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DYNAMIC APERTURE OF THE EIC ELECTRON STORAGE RING*

Y. Nosochkov†, Y. Cai, SLAC, Menlo Park, CA 94025, USA
J. S. Berg, J. Kewisch, Y. Li, D. Marx, C. Montag, S. Peggs, S. Tepikian, H. Witte
Brookhaven National Laboratory, Upton, NY 11973, USA
G. H. Hoffstaetter, M. Signorelli, J. Unger, Cornell University, Ithaca, NY 14850, USA

Abstract

Design of the electron-ion collider (EIC) at Brookhaven National Laboratory continues to be optimized. Particularly, the collider storage ring lattices have been updated. Dynamic aperture of the evolving lattices must be kept sufficiently large, as required. In this paper, we discuss the collider Electron Storage Ring, where the lattice updates include improvement of the interaction region layout and arc dipole configuration, reduced number of magnet types, and changes related to the use of existing magnets. Optimization of non-linear chromaticity correction for an updated lattice and the latest results of dynamic aperture studies are presented.

INTRODUCTION

The EIC [1] is an electron-ion collider to be built at Brookhaven National Laboratory. It is being designed to provide high luminosity of up to 10^{34} $cm^{-2}s^{-1}$, high average polarization, and a wide range of colliding beam energies. The collider consists of separate electron and hadron storage rings, where the baseline lattice has one low-beta interaction region (IR6), while an upgrade lattice also includes the second low-beta IR (IR8).

The IR optics presents a challenge for the beam dynamic aperture (DA) due to the high beta functions in the final focus (FF) quadrupoles near the interaction point (IP), which create very large linear and non-linear chromaticity and high sensitivity to errors in these magnets. The chromatic and error effects are further enhanced by the proximity of the design betatron tunes to integer values.

In this paper, we present the latest DA studies for the electron storage ring (ESR), including the non-linear chromaticity correction and effects of errors. Per specifications, the ESR DA should be $\geq 10\sigma$ in both transverse and momentum dimensions, without beam-beam effects.

The ESR ring consists of six periodic FODO arcs and six straight sections (called IRs), labelled according to the clock. For the EIC energy range, several ESR lattice configurations have been designed for electron energies of 18 GeV, 10 GeV and 5 GeV with one and two low-beta IRs. Reaching the specified DA is most challenging for the 18 GeV lattice due to the lowest IP beta functions, strong 90° FODO arc optics which is used to offset emittance growth with energy, and a large rms energy spread of $\sigma_p \approx 0.1\%$. Hence, the target momentum range at 18 GeV is $\delta = \pm 1\%$. The 10 GeV and 5 GeV lattices have weaker 60° arcs and smaller rms energy spread of 0.06% and 0.05%, respectively. The DA of two-IR lattices is more challenging due to twice as many high-beta IR magnets contributing to the chromatic and error effects.

The ESR lattice continues to be optimized, which requires that the chromaticity correction and dynamic aperture evaluations are updated as well. Below, we first describe the non-linear chromaticity correction for the recent 18 GeV lattice with two IRs (v6.2). Then, the latest studies of DA with magnet errors are presented for the earlier lattice design (v5.6).

CHROMATICITY

This section describes the non-linear chromaticity correction for the more difficult 18 GeV lattice with two IRs. The updated lattice (v6.2) includes an improved layout of the IR spin rotator sections, space for IR6 polarimeter, optimized arc dipole lengths, reduced number of dipole types, and adjustments related to the use of existing quadrupoles and sextupoles from APS [2]. Beta functions and dispersion are shown in Fig. 1, where the betatron tune is ν_x = 50.08, ν_y = 46.14, the natural chromaticity is ξ_x = -108, ξ_y = -114, the IP beta functions are β_x^* = 59 cm, β_y^* = 5.7 cm, and the natural emittance is ε_x = 30.5 nm.

