FCC-ee beam-gas beam losses

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FCC week 2024, San Francisco, CA, USA, 13/06/2024

Many for discussions and support to:
H. Burkhardt, B. Francois, G. Iadarola, L. Nevay, A. Natochii

Outline

- **Introduction**
  - Motivation and goal
  - Pressure profile in the FCC-ee (*Z*)
- **FCC-ee Z beam-gas interactions**
  - Cross sections
  - Interaction effect
  - Considerations
- **Simulation set-up**
  - Simulation workflow
  - Simulation parameters
- **First results**
  - FCC-ee Z beam-gas loss map
- **Summary and next steps**

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Introduction: motivation and goal

- 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

- In the FCC-ee **the driving vacuum degradation process** is **Photo-Stimulated Desorbtion** (**PSD**)

- **Vacuum system under study** (R. Kersevan, FCCIS'23 talk)
  - **SR absorbers** { SR photon flux suppression → PSD suppression; radiation shields for environment outside the vacuum pipe }

    ➢ B. Humann, Radiation environment in the FCC-ee arcs, FCC week 2024

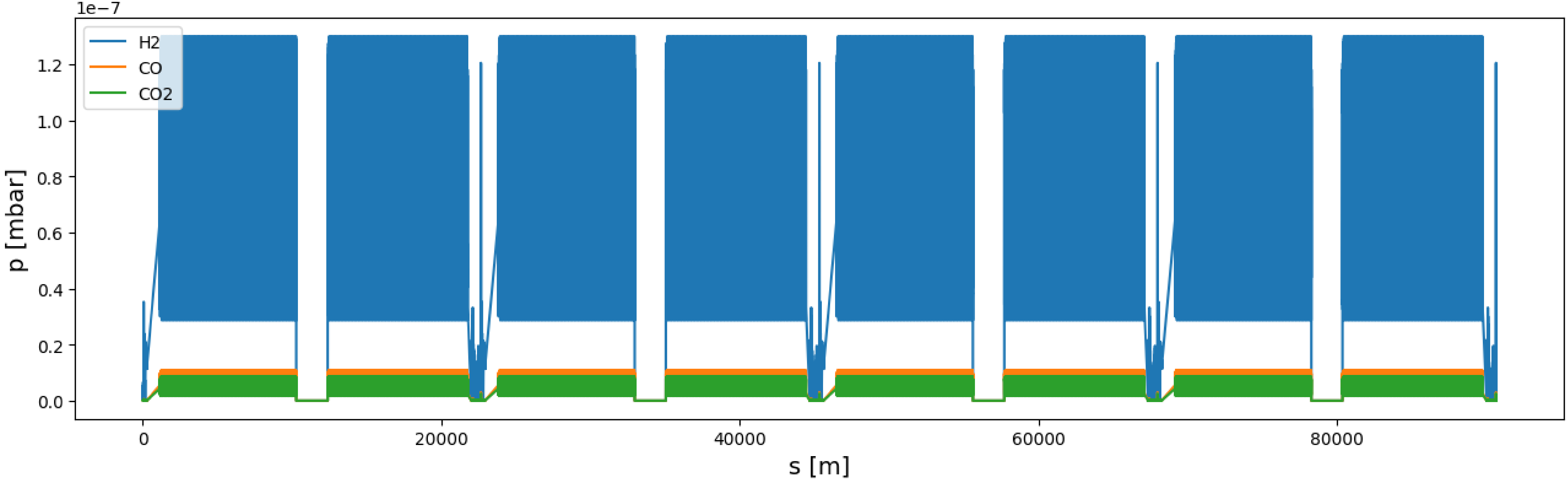
  - **NEG** coated vacuum pipe **strongly recommended**

- **GOAL**
  - Study effects of losses from beam-gas interactions around the ring in the FCC-ee
    ➢ Using combined tracking and Monte-Carlo simulations developed for collimation studies tracking beam particles interacting with residual gas (**WORK IN PROGRESS**)
    ➢ Current focus on the Z operation mode (45.6 GeV beam energy) – highest stored beam energy (**17.5 MJ**)

