

INTERPLAY BETWEEN SEXTUPOLE SETTINGS AND SINGLE PARTICLE INSTABILITIES DURING THE FCC-ee COMMISSIONING*

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Abstract

The Future Circular Collider of electrons and positrons (FCC-ee) is designed to achieve high luminosity at center-of-mass energies ranging from the Z boson peak to the top quark threshold. During the commissioning phase, specialized optics are essential to accommodate the dynamic needs of machine tuning and beam stabilization. This paper investigates the role of sextupoles in the various FCC-ee commissioning optics, focusing on their influence on nonlinear beam dynamics. Using advanced simulation tools, we analyze how sextupole configurations impact key performance indicators, including the dynamic aperture, emittance evolution and lifetime. Strategies for optimizing sextupole strengths are explored. The findings provide critical insights for the design and optimization of the commissioning optics, ensuring efficient and reliable ramp-up to nominal operation. These results are instrumental in refining the FCC-ee commissioning strategy, supporting its broader objectives for particle physics research.

INTRODUCTION

The commissioning of the FCC-ee [1–5] poses unique challenges, requiring precise beam control from the very beginning of operation. Unlike nominal running conditions, the commissioning phase requires special optics configurations that prioritize beam stability and machine protection. Nonlinear magnetic elements such as sextupoles, while essential for chromatic correction during normal operation, can introduce unwanted complexities when linear optics corrections and orbit threading are still underway. Therefore, understanding the interplay between sextupole settings and beam stability is fundamental for commissioning the machine.

To support commissioning activities, three optics configurations are currently under consideration: ballistic [6], relaxed (high-beta), and nominal (collision) optics [7]. The first two stages, in particular, are characterized by significantly larger beta functions at the interaction points, which inherently reduce chromatic aberrations and consequently lessen the demand for strong sextupolar corrections. This opens the possibility of operating with reduced sextupole strength—or even turning them off—during early commissioning.

This study focuses on evaluating the impact of sextupole settings across different commissioning optics for the GHC [8] and LCC [9] lattices at Z-mode energy (45.6 GeV).

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For the multi-turn tracking simulations, Xsuite [10] is used while the observables are the dynamic aperture, beam lifetime, emittance evolution, and momentum acceptance. The work aims to contribute in developing effective commissioning strategies and improve the understanding of single-particle instabilities associated with nonlinear magnetic fields.

RELAXED OPTICS PERFORMANCES

The characteristic parameters of the studied relaxed optics, high-beta and ballistic, with ideal sextupole strength (optimized for best beam lifetime) are shown in Table 1. In order to assess the available time for commissioning - threading, closed orbit and linear optics correction - the beam lifetime (bunch population over turns) for different sextupolar strength is calculated. Additionally to these, other observables like emittance evolution are also calculated when needed.

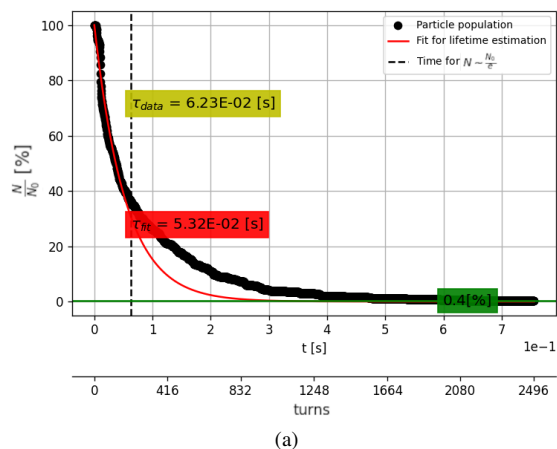
Table 1: Relaxed Optics Parameters And Performances With Nominal Sextupole Strength

Parameters	high-beta GHC	ballistic GHC	high-beta LCC
β_x^* [m]	0.33	152.6	0.3
β_y^* [mm]	7	296380.2	7
ε_x [nm]	0.71	1.2	0.68
ε_y [pm]	1.9	1.9	1.34

