FUTURE CIRCULAR COLLIDER

FCC-ee IR Beam Losses

A. Abramov, G. Broggi, R. Bruce, M. Hofer, S. Redaelli

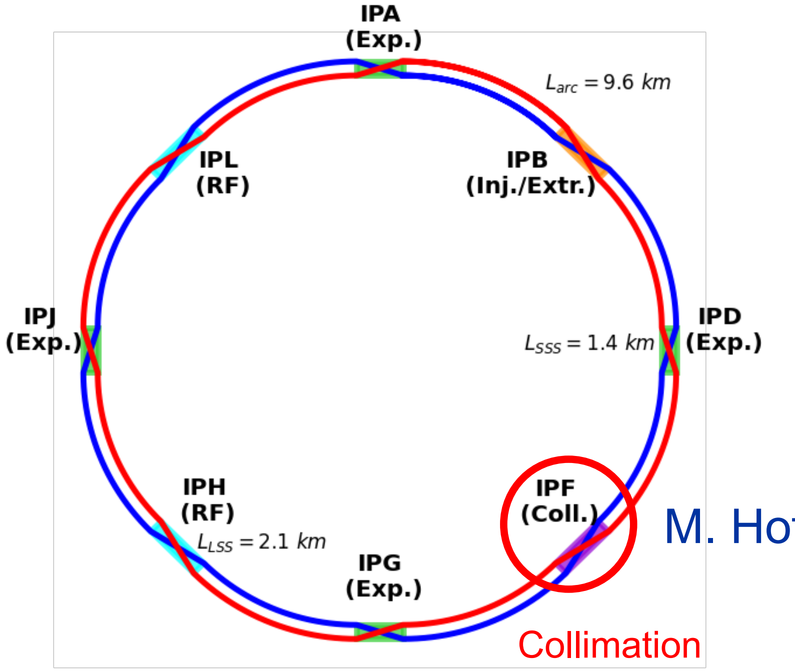
44th FCC-ee MDI meeting – 20/02/2023

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

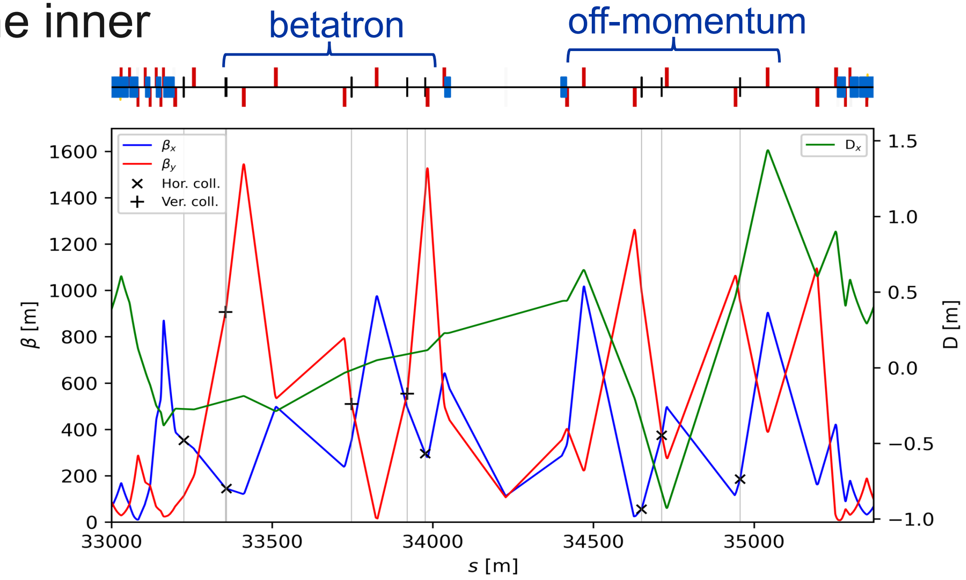
FCC-ee collimation system

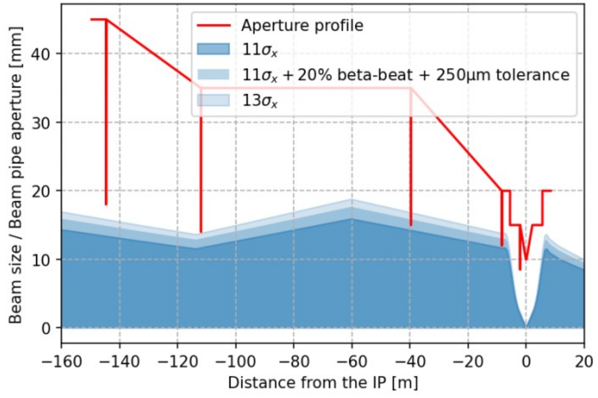
- **Dedicated halo collimation system in PF**
  - Two-stage betatron and off-momentum collimation in one insertion
  - Defines the global aperture bottleneck
  - Dedicated collimation optics (M. Hofer)
  - First collimator design for beam cleaning performance (G. Broggi)
- **Synchrotron radiation collimators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

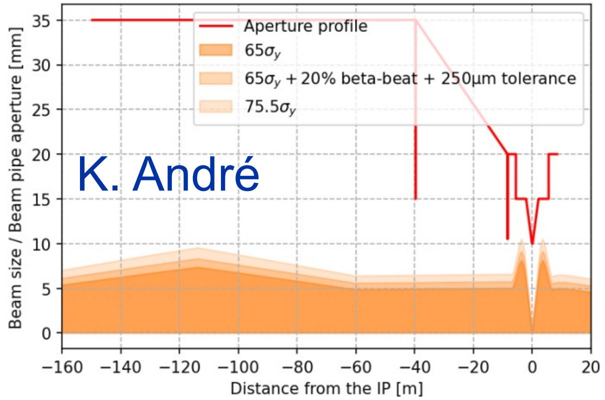


M. Hofer

Collimation insertion







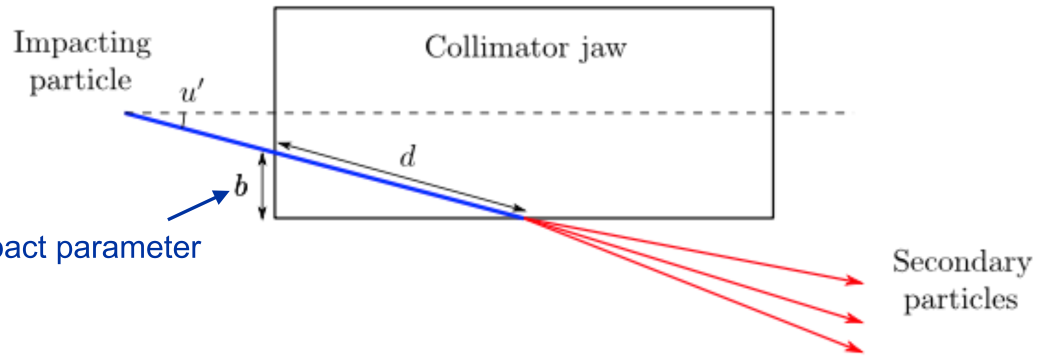
Beam loss sources

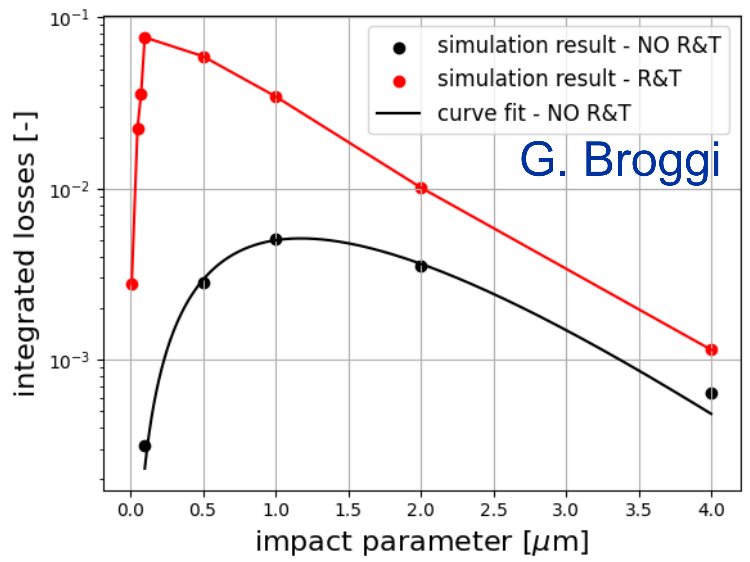
- **Many processes can lead to beam losses in the FCC-ee**
  - See talk by **H. Burkhardt** (**link**)
  - Beam losses can lead to:
    - Detector backgrounds
    - Superconducting magnet quench risk and material damage
    - Radiation damage and material activation

- **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

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**

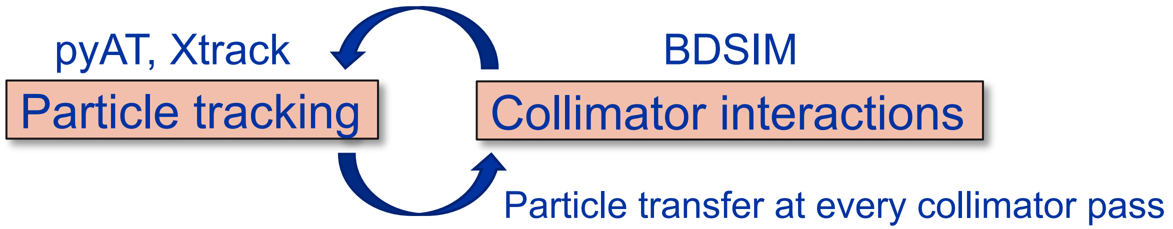


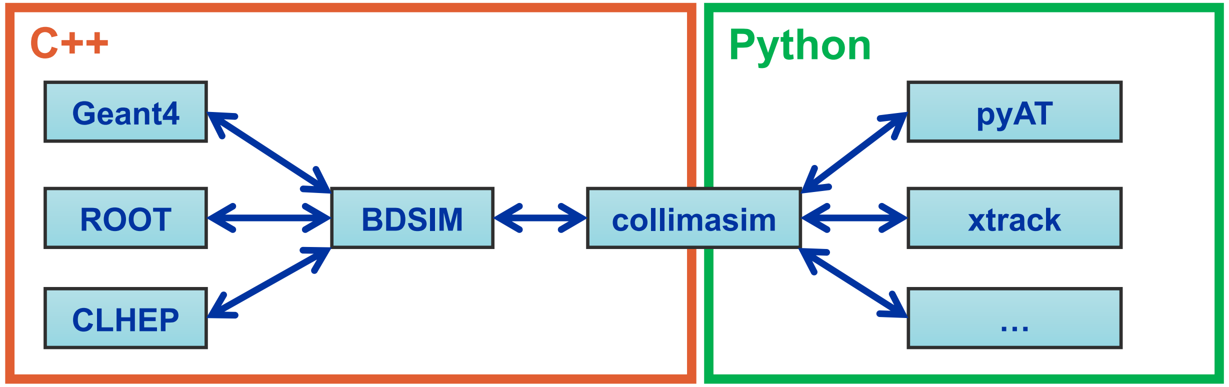


Impact parameter scan for 2 IP CDR lattice with MoGr primary collimator, with and without radiation and tapering (R&T)

