CERN

A multiplatform Python toolkit for beam dynamics

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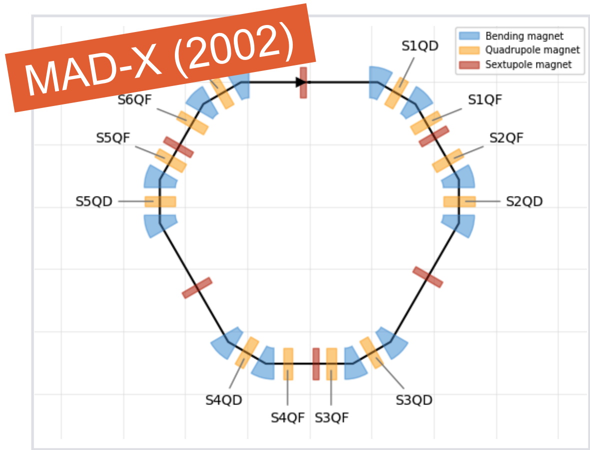
We sincerely thank the Xsuite users and contributors for their enthusiasm and invaluable input.

For more material: *https://xsuite.web.cern.ch*

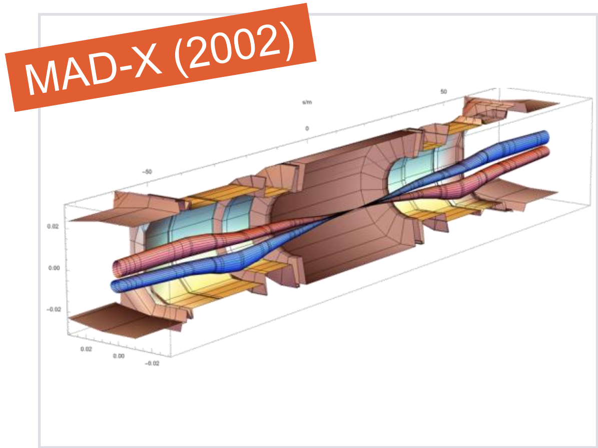
Work supported by: CHART

CERN software for beam dynamics

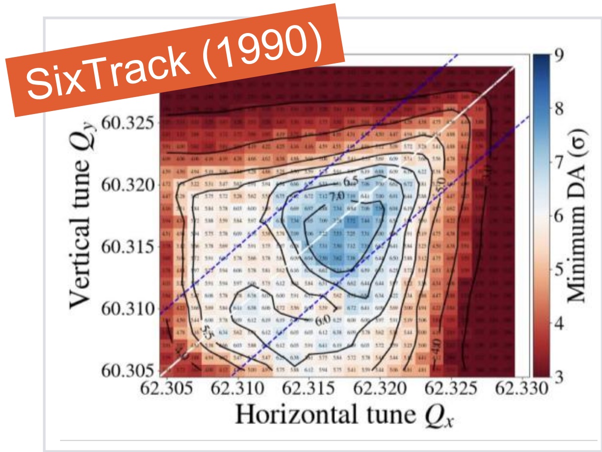
CERN has a long history of **powerful software tools for beam physics applications**, typical examples (BE-ABP):



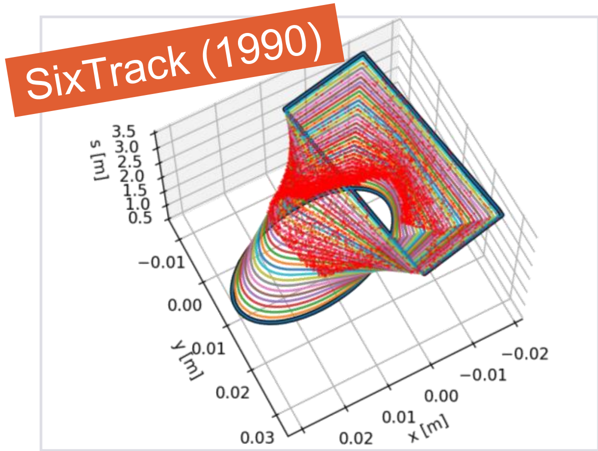
Lattice Design



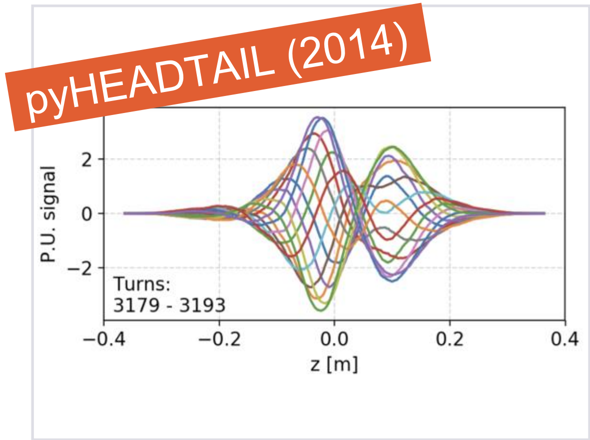
Optics (calculation & design)



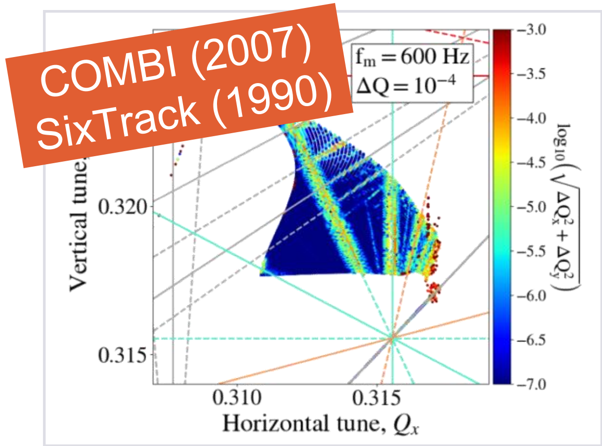
Tracking (dynamic aperture)



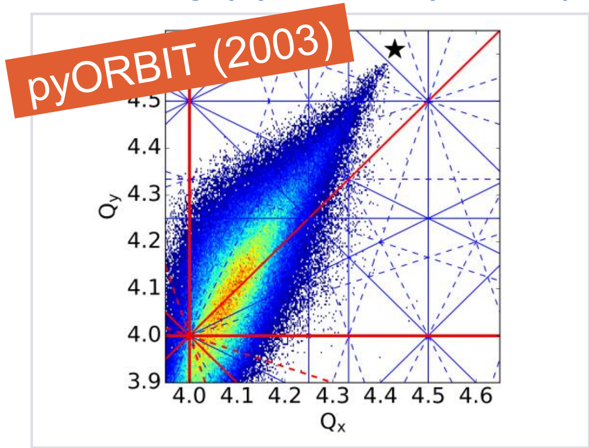
Collimation



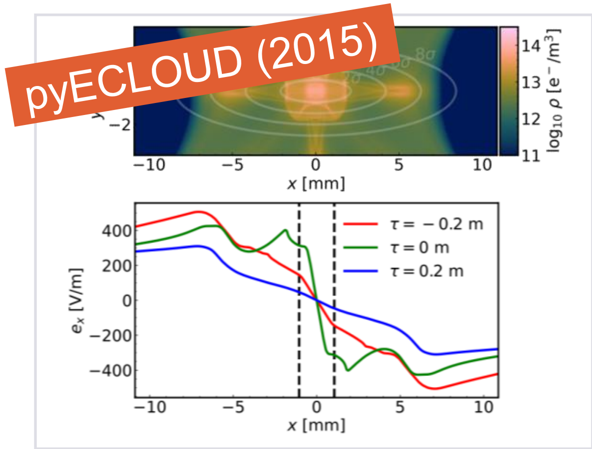
Impedances



Beam-Beam Effects



Space Charge

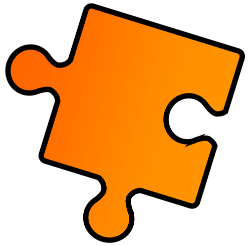


Electron/Ion Cloud

Key requirements and limitations of legacy tools

Legacy tools have several limitations, which became **apparent when approaching FCC-ee**

- **Extendibility**
  - Difficult and expensive to extend old tools for modeling additional effects
  - Many experts have left or retired; working on old Fortran does not match skill set and interest of younger colleagues
- **Integration issues**
  - Often addressing interplay of optics, non-linear tracking, collective effects, collimation, etc.
  - With legacy tools this means dealing with model translations, ad-hoc interfaces between codes, which is complicated, time-consuming, error prone, and slow.
- **Outdated user interfaces – today users want Python**
  - Python is a standard in scientific computing, especially among younger researchers.
  - Many high-quality tools are available in the Python ecosystem also due to ML boom.
  - Maintaining custom tools for plotting, scripting, etc. wastes effort, increases complexity, and lowers quality.
- **Performance**
  - GPU acceleration is a must-have in many applications, but often infeasible to retrofit.



python™

Xsuite project launched in 2021 to address these issues using the know-how acquired in the development of the earlier tools.

Goals: 1st class Python, 1st class collective, 1st class GPU.

– One toolkit for many applications: from low-energy hadron rings to high-energy lepton colliders.

– Heterogeneous simulations made natural.