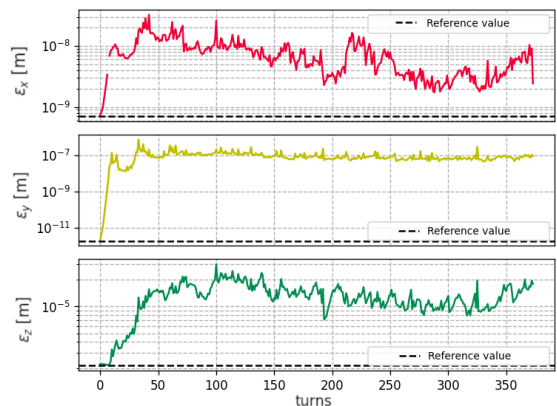
High-beta GHC and LCC with Reduced Sextupoles

The high-beta GHC and LCC optics studied, are developed for version 24.3 and demonstrate comparable performances with no particle losses ($N/N_0 = 100\%$ with $N_0 = 1000$) after two longitudinal damping times (≈ 2500 turns).

The similarities in performance do not hold once the sextupole strength is reduced. Reducing to half of the nominal strength ($k_2/2$), the beam lifetime in GHC is drastically reduced while the LCC lattice can keep the beams circulating for a longer time as can be seen in Fig. 1a, 2a. The emittance evolution for the two lattices are plotted in Fig. 1b, 2b. The GHC emittances are significantly increased raising issues with the aperture limitations. On the other hand, the LCC lattice seems to better preserve the design (reference) emittances without surpassing the aperture limitations. However, more studies with different types of errors should be performed. Given the performance margin with the LCC lattice, the case with zero sextupoles strength ($k_2 = 0$) is



(a)



(b)

Figure 1: (a) lifetime and (b) emittance for GHC lattices with half sextupole strength.

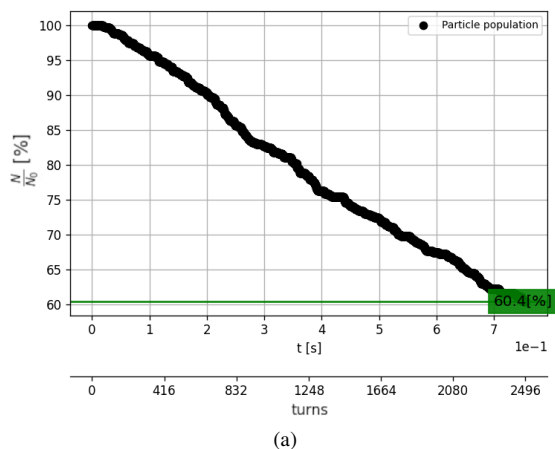
also studied and the resulting lifetime is close to double the one obtained with GHC, in the case with $k_2/2$, while the emittances are now comparable.

It is important to understand the mechanism causing the significant emittance increase and reduction of lifetime to find potential mitigations. Focusing on the case with half sextupole strength, we calculated the contributions from both the arcs and the interaction region (IR), and found that the performance degradation is primarily caused by the arc sextupoles—an expected result due to the relaxed optics in the IRs.

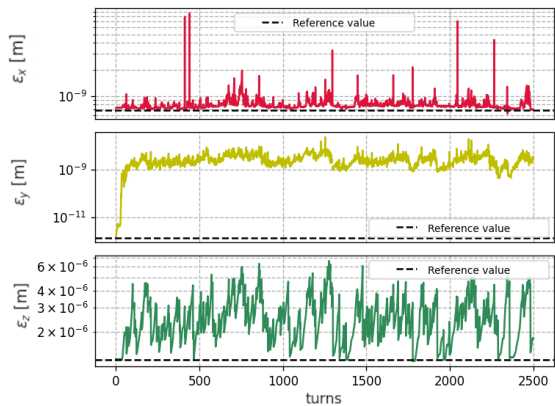
In order to find ways to mitigate the poor performance the contribution of the resulted large chromaticity ($\xi_{x,y} = (-247.4, -596.6)$ for the case with all k_2 to half) is studied. Initially the impact of the large chromaticity on path lengthening [11] for particles with large betatron oscillation amplitudes is studied. In order to mitigate this effect, the RF phase should be optimized so as to keep these particles longer in the machine. Assuming only the linear contribution, the needed change of the RF phase can be calculated from the equations:

