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Development of Collimation Simulations for the FCC-ee

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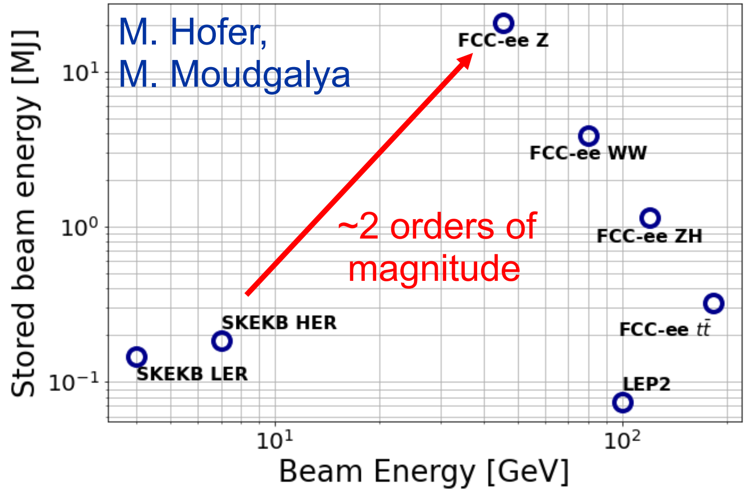
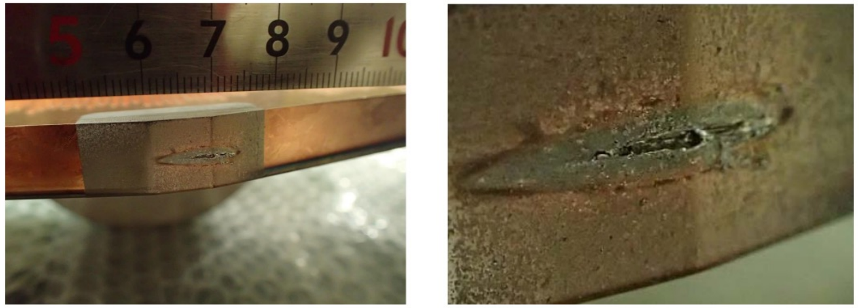
Collimation for the FCC-ee

- **The FCC-ee is the FCC first stage e+e- collider**
  - 90.7 km circumference, tunnel compatible with the FCC-hh
  - 4 beam operation modes, optimized for production of different particles: ***Z*** (45.6 GeV), ***W*** (80 GeV), ***H*** (120 GeV), $t\bar{t}$ (182.5 GeV)



Comparison of lepton colliders

- **The FCC-ee presents unique challenges**
  - The stored beam energy reaches **17.8 MJ** for the **45.6 GeV (*Z*)** mode, which is comparable to heavy-ion operation at the LHC
  - Such beams are highly destructive: a collimation system is required
  - The main roles of the collimation system are:
    - Protect the equipment from unavoidable losses
    - Reduce the backgrounds in the experiments
  - Two types of collimation foreseen for the FCC-ee:
    - The beam halo (global) collimation
    - Synchrotron Radiation (SR) collimation – near the IPs



Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

Beam collimation simulation tools

- Tracking studies are essential for designing the collimation system

- Effects such as synchrotron radiation and optics tapering make the tracking studies more challenging for the FCC-ee

*Optics tapering: modulating the magnetic strengths around the ring to account for SR energy loss

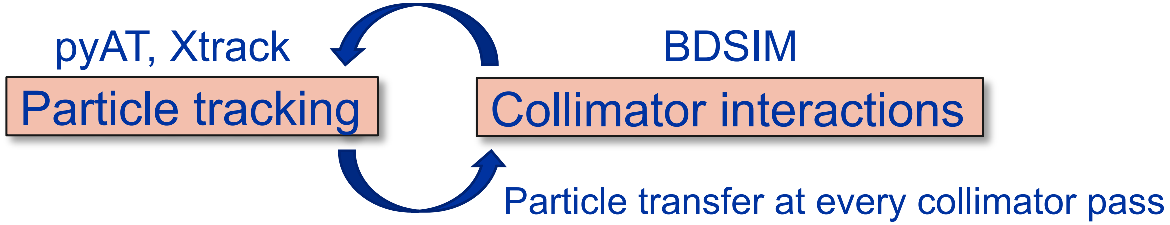
- The requirements for collimation simulation tools are:
  - **Tracking of beam electrons (and positrons) in the magnetic lattice**
  - **Particle-matter interactions inside the collimators**
  - **Synchrotron radiation and optics tapering**
  - **Aperture modelling and loss recording**
  - **Accurate and efficient tracking over many turns**
  - **Beam-beam effects (beam-beam kick, Beamstrahlung, radiative Bhabha scattering)**

- Studied several different simulation tools:
  - MAD-X, SixTrack-FLUKA coupling, BDSIM, Merlin++, pyAT, Xsuite
  - No established frameworks fit all the requirements
  - **Implement a coupling between a particle tracking engine and a particle-matter interaction engine**

FCC-ee collimation simulation setup

- **The first collimation simulation tools developed for the FCC-ee**
  - **Xsuite-BDSIM** coupling, **pyAT-BDSIM** coupling (ICFA newsetter paper submitted)
  - Xsuite-BDSIM currently used in production, further developments ongoing

- **Xsuite-BDSIM (Geant4)**
  - Benchmarked against other codes for FCC-ee – MAD-X, pyAT, SixTrack-FLUKA coupling (IPAC’22 paper)
  - Used for for the latest FCC-ee collimation studies
  - Tests / benchmarks in other machines:
    - LHC – G. Broggi
    - PS – T. Pugnat

