UPDATE ON THE JLEIC ELECTRON COLLIDER RING DESIGN *

Y. Nosochkov†, Y. Cai, M. Sullivan, SLAC National Accelerator Laboratory, Menlo Park, CA, USA
Ya. S. Derbenev, F. Lin, V. S. Morozov, F. Pilat, G. H. Wei, Y. Zhang,
Jefferson Lab, Newport News, VA, USA
M.-H. Wang, Mountain View, CA, USA

Abstract

We present an update on the lattice design of the electron ring of the Jefferson Lab Electron-Ion Collider (JLEIC). The electron and ion collider rings feature a unique figure-8 layout providing optimal conditions for preservation of beam polarization. The rings include two arcs and two intersecting long straight sections containing a low-beta interaction region (IR) with special optics for detector polarimetry, electron beam spin rotator sections, ion beam cooling sections, and RF-cavity sections. Recent development of the electron ring lattice has been focused on minimizing the beam emittance while providing an efficient non-linear chromaticity correction and large dynamic aperture. We describe and compare three lattice designs, from which we determine the best option.

INTRODUCTION

We discuss a recent development of the electron ring lattice for the Jefferson Lab Electron-Ion Collider (JLEIC) [1]. The JLEIC ring design is based on a figure-8 layout, as shown in Fig. 1 for the electron ring. An advantage of this layout is an optimal preservation of the ion and electron polarizations [2]. The 2.2-km electron and ion rings are housed in the same tunnel, and cross each other at an interaction point (IP). The baseline design includes one IP, where $\beta_x^* = 10$ cm, $\beta_y^* = 2$ cm, and the horizontal crossing angle is 50 mrad. A second IP can be added as a future upgrade. The JLEIC design provides a large range of collision beam energies: 3-12 GeV for electrons, 20-100 GeV for protons, and up to 40 GeV per nucleon for ions.

The electron ring consists of two arcs and two long straight sections. The straights contain an interaction region (IR), spin rotator sections, RF-cavities, tune trombones, and a chicane for forward electron detection and polarimetry. The "baseline" electron ring lattice is designed with the intent of re-using the PEP-II High Energy Ring [3] magnets and other components. The arc lattice in this design resembles that of the PEP-II with 15.2 m long FODO cells, except that the cell phase advance is increased to 108° for a lower emittance. This phase advance also provides conditions for cancellation of sextupole second order effects in every 10 cells [4].

The original baseline lattice without non-linear chromaticity correction sections has an emittance of 14 nm-rad at 5 GeV. Later, the optics, where dispersion is not zero, was optimized for a lower emittance of 8.9 nm-rad (per MAD8 [5] calculation). This updated design is called an "optimized baseline".

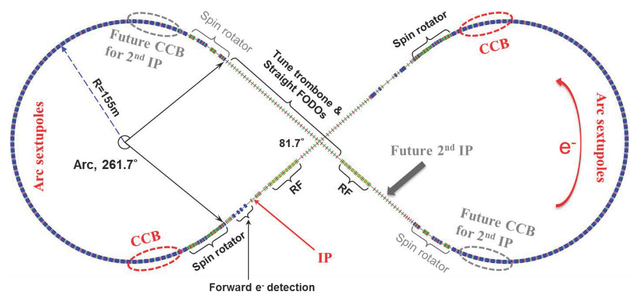

Figure 1: Layout of the 2.2-km electron collider ring.

Recent studies of the electron ring lattice have been focused on further reduction of the emittance, desired for high luminosity. Two new designs have been investigated, where the arc lattice is based on: 1) TME-like cells, and 2) short-FODO cells. These designs require new magnets, although with a modest limitation of maximum energy some of the PEP-II magnets may be used. Below, we describe the performance of these lattices and compare with the optimized baseline design for various options of chromaticity correction. The goal of the study is to identify the optimal lattice with the best overall properties: low emittance, good chromatic correction and large dynamic aperture (DA).