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** → currently neglecting residual gas in the straight sections
- Arc pressure profile merged with the MDI and straight section pressure profiles to get a **full ring pressure profile**



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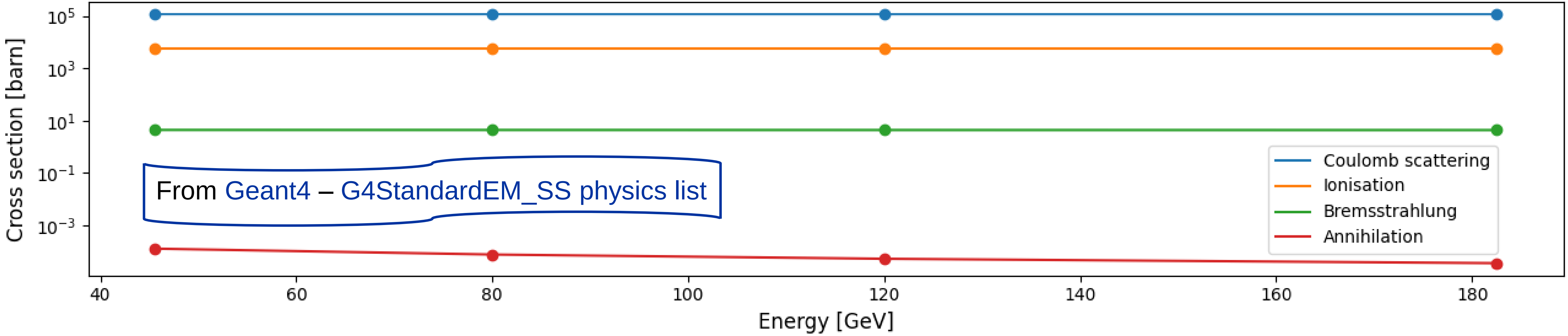
FCC-ee Z beam-gas interactions: cross sections

- Total cross sections per interaction type (e^+) in the FCC-ee beam energy spectrum:



- Cross sections at the FCC-ee Z energy (45.6 GeV):

H_2

$\sigma_{CoulombScat, H_2} = 54401.4\ b$
$\sigma_{eIoni, H_2} = 5099.1\ b$
$\sigma_{eBrem, H_2} = 1\ b$
$\sigma_{annihil, H_2} = 69.87\ ub$

$\boldsymbol{\sigma_{tot, H_2} = 59501.5\ b}$

CO

$\sigma_{CoulombScat, CO} = 390876\ b$
$\sigma_{eIoni, CO} = 5844.3\ b$
$\sigma_{eBrem, CO} = 19.2\ b$
$\sigma_{annihil, CO} = 434.1\ ub$

$\boldsymbol{\sigma_{tot, CO} = 396739.5\ b}$

CO_2

$\sigma_{CoulombScat, CO_2} = 617467\ b$
$\sigma_{eIoni, CO_2} = 11685.7\ b$
$\sigma_{eBrem, CO_2} = 32.7\ b$
$\sigma_{annihil, CO_2} = 682.2\ ub$

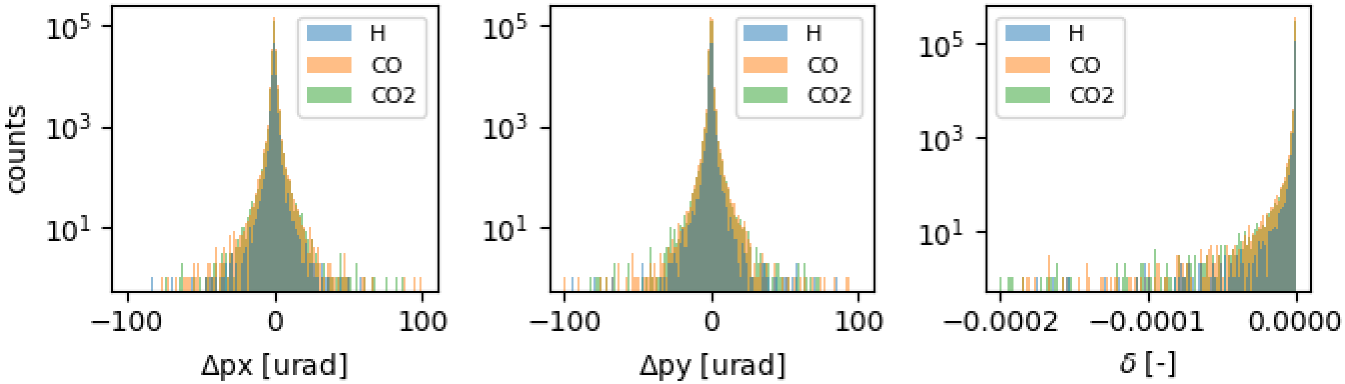
$\boldsymbol{\sigma_{tot, CO_2} = 629185.3\ b}$

