TOLERANCE STUDIES AND DISPERSION FREE STEERING FOR EXTREME LOW EMITTANCE IN THE FCC-ee PROJECT

S. Aumon *, B. Holzer, CERN, Geneva, Switzerland; Katsunobu Oide, KEK, Japan
A. Doblhammer, Technische Universität Wien, Austria; B. Haerer, KIT, Karlsruhe, Germany

Abstract

The FCC-ee study is investigating the design of a 100 km e+/e- circular collider for precision measurements 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 such performances, an extreme focusing of the beam is required in the interaction regions with a low vertical beta function of 2 mm at the IP. Moreover, the FCC-ee physics program requires very low emittances never achieved in a collider with 2 nm for ϵ_x and 2 pm for ϵ_y, reducing the coupling ratio to 1/1000. With such requirements, any field errors and sources of coupling will introduce spurious vertical dispersion which degrades emittances, limiting the luminosity of the machine. This paper describes the tolerance study and the impact of errors will affect the vertical emittance. In order to preserve the FCC-ee performances, in particular ϵ_y, a challenging correction scheme is proposed to keep the coupling and the vertical emittance as low as possible.

INTRODUCTION

Electron-positron circular colliders profit from small vertical beam size due to vertical emittances close to the quantum excitation. The FCC-ee machine is foreseen to run at 4 different energies in order to perform precision measurements of the Z and W resonance and the Higgs and top. In order to produce a high luminosity, an extreme focusing of the beam is required in the interaction regions with a low vertical beta function of 2 mm at the IP. The baseline foresees very low emittance never achieved in a collider with 2 nm for ϵ_x and 2 pm for ϵ_y, bringing down the coupling ratio to 1/1000. The main parameters are presented in Tab. 1. With such performances, the chromaticities reach several hundred units and the high beta functions in the interaction regions cause the machine to be very sensitive to lattice errors, resulting in large distorsion of the vertical dispersion. As a consequence, the vertical emittance can be enlarged, since

$$\epsilon_y = \left(\frac{dp}{p}\right)^2 (\gamma D^2 + 2\alpha D D' + \beta D'^2) \qquad (1)$$

where D is the vertical dispersion, D' the dispersion derivative with s, $\frac{dp}{p}$ the momentum spread, γ, β, α are the lattice parameters. This article present the status of the tolerance of the FCC-ee lattice to errors such as magnet misalignements, rolled angles, which are the main cause of vertical dispersion and emittance blowup. The main challenge is to establish an optics correction methodology suitable for large machines with such challenging beam parameters baseline such as FCC-ee.

PRELIMINARY STUDIES ON A 12-FOLD LATTICE

The FCC-ee machine is foreseen to run at 4 different energies and in term of tolerance, the biggest challenges come from the 120 and 175 GeV cases. Several lattice scenarios with different interaction regions and sextupole layouts are under study (See [1]), however to get a first overview of the tolerance problem, a 12-folds lattice has been used: the RF sections and the losses in energy by synchrotron radiation are smoothly distributed around the ring. For FCC-ee, the so-called sawtooth effect can be particulary important: with 8 GeV of energy loss per turn, the off-momentum particles are following the dispersive orbit until they reach the next RF section. This effect can cause orbit distorsion of about several mm, which can be very problematic when the beam goes through strong sextupoles. The parameters at 120 and 175 GeV are given in Tab. 1 and the optics for this layout in Fig. 1. With targeted emittances of the order of nm and pm, FCC-ee is a collider with foreseen performances of light sources (ESRF, SLS).

