Collimation studies for FCC-ee

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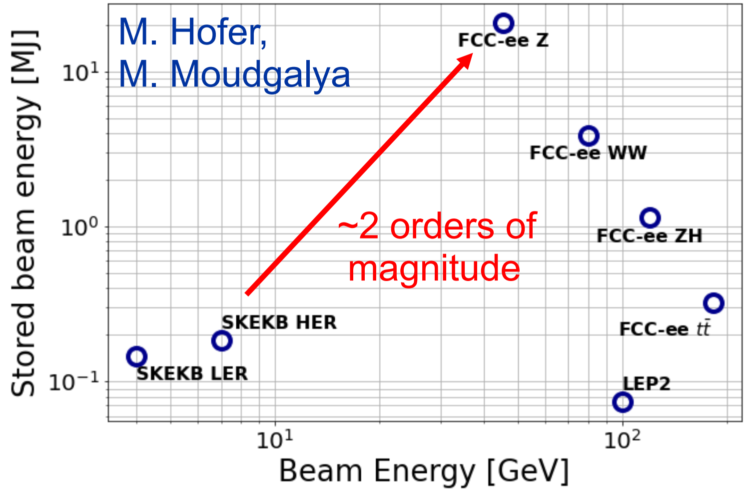
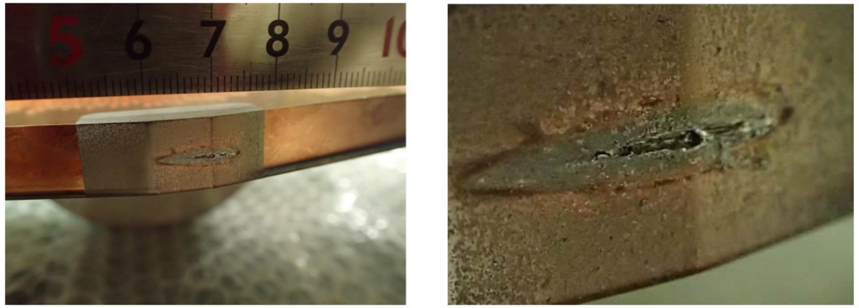
Collimation for the FCC-ee

- **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)
  - The stored beam energy reaches **17.5 MJ** for the 45.6 GeV ***Z*** mode, which is comparable to heavy-ion operation at the LHC



Comparison of lepton colliders

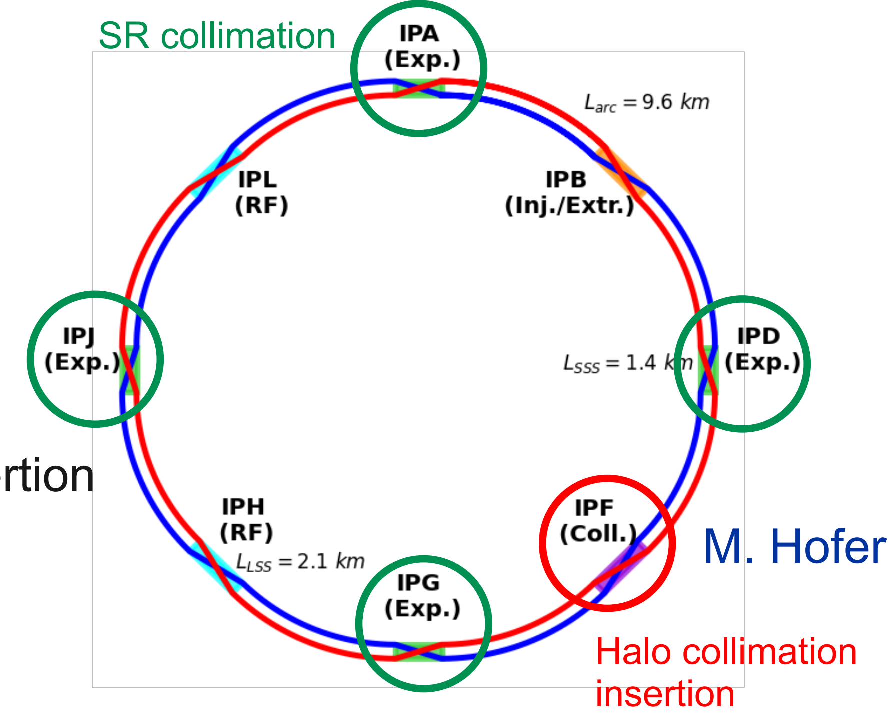
- **The FCC-ee presents unique challenges**
  - Such beams are highly destructive: a collimation system is required
  - The main roles of the collimation system are:
    - Protect the equipment from unavoidable losses
    - Reduce the backgrounds in the experiments



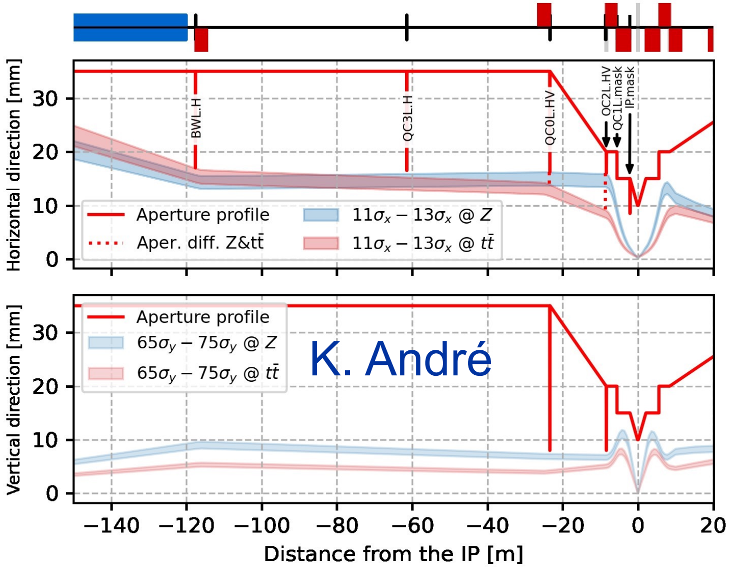
Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

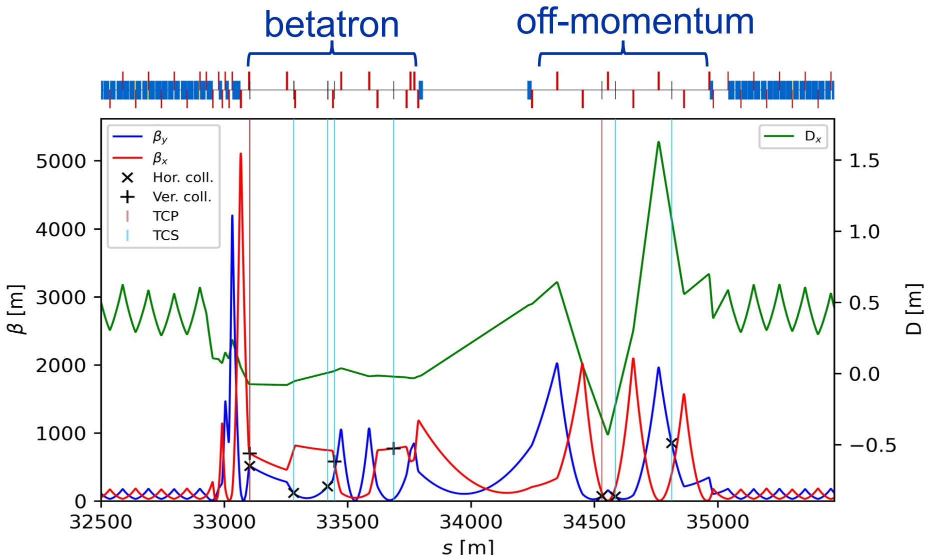
FCC-ee collimation system

- **Two types of collimation foreseen for the FCC-ee:**
  - The beam halo (global) collimation
  - Synchrotron Radiation (SR) collimation – near the IPs
- **Halo collimation in a dedicated insertion**
  - Two-stage betatron and off-momentum collimation systems in one insertion
  - Ensure protection of the aperture bottlenecks in different conditions
  - Collimation optics (M. Hofer) and collimator parameters (G. Broggi)



- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs (K. André)
  - Designed to absorb SR photons

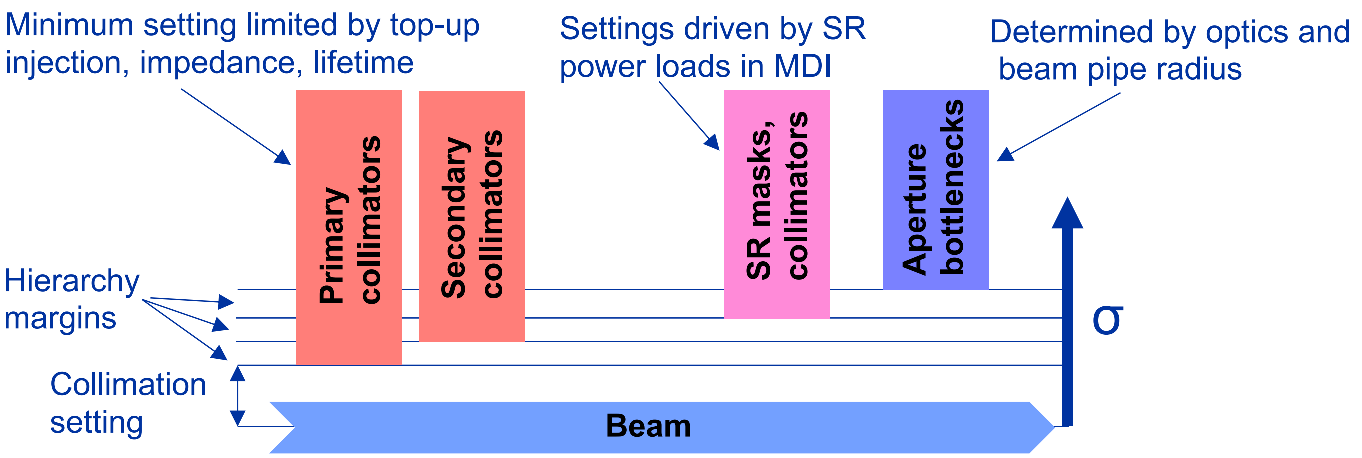




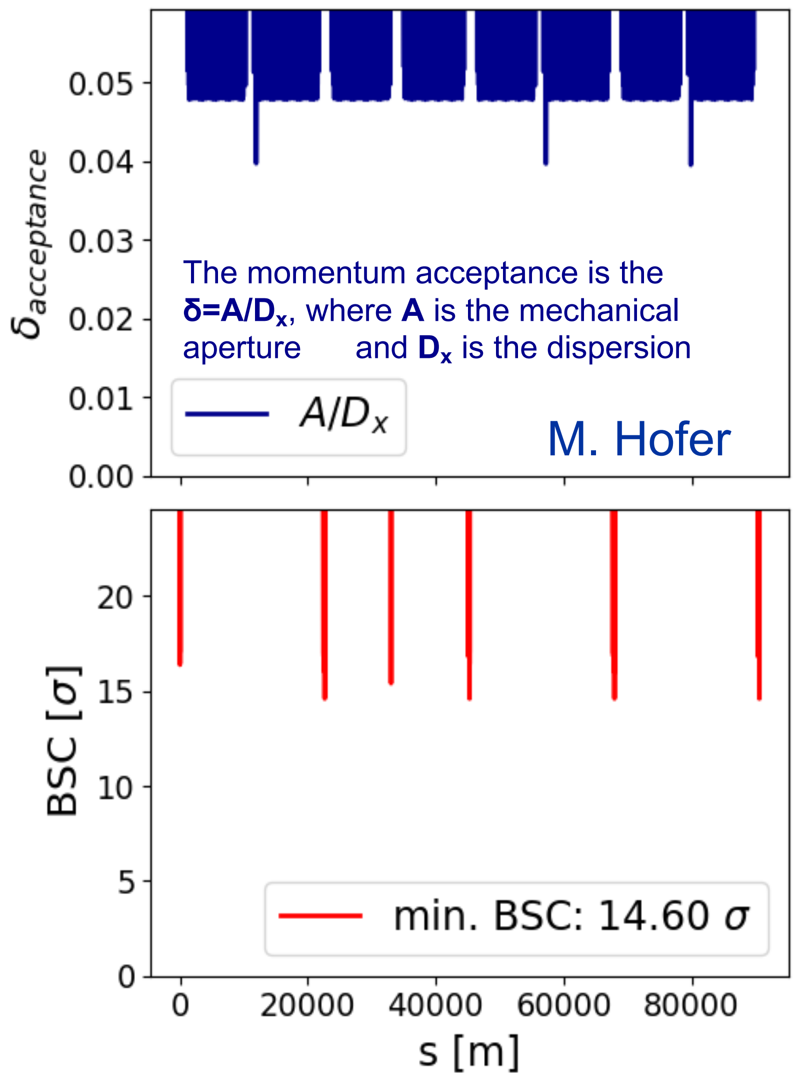
FCC-ee aperture

- **The aperture bottlenecks are in the experimental interaction regions (IRs)**
  - Depend on the optics, layout, and mechanical aperture in the 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



Aperture bottleneck for *Z*-operation mode



FCC-ee halo collimation

- **New collimation system optics and settings**
  - Based on a triple double doublet (tridodo) scheme by M. Hofer
  - Designed to maintain optimal collimator phase advances at acceptable mechanical gaps and flat β-functions at primary collimators
  - Compatible with the new V23 layout, improved dynamic aperture

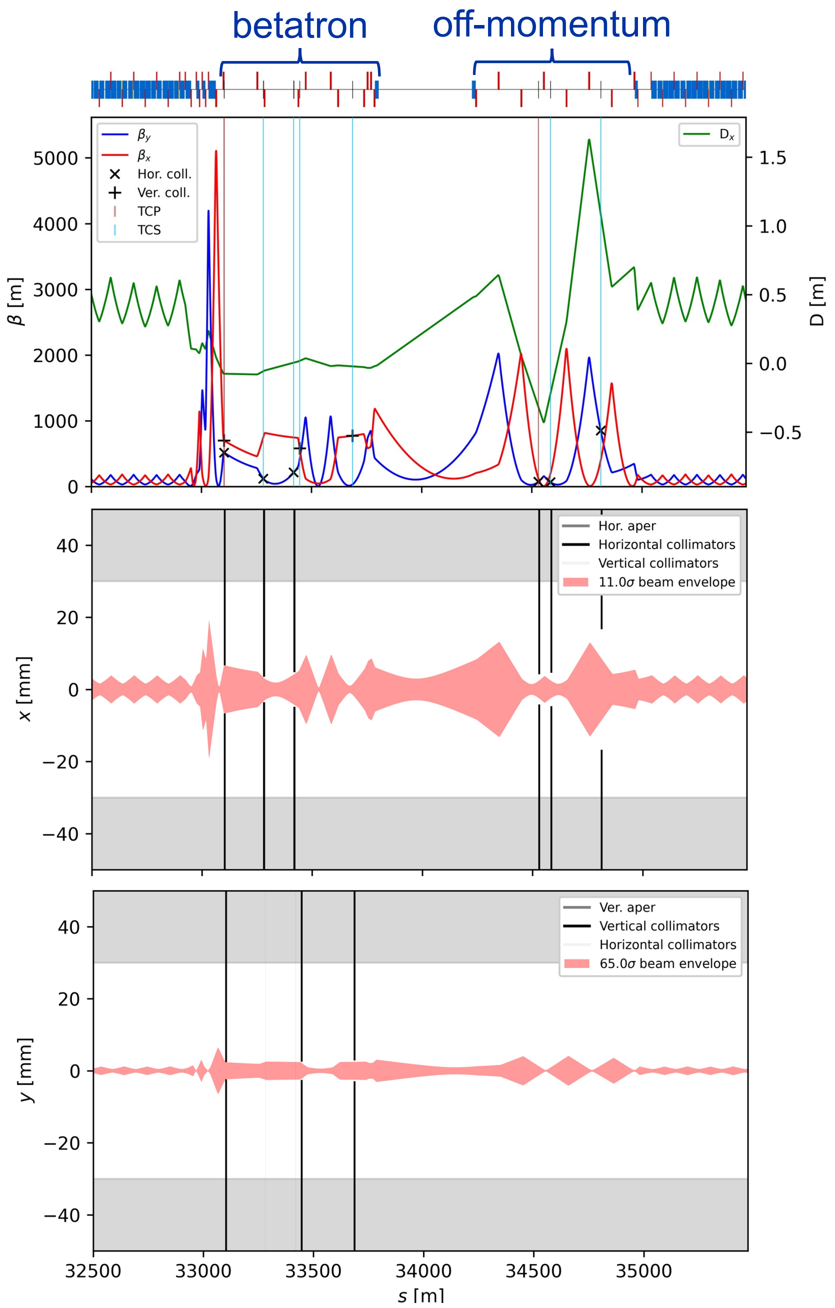
Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	MoGr	25	11	6.7	8.9
TCP.V.B1	V	MoGr	25	65	2.1	-
TCS.H1.B1	H	Mo	30	13	3.7	6.7
TCS.V1.B1	V	Mo	30	75	2.2	-
TCS.H2.B1	H	Mo	30	13	5.1	90.6
TCS.V2.B1	V	Mo	30	75	2.5	-
TCP.HP.B1	H	MoGr	25	18.5	4.2	1.3
TCS.HP1.B1	H	Mo	30	21.5	4.7	2.1
TCS.HP2.B1	H	Mo	30	21.5	26.7	1.6

