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DYNAMIC APERTURE OF THE EIC ELECTRON STORAGE RING*

Y. Nosochkov†, Y. Cai, SLAC, Menlo Park, CA, USA
J. S. Berg, J. Kewisch, Y. Li, D. Marx, C. Montag, S. Tepikian, H. Witte,
Brookhaven National Laboratory, Upton, NY, USA
G. H. Hoffstaetter, J. Unger, Cornell University, Ithaca, NY, USA

Abstract

The Electron Ion Collider (EIC) is under design at Brookhaven National Laboratory. The EIC aims at providing high luminosity and high polarization collisions for a large range of beam energies. Dynamic aperture (DA) of the EIC Electron Storage Ring (ESR) must be sufficiently large in both transverse and momentum dimensions. The latter is a challenge due to low-beta optics in up to two interaction regions (IR). We have developed an advanced technique for efficient non-linear chromaticity compensation compatible with the different ESR lattice configurations at different energies. The solution for the most challenging lattice with two IRs at 18 GeV is presented. The lattice is then evaluated with magnet errors, where the error tolerances are determined for reaching the desired DA.

INTRODUCTION

The Electron Ion Collider (EIC) [1, 2] is under design at Brookhaven National Laboratory. The important goals are the high luminosity up to 10^{34} cm^{-2}s^{-1}, high average polarization, and a large range of beam energies in electron-hadron collisions. In this paper, we focus on the Electron Storage Ring (ESR) designed for beam energies from 5 to 18 GeV. Satisfying the EIC requirements results in a rather crowded ESR low-beta interaction region (IR) featuring strong final focus system, spectrometer magnets, crab cavities, and spin rotator sections [3] significantly constraining the IR optics. Emittance requirements also call for stronger focusing in the ESR arcs at top energy.

The ESR dynamic aperture (DA) must be sufficiently large both in transverse size and momentum range. This is a challenge due to high error sensitivity and large chromaticity characteristic of the IR final focus quadrupoles (FFQ) where beta functions are very high. In this paper, we consider the most difficult ESR configuration at 18 GeV with two low-beta IRs and strong arc focusing, where achieving the desired momentum range of $\delta = 1\%$ is extremely challenging. The proximity of the betatron tunes to integer values makes this task more difficult. In the course of the ESR study, we have developed an advanced technique for efficient non-linear chromaticity correction [4] which meets the design requirements for the different ESR optics at different energies. The lattice is then evaluated with magnet errors, where the error tolerances are determined for reaching the desired DA of 10σ without beam-beam effects.

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† yuri@slac.stanford.edu

CHROMATICITY CORRECTION

The ESR lattice functions at 18 GeV are shown in Fig.1, where the tune is $\nu_{x,y}$ = 52.12, 45.1. The ring consists of six arcs made of 90° FODO cells and six straight sections labelled according to the clock. The two low-beta IRs (IR6 and IR8) have identical β_x^* = 59 cm, β_y^* = 5.7 cm at the interaction points (IP). The very large beta functions at the IR final focus quadrupoles make them the largest sources of linear chromaticity. The FFQs also create most of the ring non-linear chromaticity in the form of chromatic beta beating and higher order tune shift, which severely limit the momentum range. The beta beating is traditionally described by the Montague functions [5] or W-functions. Due to the complexity of the IRs which include crab cavities, spin rotator sections, and spectrometer dipoles, there is no suitable optics near the IP for a conventional local chromaticity correction based on -I non-interleaved sextupole pairs [6]. Hence, the chromaticity correction has to be carried out by sextupoles located farther away from the IPs in the arcs. The goal is to achieve the momentum range of $10\sigma_p = 1\%$ at 18 GeV.

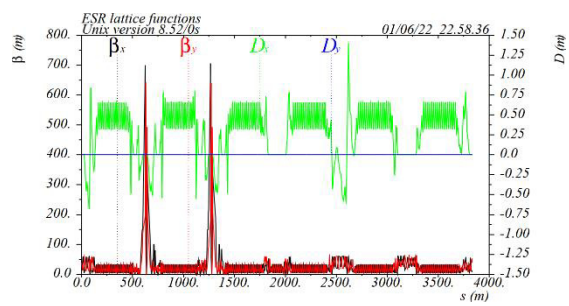

Figure 1: ESR lattice functions starting from IP4.

