Swiss Accelerator Research and Technology

CHART Scientific Report

Accelerator design and collective effects studies for the FCC-ee

(FCC-ee Beam Dynamics 2)

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1. Introduction

The project aims to advance the beam-dynamics understanding and simulation capabilities required for the design and optimization of the Future Circular Collider – Electron-positron (FCC-ee). Achieving the ambitious luminosity targets of the FCC-ee demands precise control of collective effects that can limit performance, including beam–beam interactions, electron cloud formation, machine impedance, and space-charge forces in a realistic lattice with magnet imperfections. Addressing these challenges requires both improved theoretical models and advanced numerical tools capable of capturing the complex interplay between these effects.

A central component of the project is the study of nonlinear optics and the development of correction strategies to preserve dynamic aperture, momentum acceptance, and beam lifetime in the presence of strong beam–beam forces. This includes refining optics configurations, introducing new tuning knobs, and constructing correction schemes that remain effective when beam–beam interactions modify the underlying lattice properties.

Electron cloud effects constitute another major focus. In particular, the project investigates the role of photoelectrons generated by synchrotron radiation and their contribution to cloud buildup, which can drive instabilities and degrade beam quality. New semi-analytical and numerical models are being developed to incorporate photoelectron production, explore mitigation strategies such as surface treatments and evaluate alternative beam structures that may reduce cloud formation at design.

The project also addresses luminosity and betatron-coupling effects in high-luminosity colliders, including both the FCC-ee and the HL-LHC. Understanding how coupling interacts with beam–beam forces and impacts the luminous region is essential for optimizing performance in precision-measurement regimes. Experimental studies at existing facilities provide valuable benchmarks for these investigations.

Building on the Xsuite framework developed during CHART2, the project continues to expand and refine advanced simulation tools. These include self-consistent beam–beam models, multi-turn tracking with radiation effects, and improved representations of nonlinear dynamics and lattice imperfections. In addition the energy recovery linac studies, supported by competitive European fund, will also help in exploring ERL based collider options with the intention to design for more sustainable colliders. The ongoing development of these tools is essential for realistic start-to-end simulations and for demonstrating the feasibility and performance potential of future collider designs.

2. Research Goal

The overarching goal of this project is to advance the beam-dynamics understanding and simulation capabilities required for the design and optimization of the FCC-ee. The work targets the key collective effects that limit performance in high-luminosity lepton colliders, with the aim of developing robust strategies to maximize luminosity, beam stability, and operational efficiency.

More specifically, the project seeks to:

- **Develop advanced nonlinear-optics and correction tools**, including resonance-driving-term (RDT) analysis and beam–beam-aware tuning strategies, to ensure sufficient dynamic aperture and momentum acceptance in realistic lattices with imperfections.
- **Improve the modeling of collective effects**, with particular emphasis on beam–beam driven instabilities, electron cloud formation (including photoelectron contributions), machine impedance, and their interplay in high-intensity regimes.
- **Extend and validate numerical simulation frameworks**, especially Xsuite, to enable realistic multi-physics, multi-turn tracking that incorporates radiation effects, insertion devices and electron cloud dynamics.
- **Support experimental benchmarking** through measurements at existing facilities such as the LHC, SLS2, and SuperKEKB, ensuring that models and correction strategies are grounded in operational machine behavior.
- **Contribute to the design of future accelerator technologies**, including insertion devices and energy-efficient ERL-based systems, by developing accurate tracking tools and studying collective-effect limitations. Also supporting existing project under construction for proof of principle as PERLE for ERL concept.

Together, these goals aim to provide the theoretical, numerical, and experimental foundations needed to demonstrate the feasibility and optimize the performance of the FCC-ee and related future accelerator concepts creating a robust design and define tolerances and technical solutions for the hardware involved as magnets, bam chamber design etc.

3. Results

3.1 Nonlinear Optics and Resonance Driving Terms Studies in Presence of Beam–Beam

A major achievement of the first project year is the development of the first Resonance Driving terms RDT-based analysis and correction framework that explicitly includes beam–beam interactions. Using Xsuite and MAD-NG, two complementary methods for extracting RDTs were established: analytical computation from the lattice model and tracking-based reconstruction using turn-by-turn data analyzed with OMC3 tool. The two approaches were validated against each other, demonstrating excellent agreement and enabling the study of nonlinear dynamics in realistic conditions.

A systematic sensitivity study was performed in which individual RDTs were varied using a response-matrix approach. Tracking simulations including synchrotron radiation, beamstrahlung, tapering, and weak–strong beam–beam interactions were used to quantify the impact of each term on beam losses, emittance growth, and luminosity. The results show that the third-order terms f1011 and f3000 are the most detrimental in the presence of beam–beam, while fourth-order terms have a significantly weaker effect. This provides a clear prioritization for future correction strategies.

