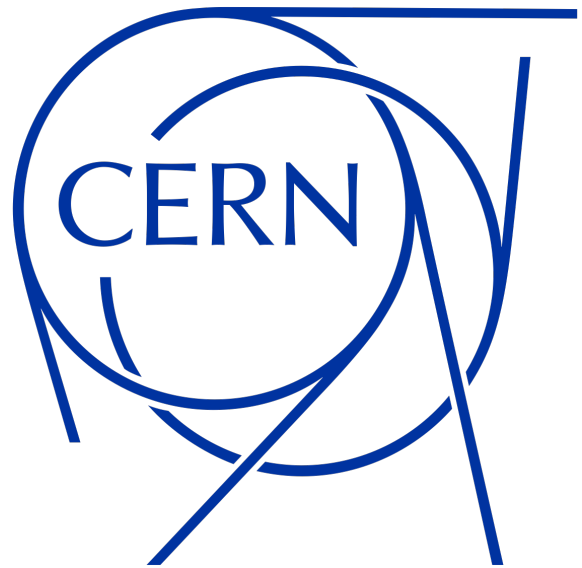

CERN

Xsuite developments for high brightness rings

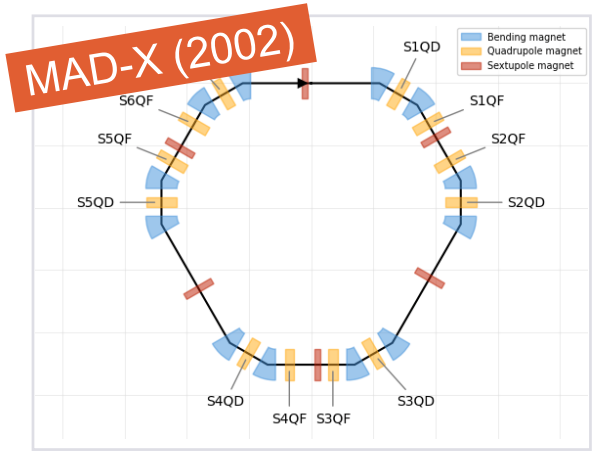
Szymon Łopaciuk, Giovanni Iadarola, Riccardo De Maria, Frederik F. Van der Veken, CERN, Geneva, Switzerland

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

Beam dynamics software landscape at CERN

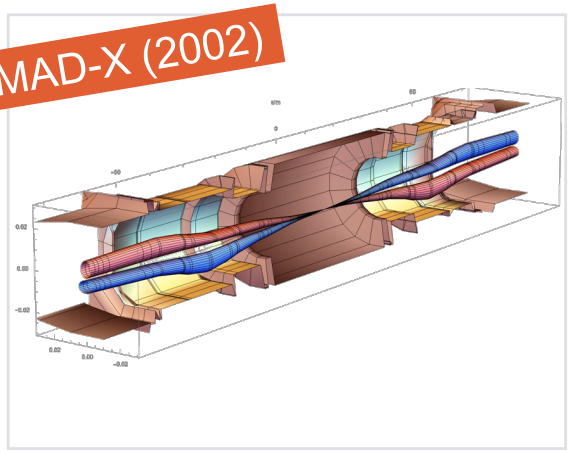
CERN has a long history of **powerful software tools for beam physics** applications, typical examples:

MAD-X (2002)



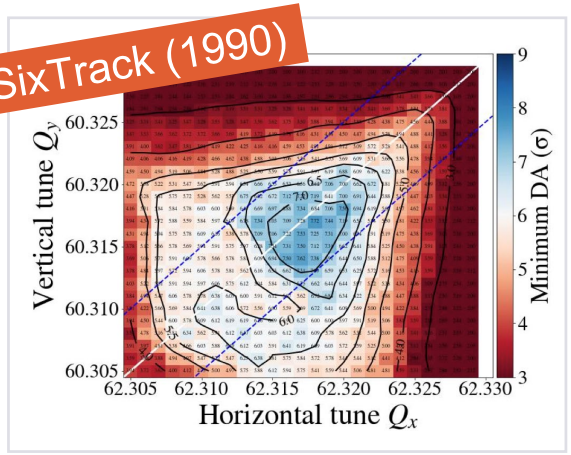
Lattice Design

MAD-X (2002)



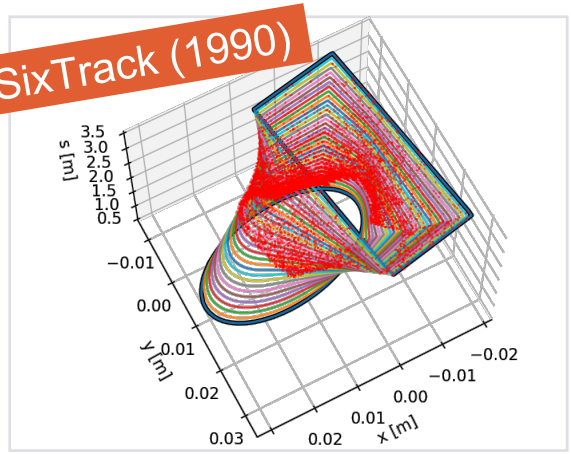
Optics (calculation & design)

