Swiss Accelerator Research and Technology

Accelerator design and simulation framework for FCC-ee: optics and collective effects.

(FCC-ee Dynamics)

EPFL:

Dr. T. Pieloni, Dr. L. Van Riesen-Haupt, Dr C. Garcia,

CERN:

Dr. G. Iadarola, Dr. X. Buffat, Dr R. De Maria, Dr. R. Tomas, K. Oide, F. Zimmermann.

30.06.2024

1. Introduction / Original goals of this project

In FCC-ee, beam-beam effects are important, both for the experimental conditions and the preservation of the beam quality. At the beginning of the project simulations were performed using tools which have been developed for linear colliders and the interaction regions are modeled independently and with no impact to the accelerator lattice. This is known not to be representative of the beam dynamics in circular colliders and represents a limitation to the present understanding of the possible performance reach and feasibility of such a collider. The project aims to develop the proper modeling of the particle dynamics and propose a possible operational scenario to avoid limitations and reach the project goals. A study of the multiple beam-beam interactions and dynamics effects for different optical configurations in a self-consistent manner will be the basis of such modeling.

2. Realisation

In order to meet the project goals, three main areas for development were identified. These areas consist of creating a software suite that allows for an efficient management of the FCC-ee lattice and conversion between different codes; new beam-beam simulation tools that can be integrated into the software framework and include the relevant physics mechanism; a overhaul of existing optics and tracking tools to ensure that they are fit for simulations with high synchrotron radiation. The new software framework developed is now also benchmarked against observations at the SuperKEKB lepton collider in Japan. A post-doc and two PhD students were hired for these efforts. On top of this a further PhD student was hired with the

aim to gain expert knowledge on lattice design and apply this to create alternative lattice options to compete with the baseline designs and to give feedback to the High Temperature Superconducting magnet development project in terms of tolerances of unwanted magnetic multiples.

3. Results / Conclusions / Deliverables

The project aimed to establish a framework for realistic simulations of the FCC-ee machine's commissioning and operations, incorporating multiple physics effects to assess performance and design feasibility. The primary goal was to develop either an infrastructure or, ideally, a comprehensive software system capable of simulating collision processes, the accelerator lattice, and their interplay, including synchrotron radiation and beamstrahlung effects. These efforts culminated in the creation of a new software framework for beam dynamics studies called XSUITE, developed in collaboration with CERN's accelerator beam physics group, called XSUITE. This new model replaces many of the well-established models still in use at the LHC.

Sequence Manager and xsequence
The initial focus was on the development of "xsequence," a tool that allowed sequence management for different simulation tools, ensuring they used identical lattices.
Key contributions included the creation of scripts to maintain crucial optics properties during lattice conversions, such as the beta function and phase advances, which are essential for correction schemes. The "xsuite" photon emission spectrum was rigorously tested and found to align with theoretical predictions. Studies also benchmarked alignment error effects on emittance, comparing various methods and highlighting the precision of "xsuite" tracking.

Beam-Beam Simulations
The beam-beam simulation effort began with the development of a strong-strong beam-beam model in "xsuite," aimed at simulating Beamstrahlung effects. The model was successfully benchmarked against existing codes, such as COMBI and GUINEA-PIG, and optimizations using parallelization techniques like MPI and OpenMP showed significant speedups.
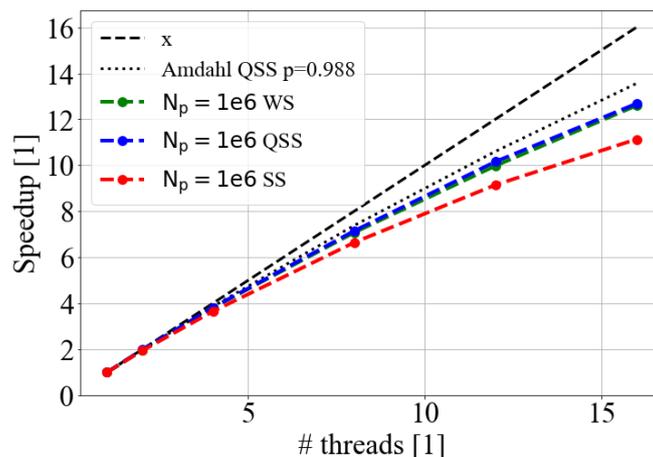

Figure 1: Performance scaling of the xsuite beam-beam model in the different approximations (WS: weak-strong, QSS: quasi strong-strong, SS: strong-strong), using CPU multithreading with OpenMP.

