Beam losses in the IR

G. Broggi [1,2,3], A. Abramov [2], M. Boscolo [3], R. Bruce [2], S. Redaelli [2]

[1] Sapienza University of Rome, Italy [2] CERN, Meyrin, Switzerland [3] INFN-LNF, Frascati, Italy

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Outline

- **Introduction**
  - FCC-ee beam losses simulations: overview
  - FCC-ee 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
- **Outlook and next steps**

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FCC-ee beam losses simulations: overview

- **Simulations of beam losses** in the FCC-ee are being performed to study:

Optimization of the FCC-ee collimation system design

Minimization of beam losses on sensitive components (e.g. superconducting magnets)

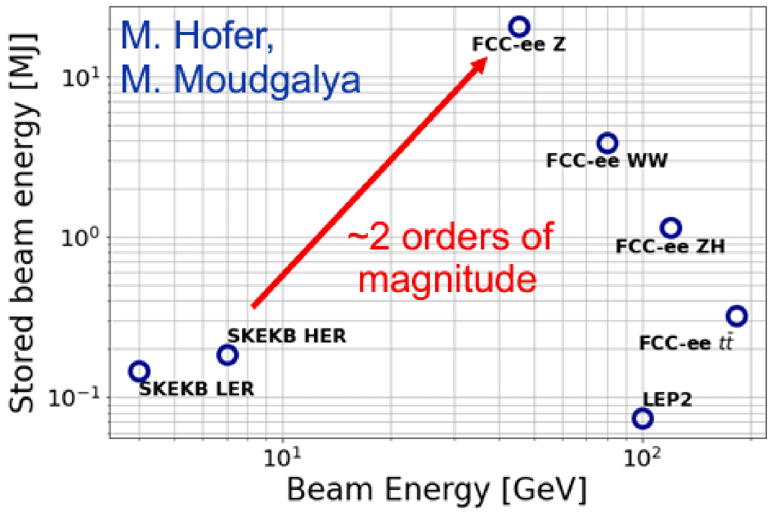
Minimization of beam losses in the experimental interaction regions (IRs): can be source of backgrounds

- **FCC-ee presents unique challenges**:
  - ➢ **17.5 MJ** stored beam energy in the ***Z* mode** (45.6 GeV)
  - ➢ New regime for collimation of e± beams (highly destructive beams)

- **Two types of collimation** currently foreseen for the FCC-ee
  - Beam halo (global) collimation (+ local protection collimators)
  - Synchrotron radiation (SR) collimation – upstream of each IP

- Secondary particle shower absorbers under study (CERN FLUKA team)

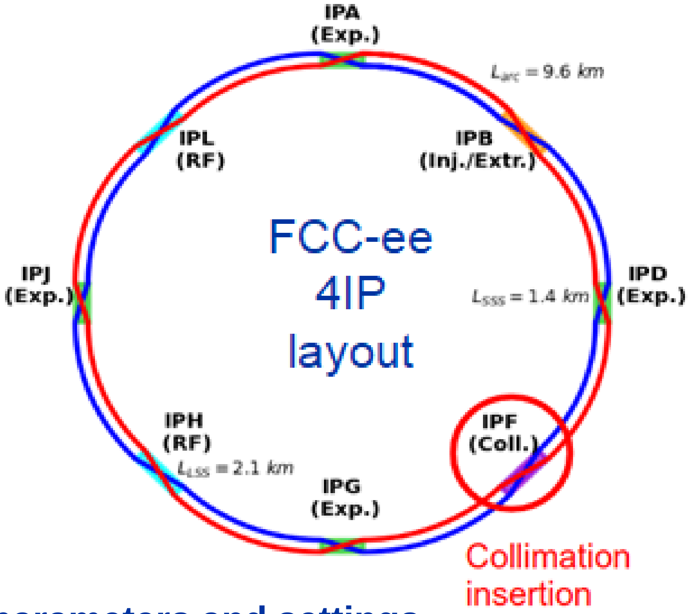
Comparison of lepton colliders

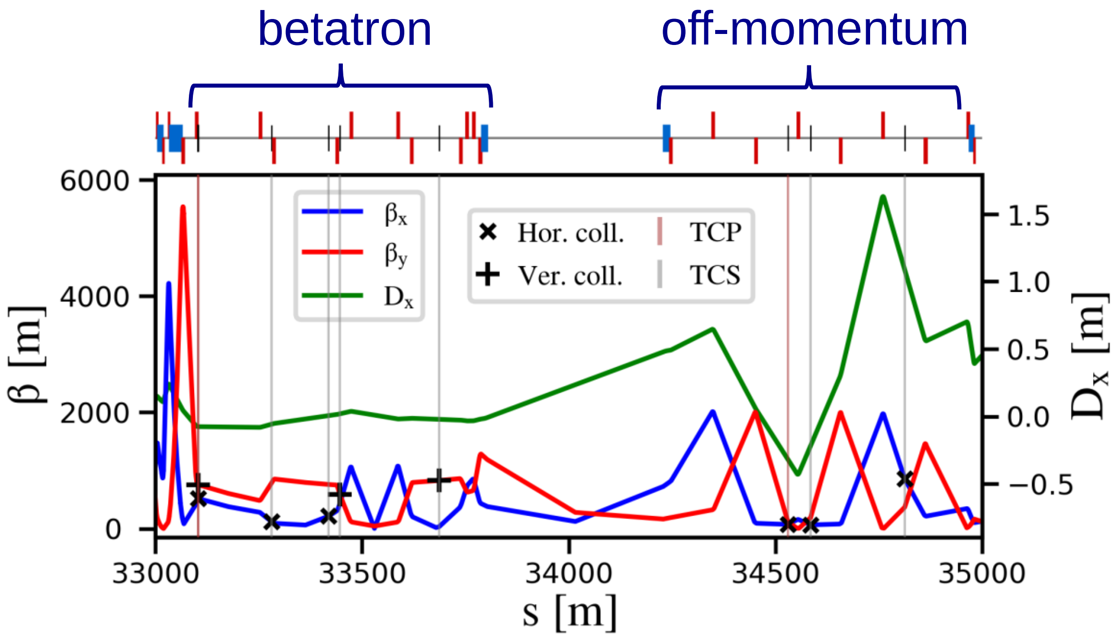


FCC-ee halo collimation system

- **Dedicated halo collimation system in PF**
  - ➢ Two-stage betatron and off-momentum collimation system in one insertion
  - ➢ Ensure protection of the aperture bottlenecks in different conditions
    - ➢ **Aperture bottleneck at *Z***: 14.6σ (H plane), 84.2σ (V plane)

- **First collimator design for cleaning performance**
  - ➢ Ongoing studies to further optimize the collimator design (IPAC'24 paper)
  - ➢ Crystal collimation being explored (CHANNELING'24 talk)





