FCC-ee collimation system design

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Outline

- **Introduction**
  - FCC-ee: the Future Circular electron-positron collider
  - Collimation for the FCC-ee
- **FCC-ee collimation system**
  - FCC-ee halo collimation system (and local protection collimators)
  - FCC-ee SR collimation system
- **Studies and simulations of beam losses in the FCC-ee**
  - FCC-ee beam loss scenarios
  - FCC-ee collimation simulations
- **Results**
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  - Beam-gas beam losses
  - Spent beam losses
- **Bent-crystal assisted collimation for the FCC-ee: an alternative design**
- **Outlook and future work**

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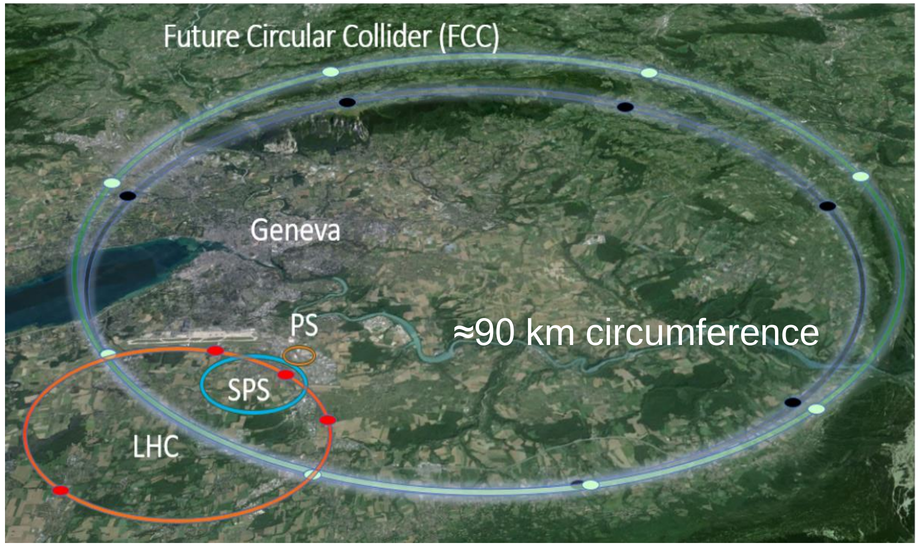
FCC: the Future Circular Collider



1st stage

FCC-ee
luminosity-frontier highest-energy electron-positron collider

2nd stage

FCC-hh
energy-frontier hadron collider

FCC tunnel construction (~2030)

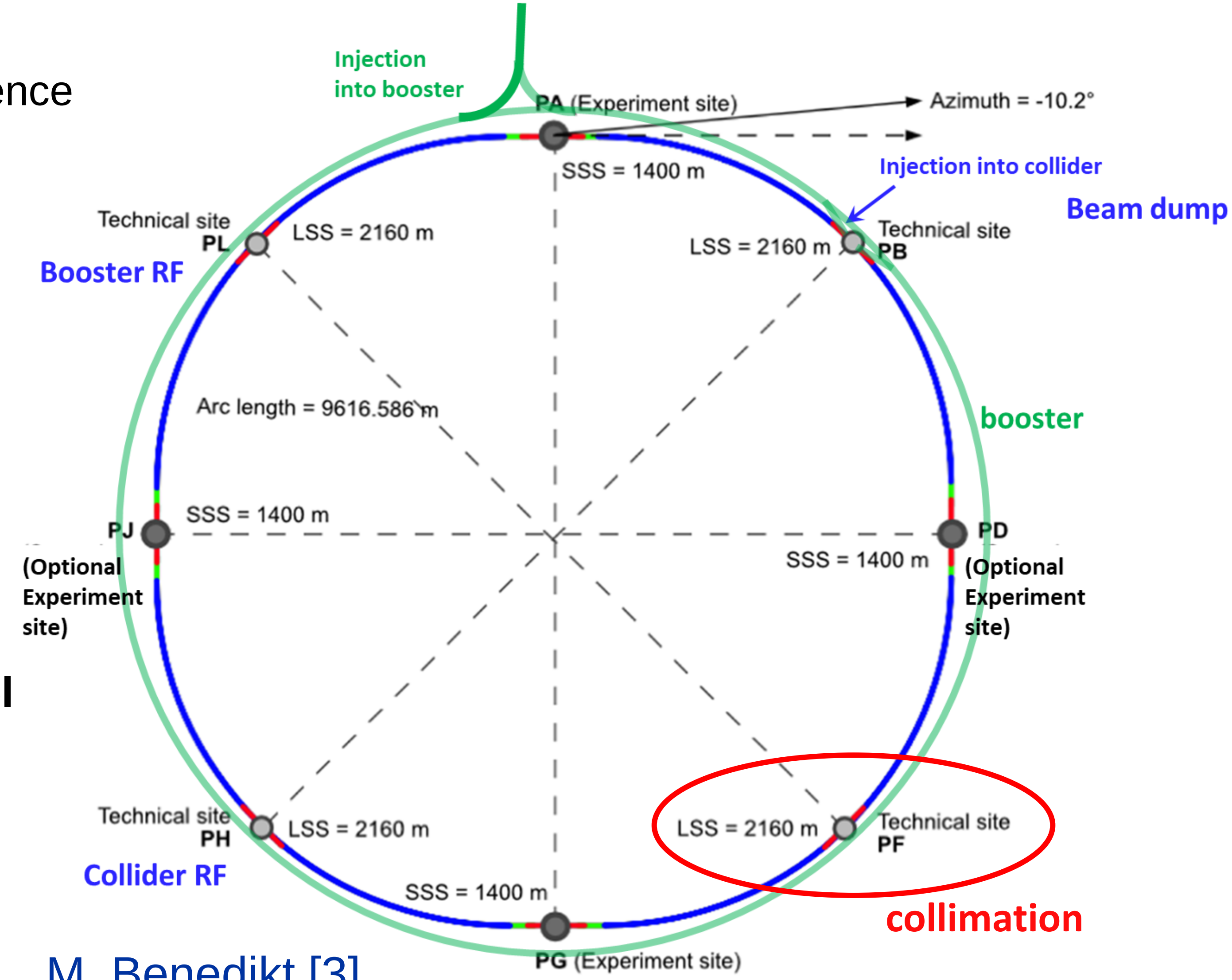
LEP	LEP2	LEP shutdown	LHC	HL-LHC	FCC tunnel construction	LHC shutdown	FCC-ee	FCC-hh
1989	1995	2000	2008	2029	~2030	~2040	~ 2045	~ 2070

year

- **FCC-ee is the FCC first stage e^+e^- collider** [1, 2]
  - 90.7 km circumference, tunnel compatible with FCC-hh
  - 4 beam operation modes with beam energies optimized for the production of different particles: ***Z*** (45.6 GeV), ***W*** (80 GeV), ***H*** (120 GeV), ***ttbar*** (182.5 GeV)

FCC-ee layout and technical baseline

- **Double ring** e+e- collider with 90.7 km circumference
- **Common footprint with FCC-hh**, except around IPs
- **Perfect 4-fold super-periodicity allowing 2 or 4 IPs; large** horizontal crossing angle **30 mrad, crab-waist collision optics**
- **Synchrotron radiation power 50 MW/beam** at all beam energies
- **Top-up injection** scheme for high luminosity.
- Requires **booster synchrotron in collider tunnel and 20 GeV e+/e- source and linac**



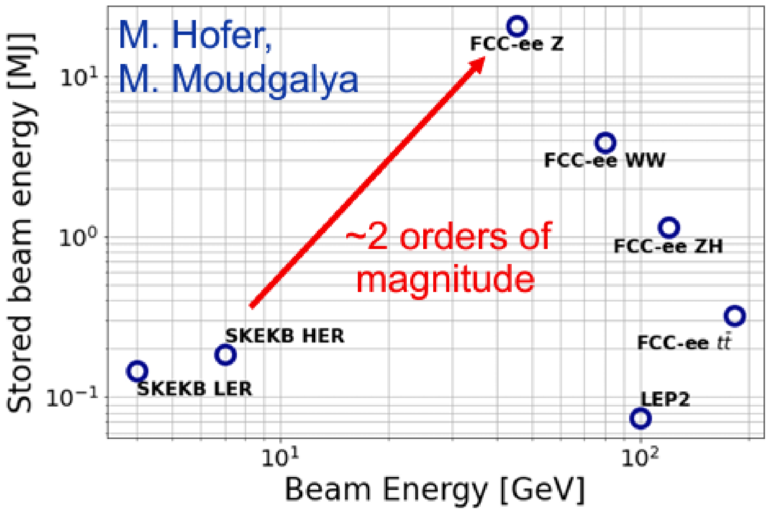
M. Benedikt [3]

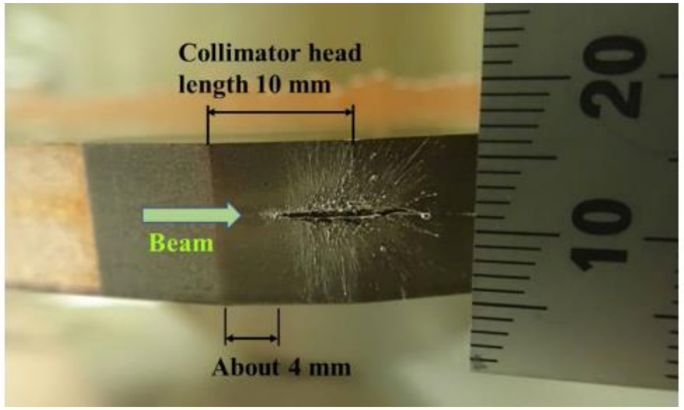
Collimation for the FCC-ee

- **FCC-ee presents unique challenges for collimation**
  - ➢ Unprecedented stored beam energy for a lepton collider: up to **17.5 MJ** in the ***Z*** operation mode (45.6 GeV)
  - ➢ New regime for e+e- colliders
  - ➢ 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

- FCC-ee collimation foresees:
  - Beam halo (global) collimation (+ local protection collimators)
    - ➢ Focus of this PhD thesis project
  - Synchrotron Radiation (SR) collimation – around the IPs
  - Secondary particle shower absorbers under study (CERN FLUKA team)

Comparison of lepton colliders





Damaged Cu coated Ta collimator in SuperKEKB (LER) due to sudden beam loss [4]

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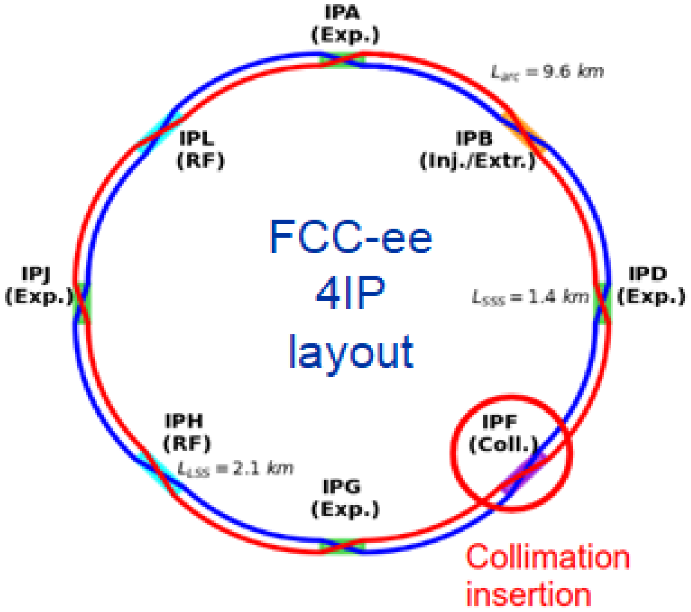
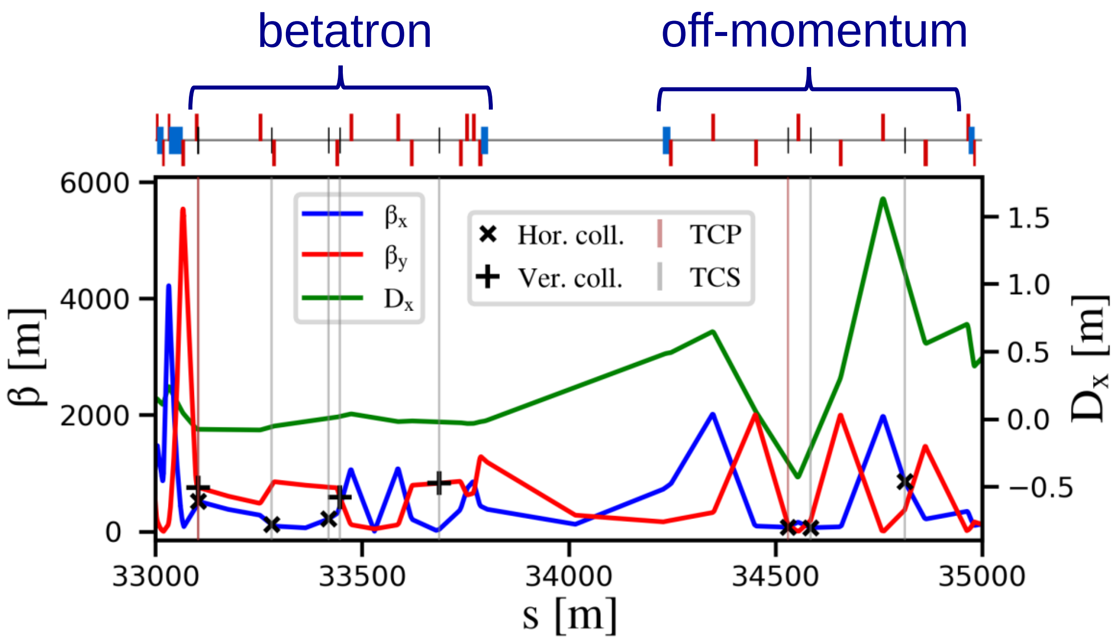
FCC-ee halo collimation system

