Collimation studies for the FCC-ee

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Outline

- **Introduction**
  - Collimation for the FCC-ee
  - FCC-ee collimation system
- **FCC-ee beam losses and collimation simulations**
  - Simulation benchmark with SuperKEKB data
- **Updates on FCC-ee beam loss simulations**
  - Beam halo losses
  - Beam-gas losses
  - Beam-beam losses
  - Top-up injection losses
  - Losses from fast instabilities
- **FCC-ee collimation summary**

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  - Touschek scattering losses (tbd)
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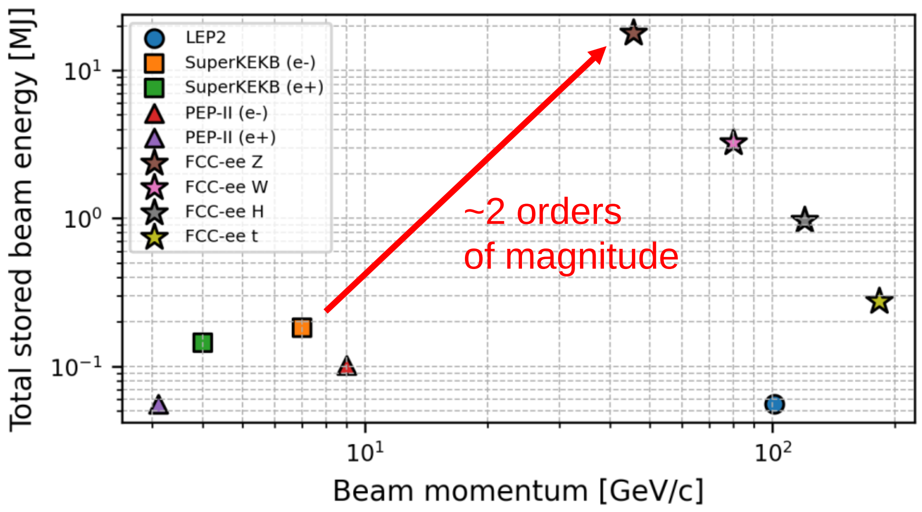
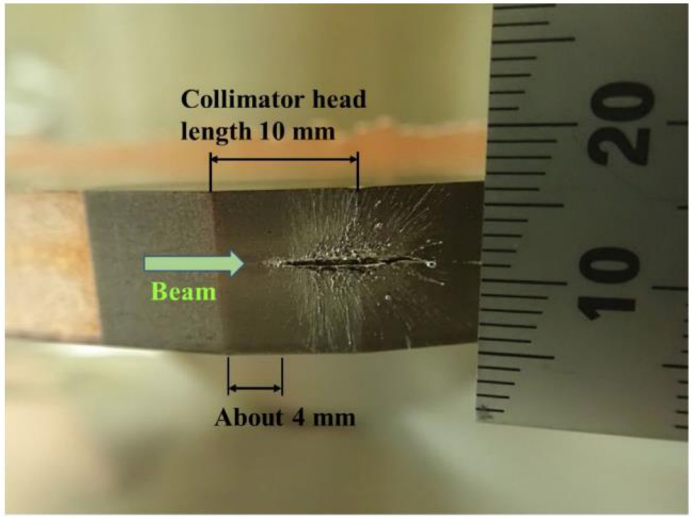
Collimation for the FCC-ee

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

- FCC-ee presents unique collimation challenges
  - Unprecedented stored beam energy for a lepton collider
    - **17.5 MJ** in the Z operation mode
  - Highly destructive beams: **collimation system indispensable**
    - Reduce background in the experiments
    - Protect the machine from unavoidable beam losses

- **Collimation strategy for the FCC-ee**
  - Beam-halo (global) collimation
    - + local protection collimation
  - Secondary particle shower absorbers
  - Synchrotron radiation (SR) collimation – upstream of the IPs

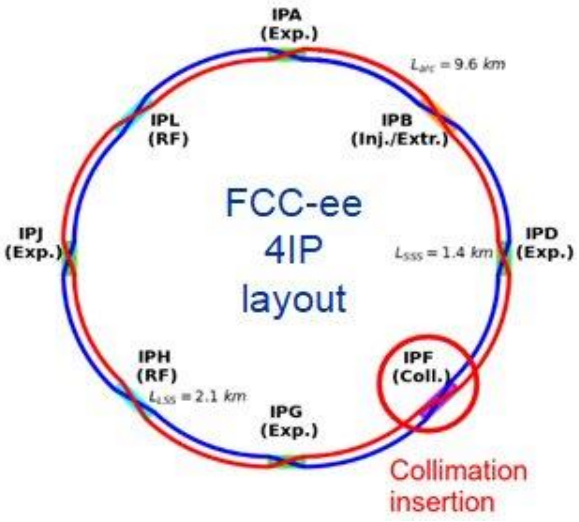


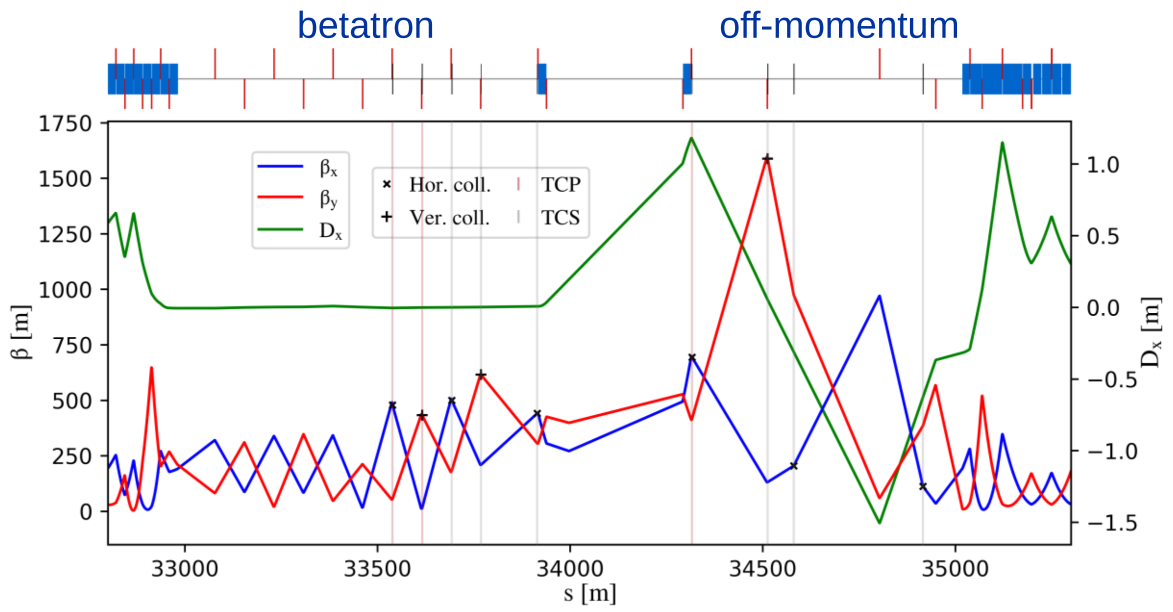


Damage to coated collimator jaw due to accidental beam loss in SuperKEKB – T. Ishibashi (talk)

