LOW EMITTANCE TUNING OF FCC-ee

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Abstract

The FCC-ee project studies the design of a future 100 km e+/e circular collider for precision studies and rare decay observations in the range of 90 to 350 GeV center of mass energy with luminosities in the order of 10^{35} cm^{-2} s^{-1}. In order to reach these luminosity requirements, strong focusing is needed in the interaction regions. Large maximum beta values (of 7736 m for the Z energy) and the small beta star values, make the FCC-ee lattices particularly susceptible to misalignments and field errors. FCC-ee therefore presents an appreciable challenge for emittance tuning. In this paper, we describe a comprehensive correction strategy used for the low emittance tuning. The strategy includes programs that have been developed to optimise the lattice based on Dispersion Free Steering, linear coupling compensation based on Resonant Driving Terms and beta beat correction utilising response matrices. One hundred misalignment and field error random seeds were introduced in MAD-X simulations and the final corrected lattices are presented.

INTRODUCTION

The e+/e- Future Circular Collider (FCC-ee) will provide unprecedented sensitivity [1]. Implemented in stages, the collider will be operated at four energies: Z-pole (45.6 GeV), WW threshold (80 GeV) and ZH production peak (120 GeV) and the ttbar production threshold (182.5 GeV). Table 1 summarizes some of the key accelerator parameters. A complete list of parameters can be found in the Conceptual Design Report (CDR) [2]. In this paper we will present the correction strategies used, and the resulting corrected lattice results for the lowest and highest energies, Z and ttbar.

Table 1: Baseline Beam Parameters of the Four Operational Energies for FCC-ee [2]

Parameters	Z-pole	WW	H(ZH)	$t\bar{t}$
Beam Energy [GeV]	45.6	80	120	182.5
ε_x [nm·rad]	0.27	0.28	0.63	1.45
ε_y [pm·rad]	1	1	1.3	2.7
β_x^* [mm]	0.15	0.2	0.3	1
β_y^* [mm]	0.8	1	1	1.6
Number of bunches	16640	1300	328	33
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	230	32	8	1.5

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In order to achieve the high luminosities listed in Table 1, small beta star values are required, which implies strong focusing in the interaction region. The maximum beta function values in the horizontal and vertical planes for the ttbar lattice are $\beta_{x,\mathrm{max}} = 1625.10$ m and $\beta_{y,\mathrm{max}} = 6958.63$ m. For the Z lattice, $\beta_{x,\mathrm{max}} = 3653.87$ m and $\beta_{y,\mathrm{max}} = 7736.03$ m. Figure 1 presents the asymmetrical optics near the interaction region, showing that over many magnetic elements, the beta functions is large, often exceeding 1000 m in β_y.

Typically, the smaller the value of the beta function at the Interaction Point (IP), the larger the chromaticity, and the stronger the chromaticity correction required [3]. The strong sextupoles required for local chromaticity correction [4] pose two challenges. Firstly, the strong sextupoles make the machine particularly sensitive to misalignments and field errors by introducing non-linearities that are not easily accounted for by the inherently linear correction techniques outlined in the following sections. Secondly, any residual beta-beating presented in the corrected lattice can result in growth of the horizontal emittance. A degradation of the linear transfer matrix between paired sextupoles gives rise to residual nonlinear aberrations. For the reasons listed above, FCC-ee poses a unique challenge when it comes to emittance tuning.
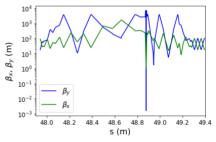

Figure 1: Beta functions near the IP of the 182.5 GeV lattice.

Initial Assessment of Errors

In order to assess the potential sensitivity of the FCC-ee lattices to magnet misalignments, small errors were introduced and the effect on vertical dispersion and orbit simulated. Due to the differing maximum beta values and the different phase advance in the arcs (resulting in different values of the beta function at the quadrupoles), the Z and ttbar lattices respond differently to misalignments of quadrupole magnets. This is demonstrated in Fig. 2, which shows the maximum vertical dispersion introduced by a 2 μm RMS vertical offset of the quadrupoles for 100 random seeds.