Table 1: Baseline Beam Parameters in FCC-ee

Beam Energy (GeV)	**120**	**175**
Beam current (mA)	30	6.6
Bunch/beam	780	81
Bunch population (10^{11})	0.8	1.7
Horizontal ϵ (nm)	0.61	1.3
Vertical ϵ (nm)	0.0012	0.0025
Momentum compaction (10^{-5})	0.7	0.7
Hor. β^* at the IP (mm)	1000	1000
Vert. β^* at the IP (mm)	2	2
Energy loss/turn (GeV)	1.67	7.55
Total RF Voltage (GV)	3	10

Transverse displacements and roll angles in the quadrupoles are introduced and the orbits are corrected with MICADO in MADX [2]. The chromaticities are brought down to zero (natural vertical chromaticity close to -1000 units), and finally an attempt of simultaneous coupling/vertical dispersion correction is applied. The resulting vertical emittance is presented in Fig. 2. The required vertical emittance is already reached at 50 μrad/50 μm due to a large vertical dispersion. This result shows that FCC-ee is very sensitive to alignement errors and the tolerance is closer to a linear collider than a ring such as LHC. The standard alignement precision of 150 μm used

* sandra.aumon@cern.ch

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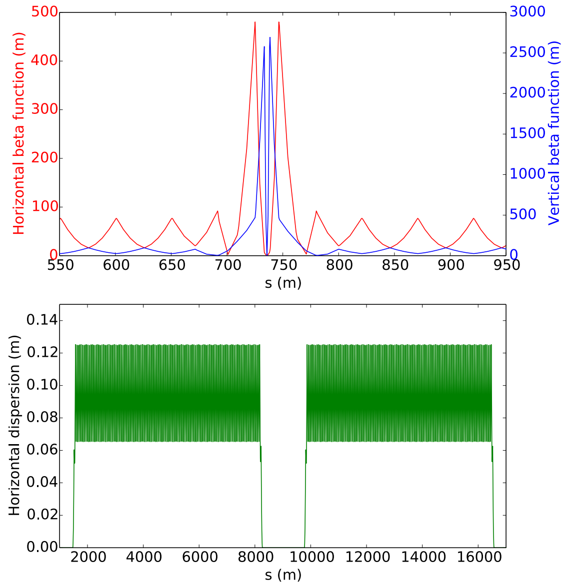

Figure 1: Optics at the IP for the 12 folds lattice at 120GeV.

for the accelerator chain at CERN might not be sufficient, and therefore lattice correction method and alignement techniques inspired from light sources have to be applied. So far, no BPM errors were taken into account, and a different method has been used to prioritize the vertical dispersion correction and minimize the vertical emittance.

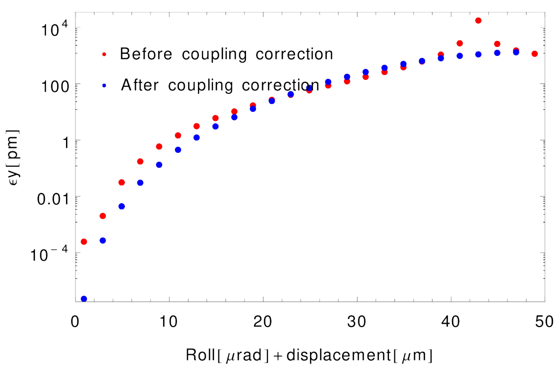

Figure 2: Emittances as a function of roll and displacement errors into the lattice.

BPM ERROR TOLERANCE

In order to be consistent with the layout of the FCC-hh project, the racetrack layout ([1], [3]) presented in Fig. 3 with a significant number of reduced RF sections, was adopted. With 2 RF sections, the magnets needs a tapering at 175 GeV [5]. The BPM tolerance was evaluated at 175 GeV for this type of lattice by introducing BPM reading errors, the "wrong" orbits are then corrected with MICADO, creating then vertical dispersion, and the vertical emittance is then evaluated without sextupoles. The results are showns in Fig. 4 and Fig. 5.