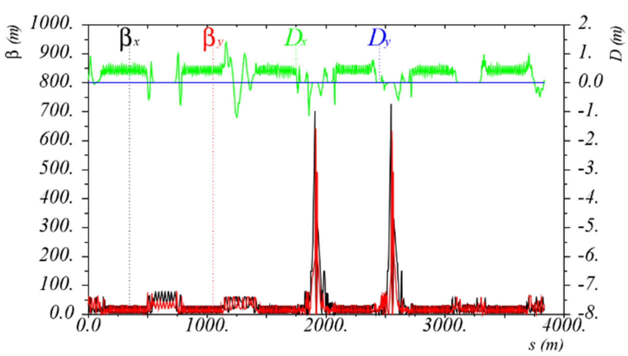

Figure 1: ESR lattice functions at 18 GeV with two IRs.

Correction of only linear chromaticity in this lattice yields a very small momentum range of $\delta = \pm 0.3\%$. The goal of the non-linear correction is to increase the range to the ±1% specification while maximizing the on-momentum DA. The correction is done without magnet errors.

The main sources of ESR non-linear chromaticity are the IR final focus quadrupoles, where beta functions are high. These magnets create very large chromatic beta beating around the ring (described by W-function) which drives the non-linear chromatic tune shift. IR sextupoles for local compensation of the FF quadrupoles are not feasible due to complexity of the ESR IR optics and layout. Instead, we use a semi-local scheme [3, 4], where such correction is

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† yuri@slac.stanford.edu

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done by sextupoles in the adjacent to the IR periodic arcs. Sextupoles in the other arcs primarily correct the linear chromaticity. Multiple sextupole families allow the non-linear correction to high order. The scheme can also include sextupoles for correction of second-order dispersion, as well as dispersion-free harmonic sextupoles for compensation of the sextupole third-order resonance driving terms.

Schematic of the semi-local scheme on one side of IP for 18 GeV lattice is shown in Fig. 2. The sextupoles are repeated four times in 16 cells of the 90º arc. The main function of these sextupoles is to cancel the chromatic beta beating coming from the neighboring FF quadrupoles by creating an opposite chromatic beta wave in the same phase. The latter is achieved by IR phase tuning indicated by "phase trombone" in Fig. 2.

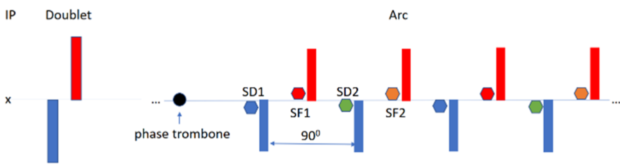

Figure 2: Schematic of 18 GeV semi-local sextupole scheme on one side of IP, where the columns are quadrupoles and the hexagons are four-family sextupoles.

The chromatic beta beating propagates with twice the betatron frequency, hence four sextupole families are suitable per each arc 5, 7, and 9. The same family sextupoles are arranged in –I pairs separated from each other by 180º. This way, the chromatic beta beating from the family sextupoles adds up, while the sextupole third-order resonance driving terms are cancelled [5], thus maximizing the on-momentum DA. The second-order dispersion from each –I pair is also cancelled.

The remaining three arcs 1, 3, and 11 contain four more sextupole families, arranged similarly to the semi-local families, where phase advance between the arcs is also optimized. Overall, the strengths of 16 sextupole families and the *x*/*y*-phase tuning at 8 locations (each half of IR6 and IR8, and four other IRs) are sufficient to control the linear chromaticity and minimize the first and second-order W-functions and the non-linear chromatic tune shift. The optimization is done using LEGO code [6], capable of computing the chromatic terms to high order [7]. The optimized correction is able to achieve the specified momentum range of ±1% while maximizing the on-momentum DA. The linear chromaticity is kept at +1, and the sextupole field is within the magnet limit. Sextupoles for second-order dispersion correction and harmonic sextupoles are not required for this lattice.

The resulting W-functions and momentum dependent tune are shown in Fig. 3. The W-functions are suppressed at IP6 (s = 0), IP8 and in arcs 1, 3, and 11. The arc 7 is between the IP6 and IP8, where W-functions are optimized. The DA vs δ is presented in Fig. 4, where the higher order terms of momentum tune shift are minimized. The DA is calculated in LEGO tracking with synchrotron oscillations and radiation damping included, assuming a conservative rms beam size (σ) based on fully coupled emittance with $\varepsilon_y = \varepsilon_x / 2$.

