COMPENSATION OF CHROMATICITY IN THE JLEIC ELECTRON COLLIDER RING *

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Abstract

The Jefferson Lab Electron-Ion Collider (JLEIC) is being designed to achieve a high luminosity of up to 10^{34} cm^{-2}s^{-1}. The latter requires a small beam size at the interaction point demanding a strong final focus (FF) quadrupole system. The strong beam focusing in the FF unavoidably creates a large chromaticity which has to be corrected in order to avoid a severe degradation of momentum acceptance. This has to be done while maintaining sufficient dynamic aperture. An additional requirement in the electron ring is preservation of a low beam emittance. This paper reviews the development of a chromaticity correction scheme for the electron ring.

INTRODUCTION

The Jefferson Lab Electron-Ion Collider (JLEIC) [1] is being designed to achieve a high luminosity of up to 10^{34} cm^{-2}s^{-1}. The latter requires a small beam size and, therefore, small beta function (β^*) at the interaction point (IP). Consequently, beta functions in the IP final focus (FF) quadrupoles are very high ($\sim 1/\beta^*$) making the FF a large source of chromaticity in the ring. Since the linear chromaticity (first order chromatic tune shift) is straightforward to cancel with conventional two-family sextupoles in the arcs, the main concern is the FF non-linear chromaticity causing a large momentum distortion of beta functions and non-linear chromatic tune shift. These effects increase the tune spread exposing the beam to more betatron resonances limiting momentum acceptance and dynamic aperture; and cause chromatic beam smear at IP resulting in a larger beam size limiting luminosity. Compensation of the FF non-linear chromaticity requires a dedicated local correction system which has been already studied for the JLEIC ion ring [2]. An additional requirement for such correction in the electron ring is that it does not significantly increase the beam emittance. This paper reviews the development of the electron ring chromaticity correction system including low emittance options.

LATTICE

The JLEIC rings have a figure-8 layout, as shown in Fig. 1 for the electron ring. The electron and ion rings are stacked vertically in the same tunnel. The baseline design includes one IP, where $\beta^*_{x,y} = 10 \times 2$ cm and the horizontal crossing angle is 50 mrad. A second IP can be added as a future upgrade. The design colliding beam energies are: 3-10 GeV for electrons, 20-100 GeV for protons, and up to 40 GeV per nucleon for ions. The figure-8 layout provides an optimal preservation of the ion polarization [3]; and the large enough circumference of ≈2.2 km allows to use the PEP-II High Energy Ring [4] components in the electron ring.

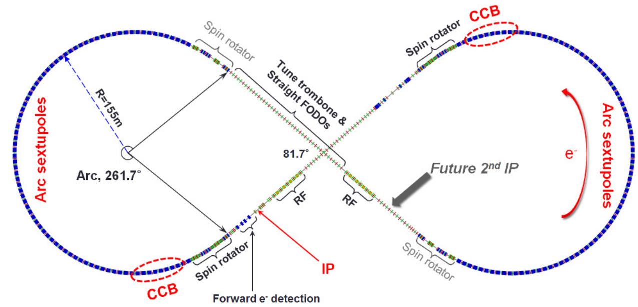

Figure 1: Top view layout of the electron ring.

The electron ring consists of two arcs and two long straight sections. The straights contain the interaction region (IR), spin rotators, RF-cavities, tune trombones, and a chicane for forward electron detection and polarimetry. The arc lattice is based on 15.2 m long FODO cells with 108° phase advance. The latter produces a relatively low emittance while providing conditions for cancellation of sextupole non-linear geometric and chromatic effects.

Optics of the straight section with the IR, before including the FF chromaticity correction, is shown in Fig. 2. The IR and the FF beta functions are asymmetric relative to the IP due to the detector requirements. Without the FF chromaticity correction optics, the electron ring equilibrium horizontal emittance is 8.9 nm-rad at 5 GeV from MAD8 [5] calculation, and the natural chromaticity is $\xi_{x,y} = [-113, -120]$.