Semi-local Correction

Correction of the FFQ chromaticity is performed independently on each side of the IR using the adjacent arc sextupoles. Hence, this is a semi-local scheme. Since the non-linear chromatic tune shift is mostly driven by the large chromatic beta beating created in the FFQs, the main function of the arc sextupoles, in addition to correcting the linear chromaticity, is to cancel the FFQ beta beating by creating an opposite beta wave in phase with the FFQ.

We use a multi-family sextupole scheme where the sextupoles are placed in 16 periodic 90° cells of each arc next to F and D quadrupoles. In order to generate the net beta beating, sextupoles of the same family must be separated by 180° (two cells). This creates -I sextupole pairs where the sextupole non-linear geometric aberrations are cancelled [7]. A schematic of the semi-local scheme for one-

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half IR is shown in Fig. 2, where the four sextupole families compensate the chromatic beta beating from the nearest FFQ doublet. The difference in strengths of two sextupoles one cell apart creates beta beating which adds up linearly in the arc, while the sum of the strengths corrects linear chromaticity. However, the phase of this beta wave in 90° arc is essentially fixed, therefore it is necessary to align it with the FFQ by a phase match represented by a thin-lens trombone in Fig. 2. The strengths of the four-family sextupoles and the trombone *x, y* phase shift values allow us to correct the Montague functions $A_{x,y}$, $B_{x,y}$ and the linear chromaticity $\xi_{x,y}$ in one half-IR and the adjacent arc.

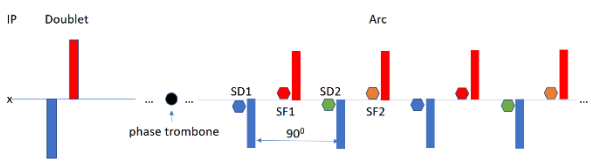

Figure 2: Schematic of semi-local sextupole scheme on one side of IR where the columns are F and D quadrupoles.

In the two-IR lattice, we first apply this correction independently to the regions from IP4 to IP6 and IP8 to IP10. Note that we use the IP symbol for the centers of both the IR and non-IR straights. The sextupole strengths and the trombone phase values are optimized with LEGO code [8], which is able to compute an arbitrary order of the lattice function derivatives with momentum [9]. We match the Montague functions to zero at the IPs, while the values of $\xi_{x,y}$ in each region are optimized for maximum DA of the ring. The optimal ξ_x, ξ_y are -6, -2 between IP4 and IP6 and +3.5, +7 from IP8 to IP10. The corrected W-functions from IP8 to IP10 are shown in Fig. 3. The result is similar in the IP4-IP6 region. This correction also significantly reduces the second-order W-functions, which may be a critical factor for a large momentum DA.

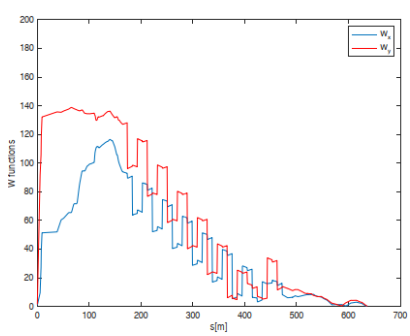

Figure 3: W-functions from IP8 to IP10 after correction.

Correction Between IP6 and IP8

Correction between the IP6 and IP8 must be carried out in arc-7. Using four sextupole families does not bring an adequate compensation, partly because the two IR halves are not identical. To improve the correction, we double the number of arc-7 sextupole families and optimize the IR6 and IR8 trombones independently. This brings the number of variables to 12, which allows us to minimize the chromatic tune shift and W-functions to third order. It should be noted that the phase advance from IP6 to IP8 must be near $\pi/2$ (mod π) for natural cancellation of the FFQ W-functions. Since the β^* and α^* at the IP6 and IP8 are identical, and the W-functions are set to zero there, the section from IP6 to IP8 is periodic, and the chromatic optics of this region is optimized as a periodic system. The optimal linear chromaticity between the IP6 and IP8 is -13 in both planes.