Beam halo collimator parameters and settings

G. Broggi

Note: 25 cm primary collimators adopted (FCC week 23 talk)

V23, tridodo_572 collimation optics, https://gitlab.cern.ch/mihofer/fcc-ee-collimation-lattice



FCC-ee beam loss scenarios

- **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
  - Must study the equipment loss tolerances, for both regular and accidental losses

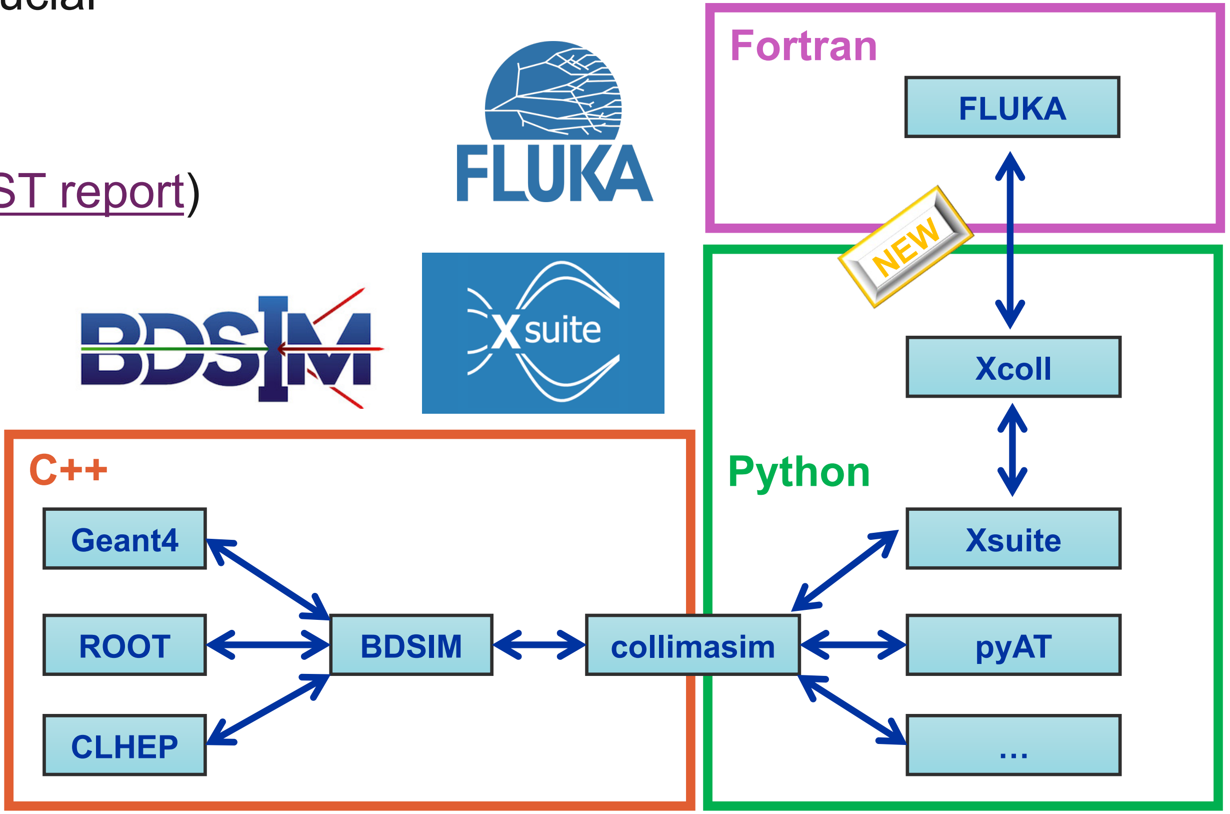
- **Important loss scenarios for particle tracking studies:**
  - **Beam halo** → Current studies
  - **Spent beam due to collision processes** (Beamstrahlung, Bhabha scattering) → Preliminary consideration
  - Beam tails from Touschek scattering and beam-gas interactions
  - Top-up injection
  - Failure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

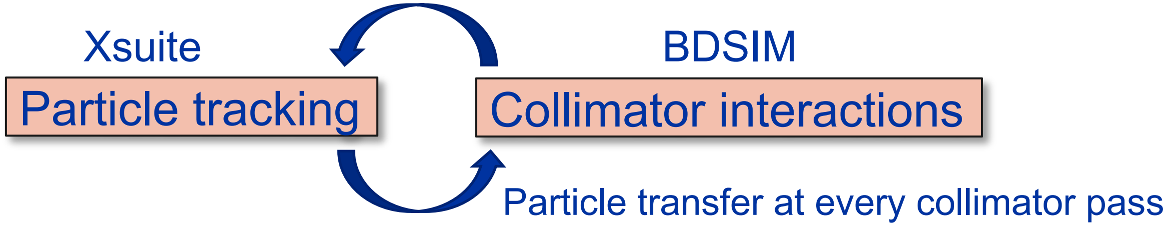
  } Setting up studies, Inputs required to set up models

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

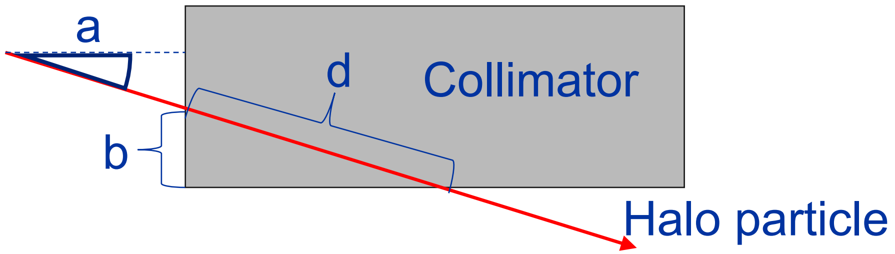
- **Xsuite + BDSIM (Geant4)**
  - Benchmarked against other codes for FCC-ee (JINST report)
  - Used for for the latest FCC-ee collimation studies
  - Tests / benchmarks in other machines:
    - LHC (FCC-ee optics meeting talk) – G. Broggi
    - PS (NDC section meeting talk) – T. Pugnat



