FCC-ee collimation status

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Outline

- **Introduction**
  - Collimation for the FCC-ee
  - FCC-ee collimation system
  - FCC-ee aperture
- **New collimation insertion optics**
  - Updated beam halo collimator settings
- **FCC-ee beam losses and collimation simulations**
- **Updates on current studies**
  - Beam halo losses
  - Collimation studies including beam-beam effects: preliminary considerations
- **FCC-ee collimation summary**

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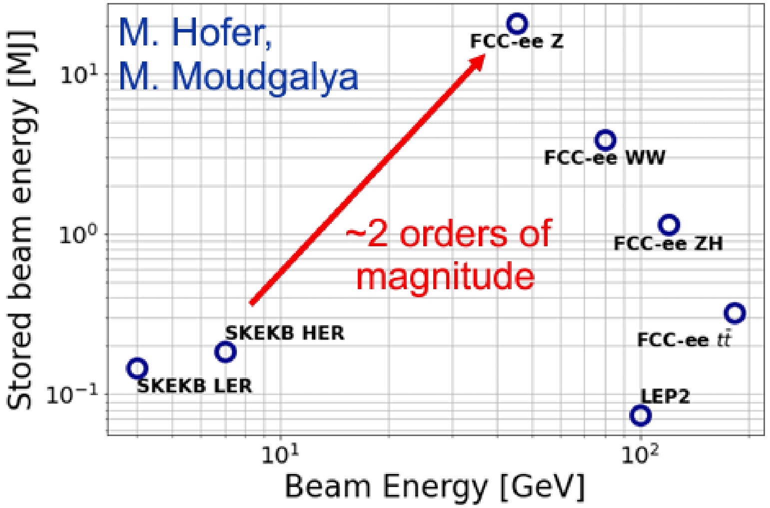
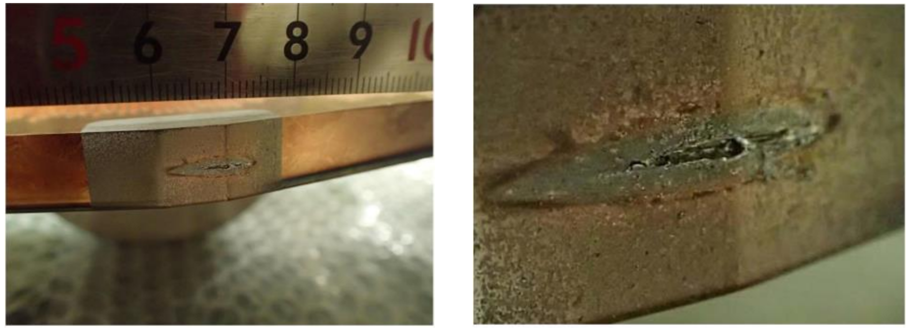
Collimation for the FCC-ee

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

- **FCC-ee presents unique challenges**
  - Unprecedented stored beam energy for a lepton collider: up to **17.5 MJ** in the ***Z*** operation mode (45.6 GeV)
  - Highly destructive beams: **collimation system indispensable**
  - The main roles of the collimation system are:
    - Reduce background in the experiments
    - Protect the machine from unavoidable losses
  - Two types of collimation foreseen for the FCC-ee:
    - Beam halo (global) collimation
    - Synchrotron Radiation (SR) collimation – around the IPs

