Swiss Accelerator Research and Technology

# Project: FCC-ee Dynamics

## Accelerator design and simulation framework for the FCC-ee optics and collective effects

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### 1. Scientific Report

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 and to give feedback to the High Temperature Superconducting magnet development project in terms of tolerances of unwanted magnetic multiples.

#### 1.1 Sequence Manager

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

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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.

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.

The photon emission spectrum of xsuite was thoroughly tested against theory and found to be correct. The testing script was handed to the XSuite team to allow them to do tests internally. The effect of alignment errors on emittance was benchmarked by applying identical errors in MAD-X SAD and Xsuite and computing the emittance using matrix and tracking methods.

The matrix method in XSuite is not as accurate as the other codes and it is being debugged in close collaboration with the developers. However, the tracking method has proven to be very accurate, allowing for tracking studies that include alignment errors and beam-beam effects. These effects were similarly benchmarked, providing valuable insights into the performance and accuracy of the tracking method.

Different methods of simulating the tilted solenoid are under investigation, including field map approaches that have been shown to work well in MADX. The optics and orbit tuning tools have been further improved, and first studies with relaxed optics were launched. These studies are crucial as they pave the way for realistic studies that aim to scan the effect of different machine configurations. This will provide a comprehensive understanding of the machine's performance under various conditions and configurations, thereby aiding in the optimization of the FCC-ee's performance.

### 1.2 Beam-Beam Simulations

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

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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).

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 yielded good scaling for all beam-beam models with up to a factor 12 speedup with 16 threads compared to sequential execution. The numbers on the plot labels indicate the number of macroparticles in each beam. The speedup in the strong-strong case is slightly less than in the other two models due to the repeated computation of the statistical moments.

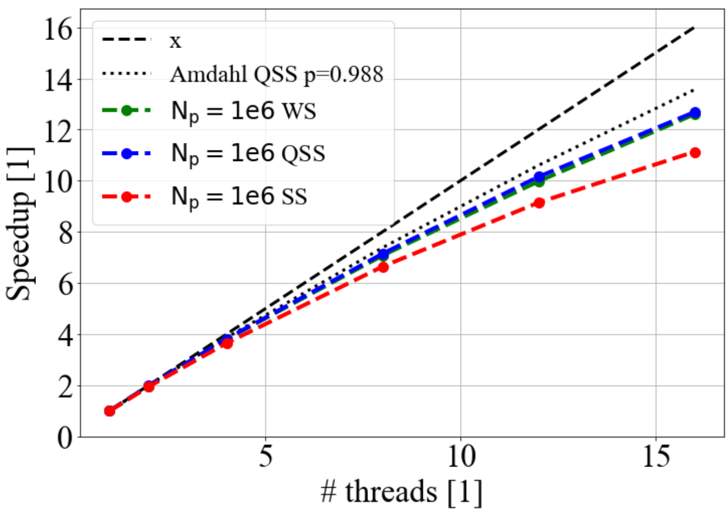


Figure 1: Performance scaling of the xsuite beam-beam model in the different approximations (WS: weak-strong, QSS: quasi strong-strong, SS: strong-strong), using CPU multithreading with OpenMP. The dotted line shows the theoretical speedup by measuring execution time in the sequential case with 1 thread.

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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 on the plot below, as an example.

