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FCC-ee collimation studies

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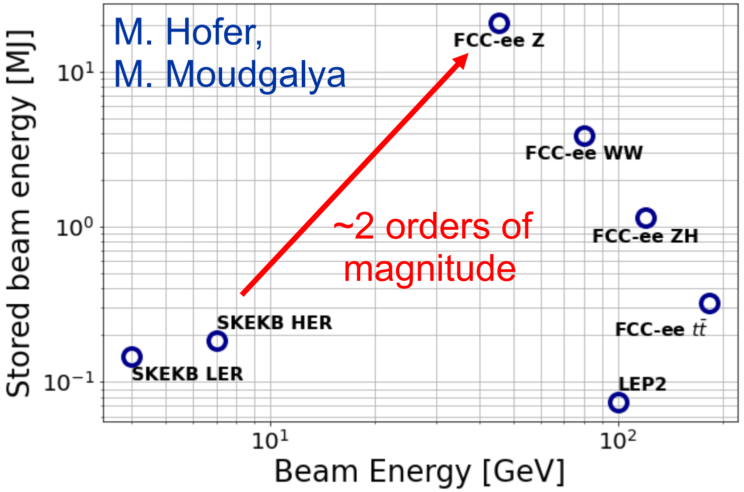
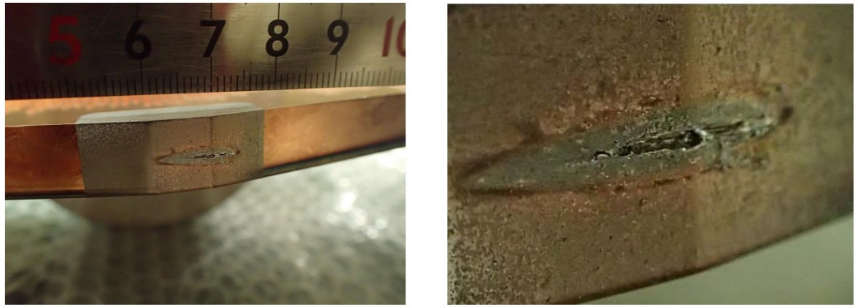
Collimation for the FCC-ee

- **The FCC-ee is the FCC first stage e+e- collider**
  - 91 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)

- **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



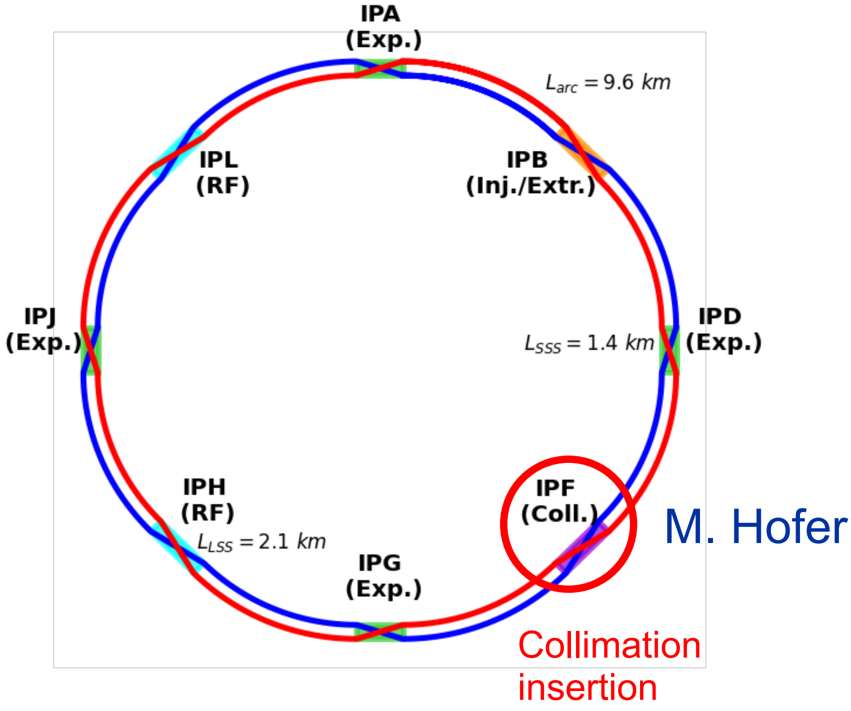
Comparison of lepton colliders

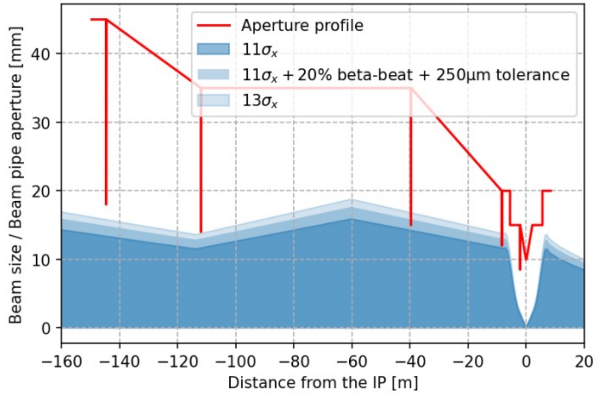


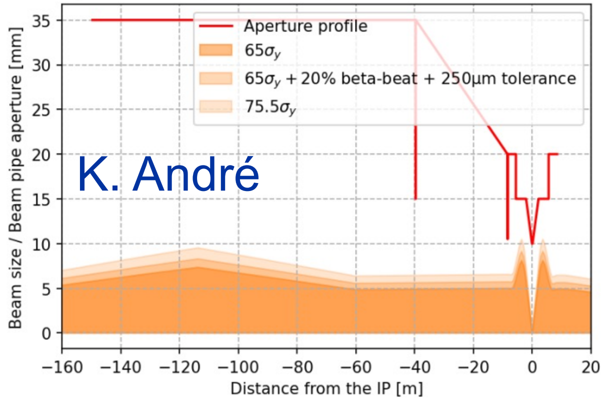
Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

