Including beam-beam effects in collimation studies for the FCC-ee

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ICFA mini workshop on Beam-Beam Effects in Circular Colliders 2024 – Lausanne, Switzerland, 05/09/2024

Many thanks to:

A. Lechner, S. Marin, M. Migliorati, L. Nevay, G. Iadarola, A. Perillo-Marcone, L. van Riesen-Haupt, F. Zimmermann

Outline

- **Introduction**
  - Collimation for the FCC-ee
  - FCC-ee collimation system
  - Collimation and beam-beam effects
- **FCC-ee collimation simulations**
- **FCC-ee Z mode spent beam losses**
- **Addition of tertiary collimators for local protection**
- **Summary and next steps**

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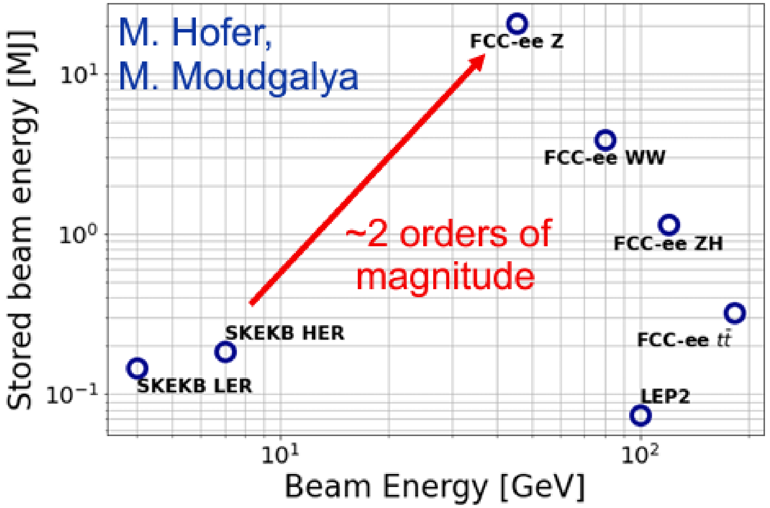
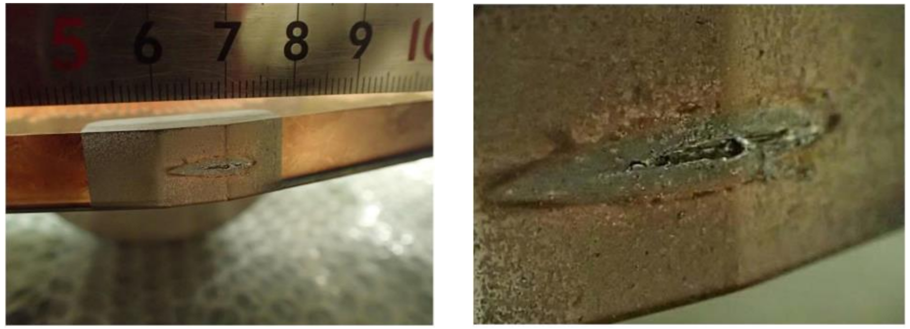
Collimation for the FCC-ee

- **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 currently foreseen for the FCC-ee:
    - Beam halo (global) collimation
    - Synchrotron Radiation (SR) collimation – around the IPs
    - Secondary particle shower absorbers: under study (S. Marin, A. Lechner)