Complete Chromaticity Correction

So far, we have described correction in the half of the ring where the two IRs are located. The other half of the ring does not have strong individual sources of chromaticity; therefore, it is sufficient to use four-family sextupoles in the remaining three arcs. Two phase trombones are included at IP12 and IP2 to help minimize the W-functions over the whole section. Two more trombones with equal phase shift are inserted at the IP4 and IP10 to maintain the design tune. As in the other half-ring, the local linear chromaticity is optimized, but with the constraint that the ring chromaticity is always +1 in this study. Since the W-functions in each half of the ring are matched to zero at the boundaries, the two half-rings are chromatically matched to each other.

One remaining chromatic effect is a relatively large second-order dispersion caused mostly by dipoles outside of the arcs. It drives synchro-betatron resonances affecting the momentum DA. Fortunately, it can be well reduced by two additional sextupoles inserted in non-periodic cells at end of the arcs 3 and 11. As a small drawback, these sextupoles somewhat increase the W-functions in this half-ring, even after the re-optimization. Nonetheless, the ESR goal of $\delta = 1\%$ at 18 GeV is reached, as demonstrated in Fig. 4.

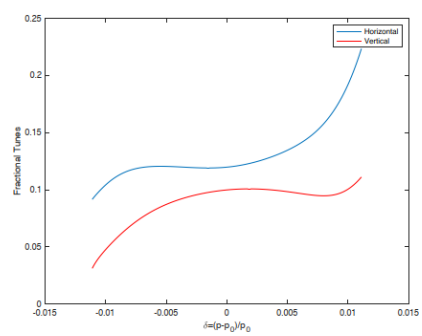

Figure 4: Fractional tune vs δ after correction.

The two second-order dispersion sextupoles are not part of -I pairs; therefore, their non-linear geometric aberrations are not cancelled, and the resulting resonance driving terms lead to reduction of the on-momentum DA. To compensate this effect, we use 12 harmonic sextupoles in the straight section-2 where there is no dispersion, hence the chromatic correction is not affected. The sextupole strengths are optimized in LEGO, where the best DA is achieved with a partial cancellation of the one-turn third-order resonance driving terms from all sextupoles. As shown in Fig. 5, the driving terms from periodic sextupoles are locally cancelled in each arc. The residual terms are due to the second-order dispersion sextupoles and harmonic sextupoles. The on-momentum DA without errors is ≈15σ, where effects of radiation damping are included, as shown in Fig. 6. The rms

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beam size (σ) is determined for the so-called fully coupled emittance of ε_x = 28 nm and $\varepsilon_y = \varepsilon_x / 2$. The DA versus the relative momentum offset δ is also shown in Fig. 6.

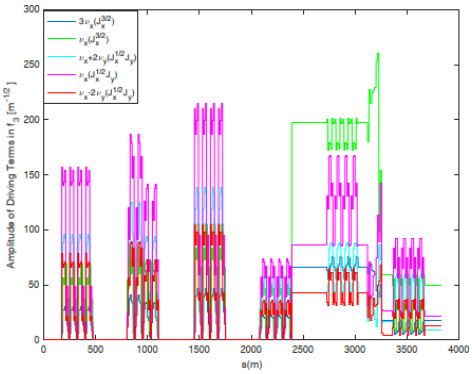

Figure 5: Third-order one-turn resonance driving terms from all sextupoles after correction.

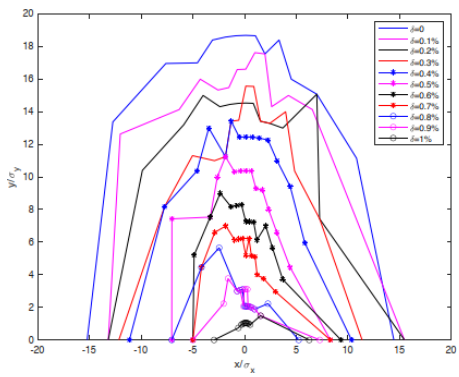

Figure 6: ESR DA without errors vs δ after correction.