- $\boldsymbol{\sigma_{tot} = 0.85\sigma_{tot, H_2} + 0.1\sigma_{tot, CO} + 0.05\sigma_{tot, CO_2} = 121709.5\ b}$ assuming 85% H_2, 10% CO and 5% CO_2

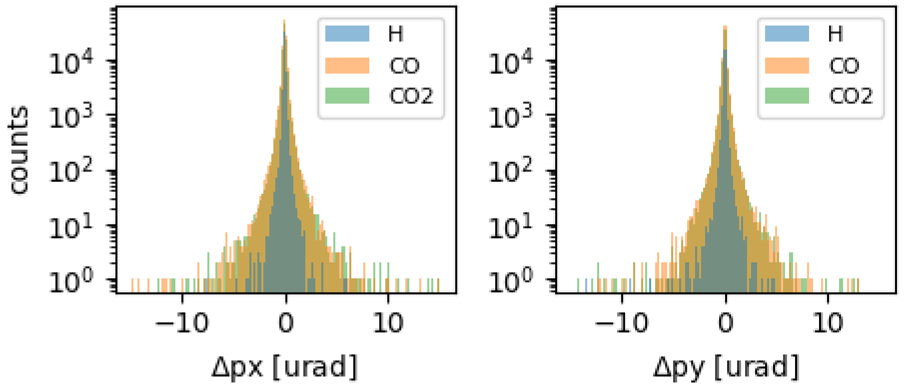
FCC-ee Z beam-gas interactions: interaction effect

- 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

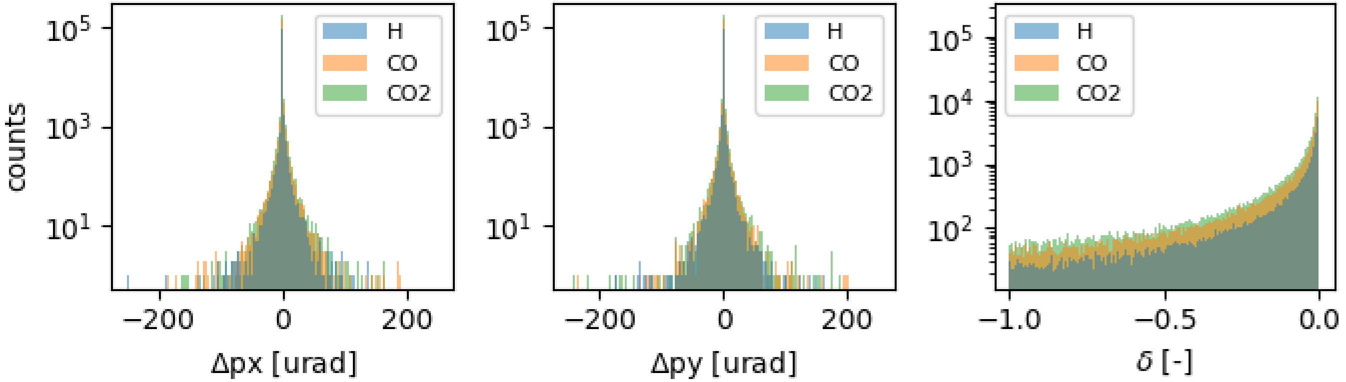
Ionisation (G4StandardEM_SS physics list)



