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STATUS OF THE FCC-ee OPTICS TUNING*

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Abstract

With a circumference of approximately 91 km, the Future Circular electron-positron Collider, FCC-ee, aims for unprecedented luminosities at beam energies from 45.6 to 182.5 GeV. A major challenge is reaching its design performance in the presence of magnet misalignments and field errors. The FCC-ee optics tuning working group studies all related aspects, and applies state-of-the-art techniques for beam-based alignment, commissioning simulations, beam threading, optics measurements and corrections, which are probed at numerous world-leading accelerator physics facilities. Advanced optics correction simulations include interaction-point tuning, magnetic tolerances are studied, and a new optics is under scrutiny. The current status of tuning simulations for different FCC-ee lattices is presented.

INTRODUCTION

The work of the FCC-ee optics tuning group during 2023 [1] was devoted to preparing the input for the midterm report [2]. The arc quadrupoles and sextupoles are placed on 6 m long girders with a target 50 µm RMS alignment tolerance in the horizontal and vertical directions. In the Z lattice the arc girders are separated by about 50 m with a target alignment tolerance of about 200 µm RMS on this length scale. For longer scales, this tolerance increases up to 5 mm RMS over 10 km.

The midterm report highlighted the importance of demonstrating the feasibility of reaching the FCC-ee design performance in the presence of realistic imperfections. As an illustration of the challenge, applying 1 µm Gaussian misalignments to all elements results in an unstable optics, due to magnet displacements in the Interaction Region (IR). Since then, the tuning strategies, including beam-based alignment (BBA), have been carefully examined in search of the optimal sequence of measurements and corrections.

Initially, field quality tolerances were found to be prohibitively tight, with maximum acceptable relative deviations of 10^{-6} at a reference radius of 10 mm [1]. Updated tolerances taking into account synchrotron radiation effects, presented below, are found to be more relaxed.

The FCC-ee baseline [3–5] optics, and an alternative optics [5, 6] are being further developed. Other optics design options are also being investigated such as the use of combined function magnets in the arc short straight sections [7].

FCC-ee LATTICE OPTIONS

Placement studies have converged on a tunnel with 8 surface sites, a four-fold super-periodicity, with roughly 91 km circumference in the Geneva basin. In the current baseline physics schedule, four operation stages are foreseen, corresponding to beam energies from 45.6 to 182.5 GeV, from the Z-pole to above the top-pair-threshold. Two different lattice designs are currently being investigated: the so-called Global Hybrid Correction optics (GHC) [4] and the Local Chromaticity Correction (LCC) [6] optics. Both designs feature four Interaction Points (IPs), where beams are brought into collision from the inside outwards. The other four long straights, where the beams also change aperture again, host collimation, RF cavities, injection and extraction.

The arcs for the GHC optics consist of FODO cells with 90° phase advance, a cell length of about 100 m till 80 GeV and half this value above. It includes pairs of sextupoles separated by a $-I$-transform. The LCC arcs are based on a hybrid FODO lattice [8], with a FODO length of about 65 m at all energies, and a periodic unit-cell length of about 300 m, comprising 10 quadrupoles. Sextupoles are symmetrically interleaved. While the LCC experimental IR design features local horizontal and vertical chromaticity correction using sextupoles, only the latter is corrected locally in the GHC optics. In the GHC horizontal chromaticity is corrected globally using arc sextupoles, while the vertical IR chromaticity is compensated by a sextupole at a location with nonzero dispersion, whose geometric aberrations are cancelled by a second sextupole at zero dispersion. Although both designs include the crab-waist collision scheme, in the GHC the crab waist is generated, as the dominantly appearing aberration,

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by reducing the strength of this second sextupole, which is also known as the virtual crab-waist scheme [4], whereas the LCC scheme uses a dedicated additional sextupole.

Sensitivities to misalignments of the different components of the GHC and LCC lattices have been presented in [9] showing that the LCC optics is less sensitive to misalignments in the arcs while, for both optics, similar sensitivities are found in the IRs. As an illustration, misalignments on the order of 0.1 µm in the IRs generate vertical orbit perturbations of about 100 µm, 2% β-beating and 50 mm of rms vertical dispersion beating for both optics.

High-order chromaticity and amplitude detuning terms are computed using MAD-NG [10] for both optics, showing that the LCC features lower high-order chromatic terms than GHC at Z and $t\bar{t}$. The higher-order detuning with amplitude is similar for GHC and LCC [11]. Improving these higher-order aberrations could help increase Dynamic (DA) and Momentum Aperture (MA), as foreseen in future studies.