FCC-ee halo collimation system

- **Dedicated long straight section in PF**
  - Common technical insertion optics by K. Oide (V25.2 GHC - talk)
  - Two-stage betatron and off-momentum collimation
  - Ensure protection of the aperture bottlenecks in different conditions
    - **Aperture bottleneck at Z:** 11.5σ (H plane), 81.5σ (V plane)
  - **First collimator design for cleaning performance**
    - Sizeable impedance increase driven by TCP.V collimator (D. Gibellieri, FCC week 2025 talk)
    - Collaboration with optics, impedance, FLUKA, and engineering team to optimize the design
    - First exploratory study on crystal collimation for FCC-ee (NIMA paper)





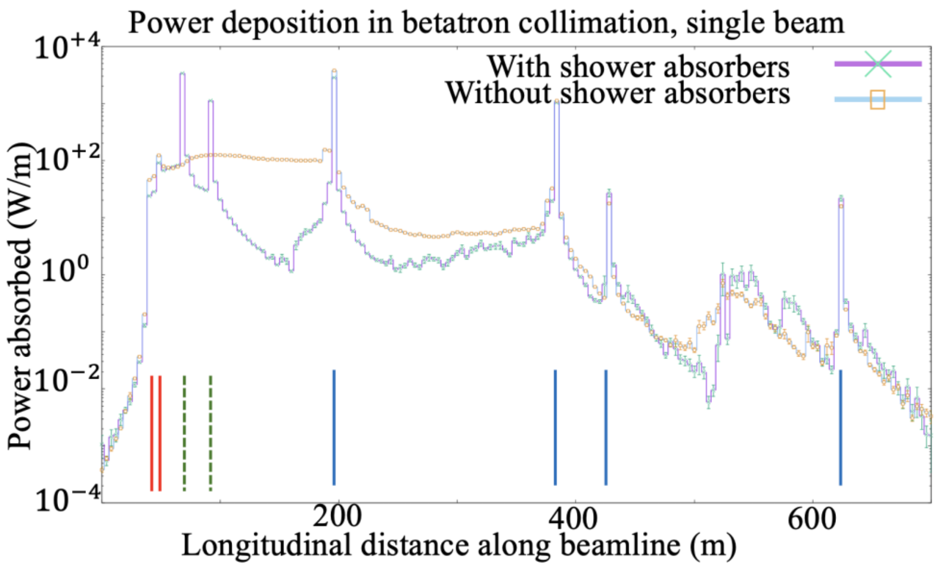
FCC-ee (*Z*) beam halo collimator parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	C-based	25	9.5	5.6	-
TCP.V.B1	V	C-based	25	50	1.4	-
TCS.H1.B1	H	Mo-based	30	10.5	6.2	-
TCS.V1.B1	V	Mo-based	30	65	2.2	-
TCS.H2.B1	H	Mo-based	30	10.5	6.5	-
TCS.V2.B1	V	Mo-based	30	65	3.6	-
TCP.HP.B1	H	C-based	25	18	12.5	1.1
TCS.HP1.B1	H	Mo-based	30	28	11.0	3.5
TCS.HP2.B1	H	Mo-based	30	28	8.3	1.3

Shower absorbers

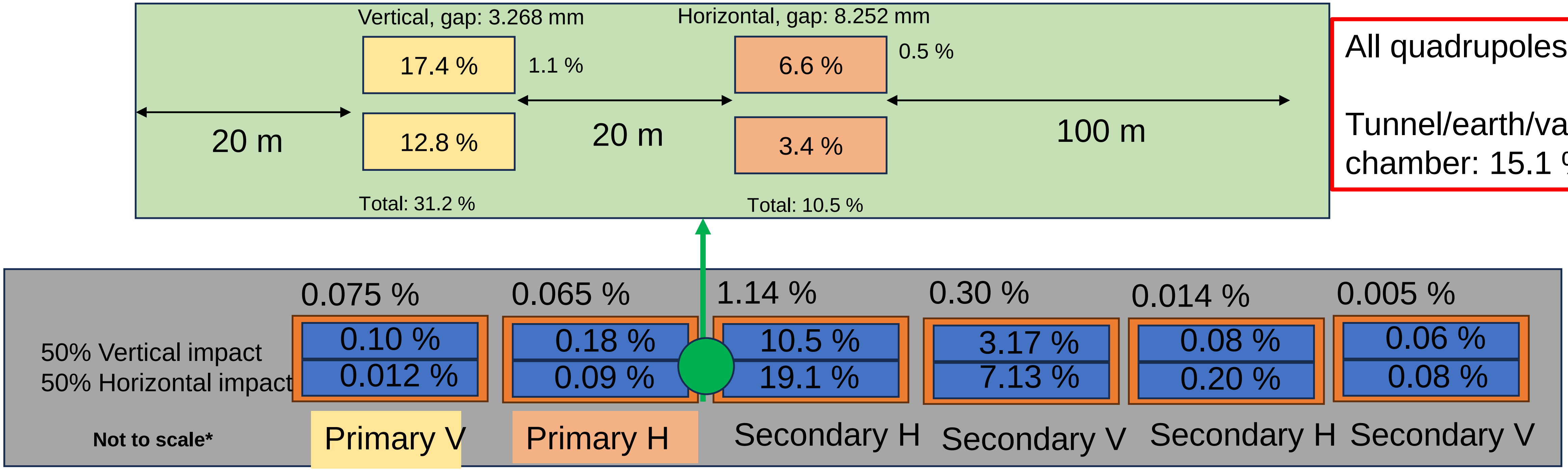
The use of a few (~2 per beam) strategically placed shower absorbers can reduce the fraction of the power absorbed by vacuum chamber, tunnel, and environment:

- From ~50 %, close to the LHC values, to ~15 %
- Quadrupole magnets receive a small fraction of power, even without absorbers.