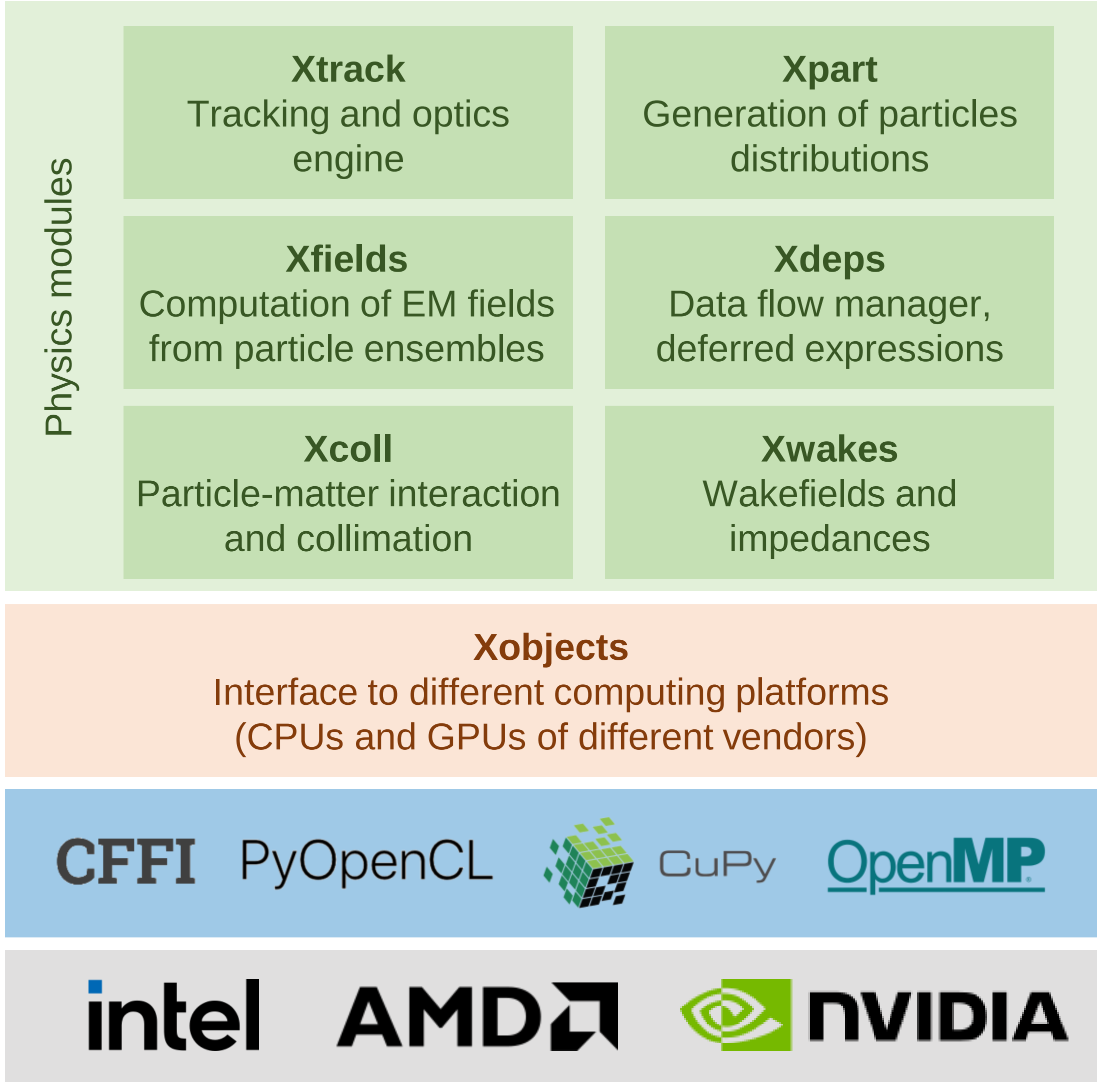
– Support different computing platforms – single- and multi-threaded CPU, GPU acceleration.

References for full list of features:

- *Documentation: xsuite.web.cern.ch.*
- *"Xsuite: An Integrated Beam Physics Simulation Framework," JACoW HB2023 (2024), TUA2I1.*
- *"Xsuite: a multiplatform toolbox for optics design, fast tracking, collimation and collective effects," ICAP'24*

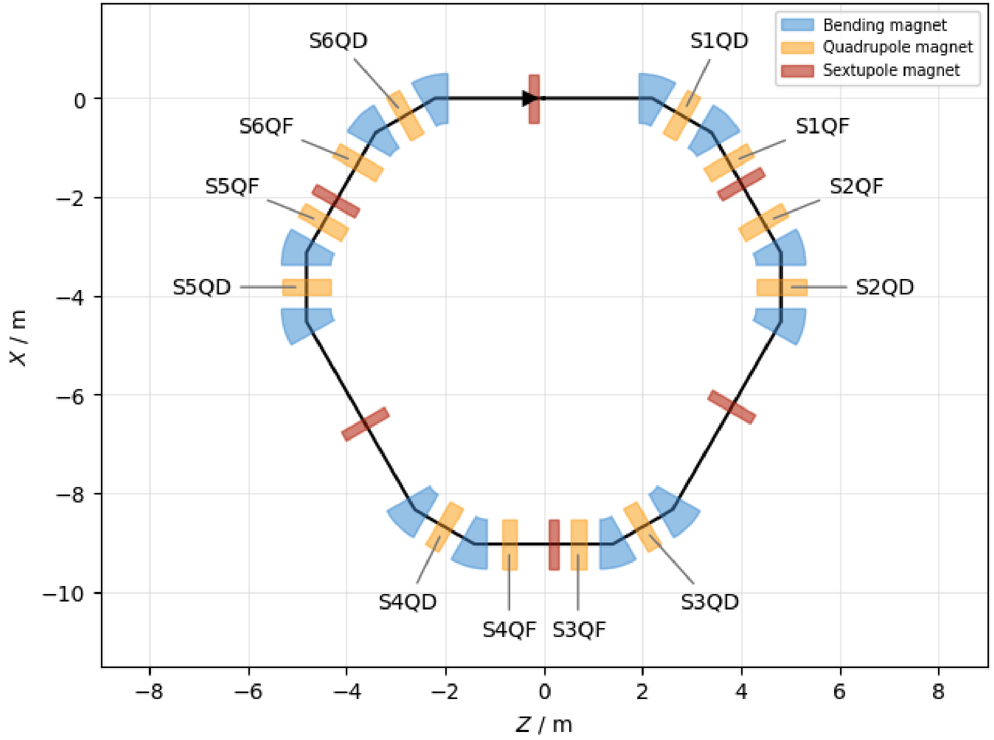
Xsuite approach

- **Orthogonal architecture:** split the software into independent functional blocks at all levels.
  - Well structured codebase scales better and makes easier to add new features.
  - Lower learning curve for users & developers ⇒ users can (and do!) become developers.
- **Agile development:**
  - From the beginning big effort to support users: user feedback and involvement visibly increases the quality of the package.
  - Thanks to investment in continuous testing, we can afford a fast release cycle with new versions coming out multiple times a month
  - Continuously incorporating fixes and modifications based on user feedback.



Xsuite features - lattice modelling

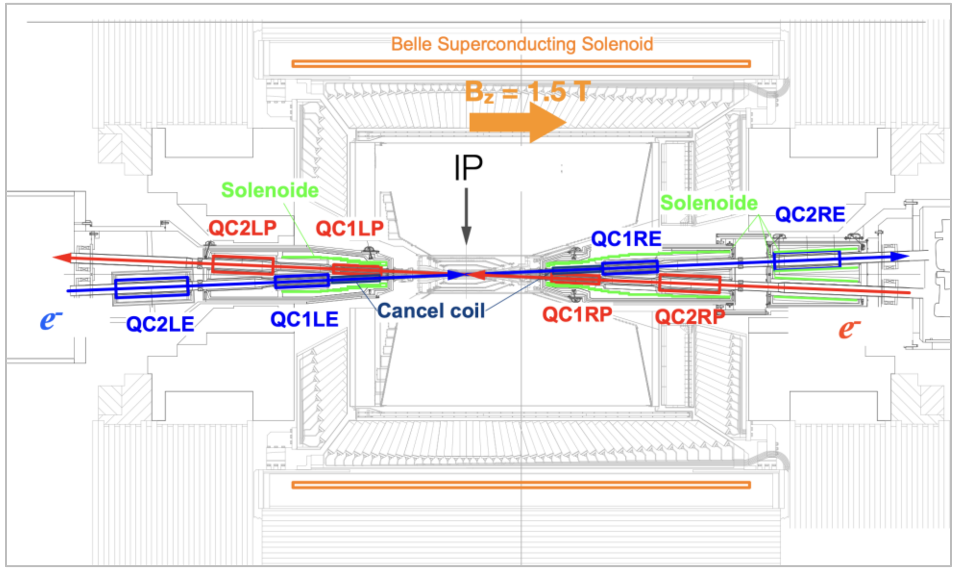
- The full set of **lattice elements required to model all CERN synchrotrons** is now available
    - Bends, multipoles, solenoids, combined-function magnets RF cavities, crab cavities, etc.
- Provide **thick and thin lattice modeling**
- Include **dipole-edge effects** and **fringe fields** (profited of PTC and MAD-NG experience)
- Support **tilt**, **misalignments**, **multipolar errors**
- Circuits can be handled through **deferred expressions** (as in MAD-X)

