STUDIES OF MAGNETS MISALIGNMENT IN RING-BASED ELECTRON COOLER

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Abstract

Performance of Electron Ion Collider (EIC) will benefit from cooling of protons at the highest collision energy (γ=294). The required cooling can be provided by the Ring Electron Cooler (REC) – a non-magnetized RF-based electron cooler, employing an electron storage ring. The REC is a "racetrack" consisting of a 170 m long cooling section (CS), a wiggler section opposing the CS and containing eighteen 2.4 T damping wigglers with highly nonlinear field profile, and two matching arcs. The REC utilizes an elaborate correction scheme to achieve the target dynamic aperture (DA) in the baseline lattice. Alignment errors in magnet placement will be present in a constructed ring and will disrupt the DA correction scheme. In this paper, we describe studies of alignment errors, their effect on the dynamic aperture, define tolerances to various misalignments and propose a procedure for misalignment correction.

INTRODUCTION

To achieve high luminosity, the Electron-Ion Collider's (EIC) Hadron Storage Ring must mitigate emittance growth driven by intra-beam scattering (IBS). At the highest collision energies ($\gamma \approx 294$ for protons), a proposed solution is the Ring Electron Cooler (REC): a non-magnetized, RF-based electron cooling cooler [1] featuring a dedicated electron storage ring [2]. The REC lattice integrates of a 170 m cooling section, a damping wiggler section containing eighteen 2.4 T wigglers, and two matching arcs. The strong nonlinearities introduced by the wigglers require careful optimization of the dynamic aperture (DA).

Previous studies of the REC lattice demonstrated that the baseline optics and correction schemes are capable of achieving the required DA under ideal conditions [3]. In a realistic machine, however, construction and installation tolerances will introduce magnet misalignments that perturb the closed orbit, modify the optics, and potentially reduce the DA below acceptable levels. In particular, the REC lattice is highly sensitive to orbit distortions in the wiggler section, where increased dispersion and betatron oscillations pose a risk of increasing the electron beam emittance and degrade cooling performance.

In this paper, we study the effects of magnet alignment errors on the REC dynamic aperture and emittance. Translation and tilt errors for all major magnet families are investigated to establish alignment tolerances. Orbit correction schemes utilizing beam position monitors (BPMs) and corrector kickers are then evaluated to determine their effectiveness in restoring acceptable machine performance under realistic error conditions. Finally, the resulting emittance growth, including the effects of IBS and beam-beam scattering (BBS), is examined.

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ALIGNMENT ERRORS

Initially, all magnet types were tested for different rms translation errors and rms tilts about the longitudinal axis to meet the criteria of meeting the DA goal in 50% of ran error seeds, with the number of seeds chosen at 1000. No orbit, tune, or other correction was applied at this stage and all combinations of magnet and error type were run individually. Quadrupoles were further split, showing the quadrupoles near the cooling section to be more sensitive than those in the arcs or wiggler section These results are used to inform relative tolerances of magnet types when combined with each other and correction and are shown in Table 1.

Table 1: Tolerances for individual magnet type translations and tilts without orbit correction. Used as baseline for magnet sensitivity to errors.

Magnet type	Translations	Tilts
Wiggler	10 µm	0.5 mrad
Sextupole	100 µm	>25 mrad
Dipole	500 µm	0.5 mrad
Quadrupole	5 µm	1 mrad

ORBIT CORRECTION

Translations and tilts in wigglers and dipoles could largely be corrected by the two sets of BPMs and correctors on either side of each magnet. Quadrupole translation errors have the strictest tolerances of all magnet types, but as mentioned previously, this could be partially mitigated by a determination of which quadrupoles have the largest contribution to the reduction of DA. Sextupole tolerances are large compared to other magnet types and do not present any particular concerns.

The orbit correction scheme chosen for this study, while including translation errors for all magnet types, uses a BPM and a dual-plane corrector kicker at each quadrupole. An RMS BPM error also assumed during orbit correction. The splitting of errors between magnet types after correction are placed in Table 2, and are chosen to keep >90% of runs above 5σ. This was achieved with BPM errors of 5 µm or 10 µm and shown in Figs. 1 and 2.