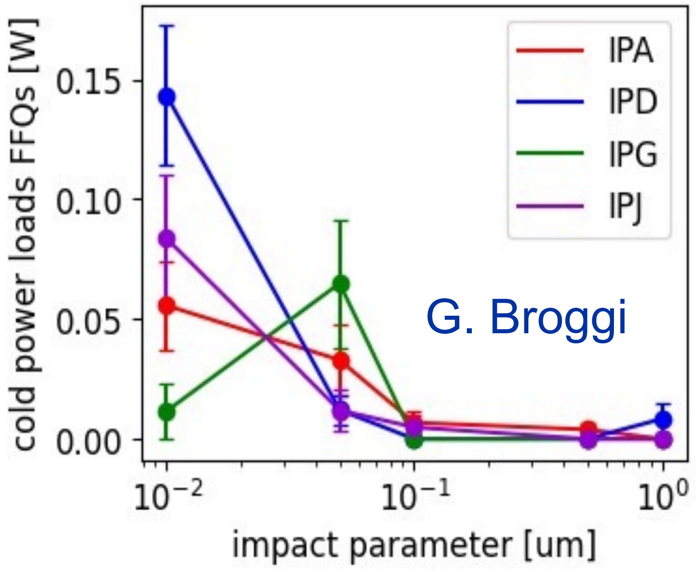


Current study: beam halo losses

- **“Generic beam halo” beam loss scenario:**
  - 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



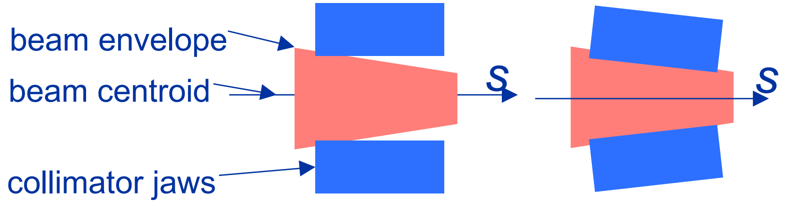
a = angle of incidence
b = impact parameter
d = distance traversed



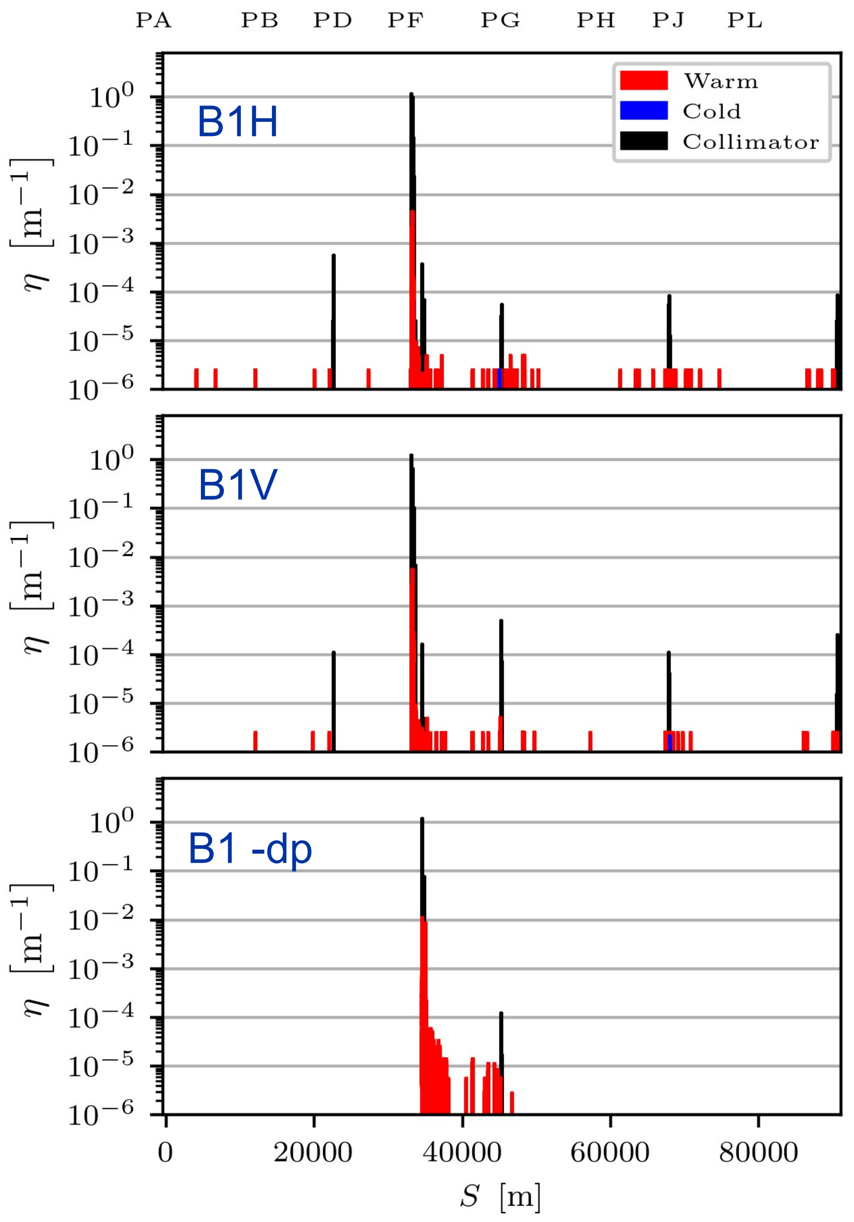
Impact parameter scan (Z mode) tridodo_572

Beam halo losses for the Z-mode

- The Z mode is the current focus (Beam 1, 45.6 GeV, e^+), **17.5 MJ** stored beam energy
- The **5 minute** beam lifetime → total loss power **58.3 kW**
- 3 cases considered:
  - **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



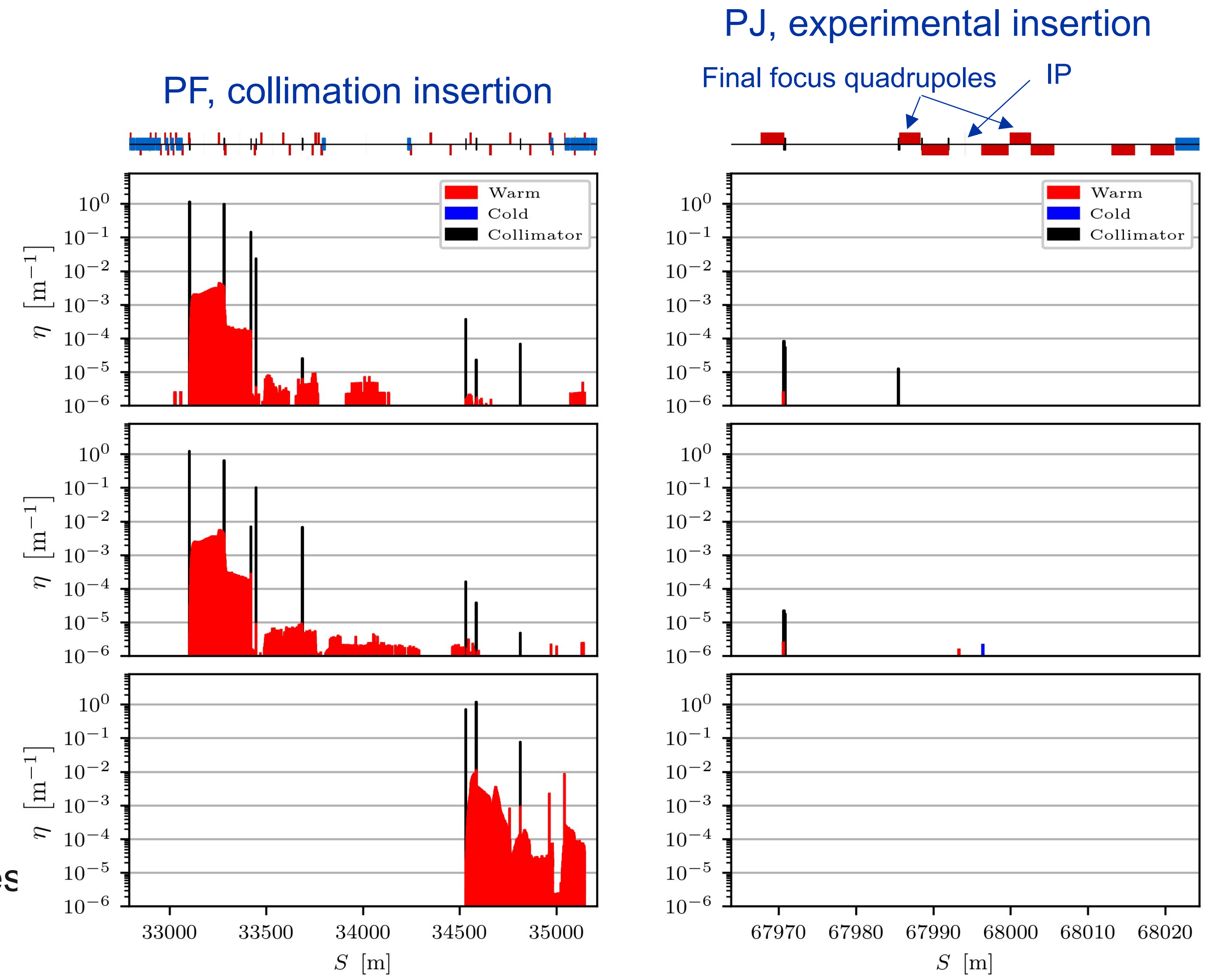
- Good loss cleaning performance performance observed
  - **Minimal losses on the final focus quadrupoles in all scenarios**
  - **Residual losses on superconducting crab sextupoles**



