Accelerator Design and simulation framework for FCC-ee optics and collective effects studies

Team:

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1. Software Framework for collaborative beam dynamics studies for the FCC-ee

In order for the software needs of the FCC-ee collaboration to be met, 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; a overhaul of existing optics and tracking tools to ensure that they are fit for simulations with high synchrotron radiation. 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.

1.1. Sequence Manager: Xsequence and Xconverter

Following the initial review period and developments of tapering schemes for Bmad and pyAT, work started on the development of a lattice manager to improve the interface between different simulation tools. The purpose of this lattice manager is to provide a central place where conversion tools between simulation codes can be implemented, as well as have a robust and flexible framework in Python to adapt FCC-ee lattices, assign errors and misalignments, and control the state of the lattice. This can greatly improve model creations and facilitate simulation campaigns on computing clusters, as well as ensure consistency of lattices between different codes in order to perform comparative studies.

A first working version of this framework, named ’xsequence’, has been developed and presented. This framework contains several conversion codes to or from MAD-X, cpymad, pyAT, SAD and xline. It furthermore includes specific functionalities to adapt and adjust models for simulations. A robust workflow, including automatic tests of the code, has been implemented in Github to improve maintainability and provide a clear path for stable future developments. The developments have been coordinated with recent developments of the new simulation tools at CERN named ’xsuite’, and strong synergies have been found to use the new simulation tools for improved FCC-ee modelling. In Figure 1 a schematic of the on-going developments for the Large Hadron Collider (green boxes in XSUITE) with the EPFL_LPAP contributions to extend XSUITE to beam dynamics for FCC and in particularly FCC-ee (RED boxes) are shown.

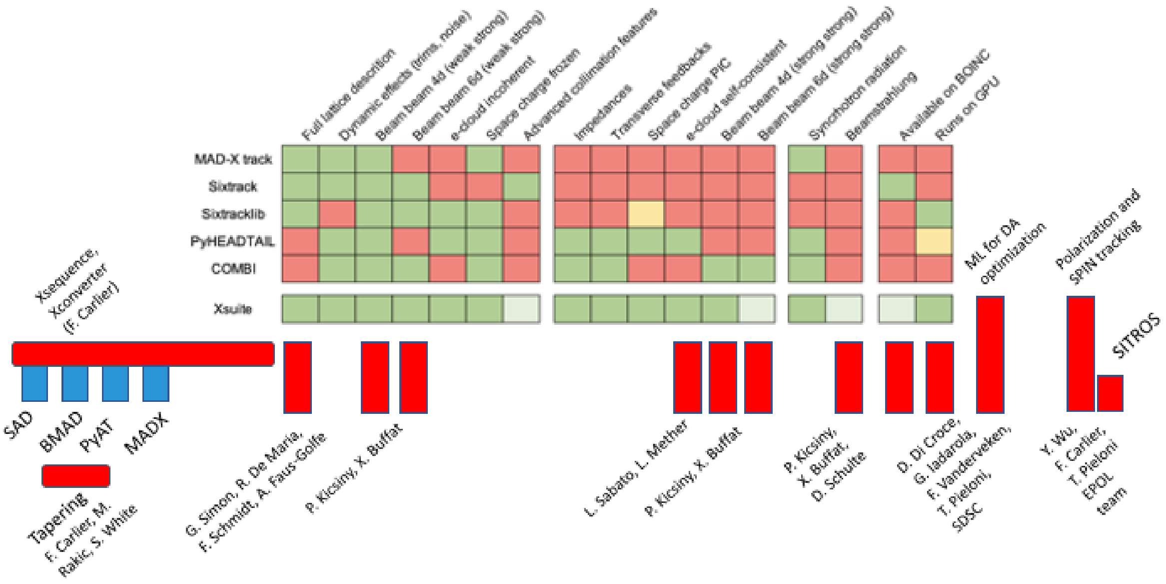

Figure 1 Schematic of the software developments around XSUITE for the Large Hadron Collider studies (green boxes) and the needed tools for the Future Circular Colliders (red boxes) where EPFL-LPAP contributes and leads the development under the auspice of CHART. The name of the people involved in the associated CHART projects are also indicated.