A potential concern in this orbit correction scheme is the placement of a kicker and BPM at each quadrupole is difficult to obtain in the arcs, where the separation between quadrupole and dipole magnets in the current lattice is 10cm.

Table 2: Translation Errors with Orbit Correction

Magnet Type	Translation Error
Dipole	100 µm
Quadrupole	50 µm
Sextupole	100 µm
Wiggler	50 µm
BPM	5 µm or 5 µm

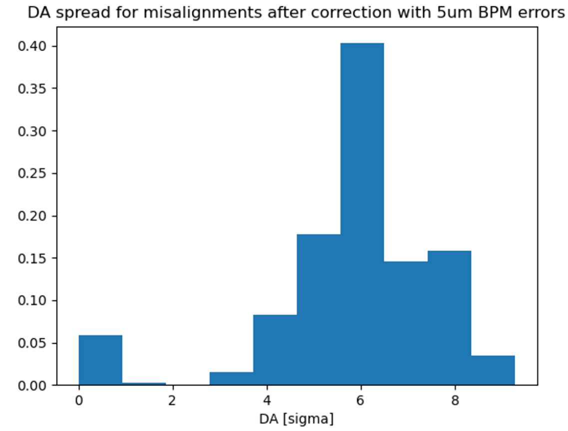

Figure 1: Dynamic aperture spread with misalignments from Table 2 orbit correction and RMS BPM error of 5 µm.

This correction was tested without BPMs and kickers in the arcs, leading to only a minor loss in dynamic aperture, with results compiled in Fig. 3

EMITTANCE INCREASE

As a major design consideration is minimizing the equation

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2 \quad (1)$$

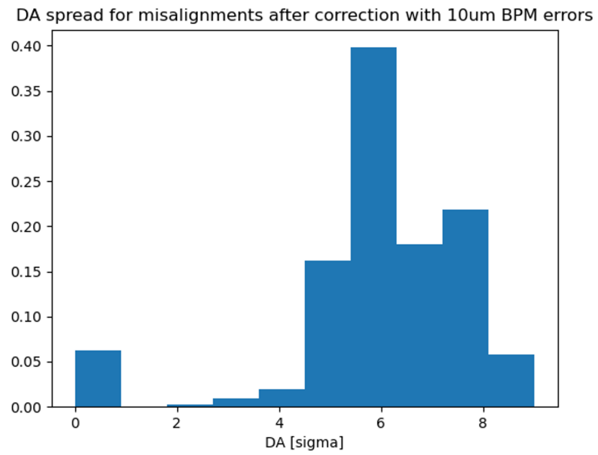

Figure 2: Dynamic aperture spread with orbit correction and RMS BPM error of 10 µm.

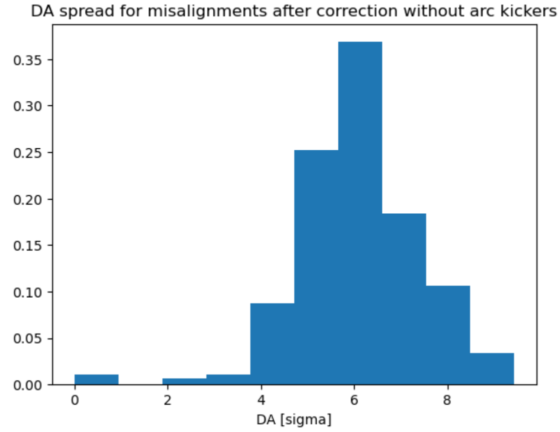

Figure 3: Dynamics aperture over error seeds with BPMs and kickers at all quadrupoles except in arcs.

in the wigglers, this was checked against the orbit errors expected in wigglers after correction, yielding a small change seen in Fig. 4.