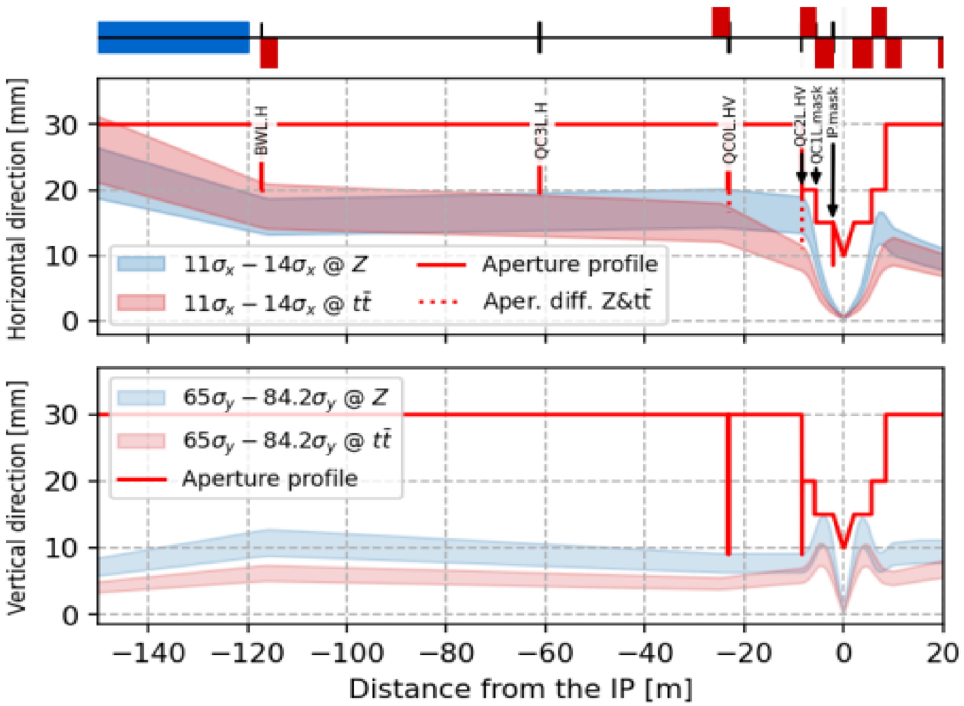
FCC-ee beam halo collimator parameters and settings

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

Other materials being considered (C-based for TCP, Mo-based for TCS)

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

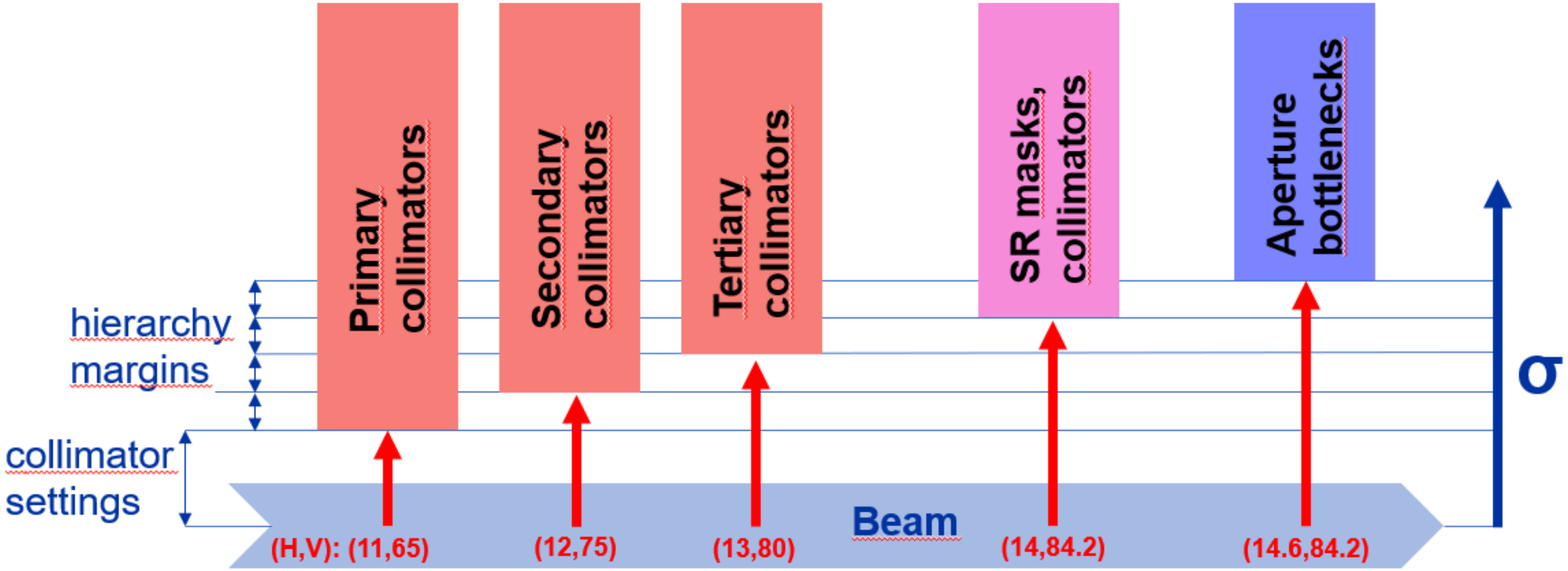
Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCR.H.WL.B1	H	Inermet180	10	14.0	17.0
TCR.H.C3.B1	V	Inermet180	10	14.0	16.5
TCR.V.C0.B1	V	Inermet180	10	84.2	8.0
TCR.H.C0.B1	H	Inermet180	10	14.0	16.2
TCR.V.C2.B1	V	Inermet180	10	84.2	8.0
TCR.H.C2.B1	H	Inermet180	10	14.0	16.0

Inermet180: tungsten heavy alloy

- More details in K. Andre's talk, this workshop

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

Other C-based materials are being considered

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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**

  } In this talk

  - Beam losses from **spent beam** due to the collision processes (BB'24 talk – detailed checks ongoing)

  - 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

  } Work in progress

  - Beam losses due to **fast instabilities**: first results in G. Nigrelli's talk, this workshop

  - Beam losses from **top-up injection**
  - Beam losses from interactions with **thermal photons**

  } Studies planned for 2025

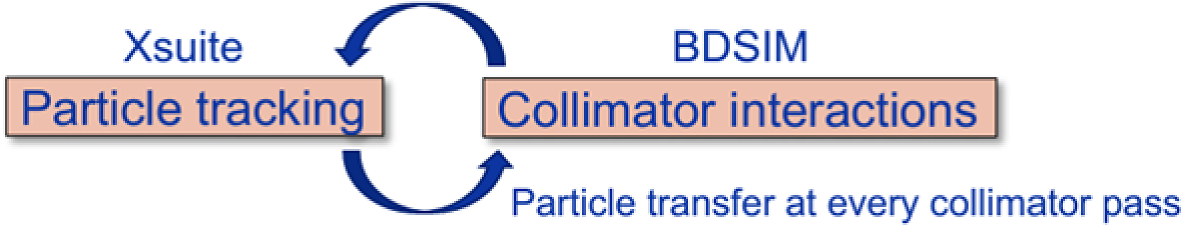
  - Accidental scenarios (inj. failure, asynchronous dump, others): waiting for inputs to set up models

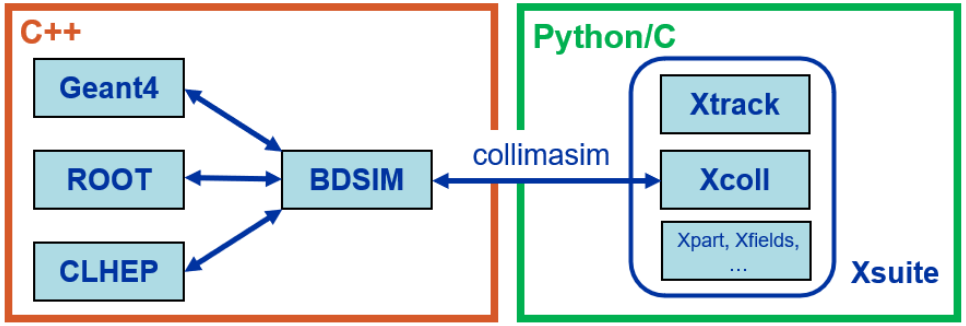
FCC-ee collimation simulations

- **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, DAΦNE)