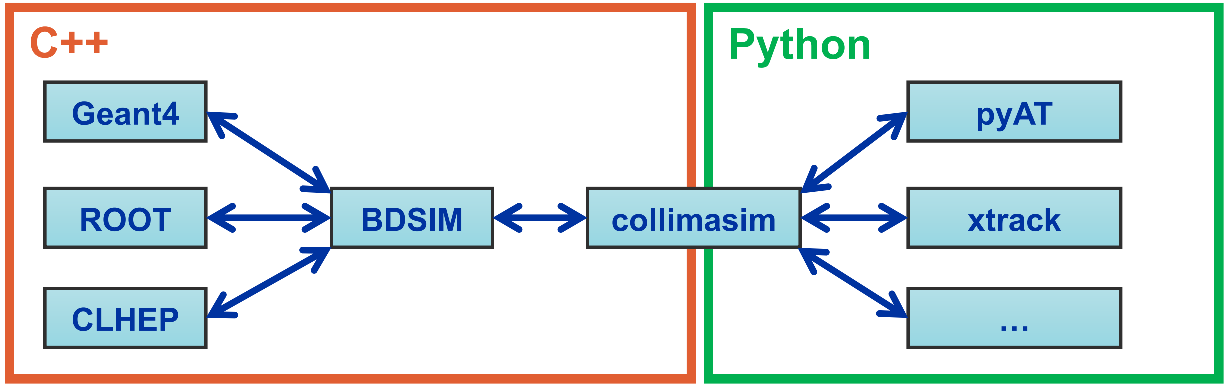

pyAT, Xtrack

Particle tracking

BDSIM

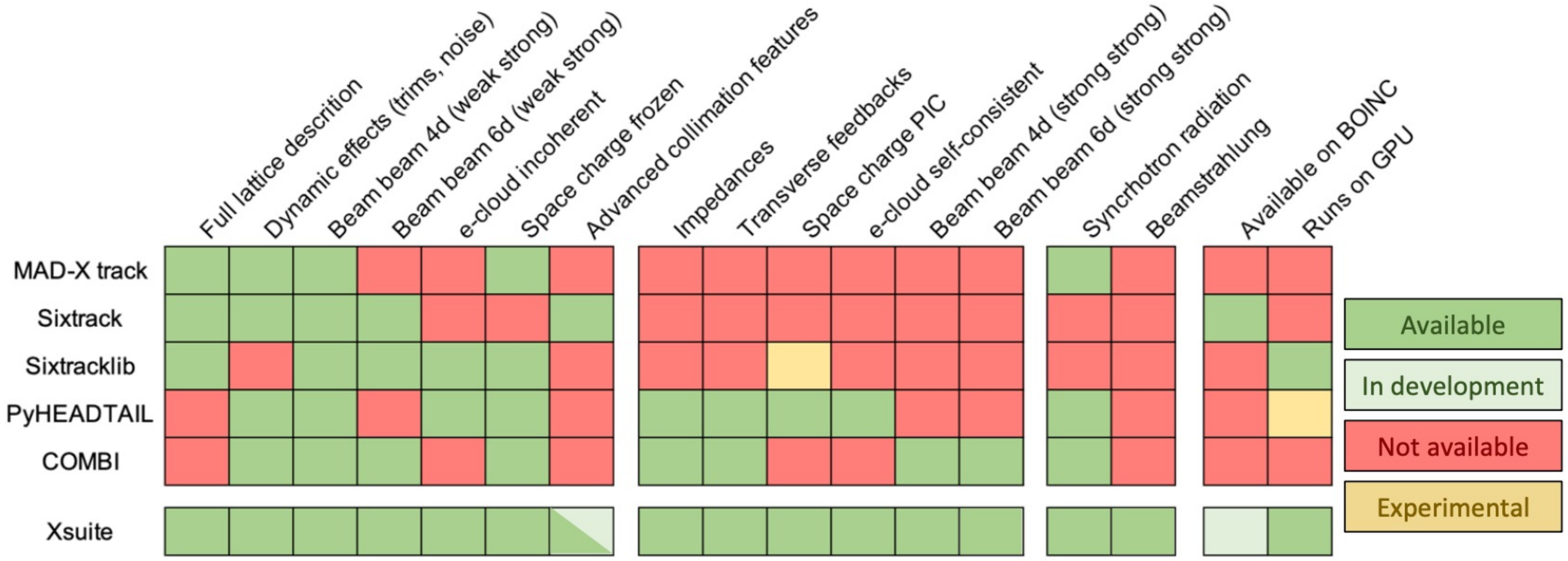
Collimator interactions

Particle transfer at every collimator pass



Xsuite

- **New tracking tool, part of the Xsuite toolkit** https://xsuite.readthedocs.io/en/latest/
  - Core development at CERN, extensive collaboration with EPFL
  - Designed to consolidate a range of studies for different machines in one modern toolkit
  - **Python** on the top level, auto-generated **C** and extensions for performance-critical tasks
  - Multi-platform, compatible with **CPU** and **GPU**
  - A range of features relevant for the FCC-ee developed under an EPFL-CERN collaborative project



	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	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
Sixtrack	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥
Sixtracklib	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟩
PyHEADTAIL	🟥	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟨
COMBI	🟥	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥
Xsuite	🟩	🟩	🟩	🟩	🟩	🟩	⬜/🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩