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

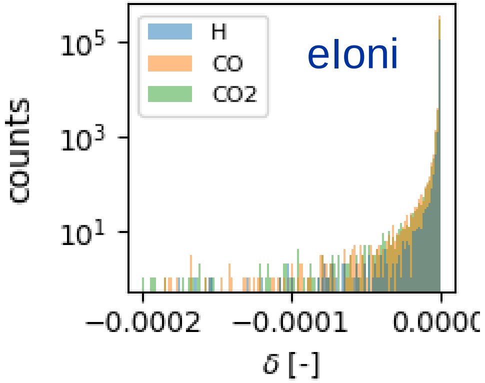
- Coulomb scattering introduces extremely small deflections compared to ionisation and bremsstrahlung
- Ionisation introduces smaller deflections compared to bremsstrahlung

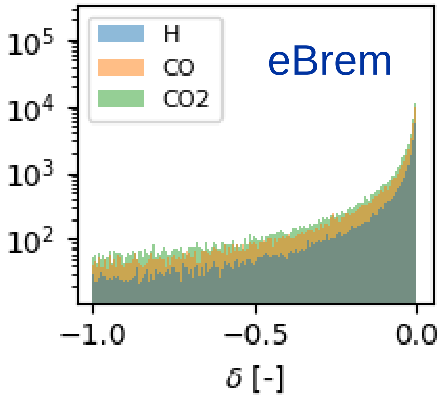
$$\Delta px_{CoulombScat} \sim 0.004\sigma_{px}$$
$$\Delta py_{CoulombScat} \sim 0.2\sigma_{py}$$

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

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

- 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**

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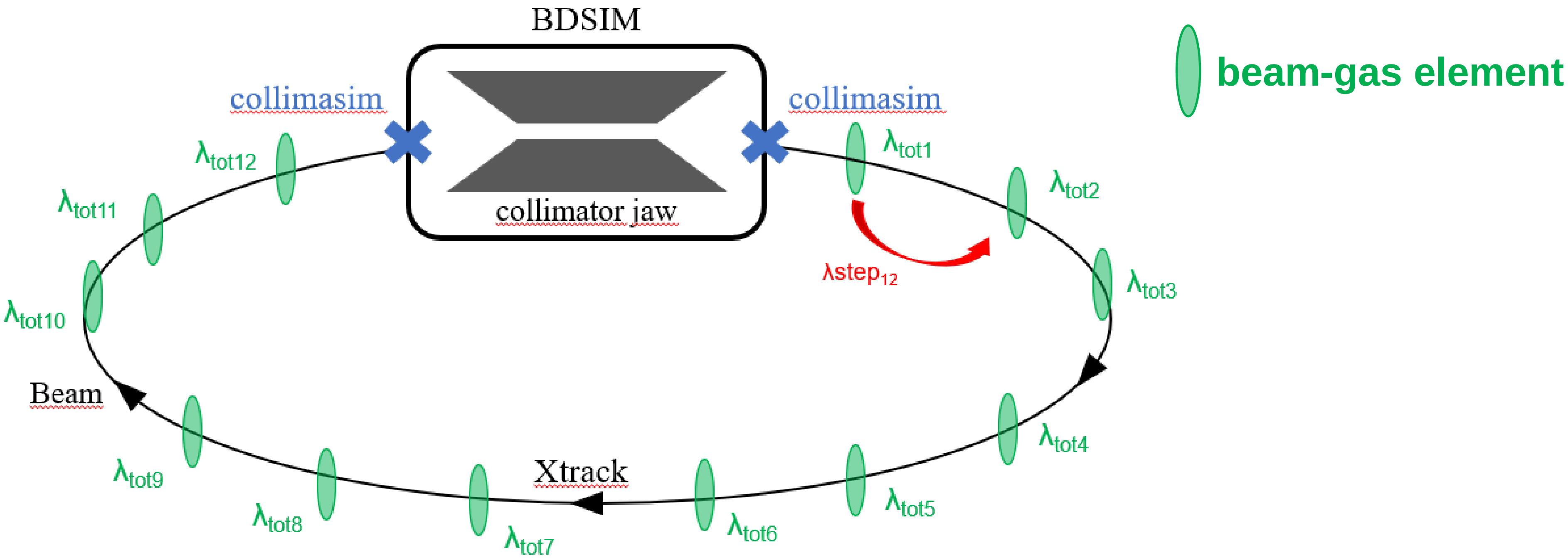
Simulation workflow

