FCC-ee OPTICS TUNING – TOWARDS THE REFERENCE DESIGN

J. Keintzel[1]*, R. Tomás[1], J. Bauche[1], C. Carli[1], R. De Maria[1], C.J. Eriksson[1], V. Gawas[1], C. Goffing[1], S.S. Jagabathuni[1], I. Garcia-Aguirrebeitia Sanchez[1], A. Kastrinellis[1], G. Katsanevakis[1], T. Lefevre[1], M. Liebsch[1], E.H. Maclean[1], H. Mainaud[1], Y. Papaphilippou[1], P. Raimondi[1], G. Roy[1], K. Skoufaris[1], L. Todorovic[1], F. Valchkova-Georgieva[1], W. Van Goethem[1], A. Vorozhtsov[1], F. Zimmermann[1], T.K. Charles[2], K. Andre[3], S. Liuzzo[3], S. White[3], E. Ahmadi[4], I. Agapov[5], E. Musa[5], A. Chance[6], B. Dalena[6], Q. Bruant[6], X. Huang[7], C. García-Jaimes[8], T. Pieloni[8], T. Prebibaj[8], L. van Riesen-Haupt[8], Y. Wu[8], H. Sugimoto[9], Y. Ohnishi[9], K. Oide[9], A. Hussain[10], M. Boland[11], P. Hunchak[11], M. Le Garrec[12],
[1]CERN, Geneva, Switzerland, [2]ANSTO - Australian Synchrotron, Australia,
[3]ESRF, Grenoble, France, [4]IPM, Tehran, Iran, [5]DESY, Hamburg, Germany, [6]CEA, Paris, France,
[7]SLAC, Stanford, USA, [8]EPFL, Lausanne, Switzerland, [9]KEK, Tsukuba, Japan,
[10]PAEC, Pakistan, [11]USASK, Canada, [12]LAPP, France.

Abstract

The Future electron positron Circular Collider, FCC-ee, is a proposed next-generation facility designed to deliver very high luminosities across a broad beam-energy range, from the Z pole at 45.6 GeV up to 182.5 GeV. Achieving the target performance in the presence of realistic lattice imperfections represents a significant challenge. To address this, a comprehensive commissioning strategy is being developed, featuring dedicated optics configurations, robust beam-based alignment procedures, and advanced optics-correction techniques supported by refined beam-based measurements. In parallel, specifications for the main magnet families, corrector circuits, and required instrumentation are being explored to ensure compatibility with the expected tuning procedures. This contribution summarizes the current status of these developments and outlines the key steps and milestones envisioned on the path toward the reference design.

INTRODUCTION

Achieving the ambitious luminosity targets of the Future electron-positron Circular Collider, FCC-ee [1–3], requires precise control of the machine optics in the presence of realistic imperfections. Correcting linear optics distortions alone is not sufficient to fully restore dynamic aperture (DA) and momentum acceptance (MA), see e.g. [4–7]. In this context a staged tuning strategy is foreseen, starting from Beam-Based Alignment (BBA), orbit and global linear optics correction, followed by non-linear optimisation and dedicated local knobs to restore Interaction Point (IP) parameters. As part of the tuning strategy, novel optics, either with switched-off final focus or larger β^* have been developed, to ease start of commissioning.

Over the past years, optics design and tuning studies have been pursued for two versions of the FCC-ee, namely for the Global Hybrid Collider (GHC) [8] and the Local Chromaticity Correction (LCC) [9] lattices. At the end of 2025 a comprehensive comparison exercise has been carried out, including simulation studies which fall in the mandate of the FCC-ee optics tuning. These studies provide important insight into correction strategies and tolerances in the presence of realistic errors. Some findings of this are also given [10, 11] , with the full report being available in [12].