Studies focused on the tune footprint of the FCC-ee collider, with successful comparisons made between "xsuite" and other reference codes. Additionally, the beam-beam model was optimized for GPU execution, resulting in further computational speed improvements. Investigations into beam instability, such as the x-z instability and 3D flip-flop instability, were conducted, contributing to a better understanding of the machine's behavior under varying conditions.

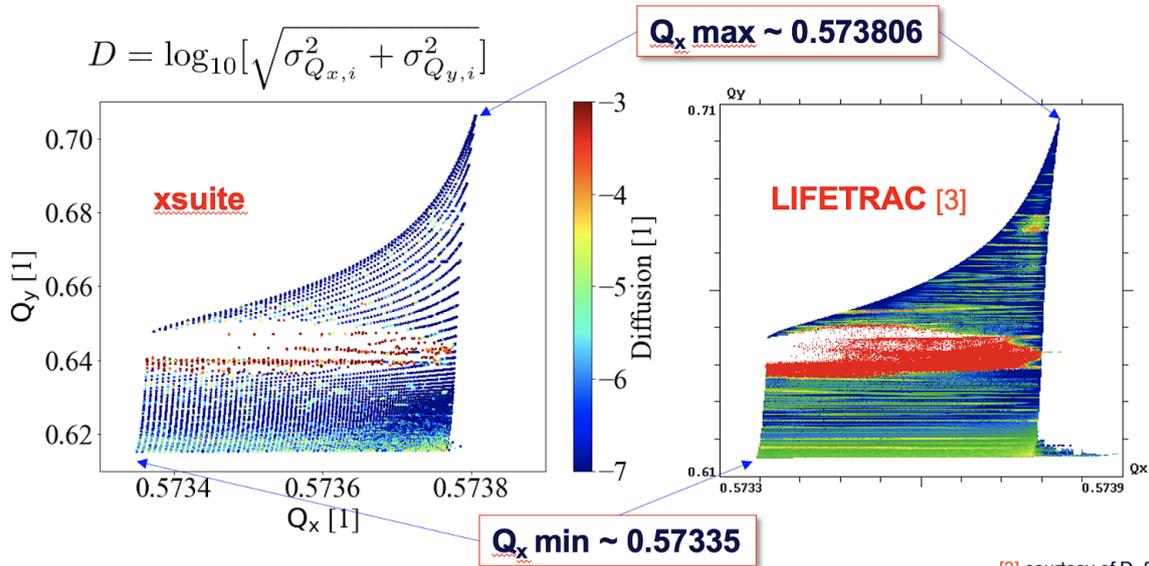$$D = \log_{10}\left[\sqrt{\sigma_{Q_{x,i}}^2 + \sigma_{Q_{y,i}}^2}\right]$$

Figure 2: Tune footprint of the FCC-ee Z configuration in a 2 IP model. The left plot shows the footprint produced in xsuite while the right plot shows the same footprint produced by the reference code LIFETRAC. The colormap shows the diffusion computed

[3] courtesy of D. Shatilov

Optics and Tracking Codes

Work on optics and tracking codes involved updates to the MAD-X code for the Future Circular Collider (FCC-ee) simulation. This included enhancing MAD-X's ability to simulate synchrotron radiation (SR) effects, which are significant in high-energy colliders like the FCC-ee. An important task was to review the MADX modules where the SR has an impact, more in detail in the modules: TWISS, TRACK and EMIT. This work was complemented with a bibliographic work on the physics and mathematics of SR effect in accelerators.