BEAM BASED ALIGNMENT

BBA simulations for the arcs of the GHC optics [12] show that an rms beam alignment as good as 20 µm can be achieved when simultaneously modulating the strengths of 10 quadrupoles by 2%, and detecting the orbit response. For the Z lattice, 142 such modulations would be needed to center the orbit in all arc quadruples. By contrast, at most 50 µm RMS alignment is achieved by modulating the strengths of individual sextupole magnets, which would require a total of 600 modulations for the ZH and $t\bar{t}$ optics. These studies assumed a BPM resolution of 1 µm. The primary limitations appear to be lattice nonlinearities and quadrupole lengths.

TUNING SIMULATIONS

A previous report on tuning simulations [1] uncovered some discrepancies between the simulations performed with MADX and pyAT. To discard discrepancies in the models used by these two computer codes, dedicated comparisons were performed using identical errors and exactly the same simulation steps up to orbit correction, but excluding optics corrections. This comparison helped in finding better parameters for the orbit correction and an optimized sequence of correction steps [9]. Figure 1 illustrates the good agreement between the two codes up to orbit correction. Therefore, the discrepancy from the two studies is likely to arise from the different optics correction strategies. The pyAT studies implement a LOCO-like optics correction approach, while the current MAD-X simulations [13] exploit a response matrix for phase advance, dispersion and coupling Resonance Driving Terms (RDTs) [14]. This explanation is corroborated by another, independent study for a simplified lattice, which also successfully achieved linear optics corrections based on phase advance and coupling correction [15].

Figure 2 presents the DA obtained in optics tuning simulations with pyAT for various scenarios. When assigning errors to the full lattice a maximum RMS misalignment of about 30 µm can be applied, while still succeeding in correcting the linear optics, yet with low DA. However, assigning errors only to the arc elements increases the allowed misalignments to about 70 µm and with significantly better DA than for the previous case. The last scenario, shown by the red dots in Fig. 2, implements a slow ramp-up of the lattice errors during correction iterations to approximate the effect of commissioning the optics in a β^* squeeze sequence [16]. This scenario does not strikingly improve the DA. However, a recent preliminary study with pyAT considering rms misalignments in the arcs of up to 80 µm and including phase advance corrections has yielded clear DA improvements [17].

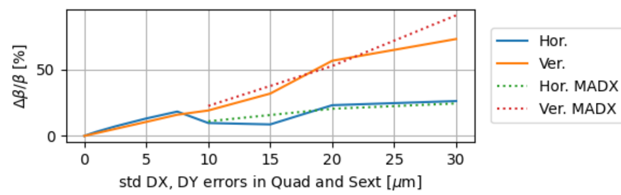

Figure 1: Comparison of β-beating from PyAT and MAD-X codes by assigning misalignments errors (horizontal axis) and performing orbit and tune corrections for the Z GHC lattice.

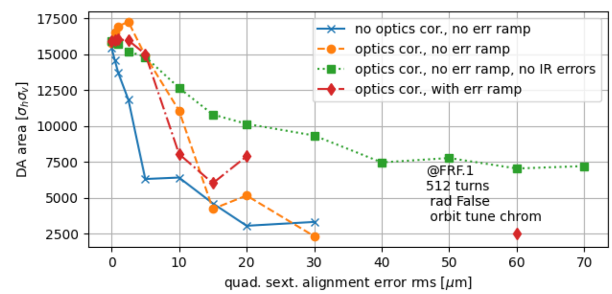

Figure 2: DA obtained with pyAT after optics tuning simulations for difference scenarios and versus the size of the transverse misalignments.

IP Tuning

Dedicated IP tuning studies aim at recovering nominal optics parameters around the IPs [18]. Their effect on luminosity in the presence of beam-beam effects is being examined [19]. Several knobs allow independently tuning the linear IP optics parameters, including the β-functions, the waist (longitudinal offset of the minimum β-function), coupling RDTs, and vertical dispersion. The detailed description of these knobs, including the magnets used, can be found in [18, 19]. Through these knobs, the optics parameters at multiple IPs can be accurately controlled, even when including corrected orbit deviations arising from arc misalignment. Further studies will combine these IP tuning knobs with the global tuning efforts and beam-beam studies, to reveal the complete tuning capabilities.

Tuning Studies for the High Energy Booster Ring

The orbit correction strategy presented in [20] has been updated to account for the girder misalignment and to quan-

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Table 1: Preliminary bare field quality tolerances, without correction, in 10^{-4} units at a reference radius of 10 mm from 6D tracking studies with radiation for the Z GHC lattice.

