

# CHART Scientific Report

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## Optimizing FCC-ee Luminosity (FCCee Lumi)

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### 1. Introduction / Original goals of this project

The objective of this project was, or is, to deliver an optimized optics of the FCC-ee collider rings in four modes of operation for both two and four interaction points (IPs), including the final focus optics. It also develops final-focus tuning knobs for linear and nonlinear IP optics control, and, from the knob performance, and it derives alignment tolerances for the final-focus elements. Finally, the project characterizes the expected luminosity-related signals recorded by luminometer, beamstrahlung monitor, and silicon vertex detector, and explores the efficiency of luminosity tuning based on realistic signals and tuning knobs. As a result, the achievable performance and possible directions of further improvement can be deduced.

This project had also been meant to prepare the ground for a longer-term activity in accelerator physics at the University of Geneva, situated in an ideal place close to CERN, for mutual benefit.

### 2. Realisation

#### a. Personnel

A visiting senior scientist had been expected to be supported for four years to develop and optimize the optics lattices for the two FCC-ee collider rings at four different beam energies, that are consistent with the optimized lowest-risk placement, layout, and preferred RF configurations.

The visiting professorship was prematurely terminated in 2025 after only three years.

This senior scientist was adapting the optics and interaction-point beam parameters as required for optimized luminosity and beam-beam performance, e.g. for possibly further reduced vertical beta\*. This

work also ensured that the FCC-ee optics footprint matches the footprint of the hadron collider FCC-hh optics. The FCC-ee optics was refined and completed so as to include injection, elements for energy calibration (wiggler, polarimeters...), collimation, additional beam dumps, etc.

Effort was spent on the design of splitters and combiner sections in the radiofrequency straight section, which need to be as compact as possible.

The senior scientist was also co-supervising the work of two doctoral students, enrolled at U Geneva and financed by CERN.

The first student has been examining final-focus alignment tolerances, developing interaction-point tuning knobs, refined techniques for optics corrections and tuning, and computed the dynamic aperture under various conditions. The second student has been studying if and how the information from the luminosity monitor, beamstrahlung signals, and vertex detector data, can be used together with the aforementioned tuning knobs to infer, control and optimize the interaction-point beam and optics parameters.

## **b. Optics development**

The following key revisions were made, by the senior scientist, on the FCC-ee layout and beam optics:

- 4 IPs, 8 shafts.
- Adopted the new tunnel layout of PA-31 series, from 1.0 to 3.0 (newest), characterized by SLSS = 1400 m, LLSS = 2032 m, Circ = 90657.4 m,  $\Delta_{IP} = 10.201$  m.
- Changed the beam-line separation of e+e- from 30 to 35 cm.
- Designed the long-long straight section (LLSS) for inside-outside beam exchange and the RF in one of them.
- Designed the RF section for Zh/tt with shared RF.
- Designed the short-long straight section (SLSS) including the IP.
- Each SLSS incorporates sections for polarimeters and polarization wigglers.

## **c. Dynamic aperture and beam lifetime**

The senior scientist noticed that the legacy way of optimization of dynamic aperture (DA) was not sufficient to ensure an adequate beam lifetime given by the lattice nonlinearity. The senior scientist found the survival rate or the lifetime of the particles under the beam-beam interaction to be most important. The legacy view of the DA or MA had been calculations starting at a particular point of the lattice over a relatively small number of turns, i.e., a few radiation damping times, which was not enough to properly sample the phase space and evaluate the effect. Instead, simulations over a longer time were shown to be necessary and, indeed, performed in this study at least with a weak-strong model for the beam-beam effect. With this approach a more solid estimate of the DA and beam lifetime were obtained. Such an evaluation was possible within a reasonable time on the CERN computer cluster, typically requiring about 12 hours at the Z-pole energy. For higher beam energies the computation is faster thanks to stronger damping.

## **d. Vibration impact and BPM requirements**

In view of the small beam spot size at the IP ( $\sigma_y^{\square} \approx 35$ nm), the estimation of the beam vibration is crucial. As the first step, the beam vibration caused by the coherent and random ground motions has been estimated. As a result, it was found that beam feedback based on the detection of beam-beam

deflection is necessary up to 10 Hz. The requirements on the beam position monitors (BPMs) are within reachable range of performance reached by currently available technology, at first glance.

