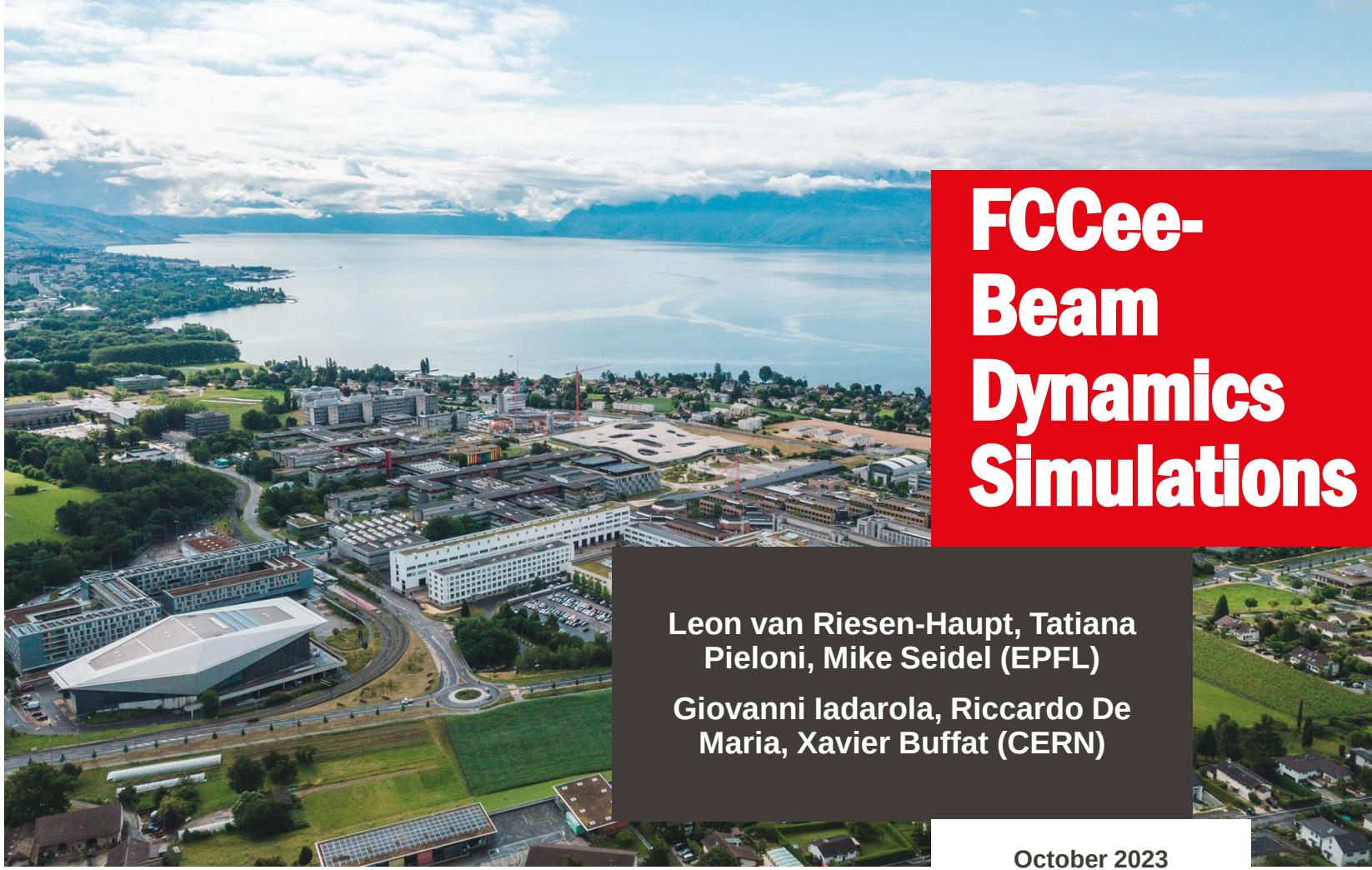


FCCee-Beam Dynamics Simulations

Leon van Riesen-Haupt, Tatiana Pieloni, Mike Seidel (EPFL)

Giovanni Iadarola, Riccardo De Maria, Xavier Buffat (CERN)

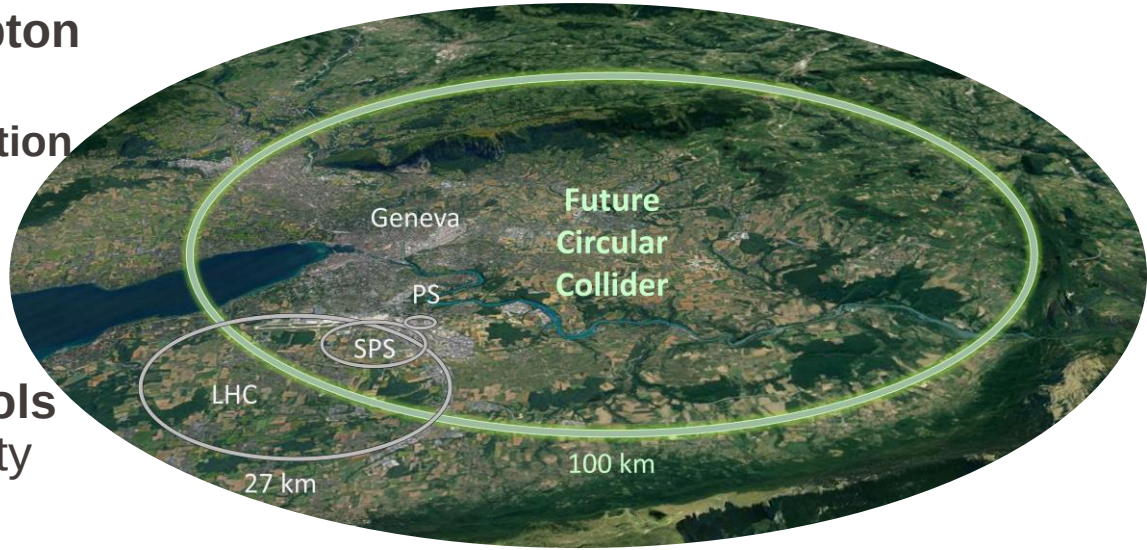
October 2023

École polytechnique fédérale de Lausanne

Motivation

- Challenges set out by Future Circular electron-positron Collider (**FCC-ee**)
  - **Large** and **complex** machine with many components
  - Challenging **collision parameters** and insertion region design
  - Tight **alignment**, **manufacturing** and **correction** tolerances

- Challenges unique to **lepton colliders**
  - E.g. **synchrotron radiation** effects
  - Recent focus in CERN on **hadron machines**
- Work with **experts** in the **community** to create **tools** for the broader community