OPTIMIZED BASELINE

Performance of the optimized baseline design has been previously discussed in Ref. [6, 7]. Chromaticity correction in this lattice has been studied in detail. It consists of linear and non-linear chromaticity compensation. The linear correction is done using two-family sextupoles in regular FODO arc cells; the non-linear correction is performed using two chromaticity correction blocks (CCB) included at the end of each arc nearest to IP, as schematically shown in Fig. 1. The CCB sextupoles make a local compensation of a very large linear and non-linear chromaticity created by the final focus quadrupoles (FFQ). Phase advance between the CCB sextupoles and the corresponding FFQ is optimized ($\approx n\pi$ in the correcting plane) for a minimum chromatic variation of betatron tune and β^*.

Several options of non-linear chromaticity correction were compared:

1. No CCB
2. Interleaved $-I$ sextupole pairs in regular arc cells

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† yuri@slac.stanford.edu

3. Non-interleaved $-I$ sextupole pairs in arc cells, where large β-functions are created at the sextupoles
4. Same as scheme-3, but with 40% reduced β-functions at the sextupoles for a lower emittance
5. Compact CCB [8], based on arc cells, with three interleaved sextupoles and large β-functions
6. SuperB-type CCB (SBCC) [9] with non-interleaved $-I$ sextupole pairs and regular dipoles with large bending angles
7. Same as scheme-6, but shorter length and shorter dipoles with smaller angles for a lower emittance

Comparison of these schemes is presented in Table 1 showing emittance ϵ relative to the emittance $\epsilon_0 = 8.9$ nm-rad without CCB, a horizontal DA without errors for on-momentum and $\delta = 0.4\%$ off-momentum particles in units of rms beam size (σ_x), and the momentum range normalized to $\sigma_\delta = 4.5 \cdot 10^{-4}$. The vertical DA in σ_y units is a factor of two larger than the horizontal DA in these schemes.

Results in Table 1 show that CCB schemes with non-interleaved $-I$ sextupole pairs provide a good chromaticity correction and larger off-momentum DA. The schemes based on arc FODO cells with large β-functions (schemes 3,4,5) yield a larger emittance due to the dipoles located near high peaks of β_x functions. The SBCC schemes (5,6), where dipoles are removed from high-β_x locations, yield a lower emittance. The best scheme for emittance preservation is the SBCC scheme-7 with shorter dipoles and smaller bending angles. Emittance with this scheme is 8.3 nm-rad (at 5 GeV), smaller than the 8.9 nm-rad emittance without CCB.

TME CELL DESIGN

With the intent of further reducing the electron ring emittance, a new lattice design based on TME-like arc cells [10, 11] has been studied. Optics of one TME-like arc cell is shown in Fig. 2, where the cell length of 22.8 m is the same as in the ion ring, and cell phase advance is 270°/90° (x/y). The latter provides conditions for cancellation of sextupole second order effects in every four cells [4]. This cell design is based on new magnets: four 4-m long dipoles with the field of 0.37 T at 12 GeV, four quadrupoles with 24 T/m gradient at 12 GeV, and four 2-family sextupoles located at center of the cell as shown in Fig. 2.

Table 1: Emittance, DA and Momentum Range for the Optimized Baseline Design Chromaticity Correction Options

Scheme	ϵ/ϵ_0	**Horiz. DA** (σ_x)		**Range of**
		$\delta = 0$	$\delta = 0.4\%$	δ/σ_δ (±)
1	1.0	20	0	9
2	1.0	20	0	9
3	2.1	15	4.5	9
4	1.7	17	5	9
5	1.7	8.5	5	9
6	1.4	25	10	9
7	0.93	23	7	11

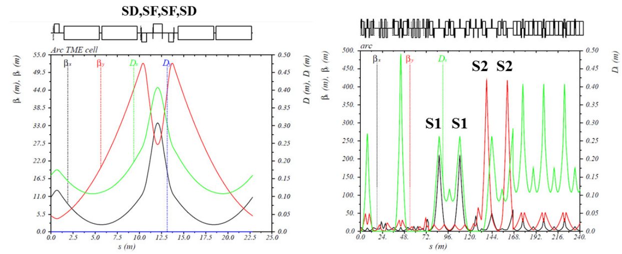

Figure 2: Optics of the TME-like arc cell (left) and SBCC (right), where S1, S2 are non-interleaved $-I$ sextupole pairs.