FCC-ee collimation simulation setup

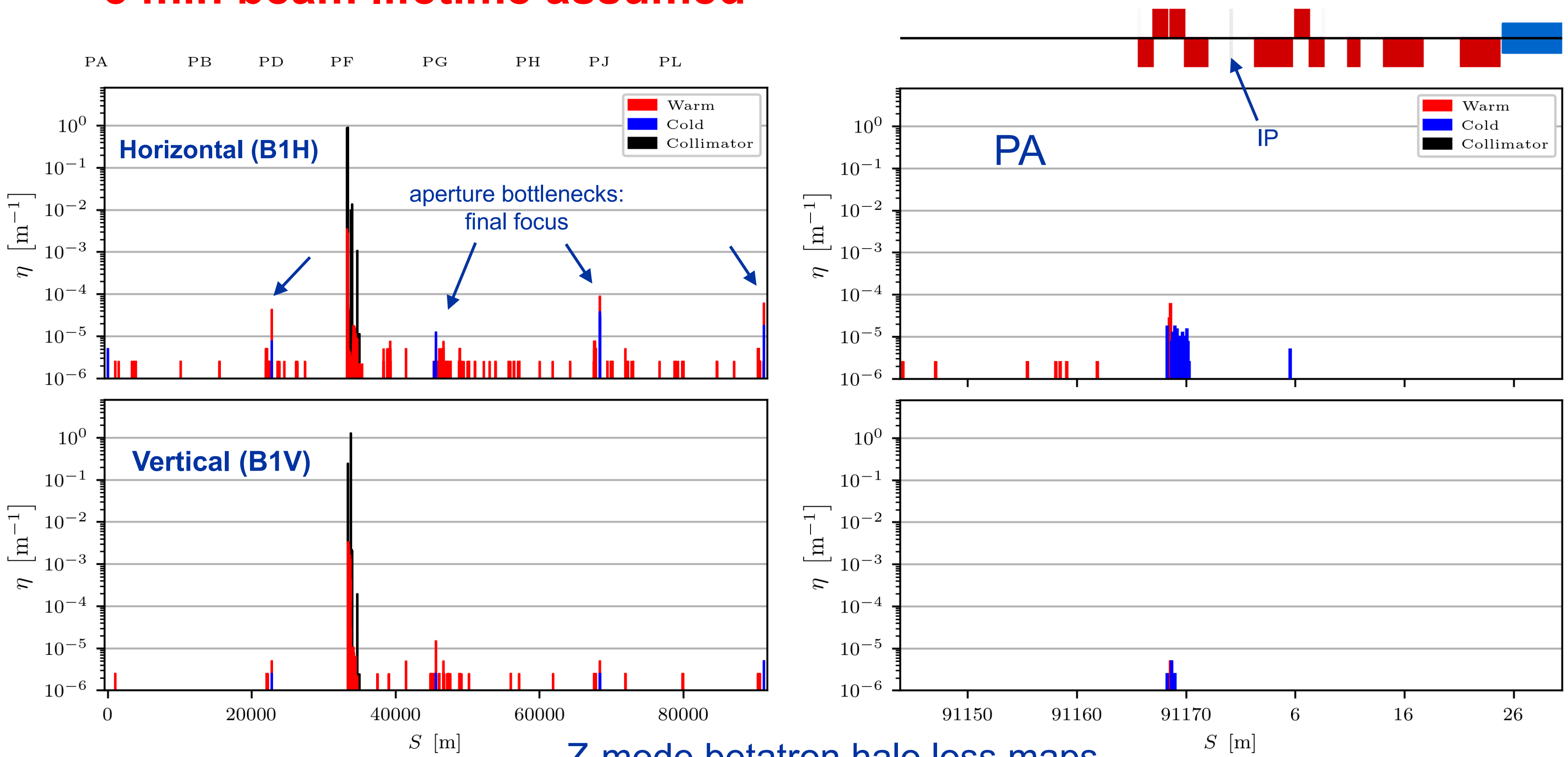
- **The FCC-ee presents unique challenges for collimation simulations:**
  - Synchrotron radiation and magnet strength (optics) tapering to compensate it
  - Complex beam dynamics – strong sextupoles in lattice, strong beam-beam effects (Beamstrahlung)
  - Electron/positron beam particle-matter interactions
  - Large accelerator – 91 km beamline, efficiency is crucial
- **Xsuite + BDSIM (Geant4)**
  - Benchmarked against other codes for FCC-ee – MAD-X, pyAT, SixTrack-FLUKA coupling (IPAC'22 paper)
  - Used for for the latest FCC-ee collimation studies (A. Abramov, G. Broggi)
  - Tests / benchmarks in other machines:
    - LHC (FCC-ee optics meeting talk) – G. Broggi
    - PS (NDC section meeting talk) – T. Pugnat





Z mode 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

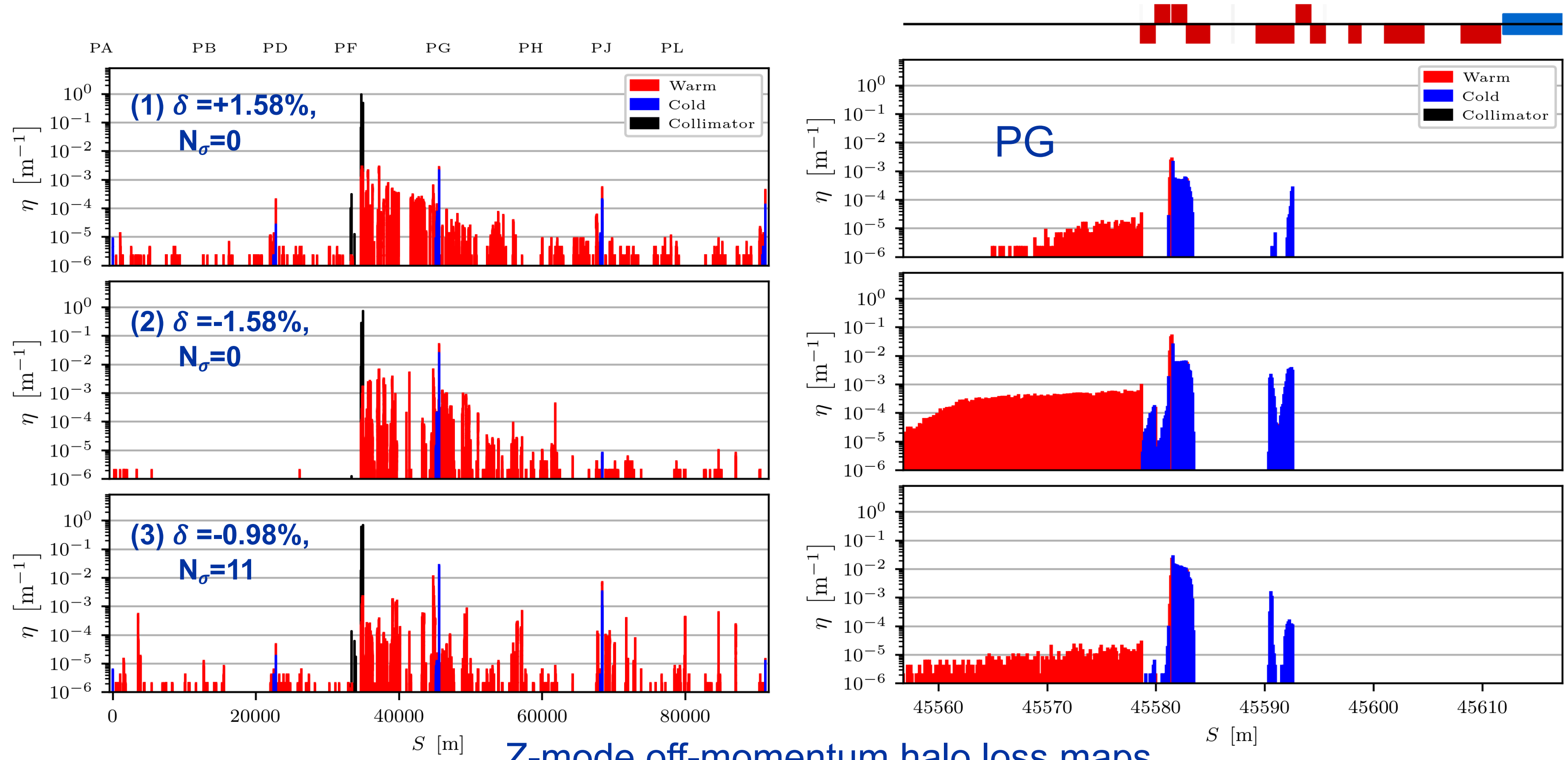
significant protection from the collimation system

Power loads in the MDI for 5 min beam lifetime

Z mode 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 δ 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

