SIMULATIONS OF NONLINEAR BEAM DYNAMICS IN THE JLEIC ELECTRON COLLIDER RING*

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Abstract

The short lengths of colliding bunches in the proposed Jefferson Lab Electron-Ion Collider (JLEIC) allow for small beta-star values at the interaction point (IP) yielding a high luminosity. The strong focusing associated with the small beta-stars results in high natural chromaticities and potentially a beam smear at the IP. Rapid growth of the electron equilibrium emittances and momentum spread with energy further complicates the situation. We investigated nonlinear dynamics correction schemes that overcome these problems and allow for stable beam dynamics and sufficient beam lifetime at the highest electron energy. In this paper, we present and compare tracking simulation results for various schemes considering their emittance contributions.

INTRODUCTION

The Jefferson Lab Electron-Ion Collider (JLEIC) [1] is designed to have small beta-stars at the IP to achieve the high luminosity requirement. This unavoidably introduces large chromaticities due to the strong focusing of the final focusing quadrupoles (FFQs) and chromatic beam smear at the IP. In the JLEIC electron collider ring baseline design, the large phase advance 108^o in the arc FODO cell was chosen to be close to 135^o that generates a minimum emittance in a FODO cell lattice [2, 3]. Hence, in addition to the FFQs, such large phase advance requires strong focusing from quadrupoles resulting in a significant chromaticity contribution from the two arcs, ~40% in the baseline design. Linear chromaticities can be straightforwardly compensated using two sextupole families globally distributed in the arcs. The sextupoles are arranged to have the –*I* phase advance to cancel the sextupole introduced non-linear geometric and chromatic effects. Compensation of the FFQs-induced non-linear chromaticities requires a local compensation system where sextupoles generate an opposite chromatic kick in phase to compensate the one from the FFQs at the IP. This local compensation system should have large beta functions and dispersion at the sextupole locations to obtain reasonable sextupole strengths and large ratio of horizontal and vertical beta functions for seperate correction in two transverse planes. Again, sextupoles are located with –*I* phase advance to suppress the sextupole induced nonlinear resonances. Besides, the local compensation optics should be designed not to increase the electron beam emittance significantly. Several chromaticity correction systems in the electron collider ring considering the emittance control have been reviewed [4]. This paper summarizes all studied compensation schemes and reports the tracking simulation results.

COMPENSATION SCHEMES AND SIMULATION RESULTS

The JLEIC electron collider ring is designed using major PEP-II High Energy Ring (HER) magnets within their magnet specification in two arcs and straights and new magnets in special machine blocks, such as spin rotators, interaction regions, etc [2,3]. Electron equilibrium emittance is primarily determined by the arc optics design. Two arcs, consisting of regular FODO cells, spin rotators and matching sections, contribute more than 90% of the natural horizontal emittance. Phase advance 108^o in the regular arc FODO cell allows one to have a 3π phase advance between sextupoles so that the sextupole introduced geometric resonance driving terms can be cancelled every 5 cells. Without any chromaticity correction optics inserted, the electron horizontal emittance is 8.9 nm-rad at 5 GeV and the natural chromaticity is $\xi_{x,y}$= [-113, -120]. Note that chromaticities and emittance vary in different chromaticity correction schemes due to the local excitation of optics functions.

Philosophy of chromatic correction is described in [4] in detail. A brief description of each studied compensation scheme is given as follows.

1. Only linear chromaticities are compensated using two sextupole families distributed in the arcs. Since no local correction, the large beta functions in the FFQs near the IP create large chromatic perturbations resulting in large non-linear momentum variations of beta functions. This leads to a beam smear at the IP affecting the luminosity. Since there is no optics modification, this scheme does not introduce any emittance growth.
2. A local chromaticity compensation block (CCB) on each side of the IP is placed for a local and independent correction of up- and downstream FFQs. Each CCB has two –*I* interleaved sextupole pairs in each horizontal and vertical planes. The interleaved sextupoles generate residual sextupole non-linear geometric effects due to the overlap of

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–*I* sextupole pairs. The remaining linear chromaticity is corrected using two distributed sextupole families in two arcs. There is no emittance growth due to the intact optics.

3. Similar to scheme 2, except that each CCB has one –*I* non-interleaved sextupole pair in each horizontal and vertical planes and sextupole strengths and phase advances are adjusted to improve the chromatic tune and beta-star. The non-interleaved sextupole pairs provide a complete compensation of the sextupole introduced non-linear geometric effects. The beta functions and ratios of horizontal and vertical beta functions at the sextupoles are made relatively large to reduce the sextupole strengths. There is a significant emittance growth due to the enlarged beta function and dispersion in the dipoles.
4. Similar to scheme 3, except that the beta functions in the dipoles in the CCBs are reduced to suppress the emittance growth.
5. The local chromaticity compensation block is designed within a compact optics to have two focusing sextupoles separated by one defocusing sextupole in the middle [5,6]. Because of large beta functions and dispersion at the sextupoles, it requires relatively weak sextupoles. However, there are residual non-linear geometric effects caused by interleaved sextupoles limiting the dynamic aperture. This scheme has a large emittance growth due to large optics functions in the dipoles.
6. A SuperB-like chromaticity correction block [7] has a low or zero emittance contribution. This can be achieved by removing the dipoles from large beta function and dispersion locations, while locating –*I* sextupole pairs at large beta functions and dispersion locations to reduce the sextupole strengths. Meanwhile, lowering dipole bending angles can significantly reduce the emittance contribution because the emittance is proportional to the 3rd power of the dipole bending angle. If the total bending angle is preserved, the remaining dipoles need to leverage the less bending in the CCB resulting in an increased emittance from the rest dipoles. Therefore, one has to balance the bending angles in the CCB and the emittance.