🟩 Available
⬜ In development
🟥 Not available
🟨 Experimental

G. Iadarola talk, L. van Riesen-Haupt talk

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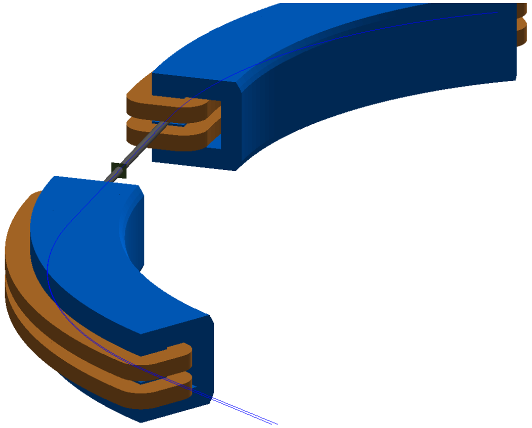
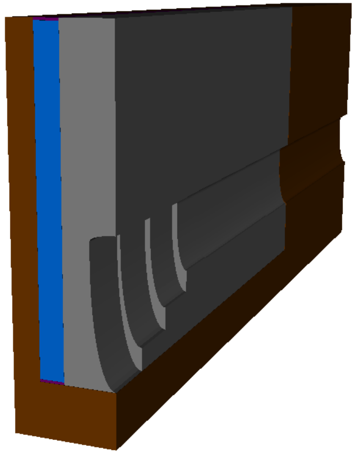
BDSIM

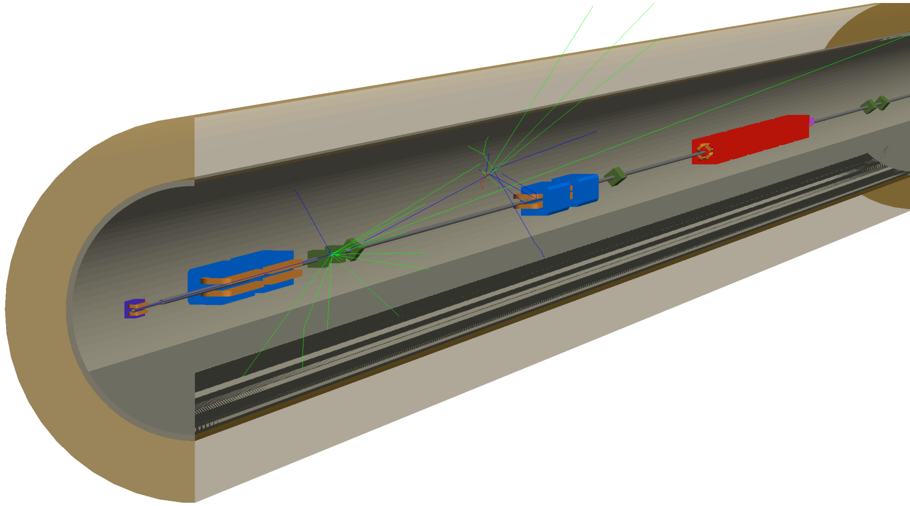
- **Beam Delivery Simulation (BDSIM)** http://www.pp.rhul.ac.uk/bdsim/manual/
  - Software package for simulating energy deposition and charged particle backgrounds in accelerator beamlines, developed at RHUL
  - **C++** program, based on the **Geant4** library (geometry, materials, physics lists)
  - Currently used for SR collimation simulations for the FCC-ee, also used previously for collimation studies in the LHC with proton and heavy-ion beams
  - Originally designed to simulate entire beamlines, but has flexible and modular features
  - Selected as a starting point for a collimator scattering routine for FCC-ee tracking studies



Exaggerated example of automatic bend geometry

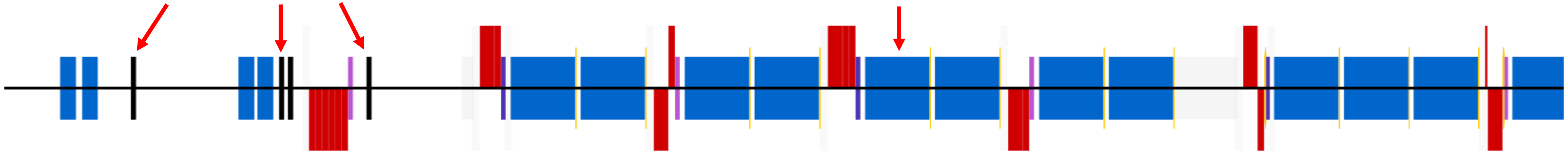


CLIC PCL intermediate dump (R. Bodenstein, IPAC'19 paper)



Part of IR7 in the BDSIM LHC model

Coupling to BDSIM for collimation – general principle

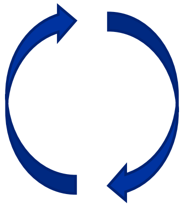


collimators – Geant4

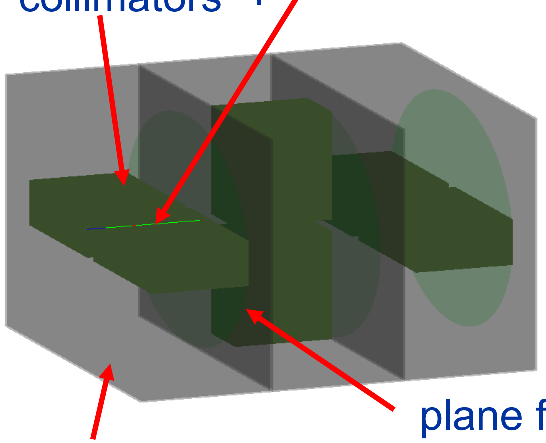
rest of the lattice – tracking code

example lattice section

- **Only collimators in the Geant4 world, with particle transfer mechanisms (like the SixTrack-FLUKA coupling)**
- **Same general workflow, regardless of the tracking code connected:**
  1. Define all collimators
  2. Select a collimator and add particles
  3. Run the physical interaction simulation
  4. Return eligible particles