SixTrack (1990)



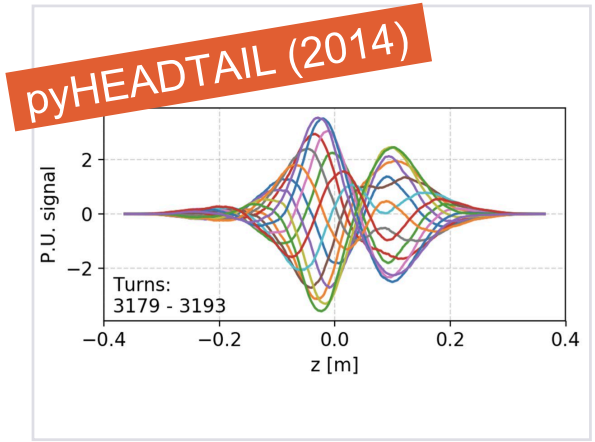
Tracking (dynamic aperture)

SixTrack (1990)



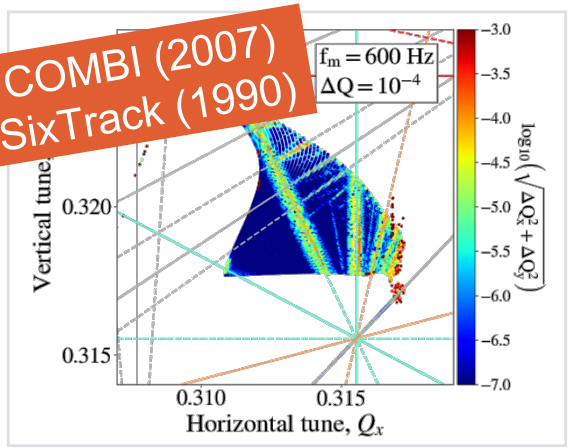
Collimation

pyHEADTAIL (2014)



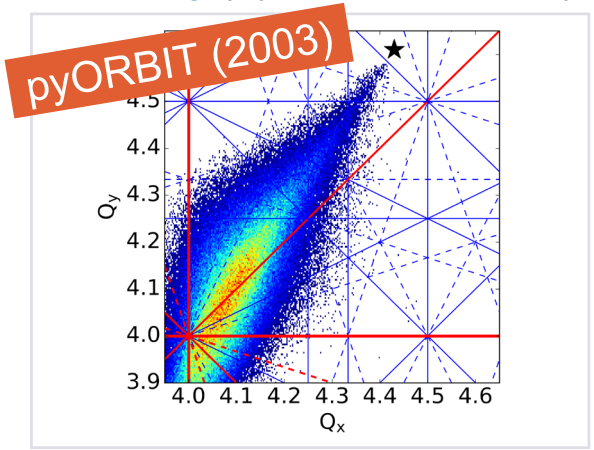
Impedances

COMBI (2007)
SixTrack (1990)



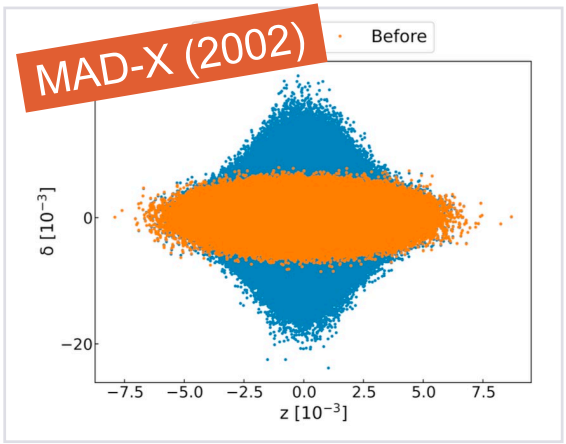
Beam-Beam Effects

pyORBIT (2003)



Space Charge

MAD-X (2002)



Intra-Beam Scattering

Requirements:

- One toolkit for many applications: from low-energy hadron rings to high-energy lepton colliders.
- Heterogeneous simulations made natural, as opposed to having to deal with ad-hoc scripts or model translations between tools.
- Extendable by default, while legacy tools are much harder to extend. They weren't designed for that. Lack of expertise to do so anymore.
- Modern user-interface: Python, with its ecosystem of scientific computing tools. No need to maintain own plotting tools, or scripting languages anymore – saves effort, less complexity.
- GPU support built-in, in addition to single- and multi-threaded CPU.

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

Xsuite project launched in 2021 to address issues arising from the fragmented landscape, using the know-how acquired in development of the earlier tools.