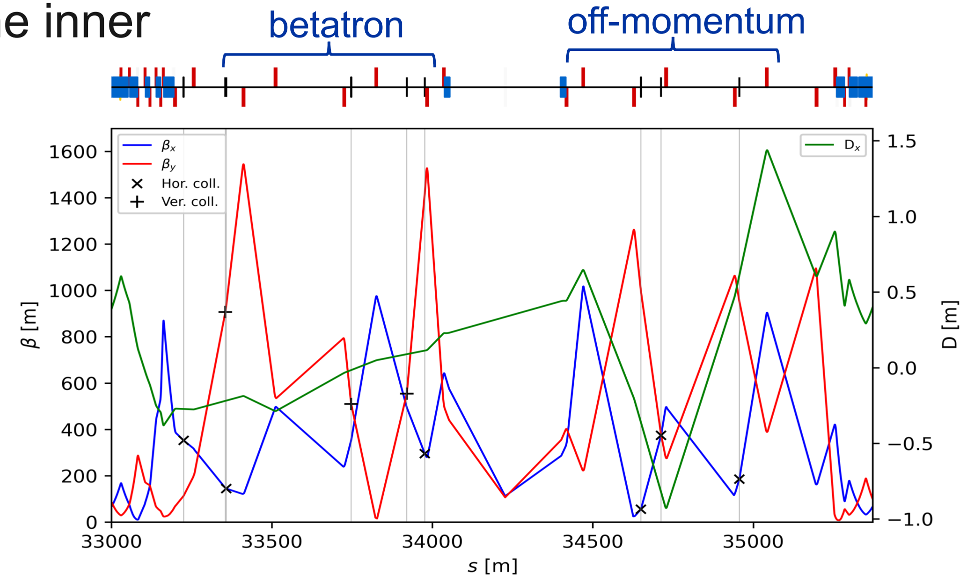
FCC-ee collimation system

- **Dedicated halo collimation system in PF**
  - Two-stage betatron and off-momentum collimation in one insertion
  - Defines the global aperture bottleneck
  - Dedicated collimation optics (M. Hofer)
  - First collimator design for beam cleaning performance (G. Broggi)
- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs (K. André, talk)
  - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses