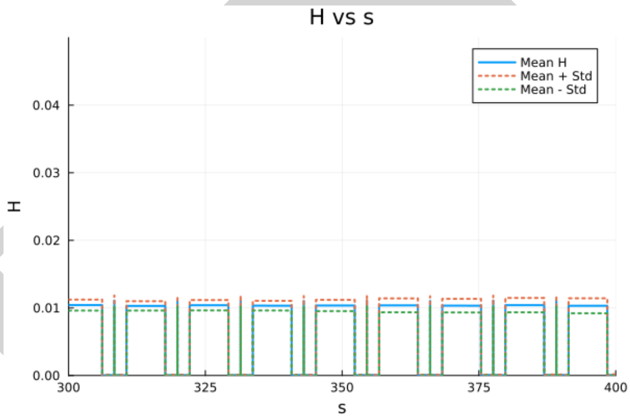

Figure 4: $\mathcal{H}_x$ function zoomed into wiggler section after errors, showing small change from baseline.

As seen previously with the wiggler misalignments, keeping the orbit under control in the wigglers leads to small changes in the $\mathcal{H}_x$ function which can drive emittance increase. With the alignment errors and orbit correction applied from the previous section, the emittance was calculated for many error seeds using GETRAD8. This simulation included emittance increase from IBS and BBS from the proton beam using the latest cooling parameters [2]. The results of these runs are compiled in Fig. 5 and show an emittance increase of $< 10\%$ for almost all runs. This emittance increase is acceptable and keeps the emittance around the assumed 8 nm used in cooling simulations.

CONCLUSION

Studies of alignment errors in the Ring Electron Cooler demonstrate that the REC lattice can maintain acceptable dynamic aperture and emittance performance under realistic magnet misalignments when appropriate orbit correction is applied. Initial tolerance studies identified quadrupole

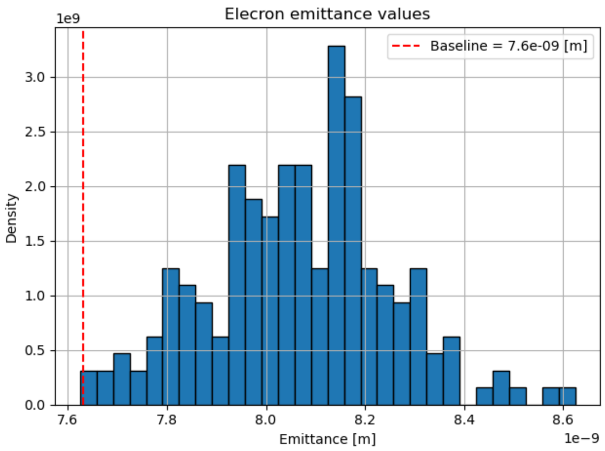

Figure 5: Emittance with IBS and BBS for 1000 error seeds.

translations and wiggler alignment errors as the dominant sources of DA reduction.

An orbit correction scheme employing BPMs and dual-plane correctors at quadrupole locations was shown to substantially mitigate the effects of alignment errors. With realistic BPM resolutions of 5–10 µm and magnet translation, more than 90% of simulated error seeds maintained dynamic apertures above the required 5σ threshold. Furthermore, acceptable performance was retained even when BPMs and correctors were removed from the arc sections, indicating additional flexibility for practical implementation of the correction system.

ACKNOWLEDGMENTS

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REFERENCES

[1] G. I. Budker, “Effective method of damping of particle oscillations in proton and antiproton storage rings”, *At. Energ.*, vol. 22, pp. 438–440, May 1967. doi:10.1007/BF01175204

[2] S. Seletskiy *et al.*, “Design of ring electron cooler”, in *Proc. NAPAC’25*, Sacramento, CA, USA, pp. 1151–1154, Aug. 2025. doi:10.18429/JACoW-NAPAC2025-FRAD02

[3] J. Unger, G. Hoffstaetter, A. Fedotov, J. Kewisch, and S. Seletskiy, “Dynamic aperture correction for ring electron cooler”, in *Proc. NAPAC’25*, Sacramento, CA, USA, pp. 426–428, Aug. 2025. doi:10.18429/JACoW-NAPAC2025-TUP031