DYNAMIC APERTURE WITH ERRORS

Magnet misalignment, strength errors, and non-linear field errors (multipoles) perturb the design optics causing distortions of beam orbit, dispersion, beta functions, *x-y* coupling, chromaticity, betatron tune, and excitation of non-linear resonances. These effects reduce dynamic aperture, and therefore must be corrected. The DA is most sensitive to errors in the low-beta IR magnets where beta functions are very large. The goal for the on-momentum DA is 10σ assuming the fully coupled emittance, without beam-beam effects.

We obtain the DA using particle tracking in LEGO. The chromaticity correction described earlier is fully implemented, where the thin-lens phase trombones are replaced with an equivalent quadrupole match. As a first step, the misalignment, strength errors, and multipoles are generated in dipoles, quadrupoles and sextupoles, including BPM misalignment. Then the optics distortions are corrected using the correction schemes in LEGO. The betatron tune (52.12, 45.1) and linear chromaticity (+1) are maintained using periodic arc quadrupoles and sextupoles. The orbit is corrected using dipole correctors and BPMs, where the vertical correctors are also used to minimize the vertical dispersion. The *x-y* coupling is corrected using the technique of vertical offsets at the sextupoles. Finally, perturbed beta functions are corrected by quadrupole strength adjustment. SVD method is applied to find the most efficient set of correctors. To avoid unstable optics, the errors are assigned in small steps, while applying the corrections at each step, until the full error values are reached.

After the correction is done, a 2000-turn tracking is performed for 10 seeds of random errors. Synchrotron oscillations, effects of non-linear fringe field in quadrupoles and dipoles [10], and radiation effects are included. The DA size is defined as the minimum DA among the 10 seeds.

Random misalignment and strength errors in this study are similar to the PEP-II CDR [11] values. Magnet rms *x,y* offsets and roll angles are 0.2 mm and 0.5 mrad, respectively. The *x,y* offsets at the large-beta final focus quadrupoles are twice as small; these values are also used for the BPMs. The rms strength error is 0.1% in dipoles and quadrupoles, 0.2% in sextupoles, and 0.05% in FFQs and two high-beta dipoles around each IP. Correction of these errors in the simulations typically yields the following rms distortions: 0.3-0.4 mm of *x,y* orbit, ~1 m of Δβ, ~9 cm of horizontal and ~4 cm vertical dispersion.

Systematic and random multipoles, order 3 to 14, in the standard ESR quadrupoles have been provided by the EIC magnet design group [12]. Estimates for dipoles and sextupoles are not yet available; for this reason, we use measured data from the similar PEP-II magnets [11] scaled to the ESR magnet aperture. The most critical multipoles are in the FFQs and the IR high-beta dipoles which dominate the impact on the DA. Tolerances for these multipoles were determined in the DA study.

The final dynamic aperture is calculated for two cases: (1) without radiation effects and (2) with radiation damping. The two cases give the pessimistic and optimistic DA estimates of 10.1σ and 11.0σ, respectively. Without damping, the electron amplitude remains the same over the 2000 turns, while the damped amplitude reduces the impact of multipole errors resulting in larger DA. Dynamic aperture with both damping and quantum excitation is not yet estimated, but it should be between the above two values, hence satisfying the DA goal of 10σ. The pessimistic DA without radiation for 10 seeds of errors is shown in Fig. 7.

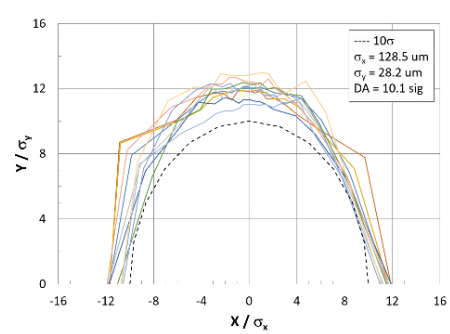

Figure 7: DA at δ = 0 with errors without radiation.

In conclusion, we have demonstrated that the design goals of 10σ DA with errors and 1% of momentum range for the ESR two-IR lattice at 18 GeV are achieved. Similarly, the described chromaticity correction works for one-IR lattice and for lower energy lattice with 60° arcs.

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