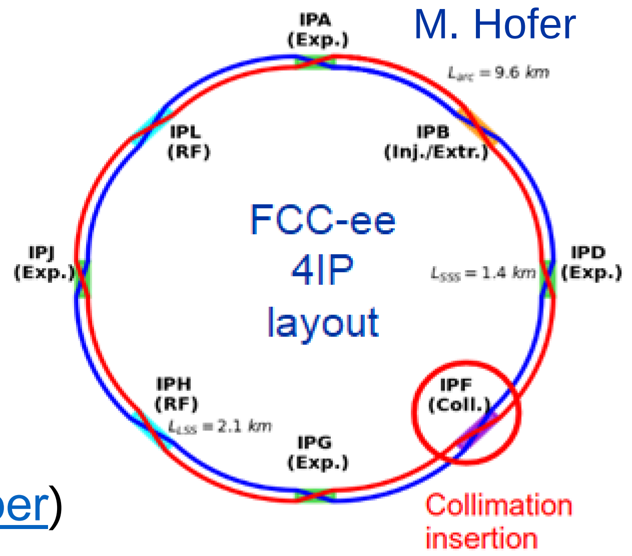
Comparison of lepton colliders



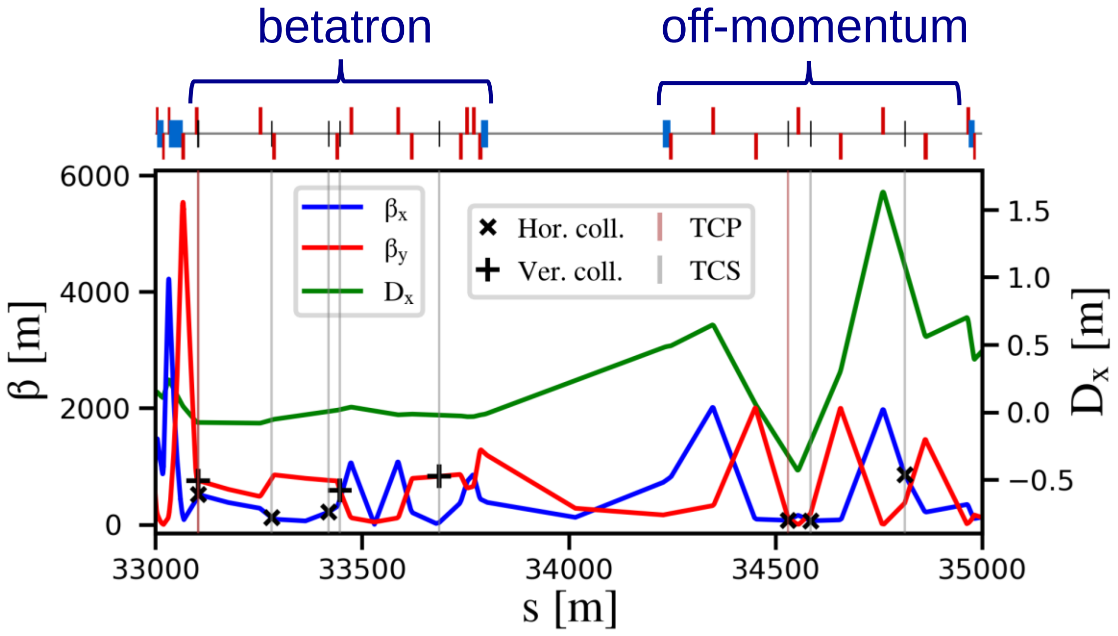


Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

FCC-ee halo collimation system



- **Dedicated halo collimation system in PF**
  - Dedicated collimation optics (M. Hofer)
  - Two-stage betatron and off-momentum collimation system in one insertion
  - Ensure protection of the aperture bottlenecks in different conditions
    - **Aperture bottleneck at *Z***: 14.6σ (H plane), 84.2σ (V plane)
  - First collimator design for cleaning performance
    - Ongoing studies for optimizing the collimator design (G. Broggi – IPAC'24 paper)



FCC-ee V23, tridodo_572 collimation optics

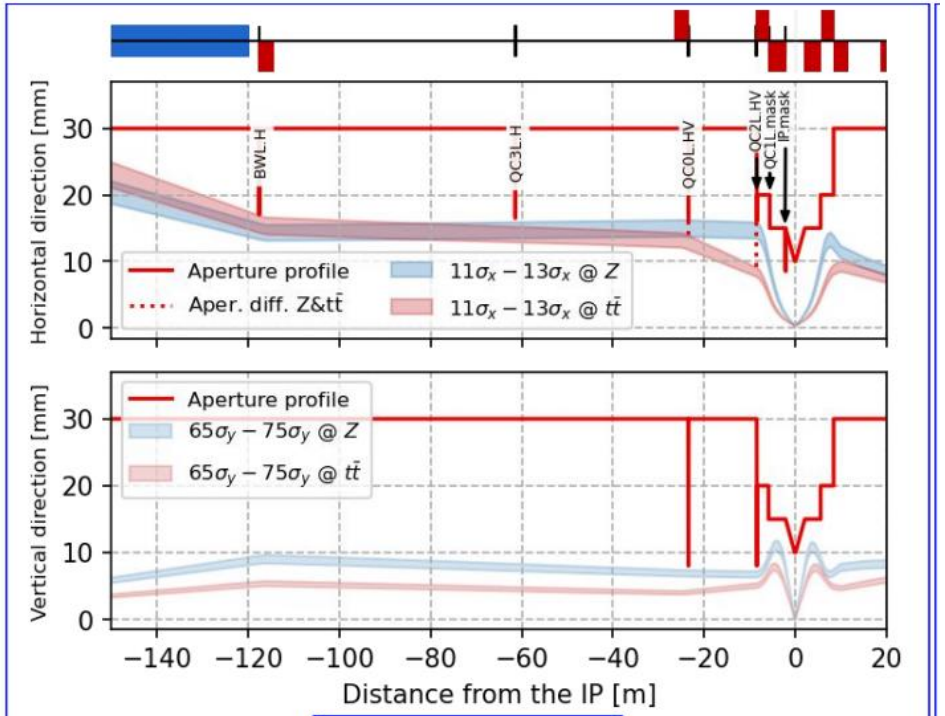
FCC-ee beam halo collimator parameters and settings

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	2.4	-
TCS.H1.B1	H	Mo	30	13	3.8	6.7
TCS.V1.B1	V	Mo	30	75	2.5	-
TCS.H2.B1	H	Mo	30	13	5.1	90.6
TCS.V2.B1	V	Mo	30	75	3.0	-
TCP.HP.B1	H	MoGr	25	18.5	4.2	1.3
TCS.HP1.B1	H	Mo	30	21.5	4.6	2.1
TCS.HP2.B1	H	Mo	30	21.5	16.8	1.6

Further materials will be studied

FCC-ee SR collimation system

- **Synchrotron radiation collimators around the IPs**
  - 6 movable collimators and 2 fixed 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 SR collimators parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCR.H.WL.B1	H	W	10	14.1	17.0
TCR.H.C3.B1	V	W	10	13.5	16.5
TCR.V.C0.B1	V	W	10	80.1	8.0
TCR.H.C0.B1	H	W	10	13.0	16.2
TCR.V.C2.B1	V	W	10	82.0	8.0
TCR.H.C2.B1	H	W	10	13.1	16.0

- More details in K. André, FCC week 2024 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
  - Can 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
  - 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**
  - Multi-turn beam dynamics and beam losses of spent beam particles
  - Effect of beam-beam interaction on collimation losses and distributions during collimation tracking