References for full list of features:

- *Documentation: xsuite.web.cern.ch.*
- *"Xsuite: an integrated beam physics simulation framework," IPAC'24.*
- *"Xsuite: a multiplatform toolbox for optics design, fast tracking, collimation and collective effects," ICAP'24.*
- *"Xsuite: a multiplatform Python toolkit for beam dynamics," ATS Seminar (2025).*

Development approach

– **Orthogonal architecture:** split the software into independent functional blocks at all levels.

  ⇒ Well-defined, cleaner interfaces

  ⇒ Lower codebase complexity

  ⇒ Better scaling, easier to understand

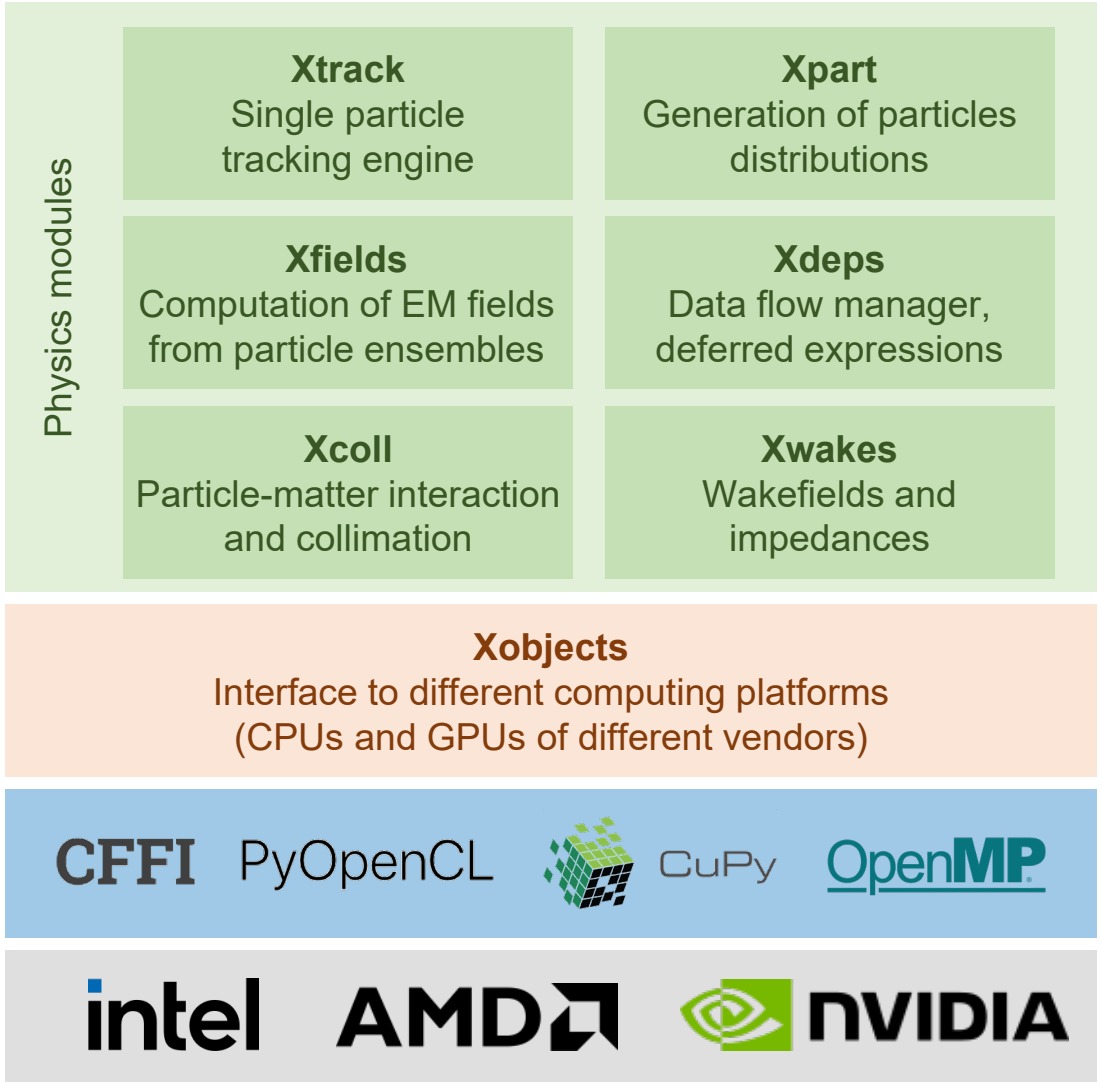
  ⇒ Lower learning curve for users & developers

  ⇒ 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.

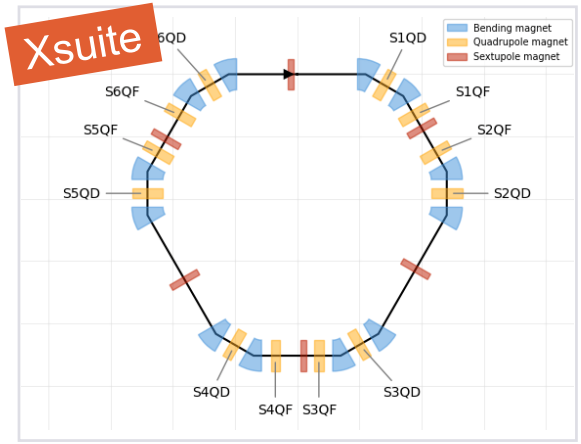
  – Thanks to investment in continuous testing, we can afford a fast release cycle with new versions coming out multiple times a month, incorporating modifications/extensions based on user feedback.



