SIMULATIONS OF PHASE-ADVANCE CORRECTION FOR FCC-ee AND IMPACT ON ITS PERFORMANCE

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Abstract

The control of the optics in the Future Circular electron–positron Collider (FCC-ee) is a challenging but crucial task for meeting its performance goals. Lattice imperfections, such as magnet misalignments and field errors, introduce distortions in the phase advance between the Interaction Points (IPs), which could affect the Dynamic Aperture (DA) and degrade luminosity, particularly in the presence of strong beam–beam interactions. This work presents simulation studies of modeling such imperfections, quantifying their impact on the optics and in particular on the phase advance between the IPs, and developing correction schemes aimed at restoring the nominal phase advance. Implications for the DA and beam quality are discussed.

INTRODUCTION

Achieving the performance goals of the Future Circular electron–positron Collider (FCC-ee) [1–3] requires precise control of the linear and non-linear optics [4–6]. Lattice imperfections, such as magnet misalignments and field errors, distort the closed orbit, beta functions, phase advance, dispersion, coupling, and resonance driving terms. In the presence of strong beam-beam interactions, these distortions can significantly reduce the Dynamic Aperture (DA) and Momentum Acceptance (MA), and degrade beam lifetime and luminosity.

This work presents first simulation studies of combined lattice imperfections, optics corrections, and beam-beam interactions, and their impact on beam performance. As a first step, the phase advance between the Interaction Points (IPs) is investigated, as its distortion directly affects the beam-beam-induced optics distortions and β^* at the IPs. A dedicated IP phase advance correction is presented, and its effect on beam quality is discussed. All results are obtained for the LCC lattice [7] at the Z energy.

IMPERFECTIONS MODELING IN XSUITE

Modeling and correcting lattice imperfections in FCC-ee is an active area of research across multiple codes and groups [8–11]. In this work, we adopt an imperfections model for the LCC within the Xsuite simulation framework [12], that includes random transverse and longitudinal misalignments, transverse rotations, and field errors, applied to all dipoles, quadrupoles, and sextupoles in the FCC-ee lattice. Different tolerances are assumed for arc elements and final-focus elements, following the specifications in [13]. To obtain statistically representative results, approximately 300 different random seeds are used for the assignment of these imperfections.

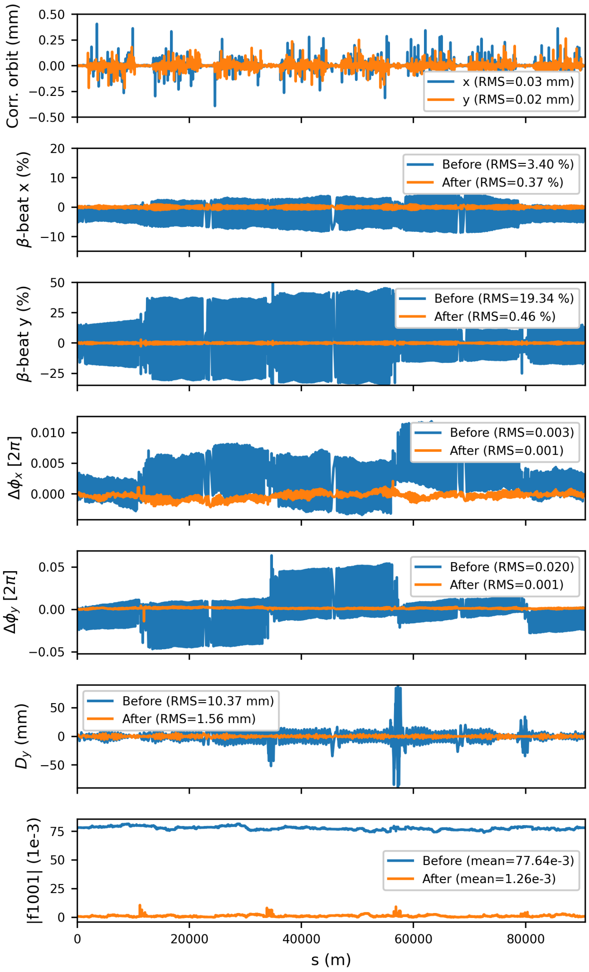

Figure 1: Closed orbit (shown only after correction), beta-beating, phase error, vertical dispersion, and coupling for a representative FCC-ee lattice seed with imperfections, before and after global optics correction.

Figure 1 shows the impact of these errors on the lattice optics, for one representative seed with the above assumptions. Before correction the machine shows large closed-orbit distortions (not shown in the figure), beta-beating, phase errors, vertical dispersion, and coupling, all of which must be cor-

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rected to a good extent before beam-beam interactions can be studied.