Fitting scripts were written that aim to recover optics as intended after lattice conversion. This is done by identifying key properties that are intrinsic to the definition of the FCC-ee optics. These properties include the beta function at the interaction point, phase advances between different sections that are required for correction schemes and functionalities of dispersion suppressors. A dialogue has been initiated to motivate stakeholders to define further defining features and it is envisioned to store these with traditional lattice descriptions. A first application of these scripts was implemented in MAD-X to allow for optics preservation after lattice slicing.

There is a continued close collaboration with the CERN MAD-X team and Xsuit developers to further understand the simulation requirements for FCC-ee. More specifically the tilted solenoid as defined in SAD was explored and a successful MAD-X implementation was found. In the close future these methods should be implemented in Xsuite and benchmarked against MAD-X and SAD for uses in FCC-ee and other accelerators.

1.2. Beam-Beam Simulations: BB4D, BB6D and Beamstrahlung.

The study on beam-beam effects has started with the hiring of a PhD student Peter Kicsiny in May 2021. The first phase of the study was dedicated to the study of the impact of the linearized beam-beam force and its impact on the beam orbit and optics. This study allowed for the learning of the basics of beam dynamics as well as the usage of MAD-X and its python interface cpymad. The need for self-consistency in the modelling of the two beams was approached and an algorithm based on the code TRAIN was implemented within cpymad.

In 2021 the main task was the implementation of a soft-Gaussian strong-strong beam-beam simulation model and its extension to simulate Beamstrahlung. The model has been developed and optimized to an efficiency that is on par with other state of the art frameworks, such as COMBI. An initial parallelized version of the code using MPI has also been developed. Preliminary benchmark studies have been performed using COMBI (runtimes, tune spectra) and GUINEA-PIG (Beamstrahlung). Some limitations of the current implementation have been identified and are currently being addressed.

Over the year of 2022, several benchmark studies of the Xsuite beam-beam implementation have been carried out against reference codes e.g. computation times, beamstrahlung spectrum, various parameter scans. The beamstrahlung feature has been added to the main release of Xsuite, ready for public use. Scripts for Frequency Map Analysis (FMA) have been developed (computation of the tunes, diffusion and resonance lines).

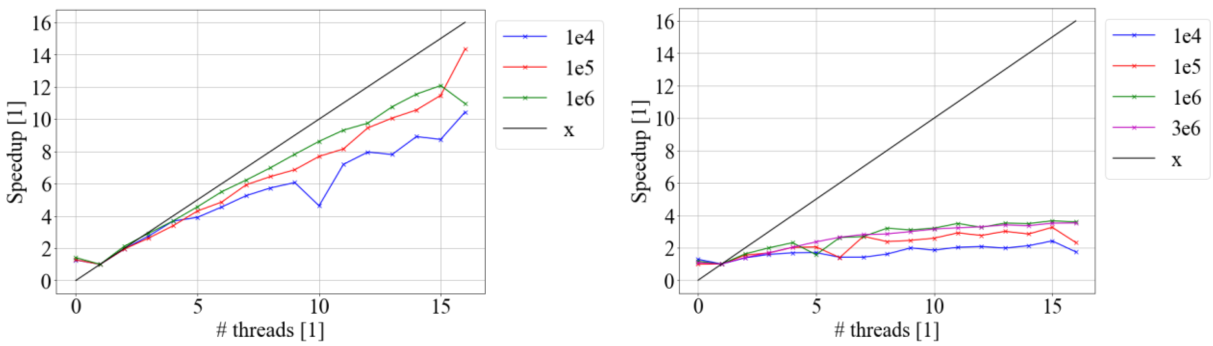

Figure 2 Performance evaluations of the developed module for beam-beam and beamstrahlung effects for the FCC-ee. The left plot shows the evaluations for the so called weak-strong model while the right plot shows the performances for the strong-strong model.

Experiments with parallelizing the code using MPI have been performed but did not lead to a desired performance gain due to the nature of the algorithm. The parallelization with OpenMP has been optimized. Performance scans of Figure 2 shows good scaling in the weak-strong model (left plot) and a scaling with saturation after a factor 4-5 speedup in case of the strong-strong model (right plot). The numbers on the plot labels indicate the number of macroparticles in each beam.
Several benchmark studies of the tune footprint for LHC and FCC-ee settings have been performed using a linear lattice. The FCC-ee footprint has been compared to several reference codes such as PySBC, LIFETRAC and BBWS. After an optimization of the bunch slicing algorithms in Xsuite a good qualitative and quantitative (in terms of the diffusion and extent of the footprint) agreement was found. A benchmark of the FCC-ee Z tune footprint is shown in Figure 3 as an example.