The updates also addressed high-order terms in magnet transfer matrices to mitigate the "sawtooth effect" caused by SR losses in long dipoles. Improved tapering algorithms yielded better results in tracking and emittance calculations.
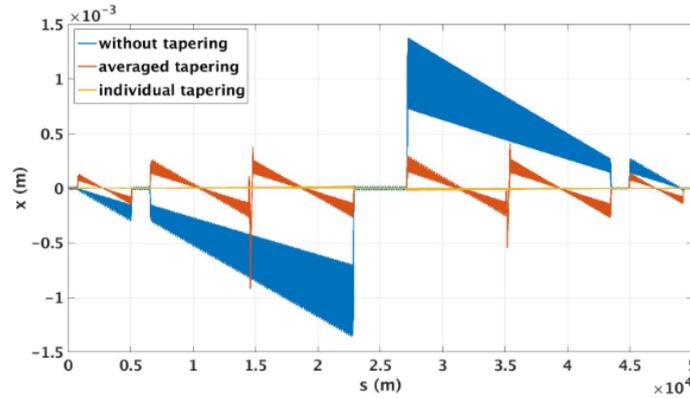
Figure 7: Same scale comparison of the orbit without tapering (blue), with individual tapering (yellow) and with averaged tapering (orange).

Lattice Design

The project explored Nested Magnets (NMs) to counter the energy loss due to synchrotron radiation by increasing the filling factor for bending magnets in the machine. This approach necessitated modifications to the lattice, such as introducing an unbalanced bending angle between quadrupoles. The studies showed reduced power consumption and synchrotron radiation of 17% of the 50MW per beam requires by the project, leading to a more energy-efficient design. Further investigations into Nested Sextupoles and their potential for simplifying alignment and tuning will continue to refine the machine's design.
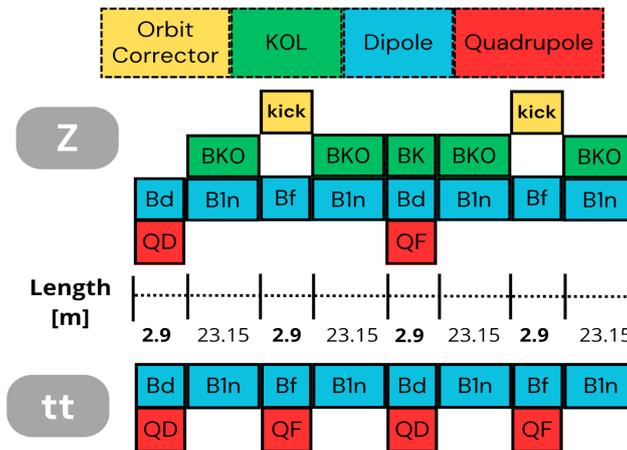

Figure 8: The different elements in Nested Magnets are presented here, with K0L representing the bending angle when the geometric angle is different from it.

In summary, this work made significant progress in advancing the simulation tools necessary for the FCC-ee project, contributing both to the development of the XSUITE software and the validation of critical physics effects. The project laid a solid foundation for future studies aimed at optimizing the machine's performance, while also identifying key effects that will require careful consideration during its operation. Additionally, the new software has inspired further developments related to machine protection studies, enabling the integration of collision effects with phenomena such as machine impedance and electron cloud effects for a

comprehensive analysis of the FCC-ee. Lastly, a benchmark of the model on an operational collider, SuperKEK in Japan, has just commenced.

4. **Publications and Outreach**

Status reports of the project activity have been presented at the dedicated EPFL-LPAP meetings (https://indico.cern.ch/category/9606/) and at the FCCIS workshop, IPAC and FCC Week 2023. An international workshop has been organized at EPFL on Beam-beam effects in Circular Colliders https://indico.cern.ch/event/1344947/.