EPFL

CERN

CHART
Swiss Accelerator Research and Technology

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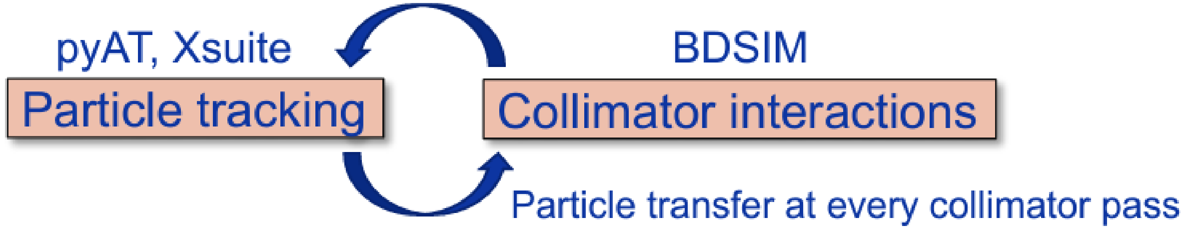
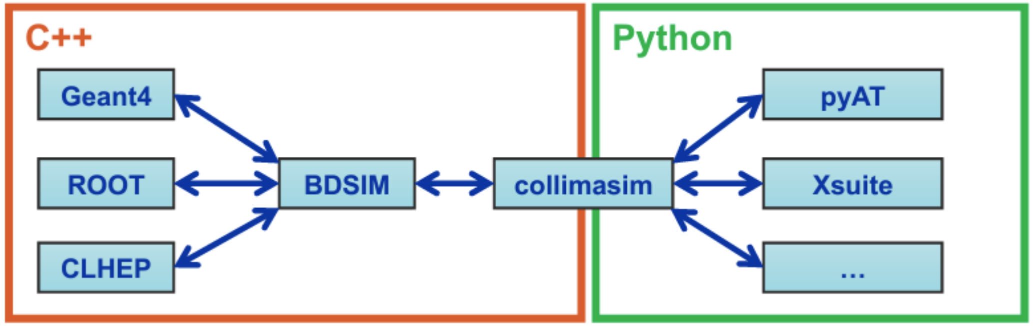
FCC-ee collimation simulations

- **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
  - Detailed aperture and collimator geometry modelling
  - Electron/positron beam particle-matter interactions
  - Large accelerator system – 90+ km beamline

Ongoing effort for benchmarking Xsuite-BDSIM with data from lepton machines (SuperKEKB, DAΦNE)

- **Xsuite + BDSIM (Geant4) coupling**
  - Developed for FCC collimation simulations (A. Abramov, IPAC'22 paper, JINST 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 being set up (F. Van der Veken, HB'23 paper, K. Skoufaris, FLUKA team)





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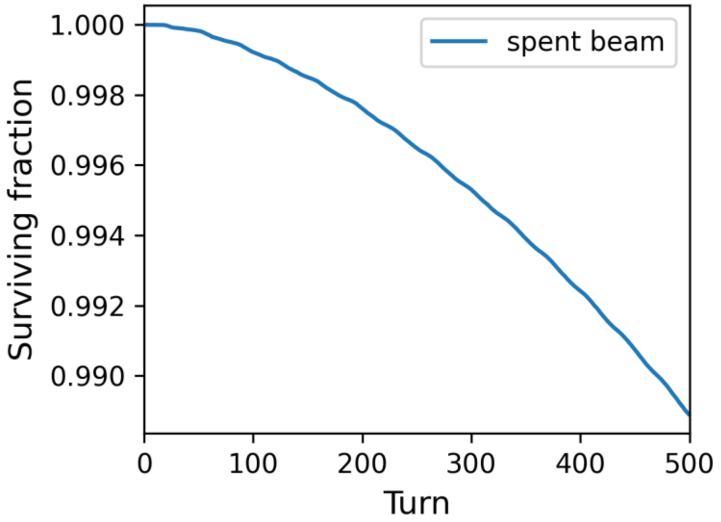
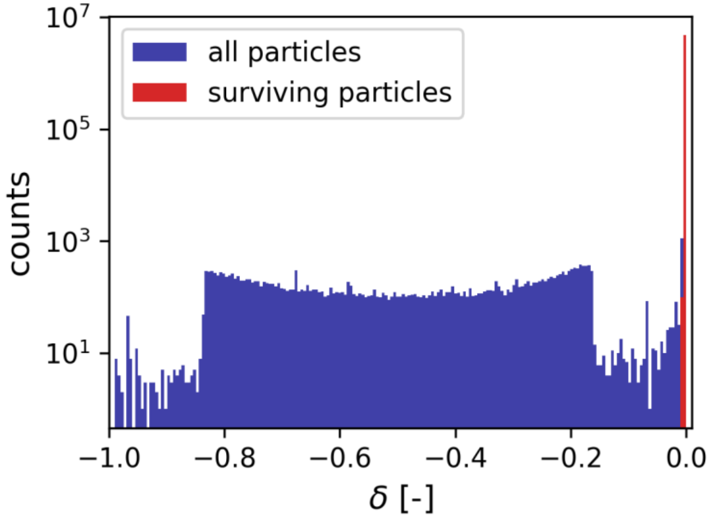
FCC-ee *Z*-mode spent beam losses

- **Goal: study collimation with beam-beam integrated**
  - Full non-linear lattice
  - Crab-waist
  - Detailed aperture and collimator models
  - Radiation (quantum) and tapering
  - Vertical emittance generation (wiggler)
  - Weak-strong beam-beam, Beamstrahlung, Bhabha scattering in 4 Ips

