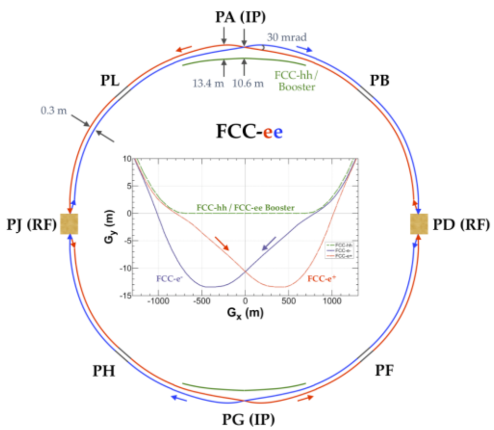
Code developments

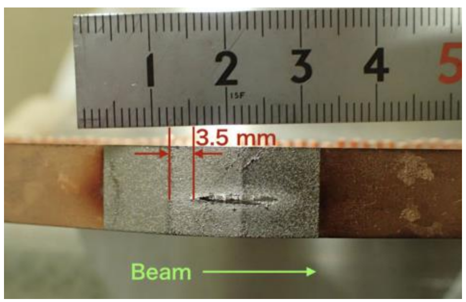
F. Carlier, R. DeMaria, G. Iadarola, T.Pieloni

X. Buffat, D. Schulte, P. Kicsiny, G. Simon, F. Schmidt, L. Mether, Y. Wu, M. Maitreyee, A. Abramov, M. Rakic, S. White, M. Hofer, R. Tomas, R. Bruce and L. van Riesen-Haupt

Acknowledgements: F. Zimmermann, K. Oide, D. Shatilov, K. Ohmi, E. Gianfelice, T. Persson, A. Faus-Golfe, D. Sagan, W. Herr, A. Blondel, M. Benedikt, M. Seidel, M. Boscolo, J. Wenninger, G. Rumolo, Y. Papaphilippou, all ABP colleagues.

FCC-ee beam dynamics simulation challenges





Damaged collimator in SuperKEKB, PRAB 23, 053501 (2020)

F. Zimmermann
D. Shatilov
K. Oide
T. Charles

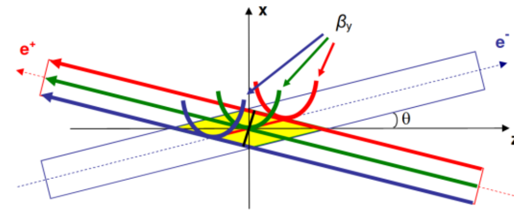
Optics & Tracking
- Collision point optics optimization
- Linear & nonlinear optics corrections
- Dynamic aperture + off-momentum

Beam-beam and collective effects
- Control of instabilities, multi IPs
- Self-consistent optics & dynamic beta
- Crab-waist and beamstrahlung
- Impedances
- Electron Cloud

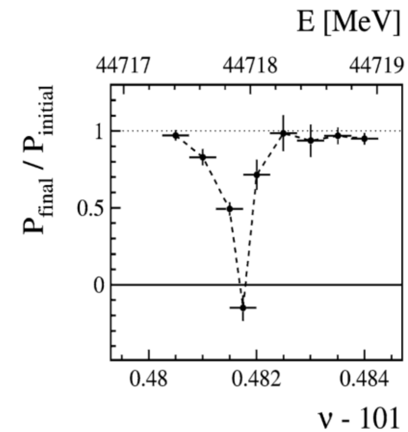
Collimation and MDI
- Develop physical aperture model
- Particle-matter interaction simulations
- Model impedance from collimators
- Lifetime

Spin dynamics
- Spin depolarization for energy meas.
- Correction of spin perturbations and resonances

Collaborative development, maintainability, easy access to new comers and reproducible results
- Optics and tools repository (G. Roy)
- Integrity testing



Crabbed waist scheme
https://arxiv.org/pdf/physics/0702033.pdf



LEP depolarization for energy calibration
https://doi.org/10.1016/S1631-0705(02)01401-9

Many different simulation codes exist to address the physics challenges
Each with specialized functionality

- **Optics, Tracking and Tuning** → SAD, MAD-X, Bmad, PTC, pyAT, MAD-NG, SixTrack, Elegant, + many more…
- **Beam-beam and collective effects** → LifeTrack, COMBI, BeamBeam3D, BBSS, BBWW, GUINEA PIG, IBB, pyHEADTAIL, SpaceCharge
- **Collimation and MDI** → SixTrack, Merlin++, GEANT4, Fluka, AT, BDSIM…
- **Spin** → Bmad, PTC, SITROS, Zgoubi, …

FCC-ee requires combinations of different codes for specific simulations
Not easy…

- Little to no mutual interface
- Different languages
- Different conventions
- Different philosophies
- Different maintainers and laboratories

A CHART funded project to address simulation challenges and physics questions of the FCC-ee design

Establish a modern and maintainable simulation framework to address key limitations for the FCC-ee

- Integrate and merge functionalities of different established simulation tools
- Develop new simulation modules to replace outdated legacy codes
- Perform key simulation campaigns with developed tools: beam-beam, spin dynamics, collective effects, collimation...
- Collaboration between FCC-ee collaboration, EPFL and CERN
- In strong synergy with current ABP based efforts at CERN for synchrotrons.
- Make simpler the access and contribution of newcomers to the accelerator modelling tools and studies

EPFL contribution to few physics challenges of the FCC-ee!

Iadarola,
De Maria & Co.