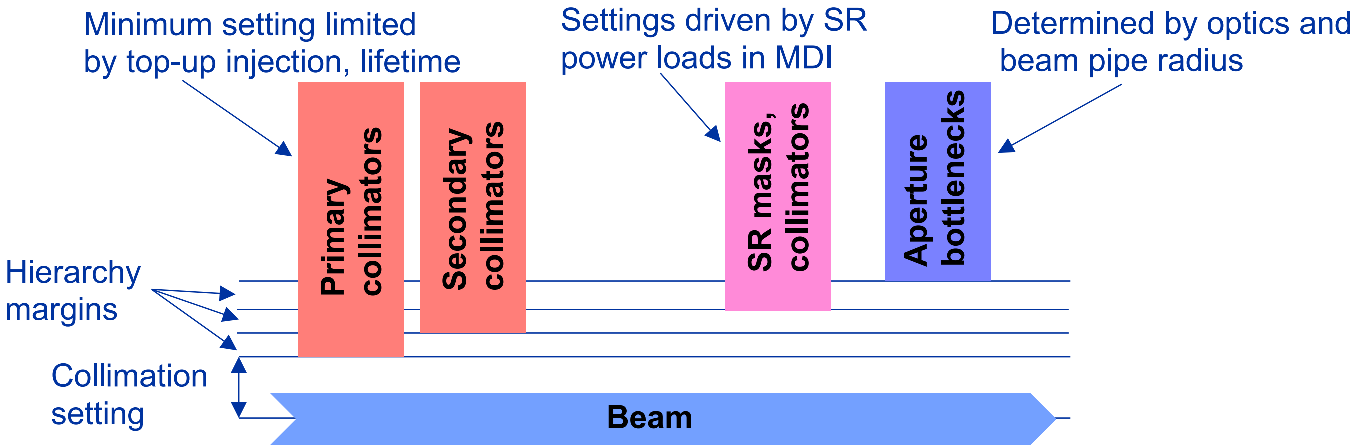






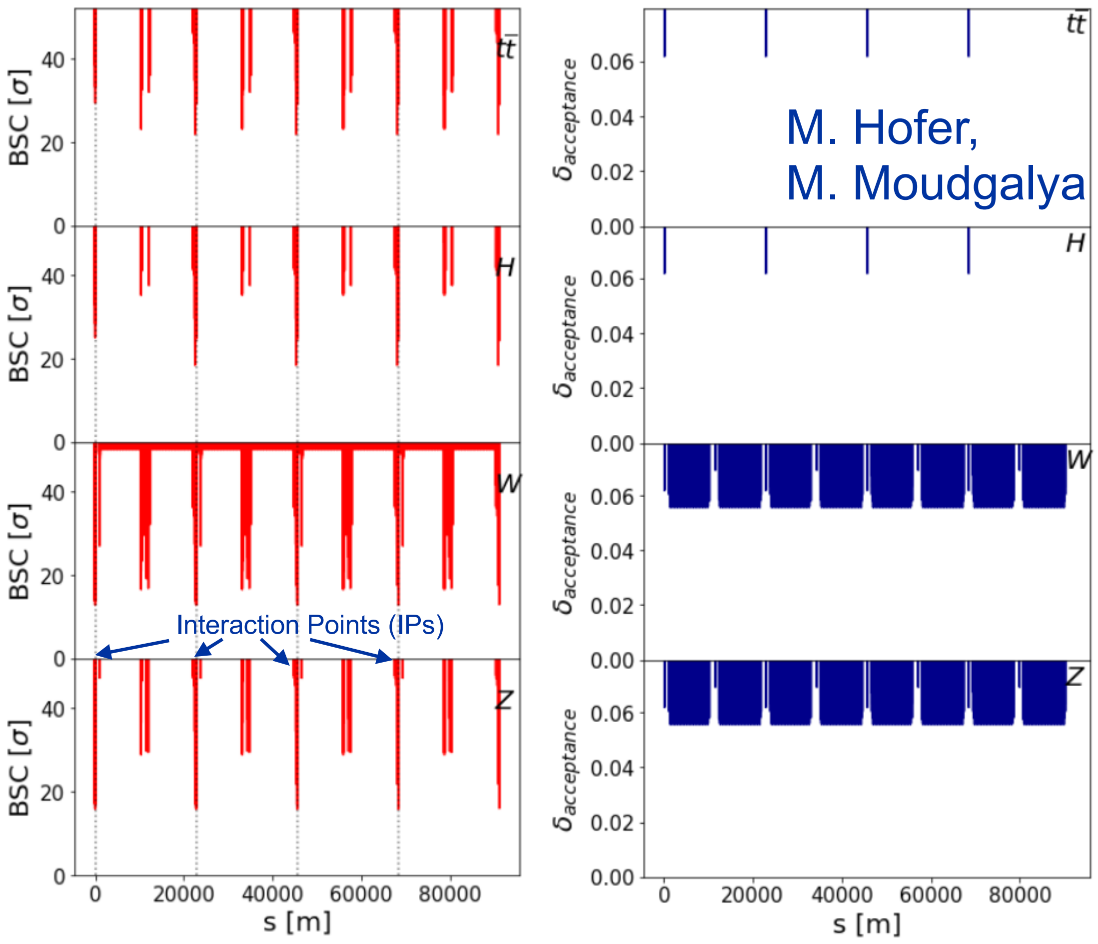
FCC-ee aperture

- **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 tolerances are tight (M. Hofer, talk)



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



Aperture bottlenecks for the different operating modes

FCC-ee beam losses

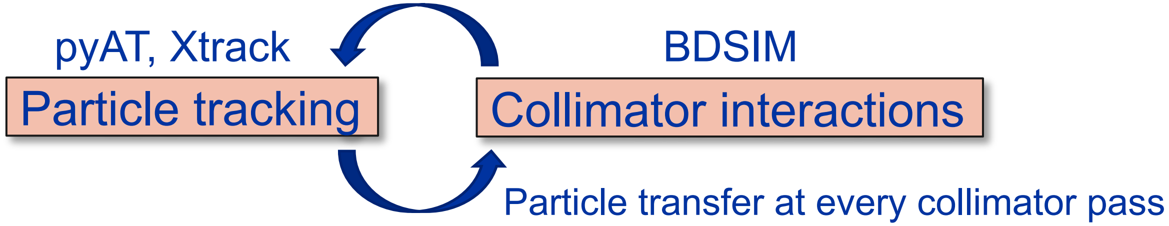
- **The FCC-ee will operate in a unique regime**
  - Electron / positron beam dynamics and beam-matter interactions
  - Stored beam energy exceeding material damage limits
  - Superconducting final focus quadrupoles, crab sextupoles, and RF cavities
  - Must study the beam loss processes and define the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

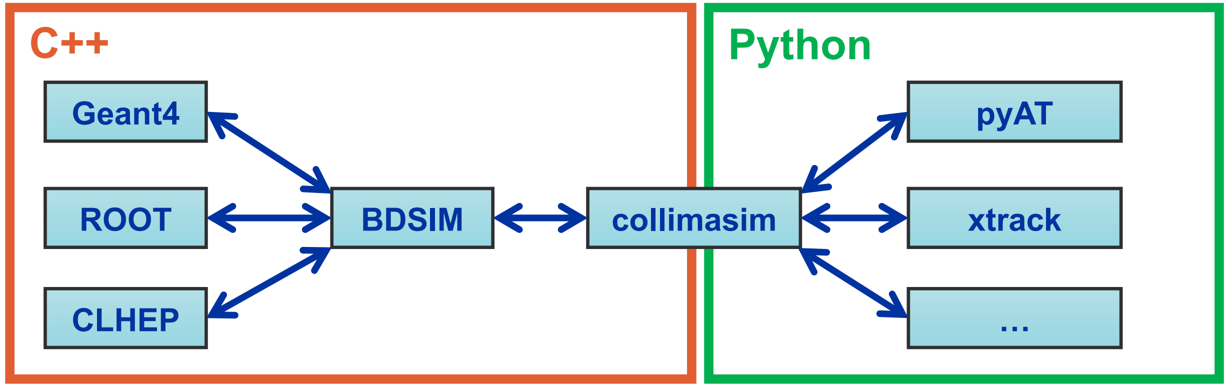
- **Loss scenarios selected for particle tracking studies:**
  - Beam halo
  - Top-up injection
  - Spent beam due to collision processes (Beamstrahlung, Bhabha scattering)
  - Failure modes (injection failures, asynchronous dump, others)
  - Beam tails from Touschek scattering and beam-gas interactions