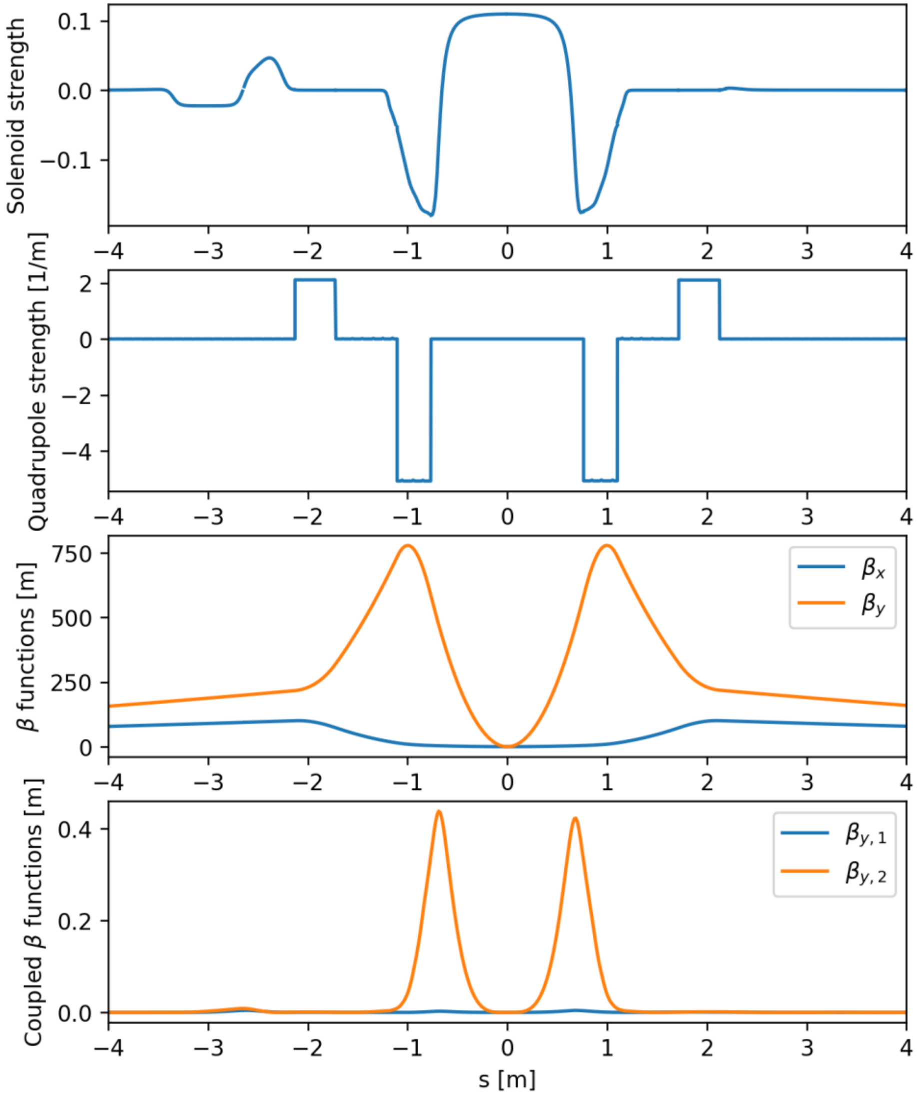


Modelling of experimental regions

Capability of modelling **experimental solenoids** also in the presence of **tilted and overlapping multipole fields**

- Already tested for the case of FCC-ee
- Profited of these developments to build a detailed model of **SuperKEKb collider**
  - Being used for several studies in view of FCC including luminosity feedback and collimation studies



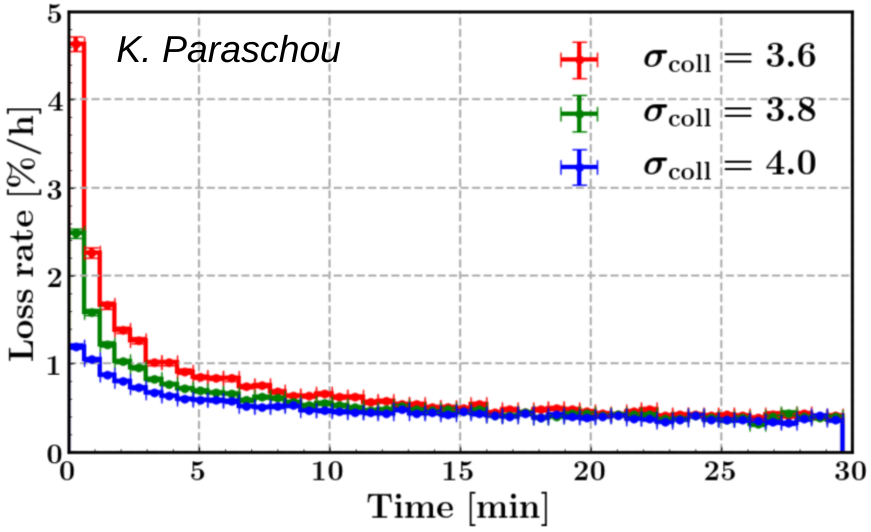


More info: J. Salvesen, presentation at [BELLE2 meeting 29 Jan 2025](#)

Single particle tracking

Multiturn element-by-element **tracking speed** is critical for several application

- To speed up tracking simulations, **Xsuite assembles a C kernel** (called from Python) optimized for the given beamline and **specialized for the chosen platform (CPU or GPU)**
  - The tracking speed is found to be in line with Sixtrack for single-core CPU and about two orders of magnitudes faster than that on high-end GPUs

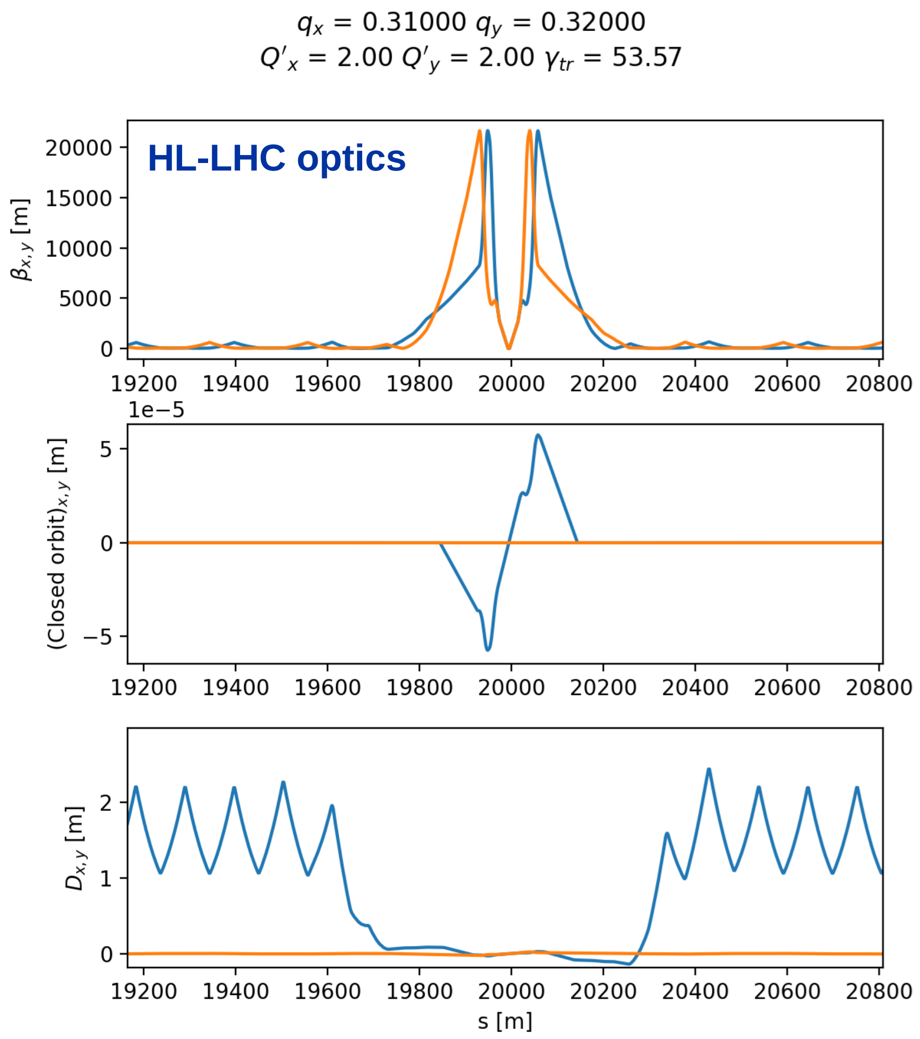


Example for LHC:

- **Direct element-by-element simulation of the first 30 minutes** after bringing beams in collision (**20 M turns!**) to study lifetime, and tail depopulation
- Simulation of **20 000 particles**
  - On **CPU** (single process) would take **> 2 years sim. time**
  - On **GPU** (NVIDIA V100) was done **< 3 days sim. time**

Optics calculation

- The **Xsuite Twiss** module can be used to extract **lattice functions** of a ring or a beamline
- The calculation **probes the lattice simply by tracking particles**:
  - Closed orbit obtained by applying a Python root finder on the tracking
  - The Jacobian matrix obtained by tracking (central differences)
  - Compute "Linear Normal Form" of the Jacobian matrix (diagonalization)
  - Propagate eigenvectors by tracking
  - Obtain from the eigenvectors Twiss parameters (α, β, γ), dispersion functions, phase advances, coupling coefficients
- Computation can be done with **assigned beam momentum** to get off-momentum beta-beating, non-linear chromaticity, non-linear dispersion, etc.



