



SAPIENZA
UNIVERSITÀ DI ROMA



FCC-ee collimation system design

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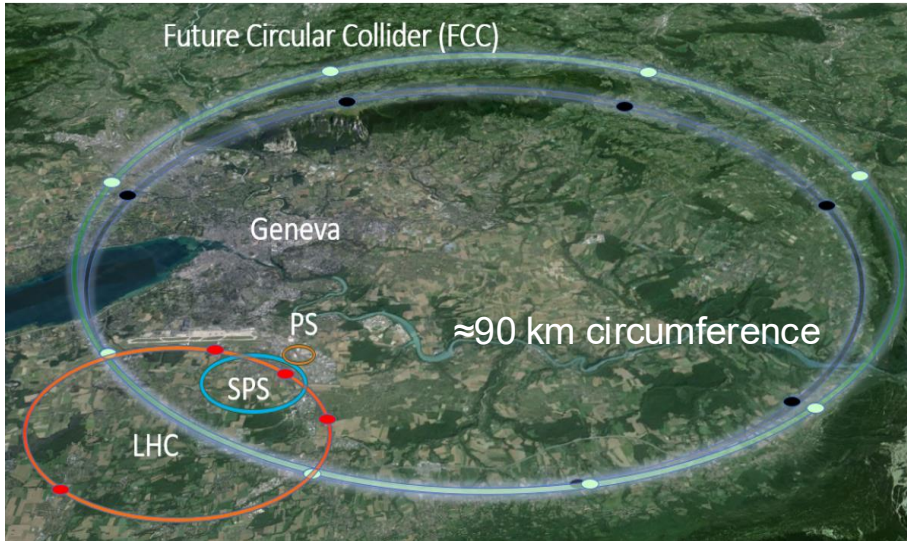
Outline

- **Introduction**
 - FCC-ee: the Future Circular electron-positron collider
 - Collimation for the FCC-ee
- **FCC-ee collimation system**
 - FCC-ee halo collimation system
 - FCC-ee SR collimation system
- **Studies and simulations of beam losses in the FCC-ee**
 - FCC-ee beam loss scenarios
 - FCC-ee collimation simulations
 - Simulation tool benchmark at SuperKEKB
- **FCC-ee collimation performance under selected beam loss scenarios**
 - Generic beam halo, off-momentum, beam-gas, Touschek, beam-beam losses
 - Generic failure scenario
- **Crystal collimation for the FCC-ee: an alternative design**
- **Outlook and future work**

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FCC: the Future Circular Collider



1st stage

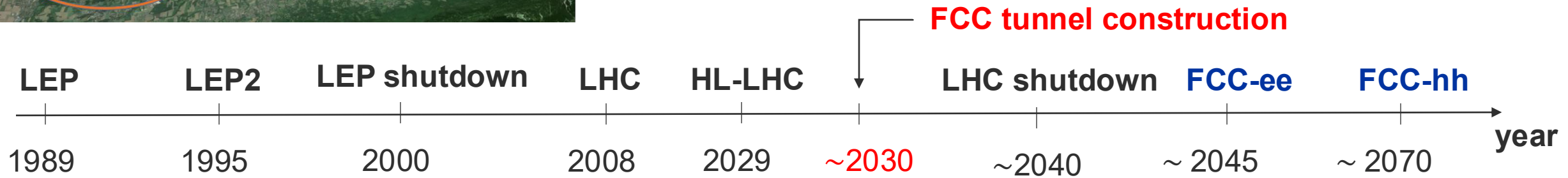
FCC-ee

luminosity-frontier highest-energy
electron-positron collider

2nd stage

FCC-hh

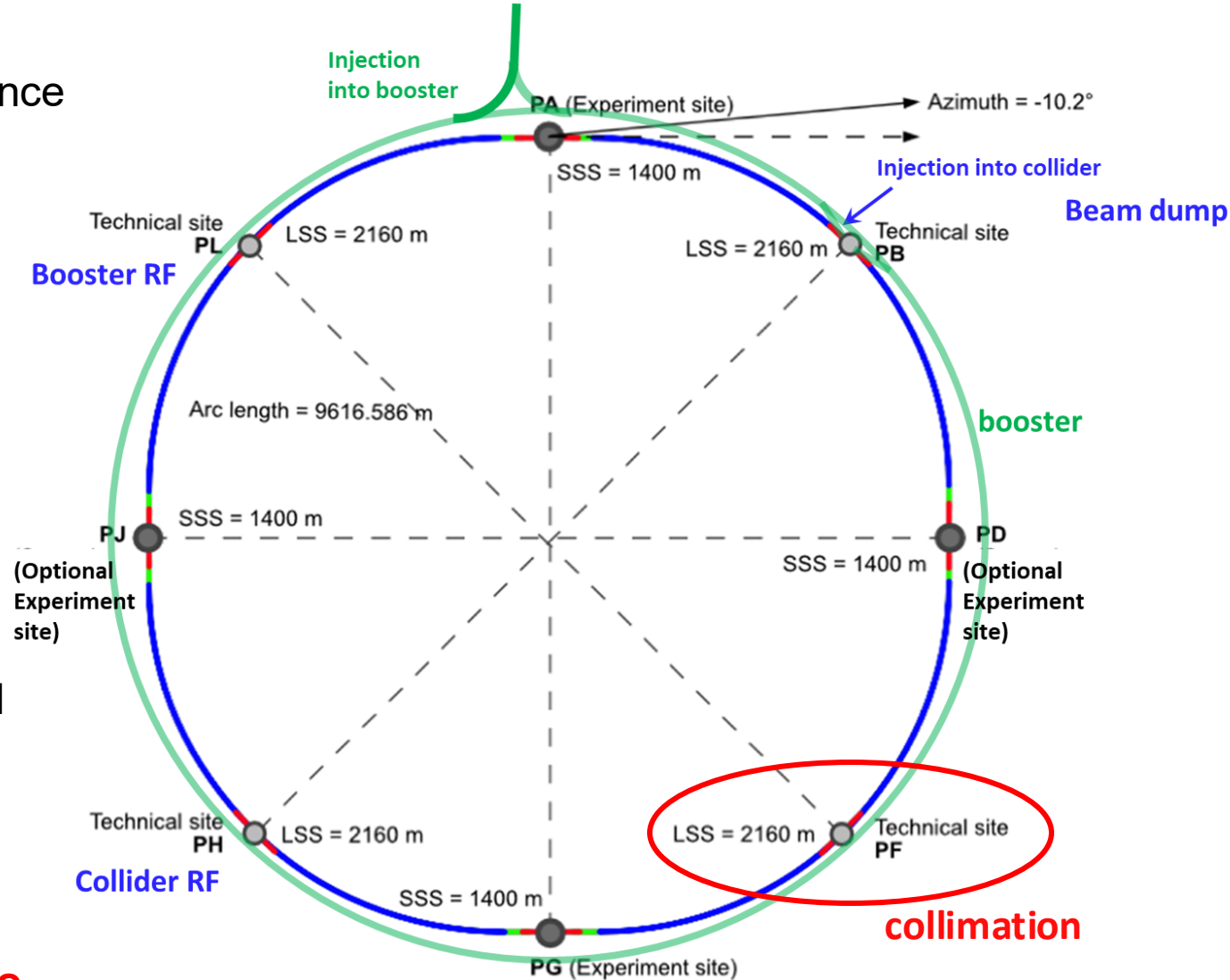
energy-frontier
hadron collider



- **FCC-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), **$t\bar{t}$** (182.5 GeV)

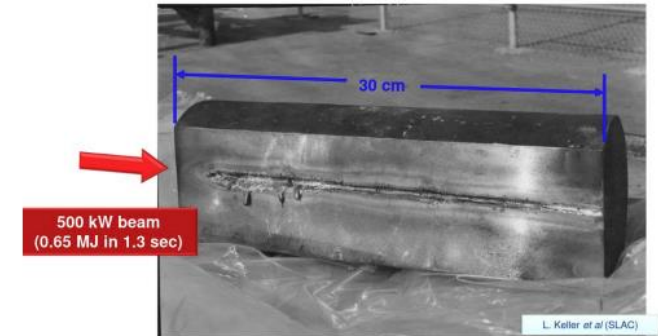
FCC-ee layout and technical baseline

- **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**
- **Collimation in PF**
 - **Why do we need collimation in the FCC-ee?**



Why do we need collimation in the FCC-ee?

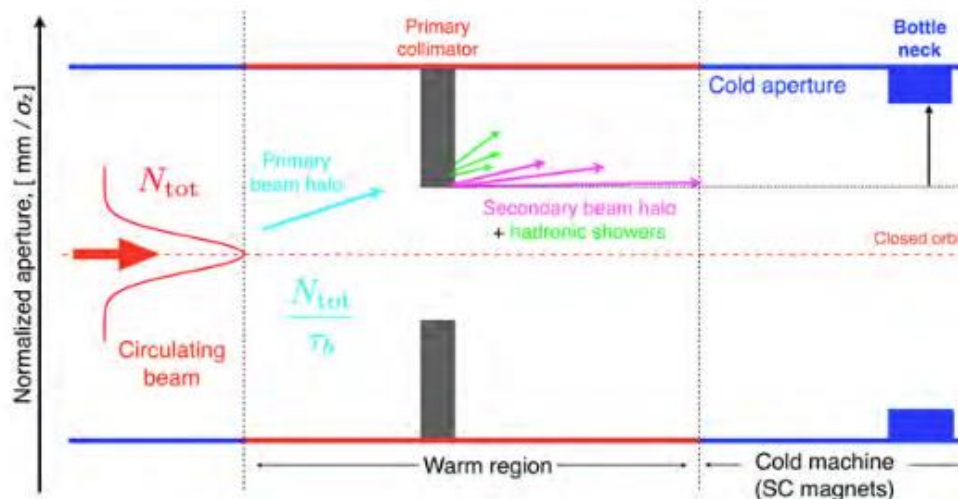
- **FCC-ee**: up to **17.7 MJ** stored beam energy
 - Corresponds to the kinetic energy of a middle-size car at 155 km/h
- **Typical beam sizes in the FCC-ee** are $\sigma_x \sim 200\text{-}300\text{ }\mu\text{m}$; $\sigma_y \sim 10\text{ }\mu\text{m}$
 - 17.7 MJ concentrated into a spot size of $\sim 0.002\text{ mm}^2$
 - **Energy densities up to several thousands of MJ/mm²**
 - **The FCC-ee beams are highly destructive**
- We need a **collimation system** to safely dispose of any beam losses
 - **Collimation system**: set of dedicated movable absorbers that intercept stray particles before they hit sensitive components



Damage of a copper block in a 18 GeV electron beam test at SLAC (1971).

This was a slow beam loss (0.65 MJ in 1.3 s) with a large beam spot size (2mm).

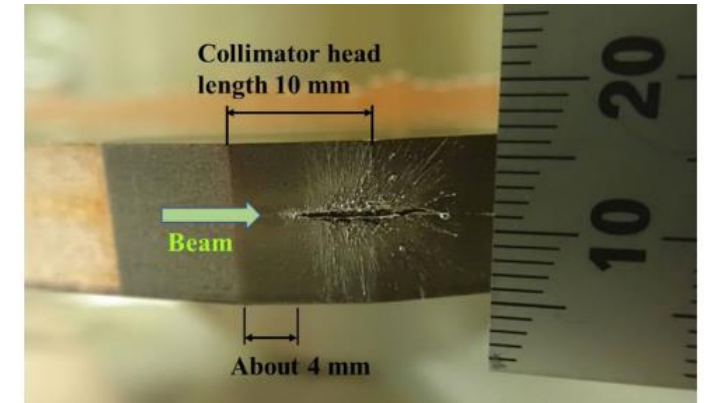
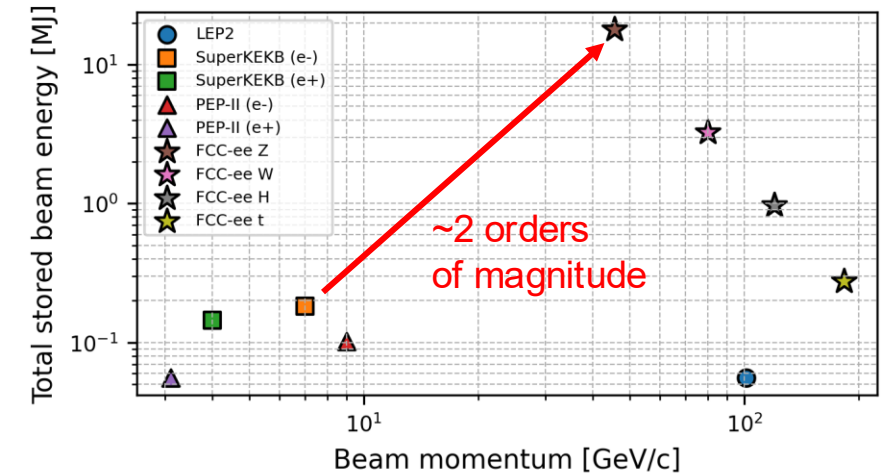
For comparison: stored beam energy in FCC-ee (Z) is 17.5 MJ, with a MUCH smaller spot size (=higher energy density)



From [3].