Comparison of lepton colliders

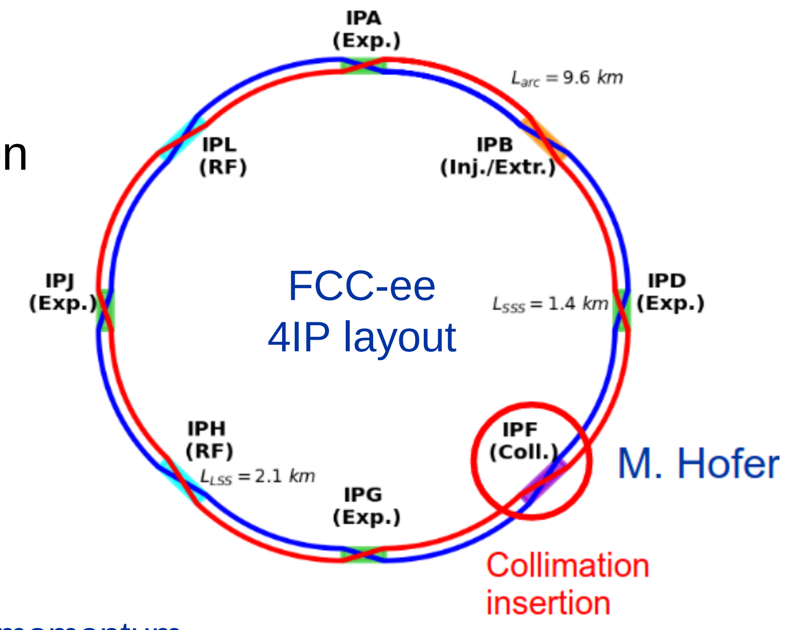


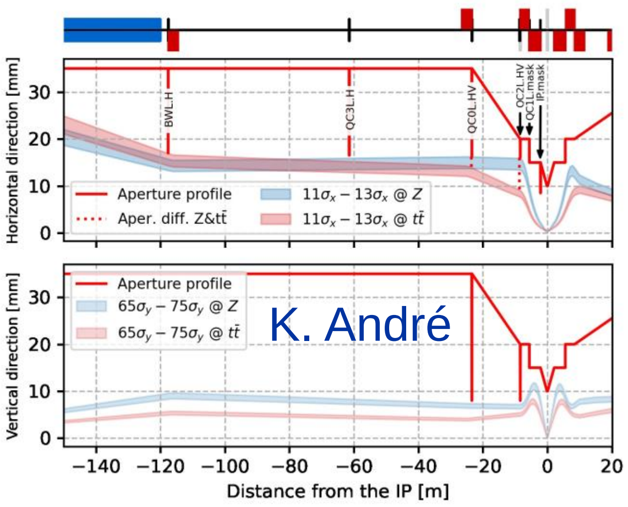


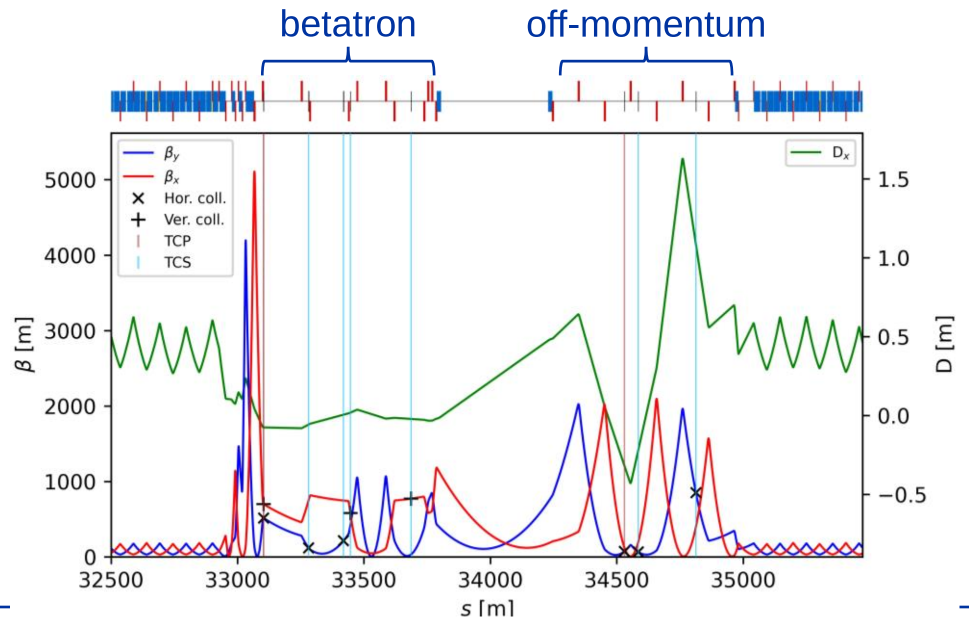
Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

FCC-ee collimation system

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



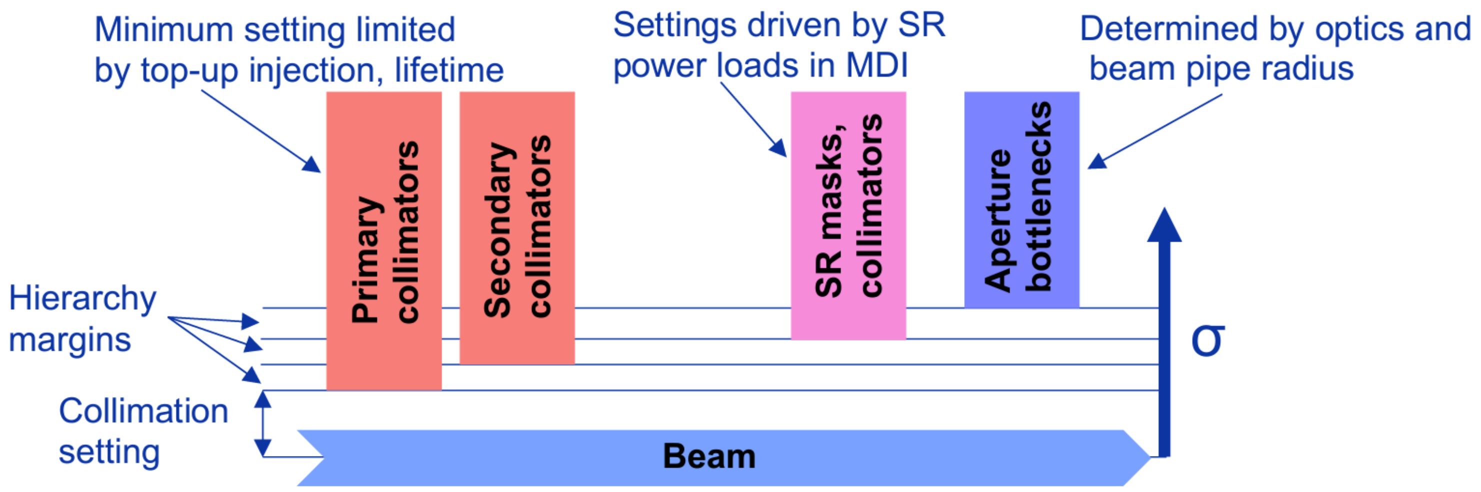




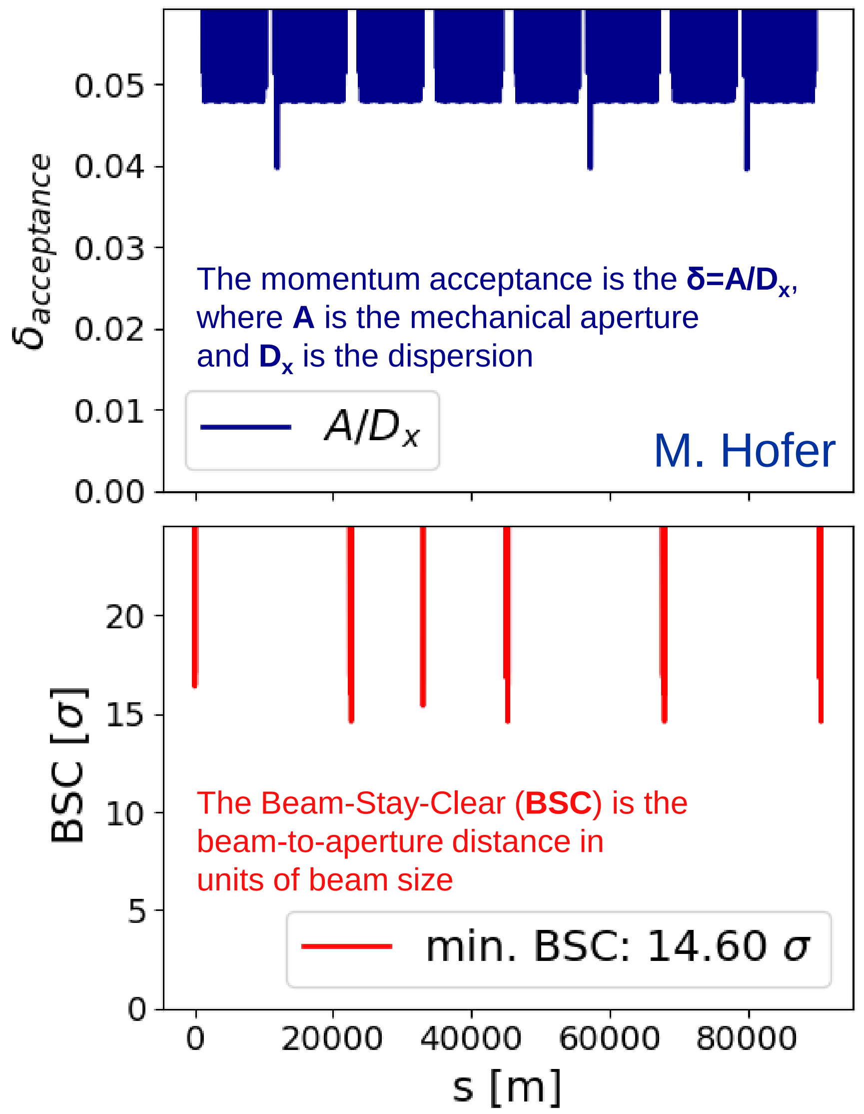
FCC-ee aperture

- The **aperture bottlenecks** are in the **experimental interaction regions (IRs)**

- The **bottlenecks must be protected**
  - ➢ The **final focusing quadrupoles** are **superconducting** → **risk of quenches**
  - ➢ The detectors are sensitive to backgrounds from beam losses
  - ➢ The SR collimators and masks are not robust to large direct beam impacts and they can also produce backgrounds



