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FCC-ee Beam Collimation

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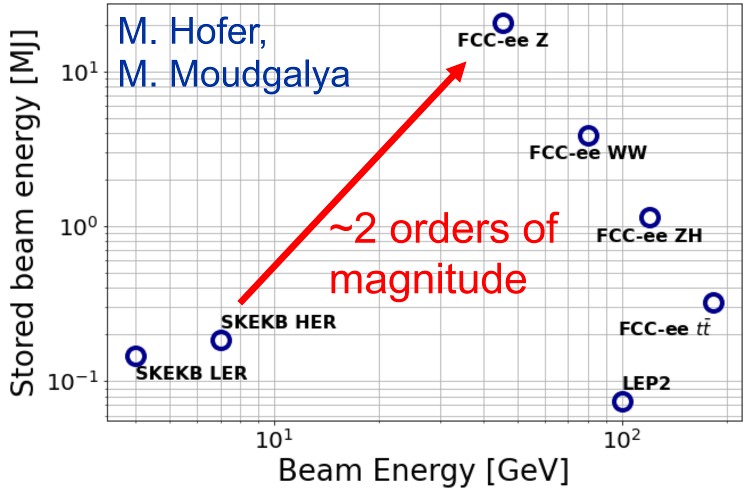
FCCIS workshop 2022 - 07/12/2022

Many thanks for discussions and input to:

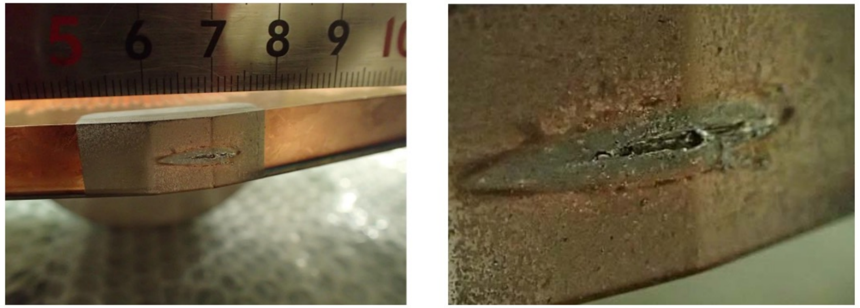
M. Boscolo, H. Burkhardt, A. Ciarma, Y. Dutheil, P. Hunchak, A. Lechner,
G. Lerner, K. Oide, R. Ramjiawan, T. Raubenheimer, F. Zimmermann

FCC-ee beam halo collimation

- **Collimation system in the FCC-ee:**
  - The stored beam energy in the FCC-ee reaches **17.8 MJ**
  - 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 experiment
  - **The beam halo collimation system:**
    - Betatron and off-momentum collimation in one insertion
    - Define the global aperture bottleneck
    - Protect against regular and anomalous beam losses
    - Localise the beam losses away from the experiments
  - **The Synchrotron Radiation (SR) collimation system:**
    - Collimators and masks around each IP
    - Absorb SR photons from upstream magnets
    - Reduce detector backgrounds and MDI power loads



Comparison of lepton colliders



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

FCC-ee parameters used

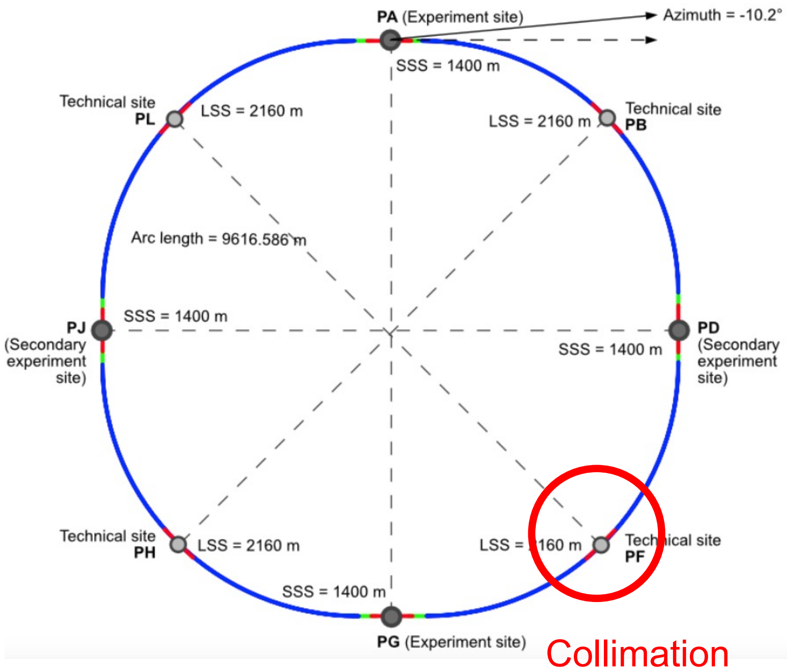
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
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}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS)	[sec]	–		1065	4062
Lifetime (lum)	[sec]	1129	1070	596	744

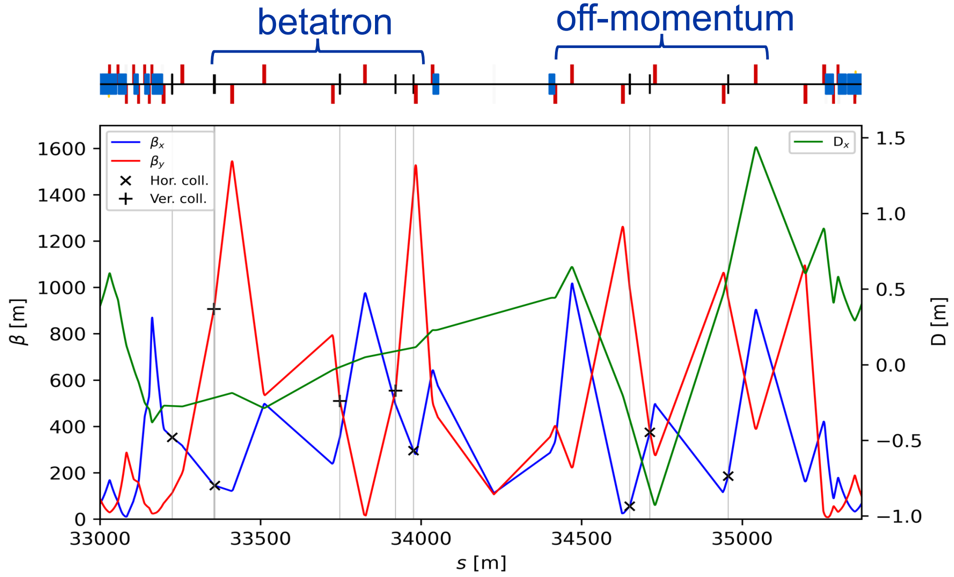
^{a}incl. hourglass.

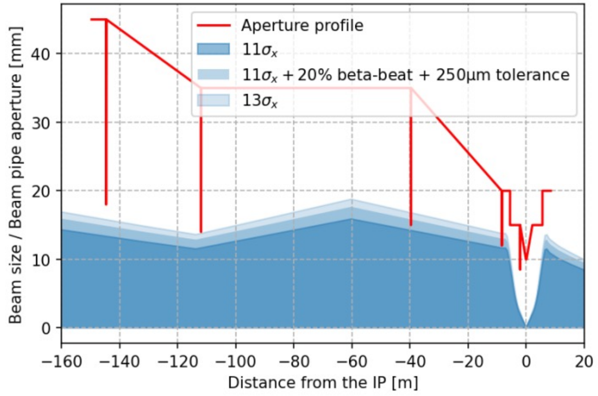
K. Oide (talk)

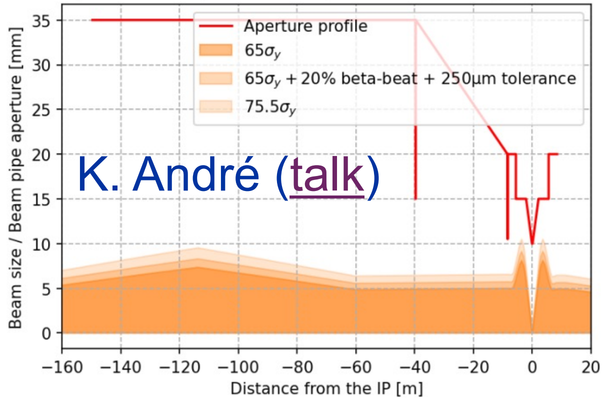
Collimation system status

- **Dedicated halo collimation system in PF**
  - 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 MDI due to photon losses







