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# OPTICS TUNING OF THE FCC-ee*

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*Abstract*

The Future electron-positron Circular Collider, FCC-ee, is a proposed next generation collider aiming to provide large luminosities at beam energies from 45.6 up to 182.5 GeV. This collider faces a major challenge to deliver the design performance in the presence of realistic lattice errors. A commissioning strategy has been developed including dedicated optics designs, efficient beam-based alignment and optics corrections based on refined optics measurements. First specifications on main magnets, corrector circuits, and instrumentation have also been investigated. A summary of all these aspects is presented in this paper.

## INTRODUCTION

Lattice imperfections in the FCC-ee collider affect momentum acceptance (MA), dynamic aperture (DA), beam lifetime, luminosity at the interaction points (IPs), emittance blow-up, injection efficiency, polarisation, energy calibration, and machine protection. Previous studies [1–3] already indicated that linear optics corrections alone do not ensure a good DA. The tuning simulations need to be extended by beam-based alignment (BBA) techniques, dispersion-free steering (DFS), IP tuning and non-linear corrections. In addition, a single particle instability has recently been observed when reducing the sextupole strength to ease orbit steering in the first phases of commissioning [4]. This phenomena is mitigated by implementing an optics with the Final Doublet quadrupoles and the IR sextupoles switched off. Such optics is called ballistic and has been designed in [5] for the FCC-ee. Ballistic optics have been also used for alignment at the SLC [6] and for BPM calibration in LHC [7]. The steps during commissioning are illustrated in Fig. 1.

The simulations are mostly carried out for the Global Hybrid Correction (GHC) lattice [8–10], since, in general, the alternative, the Local Chromaticity Correction (LCC) lattice [11, 12] is less sensitive to lattice imperfections in the arcs. Other optics design options are also being investigated such as the use of combined function magnets in the arc short straight sections [13].

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## BEAM BASED ALIGNMENT (BBA)

Performing BBA for individual magnets would be a very time-consuming procedure, hence various promising parallel approaches are explored, aiming to achieve 10 to 20 µm effective alignment. Using a Parallel Quadrupole Modulation System (PQMS), with 10 arc quadrupoles in parallel and a $\Delta K/K$ of 2 %, distributed equally over one arc with 1 µm BPM resolution, yields an accuracy below 20 µm [14]. Performing BBA based on modulating 8 arc quadrupoles in parallel with $\Delta K/K$ of 1 %, and a BPM resolution of 1 µm, by correcting induced orbit shifts with vertical orbit correctors nested inside quadrupoles yields a rms accuracy achieving the target value. Another technique uses individual orbit correctors next to quadrupoles and achieves the target by modulating up to 20 quadrupoles in parallel [15]. Preliminary studies for arc sextupoles, based on response matrices and modulating 6 elements in parallel achieve 20 to 50 µm [16]. BBA concepts for the IR remain to be studied. Various quadrupole BBA routines are explored at SuperKEKB [17] and KARA [18] requiring further developments.

## TUNING SIMULATIONS

The proposed optics commissioning steps are shown in Fig. 1 including typical optics corrections [20]. Tuning simulations with the ballistic optics have been successfully demonstrated [21] using the nominal misalignment and strength errors given in Table 1. It is assumed that all Beam Position Monitors (BPMs) have been aligned to the quadrupole centres within 10 µm rms thanks to BBA. Circulating beam with limited lifetime is obtained after orbit threading.

For the nominal optics arc tuning simulations it is important to note that neither IR, nor non-linear errors are

Table 1: Arc Alignment and Strength Tolerances

| Element | $\sigma_{x/y}$ [µm] | $\sigma_\theta$ [µrad] | $\Delta k/k$ [$10^{-4}$] |
|---|---|---|---|
| Arc quads & sext. | 50 | 50 | 2 |
| Dipoles | 1000 | 1000 | 2 |
| Girders | 150 | 150 | - |
| BPMs-to-quad | 100→10 | - | - |

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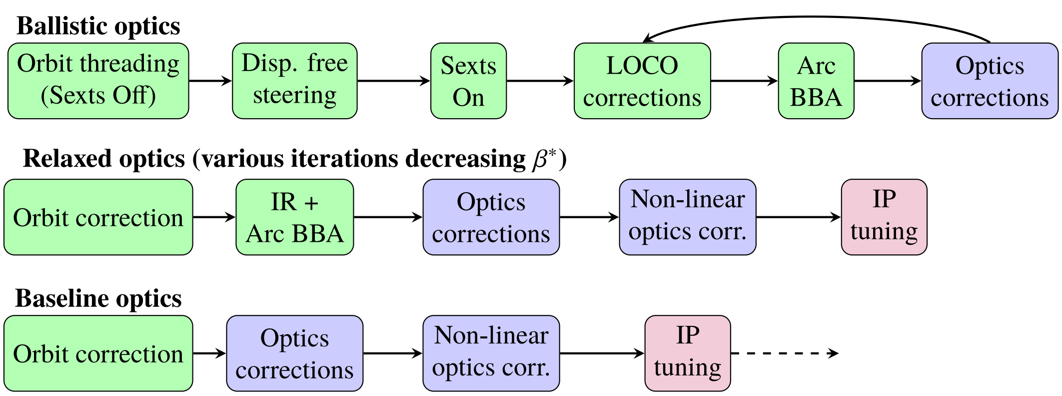