Steps 2 – 4 repeated for every collimator pass



collimators

particle interacting

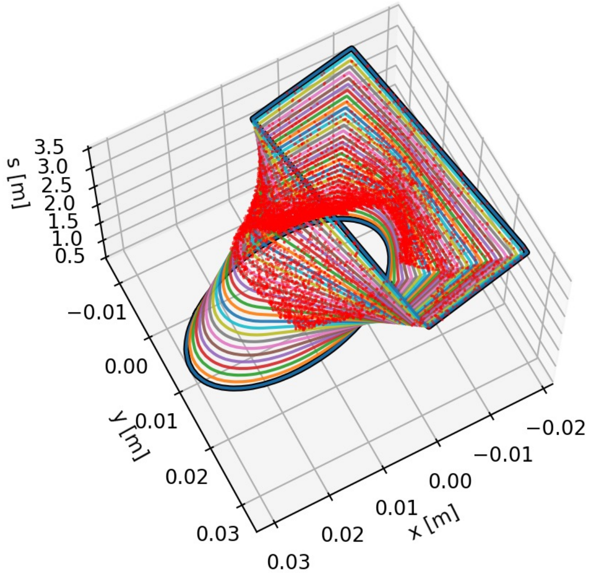
isolated cells

plane for back-transfer (green disk)

- **Interfaces developed for communication between the codes**

Workflow for FCC-ee collimation tracking studies

- **Lattice model**
  - Design, matching, tapering, etc. done in MAD-X
  - Model exported to the tracking engine (**Xtrack**, **pyAT**)
- **Aperture model**
  - Base model comes from MAD-X
  - The aperture model is interpolated to a desired precision, to ensure a good resolution of the loss location
- **Collimation configuration**
  - Materials and settings for the collimators supplied (the geometry preparation is automatic)
  - Physics lists, interaction cuts and other settings given to **BDSIM**
- **Beam generation**
  - Generated online for simple cases or loaded from file
- **Analysis**
  - Loss maps: normalised distribution of losses around the ring
  - Detailed per-particle analysis – loss coordinates, survival



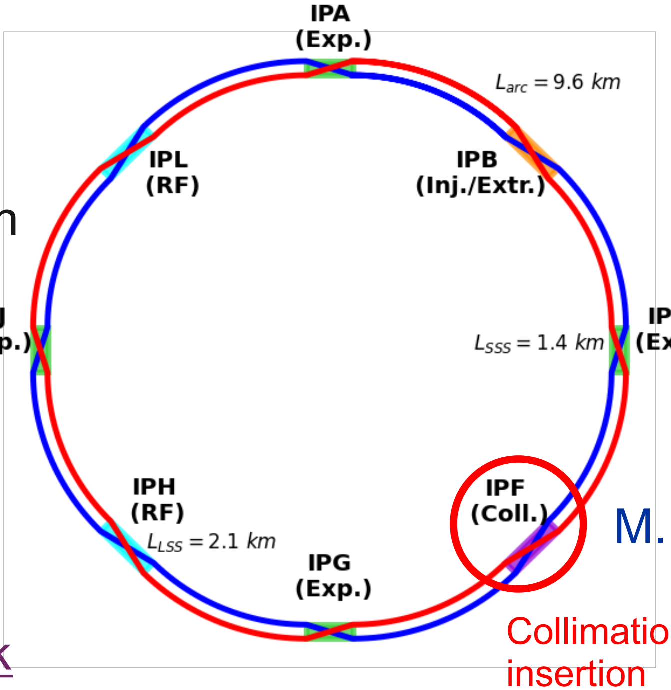
Example of aperture loss interpolation in Xtrack

$$\eta(s) = \frac{E_\mathrm{loc}}{E_\mathrm{tot}\Delta s}[\mathrm{m}^{-1}]$$

$\eta(s)$	Cleaning inefficiency
E_loc	Energy lost in $[s, s+\Delta s]$
E_tot	Total energy lost