- **Dedicated halo collimation system in PF** [5]
  - 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** [6-11]
  - Ongoing studies to further optimize the collimator design
  - Crystal collimation being explored [12]



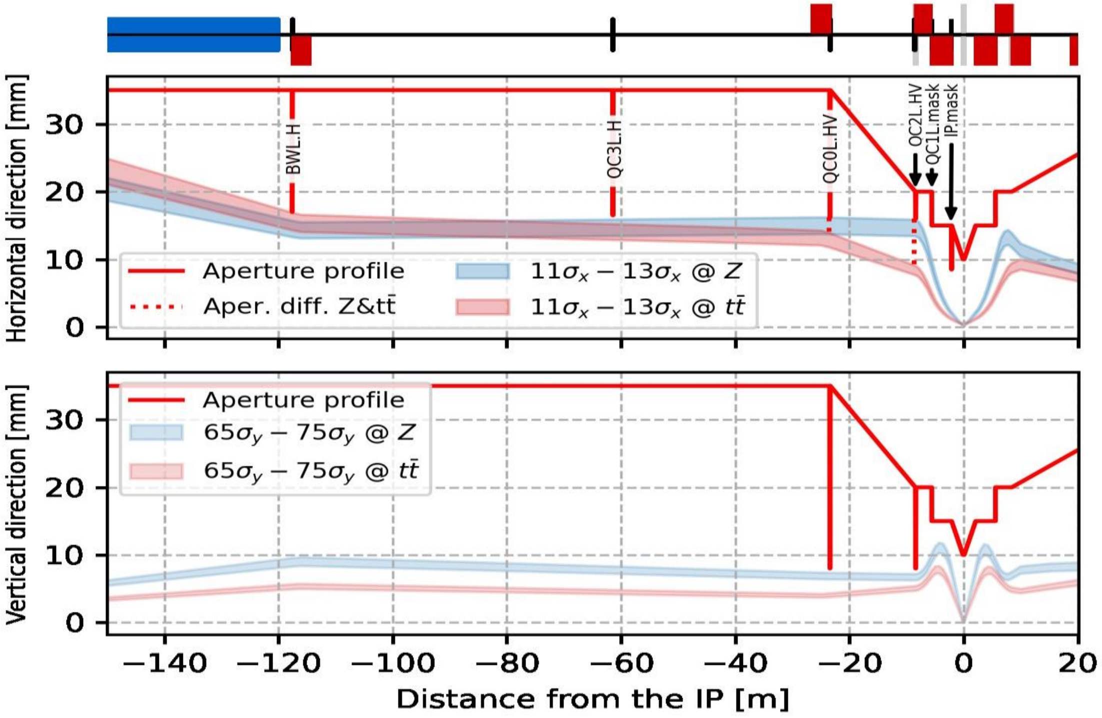


FCC-ee beam halo collimator parameters and settings

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	12	5.0	6.0
TCS.V1.B1	V	Mo	30	75	2.5	-
TCS.H2.B1	H	Mo	30	12	7.0	22.8
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

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



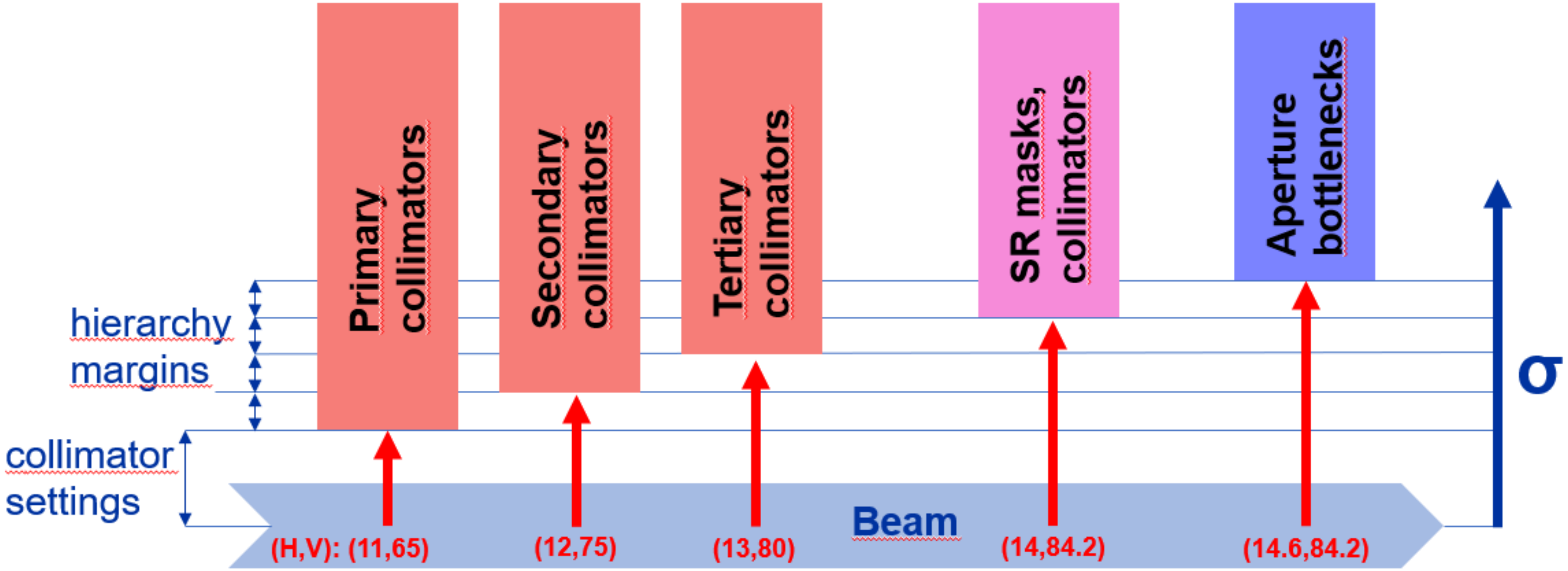
FCC-ee SR collimators parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCR.H.WL.B1	H	W	10	14.0	17.0
TCR.H.C3.B1	V	W	10	14.0	16.5
TCR.V.C0.B1	V	W	10	84.2	8.0
TCR.H.C0.B1	H	W	10	14.0	16.2
TCR.V.C2.B1	V	W	10	84.2	8.0
TCR.H.C2.B1	H	W	10	14.0	16.0

- More details in Ref. [13]

Tertiary collimators for local protection

- Studying different beam loss processes, sizeable beam losses on SR collimators observed
- SR collimators not primarly designed to intercept large beam losses: risk of damages/background
- **Two** (**H+V**) **tertiary collimators** (**TCTs**) for local protection added
  - ➢ Placed ~690 m (H) ~420 m (V) upstream of each IP
  - ➢ s-location optimized for optimal phase-advance (multiple of π) between TCTs and { SR collimators / aperture bottlenecks }
- Collimation hierarchy must be respected:



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 local protection collimator parameters and settings

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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 **spent beam** due to the collision processes

  } Simulation models available

  - Beam losses from **Touschek scattering**
    - Most likely negligible at FCC-ee beam energies
    - Interesting in the view of benchmarking simulation tools with operating e+e- colliders

  - Beam losses from interactions with **thermal photons**
  - Beam losses due to **fast instabilities**

  } Work in progress (H. Burkhardt, G. Nigrelli)

  - Beam losses from **top-up injection**
  - Accidental scenarios (inj. failure, asynchronous dump, others)

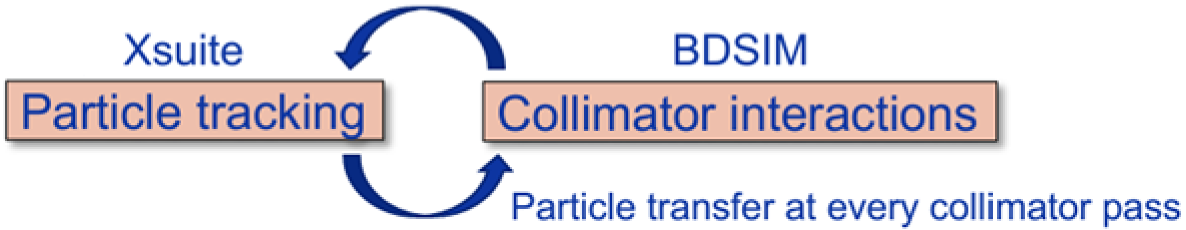
  } Waiting for inputs to set up models

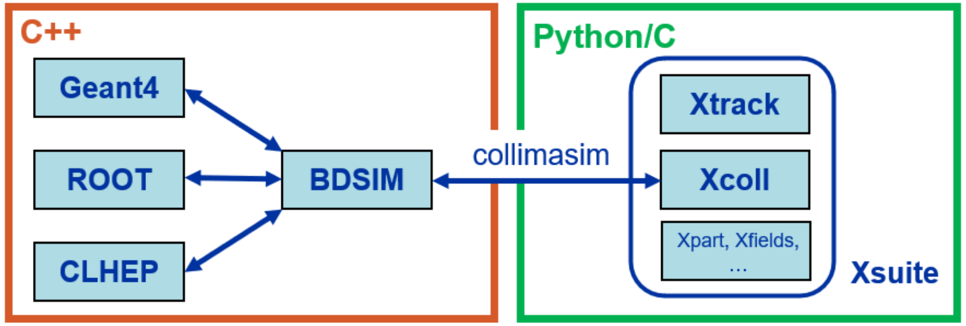
FCC-ee collimation simulations

- **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

Ongoing effort to benchmark Xsuite-BDSIM with data from e+e- colliders (SuperKEKB [23], DAΦNE [24])

- **Xsuite + BDSIM (Geant4) coupling** [14-20]
  - Developed for FCC collimation simulations
  - Benchmarked against
    - other simulation codes: MAD-X, pyAT, Sixtrack-FLUKA [6, 21]
    - measured data from proton machines: SPS [22], LHC [6]
  - Coupling to BDSIM now available with the **Xcoll** package [25, 26]
  - Other tools available (e.g., Xsuite-FLUKA coupling) [25, 26]





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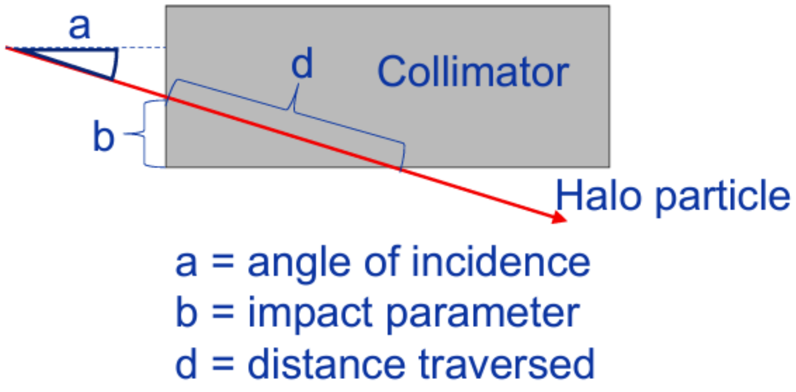
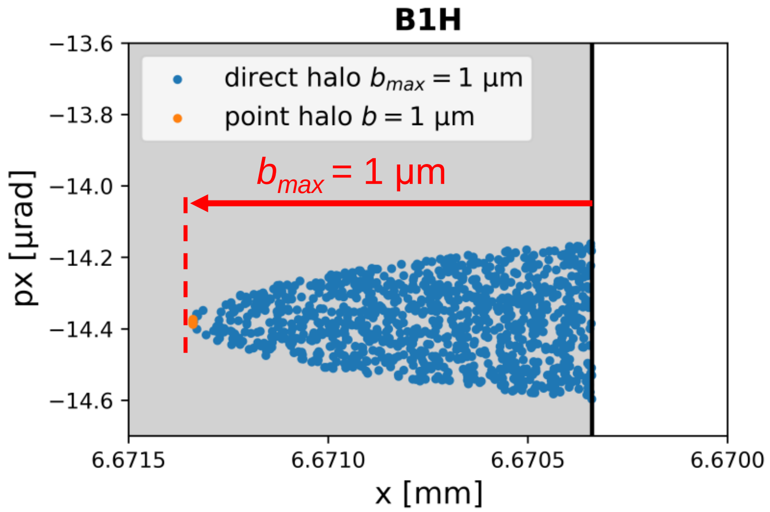
Generic beam halo losses

- **«Generic beam halo» beam loss scenario**
  - Specify a minimum beam lifetime that must be sustained during normal operation - preliminary specification of a **5 min** lifetime
  - Assume a slow loss process – halo particles always intercepted by the primary collimators
  - **Loss process not simulated**: all particles start impacting a collimator from the collimator edge to a maximum impact parameter b_{max} (*direct halo* [27])
  - Currently assuming $b_{max} = 1$ μm
  - Studies needed to asses the most realistic b_{max} value
    - Impact parameter scans showed monotonically worsening collimation performance with decreasing impact parameters [28]
  - Particles scattered out from the collimator tracked for a given number of turns (~500), and losses on the aperture are recorded → **loss maps**