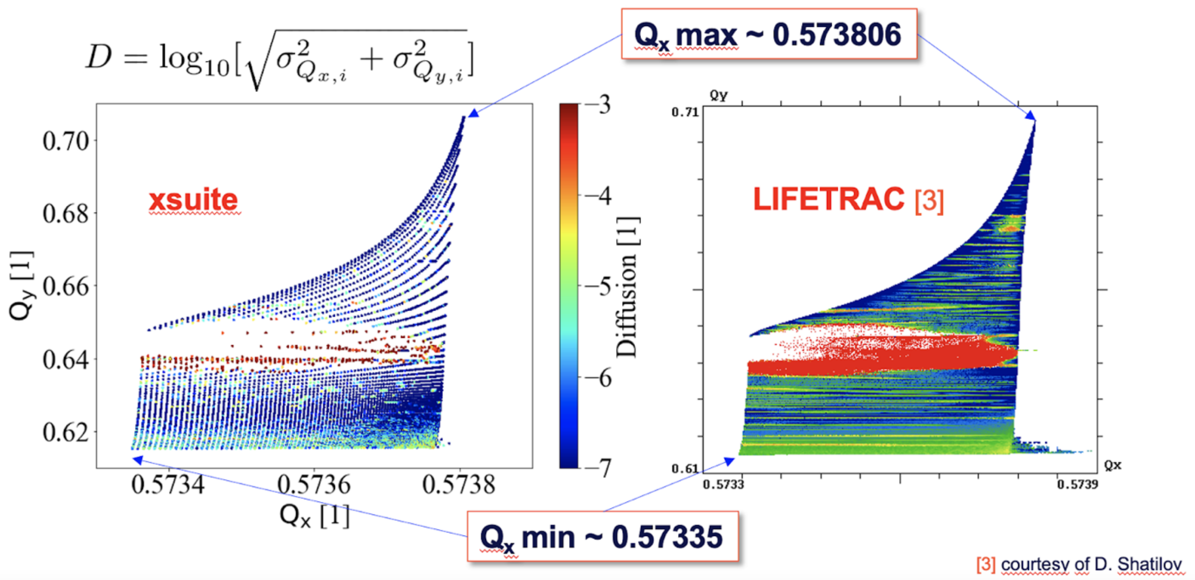


Figure 2: Tune footprint of the FCC-ee Z configuration in a 2 IP model. The left plot shows the footprint produced in xsuite while the right plot shows the same footprint produced by the reference code LIFETRAC. The colormap shows the diffusion computed from the standard deviation of a set of partial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

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, as the plot below, 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.

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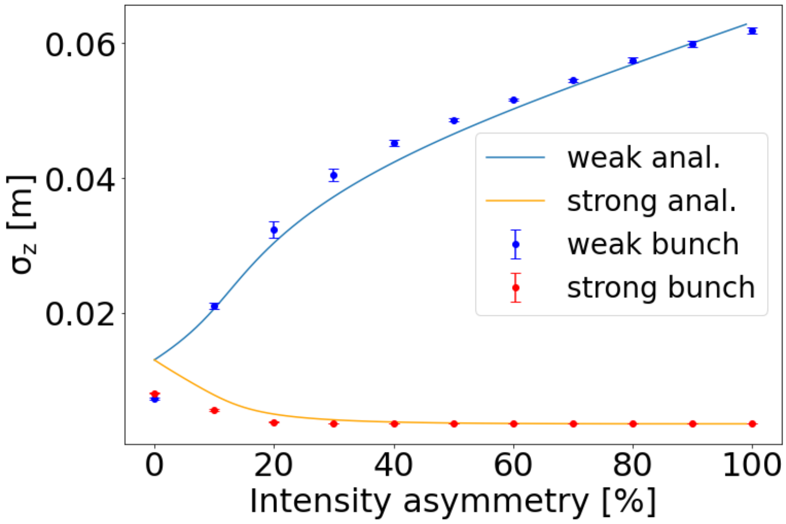


Figure 3: Equilibrium bunch length with different bunch intensity asymmetries in the two beams. The intensity of the beam called weak bunch is decreased. That of the strong bunch is increased.

The Xsuite beam-beam model has been optimized for GPU execution. Figure 4 shows the speedup obtained compared to a single core CPU execution, when simulating a single beam-beam collision in the 3 models: weak-strong (WS), quasi-strong-strong (QSS) and strong-strong (SS). Running the multi-turn simulations on GPU reduces the computation time from the order of weeks to the order of a few days, depending on the model used.