Aperture bottleneck for Z operation mode



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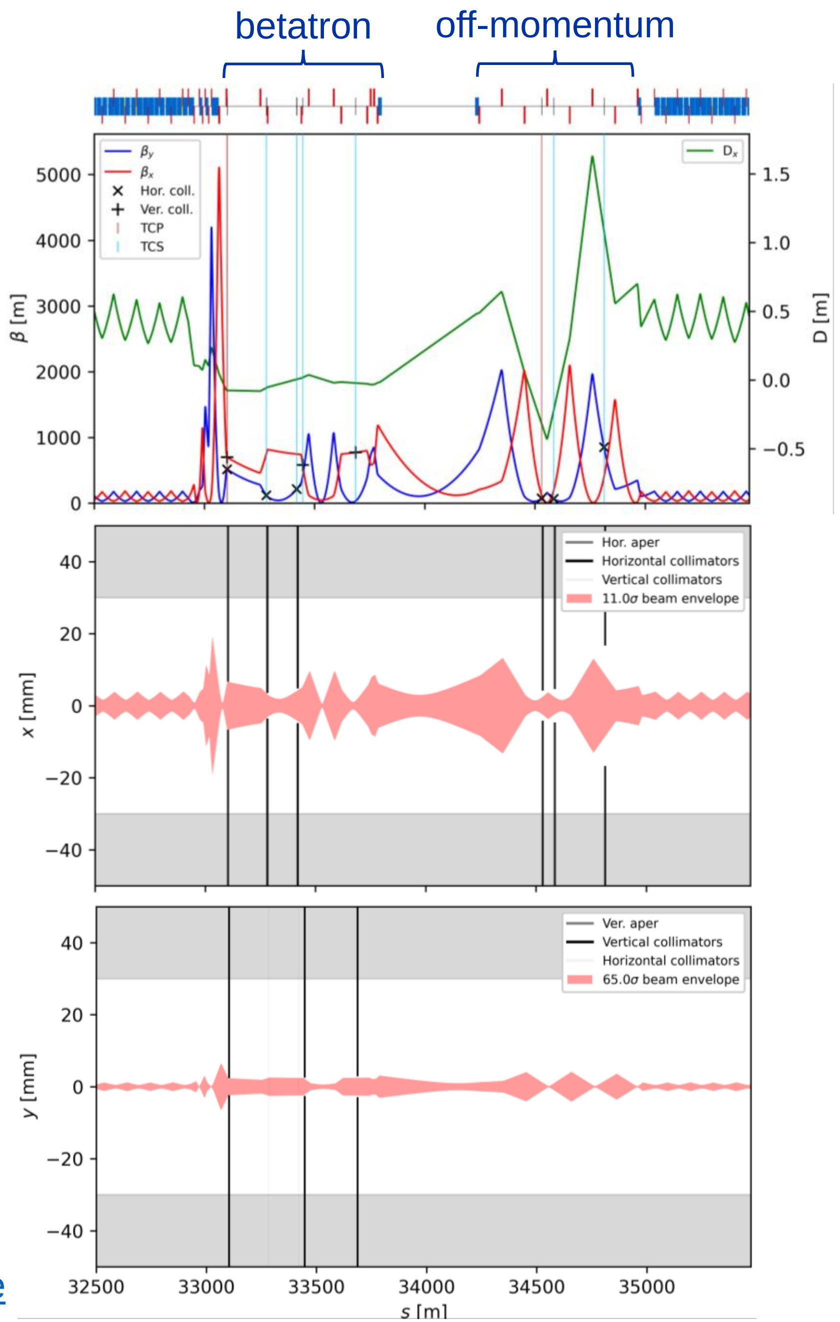
New collimation insertion optics

- **New collimation optics for the new baseline**
  - Developed by M. Hofer
  - Based on a triple double doublet (tridodo) scheme
  - Split-function betatron and off-momentum collimation
  - Designed to maintain optimal collimator phase advances at acceptable mechanical gaps and flat β-functions at primary collimators

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

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

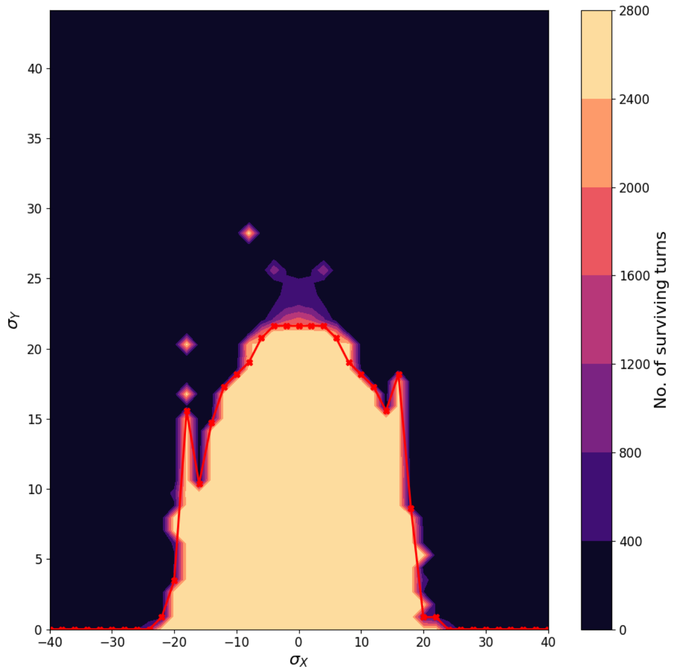


V23, tridodo_572 collimation optics, https://gitlab.cern.ch/mihofer/fcc-ee-collimation-lattice

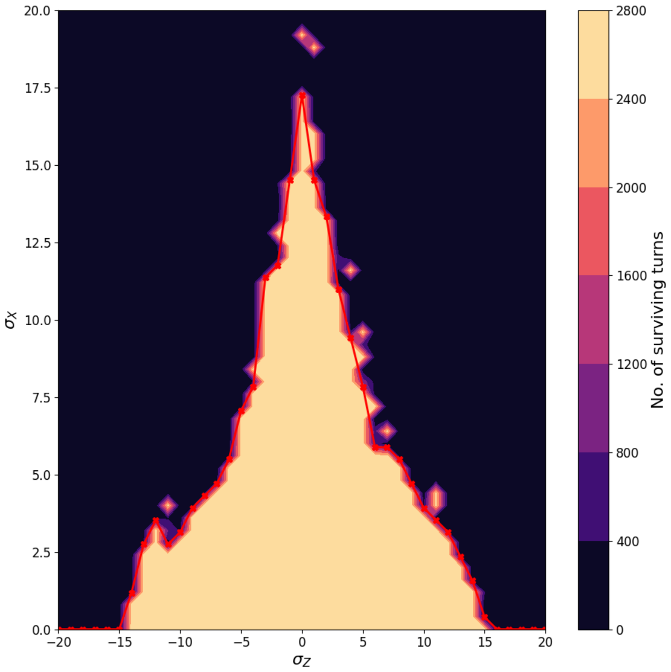
New collimation insertion optics

- **New collimation optics is integrated with the ring optics**
- **The DA and momentum acceptance are satisfactory**
  - ➢ Improved compared to previous optics
  - ➢ Further tuning and optimization are possible
  - ➢ This will help in performing collimation studies with effects like beam-beam, where beam tails need to be tracked long-term
  - ➢ **First collimation studies including beam-beam effects have started** (A. Abramov)