  - Clockwise beam 1 (positrons), 45.6 GeV
  - Track a matched Gaussian beam of 10^7 macroparticles from first arc dipole after IPA for 500 turns
  - Equilibrium beam-beam emittance and bunch length:
    - $\epsilon_x = 0.71\ nm,\ \epsilon_y = 1.9\ pm,\ \sigma_z = 15.5\ mm$

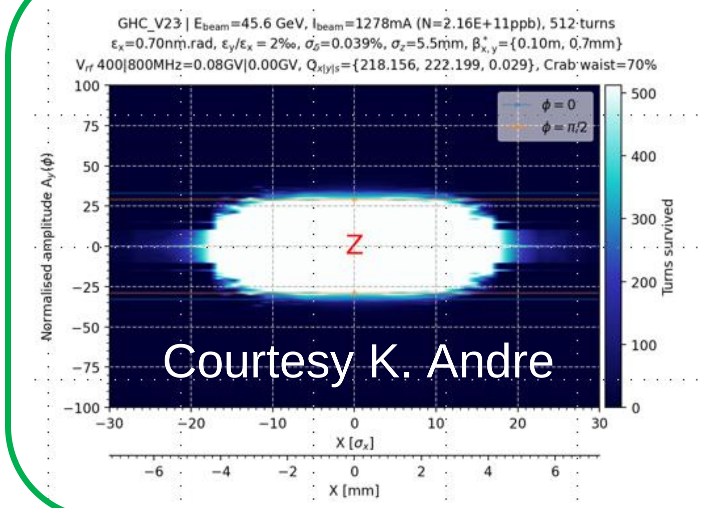
  - Cumulative loss over 500 turns is ~1%, check in detail:
    - The full aperture and collimator model, worse DA and MA due to inclusion of the collimation insertion optics likely play a role

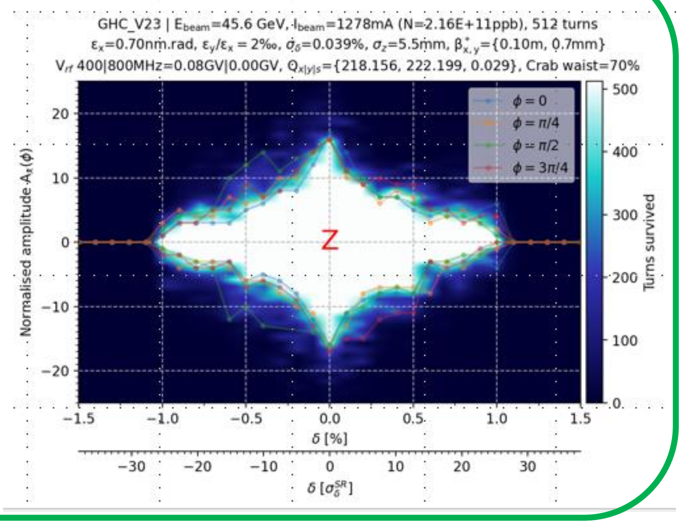




→ Needs to be understood and corrected in the future

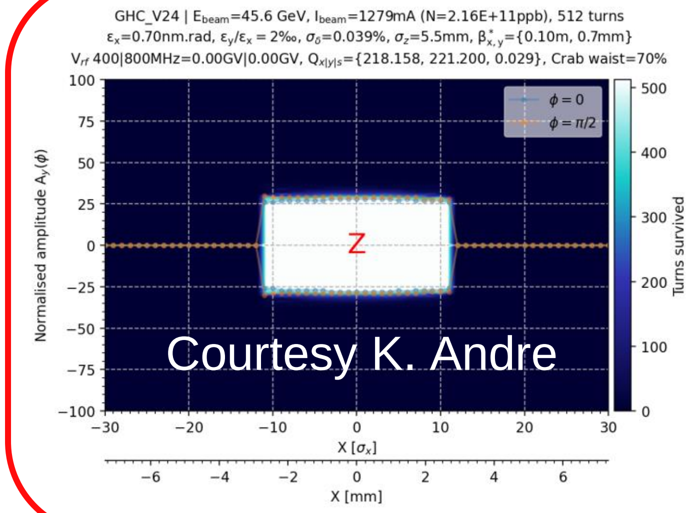
DA and MA with collimation insertion optics