Relying only on orbit corrections to reduce the vertical dispersion increases of the vertical emittance when BPM errors are taken into account. LEP and light sources used to

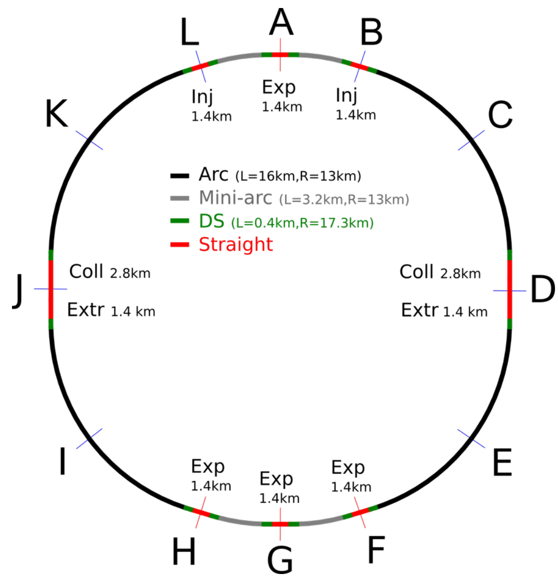

Figure 3: FCC-ee racetrack layout.

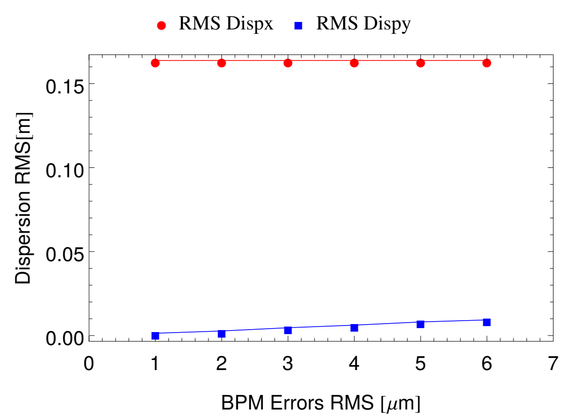

Figure 4: Resulting RMS vertical dispersion with BPM error readings.

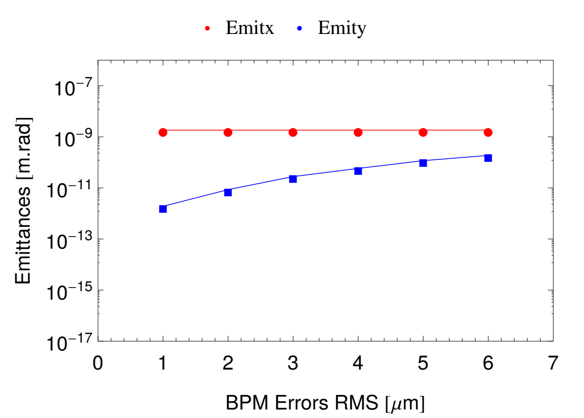

Figure 5: Resulting emittances with BPM error readings.

minimize ϵ_y by rather correcting the vertical dispersion than the orbit via a method called Dispersion Free Steering. This algorithm allows to overcome the problem of BPM errors and put more weight on the vertical dispersion correction.

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DISPERSION FREE STEERING

Dispersion Free Steering (DFS) is an efficient method which was used in LEP to minimize the vertical emittance [4]. Response matrices for orbits and dispersions are built with correctors with and without sextupoles, and the following system has to then to be solved [4].

$$\begin{pmatrix} (1-\alpha)\vec{y} \\ \alpha\vec{D_y} \end{pmatrix} + \begin{pmatrix} (1-\alpha)\mathbf{A} \\ \alpha\mathbf{B} \end{pmatrix} \vec{\theta} = 0 \qquad (2)$$

where $\mathbf{A}, \mathbf{B}$ are the response matrices of the orbit and the dispersion due to a corrector kick, θ is the corrector strength, α is a weight. When α is 0, the correction is only on the orbit. With $\alpha = 1$, the correction is purely dispersive. A singular value decomposition (SVD) is then applied

$$T = UWV^t \qquad (3)$$

where W is a diagonal matrix, composed by the singular values w_i, on which a cut-off has to be applied to optimize the efficiency of the correction. More singular values means more local correction but more noise, while less singular values will put the emphasis onto more global correction: a compromise has to be found between noise and local correction, in particular in a machine with large distortion of the orbit and of the dispersion which would then necessitate local correction at the IPs. As a first approach, a pure dispersion correction was used on a 2μm vertical displacement in the quadrupoles of the lattice, with random gaussian distribution cut at 3 sigma. The response matrice for FCC-ee is very large (2006x2006), and a scan of the number of singular values taken into account was performed in order to identify whether a minimum in emittance can be found Fig. 6. From this misaligned lattice, 20 iterations of DFS are applied, and finally, a sextupole scheme of chromaticity correction is applied [1], and the emittance is computed at the end by MADX. The machine is as well tapered [5] in order to counteract the sawtooth effect of about 1mm at 175 GeV.