FCC-ee collimation simulation setup

- **The FCC-ee presents unique challenges for collimation simulations:**
  - Synchrotron radiation and magnet strength (optics) tapering to compensate it
  - Complex beam dynamics – strong sextupoles in lattice, strong beam-beam effects (Beamstrahlung)
  - Electron/positron beam particle-matter interactions
  - Large accelerator – 91 km beamline, efficiency is crucial

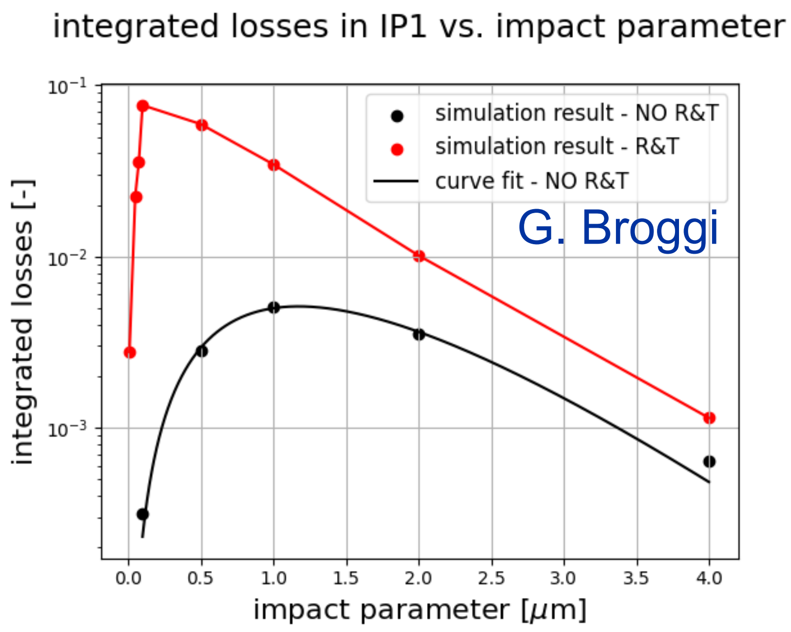
- **Xsuite + BDSIM (Geant4)**
  - Benchmarked against other codes for FCC-ee – MAD-X, pyAT, SixTrack-FLUKA coupling (IPAC'22 paper)
  - Used for for the latest FCC-ee collimation studies
  - Tests / benchmarks in other machines:
    - LHC (FCC-ee optics meeting talk) – G. Broggi
    - PS (NDC section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





Current study: beam halo losses

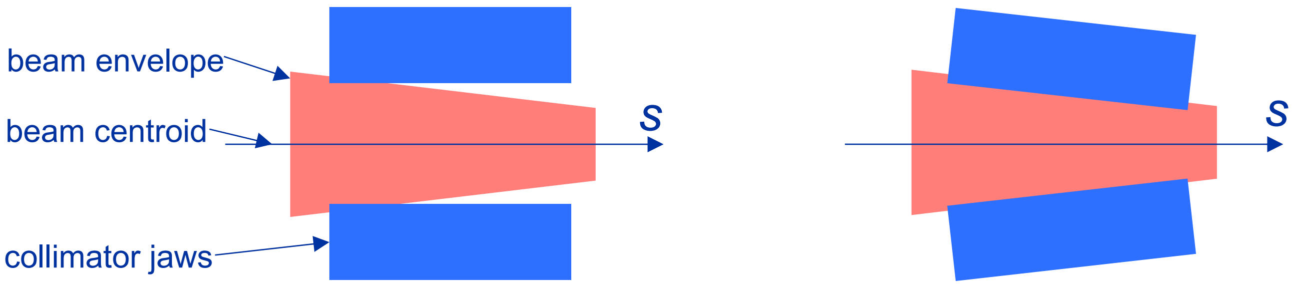
- **"Generic beam halo" beam loss scenario:**
  - Assume a slow diffusion process – halo particles intercepted by the primary collimators
  - The diffusion is not simulated, all particles start impacting a collimator
  - The particles have the "worst" impact parameter
    - Determined with an impact parameter scan
    - Provides a conservative performance estimate
  - Study horizontal and vertical betatron halo, and off-momentum halo impacts
  - Track the particles scattered out from the collimator and record losses on the aperture
  - Specify a beam lifetime that must be sustained
    - Currently assuming a **5 minute** lifetime



Impact parameter scan for $t\bar{t}$ in the 2 IP CDR lattice with MoGr primary collimator, with and without radiation and tapering (R&T)