CERN-ABP-developed multiparticle codes and synergies

	Full lattice descrition	Dynamic effects (trims, noise)	Beam beam 4d (weak strong)	Beam beam 6d (weak strong)	e-cloud incoherent	Space charge frozen	Advanced collimation features	Impedances	Transverse feedbacks	Space charge PIC	e-cloud self-consistent	Beam beam 4d (strong strong)	Beam beam 6d (strong strong)	Synchrotron radiation	Beamstrahlung	Available on BOINC	Runs on GPU
MAD-X track	Available	Available	Available	Not available	Not available	Available	Not available	Not available	Not available	Not available	Not available	Not available	Not available	Available	Not available	Not available	Not available
Sixtrack	Available	Available	Available	Available	Not available	Not available	Available	Not available	Not available	Not available	Not available	Not available	Not available	Not available	Not available	Available	Not available
Sixtracklib	Available	Not available	Available	Available	Available	Available	Not available	Not available	Not available	Experimental	Not available	Not available	Not available	Not available	Not available	Not available	Available
PyHEADTAIL	Not available	Available	Available	Not available	Available	Available	Not available	Available	Available	Available	Available	Not available	Not available	Available	Not available	Not available	Experimental
COMBI	Not available	Available	Available	Available	Not available	Available	Not available	Available	Available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available

Available | Not available | Experimental

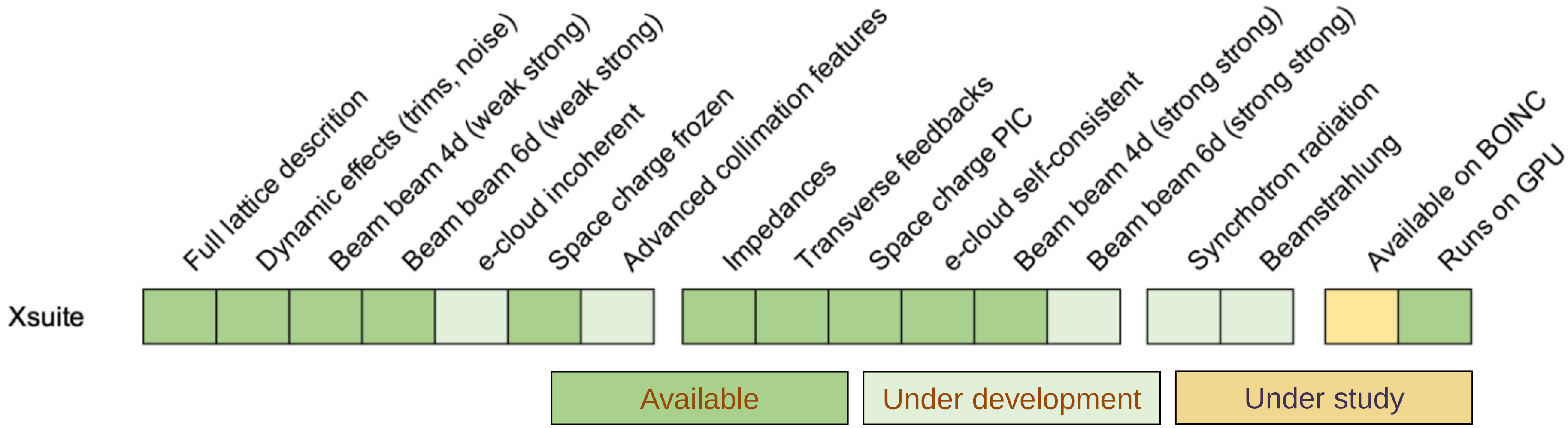
Several **CERN-developed multiparticle codes** that are **used in production** studies for CERN synchrotrons

Adapting one of the existing codes to fulfil all the needs would be **very difficult →** opted to start a **new design (Xsuite)**

Big effort in code development within ABP

Iadarola,
De Maria & Co.

Xsuite Summary



Xsuite development **experience so far**:

- Shows **feasibility of integrated modular code** covering the application of our interest
- Demonstrates a **convenient approach to handle multiple computing platform** while keeping compact and readable physics code
- Easy learning curve for newcomers thanks to the design choices (i.e. Python, packages approach)

Some specific FCC-ee needs to be developed but gives access to several tools and models

FCC-ee Objectives and synergies with Xsuite

- FCC-ee specific needs (lepton synchrotrons):

  - allow "transparent" use of different lattice descriptions among the collaboration (i.e. SAD-MADX-BMAD-pyAT), testing, analysis

  - optics challenges need to be addressed i.e. robust tuning

  - develop needed modules and perform physics studies: BB6D, SPIN studies, Solenoid, Synchrotron radiation

  - develop expertise and knowledge among young scientists
- Sustainability of tools: easy development/maintainance even beyond the CDR+ study
- Favor modern technologies (i.e. python, GPU) to:
  - Attract and ease the learning curve for newcomers
  - Profit of present knowhow in the FCC-ee collaboration and the ABP
  - Use available and extensively benchmarked tools (i.e. pic solvers)
  - Extend to a larger community for testing and debugging
- Easy to interface with many simulation tools
- Speed: GPU, parallel computing MPI Open MP technologies
- Explore modern ways for optimization (i.e. explore AI and ML)

Goal: Provide a framework for FCC-ee code dev

Central point for coordinating the FCC-ee code developments as a working group

- Identify the open physics questions in FCC-ee
- Address the technical code and model limitations based on collaborators experience and knowhow
- Advance the physics studies for the CDR+
- Fill in gaps and missing pieces in Xsuite for tracking studies to profit of larger community and well established and benchmarked tools
- Expand studies to more complex physics cases using the merged tools i.e. Interplay of effects
- Make tools available to the collaboration
- Train next generation of accelerator physicists

FCC-ee related developments

Current relevant efforts within EPFL project:

● Development of a generalized lattice manager to improve model creation and interface between different codes (F. Carlier)

● Development of self-consistent 6D beam-beam in Xsuite with the goal to perform FCC-ee tuning including beam-beam (P. Kicsiny)