SHOWER ABSORBERS

Courtesy S. Marin, A. Lechner

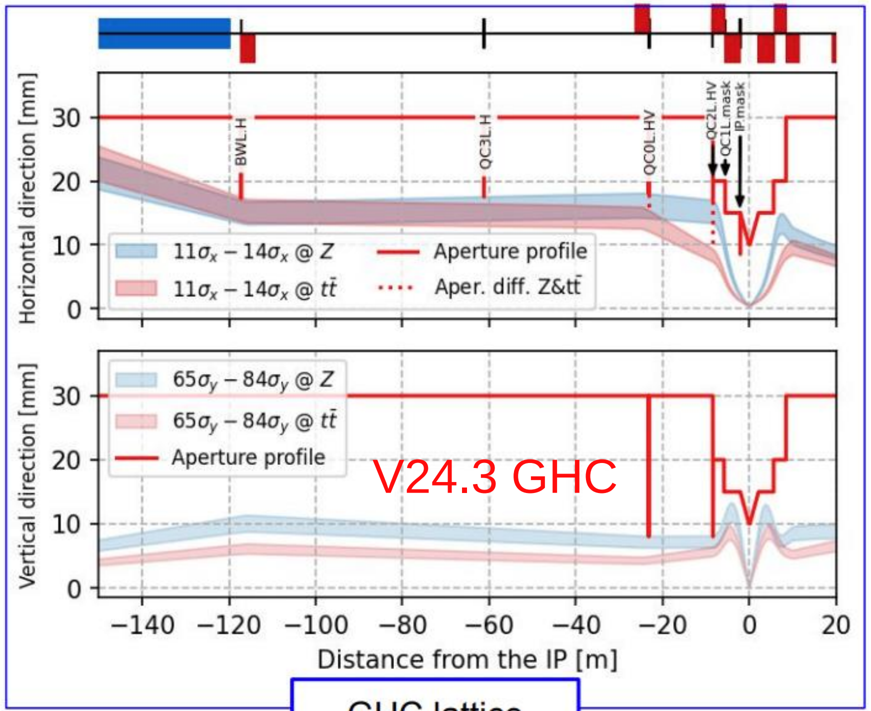


All quadrupoles : 0.78 %

Tunnel/earth/vacuum chamber: 15.1 %

FCC-ee SR collimation system

- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs
  - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses



GHC lattice

FCC-ee (*Z*) SR collimators parameters and settings (V25.2 GHC)

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCR.H.WL.B1	H	W-based	10	11.5	20.4
TCR.V.C0.B1	V	W-based	10	81.5	7.1
TCR.H.C0.B1	H	W-based	10	11.5	25.0
TCR.H2.C0.B1	V	W-based	10	11.5	21.3
TCR.V.C2.B1	V	W-based	10	81.5	8.2
TCR.H.C2.B1	H	W-based	10	11.5	18.0

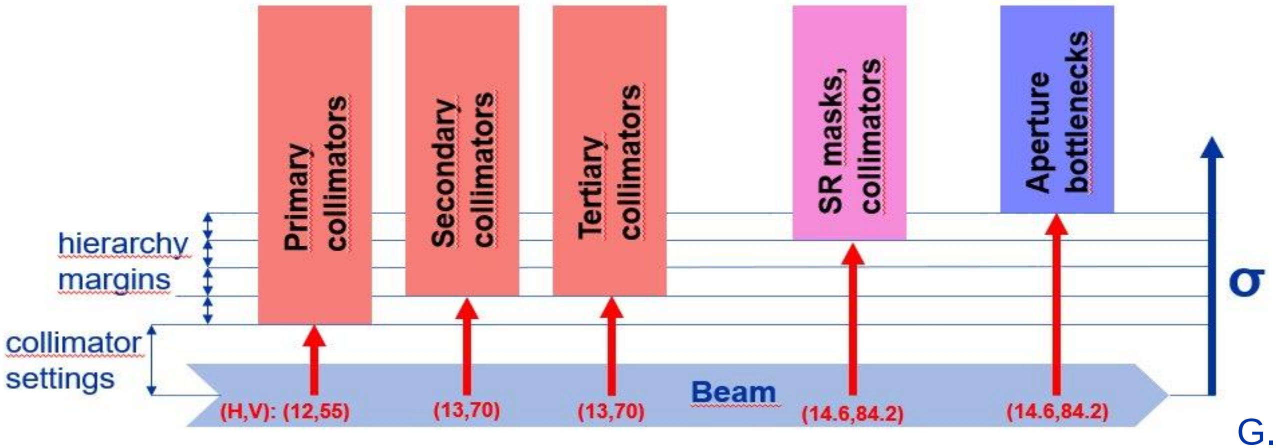
- SR collimator apertures = estimated aperture bottlenecks
- Studies carried out by K. Andre up to V24.3 GHC
  - FCC physics workshop 2025 talk

Tertiary collimators

- **Beam loss simulations have shown that SR collimators or even final focus magnets may be exposed to beam losses**
  - ➢ SR collimators not primarly designed to intercept large beam losses: risk of damages/backgrounds

- **Two** (**H+V**) **tertiary collimators** (**TCTs**) for local protection added
  - ➢ Placed upstream of each IP
  - ➢ s-location optimized for optimal phase-advance (multiple of π) between TCTs and { SR collimators, aperture bottlenecks }
  - ➢ Need for shower absorber downstream of TCTs to be studied

- Further local protection devices (e.g., injection protection) to be studied by energy deposition (FLUKA), beam transfer and engineering team



FCC-ee (Z) collimation hierarchy

- Hierarchy margins set to 100-300um
  - ~1 $\sigma_{\beta x}$, ~15 $\sigma_{\beta y}$

Name	Plane	Material	Length [cm]	Half-gap [σ]	Half-gap [mm]
TCT.H.B1	H	C-based	25	10.5	2.4
TCT.V.B1	V	C-based	25	65	7.3

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FCC-ee beam loss scenarios

- The FCC-ee Z mode is the current focus: has the highest stored beam energy **17.5 MJ**
- **Important to identify different beam loss scenarios and define the ones to protect against**

- Current selection of beam loss scenarios to study and simulate:
  - **Generic beam halo losses**
  - Beam losses from **interactions with residual gas**
  - Beam losses from **beam-beam interactions**
  - Beam losses due to **fast instabilities**
  - Beam losses from **top-up injection**

  } In this talk

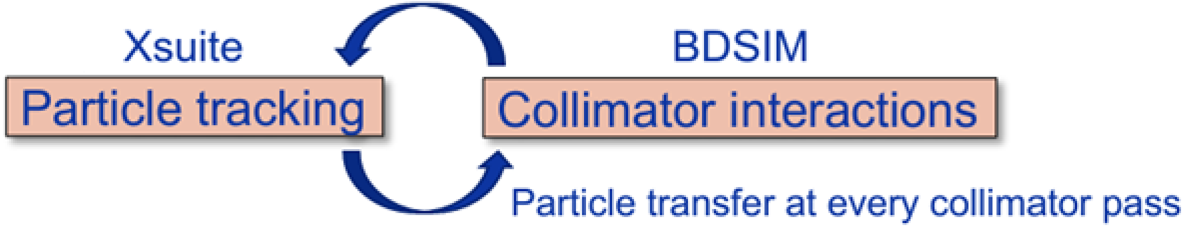
  - Beam losses from **Touschek scattering**: simulation model available – being extended to FCC-ee case