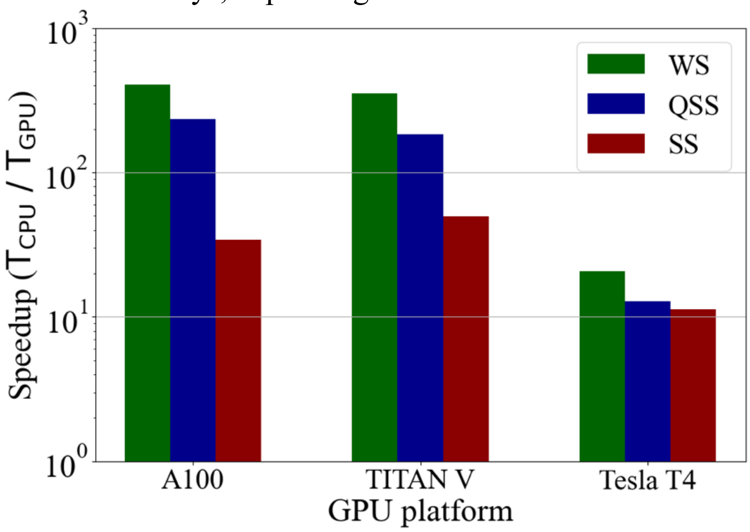


Figure 4: GPU / CPU speedup of simulating a single beam-beam collision on different GPU platforms, compared to a sequential execution on a CPU, for all Xsuite beam-beam models, using the FCC-ee Z parameters, 100 slices and 1e6 macroparticles per bunch.

The model has been used to study various instabilities in the FCC-ee machine. One such effect is the so called x-z instability, in which the presence of a beam-beam interaction in the accelerator lattice increases the number of resonance lines in the tune space, thus reducing the

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domain of stable working points. This effect has been studied in the context of the FCC-ee Z configuration. The plot below shows the equilibrium horizontal rms beam size in units of the initial beam size. The horizontal axis denotes the horizontal tune working point. In the study the horizontal tune has been scanned in the shown domain and the blowup of the transverse beam size was observed, using the quasi-strong-strong model. The study serves as a verification of the modeling of coherent behavior in the simulation code.

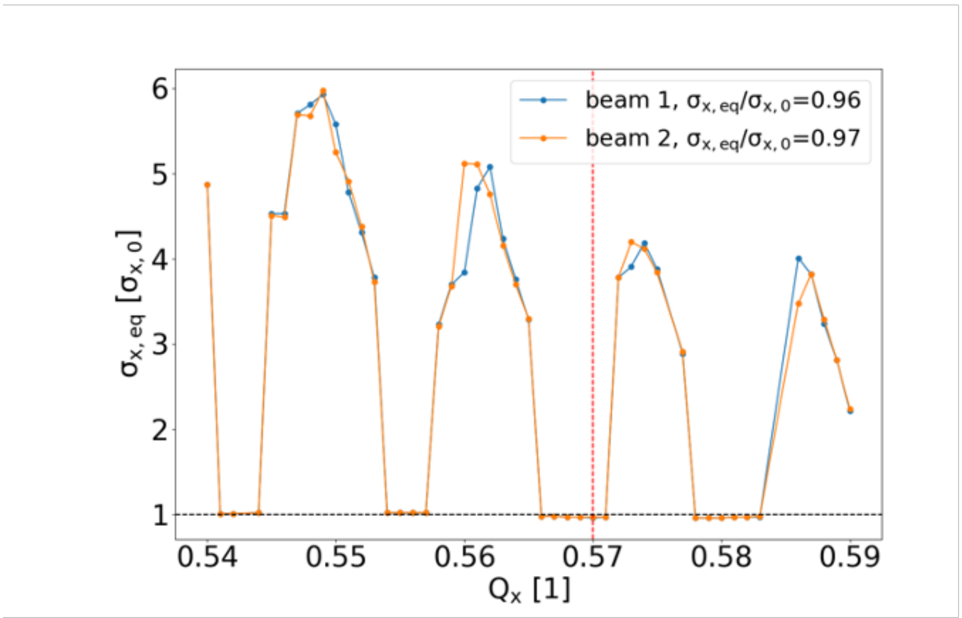


Figure 5: Equilibrium horizontal beam size as a function of the horizontal tune observed after tracking for 10,000 collisions in the FCC-ee Z setup using the quasi-strong-strong model of Xsuite. The red vertical line indicates the nominal working point as presented in the FCC-ee CDR. The numbers in the legend show the beam size blowup in case of this nominal working point.

