Swiss Accelerator Research and Technology

CHART Scientific Report

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

(FCC-ee Dynamics)

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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.

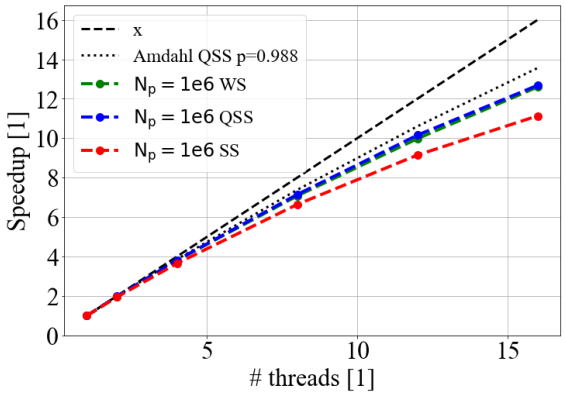

Figure 1: Performance scaling of the xsuite beam-beam model in the different approximations (WS: weak-strong, QSS: quasi strong-strong, SS: strong-strong), using CPU multithreading with OpenMP.

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. The development has also been tested on the SuperKEKb collider observations and a publication shows the interpretation of the effects for the Japanese collider. For the FCC-ee numerical evidence of severe instabilities and tolerance to beams differences in emittances and

intensities have been defined. The implementation has enabled the full simulation possibilities for the FCC-ee, before not possible.

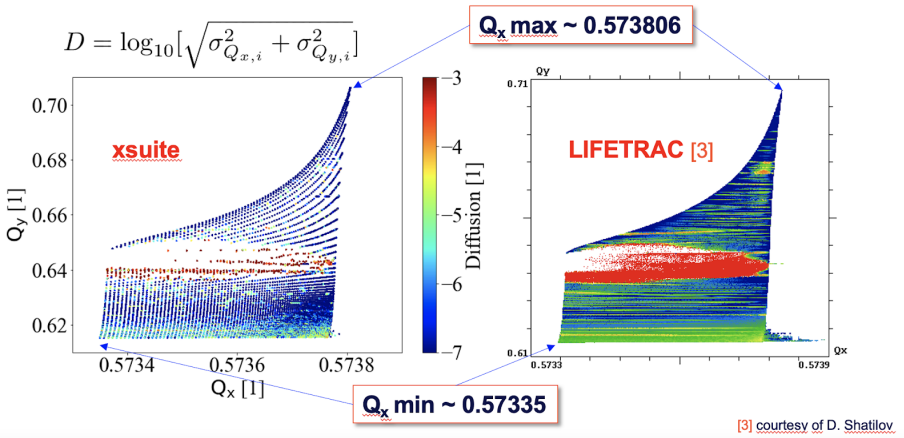

Figure 2: Tune footprint of the FCC-ee Z configuration in a 2 IP model. The left plot shows the footprint produced in xsuite while the right plot shows the same footprint produced by the reference code LIFETRAC. The colormap shows the diffusion computed

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.

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.

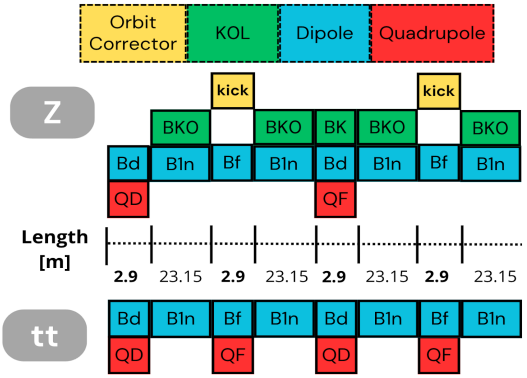

Figure 8: The different elements in Nested Magnets are presented here, with K0L representing the bending angle when the geometric angle is different from it.

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:

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- L. van Riesen-Haupt et al., Equilibrium Emittances for FCC-ee: Tracking and Matrix Methods, FCCIS 2023 WP2 Workshop Rome, Italy, 2023.
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