Z-mode betatron and off-momentum 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
  - Almost no losses reach any of the IRs
  - Energy deposition studies and thermo-mechanical studies are required for the collimators and most exposed magnets
- Collaborative studies ongoing:
  - SR collimation (K. Andre, FCC Physics Workhsop talk)
  - Detector backgrounds (A. Ciarma, FCC week 23 talk)
  - Impedance (M. Migliorati, FCCIS 23 talk)
  - Energy deposition & thermomechanical studies (G. Lerner, A. Frasca, R. Andrade)
  - Studies provide input to a detailed, iterative design effort



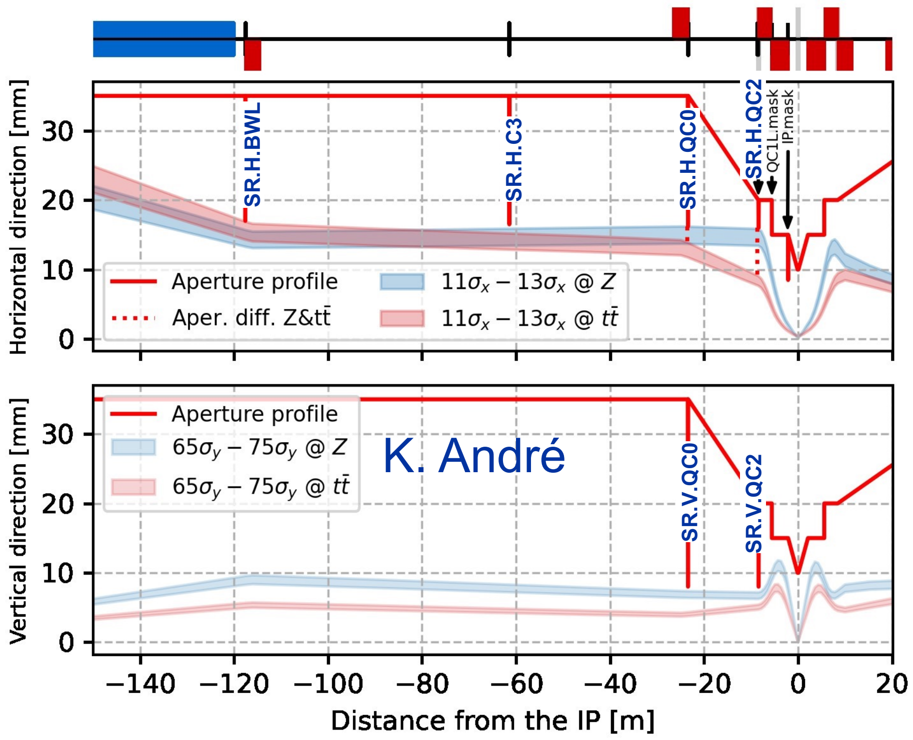
Z-mode betatron halo loss maps for selected regions

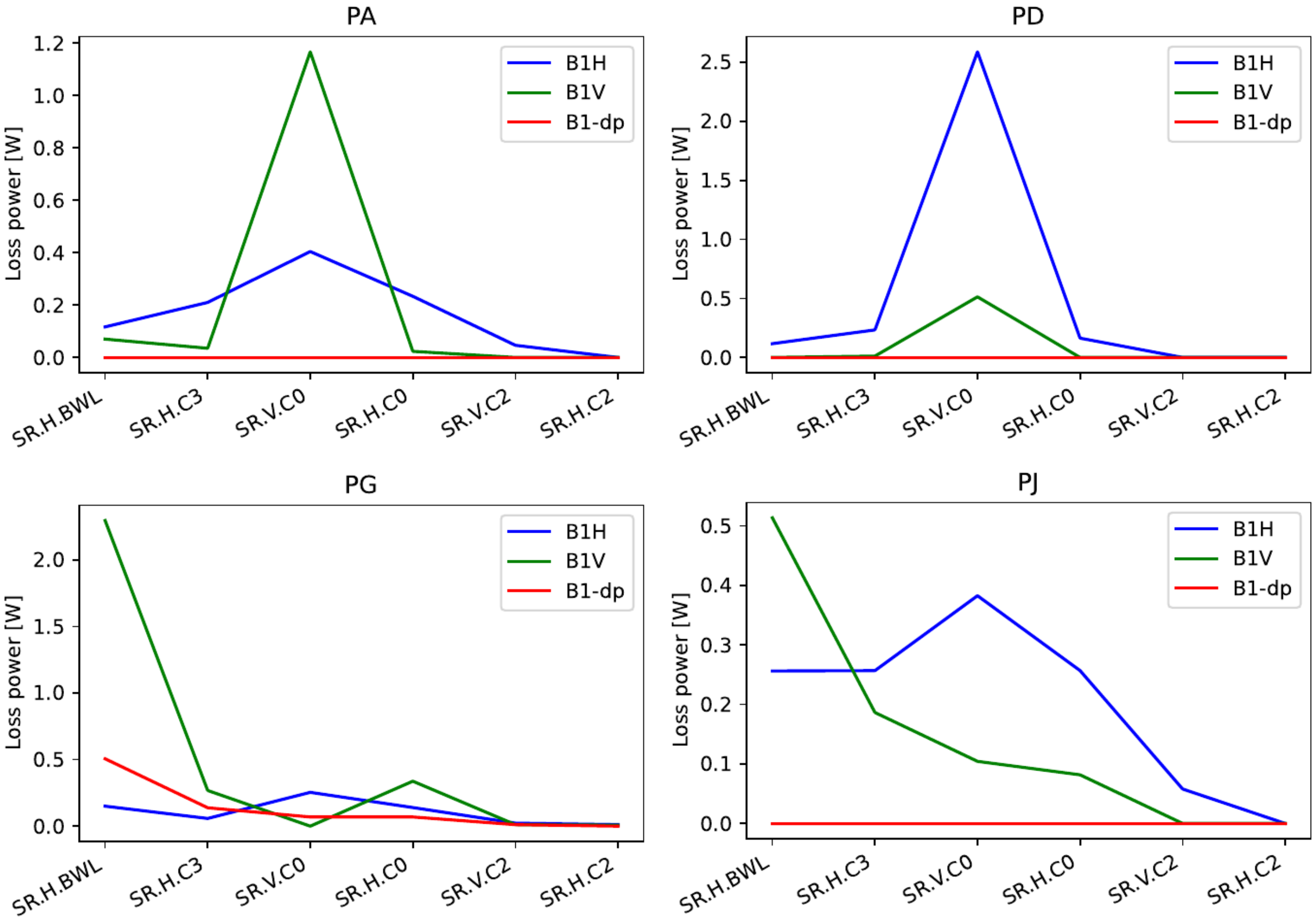
Z-mode losses on SR collimators

- **The SR collimators intercept losses for all cases**
  - Highest load on C0 vertical and BWL horizontal SR collimators, up to 2.6 W
  - Lowest load on C2 horizontal and vertical SR collimators