The second effect which was studied was the 3D flip-flop instability, also described in the earlier parts of this chapter. The simulated equilibrium bunch length has been compared to the phenomenological model, described earlier. The model has proven to be remarkably successful in predicting the blowup of the bunch length at small bunch intensity asymmetries, which are the most relevant for realistic scenarios, namely for the top-up injection scheme. Simulations with the other FCC-ee energies as well as scans in various parameters are ongoing. A publication about the results in this topic is planned.

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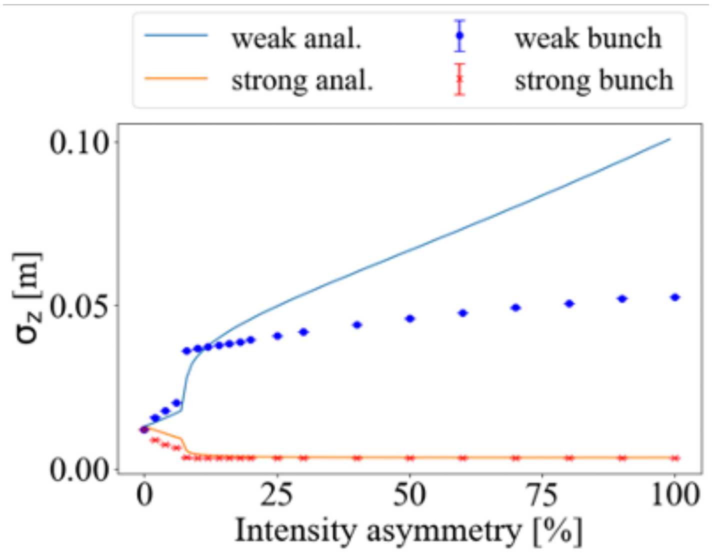


Figure 6: Equilibrium bunch length as a function of the initial bunch intensity asymmetry for the FCC-ee Z setup. The dots indicate the simulation results after 50,000 collisions using the quasi-strong-strong model, with 1e7 macroparticles. The solid curves show the predictions with our phenomenological model. Note the accuracy of the model below ~10% asymmetry as well as the sudden blowup at this asymmetry value, which is correctly predicted.

A Monte Carlo event generator for Bhabha scattering has been added to Xsuite. This process is important for determining luminosity in lepton colliders with high precision by counting the scattered primaries. In addition, it is one of the main limitations of the FCC-ee beam lifetime (alongside beamstrahlung). The event generator has been successfully benchmarked against a reference code (GUINEA-PIG) and it is now being optimized for multi turn tracking studies.

In the frame of the EAJADE exchange program Peter spent one month at KEK where hismain topic was to Investigate a single-beam instability which is caused by the interplay of beam-beam collisions and longitudinal wakefields. This interplay can result in a horizontal blowup of the bunches of one beam. Several simulation benchmarks were performed between Xsuite, PyHEADTAIL, BBWS and a numerical Vlasov solver to verify the correct physics in the codes, when adding both beam-beam and longitudinal wakes, and to make sure that the resonance can be studied with Xsuite. These benchmarks were successful and there is ongoing work to derive an analytical formulation to predict the location and shape of the resonance.

