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PROGRESS OF THE FCC-ee OPTICS TUNING WORKING GROUP

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Abstract

FCC-ee is a proposed lepton collider with a circumference close to 100 km to produce an unprecedented amount of luminosity. The FCC-ee optics tuning working group is addressing one of the most critical aspects of the FCC-ee, that is the recovery of the optics design performance in presence of realistic imperfections. Various teams from laboratories all around the world have got together to assess field quality tolerances and review and share experience gained at synchrotron light sources and lepton colliders such as SuperKEKB. This paper reports the latest results on optics measurements and tuning simulations for various techniques, the development of simulation tools, and possible layout design changes to optimize the tuning performance.

INTRODUCTION

The FCC-ee [1] baseline optics design [2], named here V22 [3], implements local vertical chromaticity correction in the Iinteraction Region (IR) along with virtual crab waist using the chromaticity sextupoles. Arc sextupoles are used to correct chromaticity at the same time as optimizing the Dynamic Aperture (DA). A new optics design proposal is under development [4], named here HFD51, featuring both horizontal and vertical chromaticity correction in the IR together with dedicated sextupoles to generate the crab waist at the IP. Other optics design options are being investigated as the use of combined function magnets in the arc short straight sections [5].

Successful optics tuning in the FCC-ee is highly challenging and critical to reach design performance. Good optics quality is needed to achieve design emittances, sufficient DA, Momentum Acceptance (MA), lifetime, polarization at the W and Z energies [6] and accurate Interaction Point (IP) parameters to ensure stable collisions and achieve design luminosity.

Preliminary considerations of sextupole alignment tolerances for the V22 lattice, comparing to SuperKEKB [7, 8] and CEPC [9], suggest that FCC-ee arc and IR sextupoles should implement Beam-Based Alignment (BBA) techniques to reach rms offsets in the order of 10 µm and 1 µm with respect to the beam, respectively [10]. From beam-beam simulations an acceptable lifetime is achieved for arc sextupoles vertical misalignments up to 10 µm, without applying corrections [11]. From first polarization simulations it is observed that vertical orbits with rms deviations up to 150 µm from the flat machine achieve above 80% polarization [12].

Achieving good optics quality and maintaining it will require sophisticated optics measurement and BBA techniques that can be performed with design beam parameters. Current colliders as SuperKEKB and LHC can only perform optics measurements at low intensity which results in unforeseen perturbations at high intensity from collective effects, temperature shifts [8] or the need to introduce Landau damping [13].

TUNING SIMULATIONS

Optics correction algorithms have been developed over the last years using MAD-X and Python [14] including magnet strength errors and realistic misalignments with girders (resulting in about 170 µm and 140 µm rms transverse misalignments for arc quadrupoles and arc sextupoles, respectively) [15]. After applying a series of optics corrections iteratively rms orbits of 50 µm are typically achieved in both transverse planes reaching design emittances and with rms β-beating below 6% but with insufficient DA [16, 17]. Adding chromaticity correction significantly deteriorated the tuning performance. To mitigate this, it is assumed that BBA techniques are implemented for both arc and IR sextupoles, reducing their rms misalignments to 10 µm. Design emittances are reached but with larger optics aberrations. Further iterations and improved correction algorithms will be required to reach good optics quality and DA.

An alternative strategy has been implemented for the definition of tolerance and orbit correctors specifications for the FCC-ee booster [18]. The present target specifications for arc quadrupoles, sextupole and BPMs alignment tolerances are 150 µm. Simulations demonstrate good orbit control in agreement with analytical expectations. Further studies are needed to demonstrate good optics quality and include the impact of the full emittance tuning and of the energy ramp during the booster cycle.

pyAT Commissioning Simulations

A new set of functions has been developed for commissioning simulations based on pyAT [19–21]. This software

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has been applied to the FCC-ee V22 Z lattice with random alignment errors of 10 µm only in arc dipoles, quadrupole and sextupoles. Corrections include: first turns beam threading (trajectory correction with all sextupoles at nominal strength), orbit, tune, chromaticity, optics and coupling. This list has been iterated 3 times (excluding beam threading). The optics corrections have been performed based on a reduced orbit response matrix measurements using orbit steerers at 14 arc QF4 magnets. The orbit response matrix derivative needed for the determination of an error model to be corrected have been computed based on analytic formulas described in [22, 23] including corrections for thick quadrupoles and thick steerers. BPMs, steerers, and quadrupole correctors are assumed available at every quadrupole in the lattice. Optics parameters are successfully corrected as shown in Table 1. However, DA is clearly insufficient, see Fig. 1, even though the considered scenario has no IR errors and no magnet strength errors. Again, further developments are being pursued.

