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ORBIT-RESPONSE BASED OPTICS CORRECTIONS FOR FCC-ee *

E. Musa[†], I. Agapov[‡], The Deutsches Elektronen-Synchrotron, Hamburg, Germany
T. Charles[§], University of Liverpool, Liverpool, England

Abstract

In this study we demonstrate the application of closed orbit-based optics correction LOCO for FCC-ee lattices. The code was implemented using the Python accelerator toolbox (PyAT). The impact of alignment errors on FCC the lattice optics parameters were studied.

INTRODUCTION

The Future Circular Collider (FCC-ee) with a 90 km circumference [1] is one of the next planned machines in High Energy Physics that aims to push the limits of the luminosity and the size of the electrons beam that can be achieved.

The machine is planned to be run at several stages with different types of energies, as summarized in Table 1.

Table 1: FCCee Lattice Parameters

Lattice	Z	$t\bar{t}$
Energy (GeV)	45.6	182.5
Horizontal Tune Q_x	214.26	402.224
Vertical Tune Q_y	214.38	394.36
Hor. emittance (nm)	0.71	1.49
Vert. emittance (pm)	1.42	2.98
$\beta_\star$ at IP x/y (mm)	150/0.8	1000 / 1.6
Hor. beam size $\sigma_{\star x}$ at IP (µm)	10.3	38.6
Vert. beam size $\sigma_{\star y}$ at IP (nm)	34	68.9

The lattice components are subject to different types of errors: randomly distributed misalignments and field errors. These errors impact the beam closed orbit and the beam optics properties that can strongly reduce the performance of the collider. Several correction steps are required to reach design collider performance including the optics and orbit corrections.

The aims of orbit and optics corrections algorithms are to minimize the lattice errors by fixing the magnet's strength and finding the proper orbit correctors strength values, the primary aim is to achieve a well focused beam by minimizing the beta function at the IPs, increasing the dynamic aperture to increase the life time and achieving the desired momentum acceptance. this will lead to achieving high machine luminosity and hence increase the machine efficiency. Over the past few years, many algorithms for correcting the optics have been developed using MAD-X and Python [2]. These algorithms can correct the magnet strength errors and the realistic misalignments with girders. To achieve better optics and DA, further improvements to the correction algorithms are required. In this paper we are discussing the potential of the linear optics from closed orbit (LOCO) method using the code which we implemented in python accelerator toolbox (PyAT) for FCC-ee lattice optics measurement and correction and the resulting DA.

* EU Grant FCCIS
† elaf.musa@desy.de
‡ ilya.agapov@desy.de
§ tessa.charles@liverpool.ac.uk

ERROR CORRECTION FOR THE $t\bar{t}$ LATTICE

To investigate the possibility of using LOCO for FCC-ee lattices we used the Python accelerator toolbox (PyAT) [3] to implement the code and utilised it to produce preliminary results for the FCCee-t-v22 optics lattice using arc quadrupole families and a number of correctors. We converted the FCCee-t-v22 sequence file [4] to PyAT using the the xsequense tool [5], then we introduced number of correctors and BPMs to the lattice using PyAT. The FCCee-t-v22 lattice optics is shown in Fig. 1. The nominal horizontal and vertical tune values of this lattice are Q_x= 402.224 and Q_y= 394.36.

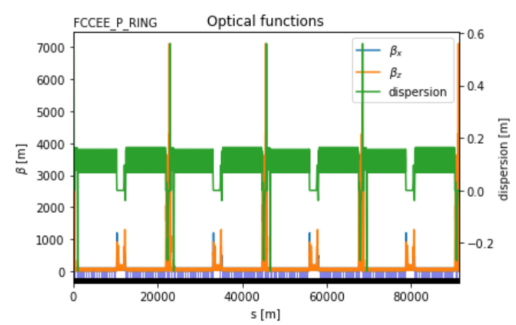

Figure 1: FCCee-t-v22 lattice optics before errors.

Applying horizontal and vertical random alignment errors of 10 µm and 20 µm truncated at at 2.5 σ and random relative field errors of value 2.e-04 to the lattice arc quadrupoles resulted in a notable reduction in the calculated dynamic aperture (DA) shown in Figs. 2 and 3 at β_x = 1.000072 m and β_y = 0.001597 m.

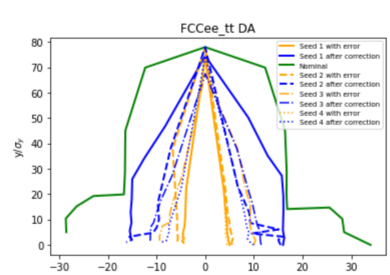

Figure 2: Arc quads subjected to 10 µm alignment errors.