Dynamic Aperture (DA)



Momentum Acceptance (MA)



DA and MA with radiation and tapering (M. Hofer)

https://gitlab.cern.ch/mihofer/fcc-ee-collimation-lattice

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FCC-ee beam losses

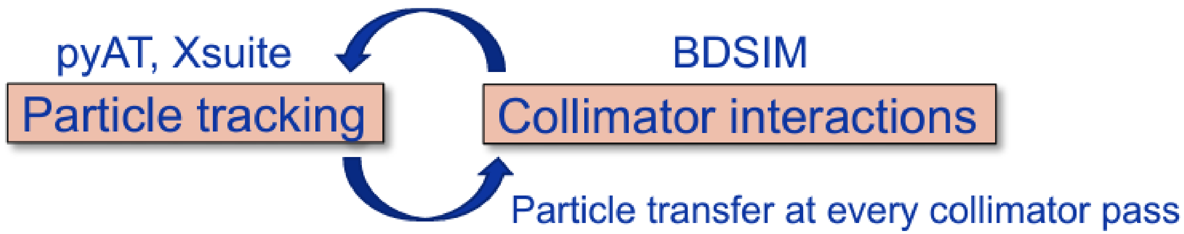
- **FCC-ee will operate in a unique regime → collimation not only to reduce background in experiments but also to protect the machine from unavoidable beam losses**
  - Electron/positron beam dynamics and beam matter interactions
  - Stored beam energy exceeding material damage limits
  - Superconducting final focus quadrupoles, crab sextupoles, and RF cavities
  - Must study beam loss processes and define the ones to protect against (H. Burkhardt, talk)
  - Must study equipment loss tolerances, for both regular and accidental losses

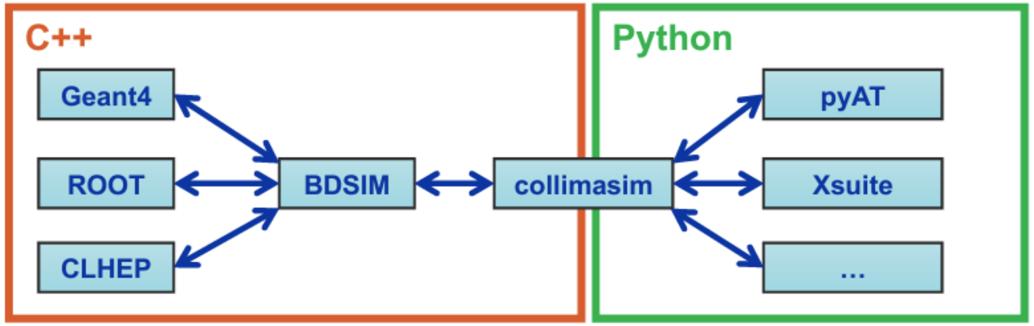
- **Important loss scenarios for particle tracking studies**:
  - **Beam halo** ← current studies
  - **Spent beam due to collision processes** (Beamstrahlung, Bhabha scattering) ← preliminary considerations
  - Top-up injection
  - Beam tails from Touschek scattering and beam-gas interactions
  - Failure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

} Inputs required to set up models

FCC-ee collimation simulations

- **FCC-ee presents unique challenges for collimation simulations**
  - Synchrotron radiation and magnet strength adjustment (tapering) to compensate it
  - Complex beam dynamics – strong sextupoles in the lattice, strong beam-beam effects (beamstrahlung)
  - Detailed aperture and collimator geometry modelling
  - Electron/positron beam particle-matter interactions
  - Large accelerator system – 90+ km beamline
- **Xsuite + BDSIM (Geant4) coupling**
  - Developed for FCC collimation simulations (A. Abramov, IPAC'22 paper)
  - Benchmarked against
    - other simulation codes: MAD-X, pyAT, Sixtrack-FLUKA (A. Abramov)
    - measured data from proton machines: SPS (T. Pugnat), LHC (G. Broggi)
  - Xsuite-FLUKA coupling recently implemented (F. Van der Veken, HB'23 paper)
  - New features continuosly added





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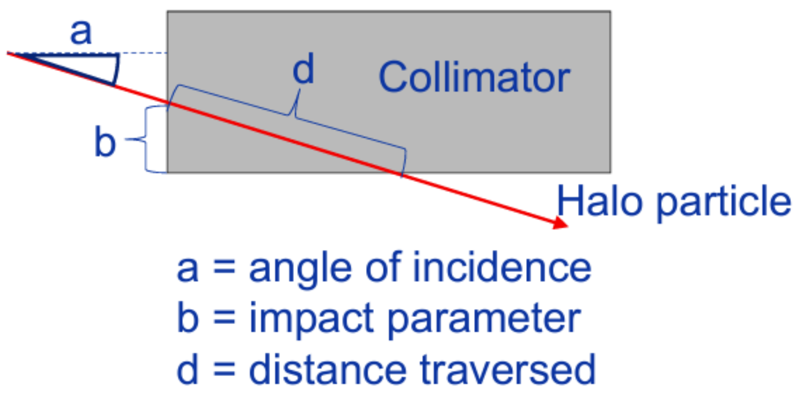
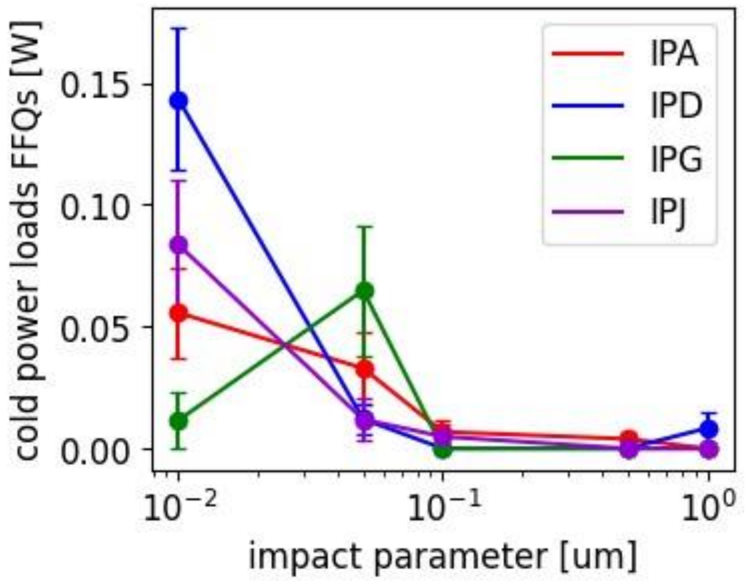
Current study: beam halo losses