- **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 parameters

- 10×10^6 macroparticles (e+) 45.6 GeV tracked through the **FCC-ee *Z*** lattice including nonlinearities, SR (mean model), RF cavities, magnet tapering, detailed aperture model, halo collimators, SR collimators and **residual gas** for 100 machine turns.

- **Residual gas** modelled with 1000 equispaced beam-gas elements (~90 m spacing)
  - ➢ final number of beam-gas elements should be fine-tuned by scanning over the number of elements

- Beam-gas bremsstrahlung interactions only

- A bremsstrahlung interaction takes place, on average, once per bremsstrahlung mean free path $\lambda_{mfp,\ eBrem}$
  - ➢ $\lambda_{mfp,\ eBrem} \sim 16.7e6$ turns

- **Cross section biasing** is **necessary** to perform simulations with reasonable computing time
  - **Biasing choice**: cross sections are scaled up such that $\lambda_{mfp,\ eBrem} = 1$ turn
  - **(1 – 1/e) ≅ 63.2% macroparticles interact by bremsstrahlung in the first turn**
    - ➢ Constraint: a macroparticle can not interact twice

- The macroparticles are then tracked through the lattice for the remaining number of turns (99)
  - ➢ First studies show that once a macroparticle undergoes bremsstrahlung, it is lost within few turns
  - ➢ Likely not necessary to track particles for a significantly larger number of turns

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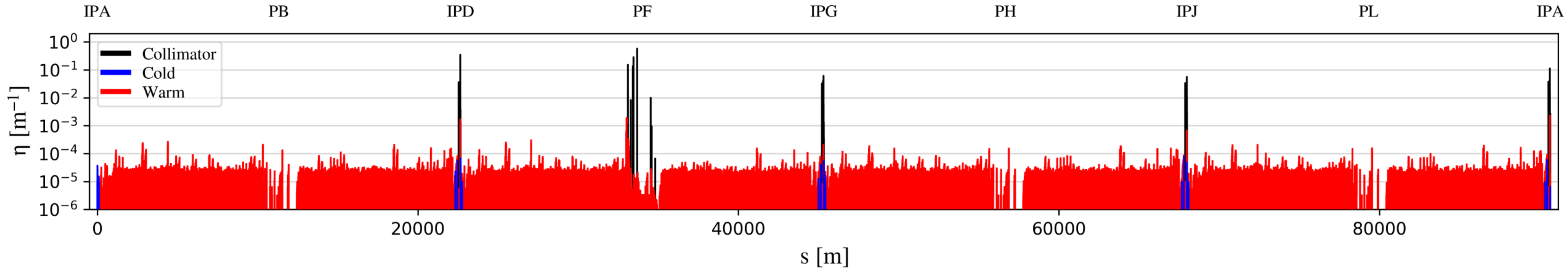
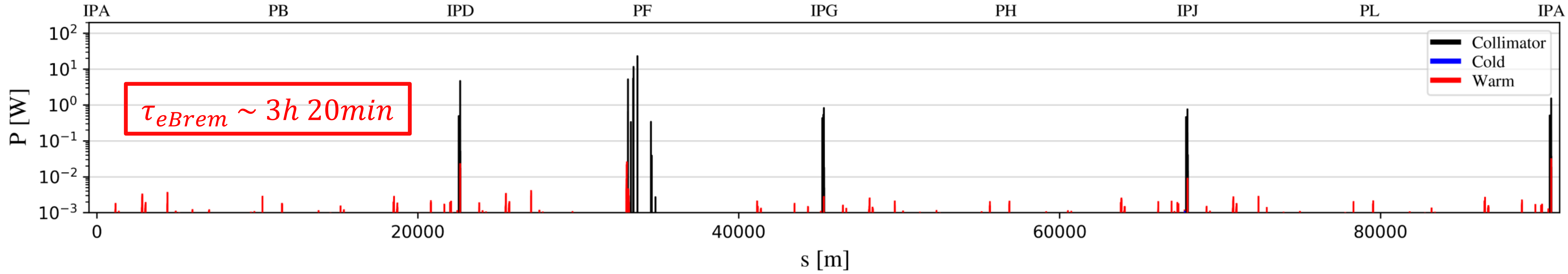
First preliminary FCC-ee Z beam-gas loss map