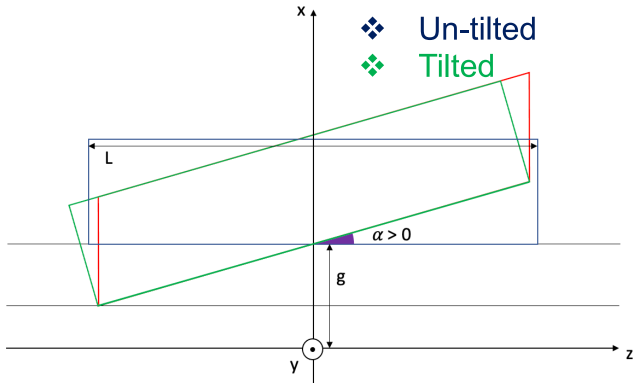
Total loss power: **59.2 kW**

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

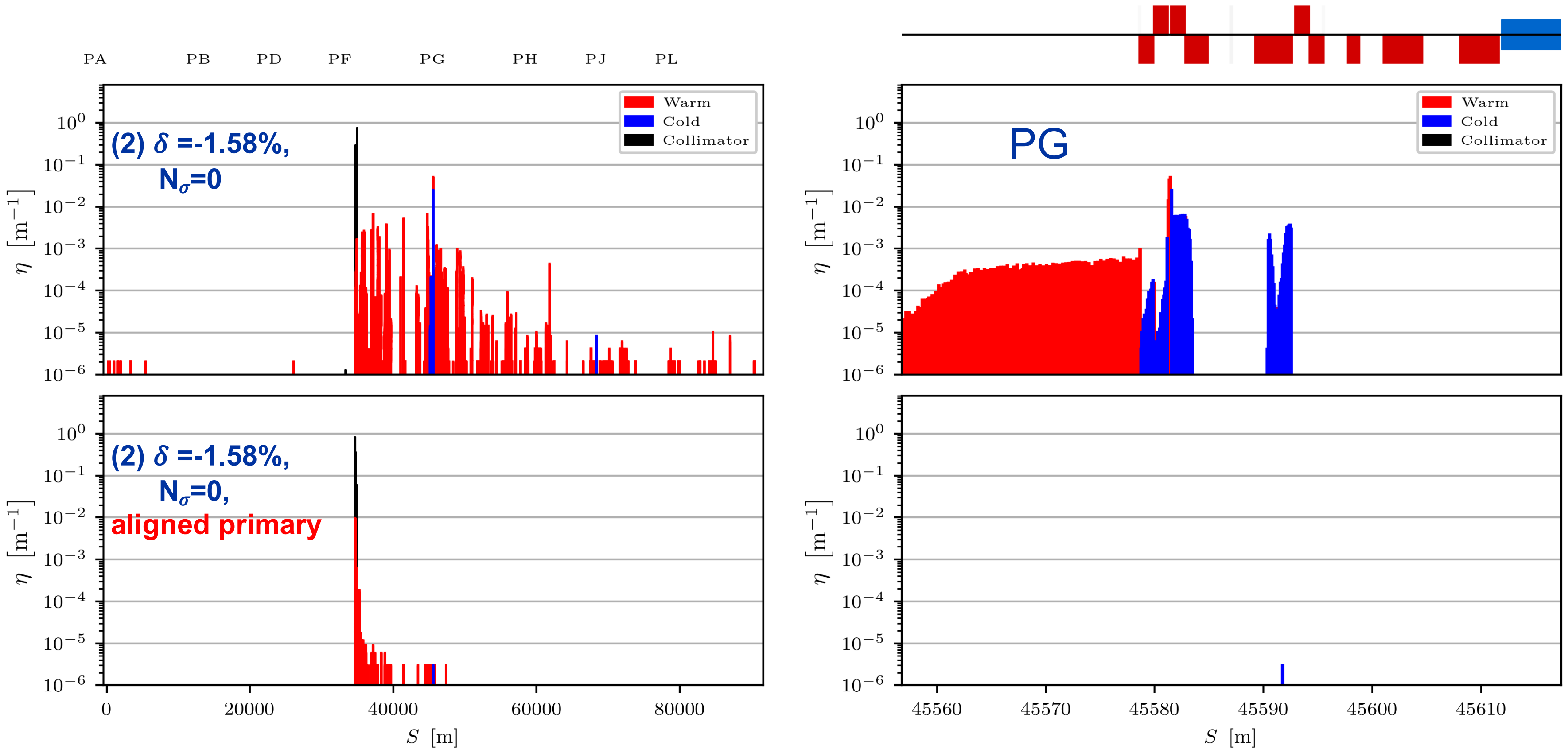
Power loads in the MDI for 5 min beam lifetime

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



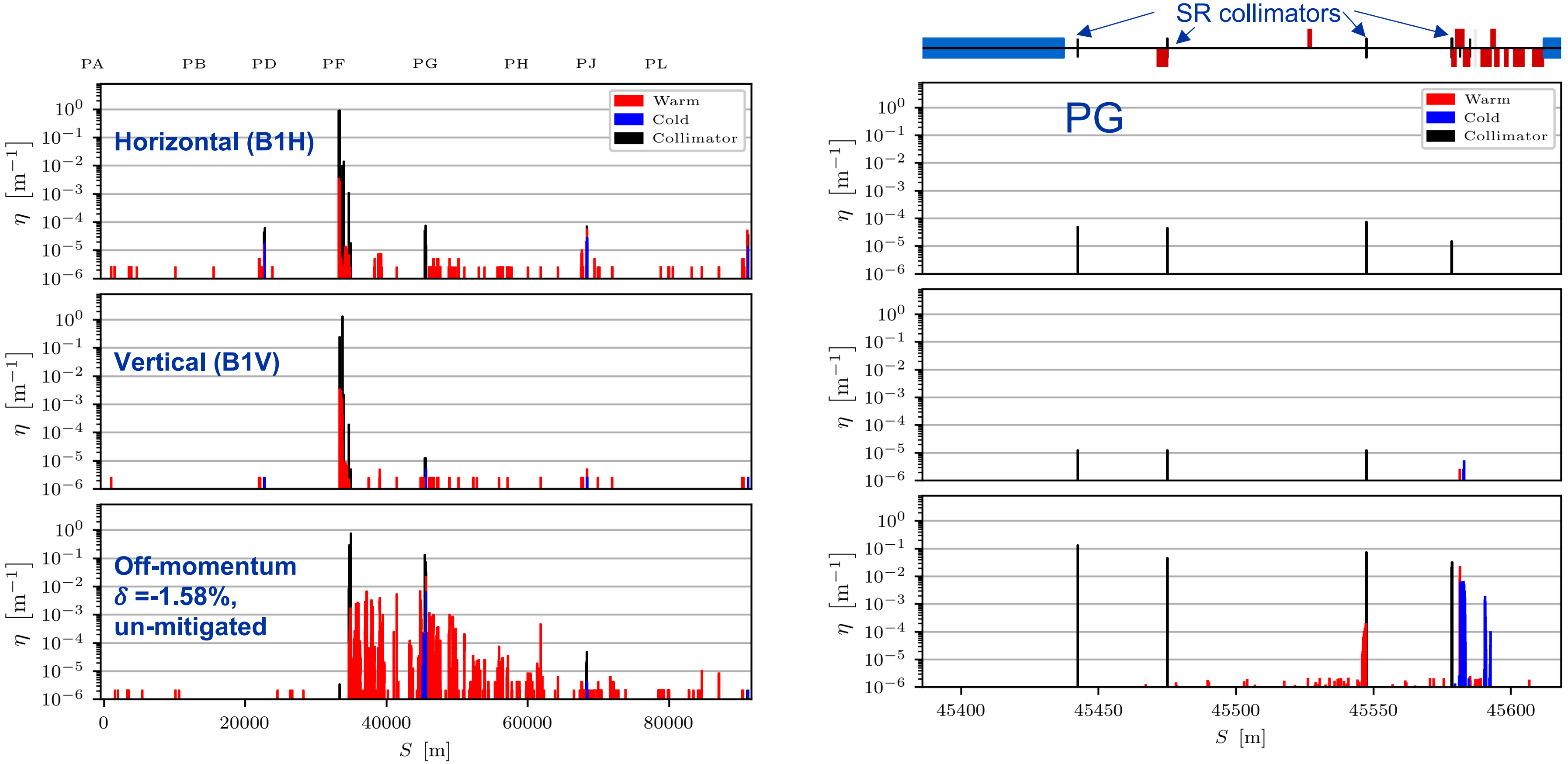
Schematic of collimator jaw tilt



Z-mode off-momentum halo loss maps

Z mode halo losses – with SR collimators

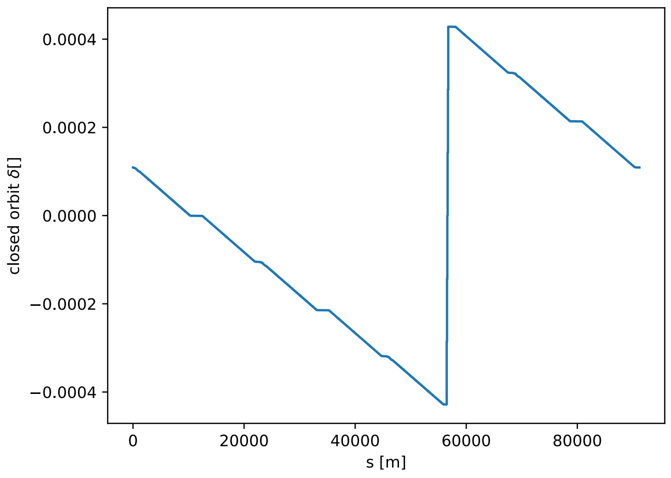
- The SR collimators upstream of the IPs have been integrated in the model
- The collimators intercept losses locally upstream of the IPs
- The energy deposition in the collimators and the backgrounds in the detector should be evaluated



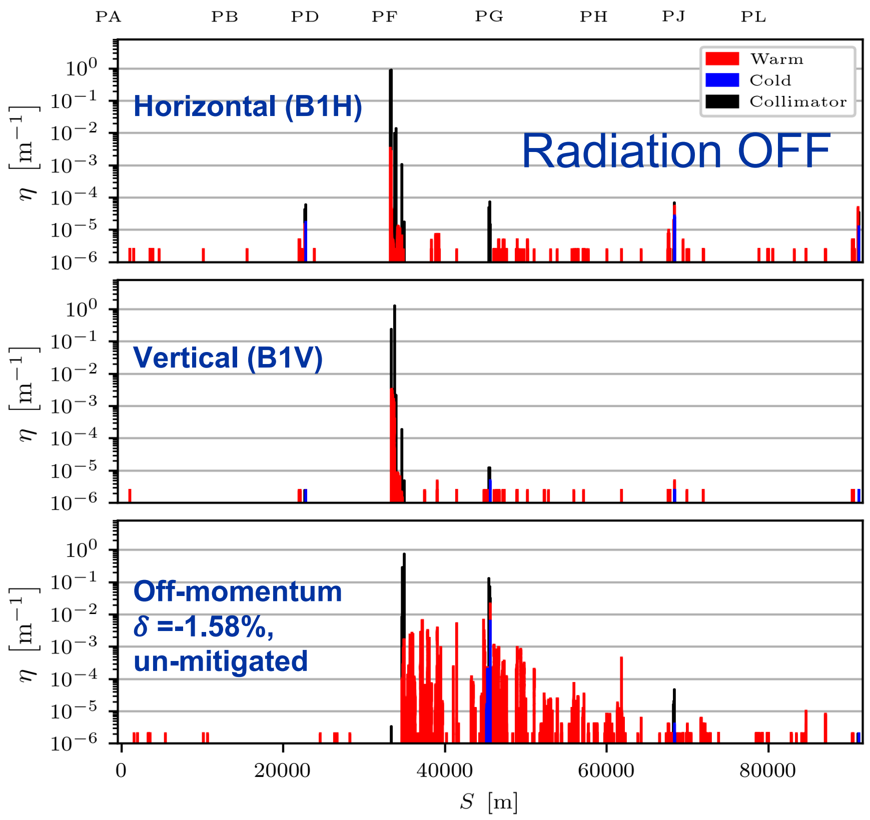
Z-mode off-momentum halo loss maps with SR collimators