beam →

Total loss power: **58.3 kW**



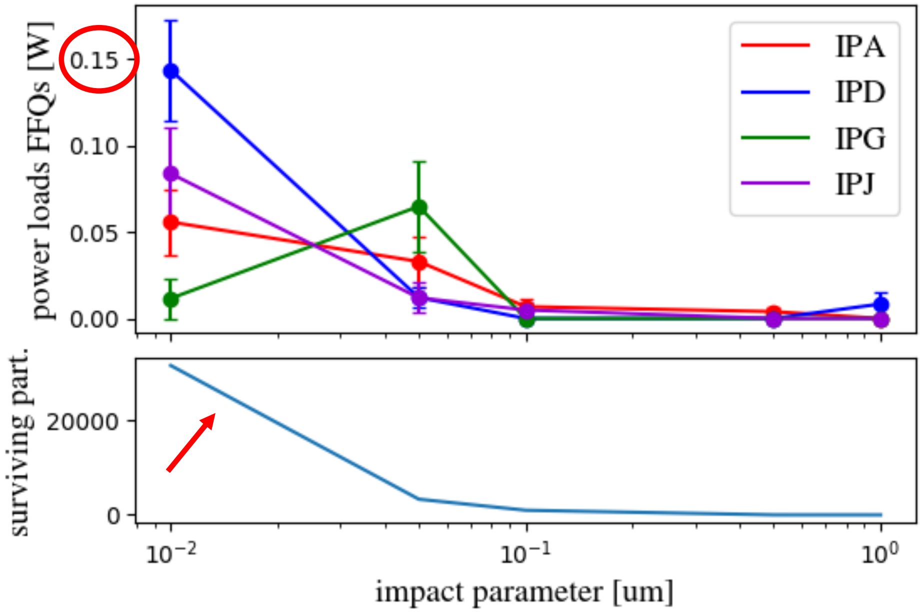


Z mode impact parameter scan

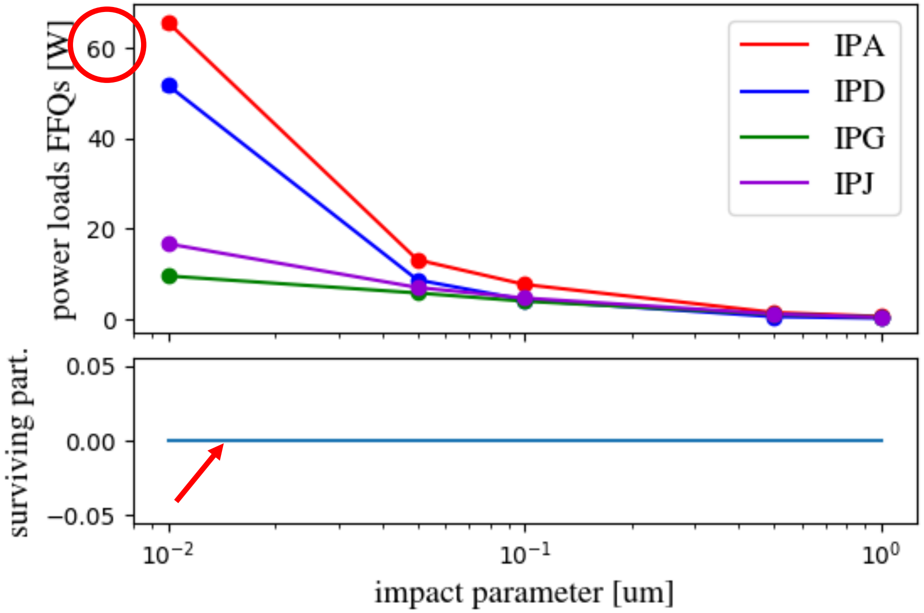
- Using 1 μm impact parameter, but also studying the sensitivity with impact parameter scans
  - 5×10^6 primary particles tracked for 700 turns at each step
- The new lattice and collimation system demonstrates lower losses across the board
  - Most likely due to the new collimation insertion optics and better resulting dynamic aperture (M. Hofer)
  - Absence of a clear critical impact parameter b > 0 um, which presents challenges for modelling
  - Surface roughness effects not considered – can play a role for b ≲ 0.1 um

G.Broggi

V23, tridodo_572 collimation optics



V22, splitinsertion_529 collimation optics



FCC week 23, talk

Collimation and beam-beam effects

- **Interactions at the IPs have a crucial role in FCC-ee beam dynamics**
  - Beamstrahlung, radiative Bhabha scattering, beam-beam kicks
  - Main contribution to the beam lifetime in nominal operation
  - Produce distinct beam loss distributions around the ring

- **Large effort to model these effects in Xsuite** (P. Kicsiny, X. Buffat, T. Pieloni)
  - See P. Kicsiny, FCC Physics Workshop 2023 talk
  - EPFL-led effort, part of a CHART-funded FCC software collaboration project
  - Recent benchmarks show good agreement with established tools
  - The models are modular and can be combined with other studies

- **Goal: integrate beam-beam effects in collimation tracking studies**
  - Long-range loss distribution from spent beam
  - Effect of beam-beam interaction on distributions during collimation tracking

EPFL

CERN

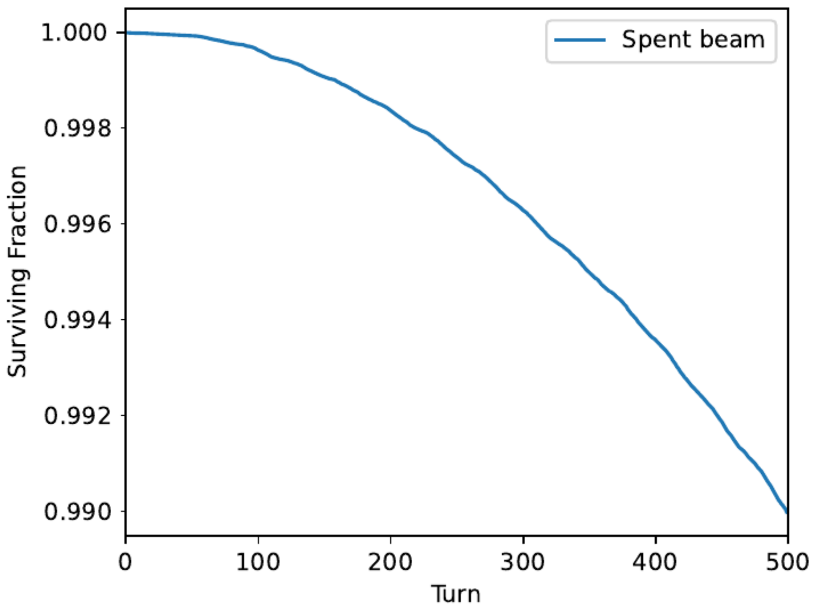
CHART
Swiss Accelerator
Research and
Technology

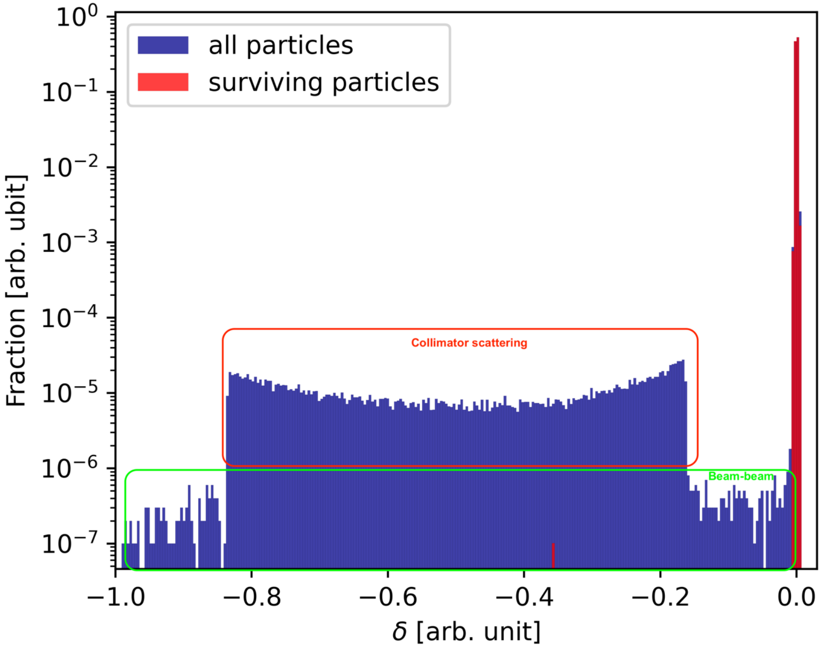
FCC-ee Z-mode spent beam losses

- **Study for the first time collimation with beam-beam integrated**
  - Full non-linear lattice, crab-waist, detailed aperture and collimator models, radiation and tapering, weak-strong beam-beam, Beamstrahlung, and Bhabha scattering in 4 IPs