- **Xsuite + BDSIM (Geant4) coupling** (JINST paper)
  - Developed for FCC collimation simulations
  - Benchmarked against
    - other simulation codes: MAD-X, pyAT, Sixtrack-FLUKA
    - measured data from proton machines: SPS, LHC
  - Other tools available (e.g., Xsuite-FLUKA coupling)





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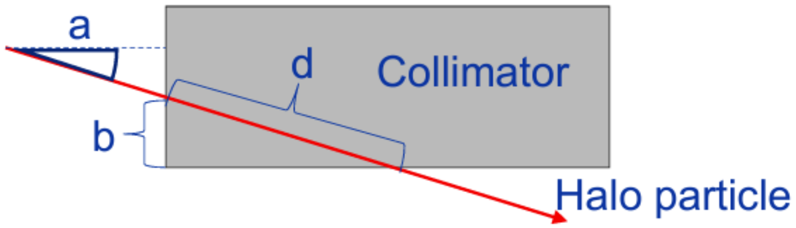
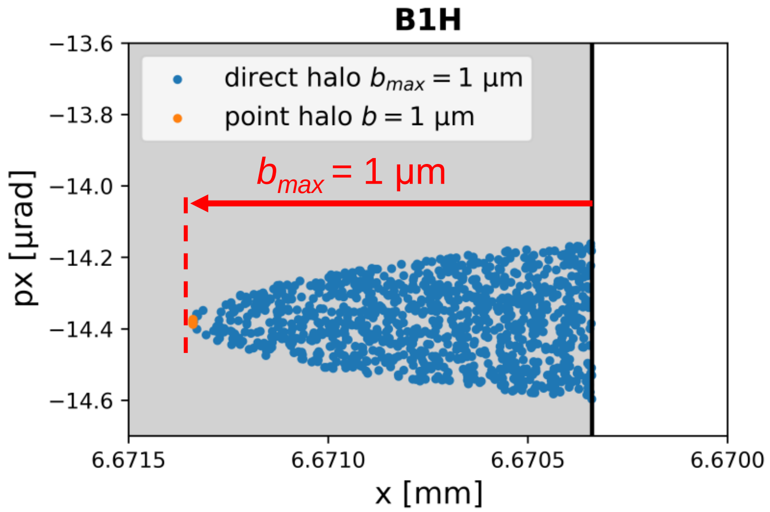
Generic beam halo losses

- «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*)
  - 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
  - Particles scattered out from the collimator tracked for a given number of turns (~500), and losses on the aperture are recorded → **loss maps**



a = angle of incidence
b = impact parameter
d = distance traversed



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

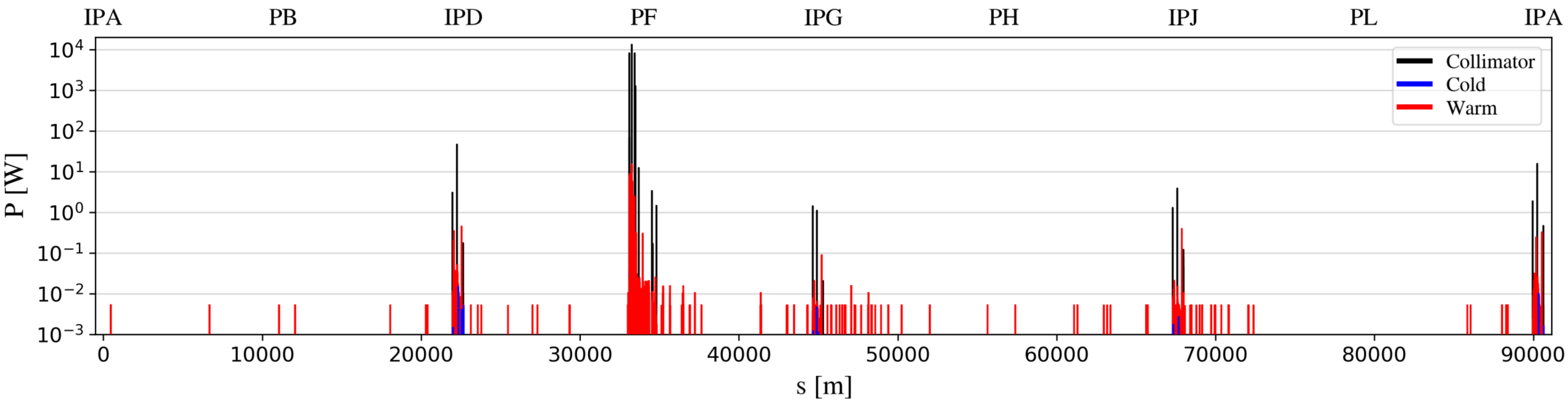
  - Detailed aperture and collimator (BDSIM-Geant4) model

  - SR emission («quantum» model)
    - Radiation damping
    - Quantum excitations

10×10^6 macroparticles tracked for 500 machine turns

Generic beam halo losses: results

- FCC-ee *Z* loss map for horizontal (B1H) betatron collimation losses:

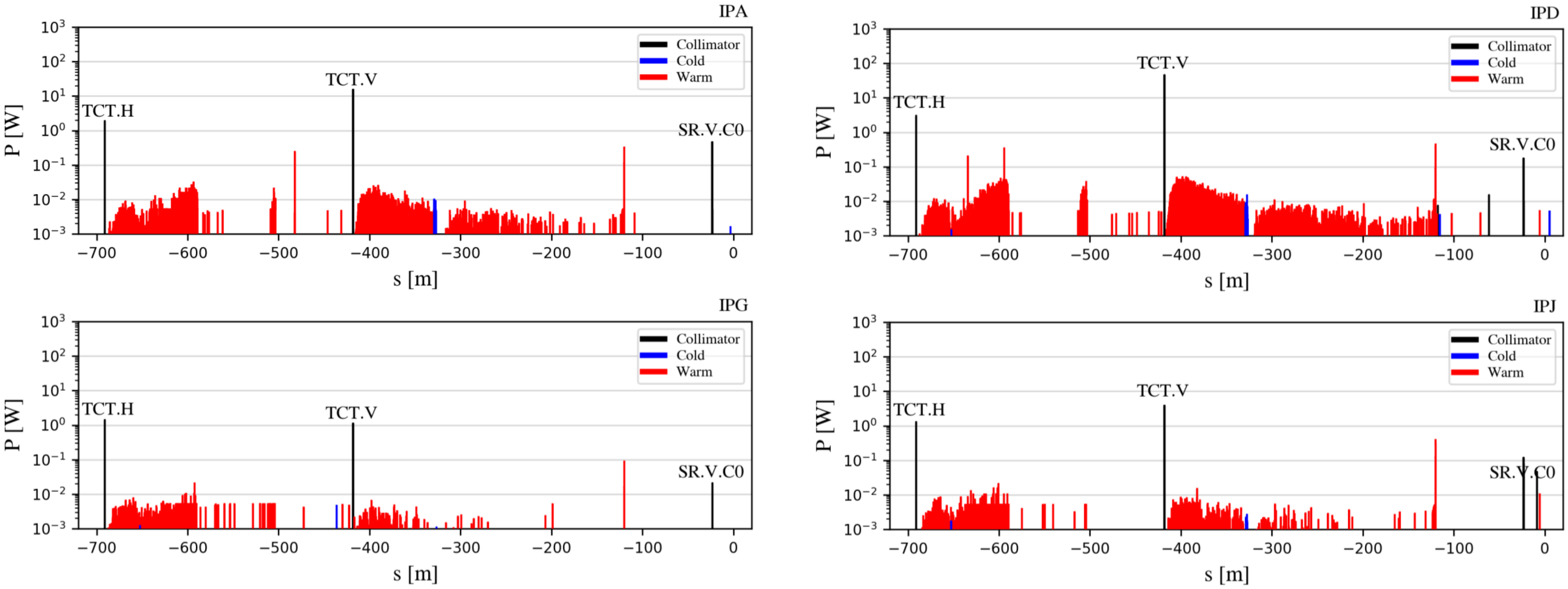


- Power loads evaluated assuming a lifetime drop to **5 min**

- **Losses well contained in the collimation insertion PF** (>99.6%)
- **Losses leaking out the collimation insertion PF mostly intercepted by the local protection TCTs**
  - ➢ Nearly absence of losses reaching the detector regions / final focus superconducting quadrupoles