The non-linear chromaticity correction is implemented using the SBCC design similar to the scheme-7 described earlier, with short dipoles and small bending angles. The SBCC optics is shown in Fig. 2. The complete ring lattice yields the emittance of 3 nm-rad at 5 GeV, three times lower compared to the optimized baseline design.

Four SBCC sections are included in this design: two near the IP for non-linear correction, and two at the other end of each arc. The latter could be used in the future upgrade with the second IP. Two options have been studied, where: 1) all four SBCCs have high β-functions at the sextupoles, and 2) two SBCCs near the IP have high β-functions, while the other two have low β-functions using adjustment of the SBCC quadrupole strengths. The second option yields a lower ring chromaticity. The complete ring optics for option-2 is shown in Fig. 3.

TME cells require stronger chromaticity correction sextupoles due to a lower dispersion. The stronger sextupole non-linear field can affect the dynamic aperture. For this reason, we also explore alternative schemes for the linear correction using non-interleaved or interleaved $-I$ sextupole pairs in the arcs. The number of sextupoles in these schemes is reduced compared to the conventional two-family scheme, which makes the sextupoles even stronger. The $-I$ pairs are separated by 90° phase advance to cancel first order chromatic β-distortion from every two pairs. Still, the local perturbation of the chromatic β-functions is large due to the strong sextupoles, resulting in higher order chromaticity and poor correction with a limited momentum range. The conventional scheme of two-family sextupoles in every cell (multiple of 4) is therefore the preferred option.

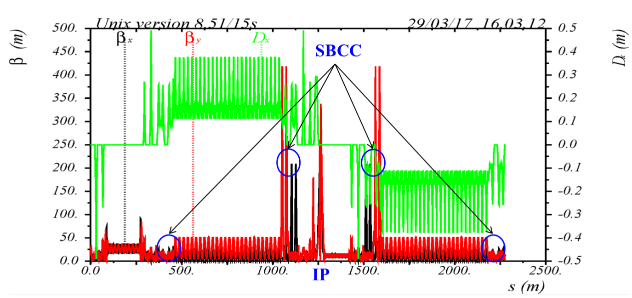

Figure 3: Electron ring optics with TME-like arc cells, two high-β SBCCs near the IP, and two low-β SBCCs at the other arc ends. Betatron tune is 65.22, 35.16 (x, y).

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The study also includes an option of a different position of the SF sextupoles. Nominally, they are located at the cell center (see Fig. 2), where β_x and β_y at the SF are nearly the same. This limits the orthogonality and efficiency of the SF and SD correction. A new SF position at the left end of the cell is studied, where β-functions are lower, but β_x/β_y ratio is higher. The SF in this scheme becomes much stronger, but the SD is weaker. The resultant correction performance, however, is worse compared to the nominal SF position.

Due to the poor performance of the alternative correction options, dynamic aperture is only calculated for the conventional linear chromaticity correction with two-family sextupoles in the arc cells (multiple of 4 cells). Table 2 presents a short summary for two SBCC options: 1) four high-β SBCCs – all used for correction; and 2) two high-β SBCCs near IP – used for FFQ correction, and two low-β SBCCs – not used for correction.

Chromaticity correction is sufficient in both options, however option-2 yields a larger on-momentum horizontal dynamic aperture of $15\sigma_x$. This is due to the lower natural chromaticity and lower arc sextupole strengths in option-2. Vertical DA in units of σ_y is a factor of two larger than the horizontal DA. The $15\sigma_x$ dynamic aperture, however, is smaller than the $23\sigma_x$ DA of the optimized baseline lattice. We consider that the TME lattice DA may not be sufficient, taking into account that magnet errors are not yet included.

SHORT-FODO CELL DESIGN

A second low emittance option of the electron ring lattice is based on short-FODO arc cells. A shorter cell corresponds to a smaller bending angle θ per dipole and, hence, to a lower emittance ($\propto\theta^3$). In this design, the arc cell length is 11.4 m (half of the ion ring cell length), and the cell phase advance is 108°. The cell includes two new 3.6-m long dipoles with maximum field of 0.41 T at 12 GeV, two quadrupoles with 21 T/m gradient at 12 GeV, and two sextupoles. PEP-II quadrupoles could be used if the maximum energy is limited to 10 GeV. The SBCC optics in this design is similar to the one shown in Fig. 2 for the TME design.