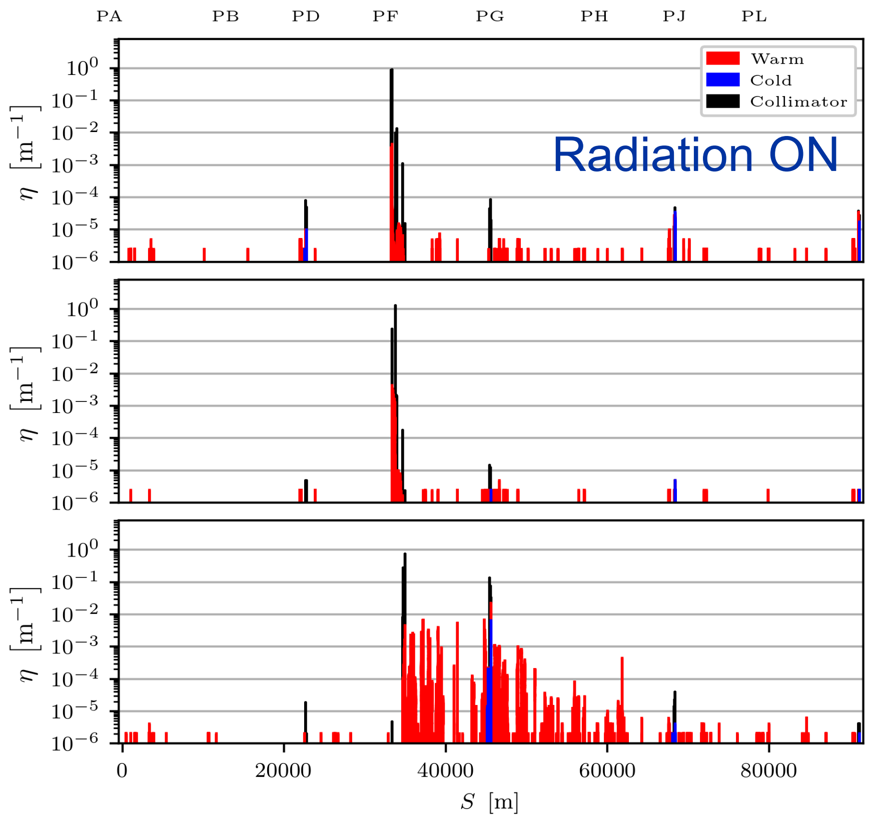
Z mode halo losses – with radiation and tapering

- **No significant differences in losses observed for the Z mode with radiation and optics tapering.**
- **Some indications of issues with the DA affecting the tracking**



Closed orbit δ due to SR, used to adjust magnet strengths



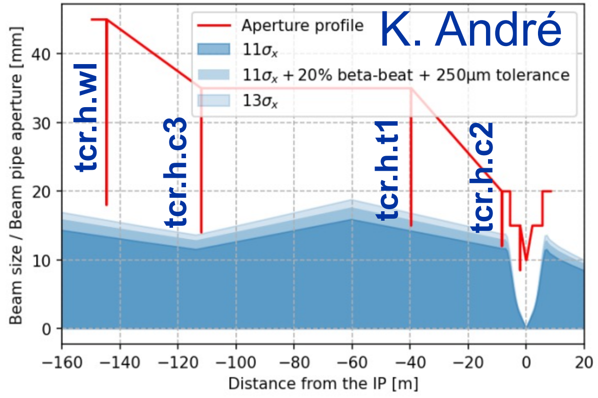


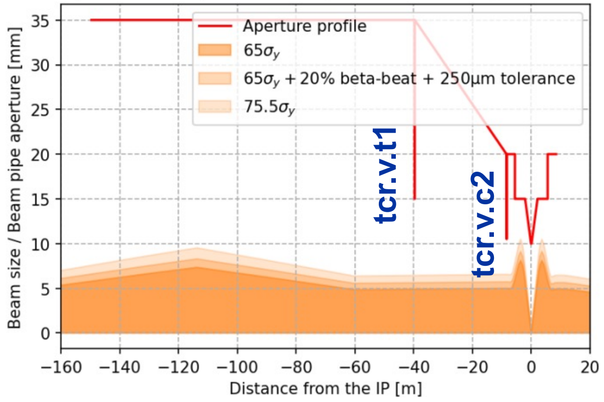
Z mode losses on SR collimators

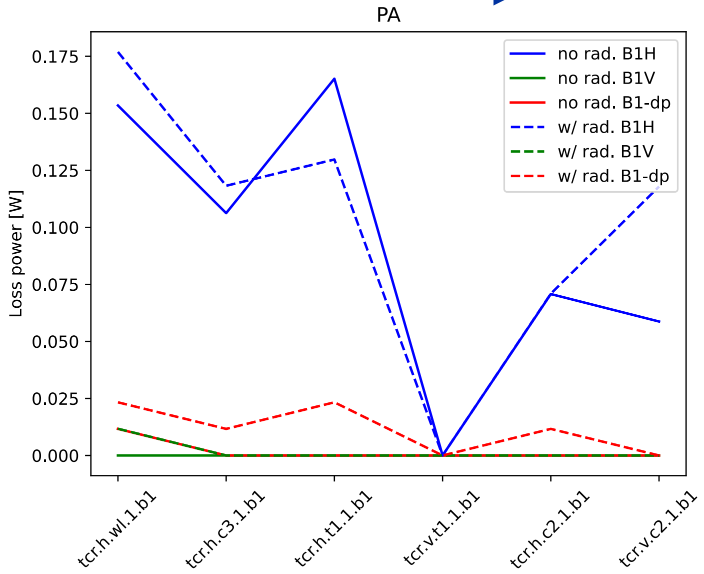
- **The SR collimators intercept losses for all cases**
  - Highest load on WL and C3 horizontal collimators
  - Lowest load on the vertical T1 collimator