Generic beam halo losses: simulation parameters

- **FCC-ee *Z* operation mode**
  - Clockwise positron beam (B1) - 45.6 GeV beam energy
  - Initial conditions (SR: synchrotron radiation; BS: beamstrahlung)

$\varepsilon_x = 0.71\ nm$

equilibrium horizontal emittance from SR

$\varepsilon_y = 1.9\ pm$

equilibrium vertical emittance from SR+BS

$\sigma_z = 15.5\ mm$

equilibrium bunch length from SR+BS

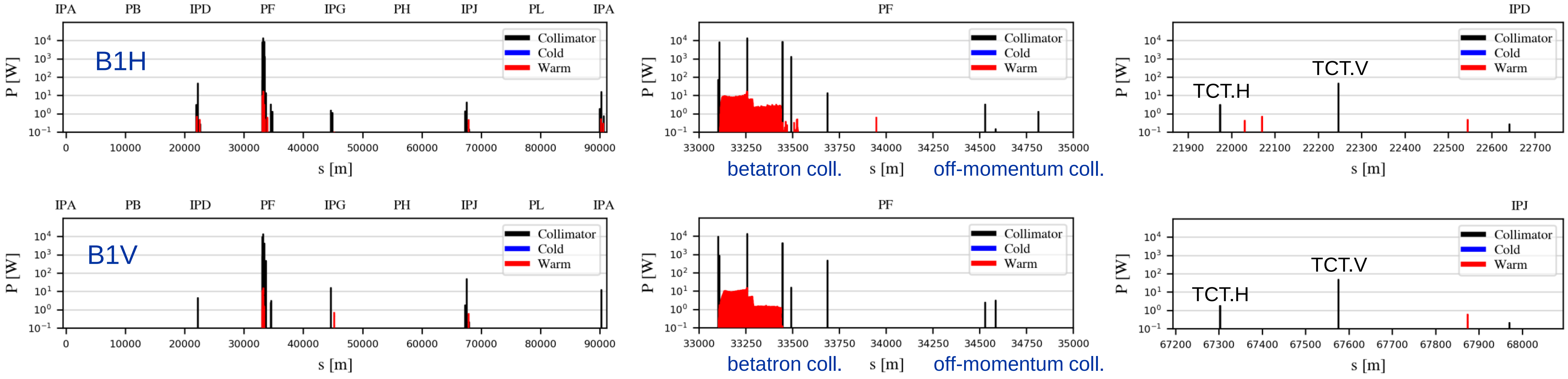
  - Equilibrium vertical emittance from SR + BS kept constant with addition of vertical wiggler in the lattice
  - Full nonlinear lattice
  - Crab-waist
  - Detailed aperture and collimator (BDSIM-Geant4) model
  - SR emission («quantum» model)
    - Radiation damping
    - Quantum excitations

5 x 10^6 macroparticles tracked for 500 machine turns

Generic beam halo losses: results

- FCC-ee *Z* loss maps for horizontal (B1H) and vertical (B1V) betatron collimation losses:

full 90 km ring | collimation insertion | most exposed IP



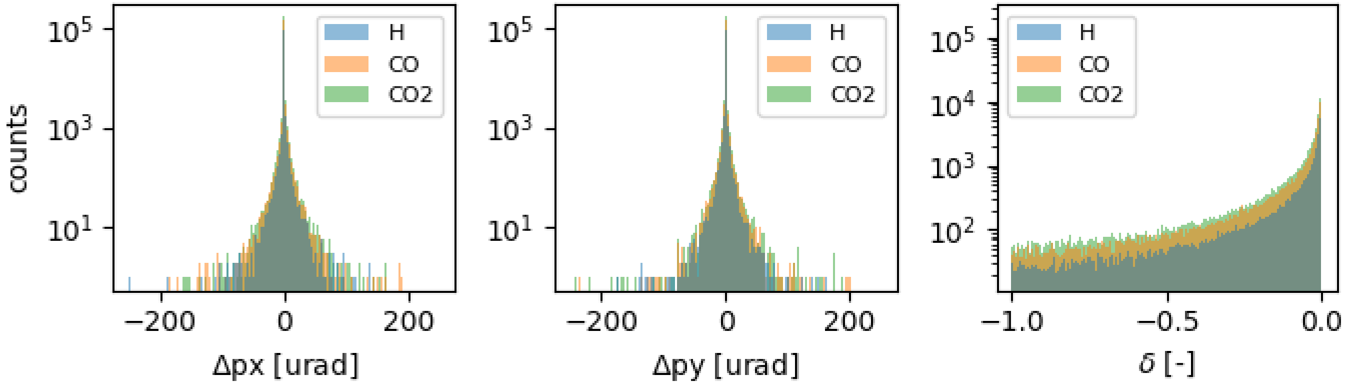
- **Losses well contained in the collimation insertion PF** (>98%)
- **Losses leaking out the collimation insertion PF mostly intercepted by tertiary local protection collimators**
  - ➢ Shower simulations needed to check possible backgrounds generated by these beam losses
  - ➢ Nearly absence of losses reaching the detector regions / final focus superconducting quadrupoles

Beam losses from beam-residual gas interactions

- The **interaction between the beam and residual gas in the vacuum chamber** is an **important aspect to study**
  - Can produce distinct beam loss distributions
  - Can be source of lifetime/luminosity degradation and background in the experimental interaction regions

- **Pressure profile in the FCC-ee** (*Z*) provided by the vacuum team (85% H_2, 10% CO, 5% CO_2)
  - NEG coated vacuum pipe, 1h beam conditioning at full nominal current (1.27 A)
  - Focus on bremsstrahlung beam-gas interactions (dominant process in determining beam-gas losses)

Bremsstrahlung of 45.6 GeV e+ on different gas species



- **Beam-gas elements implemented in Xsuite-BDSIM** to model the interaction with residual gas in the vacuum pipe [29]

Beam-gas beam losses: simulation parameters

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  - Full nonlinear lattice
  - Crab-waist
  - Detailed aperture and collimator (BDSIM-Geant4) model
  - SR emission («quantum» model)
    - ➢ Radiation damping
    - ➢ Quantum excitations

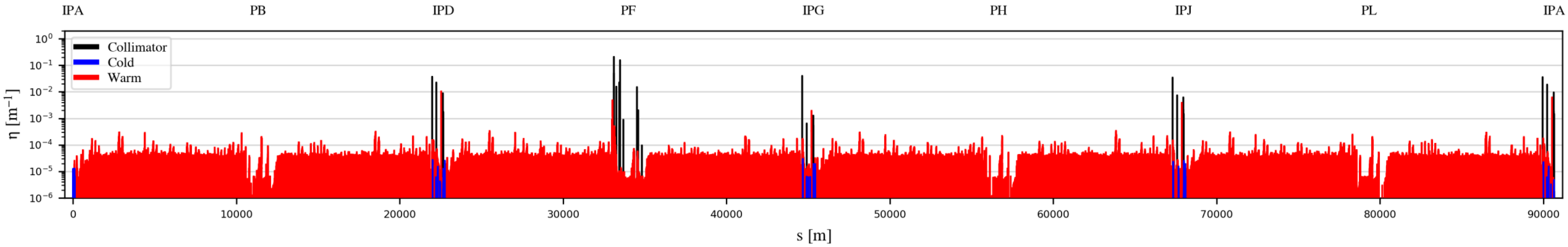
10 x 10^6 macroparticles tracked for 17 x 10^6 equivalent machine turns

  - + 10000 equispaced (~9 m spacing) beam-gas elements to model beam-gas bremsstrahlung interactions

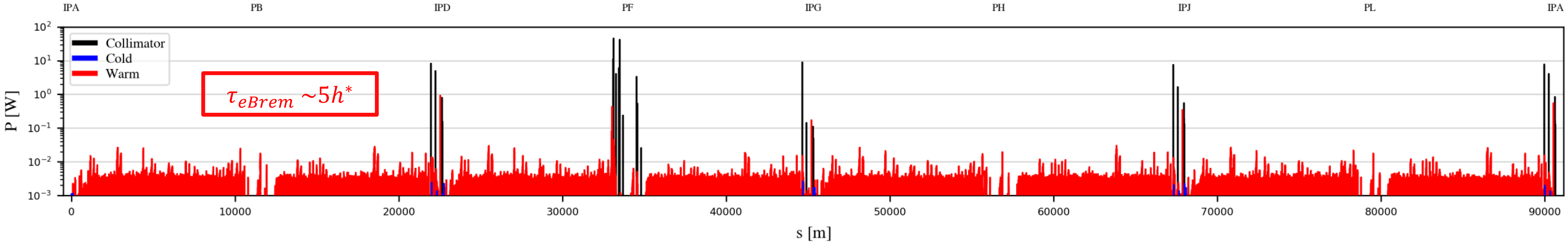
FCC-ee Z beam-gas loss map

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

- FCC-ee (Z) beam-gas beam loss pattern:



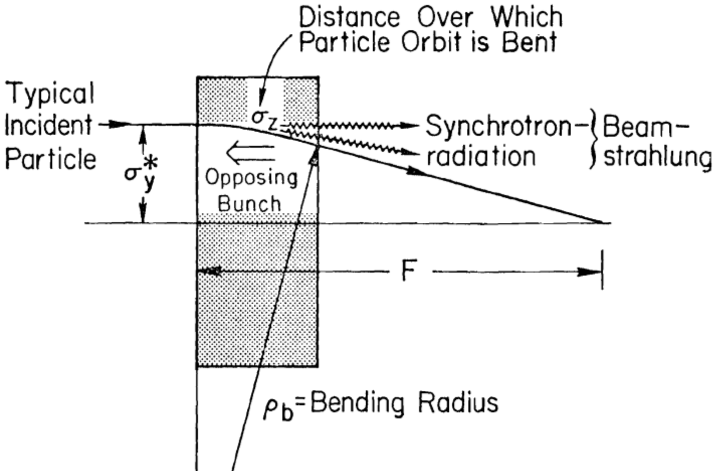
- Rescaling according to the estimated beam-gas lifetime τ_{eBrem} to evaluate the power load distribution:



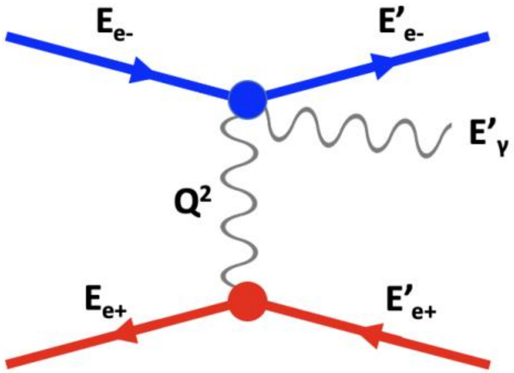
- Low power loads (<0.1 W) on the vast majority of elements and minimal cold power loads
- Highest loads on halo collimators (~10-100 W) and SR collimators (~1 W) – no show stoppers identified

FCC-ee Z spent beam losses

- **Interactions at the IPs have a crucial role on the FCC-ee beam dynamics**
  - ➢ Beamstrahlung, Bhabha scattering, beam-beam kicks



Schematic illustration of **beamstrahlung** [30]:
an incoming bunch emits beamstrahlung radiation
because of the electromagnetic field of the opposing bunch



Schematic illustration of **Bhabha scattering** (electron-positron scattering) [31]
The scattering particles exchange a virtual photon. The process can occasionally result in the emission of extra real photons, in which case the process takes the name radiative Bhabha scattering.

  - ➢ Main contribution to the beam lifetime in nominal operation
  - ➢ Can produce distinct beam loss distributions around the ring

- **GOAL: integrate beam-beam effects in collimation tracking studies**
  - ➢ Multi-turn beam dynamics and beam losses of spent beam particles

Spent beam losses: simulation parameters

- **FCC-ee *Z* operation mode**
  - Clockwise positron beam (B1) - 45.6 GeV beam energy
  - Initial conditions (SR: synchrotron radiation; BS: beamstrahlung)

* In this simulation the contribution from BS is directly simulated including beam-beam interactions

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equilibrium horizontal emittance from SR