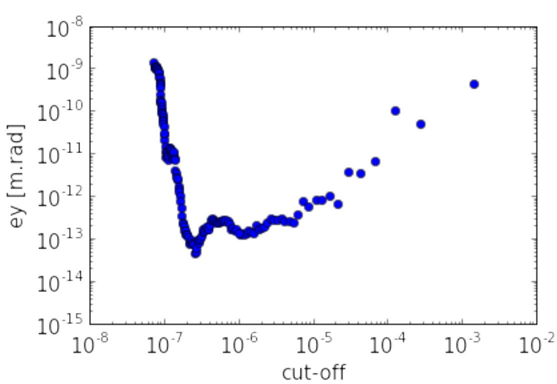

Figure 6: Resulting vertical emittance after dispersion free steering and chromaticity correction as a function of the number of singular values taken into account into the system.

2μm vertical displacement in the quadrupoles results in 25 m vertical dispersion which goes down to 50mm in the arcs after 20 iterations of DFS. After chromaticity correction, the sextupoles squeeze down D_y to 0.5mm, resulting in a vertical emittance of $\epsilon_y = 4 \times 10^{-14}$m. Likely, this is due to a feed-down effect of the vertical dispersion due to the vertical displacement in the sextupoles. From this result, the misalignements were then increased, as shown in Fig. 7. According to the seed, 5 or 6 μm are enough to reach the foreseen vertical emittance. This tight tolerance comes from the high vertical dispersion at the IPs, and any errors in the quadrupoles at the final focus are amplified.

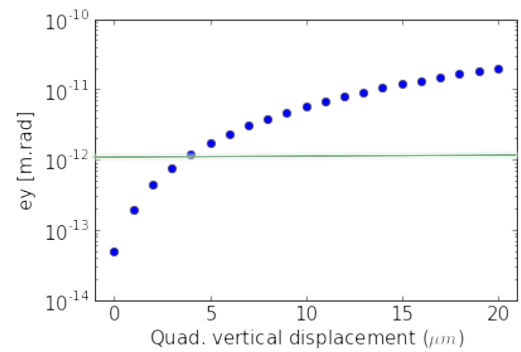

Figure 7: Resulting vertical emittance after dispersion free steering and chromaticity correction as a function of transverse displacement into the quadrupoles at 175GeV.

In order to reduce the vertical emittance, the vertical dispersion at the IPs should be locally corrected and treated separately from the arcs. Four correctors around the IPs are used to created a vertical dispersion dump in order to minimize D_y where the β_y is the largest. With local correction of the vertical dispersion around the IPs, 2% emittance ratio ϵ_y/ϵ_x in a lattice with alignment errors can be reduced to 0.5%. Such local correction will be integrated in the future studies.

SUMMARY-CONCLUSION

Lattice errors have a very large impact on the vertical dispersion and emittance due the high beta functions in the interaction regions. The challenges come from the the very low emittances of the order of pm in vertical plane with a very strong focus at the IPs resulting in a β_y^* of 2mm, which makes into a machine very sensitive to alignement errors. The other challenge is to establish a correction algorithm inspired from light sources and adapt them to 100km machine. It was shown that to overcome tolerance limitations due to BPM errors, a DFS method was implemented in FCC-ee. Further optimizations are on going to improve the tolerance of the machine with respect to errors. In future studies, the IPs will be corrected separately from the arcs, since the vertical emittance is driven by the vertical dispersion at the IPs. Therefore a local correction is needed.

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