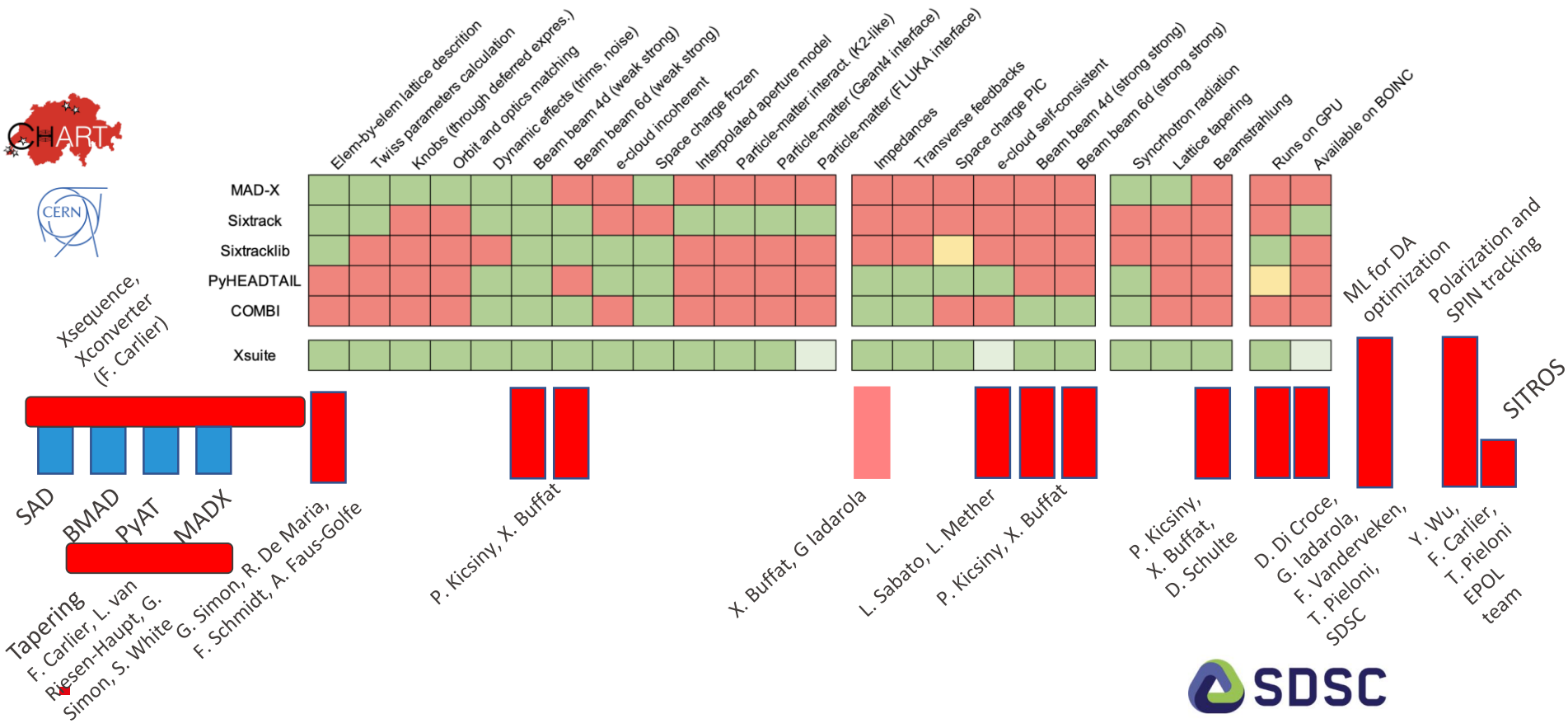
Software Tools

- Large **number of tools** used in FCC study
  - Often **specialised** to one purpose/aspect of beam physics
  - Sometimes tools with **overlapping purpose** used, depending on the **user's expertise**
- Vast and very active community in the **CERN ABP Computing Working Group**
  - Maintenance, improvement, complement **existing codes**
  - **Development** of modern, robust and broad tools for the **entire accelerator community**
- **Large community** outside of FCC and CERN with overlapping interests
  - **Potential for synergies** and **cooperation**

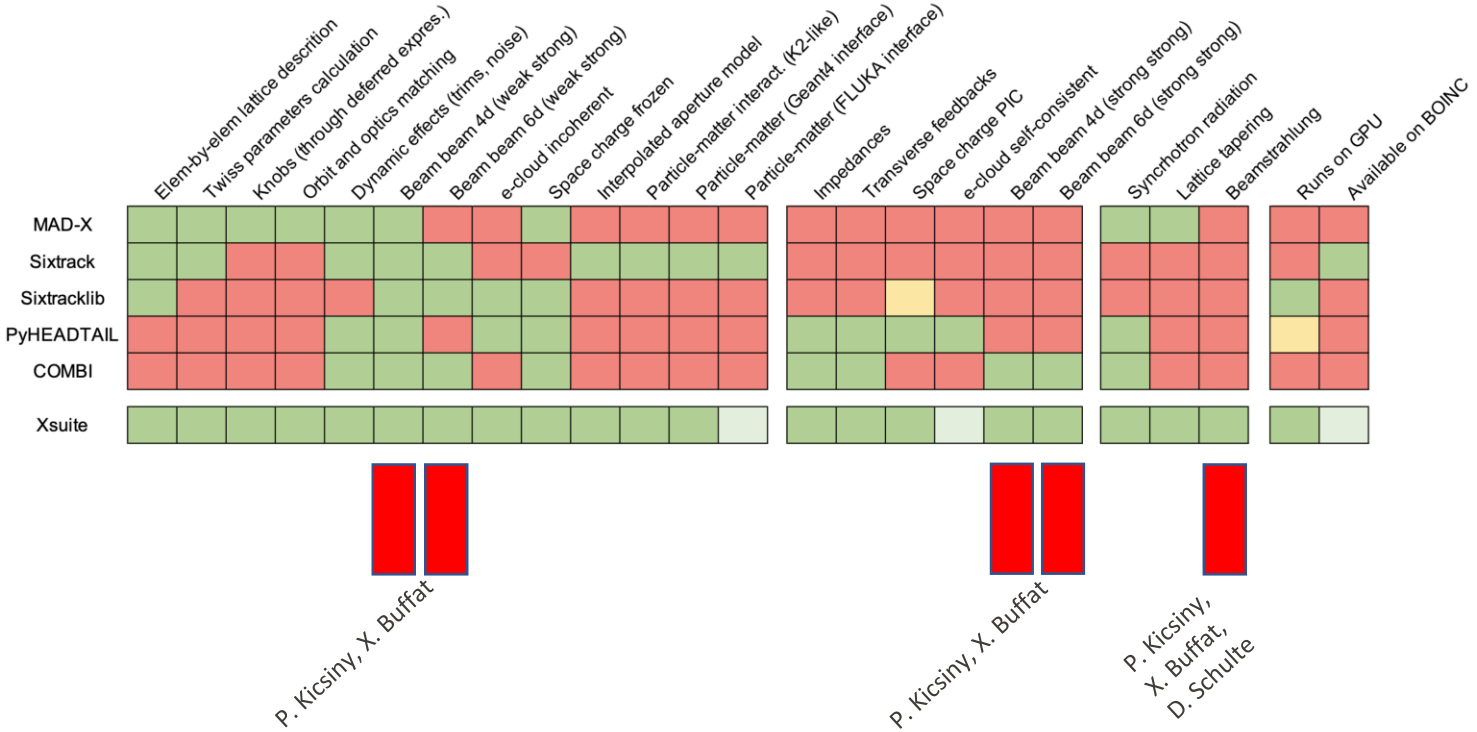
FCC Software Framework Project

- **Understand requirements** for the development and simulation of FCC
  - **Which effects** need to simulated and which **tools exist** or **need to be developed/optimised** for these purposes
  - Identify which simulations need to **interplay/overlap** and understand how they fit together in the **“bigger picture”**
- Ensure that the needs of the FCC study are met by
  1. **Maintaining, benchmarking** and **improving current simulation tools**
  2. Actively contributing to the **development** of **new simulations tools**
  3. Create tools to allow for **interfacing** between different simulation tools
- Work closely with the **ABP Computing WG** and identify synergies and come up with a **common strategy**
- Offer a **first point of contact** for external collaborators that see synergies
- Perform simulations to realistically model FCC using advanced techniques