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equilibrium vertical emittance from SR+BS

$$\sigma_z = 15.5\ mm$$

equilibrium bunch length from SR+BS

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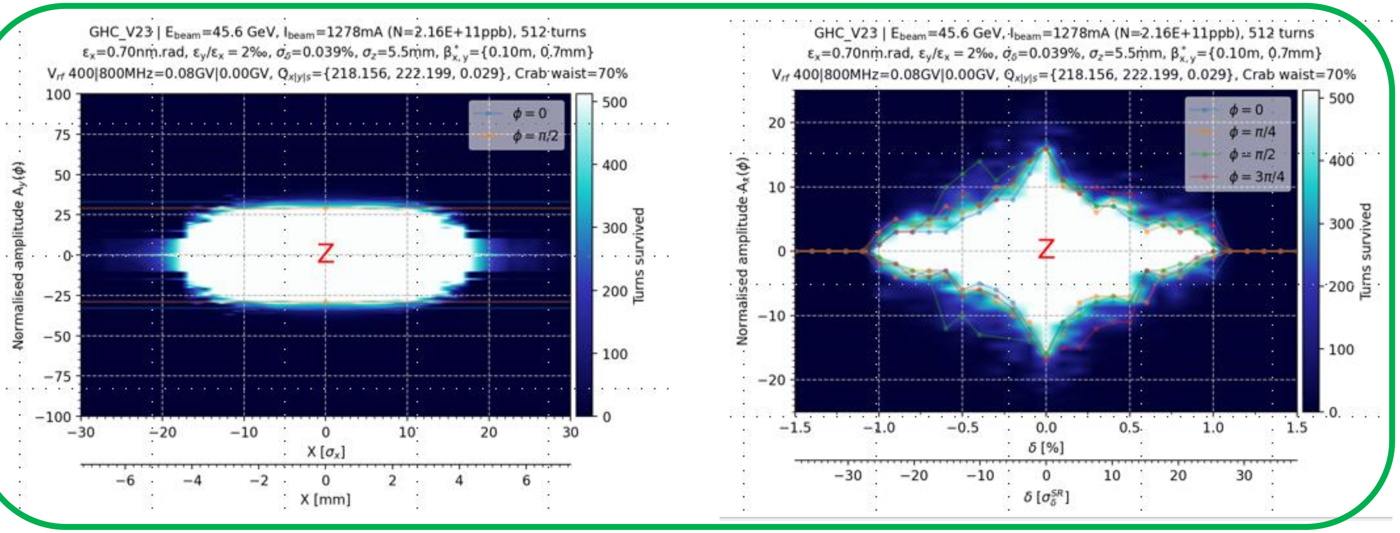
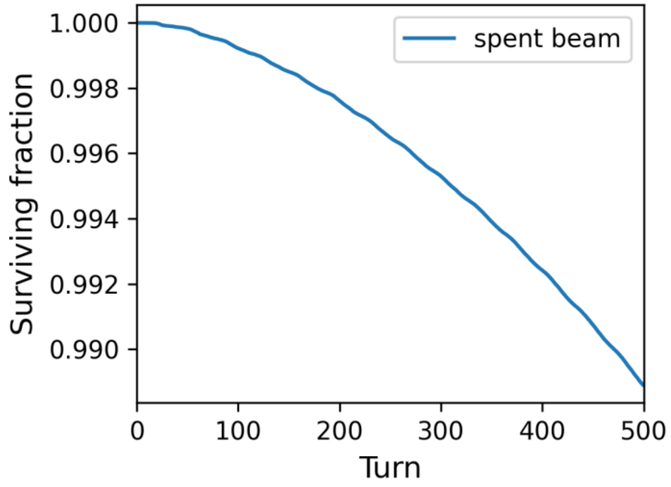
10 x 10^6 macroparticles tracked for 500 machine turns

  - \+ weak-strong beam-beam, Beamstrahlung, Bhabha scattering in 4 IPs

FCC-ee *Z* spent beam losses: results

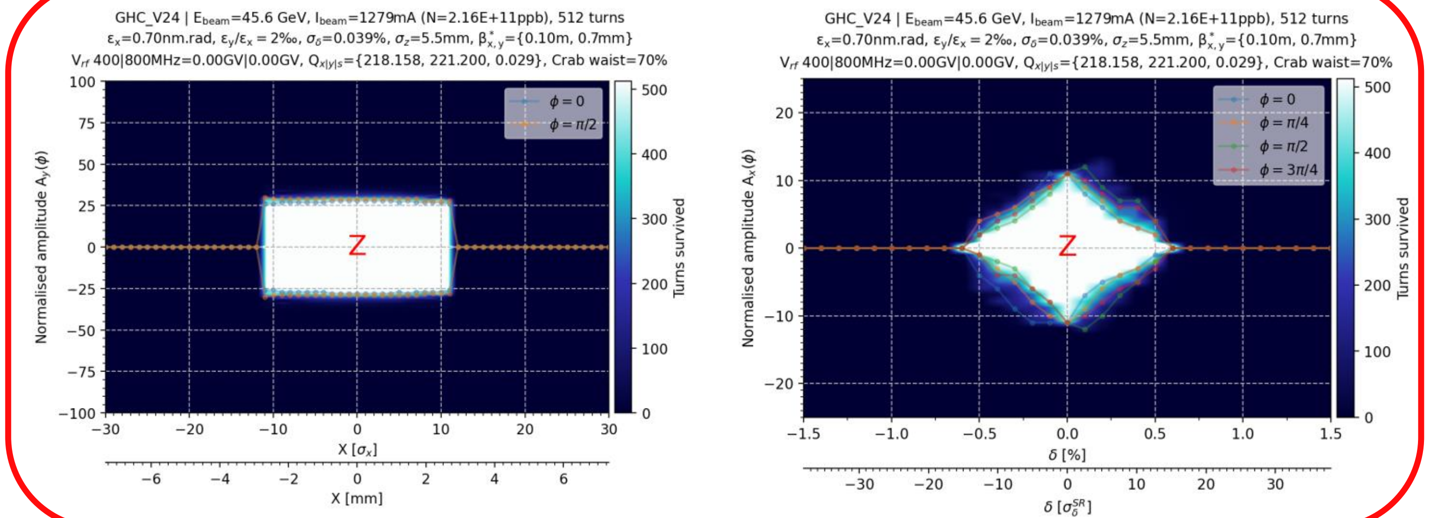
- Cumulative loss over 500 turns is ~1%





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**

N.B.: This can also affect beam-gas lifetime estimates!

FCC-ee *Z* spent beam losses: results

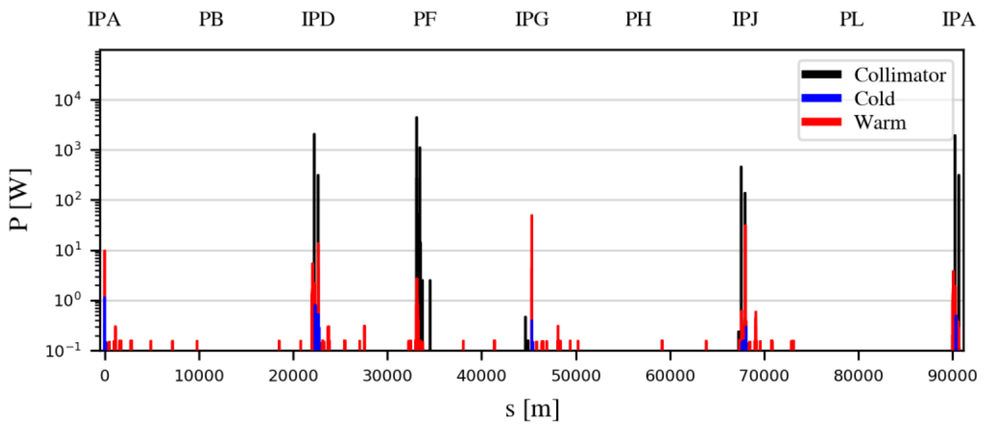
Lifetime for the *Z* mode [32]

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

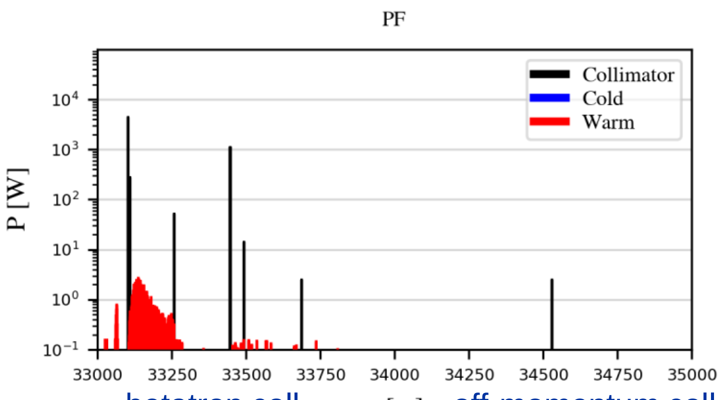
- The loss maps are scaled to the **combined nominal beam lifetime** from lattice, SR, beamstrahlung and luminosity

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

full 90 km ring

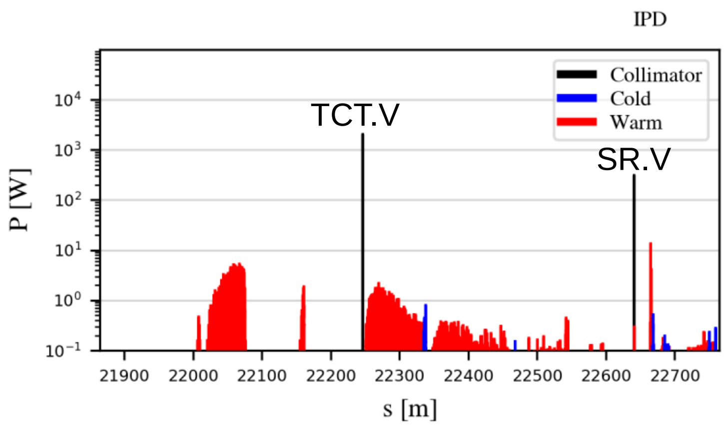


collimation insertion



betatron coll. off-momentum coll.

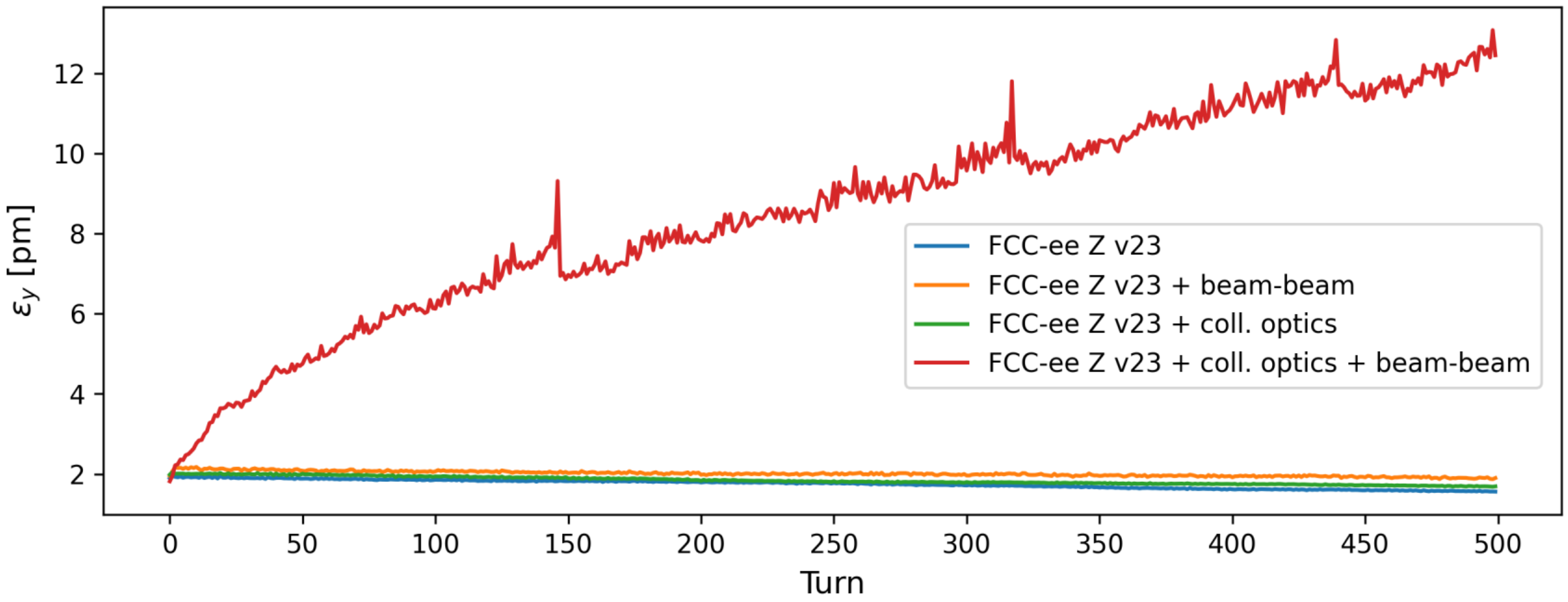
most exposed IP



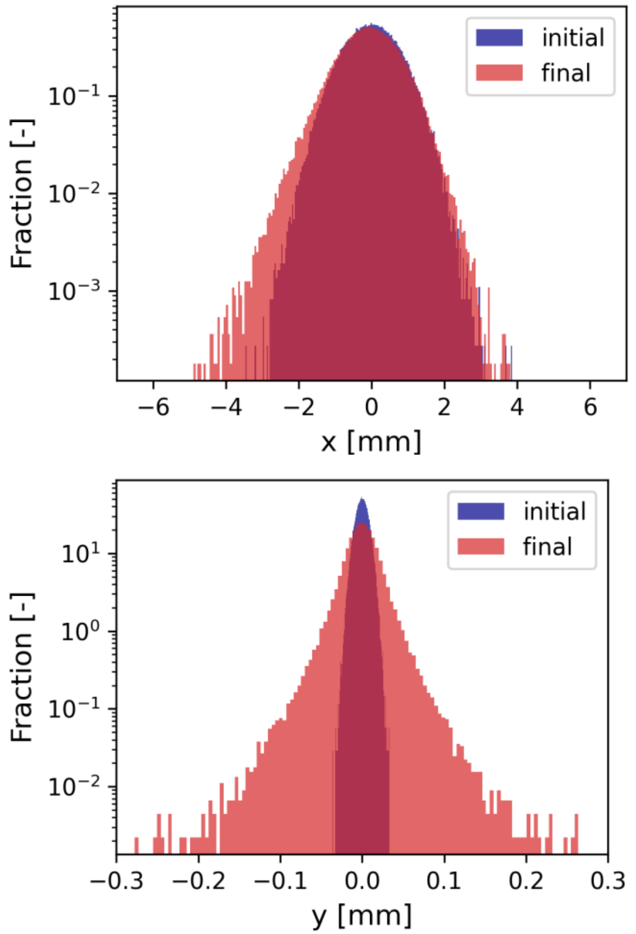
- Losses intercepted by betatron collimators in PF (43%)
- Large losses on the TCT.V and SR.V collimators in IPD, IPA and IPJ with minimal losses in IPG
  - ➢ Up to 2.1 kW on a vertical TCT and 300 W on a vertical SR collimator
  - ➢ Likely single-pass losses that cannot be intercepted by the halo collimation system in PF
    - ○ Physics debris collimators (like in the CERN LHC) might be an option