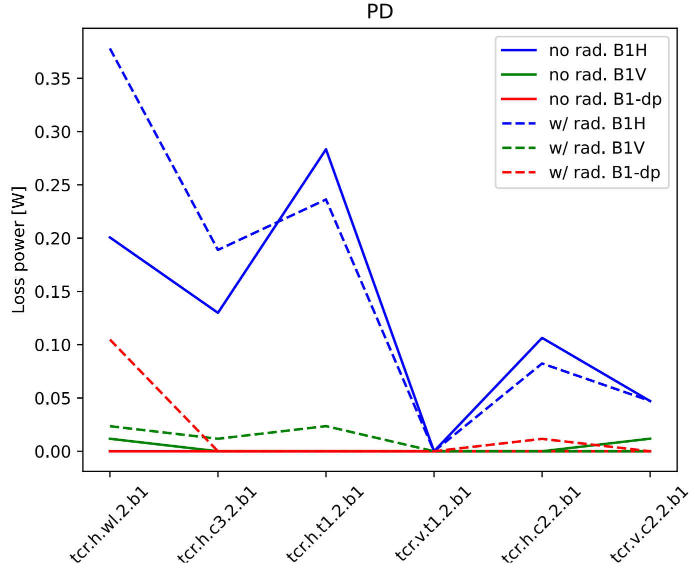
beam →

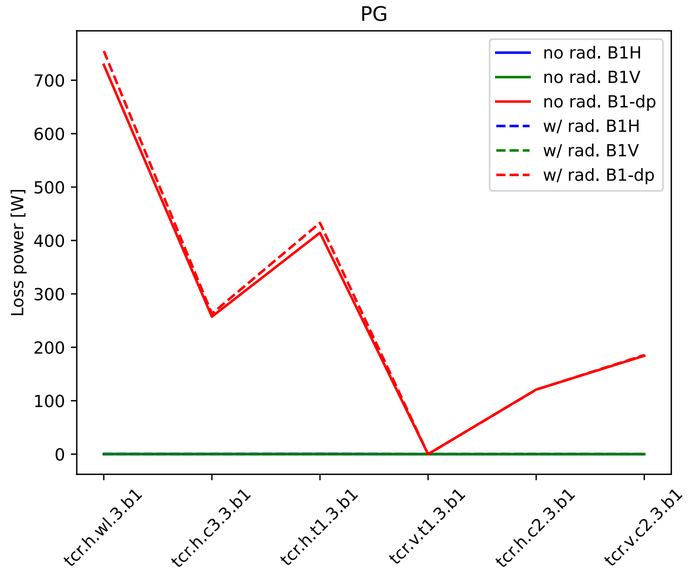
Total loss power: **59.2 kW**

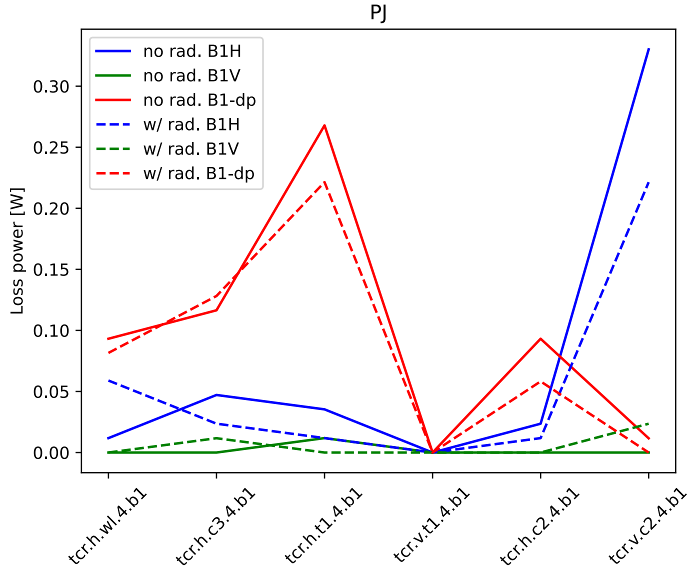






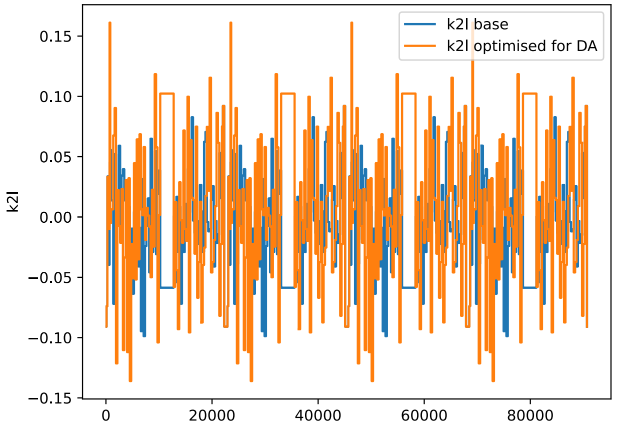


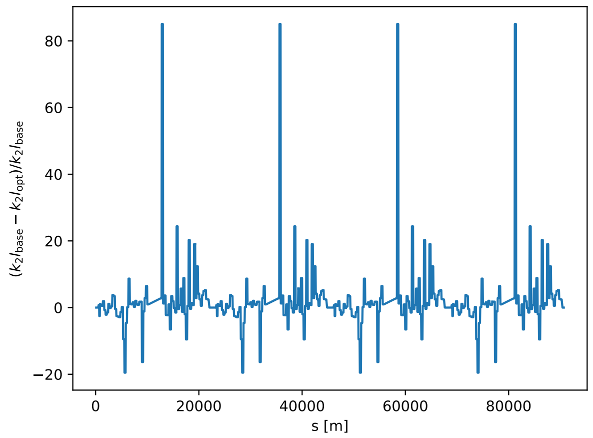




Issues with the sextupoles

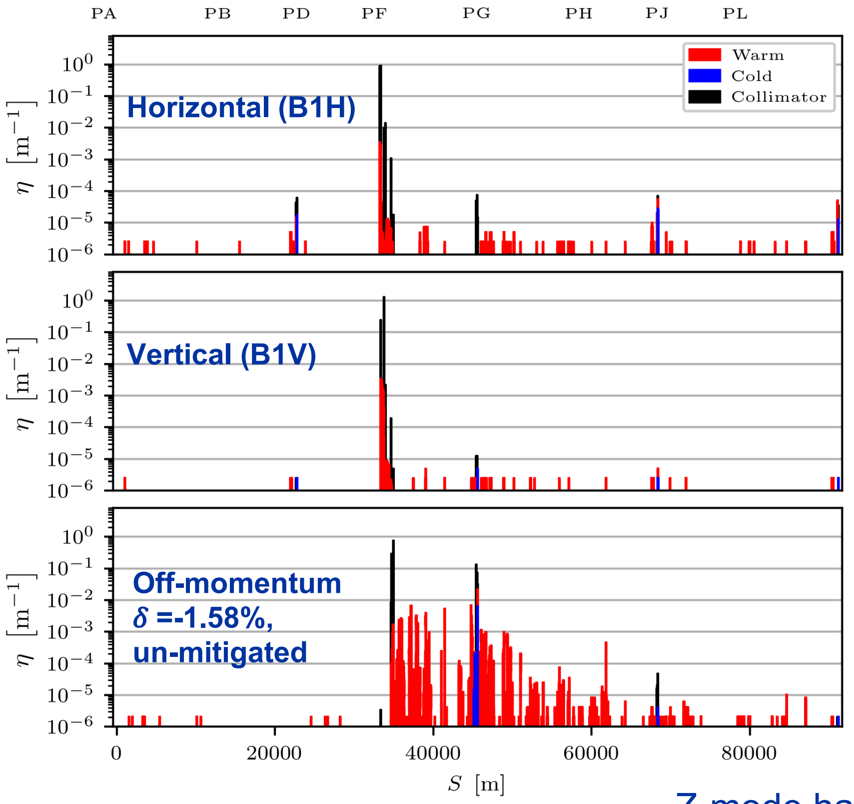
- Comparing the base Z mode sextupole configuration and a configuration optimized for DA (M. Hofer)
- The optimized configuration leads to faster loss of particles scattered from collimators
- The effect is most notable for the off-momentum case



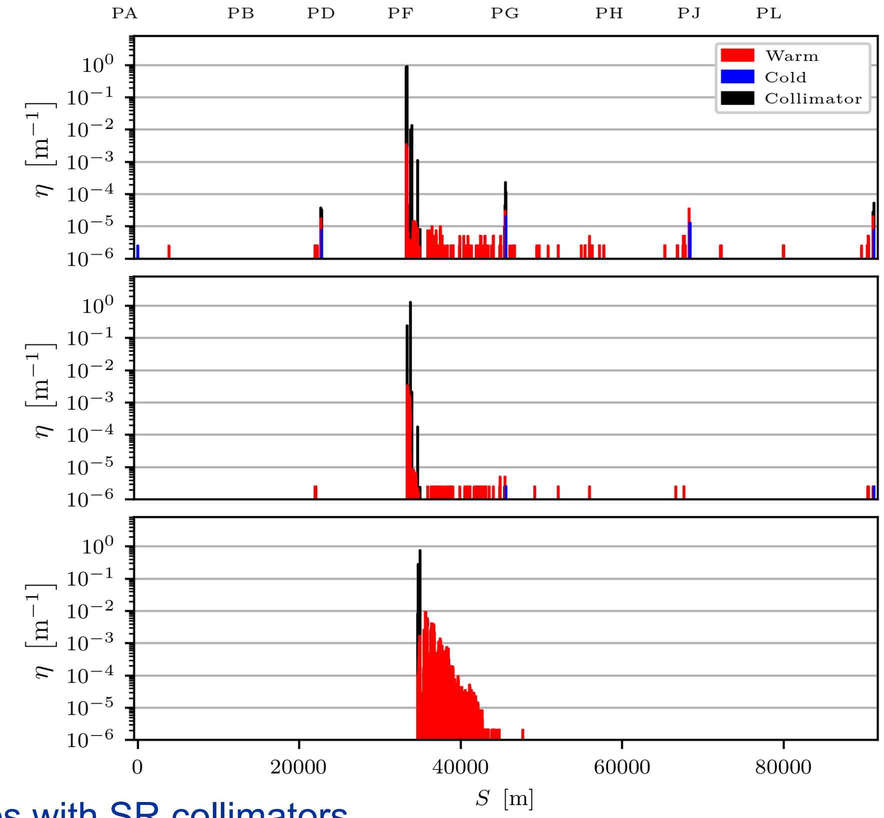


No radiation and tapering

Base sextupole settings



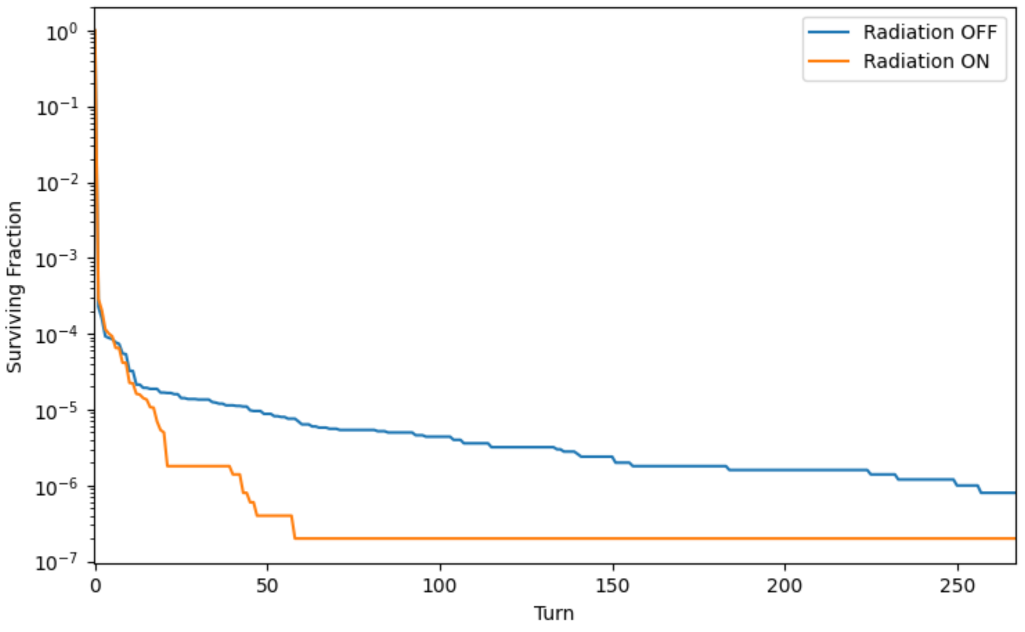
Optimized sextupole settings



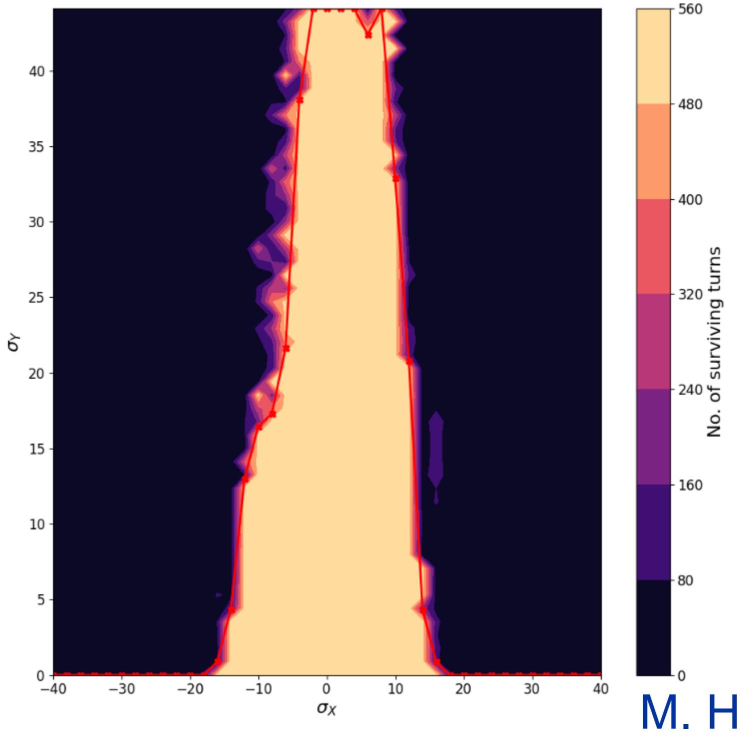
Z-mode halo loss maps with SR collimators