The FCC-ee project is currently in the reference design phase until roughly end of 2027. A central objective of this phase is to establish a coherent machine design. This includes, incorporating magnet and alignment errors, linear and non-linear corrections, optics measurement strategies and corrector circuit specifications. Furthermore, robust performance under realistic conditions should be demonstrated by comprehensive simulation studies and experiences from existing machines, such as SuperKEKB.

MACHINE IMPERFECTIONS

The definition of magnetic field tolerances relies on a strong interplay between magnet design and beam dynamics requirements. First estimates of achievable field quality are derived from magnet design studies and prototype measurements for the arc dipole, given at a reference radius of 10 mm [13], and summarised in Table 1 [14]. Effort for other magnet types is currently ongoing.

Sensitivity simulations provide complementary constraints to ensure that performance targets can be met in the presence of realistic errors. Multipole random error sensitivity studies at Z energy are performed including beam-beam effects, by determining the field error level at which the MA is reduced by 10 % using 40 seeds with Synchrotron Radiation (SR) and Quantum Fluctuation (QF), and are sum-

Table 1: Arc Dipole Manufacturing Field Errors, in 10^{-4} Relative Units at a Reference Radius of 10 mm

Component	Systematic	Random
b_1	–	10
b_2 / a_2	10 / 1	5 / 2
b_3 / a_3	0.5 / 0.5	0.5 / 0.5
b_4 / a_4	0.5 / 0.1	0.5 / 0.1
$b_{n>4}$ / $a_{n>4}$	0.1 / 0.1	0.1 / 0.1

---

* jacqueline.keintzel@cern.ch

Table 2: Comparison of GHC and LCC Random Multipole Error Sensitivities, in 10^{-4} of the main field at a Reference Radius of 10 mm

	GHC	LCC	GHC	LCC
Multipole	**Arc Dipoles**		**IR Dipoles**	
a_3	0.15	0.17	0.10	0.10
b_3	1.50	2.00	1.10	0.40
b_4	1.50	3.25	1.50	0.40
a_4	0.30	0.50	0.20	0.10
b_5	2.00	2.75	1.50	0.70
b_6	4.00	> 4.0	0.90	0.40
Multipole	**Arc Quadrupoles**		**IR Quadrupoles**	
a_3	1.8	0.5	2.0	0.30
b_3	9.0	1.5	20.0	0.50
b_4	10.0	1.5	> 20.0	0.50
a_4	2.3	0.6	2.5	0.05
b_5	14.0	3.5	> 20.0	1.25
b_6	15.0	5.0	20.0	0.50
Multipole	**Arc Sextupoles**		**IR Sextupoles**	
a_4	40	> 50	> 50	30
a_5	50	> 50	> 50	> 60
b_5	> 50	> 50	> 50	> 60

marized in Table 2 [12]. For dipoles, values below magnetic tolerances are in red. For quadrupoles, values below 0.5 units are considered challenging and marked in red. We note that LCC features a larger design MA than GHC, together with more elements in the IR. Both show a strong sensitivity to the skew sextupole component a_3. The situation is much more favourable for the high energy booster [15, 16].

Arc alignment errors remain as initially foreseen in [4] and IR errors are under study reaching down to 10 µm transversely [12]. All these tolerances are considered challenging and are being reviewed within a dedicated working group [17].

BEAM BASED ALIGNMENT

BBA is used to reduce the relative orbit offset between quadrupoles or sextupoles and Beam Position Monitors (BPMs), with the current target being below 20 µm. Modulating 20 adjacent quadrupoles with a strength variation of 0.5 %, assuming 100 µm mechanical misalignment, together with a BPM resolution of 1 µm achieves this [18]. Currently, no misalignments are applied in the Interaction Regions (IRs). Complementary studies are investigating sextupole BBA, with more details in [19]. Sextupole BBA could be explored for the IR sextupoles with larger β-functions. Let us finally stress that first parallel BBA in the LHC has been demonstrated [20] but BBA in SuperKEKB shows large errors.