● Study spin polarization simulations under perturbations of misalignments and magnetic errors for FCC-ee energy calibration studies (Y. Wu, F. Carlier), with help from D. Sagan (Cornell) and E. Gianfelice (Fermilab)

● Optics and tracking developments (G. Simon just started)

Planned efforts within EPFL project → later slides

EPFL software framework meetings held regularly involving experts of respective fields
https://indico.cern.ch/category/9606/

FCC-ee work and advancements are reported at the ABP Computing working Group to share with ABP teams and get feedback

Collaborations with activities beyond EPFL

- Development of Xsuite, a framework for efficient particle tracking (G. Iadarola & R. de Maria) & FCCIS workshop → Tuesday 30 November
- Development of Xdeps, package to describe dependencies and circuits in python (R. de Maria)

- Development of tracking tools for collimation studies in the FCC-ee (A. Abramov) & FCCIS workshop → Wednesday 1 December

- New optics repository (G. Roy & M. Hofer) & FCCIS workshop → Tuesday 30 November

- pyAT developments for FCC-ee functionalities (S. White ESRF) FCCIS workshop → Monday 6 December

- Optics code development: MADX L. Van Riesen-Haupt Tuesday 30 Nov

- FCC-ee tuning studies plan/wish to have optics tuning code into general repository

Xsequence

F. Carlier

Codes currently used for FCC-ee optics & tracking studies

Many different codes are currently used for the FCC-ee feasibility studies.

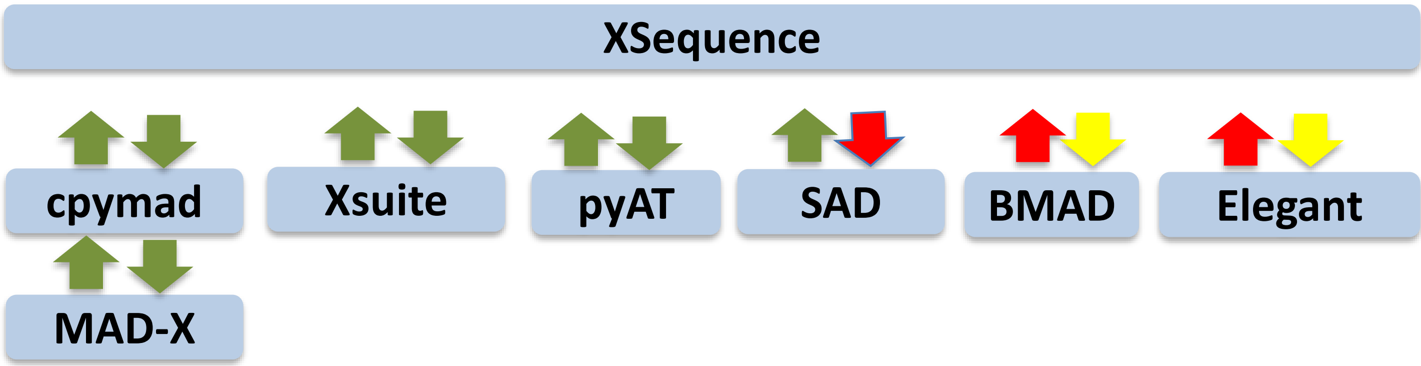
- Conversions and control of lattices between platforms is often complicated
- Managing errors and tuning knobs is complicated between platforms.

The goal of xsequence

- Simplify lattice conversions to the different codes of interest
- Offer an expandable platform for users to contribute tools for specific conversions
- Simplify the creation of models for the large simulation campaigns by controlling errors and tuning knobs
- Ensure model consistency between platforms for comparative simulations

F. Carlier

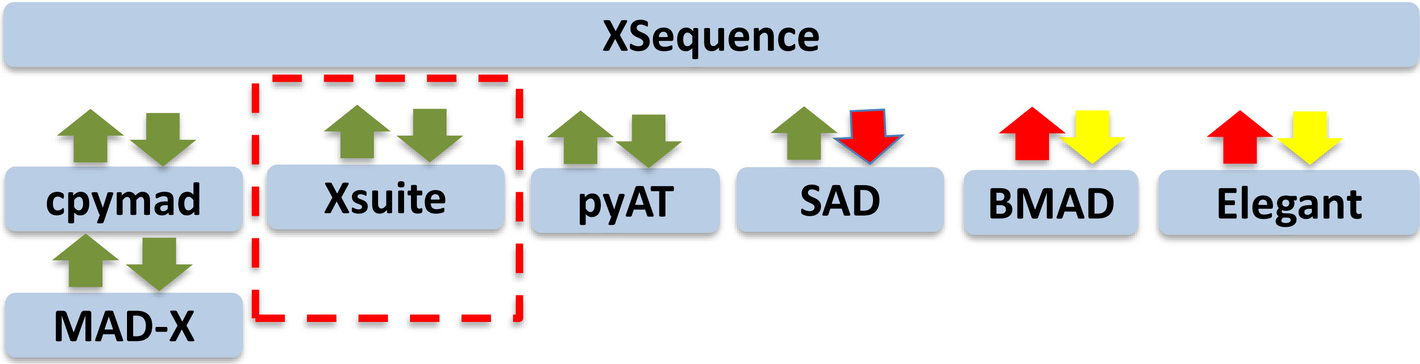
Xsequence



- Integrate codes to the framework for efficient lattice conversions and simulations
- Include basic optics calculations through framework as first step towards framework based simulations
- Explore circuits and knobs descriptions in Python for advanced lattice options (together with R. de Maria)
- Individual users can create their own converters (i.e. Elegant on-going by M. Hofer)