Finding an effective correction scheme, whether global or local, is a non-trivial task with different solutions studied for the LCC optics [11]. For this study, we employ a baseline correction scheme using orbit correctors at every quadrupole, as well as normal quadrupole corrector trims at every quadrupole and skew quadrupole corrector trims at every sextupole. The correction relies on a pseudo-inversion of a response matrix using Singular Value Decomposition (SVD) at the location of Beam Position Monitors (BPMs). BPMs are assumed to be located at almost all quadrupoles. The present study includes BPM resolution and misalignment errors, but does not yet consider faulty or missing BPMs, or more advanced correction strategies (e.g. MICADO), which are left for future studies. Linear coupling correction is included through skew quadrupole trims. After the correction procedure, the tunes and chromaticities are re-matched to their nominal values. The residual optics distortions after correction are also shown in Fig. 1, confirming that they are greatly reduced after correction. The shown seed is representative of the overall statistical behavior.

The corrected lattices described above serve as the baseline for the beam-beam studies presented in the following section.

BEAM-BEAM INDUCED OPTICS DISTORTIONS AND PHASE CORRECTION

The large vertical beam-beam parameter $\xi_y \approx 0.09$ of FCC-ee at Z-energy [13] means that residual lattice imperfections can have a substantial impact on the beam-beam dynamics. Beam-beam interactions are modeled in Xsuite using a weak-strong scheme, which accounts for crossing angle and hourglass effects. The beam-beam force is nonlinear, so its effect on the optics is amplitude dependent.

In the ideal lattice, assuming certain bunch intensity and emittances, the beam-beam kick at each IP introduces to first order a linear tune shift and beta-beating along the ring. Due to the lattice symmetry, the contributions from individual IPs are in phase and combine as shown in Fig. 2 (top, blue). For the design working point $(Q_x, Q_y) = (194.16, 170.20)$, the beta-beating results in a reduction of β_y^* by more than 40% relative to its design value of 0.7 mm ('dynamic beta'), which can lead to enhanced luminosity. On the other hand, across the ring the beam-beam induced beta-beating can reach up to 60%.

In the presence of lattice imperfections, even after global optics correction, residual phase errors at the IPs break this symmetry. The beam-beam kicks from individual IPs no longer combine as in the ideal case, and their contributions to the beta-beating can interfere constructively or destructively depending on the seed-dependent residual phase errors. For the lattices studied here, the residual phase error between IPs can reach up to 0.03 in units of 2π. As shown in Fig. 2 (top) for a representative corrected seed, the RMS beta-beating increases overall, reaching up to 100% locally. In addition, the β_y^* reduction is no longer uniform across IPs, as shown in Fig. 3, which can also impact luminosity.

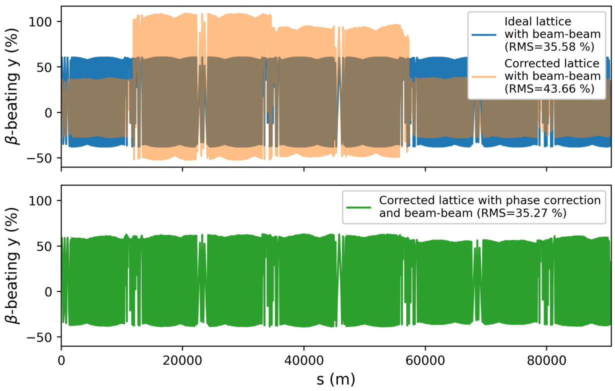

Figure 2: Top: vertical beta-beating induced by beam-beam in the ideal lattice (blue) and in the corrected lattice of Fig. 1 (orange). Bottom: vertical beta-beating induced by beam-beam in the corrected lattice after phase correction between the IPs.

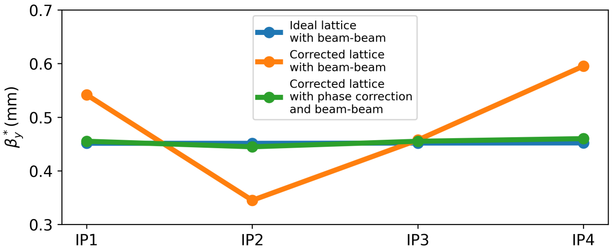

Figure 3: Comparison of the vertical beta* at the four IPs for the ideal lattice with beam-beam (blue), the corrected lattice with beam-beam (orange) and the corrected lattice with beam-beam and phase correction (green).

A dedicated phase advance correction between IPs is applied on top of the standard global correction, using individually powered trim quadrupoles in the dispersion suppressor regions to restore the nominal IP phase advance. The impact on the standard global optics correction and on the tune is minimal. As shown in Fig. 2 (bottom), this correction reduces the RMS beta-beating and recovers the beam-beam induced beta-beating close to the ideal-lattice case. Importantly, it also restores the uniform β_y^* reduction across IPs, which was broken by the residual phase errors, which is expected to improve the luminosity balance between IPs.

TRACKING SIMULATIONS WITH BEAM-BEAM

To assess whether the beam-beam induced optics distortions and the phase corrections translate into measurable beam performance differences, DA and MA simulations as well as tracking studies are performed in Xsuite.

DA and MA simulations are performed for three cases: the corrected lattice without beam-beam and the same lattice with beam-beam and with or without the IP phase advance correction. Results for 50 different seeds are shown in Fig. 4.