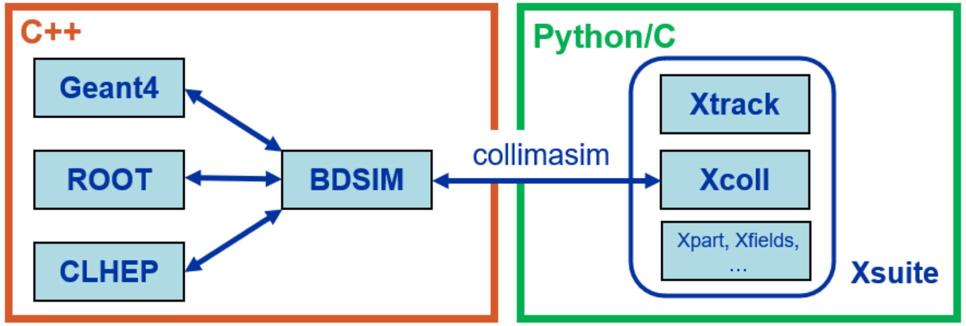
  - Beam losses from interactions with **thermal photons**: study planned for 2025-2026
    - Important effect at LEP - analytical estimates first to understand potential impact on FCC-ee

  - Accidental scenarios
    - Injection failure: work in progress
    - asynchronous dump, others: waiting for inputs to set up models
    - SuperKEKB-like sudden beam loss events presently not accounted for by design

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 and strong beam-beam effects
  - Detailed aperture and collimator geometry modelling
  - Electron/positron beam particle-matter interactions
  - Large accelerator system – 90+ km beamline
- **Xsuite + BDSIM (Geant4) coupling** (A. Abramov, JINST paper)
  - Developed for FCC collimation simulations
  - Benchmarked against
    - other simulation codes: MAD-X, pyAT, Sixtrack-FLUKA
    - measured data from: SPS, LHC, SuperKEKB, DAϕNE is also being considered
  - Other tools available (e.g., Xsuite-FLUKA coupling)

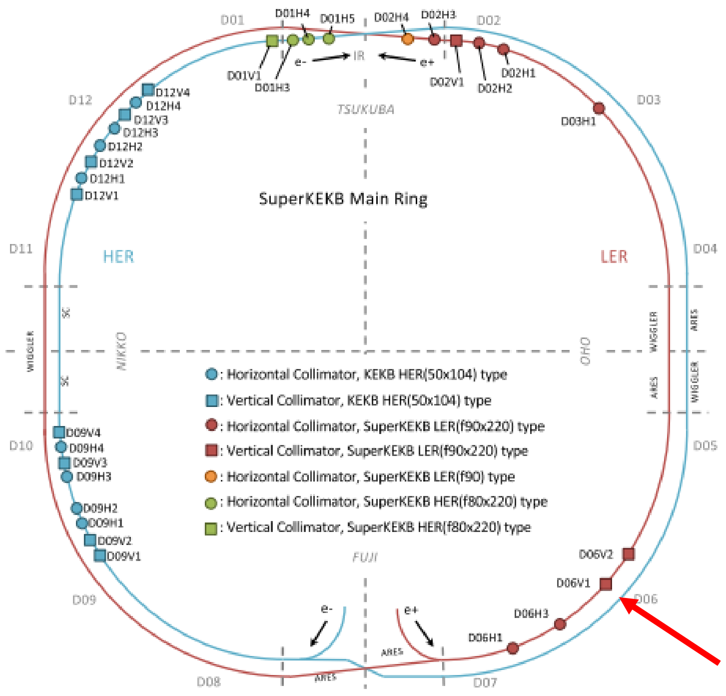




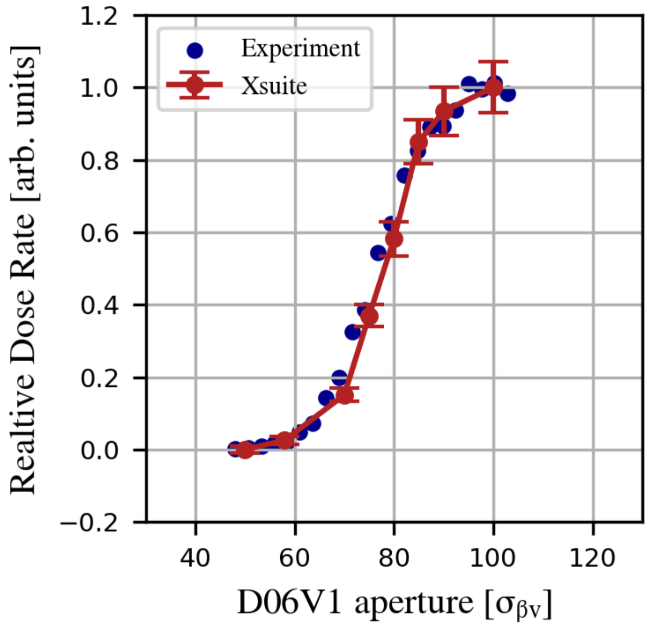
Xsuite-BDSIM benchmark at SuperKEKB

- Comparison of Xsuite–BDSIM simulations with measured backgrounds at SuperKEKB (IPAC'25 paper)
- Dedicated single-beam background study at SuperKEKB LER (June 2020, A. Natochii, PRAB)
  - D06V1 collimator aperture scan
  - Radiation dose rates measured by Belle II radiation monitors

SuperKEKB collimator layout as of June 2020



Relative total dose rate for QCS-FW diamond detector vs. D06V1 collimator aperture in units of σβV



- Simulations accurately reproduce the measured background trend
- Validates Xsuite–BDSIM for collimation and background studies in e+e− machines

Many thanks to G. Iadarola, A. Natochii, J. Salvesen, KEK colleagues and EAJADE programme for the support!

*background sources included in simulations: beam-gas (Brems, Coulomb) and Touschek scattering