The two main sources of vertical emittance growth are coupling between the horizontal and vertical planes, and
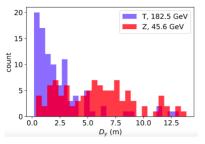
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Figure 2: Distribution of the maximum vertical dispersion from introducing quadrupoles vertical offsets of 2 μm.

residual vertical dispersion. The betatron coupling poses a large threat due to the small required emittance ratio (or coupling ratio), which is limited to $\varepsilon_y/\varepsilon_x = 0.1$ %. This constraint on the coupling ratio is not only to ensure the small vertical emittance growth, but also to reduce beam-beam blow up, which is thought to increase when the coupling ratio is greater than 0.1 % [5].

CORRECTION METHODS

Reducing the x-y coupling and residual vertical dispersion around the ring are key to minimizing the vertical emittance and reaching high luminosity. Corrector magnets and Beam Position Monitors (BPMs) are installed at every quadrupole magnet, tallying 1598 in the horizontal plane and 1596 in the vertical plane, around the 100 km ring. One skew quadrupole and one trim quadrupole are installed at every sextupole magnet for dispersion-free steering and beta-beat correction. The following subsections very briefly outline the main components of the correction techniques used.

Dispersion-Free Steering

DFS aims to correct the orbit and dispersion simultaneously. The method is based upon response matrices relating the orbit, y, and dispersion, D_y, to the corrector kick, θ,

$$\begin{pmatrix} (1-\alpha)\vec{y} \\ \alpha\vec{D}_y \end{pmatrix} = \begin{pmatrix} (1-\alpha)\mathbf{A} \\ \alpha\mathbf{B} \end{pmatrix}\vec{\theta}$$

where $\mathbf{A}$ and $\mathbf{B}$ are the response matrices of the orbit and the dispersion due to a corrector kick respectively, and α is a weighting factor, which can shift the emphasis to or from correcting the vertical orbit or the vertical dispersion [6].

Coupling Correction

Coupling introduced by sextupole misalignment and rolled quadrupoles, can be counteracted through skew quadrupoles installed at every sextupole magnet. The coupling can be quantified through two coupling Resonant Driving Terms (RDTs) f_{1001} and f_{1010}.

A response matrix, $\mathbf{M}$ of the RDTs can be written to measure the response of the RDTs to a skew quadrupole field, $\vec{\mathbf{J}}$. The system, which can be inverted via SVD, is [7]:

$$\begin{pmatrix} \vec{f}_{1001} \\ \vec{f}_{1010} \end{pmatrix}_{meas} = -\mathbf{M}\,\vec{\mathbf{J}}$$

where $\vec{f}_{1001}$ and $\vec{f}_{1010}$ are the complex coupling RDTs computed at the BPM locations.

Beta-beating Correction

Beta-beating can compromise the value of β^* and reduce the achievable luminosity. Beta-beating can also distort the optics model, affecting the efficiency of the correction schemes. Trim quadrupole fields installed at the sextupole magnets can be used to counteract beta-beating. A response-matrix method is used in two stages. Firstly, a response matrix representing the change in phase advance between the sextupoles where the trim quardupoles are installed is used [8]. It has been previously shown [9] that correction of the phase advance is as effective as correcting the actual beta function. In a second response matrix the beta functions are measured and the correction applied with a weighted SVD [10]. The weighted SVD approach places additional emphasis to the quadrupoles where large values of the beta function are expected. In this case, a weighting factor of 10 was applied to the quadrupoles where the β_y was above 3000 m and a weighting factor of 1 was applied to every other quadrupole [11].

Correction Strategy

A correction strategy was devised and implemented in order to minimize the final vertical emittance. The first step of this strategy is to set all of the sextupole strengths to zero. Throughout the correction algorithm, the sextupole strengths were increased by 10 % at a time.

All of the corrections were applied in MAD-X [12], calling macros written in python. The beam energy was set to 1 GeV, the RF turned off, and energy loss from synchrotron radiation was not included to begin with. This allows for faster computation and is considered valid for a fully tapered machine [2, 13]. At the final stage, synchrotron radiation is turned on for the emittance calculation, which is based upon the Chao formalism for equilibrium emittance [14].