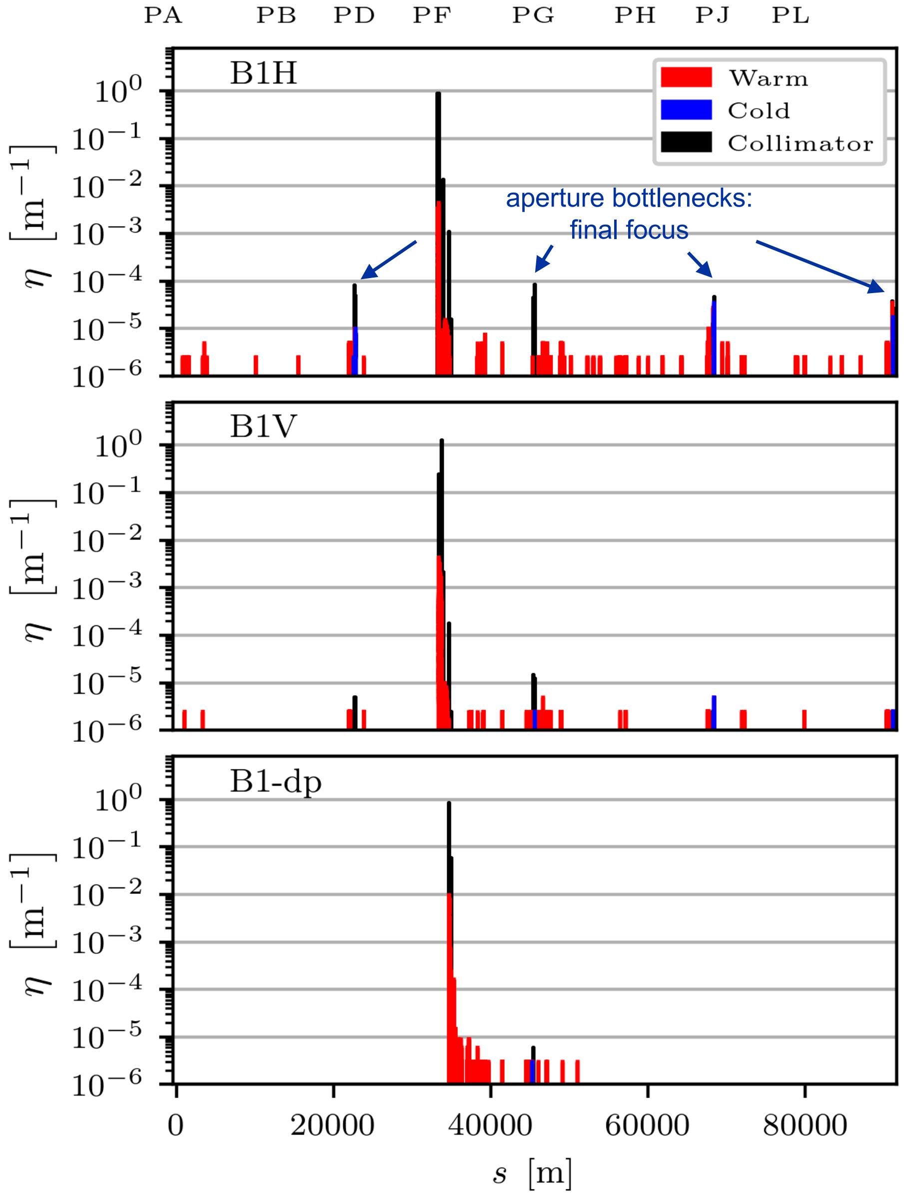
Beam halo losses for the *Z* mode

- The *Z* mode is the current focus (Beam 1, 45.6 GeV positrons), **17.8 MJ** stored beam energy
- Particles simulated directly impacting the primary collimators
- Radiation and tapering included, **1 μm** impact parameter
- **5 min** beam lifetime assumed, total loss power **59.2 kW**
- Studied 3 cases:
  - **Horizontal betatron losses (B1H)**
  - **Vertical betatron losses (B1V)**
  - **Off-momentum losses δ < 0 (B1-dp)**
- For the off-momentum case, using a tilted collimator, aligned to the beam divergence



Parallel jaw and tilted collimator schematic (See G. Broggi, IPAC'23)