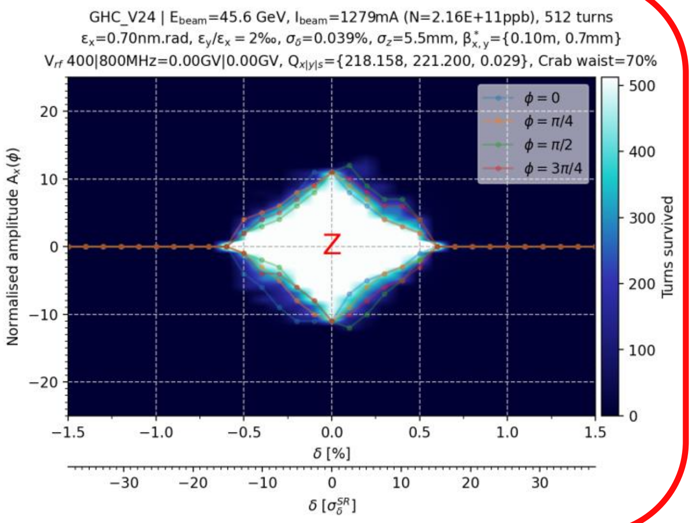




Collimation insertion optics not included

Including collimation insertion optics and full aperture and collimator model





Collimation insertion optics included

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**

FCC-ee *Z*-mode spent beam losses

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

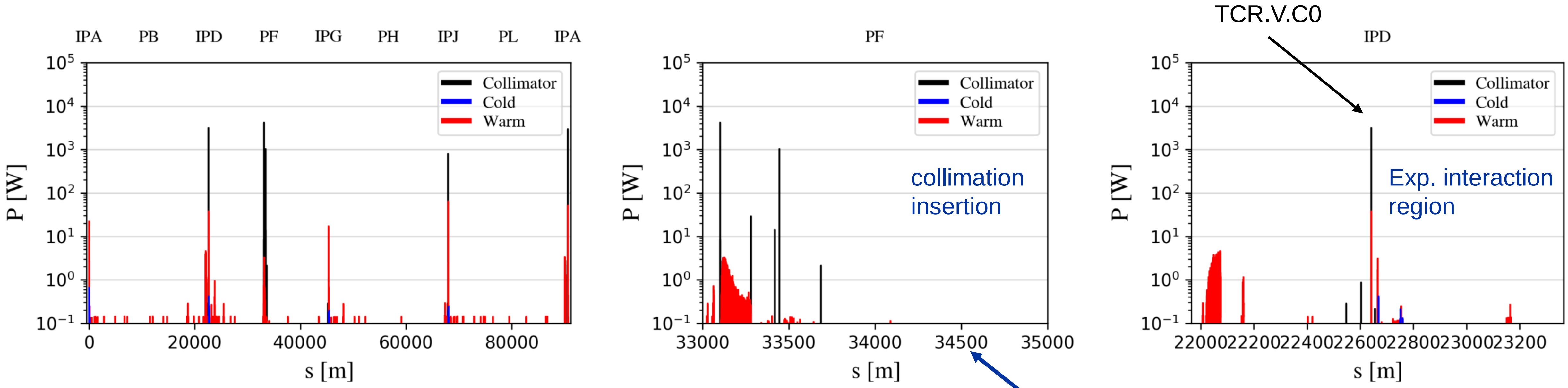
Lifetime (q + BS + lattice)	[sec]	10000
Lifetime (lum)^{b}	[sec]	1330

- Lost particles accumulated to obtain **loss maps**
- The loss maps are scaled to the **combined nominal beam lifetime** from lattice, SR, beamstrahlung and luminosity

$$\tau = \left(\frac{1}{\tau_{q+BS+lattice}} + \frac{1}{\tau_{lum}}\right)^{-1} \cong 1174\ s$$

- Losses intercepted by betatron collimators in PF (43%)
- Large losses on the TCR.V.C0 collimators in IPD, IPA and IPJ with no losses in IPG
  - ➢ Up to 3.1 kW on a vertical SR collimator (TCR.V.C0)
  - ➢ Likely single-pass losses that cannot be intercepted by the halo collimation system in PF