### e. Impact of machine errors on CM energy

The determination of the center-of-mass energy is an essential point for the physics programme of FCC-ee. Various machine errors such as misalignments of magnets alter the beam energy along the beam orbit. An estimation was done by a simulation with possible misalignment of magnets. The resulting deviation of the Centre-of-Mass (CM) energy is about 0.5 ppm.

### f. Final-focus knobs and IP tuning

The primary tools crucial for precise adjustments of optics at the interaction regions in the event of mismatches caused by machine errors are tuning knobs. These knobs, namely beta-star (both horizontal and vertical planes), waist (both horizontal and vertical planes), vertical dispersion (with an ongoing study on the horizontal dispersion knob), linear coupling (F1001, F1010 driving terms), and orbit (both horizontal and vertical planes), have been developed thus far.

To address further complexities expected during real machine operation, magnet field and misalignment errors were introduced in the lattice, leading to orbit and optics distortion. A sophisticated linear optics tuning framework was developed in Xsuite to simulate more realistic machine tuning, including measurement errors. This tuning comprises orbit threading and orbit correction, and linear optics corrections based on response matrices, respecting phase advance constraints. Following this tuning procedure dynamic aperture and momentum acceptance are obtained, also including the effect of quantum fluctuation. Despite a good correction of the global optics, the developed IP tuning knobs were proven indispensable to restore nominal values at the collision points. It was demonstrated that after global optics corrections and additional IP tuning knobs, the DA and MA remain at the same level, while the IP optics is restored to the nominal values. DA and MA after the global tuning and after applying IP knobs are shown in, Figs. 1 and 2, respectively.

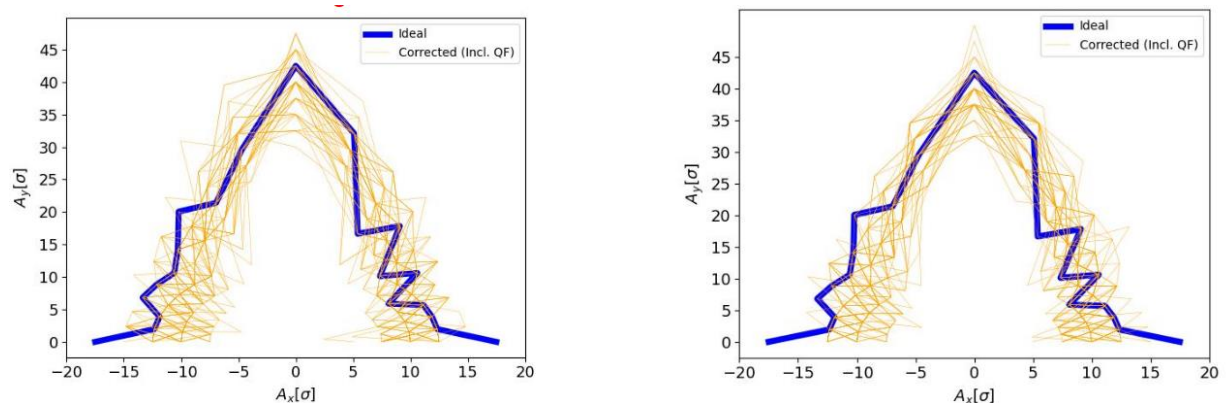


Figure 1: DA before (left) and after (right) applying IP tuning knobs after global linear optics tuning.