Accuracy compared to MAD-X: $\Delta\beta$ / β << 10^{-4}
Computation time is very similar

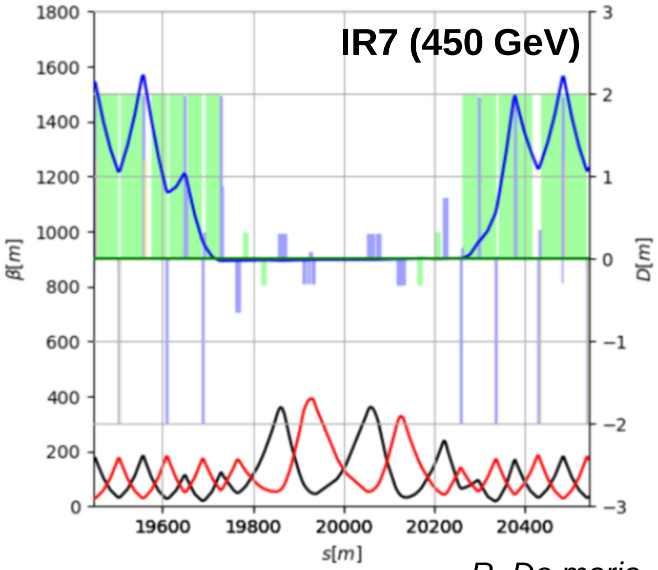
```
In [39]: t_mad_ms
Out[39]: 202.0

In [40]: t_xsuite_ms
Out[40]: 185.0
```

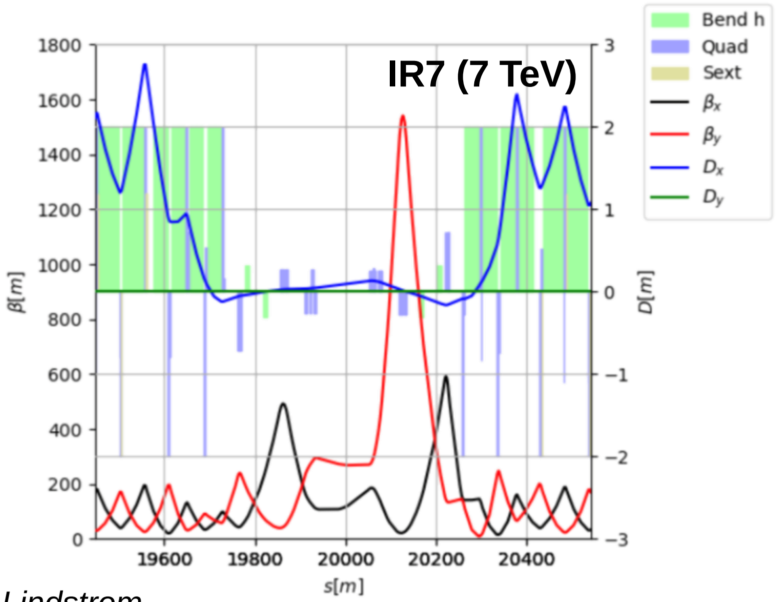
Optics design

Xsuite provides a **multi-objective optimizer** to "match" model parameters to assigned constraints (e.g. control tunes, chromaticity, build orbit bumps, design the optics)

- Based on the **extensive experience of MAD-X** → **Provides** several optimization algorithms (including Jacobian algorithm developed for MAD-X) + easy plug-in of external python optimizers
- Interface **designed for usage flexibility**. User can **intervene in the optimization** by:
  - Enabling/disabling targets or knobs, rolling back optimization steps, changing knob limits, target values, convergence tolerances
- Used for **optics matching of the LHC and of FCC-ee colliders**

First full cycle designed with Xsuite tested at the LHC in 2024
(including combined ramp&squeeze for all insertions)





R. De maria, B. Lindstrom

Particle-matter interaction

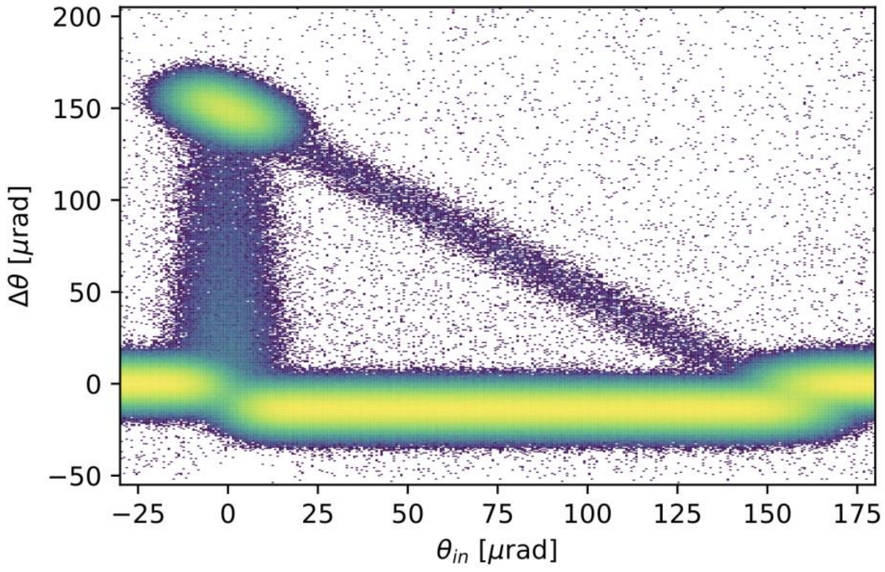
For collimation studies, the **Xcoll module** provides **three particle-matter simulation engines**:

- The **"Everest" engine** embedded in Xcoll (evolution of K2 module from Sixtrack)
- The **"Geant 4" engine**, based on an interface with BDSIM-Geant4 (used for FCC-ee collimation studies)
- The **"FLUKA" engine**, based on an interface with the FLUKA Monte Carlo code

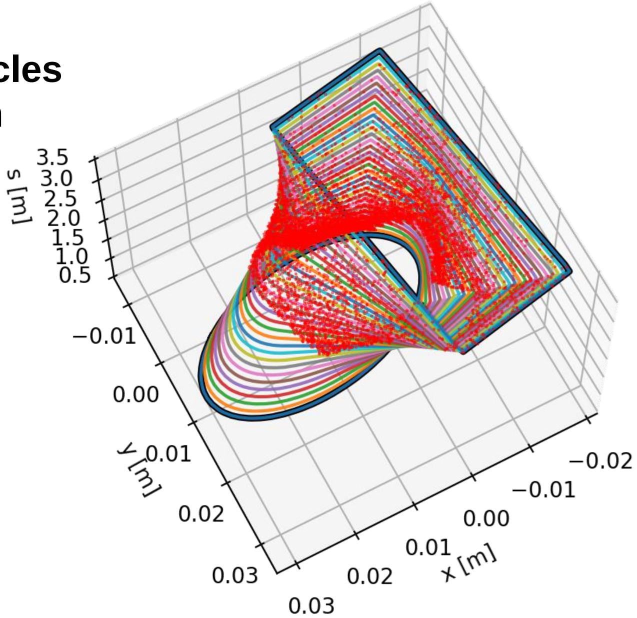
Additionally, Xsuite provides:

- Tools to **automatically install and configure collimators** in the simulation model
- Support for **complex aperture modelling** and **accurate localization of the lost particles** along the beam line (typically within 1-10 cm)

Particle deflection from a bent crystal (Everest engine)



Localization of lost particles along a beam pipe with changing cross section



Synchrotron radiation

The effect of **synchrotron radiation** can be included in Xsuite tracking simulations. Two models available:

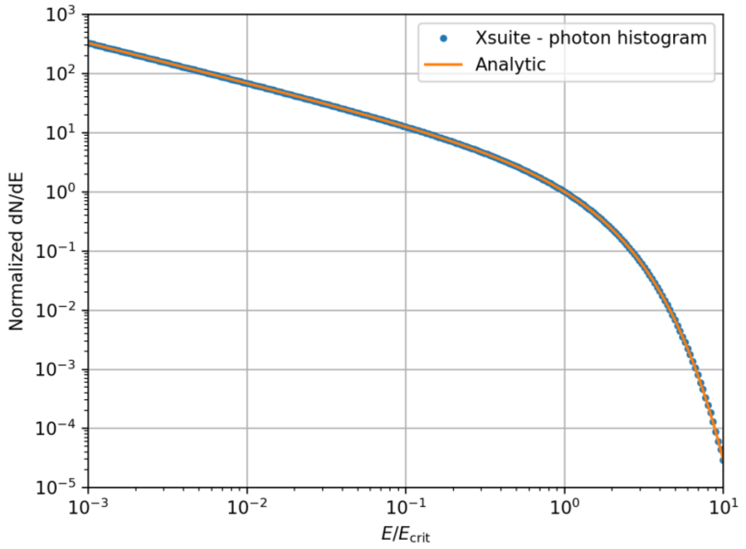
- The **"mean" model**, for which the energy loss from the radiation is applied particle by particle without accounting for quantum fluctuations;
- The **"quantum" model** for which the actual photon emission is simulated.