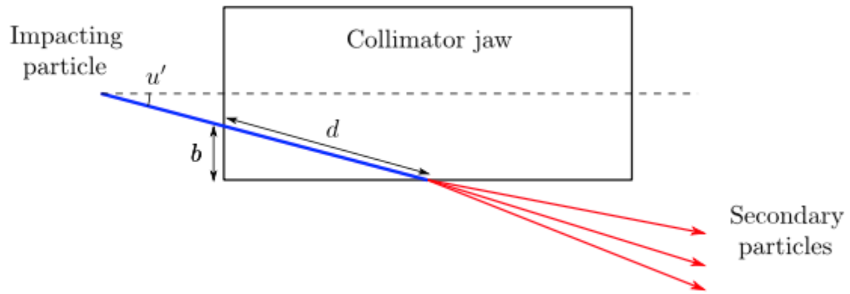


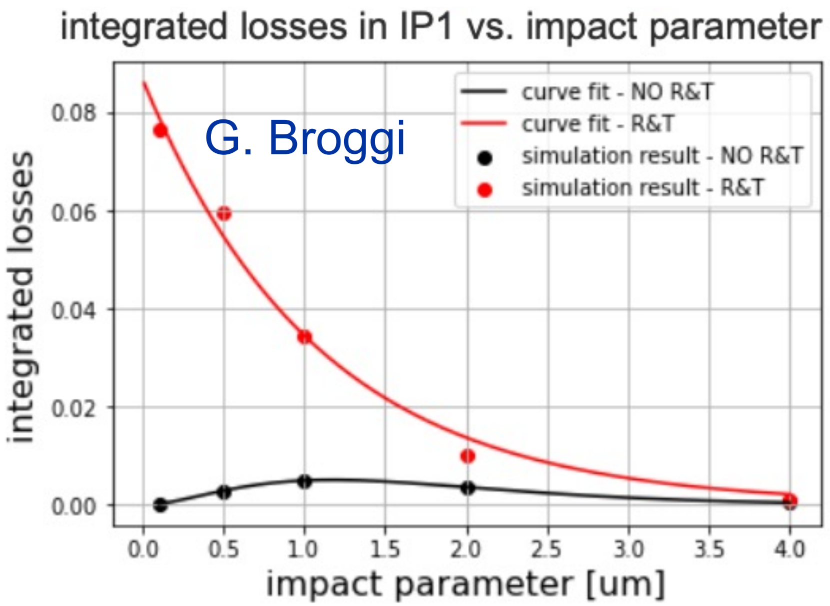
Collimator design studies

See talk by G. Broggi

Primary collimators (TCPs): MoGr - 2.8 r.l. (33cm)
Secondary collimators (TCSs): Mo – 30 r.l. (30cm)

- **Design for collimation efficiency**
  - First studies of optimized collimator parameters for loss cleaning (G. Broggi)
  - Results available for the ttbar 2 IP CDR lattice
  - Preliminary choice of collimator material and length
  - Studies of loss scaling with impact parameter
  - Studies of impedance and collective effects (M. Behtouei, E. Carideo, M. Migliorati - talk)
- **Energy deposition studies**
  - FLUKA energy deposition studies in the collimators ongoing (G. Lerner talk)
  - Preliminary results for the ttbar case available
  - High peak energy loss power and low overall absorption observed, very challenging
  - May require material and design changes

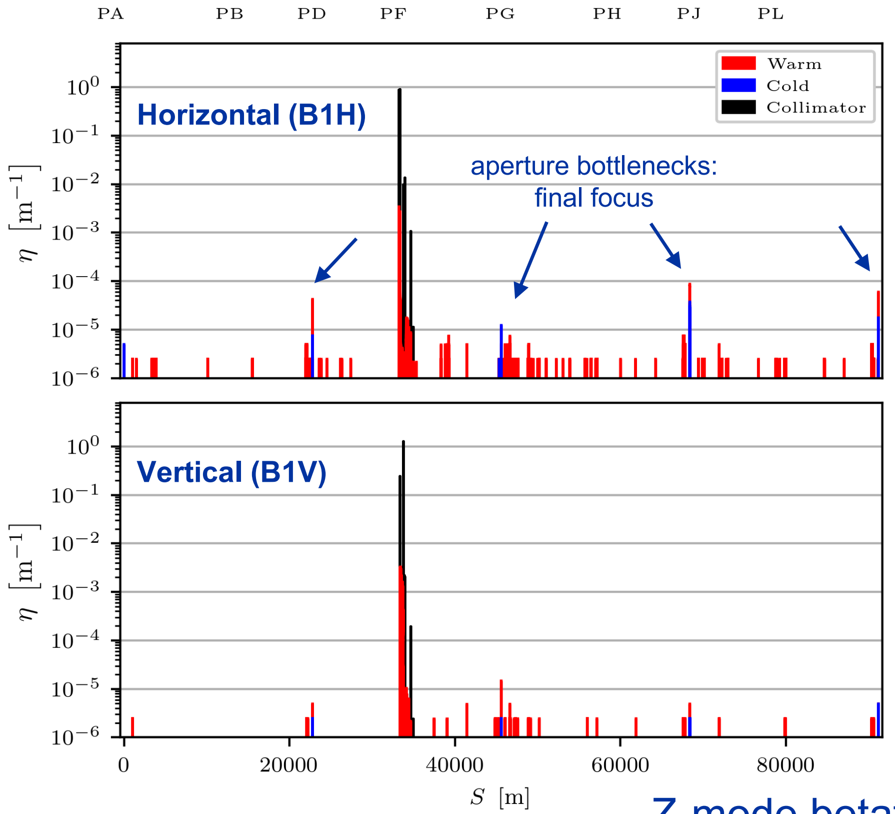


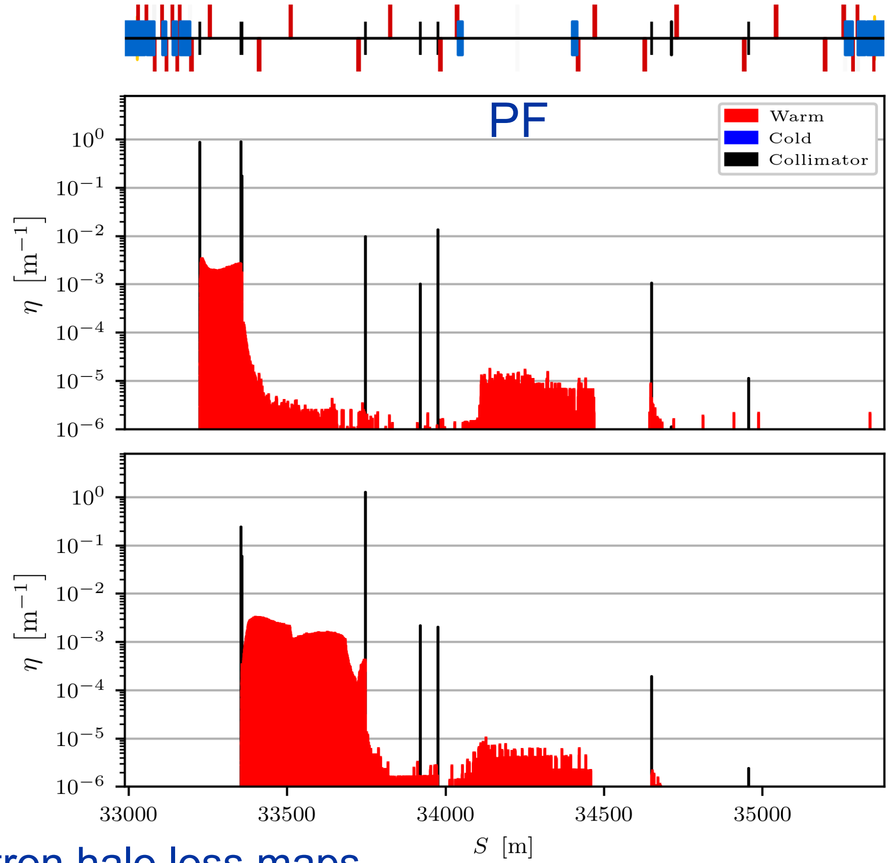


Impact parameter scan for ttbar 2 IP CDR lattice with MoGr primary collimator, with and without radiation and tapering (R&T)