Issues with the radiation and tapering

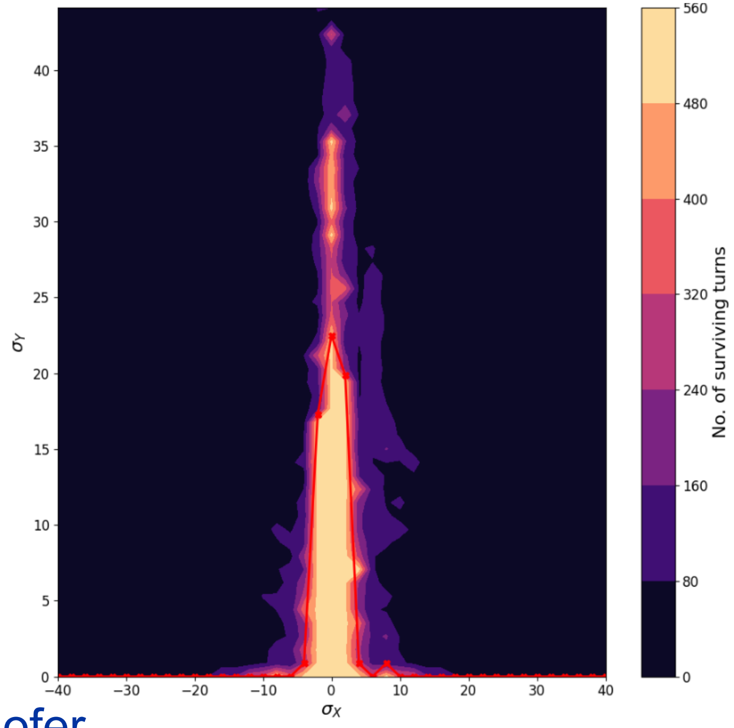
- **There are more losses observed with radiation and tapering for the Z mode**
  - This is not expected, due to the damping from the radiation
  - However, the DA seems a lot worse with radiation and tapering
  - Using the old sextupole settings, as the new optimised settings are paradoxically destructive for the halo
  - Need to resolve this before running spent beam and injected beam studies



DA@Z, no rad. / tap.



DA@Z, with rad. / tap.



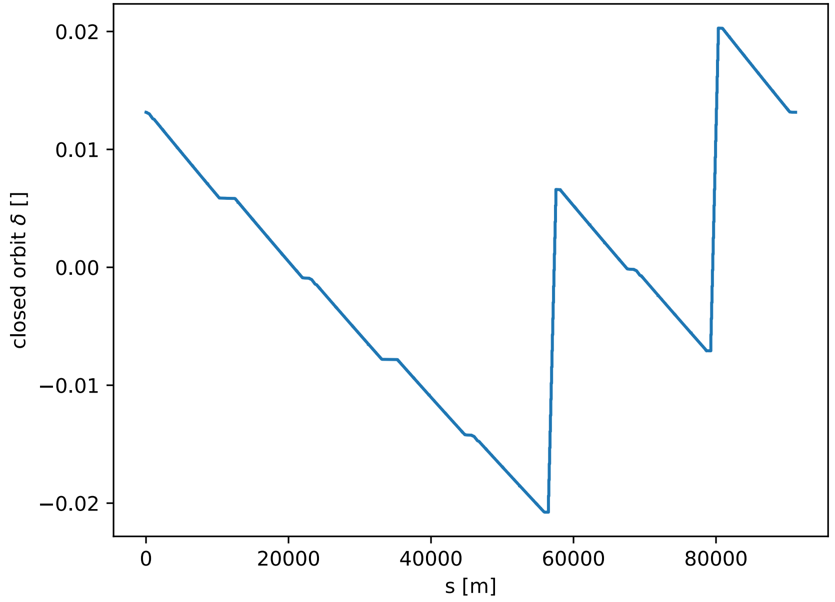
M. Hofer

Z mode halo losses - summary

- **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, up to 700 W on a single SR collimator
  - 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)**
- **Very sensitive configuration at the Z – sextupole settings, DA, MA**
- **Need to resolve the DA before studying the spent beam and injected beam cases**

Beam halo losses for the ttbar mode

- **Collimation studies for the ttbar mode were first presented for FCC week 2022 (link)**
- **Added synchrotron radiation collimators to the ttbar mode**
  - Some beta-beating at the SR collimation locations near the 4 IPs (around 3%)
- **Added radiation and tapering**
  - Previous issues with this – problematic RF matching and tapering in MAD-X
  - Tapering now done in Xsuite, based on approximately equal positive and negative delta, e.g sum(delta) = 0



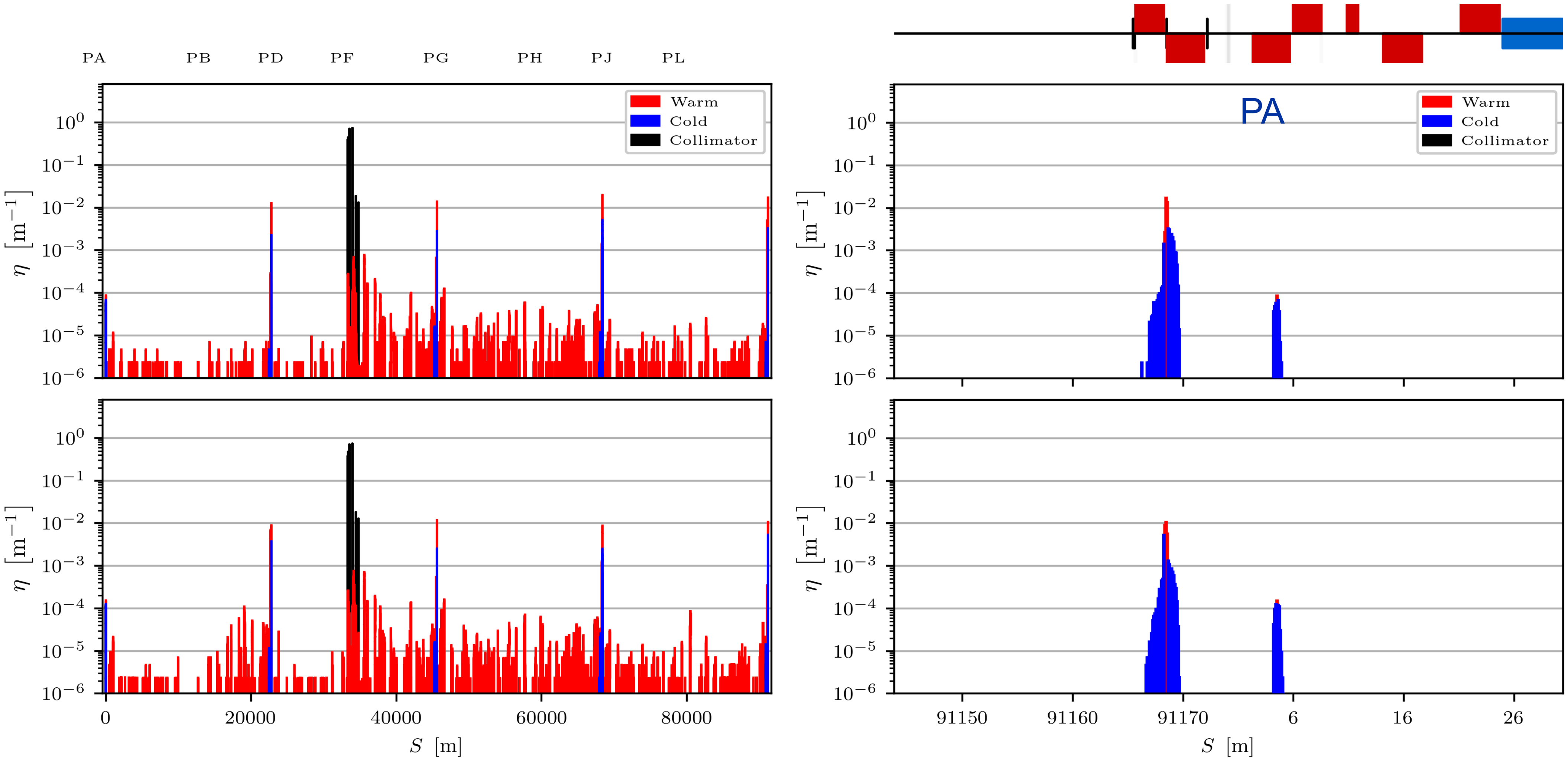
Closed orbit δ due to SR, used to adjust magnet strengths

ttbar mode halo losses - betatron

- Beam 1 horizontal (B1H), 1 um impact parameter, no SR collimators

B1H
No rad. / tap.

B1H
With rad. / tap.