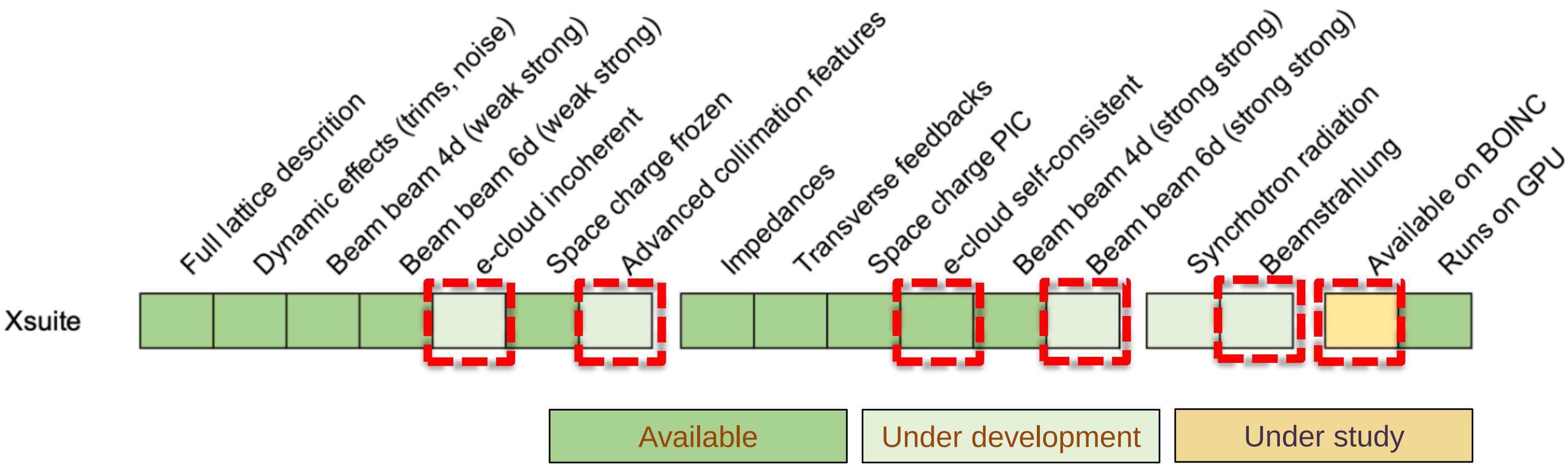
F. Carlier

Developments in Xsuite

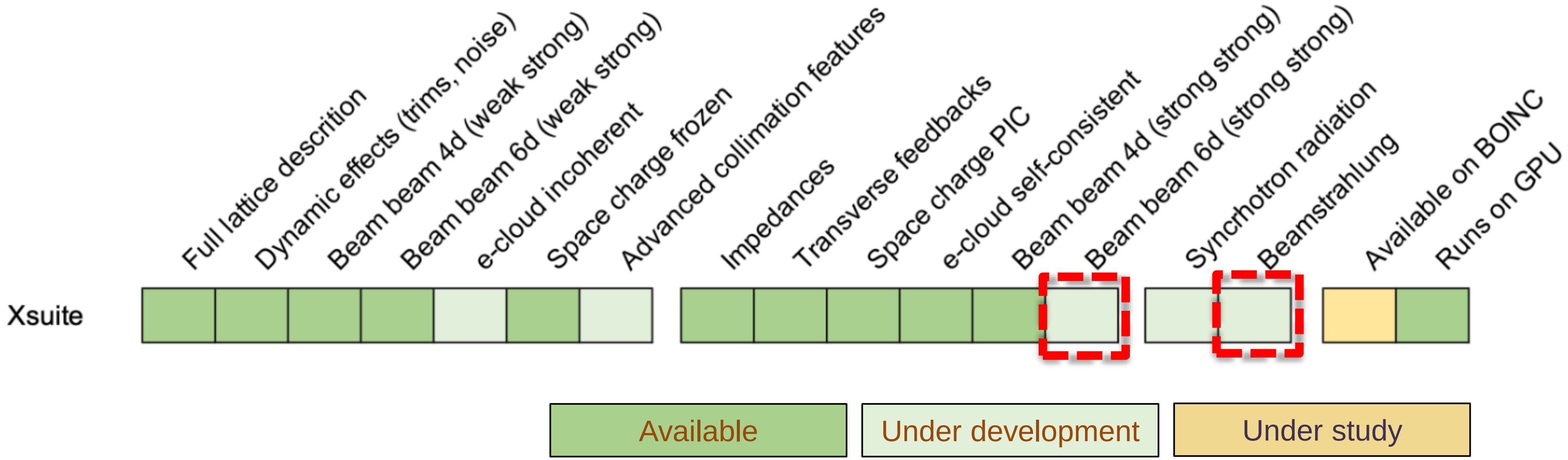


- Xsequence is part of a broader effort in code development
- The development of xsequence fits nicely in current efforts of code developments with ABP at CERN in the frame of Xsuite.

Allows to bring current code development efforts for the LHC to the FCC-ee community



Beam-Beam Studies



Goals:

- 6D Beam-beam modules with Crab Waist, beamstrshlung and realistic IR design
- Optimize speed and calculations to physics problems
- Benchmark to known effects and codes (lifetrack)where possible
- Study Multiple IP cases with realistic lattice and other collective effects for the FCC-ee CDR+

P. Kincky, X. Buffat, D. Schulte

Beam-beam code developments

D. Shatilov

At IPs, both bunches act on each other. Is it necessary to take into account the change in their distribution functions *during collision* Which BB model to use?

- The magnitude of change in the transverse coordinates during collision is described by the disruption parameter (here $\xi_{x,y}$ refers to one IP):

$$D_{x,y} = 4\pi\xi_{x,y}\frac{\sigma_z}{\beta^*_{x,y}}$$

- In crab waist collision, we have D_x << 1, but large ξ_y and β_y^* << σ_z. Does it mean that D_y >> 1? No, σ_z in the above formula should be replaced by $L_i \approx \beta_y^*$, so we have $D_y \sim 1$.