The following correction strategy was implemented:

1. Sextupoles are turned off, and an orbit correction performed with MICADO in MAD-X [12].

2. Coupling correction is performed, followed by rematching of the tune, followed by beat-beating correction.

3. DFS (D_y correction) is performed followed by coupling correction (which is needed due to the change in the corrector strengths brought about by DFS).

4. Sextupoles are then set to 10% of their design strength.
   (a) orbit corrections
   (b) coupling correction
   (c) tune matching
   (d) beta-beating correction
   (e) coupling + dispersion correction
   (f) sextupole strengths are increased by 10% and Step 5 repeated until the design sextupole strength is reached.

5. A last correction of coupling and beat-beating correction is applied in the final step.

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Throughout the correction algorithm, the tunes, orbit and beta max are continuously monitored. If the maximum orbit deviation in x or y becomes larger than 1 mm, or if either tune moves ±0.1 from the nominal tune, then the sequence is redirected to orbit correction or tune rematching as appropriate. Similarly, if the beta max value (which was used as a proxy to indicate the level of beta-beating) becomes ±10 % of the design value, then beta-beating correction is immediately applied. These measures ensure that the orbit remains under control and minimizes the risk of running into a resonance.

Table 2: Misalignment Errors Introduced into the Lattice, via a Gaussian Distribution Truncated at 2.5 sigma (BPM Misalignments Positioned Relative to Quadrupoles)

	σ_x (μm)	σ_y (μm)	σ_θ (μrad)
quadrupoles	100	100	100
sextupoles	100	100	100
dipoles	100	100	100
BPM	20	20	150

(a)

(b)

(c)
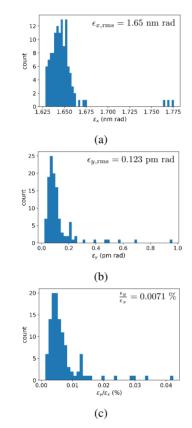
Figure 3: Distribution of (a) horizontal emittance, (b) vertical emittance, and (c) coupling ratio of the corrected ttbar lattices. The errors introduced are summarized in Table 2.
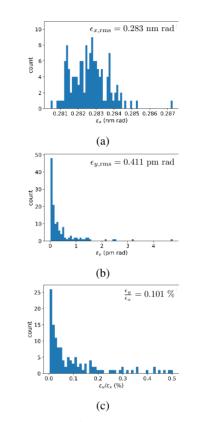

(a)

(b)

(c)

Figure 4: Distribution of (a) horizontal emittance, (b) vertical emittance, and (c) coupling ratio of the corrected Z lattices. The errors introduced are summarized in Table 2.

CORRECTED LATTICES

After applying the correction scheme, the final emittances can be greatly reduced. Figures 3 and 4 show the distributions of horizontal and vertical emittances for the ttbar and Z lattices respectively. One hundred of random seeds were used to introduce magnet misalignments and roll angles as defined in Table 2 . For the ttbar lattice, the mean value of the vertical emittances achieved is 0.123 pm·rad, and the mean coupling ratio is $\varepsilon_y/\varepsilon_x = 0.007$ %.

Future work includes, study of realistic BPM errors. This will include non-linear response of BPMs and overpopulation of non-Gaussian tails of misalignment distributions.

CONCLUSION

FCC-ee presents unique challenges when it comes to emittance tuning. The large ring size, the small vertical emittance and the low coupling ratio makes the FCC-ee design particularly susceptible to misalignment and field errors. For magnet misalignments of 100 μm in the transverse planes and a roll angle error of 100 μrad for all magnet types, and with relative BPM errors misalignment of 20 μm and and BPM roll angles of 150 μrad , the average final vertical emittance achieved for the ttbar lattice, after correction is 0.123 pm·rad and the average coupling ratio $\varepsilon_y/\varepsilon_x = 0.007$ %. For the Z-pole lattice, the final average final vertical emittance achieved is 0.411 pm·rad and the average coupling ratio $\varepsilon_y/\varepsilon_x = 0.101$ %.

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