Collimation for the FCC-ee

- **FCC-ee presents unique collimation challenges**
 - Unprecedented stored beam energy for a lepton collider
 - **17.7 MJ** in the **Z** operation mode (**45.6 GeV** beam energy)
 - 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 beam losses
- **Collimation strategy for the FCC-ee**
 - Beam-halo (global) collimation (+ local protection collimation)
 - Focus of this PhD thesis project
 - Secondary particle shower absorbers
 - Studied in the CERN SY-STI group
 - Synchrotron radiation (SR) collimation – upstream of the IPs
 - Studied in the FCC-ee MDI group



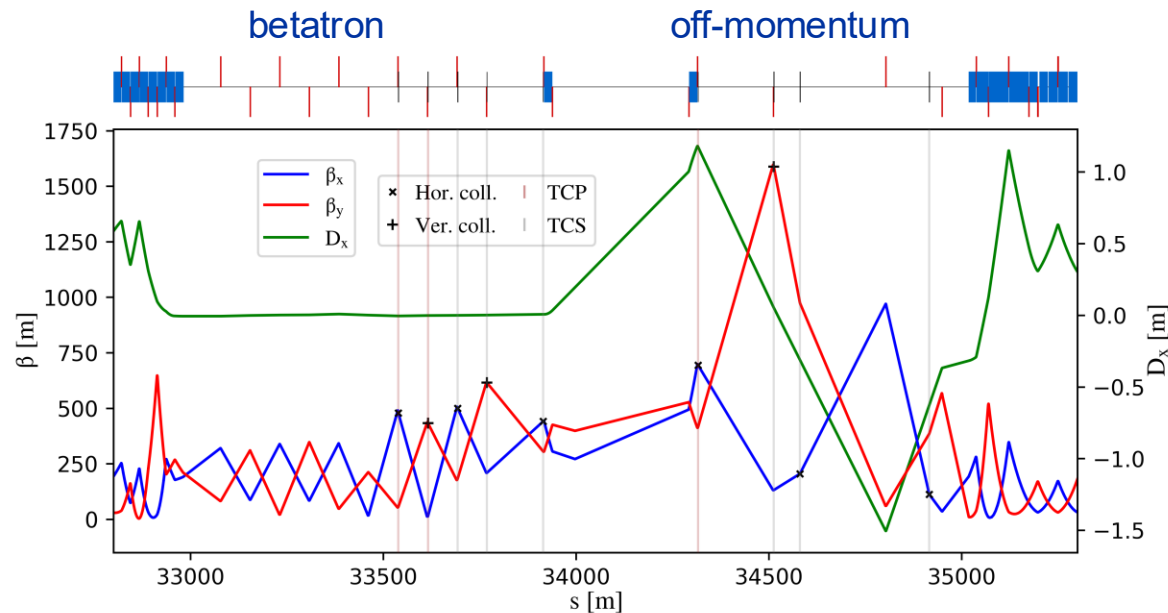
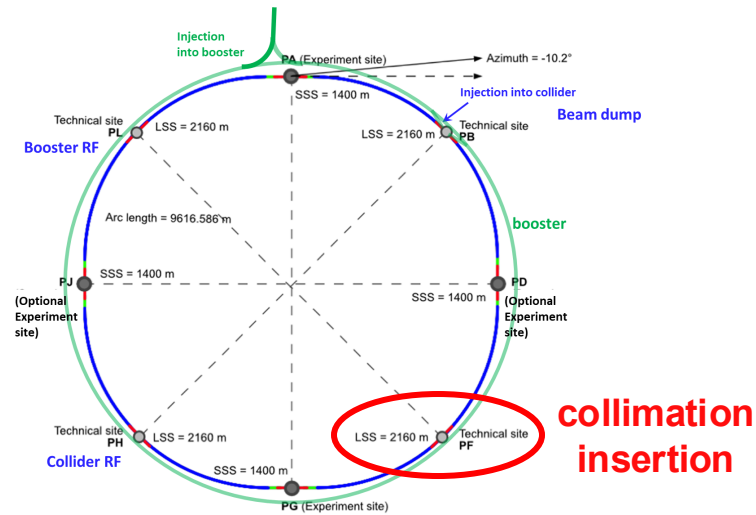
Damaged Cu coated Ta collimator in SuperKEKB (LER) due to sudden beam loss [4]

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FCC-ee halo collimation system

- Dedicated long straight section in PF
 - Universal technical insertion optics [5]
 - Primary and secondary betatron and off-momentum collimators
 - Ensure protection of the aperture bottlenecks in different conditions
 - **Aperture bottleneck at Z: 11.5σ (H plane), 81.5σ (V plane)**
 - First collimator design for cleaning performance
 - **Sizeable impedance contribution by vertical primary collimator [6]**
 - Collaboration with optics, impedance, energy deposition, and engineering team to optimize the design
 - Crystal collimation for the FCC-ee has also been explored [7]

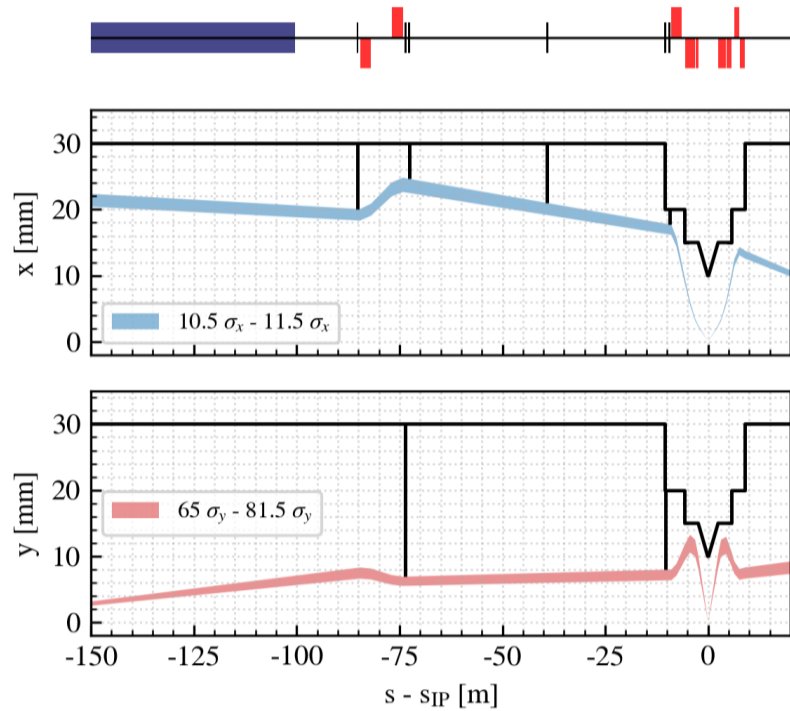


FCC-ee (Z) beam halo collimator parameters and settings

Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	C-based	25	9.5	5.6	-
TCP.V.B1	V	C-based	25	50	1.4	-
TCS.H1.B1	H	Mo-based	30	10.5	6.2	-
TCS.V1.B1	V	Mo-based	30	65	2.2	-
TCS.H2.B1	H	Mo-based	30	10.5	6.5	-
TCS.V2.B1	V	Mo-based	30	65	3.6	-
TCP.HP.B1	H	C-based	25	18	12.5	1.1
TCS.HP1.B1	H	Mo-based	30	28	11.0	3.5
TCS.HP2.B1	H	Mo-based	30	28	8.3	1.3

FCC-ee SR collimation system

- **Beam particles radiate SR photons**
 - SR photons may impact the experimental detectors and cause backgrounds
- **Synchrotron radiation collimation [9, 10]**
 - 6 collimators and 2 masks upstream of the IPs
 - Designed to reduce SR-induced detector backgrounds and power loads in the inner beampipe



FCC-ee (Z) SR collimators parameters and settings (V25.2 GHC)

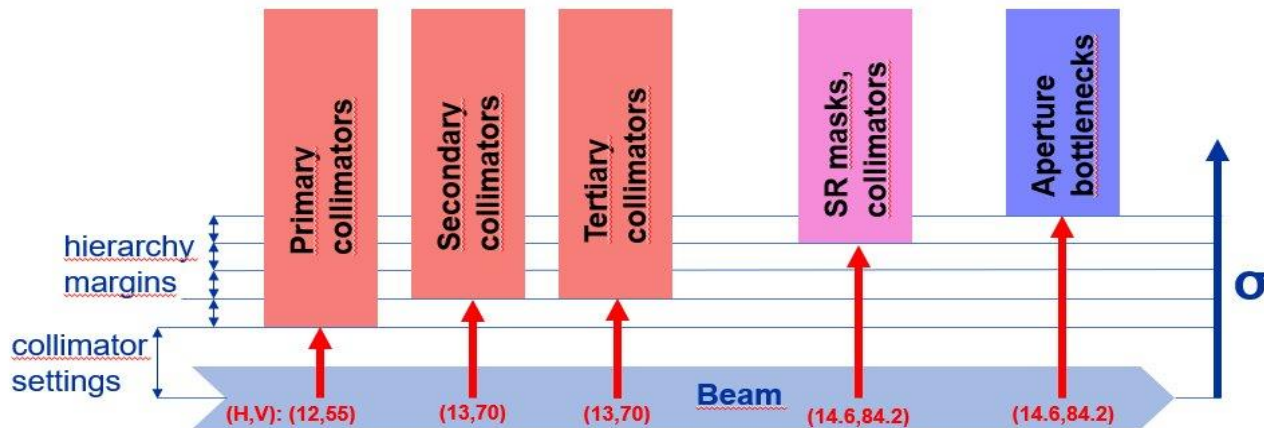
Name	Plane	Material	Length [cm]	Gap [σ]	Gap [mm]
TCR.H.WL.B1	H	W-based	10	11.5	20.4
TCR.V.C0.B1	V	W-based	10	81.5	7.1
TCR.H.C0.B1	H	W-based	10	11.5	25.0
TCR.H2.C0.B1	V	W-based	10	11.5	21.3
TCR.V.C2.B1	V	W-based	10	81.5	8.2
TCR.H.C2.B1	H	W-based	10	11.5	18.0

- SR collimator apertures = estimated aperture bottlenecks

Courtesy K. Andre, FCC-ee MDI team

Tertiary collimators

- In case of fast loss events SR collimators or even final focus magnets may be exposed to beam losses
 - SR collimators are not designed to intercept large beam losses: **risk of damages/backgrounds**
- **Two (H+V) tertiary collimators (TCTs)** for **local protection** included in the collimation system
 - Placed **upstream** of each IP
 - position optimized for optimal phase-advance (multiple of π) w.r.t. **SR collimators aperture bottlenecks**
- Further shower absorbers and local protection devices (e.g., injection protection) to be studied in the future by energy deposition, beam transfer and engineering team



FCC-ee (Z) collimation hierarchy

- Hierarchy margins set to 100-300um
 - $\sim 1 \sigma_{\beta x}$, $\sim 15 \sigma_{\beta y}$

Name	Plane	Material	Length [cm]	Half-gap [σ]	Half-gap [mm]
TCT.H.B1	H	C-based	25	10.5	2.4
TCT.V.B1	V	C-based	25	65	7.3