Conferences and Workshops:

- L. van Riesen-Haupt et al., Nested Magnet Optics for FCC-ee, FCC Week 2024 San Francisco, CA, USA, 2024.
- L. van Riesen-Haupt et al., Equilibrium Emittances for FCC-ee: Tracking and Matrix Methods, FCCIS 2023 WP2 Workshop Rome, Italy, 2023.
- L. van Riesen-Haupt et al., Simulation Tools for Future Colliders, Joint Annual Meeting of the Swiss and Austrian Physical Societies Basel, Switzerland, 2023.
- L. van Riesen-Haupt et al., FCCee-Beam Dynamics Simulations, CHART Workshop 2023 Villigen, Switzerland, 2023.
- L. van Riesen-Haupt et al., Simulations of IR tuning, FCC Week 2023 London, United Kingdom, 2023.
- L. van Riesen-Haupt et al., Code development status, FCC Week 2023 London, United Kingdom, 2023.
- L. van Riesen-Haupt et al., IP Tuning, FCC-IS Workshop Geneva, Switzerland, 2022.
- L. van Riesen-Haupt et al., EPFL-CERN Software Collaboration, FCC-EIC Joint & MDI Workshop Geneva, Switzerland, 2022.
- L. van Riesen-Haupt et al., IP Optics Corrections in FCC-ee, FCC-EIC Joint & MDI Workshop Geneva, Switzerland, 2022.
- L. van Riesen-Haupt et al., MAD-X Benchmarking and Solenoid Models, FCC Week 2022 Paris, France, 2022.
- P. Kicsiny et al., "Towards beam-beam simulations for FCC-ee", FCCIS 2022 Workshop, 06 Dec 2022. (Oral Presentation)
- P. Kicsiny et al., "Benchmark and performance of beam-beam interaction models for XSUITE", IPAC'23, Venice, Italy, May 2023.
- P. Kicsiny et al., "Bhabha scattering model for multiturn tracking simulations at the FCC-ee", IPAC'23, Venice, Italy, May 2023.
- P. Kicsiny et al., "Beam-beam code progress", FCC week 2023, London, United Kingdom, June, 2023. (Oral Presentation)
- P. Kicsiny et al., "Beam-beam simulation: Top-up injection, dynamic aperture and Bhabha lifetime, bunch length vs intensity", FCC Innovation Study, Rome, Italy, November, 2023. (Oral Presentation)
- P. Kicsiny et al., "Modelling of beam-beam effects in future lepton colliders", Swiss Physical Society Meeting 2022, Fribourg, CH. (Oral presentation)
- T. Pieloni et al., "**Overview of the Software framework and developments for the FCC-ee**", FCC week 2022, 30 May-3 June, Paris, France.
- P. Kicsiny et al., "**Simulations of FCC-ee beam-beam effects with xsuite",** FCC week 2022, 30 May-3 June, Paris, France.
- R. De Maria et al., "MAD-X Status and progress", FCC week 2022, 30 May-3 June, Paris, France.
- Abramov et al., "FCC-ee collimation studies", FCC week 2022, 30 May-3 June, Paris, France.

- P. Kicsiny et al., "Towards beam-beam simulations for the FCC-ee", presentation & publication at the ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), 12-16 Sept. 2022 INFN Frascati National Laboratories, Rome.
- G. Simon et al., "Realistic Optics & Simulation Modelling in the FCC-ee Era : update", BIMP meeting at Université Paris-Saclay, 8th March 2022.
- G. Simon et al., "SR radiation issues in FCC-ee ", FCC week 2022, 2nd June 2022.
- G. Simon et al., "Synchrotron Radiation issues in MADX", FCC- France & Italy workshop 2022, 22nd November 2022.
- García-Jaimes et al., "Optics Matching with Arc Errors", FCCIS 2022 Workshop, 08 Dic 2022. (Oral Presentation)
- García-Jaimes et al., "Combined function lattice with constant partition numbers for FCC-ee". FCC Week 2023. London. 08.06.2023.
- García-Jaimes et al., "HTS FCC-ee energy efficient beam optics". CHIPP/CHART Workshop on Sustainability in Particle Physics and CHIPP 2023 plenary, Sursee. 14.06.2023
- C. Garcia-Jaimes et al., "HTS FCC-ee energy efficient beam optics". Joint Annual Meeting of the Swiss and Austrian Physical Society 2023. Basel, Switzerland 04.09.2023.
- G. Simon et al., "Review of MAD-X for FCC-ee studies", FCC week 2023, London, United Kingdom, June, 2023.