$$\Delta C = -2\pi(\xi_x J_x + \xi_y J_y),$$

$$\delta = -\frac{\Delta C}{C_0 \cdot \alpha_1}, \quad \Delta\phi_s = -J_\epsilon \cdot \delta \cdot \tan(\phi_s)$$



(a)



(b)

Figure 2: (a) lifetime and (b) emittance for LCC lattices with half sextupole strength.

where J_ϵ is the longitudinal partition number, C_0 the reference machine circumference, α_1 the linear compaction factor, ϕ_s the RF synchronous phase and $J_{x,y}$ the linear actions. In Fig. 3a and 3b it can be seen that the target particles, 11 σ_x (dark red line deviating from zero), stayed for longer in the machine but is again eventually lost. This indicates that further investigation is needed where possibly higher order terms ($\Delta C = -2\pi \frac{d\tilde{Q}}{d\delta} \cdot \vec{J} - \delta^2 \oint k_2 (D_x^3 - 3D_x D_y^2) ds$) should be considered [12] as well as understanding how the partition number could potentially change with action.

Another issue driven by the reduced sextupole strength (large chromaticity), is the tune shift experienced by particles with sizable energy spread (δ). These particles execute significant energy oscillation (due to synchrotron radiation) and are affected from different tune resonances. Therefore, the most important resonance driving terms (RDTs) for different δ s can be quite informative to be calculated and if possible to be mitigated. This study is ongoing and any further findings will be presented in future reports.

Ballistic GHC with Reduced Sextupoles

A ballistic optics for the GHC v23 is under development and is intended for initial use during commissioning, prior to transitioning to the high-beta version. This optics config-

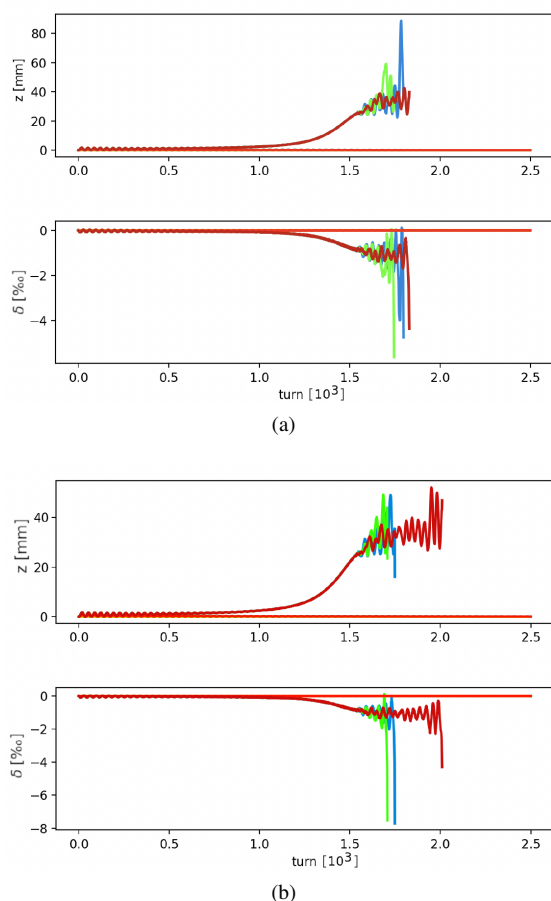


Figure 3: (a) longitudinal motion without any correction and (b) longitudinal motion with RF phase optimization.

uration was driven by the need to switch off the sextupole magnets during the initial beam steering around the ring. In this dedicated commissioning optics—referred to as ballistic—both the quadrupole and sextupole magnets near the IP are switched off. As a result, it exhibits lower natural chromaticity and reduced peak beta functions across the interaction region (Table 1), while also eliminating synchrotron radiation from the final doublet. The absence of focusing elements around the IP allows for the establishment of a straight reference trajectory and for BPM calibration [13], which are essential during the early stages of commissioning.