X-Suite


Elem-by-elem lattice descrition
Twiss parameters calculation
Knobs (through deferred expres.)
Orbit and optics matching
Dynamic effects (trims, noise)
Beam beam 4d (weak strong)
Beam beam 6d (weak strong)
e-cloud incoherent
Space charge frozen
Interpolated aperture model
Particle-matter interact. (K2-like)
Particle-matter (Geant4 interface)
Particle-matter (FLUKA interface)
Impedances
Transverse feedbacks
Space charge PIC
e-cloud self-consistent
Beam beam 4d (strong strong)
Beam beam 6d (strong strong)
Synchrotron radiation
Lattice tapering
Beamstrahlung
Runs on GPU
Available on BOINC
MAD-X
Sixtrack
Sixtracklib
PyHEADTAIL
COMBI
Xsuite
Xsequence, Xconverter (F. Carlier)
ML for DA optimization
Polarization and SPIN tracking
SITROS
SAD
BMAD
PyAT
MADX
Tapering
F. Carlier, L. van Riesen-Haupt, G. Simon, S. White
G. Simon, R. De Maria, F. Schmidt, A. Faus-Golfe
P. Kicsiny, X. Buffat
X. Buffat, G Iadarola
L. Sabato, L. Mether
P. Kicsiny, X. Buffat
P. Kicsiny, X. Buffat, D. Schulte
D. Di Croce, G. Iadarola, F. Vanderveken, T. Pieloni, SDSC
Y. Wu, F. Carlier, T. Pieloni EPOL team

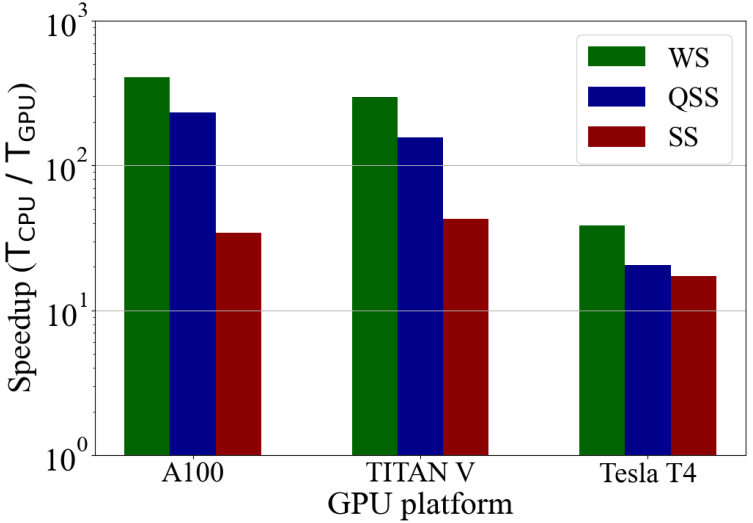
Beam-Beam, Beamstralung, bhabha scattering Code



Xsequence, Xconverter (F. Carlier)

Beam-Beam Code

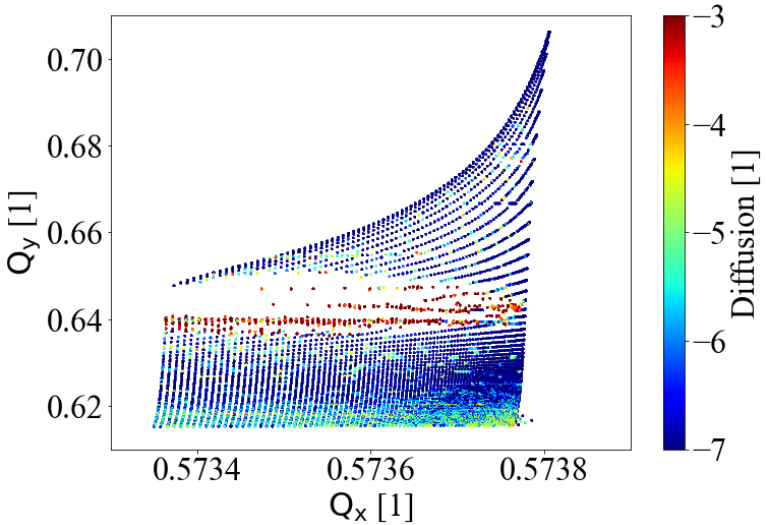
- Efforts led by **P. Kicsiny**, **X. Buffat, D. Schulte, K. Oide**
- Aim to simulate **beam-beam**, **beamstrahlung**, **bhabha scattering**
- Implement different **beam-beam models** in XSuite (WS, QSS, SS)
  - **Benchmarking** against other codes (lifetrac)
  - Make use of modern **technologies** such as **GPUs, open MP**



Speed up of beam-beam simulations using different GPU platforms

Beam-Beam Studies

- Numerous simulations with beam-beam modules performed
  - Using linear description of the rest of the machine
  - Dynamic aperture, emittance blow up, frequency map analysis…
  - Flip-flop simulations to study effect from asymmetric bunch intensity
  - To be benchmarked with SKEKB in the coming months
- X-suite implementation can be combined with **other effects**
  - E.g. errors, radiation in the arcs, impedance …

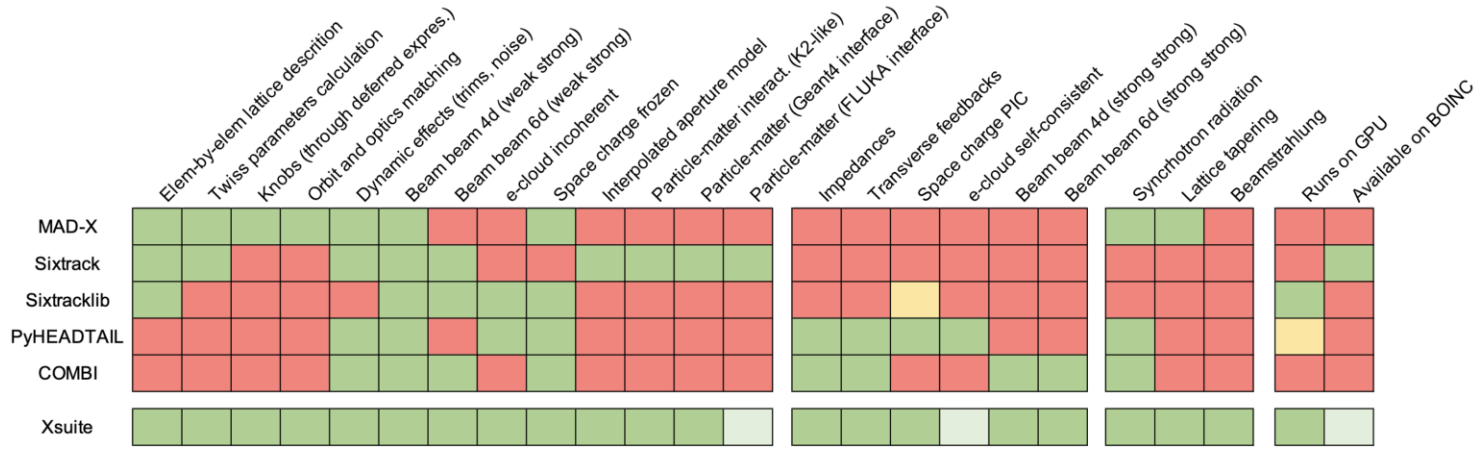


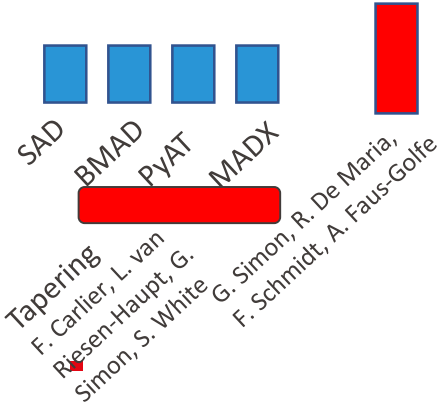
FMA analysis with beam-beam effects.