- First FCC-ee beam-gas beam loss pattern (*Z* operation mode):



- Rescaling according to the applied biasing factor to evaluate the power loads from beam-gas

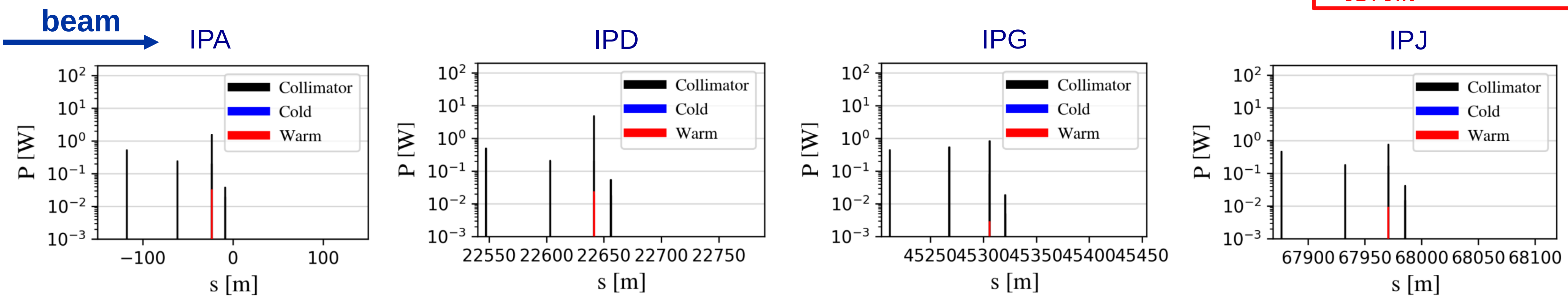


- Low power loads (<0.1 W) on the vast majority of elements and minimal cold power loads
- Highest loads on halo collimators and SR collimators (~10 W) – likely not an issue

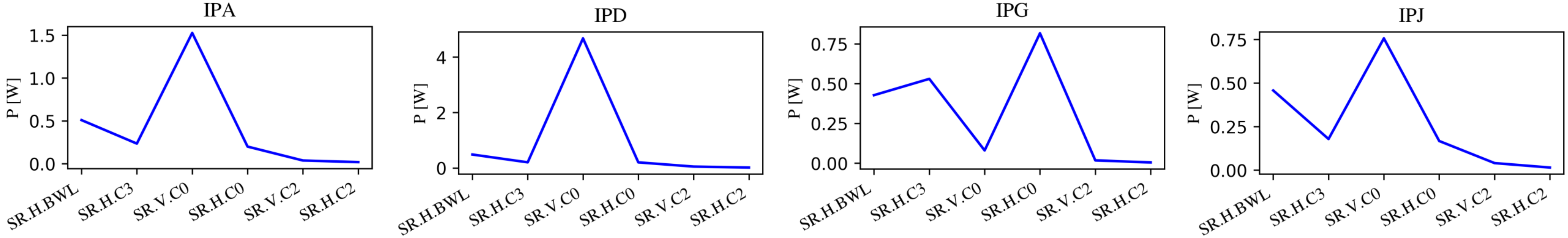
Preliminary FCC-ee *Z* beam-gas loss map: IRs