### 1.3 Optics and Tracking Codes

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

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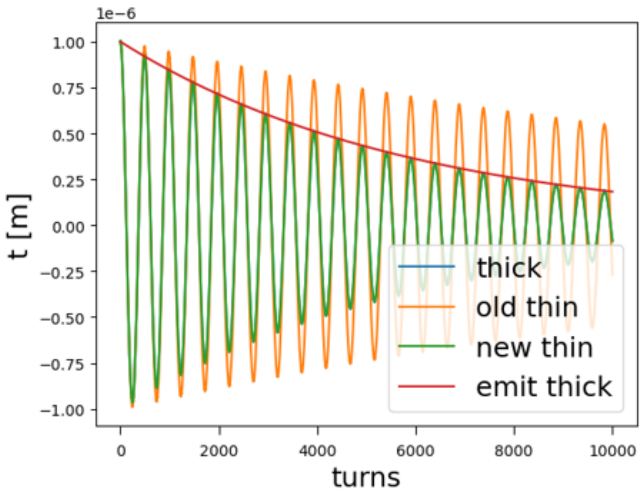
(Methodical Accelerator Design) code to the Future Circular Collider FCC-ee. This update includes a more accurate and realistic way to simulate the Synchrotron Radiation (SR) important at high-energies as in the FCC-ee (45-182 GeV per beam) and the fringe field solenoidal detector. Firstly, the aim was 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.




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”.

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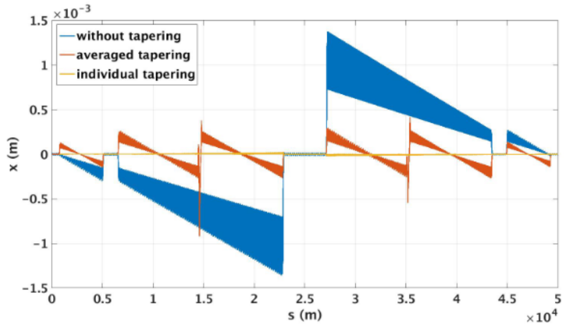


Figure 7: Same scale comparison of the orbit without tapering (blue), with individual tapering (yellow) and with averaged tapering (orange).

By gaining a better understanding in how momentum offsets affect the computed Twiss parameters and particle trajectories, the tapering implementation in MAD-X has been significantly improved. Whilst an earlier implementation gave satisfactory results for the computed Twiss parameters, it fell short in the tracking and emittance modules. The tapering implemented in MAD-X version 5.09.00 in the scope of the CHART project, circumvents these shortcomings and produces results that are satisfactory in all three modules. Furthermore, this tapering has now been extended to higher order multipoles to improve simulation results.

### 1.4 Lattice Design

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. By modeling the expected magnetic quadrupolar errors in MAD-X it is possible to determine maximum error to obtain a given β-beating. In the case of 1%, the b2 error in the dipoles should be 1.6x10-4at a radius of 10 mm, as shown in Fig. 8.

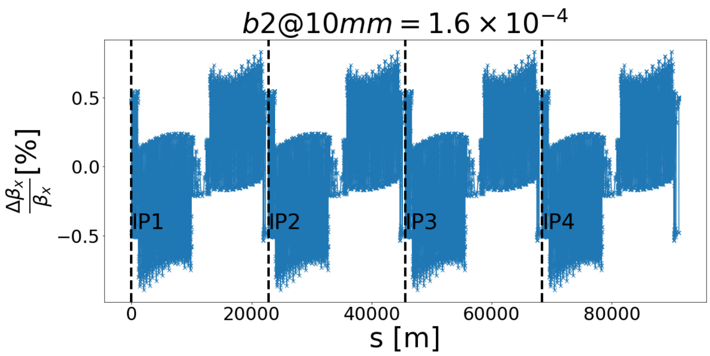


Figure 8: β-beating in percentage along the collider lengths due to quadrupolar errors in the dipole magnets of b2 at 10mm= 1.6×10−4.

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To recover an appropriate behaviour in the IPs is mandatory to change the strength values for the quadrupoles. MAD-X Matching can be used to recover the correct phase advance in the arcs (and the horizontal and vertical betatron tune) and the periodic behaviour in the IPs.