- «Generic beam halo» beam loss scenario
  - Specify a minimum beam lifetime that must be sustained during normal operation - preliminary specification of a **5 min** lifetime
  - Assume a slow loss process – halo particles always intercepted by the primary collimators
  - **Loss process not simulated**: all particles start impacting a collimator
  - To get a **conservative performance estimate**, particles impact the collimator at the **critical impact parameter**
    - Currently using 1 μm impact parameter as standard
    - Previous studies were suggesting smaller critical impact parameters (FCC week 23 talk)
    - **Latest study**: no evidence of a critical impact parameter (G. Broggi, MDI workshop talk on Friday)
  - Particles scattered out from the collimator tracked for a given number of turns, and losses on the aperture are recorded (**loss maps**)

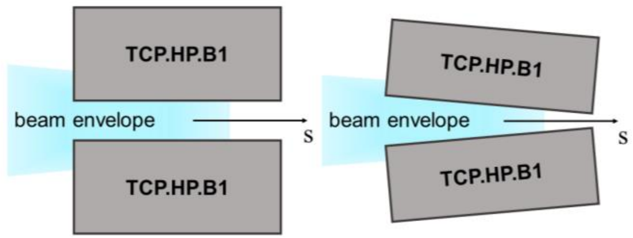


Impact parameter scan (Z mode) tridodo_572 optics



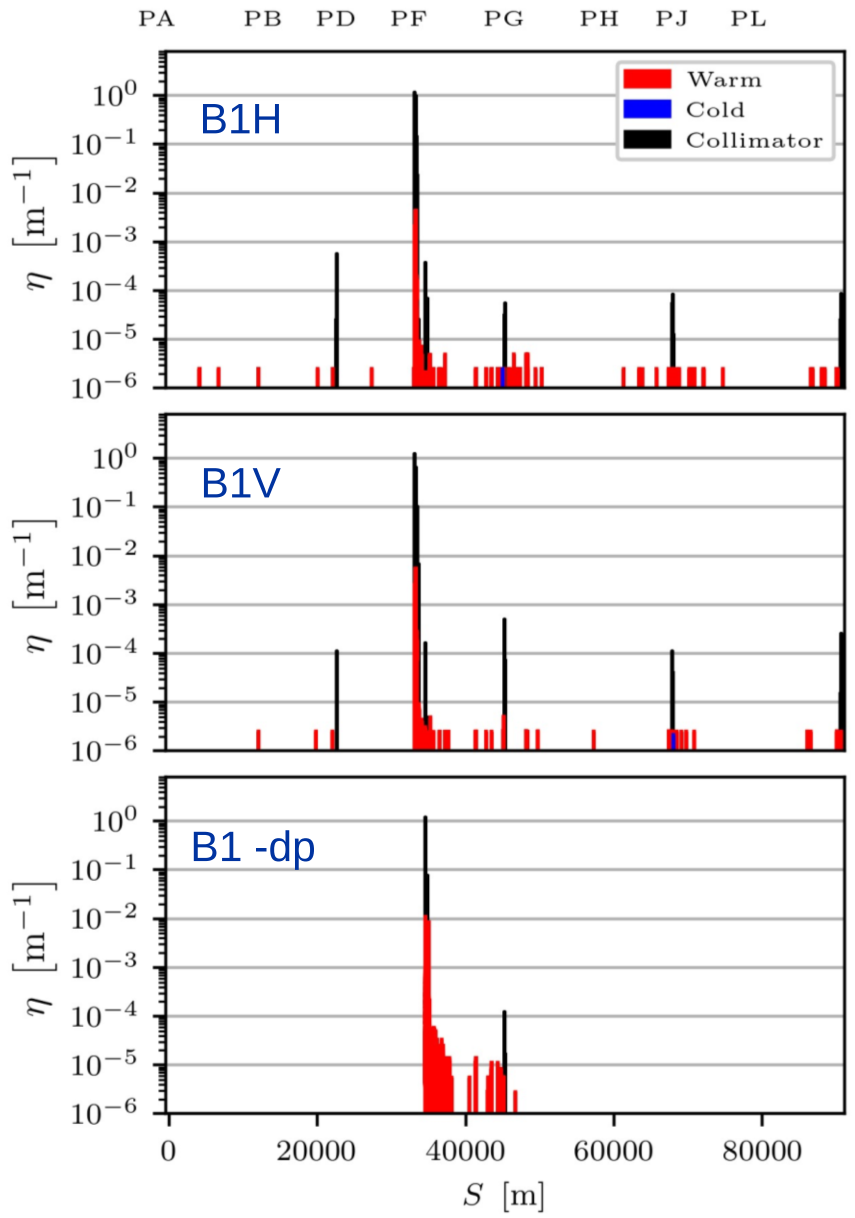
Beam halo losses for the Z mode

- The ***Z* mode** is the **current focus** (Beam 1, 45.6 GeV e+)
  - ➢ **17.5 MJ** stored beam energy
- **5 min** beam lifetime assumed → **58.3 kW** total loss power
- Radiation and tapering included
- 3 cases considered:
  - **Horizontal betatron losses (B1H)**
  - **Vertical betatron losses (B1V)**
  - **Off-momentum losses (B1 -dp)**
- For the off-momentum case only, the primary collimator TCP.HP.B1 is aligned to the beam envelope



TCP.HP.B1 parallel to the closed orbit and aligned to the beam envelope

- **Good halo cleaning performance overall**
  - ➢ Minimal cold losses on final focusing quadrupoles in all scenarios
  - ➢ Residual cold losses on crab sextupoles