Relevant Publications

1. P. Kicsiny, “6D Beam-beam Modelling in Xsuite”, FCCIS WP2 Workshop 2021, 1. Dec. 2021. (Oral Presentation)
2. P. Kicsiny “Beam-beam effects in future circular lepton colliders, EPFL-LPAP Activity Meeting, EPFL, 11/02/2022. (Oral Presentation)
3. P. Kicsiny “6D beam-beam modeling in Xsuite “, BE-ABP-CEI section meeting, CERN,17/01/2022. (Oral Presentation)
4. P. Kicsiny “6D beam-beam modeling in Xsuite”, EPFL-LPAP FCC-ee Software Framework Meeting, EPFL, 11/11/2021. (Oral Presentation)
5. 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)
6. P. Kicsiny, “Modelling of beam-beam effects in future lepton colliders”, Swiss Physical Society Meeting 2022, Fribourg, CH. (Oral presentation)
7. P. Kicsiny et al., “**Simulations of FCC-ee beam-beam effects with xsuite”,** FCC week 2022, 30 May-3 June, Paris, France.
8. 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
9. P. Kicsiny, “Towards beam-beam simulations for FCC-ee”, FCCIS 2022 Workshop, 06 Dec 2022. (Oral Presentation)
10. P. Kicsiny, “Benchmark and performance of beam-beam interaction models for XSUITE”, IPAC’23, Venice, Italy, May 2023.
11. P. Kicsiny, “Bhabha scattering model for multiturn tracking simulations at the FCC-ee”, IPAC’23, Venice, Italy, May 2023.
12. P. Kicsiny, “Beam-beam code progress”, FCC week 2023, London, United Kingdom, June, 2023. (Oral Presentation)
13. P. Kicsiny, “Simulation of beam-beam effects at the FCC-ee using Xsuite”, ABP Group Information Meeting, CERN, August 2023

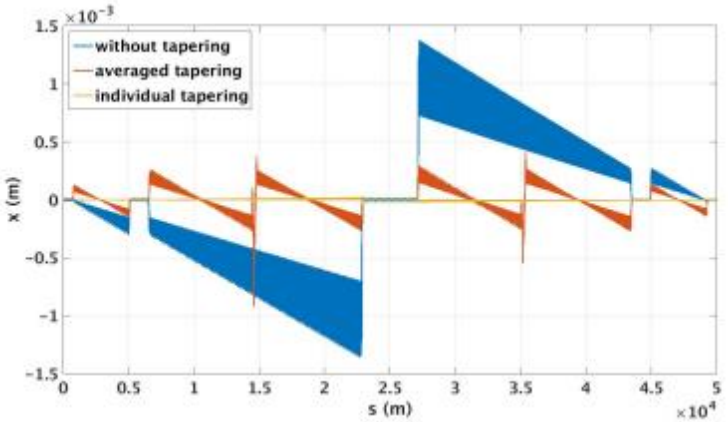
Optics and MAD-X for FCC-ee





Optics and MAD-X for FCC-ee

- Efforts led by **G. Simon**, R. De Maria, A. Faus-Golfe and F. Schmidt
- Ongoing **review** of **MAD-X** for FCC-ee simulations
  - Investigation of **Twiss**, **Emit** and **Track** modules
  - Improved modelling in presence of energy deviations (**tapering**)
  - Implement more accurate twiss **computation** considering **energy offset**
  - Review of **radiation damping** modelling
- Feeds directly into optics tools in XSuite

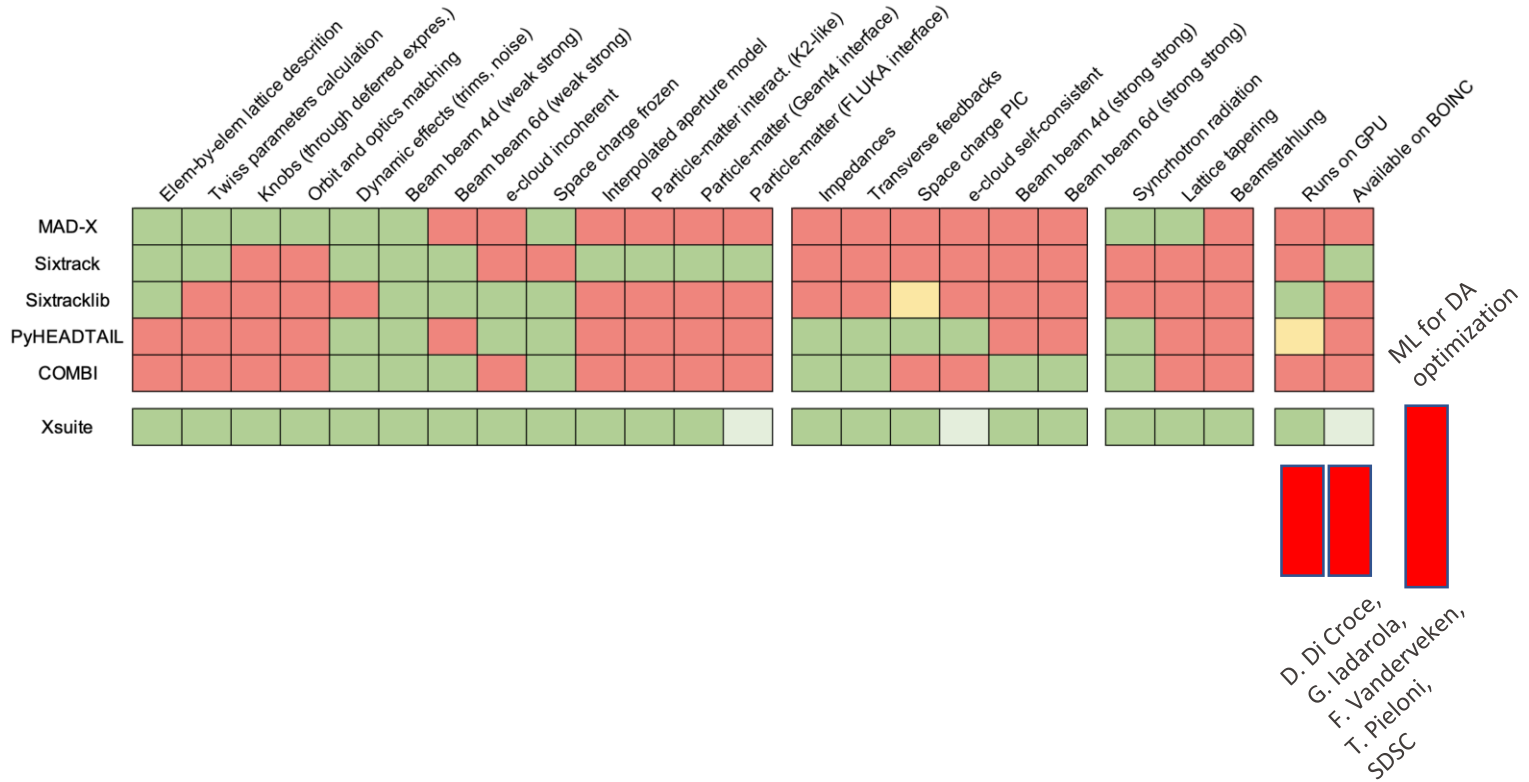


Orbit in FCC-ee Z configuration without tapering and with different tapering schemes.