The **Xsuite Twiss** also includes:

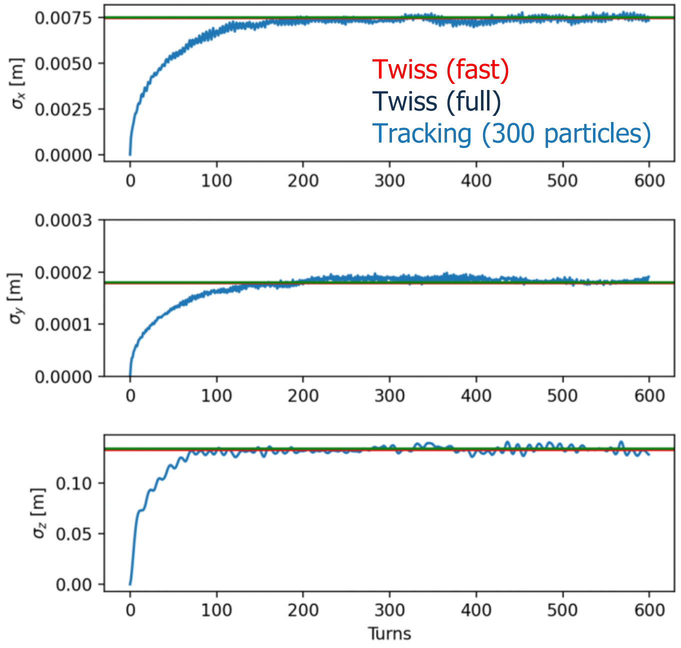
- Dedicated algorithm for optics function with **non-symplectic one-turn map**
- Module extended to compute **radiation energy loss, damping times and equilibrium emittances**

To **compensate the radiation energy loss ("tapering"),** an automatic tool is provided for phasing the RF cavities and adjusting magnet strengths.

Validation against analytical photon spectrum



Eq. emittance twiss vs track



Beam-beam modeling

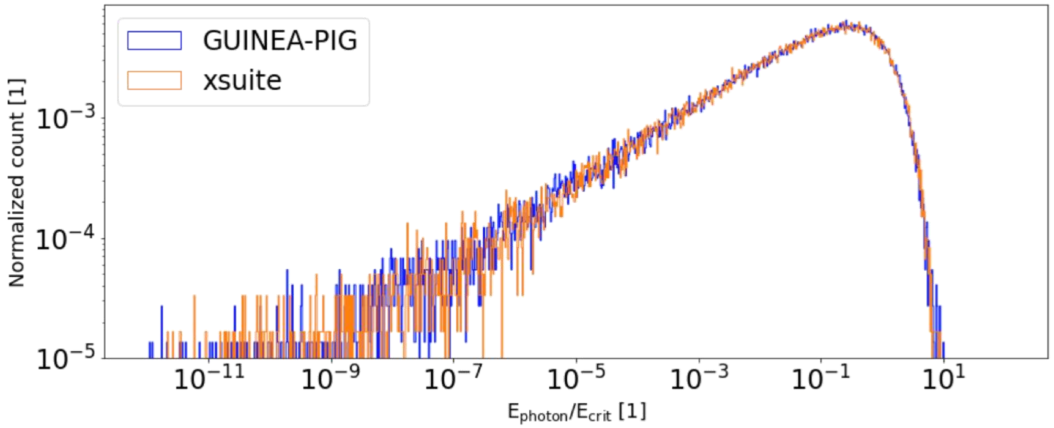
Largely **profited from developments made for LHC**

- 4D and 6D modelling based on Gaussian distribution
- Weak-strong and strong-strong methods

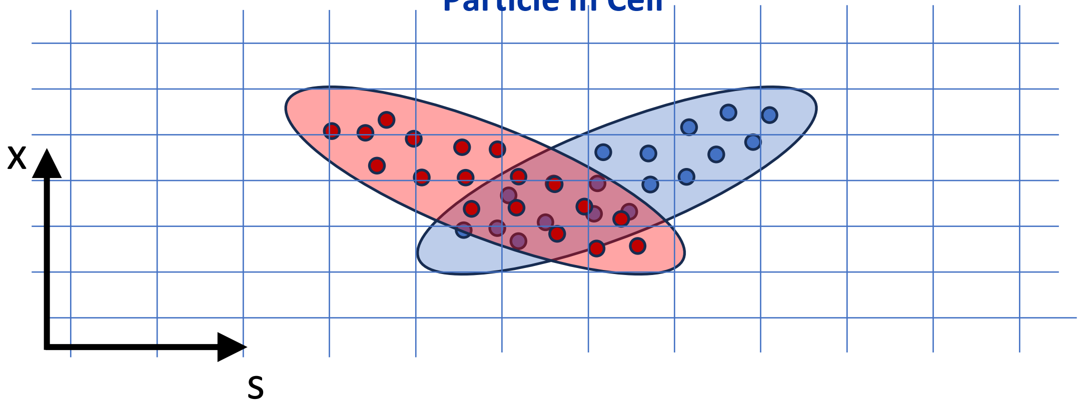
Additional **features added specifically for FCC-ee**

- Self-consistent Particle-In-Cell model
- Beamstrahlung radiation
- Bhabha scatting estimates

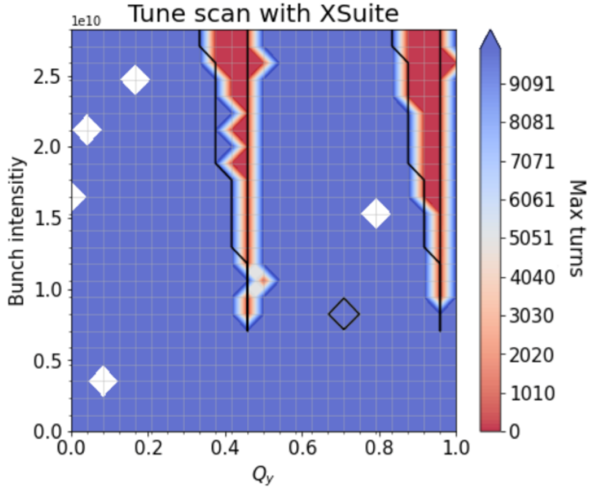
Beamstrahlung – validation against Guinea Pig



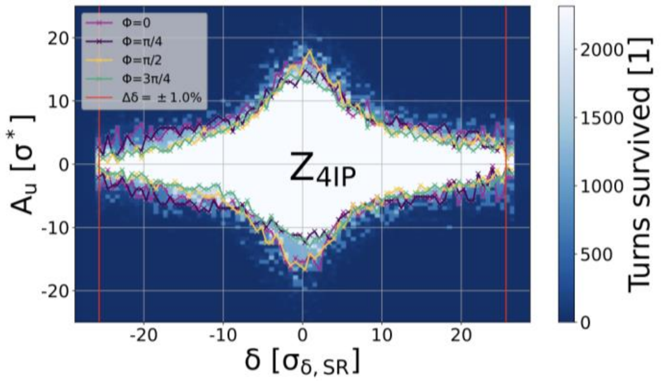
Particle In Cell



Coherent bb effects at FCC-ee



FCC-ee DA with BB



More info: P.Kicsiny, presentation at [FCC Week 2024]

Collective effects

Space-charge: different models are implemented:

- "Frozen" model, fixed charge distributions
- "Quasi frozen", beam intensity and beam sizes are recomputed at each interaction
- The "Particle In Cell (PIC)" model

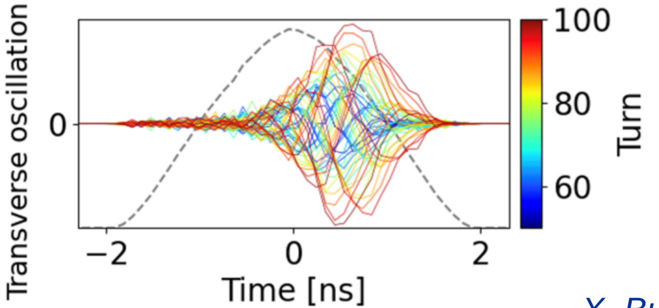
Wakefields

- Longitudinal, transverse dipolar and quadrupolar
- Single-bunch and multibunch

Intra Beam Scattering (IBS) simulation capabilities have been recently introduced:

- IBS growth rates computation from beam parameters and optics.
- Effect of IBS can be included in multiparticle simulations.