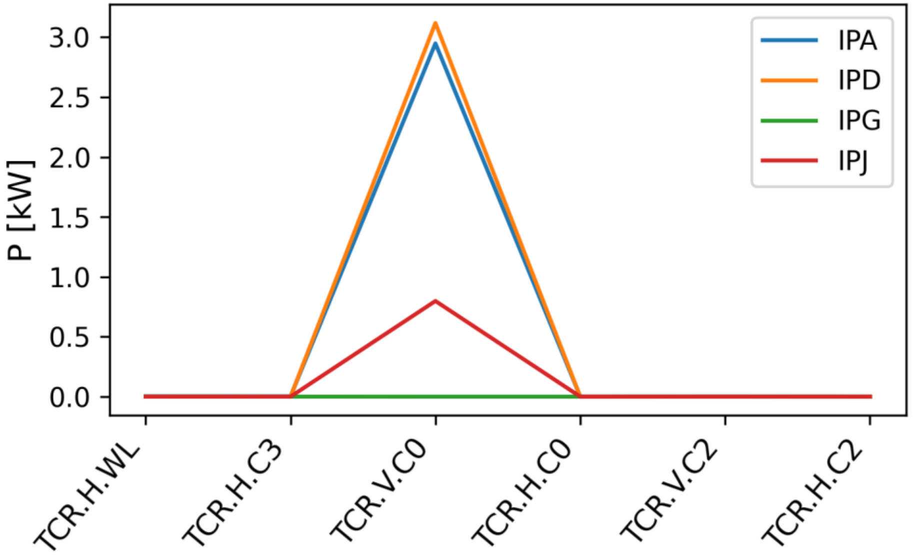
Total loss power: **15 kW**



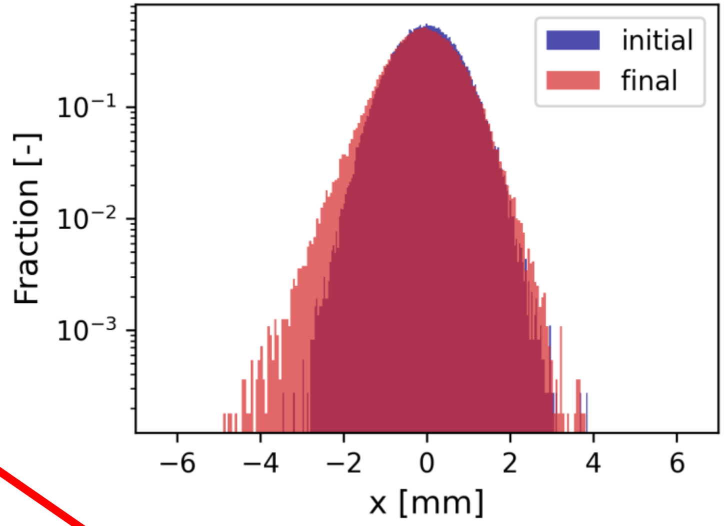
NO losses on off-momentum collimators

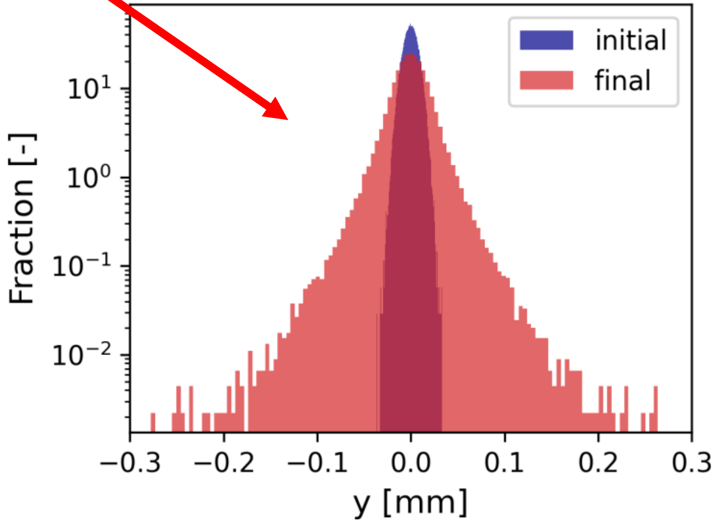
FCC-ee *Z*-mode spent beam losses

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



Transverse distribution after 500 turns





- SR collimators are not primarily designed for intercepting beam losses
  - They might be damaged
  - Being close to the IPs, they might induce backgrounds

- Tertiary collimators (TCTs) for local protection ?

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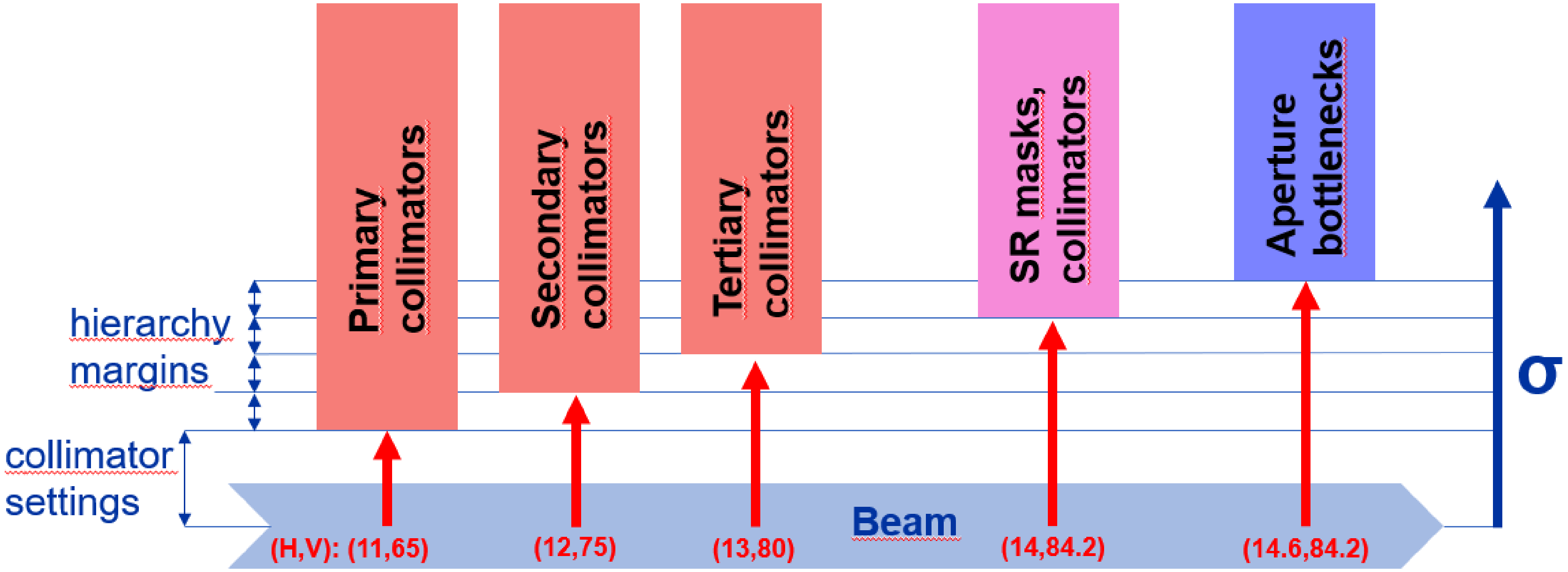
Tertiary collimators for local protection