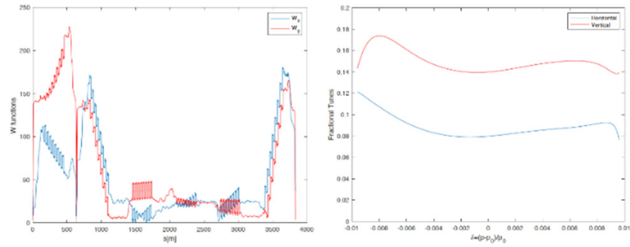

Figure 3: W-functions in 18 GeV lattice with two IRs, starting from IP6 (left), and fractional tune vs δ (right).

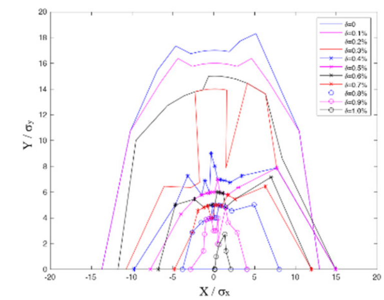

Figure 4: DA of 18 GeV lattice with two IRs, without errors, for momentum range from δ = 0 to 1%.

DYNAMIC APERTURE WITH ERRORS

Below, we present the current estimates of the ESR on-momentum DA with magnet errors, including other recent studies. The ESR lattice version 5.6 is used.

The DA is obtained in particle tracking simulations using LEGO. Randomly generated misalignment and strength errors, and systematic and random multipoles are applied to dipoles, quadrupoles and sextupoles, including BPM misalignment. The errors perturb beam orbit, dispersion, beta functions, *x-y* coupling, chromaticity, betatron tune, and excite non-linear resonances. The strongest effects come from errors in the IR high-beta magnets. The error effects can lead to unstable optics or significant DA reduction.

The following corrections are performed in the simulations before the tracking. The betatron tune and linear chromaticity are corrected using the F and D arc quadrupoles and sextupoles as two-family correctors, respectively. The orbit is minimized at BPMs with dipole correctors, where the vertical correctors are also used to minimize the vertical dispersion. The transverse coupling is corrected using the technique of sextupole vertical offsets creating the skew quadrupole field. Finally, beta function distortions are minimized with adjustment of quadrupole strengths. SVD optimization method is used for finding the most efficient correcting magnets. The errors before correction can make the optics unstable. To avoid such condition, the misalignment and strength errors are applied incrementally in small steps, where the corrections are done at each step, until the errors reach their full values.

The DA is estimated in 2000-turn tracking performed for 10 seeds of random errors. Synchrotron oscillations and effects of non-linear fringe field in quadrupoles and dipoles [8] are included. The DA is defined as the minimum DA among the 10 seeds. It is expressed in terms of rms beam size (σ), taking into account the increased emittance with

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errors. Simulations without radiation effects yield a pessimistic DA estimate, while adding the radiation damping reduces the impact of non-linear field leading to a larger DA.

Conservative misalignment is used, where rms *x,y* offsets and roll angles are 0.2 mm and 0.5 mrad, respectively. Smaller rms *x,y* errors of 0.1 mm are used for BPMs and sensitive FF quadrupoles. The rms strength error is 0.1% in dipoles and quadrupoles, 0.2% in sextupoles, and 0.05% in IR high-beta quadrupoles and dipoles. Typical rms distortions after correction are: 0.3-0.4 mm of orbit, 1 m of Δβ, 10 cm of horizontal and 3 cm vertical dispersion, and 5% of emittance growth.

ESR will use the APS quadrupoles and sextupoles [2], hence their multipoles are based on measurements [9-12]. Systematic multipoles in dipoles come from magnetic design [13], random terms are based on a model, and uncertainty terms [14] are added to simulate changes of systematic terms due to fabrication process. Multipoles in the high-beta IR quadrupoles and dipoles are based on tolerances determined in DA studies.

The current estimates of the on-momentum DA for 18 GeV, 10 GeV, and 6 GeV lattices (v5.6) with errors, without radiation, are presented in Fig. 5 and 6. The DA of the most challenging 18 GeV lattice with two IRs is 9.5σ, while the DA at 10 GeV and 6 GeV are 11.8σ and 12.8σ, respectively, exceeding the requirements.