- Disruption parameters in FCC-ee is not large, which allows the use of a quasi-strong-strong model instead of a strong-strong one. The advantages are simplicity and speed.

- However, since $D_y \sim 1$, strong-strong model also is needed just in case, and to confirm the results.

- INTERPLAY between other effects (i.e. Multiple IP, lattice, impedances, space charge, …) and beam-beam is important to explore and might reserve unexpected effects!

Beam-beam Developments

P. Kicsiny Talk

Overview of existing simulation tools for circular machines

	Weak-strong 6D	Quasi strong-strong 6D	Strong- strong 6D	Beamstrahlung	Transverse wakefields	Longitudinal wakefields	Tracking with simplified maps	Tracking element-by-element	Background generation	Crab waist of the strong beam	Synchro-beam mapping with solenoid field
GUINEA PIG [1]	Available	Not available	Available	Available	Not available	Not available	Not applicable	Not applicable	Available	Not applicable	No info
COMBI [2]	Available	Available	Available	Not available	Available	Not available	Available	Not available	Not available	Not available	Not available
BBWS [3]	Available	Not available	Not available	Available	Available	Available	Available	Available	Not available	Not available	Not available
BBSS [4]	Not available	Not available	Available	Available	Available	Available	Available	Available	Not available	Not applicable	No info
IBB [5]	Not available	Not available	Available	Available	Available	Available	Available	Not available	Not available	No info	Not available
LIFETRAC [6]	Available	Available	Not available	Available	Not available	Not available	Available	Available	Not available	Available	Not available
BeamBeam3D [7]	Available	Not available	Available	Available	Available	Not available	Available	Not available	Not available	Not applicable	Not available

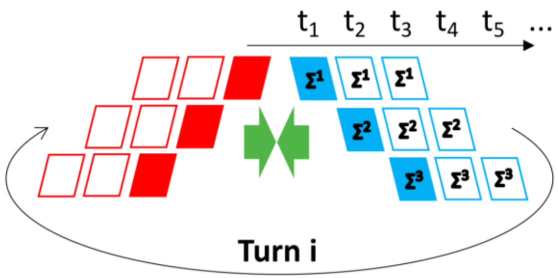
Available | Not available | No info | Not applicable

- Several codes have been used for beam-beam simulations in various colliders
  - They were used for different kinds of studies with different models
  - No cross-framework communication

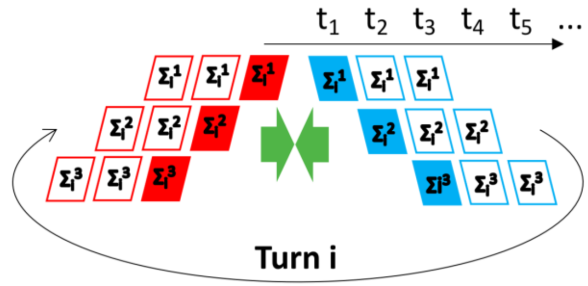
[1] D. Schulte [https://cds.cern.ch/record/331845/files/shulte.pdf]
[2] T. Pieloni, W. Herr [https://accelconf.web.cern.ch/p05/PAPERS/TPAT078.PDF]
[3] K. Ohmi [https://indico.cern.ch/event/438918/contributions/1085290/attachments/1147002/1644777/BenchBBcodes.pdf]
[4] K. Ohmi [https://oraweb.cern.ch/pls/hhh/code_website.disp_code?code_name=BBSS]
[5] Y. Zhang [https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.104402]
[6] D. Shatilov [http://cds.cern.ch/record/1120233/files/p65.pdf]
[7] J. Qiang [https://amac.lbl.gov/~jiqiang/BeamBeam3D/]

- Review of existing Models
- Discussions with Experts to define needs, challenges and strategy
  (Shatilov, Ohmi, Oide, Frank)