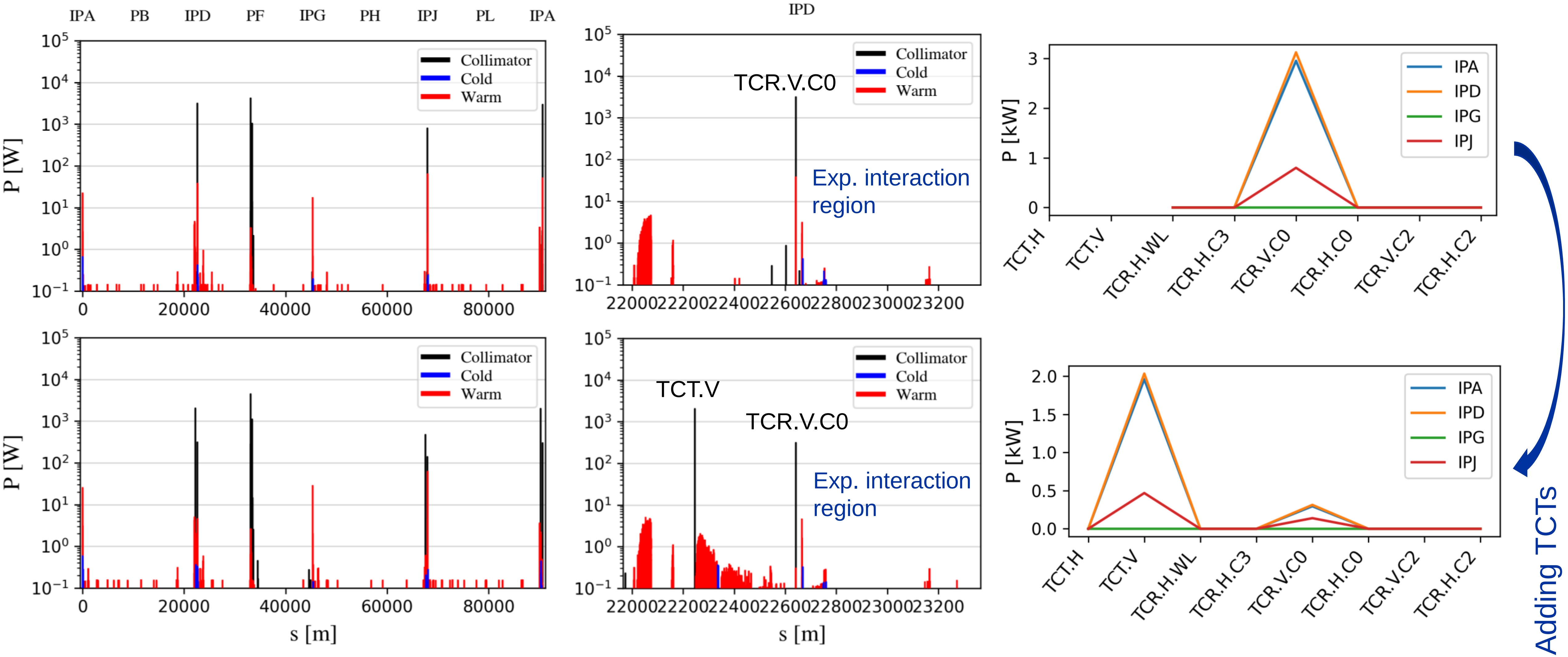
- Spent-beam losses shows the highest beam losses on SR collimators upstream of the IPs
- Addition of **two** (**H+V**) **tertiary collimators** (**TCTs**) for local protection
  - Placed ~690 m (H) ~420 m (V) upstream of each IP
  - s-location optimized to have optimal phase-advance (multiple of π) between TCTs and { SR collimators / aperture bottlenecks }
- Collimator settings adjusted to fit the TCTs in the collimation hierarchy:



Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCT.H.B1	H	MoGr	25	13	3.4
TCT.V.B1	V	MoGr	25	80	6.1

FCC-ee tertiary beam halo collimator parameters and settings

Collimation performance with beam-beam and TCTs



- Addition of TCTs suppresses by <u>one order of magnitude</u> the power loads on the SR collimators

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Summary

- **First integrated beam-beam and collimation studies performed**
  - Spent beam losses for the FCC-ee *Z*-mode
  - Demonstrate the feasibility of combining collimation and beam-beam studies in the same model
  - Important input for the optimization of the FCC-ee collimation system design

- **Spent beam losses show the highest power loads on the SR collimators upstream of the IPs**
  - Tertiary beam halo collimators (TCTs) for local protection included in the FCC-ee collimation system
  - Integrated beam-beam and collimation simulations show their effectiveness in suppressing the power loads on the SR collimators: suppression of up to one order of magnitude