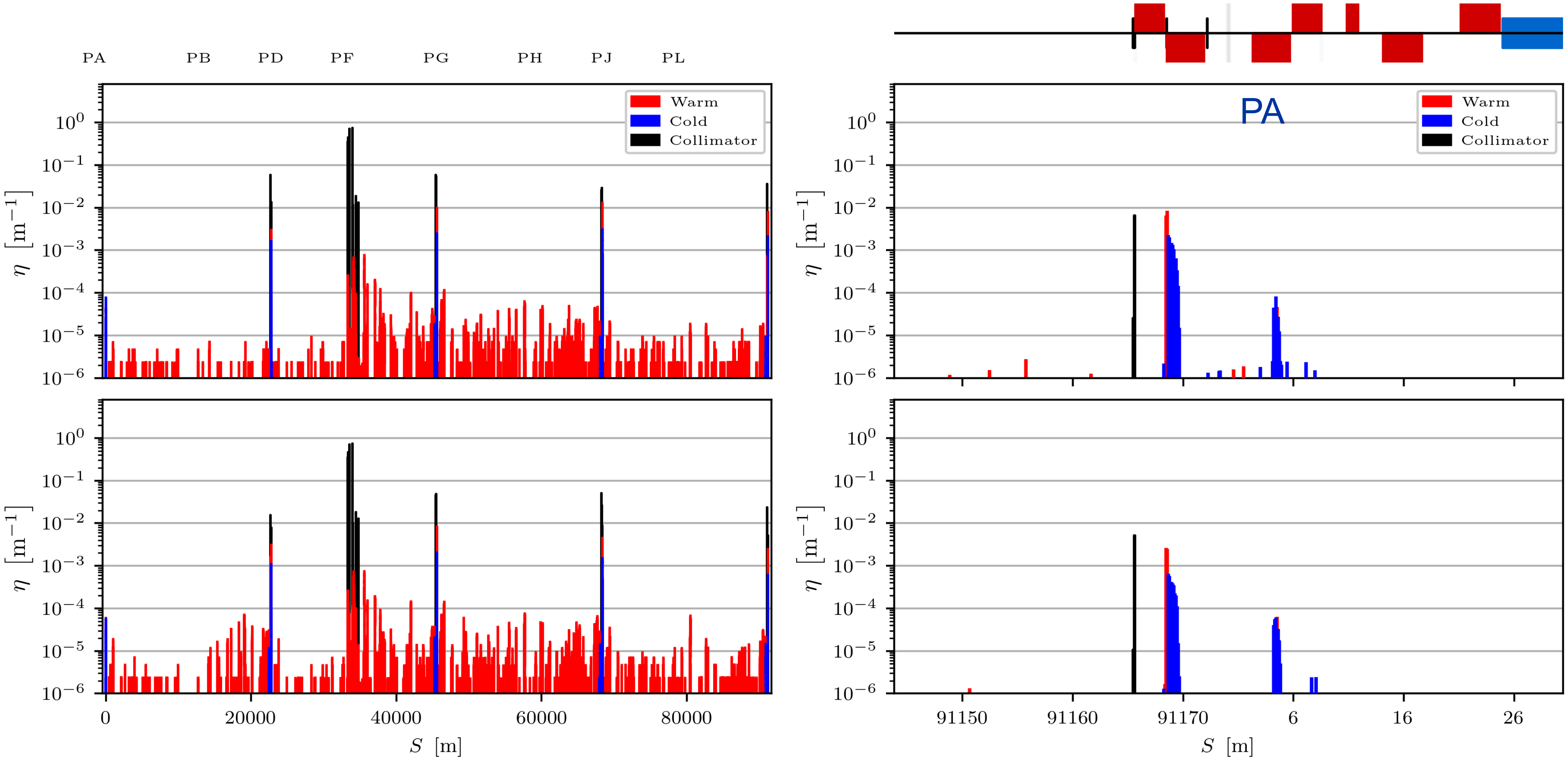


ttbar mode halo losses - betatron

- **Beam 1 horizontal (B1H), 1 um impact parameter, with SR collimators**

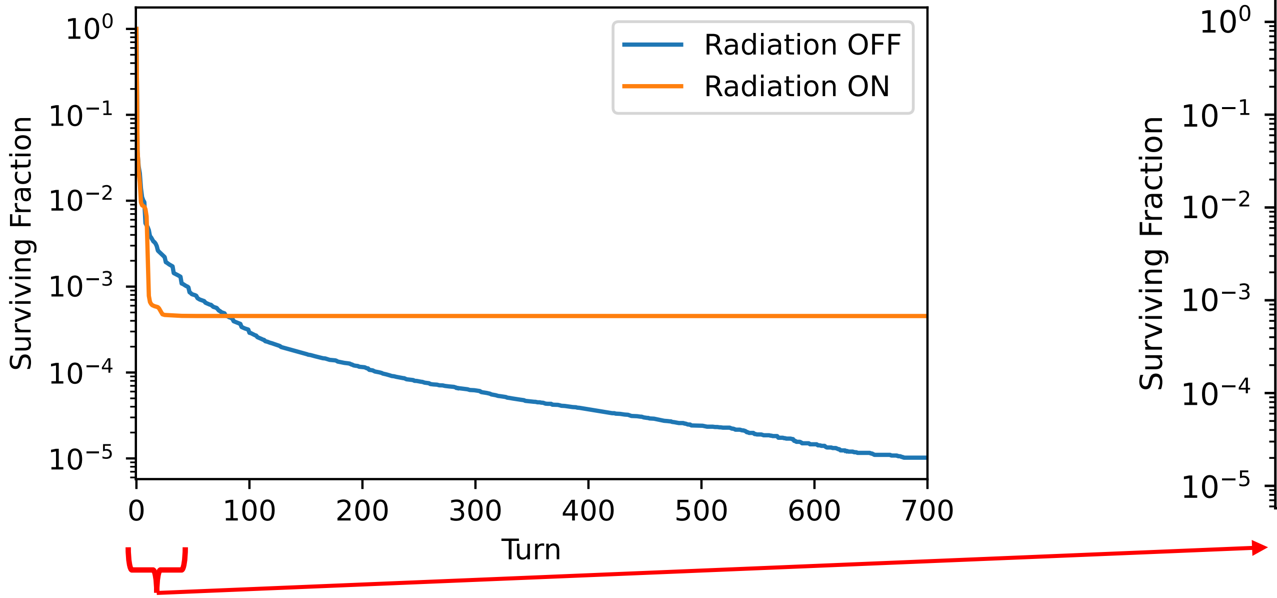
B1H
No rad. / tap.

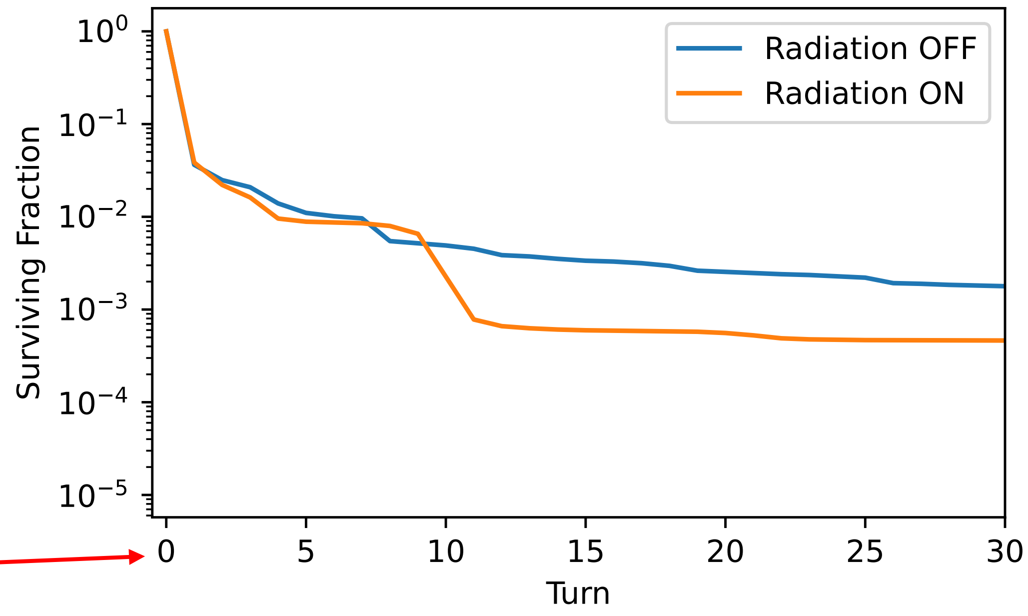
B1H
With rad. / tap.



ttbar mode halo losses – effect of radiation

- **The turn-by-turn losses show the effect of radiation damping**
  - The losses exhibit a cut-off as surviving particles are damped inside the primary collimator aperture
  - This effect was observed also in the studies for the 2 IP CDR layout (IPAC paper)
- **Interesting loss step around turn 10 with radiation**
  - Need to understand in detail the multi-turn losses



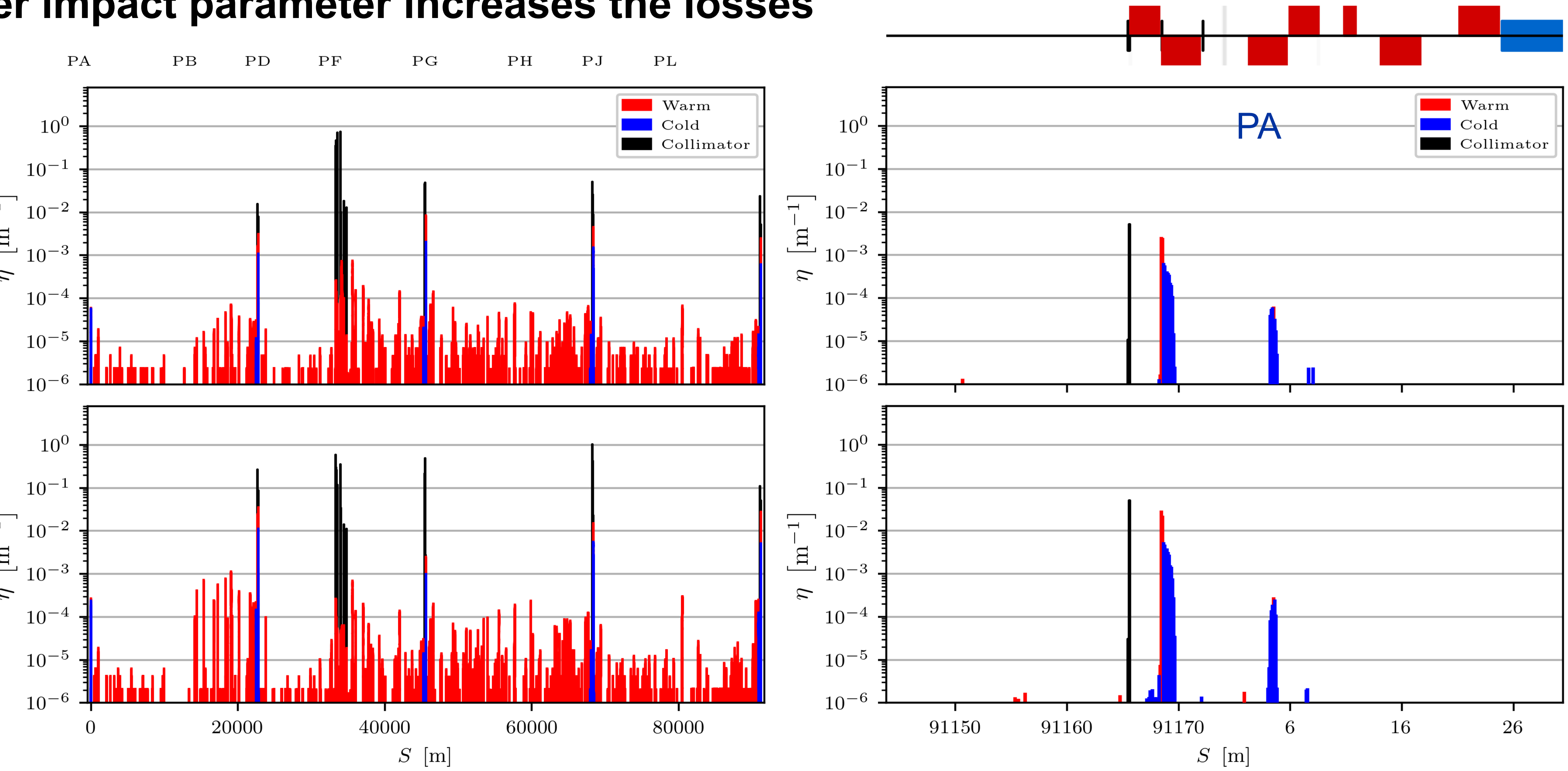


ttbar mode halo losses - betatron

- Tested a smaller impact parameter, as found by G. Broggi for the 2 IP ttbar lattice (talk)
- The smaller impact parameter increases the losses

B1H,
1 µm imp. par.