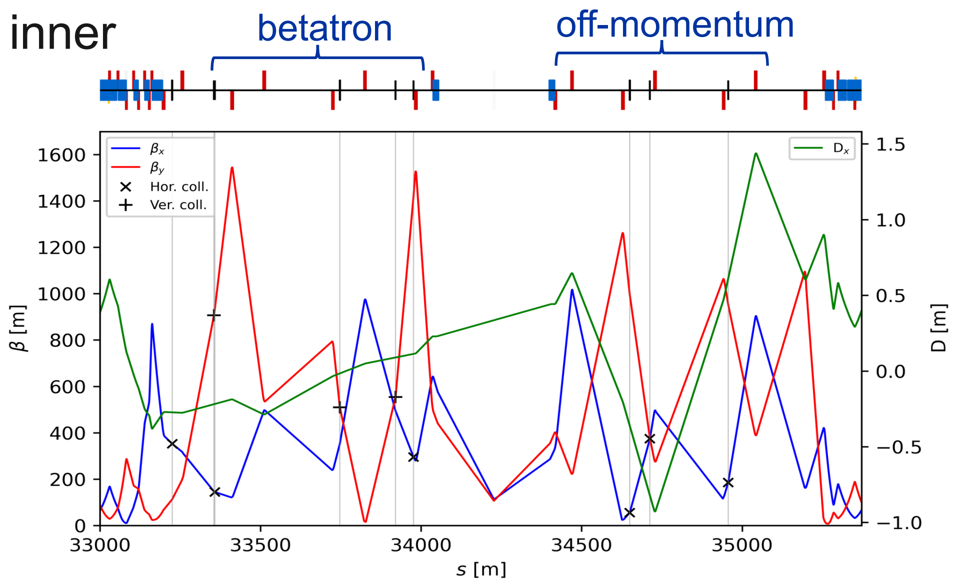
FCC-ee collimation system

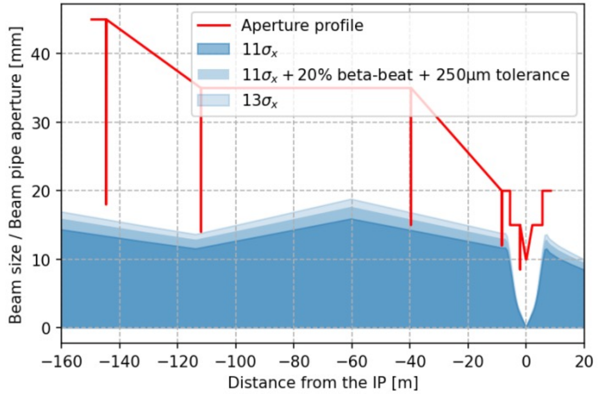
- **Dedicated halo collimation system in PF**
  - Two-stage betatron and off-momentum collimation systems in one insertion
  - Ensure protection of the aperture bottlenecks in different conditions
  - Dedicated collimation optics (M. Hofer)
  - Collimator design for cleaning performance G. Broggi, FCC week 23 talk
- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs K. André, FCC week 23 talk
  - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses

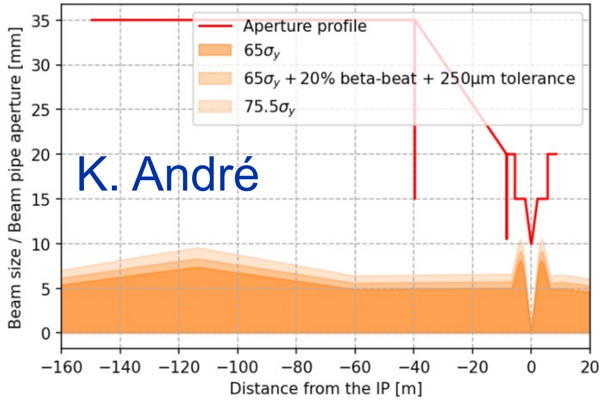


M. Hofer

Collimation insertion



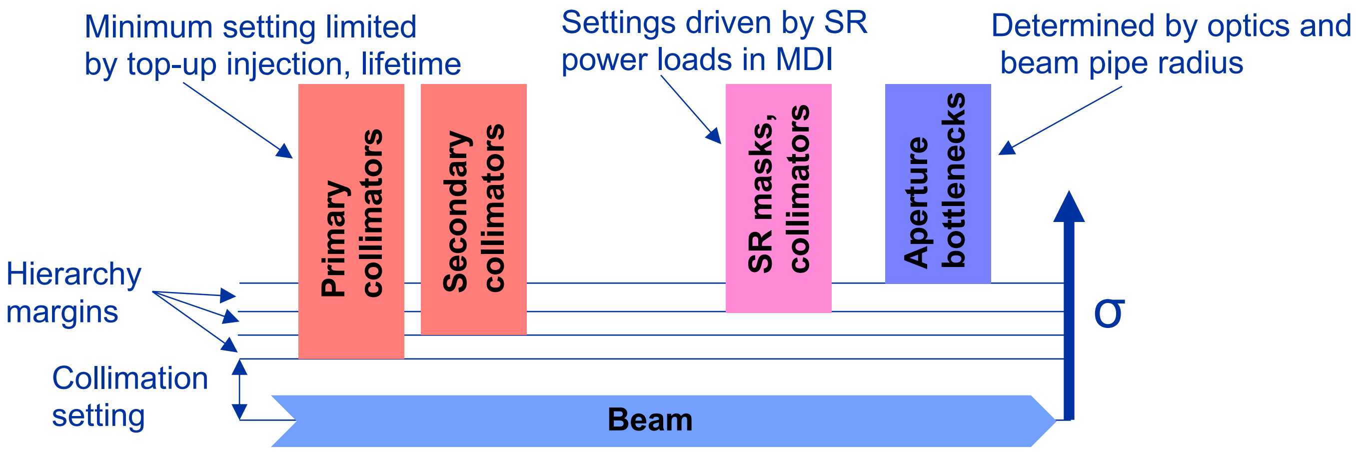




K. André

FCC-ee aperture

- **The aperture bottlenecks are in the experimental interaction regions (IRs)**
- **The bottlenecks must be protected**
  - The final focus quadrupoles are superconducting and there is a risk of quenches
  - The detector is sensitive to backgrounds from beam losses
  - The SR collimators and masks are not robust to large direct beam impacts, can also produce backgrounds
  - The collimation margins are tight