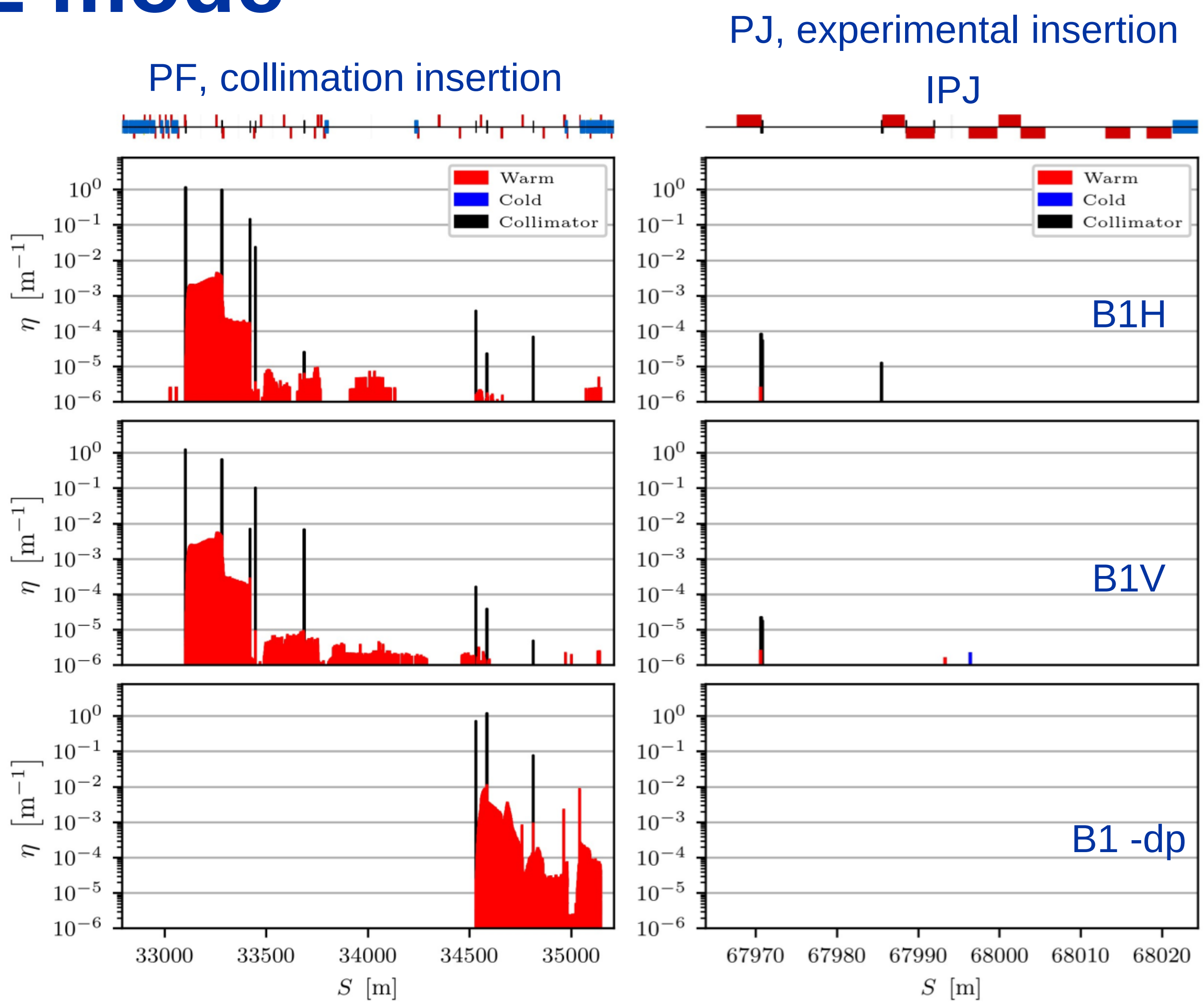


Z mode betatron and off-momentum halo loss maps

Beam halo losses for the Z mode

- **The beam collimation system shows significant loss suppression**
  - ➢ More than 99.98% of losses contained within the collimation insertion PF
  - ➢ Almost no losses reaching any of the IRs
  - ➢ Energy deposition and thermo-mechanical studies required for collimators and most exposed magnets

- **Collaborative studies ongoing**
  - Impedance and collective effects (M. Migliorati, FCCIS 23 talk)
  - Tracking of collimation losses in the detector (A. Ciarma, FCC week 23 talk)
  - Energy deposition (G.Lerner - talk, A. Frasca) and thermo-mechanical studies (R. Andrade, talk)

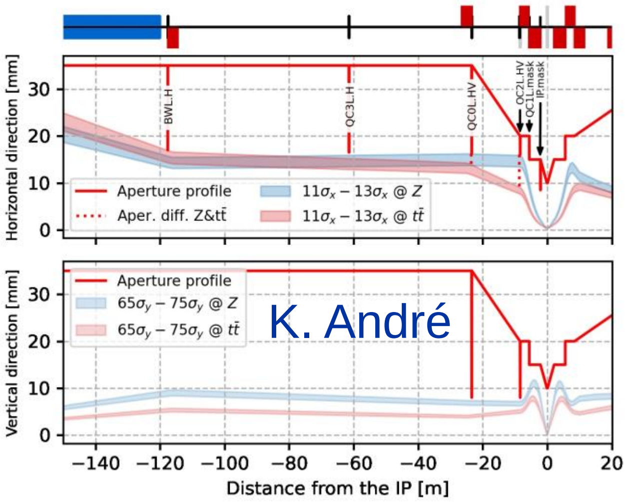


Z mode betatron and off-momentum halo loss maps for selected regions

Z mode beam losses on SR collimators

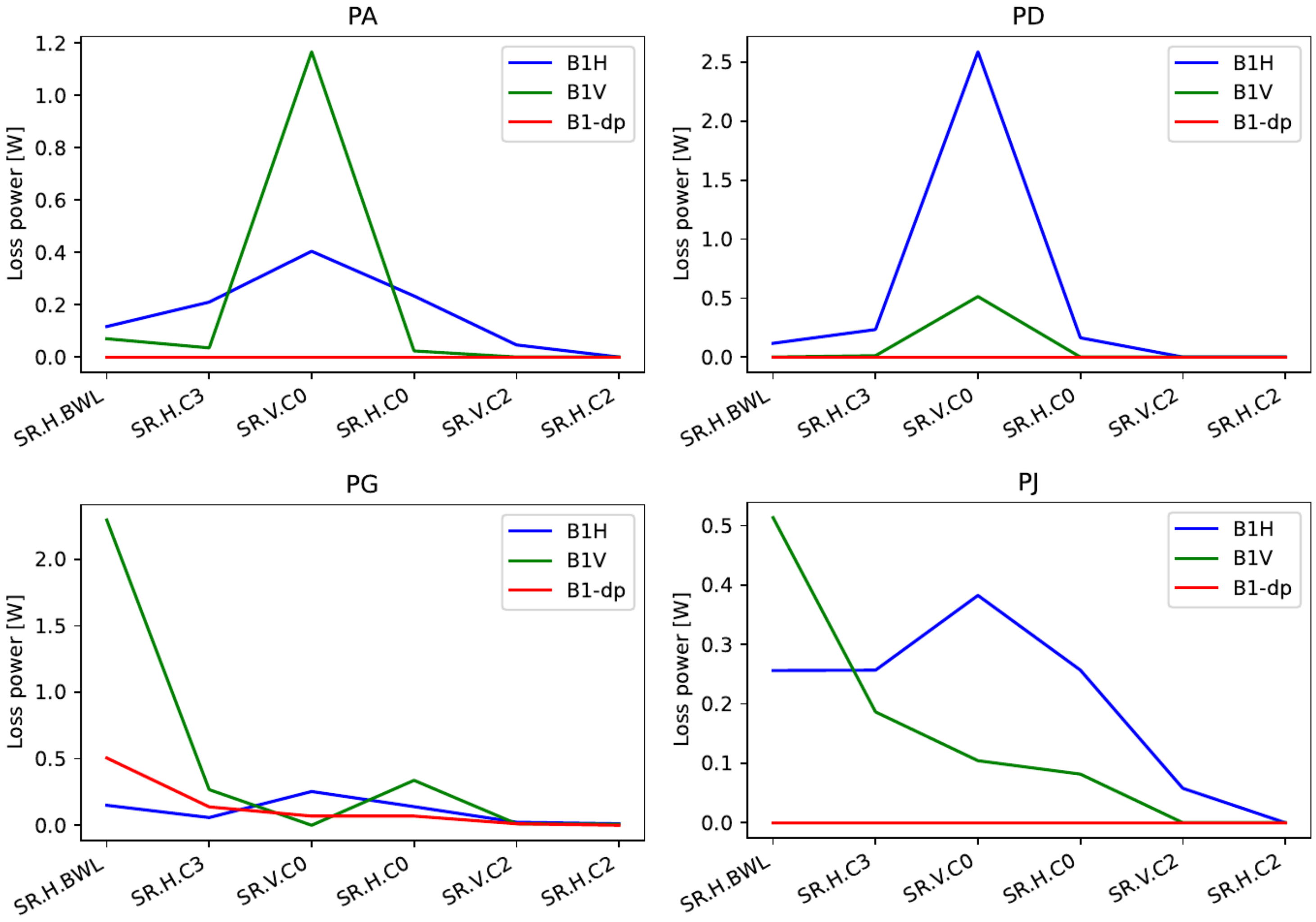
- **The SR collimators intercept losses for all cases**
  - ➢ Highest load on C0 vertical and BWL horizontal SR collimators, up to 2.6 W
  - ➢ Lowest load on C2 horizontal and vertical SR collimators