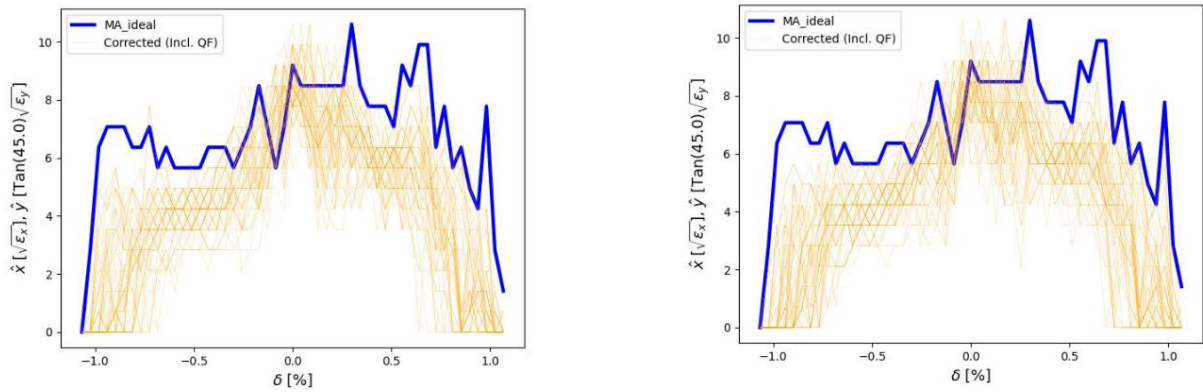


Figure 2: MA before (left) and after (right) applying IP tuning knobs after global linear optics tuning.

### g. Assessment of luminosity-related signals

Luminosity optimization relies on measuring the realistic signals from Bhabha scattering, beamstrahlung and/or radiative Bhabha photons. The initial assessment used single-pass simulations with the code Guinea-Pig to determine the change in luminosity and beamstrahlung signals with respect to waist-shifts, vertical dispersion, and skew coupling introduced in the beam. These studies unveiled signals in the energy spectrum of the beamstrahlung photons to be used for measuring the transverse beam sizes, while shifts in the angular distributions are linked to the IP beam-beam steering.

### h. Bayesian optimization for IP tuning

A Bayesian optimization framework was applied to single-turn simulations to explore the parameter space of waist, dispersion, and coupling at the IP. Using an acquisition function designed to optimize scan windows, the method identified configurations that optimize luminosity. These results were presented at the eeFACT 2025 and IPAC 2025. They demonstrated the potential of Bayesian approaches for IP aberration reconstruction and tuning in FCC-ee.

### i. Simulations with Xsuite

Single-turn studies of interaction point (IP) aberrations were next carried out using the novel Xsuite framework, with results benchmarked against the earlier Guinea-Pig simulations. This validation ensured that the linear lattice modeling accurately captures the key beam dynamics at the FCC-ee IP, providing a reliable foundation for subsequent multiturn and beam-beam studies.

A multiturn simulation setup was developed within Xsuite's linear lattice, incorporating damping and Gaussian noise to simulate beam dynamics. This setup allowed for the extraction of changes in beam size, emittance, luminosity, beamstrahlung, and tune shifts due to beam-beam effects in a strong-strong collision scenario.

Coupled linear maps were implemented and benchmarked in Xsuite, including detailed studies using both the Mais-Ripken and Edwards-Teng coupling formalisms. Coupling matrices were derived and connected to linear resonance driving terms (RDTs), enabling a systematic study of shifts in Twiss parameters induced by non-zero coupling in the linear lattice. Results are being validated against the full non-linear FCC-ee lattice, to allow for a quantitative understanding of interaction-point coupling effects on the beam dynamics.

The multiturn simulation package was extended to include the full nonlinear lattice and beam-beam effects with adjustable waist and dispersion parameters at the IP.

A framework for global optics tuning was developed in Xsuite, and used extensively for simulations for the baseline lattice, especially at the Z-energy. The corresponding code assigns misalignments, field errors, and measurement errors, and then applies a global linear optics and emittance tuning algorithm, which is based on response matrices. The first response matrix corrects tunes, phase advance and horizontal dispersion, while the second one addresses the linear coupling RDTs and vertical dispersion. Dedicated IP tuning knobs for beta star, waist shift, linear coupling and dispersion were also generated using Xsuite and applied after the global linear tuning. Results were presented at various international conferences (eeFACT'25, IPAC'25, FCC Week 2025) and internal meetings. This framework represents one of the cornerstones of the FCC-ee tuning efforts.

#### **j. IP aberrations and signals**

Simulations revealed the luminosity variation with various IP aberrations. The changes in beamstrahlung power, beamstrahlung photon spectra, and photon angular distribution were simulated with respect to residual vertical dispersion and waist-shifts. The characterization of the relevant IP signals is used to formulate functional specifications for the beamstrahlung monitor.