Generic beam halo losses: IR beam losses

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



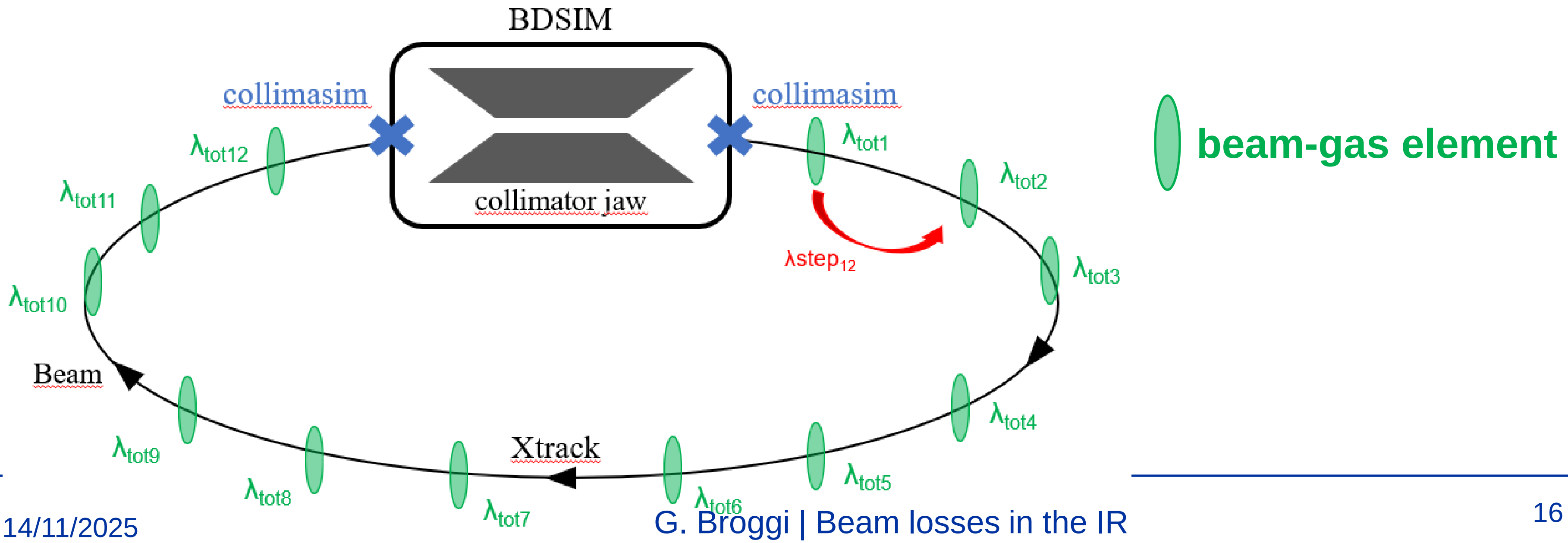
- IR beam losses efficiently intercepted by the local protection TCTs (Pmax ~50 W)
- Dedicated shower simulations needed to assess backgrounds from these beam losses
  - FLUKA IR model + impacting distributions on IR collimators and aperture as input

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)
  - Main focus on beam-gas bremsstrahlung interactions (dominant process in determining beam-gas losses)
  - First preliminary results for beam-gas Coulomb scattering interactions

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



Beam-gas beam losses: simulation parameters

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  - Clockwise positron beam (B1) - 45.6 GeV beam energy
  - Initial conditions (SR: synchrotron radiation; BS: beamstrahlung)

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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

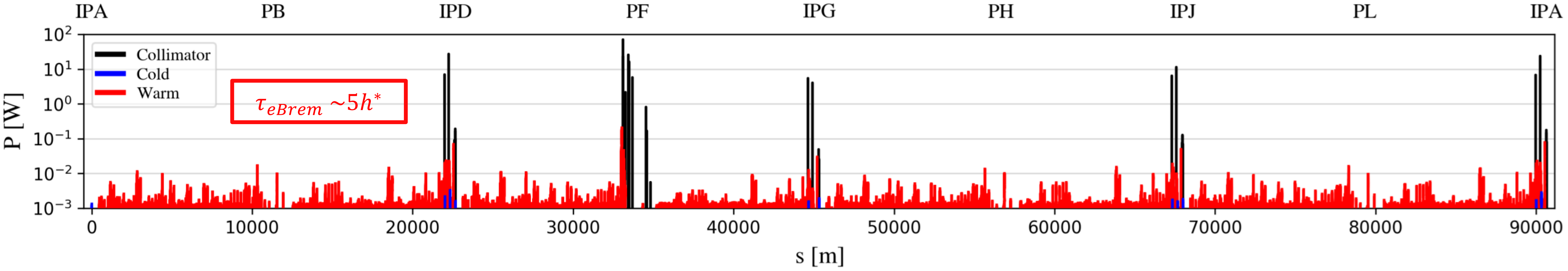
eBrem: 45×10^6 macroparticles tracked for 17×10^6 equivalent turns
CoulombScat: 40×10^6 macroparticles tracked for 17×10^7 equivalent turns

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

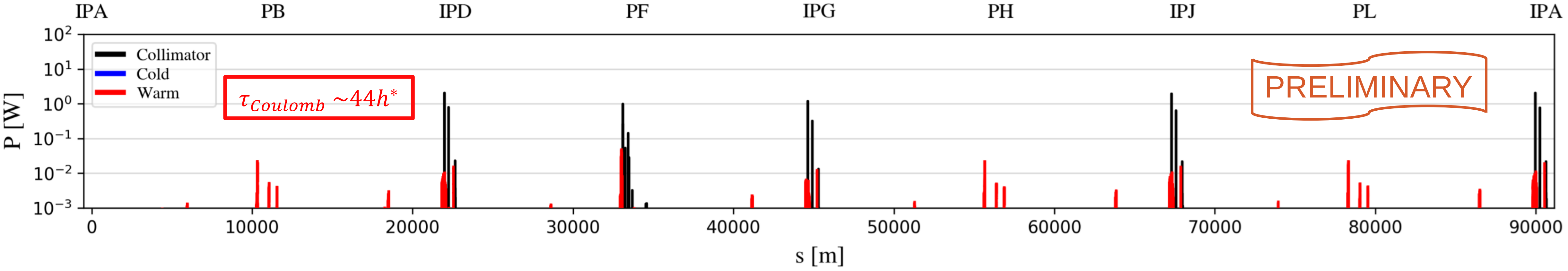
FCC-ee Z beam-gas loss map

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

- Power loads evaluated considering the estimated beam-gas lifetime τ from the simulations:



bremsstrahlung

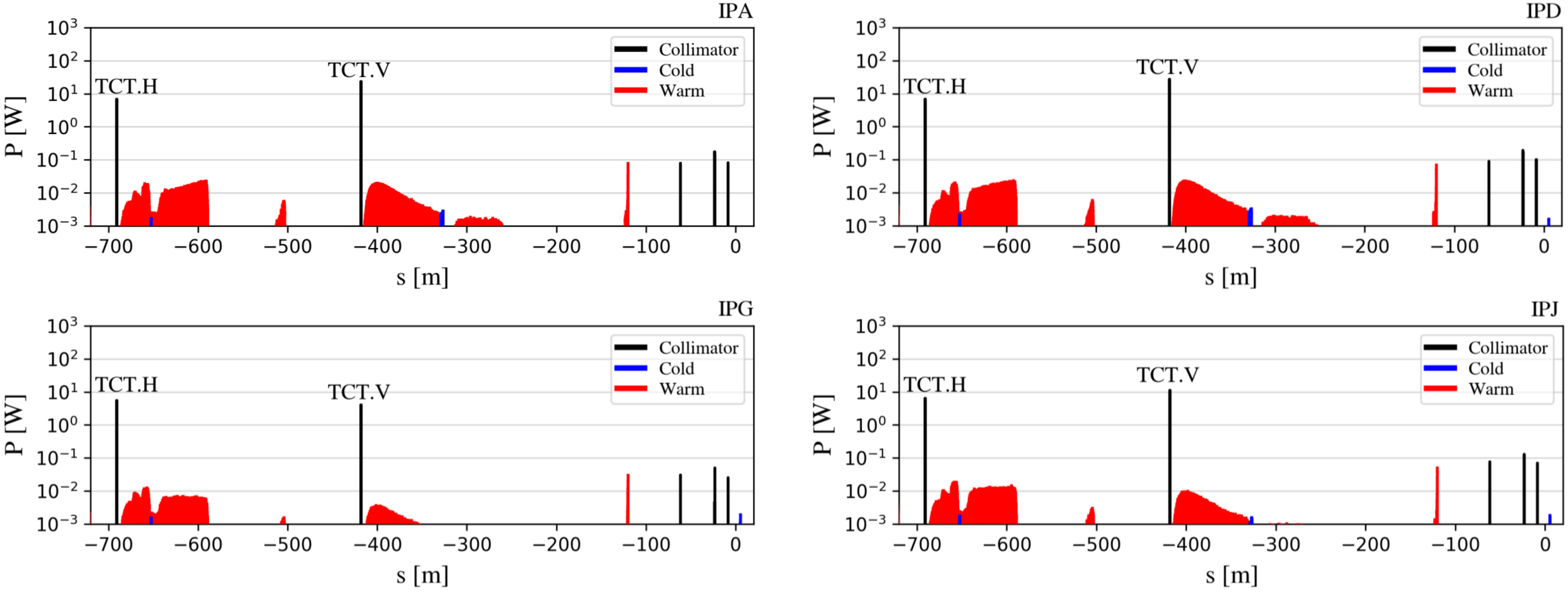


Coulomb scattering

- 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

Beam-gas bremsstrahlung IR losses

- FCC-ee *Z* IR loss maps for beam-gas bremsstrahlung losses:

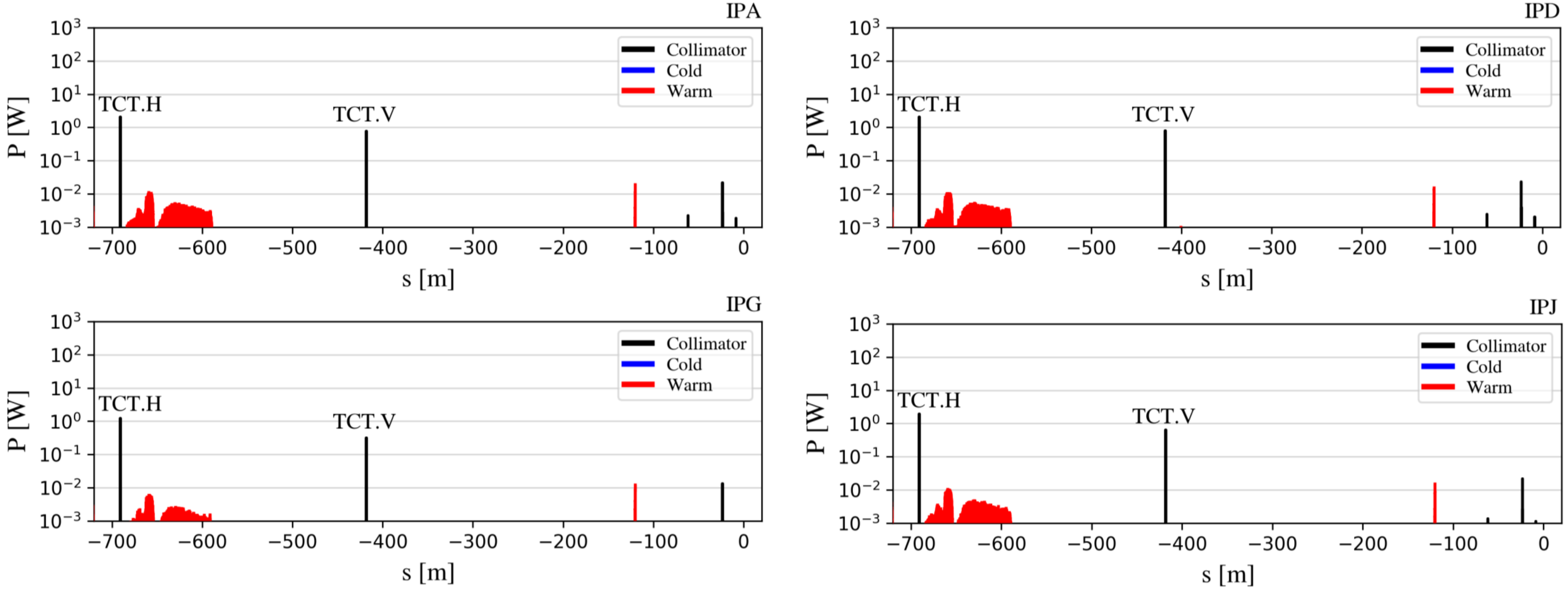


- IR beam-gas bremsstrahlung losses efficiently intercepted by the local protection TCTs (Pmax ~30 W)
- Dedicated shower simulations needed to assess backgrounds from these beam losses
  - ➢ FLUKA IR model + impacting distributions on IR collimators and aperture as input

Beam-gas Coulomb scattering IR losses

PRELIMINARY

- FCC-ee *Z* IR loss maps for beam-gas Coulomb scattering losses:



- IR beam-gas Coulomb scattering losses efficiently intercepted by the local protection TCTs (Pmax ~1 W)
- Dedicated shower simulations needed to assess backgrounds from these beam losses
  - ➢ FLUKA IR model + impacting distributions on IR collimators and aperture as input