Relevant Publications

1. G. Simon, "Realistic Optics & Simulation Modelling in the FCC-ee Era : update", BIMP meeting at Université Paris-Saclay, 8th March 2022:.
2. G. Simon, "Comparisons of radiation and damping", EPFL-LPAP FCC-ee Software Framework Meeting, 24th March 2022.
3. G. Simon, "SR radiation issues in FCC-ee ", FCC week 2022, 2nd June 2022.
4. G. Simon, "Synchrotron radiation improvements in MAD-X for FCC-eestudies", EPFL CERN FCC Coffee, 20th June 2022.
5. G. Simon, "Synchrotron Radiation issues in MADX", FCC- France & Italy workshop 2022, 22nd November 2022.
6. G. Simon, "MAD-X modules review for FCC-ee", LNO section meeting on MADX and Xsuite for FCC-ee, 9th December 2022.

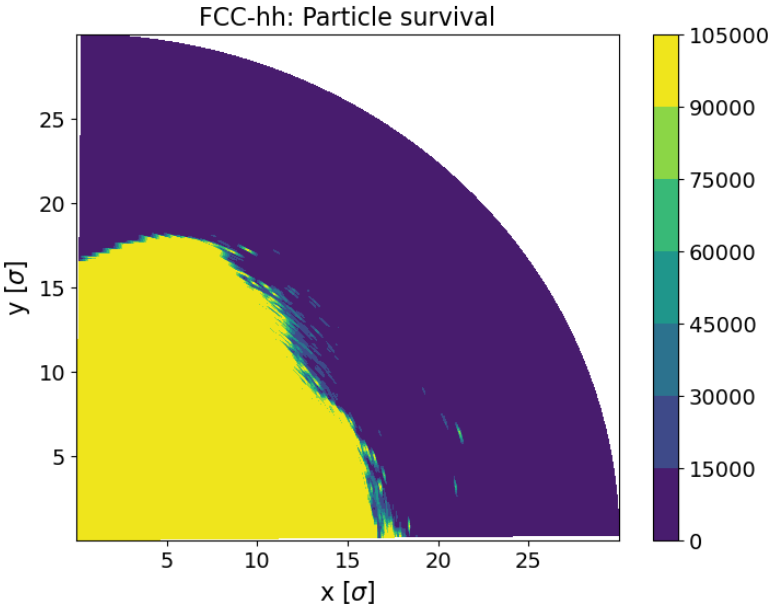
XBoinc and Machine Learning



D. Di Croce,
G. Iadarola,
F. Vanderveken,
T. Pieloni,
SDSC

XBoinc

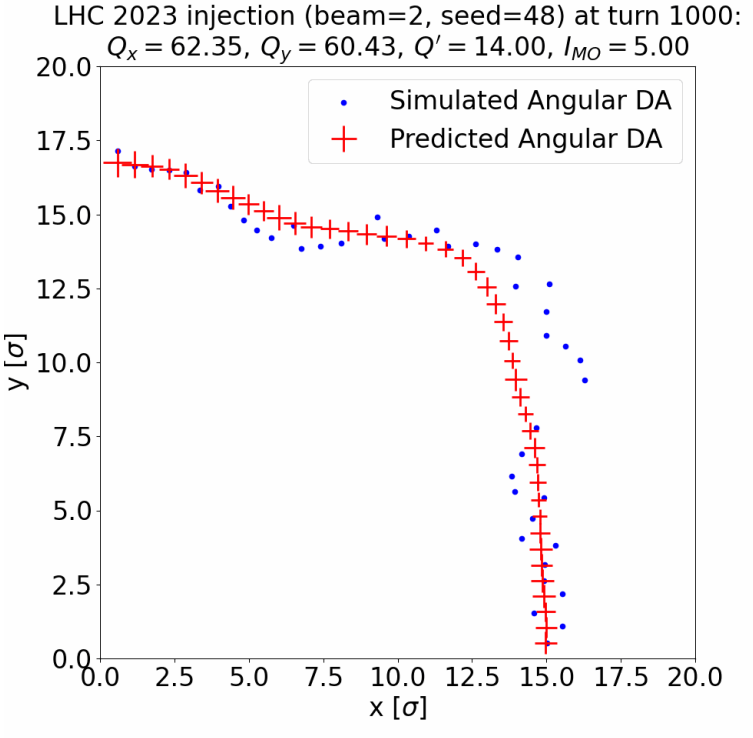
- Efforts led by **D. di Croce, F. van der Veken, G. Iadarola, M. Giovannozzi, T Pieloni** and **SDSC**
- XBoinc feature for XSuite under developement
  - Allows submission of XSuite studies to LHC@Home via Boinc
  - Additional capacities for computationally intense studies
    - E.g. for dynamic aperture studies
- More volunteers for LHC@Home welcome!



FCC Dynamic Aperture obtained using XBoinc

Machine Learning

- Use of machine learning to speed up dynamic aperture studies
  - Conventional methods are computationally demanding
- Predict DA for different machine configurations
- Using Deep Neural Networks in an Active Learning Framework
  - Data generated from simulations using XBoinc
  - Create framework to store data from current studies for possible future training

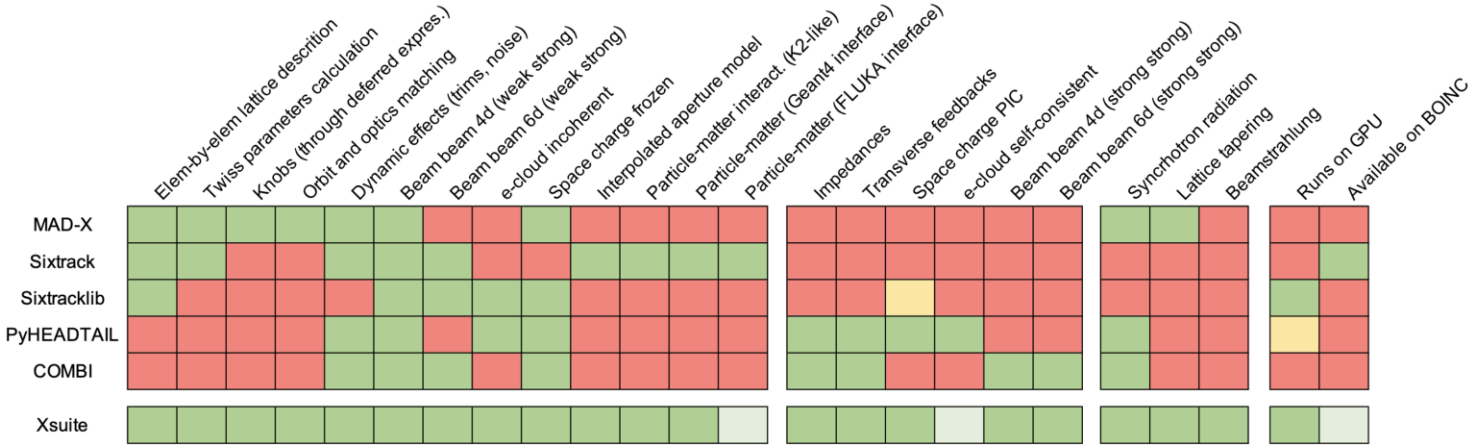


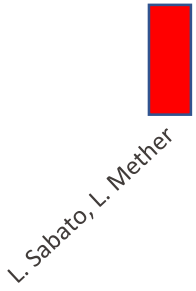
Simulated DA and DA predicted using machine learning for LHC.