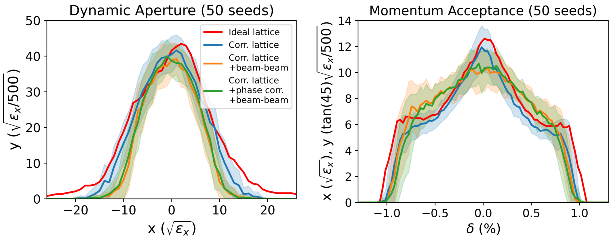

Figure 4: DA (left) and MA (right) for the ideal lattice (red), corrected lattices without (blue) and with (orange) beam-beam, as well as corrected lattices with phase advance correction between IPs and beam-beam (green), averaged over 50 seeds.

Beam-beam interactions reduce the DA and, to a smaller extent, the MA. The phase advance correction does not produce a significant change in either of the two quantities, within the statistical uncertainty of the simulations, suggesting that it has a limited effect on the non-linear dynamics at larger amplitudes that mostly affect the DA and MA.

Tracking simulations are performed to further characterize beam behavior over longer times. The lattice includes tapering, synchrotron radiation with quantum excitations, and beamstrahlung. Beam-beam interactions are modeled in the 'quasi-weak-strong' approximation: the strong beam is initialized using an initial estimate of the equilibrium emittances, and re-evaluated every 30 turns, and is represented by 251 longitudinal slices. An ensemble of 10^4 macro-particles is tracked for 10×10^3 turns. Transverse emittances are monitored at a dispersion-free region close to the RF, an artificial aperture is imposed at 20σ in both transverse planes, and particles exceeding the RF bucket length longitudinally are considered lost.

Figure 5 compares three scenarios for one seed: the corrected lattice without beam-beam, with beam-beam but without phase correction, and with beam-beam and phase correction applied. Without beam-beam, the lattice reaches the expected equilibrium emittance, with no measurable particle losses, which confirms the quality of the global orbit and optics correction.

When beam-beam interactions are introduced, the vertical emittance grows beyond its initial equilibrium (the horizontal emittance remains approximately constant), there is a different equilibrium bunch length due to beamstrahlung, and some lost particles are observed. The difference between the cases with and without phase correction is marginal, which is nevertheless consistent with the expectation of the DA and MA results. These simulations indicate that the residual emittance growth is not dominated by the remaining linear phase advance errors alone. Other effects, such as residual vertical dispersion and coupling at the IPs, which are not corrected beyond the global scheme, as well as nonlinear effects, may have stronger contributions. Understanding and mitigating this emittance growth is the subject of ongoing studies.

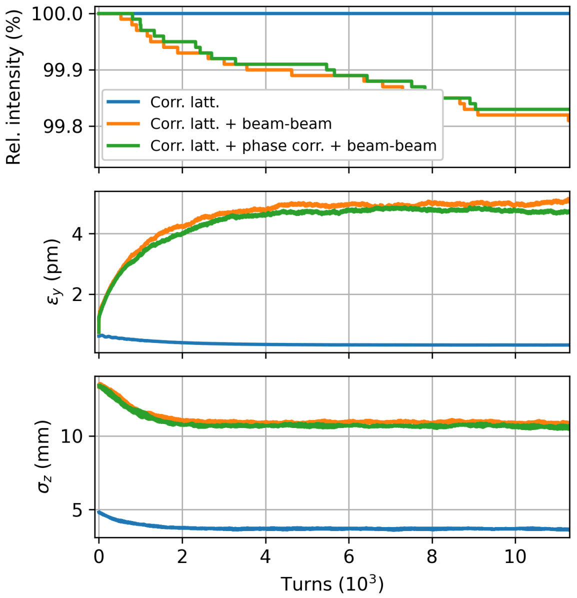

Figure 5: Evolution of relative intensity (top), vertical emittance ε_y (middle), and bunch length σ_z as a function of turn number, for a corrected lattice without beam-beam (blue), with beam–beam without phase correction (orange) and with phase correction (green).

SUMMARY AND OUTLOOK

Simulation studies of combined lattice imperfections, optics corrections, and beam-beam interactions have been presented for the FCC-ee LCC lattice at Z energy. Lattice imperfections, even after global optics correction, introduce residual phase errors between IPs that break the symmetry of the beam-beam induced optics distortions, amplifying beta-beating and breaking the β_y^* balance across IPs. A dedicated IP phase advance correction, using trim quadrupoles in the dispersion suppressor regions, restores the beam-beam induced beta-beating pattern of the ideal lattice and recovers the β_y^* balance across IPs. However, DA, MA, and tracking simulations indicate that the impact of this phase correction on beam-beam induced emittance growth and particle losses is relatively small for the present study. This suggests that additional effects, beyond the residual linear phase advance errors, may contribute to the observed degradation. Future work will focus on further understanding the sources of beam-beam induced emittance growth, exploring possible compensation schemes, and extending these studies to the other FCC-ee energies.

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