The complete ring lattice is shown in Fig. 4; it yields the emittance of 5.5 nm-rad at 5 GeV. Linear chromaticity is corrected using two-family sextupoles in 50 cells in each arc. The two SBCCs compensate the FFQ non-linear chromaticity, where the correction is optimized by fine tuning the phase advance (ϕ) between the SBCC sextupoles and the IP. The resulting momentum range is sufficiently large (>$10\sigma_\delta$) as can be seen in Fig. 5. Dynamic aperture without errors is calculated using `elegant` [12] and is sufficiently

Table 2: Natural Chromaticity, DA and Momentum Range for the TME Lattice Chromaticity Correction Options

Scheme	ξ_x, ξ_y	Horiz. DA (σ_x)		Range of
		$\delta=0$	$\delta=0.4\%$	δ/σ_δ (±)
1	-159, -196	9	7	12
2	-145, -166	15	7	12

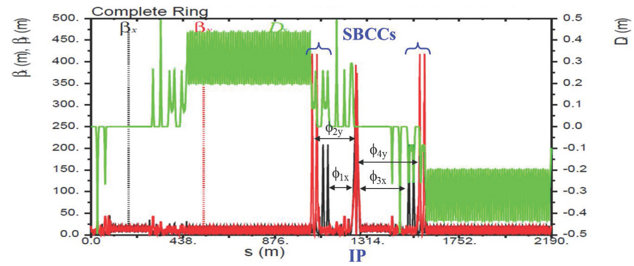

Figure 4: Electron ring optics with short-FODO arc cells and two SBCCs. Betatron tune is 57.22, 55.16 (x, y).

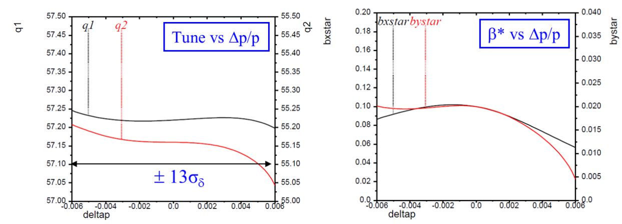

Figure 5: Momentum dependence of tune and β^* for the short-FODO-cell lattice.

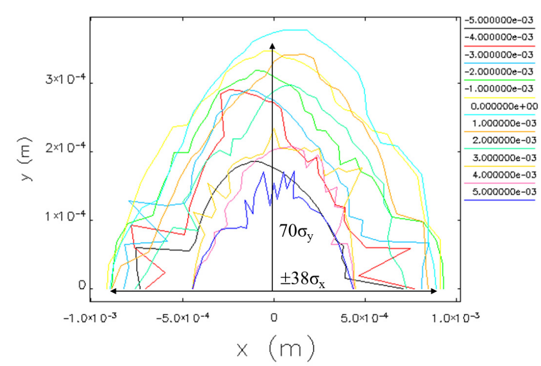

Figure 6: Dynamic aperture of the short-FODO-cell lattice without errors for a range of δ from -0.5% to 0.5%.

large, both for on-momentum and off-momentum particles as shown in Fig. 6. The on-momentum horizontal DA of $38\sigma_x$ exceeds the DA of both the optimized baseline and the TME-cell designs. Based on this study, the short-FODO-cell lattice design provides the best overall properties: adequate chromaticity correction, large DA, and reduced emittance compared to the optimized baseline design.

CONCLUSIONS

Two new designs of the JLEIC electron ring lattice, based on TME-like arc cells and short-FODO arc cells, have been compared to the optimized baseline design. The comparison is based on chromaticity correction performance, dynamic aperture and beam emittance. It shows that the short-FODO-cell design yields the best overall properties with large dynamic aperture and low emittance. This design is selected as the best candidate for further beam dynamics studies including magnet errors and DA optimization.

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