Beam halo losses - betatron

- Z mode is the current focus (Beam 1, 45.6 GeV positrons)
- Particles simulated directly impacting the primary collimators
- No radiation and tapering, SR collimators not included, **1 µm** impact parameter
- **5 min beam lifetime assumed (P_{loss} = 59.2 kW)**





Z-mode betatron halo loss maps

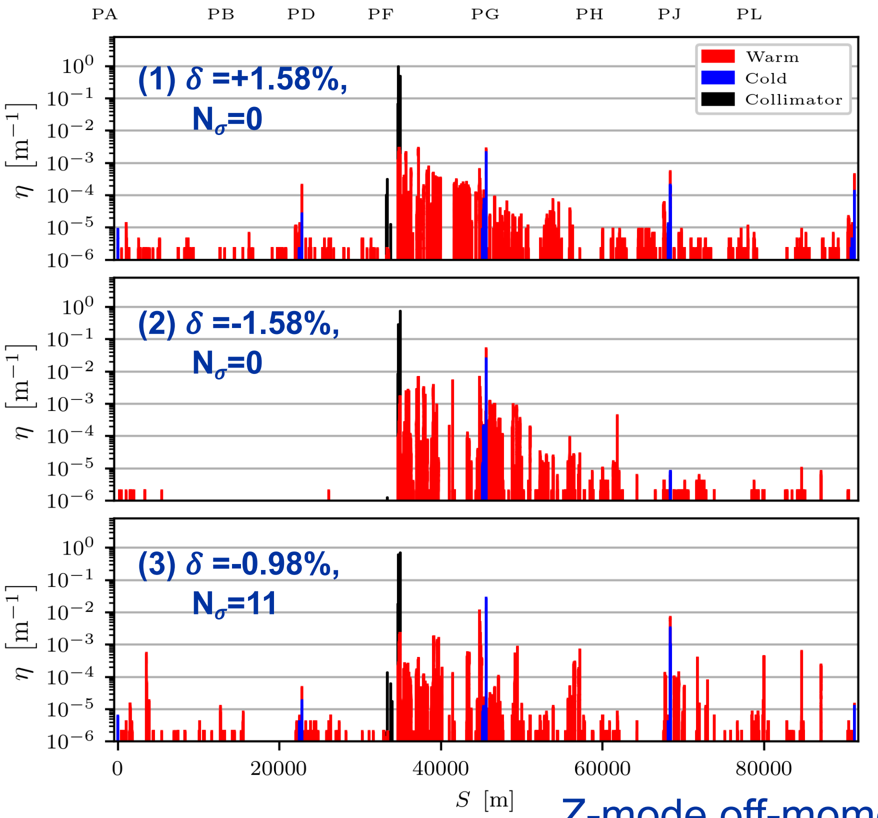
Case	Max. int. power ± 100 m from IP [W]
B1H	2.80
B1V	0.09

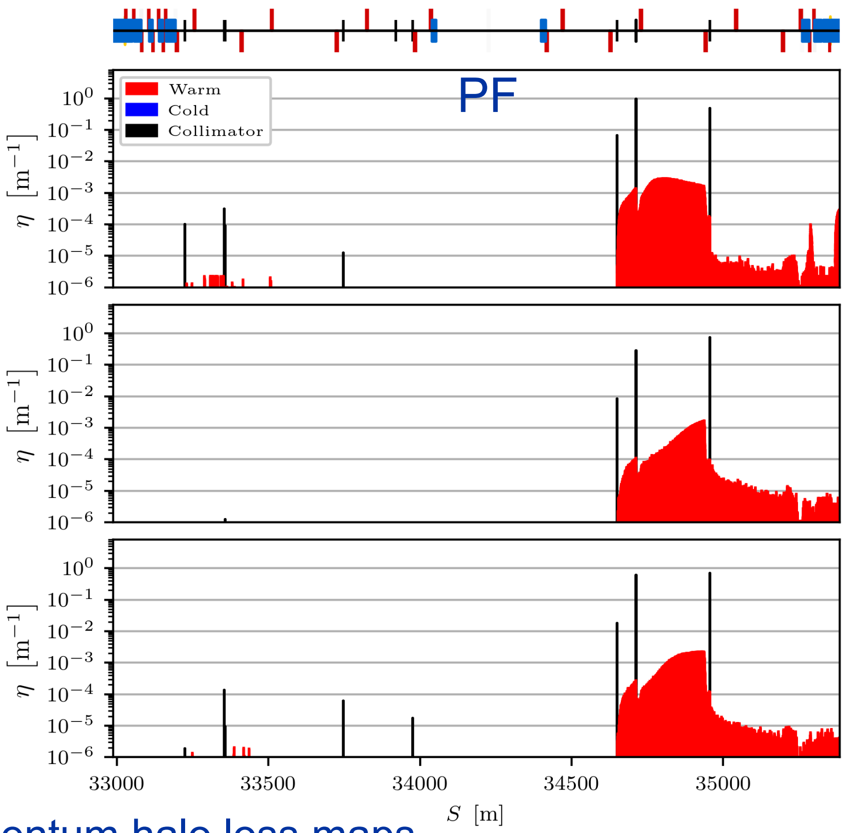
Power loads in the MDI for 5 min beam lifetime
P_{loss} = 59178 W

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 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

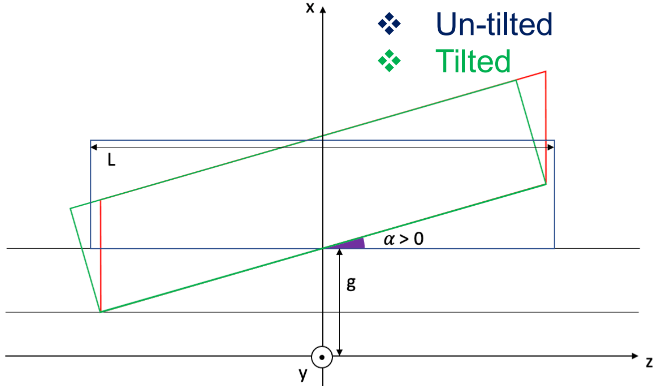
Case	Max. int. power ± 100 m from IP [W]
(1) $+\delta$	88.848
(2) $-\delta$	1810.754
(3) $-\delta$, N_σ	1310.374