After the implementation of magnetic quadrupole errors in the arc dipoles and the recovery of the nominal parameters using MAD-X Matching the first attempt to use high temperature superconductors (HTS) fir combined function magnets (CFMs) in the FCC-ee was carried on.

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 initial approximation shows a promising 17.22% reduction in energy loss per turn.

However, the implementation of CFMs leads to changes in the Damping Partition Numbers, resulting in unphysical results for the emittance. To address this issue, a scanning process was conducted with an unbalanced distribution of bending angles for the quadrupoles, because the CFMs introduce a K1-factor in Synchrotron Radiation Integrals.  Different ratios were applied, and it was found that in order to achieve the nominal emittance, the ratio between the bending angles for quadrupoles should be around 0.53, as shown in Figure 9. This solution was published in Accelerating News in March.

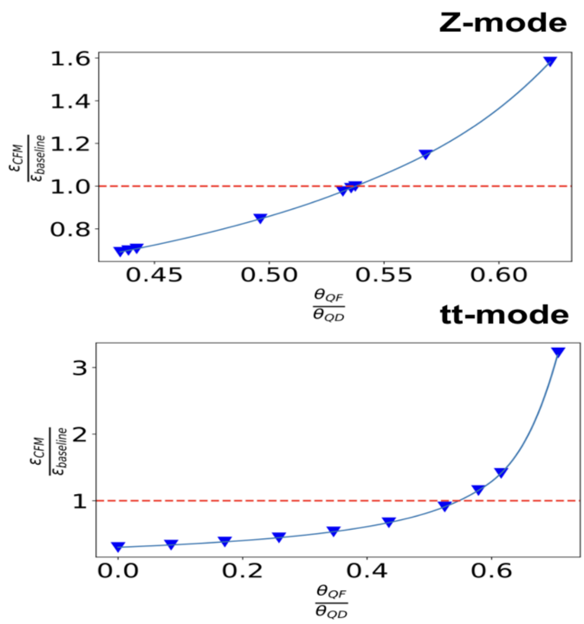


Figure 9: Emittance, as a fraction of the nominal design emittance for the different bending angle ratios.

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Upon further examination, potential problems associated with unbalanced flex angle distribution were investigated. One notable problem is the incompatibility between the Z and tt modes due to a "missing" bending angle when QF < QD. Also, there is a different displacement between the positron and electron bundles due to their different charges, resulting in a "zig-zag" displacement. This was discussed in detail in an IPAC´23 paper and during a presentation at FCC Week 2023.

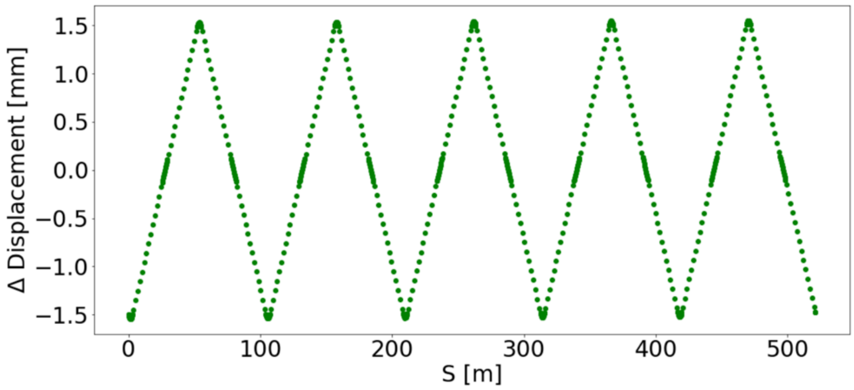


Figure 10: **Δ** Displacement due to the fluctuation of the beam separation between the $e+$ & $e-$ layouts for the Z-mode (the length of one FODO cell is 104.22 m).

One way to mitigate the missing bending angle is through a new distribution approach and the introduction of the K0 parameter in MAD-X. However, this task has been challenging due to a bug in MAD-X that affects the SR calculation. As a result, two options were being worked on simultaneously: using a Python script developed by Leon van Riesen-Haupt and applying the MULTIPOLE definition in MAD-X for the magnets.