The response-matrix framework developed for these scans incorporates SVD truncation and Tikhonov regularization, allowing controlled manipulation of individual RDTs while suppressing cross-talk. First applications to lattices with realistic imperfections show that global optics correction restores most nonlinear features close to the ideal lattice, although residual deviations—particularly in f1011—may contribute to the vertical emittance growth observed in beam–beam simulations. These findings will guide the development of targeted nonlinear correction knobs in the next project phase. In parallel a lattice description with errors and orbit, and optics corrections with Beam-beam and compensating for it's optical impacts in under development and provides a very solid basis for a realistic study of the collider performances since it mimics a realistic construction. With this we will be able to define real performances and define tolerances for the lattice elements. First results will be presented at coming International Particle Accelerator Conference 2026.

3.2 Electron Cloud Modeling with Photoelectrons and Magnetic Fields

Significant progress has been made in extending semi-analytical models of electron cloud (EC) buildup. Building on the Furman formalism, an expanded model was developed that characterizes the EC evolution using three parameters (α, β, and yc), which can be predicted from key machine inputs such as SEY and bunch intensity. This predictive capability reduces the number of full PyECLOUD simulations required to characterize EC behavior for a given configuration.

The model was validated in drift regions and then extended to include the effects of magnetic fields. Simulations performed in dipole, quadrupole, and sextupole fields show that magnetic confinement increases the saturation density yc and modifies the growth rate of the cloud. While the current model captures the saturation behavior, discrepancies remain during the growth phase, indicating that additional magnetic-field-dependent parameters will be needed. This provides a clear direction for future model refinement.

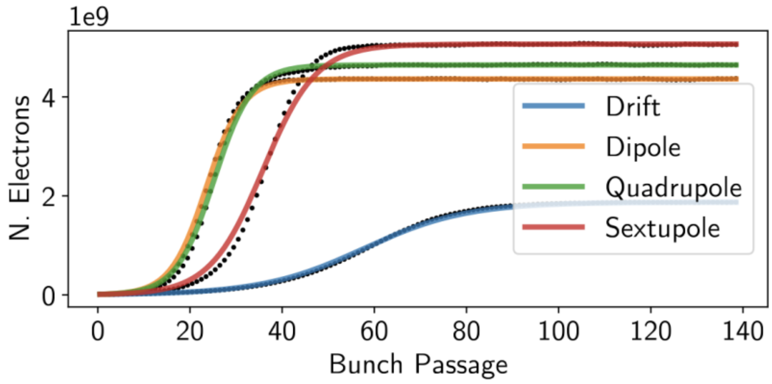

Fig. 1: Number of electrons produced by secondary emission and the build up as a function of the positrons bunches passages. Results from PyECLOUD Montecarlo simulation code are dots are compared to parametric model expectations (solid lines). The comparison is shown for the formation of electron clouds in different magnetic elements and drifts. To be published at IPAC26.

In the long term, the goal is to integrate these predictive models into a tool that complements PyECLOUD by filling parameter sweeps analytically, enabling faster exploration of operational scenarios and material constraints for FCC-ee.

3.3 Tracking in Insertion Devices and Longitudinally Varying Fields

A new general framework for tracking in three-dimensional magnetic fields with strong longitudinal variation has been developed. The method combines a Maxwell-consistent field expansion with a Boris integrator, enabling accurate and efficient particle tracking in arbitrary field maps, including those without analytical expressions.

Validation studies using an analytical solenoid field demonstrate convergence to the reference solution and confirm that the observed error floor is consistent with the truncation of the field expansion. The framework is now ready to be applied to realistic undulator and wiggler field maps, with particular relevance for SLS2 and future FCC-ee insertion devices. This work strengthens the simulation capabilities required for beam-based measurement studies planned in later stages of the project. Also shows how the developments for FCC can be beneficial to advance also the understanding at present light sources.

3.4 Coupling and Beam–Beam Effects: Experimental Preparations

Work on coupling and luminosity degradation is in an early stage, as the PhD students assigned to this task began only recently. However, important preparatory steps have been completed. Experimental tests at the LHC have been carried out with few hours of beam time to collect data on the impact of transverse coupling and beam-beam interactions on luminosity. These measurements will serve as essential benchmarks for the analytical and numerical models to be developed in the coming year without data from the LHC due to the long shut down (LS3) of ~4 years to prepare for the HL-LHC upgrade. The experimental component ensures that the project remains anchored to operational machine behavior and will support validation of future FCC predictions.