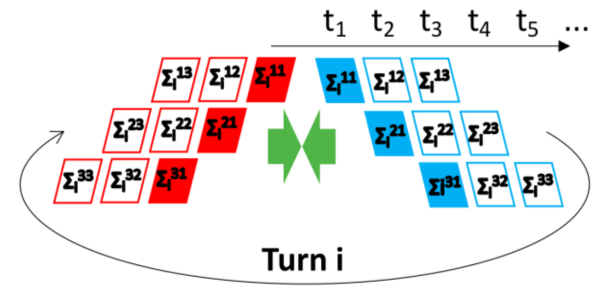
Beam-beam development status



Weak-Strong

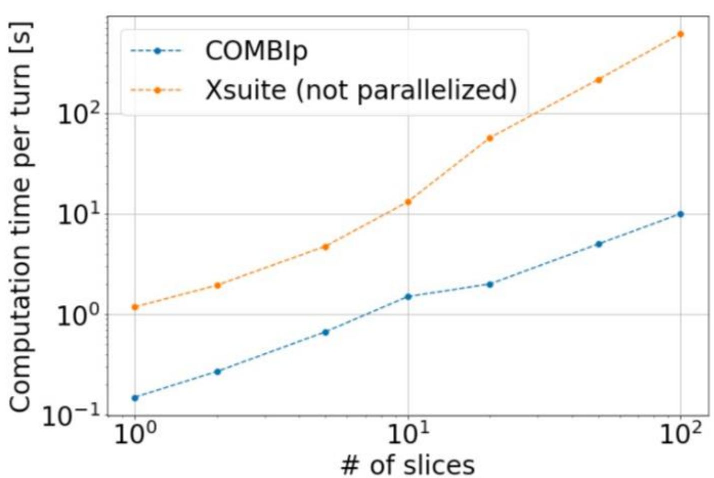


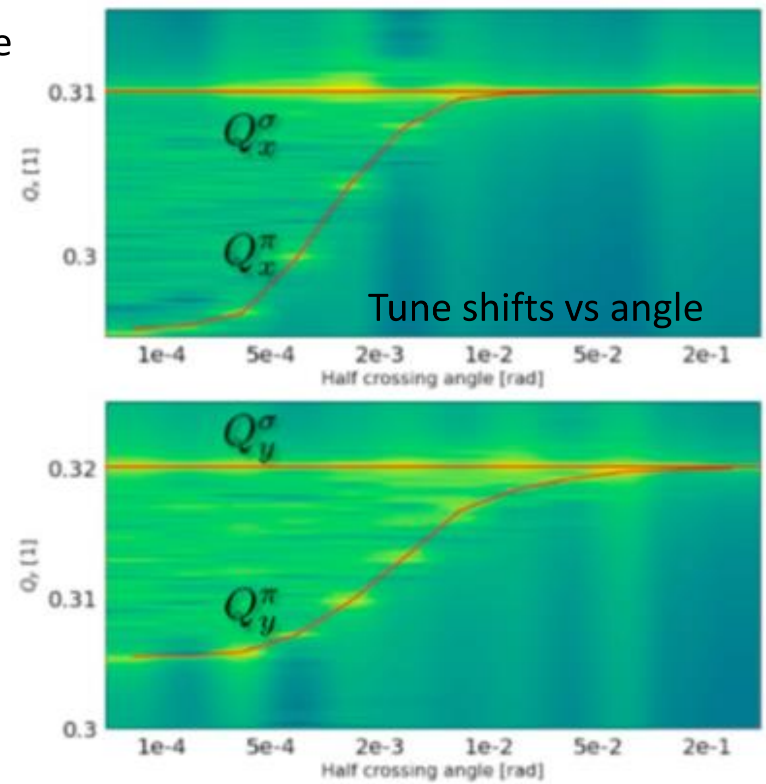
Quasi
Strong-Strong



Strong-Strong

- 3 Models developed fully implemented in the Xsuite package
- First Benchmarks for Soft Gaussian model gives good results
- Parallelization and Speed Optimization on going to enable Multiple IP studies

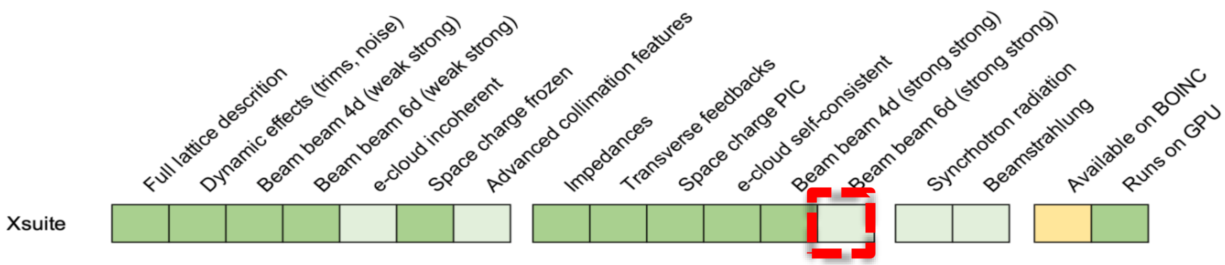




Future plans from Beam-Beam

Plans

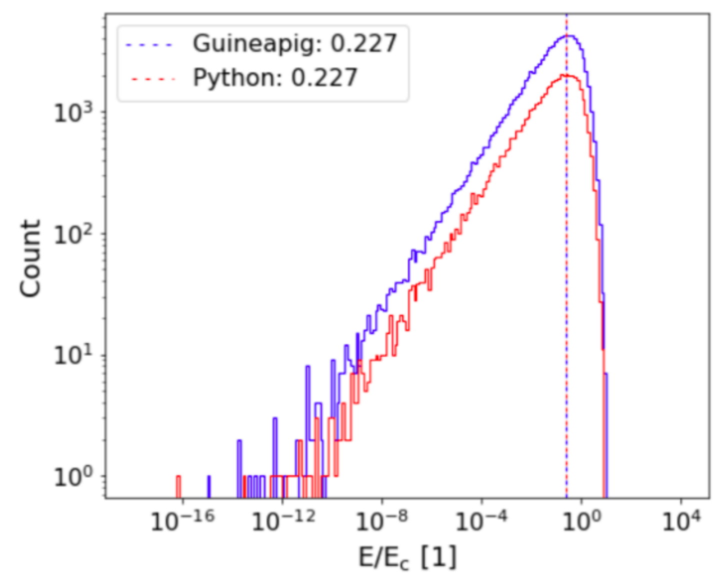
- 6D strong-strong with field solver and Beamstrahlung (adapting field solvers already implemented in xsuite)
- Synchro-beam mapping including solenoid field
- 6D weak-strong model with non-Gaussian distributed charges (crab-waist of the strong beam)
- Background (Beamstrahlung photons, Bhabha scattering, pair production)
- GUINEA PIG interface for direct benchmarks



Very preliminary example of the BB developments

Easy concatenation of different modules
BB lens + Beamstrahlung

→ Emitted Beamstrahlung photons from BB6D compared to Guineapig (differences related to slicing)



Simulation tools for Collimation

Talk A. Abramov

- **No framework that currently has the requirements for collimation**
- **Collimation developments focus on a connection between a tracker and a physics engine**