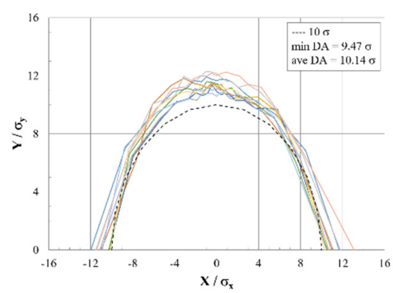

Figure 5: ESR DA at 18 GeV with two IRs (v5.6).

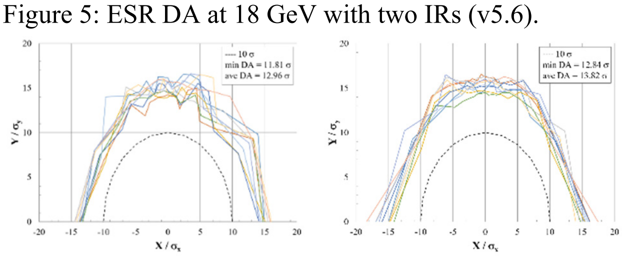

Figure 6: ESR DA at 10 GeV with one IR (left) and 6 GeV with two IRs (right) (v5.6).

We have also considered a scenario, where the APS magnet multipoles might have degraded by a factor of two since their measurement. Tracking of 18 GeV lattice with two IRs (v5.6) indicates a potential DA reduction of 0.2-0.3σ due to such degradation. There is a plan to verify these magnet multipoles in new measurements.

Recently, systematic multipoles of the FF quadrupole Q0EF have been estimated in magnetic design [15]. In this estimate, only the b3 and b4 terms are comparable or larger than the Q0EF tolerances from the DA studies, while the higher order terms are smaller. Tracking with the Q0EF estimated systematic multipoles (without random terms) and all multipoles in other magnets, without misalignment and strength errors, yields ~0.5σ DA improvement at 18 GeV with two IRs and >1σ gain at lower energies.

Impact of large dipole orbit

The ESR arc cells use "super-bends" made of two long dipoles and a short dipole between them. They allow to attain the required emittance at different energies by changing the field in the long and short dipoles without affecting the outside orbit. The design horizontal orbit in the three dipoles at different energies (lattice v6.1) is shown in Fig. 7, where the 18 GeV and 10 GeV orbits are the same, and the dipoles are schematically indicated by dashed boxes.

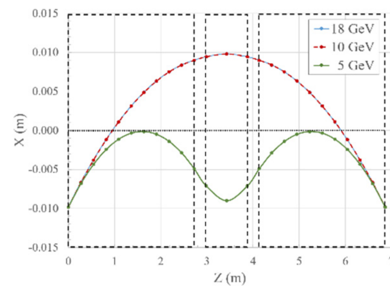

Figure 7: Orbit in the three arc dipoles at different energies.

In the dipoles, the beam sees a non-zero multipole field along the path, enhanced by the large orbit offsets (±10 mm). This field effect is not included in the tracking, where the reference orbit is assumed to be on magnet axis. To estimate the impact of this field on the DA, we replace in tracking the multipoles defined relative to dipole axis by multipoles relative to the orbit, which create the correct field. Variation of the multipoles along the orbit is modelled by slicing the long dipoles in five pieces, and using average orbit (x_i) at the slices and the short dipole to obtain the corresponding multipoles relative to the orbit

$$\tilde{b}_{ni} = \sum_k b_k \frac{(k-1)!}{(n-1)!(k-n)!} \left(\frac{x_i}{r_0}\right)^{k-n}, \quad (1)$$

where $k \geq n$, b_k is k-th order original multipole relative to axis, i is slice number (including short dipole), and r_0 is reference radius.

We verified the impact of the dipole systematic multipoles on the orbit, where the random terms were off. The tracking was done for the 18 GeV lattice with two IRs (v5.6) with all errors in other magnets. The result shows no DA degradation due to the systematic multipoles on the large orbit. This may be due to partial compensation of the multipole values summed along the negative and positive parts of the orbit. Specifically, the most critical b_4 multipole is small, when integrated along the orbit.

CONCLUSION

The ESR non-linear chromaticity correction and dynamic aperture studies demonstrate that the DA requirements are exceeded for the medium and low energy lattices and nearly satisfied for the most challenging 18 GeV lattice with two IRs, where further improvements are possible.

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