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FCC-ee beam loss scenarios

- The FCC-ee Z mode is the **focus**: has the **highest stored beam energy 17.7 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**
 - **Off-momentum beam halo losses**
 - Beam losses from **interactions with residual gas**
 - Beam losses from **Touschek scattering**
 - Beam losses from **beam-beam interactions**
 - Beam losses from a **generic failure scenario**

In this PhD thesis work

 - Beam losses due to **impedance-driven fast instabilities**
 - Beam losses from **top-up injection**
 - **Sudden beam losses** from **beam-dust interactions** as observed at SuperKEKB
 - Beam losses from interactions with **thermal photons**: **future study planned for 2026**

Being studied in parallel (G. Nigrelli, PhD student XXXIX cycle)

 - **Accidental scenarios**
 - Injection failure: **work in progress**
 - asynchronous dump, others: **waiting for inputs to set up models**

FCC-ee collimation simulations

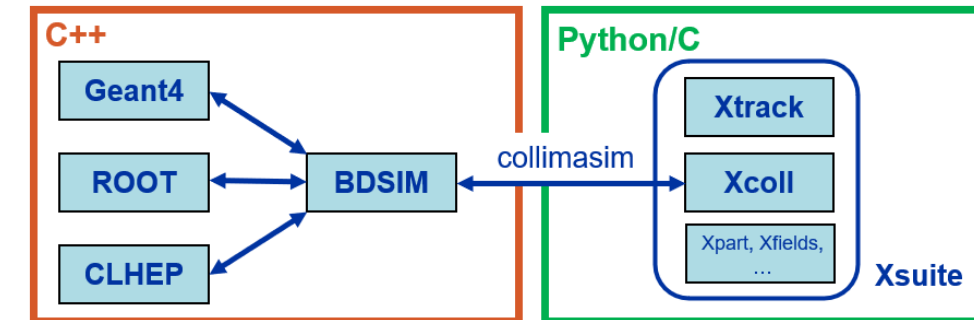
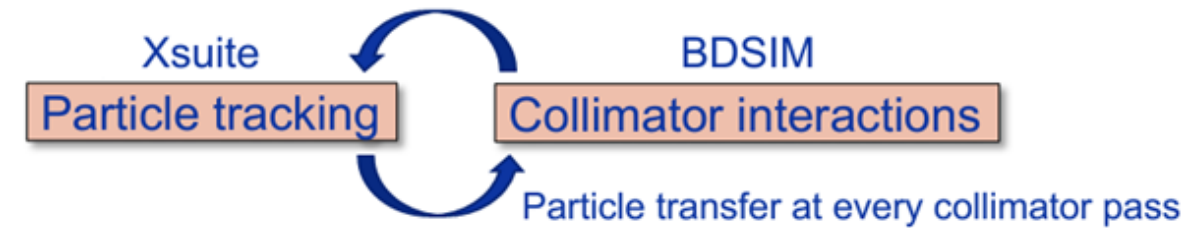
- **FCC-ee presents unique challenges for collimation simulations**
 - Synchrotron radiation and magnet strength adjustment (tapering) to compensate it
 - Complex beam dynamics – strong sextupoles in the lattice and strong beam-beam effects
 - Detailed aperture and collimator geometry modelling
 - Electron/positron beam particle-matter interactions
 - Large accelerator system – 90+ km beamline

- **Xsuite + BDSIM (Geant4) coupling [11-19]**

- Developed for FCC collimation simulations
- Benchmarked against
 - other simulation codes: MAD-X, pyAT, Sixtrack-FLUKA
 - measured data from: SPS, LHC, SuperKEKB
- Other tools available (e.g., Xsuite-FLUKA coupling)

- **Simulation routines for specific processes**

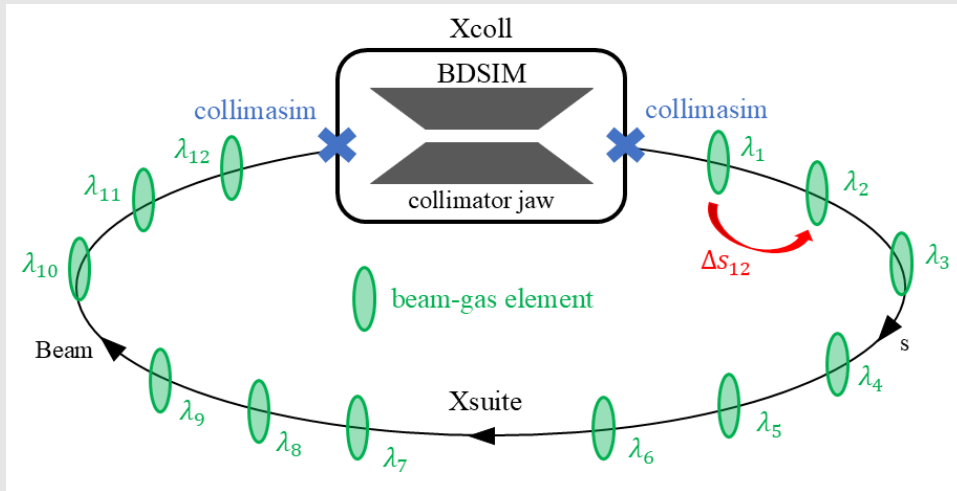
- **Beam-residual gas interactions** and **Touschek scattering**
- Developed in this work



Simulation of beam-gas and Touschek scattering

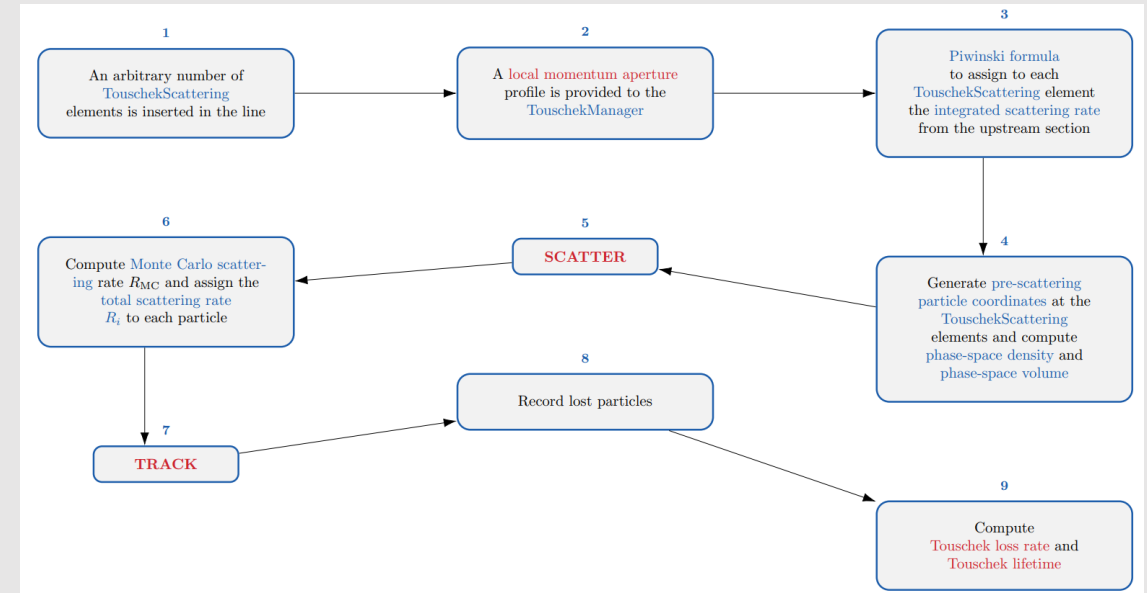
Beam-gas

- A Monte Carlo routine to simulate beam-gas interactions in Xsuite has been developed [20]
 - Beam-gas **bremsstrahlung** interactions
 - Beam-gas **Coulomb scattering** interactions
- Arbitrary pressure profile and gas composition provided as input



Touschek*

- A Monte Carlo routine to simulate Touschek scattering in Xsuite has been developed
 - Follows the Xiao-Borland approach [21, 22] implemented in **ELEGANT** [23]
 - Combines Monte Carlo and Piwinski formula [24]

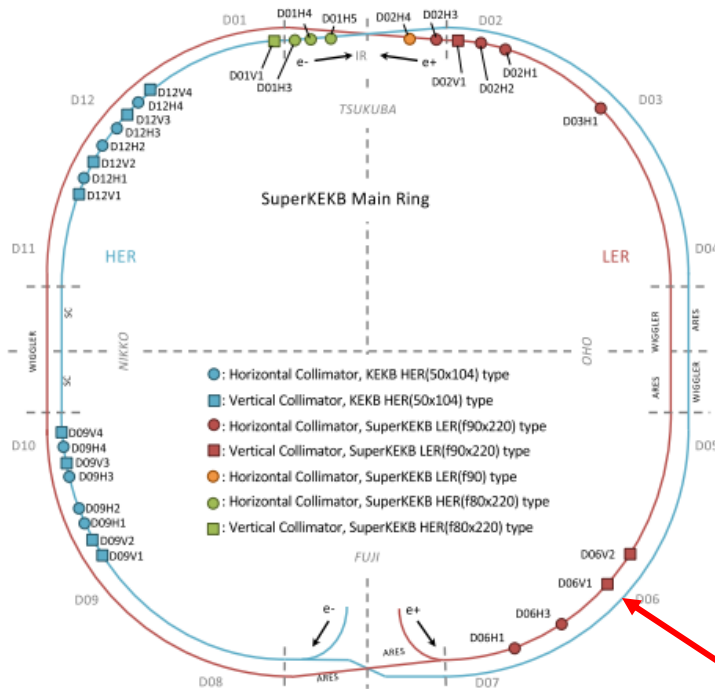


***Touschek scattering** refers to intra-bunch Coulomb scattering in which the transfer of transverse to longitudinal momentum causes particles to be lost from the beam.

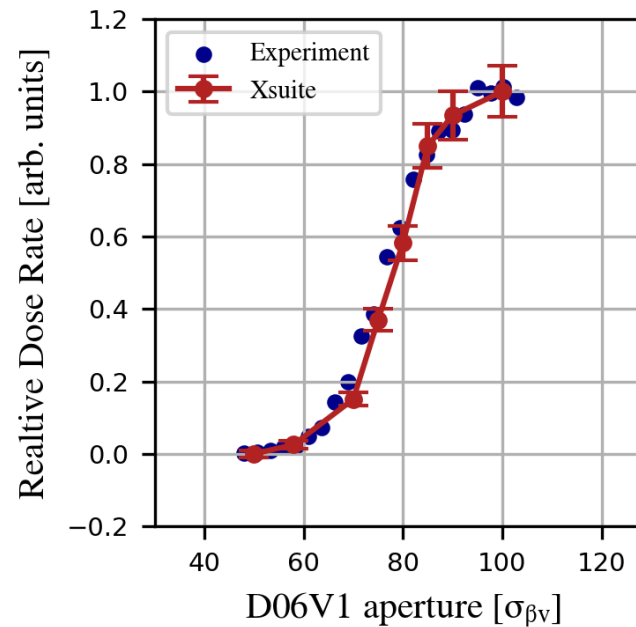
Xsuite-BDSIM benchmark at SuperKEKB

- **Comparison of Xsuite–BDSIM simulations with measured Belle II backgrounds at SuperKEKB [25]**
 - Carried out during an exchange at KEK ([EAJADE programme](#))
- **Dedicated single-beam background study at SuperKEKB LER (e⁺ ring) [26]**
 - D06V1 collimator aperture scan
 - Radiation dose rates measured by Belle II radiation monitors

SuperKEKB collimator layout as of June 2020



Relative total dose rate for QCS-FW diamond detector
vs. D06V1 collimator aperture in units of $\sigma_{\beta V}$



- Simulations reproduce the measured background trend with excellent accuracy
- **Validates Xsuite–BDSIM for collimation and background studies in e⁺e⁻ machines**