Upon first beam threading using the ballistic optics with sextupoles turned off, significant dispersion errors and large vertical emittance are typically observed. Although precise optics measurements are not yet possible at this stage, dispersion-free steering (DFS), or dispersion correction using orbit correctors, proves highly effective in mitigating these effects and enabling continued commissioning. The current GHC v23 ballistic optics, despite its nonlinear behavior still being under optimization, presents quite similar performances as the high-beta versions, no particle losses ($N/N_0 = 100\%$) after two longitudinal damping times (≈ 2500 turns). When all sextupole strengths are reduced to half, the resulting lifetime (Fig.4a) slightly exceeds that of

the high-beta GHC (Fig.1a) while the corresponding emittances (Fig.4b)—especially the vertical one (ε_y)—show a marked improvement (Fig.1b).

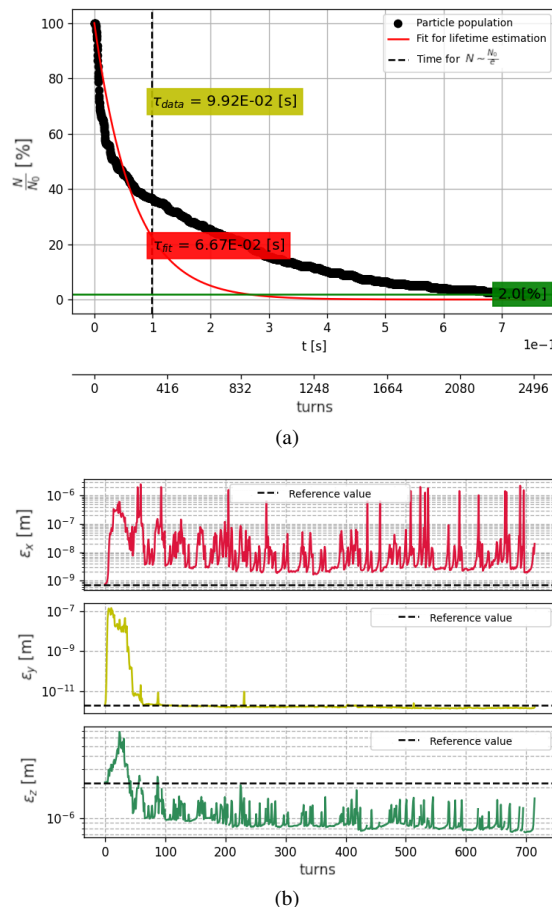


Figure 4: (a) lifetime and (b) emittances evolution, for ballistic GHC lattice with half k_2s .

CONCLUSIONS

This study examines the influence of sextupole strength on beam dynamics during the commissioning phases of the FCC-ee, focusing on relaxed (high-beta) and ballistic optics configurations. Simulations suggest that reducing sextupole strength affects beam lifetime, momentum acceptance, and emittance evolution. The high-beta LCC lattice appears to perform better under reduced nonlinear contributions than the GHC variant, with improved beam stability even in the absence of sextupole fields. The ballistic GHC optics also shows good potential to be used during the early stages of commissioning, given the relatively moderate nonlinear behavior. These results indicate that careful adjustment of sextupole settings are mandatory for early commissioning. Further investigation into emittance growth, transverse-longitudinal coupling, and the role of resonance driving terms may help refine the understanding of beam stability in these early phases.

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