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Outlook and next steps

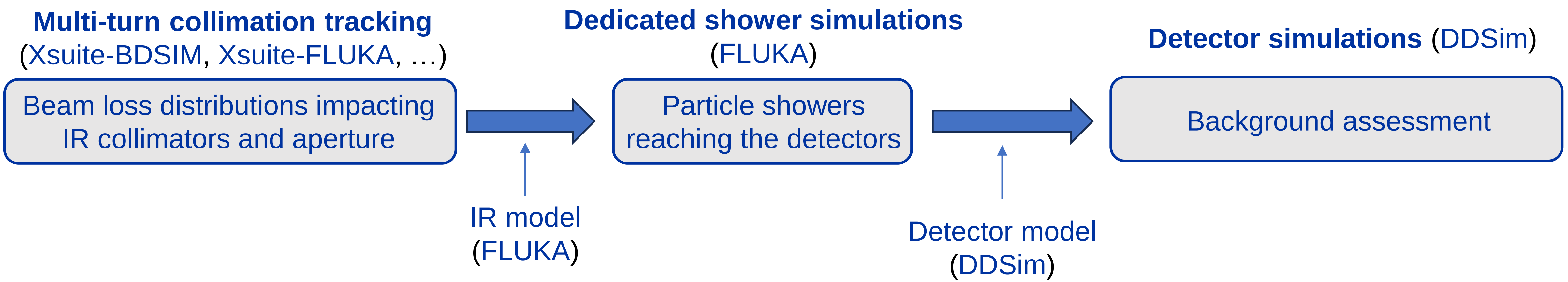
*1h beam conditioning at full nominal current (1.27 A): pressure is expected to condition down further (up to a factor ~100) over time

- **Simulations of FCC-ee beam loss scenarios ongoing.** In this talk:
  - **Beam halo losses** studied for the **most critical *Z* mode**
  - **Beam-gas beam losses** studied for the **most critical *Z* mode**
    - Estimated beam-gas bremsstrahlung lifetime ~5 h*
    - Estimated beam-gas Coulomb scattering lifetime ~44 h* (PRELIMINARY)

  } NO show stoppers identified

- To be studied in the future: top-up injection, thermal photons, accidental scenarios…

- The impact of these beam losses on **detector backgrounds** need to be assessed:
  - It can't be directly assessed from collimation tracking simulations: dedicated shower simulations are needed



Thank you!

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 $\varepsilon_{y,\text{lattice}}$	[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 $(\theta_x \sigma_{z,\text{BS}})/\sigma^*_x$		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	$[10^{34}/\text{cm}^2\text{s}]$	141	20	6.3	1.38
Luminosity / IP (CDR)	$[10^{34}/\text{cm}^2\text{s}]$	230	28	8.5	1.8

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

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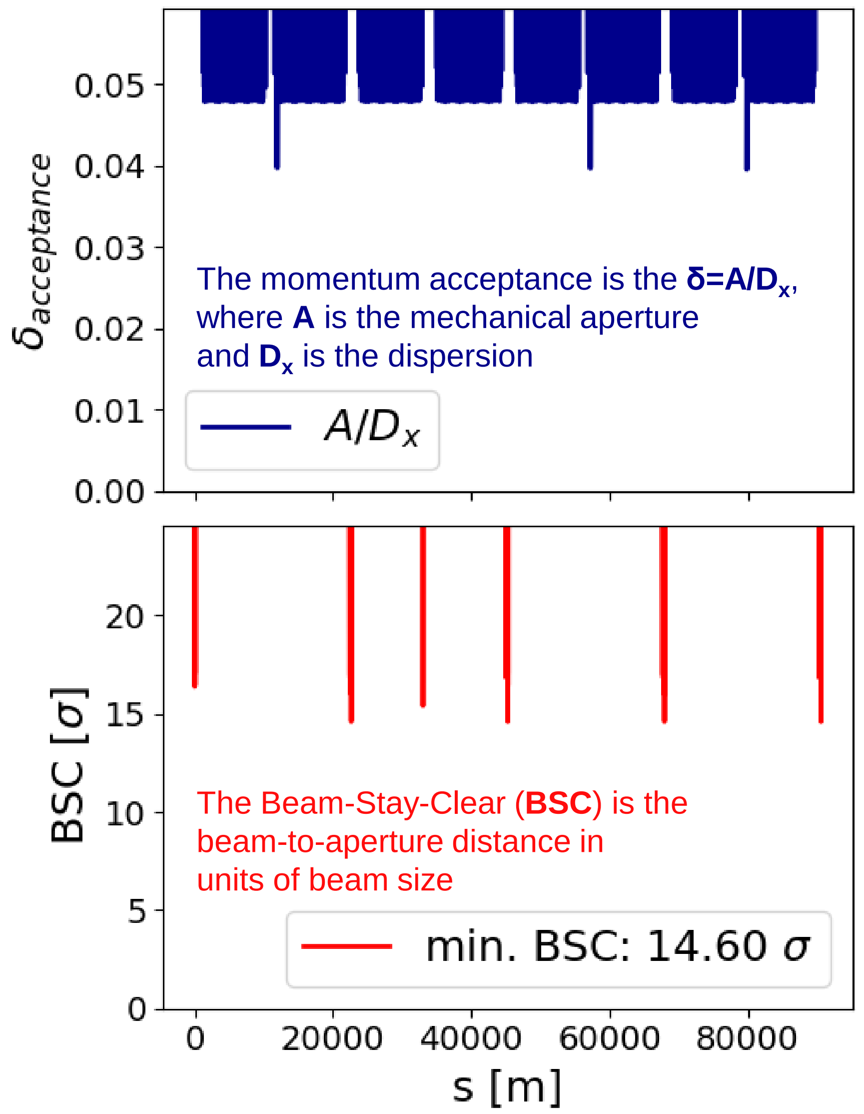
FCC-ee collider parameters

FCC-ee aperture

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

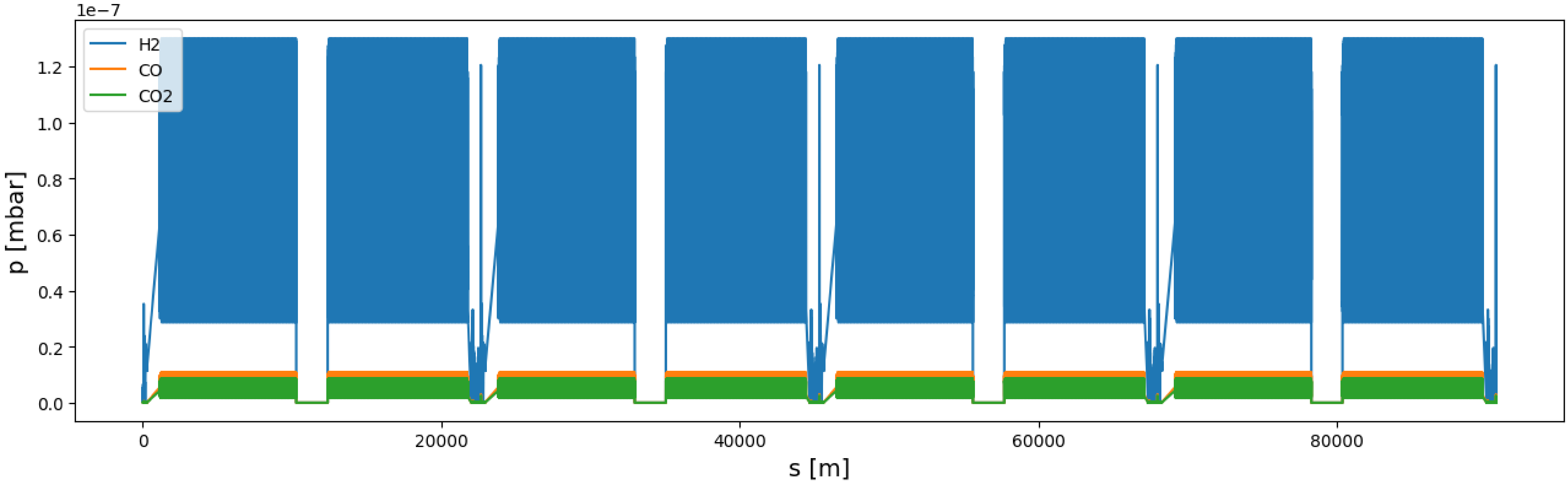
Aperture bottleneck for Z operation mode