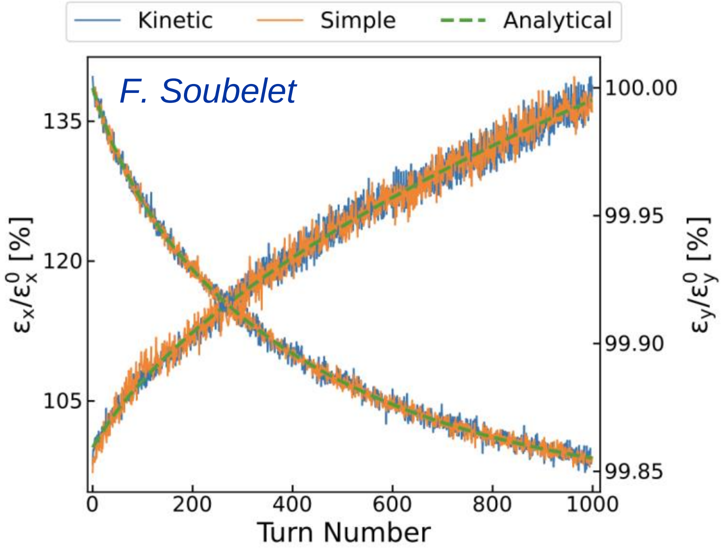
Coherent instability simulation with wakefields and space charge



X. Buffat

N. simulations	400
Number of PIC calculations per turn	540
Number of turns per simulation	40'000
Computing time per sim. (GPU)	~3 days
Computing time per sim. (CPU serial)	> 12 months

IBS Benchmark for the SPS (Pb ions)



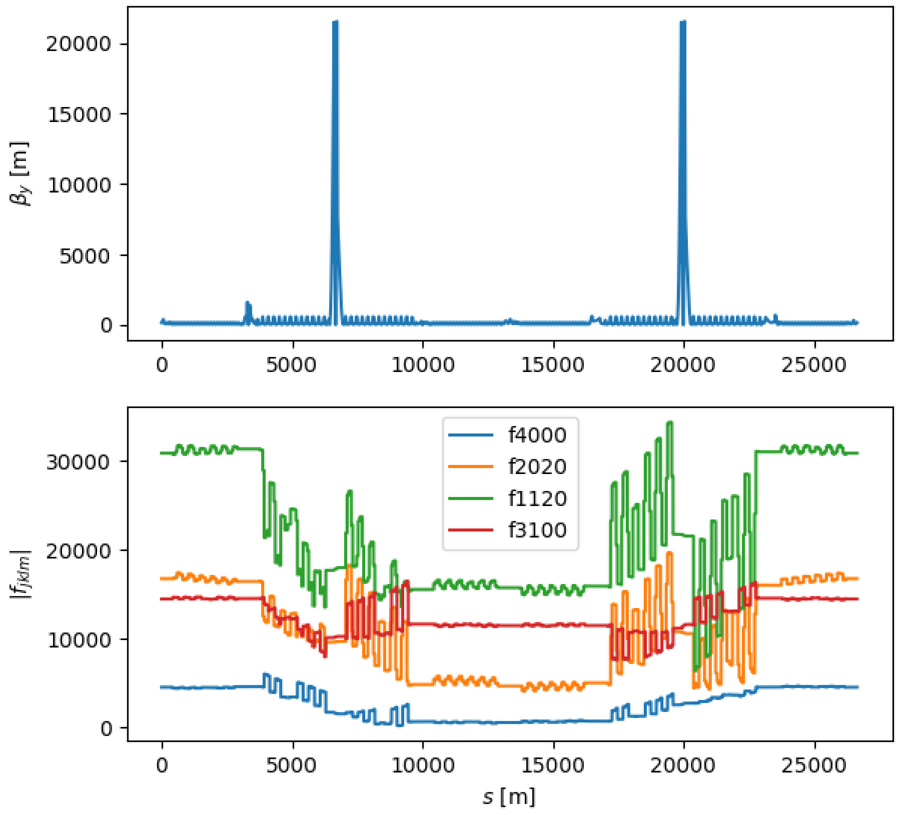
Interfaces to other tools

By design Xsuite is **easy to interface** and extend using other tools providing a Python API.

Several examples of interfaces providing Xsuite with features that are not natively available:

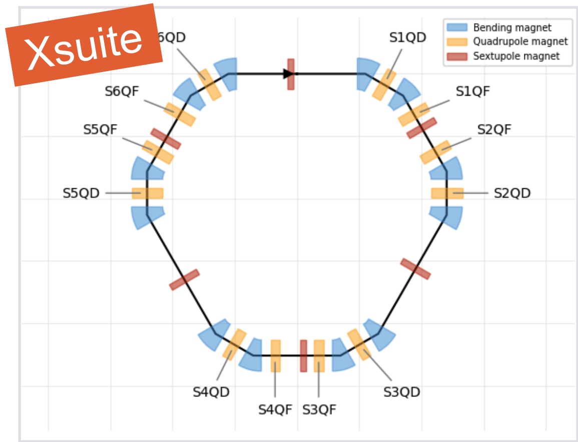
- **MAD-NG** – computation and optimisation of parametric nonlinear normal forms, resonant driving terms, automatic differentiation.
- **RF-Track** – particle tracking in complex field maps.
- **FLUKA** – simulation of particle-matter interaction (e.g. LHC collimation studies).
- **BDSIM-GEANT4** – particle-matter interaction (mostly for FCC).
- **BLonD** – advanced modelling for RF systems.

```
rdts = ["f4000", "f3100", "f2020", "f1120"]
twiss_ng = hllhc15_line.madng_twiss(rdts=rdts)
```

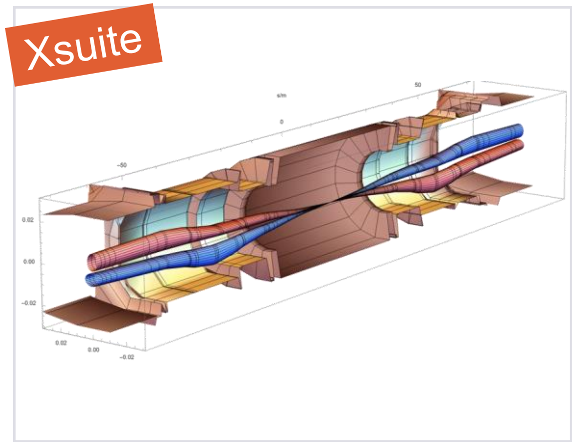


Where we do we stand today

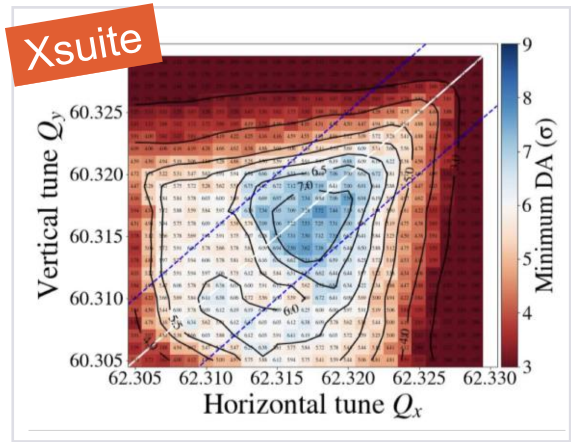
By now Xsuite became a **production tool** for many beam dynamics studies, allowing development discontinuation for many legacy tools.



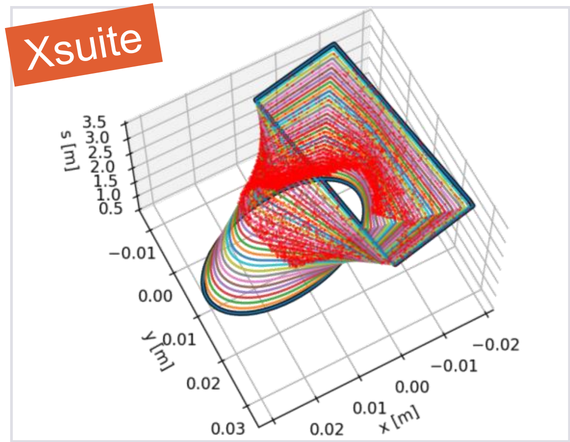
Lattice Design



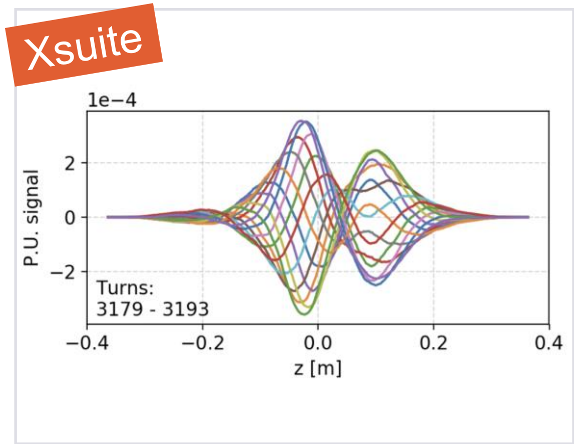
Optics (calculation & design)