FCC-ee *Z*-mode spent beam losses: results

- High losses observed in the V plane
  - ➢ Driven by a vertical emittance blow-up due to an interplay between the collimation insertion optics and beam-beam interactions



Transverse distribution after 500 turns



- Inclusion of collimation insertion optics breaks the super-periodicity of the lattice
  - ➢ New resonance lines appear
- Because of beam-beam interactions a larger region of tune space is probed
- Avoiding such new resonances might become an additional design constraint for collimation optics

Outline

- **Introduction**
  - FCC-ee: the Future Circular electron-positron collider
  - Collimation for the FCC-ee
- **FCC-ee collimation system**
  - FCC-ee halo collimation system (and local protection collimators)
  - FCC-ee SR collimation system
- **Studies and simulations of beam losses in the FCC-ee**
  - FCC-ee beam loss scenarios
  - FCC-ee collimation simulations
- **Results**
  - Generic beam halo losses
  - Beam-gas beam losses
  - Spent beam losses
- **Bent-crystal assisted collimation for the FCC-ee: an alternative design**
- **Outlook and future work**

Crystal collimation for the FCC-ee

- As an alternative to the baseline design relying on amorphous collimators, crystal collimation is also being explored:

Cleaning efficiency

Angular deflection by bent crystals increases the impact parameter of beam halo particles on the absorbers (secondary collimators)

Impedance

Short (sub-mm) bent crystals in place of tens of cm long amorphous primary collimators

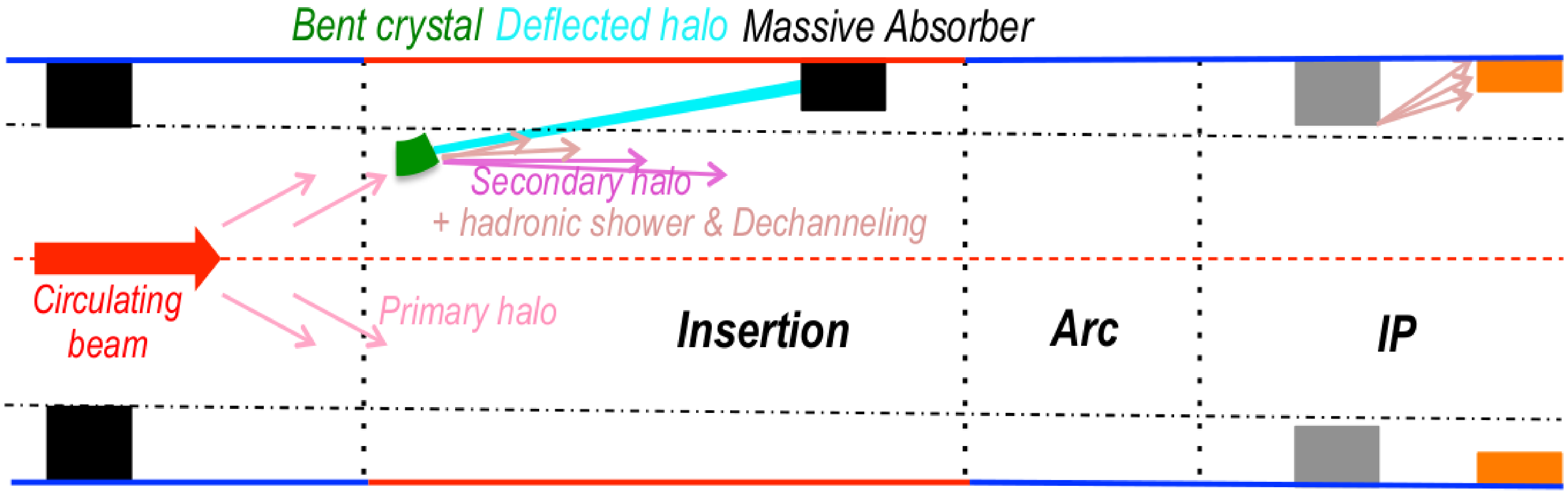
Potentially larger absorber (secondary collimator) mechanical gaps

Power deposition on collimators

Short (sub-mm) bent crystals in place of tens of cm long amorphous primary collimators

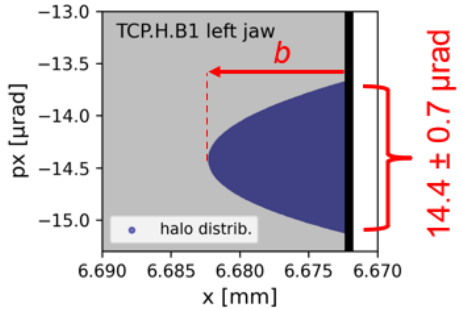
Potentially increase beam halo spot size at the absorbers employing bent crystals

Power deposition on absorber could still be challenging

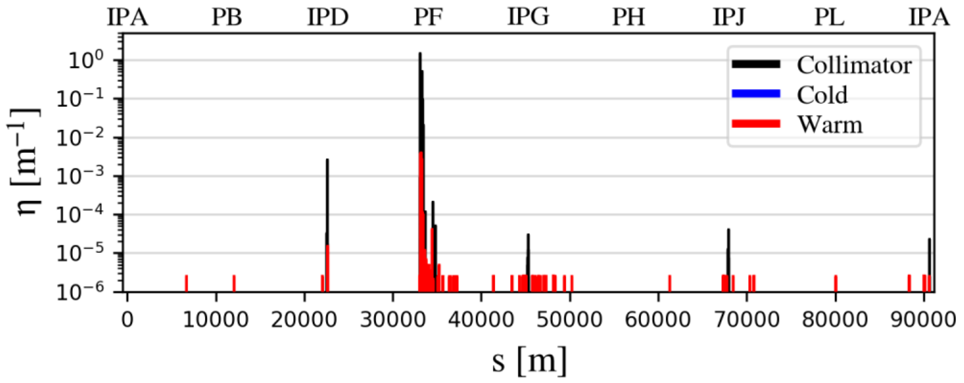


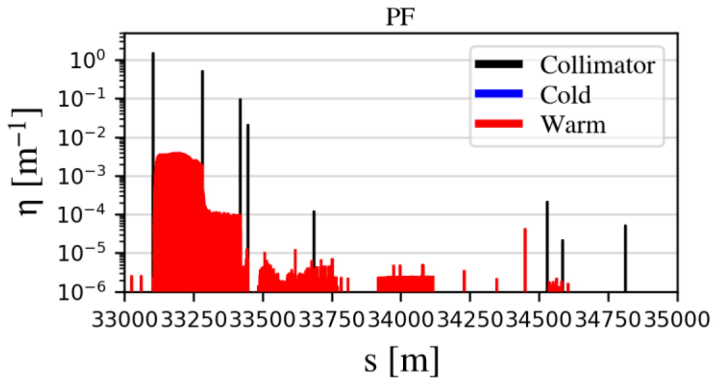
Working principle of a crystal collimation system [33]

One-turn cleaning of the e+ beam

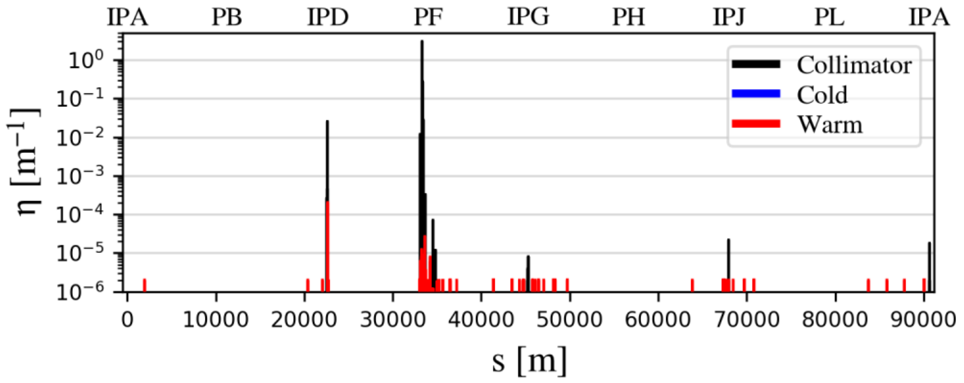


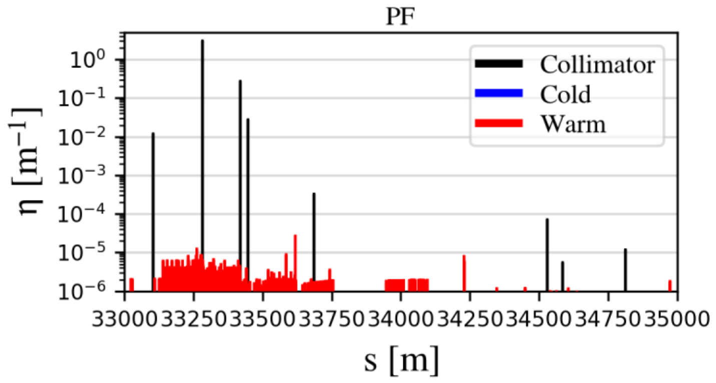
- Replacement of primary collimators with 200 μm bent Si crystals (100 μrad bending angle)





Standard collimation





Crystal collimation

- One-turn cleaning is comparable – compare again the performance considering smaller impact parameters *b*
- In the crystal collimation case:
  - Most beam halo losses end up on the absorbers – as expected
  - Significant reduction (up to a factor >100) of local losses in PF
  - Increase of losses on a vertical SR collimator upstream IPD – investigating

Outline

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  - Beam-gas beam losses
  - Spent beam losses
- **Bent-crystal assisted collimation for the FCC-ee: an alternative design**
- **Outlook and future work**

Outlook

- **Collimation studies for the FCC-ee have significantly advanced**
  - First collimation system design available, including beam halo, SR, and local protection collimators
  - Simulations of beam loss scenarios ongoing
    - ➢ **Beam halo losses** studied for the **most critical *Z* mode**
    - ➢ **Beam-gas beam losses** studied for the **most critical *Z* mode**
      - ➢ Estimated beam-gas lifetime 5 h

    NO show stoppers identified

    - ➢ **Spent beam losses** for the **most critical Z mode**
      - ➢ MA reduction with inclusion of collimation insertion optics
      - ➢ Vertical emittance blow-up due to interplay between collimation insertion optics and beam-beam
      - ➢ Lower than nominal beam lifetime – checks and optimizations ongoing
  - Collaboration with the MDI, impedance, engineering, FLUKA studies

- A **bent-crystal-assisted collimation scheme** has been studied
  - Potentially an interesting solution – no show stoppers identified
  - Performance gain over standard (amorphous) collimation cannot be demonstrated yet
  - Further studies are needed

Future work

- **Benchmark the FCC-ee collimation simulation tools with measured data from e+e- colliders**
  - SuperKEKB
  - DAFNE (if possible)

- **Further studies on bent-crystal assisted collimation**
  - Study different impacting conditions on the crystals
  - Multi-turn tracking, channeling radiation, strong field effects, …

- Study **other beam loss scenarios** – failure scenarios, top-up injection, …

- **Study all beam modes** (*Z*, *W*, *H*, *ttbar*)

Thank you!