- First preliminary evaluation of beam-gas power loads in the FCC-ee interaction regions (IRs)

$\tau_{eBrem} \sim 3h\ 20min$



- SR collimators intercept the vast majority of beam-gas beam losses in the IRs



- Highest load on C0 vertical SR collimators, **up to 4.7 W**
  - ➢ Value much lower than the **max. recorded power from SR** about **200 W** (K. André – IPAC'24 paper)
- Shower simulations needed to check the background signals generated in the detectors from these beam losses

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Summary

* It is already a pessimistic scenario: vacuum conditions expected to improve with increasing beam conditioning time

- **Beam-residual gas interactions implemented in the Xsuite-BDSIM simulation tool** (already used in the context of FCC-ee collimation studies)
  - Allows for integrated beam-gas and collimation studies
- **First preliminary FCC-ee beam-gas beam loss pattern and power load distribution evaluated** (FCC-ee Z)
  - Pressure profile considering 1h beam conditioning at full nominal current* (1270 mA)
  - First estimated beam-gas lifetime (dominated by bremsstrahlung): $\tau_{eBrem} \sim 3h\ 20min$
  - NO show stoppers identified

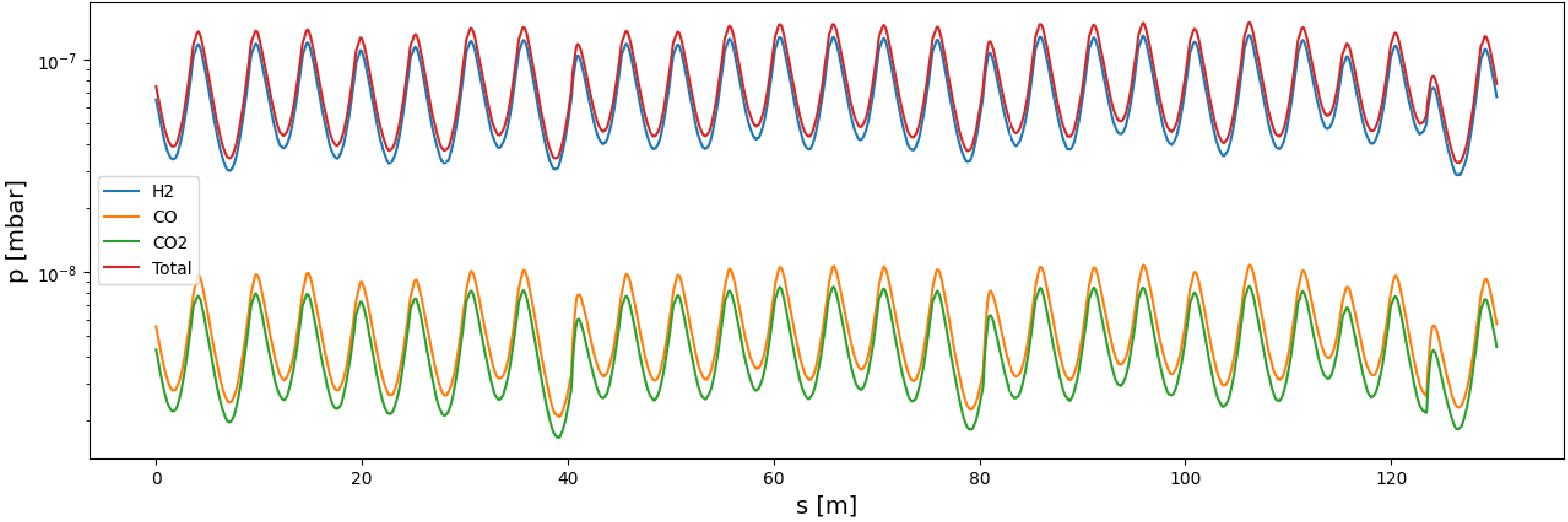
Next steps

- These are the very first result for this type of studies: further detailed analysis will be performed
- **Refine the simulation model**
  - Quantum model for SR
  - Scan over the number of beam-gas elements
- Study the **impacting condition on beam halo collimators** – important input for general collimation studies
- **Iterate the studies with the vacuum team** as the lattice, collimation and vacuum system designs progress
- Impact on experimental background to be evaluated
- Study other beam operation modes

Thank you!