IP TOLERANCES AND TUNING

Beam-beam simulations [21] demonstrated that IP parameters must be strictly controlled to stay within 1 % instantaneous luminosity loss, as summarized in Table 3. Dedicated IP tuning knobs for β^*, $D_{x,y}$ and waist, are, therefore designed individually for each IP and applied after global tuning studies for the GHC [22].

Table 3: IP Tolerances for 1% Luminosity Loss

Aberration	**Z**	**tt**
Vertical waist [mm]	0.1	0.2
Vertical dispersion [μm]	2	1
Vertical dispersion angle [mrad]	18	1
Horizontal dispersion [mm]	3	2
Horizontal dispersion angle [mrad]	4	1
$\lvert f_{1001\,/\,1010}\rvert$ [10^{-3}]	1 / 0.5	2 / 1

GLOBAL TUNING SIMULATIONS

In all global tuning studies, measurement errors on orbit, phase, dispersion and coupling are included. Additionally to misalignment, field errors corresponding to systematic gradient offsets of 2 units and random a_2 components of 0.1 units are included. At the start of simulations, non-linear elements are switched off and ramped up step-wise with orbit, tune, and chromaticity corrections in various steps. Linear coupling correction is based on RDTs. All results are summarized in Table 4, where not-met targets are red.

For GHC, Z-pole studies [23] using Xsuite [24], orbit correctors are next to the main quadrupoles and optics correctors inside sextupoles. IP tuning knobs are applied. DA and MA for GHC are shown in Figs. 1 and 2. First preliminary studies at the W-energy, assume the same corrector scheme [25], with reduced errors, without QF, are done using pySC.

For LCC, pyAT is used for various energies [26]. Alternative corrector layouts are investigated, aiming to define the optimal layout. Latest results include horizontal orbit correctors in dipoles, vertical orbit and skew quadrupoles correctors in sextupoles (inducing b_1 and a_4 [27]), and normal quadrupole correctors in quadrupoles. However, the vertical correctors turn out too strong to be inserted in the sextupoles and, hence, they will be moved to the quadrupoles, as presented in [27]. On the other hand, these would introduce large a_3 components (91 units at tt) which will need skew sextupolar correctors as for the dipole a_3 errors (see below).

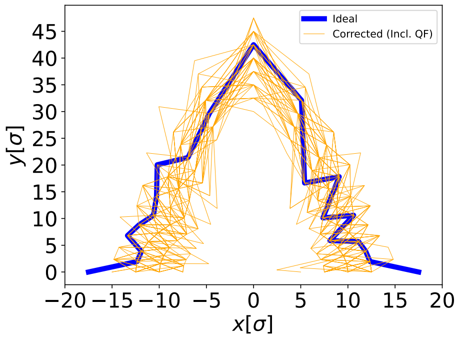

Figure 1: DA for GHC V25.3 after linear optics tuning.

Table 4: Summary of Tuning Results

	GHC		LCC		
Observable	**Z**	**WW**	**Z**	**WW**	**ttbar**
Failed seeds	1 / 50	0 / 50	0 / 100	0 / 50	1/100
rms orbit H / V [μm]	132 / 132	89.31 / 98.36	141 / 141	101.9 / 87.7	141 / 140
rms arc orbit cor. str. H / V [μrad]	6.0 / 6.0	2.82 / 4.34	12.65/11.96	1.15 / 1.17	12.87 / 12.34
rms IR orbit cor. str. H / V [μrad]	9.3 / 9.0	2.68 / 4.12	3.46/4.13	0.17 / 0.13	3.49/4.40
rms LSS orbit cor. str. H / V [μrad]	3.9 / 3.8	0.40 / 1.64	7.31/8.98	0.20 / 0.22	7.70/8.16
rms norm./skew quad. corr. str. [mT]	4.50 / 6.37	1.18 / 1.33	10.19 / 4.10	0.16 / 0.13	37.89/30.27
rms $\Delta D_{x/y}$ [mm]	1.0 / 0.9	5.19 / 0.64	0.6 / 2.2	0.12 / 0.52	0.8 / 0.7
rms phase advance H / V [$10^{-4} 2\pi$]	5.4 / 9.8	4.0 / 12.0	10.0 / 19.7	0.73 / 0.65	73.1 / 90.3
rms $\Delta\beta_{x/y}/\beta_{x/y}$ [%]	0.4 / 0.5	0.4 / 1.2	0.3 / 0.3	0.11 / 0.11	0.3 / 0.4
rms $\|f_{1001}\|$ / $\|f_{1010}\|$ [10^{-4}]	17.3 / 14.39	0.12 / 0.02	93.5/27.2	1.02 / 0.06	8.8 / 11.1
median ε_x [nm] / ε_y [pm]	0.74 / 18.14	2.24 / 3.58	0.72 / 0.89	2.07 / 0.46	2.09 / 3.76