- At lower impact parameters on halo collimators power loads increase (G. Broggi, [MDI workshop talk](#) on Friday)



beam →

Total loss power: **58.3 kW**



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 talk by P. Kicsiny (FCCIS 23 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

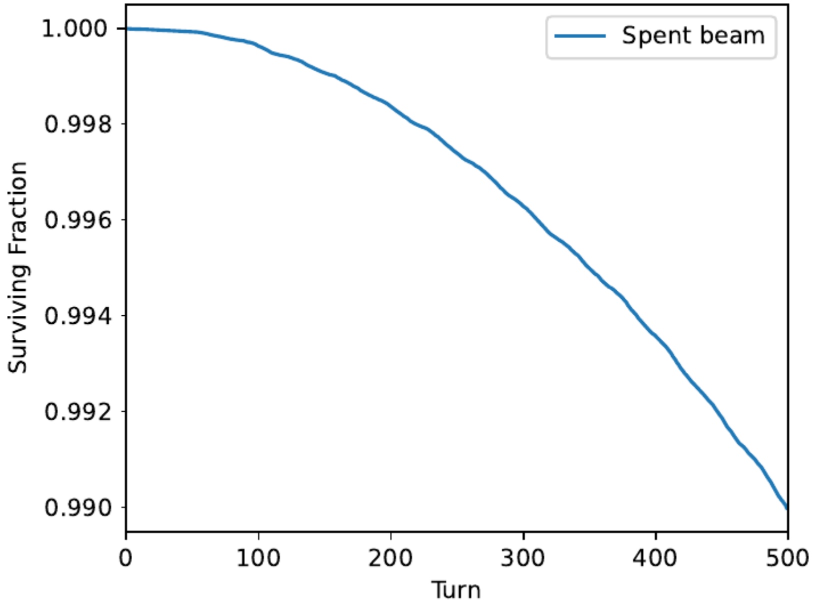
CHART
Swiss Accelerator Research and Technology

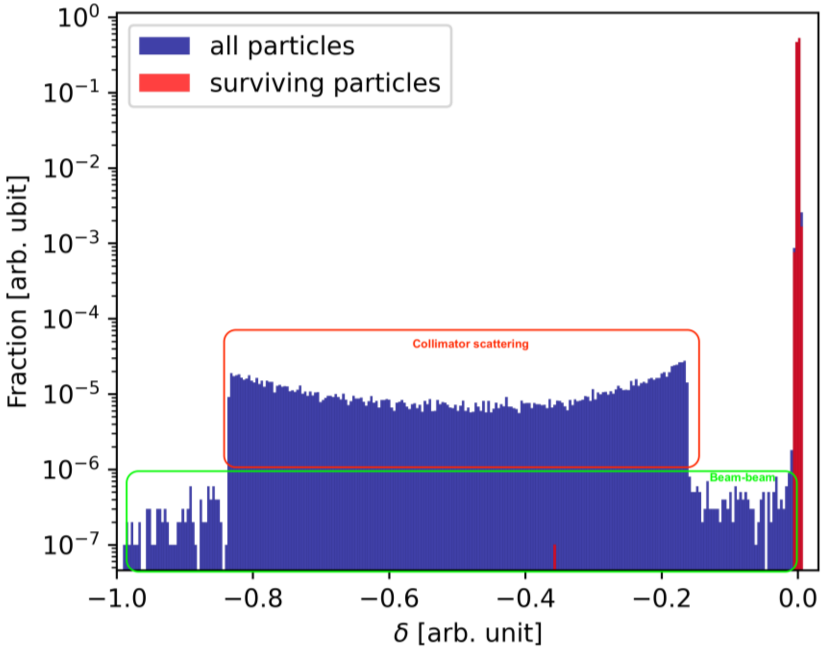
FCC-ee *Z*-mode spent beam losses

- **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 (A. Abramov):
  - 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: **we cannot estimate the lifetime from this simulation**

PRELIMINARY





FCC-ee *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
- Large losses on the vertical SR.C0 collimators in PD, PA and PJ with no losses in PG. Losses also in the collimation insertion PF.
- Up to 3.4 kW on a SR collimator, investigate the source
- These are first preliminary results, detailed analysis will be carried out

