FUTURE CIRCULAR COLLIDER

# FCC-ee IR Beam Losses

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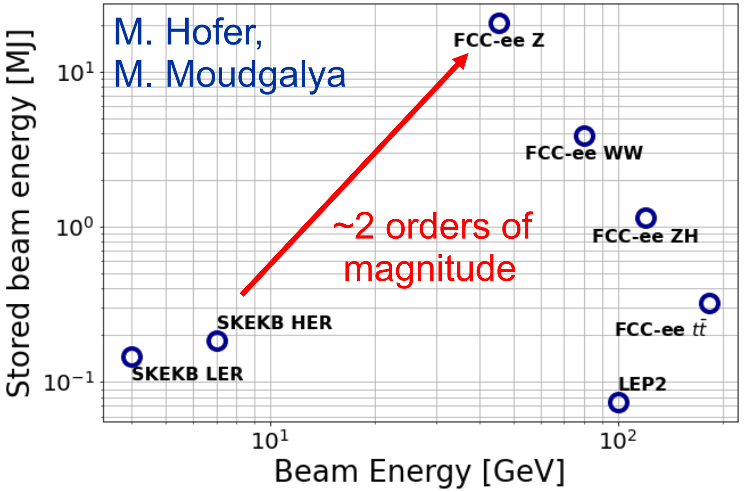
Many thanks for discussions and input to:

K. André, M. Boscolo, H. Burkhardt, A. Ciarma, Y. Dutheil, P. Hunchak, A. Lechner, K. Oide, R. Ramjiawan, T. Raubenheimer, F. Zimmermann

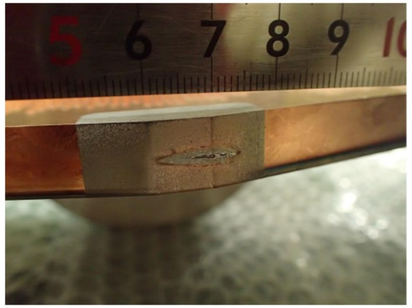
# FCC-ee beam losses and collimation

- **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

- **Beam loss and collimation studies are essential to ensure the safe and efficient operation of the FCC-ee**




Comparison of lepton colliders




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

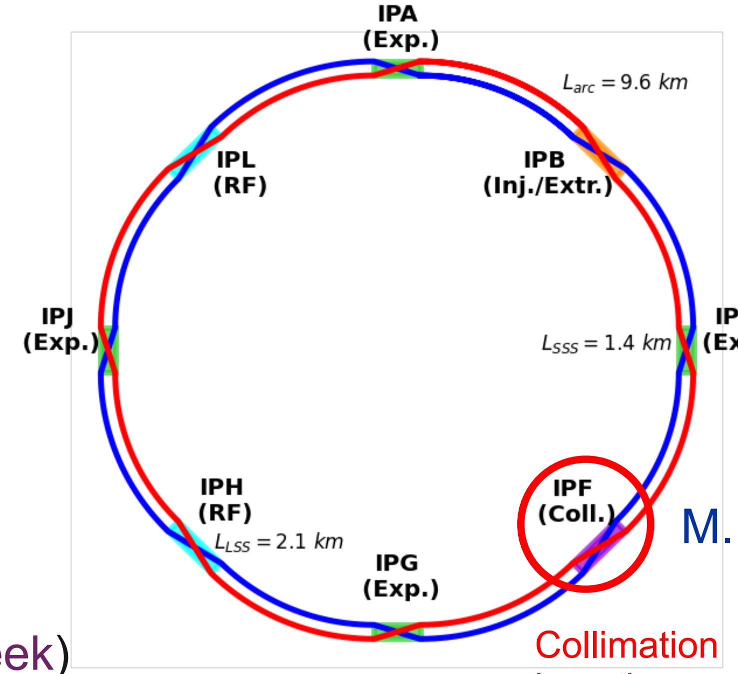
# Beam loss sources

- **Many processes can lead to beam losses in the FCC-ee**
  - See talk by **H. Burkhardt** (**link**)
  - Beam losses can lead to:
    - Detector backgrounds
    - Superconducting magnet quench risk and material damage
    - Radiation damage and material activation

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

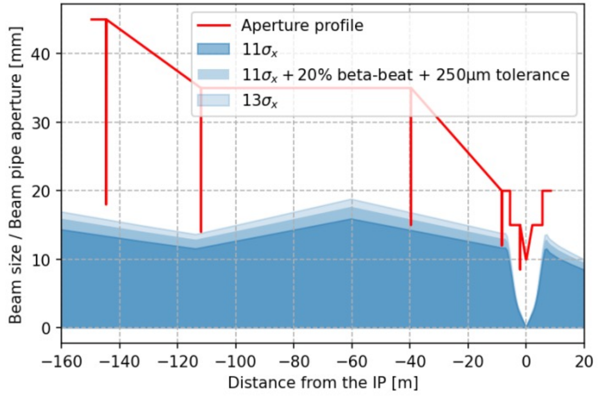
# FCC-ee collimation system

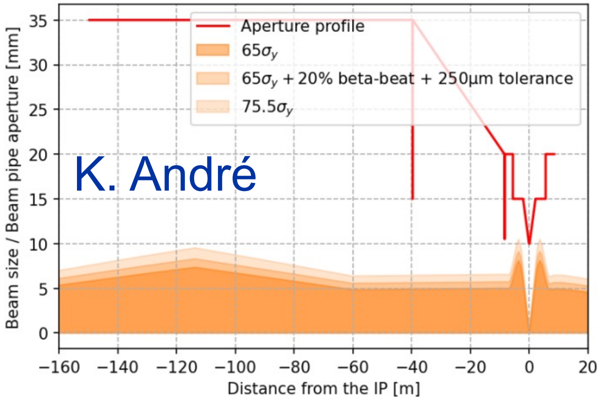
- **Dedicated halo collimation system in PF**
  - Two-stage betatron and off-momentum collimation in one insertion
  - Defines the global aperture bottleneck
  - Dedicated collimation optics (M. Hofer)
  - First collimator design for beam cleaning performance (G. Broggi)
- **Synchrotron radiation collimators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