Minimum setting limited by top-up injection, lifetime

Settings driven by SR power loads in MDI

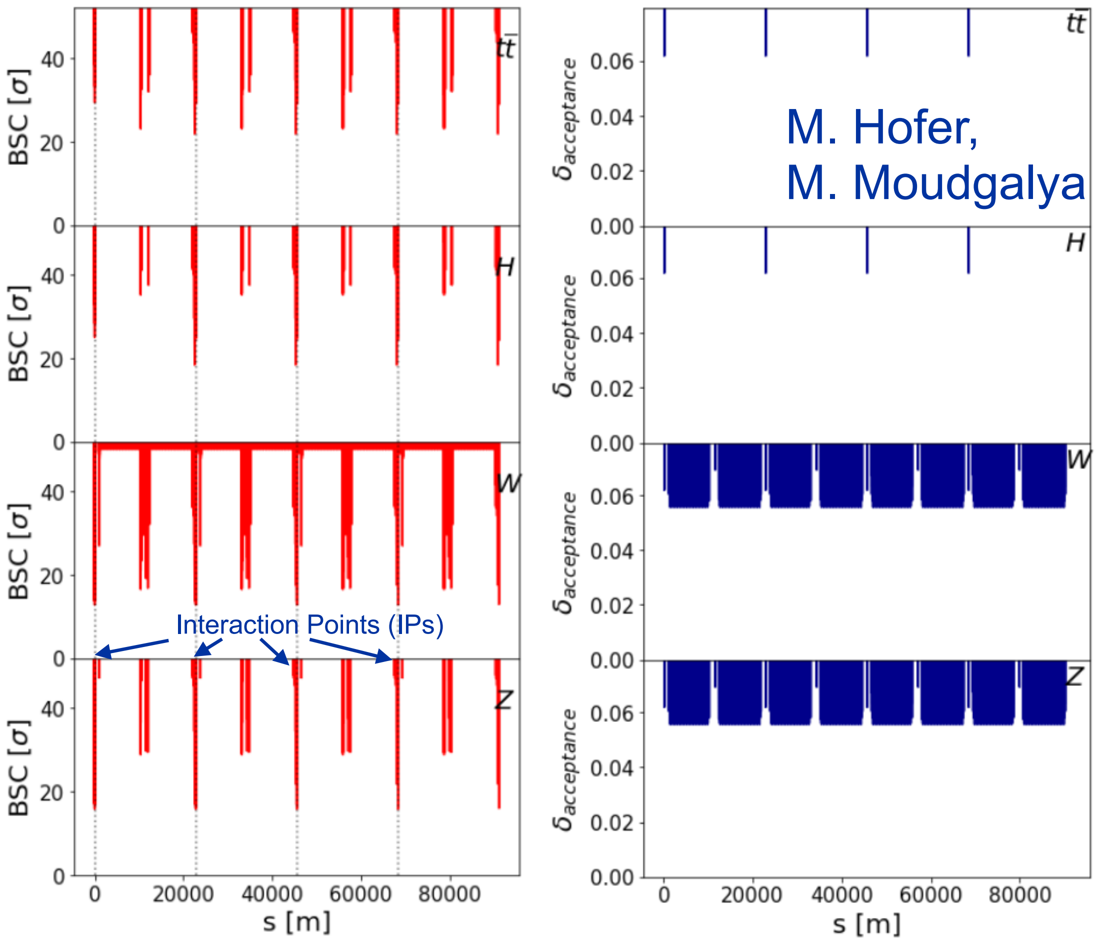
Determined by optics and beam pipe radius

Hierarchy margins

Collimation setting

Beam stay-clear (**BSC**) is the distance from the beam to the aperture in units of beam size

The momentum acceptance is the **δ = A / D**, where **A** is mechanical aperture and **D** is dispersion



M. Hofer, M. Moudgalya

Aperture bottlenecks for the different operating modes

FCC-ee beam losses

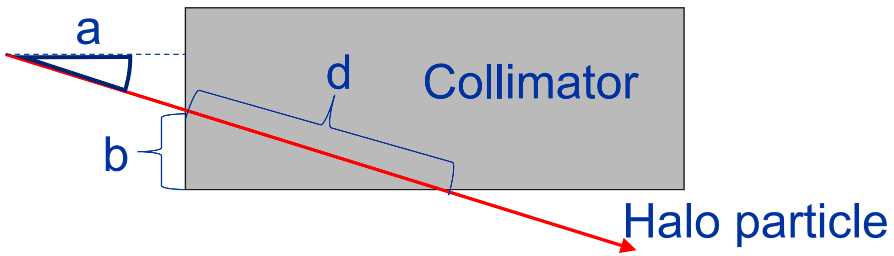
- **The FCC-ee will operate in a unique regime**
  - Electron / positron beam dynamics and beam-matter interactions
  - Stored beam energy exceeding material damage limits
  - Superconducting final focus quadrupoles, crab sextupoles, and RF cavities
  - Must study the beam loss processes and define the ones to protect against (H. Burkhardt, talk)
  - Must study the equipment loss tolerances, for both regular and accidental losses

- **Important loss scenarios for particle tracking studies:**
  - **Beam halo** ⟵ Current studies
  - Top-up injection
  - Spent beam due to collision processes (Beamstrahlung, Bhabha scattering)
  - Beam tails from Touschek scattering and beam-gas interactions
  - Failure modes (injection failures, asynchronous dump, others)
    - The SuperKEKB fast beam losses should, if possible, be understood and modelled

} Input required to set up models

Current study: beam halo losses

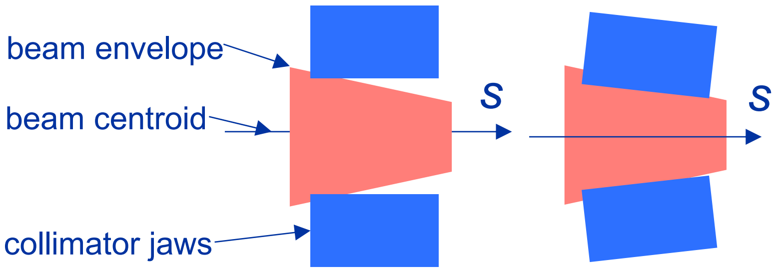
- **"Generic beam halo" beam loss scenario:**
  - Specify a minimum beam lifetime that must be sustained during normal operation
    - Preliminary specification of a **5 minute** lifetime
  - Assume a slow loss process – halo particles always intercepted by the primary collimators
  - The loss process is not simulated, all particles start impacting a collimator
    - Track the particles scattered out from the collimator and record losses on the aperture
  - Currently using 1 μm impact parameter as standard
    - Selected to give a conservative performance estimate
    - Impact parameter scans ongoing G. Broggi, FCC week 23 talk