3.4 Energy Recovery Linacs for sustainable colliders studies

Significant progress has been achieved in the development of simulation tools for Energy Recovery Linacs (ERLs), addressing one of the key objectives of the project: enabling realistic, self-consistent modelling of multi-pass beam dynamics in energy-efficient accelerator architectures. A new flexible simulation scheme has been implemented as a high-level wrapper around RF-Track, allowing the tracking of recirculating and energy-recovery beams through arbitrary lattice configurations while preserving full six-dimensional phase-space information.

A central feature of this framework is its dynamic routing algorithm, which determines the appropriate beamline for each bunch based on its instantaneous energy and phase-space coordinates. This enables the correct handling of accelerating and decelerating arcs, as well as multi-turn recirculation, without requiring manual intervention or static lattice duplication. The scheme is fully integrated into the RF-Track workflow, ensuring that collective effects such as wakefields and beam loading accumulate consistently across successive passes. These effects are implemented through the UserEffect interface, which allows custom physics models to be injected directly from Python while maintaining physical consistency.

Two independent benchmarking campaigns were carried out to validate the implementation. First, the wakefield and beam-loading models were benchmarked against Xwakes, demonstrating excellent agreement and confirming the correct treatment of collective effects. Second, the recirculation logic and optics handling were benchmarked against MAD-X and Bmad, showing consistent transport and routing behaviour across multiple passes. Together, these results establish the robustness of the approach and its suitability for realistic ERL studies, including the investigation of Beam Breakup (BBU) instabilities and transient beam-loading phenomena.

A major milestone achieved this year is that full recirculation simulations of the PERLE ERL are now possible within this framework**.** Preliminary results have already been presented at the iSAS yearly meeting, demonstrating the capability of the tool to model multi-pass transport, energy recovery, and the interaction between accelerated and decelerated beams. Further results will be presented at IPAC'26, where the methodology and benchmarking outcomes will be disseminated to the broader accelerator community.

This new simulation capability provides a powerful platform for future studies of energy-efficient cryomodules and ERL-based collider concepts, including potential applications to FCC-ee injector or recovery schemes. It also positions the project to contribute meaningfully to the iSAS initiative and to the broader European effort toward sustainable accelerator technologies.

4. List of Presentations

- Presentation at FCC Week 2025, Beam-Beam Effects in the presence of errors https://indico.cern.ch/event/1408515/contributions/6526702/attachments/3071233/5433864/Beam-beam%20Effects%20in%20the%20Presence%20of%20Errors.pdf
- Presentation at FCC Week 2025, Electron Cloud effects in the FCC-ee, https://indico.cern.ch/event/1408515/contributions/6515085/attachments/3071179/5433274/2025_05_20_FCC_week.pdf
- Presentation at FCC Week 2025, Nested Magnets and Balistic Optics design, https://indico.cern.ch/event/1408515/contributions/6515072/attachments/3071073/5433047/FCCWEEK2025_final.pdf
- Presentation at FCC Week 2025, Xsuite Evolution for FCC studies, https://indico.cern.ch/event/1408515/contributions/6515071/attachments/3070908/5433338/006_xsuite_fcc_week.pdf
- Presentation at FCC Week 2025, Numerical Tools for Beam-beam Studies, https://indico.cern.ch/event/1408515/contributions/6526696/attachments/3071010/5432950/pkicsiny_fccweek_2025.pdf
- NAPAC 2025 Talk, XSUITE contributions to Modeling of Collective effects in Present and Future Colliders: Synergies Between FCC and EIC, https://epaper.kek.jp/napac2025/pdf/FRAD01_talk.pdf
- IAS Program 12-15th January 2026, HONG KONG, On Electron Cloud Effects and Possible Mitigation Strategies, https://indico.global/event/15407/contributions/142240/attachments/66096/127877/Pieloni_ecloud_IAS_HK26.pdf

5. List of Publications

- Sabato L, et al. "Electron Cloud mitigation techniques for the FCC-ee", JACoW IPAC2025 (2025), WEPS050 doi:10.18429/JACoW-IPAC2025-WEPS050
- Phys. Rev. Accel. Beams 28, 051002 – Published 27 May, 2025.
- *Computers* **2025**, *14*(7), 287; **https://doi.org/10.3390/computers14070287**
- Wańczyk, J., Pieloni, T., Buffat, X. *et al.* First measurements of beam-beam effects in beam-separation, luminosity-calibration scans at the LHC. *Eur. Phys. J. C* **86**, 282 (2026). https://doi.org/10.1140/epjc/s10052-026-15476-8