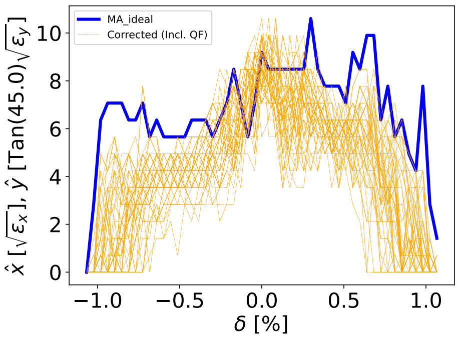

Figure 2: MA for GHC V25.3 after linear optics tuning.

FIELD ERROR CORRECTIONS

Systematic b_2 errors in arc dipoles primarily induce phase advance shifts, which can be effectively corrected below 10^{-4} using symmetric quadrupole variations by about 1 % [28]. Systematic b_3 errors lead to chromatic effects but are well corrected through linear chromaticity correction. It is found that in order to limit sextupole strength variations below 7 % maximum, the systematic b_3 component should remain below 0.5 units [29]. The expected random b_3 has negligible impact once linear chromaticity is corrected. Expected random a_3 errors reduce horizontal DA and MA. A first response-matrix correction using skew sextupoles in the arcs, targeting coupling, skew sextupole RDTs and second order vertical dispersion, shows significant recovery of the MA. An ideal placement of the a_3 correctors needs to be identified [30]. Systematic b_4 errors introduce significant second-order chromaticity and amplitude detuning, resulting DA and MA reduction. Studies show that these effects could be corrected by either unbalancing arc sextupoles, or by dedicated octupoles [29].

First preliminary studies evaluating the impact of beam-beam on vertical emittance indicate that this distortion could be partially compensated by rematching the optics at the end of the IR [31].

OPTICS MEASUREMENTS

Using AC-dipoles for optics measurements based on Turn-by-Turn (TbT) indicate that achieving an rms vertical phase advance error below $10^{-4}(2\pi)$, is challenging even for very idealistic assumptions [32]. First studies on non-linear measurements indicate that, even with 50 000 turns and a BPM resolution below 1 µm, most RDTs are strongly suppressed.

SKEKB EXPERIENCE

SKEKB provides relevant lessons for the FCC-ee, since it shares several key features. SKEKB faces performance limitations, partially attributed to not fully understood non-linear optics. To facilitate simulation studies a SAD to Xsuite translator for SKEKB lattice was developed. First benchmarking studies show good agreement for linear optics, while non-linear optics simulations are ongoing. Recent measurements of the Resonance Driving Term (RDT) f_{1200} for the electron ring, show good agreement between measured and model phase [33], as shown in Fig. 3, while the amplitude has a factor 3.2 discrepancy, currently under investigation.

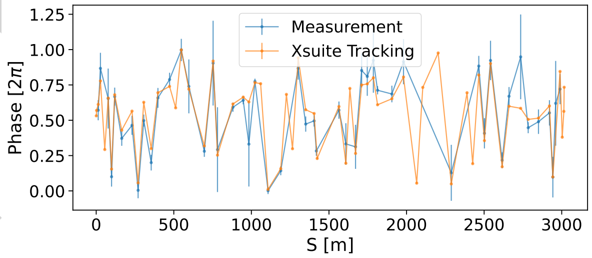

Figure 3: Phase of RDT f_{1200} for SKEKB electron ring.