a = angle of incidence
b = impact parameter
d = distance traversed

Beam halo losses for the Z mode

- The *Z* mode is the current focus (Beam 1, 45.6 GeV, e^+), **17.8 MJ** stored beam energy
- The **5 minute** beam lifetime → total loss power **59.2 kW**
- Radiation and tapering included
- 3 cases consiered:
  - **Horizontal betatron losses (B1H)**
  - **Vertical betatron losses (B1V)**
  - **Off-momentum losses $\delta < 0$ (B1-dp)**
- For the off-momentum case, using a tilted collimator, aligned to the beam divergence

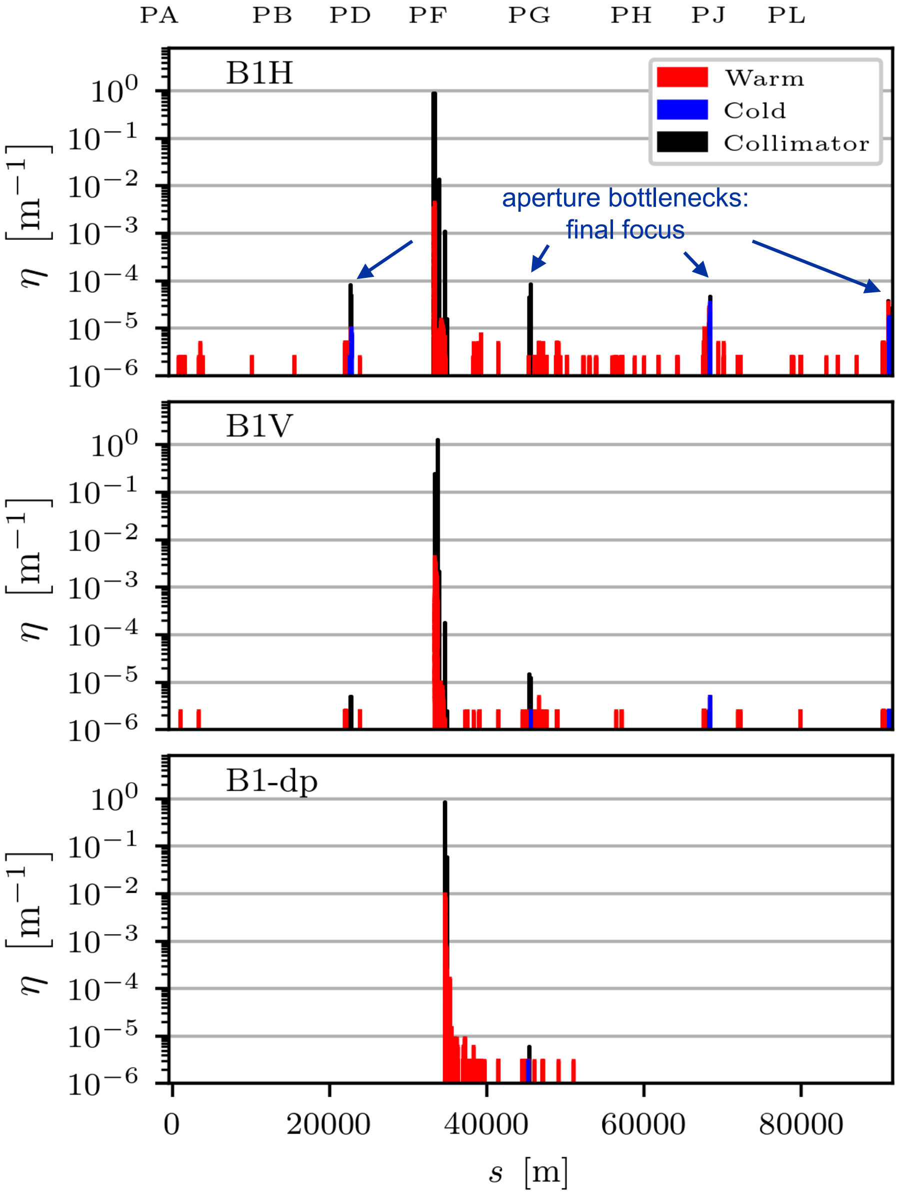


Parallel jaw and tilted collimator schematic

Type	Plane	Material	Length [m]	Gap [σ]
β prim.	H	MoGr	0.4	11.0
β sec.	H	Mo	0.3	13.0
β prim.	V	MoGr	0.4	65.0
β sec.	V	Mo	0.3	75.5
δ prim.	H	MoGr	0.4	29.0
δ sec.	H	Mo	0.3	32.0
SR BWL	H	W	0.1	18.6
SR QC3	H	W	0.1	16.7
SR QT1	H	W	0.1	14.6
SR QT1	V	W	0.1	196.4
SR QC2	H	W	0.1	14.2
SR QC2	V	W	0.1	154.2