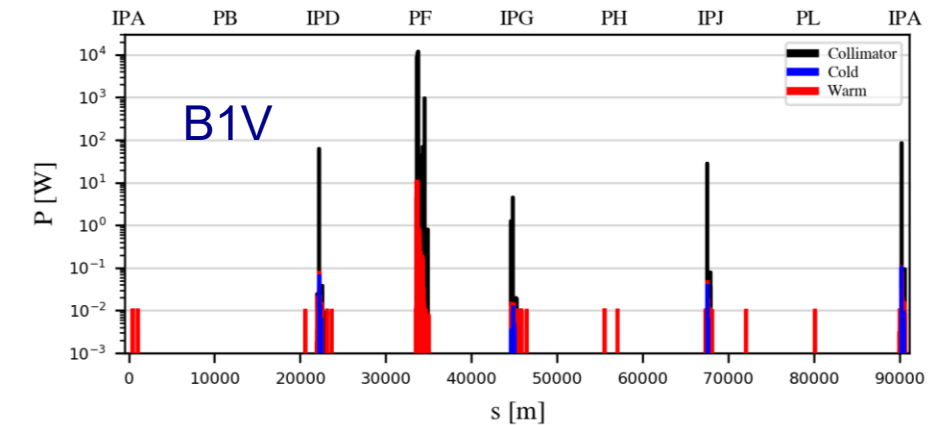
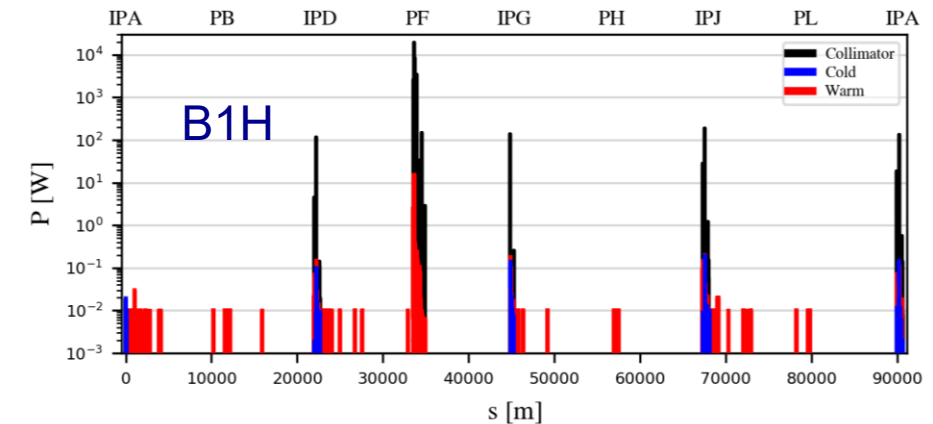
*background sources included in simulations: beam-gas (Bremsstrahlung, Coulomb) and Touschek scattering

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Generic halo losses for the Z mode

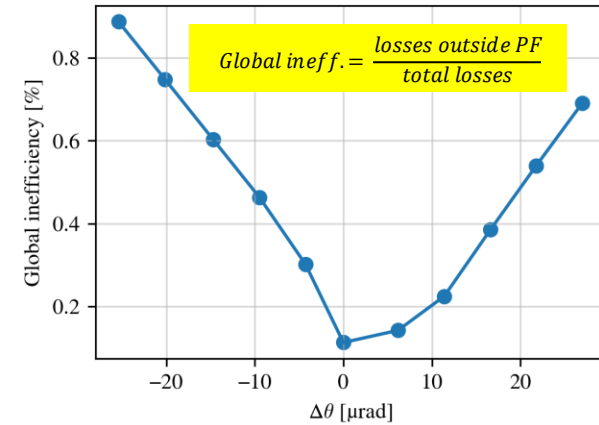
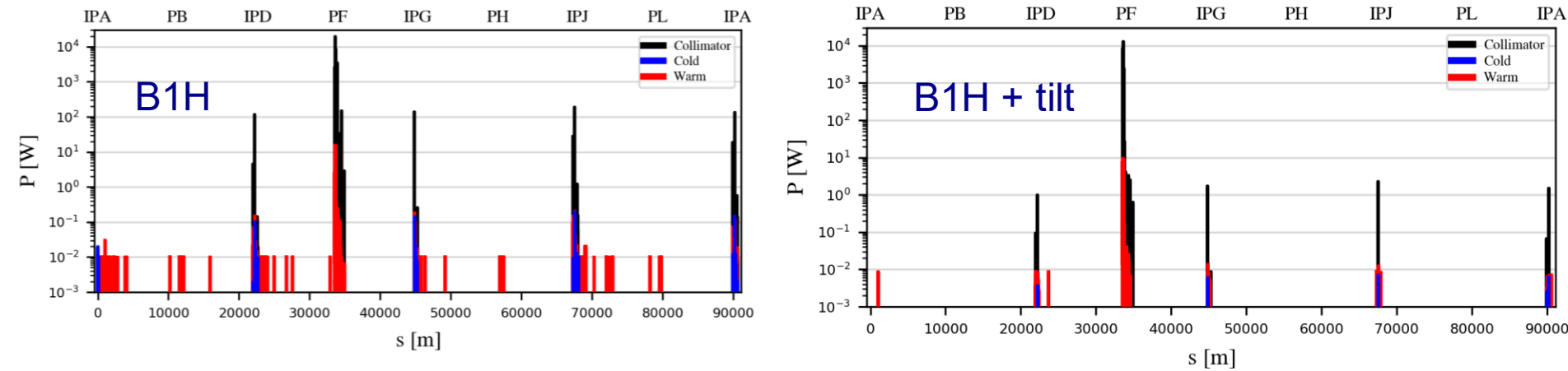
- **Generic halo losses:**
 - **Slow loss process** assumed*
 - The loss process itself is not simulated
 - Beam halo directly impacts one of the primary collimators
 - **Beam lifetime drop to 5 min** is assumed
- Horizontal and vertical betatron collimation losses (B1H, B1V)
- **Collimation system effectively localizes generic halo losses and protects sensitive components**
 - Most losses confined within PF collimation insertion for both horizontal and vertical halos.
 - **Loss suppression:**
 - ~2 orders of magnitude on the tertiary collimators
 - ~4-5 orders of magnitude on the SR collimators
 - >5 orders of magnitude on all the other elements outside PF



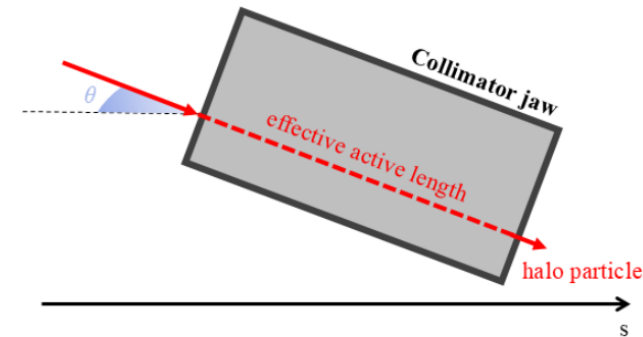
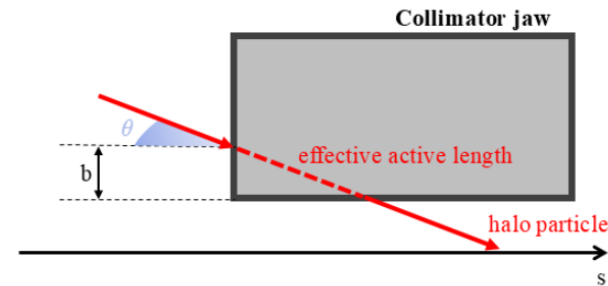
*This is strictly valid only if dynamic aperture (DA) is under control w.r.t. TCP gaps: currently, this is not the case for the V-plane

Collimator angular alignment

- Collimator angular alignment can significantly improve the collimation performance



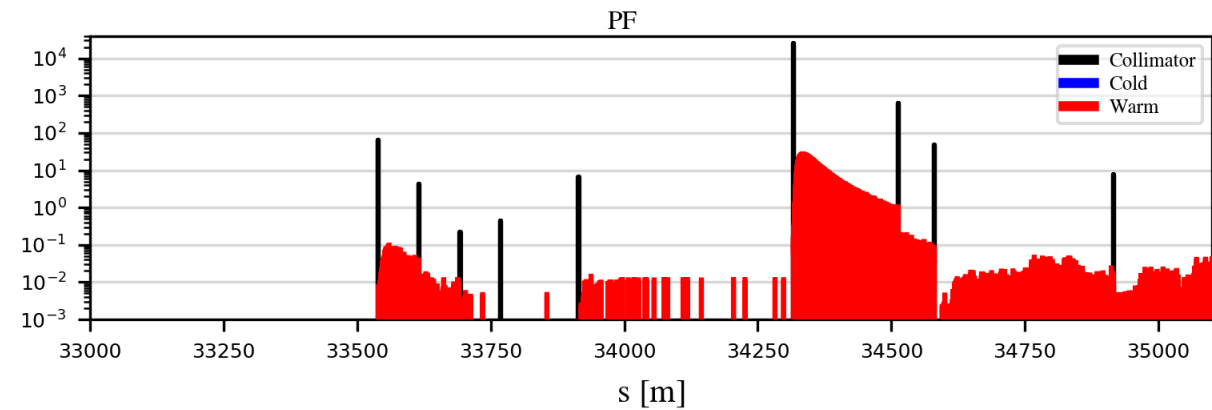
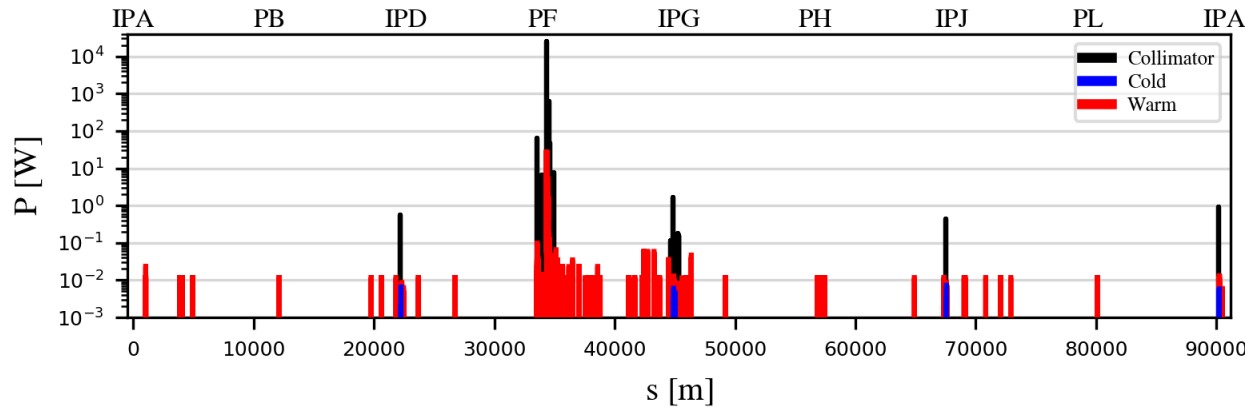
- Losses outside of PF are significantly suppressed
 - Improvement factor ~ 100
- Collimation performance remains robust against angular tilt deviations from the optimal alignment
- Important input for hardware design
 - Mechanical design of FCC-ee collimators updated based on these results



Off-momentum losses for the Z mode

- **Off-momentum losses**

- Dedicated **RF-sweep simulation** progressively shifts the bunch central momentum ($\Delta\delta_{\text{max}} \approx -2.6\%$): simulates slow RF failures or other slow off-momentum loss scenarios
- **Beam lifetime drop to 5 min** is assumed