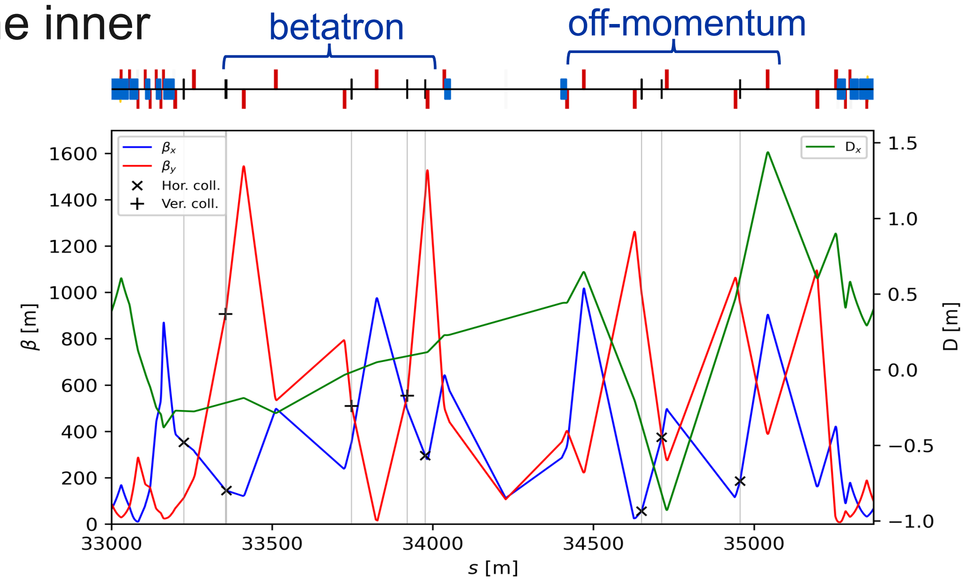



M. Hofer

Collimation insertion

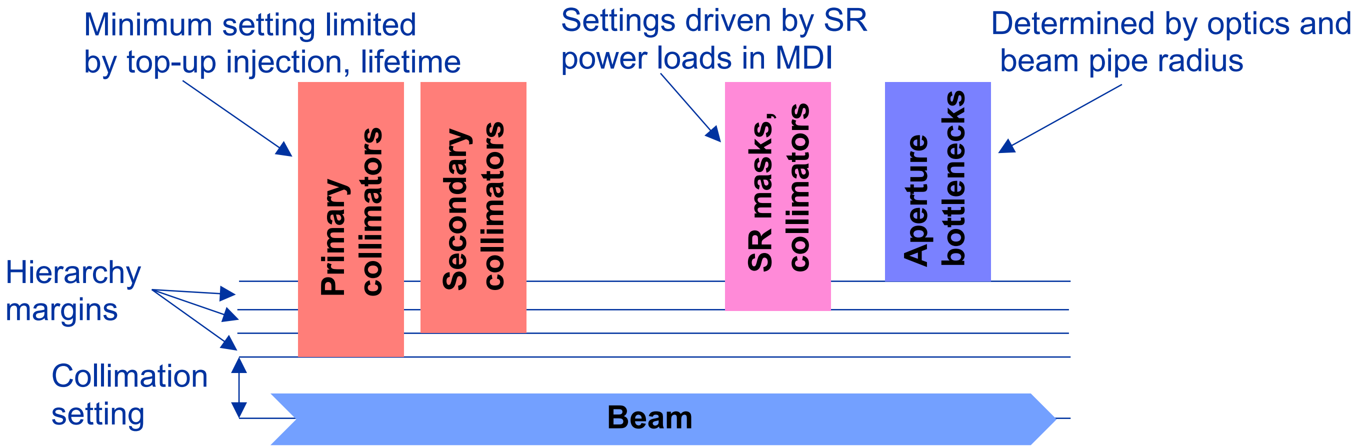


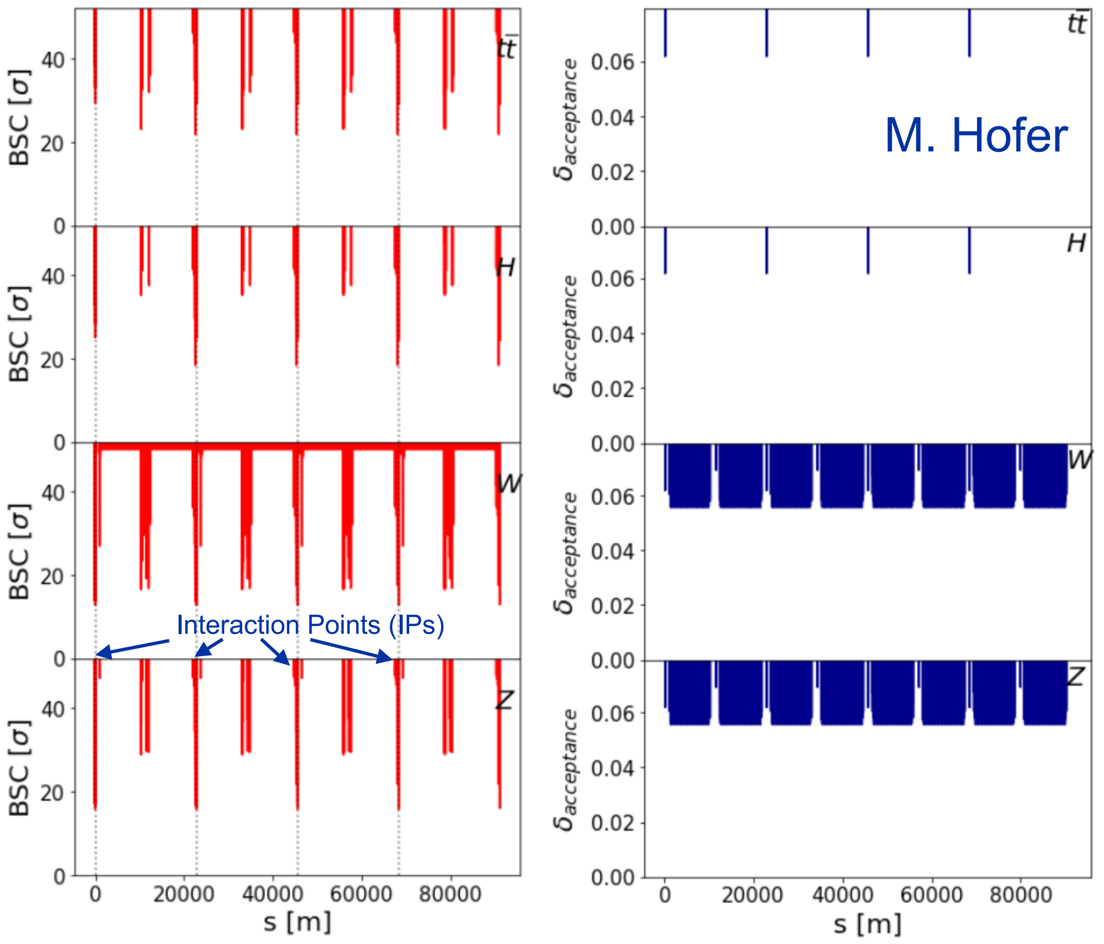
# FCC-ee aperture

- **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 (talk, M. Hofer)