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Backup

FCC-ee collider parameters as of July 30, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.85	1.25	0.65	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.360	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.4	3.7	5.4	0.99
Lifetime (q + BS + lattice)	[sec]	10000	4000	3500	3000
Lifetime (lum) [b]	[sec]	1330	970	660	650
Luminosity / IP	[10^{34}/cm^{2}s]	141	20	6.3	1.38
Luminosity / IP (CDR)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

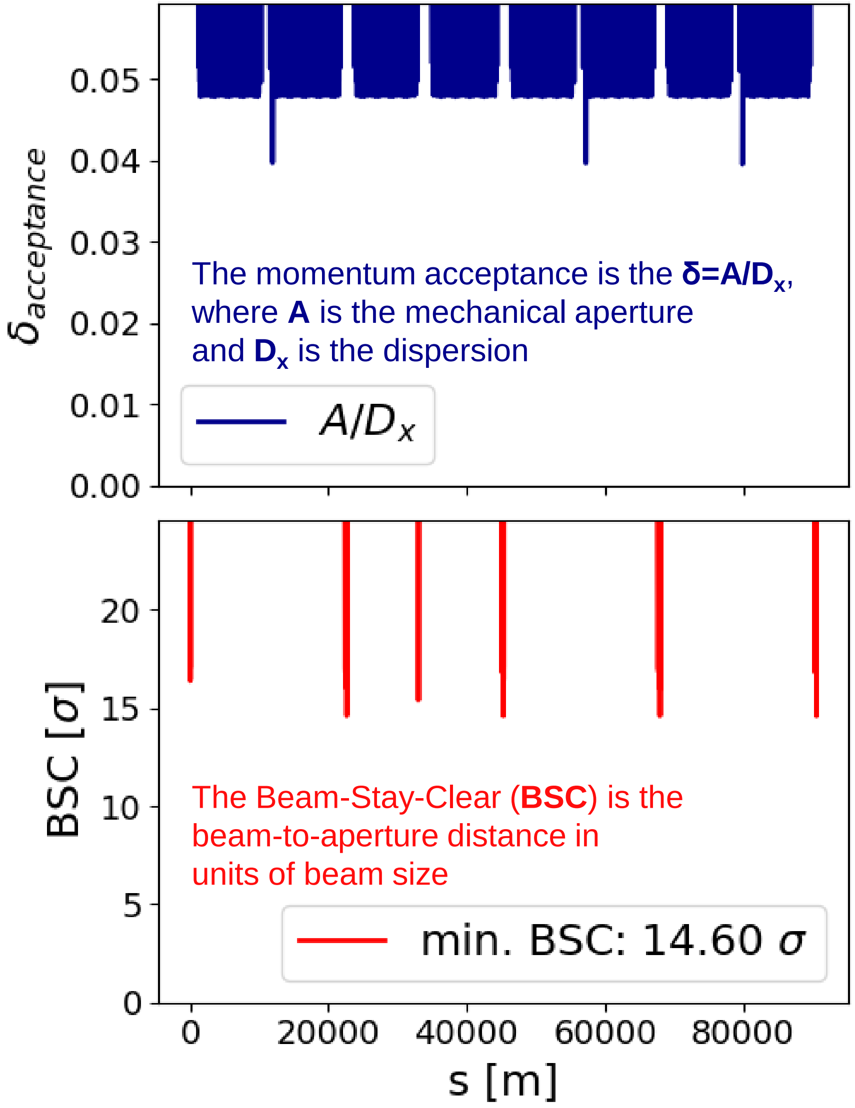
6

FCC-ee collider parameters

FCC-ee aperture

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

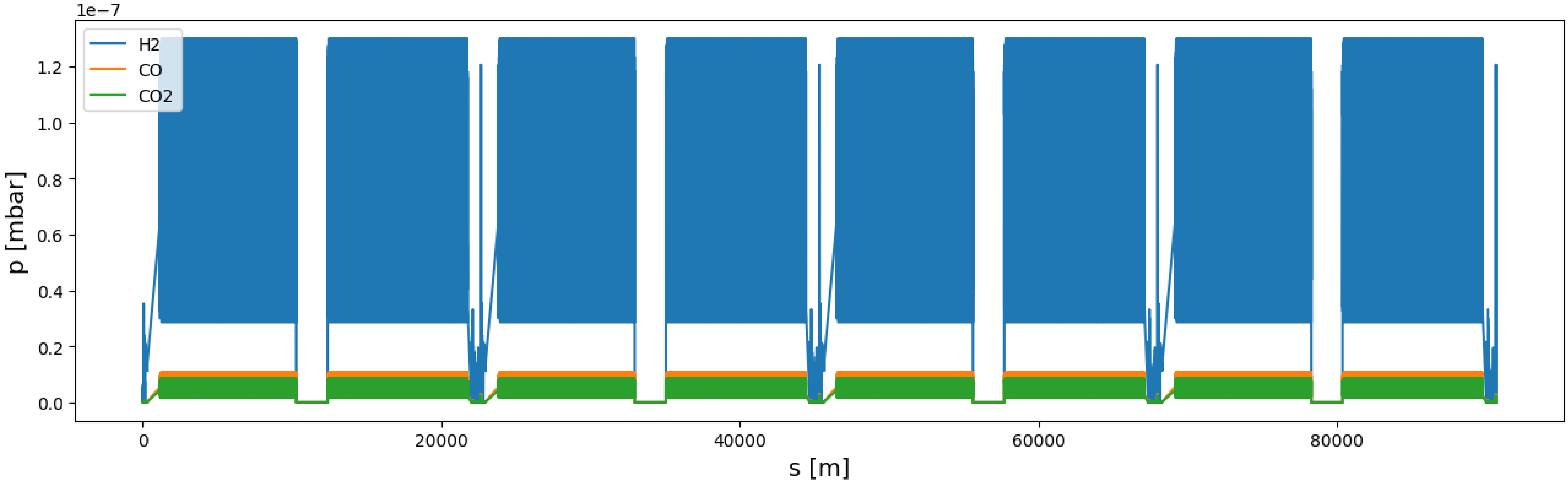
Aperture bottleneck for Z operation mode



FCC-ee Z full ring pressure profile

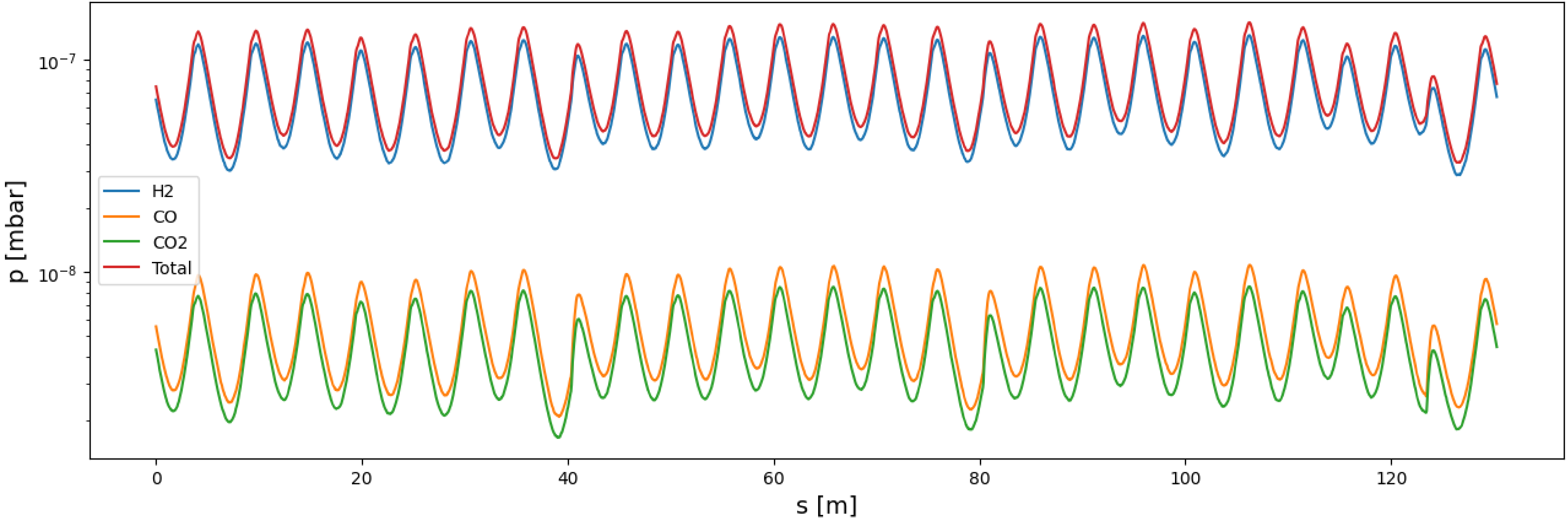
*1h beam conditioning at full nominal current (1.27 A): pressure is expected to condition down further over time

- Pressure profile for an arc section and for the MDI region provided by the vacuum team (R. Kersevan)*
- Gas species and composition: **85% H_2**, **10% CO** and **5% CO_2**
- Arc section pressure profile repeated multiple times to cover the whole arc length
- Because of the absence of dipoles generating SR the **pressure in the straight sections is much lower compared to the pressure in the MDI and in the arcs**
- Arc pressure profile merged with the MDI and straight section pressure profiles to get a **full ring pressure profile**



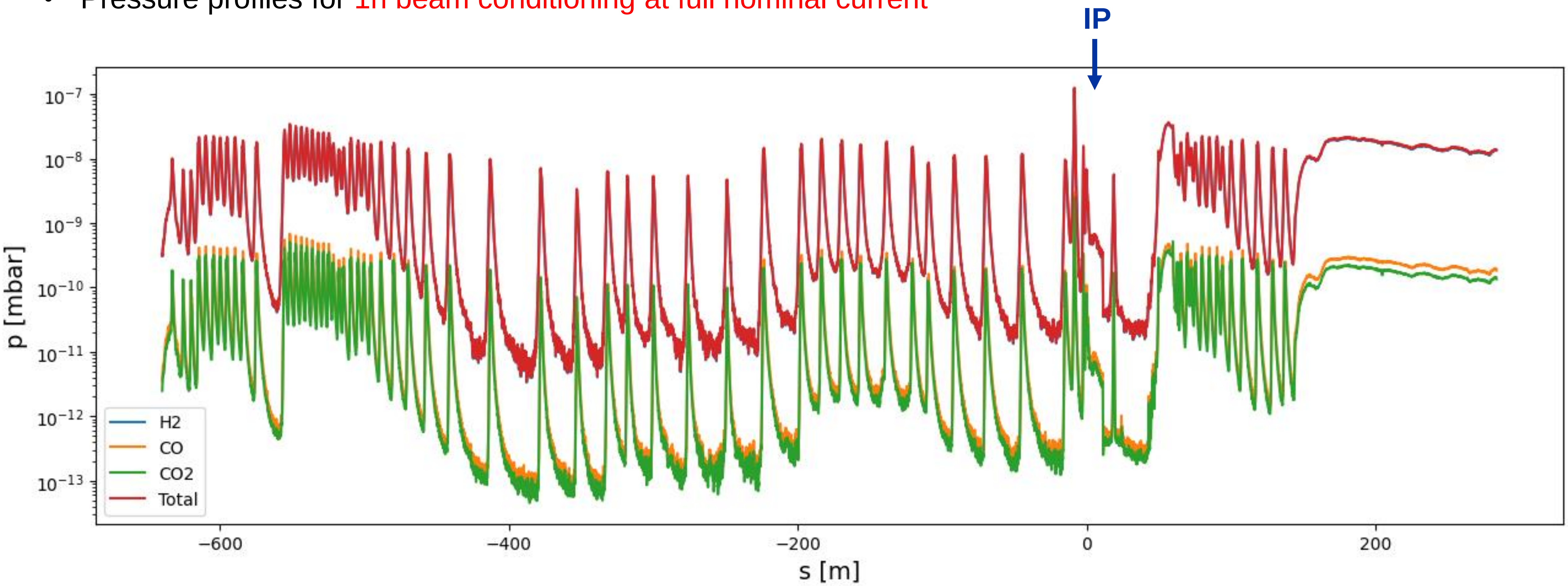
Arc pressure profile in the FCC-ee

- Provided by the vacuum team (R. Kersevan)
- FCC-ee (***Z* mode**) – beam 1 (**B1**): **45.6 GeV positron** beam, 1270 mA current
- Gas species and composition: **85% H_2**, **10% CO** and **5% CO_2**
- Pressure profiles for 1h beam conditioning at full nominal current



MDI pressure profile in the FCC-ee

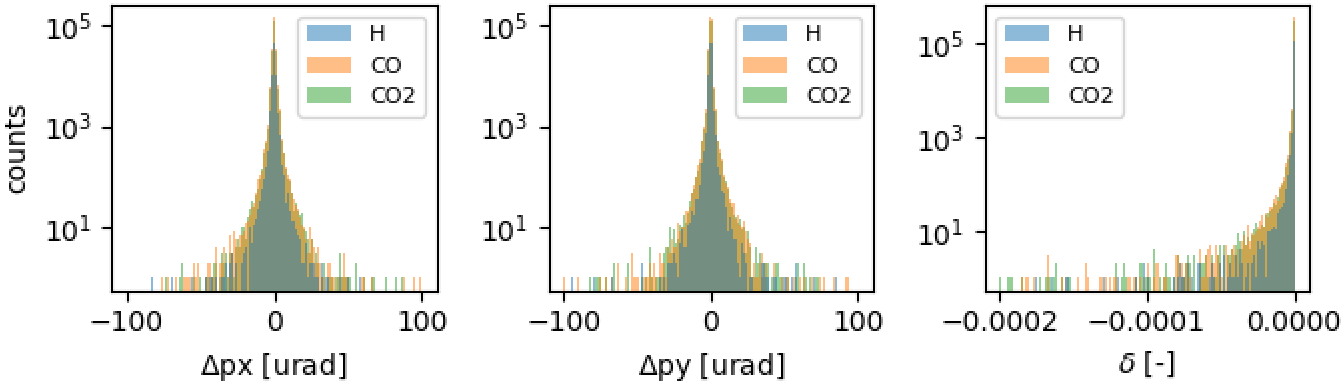
- Provided by the vacuum team (R. Kersevan)
- FCC-ee (***Z* mode**) – beam 1 (**B1**): **45.6 GeV positron** beam, 1270 mA current
- Gas species and composition: **85% H_2**, **10% CO** and **5% CO_2**
- Pressure profiles for 1h beam conditioning at full nominal current



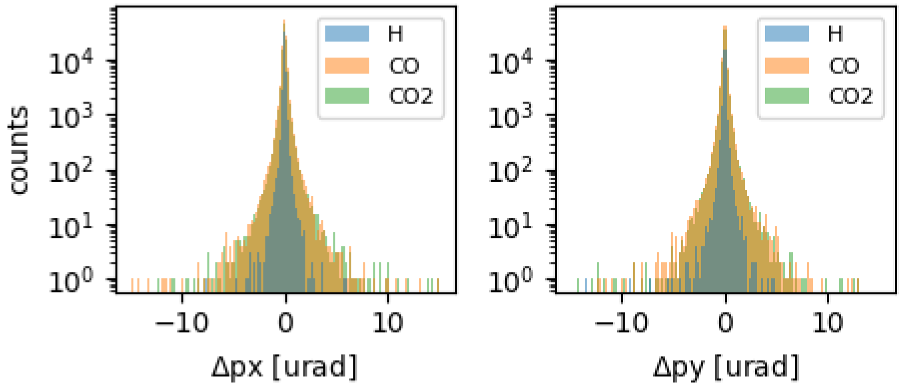
FCC-ee Z beam-gas interactions: interaction effect