Next steps

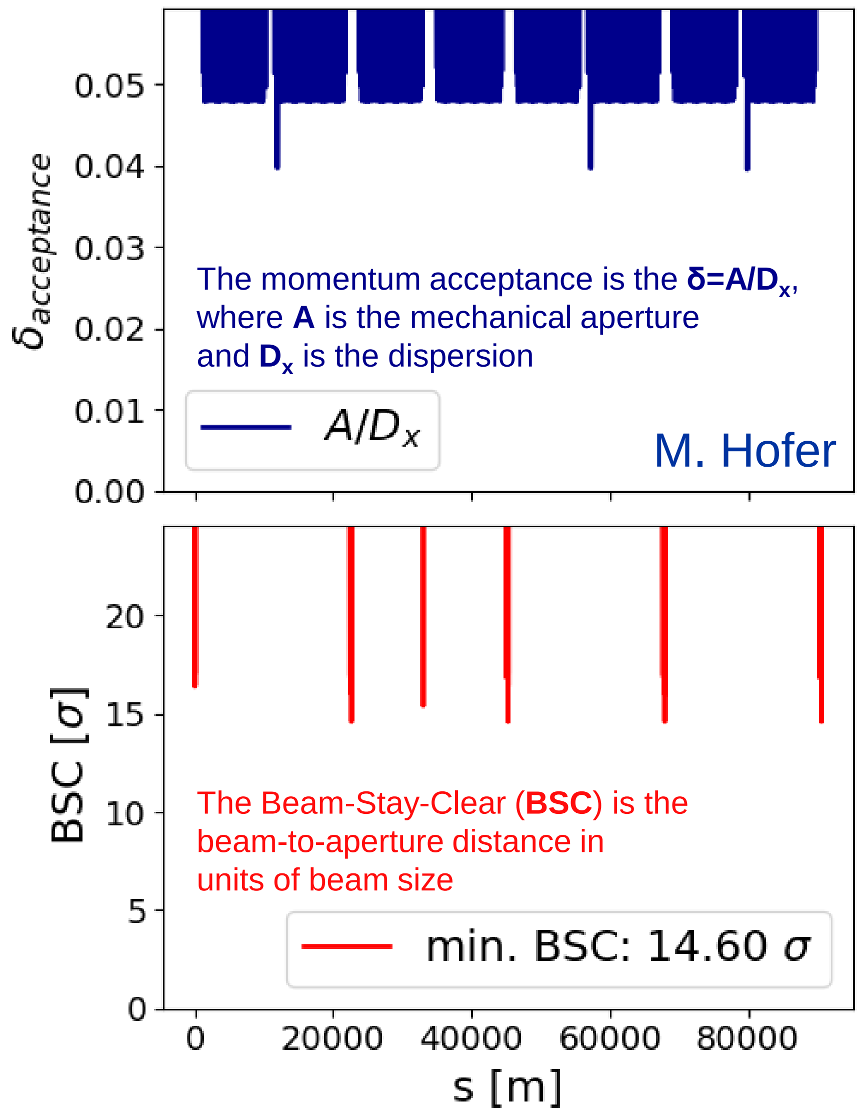
- **Lifetime from integrated beam-beam and collimation simulations cannot be estimated yet**
  - Need to optimize DA and MA with collimation insertion optics and full aperture and collimator model
- The need for **shower absorbers downstream of the TCTs** needs to be assessed
- Investigate further particle distr. after beam-beam interactions - **physics debris collimators** like in the LHC ?
- **Iterate the collimation system design** with other studies (SR backgrounds, impedance, energy deposition, radiation studies, mechanical design, …)

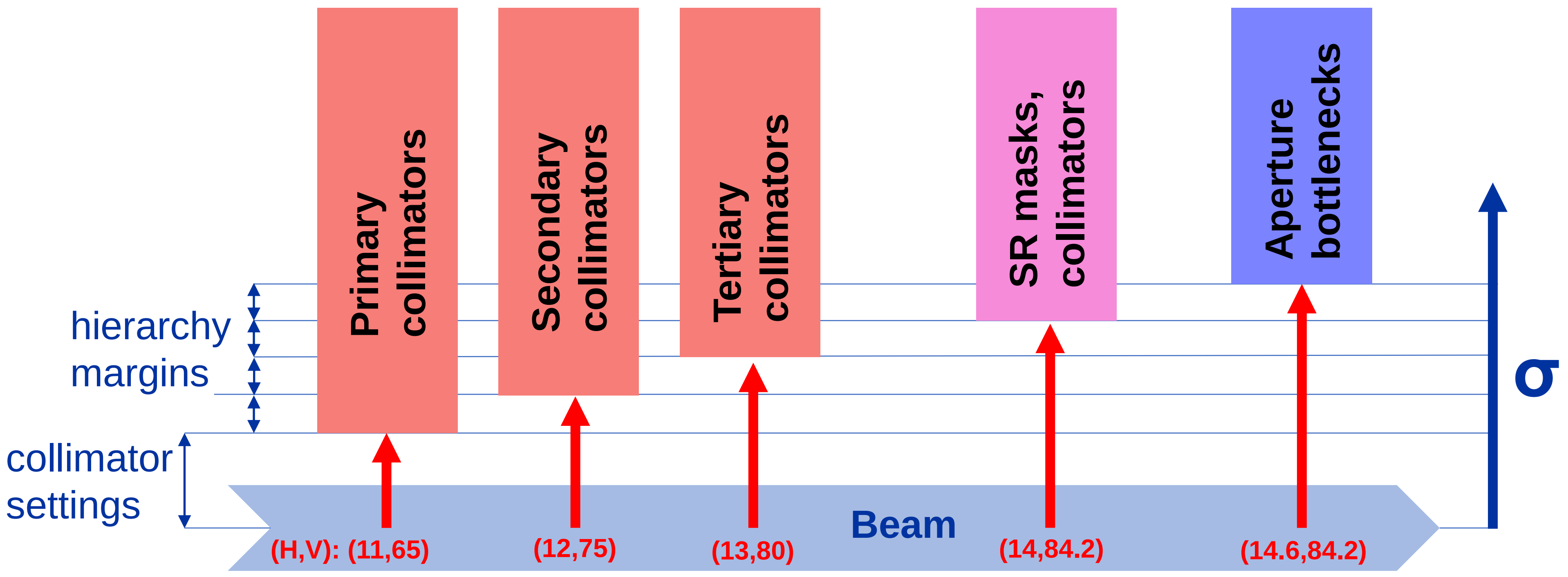
Thank you!

FCC-ee aperture

- Closed orbit tolerance: 250 µm
- Maximum beta-beating: 10%

Aperture bottleneck for Z operation mode





Primary collimators
Secondary collimators
Tertiary collimators
SR masks, collimators
Aperture bottlenecks
hierarchy margins
collimator settings
σ
Beam
(H,V): (11,65)
(12,75)
(13,80)
(14,84.2)
(14.6,84.2)