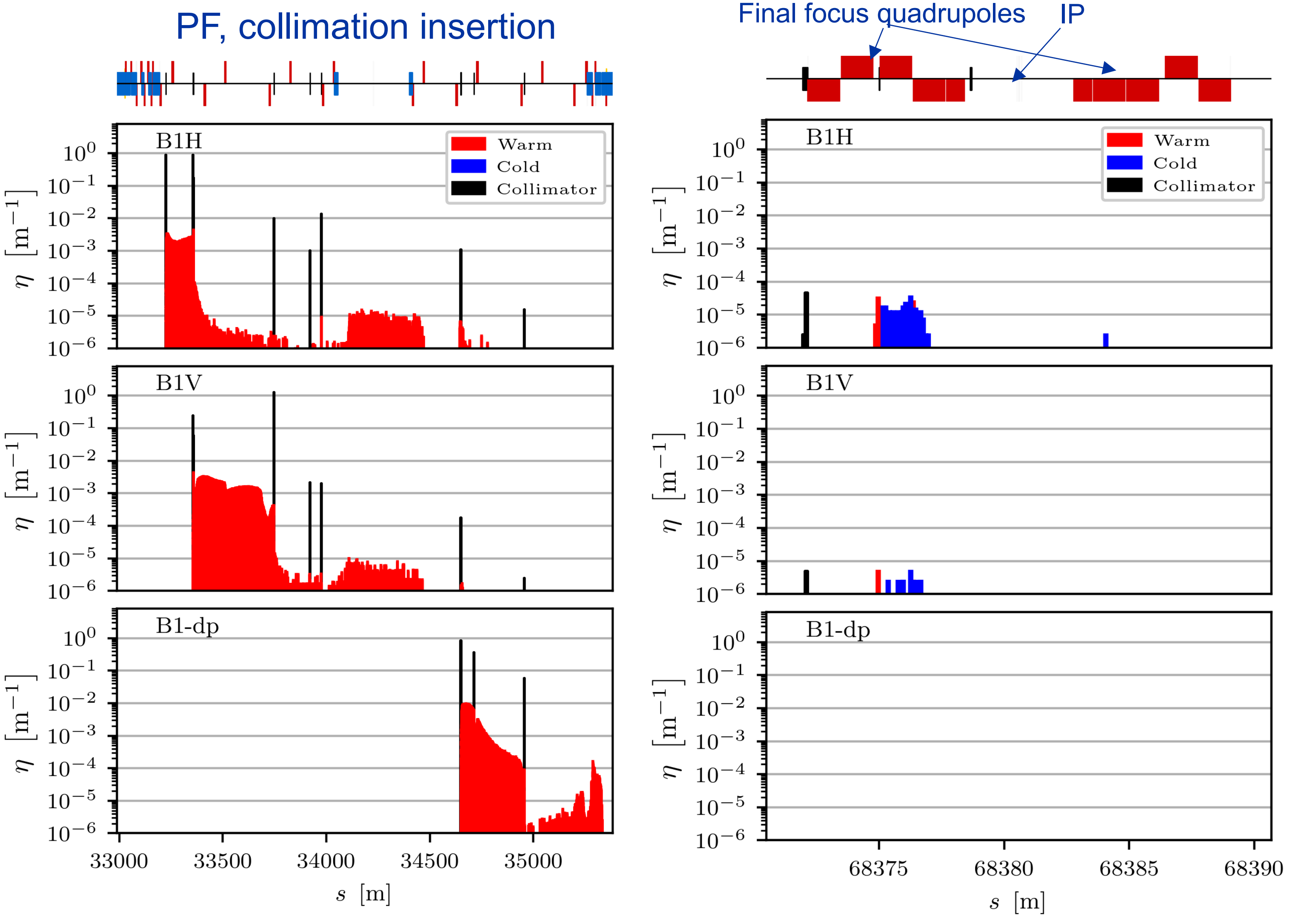
Total loss power: **59.2 kW**



Z-mode betatron halo loss maps

Beam halo losses for the Z mode

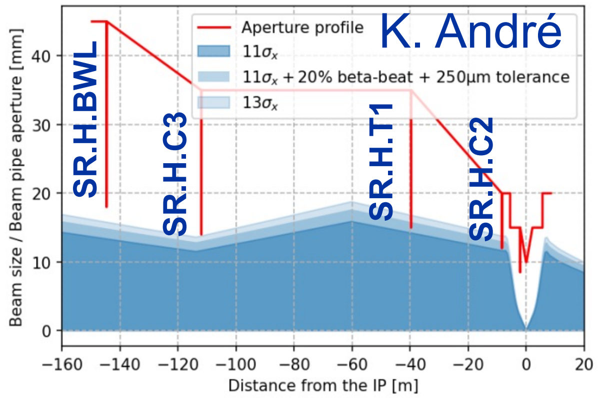
- The beam collimation system shows good performance
  - More than **99.96%** of losses contained within the collimation insertion PF
  - Only up to **1.7 W** of losses reaching the experimental IRs
  - Tilted primary collimators are essential for the performance at the Z mode
  - Energy deposition studies are required for the collimators and most exposed magnets

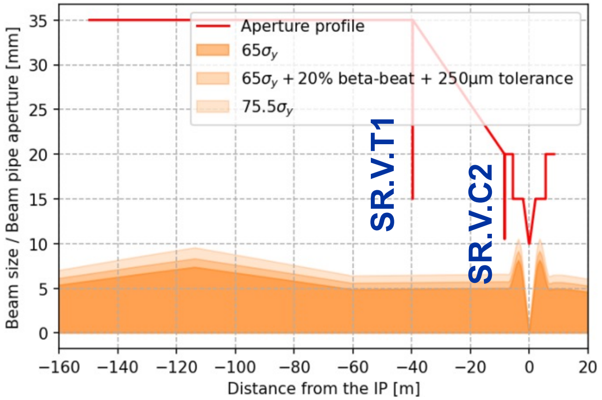


Z-mode betatron halo loss maps for selected regions

Z mode losses on SR collimators

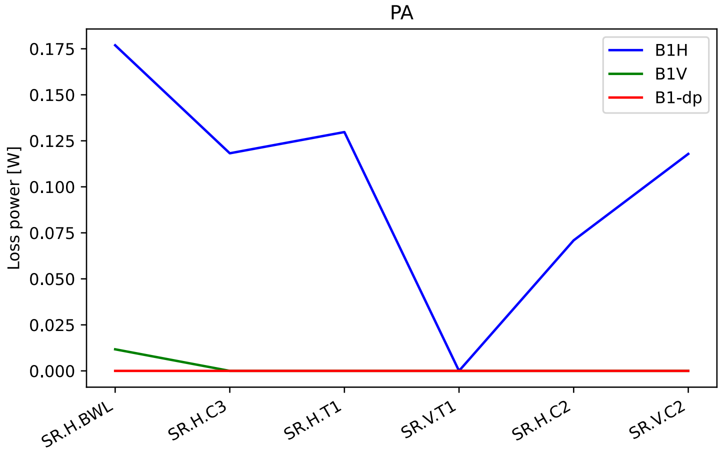
- **The SR collimators intercept losses for all cases**
  - Highest load on BWL and C3 horizontal collimators
  - Lowest load on the vertical T1 collimator