- Ionisation, bremsstrahlung and Coulomb scattering produce rather different effects
- Interactions of 45.6 GeV e+ with H, CO and CO2 studied performing **BDSIM** (Geant4) thin target simulations

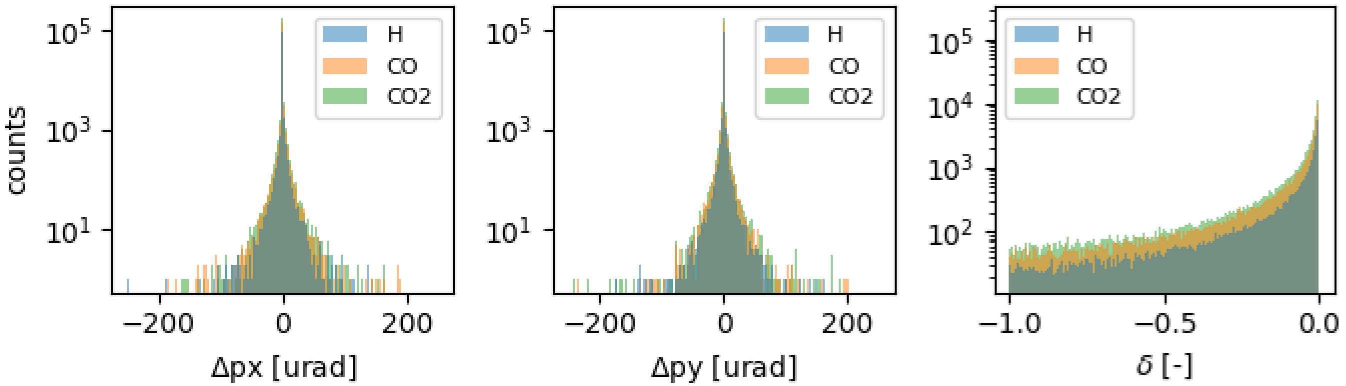
Ionisation (G4StandardEM_SS physics list)



Coulomb scattering (G4StandardEM_SS physics list)



Bremsstrahlung (G4StandardEM_SS physics list)



Pre-sampled final-state coordinates stored to be used run-time in the tracking to emulate the scattering

NOTE: Annihilation is currently not considered due to the much lower cross-section

FCC-ee Z beam-gas interactions: considerations

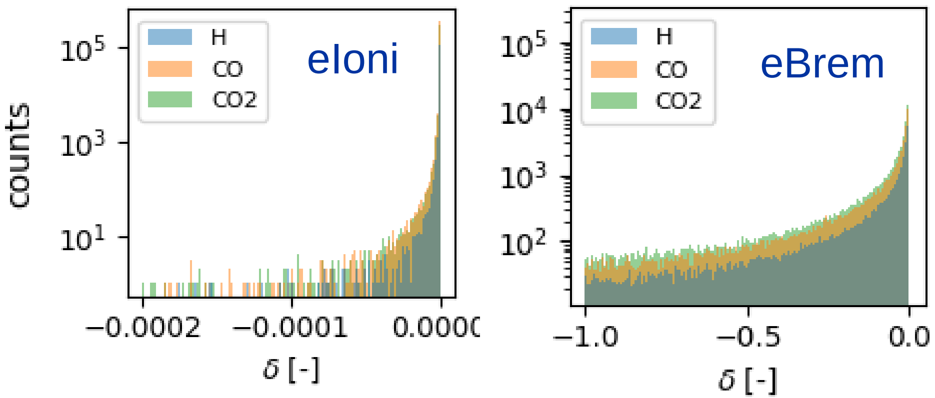
- Coulomb scattering introduces extremely small deflections compared to ionisation and bremsstrahlung
- Ionisation introduces smaller deflections compared to bremsstrahlung

$$\Delta px_{CoulombScat} \sim 0.004\sigma_{px} \qquad \Delta py_{CoulombScat} \sim 0.2\sigma_{py}$$

$$\Delta px_{eIoni} \sim 0.04\sigma_{px} \qquad \Delta py_{eIoni} \sim 1.5\sigma_{py}$$

$$\Delta px_{eBrem} \sim 0.1\sigma_{px} \; * \qquad \Delta py_{eBrem} \sim 3.4\sigma_{py} \; **$$

- Ionisation introduces very small energy variations compared to bremsstrahlung



* σ_{px} and σ_{py} computed in an arc section, where most of the beam-gas interactions take place

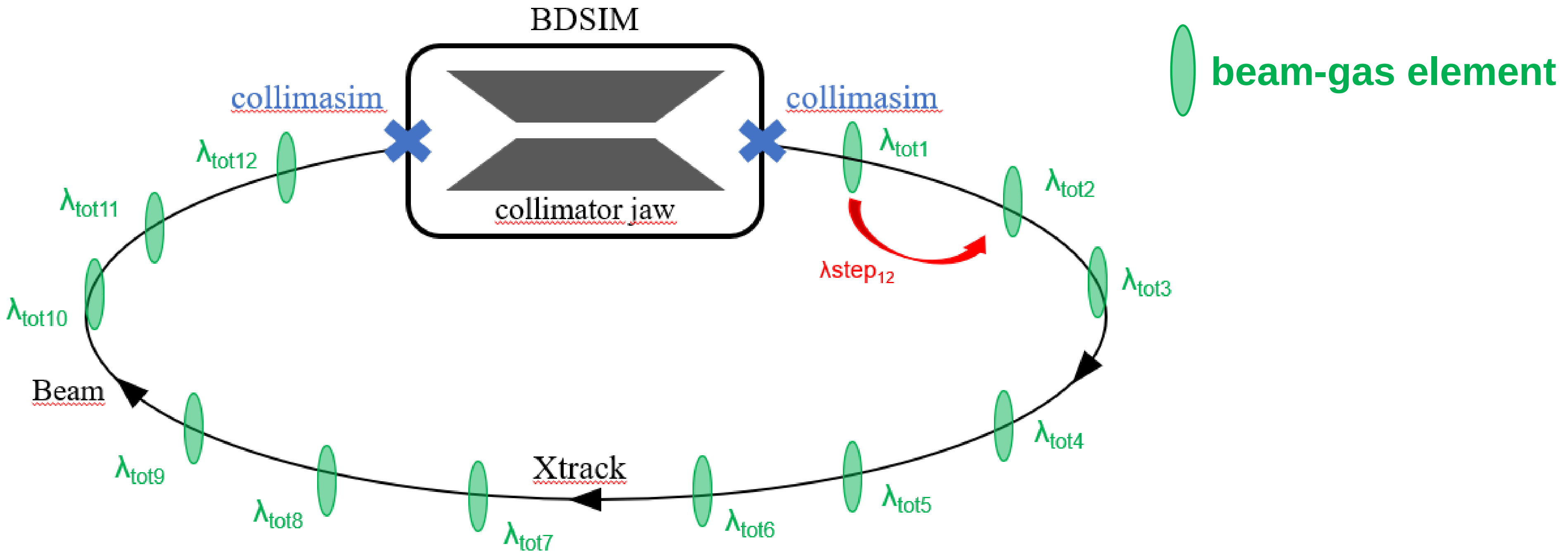
** Δpx and Δpy for H, the dominant gas species

- **Radiation damping** can cancel the effect of small angular kicks

- Despite the higher cross sections, ionisation and Coulomb scattering likely play a marginal role in determining beam-gas beam losses, which are instead dominated by bremsstrahlung interactions
  - ➢ Confirmed by first simulations
  - ➢ The **focus** is therefore on **beam-gas bremsstrahlung interactions**

Simulation workflow

- **Xsuite-BDSIM** simulation tool (already used for FCC-ee collimation studies) with addition of arbitrary number of newly implemented **beam-gas elements** (based on local gas parameters from FCC-ee full ring pressure profile)



- At each **beam-gas element**
  - ➢ The mean free path is computed from cross sections and local gas densities
  - ➢ Random number compared to mean free path to determine if beam-gas interaction takes place
  - ➢ If interaction takes place, further sampling of which gas species and which interaction type
  - ➢ Kicks in angle and energy, taken from the pre-sampled interactions, applied to particle coordinates

Simulation workflow: more details

- When using Xsuite (Xtrack) to track particles, a random number is sampled for each particle to represent the distance travelled by that particle in units of mean free paths:

$$n_\lambda = -\log(random(0,1))$$

- The number n_λ is then compared with mean free path step $n_{\lambda,\,ij}$ between two consecutive beam-gas elements

$$n_{\lambda,\,ij} = \frac{\Delta s_{ij}}{\lambda_{tot\,j}}$$

NOTE: interaction takes place at the beam-gas elements, precision can be increased by adding more elements

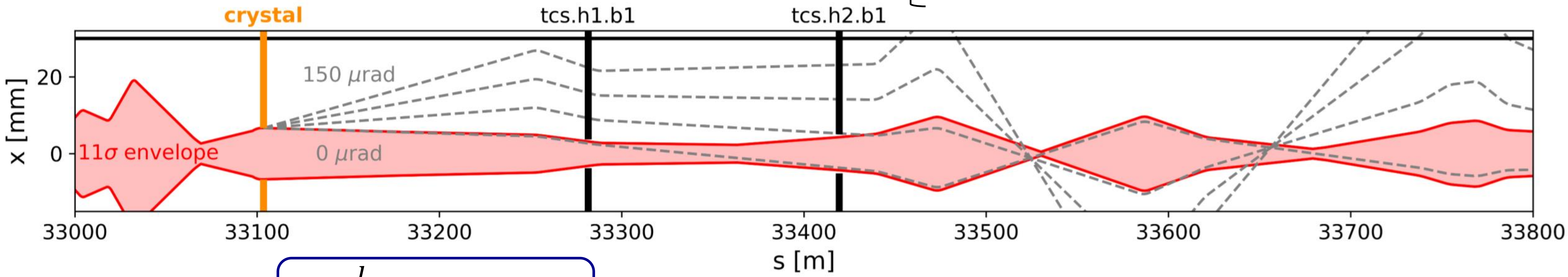
- $n_\lambda - n_{\lambda,\,ij} \leq 0$: **interaction** → a new n_λ is sampled for further tracking
- $n_\lambda - n_{\lambda,\,ij} > 0$: **NO interaction** → n_λ is updated as $n'_\lambda = n_\lambda - n_{\lambda,\,ij}$ for further tracking

- When the **interaction condition** is satisfied, **which interaction** (eIoni, eBrem or CoulombScat) and **with which gas** (H_2, CO or CO_2) is decided by sampling among all the possibilities with relative probability given by the cross-sections and the local gas densities

- Once the interaction decided, the **effect of the interaction** is sampled from the appropriate **interaction dictionary** and applied to the interacting particle (px -> px + delta_px, py -> py + delta_py, delta -> delta + delta_delta)

Crystal bending angle, bending radius and length

- First focus on H plane – the study will then be extended to the V plane
- Different **bending angles** scanned (50 μrad, 100 μrad, 150 μrad)
  - maximize impact parameter on absorber
  - safety margin w.r.t mechanical aperture (30 mm)

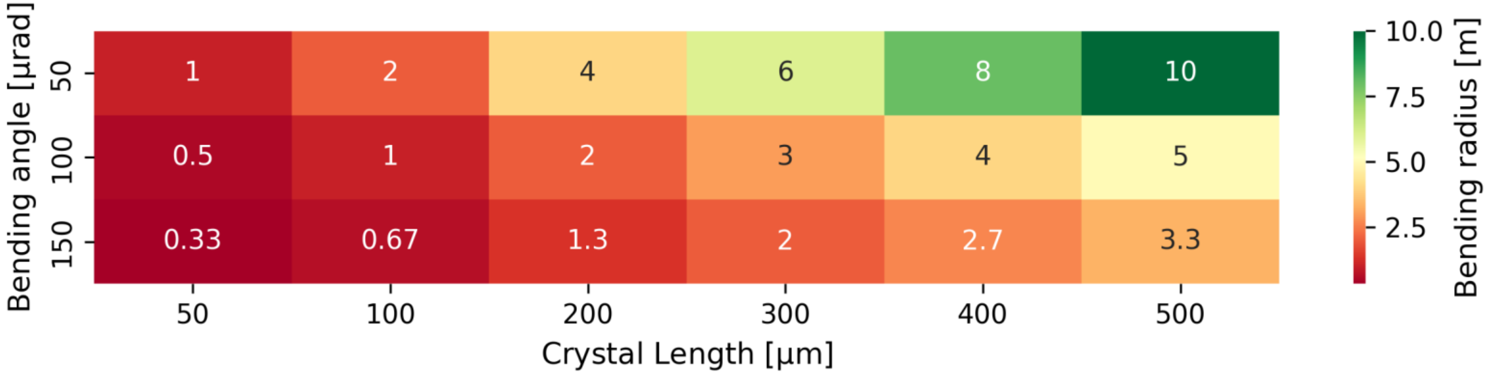


- **Bending radius R**: $R = \frac{l}{\theta} > 3R_c = 0.3\ m$ to ensure smooth particle steering and enhance channeling efficiency