Power loads in the MDI for 5 min beam lifetime

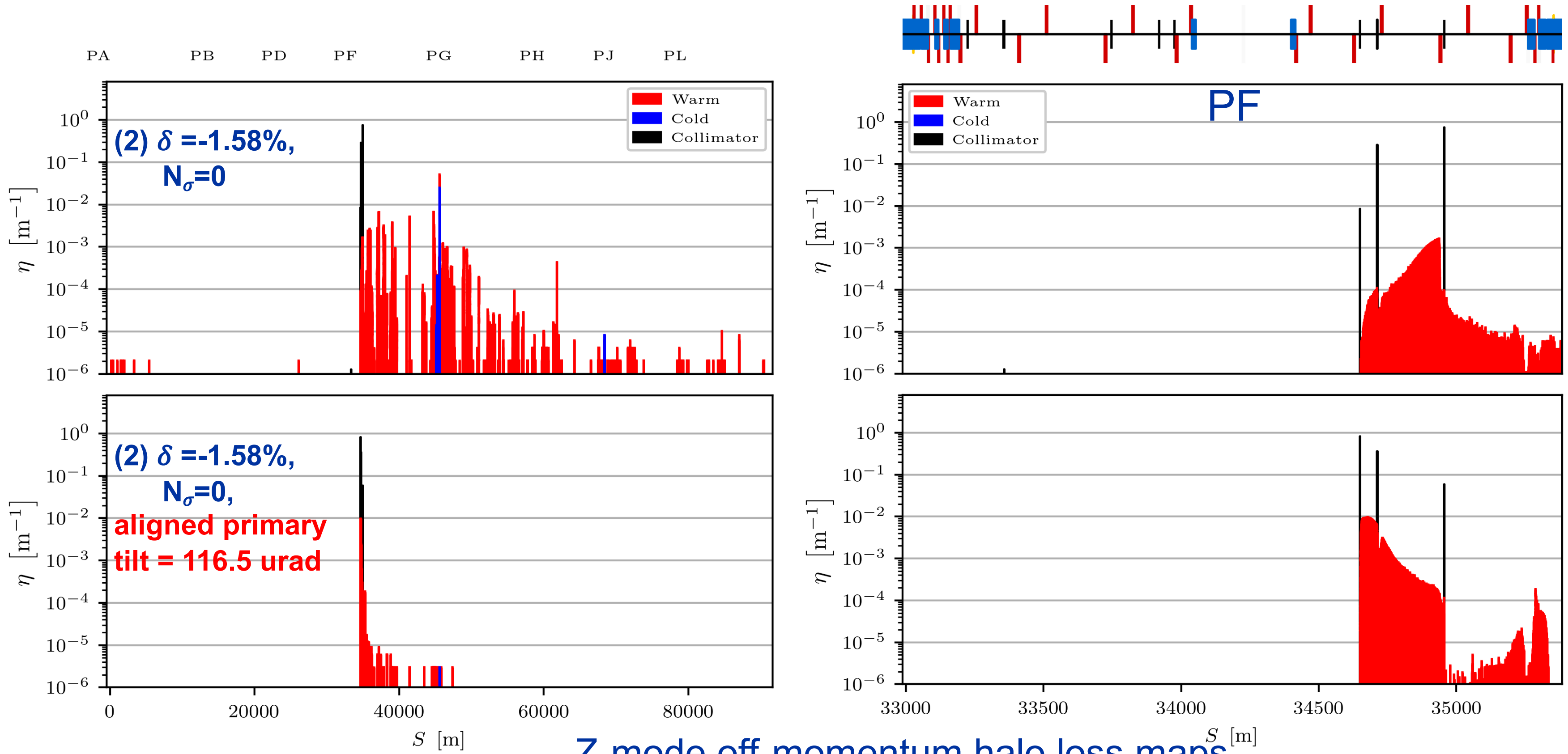
P_{loss} = 59178 W

Beam halo losses - off-momentum

- 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 the feasibility must be studied
  - Alternative mitigation strategies under study – optics, layout, settings



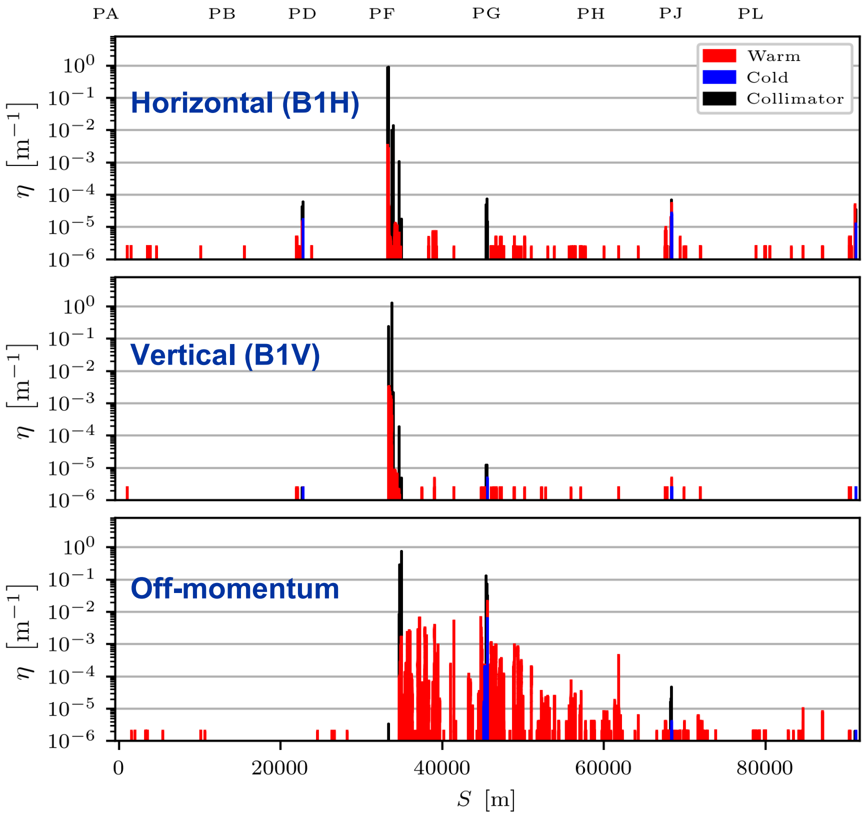
Schematic of collimator jaw tilt

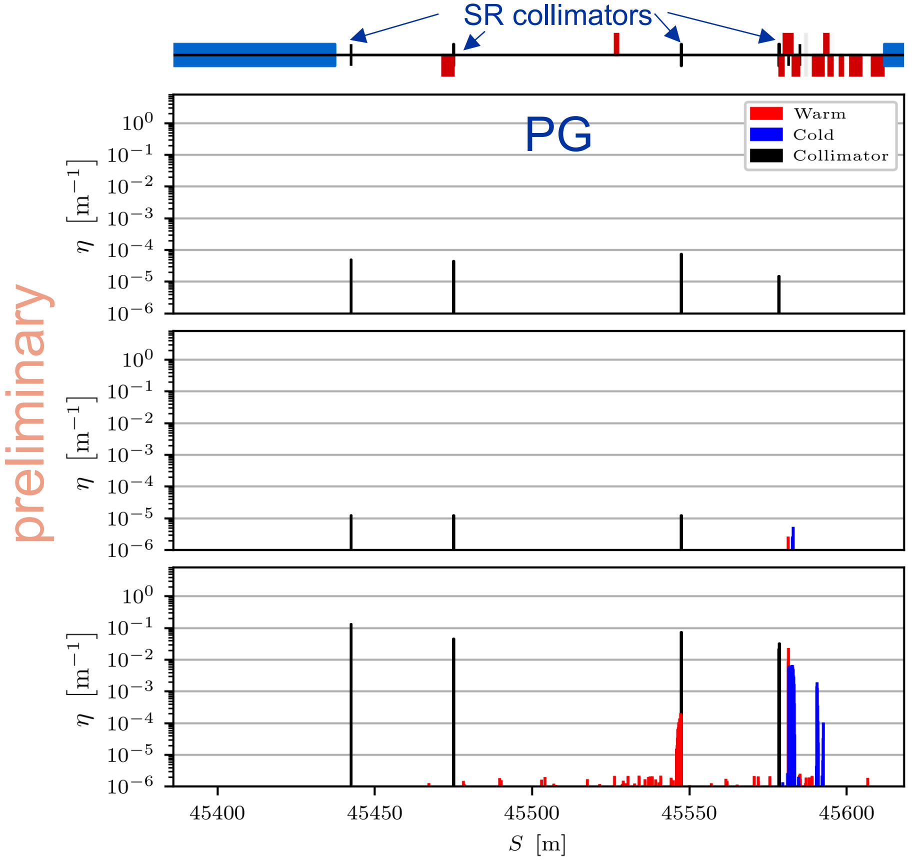


Z-mode off-momentum halo loss maps

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

Other beam loss scenarios for the FCC-ee

- **Spent beam from interactions at the IPs**
  - Beamstrahlung, Bhabba scattering, and other effects result in broad tails of particles escaping
  - Simulation of IP interactions and tracking of the spent beam in the detector by (A. Ciarma – talk)
  - Plan is to track in a model with collimators and beam-beam lenses (P. Kicsiny - talk)
- **Injected beam losses from top-up injection**
  - The continuous top-up injection can be a source of backgrounds, must be studied in detail
  - In contact with P. Hunchak, M. Hofer
- **Failure scenarios**
  - Injection and extraction failures, magnet failures, are important loss scenarios
  - In contact with R. Ramjiawan, Y. Dutheil, and others
- **SuperKEKB-type fast losses**
  - Up to 80% of beam intensity lost over 2 turns in SuperKEKB (T. Ishibashi - talk)
  - Informally referred to as ‘crazy beam’, cause not yet identified