- **Initial run carried out:**
  - Clockwise beam 1 (positrons), 45.6 GeV
  - Track a matched Gaussian beam of 10^7 primary positrons from IPA for 500 turns
  - Equilibrium beam-beam emittance and bunch length, no coupling
  - Cumulative loss over 500 turns is ~1%, **check in detail**:
    - The full aperture and collimator model, worse DA and MA due to inclusion of the collimation insertion optics, and the lack of vertical emittance generation from the lattice likely play a role
  - Only the loss distribution along the ring is considered, the lifetime from the simulation is not used:
    cannot estimate the lifetime from this simulation

PRELIMINARY





Z-mode spent beam losses

- **Lost particles accumulated to obtain loss maps**
  - The loss maps are scaled to the combined nominal beam lifetime from lattice, SR, beamstrahlung and luminosity
- **Significant losses observed on SR collimators**
  - Large losses on the vertical SR.C0 collimators in PD, PA and PJ
  - Up to 3.4 kW on a SR collimator, investigate the source
- **These are first preliminary results; detailed analysis will be carried out**

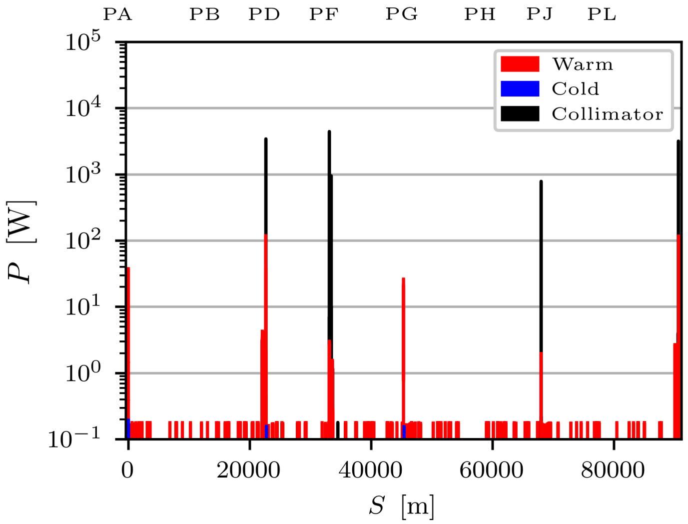
Lifetime for the *Z* mode, K. Oide talk

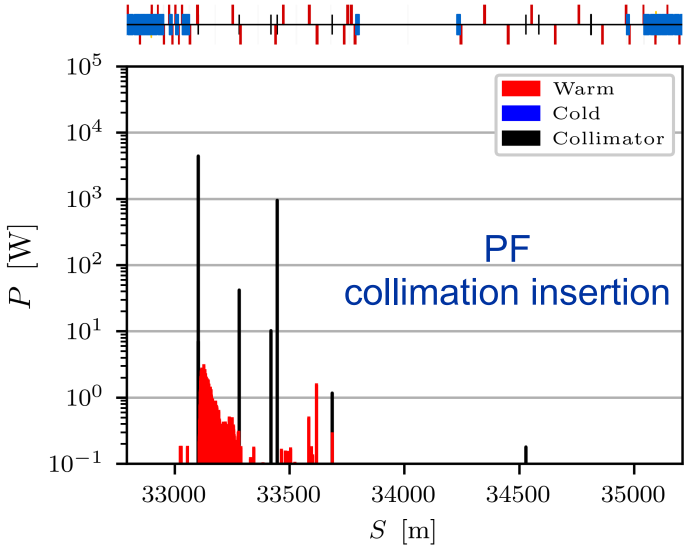
Lifetime (q + BS + lattice)	[sec]	10000
Lifetime (lum)[b]	[sec]	1330

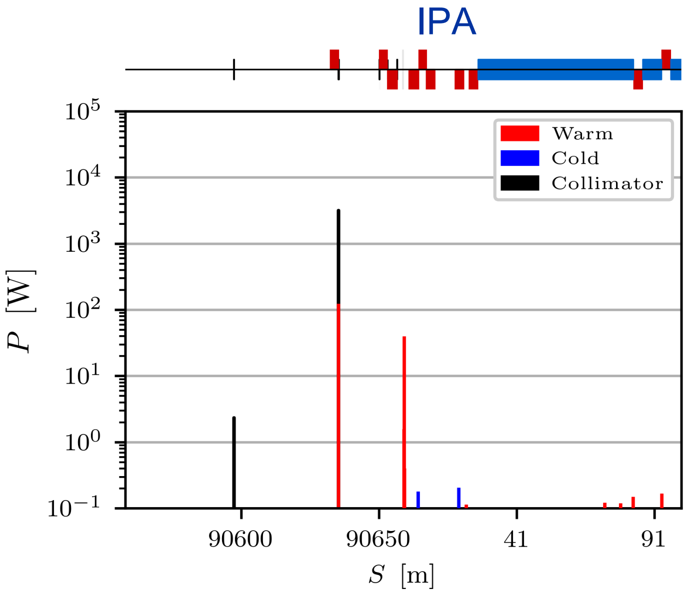
$$\tau^{-1} = \frac{1}{\tau_{q+BS+lattice}} + \frac{1}{\tau_{lum}}$$