Critical bending radius (Si, *E* = 45.6 GeV)

$$R_c = \frac{pv}{U'(x_{max})} \approx \frac{E}{U'(x_{max})} \approx 9\ cm$$

$U'(x_{max})$: maximum potential gradient [eV/cm]

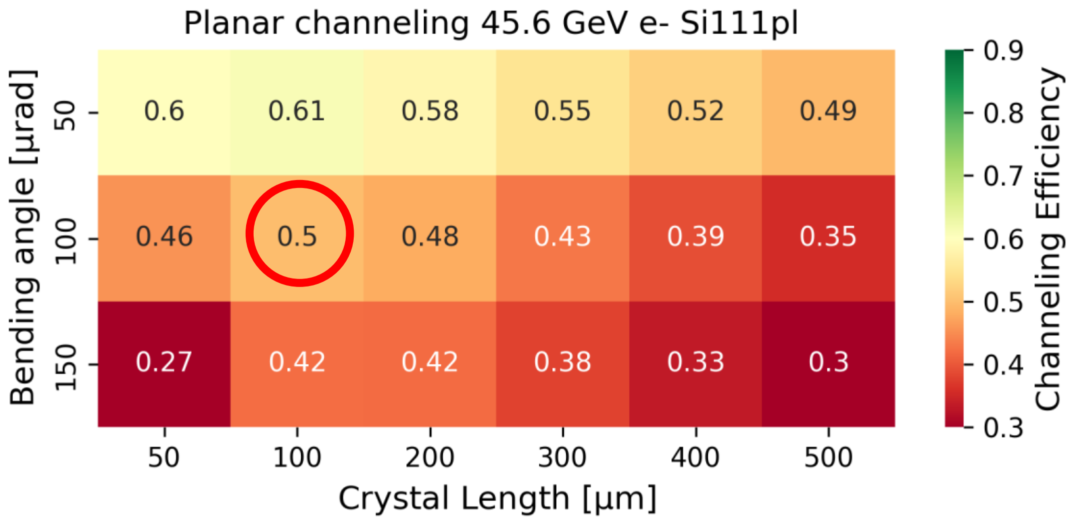


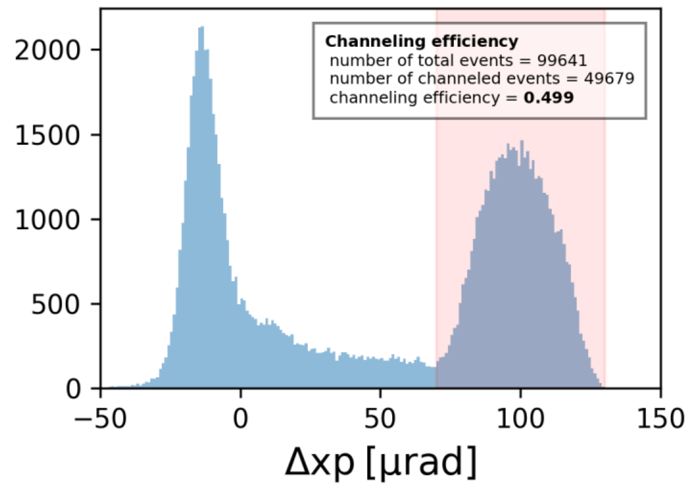
Channeling efficiency

Particles are considered channeled if:

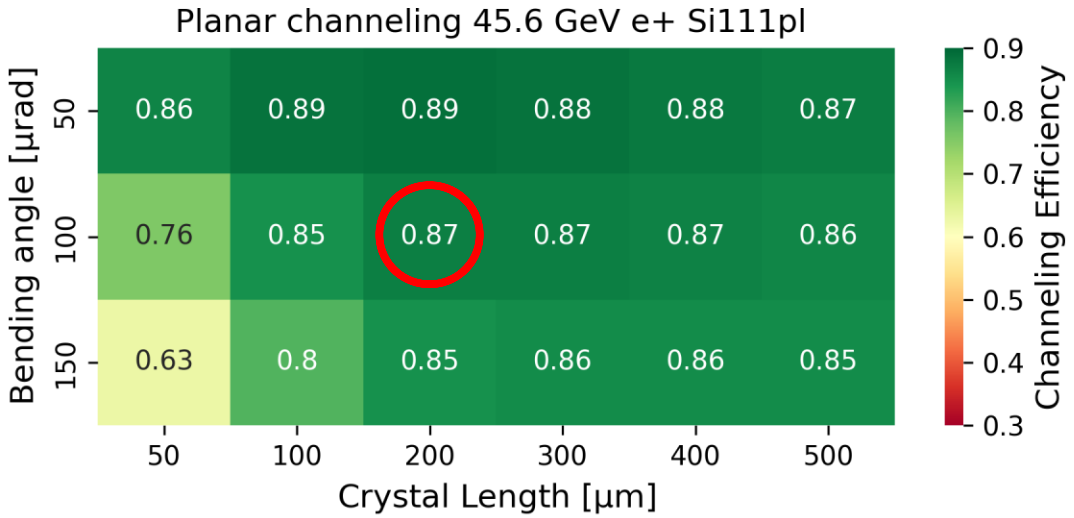
$$\Delta x_p \in [\theta_b - \theta_c, \theta_b + \theta_c]$$

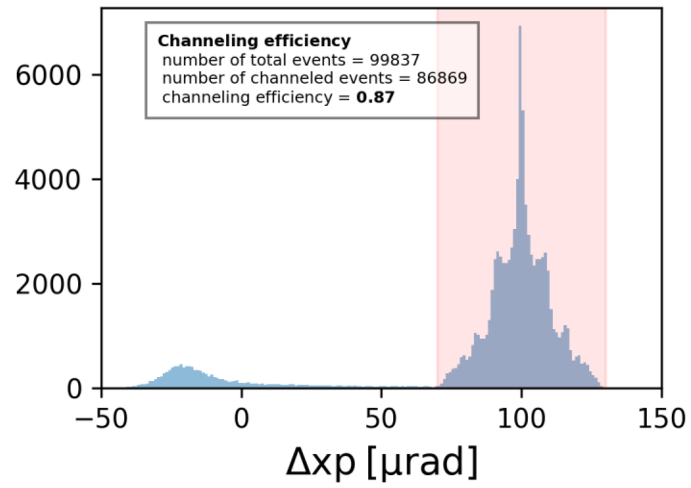
θ_b: bending angle
θ_c: critical angle





Deflection of 100 μrad of 45.6 GeV e- using the Si (111) planar potential of a 100 μm long Si crystal.



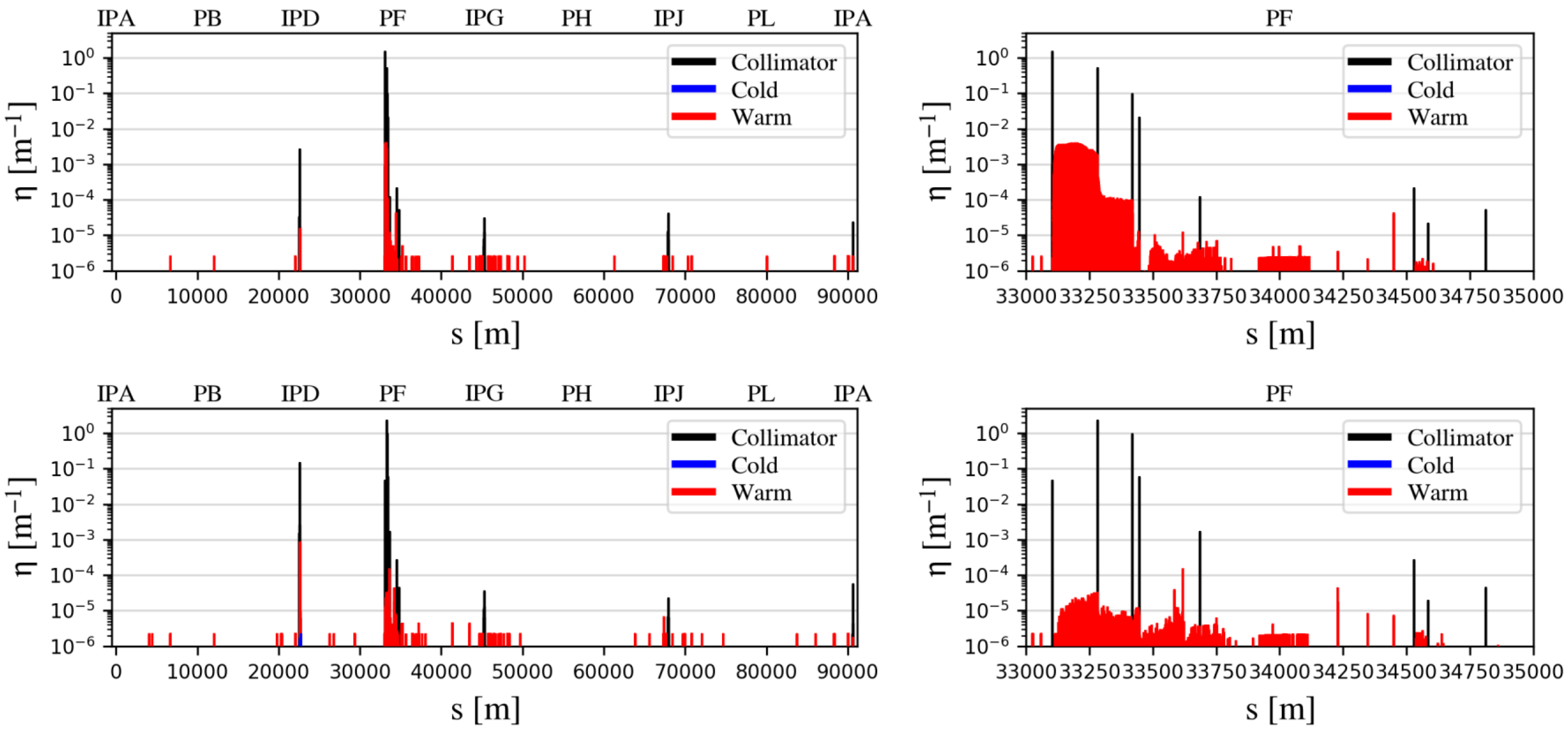


Deflection of 100 μrad of 45.6 GeV e+ using the Si (111) planar potential of a 200 μm long Si crystal.

NOTE: safety margin w.r.t mechanical aperture for 150 urad angular kick is tight.

One-turn cleaning of the e- beam

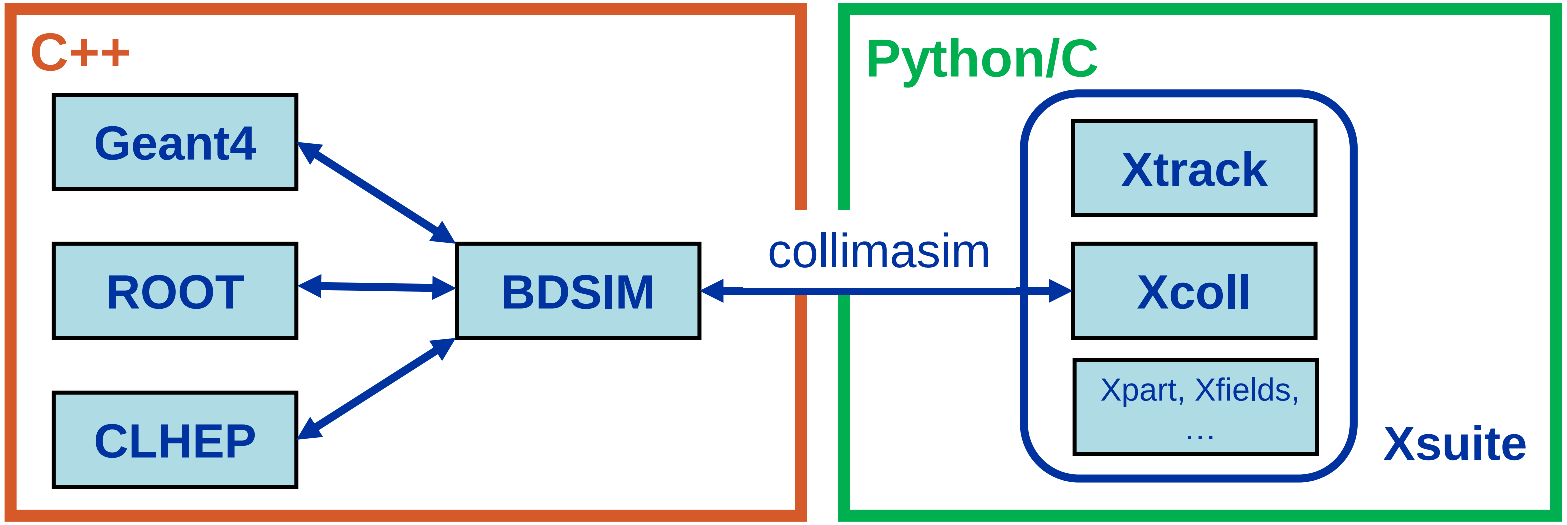
- Replacement of primary collimators (MoGr 25 cm) with 100 µm bent Si crystals (100 µrad bending angle)



Standard collimation

Crystal collimation

- One-turn cleaning is comparable
- In the crystal collimation case:
  - Most beam halo losses end up on the absorbers – as expected
  - Significant reduction (up to a factor >100) of local losses in PF
  - Increase of losses on a vertical SR collimator upstream IPD – investigating


C++
Geant4
ROOT
CLHEP
BDSIM
collimasim
Python/C
Xtrack
Xcoll
Xpart, Xfields,
…
Xsuite