B1H,
0.1 µm imp. par.



ttbar mode halo losses - summary

- **Using new models with SR collimators and radiation**
- **Performing checks for beam 1 horizontal, vertical and off-momentum cases to follow**
- **Analysis of the SR collimator and final focus quadrupole losses will be performed**
- **The DA and MA for the ttbar mode appear more stable than for the Z mode**

Summary

- **Studies of beam losses and collimation for the FCC-ee**
  - A complete model of the collimation system available, including SR collimators, for the Z and ttbar modes
  - Radiation and tapering have been added to the tracking
  - Simulations of beam loss scenarios ongoing
    - Beam halo losses studied Z and ttbar 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

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 ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_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) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_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	$[10^{34}/\text{cm}^2\text{s}]$	182	19.4	7.26	1.25
Lifetime (q + BS)	[sec]	–		1065	4062
Lifetime (lum)	[sec]	1129	1070	596	744

[a]incl. hourglass.

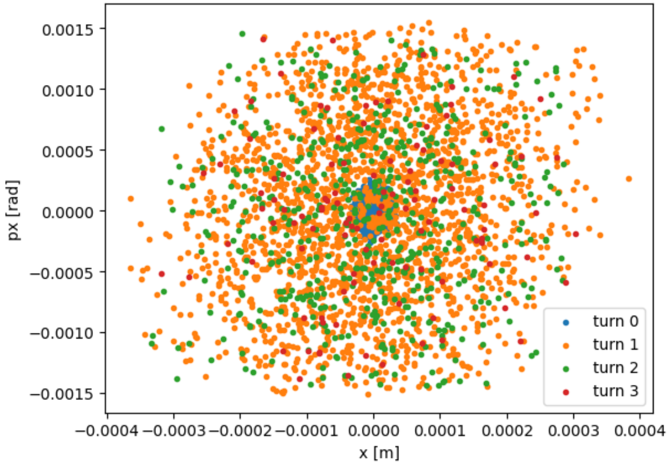
K. Oide (talk)

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

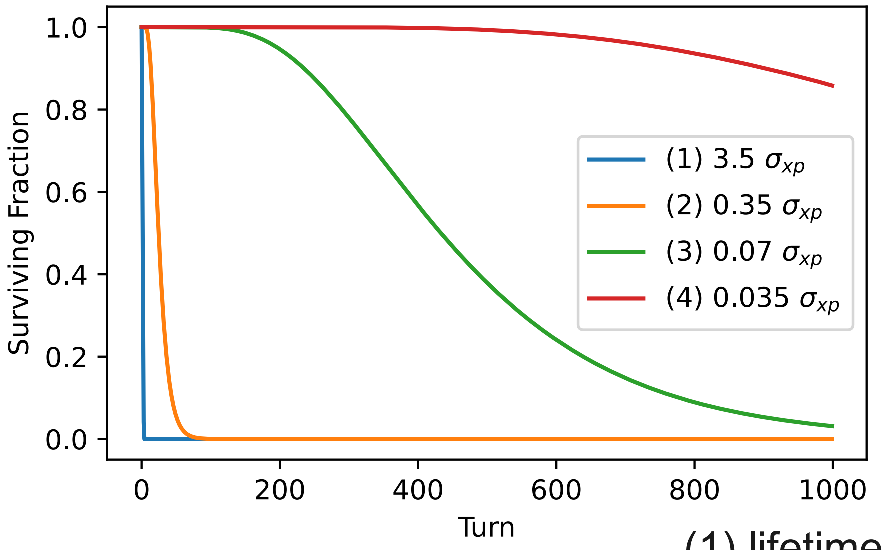
Z-mode fast losses

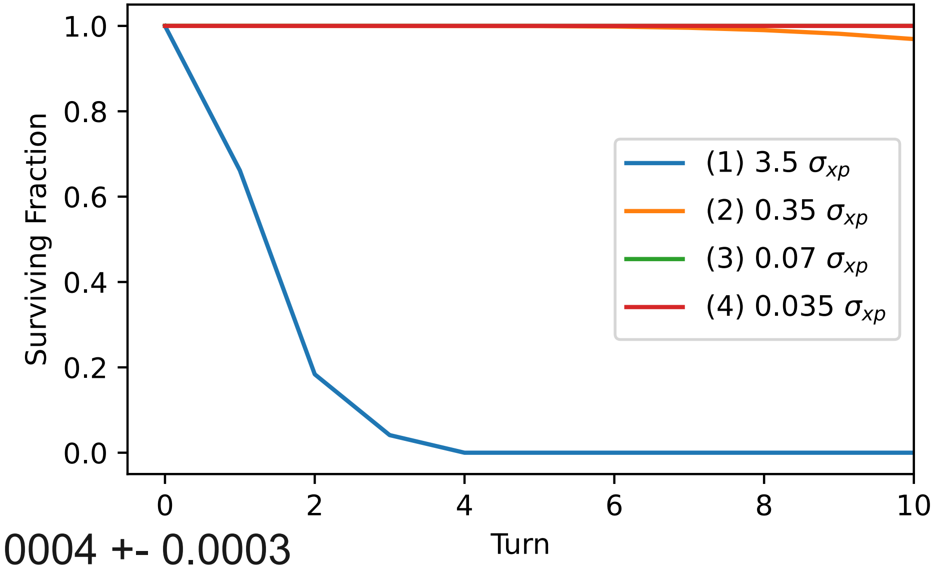
- **Study fast beam blow-up in simulations**
  - Random uniform per-particle kicks applied at 18 locations in the ring
  - Excitation amplitude adjusted to give different beam lifetime
  - **This simulation setup may not be representative of real-world losses**



Beam blow-up example (IPA)

Using different excitation amplitude for the B1H setup

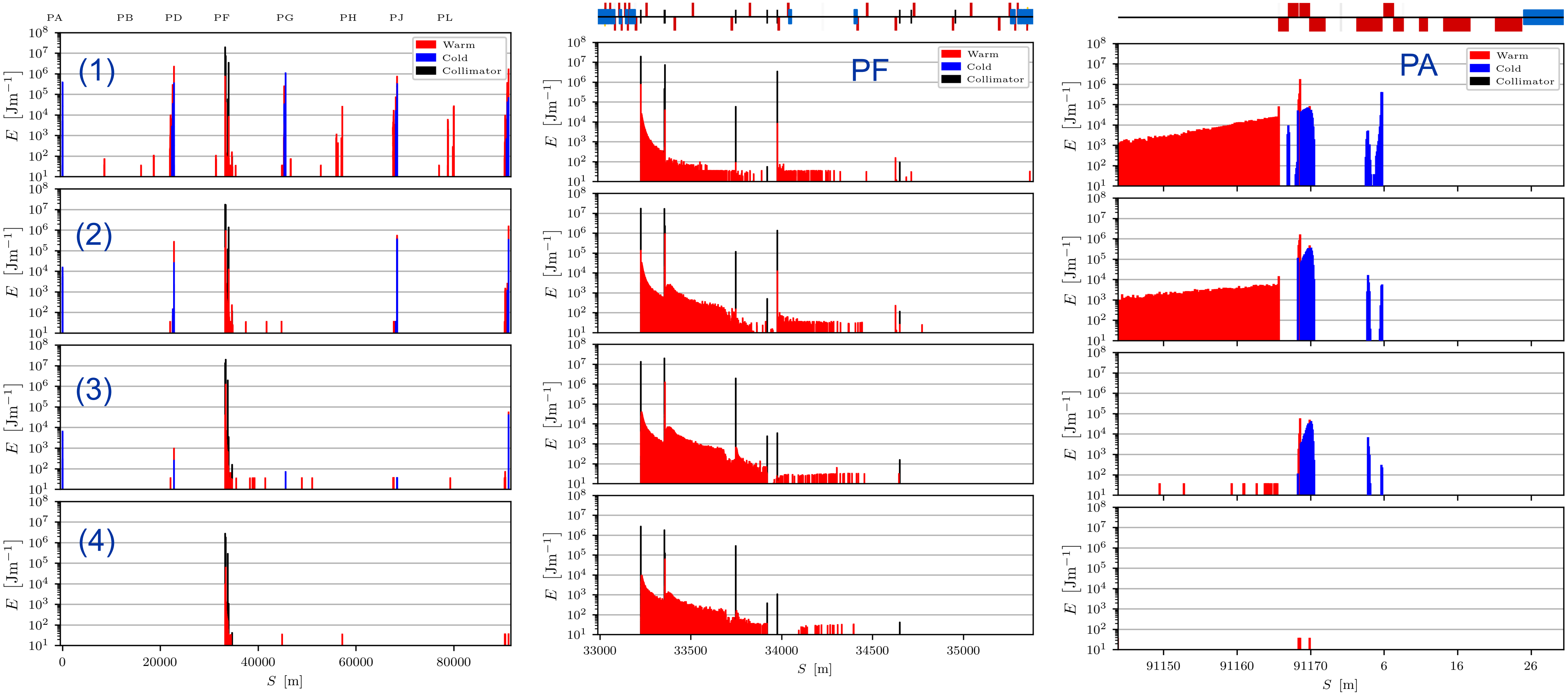




(1) lifetime [s]: 0.0004 +- 0.0003
(2) lifetime [s]: 0.0085 +- 0.0070
(3) lifetime [s]: 0.1639 +- 0.1401
(4) lifetime [s]: 4.0479 +- 4.5599

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**