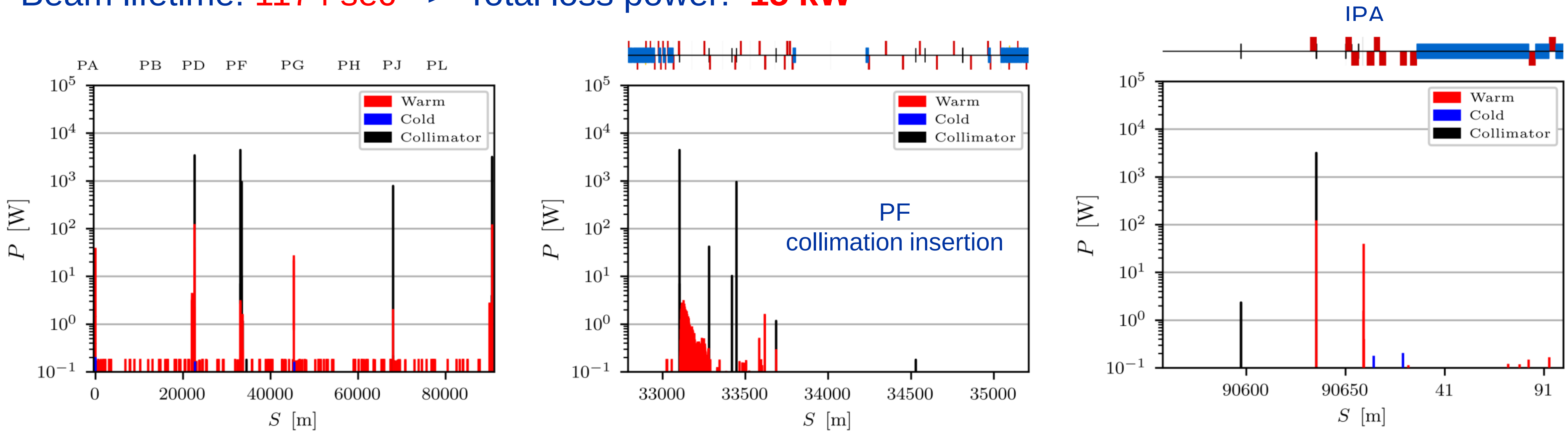
Lifetime for the *Z* mode, K. Oide talk

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

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

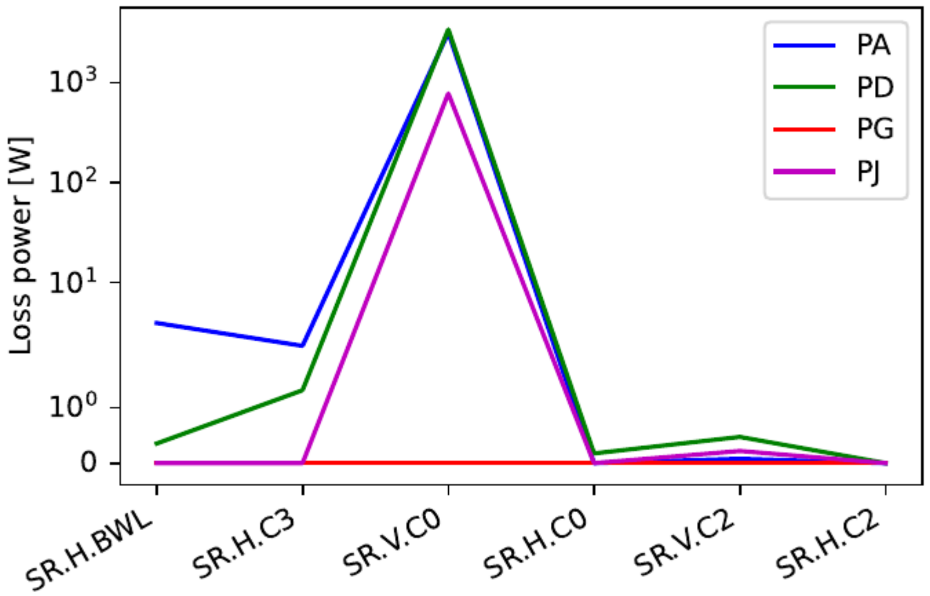
PRELIMINARY

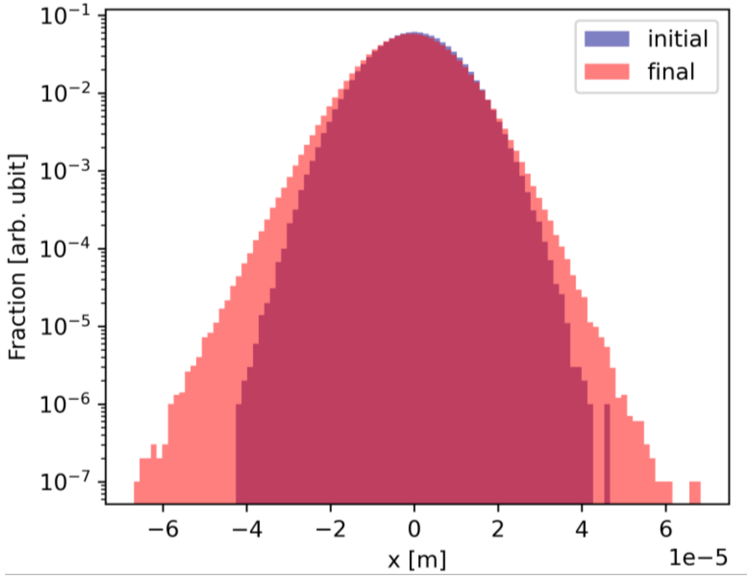
Beam lifetime: 1174 sec -> Total loss power: **15 kW**

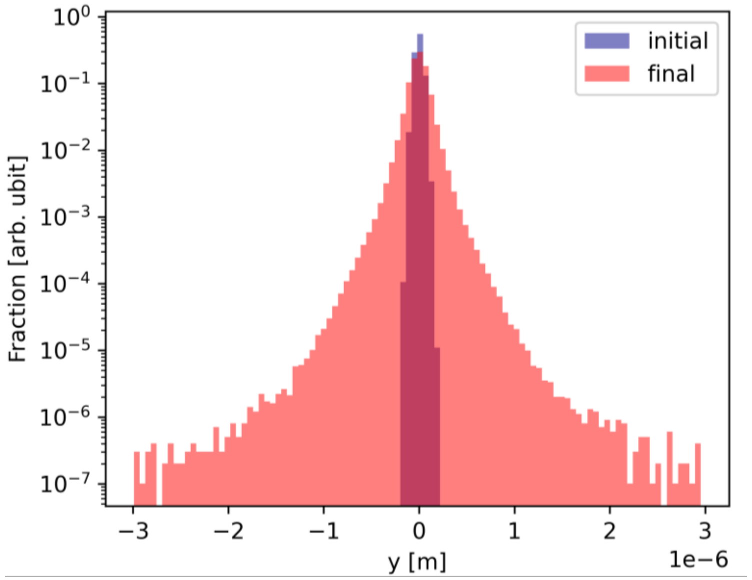


FCC-ee *Z*-mode spent beam losses

- The high losses on SR collimators are in the vertical plane
- The losses are driven by a strong blow-up in the vertical
- 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

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- **Studies of beam losses and collimation for the FCC-ee**
  - First collimation system design available, including beam halo and SR collimators
    - ➢ Newly developed collimation optics enhance betatron halo cleaning performance
  - Simulations of beam loss scenarios ongoing
    - ➢ Beam halo losses studied for the most critical Z mode, no show-stoppers identified
    - ➢ First integrated beam-beam and collimation studies
    - ➢ Collaboration with the MDI, impedance, engineering, FLUKA studies team
    - ➢ Input on equipment tolerances needed to optimize design and performance

- **Next steps**
  - Study other beam loss scenarios – failure scenarios, top-up injection, …
  - Obtain input for the **equipment tolerances** – supercondcting magnets, collimators, others…
    - ➢ Energy deposition studies required for magnets, collimators, and masks
    - ➢ Tolerance of the detectors to background required
  - Study all beam modes
  - Would be beneficial to benchmark simulation tools with operating lepton colliders

Thank you!

FCC-ee aperture

- Closed orbit tolerance: 250 µm
- Maximum beta-beating: 20%

Aperture bottleneck for Z operation mode