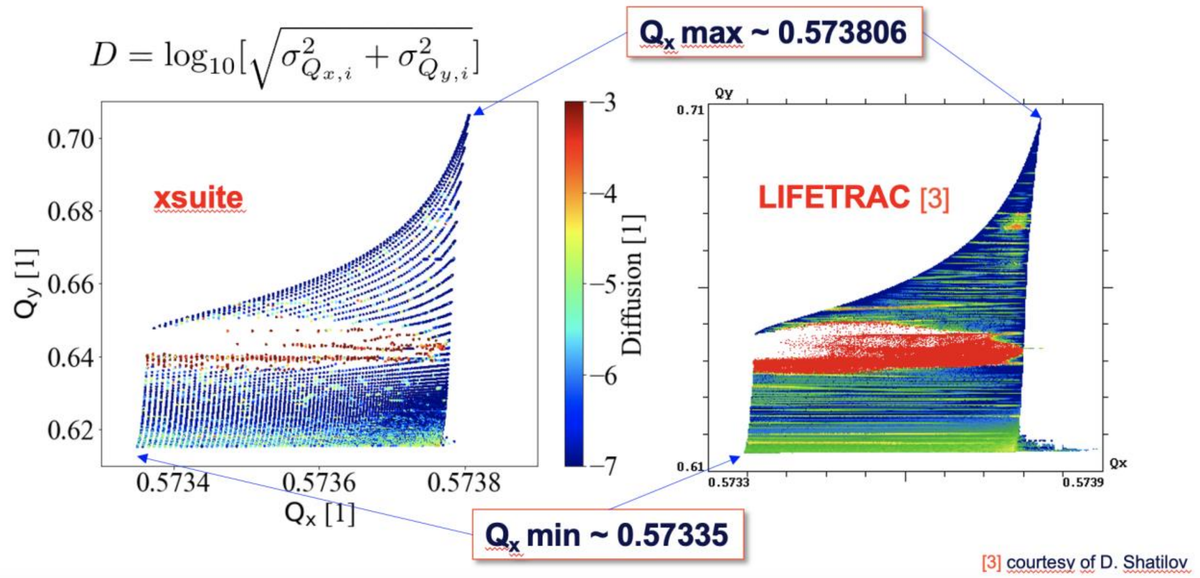

Figure 3 Beam-beam transverse footprint and frequency map analysis obtained using the XSUITE beam-beam module developed (left plot) and the known Lifetrack model from [3](right plot).

A summer student has been co-supervised, working on an analytical treatment of the 3D flip-flop in case of collisions with asymmetric bunch parameters. A paper is in preparation about the results of the work. A second paper is envisaged about the comparison of the analytical approximations with Xsuite simulations, for which simulations are currently ongoing. Preliminary results are already available, see Figure 4, showing the equilibrium bunch length of the two colliding bunches with a varying initial intensity asymmetry. The comparison is good for large asymmetries while some differences have still to be understood for smaller values.

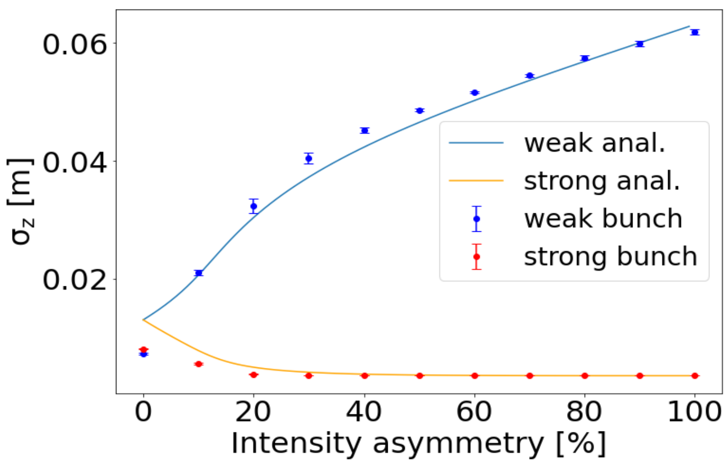

Figure 4 Equilibrium bunch length of the colliding bunches as a function of the bunch intensity asymmetry in percentage using the weak-strong model (blue line) and the strong-strong model (red line).