Beam stay-clear (**BSC**) is the distance from the beam to the aperture in units of beam size

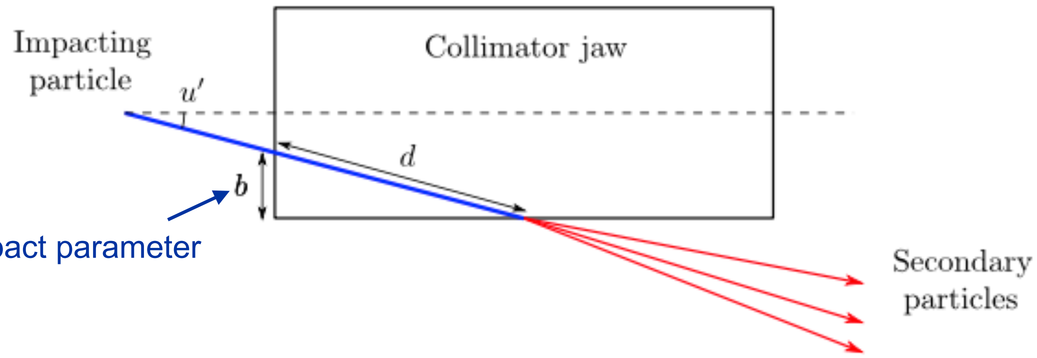
The momentum acceptance is the $\delta$ = **A / D**, where **A** is mechanical aperture and **D** is dispersion

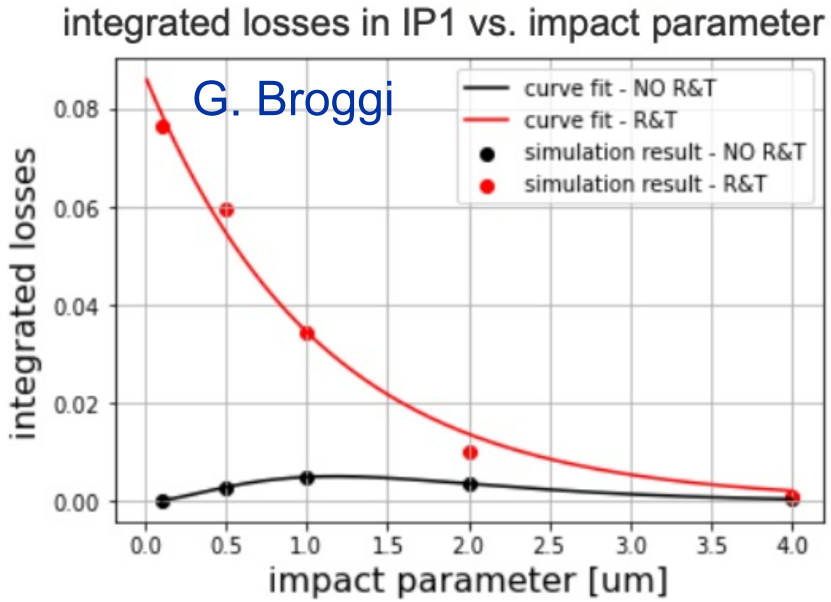



Aperture bottlenecks for the different operating modes

# Current study: beam halo losses

- **"Generic beam halo from slow diffusion" 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 **5 min**




Impact parameter scan for 2 IP CDR lattice with MoGr primary collimator, with and without radiation and tapering (R&T)