Figure 1: Steps during the FCC-ee optics commissioning starting from the ballistic optics, followed by a sequence of relaxed optics [19] and, finally, the nominal collision optics.

considered yet. The obtained median vertical emittance is 0.71 pm, below the 1 pm design value. The resulting DA and MA are shown in Fig. 2. Clear degradations in DA and MA are observed which could significantly affect lifetime and injection efficiency. Improved corrections will be investigated and dedicated non-linear corrections will be added, which should come with the addition of multipolar components.

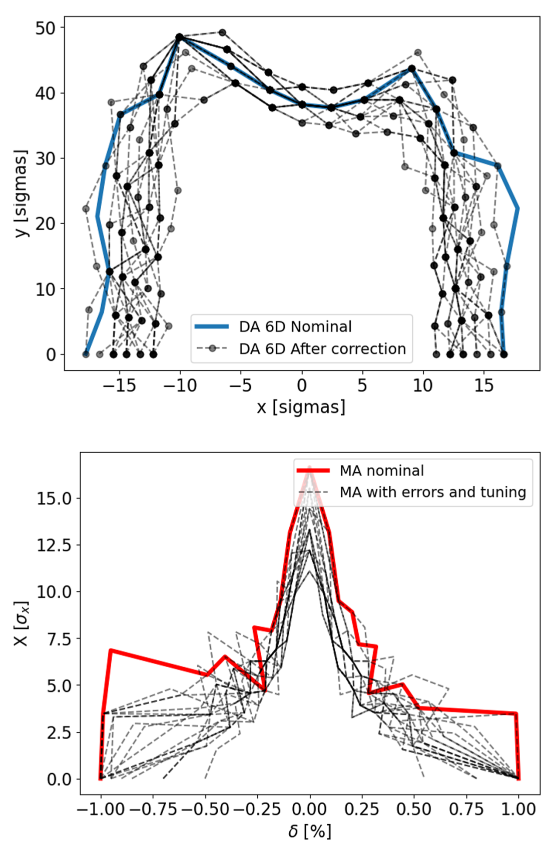


Figure 2: DA (top) and MA (bottom) after linear optics corrections having used the errors described in Table 1, which neglect IR errors and magnetic multipolar errors. The lattice used is GHC v22 with tunes 217.77 and 220.369.

In terms of IP optics parameters after corrections, the rms vertical $\beta$-beating is 3% and the rms vertical dispersion is 1 µm. Some moderate impact on luminosity performance is expected from these aberrations. Dedicated IP tuning corrections in presence of IR errors follows.

## *IP Tuning*

The tuning and correction of optics in the IP region of FCC-ee are essential for reaching the desired luminosity levels. Dedicated IP tuning knobs for $\beta^*_{x,y}$, $w^*_{x,y}$ and $D^*_y$ are employed to correct lattice errors for all IPs [22, 23].

Simulations were performed including IR alignment errors for the FCC-ee GHC lattice v22 using `pyAT`. In this first IR study arc alignment tolerances were taken to be 100 µm and 100 µrad, better than the nominal ones in Table 1. Final Doublet (FD) quadrupole alignment tolerances were 10 µm and 10 µrad. The regions with sextupoles were set to tolerances of 30 µm and 30 µrad. The median vertical emittance for the successful seeds is above 1.8 pm, which is larger than the target of about 1 pm and above the 0.71 pm value achieved in the previous arc optics tuning simulations. Reducing the FD tolerance to 1 µm and 1 µrad solved this issue but such tolerance would be unrealistic, requiring further developments. The resulting DA is shown in Fig. 3, which is

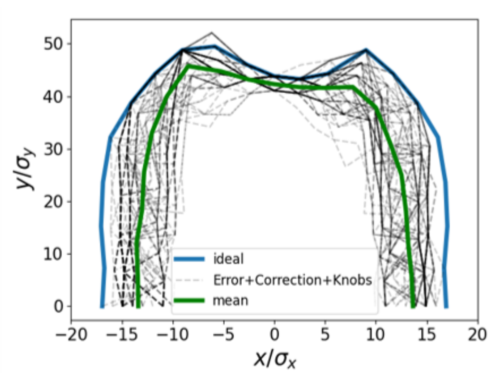


Figure 3: Dynamic aperture after 512 turns for 75% of successful seeds with IP tuning knobs for the Z lattice.