CHROMATICITY CORRECTION

The chromaticity correction study for the electron ring followed a similar study performed for the ion ring [2]. A chromaticity correction block (CCB) consisting of special optics with sextupoles for FF correction is included at one end of each arc nearest to the IP, replacing the regular arc cells, as shown schematically in Fig. 1. Initially, the studied CCB design was based on the same magnet positions and bending angles as in the arc, thus preserving the ring geometry. Later, a different CCB configuration was studied based on the low emittance design developed for SuperB [6].

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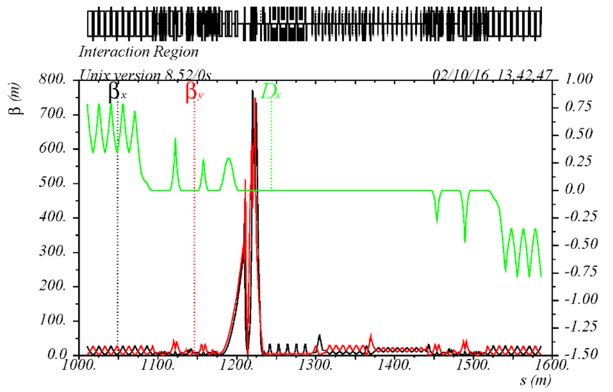

Figure 2: Optics of the electron ring long straight section with the IP before including FF chromaticity correction.

The basic principle of the FF non-linear chromaticity correction is that the CCB sextupoles on one side of IP generate a chromatic kick equal to and opposite in phase with the one from the FF on the same side, so they locally cancel the FF first order chromatic beta distortion $d\beta/dp$. An independent correction is done on the other side of IP. Ideally, this should cancel the $d\beta/dp$ at the IP and in the rest of the ring caused by the FF, as well as the second order term of chromatic tune shift [7]. The desired conditions at the CCB sextupoles for an efficient correction are: 1) large dispersion (η) and beta function to obtain reasonable sextupole strengths; 2) large ratio of x and y beta functions for orthogonal x and y correction; 3) $n\pi$ phase advance from the FF (in the correcting plane); this can be further fine-tuned to minimize higher order terms; 4) minimal optics between the CCB and the FF for minimal chromatic distortions to the correction from other quadrupoles.

Sextupoles also generate non-linear geometric (amplitude dependent) aberrations resulting in non-linear tune shift and excitation of the 3rd and higher order resonances which can significantly reduce the beam dynamic aperture. One way to cancel these aberrations is to use non-interleaved pairs of identical sextupoles separated by $-I$ transformation as shown in Fig. 3. Another method, earlier developed for the JLEIC, is based on a compact CCB [8] with three interleaved sextupoles, where however one of the tune shift terms still remains. The machine linear chromaticity after the FF correction is canceled using two-family sextupoles included in multiple of 10 periodic arc cells providing cancellation of the sextupole second order geometric and chromatic effects [9].

CCB Based on Arc Cell Configuration

Several CCB schemes based on the arc cell configuration were studied, where magnet positions and bending angles are the same as in the arc, thus preserving the geometry. The schemes include: A) two non-interleaved $-I$ sextupole pairs with large beta functions as shown in Fig. 4; B) a longer scheme with four interleaved $-I$ pairs and nominal arc beta functions at sextupoles; C) compact CCB design using two x-sextupoles interleaved with one y-sextupole as described in Ref. [8].

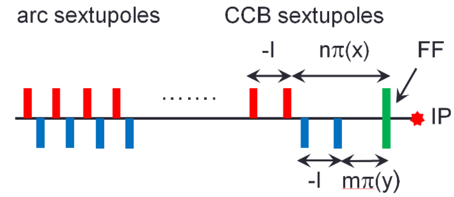

Figure 3: Schematic of two non-interleaved -I sextupole pairs on one side of IP.