Publications
- L. van Riesen-Haupt et al. The status of the fcc-ee optics tuning. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- L. van Riesen-Haupt et al. Relaxed insertion region optics and linear tuning knobs for the future circular collider. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- L. van Riesen-Haupt et al. Benchmarking equilibrium emittance simulation tools for the future circular collider. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- S. Horney et al. Sextupole RDTS in the LHC at injection and in the ramp. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- S. Jagabathuni et al. Simulated performance of fcc-ee ip tuning knobs. In Proc. 15th International Particle AcceleratorConference (IPAC'24), Nashville, TN, USA, May 2024.
- Y. Wu et al. Lattice correction and polarization estimation for the future circular collider e+e-. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- C. Garcia Jaimes et al. First fcc-ee lattice designs with nested magnets. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- C. Garcia Jaimes et al. Parameter space for the magnetic design of nested magnets in the fcc-ee arc cell. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- C. Garcia Jaimes et al. First comparison studies in dynamic aperture for nested magnets and baseline lattice in the fcc-ee. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- F. Zimmermann et al. Selected advances in the accelerator design of the future circular electron-positron collider (fcc-ee). In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- G. Simon et al. Review of mad-x for fcc-ee studies. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.
- G. Iadarola et al. Xsuite: an integrated beam physics simulation framework. In Proc. 15th International Particle Accelerator Conference (IPAC'24), Nashville, TN, USA, May 2024.

- T. K. Charles, B. Holzer, R. Tomas, K. Oide, L. van Riesen-Haupt, and F. Zimmermann. Alignment & stability challenges for FCC-ee. EPJ Tech. Instrum., 10(1):8, 2023.
- J. Dilly, V. Ferrentino, M. Le Garrec, E. H. Maclean, L. Malina, T. Persson, T. Pugnat, L. van Riesen-Haupt, F. Soubelet, and R. Tomss. First operational dodecapole correction in the lhc. Phys. Rev. Accel. Beams, 26:121001, Dec 2023.
- F. Carlier et al. Lhc run 3 optics corrections. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- C. Garcia Jaimes et al. Impact of dipole quadrupolar errors in fcc-ee. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- C. Garcia Jaimes et al. Exploring fcc-ee optics designs with combined function magnets. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- C García-Jaimes *et al* 2024 J. Phys.: Conf. Ser. **2687** 022007
- R. Tomas et al. Progress of the fcc-ee optics tuning working group. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- Y. Wu et al. Spin-polarization simulations for the future circular collider e+e- using bmad. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- F. Carlier et al. Challenges of k-modulation measurements in the lhc run 3. In Proc. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May, 2023.
- Peter Kicsiny, Xavier Buffat, Daniel Schulte, Helmut Burkhardt, Tatiana Pieloni, and Mike Seidel, Phys. Rev. Accel. Beams 27, 091001 – Published 27 September 2024
- A. Abramov *et al* 2024 JINST **19** T02004
- Abramov et al. "DEVELOPMENT OF COLLIMATION SIMULATIONS FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
- A, Abramov et al. "DESIGN OF A COLLIMATION SECTION FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
- García-Jaimes, T. Pieloni, L. van Riesen-Haupt, R. Tomas, "Combined function magnets with constant partition numbers lattice for the Future Circular lepton Collider", Accelerating News, No. 43, Mar. 2023.