Using the K0 parameter means having an orbit not centered on the arcs dipoles. To do this, one mode of operation is taken as a reference (without K0 and with the unbalanced bending angle in the quads), for example the Z mode of operation, and the other lattice will have the same value of the angles but the "missing bending angle" " will be distributed in the K0.

This attempt to design a lattice with a reference orbit not centered on the magnets is novel and addresses the challenge of missing bending angle due to the constraints of the different operating modes.

Doing all this work means looking at construction methods for the design of the entire lattice. Which often causes problems with the design software (MADX). For example, in a first attempt with only 10 FODOs cells, applying K0, it is possible to obtain the TWISS command but once inserted in the lattice, resonances are obtained. To solve this, the values for the Beta functions and Dispersion that do work (10 FODOs) were used as a reference at the end point of the arc where resonances are obtained and with this a closed orbit is finally obtained, i.e. a complete

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lattice. Finally we have a complete lattice with K0 in all the dipoles of the arcs but it needs to continue being explored due to the emergence of issues with the emit module for MADX.

```
           length              orbit5                alfa             gammatr
91174.106804577168077  -0.000000000000000   0.000009504868977 324.359731845013300

               q1                 dq1             betxmax               dxmax
402.176984171414290 -566.896579929774930 2785.757956390879372  22.175220636590648

            dxrms              xcomax              xcorms                  q2
  2.779742032517469   0.010743158759840   0.001702104113221 394.407413740119637

              dq2             betymax               dymax               dyrms
-503.259439477901253 7188.649508600561603   0.000000000000000   0.000000000000000

           ycomax              ycorms              deltap             synch_1
  0.000000000000000   0.000000000000000   0.000000000000000   0.680619545182410

          synch_2             synch_3             synch_4             synch_5
  0.000530185356955   0.000000044391774   0.000478785149076   0.000000007745322

          synch_6             synch_8              nflips               dqmin
268.391483508981878  28.394897413332110   0.000000000000000   0.000000000000000
```

Figure 11: MADX TWISS output from combined function magnet lattice.

**Presentations and Publications:**

1. 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.

2. FCC-ee Software Framework https://indico.cern.ch/event/1085318/contributions/4582723/subcontributions/354655/attachments/2355534/4019941/FCCIS_workshop_FS_Carlier.pdf
3. Status of Collimation tracking code development https://indico.cern.ch/event/1085318/contributions/4582724/subcontributions/357241/attachments/2356463/4021460/CollimationSimulations-FCCISWP2-20211201.pdf
4. P. Kicsiny, "6D Beam-beam Modelling in Xsuite", FCCIS WP2 Workshop 2021, 1. Dec. 2021. (Oral Presentation)
5. F. Carlier,"Code developments", EPFL-LPAP Activity Meeting, EPFL.
6. P. Kicsiny "Beam-beam effects in future circular lepton colliders, EPFL-LPAP Activity Meeting, EPFL, 11/02/2022. (Oral Presentation)
7. P. Kicsiny "6D beam-beam modeling in Xsuite ", BE-ABP-CEI section meeting, CERN,17/01/2022. (Oral Presentation)

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8. P. Kicsiny "6D beam-beam modeling in Xsuite", EPFL-LPAP FCC-ee Software Framework Meeting, EPFL, 11/11/2021. (Oral Presentation)
9. P. Kicsiny "Beam-beam studies with MadX and first steps with PyHEADTAIL and xsuite ", EPFL-LPAP FCC-ee Software Framework Meeting, EPFL, 08/07/2021. (Oral Presentation)
10. P. Kicsiny, "Modelling of beam-beam effects in future lepton colliders", Swiss Physical Society Meeting 2022, Fribourg, CH. (Oral presentation)
11. 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.
12. P. Kicsiny et al., "**Simulations of FCC-ee beam-beam effects with xsuite",** FCC week 2022, 30 May-3 June, Paris, France.
13. R. De Maria, "MAD-X Status and progress", FCC week 2022, 30 May-3 June, Paris, France.
14. A. Abramov et al., "FCC-ee collimation studies", FCC week 2022, 30 May-3 June, Paris, France.
15. P. Kicsiny, "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.
16. A. Abramov et al. "DEVELOPMENT OF COLLIMATION SIMULATIONS FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
17. A, Abramov et al. "DESIGN OF A COLLIMATION SECTION FOR THE FCC-ee ", 13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand.
18. G. Simon, "Realistic Optics & Simulation Modelling in the FCC-ee Era : update", BIMP meeting at Université Paris-Saclay, 8th March 2022:.
19. G. Simon, "Comparisons of radiation and damping", EPFL-LPAP 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)