Collimator parameter and settings for the Z mode

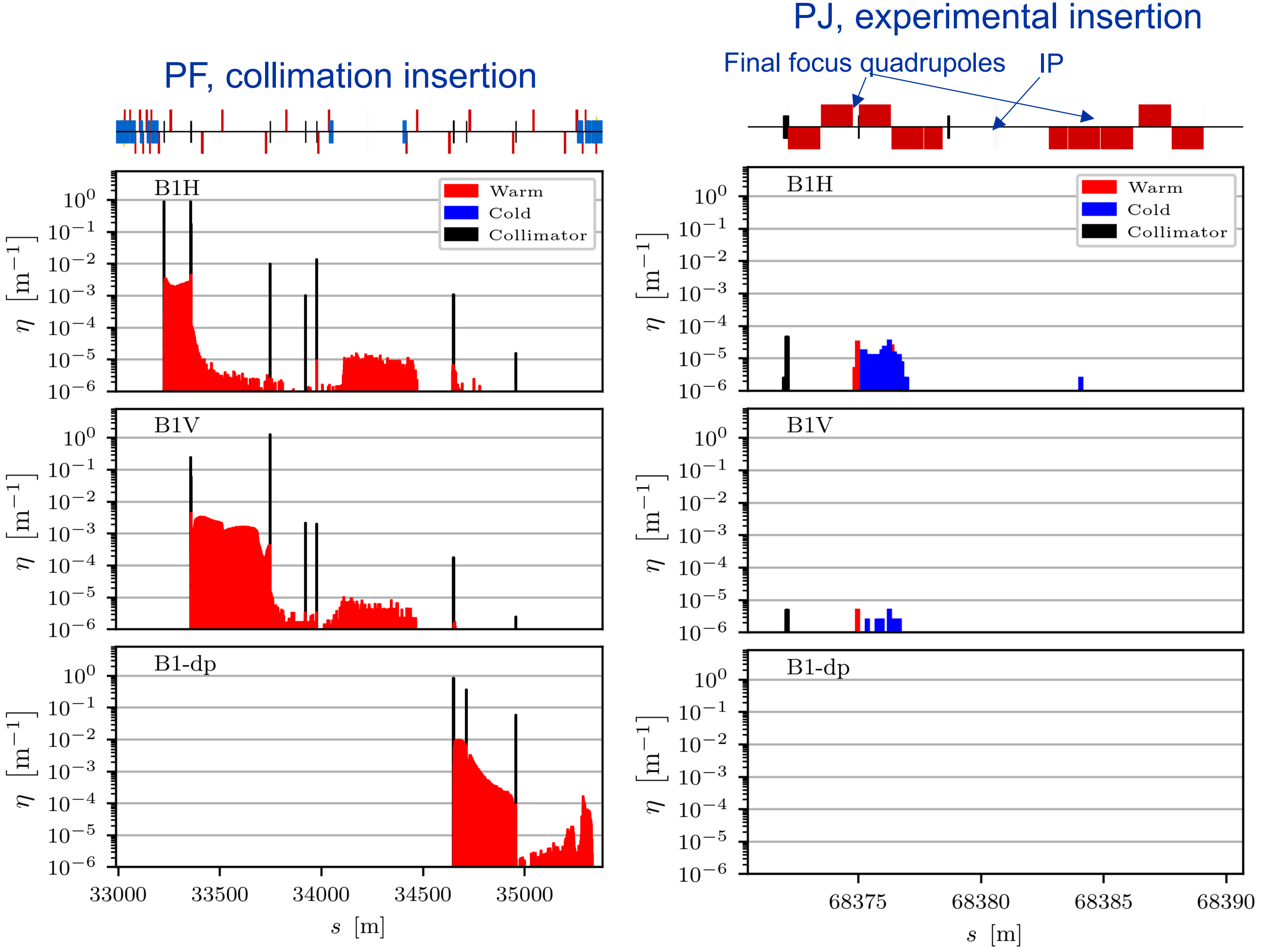
Total loss power: **59.2 kW**



Z-mode betatron halo loss maps

Beam halo losses for the Z mode

- The beam collimation system shows significant loss suppression
  - More than 99.96% of losses contained within the collimation insertion PF, only up to 1.7 W reaching any IR
  - Tilted primary collimators are essential for the performance at the Z mode
  - Energy deposition studies and thermo-mechanical studies are required for the collimators and most exposed magnets
- Collaborative studies ongoing
  - Impedance and collective effects M. Migliorati
  - IR losses and collimator parameter optimization G. Broggi
  - Tracking of the collimation losses in the detector A. Ciarma
  - First collimator energy deposition and thermomechanical studies G. Lerner, R. Andrade


PF, collimation insertion

PJ, experimental insertion

Final focus quadrupoles

IP

Z-mode betatron halo loss maps for selected regions

Planned simulation tool developments

- **Collimation simulations**
  - Ongoing work in the CERN collimation team to further develop **Xsuite** for collimation studies
    - **Xcoll** – dedicated package for collimation study management, integrated scattering routines for protons
    - Integration with **FLUKA** as a collimation scattering routine, collaboration with the CERN FLUKA team

- **FCC-ee developments**
  - Include beam-beam effects in the simulations
    - Beam-beam kick, Beamstrahlung, radiative Bhabha scattering
    - Important effect of the beam dynamics, required for specific studies like spent beam
    - Significant work on beam-beam effects as part of the EPFL–CERN software collaboration
  - Include collimator imperfections, magnetic errors and alignment tolerances

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Summary

- **Developed collimation simulation tools for the FCC-ee**
  - Based on a coupling between a particle tracking engine and a particle-matter interaction engine
  - The **Xsuite-BDSIM** coupling framework is the current tool used for production collimation studies
    - Flexible modelling enables a variety of beam loss studies
  - Applied the tools to **betatron and off-momentum beam halo collimation** in the FCC-ee lattice

- **Next steps**
  - Continue the development of the simulation tools
  - Study other beam loss scenarios:
    - **Spent beam**
    - **Top-up injection**
    - **Failure modes**
  - Obtain equipment loss tolerances, which are required to assess the collimation system performance

Thank you!