SUMMARY AND OUTLOOK

Great progress has been made towards the tuning strategy for the FCC-ee, which includes global and local optics tuning for linear and first insights for non-linear optics. First results on tuning with beam-beam are also available. Regarding future objectives for the FCC-ee tuning, fully integrated tuning simulations of commissioning and operation, should be performed. This includes applying less optimistic field and alignment errors together, and further developing linear and non-linear correction strategies at all energies. These will contribute to the FCC-ee reference design, aimed to be delivered by end of 2027, with the objective of demonstrating reliable machine performance under realistic conditions.

REFERENCES

[1] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 1: physics and experiments”, CERN, Geneva, Switzerland, Tech. Rep. CERN-FCC-PHYS-2025-0002, 2025. doi:10.17181/CERN.9DKX.TDH9

[2] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 2: accelerators, technical infrastructure and safety”, CERN, Geneva, Switzerland, Tech. Rep. CERN-FCC-ACC-2025-0004, 2025. doi:10.17181/CERN.EBAY.7W4X

[3] M. Benedikt *et al.*, “Future Circular Collider feasibility study report volume 3: civil engineering, implementation and sustainability”, CERN, Geneva, Switzerland, Tech. Rep. CERN-FCC-ACC-2025-0003, 2025. doi:10.17181/CERN.I26X.V4VF

[4] T. Charles *et al.*, “Alignment & stability challenges for FCC-ee”, *EPJ Techniques Instrum.*, vol. 10, p. 8, 2023. doi:10.1140/epjti/s40485-023-00096-3

[5] J. Bauche *et al.*, “Progress of the FCC-ee optics tuning working group”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 3158–3161. doi:10.18429/JACoW-IPAC2023-WEPL023

[6] L. van Riesen-Haupt *et al.*, “The status of the FCC-ee optics tuning”, in *Proc.IPAC’24*, Nashville, TN, USA, May 2024, pp. 2449–2452. doi:10.18429/JACoW-IPAC2024-WEPR02

[7] R. Tomás *et al.*, “Optics tuning of the FCC-ee”, in *Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, pp. 282–285. doi:10.18429/JACoW-IPAC2025-MOPM009

[8] K. Oide *et al.*, “Design of beam optics for the future circular collider e$^+$e$^-$ collider”, *Phys. Rev. Accel. Beams*, vol. 19, p. 111005, 2016. doi:10.1103/PhysRevAccelBeams.19.111005

[9] P. Raimondi, M. Hofer, S. Liuzzo, L. Farvacque and S. White, “Local chromatic correction optics for Future Circular Collider e$^+$e$^-$”, *Phys. Rev. Accel. Beams*, vol. 28, p. 021002, 2025. doi:10.1103/PhysRevAccelBeams.28.021002

[10] J. Keintzel *et al.*, “Defining the new FCC-ee baseline optics”, presented at the IPAC’26, Deauville, France, May 2026, paper MOV1002, this conference.

[11] J. Keintzel *et al.*, “FCC-ee energy calibration and polarization – towards the reference design”, presented at the IPAC’26, Deauville, France, May 2026, paper MOP1018, this conference.

[12] S. Kostoglou and G. Roy, Eds., “FCC-ee optics comparison report”, CERN, Geneva, Switzerland, 2026, unpublished.

[13] A. W. Chao and M. Tigner, Eds., *Handbook of Accelerator Physics and Engineering*, World Scientific, Singapore, 1999. doi:10.1142/8543

[14] L. Todorovic, “Magnet multipoles”, presented at the FCC-ee optics tuning WG meeting, 6 Mar. 2026. `https://indico.cern.ch/event/1658268/`

[15] Q. Bruant *et al.*, “Impact of dipole field quality on the emittance tuning and the dynamic aperture of the High Energy Booster of the Future Circular Colliders”, presented at the IPAC’26, Deauville, France, May 2026, paper MOP1069, this conference.