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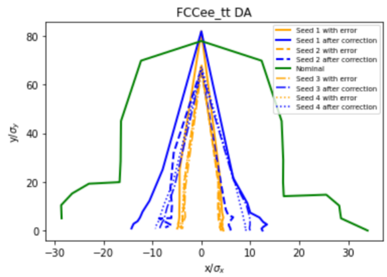

Figure 3: Arc quads subjected to 20 µm alignment errors.

The impact of these errors on the lattice parameters is illustrated in Tables 2 and 3.

SVD Orbit Correction

Optics with m-BPMS and n-correctors produces an m x n dimensional response matrix:

$$C_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin(\pi\nu)}\cos(\pi\nu - \phi(s) + \phi(s_0)) + \frac{\eta_i \eta_j}{\alpha_c L_o}. \quad (1)$$

Orbit correction aims to invert the response matrix to find the proper orbit correctors kicks θ that satisfy the relation $\Delta x + C\Delta\theta = 0$. By using the Singular value decomposition (SVD) [6], it was possible to determine the specific horizontal and vertical correctors strengths required to correct the orbit errors. Following the orbit SVD correction process, a reduction in the rms orbit was achieved as shown in Figs. 4 and 5 , The tune was recorded and corrected before and after applying the orbit correction.

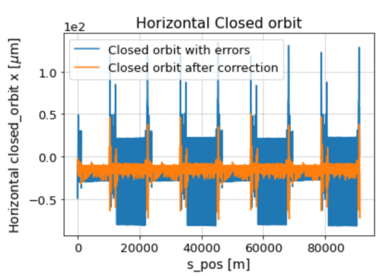

Figure 4: Horizontal closed orbit with 10 µm alignment errors before and after orbit correction.

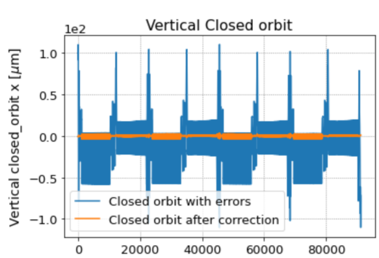

Figure 5: Vertical closed orbit with 10 µm alignment errors before and after orbit correction.

Table 2: Arc Quads Subjected to 10 µm Alignment Errors

Correction	None	Orbit	LOCO
rms orbit x (µm).	31.97	15.61	15.63
rms orbit y (µm).	34.73	2.05	3.5
rms $\Delta\beta_x/\beta_x$.	16.66	3.49	1.18
ms $\Delta\beta_y/\beta_y$.	17.04	11.42	1.39

Table 3: Arc Quads Subjected to 20 µm Alignment Errors

Correction	None	Orbit	LOCO
rms orbit x (µm).	57.64	26.83	26.84
rms orbit y (µm).	106.57	6.27	8.38
rms $\Delta\beta_x/\beta_x$.	63.45	4.95	1.56
ms $\Delta\beta_y/\beta_y$.	31.26	18.5	2.54

LOCO Optics Corrections

One of the well-known methods of optics correction is the linear optics from closed orbit (LOCO) [7] in which the measured orbit response matrix ORM is fitted to the lattice model by varying parameters in the used model to minimize the deviation between the model and measured orbit response matrices Eq. (2), in order to determine the appropriate quadrupole correction strengths in Eq. (3). This method however has not been traditionally applied to very large machines such as colliders.

$$\chi^2 = \sum_{ij}(\Delta C^{ij} - \sum_k \frac{\partial C^{ij}}{\partial g_k}\Delta g_k)^2 \quad (2)$$

$$\Delta g_k = (\frac{\partial C^{ij^T}}{\partial g_k}\frac{\partial C^{ij}}{\partial g_k})^{-1}(\frac{\partial C^{ij^T}}{\partial g_k}\Delta C^{ij}) \quad (3)$$

After performing the orbit and tune correction, the implemented LOCO code was utilized to correct the beta beating using 12 orbit correctors that have the same phase in the lattice, to generate the quadruples responses(Jacobian). Three LOCO iterations were performed, and the tune was recorded and corrected after each iteration. Figures 6 and 7 illustrates the reduction in beta beating achieved after the LOCO corrections.

After executing LOCO, the entire correction chain was completed. The orbit and LOCO corrections chain resulted in the increase of the DA as shown in Figs. 2 and 3 which present the resulting DA after corrections for different seeds. The figures displays a comparison of the dynamic aperture measurement for three different scenarios: the nominal case (green line), a case where errors were introduced (orange line), and a case where a correction chain was applied and complete (blue line). Figure 2 shows the results when a 10 micrometer alignment error was introduced, while Fig. 3 shows the results for a 20 micrometer alignment error.