The simulation results of momentum acceptance and dynamic aperture for the schemes described above are shown in Fig. 1 to 6. The energy spread $\delta=\Delta p/p$ for a 5 GeV beam in the electron collider ring is 4.5×10^{-4}. Hence, ±0.4% energy spreads shown in the momentum acceptance plots are corresponding to $\pm9\sigma_\delta$. Dynamic aperture for on momentum particles in terms of beam size is also marked on each plot. The beam sizes are calculated using the changed emittance for each compensation scheme. Table 1 lists a comparison of simulation results of all chromaticity compensation schemes. The SuperB-like correction scheme is promising by having large dynamic apertures for both on and off momentum particles and no emittance growth.

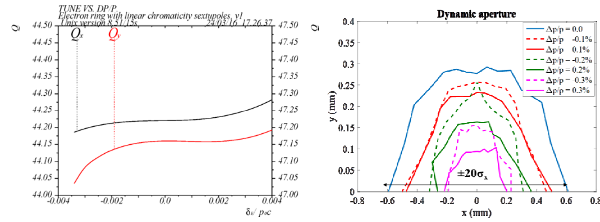

Figure 1: Momentum acceptance (left) and dynamic aperture (right) of scheme 1.

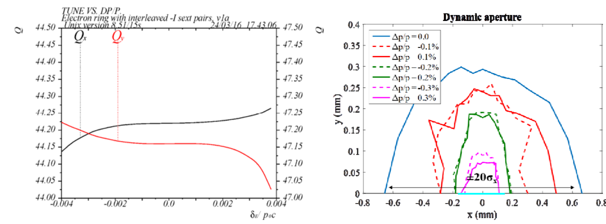

Figure 2: Momentum acceptance (left) and dynamic aperture (right) of scheme 2.

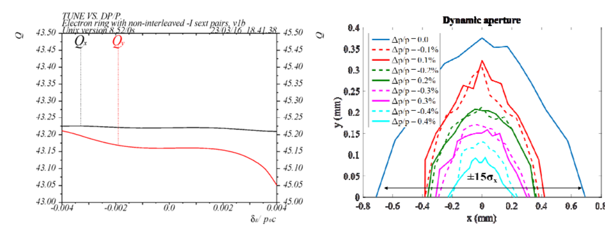

Figure 3: Momentum acceptance (left) and dynamic aperture (right) of scheme 3.

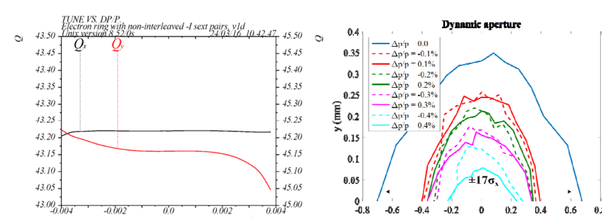

Figure 4: Momentum acceptance (left) and dynamic aperture (right) of scheme 4.

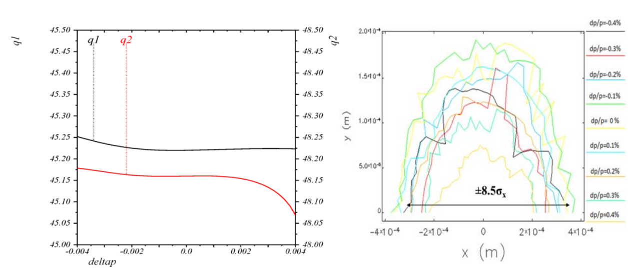

Figure 5: Momentum acceptance (left) and dynamic aperture (right) of scheme 5.

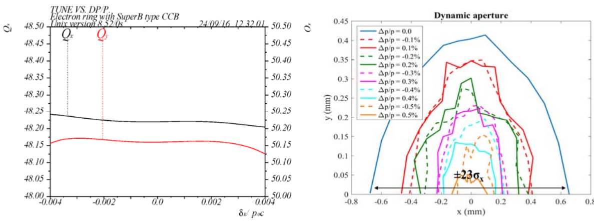

Figure 6: Momentum acceptance and dynamic aperture of scheme 6.

Table 1: Comparison of Simulation Results of Different Chromaticity Compensation Schemes

Scheme	$\varepsilon_x/\varepsilon_{x,o}$	x/σ_x , y/σ_y		δ/σ_δ
		δ=0	δ=0.4%	
1	1	±20, ±48	0,0	≤±9
2	1	±20, ±48	0,0	≤±9
3	2.1	±15, ±40	±4.5, ±10	≥±9
4	1.7	±17, ±41	±5, ±10	≥±9
5	1.7	±8.5, ±18	±5, ±7.3	≥±9
6	1	±23, ±72	±8, ±24	≥±9

SUMMARY

Several chromaticity compensation schemes have been investigated to suppress the chromatic effects in the JLEIC electron collider ring. Tracking simulations have been performed to illustrate the momentum acceptance and dynamic aperture. A SuperB-like chromaticity compensation scheme, with –I sextupole pairs and suppressed beta function and dispersion in the dipoles in the compensation system, shows an effective chromatic compensation and no beam emittance growth. Further error sensitivity study will be performed to validate this compensation scheme.

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