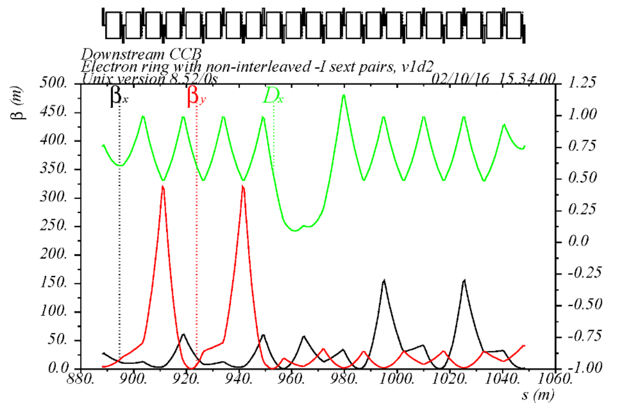

Figure 4: CCB optics with two non-interleaved -I sextupole pairs based on arc cell configuration.

Sextupole strengths are obtained in MAD [5] using a two-step procedure. First, the CCB sextupole strengths are set to minimize the chromatic beta distortion (W-function in MAD) at the IP and in the rest of the ring. This way both the IP chromatic beam smear and the 2nd order term of chromatic tune shift are minimized [7]. Secondly, the two-family arc sextupoles are set to cancel the remaining machine linear chromaticity.

The study shows a better chromaticity correction in schemes A and C. This is due to the shorter length of these CCBs relative to scheme-B, resulting in more local correction, and the high beta functions making the sextupoles weaker and x and y correction more orthogonal and efficient. Momentum dependence of tune shift and β^* for the scheme-A is shown in Fig. 5, where the third order term of the tune shift is minimized by fine-tuning of the phase advance between the CCB and the FF. In this case, the nominal tune and linear chromaticity are $\nu_{x,y} = [42.22, 46.16]$ and $\xi_{x,y} = +1$. The above correction results in sufficient momentum acceptance of at least $10\sigma_p$. Finally, tracking simulations [10] without errors show that scheme-A provides a factor of two larger dynamic aperture as compared to the scheme-C due to better cancellation of the sextupole geometric non-linear effects. Therefore, the CCB based on non-interleaved $-I$ sextupole pairs appears a preferred correction scheme.

Evaluation of beam emittance, however, reveals that both schemes A and C lead to unacceptably large beam emittance, increasing it from 8.9 nm-rad (without CCB) to more than 15 nm-rad at 5 GeV. Analysis presented in the next section indicates that the large emittance is due to contributions from CCB dipoles where dispersion and β_x values are high. As a next step, low emittance CCB schemes are studied.

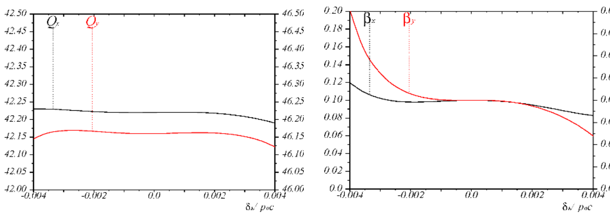

Figure 5: Tune (left) and β^* (right) versus $\Delta p/p$ with CCB based on arc cells and non-interleaved $-I$ sextupole pairs.

Low Emittance CCB

Electron beam emittance is proportional to square of beam energy and a ratio I_5/I_2, where the integrals $I_5 = \int \frac{H ds}{\rho^3}$ and $I_2 = \int \frac{ds}{\rho 2}$ are taken over all dipoles, ρ is dipole bending radius, and $H = \beta\eta'^2 + 2\alpha\eta\eta' + \frac{1+\alpha^2}{\beta}\eta^2$ [11]. Inspecting these functions, one can see that a low emittance can be obtained by reducing the CCB bending angles as well as η and β_x functions at the CCB dipoles. On the other hand, the CCB sextupoles require high dispersion and beta functions. This conflict can be resolved by removing the dipoles from high η and β_x locations as, for example, in the SuperB chromaticity correction scheme with non-interleaved –I sextupole pairs [6]. One consequence of the missing CCB dipoles is an impact on geometry. If the total CCB angle must be preserved, then the remaining dipoles need to be stronger resulting in an opposite effect on emittance. Therefore, a compromise may be needed between the CCB bending angles (geometry) and emittance.