# FCC-ee parameters used

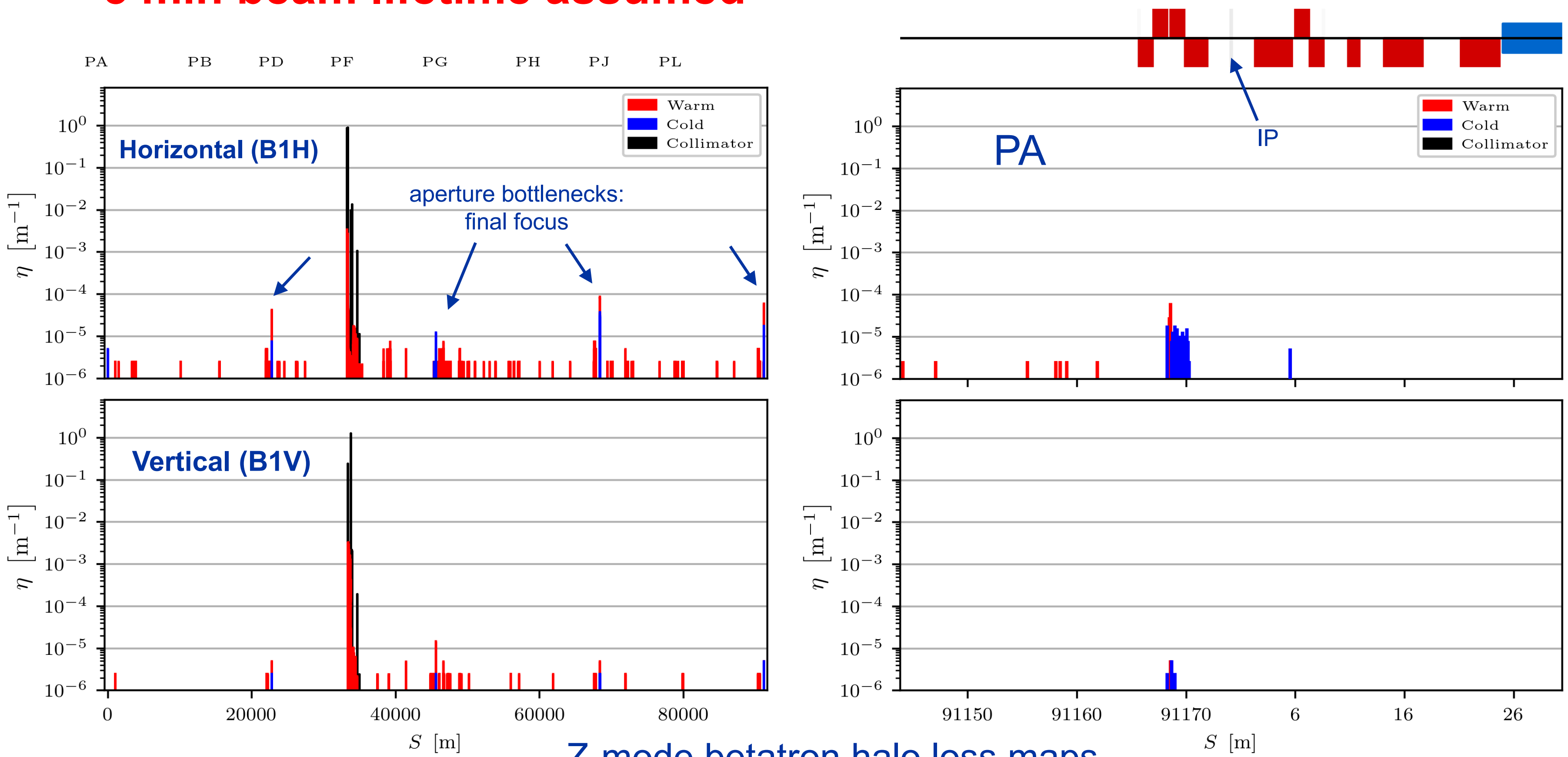
| Beam energy | [GeV] | 45.6 | 80 | 120 | 182.5 |
|---|---|---|---|---|---|
| Layout | | PA31-1.0 | | | |
| # of IPs | | 4 | | | |
| Circumference | [km] | 91.174117 | | 91.174107 | |
| Bending radius of arc dipole | [km] | 9.937 | | | |
| Energy loss / turn | [GeV] | 0.0391 | 0.370 | 1.869 | 10.0 |
| SR power / beam | [MW] | 50 | | | |
| Beam current | [mA] | 1280 | 135 | 26.7 | 5.00 |
| Bunches / beam | | 10000 | 880 | 248 | 40 |
| Bunch population | [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.37 |
| Horizontal emittance $\varepsilon_x$ | [nm] | 0.71 | 2.16 | 0.64 | 1.49 |
| Vertical emittance $\varepsilon_y$ | [pm] | 1.42 | 4.32 | 1.29 | 2.98 |
| Arc cell | | Long 90/90 | | 90/90 | |
| Momentum compaction $\alpha_p$ | [$10^{-6}$] | 28.5 | | 7.33 | |
| Arc sextupole families | | 75 | | 146 | |
| $\beta^*_{x/y}$ | [mm] | 100 / 0.8 | 200 / 1.0 | 300 / 1.0 | 1000 / 1.6 |
| Transverse tunes/IP $Q_{x/y}$ | | 53.563 / 53.600 | | 100.565 / 98.595 | |
| Energy spread (SR/BS) $\sigma_\delta$ | [%] | 0.038 / 0.132 | 0.069 / 0.154 | 0.103 / 0.185 | 0.157 / 0.221 |
| Bunch length (SR/BS) $\sigma_z$ | [mm] | 4.38 / 15.4 | 3.55 / 8.01 | 3.34 / 6.00 | 1.95 / 2.75 |
| RF voltage 400/800 MHz | [GV] | 0.120 / 0 | 1.0 / 0 | 2.08 / 0 | 2.5 / 8.8 |
| Harmonic number for 400 MHz | | 121648 | | | |
| RF freuqeuncy (400 MHz) | MHz | 399.994581 | | 399.994627 | |
| Synchrotron tune $Q_s$ | | 0.0370 | 0.0801 | 0.0328 | 0.0826 |
| Long. damping time | [turns] | 1168 | 217 | 64.5 | 18.5 |
| RF acceptance | [%] | 1.6 | 3.4 | 1.9 | 3.0 |
| Energy acceptance (DA) | [%] | ±1.3 | ±1.3 | ±1.7 | -2.8 +2.5 |
| Beam-beam $\xi_x/\xi_y$[a] | | 0.0023 / 0.135 | 0.011 / 0.125 | 0.014 / 0.131 | 0.093 / 0.140 |
| Luminosity / IP | [$10^{34}$/cm$^2$s] | 182 | 19.4 | 7.26 | 1.25 |
| Lifetime (q + BS) | [sec] | – | | 1065 | 4062 |
| Lifetime (lum) | [sec] | 1129 | 1070 | 596 | 744 |

[a] incl. hourglass.

K. Oide (talk)

# Beam halo losses - betatron

- 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
- No radiation and tapering, SR collimators not included, **1 µm** impact parameter
- **5 min beam lifetime assumed**




Z-mode betatron halo loss maps

Total loss power: **59.2 kW**

| Case | Max. int. power ± 100 m from IP [W] |
|---|---|
| B1H | 2.80 |
| B1V | 0.09 |

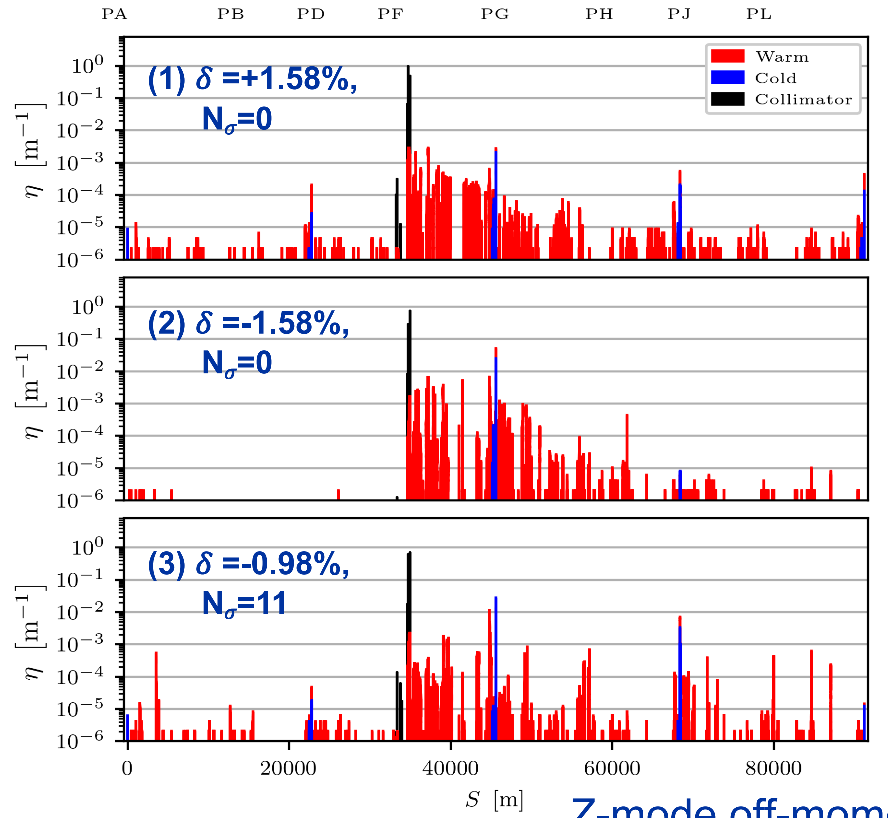
**significant protection from the collimation system**