Tables 2 and 3 illustrate the resulted reduction of the optics parameters after the corrections.

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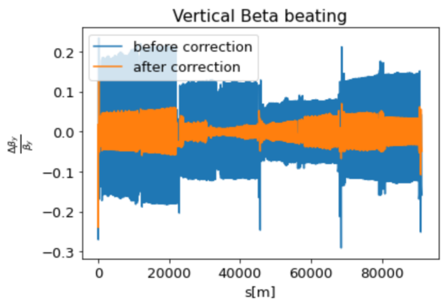

Figure 6: Arc quads subjected to 10 µm alignment errors.

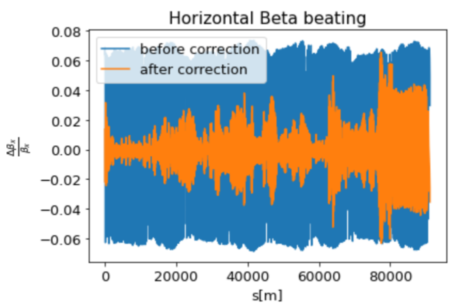

Figure 7: Arc quads subjected to 20 µm alignment errors.

Sextupoles Nonlinear Effect on the ORMs

The sextupole magnets in the lattice have allowed a significant impact on the lattice optics. The changes of correctors kick used in generating the ORMs, changes the horizontal and vertical tune values Q_x and Q_y as a result due to the sextupoles effect. The non-linearity between the kicks values and the beam position monitor (BPM) readings of the closed orbit is illustrated in Fig. 8. An acceptable range for the horizontal correctors kick within the FCCee-t-v22 lattice is between -10.e-5 and 3.75e-5 radiance.

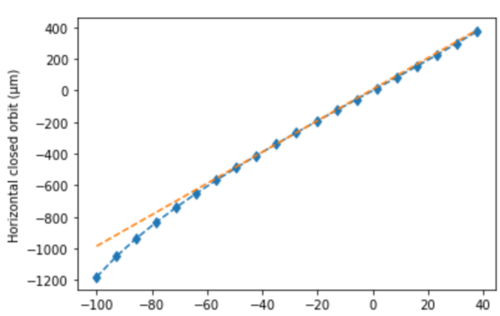

Figure 8: Resulted orbit from corrector horizontal kick.

Looking at the frequency map of the $t\bar{t}$ lattice Fig. 9 and the z lattice Fig. 10 shows that the resonance structure is compatible with the resulted DA after the correction chain. This provides evidence that our correction was sufficiently effective.

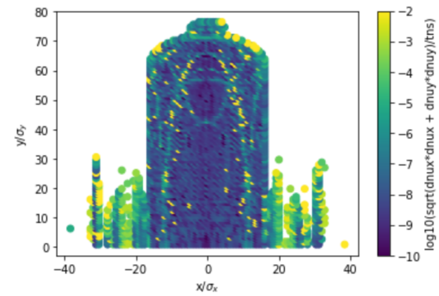

Figure 9: Frequency map for an ideal lattice of the FCCee-t-v22 lattice.

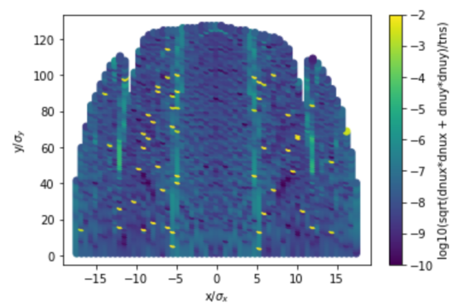

Figure 10: Frequency map for an ideal lattice of the FCCee-z-v22 lattice.

CONCLUSION AND OUTLOOK

In this study, we investigated the impact of the FCCee-t-v22 optics arc quadruples alignment errors on the beam optics. We applied closed orbit and optics corrections using the Singular value decomposition (SVD) method and linear optics from closed orbit (LOCO) method that we implemented using PyAT respectively, as a result of the correction process, we achieved a reduction in the rms orbit, a decrease in beta beating, and an increase in the dynamic aperture (DA). The frequency maps showed that the lattice resonance structure is consistent with the achieved dynamic aperture following the correction. The study results provides evidence that the implemented correction was effective. Using the developed methods, Fcc-ee performance (e.g. achievable luminosity) and the required alignment and field error tolerances will be defined in close collaboration with CERN.

Novel approaches for optics correction such as Bayesian-based correction will be investigated in the next. Finally, experimental validation of the developed methods at PETRA III [8] will be performed.

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