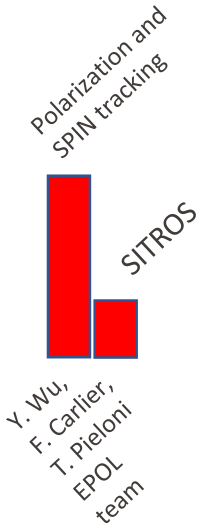
Relevant Publications

1. D. Di Croce et al., “Accelerating dynamic aperture evaluation using deep neural networks”, IPAC’23, Venice, Italy, May 2023.
2. D. Di Croce, “Active learning for DA simulations”, FCC week 2023, London, United Kingdom, June 2023. (Poster Presentation)
3. D. Di Croce, “Accelerating Beam Dynamic Simulations“, FCC week 2023, London, United Kingdom, June 2023. (Oral Presentation)
4. D. Di Croce, "Optimizing Beam Dynamics in LHC with Active Deep Learning“, HB 2023, Geneva, Switzerland, October 2023. (Oral Presentation)

Electron Cloud and Spin Polarisation







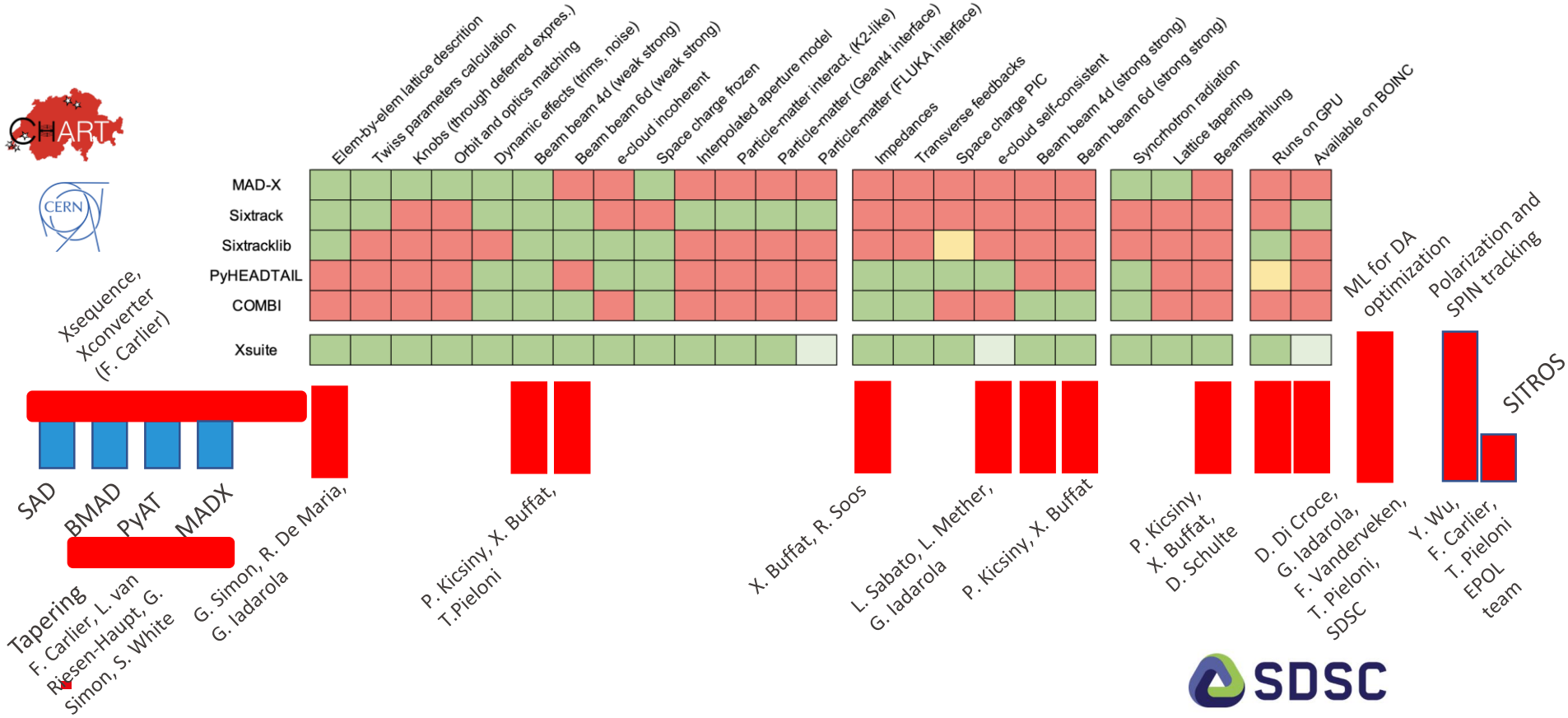
Covered in the next two talks:

Luca Sabato *FCChh Stability*

Tatiana Pieloni *FCC-ee SPIN-POL*

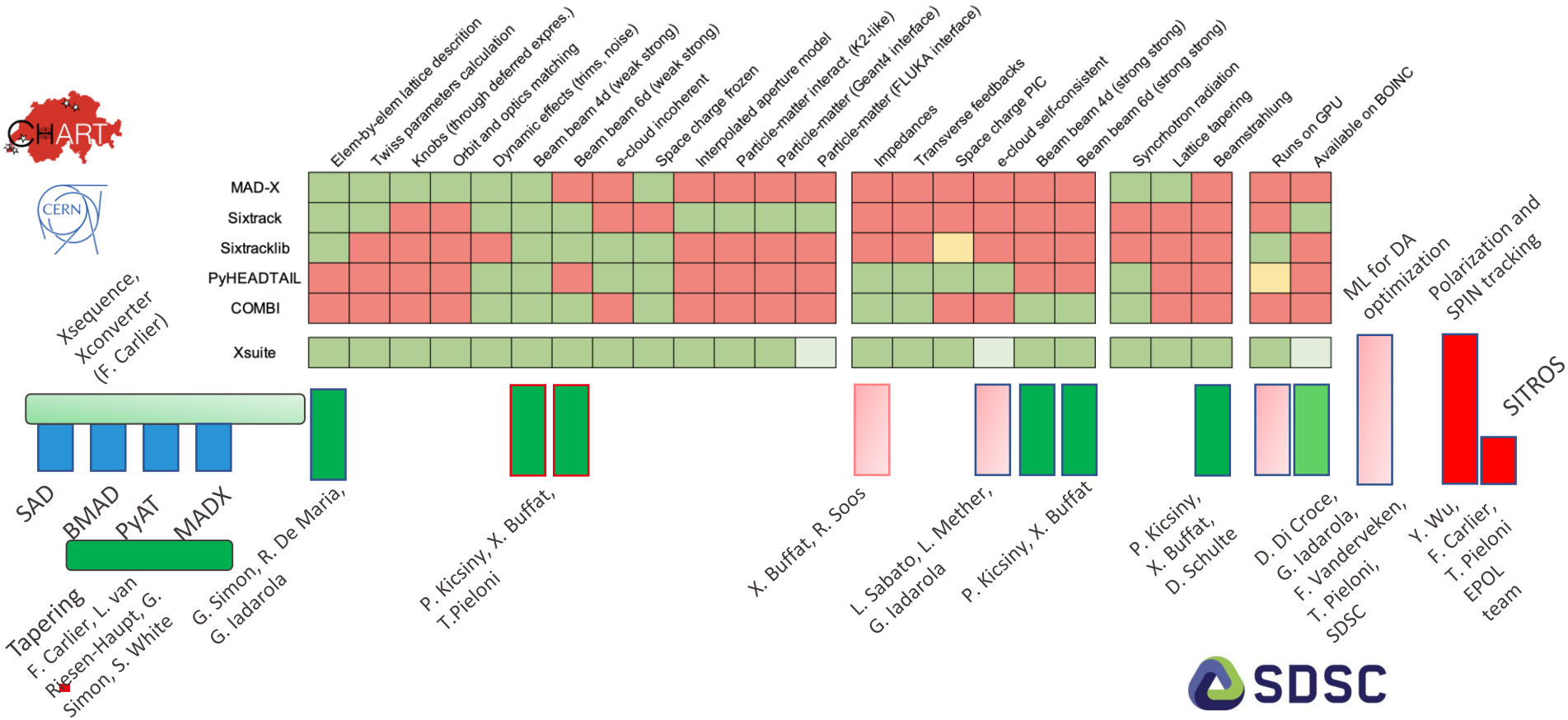
EPFL

XSuite



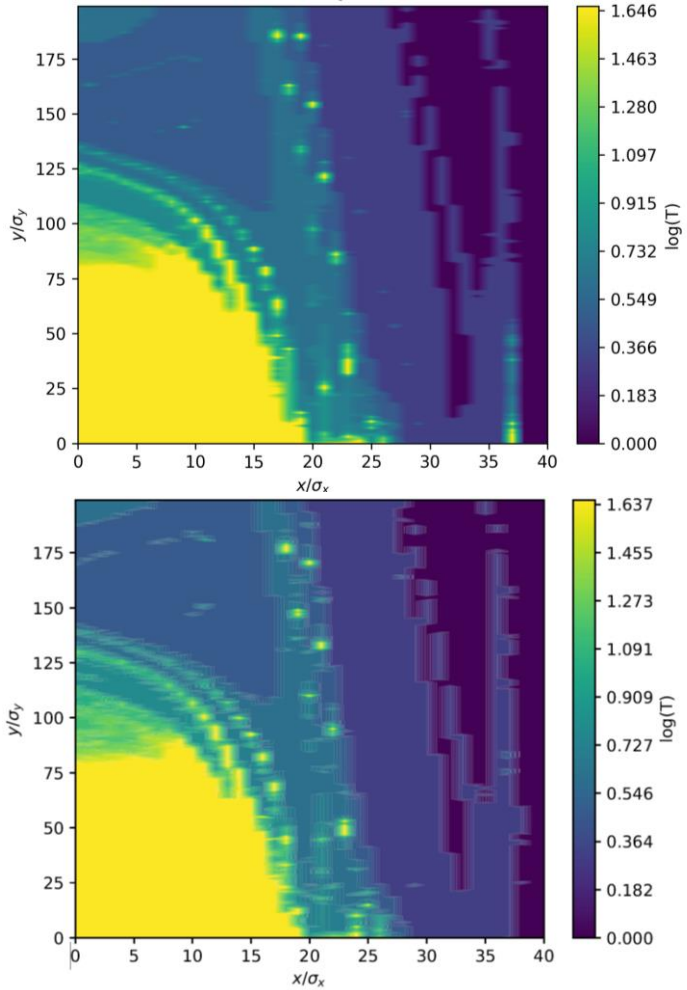
SDSC

Great Progress



Consistency - Benchmarking

- Important to **benchmark** new tools with existing codes
  - Simple examples before **multiple effects**
  - **Understand** possible inconsistencies
- Extensive study benchmarking **XSuite** since this is a primary tool
  - **Optics** with radiation and tapering compared to optics codes (MADX,SAD)
  - **Dynamic** aperture with and without radiation (MADX, SAD, MADX-PTC)
  - **Emittance** from tracking
    - Compared to other **tracking** codes
    - Compared to matrix **methods**
  - Radiated **photon spectrum**



FCC-ee survival plot with radiation using SAD (top) and Xtrack (bottom)

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- Important to **benchmark** new tools with existing codes
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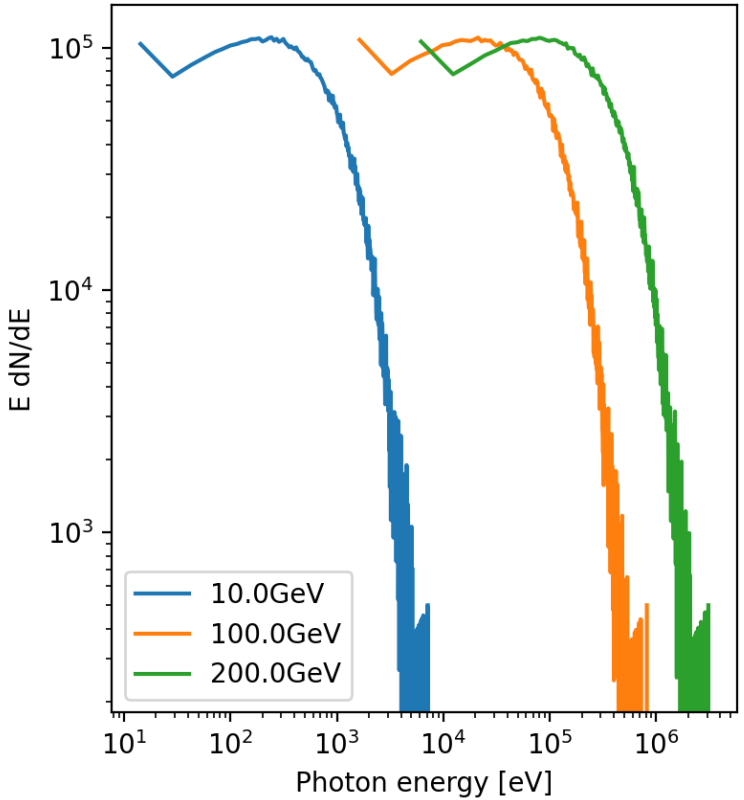
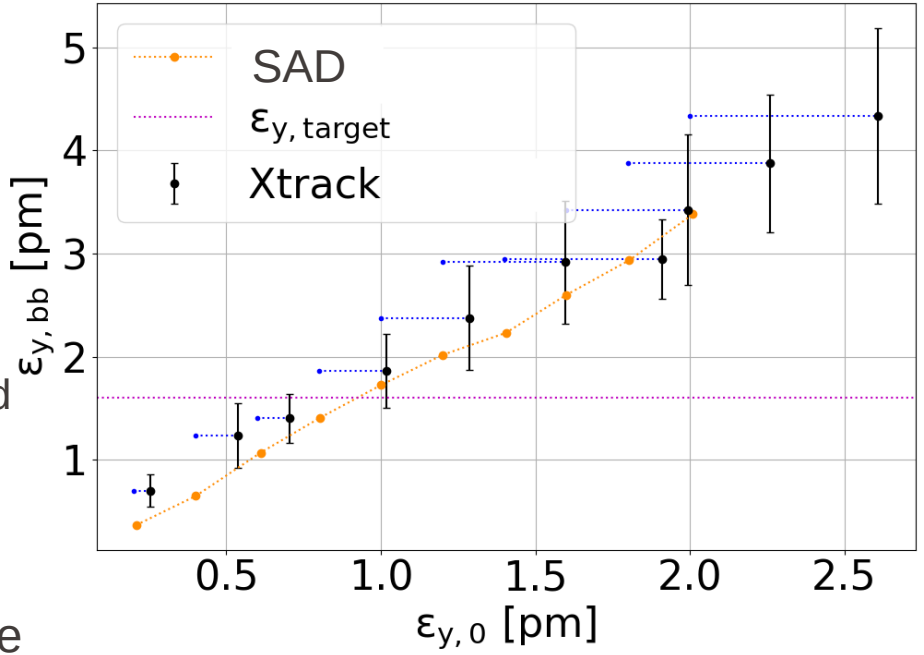