In particular, orbit and optics correction performance is being evaluated for other error scenarios as 10 µm alignment precision is challenging as it is beyond what is routinely achieved at present, e.g. 50 µm and 30 µm were achieved in ESRF-EBS [24]. LOCO-based optics correction performance is discussed in more details in [25].

Table 1: Average optics parameters before and after correction using pyAT with 10 µm random errors in dipoles, quadrupoles and sextupoles for the V22 Z lattice. Horizontal emittance without errors is $\epsilon_{h,0}$ = 688 pm. The emittances before correction could not be computed.

	Unit	Before corr.		After corr.	
		H	V	H	V
$\Delta\beta/\beta_{rms}$	%	3.6	59.5	0.8	4.3
$\Delta\eta_{rms}$	mm	120	82.6	26.0	9.4
$\Delta\epsilon_{h,v}$	pm	-	-	3.1	0.17
Orbit rms	µm	631	289	29.8	12.0

Status of IP Tuning

Optics errors in the IP have a direct impact on the machine performance but also generally on stability due to the large β functions and gradients in the final focus system. Therefore, beyond global corrections, dedicated IP tuning strategies will be needed to commission the FCC-ee. Several methods are under consideration. A segment-by-segment style correction [26] that systematically splits the machine into separate sections, uses measured conditions at the entrance of each section and matches key optics properties using the magnets within the section. This method is effective at recovering the targeted optics but is found to undo some of the global corrections [27]. Tuning knobs that aim to change only one parameter whilst keeping other parameters, including global functions, might offer an alternative, however, the matching of such knobs has so far been found to be very challenging and efforts are ongoing [27].

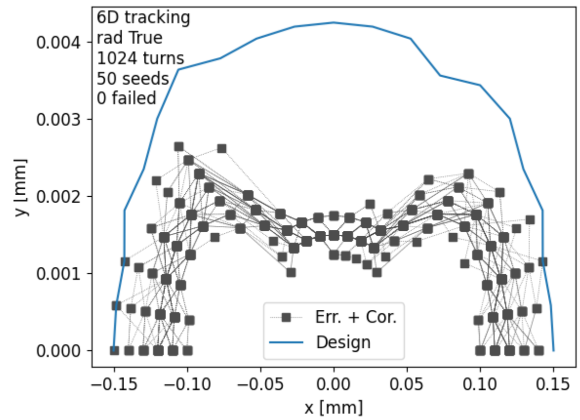

Figure 1: Dynamic aperture for the V22 Z lattice and for 50 corrected seeds of error obtained via 6D tracking for 1024 turns in pyAT.

FIELD QUALITY TOLERANCES

First explorations of magnet field quality tolerances are performed by computing the on-momentum DA without synchrotron radiation [28]. Figure 2 shows the naming convention for the IR quadrupoles in the lattice V22 and Table 2 gives preliminary field quality tolerances to avoid loss of DA. Latest estimates of the field quality in arc dipoles and quadrupoles already meet these tolerances [29]. The systematic quadrupolar component of the arc dipoles (b_2) can be absorbed by optics adjustment in the matching sections [30]. The only pending issue in the arc is the shift of the arc quadrupole magnetic axes by up to 0.1 mm when trimming the strength of the two apertures independently and requires mitigation studies. Some QY and QC (including the final doublet) require b_4 and b_6 to be below 0.1 units. This represents a significant challenge for design, production and magnetic measurements [31]. Final magnetic tolerances will be computed with particle simulations including synchrotron radiation and possibly considering the use of corrector magnets.

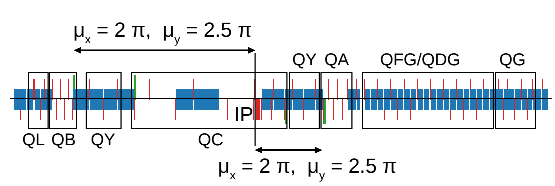

Figure 2: Terminology of quadrupoles in the FCC-ee experimental IRs. Dipoles, quadrupoles and sextupoles are shown, respectively, in blue, red and green [32].

OPTICS MEASUREMENTS & BBA

One of the most crucial devices for beam based measurements are Beam Position Monitors (BPMs), which are presently presumed being installed next to every quadrupole. BBA [33], presently aims at steering the beam through the magnetic center of quadrupoles and sextupoles using movers

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Table 2: Required Field Quality Tolerances in 10^{-4} units at a Reference Radius of 10 mm based on On-Momentum DA Calculations for the V22 Lattices.