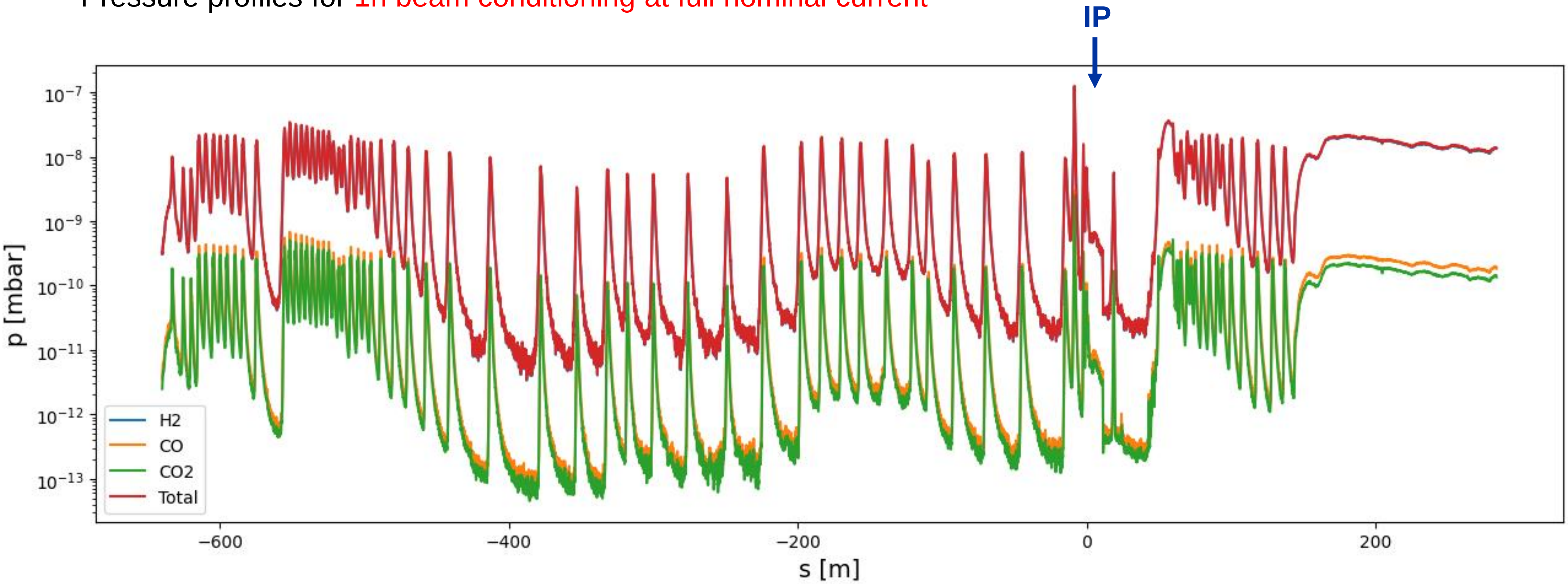
Arc pressure profile in the FCC-ee

- 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



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)

Cross sections from Geant4

- Cross sections are extracted adapting the Geant4 built-in example TestEM0
- TestEM0 example: it is not a simulation. It prints the cross sections and stopping power used by the standard electromagnetic package via G4EmCalculator, which extracts these data from the PhysicsTables.
- G4EmCalculator is a class which provides access to cross sections and stopping powers.
  - This class can be used anywhere in the user code provided the physics list has already been initialized.
  - G4EmCalculator has “Get” methods which can be applied to materials for which physics tables are already built, and “Compute” methods which can be applied to any material defined in the application or existing in the Geant4 internal database.
- TestEM0 example ran after having initialized the G4EMStandard_SS physics list
- G4EMStandard_SS made on top of default electromagnetic configurations by substitution of all multiple scattering models by single scattering models.