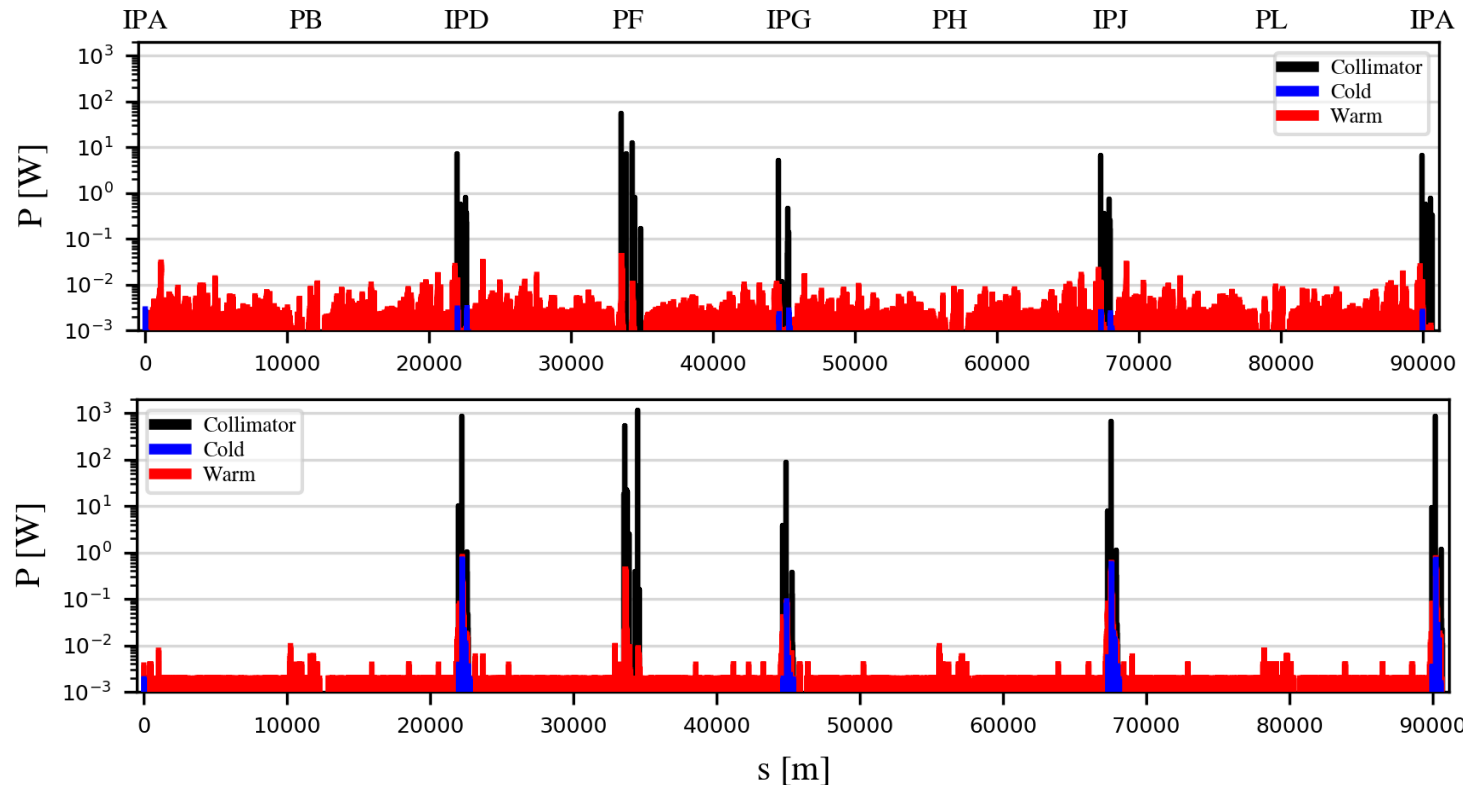
- **The FCC-ee collimation system effectively confines off-momentum losses**

- **Losses concentrated in PF collimation insertion** — primarily on the off-momentum TCP
- Secondary collimators absorb remaining debris; minimal leakage elsewhere
- **Residual losses at IPs suppressed by ~4 orders of magnitude**; negligible losses elsewhere
- Performance expected to further improve with **optimized collimator jaw tilts**

Beam-gas losses for the Z mode

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

- Using the beam-gas routine developed as a part of this work and based simulated gas pressure profiles



Beam-gas bremsstrahlung

- Estimated lifetime after only 1h of beam conditioning*: **274 min**
- Expected to increase to > 100 h in a fully conditioned machine

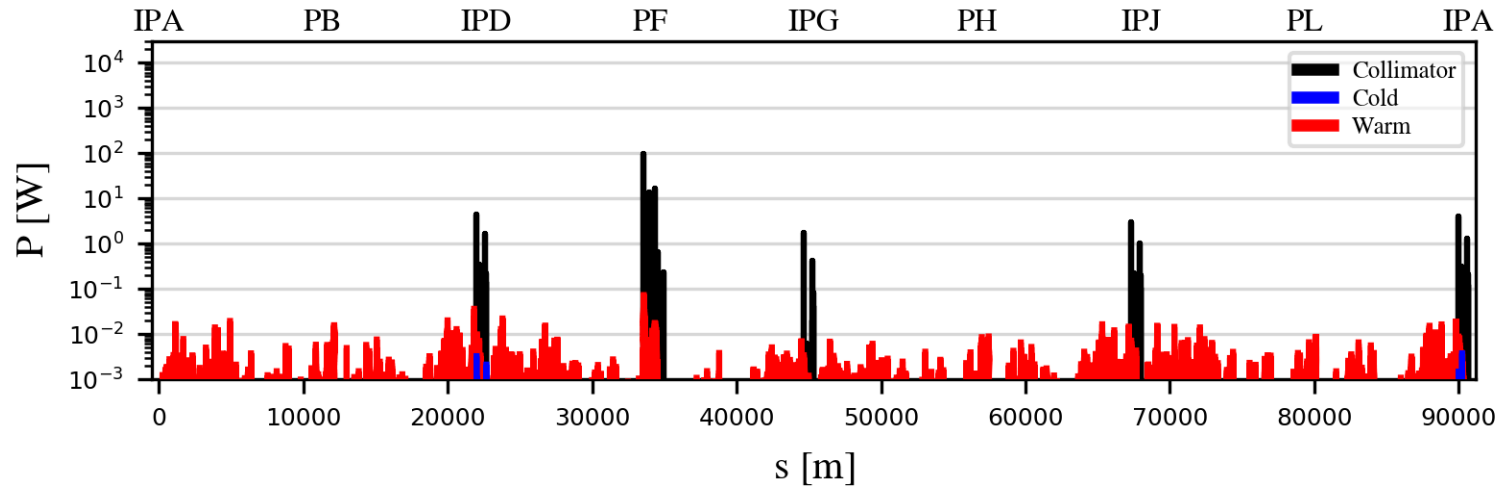
Beam-gas Coulomb scattering

- Estimated lifetime after only 1h of beam conditioning*: **41 min**
- Expected to increase to > 10 h in a fully conditioned machine

- Beam-residual gas interactions have not been identified as a performance limitation for the FCC-ee, and the FCC-ee collimation system has proven effective in mitigating related beam losses

Touschek scattering losses for the Z mode

- Using the Touschek scattering routine developed as a part of this work



- Touschek losses well localized in collimation insertion in PF**
 - Mainly on horizontal betatron and off-momentum TCP
 - Minimal leakage to the experimental IRs
 - Modest loads on tertiary and SR collimators
 - No significant loads on superconducting magnets

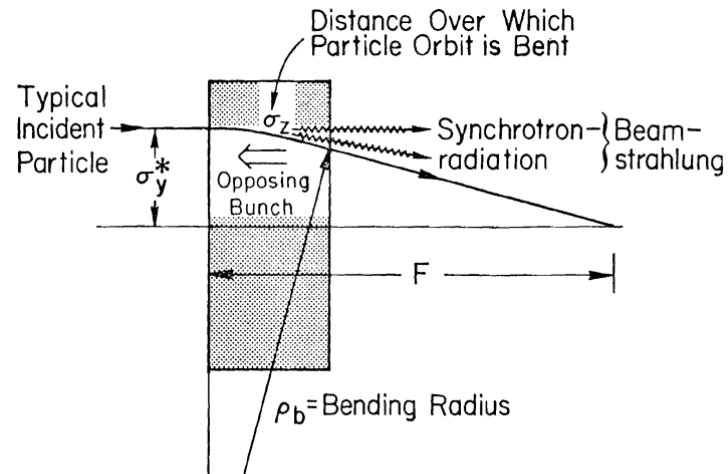
- Touschek lifetime ~13 h**
 - Consistent with prior analytical estimates [27]
 - Expectation confirmed:**
Touschek scattering is not a performance-limiting effect in the FCC-ee

Process	Beam Lifetime
Touschek scattering	13 h
Radiative Bhabha scattering	22 min
Lattice (quantum + BS* + lattice)	83 min
Beam-gas (1 h conditioning)	36 min
Beam-gas (conditioned machine)	> 10 h

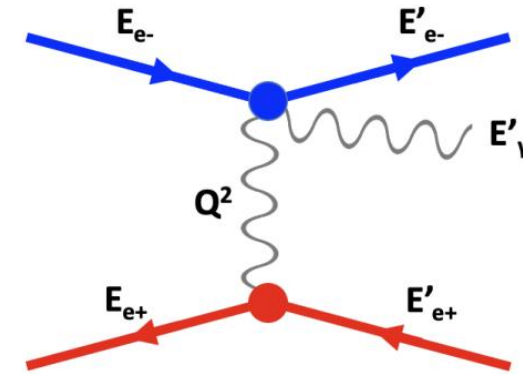
*beamstrahlung

FCC-ee Z beam-beam losses

- Interactions at the IPs have a crucial role on the FCC-ee beam dynamics
 - Beamstrahlung (BS), radiative Bhabha scattering (RBS), beam-beam kicks



Schematic illustration of **beamstrahlung** [28]:
an incoming bunch emits **beamstrahlung radiation**
because of the electromagnetic field of the opposing bunch



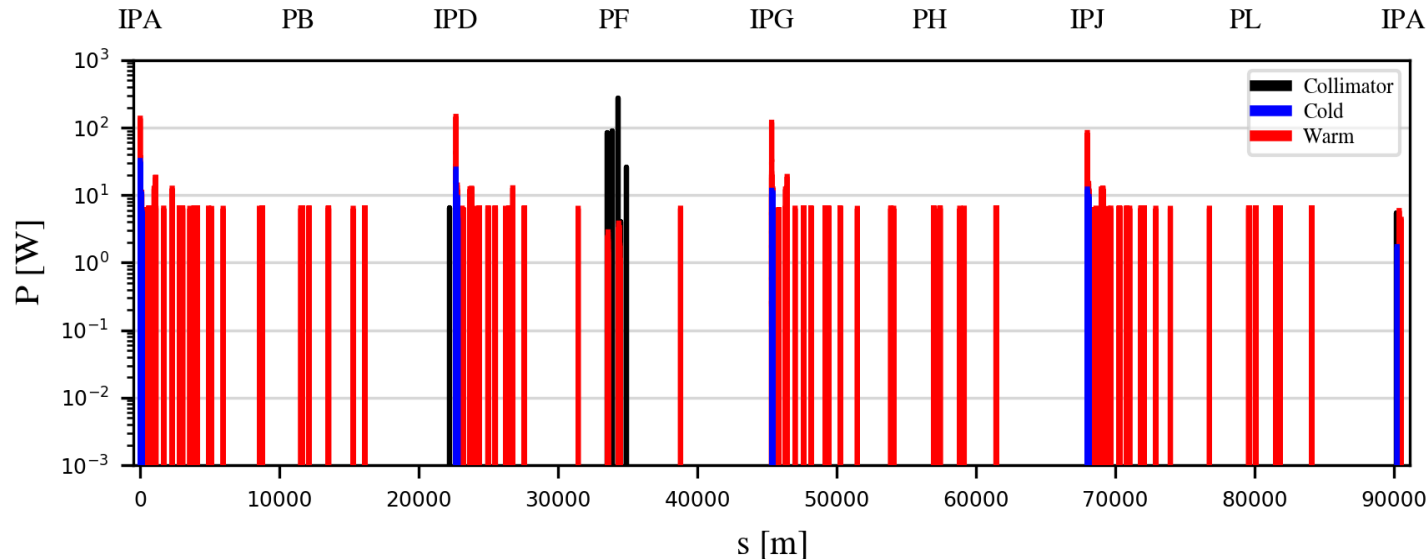
Schematic illustration of **Bhabha scattering** (electron-positron scattering) [29]
The scattering particles exchange a virtual photon. The process can occasionally result in the emission of extra real photons, in which case the process takes the name **radiative Bhabha scattering**.

- Main contribution to the beam lifetime in nominal operation
- Can produce distinct beam loss distributions around the ring
- These effects are modeled in **Xsuite** (**Xfields**)
 - Can be integrated in Xsuite-BDSIM collimation tracking simulations

Beam-beam losses for the Z mode

*quantum + lattice + BS + lum.