SuperKEKB-type fast beam losses in FCC-ee

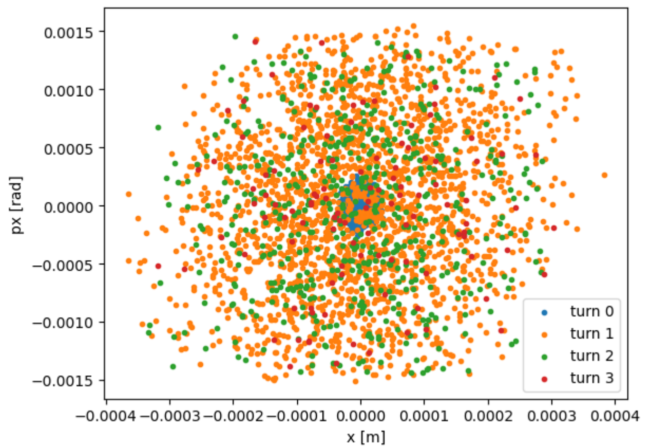
- **Start with the worst-case losses and apply directly to FCC-ee (80% over 2 turns)**
- **Not trivial to blow up the beam this quickly**
  - LHC-like transverse damper (ADT) excitation probably not suitable:
    - Random dipole kicks take longer to blow up the beam
    - Resonant kicks will make the loss location dependent on the phase advance from the ADT
  - Longitudinal excitation via RF frequency shift is also not suitable
- **Custom synthetic simulation setup as a first step:**
  - Add 18 'beam heater' elements that give uniform random per-particle kicks
  - The beam centroid should remain relatively unaffected
  - Adjust the maximum amplitude of the kicks to achieve the loss rate
    - 3.5 σ_{xp} per excitation for horizontal blow-up
    - 25 σ_{yp} per excitation for vertical blow-up

```
dist:
  start_element: 'ip.1'
  source: 'internal'
  parameters:
    type: 'matched_beam'
    sigma_z: 0

insert_element:
  -
   name: 'crazybeam'
   at_s: [5e3, 10e3, 15e3, 20e3, 25e3,
          30e3, 35e3, 40e3, 45e3, 50e3,
          55e3, 60e3, 65e3, 70e3, 75e3,
          80e3, 85e3, 90e3]
   type: 'BeamHeater'
   parameters:
     name: 'crazybeam'
     max_kick_x: 0
     max_kick_y: 0

dynamic_change:
  element:
    -
     element_regex: 'crazybeam.*'
     parameter: 'max_kick_x'
     change_function: 'sigx * 0.02'
```

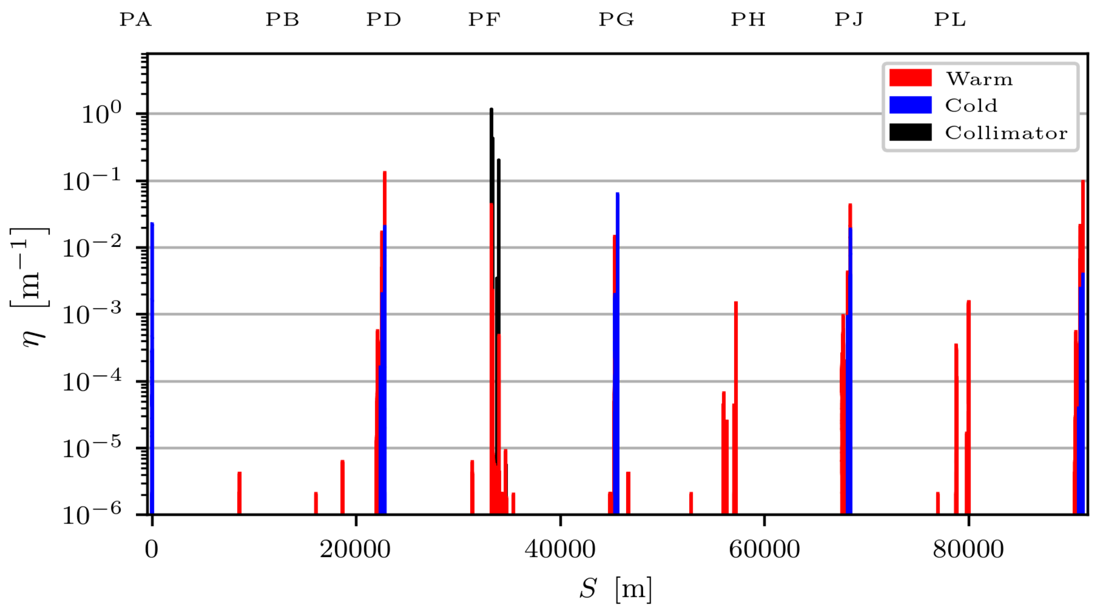
FCC-ee anomalous loss modelling

Z-mode B1H fast losses

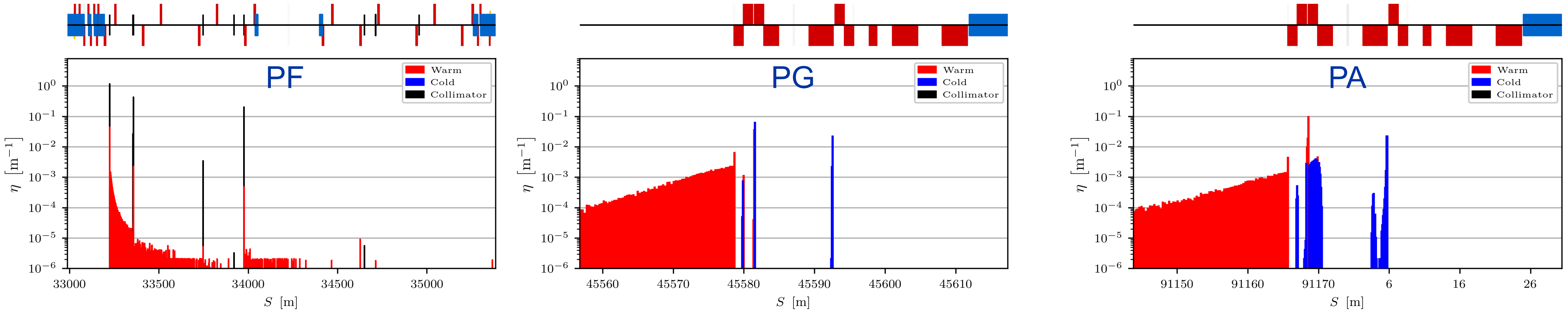
Matched gaussian beam, no radiation and tapering, SR collimators not included, 17.8 MJ stored energy



Phase space of the excitation (3e3 particles plotted)