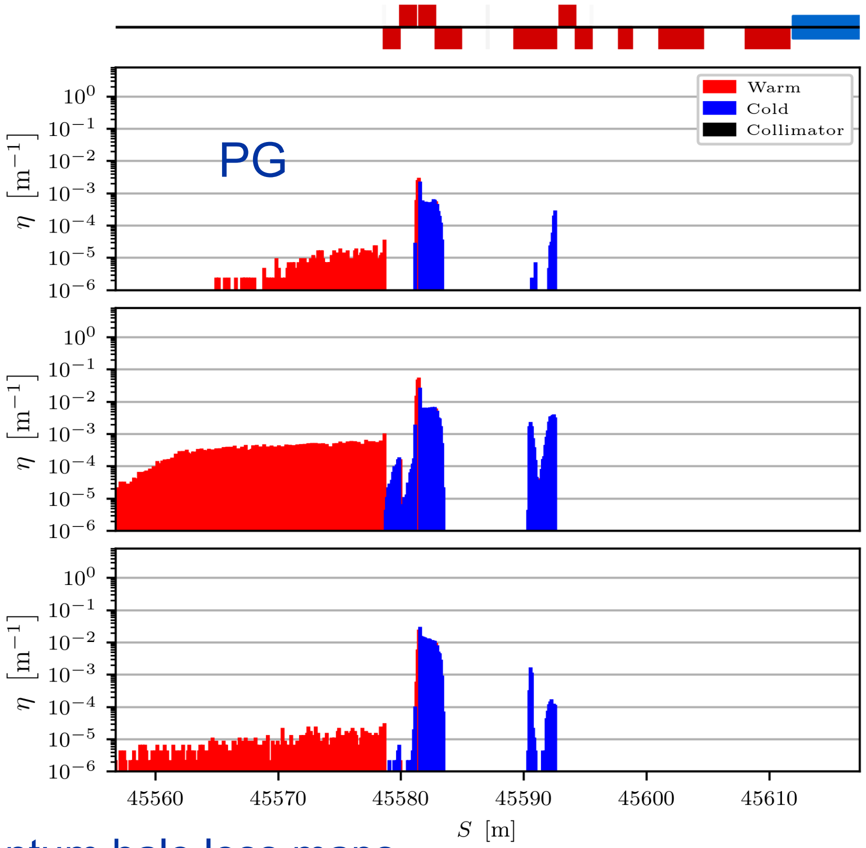
Power loads in the MDI for 5 min beam lifetime

# Beam halo losses - off-momentum

- First studies of off-momentum losses carried out
- Similar method to the betatron case:
  - Particles impacting the off-momentum primary collimator
  - Set $\delta$ and betatron amplitude to obtain **1 µm** impact parameter

$$x = N_\sigma\sqrt{\beta_x\epsilon_x} + D_x\delta$$




Z-mode off-momentum halo loss maps

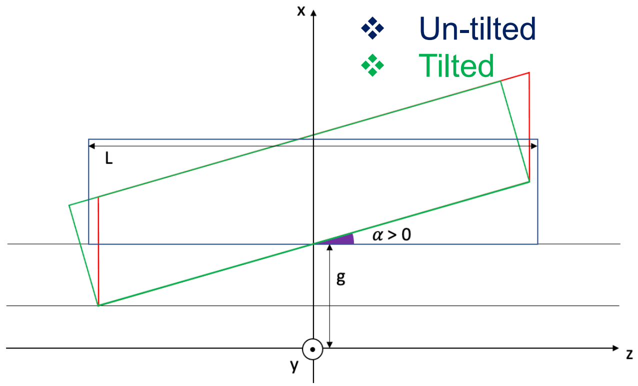
Total loss power: **59.2 kW**

| Case | Max. int. power ± 100 m from IP [W] |
|---|---|
| (1) $+\delta$ | 88.848 |
| (2) $-\delta$ | 1810.754 |
| (3) $-\delta$, $N_\sigma$ | 1310.374 |

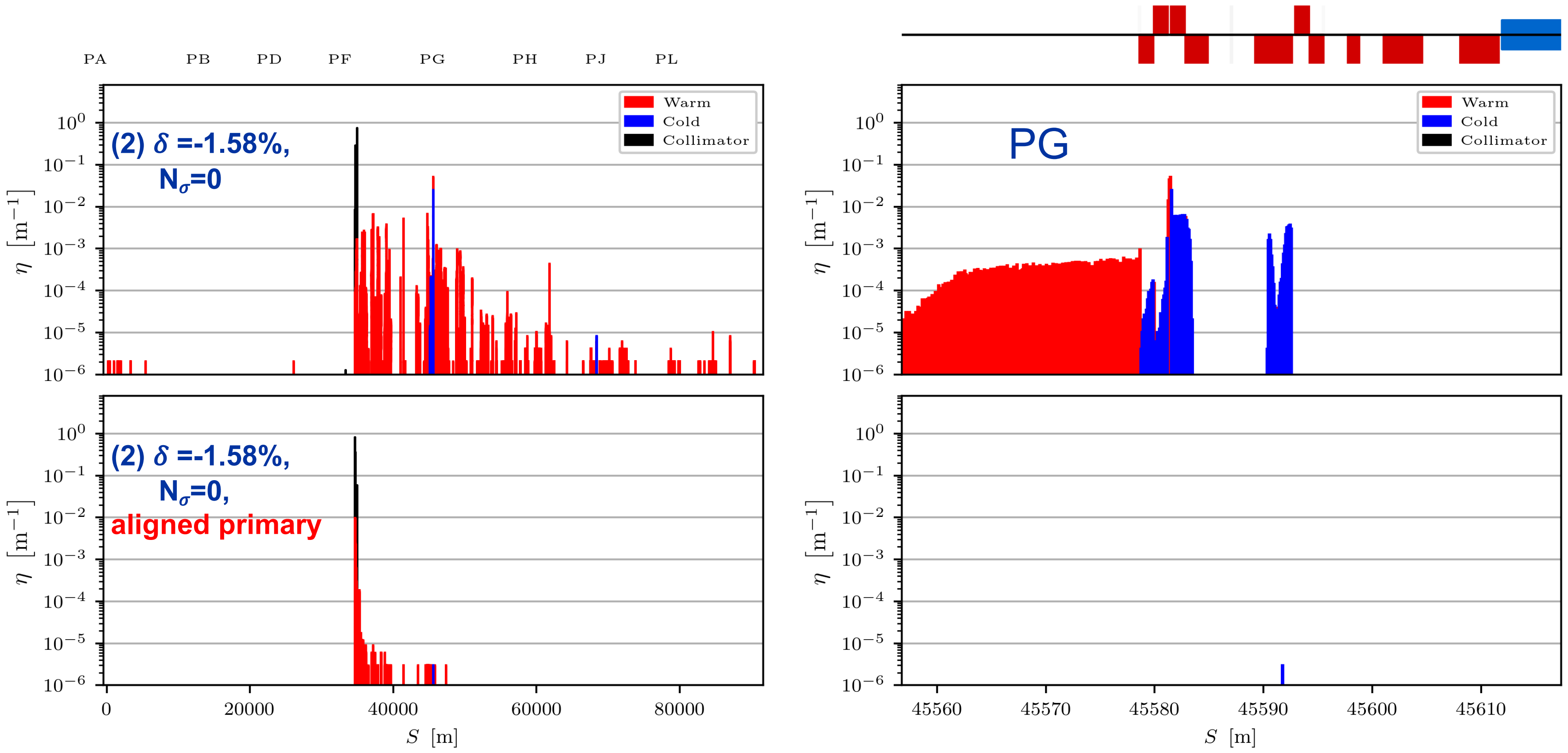
Power loads in the MDI for 5 min beam lifetime