1.3. Optics and Tracking Codes: Full Lattice Description and Tapering

For the part of the project devoted to the optics developments a student has been hired on the 10/2021 he has become familiar with Python, Fortran and C programming language, optics and tracking codes and synchrotron radiation physics. In October 2021, the PhD started in the framework of the FCC-ee simulation effort. This work consists in the update of the MAD-X (Methodical Accelerator Design) code to the Future Circular Collider FCC-ee. This update includes a more accurate and realistic way to simulate the Synchrotron Radiation (SR) important at high-energies as in the FCC-ee (45-182 GeV per beam) and the fringe field solenoidal detector. Firstly, the aim was to familiarize with the MAD-X code and symplectic tracking. Secondly, the 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.

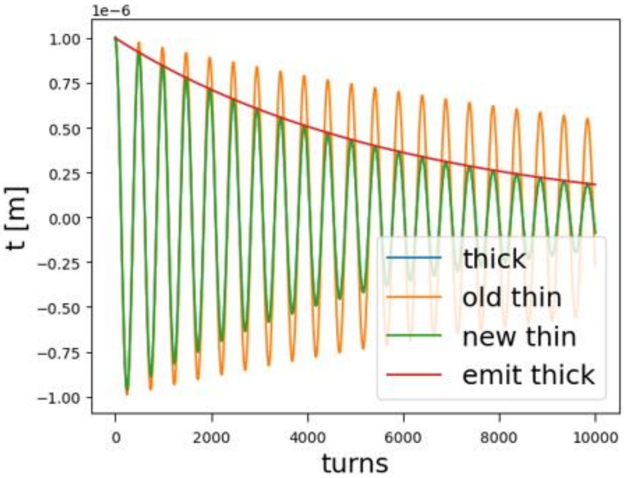

Figure 5 Betatron amplitude oscillations as a function of turns for the different modules available in MADX models with synchrotron radiation. The different colors indicate the different models used.

Then a series of simulations on FCC-ee lattices to verify the physics of SR and to analyze which of these aforementioned modules required corrections were carried out. To benchmark the impact, calculations were done via MAD-X to simulate some relevant beam parameters as: radiation damping, partition numbers and tune in the FCC-ee lattices. In the case of the tune, the "FCC-ee sawtooth effect" due to the SR losses in the long dipoles was included. The current work is on the implementation in MAD-X of high-order terms in the transfer matrix of magnets to calculate more accurately the optics functions with tapering to mitigate the impact of "sawtooth effect".

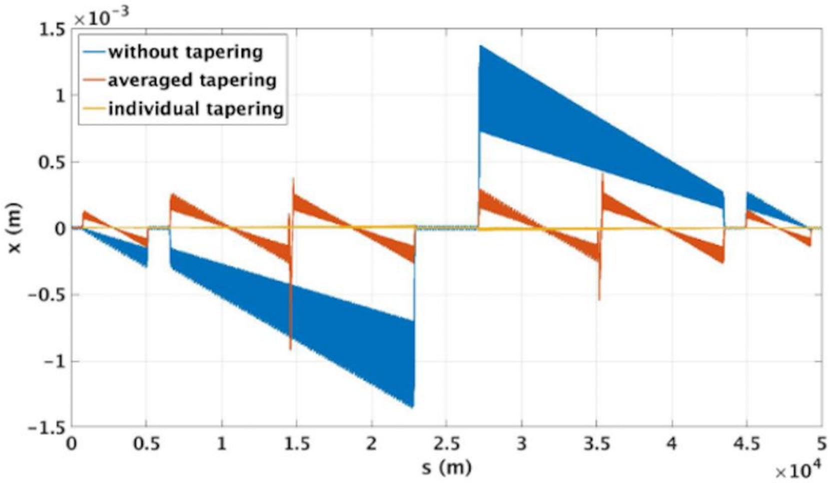

Figure 5 Same scale comparison of the orbit without tapering (blue), with individual tapering (yellow) and with averaged tapering (orange).