Power spectrum of photons emitted in 2T dipole at different energies in XSuite

First Results: Optics, Beam-Beam and Emittance

- First example of “**bringing it together**”
  - Optimising optics of the machine
  - Including beam-beam effects
  - Tracking in lattice for emittance and beam-beam
- Full **benchmarking** with previous studies
- Many upcoming studies for FCC-ee
  - **Tune spread** of particles in beam
  - **Dynamic aperture**
  - **Emittance** evolution



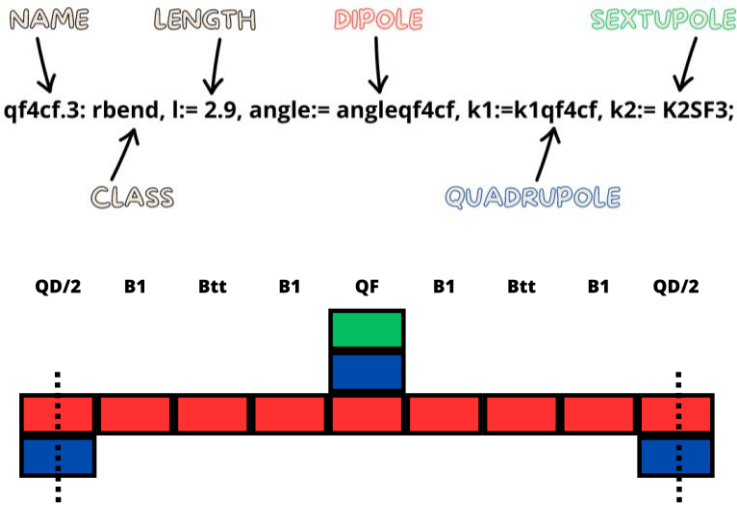
Emittance increase due to beam-beam from tracking in XSuite for various lattice emittances compared to SAD results. (Preliminary)

Relevant Publications

1. F. Carlier,"Code developments", EPFL-LPAP Activity Meeting, EPFL.
2. 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.
3. L. van Riesen-Haupt, "EPFL-CERN Software Collaboration", FCC-EIC Joint &MDI Workshop 2022, 19 Oct 2022, CERN.
4. L. van Riesen-Haupt, "IP Optics Corrections in FCC-ee", FCC-EIC Joint &MDI Workshop 2022, 21 Oct 2022, CERN.
5. L. van Riesen-Haupt, "IP Tuning", FCCIS 2022 Workshop, 6 Dec 2022 , CERN.
6. L. van Riesen-Haupt, "Testing the New Exact Solenoid in MAD-X", LNO Meeting, 16 Nov 2022 , CERN.
7. L. van Riesen-Haupt, "FCC-ee IR matching and tuning knobs", FCC-ee Tuning Meeting, 14 July 2022 , CERN.
8. L. van Riesen-Haupt, "FCC-ee IR matching with errors", FCC-ee Tuning Meeting, 25 Aug 2022 , CERN.
9. L. van Riesen-Haupt, "Code Development Status". FCC Week 2023. London. 08.06.2023
10. L. van Riesen-Haupt,"Simulations for IR Tuning". FCC Week 2023. London. 08.06.2023
11. L. van Riesen-Haupt, "IP Tuning". FCC-ee Tuning Meeting, 09 June 2022 , CERN.
12. L. van Riesen-Haupt, "Simulation Tools for Future Colliders" Joint Annual Meeting of SPS and ÖPG, 4 - 8 September 2023, Basel.

FCC-ee Alternative Optics with HTS Nested Magnets

- Effort by **C. García-Jaimes** (Global LeaderShip Student Program), T. Pieloni, L. van Riesen-Haupt, R. Tomas
- Arc optimisation using **combined function magnets** using **HTS** nested magnets
  - **Overlapping** di-, quadru- and sextupole
  - **17% reduction** in synchrotron radiation power
  - Compatible with baseline IR design
- **Extensive studies** required to investigate properties **compared** to **baseline**
  - Optics, emittance, dynamic aperture…
  - Benefits from **software framework**



Schematic of combined function magnet FODO cell and snippet of MADX implementation.

Relevant Publications

News › › Issue 43 › Topic: Future Circular Collider (FCC)

Combined function magnets with constant partition numbers lattice for the Future Circular lepton Collider

Optics developments with CFMs show promising results to improve the FCC-ee performance and efficiency.

13 MARCH, 2023 | By Cristóbal García (EPFL-LPAP), Tatiana Pieloni (EPFL-LPAP), Leon van Riesen-Haupt (EPFL-LPAP) & Rogelio Tomás (CERN)

1. C. García-Jaimes, "Impact of dipole b2", FCC-ee Tuning Meeting, 09 June 2022, CERN.
2. C. García-Jaimes, "Optics Matching with Arc Errors", FCC-ee Tuning Meeting, 29 Aug 2022, CERN.
3. C. García-Jaimes, "PHD Status report", FCC-ee Tuning Meeting, 30 Sep 2022, CERN.
4. C. García-Jaimes, "Optics Matching with Arc Errors", FCCIS 2022 Workshop, 08 Dic 2022 , CERN.
5. 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.
6. 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.
7. 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.
8. C. García-Jaimes, "Combined function lattice with constant partition numbers for FCC-ee". FCC Week 2023. London. 08.06.2023.
9. 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
10. C. García-Jaimes, "HTS FCC-ee energy efficient beam optics". Joint Annual Meeting of SPS and ÖPG, 4 - 8 September 2023, Basel.

Conclusion

- Large amount of different software used for FCC-ee and accelerators in general
  - Many different unique purposes
  - Dependent on specialised development and knowledge of few experts/labs
- Improved interoperability by
  - Facilitating conversion and model management
  - Contribute to the development of modern broader tools
    - Steer towards and use for FCC-ee purposes
    - Benchmark against established codes
    - Many meaningful contributions by CHART colleagues
- First studies using new tools underway contributing to the FCC-ee study
- Arc optimisation studies using combined function magnets to reduce synchrotron power consumption

Many Thanks