Adoption

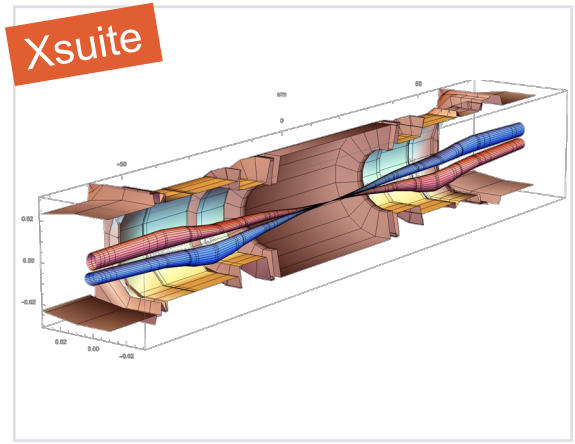
By now Xsuite became a production tool for many beam dynamics studies, allowing development discontinuation for many legacy tools.

Xsuite



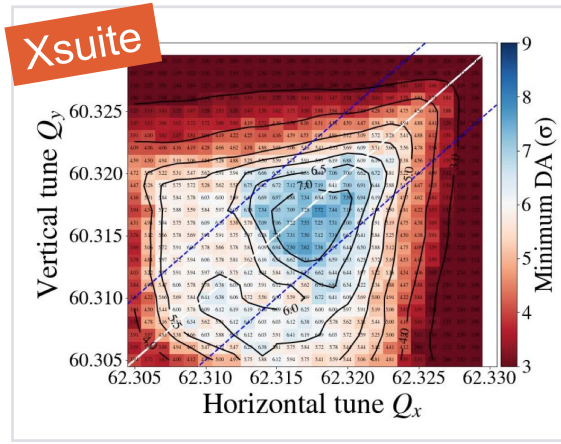
Lattice Design

Xsuite



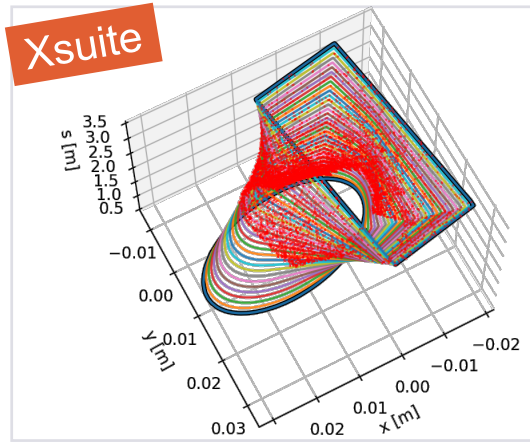
Optics (calculation & design)

Xsuite



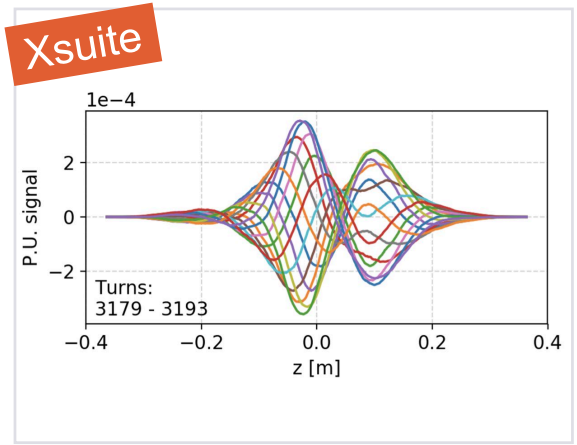
Tracking (dynamic aperture)