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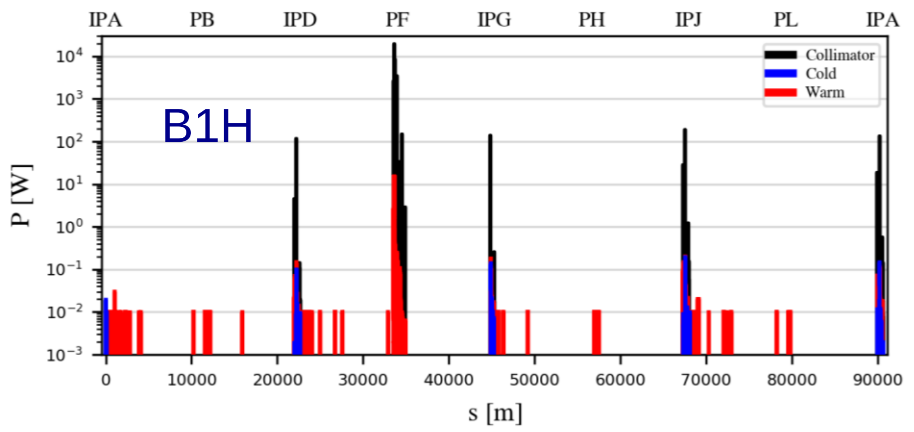
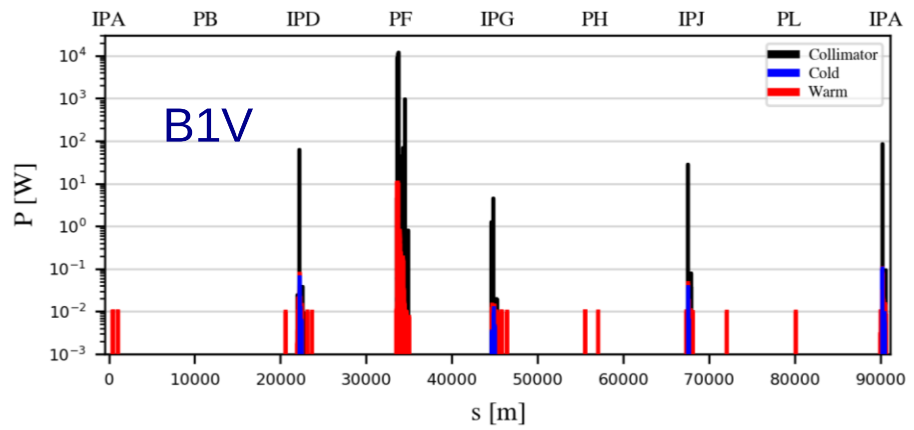
Generic halo losses for the Z mode

- **Generic halo losses**:
  - Slow loss process assumed*
  - The loss process is not simulated
  - Beam halo directly impacts one of the TCPs
  - Beam lifetime drop to 5 min is assumed

- Horizontal and vertical betatron collimation losses (B1H, B1V)

- **Good halo cleaning performance overall**
  - Losses well contained within the collimation insertion PF
  - Loss suppressed by:
    - ~2 orders of magnitude on the TCTs
    - ~4-5 orders of magnitude on the SR collimators
    - >5 orders of magnitude on all the other elements outside PF

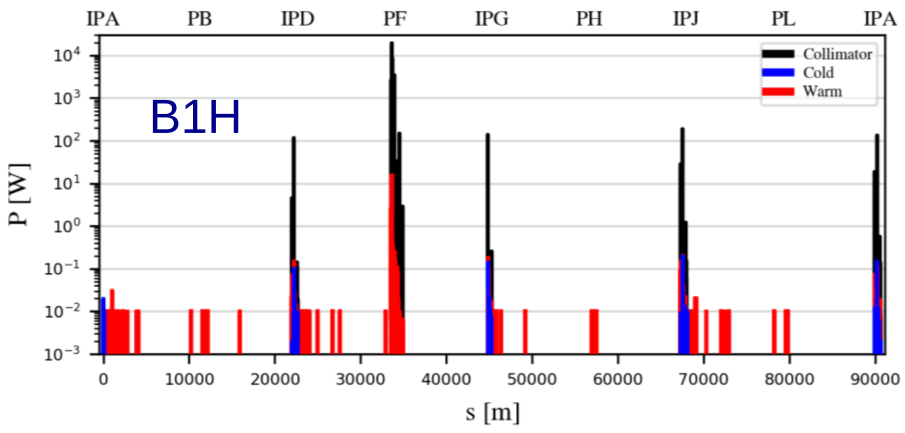


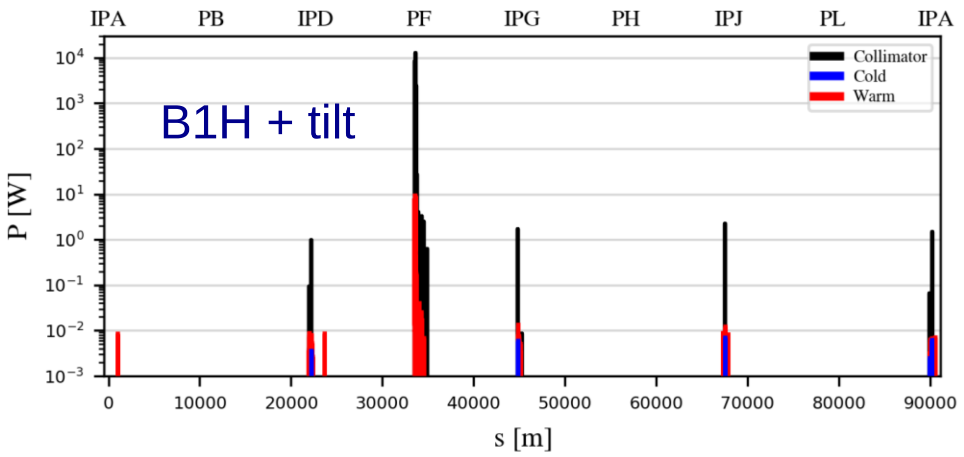


*This is strictly valid only if DA is under control w.r.t. TCP gaps: currently, this is not the case for the V-plane

Collimator angular alignment

- As found in previous studies, collimator angular alignment can significantly improve the collimation performance

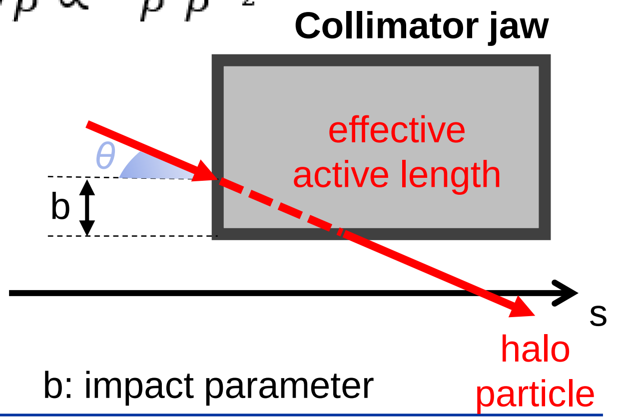




- Losses outside of PF are significantly suppressed
  - ➢ Improvement factor ~100

$$\theta \propto -\alpha\sqrt{\epsilon/\beta} \propto -\beta'\beta^{-\frac{1}{2}}$$