# Off-momentum losses mitigation

- The results show high losses at the aperture bottlenecks
- Aligning the primary collimator with the beam divergence helps
  - This mitigation strategy has shown promise, but must be studied in detail
  - Alternative mitigation strategies under study – optics, layout, settings



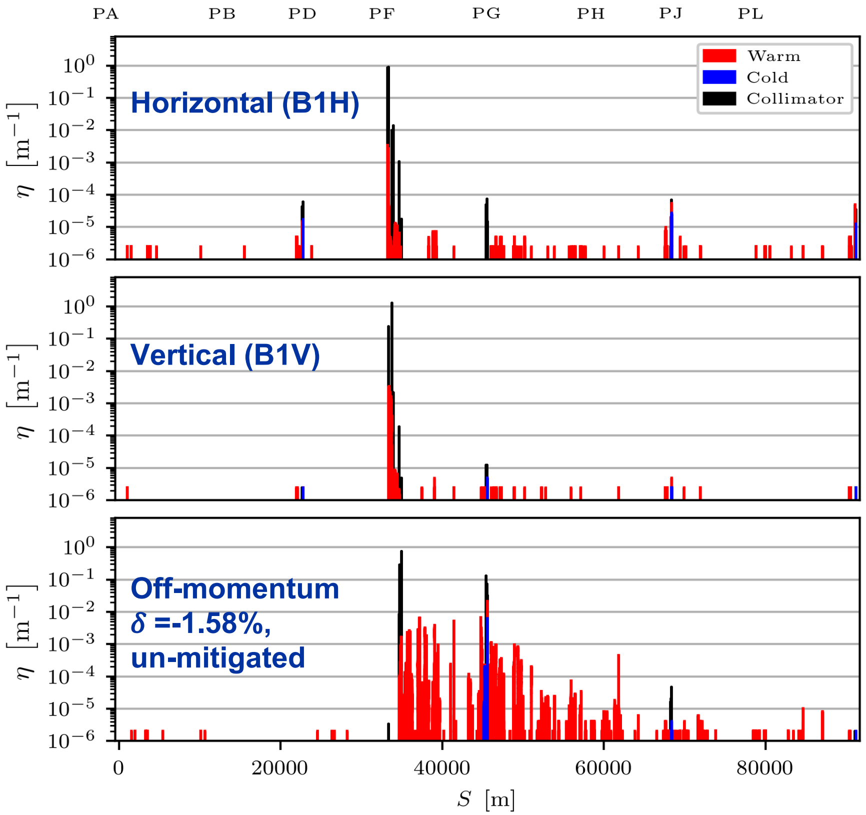

Schematic of collimator jaw tilt

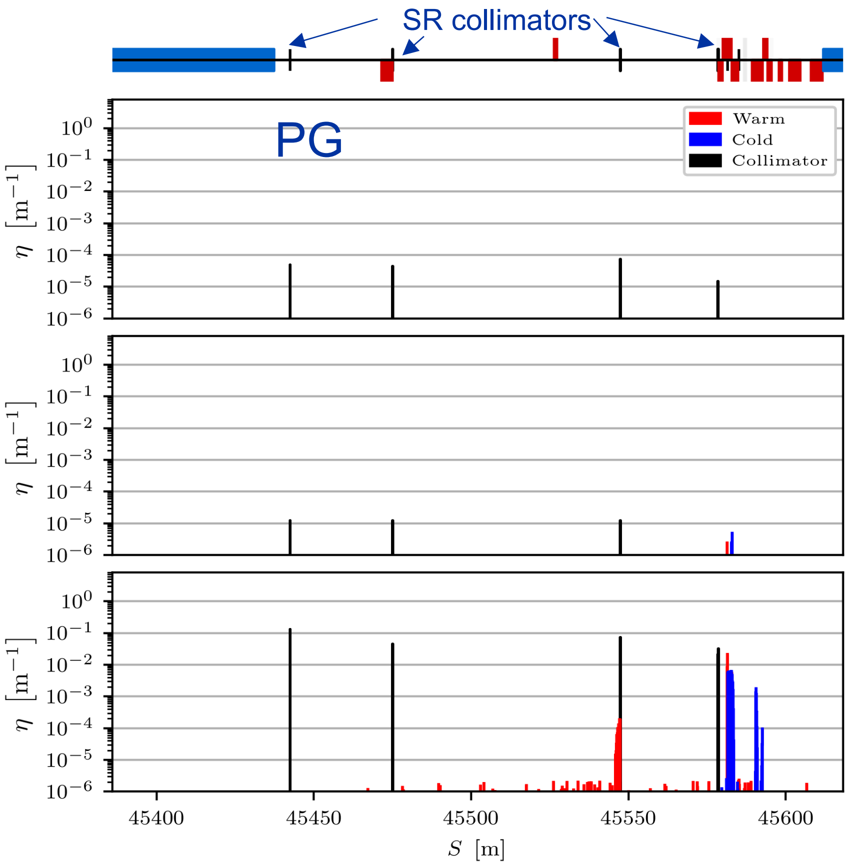



Z-mode off-momentum halo loss maps

# Beam halo losses – SR collimators

- The SR collimators upstream of the IPs have been integrated in the model
- The collimators intercept losses locally upstream of the IPs
- The energy deposition in the collimators and the backgrounds in the detector should be evaluated