- Xsuite allows to set-up complex combined-effects simulations: beam-beam + collimation
 - Beam-beam kicks, radiative Bhabha, beamstrahlung in 4 IPs + detailed aperture and collimator model

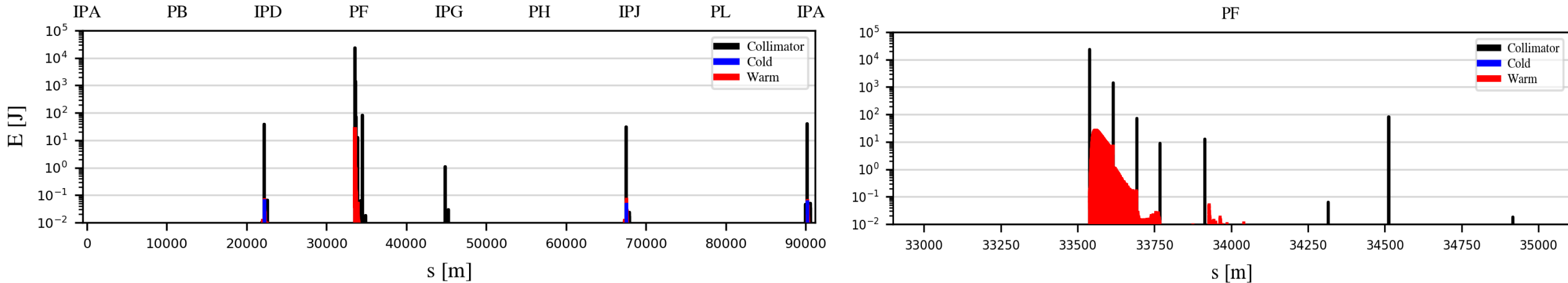


- **Beam lifetime***: **~14 min** vs. **~17 min**
estimated without aperture and collimators and without beam-size effect
 - Primary collimator gaps:
 9.5σ (H plane), **50σ** (V plane)

- **(Long-range) beam-beam losses intercepted by the collimation system in PF**
- **Local beam-beam losses downstream of the IPs unavoidably present**
 - Originate from hard RBS events
 - Tungsten shielding (few-mm) in SC quads: already proposed by CERN SY-STI group [30]
 - Additional collision debris collimators to be studied in the future

Generic failure: deep impact at TCP.H.B1 (Z mode)

- Gaussian bunch **directly hits TCP.H.B1** at $1\sigma_x$ (fast-failure proxy)
 - Result scaled to **40 bunches impacting TCP.H.B1** (estimated damage threshold for TCPs) [31]



- **Losses remain confined in PF and the impacted TCP is the only potentially vulnerable device**
 - The collimation system shows robust protection under these failure-like conditions*
- **Beam pipe in PF: ~ 100 J/m** far below a conservative **~ 70 kJ/m Cu melting threshold** [32]
 - To reach Cu melt in these conditions would require $\sim \times 350$ higher pipe load $\rightarrow$ **~ 14000 deep-impact bunches** (higher than stored 12000 stored bunches)

*Dedicated modeling of specific failure scenario is nevertheless required

Outline

- **Introduction**
 - FCC-ee: the Future Circular electron-positron collider
 - Collimation for the FCC-ee
- **FCC-ee collimation system**
 - FCC-ee halo collimation system
 - FCC-ee SR collimation system
- **Studies and simulations of beam losses in the FCC-ee**
 - FCC-ee beam loss scenarios
 - FCC-ee collimation simulations
 - Simulation tool benchmark at SuperKEKB
- **FCC-ee collimation performance under selected beam loss scenarios**
 - Generic beam halo, off-momentum, beam-gas, Touschek, beam-beam losses
 - Generic failure scenario
- **Crystal 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 was also 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

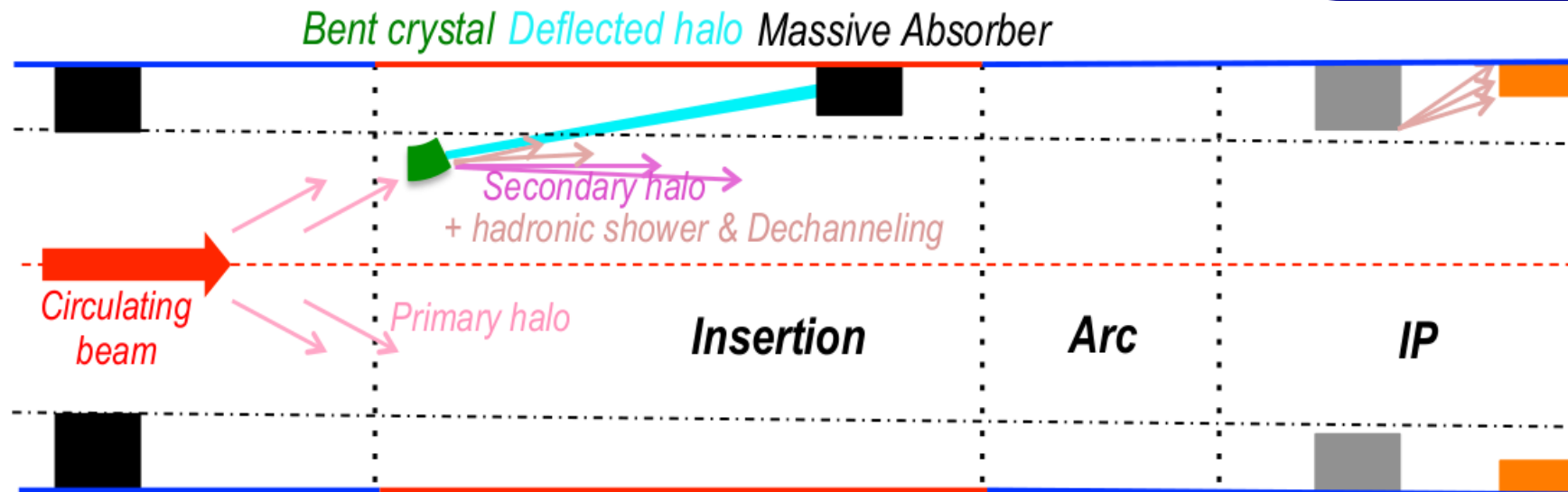
Potentially larger absorber (secondary collimator) mechanical gaps

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

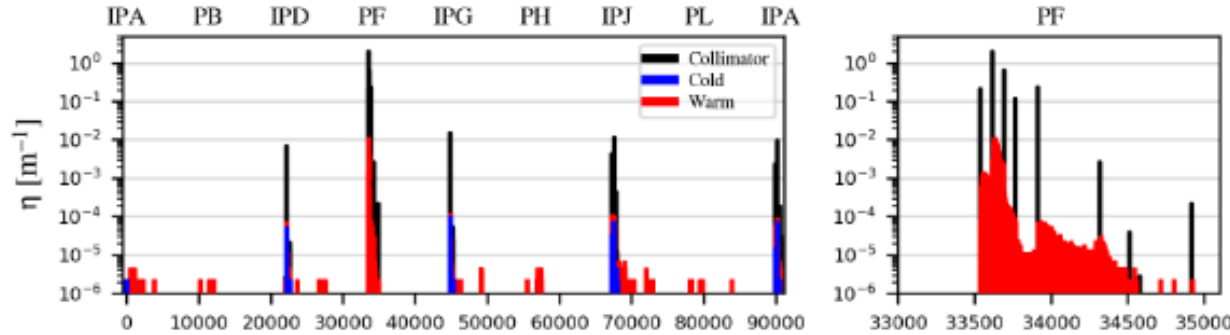


Working principle of a crystal collimation system [33]

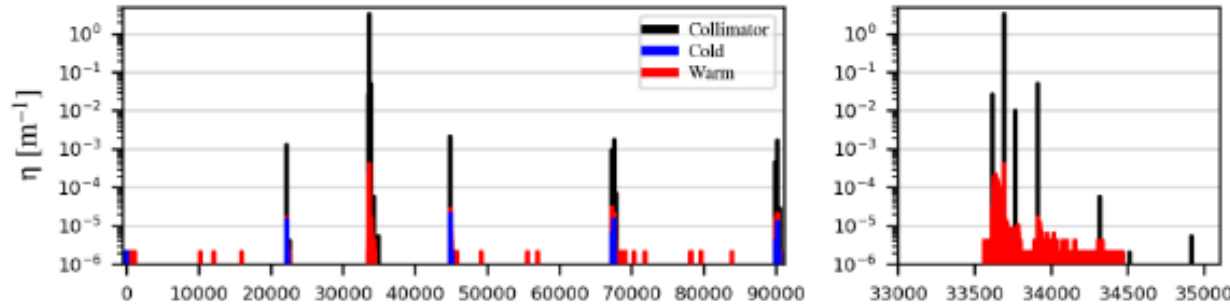
FCC-ee Z one-turn crystal collimation performance

- Replacement of 25 cm C-based primary collimators with 100-200 μm bent Si crystals (100 μrad bending angle)
- Generic beam halo impacting the horizontal betatron TCP (standard or crystal)

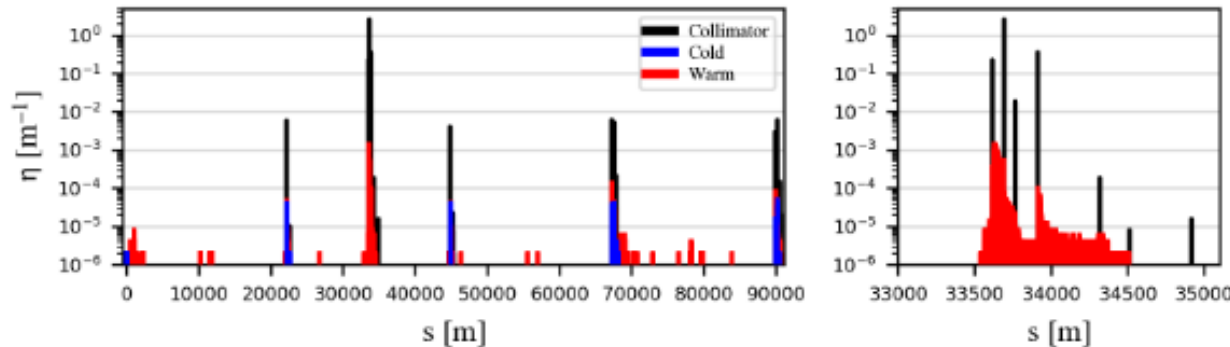
standard



crystal e⁺



crystal e⁻



- **Crystal collimation improves one-turn collimation performance** for both e^+ and e^-
- **Positron beam:**
 - TCT losses reduced by ~ 1 order of magnitude
 - Main absorber losses $\times 4$ higher, as expected from coherent channeling
- **Electron beam:**
 - Smaller improvement (TCT losses $\sim \times 0.5$)
 - Consistent with lower electron channeling efficiency
- **Additional effects:**
 - Off-momentum and aperture losses in PF reduced by > 1 order of magnitude

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 - Generic failure scenario
- **Crystal collimation for the FCC-ee: an alternative design**
- **Outlook and future work**

Outlook

- **A beam collimation system for the FCC-ee has been designed**
 - Multi-stage betatron and off-momentum collimation + local protection in sensitive regions
- **Monte Carlo simulation routines for beam-gas and Touschek scattering have been developed**
- **FCC-ee collimation performance evaluated through an extensive campaign of complex simulations**
 - Based on the Xsuite-BDSIM simulation tool
 - Focus on the **most challenging Z operation mode (17.7 MJ stored beam energy)**
 - **No show-stoppers identified** - the proposed collimation system provides
 - Effective loss localization in dedicated regions
 - Strong suppression of losses in experimental interaction regions
 - Robust protection under both steady-state and failure-like conditions
- **First validation of Xsuite-BDSIM and of the beam-gas and Touschek routines against measured data from an electron-positron collider**
 - **Excellent agreement between measured and simulated backgrounds at SuperKEKB**
- **Exploratory crystal-collimation studies** show promising performance gain
 - Crystal collimation identified as a **potential upgrade path** for the FCC-ee collimation system

Future work

- **Extend collimation performance evaluation to all FCC-ee operation modes**
 - *Z, W, H, $t\bar{t}$*
- **Extend the studies to alternative optics design** (e.g., Local Chromatic Correction design)
- **Investigate additional beam loss mechanisms**, both regular and accidental
 - Thermal photon scattering, beam-dust interactions, equipment failures, others
- **Quantify loss tolerances** for critical components (e.g., detectors, superconducting magnets)
- **Continued iterative studies** including
 - Energy deposition, radiation and activation, impedance and engineering aspects
- **Explore alternative collimation strategies**
 - Crystal collimation, nonlinear collimation
- **Converge on a fully-optimized design** for the upcoming **FCC-ee technical design phase**



Thank you!