Xsuite



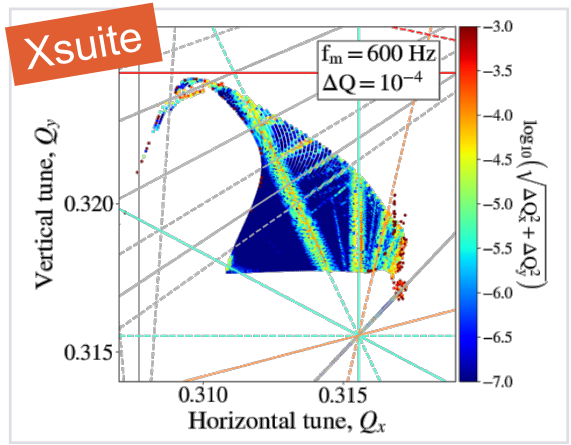
Collimation

Xsuite



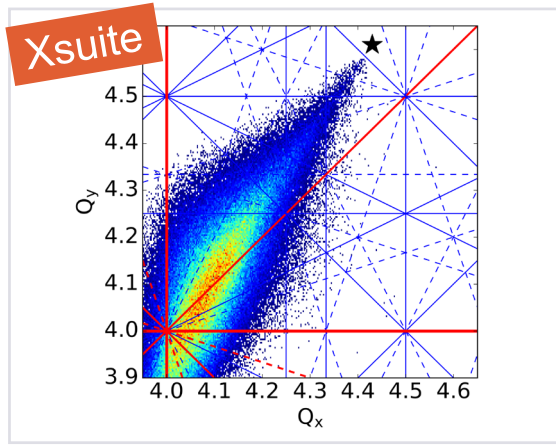
Impedances

Xsuite



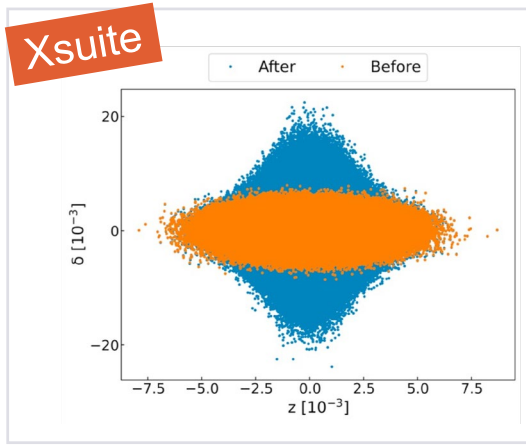
Beam-Beam Effects

Xsuite



Space Charge

Xsuite



Intra-Beam Scattering

Lively user base

Users' and developers' response well beyond our expectations!

>30 contributors
>150 active users world-wide
>400 Xsuite mentions in IPAC25 proceedings
Accelerator schools (USPAS, CAS, JUAS) now use Xsuite in tutorials.

A lively community providing mutual support, advice, lots of feedback to developers!

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

J-PARC
– Main Ring
– KEK
– SuperKEKB

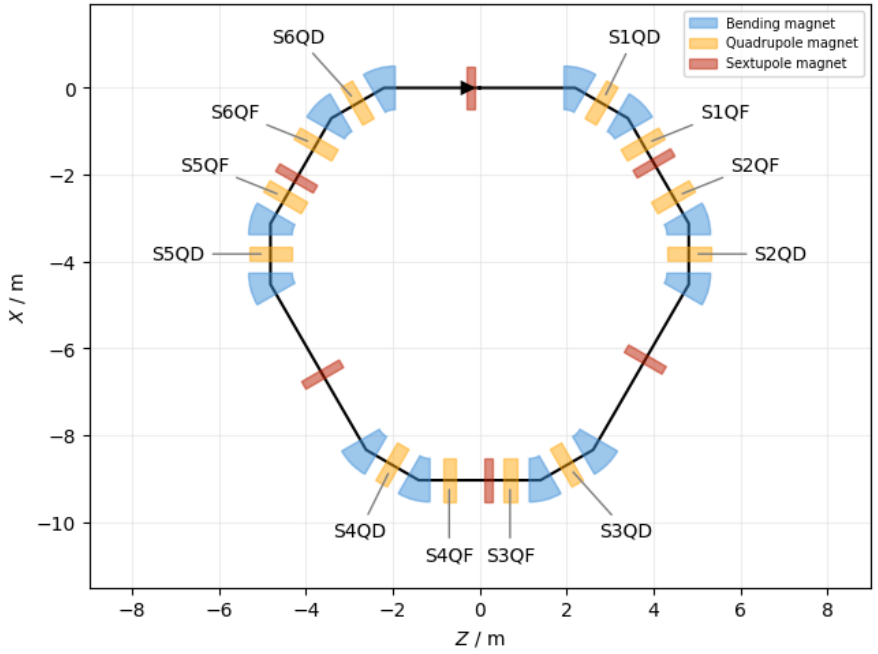
Medical facilities
– HIT (Heidelberg)
– MEDAUSTRON
– PIMMS
– NIMMS

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

and more...

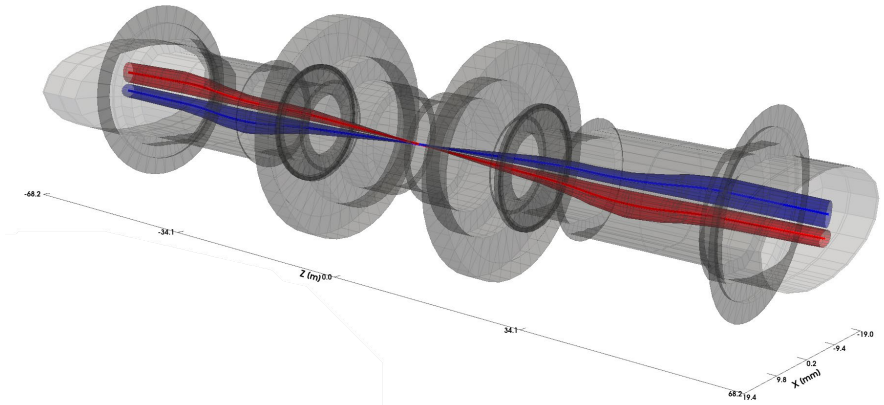
Lattice & optics design

- Comprehensive set of **lattice elements** for **thick and thin modelling**
  - Bends, multipoles, combined-function magnets, RF cavities, crab cavities, etc.
  - **Solenoids** with tilted & overlapping multipolar fields for modelling experimental regions
- **Field imperfections** and **arbitrary misalignments**
- **Dipole-edge effects** and **fringe fields**