Z-mode off-momentum halo loss maps with SR collimators

# Beam halo losses in the FCC-ee

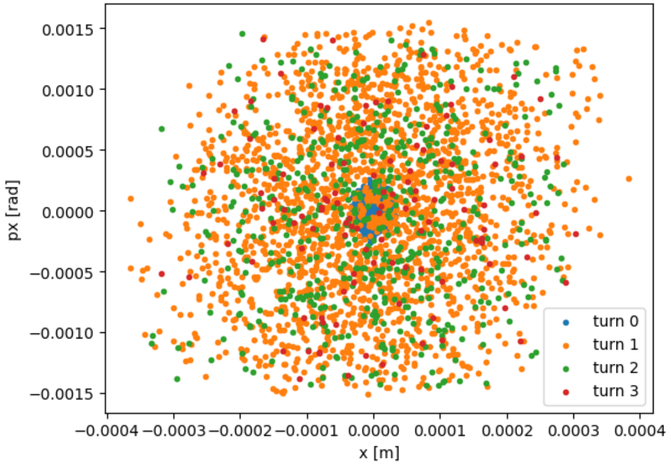
- **Halo losses studied for the Z mode**
  - For betatron losses, only a small fraction of the total loss power ends up in the IRs
  - For off-momentum losses, IRG is exposed to high power loads, up to 1.8 kW over the MDI
  - Mitigation with tilted primary collimators alleviates the off-momentum losses, but more studies are needed on the operational feasibility
  - SR collimators and masks intercept losses in all cases
  - The impact on the MDI and the detector is studied by the MDI team (A.Ciarma – talk this week)
- **The halo losses must be studied for the other beam modes**
  - The Z mode is the most critical due to the high stored beam energy

# Fast losses in the FCC-ee

- **Huge anomalous losses reported by SuperKEKB (T. Ishibashi, talk)**
  - Informally referred to as ‘crazy beam’
  - **Up to 80% of beam intensity lost over 2 turns**
  - Damage to collimators due to the beam loss
  - The cause is not identified yet
- **Some considerations for FCC-ee fast beam losses**
  - These beam loss scenarios are difficult to study without good knowledge of the driving process
    - Time-scale, location, type and magnitude of beam disturbance
  - Can consider first studies of the response to such losses in synthetic cases
    - Controlled beam excitation in simulations
    - Multi-turn tracking

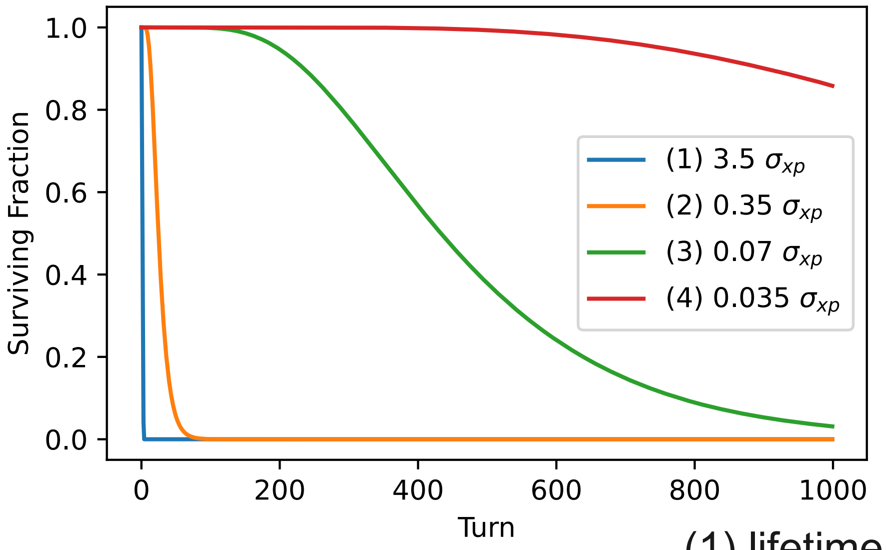
# Z-mode fast losses

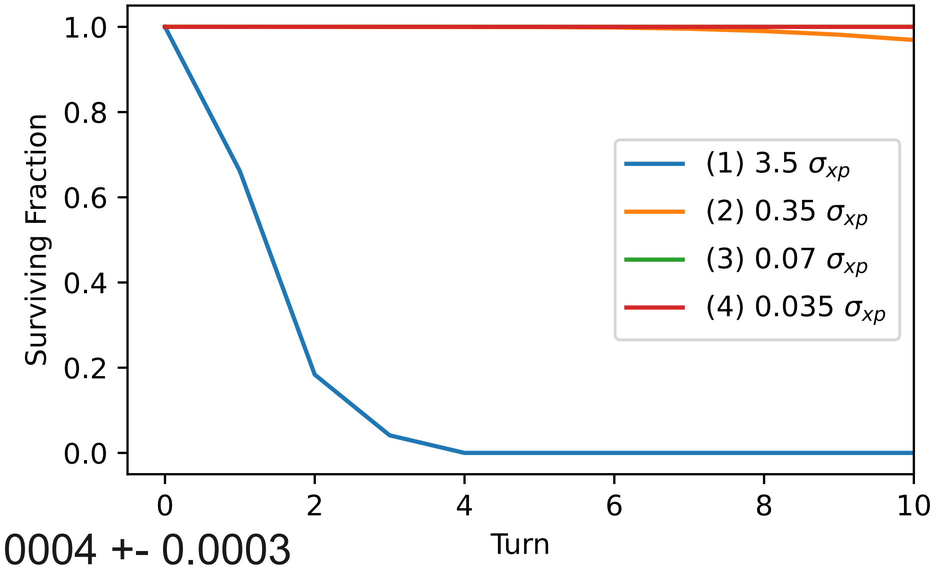
- **Study fast beam blow-up in simulations**
  - Random uniform per-particle kicks applied at 18 locations in the ring
  - Excitation amplitude adjusted to give different beam lifetime
  - **This simulation setup may not be representative of real-world losses**