PRELIMINARY

Beam lifetime: 1174 sec → Total loss power: **15 kW**

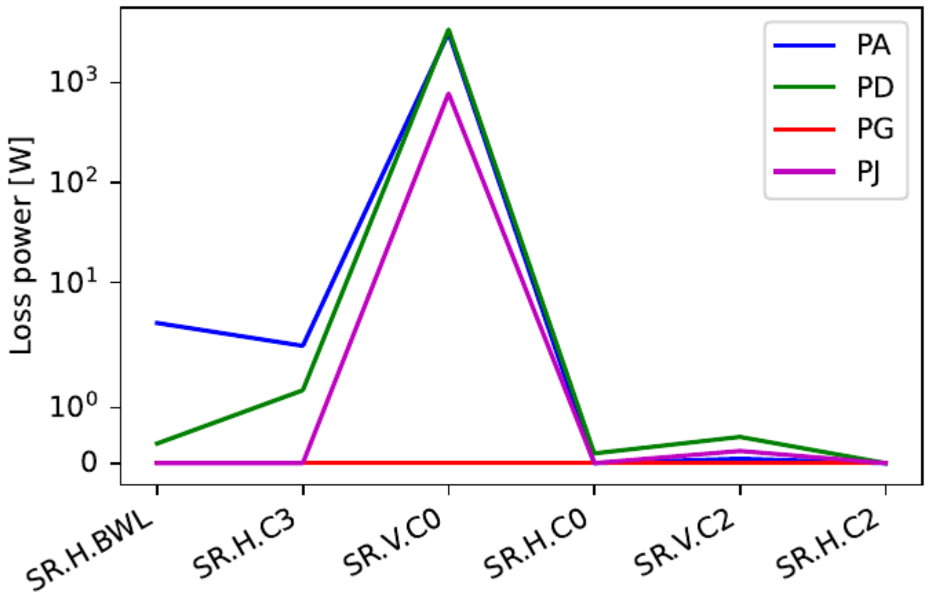


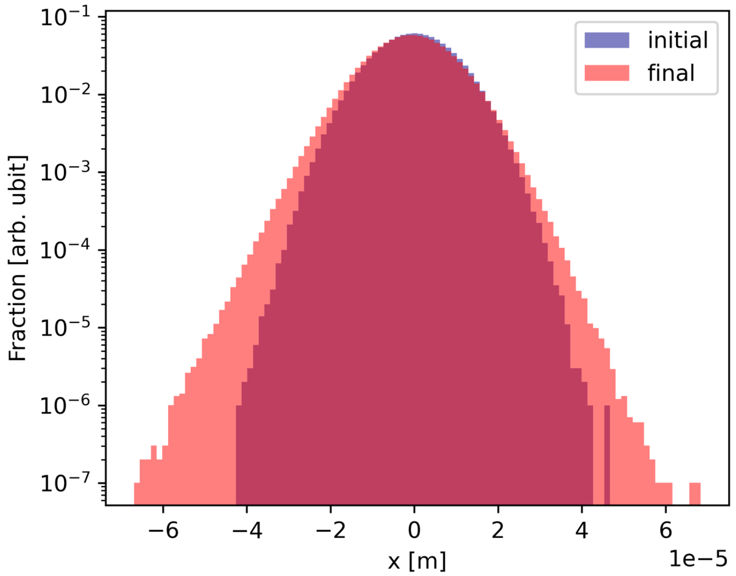


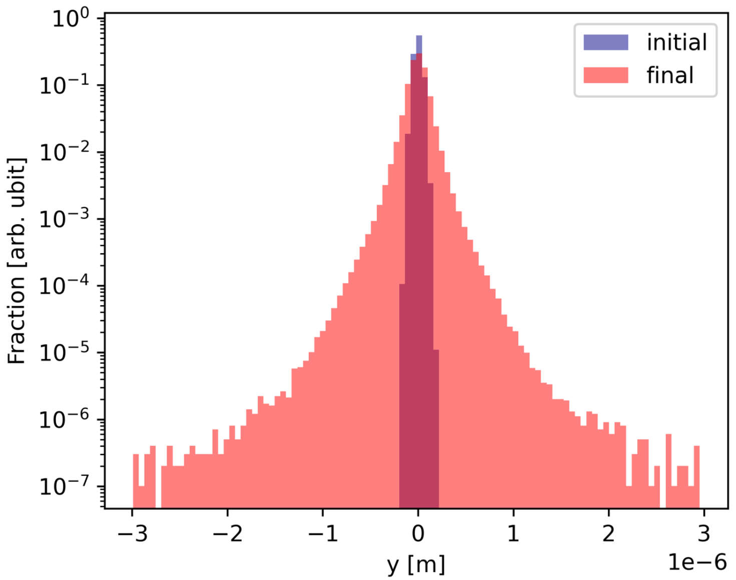


Z-mode spent beam losses

- **The high losses on SR collimators are in the vertical plane**
- **The losses are driven by a strong blow-up in the vertical**
  - This blow-up is not expected
  - Check in detail settings for the beam-beam elements and the crab sextupoles
- **While preliminary, the first results demonstrate the feasibility of combining collimation and beam-beam studies in the same model**





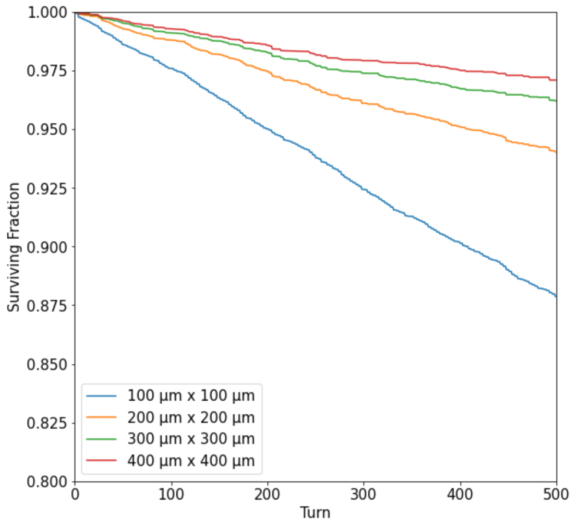


Transverse distribution after 500 turns

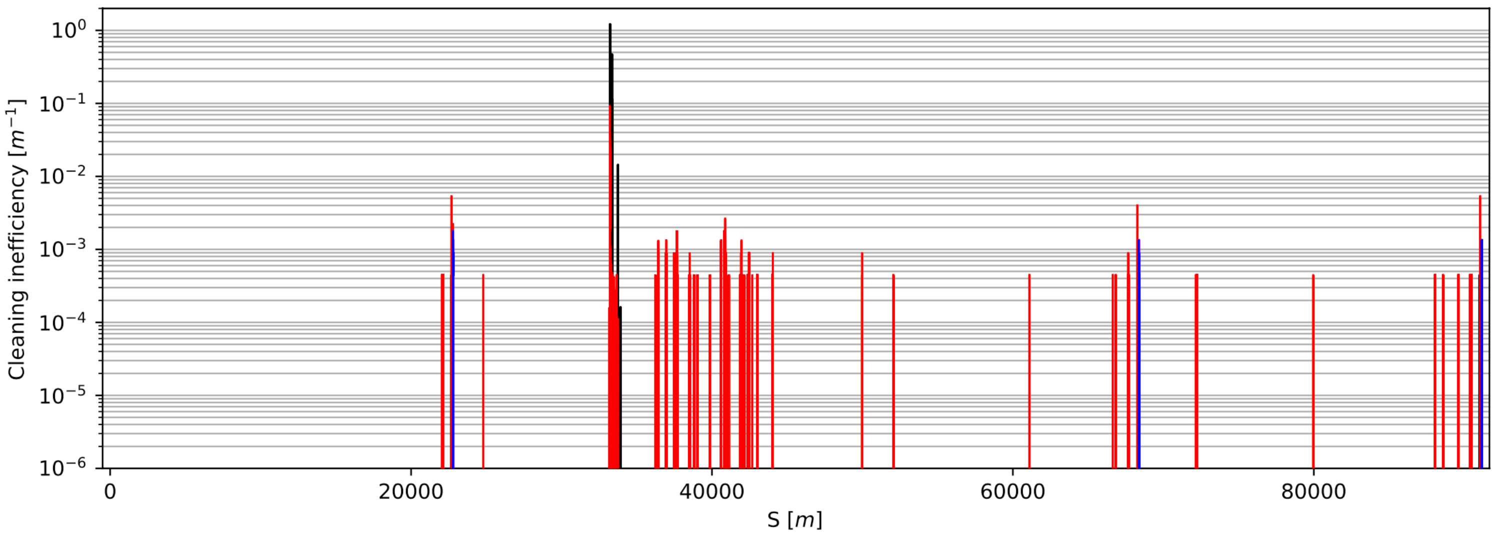
An aside: Z-mode laser intensity control losses

- **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 to follow

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

Open questions

- **Single-beam backgrounds**
  - Efforts to model tail formation due to beam-gas, Touschek, and thermal photon
  - Only long-range effects considered, local losses studied by the MDI and FLUKA teams
- **Injection and extraction protection**
  - Local protection devices will be challenging for the FCC-ee – no ramp, tight margins, high power density
  - Need to study how these devices fit in the collimation hierarchy
  - In contact with ABT and FLUKA experts about this
- **Additional protection**
  - Tertiary collimators in the IRs or additional local protection collimators may be required
  - Need to systematically study failure modes and loss sources
- **Alternative collimation system design**
  - Adaptation of the system to the new LCCO optics by P. Raimondi
  - Non-linear collimation a-la SuperKEKB, spoiler-absorber configuration, halo depletion mechanisms
  - Explore different options as the design and specification advances

FCC-ee collimation summary

- **Studies of IR beam losses and collimation for the FCC-ee**
  - The collimation system design is available, including beam halo and SR collimators
    - Adapted to the latest layout and lattice baseline, new collimation optics implemented
  - Crucial beam loss scenarios identified, with studies ongoing:
    - Beam halo losses studied for the most critical *Z* mode, no show-stoppers identified
      - Improved collimation performance with respect to the previous baseline
      - Ongoing collaboration with the MDI, impedance, injection/extraction, engineering, FLUKA studies teams
    - First integrated beam-beam and collimation studies
      - Preliminary results available, but further studies are required

- **Next steps**
  - Study other beam loss scenarios – top-up injection, beam-gas, failure scenarios
  - Obtain input for the equipment loss tolerances – superconducting magnets, collimators, other
    - Energy deposition studies required for magnets, collimators, and masks
    - Tolerance of the detectors to backgrounds required
  - Study all beam modes
  - Explore synergies with other machines – SuperKEKB, EIC, DAΦNE, Light sources

Thank you!