Code	6D symplectic tracking	Synchrotron radiation	Tapering (lattice)	Geant4 integration	FLUKA integration	Speed	Aperture modelling
MAD-X	Available	Available	Available	Not available	Not available	Partial availability	Available
SixTrack	Available	Not available	Not available	Available	Available	Available	Available
BDSIM	Not available	Available	Not available	Available	Not available	Not available	Available
Merlin++	Available	Available	Not available	Not available	Not available	Available	Available
pyAT	Available	Available	Available	Partial availability ★	Not available	Available	Available
xTrack	Available	Partial availability ★	Not available	Partial availability ★	Not available ★	Available	Available

Not available | Partial availability | Available

★ = in development

Summary

- Development of collimation simulations
  - pyAT and Xtrack were selected as the most promising tracking codes
  - Status of pyAT collimation developments
    - A Python interface to BDSIM (Geant4) for particle-matter interactions inside the collimators was developed, to enable multi-turn tracking studies
    - Testing and validation with comparisons to SixTrack-FLUKA
  - Status of Xtrack collimation developments:
    - Interface to Geant4 implemented, similar to pyAT
    - Benchmarks being set up now
    - Other developments in ABP, such as synchrotron radiation
- Future work for the simulations
  - Discussions between ABP collimation team and FLUKA team to develop a FLUKA integration with Xtrack and pyAT for collimation
  - Integrate the collimation models with other studies, such as MDI-related activities
  - Include errors, imperfections, and misalignments into the collimation models
  - Investigate the options for including beam-beam effects, including Beamstrahlung (discussions ABP, EPFL, MDI team)

Summary

- Development of collimation simulations
  - pyAT and Xtrack were selected as the most promising tracking codes
  - Status of pyAT collimation developments
    - A Python interface to BDSIM (Geant4) for particle-matter interactions inside the collimators was developed, to enable multi-turn tracking studies
    - Testing and validation with comparisons to SixTrack-FLUKA
  - Status of Xtrack collimation developments:

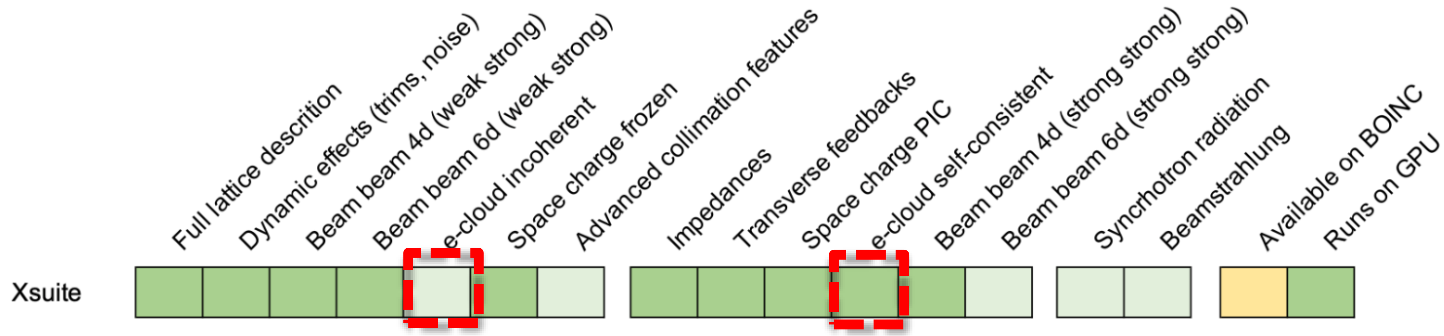
Collaboration with Collimation team :

- MADX→pyAT converter to allow pyAT tracking for coll
- Aperture model preliminary studies
- Investigation how to include BB and Beamstrahlung

Xtrack and pyAT for collimation

- Integrate the collimation models with other studies, such as MDI-related activities
- Include errors, imperfections, and misalignments into the collimation models
- Investigate the options for including beam-beam effects, including Beamstrahlung (discussions ABP, EPFL, MDI team)

Electron Cloud and fast ion instabilities Studies



- Identify open questions and challenges related to electron cloud and fast ion instabilities
- Develop, modernize or optimize the tools for the problem
- Perform the physics studies

Physics questions:

- Study e-cloud instabilities in the presence of radiation damping and other relevant effects
- Improve surface models used in simulations based on measurements
- Evaluate the requirements for e-cloud mitigation strategies

Code developments:

Contribute to the further integration of PyHEADTAIL and xsuite to allow for e-cloud studies with features available in xsuite (i.e. Beam-beam effects)

People: 1 post-doc from 1st February

L. Mether, L. Sabato, T. Pieloni and G. Iadarola

ML4FCC and BOINC system

Particle loss: main figure of merit of accelerator - goal is to minimize

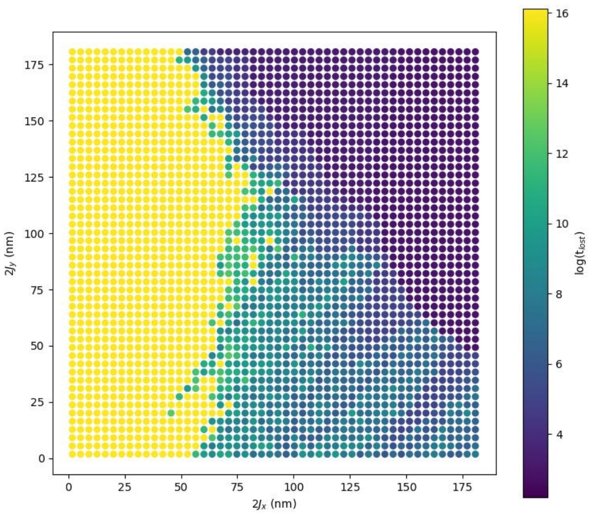
Current approaches to accelerator optimization / design

Grid search along few parameters at a time, in small subspace
(magnetc currents, beam and machine parameters)
Missing big picture and potential optima
Studies often from scratch, “ignoring” previous results