Loss map with 5e6 primary positrons



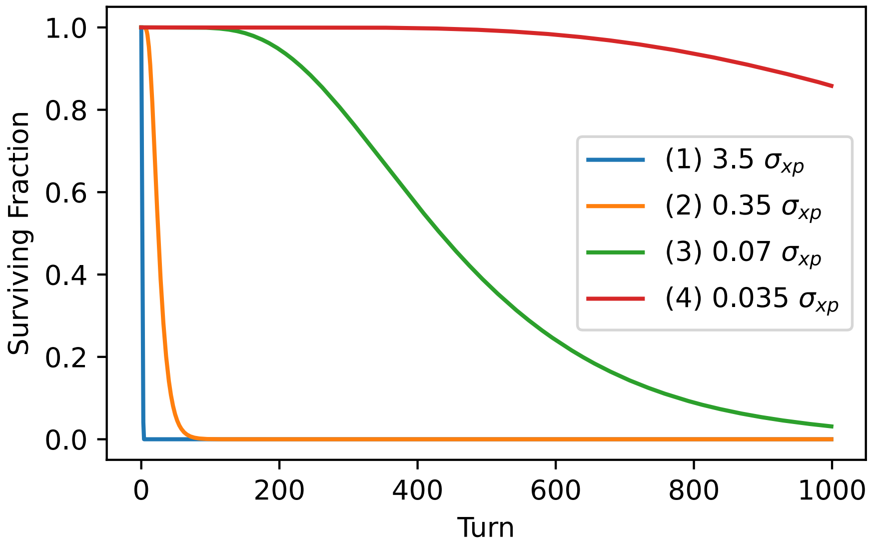
Z-mode fast losses

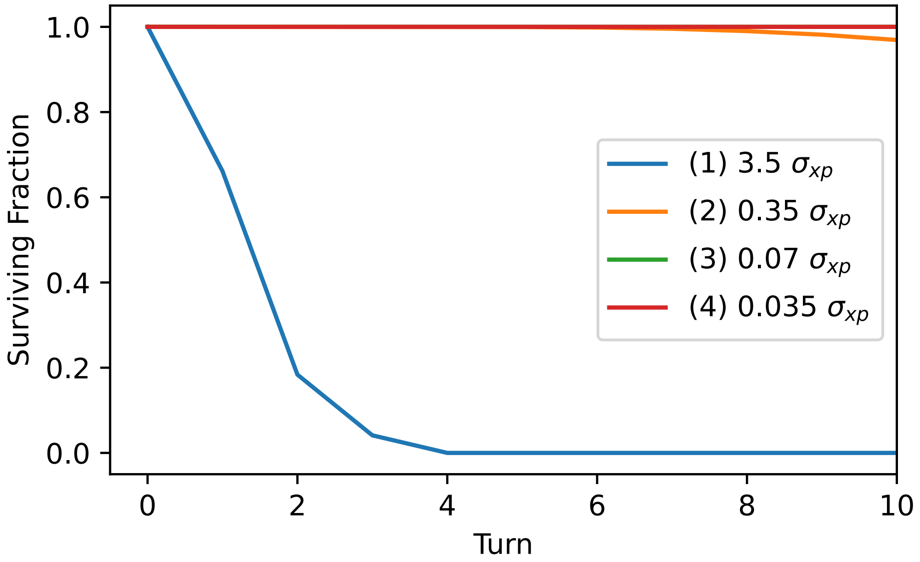
- **Huge losses observed in the simulation scenario**
  - Cleaning inefficiency of up to **0.1 m^{-1}** in the horizontal and **0.5 m^{-1}** in the vertical around the IPs
  - Translates to losses of up to **MJ / m** in the superconducting final focus quadrupoles
  - This loss energy is likely destructive for the final focus doublets, detectors, and / or the tungsten SR collimators there (not included)
  - **Due to the large excitation amplitude, primary particles impact the aperture bottlenecks directly, before being intercepted by the collimation system in PF** (may not be the same for other types of excitation)
- **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
  - **The decision whether to protect against this extreme case will have a profound impact on the design**
  - The loss scenario must be defined better for the FCC-ee
    - **Time-scale and percentage intensity loss**
    - **Driving process (location, transverse vs. longitudinal, etc.)**
    - **Specification of what losses the collimation system must handle**

Z-mode fast losses – additional investigation

- **It is possible in simulations to adjust the excitation intensity**
  - Invert the problem – what is the minimum lifetime tolerable before damage limits are exceeded
  - Need damage limits for the collimators, the halo and SR ones, and the IR magnets
  - Investigate other approaches of modelling the losses – **single kick, resonant kick, others**

Using different excitation amplitude for the B1H setup

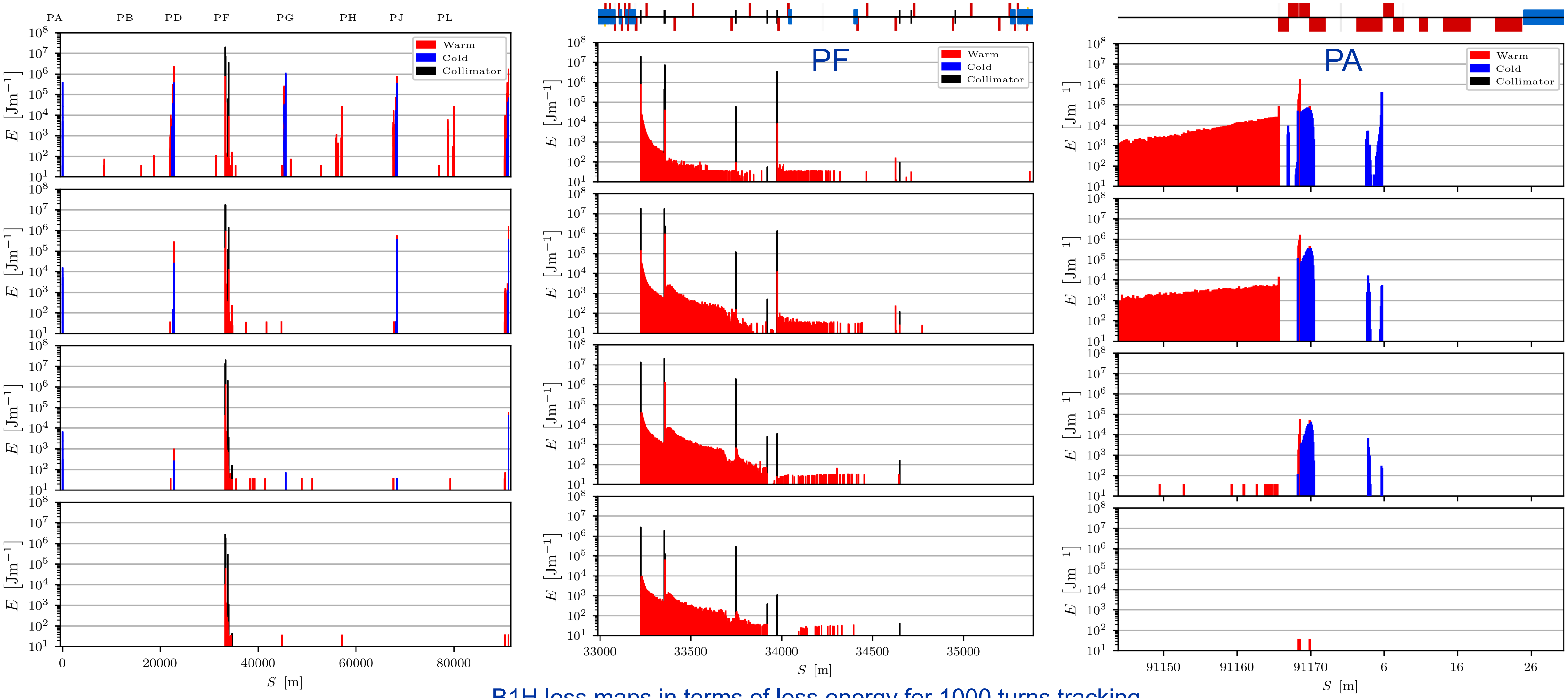




(1) lifetime [s]: 0.000434 +- 0.000274
(2) lifetime [s]: 0.008514 +- 0.007099
(3) lifetime [s]: 0.163935 +- 0.140128
(4) lifetime [s]: 4.047940 +- 4.559846

Beam lifetime from exponential fit

Z-mode fast losses – additional investigation



B1H loss maps in terms of loss energy for 1000 turns tracking

Summary

- **Studies ongoing for the collimation system in the FCC-ee:**
  - The Z mode is the current focus, as it is the most challenging for collimation
  - First fully integrated collimation models available – 4 IP lattice with halo and SR collimation
  - Collimator design studies - material, length, impedance, energy deposition studies
  - Tracking studies - beam halo losses considered, other beam loss scenarios to follow

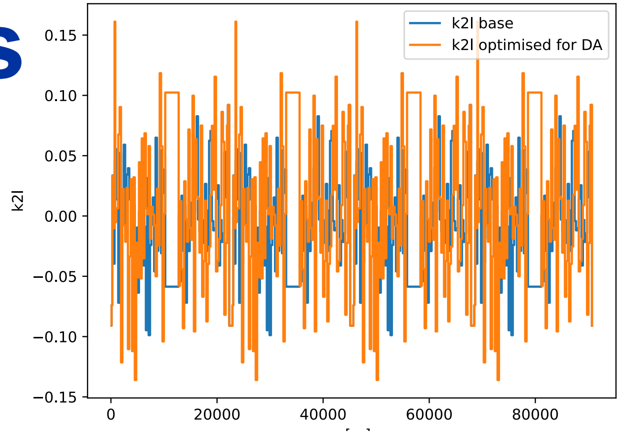
- **Next steps**
  - Select a set of beam loss processes to study for FCC week '23 and the FCC FS mid-term review
  - Obtain input for the equipment loss tolerances – superconducting magnets, collimators, other equipment
    - Detailed energy deposition studies required
  - Iterate on the collimation optics, layout, and collimator design parameters
  - Include radiation and optics tapering in all cases
  - Study all beam modes

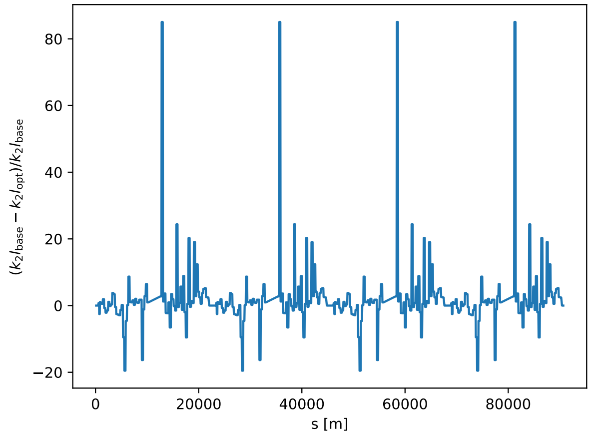
Thank you!