- **Twiss functions** obtained by tracking particles
- **Built-in multi-objective optimizer** allows for matching model parameters in a **transparent and flexible way**
- **Orbit and trajectory correction**
- Circuits can be handled through **deferred expressions**
- MAD-NG interface: compute **non-linear maps, normal forms, RDTs**

LHC Beam Envelopes at IP1 (Atlas) (3σ, β*=30cm)

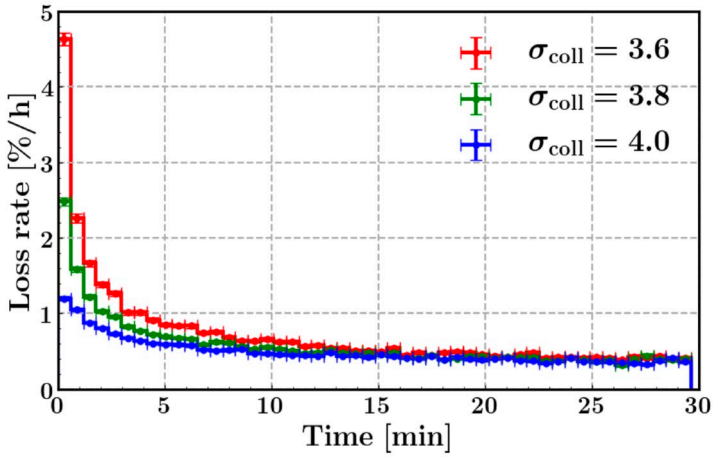


Single-particle tracking

- Multiturn element-by-element tracking speed is critical is many applications
  - Xsuite assembles a **C kernel** (transparently called from Python) optimized for the given simulation and **specialised for the chosen platform (CPU or GPU)**
  - **Single-core** speed comparable with Sixtrack
  - **Two orders of magnitude faster** on a high-end **GPU**
- RF-Track interface: track through **field maps**

LHC example:

- **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**
  - On **GPU** (NVIDIA V100) was done **< 3 days**



Synchrotron radiation

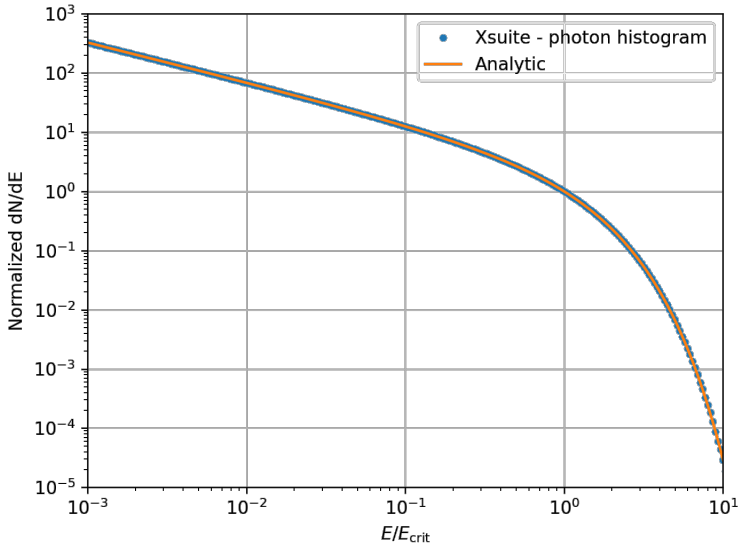
The effect of **synchrotron radiation** can be included in Xsuite simulations, using two models:

- **“mean” model** where the energy loss is applied per particle without accounting for quantum fluctuations,
- **“quantum” model** where the actual photon emission is simulated.