Multiturn Xsuite simulations provide insight into how controlled waist, dispersion and coupling knobs influence beam stability and luminosity over multiple turns.

Simulations were also extended to the horizontal plane in order to provide a more complete picture of IP dynamics, and to enable a better understanding of beam-beam interactions with errors in both transverse planes, and of their combined effect on luminosity and beamstrahlung.

Analytical calculations of beamstrahlung dependence on waist and dispersion were carried out for both vertical and horizontal planes. These calculations include the crossing angle, the crab waist collision scheme, and hourglass effect, with the aim of generating predictive models to complement the multiturn simulations.

Tolerances on the resonance driving terms, coupling parameters (using the implemented linear coupling maps), waist shifts, and dispersion and dispersion angles were determined and linked to observables related to luminosity and beamstrahlung. These tolerances will inform machine design and tuning strategies to maintain optimal performance.

### **3. Results / Conclusions / Deliverables**

The following results were achieved:

- Various FCC-ee optics for the two collider rings at four different beam energies are documented through SAD/MAD-X optics files and accompanying short descriptions made available since October 2022.
- Better parameters were identified, to improve the luminosity while keeping the same beam lifetime. For instance, the luminosity/IP at ZH can be 20% higher than in the mid-term review report.
- It was noticed that the magnitude of the crab waist affects some resonances strongly, and that, as a result, the optimum crab-waist ratio is smaller than considered previously (50% vs 97% at Z, e.g.).

- Various optics for beam injection and extraction, for realistic actual RF system configurations, and with specific optics correction elements etc. are also documented through SAD/MAD-X optics files and a short description.
- Evaluation of the impact of beam excitation and required precision of beam position monitors and feedback.
- It was found that breaking the four-fold super-periodicity leads to degraded luminosity performance at the ttbar energy.
- A set of final-focus tuning knobs for linear and nonlinear IP optics control, in the form of magnetic elements, and tuning scripts, was implemented in MAD-X and Python/Xsuite format; IP tuning knobs developed so far were tested on various versions of the GHC lattice, including the V22 and the V25.3, lattice with all global corrections, and successfully corrected the optics at the IP  
[\(https://indico.cern.ch/event/1403458/](https://indico.cern.ch/event/1403458/),  
<https://indico.cern.ch/event/1648395/contributions/6928073>).
- Raw alignment tolerances for the various final-focus magnets (sextupoles, quadrupoles, dipoles) along with the maximum tuning range of linear and nonlinear knobs including cross-talk between different knobs.
- Luminosity based tolerances on IP-aberrations (waist shift and residual vertical dispersion) were explored. At the ttbar energy, the luminosity drops by 60-70% for a waist shift of 1mm , and it drops by ~60% for 0.1 mm of vertical dispersion.
- A travelling waist effect was observed in Guinea-Pig simulations on the Z pole, whereas the ‘inverse effect’ was seen at FCC-ttbar working point.
- The beamstrahlung signal and its dependence on various parameters, including IP position, closed-orbit angle, beam sizes, etc., was explored and documented. In particular, the beamstrahlung spectra, angular distribution and radiation power were studied as a function of IP-aberrations to infer requirements on the beamstrahlung monitor.
- Preliminary benchmarking studies of X-suite with Guinea-Pig simulations yielded consistent results.
- A robust and efficient method to evaluate the beam lifetime in simulations.
- Further optimisation of the lattice including beam-beam effects, looking at the beam lifetime and emittance blowup under beamstrahlung and lattice nonlinearity, fine adjustments of the lattice considering magnet spacing, etc.
- An alternative collider optics without twin-quadrupole constraints in the arcs, to improve the power consumption and relax tolerances for misalignments.
- Optics tuning studies for the FCC-ee lattice with commissioning simulation tools based on python Accelerator Toolbox (pyAT) developed by ESRF, in order to compare tuning studies with different optics codes.
- Optics tuning studies for alternative FCC lattices using framework developed in Xsuite.
- Integration of the IP tuning knobs into the pyAT framework and dynamic aperture studies.

- Development of IP tuning knobs for alternative FCC lattices and their application after global linear tuning in simulations.
- Assessment of additional information that might be obtained from a small-radius silicon vertex detector.
- An estimate of the attainable luminosity performance, plus an indication of the relevant tolerances.