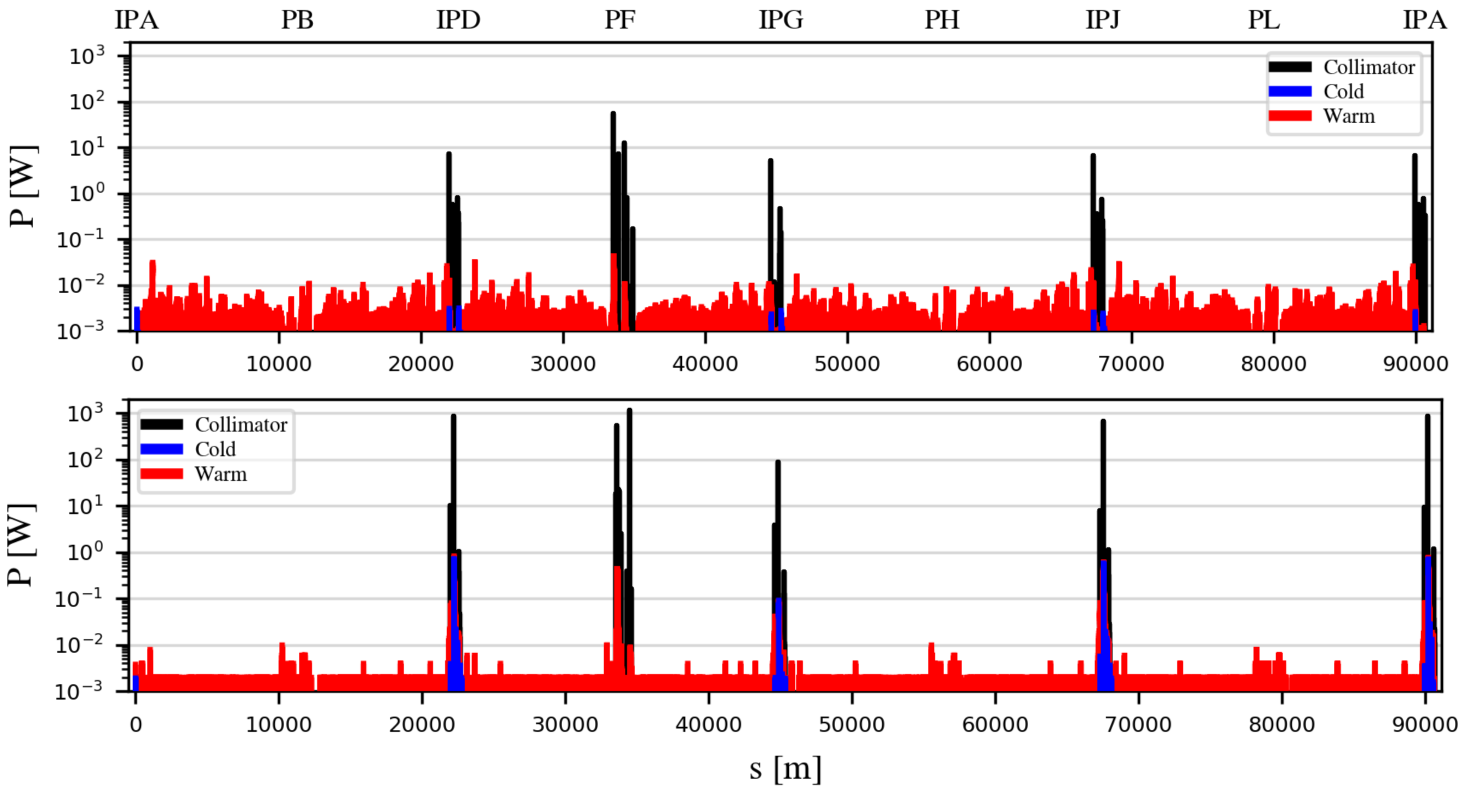
- **Important input for hardware design** (A. Perillo-Marcone, FCC week 2025 talk)
  - ➢ Collaboration with the engineering team
  - ➢ Need to collaborate with other groups (e.g., beam instrumentation) for integration of collimator BPMs
  - ➢ Tolerances on the collimator angular alignment are being evaluated



Beam-gas losses for the *Z* mode

*1h beam conditioning at full nominal current (1.27 A): pressure is expected to condition down further (up to a factor ~100) over time

- A scattering routine to simulate beam-gas interactions while tracking in Xsuite has been developed (IPAC'25 paper)
  - Based on realistic pressure and gas composition profile provided as input



Beam-gas bremsstrahlung

- Estimated lifetime after only 1h of beam conditioning*: **274 min**
- Expected to increase to > 100 h in a fully conditioned machine

Beam-gas Coulomb scattering

- Estimated lifetime after only 1h of beam conditioning*: **41 min**
- Expected to increase to > 10 h in a fully conditioned machine

- At the FCC-ee beam energies, bremsstrahlung is expected to dominate beam-gas-induced lifetime degradation
  - BUT, under particular machine conditions, such as limited DA, even small angular deflections from a single Coulomb scattering event can be sufficient to drive particles beyond the DA limit

Beam-gas losses for the Z mode

- **Vertical DA in the FCC-ee Z-mode lattice is limited to ~30 σ**
  - Beam is highly sensitive to vertical angular kicks
  - Typical vertical divergence (arcs): $\sigma_{py} \approx 0.3\ \mu rad$
  - A 10 μrad vertical kick → >30 σ_{py} → particle loss

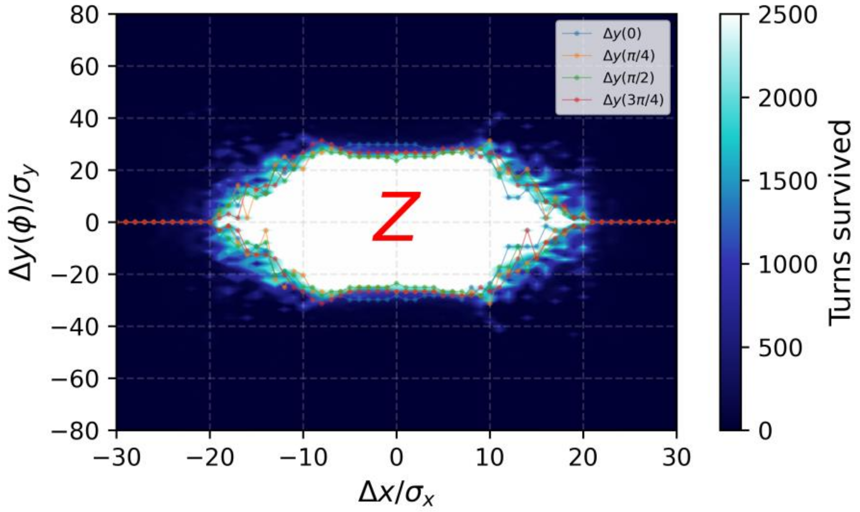
- **Sensitivity increases near IPs**
  - β_y reaches several km → σ_{py} further reduced
  - Even smaller kicks can cause losses