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Table 2: Preliminary Bare Field Quality Tolerances in $10^{-4}$ Units at 10 mm

| Error | Arc Quadrupoles | | Arc Dipoles | |
|---|---|---|---|---|
| | Random | Systematic | Random | Systematic |
| $a_3$ | 0.4 | 0.17 | — | — |
| $b_3$ | 1.1 | 0.7 | 0.25 | 0.1 |
| $b_4$ | — | — | 0.5 | 0.05 |
| $b_5$ | — | — | 0.3 | 0.06 |
| $b_6$ | 1 | 0.5 | — | — |
| | IR Quadrupoles | | IR Dipoles | |
| | Random | Systematic | Random | Systematic |
| $b_3$ | — | — | 0.17 | 0.1 |
| $b_4$ | 0.1 | 0.4 | — | — |
| $b_5$ | — | — | 0.12 | 0.05 |
| | Arc Sextupoles | | | |
| | Random | Systematic | | |
| $a_4$ | 30 | 25 | | |
| $a_5$ | 30 | 25 | | |
| $b_5$ | 36 | 25 | | |

comparable to that obtained in the previous arc study, Fig. 2. Additional non-linear correction algorithms will be required.

## HIGH ENERGY BOOSTER TUNING

Simulations [24] for the High Energy Booster (HEB) include girder-to-girder misalignment of 200 µm. Elements on top of the girder are misaligned by 50 µm. Similar orbit and optics corrections as in the collider yield successful results with emittances below the design values and $\beta$-beating below 10% for most of the seeds.

## FIELD QUALITY TOLERANCES

Field quality tolerances are re-evaluated with 6D tracking in Xsuite [25]. 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 [3, 26] or in the injection efficiency [26, 27] occurs. The most restrictive results obtained for the Z GHC lattice are shown in Table 2 in $10^{-4}$ units at a reference radius of 10 mm. These tolerances are found challenging, compared to current estimates of magnetic field errors [28]. In the future, mitigation methods, e.g. using the lattice sextupoles and dedicated corrector coils, will be studied. Further studies for additional error types are underway.

## POLARISATION WITH ERRORS

The precise beam energy measurement in FCC-ee relies on depolarising previously polarised low-intensity pilot bunches using resonant depolarisation (RDP), requiring a minimum polarisation of 10 % [29, 30]. Machine errors could significantly limit the achievable polarisation and could also lead to a shift of the measured spin tune. Around the Z-pole, the required uncertainty in the measured

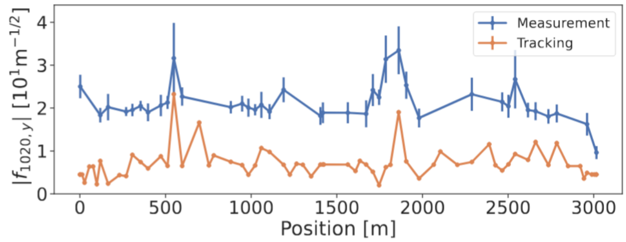


Figure 4: Measurement of the sextupolar RDT $f_{1020}$ at the SuperKEKB electron ring [34] with optics where $\beta_y^* = 81$ mm.

collision energy is 100 keV. To assess the impact of misalignments on the spin dynamics, simulation studies [31] are performed using the code BMAD. Up to 100 µm and 25 µm rms misalignments are applied to arc and IR magnets, respectively. For the vast majority of seeds at various beam energies around the Z-pole, the beam energy measurement error stays below 100 keV, with polarisation above 10%. Future studies should include larger misalignment errors along with magnetic field imperfections, as in Table 1 with specific correction techniques.

## SYNERGIES WITH SUPERKEKB

The SuperKEKB collider is experiencing performance limitations from reduced injection efficiency and degraded specific luminosity versus intensity. The minimum operational $\beta^* = 1$ mm is currently 3 times larger than the original design of 0.3 mm. It is suspected that these limitations originate from optics errors. In particular, coupling at the IP and sextupolar aberrations could explain these observations [32, 33]. First measurements of sextupolar Resonance Driving Terms (RDTs) have been performed in [34] showing preliminary discrepancies with the model, see Fig. 4. Further studies are needed to find correction strategies in SuperKEKB that could also be critical for FCC-ee.

## SUMMARY AND OUTLOOK

Parallel BBA simulations for the FCC-ee arc quadrupoles show sufficient accuracy, however experimental data in SuperKEKB and KARA feature poorer performance than expected, needing further investigations.

Linear optics correction in the arcs is well demonstrated. However, the MA after correction is lower than in the design for all seeds, affecting injection efficiency. Non-linear corrections could address this problem and relax the challenging field quality tolerances. This requires inserting dedicated correctors in the lattice and implementing algorithms in the simulations.

First IP tuning simulations required reducing FD tolerances to the micron level. A new correction scheme with skew quadrupoles next to the FD is under investigation to alleviate this tight tolerance.

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