The work is still in progress. Still under exploration are the following topics:

- Model for luminosity tuning based on realistic signals and tuning knobs;
- Study of beam-beam driven instabilities due to asymmetric IP aberrations; and
- Report on tolerances for all low-order IP optics aberrations at all working points.

#### 4. Publications and Outreach

- Presentation at 1<sup>st</sup> FCC Beam Instrumentation workshop, CERN, 21-22 November 2022:  
K. Oide, Main ring and MDI region,  
<https://indico.cern.ch/event/1209598/contributions/5092252/>
- Presentation at 2<sup>nd</sup> FCC Polarization workshop, CERN, 19-30 December 2022:  
K. Oide, Overview: Status and goals WP2,  
<https://indico.cern.ch/event/1181966/contributions/5041336>
- Presentations at Joint FCC-EIC & MDI Workshop, CERN, 17-28 October 2022:  
K. Oide, FCC IS Optics, <https://indico.cern.ch/event/1186798/contributions/5062582/> ;  
K. Oide, Vibrational Orbit Effects,  
<https://indico.cern.ch/event/1186798/contributions/5062667/>
- Presentations at FCCIS workshop 2023, Rome, 13-15 November 2023:  
K. Oide, Optics performance, beam lifetime and injection rate,  
<https://indico.cern.ch/event/1326738/contributions/5650144> ;  
S. Sai Jagabathuni, IR tuning knobs,  
<https://indico.cern.ch/event/1326738/contributions/5650259>
- Presentation at the FCCIS MDI workshop, Frascati, 16-17 November 2023:  
K. Oide, IR optics design and challenges.  
<https://agenda.infn.it/event/37720/contributions/212736> ;  
V. Gawas, Luminosity optimisation and tuning,  
<https://agenda.infn.it/event/37720/contributions/212740>
- Presentation at CEPC workshop, Marseille, 8-11 April 2024 :  
V. Gawas, Luminosity optimization and tuning at FCCee,

<https://indico.in2p3.fr/event/20053/contributions/137788/>

- IPAC'24 proceedings:  
S. Jagabathuni, F. Zimmermann, M. Hofer, L. van Riesen-Haupt, F. Carlier, Simulated performance of FCC-ee IP tuning knobs, Proc. IPAC'24 Nashville, <https://doi.org/10.18429/JACoW-IPAC2024-WEPR03> ;  
L. van Riesen-Haupt, F. Carlier, S. Jagabathuni, et al., The status of the FCC-ee optics tuning, Proc. IPAC'24 Nashville, <https://doi.org/10.18429/JACoW-IPAC2024-WEPR02> ;  
F. Zimmermann, K. Oide et al., Selected advances in the accelerator design of the Future Circular Electron-Positron Collider (FCC-ee), Proc. IPAC'24 Nashville, <https://doi.org/10.18429/JACoW-IPAC2024-WEPR14>
- Presentations at the FCC Week 2024, San Francisco, 10-14 June 2024:  
K. Oide, GHC optics and collider parameters, <https://indico.cern.ch/event/1298458/contributions/5977859> ;  
S. Sai Jagabathuni, Simulated Performance of FCC-ee IP Tuning Knobs, <https://indico.cern.ch/event/1298458/contributions/5985536/> ;  
V. Gawas, Luminosity tuning and optimization <https://indico.cern.ch/event/1298458/contributions/5987293/>
- Presentations in FCC working group meetings:  
K. Oide, Status of optics design, 161st FCC-ee Optics Design Meeting & 32nd FCCIS WP2.2 Meeting, 19 January 2023, <https://indico.cern.ch/event/1237189/contributions/5222868> ;  
K. Oide, Beam Lifetime at Z, 156th FCC-ee Optics Design Meeting & 27th FCCIS WP2.2 Meeting, 4 August 2023, <https://indico.cern.ch/event/1178975/contributions/4952198/> ;  
S. Sai Jagabathuni, IR tuning knobs for the FCC-ee, Last LNO section meeting in 2023, 15 December 2023, <https://indico.cern.ch/event/1351567/contributions/5709592/> ;  
S. Sai Jagabathuni, FCC-ee IP tuning simulations, FCC-ee optics tuning WG meeting, 10 April 2024, <https://indico.cern.ch/event/1403458/contributions/5900149/>
- ICFA Beam-Beam Workshop, Lausanne, Switzerland, September 2024:  
V. Gawas, F. Zimmermann, Luminosity tuning and optimisation, <https://indico.global/event/9305/contributions/90684>
- ICFA eeFACT Workshop, Tsukuba, Japan:  
V. Gawas, F. Zimmermann, V. Kain: Machine Learning for IP Tuning: <https://indico.jacow.org/event/75/contributions/6849/>