Several SuperB-type schemes were investigated differed by dipole length L and bending angle θ as compared to the arc dipole L_0 and θ_0, presented in Table 1. Sextupole beta functions are set to 200/400 m (x/y), except scheme-1 where β = 300/600 m. CCB schemes 1-4 provide the same total bending angle as in the same length arc, while scheme-6 has a smaller angle. All schemes have seven dipoles with the parameters listed in Table 1. In addition, schemes 4 and 6 have one more regular arc dipole helping to reduce the angles of the seven CCB dipoles. The schemes 3,4,6 are shorter than schemes 1,2 due to the shorter dipoles, and therefore have smaller bending angles. Optics of the CCB schemes 4 and 6 are shown in Fig. 6, and the complete straight section with the IP and the CCB is presented in Fig. 7.

The study shows that the longer CCB schemes 1 and 2 with regular length dipoles result in rather high emittance of 29.3 and 22.8 nm-rad at 5 GeV due to the large bending angles. Comparatively, schemes 3 and 4 reduce emittance a factor of two to 12.2 and 10.3 nm-rad due to the smaller bending angles and a factor of three lower dispersion and H-function. Scheme-6 yields 8.3 nm-rad emittance which is smaller than the 8.9 nm-rad of the ring without CCB. This is due to the smallest bending angles and the H-function, so the CCB emittance contribution is smaller than that of the arc cells. This scheme, however, requires additional arc cells to compensate for the missing bending angle, making the circumference longer by ~140 m, as well as modification to the other arc end to restore the arc symmetry.

Table 1: Bending Angle and Length of CCB Dipoles

Scheme	1, 2	3	4	6
L/L_0	1.0	0.5	0.5	0.592
θ/θ_0	2.286	1.429	1.286	0.714

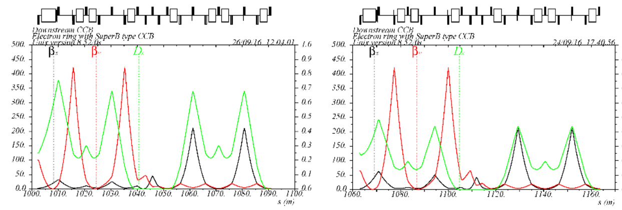

Figure 6: Optics of low emittance CCB schemes 4 and 6.

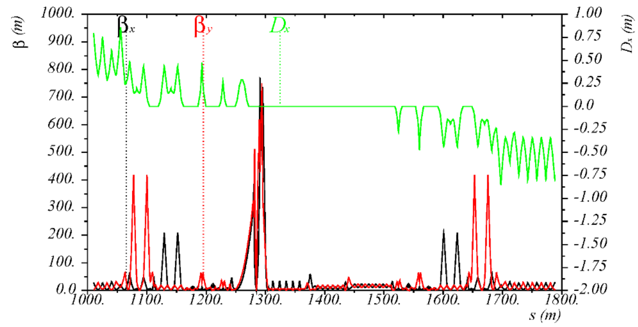

Figure 7: Straight section with the IP and low emittance CCB based on scheme-6.

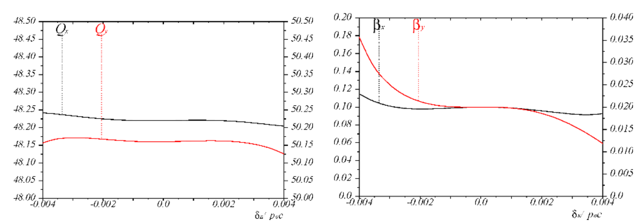

Figure 8: Tune (left) and β^* (right) versus $\Delta p/p$ with low emittance CCB scheme-6.

The above schemes provide adequate chromaticity correction with momentum acceptance of ~$10\sigma_p$, as shown in Fig. 8 for scheme-6, and dynamic aperture exceeding 20σ without errors. The non-linear chromatic tune shift in Fig. 8 is minimized by optimizing the phase advance between the CCB and the FF.

SUMMARY

The study of non-linear chromaticity correction for the JLEIC electron ring determines that the best dynamic aperture and sufficient chromaticity correction are obtained with a CCB scheme based on non-interleaved –I sextupole pairs with large beta functions at the sextupoles. Preservation of the beam low emittance is achieved using short CCB schemes with sufficiently small bending angles, based on SuperB chromaticity correction design with missing dipoles.

 ISBN 978-3-95450-180-9

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