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

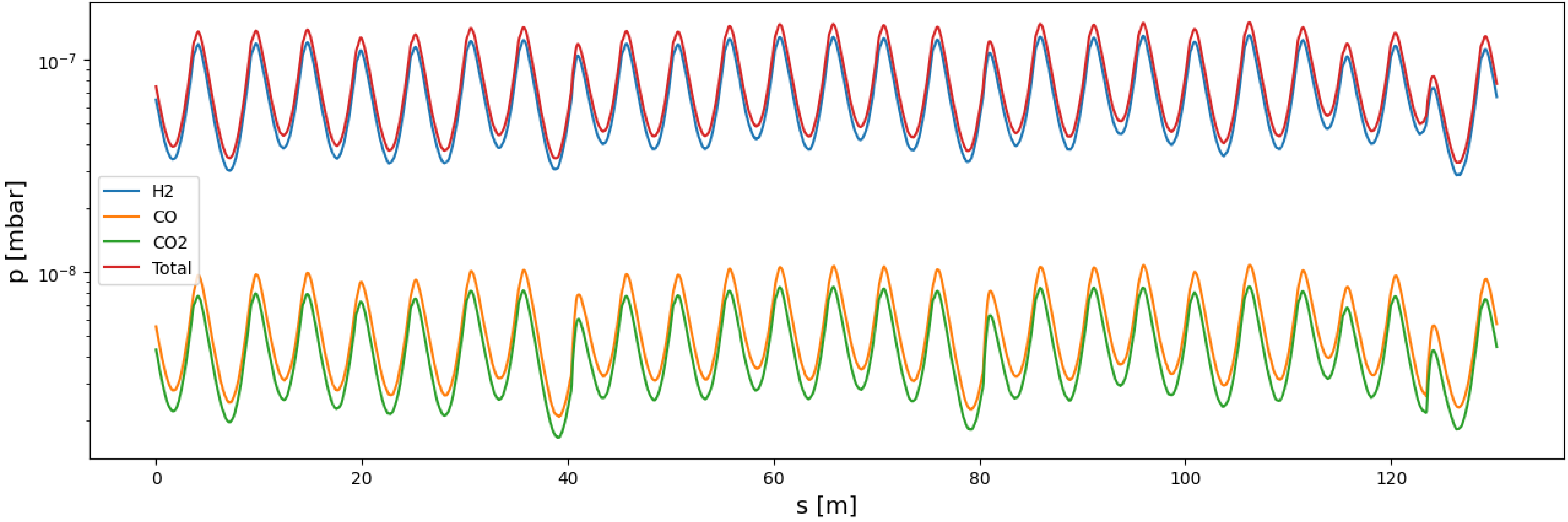
- Pressure profile for an arc section and for the MDI region provided by the vacuum team (R. Kersevan)*
- Gas species and composition: **85% H_2**, **10% CO** and **5% CO_2**
- Arc section pressure profile repeated multiple times to cover the whole arc length
- Because of the absence of dipoles generating 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**