[16] Q. Bruant *et al.*, “Emittance tuning of the FCC-ee high energy booster ring”, presented at the IPAC’25, Taipei, Taiwan, Jun. 2025, paper MOPM010, unpublished.

[17] D. Mergelkuhl, “Introduction – alignment test proposal”, presented at the Alignment Test Proposal kick-off meeting, 6 Nov. 2025. https://indico.cern.ch/event/1606243/

[18] C. Goffing *et al.*, “Parallel quadrupole beam-based alignment for FCC-ee”, presented at the IPAC’26, Deauville, France, May 2026, paper SUP5004, this conference.

[19] C. Goffing *et al.*, “Sextupole beam-based alignment for FCC-ee”, presented at IPAC’26, Deauville, France, May 2026, paper WEP5036, this conference.

[20] C. Goffing *et al.*, “First parallel arc quadrupole beam-based alignment using K-modulation at LHC”, presented at the IPAC’26, Deauville, France, May 2026, paper WEP5035, this conference.

[21] V. Gawas *et al.*, “Effect of FCC-ee optics errors in collision simulated by Xsuite”, presented at the IPAC’26, Deauville, France, May 2026, paper WEP5045, this conference.

[22] S. Jagabathuni *et al.*, “FCC-ee interaction point optics correction with alignment errors using local tuning knobs”, *in Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, pp. 1075–1078. doi:10.18429/JACoW-IPAC2025-MOPM038

[23] S. Jagabathuni *et al.*, “Optics tuning of the FCC-ee”, in *Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, pp. 394–397. doi:10.18429/JACoW-IPAC2025-MOPM037

[24] G. Iadarola *et al.*, “Xsuite: an integrated beam physics simulation framework”, in *Proc. HB’23*, Geneva, Switzerland, Oct. 2023, pp. 73-80. doi:10.18429/JACoW-HB2023-TUA2I1

[25] E. Musa, “W-tuning for GHC”, presented at the FCC-ee optics tuning WG meeting, 6 Mar. 2026. `https://indico.cern.ch/event/1658268/`

[26] K. Andre *et al.*, “Tuning strategies for the FCC-ee local chromaticity correction collider lattice”, presented at the IPAC’26, Deauville, France, May 2026, paper MOP1079, this conference.

[27] A. Vorozhtso, “Magnet updates including tuning and tapering”, presented at the FCC-ee optics tuning WG meeting, 17 Apr. 2026. `https://indico.cern.ch/event/1675106/`

[28] W. Van Goethem, “Correction of b2 errors”, presented at the FCC-ee optics tuning WG meeting, 2 Apr. 2026. `https://indico.cern.ch/event/1667088/`

[29] P. Hunchak *et al.*, “Investigations of non-linear optics control knobs for the FCC-ee”, presented at the IPAC’26, Deauville, France, May 2026, paper SUP1302, this conference.

[30] W. Van Goethem, “Impact of a3 errors”, presented at the FCC-ee optics tuning WG meeting, 27 Feb. 2026. `https://indico.cern.ch/event/1654640/`

[31] T. Prebibaj *et al.*, “Initial studies on resonance driving term correction knobs for FCC-ee with beam–beam and imperfections”, presented at the IPAC’26, Deauville, France, May 2026, paper MOP1040, this conference.

[32] J. Keintzel *et al.*, “Progress on optics measurements for the FCC-ee”, presented at the IPAC’26, Deauville, France, May 2026, paper MOP1038, this conference.

[33] M. Le Garrec, “Report from SuperKEKB”, presented at the FCC-ee optics tuning WG meeting, 27 Feb. 2026. https://indico.cern.ch/event/1654640/