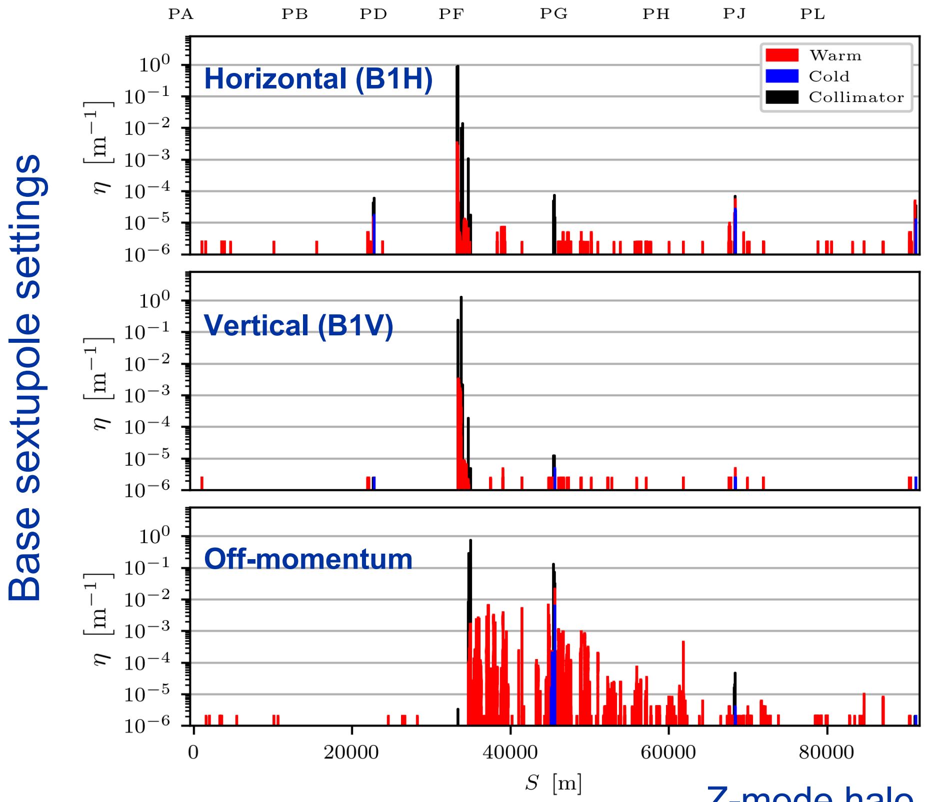
Backup slides

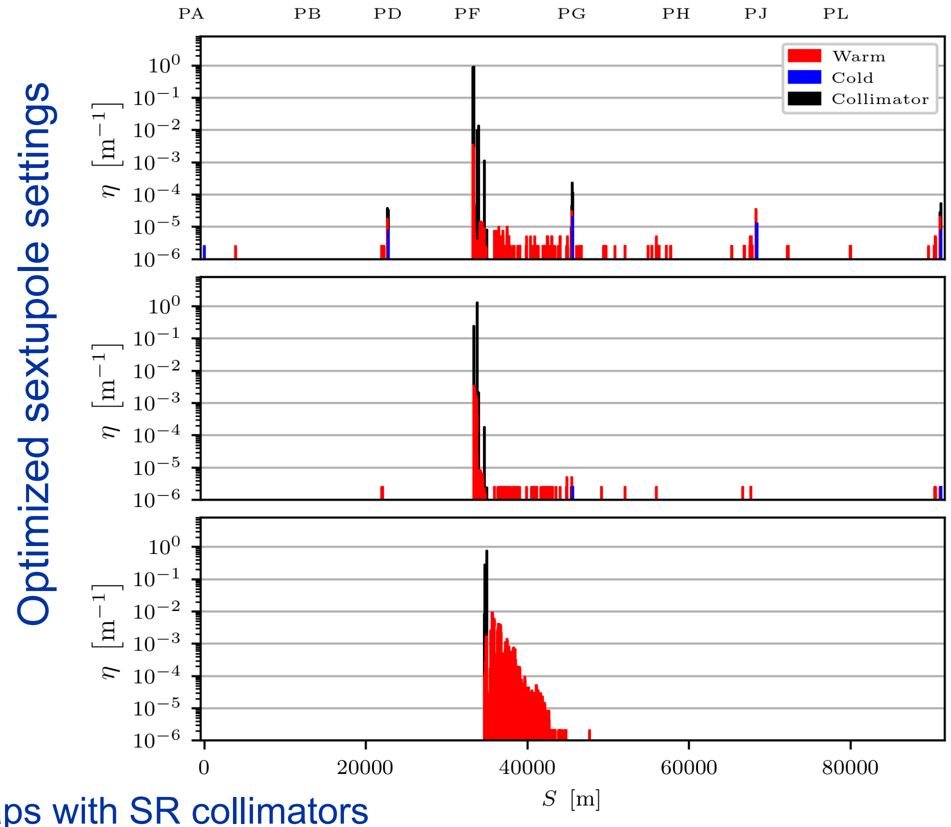
Effect of sextupole settings

- Comparing the base 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





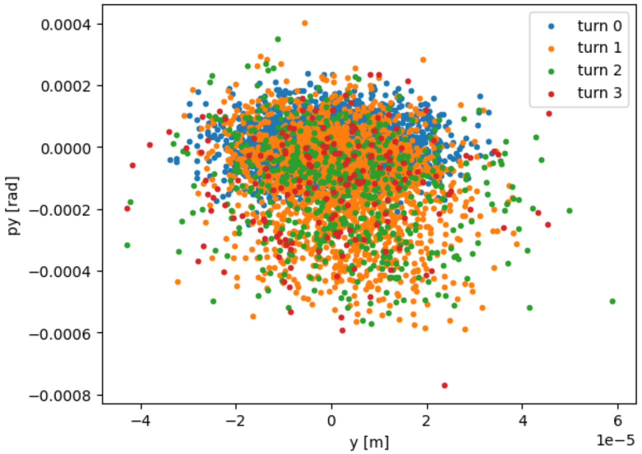




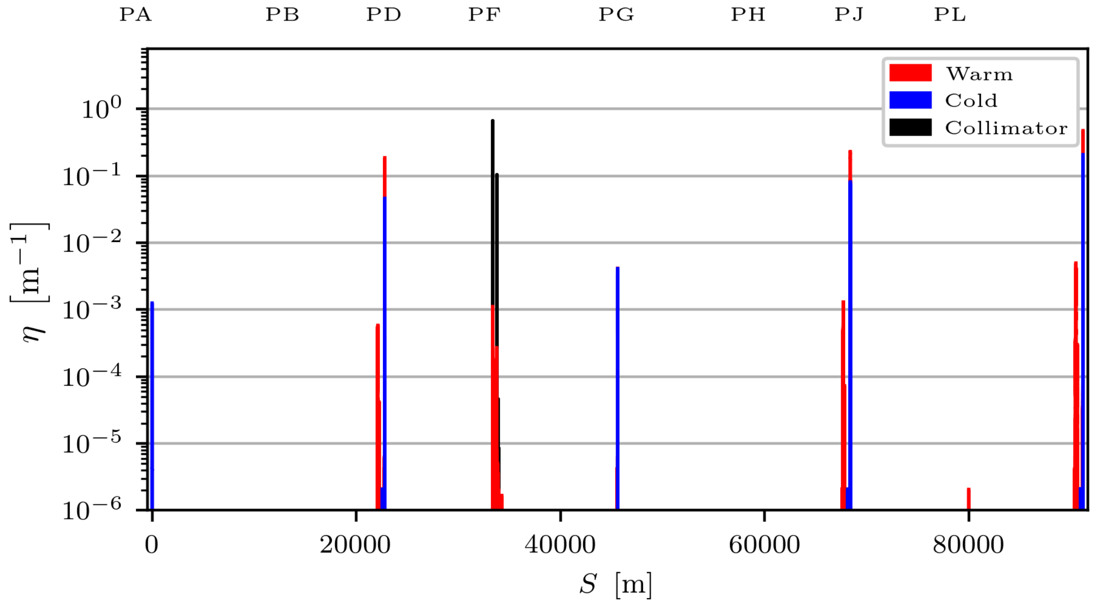
Z-mode halo loss maps with SR collimators