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Backup

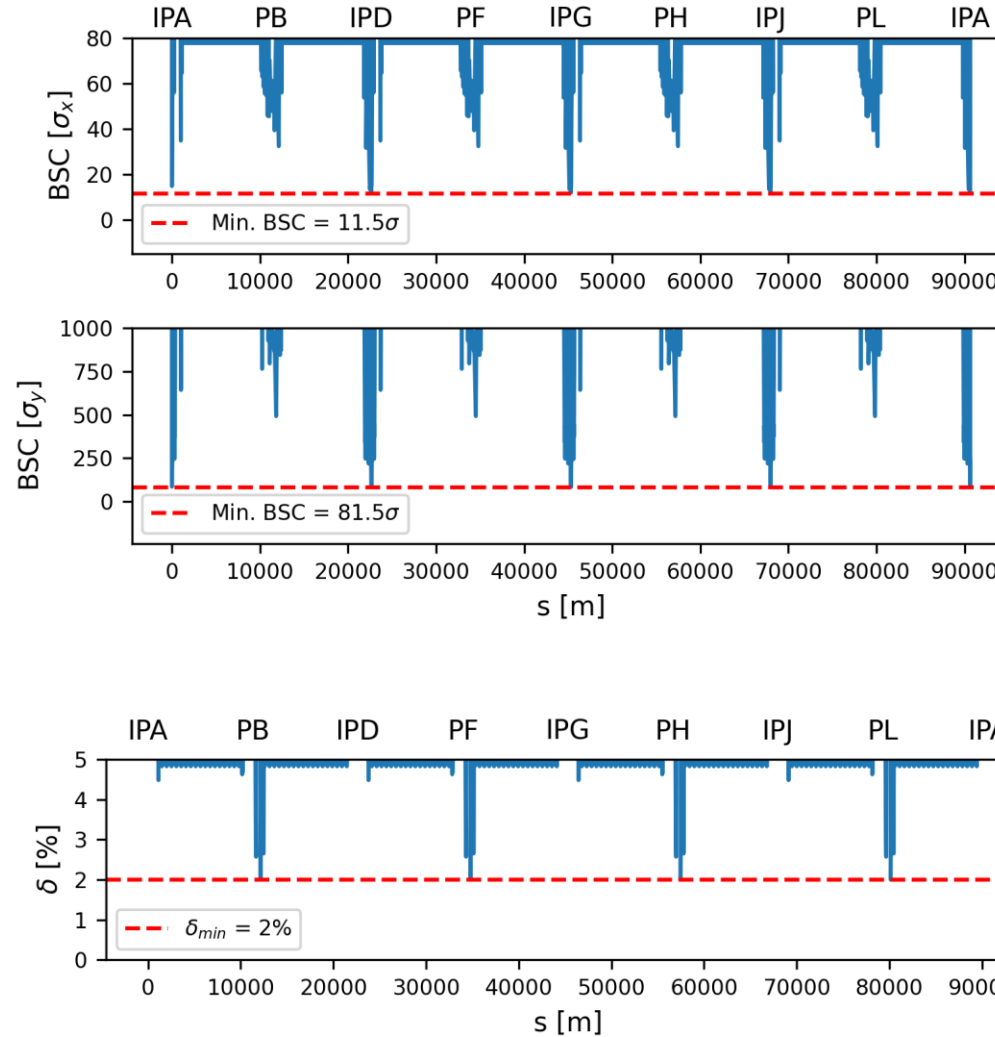
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658499	90.658509		98658.525590
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.369	1.86	9.99
SR power / beam	[MW]	50			
Beam current	[mA]	1281	135	26.8	5.0
Colliding bunches / beam		12000	1852	300	60
Colliding bunch population	[10 ¹¹]	2.02	1.38	1.69	1.57
Hor. emittance at collision ε_x	[nm]	0.74	2.16	0.66	1.69
Ver. emittance at collision ε_y	[pm]	1.9	2.0	1.0	1.39
Lattice v. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	0.65	1.20	0.57	0.81
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10 ⁻⁶]	28.55	28.67	7.52	7.47
Arc sext families		73		144	
$\beta_{x/y}^*$	[mm]	90 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		214.168 / 214.200	218.185 / 222.220	398.150 / 394.220	390.148 / 390.218
Chromaticities/ring $Q'_{x/y}$		+5 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.0395 / 0.1133	0.069 / 0.105	0.102 / 0.176	0.158 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.22 / 15.0	3.46 / 5.28	3.26 / 5.59	1.86 / 2.26
RF voltage 400/800 MHz	[GV]	0.0885 / 0	1.00 / 0	2.09 / 0	2.10 / 9.17
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.788083	400.788026		400.787964
Synchrotron tune Q_s		0.0354	0.0809	0.0334	0.0873
Long. damping time	[turns]	1169	218	65.4	19.2
RF acceptance	[%]	1.20	3.32	2.06	2.94
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	60	55	50	40
Beam-beam ξ_x/ξ_y^a		0.0018 / 0.0955	0.013 / 0.129	0.0108 / 0.130	0.067 / 0.140
Piowski ang. $(\theta_x\sigma_{z,\text{BS}})/\sigma_x^*$		27.6	3.6	6.6	0.87
Lifetime (q + BS + lattice)	[sec]	5000	4500	6000	9400
Lifetime (lum) ^b	[sec]	1324	960	600	650
Luminosity / IP / 10 ³⁴	[/cm ² s]	143	20	7.5	1.41

^aincl. hourglass.^bonly the energy acceptance is taken into account for the cross section, no beam size effect.

FCC-ee V25.2 GHC collider parameters

FCC-ee aperture

- Closed orbit tolerance: 250 μm
- Maximum beta-beating: 20%



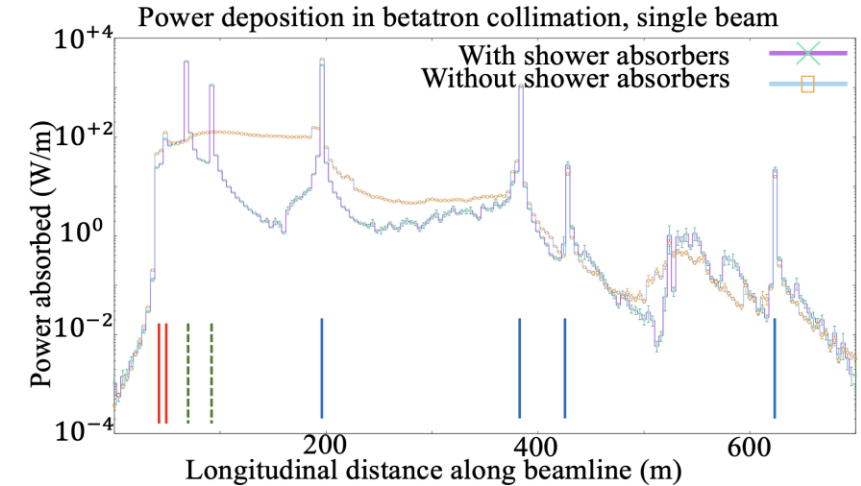
The Beam-Stay-Clear (**BSC**) is the beam-to-aperture distance in units of beam size

The linear momentum acceptance is $\delta = A/D_x$, where A is the mechanical aperture and D_x is the dispersion

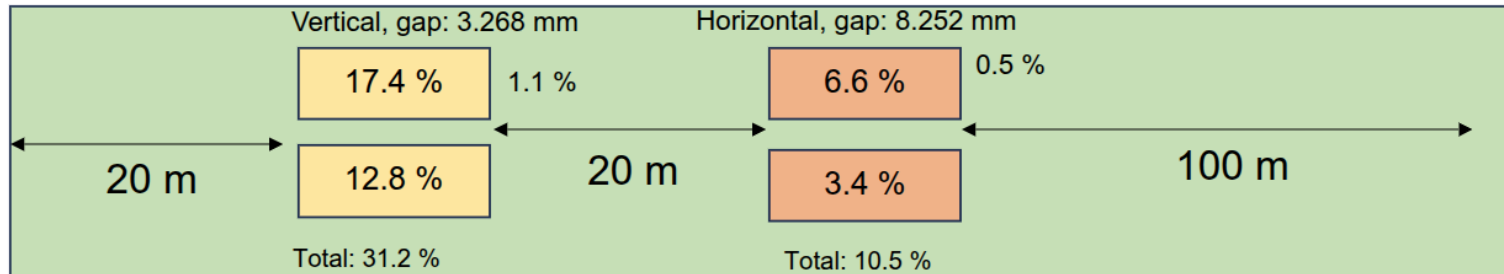
Shower absorbers

- **Collimators are not perfectly absorbing the incoming energy**
 - Particle showers typically leak out and irradiate nearby elements
- **The use of a few (~2 per beam) strategically placed shower absorbers can reduce the fraction of the power absorbed by vacuum chamber, tunnel, and environment [8]**
 - From ~50 %, close to the LHC values, to ~15 %
 - Quadrupole magnets receive a small fraction of power, even w/o absorbers.