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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. L. van Riesen-Haupt, “Code Development Status”. FCC Week 2023. London. 08.06.2023
31. L. van Riesen-Haupt,“Simulations for IR Tuning”. FCC Week 2023. London. 08.06.2023
32. L. van Riesen-Haupt., “IP Tuning”. FCC-ee Tuning Meeting, 09 June 2022.
33. L. van Riesen-Haupt, “Simulation Tools for Future Colliders”, Joint Annual Meeting of the Swiss Physical Society, September 2023. (Oral Presentation)
34. L. van Riesen-Haupt, “Equilibrium emittances for FCC-ee: tracking and matrix methods”, FCC Innovation Study, Rome, Italy, November, 2023. (Oral Presentation)
35. C. García-Jaimes, “Impact of dipole b2”, FCC-ee Tuning Meeting, 09 June 2022. (Oral Presentation)
36. C. García-Jaimes, “Optics Matching with Arc Errors”, FCC-ee Tuning Meeting, 29 Aug 2022. (Oral Presentation)
37. C. García-Jaimes, “PHD Status report”, FCC-ee Tuning Meeting, 30 Sep 2022. (Oral Presentation)
38. C. García-Jaimes, “Optics Matching with Arc Errors”, FCCIS 2022 Workshop, 08 Dic 2022. (Oral Presentation)
39. C. 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.
40. C. García-Jaimes, T. Pieloni, L. van Riesen-Haupt, M. Seidel, R. Tomas, “Impact of dipole quadrupolar errors in FCC-ee”. IPAC’23, Venice, Italy, May 2023.
41. C. García-Jaimes, T. Pieloni, L. van Riesen-Haupt, M. Seidel, R. Tomas, “Exploring FCC-ee optics designs with combined function magnets”. IPAC’23, Venice, Italy, May 2023.
42. C. García-Jaimes, “Combined function lattice with constant partition numbers for FCC-ee”. FCC Week 2023. London. 08.06.2023.
43. C. García-Jaimes, “HTS FCC-ee energy efficient beam optics”. CHIPP/CHART Workshop on Sustainability in Particle Physics and CHIPP 2023 plenary, Sursee. 14.06.2023
44. C. Garcia-Jaimes, "HTS FCC-ee energy efficient beam optics". Joint Annual Meeting of the Swiss and Austrian Physical Society 2023. Basel, Switzerland 04.09.2023.
45. G. Simon, “Review of MAD-X for FCC-ee studies”, FCC week 2023, London, United Kingdom, June, 2023.
46. G. Simon, “MADX status”, LNO meeting, CERN, June 2023.
47. P. Kicsiny, “Towards beam-beam simulations for FCC-ee”, FCCIS 2022 Workshop, 06 Dec 2022. (Oral Presentation)
48. P. Kicsiny, “Benchmark and performance of beam-beam interaction models for XSUITE”, IPAC’23, Venice, Italy, May 2023.

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49. P. Kicsiny, “Bhabha scattering model for multiturn tracking simulations at the FCC-ee”, IPAC’23, Venice, Italy, May 2023.
50. P. Kicsiny, “Beam-beam code progress”, FCC week 2023, London, United Kingdom, June, 2023. (Oral Presentation)
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