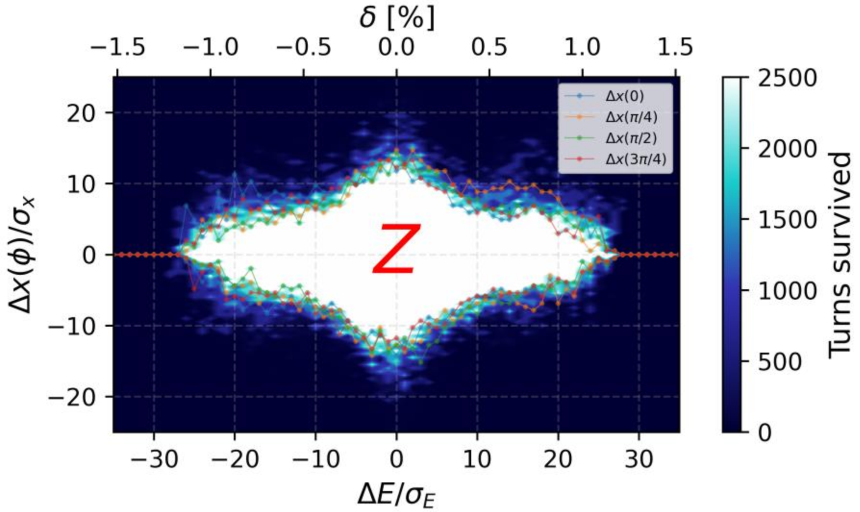
- **Horizontal sensitivity is lower**
  - $\sigma_{px} \gg \sigma_{py}$ (due to much larger ε_x and lower IR-β_x)
  - Same kick → smaller normalized deflection
  - Horizontal DA ≈ vertical DA

- **Bremsstrahlung losses more sensitive to longitudinal DA (~1%)**
  - Caused by photon emission → off-momentum particles

- **WIP to evaluate impact of beam-gas on detector background**
  - G. Broggi, A. Frasca, MDI session on Thursday

FCC-ee Z V25.2 GHC DA and MA

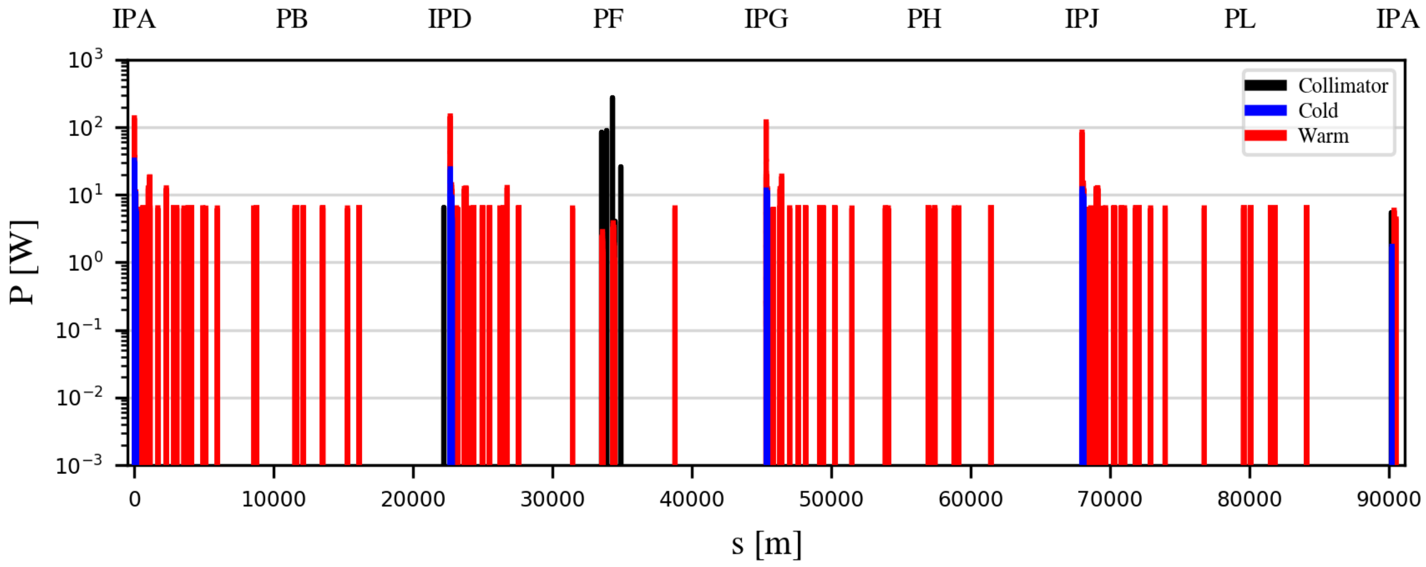




Beam-beam losses for the Z mode

*quantum + lattice + BS + lum.

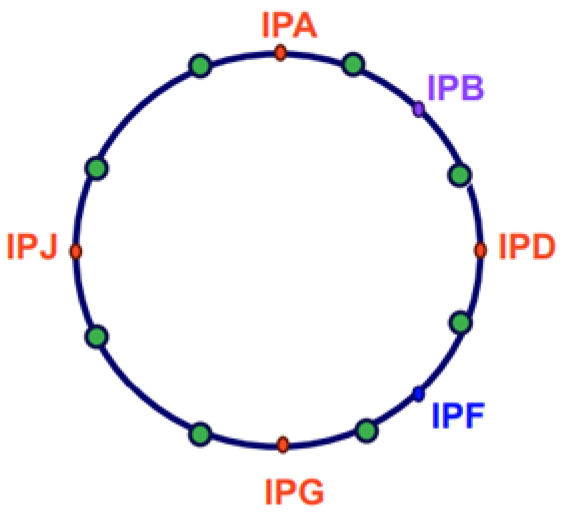
- Xsuite allows to set-up complex combined-effects simulations: beam-beam + collimation
  - Beam-beam kicks, radiative Bhabha, beamstrahlung in 4 IPs + detailed aperture and collimator model
  - Common technical insertion optics shows significant advantages
    - Absence of strong-vertical emittance blow-up previously observed (BB'24 talk)
    - Beam lifetime* in agreement with expectations: ~14 min vs. ~17 min without aperture and collimators
      - Primary collimator openings: 9.5σ (H plane), 50σ (V plane)