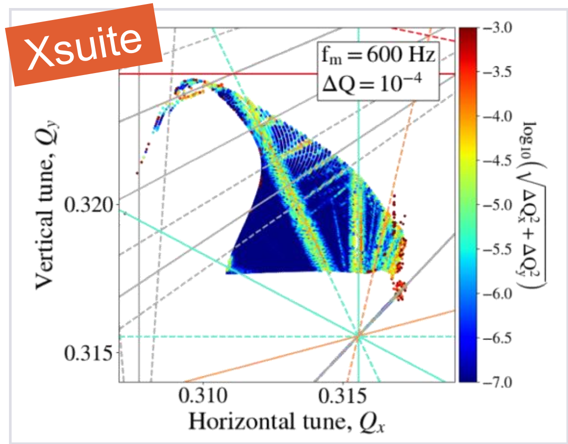
Tracking (dynamic aperture)



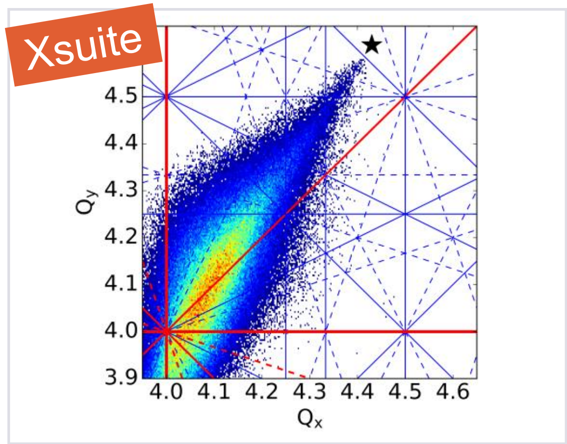
Collimation



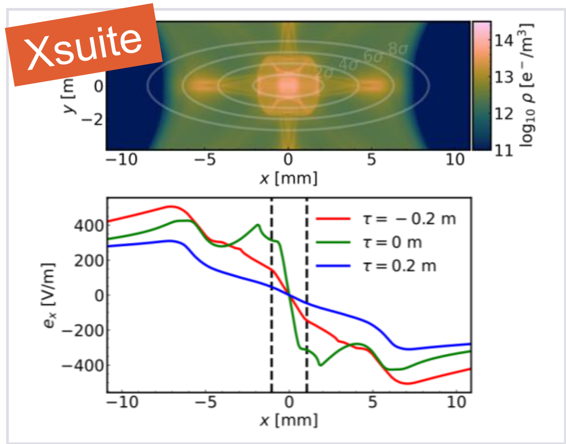
Impedances



Beam-Beam Effects



Space Charge



Electron/Ion Cloud

Xsuite adoption

Users' and developers' response was well beyond our expectations!

Xsuite adoption

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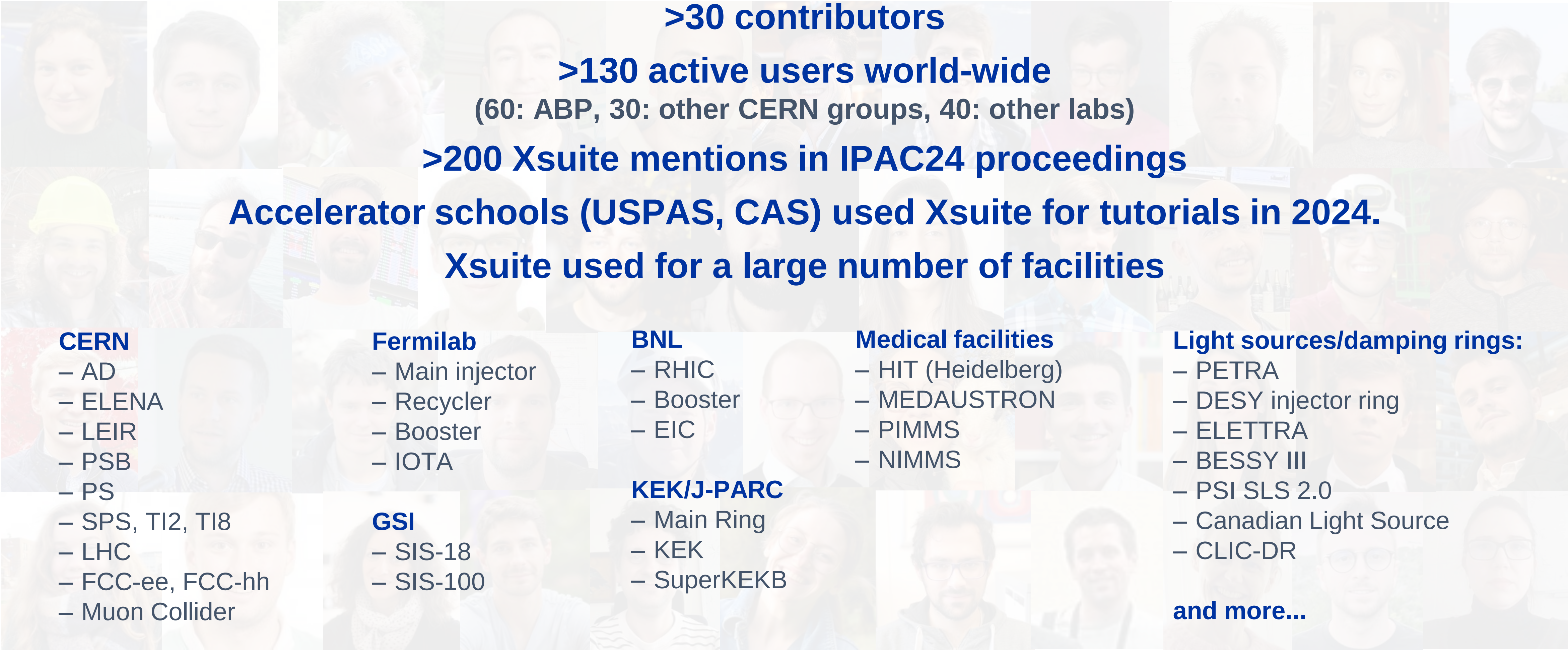


>30 contributors

>130 active users world-wide

(60: ABP, 30: other CERN groups, 40: other labs)

>200 Xsuite mentions in IPAC24 proceedings

Accelerator schools (USPAS, CAS) used Xsuite for tutorials in 2024.

Xsuite used for a large number of facilities

CERN
– AD
– ELENA
– LEIR
– PSB
– PS
– SPS, TI2, TI8
– LHC
– FCC-ee, FCC-hh
– Muon Collider

Fermilab
– Main injector
– Recycler
– Booster
– IOTA

GSI
– SIS-18
– SIS-100

BNL
– RHIC
– Booster
– EIC

KEK/J-PARC
– Main Ring
– KEK
– SuperKEKB

Medical facilities
– HIT (Heidelberg)
– MEDAUSTRON
– PIMMS
– NIMMS

Light sources/damping rings:
– PETRA
– DESY injector ring
– ELETTRA
– BESSY III
– PSI SLS 2.0
– Canadian Light Source
– CLIC-DR

and more...

Moving forward: Xsuite towards Operations

Today **operation** of the CERN complex (accelerators, transfer lines, experimental areas) uses **MAD-X as standard tool** for lattice modelling, survey, optics calculations, knob generation, etc.

First tests of Xsuite also in this context **went very smoothly**.

- Notably, the **first full LHC cycle** was designed entirely with Xsuite in 2024 and tested in MDs.
- Including **optics matching, squeeze functions design, knob design** (cross./sep. bumps, tune, chromaticity, coupling, etc.), **link with LSA**.

Moving forward: Xsuite towards Operations

Our goal: we want to **move to Xsuite also for operational tasks**, aiming at **not depending on MAD-X for critical applications by the start of Run 4**.

Several benefits:

- Advantageous to use the **same tool for the present complex and design studies for future machines** – development synergies, using same tools makes it more natural for people to work in both environments.
- Overcome **shortcomings of MAD-X** that today need workaround:
  - e.g., modelling of optics distortion from the PSB injection chicane, reference frame curvature kept independent of bend powering, general handling of tilted magnets.
- **Economy of resources**: high-quality support for MAD-X is expensive.
  - Requires a very specific skill-set training, not useful in other contexts.
  - Prefer to reinvest these resources to support users during the migration.

Moving forward: Xsuite towards Operations

Preliminary **discussions with main stakeholders** (BE-EA, BE-OP, SY-ABT) **already took place**.

- **Response so far was very positive**
  - General perception that advantages of modern and supported tools outweigh the cost of transition.
- **We will continue engaging with the user community** to get an accurate and complete overview of needs and wishes.
  - Don’t hesitate to give Xsuite a try for your applications and reach out to us with feedback.
  - Early feedback is important to ensure that all relevant needs are correctly incorporated in the design.
- The **migration of the ‘acc-models’ repositories** for all accelerators and lines **will be an important milestone**.
  - BE-ABP is committed to work on this task during LS3 in collaboration with repository owners.