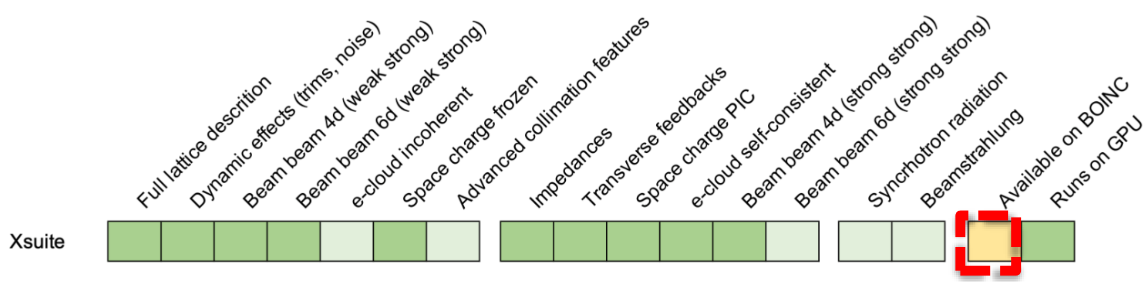
Goals:

Create surrogate model of particle loss vs. machine configurations from simulation data Build upon *(= active, efficient sampling)* over time: accumulate results as we go and update

One step further: find optimal machine design for future collider using ML?



Approved Grant
2 post-doc for 2 years
Position is open!



Spin Polarization Studies

SITROS used (E. Gianfelice)for the FCC-ee CDR Studies EPOL WG:

- well established and benchmarked model from HERA times
- quite old and difficult to "modernize"

BMAD is a simulation library (D. Sagan) that can model the needed physics process for FCC-ee:

- more modern tool, user friendly, shares many features (also uses PTC spin tracking, present also in MADX)
- needs to be used and adapted to the FCC-ee lattice (first try by Y. Wu and Felix) and needs benchmark to SITROS

Plans:

- Started some exploration of BMAD with help and support of D. Sagan
- Benchmark to SITROS for two cases: the FCC-ee lattices of CDR and a simplified lattice to distinguish lattice and codes differences (Yi, Felix and Eliana)
- Try a benchmark of models to LEP collider case (A. Blondel, J. Wenninger and W. Herr)
- Perform systematic studies in within the EPOL WG

We plan to put some resources in these developments from CHART: possibly 1 post-doc and 1 PHD student to advance the studies for the CDR+, identify possible code developments needed, and to train newcomers in this field

Spin polarization simulations in Bmad (Y. Wu, F. Carlier)

Bmad is an accelerator simulation library that forms the building blocks of different programs.

For spin simulations two main programs can be used:

- Tao → Linearized spin calculations (Using PTC)
- Long Term Tracking → Full spin tracking, can be used for nonlinear effects (Bmad standard, PTC, Runge-kutta, ..)

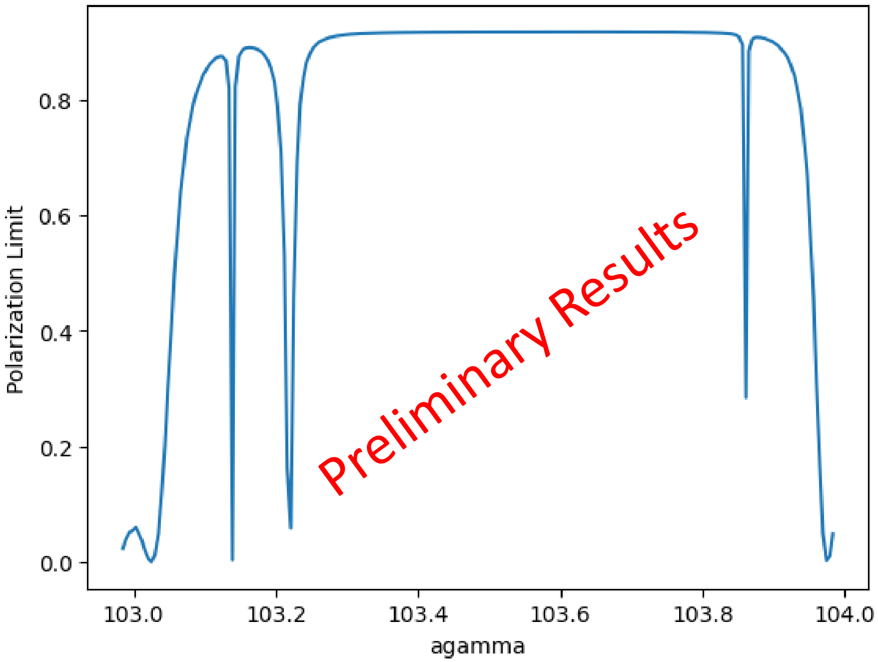
Bmad has now been compiled on HTCondor cluster

→ first simulations of energy scans are being performed

→ Benchmarks to be done to CDR studies with E. Gianfelice-Wendt

In future, Long Term Tracking will be used to study full NL lattice

Misalignments in IR and Arc Dipoles and Quadrupoles, and rolls in Sextupoles. RMS orbit error 4.1*10^-5m



Summary

In the FCC-ee several beam dynamics challenges need a development/modernization of tools

A lot of effort has started to coordinate, harmonize and modernize the code developments in within the FCC-ee studies in synergy with the ABP developments

Common goals are:

- Identify scientific challenges to be addressed
- Develop needed models and solve technical limitations
- Develop maintainable tools even beyond CDR+
- Reproducible and tested results
- Easy learning curve for newcomers
- Speed and new technologies should be pushed (i.e. GPU, ML)

Define possible testing of models to operational machine (i.e. SuperKEKB)

A lot still needs to be done and we are open to collaborators wanting to join and contribute
And we are happy to bring our help in projects within the FCC-ee collaboration

Thank you!