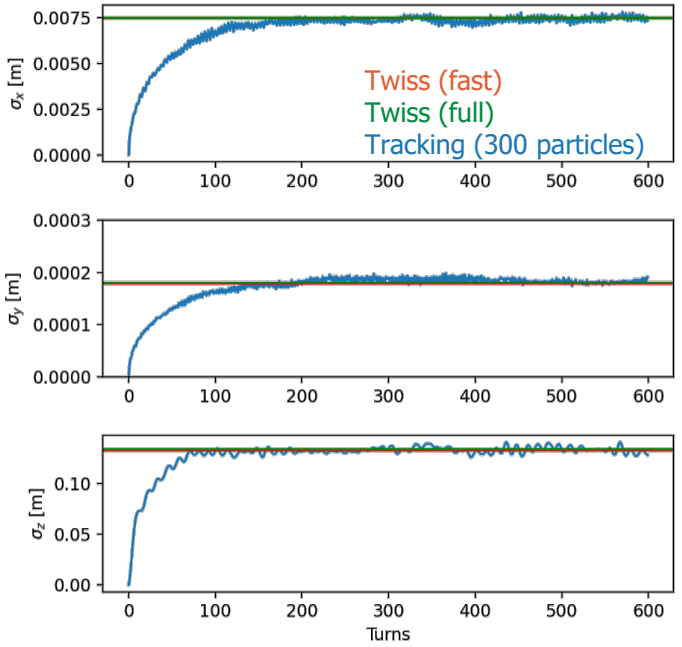
Also available in the **Xsuite Twiss**:

- Dedicated algorithm for optics function with **non-symplectic one-turn map**
- Computation of 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.



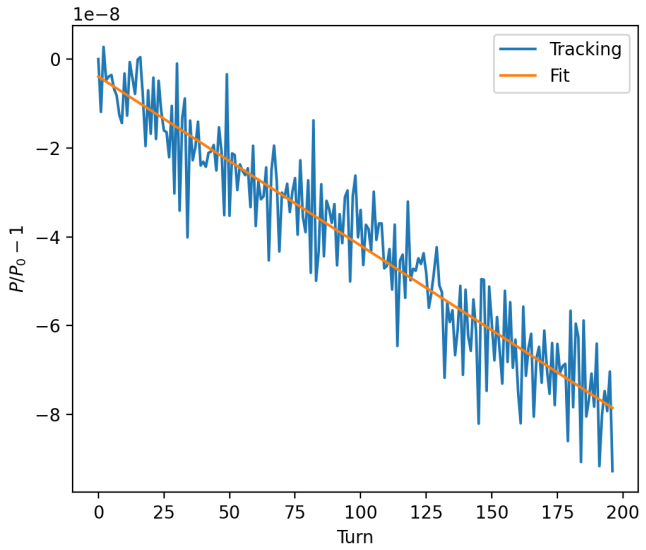
Validation against analytical photon spectrum



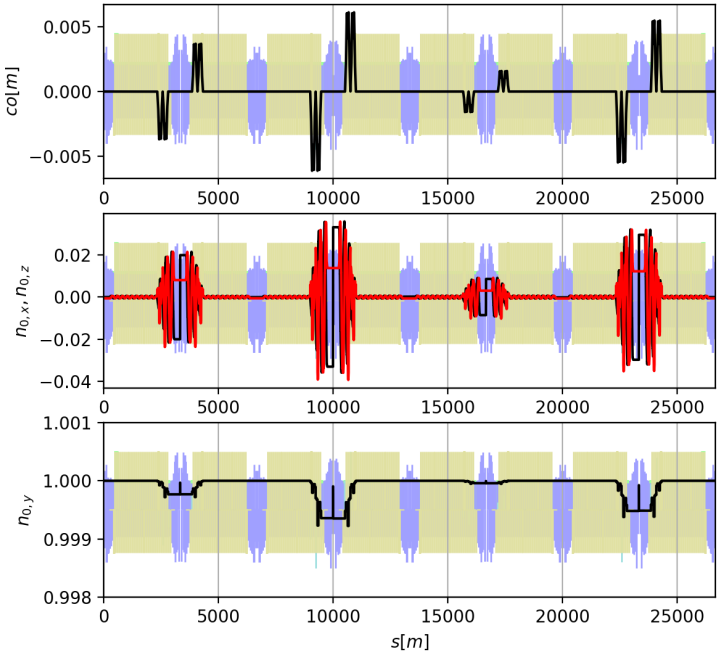
Eq. emittance twiss vs track

Spin & polarization

- The **spin of the particles** can be tracked with the other 6D phase space coordinates.
- **Equilibrium polarization** and **spin closed solution** can be computed in Twiss.



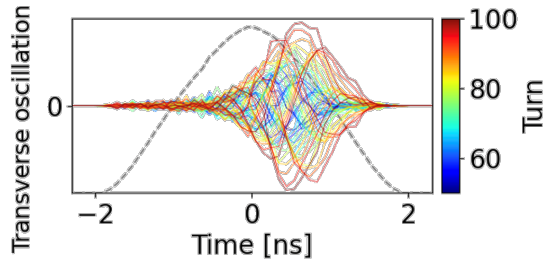
The polarization decay in LEP, obtained by tracking particles with spin, including synchrotron radiation and quantum excitation.



Spin closed solution in the LEP collider.