2. FCC-ee Lattice Design

2.1. Systematic quadrupolar Errors in the FCC-ee baseline optics

For the purpose of gaining expert knowledge, the magnetic quadrupolar errors have been added to the dipoles in the arcs and their impact on the different optical functions has been analyzed. The magnet design team for FCC-ee predicts a systematic quadrupolar error in the arc dipoles; the sign of the quadrupolar error depends on the arc in which the dipole is located because the beams cross in the Interaction Points (Ips) and Intermediate Straight Section (ISSs), moving from the inside to the outside ring or vice versa. This quadrupolar field causes a change in the β-function, which can be observed via the β-beating function, defined as:

$$\frac{\Delta\beta}{\beta} = \frac{\beta_{error} - \beta_{ideal}}{\beta_{ideal}}$$

where β_{error} is the β-function with the errors applied and β_{ideal} is the original lattice. After a detailed analysis of the lattice placed in the official FCC-ee repository, the existence of a symmetry in the lattice for the Z-mode can be observed. With 4 IPs evenly distributed in the lattice, 4 ISSs and 8 arcs between them, the entire ring can be efficiently manipulated by working with only 25% of the lattice, since the families of quadrupoles are homogeneous in the arcs.

The FCC-ee super-FODO cells consist of five FODO cells with a phase advance of π/2 [radians]. This scheme has been applied successfully at B-factories for more than 20 years. To achieve sufficient dynamic apertures, a chromaticity correction with non-interleaved pairs of sextupoles could be necessary.

This super-FODO has a phase advance of 2.5 π. The sextupoles are placed to make pairs in which two identical sextupole magnets are connected by a −I transformer.

Modeling the expected magnetic quadrupolar errors in MAD-X is possible and allows calculation of the maximum error to obtain a given β-beating, in the case of 1%, the quadrupolar error in the arc dipoles should be 1.6×10^{-4}. This error is called "b2" and is the normalized term for the quadrupolar error with a specific radius, for this exercise 10 mm. In Figure 6 the impact of such b2 error to the betatron function is plotted along the 100 Km length of the FCC-ee. A maximum beta-beating of 1 % is expected.

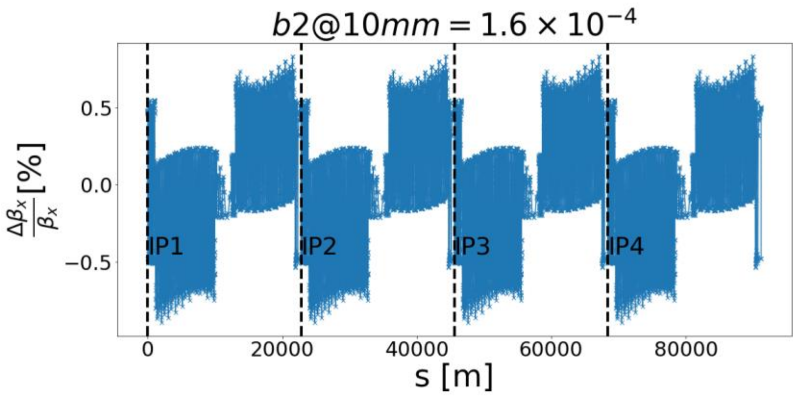

Figure 6: β-beating in percentage along the collider lengths due to quadrupolar errors in the dipole magnets of b2 at 10mm= $1.6{\times}10^{-4}$.

Such error is systematic therefore to recover an appropriate behaviour in the IPs it is mandatory to change the strength values for the quadrupole magnets (*k1*).; it is possible thanks to the existing symmetry already mentioned in the FCC-ee lattice, since the arcs 1, 3, 5 and 7 (to the right of the interaction point) contain the same families of quadrupoles (QF4 and QD3) and arcs 2, 4, 6 and 8 (to the left of the interaction point) contain QF2 and QD1 in their FODO cells. With this in consideration on the lattice symmetries it is possible to reduce the problem and absorb the systematic b2 error in the lattice design. This is done by using the MAD-X matching module constrained to recover the correct phase advance in the arcs (and the horizontal and vertical betatron tune) and the periodic behaviour at the IPs.

The summary of the parameters obtained for the entire lattice with Matching function in MAD-X is presented in Table 1.