S. Jagabathuni: First view at alignment tolerances in the FCCee Interaction Region, Tsukuba, Japan. <https://indico.jacow.org/event/75/contributions/7071>

S. Jagabathuni: FCCee Interaction Point optics tuning, Tsukuba, Japan. <https://indico.jacow.org/event/75/contributions/6762>

- IPAC'25 proceedings, Taipei, Taiwan:

V. Gawas, F. Zimmermann, V. Kain: Bayesian Optimization for IP Aberration Correction and Tuning at FCCee, Proc. IPAC'25 Taipei, Taiwan:

<https://indico.jacow.org/event/81/contributions/9167/>,

S. Jagabathuni, F. Carlier and S. Liuzzo: FCC-ee Interaction point optics correction with alignment errors using local tuning knobs, Proc. IPAC'25 Taipei, Taiwan:

[doi:10.18429/JACoW-IPAC2025-MOPM038](https://doi.org/10.18429/JACoW-IPAC2025-MOPM038)

S. Jagabathuni, F. Carlier and S. Liuzzo: FCC-ee optics tuning studies with pyAT and Xsuite, Proc. IPAC'25 Taipei, Taiwan: [doi:10.18429/JACoW-IPAC2025-MOPM037](https://doi.org/10.18429/JACoW-IPAC2025-MOPM037)

R. Tomas, J. Keintzel et al: Optics tuning of the FCC-ee, Proc. IPAC'25 Taipei, Taiwan: [doi:10.18429/JACoW-IPAC2025-MOPM009](https://doi.org/10.18429/JACoW-IPAC2025-MOPM009)

- Presentations at the FCC Week 2025, Vienna, May 2025:

S. Jagabathuni: IR alignment and Xsuite migration: <https://indico.cern.ch/event/1408515/timetable/>

V. Gawas, F. Zimmermann, V. Kain: Bayesian Optimization for IP Aberration Correction and Tuning at FCCee: <https://indico.cern.ch/event/1408515/timetable/>

- Presentations at FCC-ee tuning meetings:

S. Jagabathuni: GHC tuning; 8 December 2025  
<https://indico.cern.ch/event/1619261/>

S. Jagabathuni: GHC tuning; 21 November 2025  
<https://indico.cern.ch/event/1613765/>

S. Jagabathuni: Tuning studies GHC; 13 October 2025  
<https://indico.cern.ch/event/1599144/>

S. Jagabathuni: Tuning studies GHC; 17 September 2025  
<https://indico.cern.ch/event/1586791/>

S. Jagabathuni: Tuning in xsuite; 20 August 2025  
<https://indico.cern.ch/event/1579211/>

S. Jagabathuni: FCC-ee optics tuning simulations including girder misalignments in pyAT ; 11 April 2025

<https://indico.cern.ch/event/1537329/>

S. Jagabathuni: Progress on optics tuning simulations ; 05 December 2024

<https://indico.cern.ch/event/1484122/>

S. Jagabathuni: Tuning Simulations; 18 October 2024

<https://indico.cern.ch/event/1464944/>

S. Jagabathuni: Progress with optics tuning simulations; 02 October 2024

<https://indico.cern.ch/event/1462793/>

S. Jagabathuni: Progress with tuning simulations and with IP tuning knobs; 13 September 2024

<https://indico.cern.ch/event/1450442/>

V. Gawas, F. Zimmermann, X. Buffat: Implementation of Linear Coupling in Xsuite: <https://indico.cern.ch/event/1587412/> , Beam-Beam Meeting (internal), FCCee Tuning Meeting (internal)

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