FUTURE CIRCULAR COLLIDER
Innovation Study

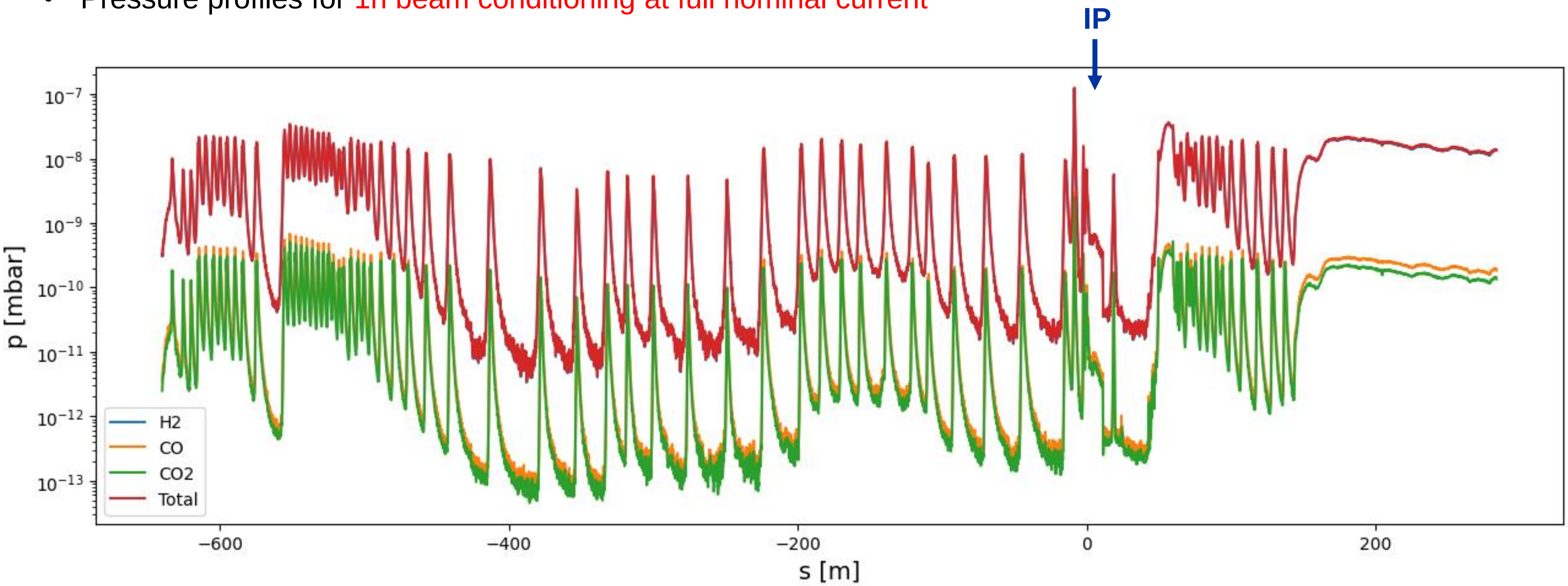
Arc pressure profile in the FCC-ee

- 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

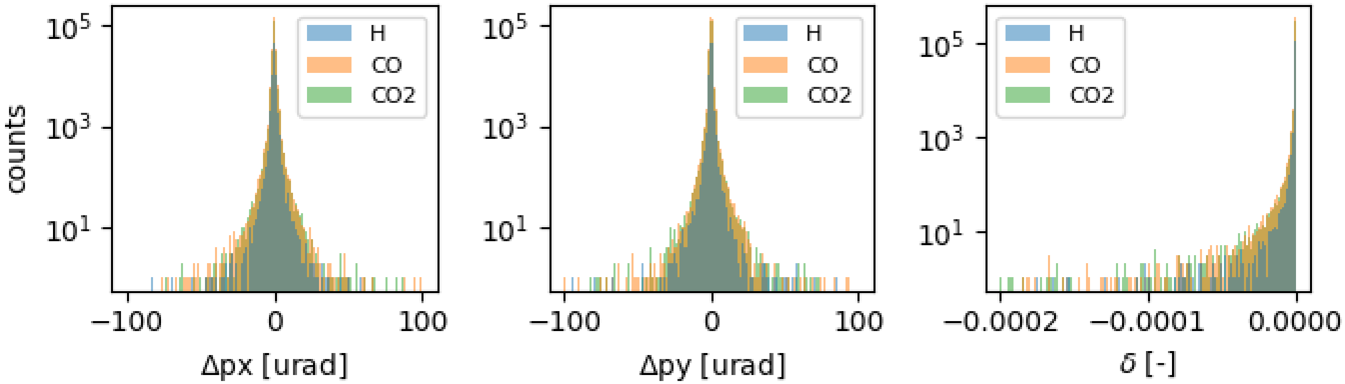
- Provided by the vacuum team (R. Kersevan)
- FCC-ee (***Z* mode**) – beam 1 (**B1**): **45.6 GeV positron** beam, 1270 mA current
- Gas species and composition: **85% H_2**, **10% CO** and **5% CO_2**
- Pressure profiles for 1h beam conditioning at full nominal current



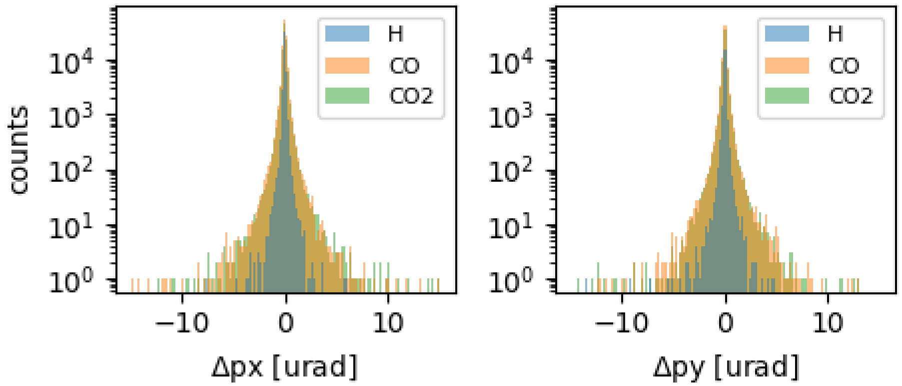
FCC-ee Z beam-gas interactions: interaction effect

- Ionisation, bremsstrahlung and Coulomb scattering produce rather different effects
- Interactions of 45.6 GeV e+ with H, CO and CO_2 studied performing **BDSIM** (Geant4) thin target simulations

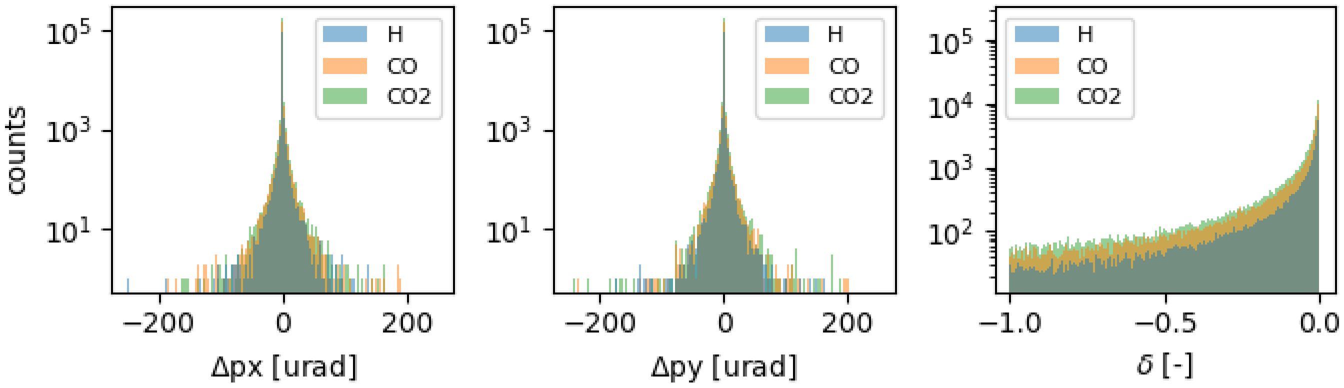
Ionisation (G4StandardEM_SS physics list)



Coulomb scattering (G4StandardEM_SS physics list)



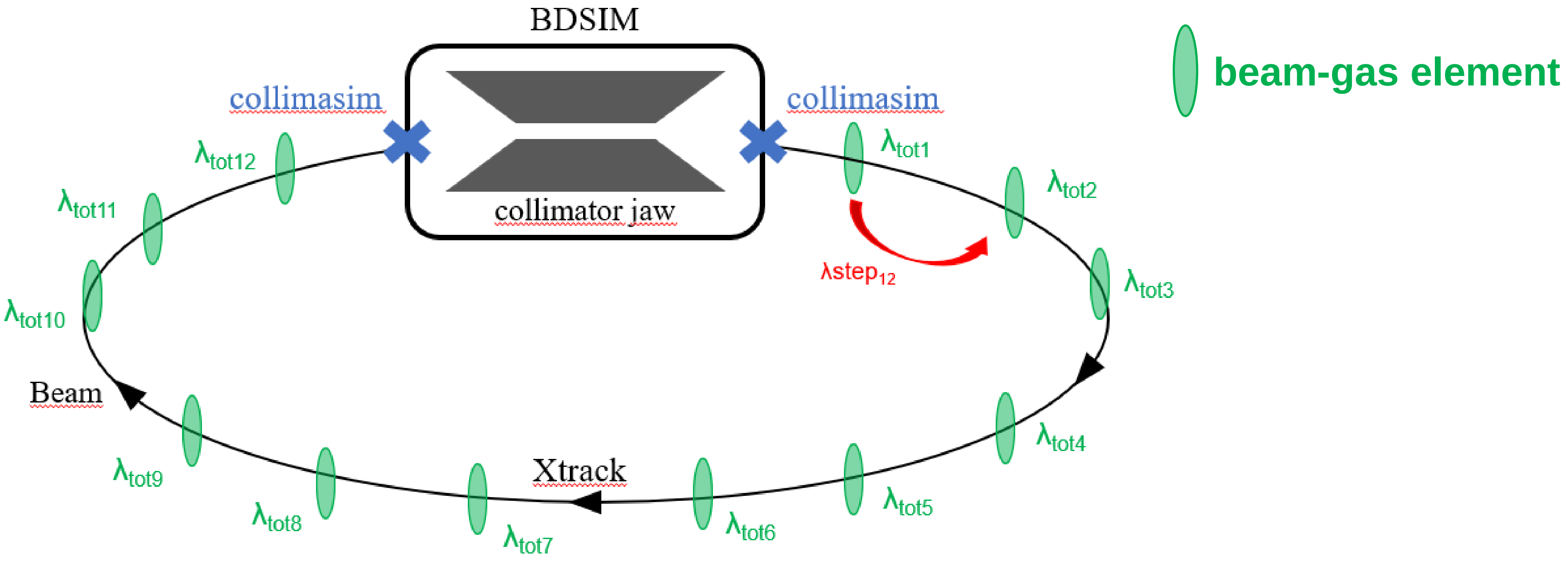
Bremsstrahlung (G4StandardEM_SS physics list)



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

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 applied to the interacting particle (px -> px + delta_px, py -> py + delta_py, delta -> delta + delta_delta)