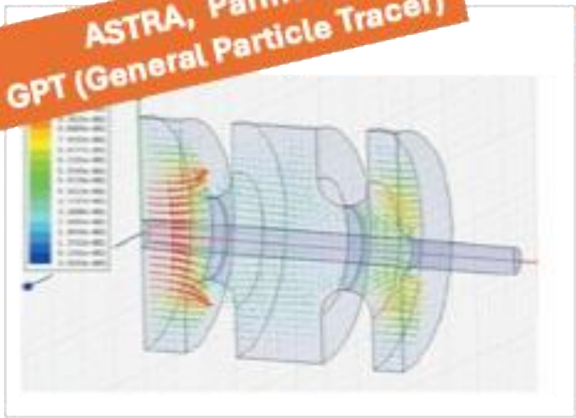
Xsuite in action

Material available at: https://github.com/xsuite/tutorial_cern_seminar

Similar effort in the world of linacs and compact beamlines

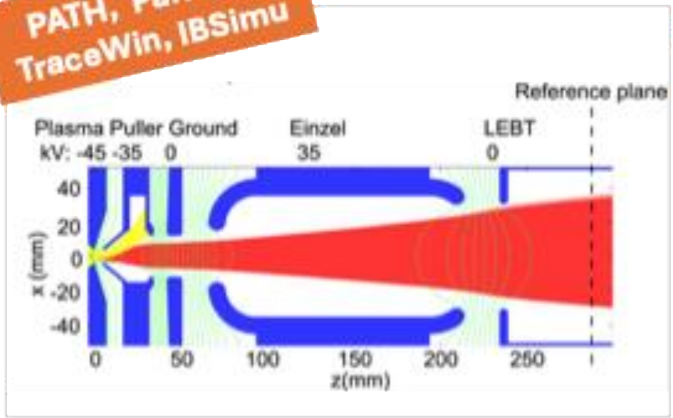
A. Latina

ASTRA, Parmela,
GPT (General Particle Tracer)



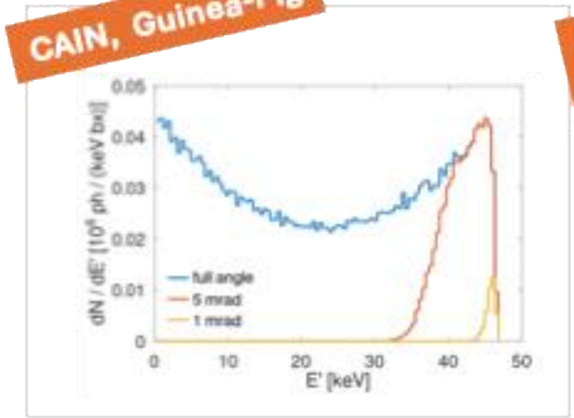
Photoinjectors and electron guns
(space-charge, IBS)

PATH, Parmila,
TraceWin, IBSimu



Positron, proton, and ion
sources & linacs

CAIN, Guinea-Pig

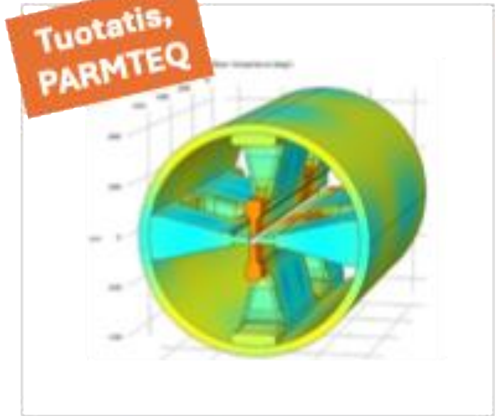


Inverse-Compton Scattering
Compact X-ray sources

ASTRA + ELEGANT ?
GPT + PLACET ?

Medical e⁻ linacs for
Flash therapy

Tuotatis,
PARMTEQ

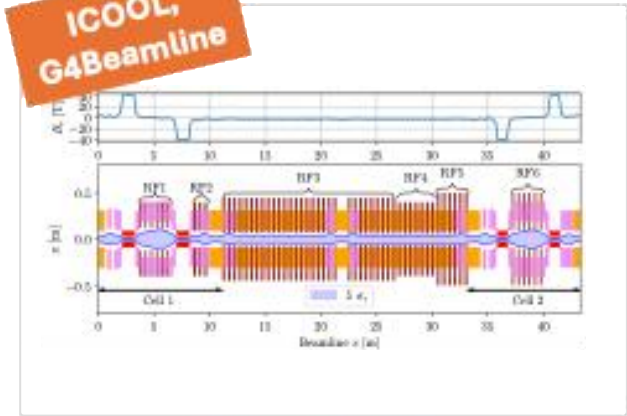


Radio-Frequency
Quadrupoles (RFQ)

PLACET,
ELEGANT

Linear Colliders, Free-Electron Lasers
(Wakefields, beam loading, ...)

ICOOL,
G4Beamline



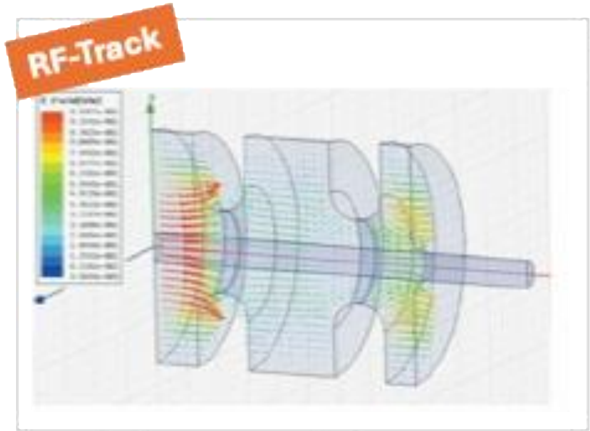
Muon Cooling
(Particle-matter interaction)

???

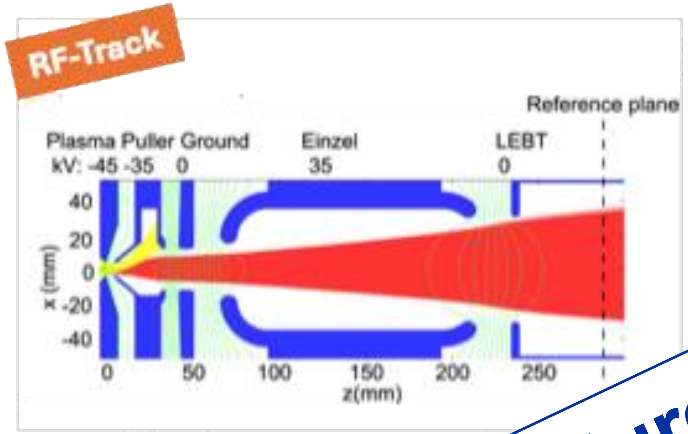
GaToroid
(Optics in complex fields)

Similar effort in the world of linacs and compact accelerators

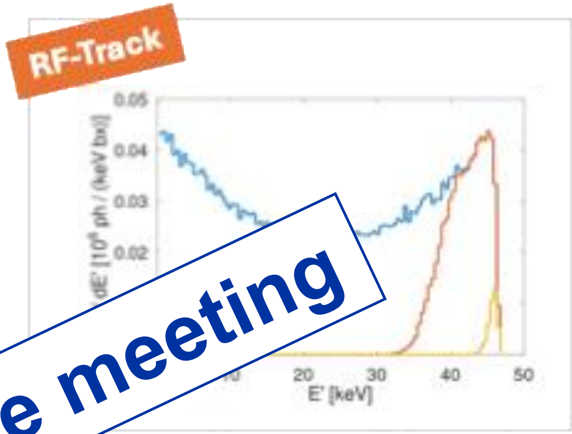
A. Latina



Photoinjectors and electron guns
(space-charge, IBS)



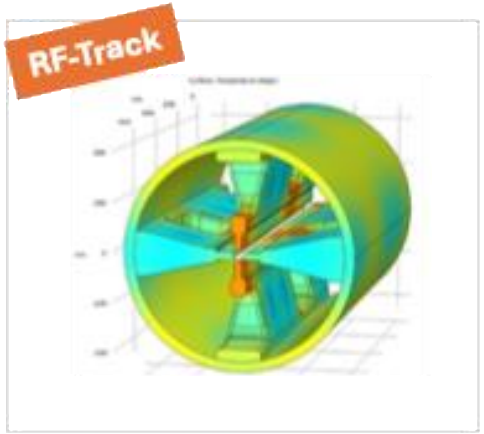
Positron, proton, a
sources



Inverse-Compton Scattering
Compact X-ray sources

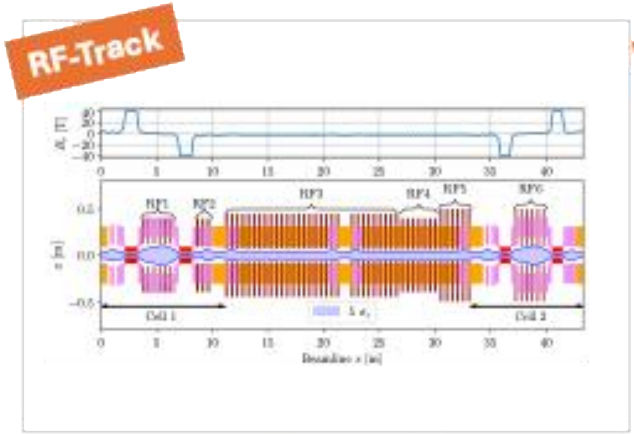
Medical e⁻ linacs for
Flash therapy

Subject for a future meeting



Radio-Frequency
Quadrupoles (RFQ)

Linear Colliders, Free-Electron Lasers
(Wakefields, beam loading, ...)



Muon Cooling
(Particle-matter interaction)

GaToroid
(Optics in complex fields)

Thank you!

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