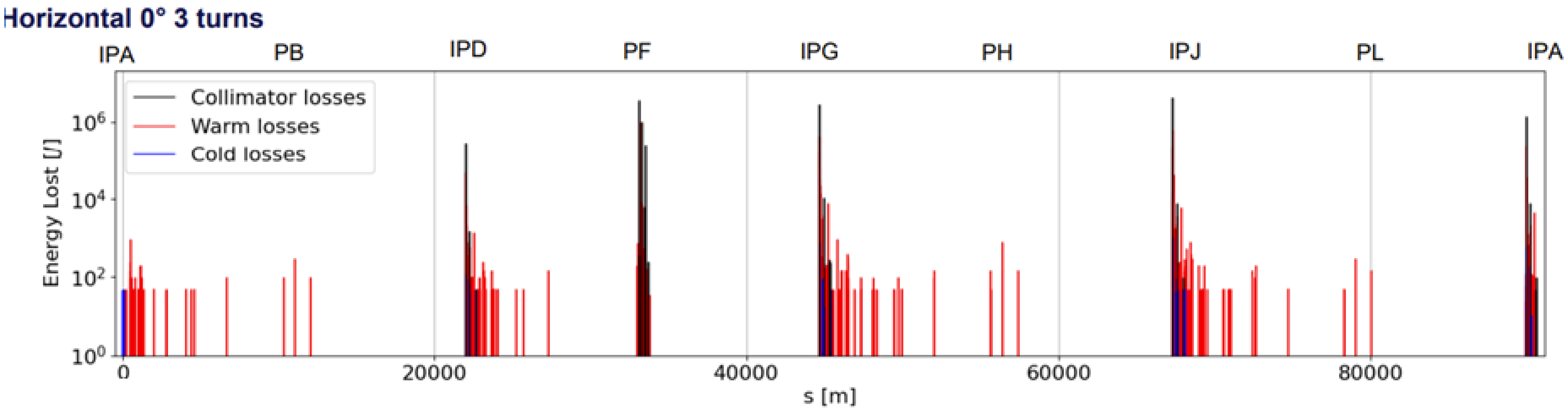


- Beam-beam losses intercepted by the collimation system in PF
- Beam-beam losses outside PF mostly on elements downstream of the IPs
  - Local losses that cannot be intercepted in PF on a second turn
  - Physics-debris-like collimators downstream of the IPs ?

Fast instability losses for the Z mode

- **Studies on fast instability losses have been performed** (G. Nigrelli – FCC physics workshop 2025 talk)
  - Fast instability modeled by synchronized kicks placed along the ring with raising strength
    - Mimic instabilities with different rise times
    - Studied beam loss distributions around the ring and across multiple turns

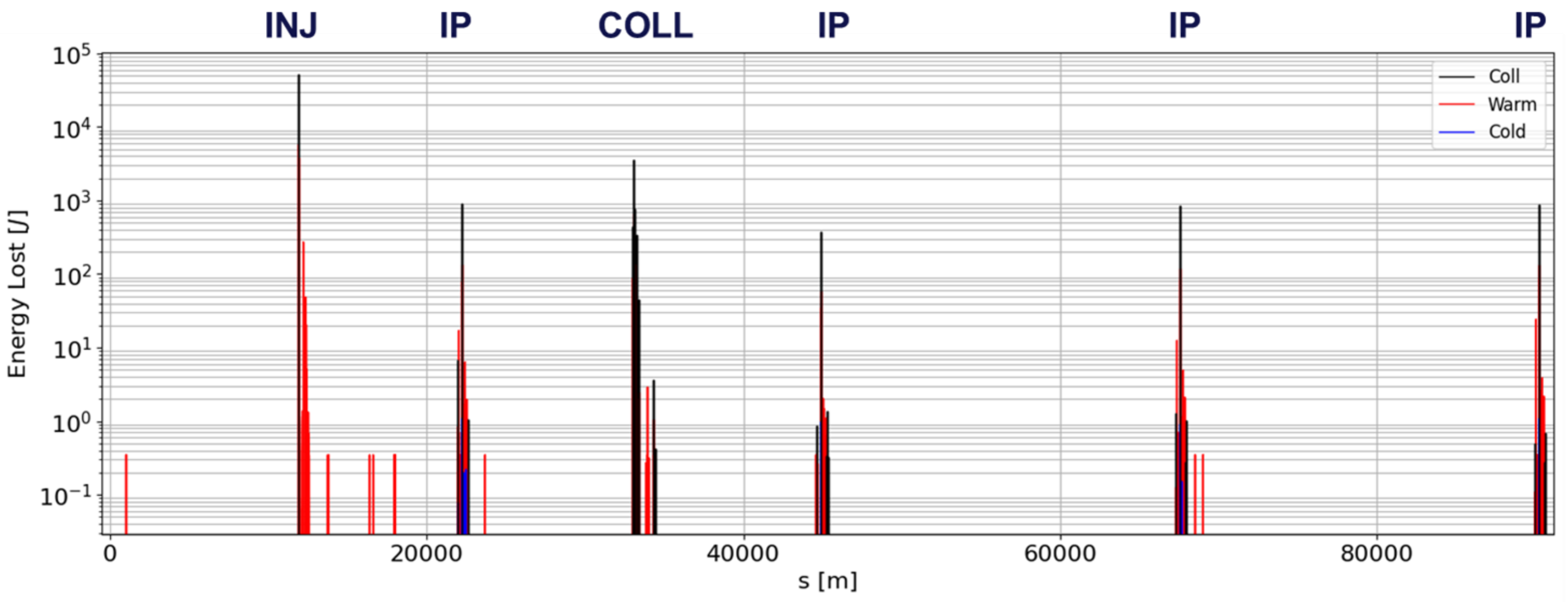




- **The fast instability could be dangerous if the feedback system fails** – feedback system redundancy ?
  - Full beam potentially lost within few turns
  - Almost 50% of beam energy lost in one turn, losses of order of MJ in the collimator can be expected
  - Important input for feedback system design: such scenario must be avoided in operation

Top-up injection losses for the Z mode

- First studies on top-up injection losses have started (G. Nigrelli)
  - Baseline injection scheme as presented by Y. Dutheil, FCC week 2025 talk



FCC-ee Z V25.2 GHC loss map showing the distribution of beam halo losses caused by the injection bump in PB

- Simulated injected beam, core beam, halo beam (lossmap above)
  - Studies of impact of injection losses on detector background have started
  - More details in G. Nigrelli – First look at injection backgrounds, FCC week 2025 talk (Thu 22/05)
- Studies of injection failure scenarios are being set up

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FCC-ee collimation summary

- **Studies of beam losses and collimation for the FCC-ee**
  - First collimation system design available, including beam halo, SR collimators and shower absorbers
  - Simulations of several beam loss scenarios ongoing:
    - Beam halo losses, beam-gas losses, beam-beam losses, top-up injection losses, losses from fast instabilities for the **most critical Z mode**
    - **No show-stoppers identified**
  - Developed simulation routines for beam-gas and Touschek scattering
  - Simulation benchmarked against measured data from an e+e- collider (SuperKEKB)
  - Collaboration with the optics, MDI, impedance, FLUKA and engineering studies team

- **Next steps**
  - Study other beam loss scenarios – e.g., failure scenarios
  - Obtain input for the **equipment tolerances** – superconducting magnets, collimators, others…
    - ➢ Energy deposition studies required for magnets, collimators, and masks
    - ➢ Impact of beam losses on experimental background as well as detector tolerances to be studied
      - Work in progress with FLUKA and MDI team
  - Extend the studies to the electron beam (B2)
  - Extend the studies to all beam modes

Thank you!

Backup