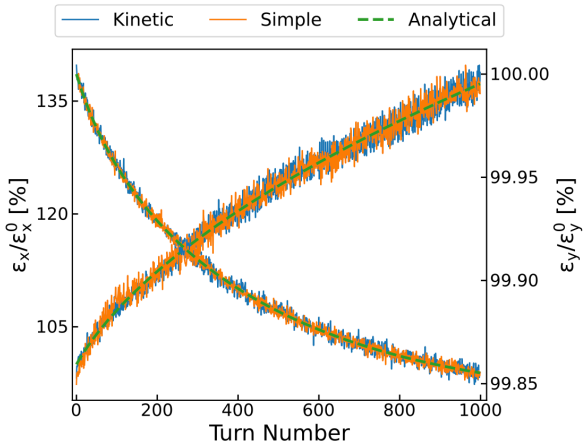
Collective effects

- **Space charge**
  - “Frozen” model, fixed charge distributions
  - “Particle-in-cell” (PIC) model
- **Wakefields**
  - Longitudinal & transverse di- and quadrupolar
  - Single-, multi bunch, & multi-turn effects
- **Beam-beam effects**
  - Weak-strong & strong-strong
  - Analytic or PIC
  - Beamstrahlung radiation
  - Bhabha scattering estimates
- **Intra-Beam Scattering**
  - IBS growth rates computation from beam parameters & optics
  - Effect can be included in multi-particle simulations



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

Coherent instability simulation with wakefields and space charge.
Courtesy of X. Buffat.



IBS Benchmark for the SPS (Pb ions).
Courtesy of F. Soubelet.

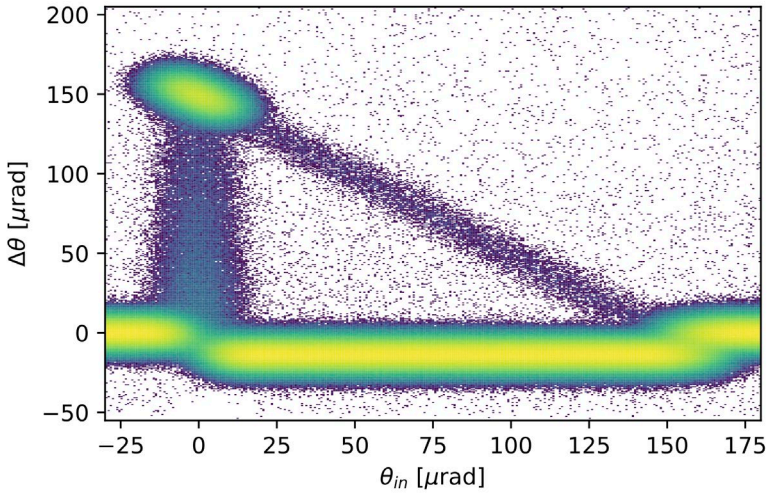
Beam-matter interactions

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

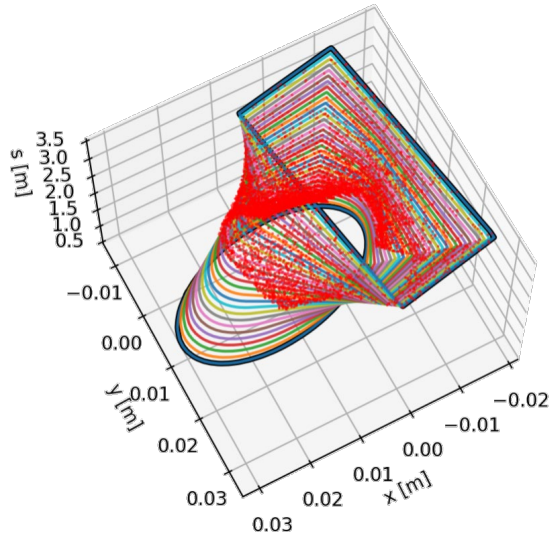
- The built-in **“Everest” engine** (evolution of K2 module from Sixtrack)
- The **“Geant 4” engine**, based on an interface with BDSIM-Geant4 (used for FCC-ee collimation studies)
- The **“FLUKA” engine**, based on an interface with the FLUKA Monte Carlo code

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

Demo 1 – Lattice design

In addition to being feature-complete, Xsuite's major benefit is its user-friendly interface.

To showcase this, we have prepared a set of demos.

These demo files are adapted from https://github.com/xsuite/tutorial_cern_seminar and are based on the PIMMS lattice (see CERN-PS-99-010-DI).

Demo 2 – Optics for slow extraction

These demo files are adapted from https://github.com/xsuite/tutorial_cern_seminar.

Demo 3 – Instability

These demo files are adapted from https://github.com/xsuite/tutorial_cern_seminar.

Summary

- Xsuite provides a **wide array of features in a single package:**
  - Lattice design and optics design and calculations
  - Tracking
  - Synchrotron radiation
  - Spin & polarization
  - Collective effects
  - Beam-matter interactions
- **GPU and multithreading** support
- Available in the **Python ecosystem**
- Adopted as a **production tool** by a **large user community**
- **Feedback and contributions** from the community fundamental in ensuring **quality & usability!**

Thank you!

xsuite.web.cern.ch