Z-mode B1V fast losses

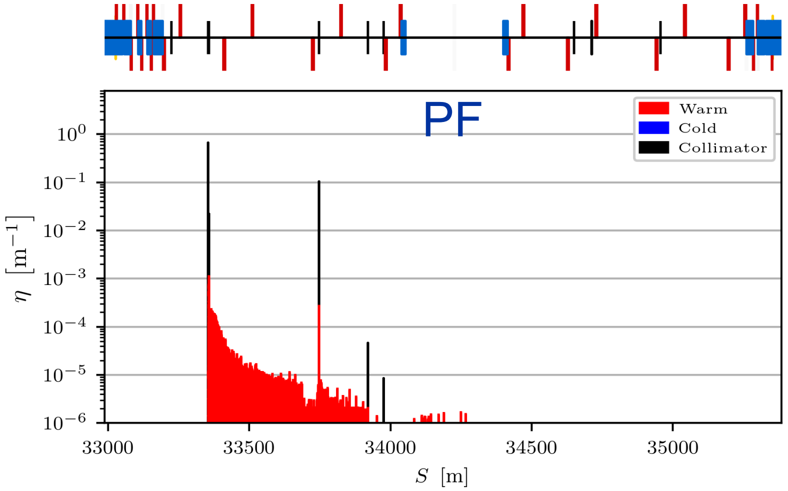
Matched gaussian beam, no radiation and tapering, SR collimators not included, 17.8 MJ stored energy

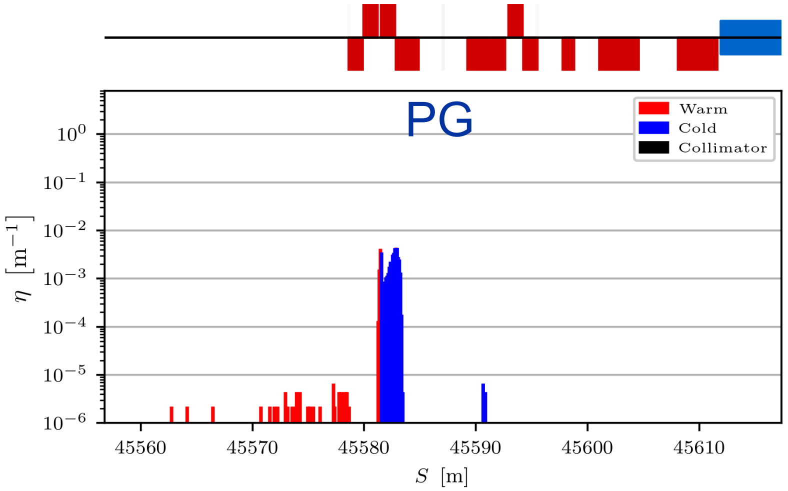


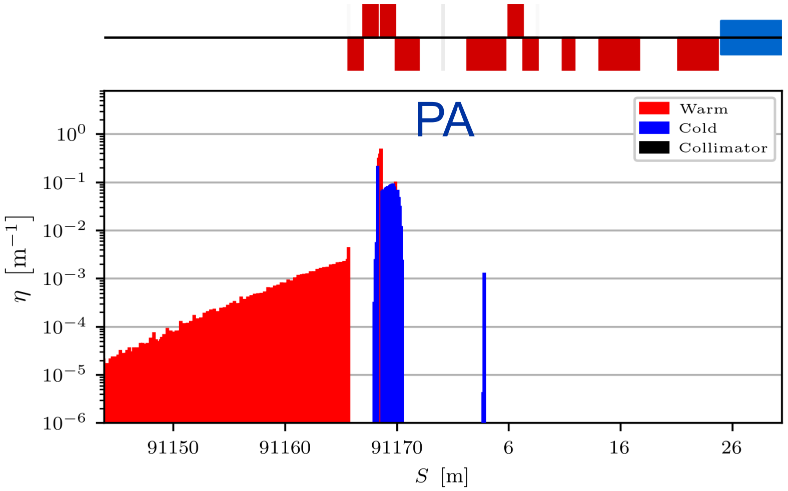
Phase space of the excitation (3e3 particles plotted)



Loss map with 5e6 primary positrons

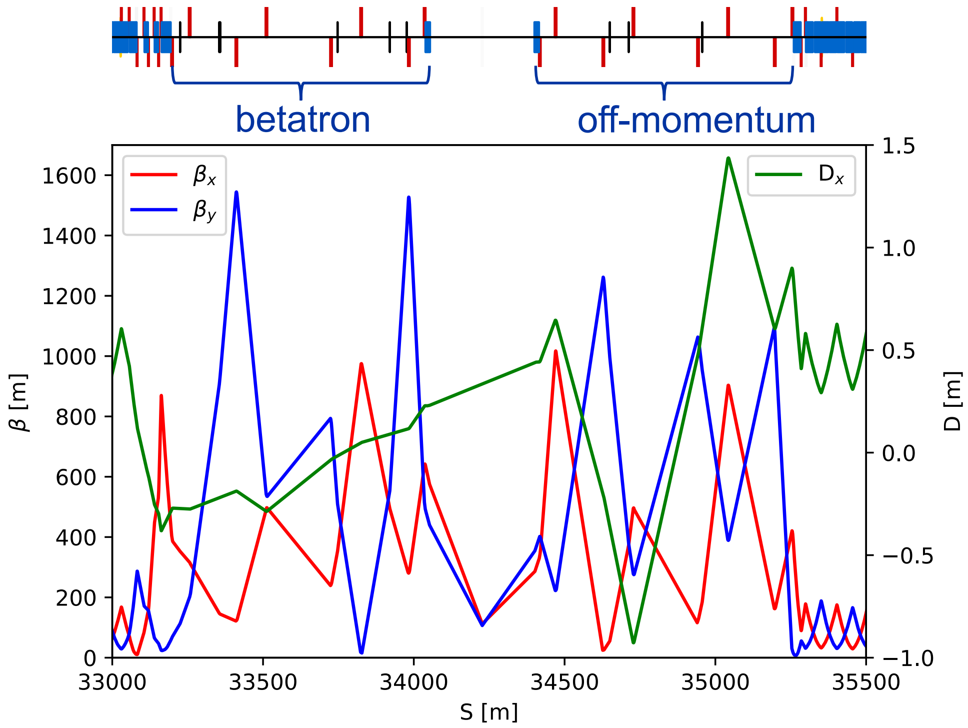






Status of Z collimation

- **Status**
  - Prepared the first layout and settings
  - Preliminary optimization for impedance performed
  - Performed first tracking studies
- **Outstanding issues:**
  - There are problems with the DA for the Z mode
  - Radiation and tapering implemented, but not used in the collimation models yet



FCC-ee optics repository: link
FCC-ee collimation optics repository: link

Collimator settings

	name	type	length[m]	nsigma	half-gap[m]	material	plane	angle[deg]	beta_x[m]	beta_y[m]	s[m]
betatron	tcp.h.b1	primary	0.4	11.0	0.005504	MoGR	H	0.0	352.57	113.05	33225.00
	tcp.v.b1	primary	0.4	65.0	0.002332	MoGR	V	90.0	147.02	906.28	33355.00
	tcs.h1.b1	secondary	0.3	13.0	0.004162	Mo	H	0.0	144.37	936.11	33357.96
	tcs.v1.b1	secondary	0.3	75.5	0.00203	Mo	V	90.0	353.43	509.32	33747.17
	tcs.h2.b1	secondary	0.3	13.0	0.005956	Mo	H	0.0	295.62	1419.37	33976.50
	tcs.v2.b1	secondary	0.3	75.5	0.002118	Mo	V	90.0	494.23	554.06	33920.50
off-mom.	tcp.hp.b1	primary	0.4	29.0	0.005755	MoGR	H	0.0	55.47	995.31	34650.00
	tcs.hp1.b1	secondary	0.3	32.0	0.01649	Mo	H	0.0	373.99	377.28	34712.66
	tcs.hp2.b1	secondary	0.3	32.0	0.011597	Mo	H	0.0	184.97	953.23	34956.50