Beam blow-up example (IPA)

Using different excitation amplitude for the B1H setup

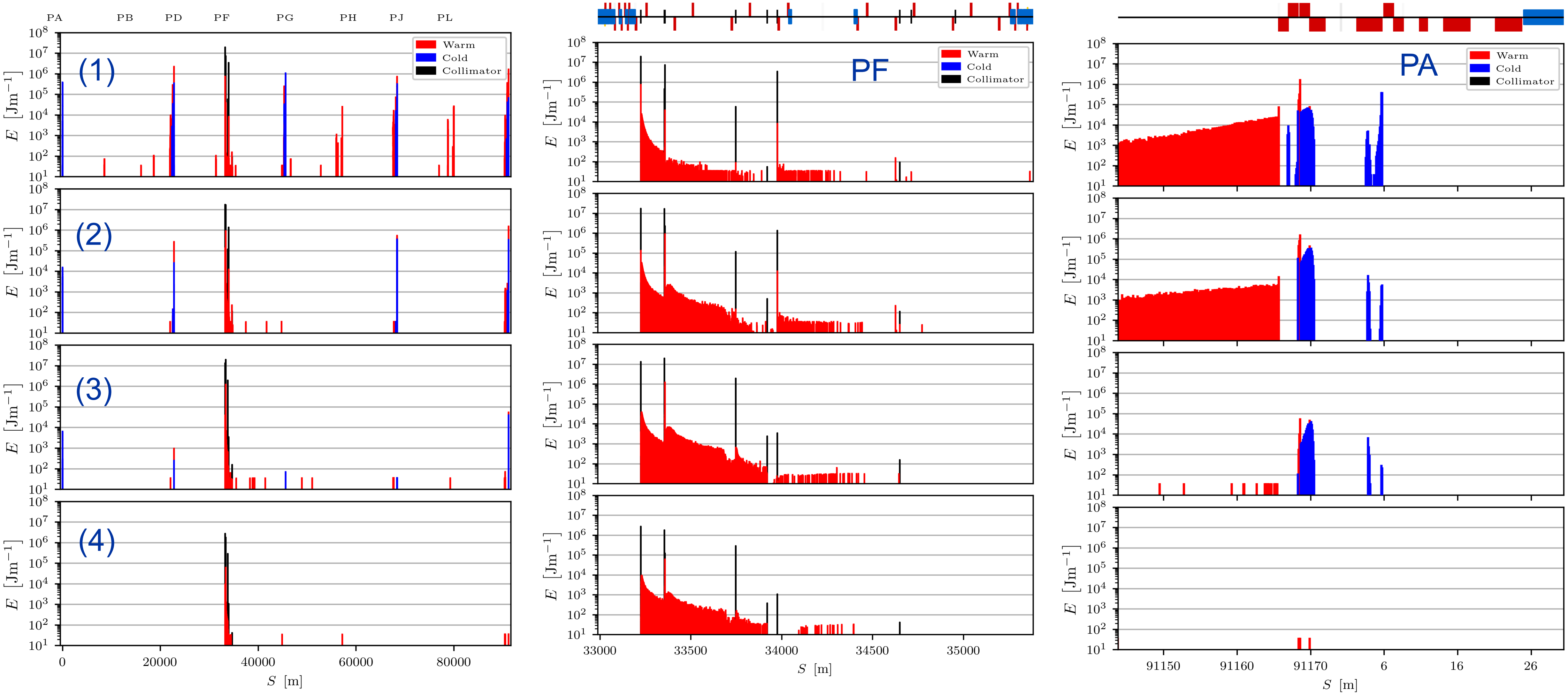



(1) lifetime [s]: 0.0004 +- 0.0003
(2) lifetime [s]: 0.0085 +- 0.0070
(3) lifetime [s]: 0.1639 +- 0.1401
(4) lifetime [s]: 4.0479 +- 4.5599

Beam lifetime from exponential fit

# Z-mode fast losses - simulation



# Z-mode fast losses

- **Huge losses observed in the simulation scenario**
  - Losses in the order of **MJ / m** in the superconducting final focus quadrupoles
  - This loss energy is likely destructive for the final focus doublets, detectors, and / or the tungsten SR collimators there (not modelled for these simulations)
  - Due to the large excitation amplitude, particles impact the aperture bottlenecks directly, before being intercepted by the collimation system in PF
    - Primary losses outside the collimation insertion are possible for other types of fast beam losses

- **Mitigation**
  - This loss scenario (**80% intensity loss over 2 turns**) is likely not tolerable without additional collimators, close to and in-phase with the aperture bottlenecks, like the LHC tertiary collimators
  - Sacrificial protection devices can also be considered
  - The loss scenario must also be defined better for the FCC-ee
    - **Time-scale and percentage intensity loss**
    - **Driving process (location, transverse vs. longitudinal, etc.)**
    - **Protection cannot be designed before it is understood how SuperKEKB losses translate to FCC-ee**

# 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 Z mode, iteration with the MDI team
    - No show-stoppers identified so far
    - Input on equipment loss tolerances needed to optimize performance

- **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

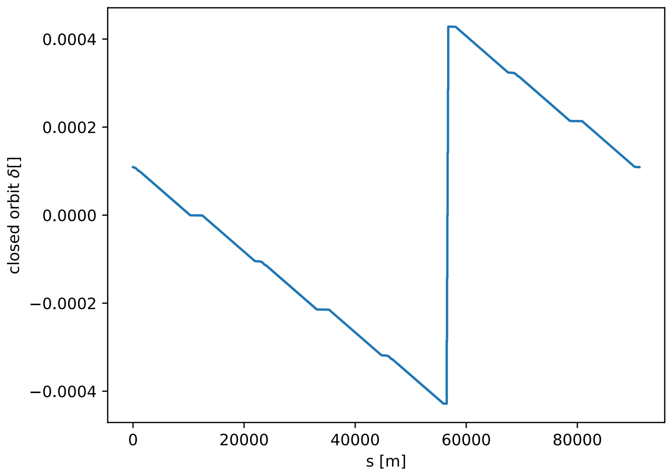
# Thank you!

# Backup slides

# Effects of synchrotron radiation for the Z mode

- **No significant differences in losses observed for the Z mode with radiation and optics tapering.**

- **The results are preliminary, more checks to be carried out.**




Closed orbit $\delta$ due to SR, used to adjust magnet strengths