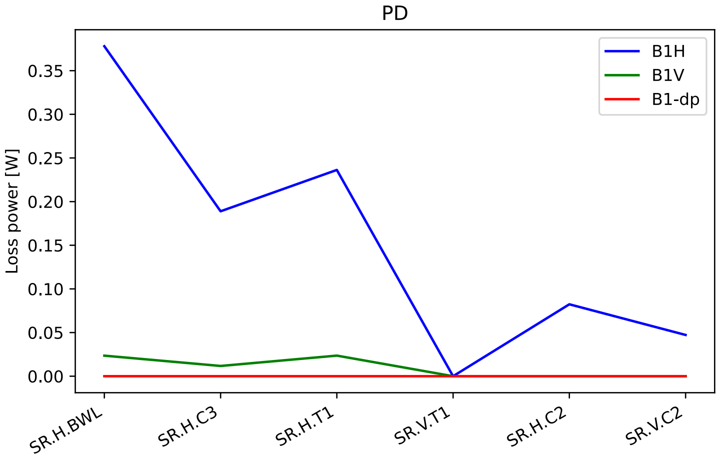


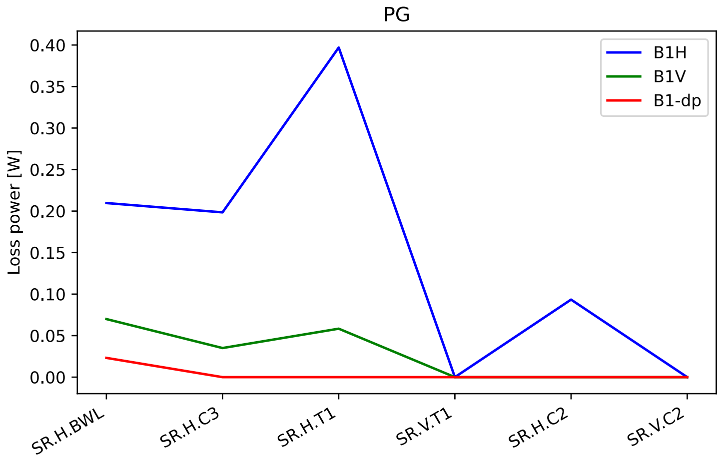


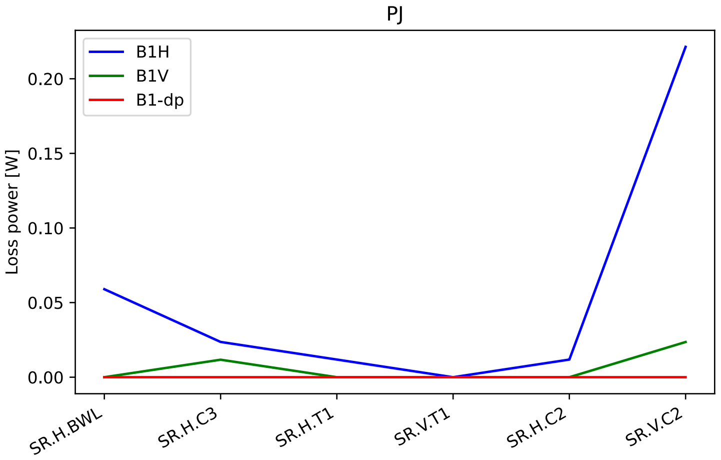
beam →

Total loss power: **59.2 kW**





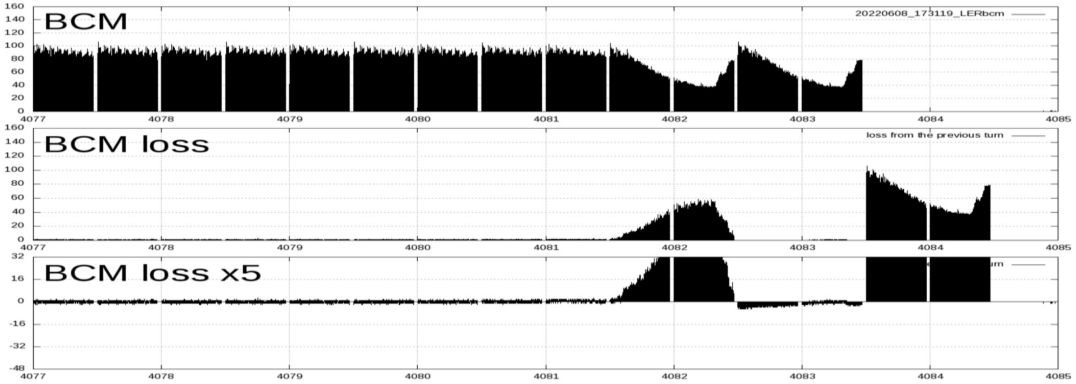




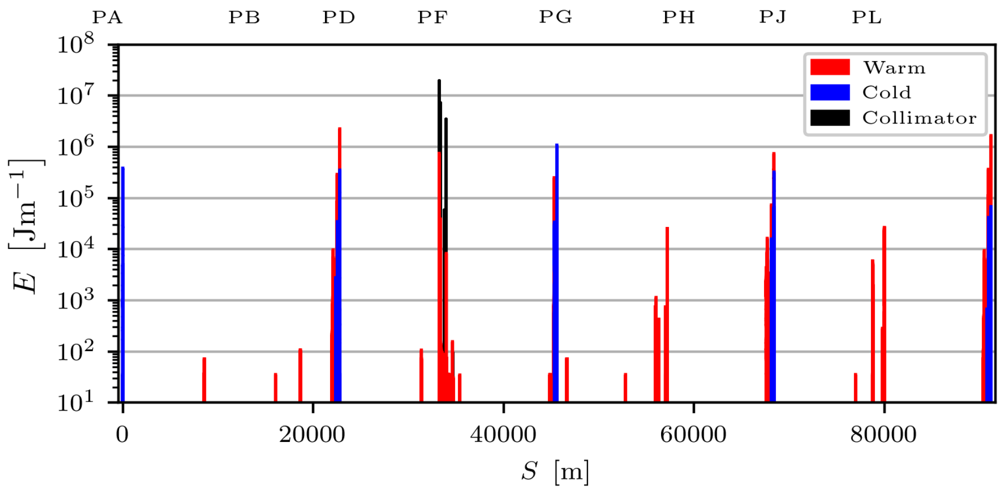
Fast beam losses for the FCC-ee

- **Fast beam losses due to failures are important to study**
  - SuperKEKB has experiences sudden beam loss, up to 80% intensity loss over 2 turns (T. Ishibashi, talk)
  - Such events have damaged collimators, and the cause is not well understood

