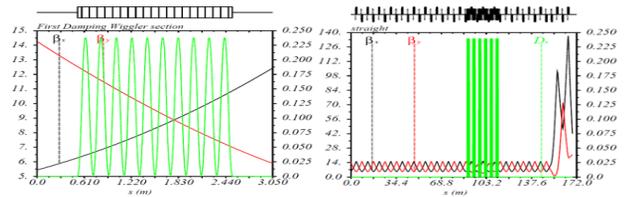
Figure 3: Optics of one dipole damping wiggler (left) and 6 dipole damping wigglers (right) located between the quadrupoles in the straight of the electron collider ring.

However, such a configuration of the damping wigglers enhances the energy spread of the stored electron beam by a factor of 2.2. This demands more effort to obtain a large momentum acceptance and a higher RF peak voltage for keeping the same bunch length. In addition, damping wigglers radiate more power. The total synchrotron radiation power in the JLEIC electron collider ring at 5 GeV is 5.5 MW, including 3 MW from the aforementioned 6 damping wigglers. Since the total synchrotron radiation power in the JLEIC electron collider ring is limited to 10 MW when considering reuse of the PEP-II vacuum chambers, introducing damping wigglers to reduce the emittance is not suitable at electron beam energies above 7 GeV with the same stored beam current. One can lower the current to reduce the amount of the synchrotron radiation power, but this obviously results in reduction of the luminosity.

Adjusting Damping Partition Number

In an electron storage ring, the damping partition number is used to describe the damping rate of the particle motion due to the natural synchrotron radiation. The damping partition number *D* is a property of the lattice configuration given by [3]:

$$D = \left[\oint \frac{D_x}{\rho} \left(\frac{1}{\rho^2} + 2K(s) \right) ds \right] \left[\oint \frac{ds}{\rho^2} \right]^{-1}. \qquad (1)$$

Here D_x is the dispersion, ρ is the dipole bending radius, $K(s)=B_1/B\rho$ is the normalized quadrupole component with $B_1=\partial B/\partial x$. Therefore, the damping rate can be adjusted by varying the damping partition number using a dipole with a quadrupole field component or offsetting the beam in a quadrupole. This leads to emittance changes in both the horizontal and longitudinal directions, without changing the ring optics design.

Offsetting the beam in quadrupoles during machine operation is perhaps more practical than building dipoles with gradients. In order to quantify the change in the horizontal emittance, the emittances in a regular FODO cell and in a combined-function FODO cell are calculated. In a regular FODO cell, the beam passes through the

centers of the quadrupoles. In a combined-function FODO cell, a dipole field is introduced in the quadrupoles to mimic a situation when the beam is offset from the centers of the quadrupoles. Figure 4 shows examples of the optics of a regular FODO cell (left) and a combined-function FODO cell (right). The quadrupole gradients $B_1 = \partial B / \partial x$ are -11.61 and 12.82 T/m, respectively, in both FODO cells. A dipole field of 0.095 T introduced in the combined-function FODO cell is sufficient to reduce the horizontal emittance (of the FODO cell only) by a factor of 2.5. This is equivalent to offsets of the beam in the quadrupoles by 8.2 and 7.4 mm, respectively. One can adjust the offset considering the balance of the physical aperture of the vacuum chambers and reduction of the horizontal emittance.
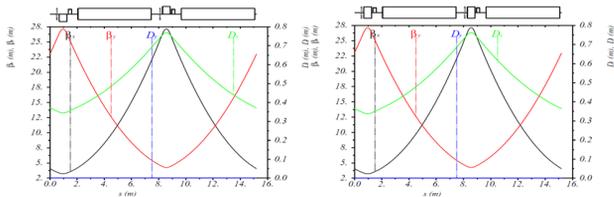
Figure 4: Optics of a regular FODO cell (left) and of a combined-function FODO cell (right).

The main disadvantage of adjusting the damping partition number to reduce the horizontal emittance is the longitudinal emittance growth. In the above example, the energy spread is increased by a factor of 2, resulting in a larger momentum acceptance requirement. In addition, the bunch length is increased by a factor of 2 with the same peak RF voltage. This may enhance the hour-glass effect at the IP with a small β^* and cause luminosity loss. One can reduce the bunch length, but it requires a higher peak RF voltage. Besides, the beam position monitors have to be rigidly attached to sextupoles rather than quadrupoles as usual, to center the beam in the sextupoles for chromaticity compensation.

Adopting Alternative Optics Designs

Instead of reusing the PEP-II magnets that constrain the optics design due to their specifications, new magnets can be used to design the electron ring lattice. This allows one to use short dipole magnets with small bending angles. There are two advantages of doing this. First, the dipoles with small bending angles do not have the issue of a large sagitta. Second, the horizontal emittance is reduced as the 3rd power of the bending angle when keeping the bending radius and phase advance fixed. Figure 5 shows optics of a FODO cell in the baseline design using PEP-II magnets (left) and of a FODO cell using new magnets (right). The PEP-II dipoles are 5.4 m long, with a bending angle of 2.8^o and a sagitta of 3.3 cm in the JLEIC baseline FODO cell optics. The new dipoles are chosen to be 3.75 m long, with a bending angle of 2.05^o and a sagitta of 1.7 cm. The emittance of the new FODO cell is reduced by a factor of 2 compared to the baseline FODO cell. However, the arcs need more of the new FODO cells because of the smaller

bending angle of each dipole. This results in large chromaticities. In addition, the dispersion is small in the new FODO cell. Both require strong sextupoles for chromaticity compensation, which may enhance higher-order sextupole-induced resonances and require an appropriate nonlinear beam dynamic study.
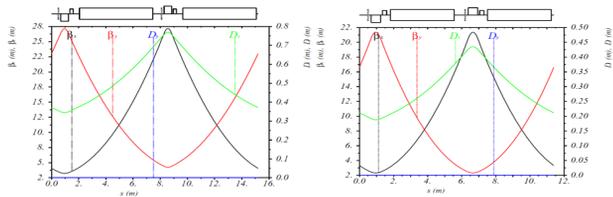
Figure 5: Optics of the FODO cell in the baseline design using the PEP-II magnets (left) and of the FODO cell using new magnets (right).

Another alternative optics design that can even further reduce the horizontal emittance is the Theoretical Minimum Emittance (TME) lattice. Figure 6 shows an example of TME-like optics. With the horizontal beta function and dispersion suppressed inside the dipoles, the horizontal emittance can be significantly reduced. Compared to a FODO lattice, this TME-like lattice reduces the emittance by a factor of 6. However, the TME-like lattice requires more quadrupoles and larger cell size with reasonable quadrupole strengths. In addition, the dispersion is again small requiring stronger sextupoles for chromaticity compensation and an appropriate nonlinear beam dynamic study.
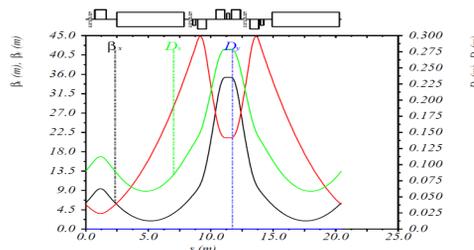
Figure 6: Example of a TME-like optics.

SUMMARY

This paper reports on a few approaches to reducing the horizontal emittance in the JLEIC electron collider ring. For each approach, the optics and expected emittance reduction are presented. The advantages and/or disadvantages are also discussed.

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