Error	Arc Quadrupoles		Arc Dipoles	
	Random	Systematic	Random	Systematic
a_3	1.0	2.0	—	—
b_3	1.5	1.5	0.25	0.1
b_4	—	—	0.5	0.25
b_5	—	—	0.3	0.1
b_6	0.1	0.5	—	—
	IR Quadrupoles		**IR Dipoles**	
	Random	**Systematic**	**Random**	**Systematic**
b_3	—	—	1.0	1.0
b_4	0.1	0.4	—	—
b_5	—	—	1.5	6.0

tify the effect of the errors on the extraction emittances. The girder-to-girder misalignment is 200 µm while elements on top of the girder are misaligned by 50 µm. The matching of tune and chromaticity after orbit correction do not improve the residual β-beating. Moreover, the vertical dispersion and coupling are at the level of 100%, resulting in a vertical emittance increase orders of magnitude greater than the factor of 5 that is acceptable for injection into the collider. Therefore, optics corrections are required for the High Energy Booster, and correction schemes similar to those used in the collider are under consideration. On average the FODO and Hybrid FODO lattice perform similarly after two orbit correction iterations. Nevertheless, the residual orbit and vertical dispersion values for the 100 error seeds analyzed show a lower variance for the Hybrid FODO lattice.

FIELD QUALITY TOLERANCES

New field quality tolerances are evaluated via 6D tracking with radiation [21] with Xsuite [22]. These studies complement previous studies that were conducted without radiation [23]. The tolerances are established by applying random and systematic errors to the different magnet types in the arcs and IRs and determining at what threshold a perceivable change in the DA occurs. The results obtained for the Z GHC lattice are shown in Table 1. These tolerances are above or close to current estimates of magnetic field errors [24]. In the future, mitigation methods, e.g., using the lattice sextupoles and corrector coils, will be studied, which are expected to significantly relax these tolerances. Further studies with 6D DA and radiation for additional error types, tolerances for the $t\bar{t}$ lattice and for sextupoles are underway.

ARC CORRECTOR MAGNETS

The arc corrector magnets for the GHC lattice could be nested with arc dipoles, quadrupoles or sextupoles to avoid reduction of the arc filling factor. Horizontal orbit correction can be nested with arc dipoles, either at one end of these elements or over their full length without any impact on the field quality, and fortuitously compatible with the requirements of energy tapering. Vertical orbit corrector coils nested with arc quadrupoles would lead to 30 units of skew sextupole and, therefore, are not considered. However, combining vertical orbit correctors with arc sextupoles seems a promising solution, since only roughly 40 units of skew decapoles would be created. Furthermore, skew quadrupole coils are envisaged also being combined with arc sextupoles, which would generate about 70 units of skew octupoles. The impact on DA and MA remains to be investigated.

POLARIZATION WITH ERRORS

Efforts have been dedicated to polarization studies, aiming to realise precise energy calibration in FCC-ee [25]. Recent studies have focused on orbit correction and optics tuning for spin polarization estimation at Z energy. The refined orbit correction procedure aims to mitigate the impact of strong sextupole feed-down by interleaving orbit correction with gradual sextupole strength recovery and tune matching. Realistic random misalignments ($\sigma_{\mathrm{dx,dy,ds}} = 30\,\mu\mathrm{m} - 100\,\mu\mathrm{m}$) were introduced to arc elements, with additional relatively smaller misalignments ($\sigma_{\mathrm{dx,dy,ds}} = 10\,\mu\mathrm{m} - 20\,\mu\mathrm{m}$) in IR elements. The impact of BPM performance, including BPM scaling error, BPM resolution, BPM misalignment and randomly missing BPMs on orbit correction and polarization was also thoroughly investigated [26].

In general, polarization remains high when a stable closed orbit is obtained through the application of a proper orbit correction procedure. Additional dispersion correction and chromaticity correction could further improve the polarization levels, particularly in a few extreme cases where polarization is relatively lower. Future studies aim to determine the maximum acceptable orbits for achieving a sufficient level of polarization. More realistic machine error models, such as long-range alignment error model, will be constructed and simulated. Innovative lattice correction strategies will be explored to improve the machine performance.

SUMMARY AND OUTLOOK

Critical points have been identified in the optics tuning of the FCC-ee collider and booster rings. For the collider, simulations show that rms arc magnet misalignments of 70 µm can be tolerated, while maintaining good optics quality, and with only a moderate reduction of DA. We expect that this will also remain the case for even larger misalignments. Further developments are planned on the correction of the phase advance and coupling RDTs and the systematic use of IP tuning knobs. Requirements for magnetic field quality are being relaxed with respect to previous studies by performing the DA calculations with synchrotron radiation and, in the future, by applying correction strategies. The options for the arc correction circuits are being narrowed down. High polarization is demonstrated thanks to refined orbit correction strategies, allowing for up to 100 µm RMS misalignments in the arcs and 20 µm in the IRs.

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