Error & maget type	Z	tt
b_3 in arc dipoles	2	2
b_3 in IR dipoles	0.1	0.5
b_3 in arc quadrupoles	10	8
b_3 in QY	0.1	8
b_3 in QC, QT, QA, QB, QG, QH, QL, QR, QU, QI	1	8
a_3 in QC1, QC2	1	5
b_4 in arc quadrupoles	10	10
b_4 in QC, QY	0.01-0.1	0.1
b_4 in QT, QA, QB, QG, QH, QL, QR, QU, QI	1	1
b_6 in arc quadrupoles	5	5
b_6 in IR quadrupoles	0.01	1

or orbit correctors to minimize feed-down effects. BBA needs to be performed regularly to monitor and correct possible drifts. Determining possible offsets and other optics errors demands accurate and suitable optics measurement techniques [34], where, in principle, three different approaches are currently being considered, namely K-modulation, measurements based on Orbit Response Matrix (ORM) using the average orbit and Turn-by-Turn (TbT) measurements [35]. Preliminary studies suggest that the required BPM resolution is in the order of 1 and 10 µm, respectively, for ORM and TbT measurements. Coupling measurements require rms BPM tilt errors of 300 µrad [36].

NEW OPTICS DESIGN

The V22 and HFD51 lattice optics at Z and $t\bar{t}$ energies have been compared in terms of sensitivity to alignment errors in the arcs. For this purpose, no errors are applied in the IRs and no corrections are applied. For each of the 4 lattice optics, figures as Fig. 3 are produced and compared. Those figures represent the evolution of beta beating, dispersion deviation, orbit and emittances as a function of the lattice errors set. Table 3 was built by visual comparison of the figures for each lattice and shows that the HFD51 lattice is for most parameters more tolerant or equivalent to V22. Note that the tunes of the lattices are different, their fractional parts (Q_x, Q_y) follow: V22 (0.26, 0.38), HFD51@Z (0.22, 0.32) and HFD51@t (0.24, 0.31). Nevertheless both lattices, V22 and HFD51, require sextupoles alignments in the order of 10 µm either at Z or at $t\bar{t}$ energies. The tighter tolerances for quadrupoles significantly relax once orbit correction is applied, here these serve for comparing the lattices.

SUMMARY AND OUTLOOK

The FCC-ee optics tuning studies have started with tentative transverse alignment specifications of about 150 µm with respect to the ideal design for quadrupoles and sextupoles. First tuning simulations show that linear global optics and design emittances can be reached, however IP parameters and DA do not meet desired performance. A new layer of BBA techniques is being considered in order to reach the 10 µm alignment level in the arcs with respect to the beam. Various teams with different tools are investigating new configurations with promising results but still requiring further developments. First estimates of magnetic field quality in the IRs also reveal to be challenging, requiring further investigations. New optics designs could, in general, help relaxing the tight tolerances.

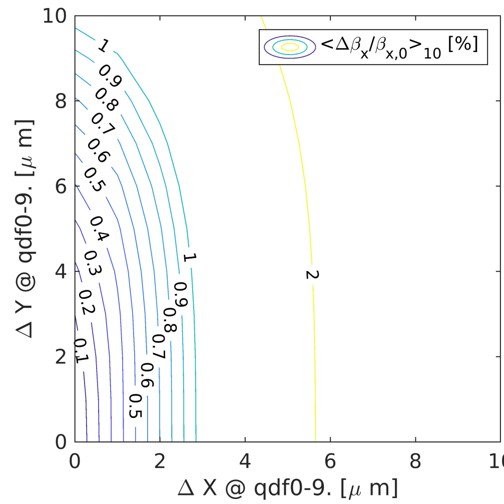

Figure 3: Horizontal β-beating versus horizontal and vertical alignment errors averaged at all BPMs over 10 seeds without corrections for the V22 lattice.

Table 3: Approximate alignment tolerances in µm for arc sextupoles and quadrupoles for β-beating of 1%, horizontal dispersion error of 1 mm, vertical dispersion error of 0.05 mm and vertical emittance 1‰ of the horizontal. The minimum among vertical and horizontal alignment is reported.

	$\Delta\beta/\beta$		$\Delta\eta$		$\Delta\epsilon$
	H	V	H	V	V
criteria	1 %	1 %	1 mm	0.05 mm	1‰ ϵ_h
arc sextupoles tolerances [µm]					
V22@Z	19	10	4	30	40
HFD51@Z	59	45	8	>100	»100
V22@t	10	8	8	85	15
HFD51@t	19	10	10	»100	32
arc quadrupoles tolerances [µm]					
V22@Z	2.8	0.9	0.05	1	0.2
HFD51@Z	3.2	0.45	0.8	4.5	0.2
V22@t	1.8	0.5	0.1	1.8	0.1
HFD51@t	2.1	0.5	1.2	8.8	0.1

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