Parameter	Ideal Lattice	Lattice with b2 errors	Lattice after the Matching
Horizontal tune	214.260	214.259	214.260
Vertical tune	214.380	214.379	214.380
Horizontal chromaticity	-1.165	-0.986	-0.945
Vertical chromaticity	-1.911	-3.461	-2.796
β_{xMAX} [m]	4663.567	4684.116	4663.567
β_{yMAX} [m]	9924.567	10037.678	9924.567
$\mathrm{Dispersion_{MAX}}$ [m]	0.624	0.632	0.787

Table 1: Summary of parameters from MAD-X for FCC-ee.

The results, as shown in Table 1, indicate that the tunes are equal to those in the ideal lattice. The maximum beta function in the arc β_{MAX} in the horizontal and vertical planes are also the same. In the lattice with b2 errors and matching the chromaticity changes by less than one unit; this is due to the changes of β functions, quadrupole strengths and the quadrupolar errors in the dipoles.

Further analysis showed that β-beating is below 0.75% in the arcs but peaks in the ISSs (Figure 7). This is not a problem as there are no IPs in these regions and large beating can be allowed.

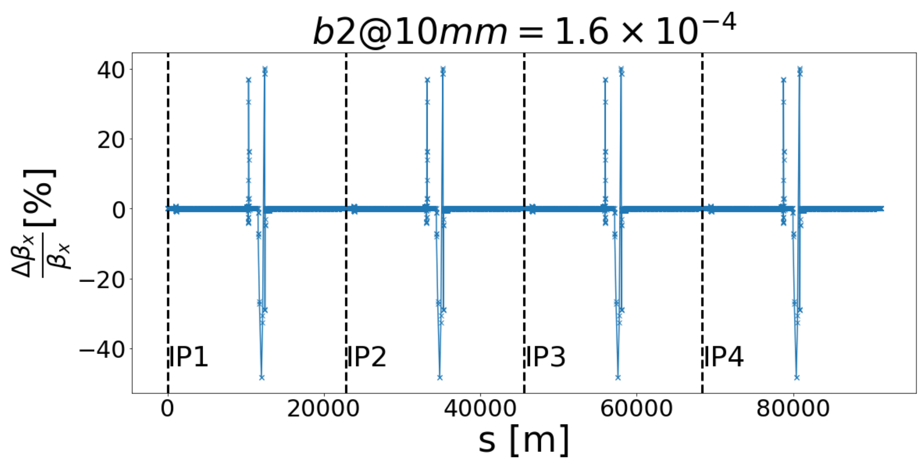

Figure 7: β-beating after Matching.

2.2. New optics design with High Temperature Superconducting (HTS) combined function magnets.

A very first step toward the design of an FCC-ee using combined function HTS magnets has started. This study aims to replace the quadrupoles with combined function magnets that include dipole components to increase the filling factor of the machine. These magnets can also include sextupolar components, that would allow for the removal of sextupoles in the lattice and give more space for arc dipoles to further improve the filling factor. The goal of this study is to also feedback to the magnet design teams of CHART possible set of design specifications and multipole errors tolerances from beam dynamics considerations and particle stability to be used for the design of a first magnet prototype as proposed in the approved CHART FCC HTS4 project. In preliminary studies it was found that such a substitution would lead to a reduction in synchrotron radiation by more than 17%, but would not be trivial as it changes the damping partition numbers in the beam and would lead to the loss of longitudinal stability. This option has to be further explored and the effects leading to this behaviour have to be studied carefully.

3. Presentations and Publications:

Status reports of the project activity have been presented at the dedicated EPFL-LPAP meetings (https://indico.cern.ch/category/9606/) and at the latest FCCIS workshop in December.