- **Fast beam losses for the FCC-ee**
  - It is not clear if such a scenario could occur in the FCC-ee
    - Accidental beam loss scenarios and their likelihood should be studied in detail to devise a protection strategy
  - If protection against SuperKEKB-type losses is needed, it could drive significant changes in the collimation design
    - Preliminary studies show that a bespoke solution would be needed to handle such losses
    - As a worst-case, sacrificial collimators can be considered



Beam current during a sudden beam loss in the SuperKEKB – T. Ishibashi (talk)

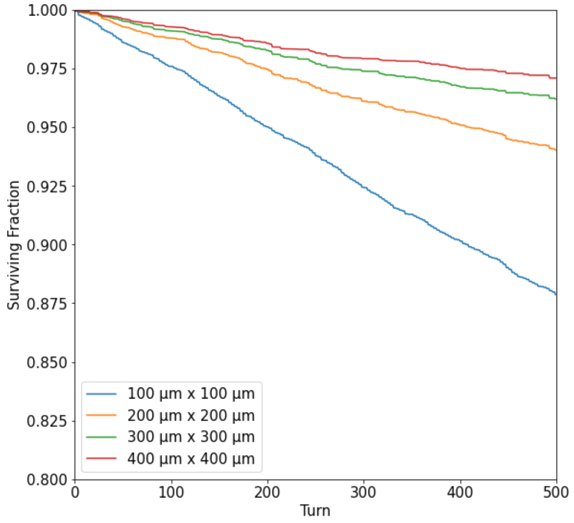


Preliminary FCC-ee Z-mode fast beam loss with 80% intensity loss over 2 turns

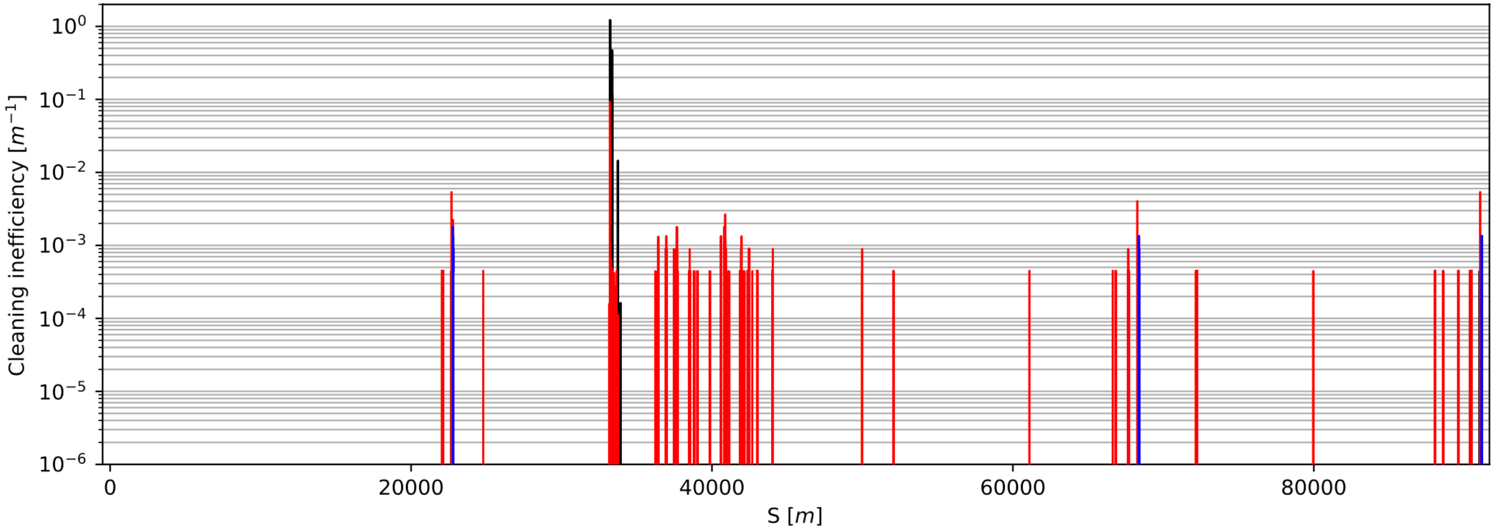
Laser intensity control

- **In the FCC-ee, mismatched bunch charge in collisions can lead to a 3-D flip flop instability**
  - Leads to a fast blow-up of a full bunch, charge asymmetry tolerance <5%
  - Control of bunch intensity with laser Compton scattering has been proposed (F. Zimmermann, IPAC'22)
  - First studies using **Xsuite + Cain + Collimasim** (I. Drebot, M. Hofer):
    - Modulated turn-by-turn laser interaction in a full model with lattice, aperture, and collimation system
    - On-line particle tracking, laser interaction, and loss location recording
    - Concept studies for the *Z* mode ongoing, full studies

I. Drebot et al, IPAC'23



Laser spot size scan for the *Z* mode



Preliminary loss map for the out-scattered particles for the 100 m size laser spot

FCC-ee collimation summary

- **Studies of beam losses and collimation for the FCC-ee**
  - First collimation system design available, including beam halo and SR collimators
  - Simulations of beam loss scenarios ongoing
    - Beam halo losses studied for the *Z* mode, no show-stoppers identified so far
    - Input on equipment loss tolerances needed to optimize performance
  - First considerations for other beam loss processes:
    - Fast beam losses, laser intensity control losses

- **Next steps**
  - Study other beam loss scenarios
  - Obtain input for the equipment loss tolerances – superconducting magnets, collimators, other
    - **Energy deposition studies required for magnets, collimators, and masks**
    - **Detailed evaluation of detector backgrounds required – shielding, muon backgrounds**
  - Study all beam modes

Thank you!