1. FCC-ee Software Framework
https://indico.cern.ch/event/1085318/contributions/4582723/subcontributions/354655/attachments/2355534/4019941/FCCIS_workshop_FS_Carlier.pdf
2. Status of Collimation tracking code development
https://indico.cern.ch/event/1085318/contributions/4582724/subcontributions/357241/attachments/2356463/4021460/CollimationSimulations-FCCISWP2-20211201.pdf
3. 6D Beam-beam Modelling in Xsuite
https://indico.cern.ch/event/1085318/contributions/4582729/subcontributions/355430/attachments/2356471/4021479/pkicsiny_beambeam_6d.pdf
4. F. Carlier,"Code developments", EPFL-LPAP Activity Meeting, EPFL.
5. P. Kicsiny "Beam-beam effects in future circular lepton colliders (Oral Presentation), EPFL-LPAP Activity Meeting, EPFL, 11/02/2022.
6. P. Kicsiny "6D beam-beam modeling in Xsuite ", (Oral Presentation), BE-ABP-CEI section meeting, CERN,17/01/2022.
7. P. Kicsiny "6D beam-beam modeling in Xsuite", (Oral Presentation), EPFL-LPAP FCC-ee Software Framework Meeting, EPFL, 11/11/2021.
8. P. Kicsiny "Beam-beam studies with MadX and first steps with PyHEADTAIL and xsuite" , (Oral Presentation), EPFL-LPAP FCC-ee Software Framework Meeting, EPFL, 08/07/2021
9. P. Kicsiny, "Modelling of beam-beam effects in future lepton colliders", Swiss Physical Society Meeting 2022, Fribourg, CH.
10. T. Pieloni and F. Carlier, "**Overview of the Software framework and developments**

for the FCC-ee", FCC week 2022, 30 May-3 June, Paris, France.
11. P. Kicsiny et al., "**Simulations of FCC-ee beam-beam effects with xsuite**", FCC week 2022, 30 May-3 June, Paris, France.
12. R. De Maria, "MAD-X Status and progress", FCC week 2022, 30 May-3 June, Paris, France.
13. A. Abramov et al., "FCC-ee collimation studies", FCC week 2022, 30 May-3 June, Paris, France.
14. P. Kicsiny, "Towards beam-beam simulations for the FCC-ee", presentation at the ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), 12-16 Sept. 2022 INFN Frascati National Laboratories, Rome. Proceedings available soon.
15. A. Abramov et al. "DEVELOPMENT OF COLLIMATION SIMULATIONS FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
16. A, Abramov et al. "DESIGN OF A COLLIMATION SECTION FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
17. G. Simon, "Realistic Optics & Simulation Modelling in the FCC-ee Era : update", BIMP meeting at Université Paris-Saclay, 8th March 2022:.
18. G. Simon, "Comparisons of radiation and damping", EPFL-LPAP
19. FCC-ee Software Framework Meeting, 24th March 2022.
20. G. Simon, "SR radiation issues in FCC-ee ", FCC week 2022, 2nd June 2022.
21. G. Simon, "Synchrotron radiation improvements in MAD-X for FCC-eestudies", EPFL CERN FCC Coffee, 20th June 2022.
22. G. Simon, "Synchrotron Radiation issues in MADX", FCC- France & Italy workshop 2022, 22nd November 2022.
23. G. Simon, "MAD-X modules review for FCC-ee", LNO section meeting on MADX and Xsuite for FCC-ee, 9th December 2022.
24. L. van Riesen-Haupt, "EPFL-CERN Software Collaboration", FCC-EIC Joint &MDI Workshop 2022, 19 Oct 2022. (Oral Presentation)
25. L. van Riesen-Haupt, "IP Optics Corrections in FCC-ee", FCC-EIC Joint &MDI Workshop 2022, 21 Oct 2022. (Oral Presentation)
26. L. van Riesen-Haupt, "IP Tuning", FCCIS 2022 Workshop, 6 Dec 2022. (Oral Presentation)
27. L. van Riesen-Haupt, "Testing the New Exact Solenoid in MAD-X", LNO Meeting, 16 Nov 2022. (Oral Presentation)
28. L. van Riesen-Haupt, "FCC-ee IR matching and tuning knobs", FCC-ee Tuning Meeting, 14 July 2022. (Oral Presentation)
29. L. van Riesen-Haupt, "FCC-ee IR matching with errors", FCC-ee Tuning Meeting, 25 Aug 2022. (Oral Presentation)
30. C. García-Jaimes, "Impact of dipole b2", FCC-ee Tuning Meeting, 09 June 2022. (Oral Presentation)
31. C. García-Jaimes, "Optics Matching with Arc Errors", FCC-ee Tuning Meeting, 29 Aug

2022. (Oral Presentation)

32. C. García-Jaimes, “PHD Status report”, FCC-ee Tuning Meeting, 30 Sep 2022. (Oral Presentation)
33. C. García-Jaimes, “Optics Matching with Arc Errors”, FCCIS 2022 Workshop, 08 Dic 2022. (Oral Presentation)