Courtesy S. Marin, A. Lechner

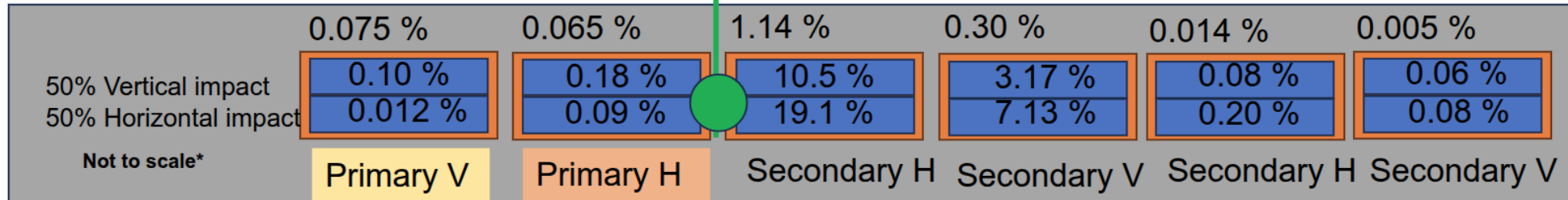


SHOWER ABSORBERS



All quadrupoles : 0.78 %

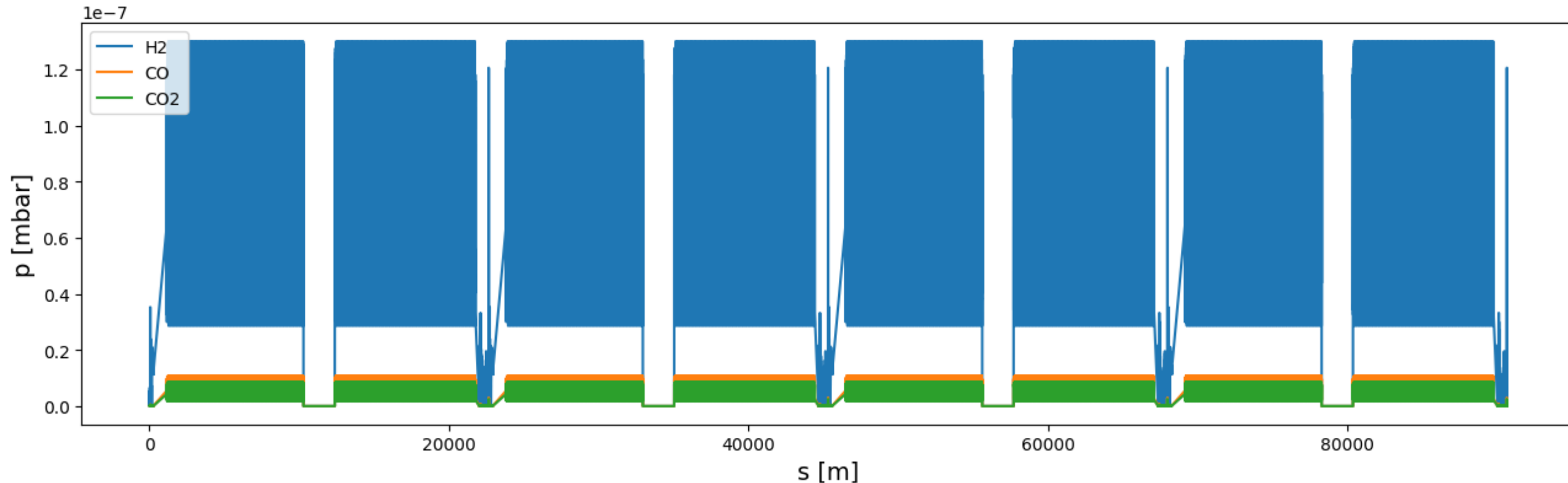
Tunnel/earth/vacuum chamber: 15.1 %



FCC-ee Z full ring pressure profile

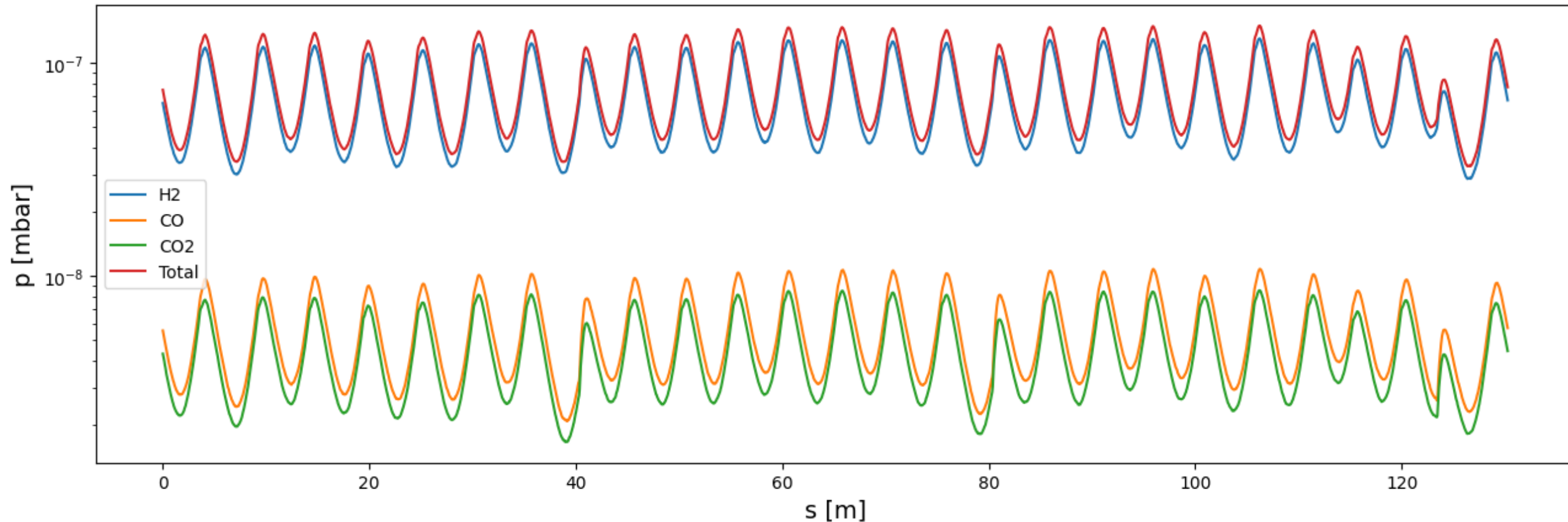
*1h beam conditioning at full nominal current (1.27 A):
pressure is expected to condition down further over time

- Pressure profile for an arc section and for the MDI region provided by the vacuum team (R. Kersevan)*
- Gas species and composition: **85% H₂**, **10% CO** and **5% CO₂**
- 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**



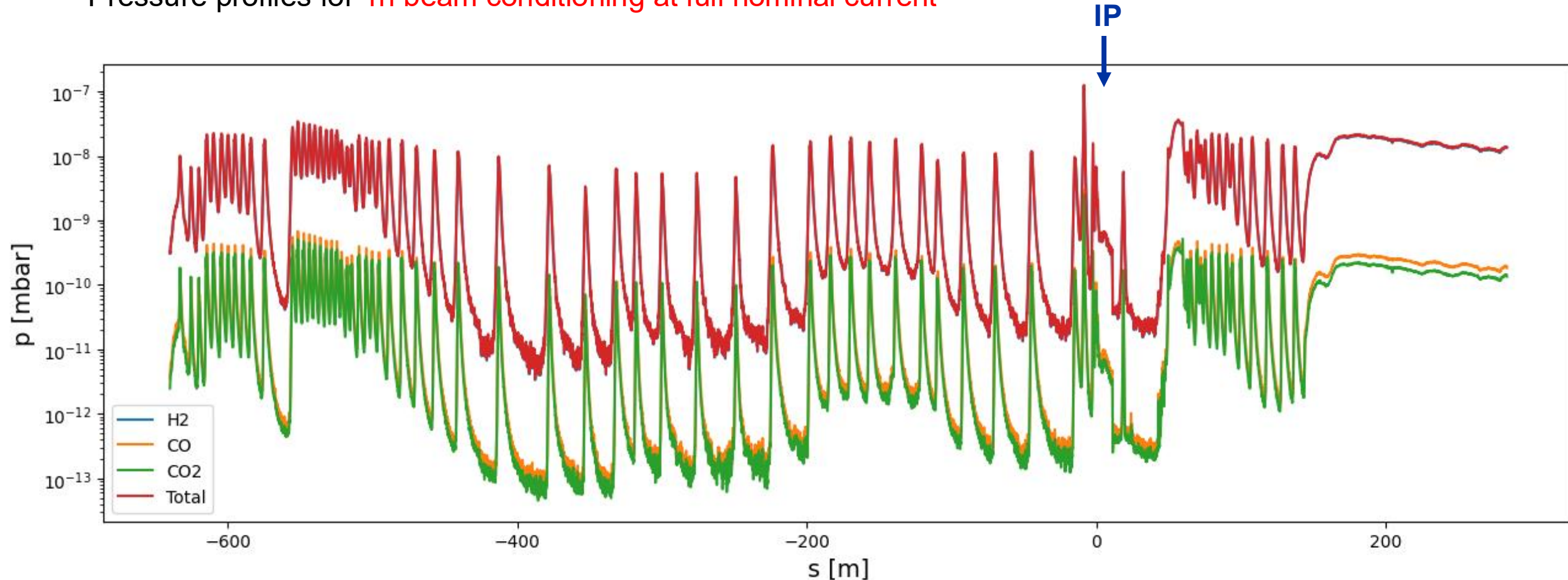
Arc pressure profile in the FCC-ee

- 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% H₂**, **10% CO** and **5% CO₂**
- Pressure profiles for **1h beam conditioning at full nominal current**



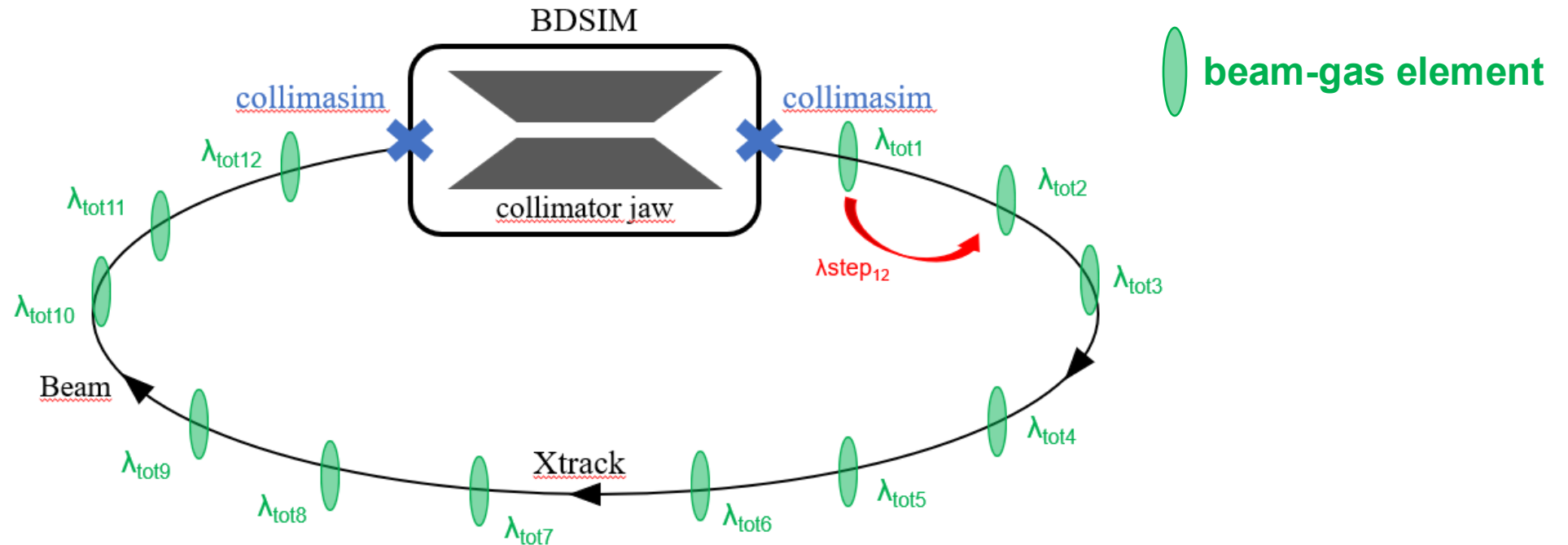
MDI pressure profile in the FCC-ee

- 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% H₂**, **10% CO** and **5% CO₂**
- Pressure profiles for **1h beam conditioning at full nominal current**



Simulation workflow

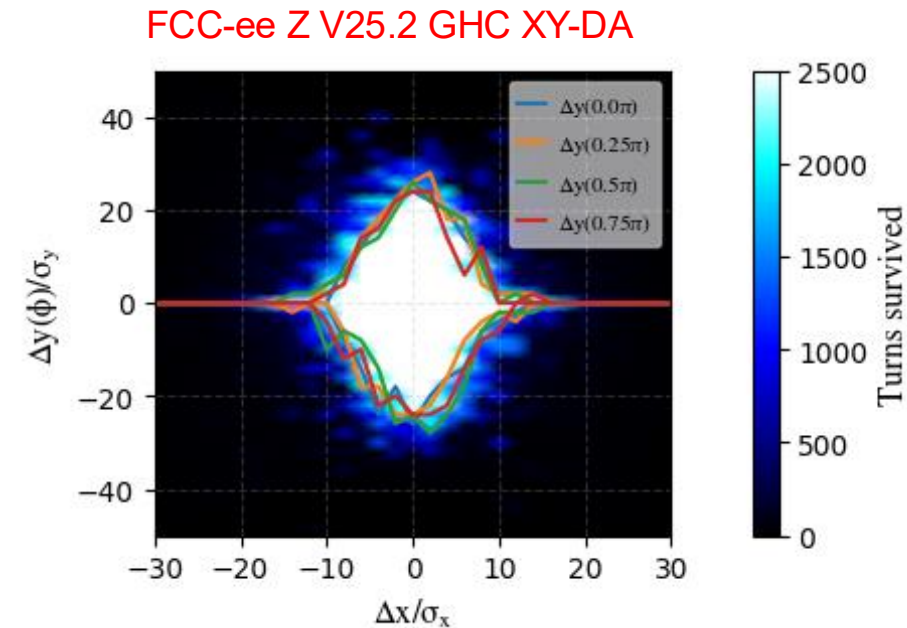
- **Xsuite-BDSIM** simulation tool with addition of arbitrary number of **beam-gas elements** (based on local gas parameters from FCC-ee full ring pressure profile)



- 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 from the relevant physics model (differential cross section)

Beam-gas losses for the Z mode

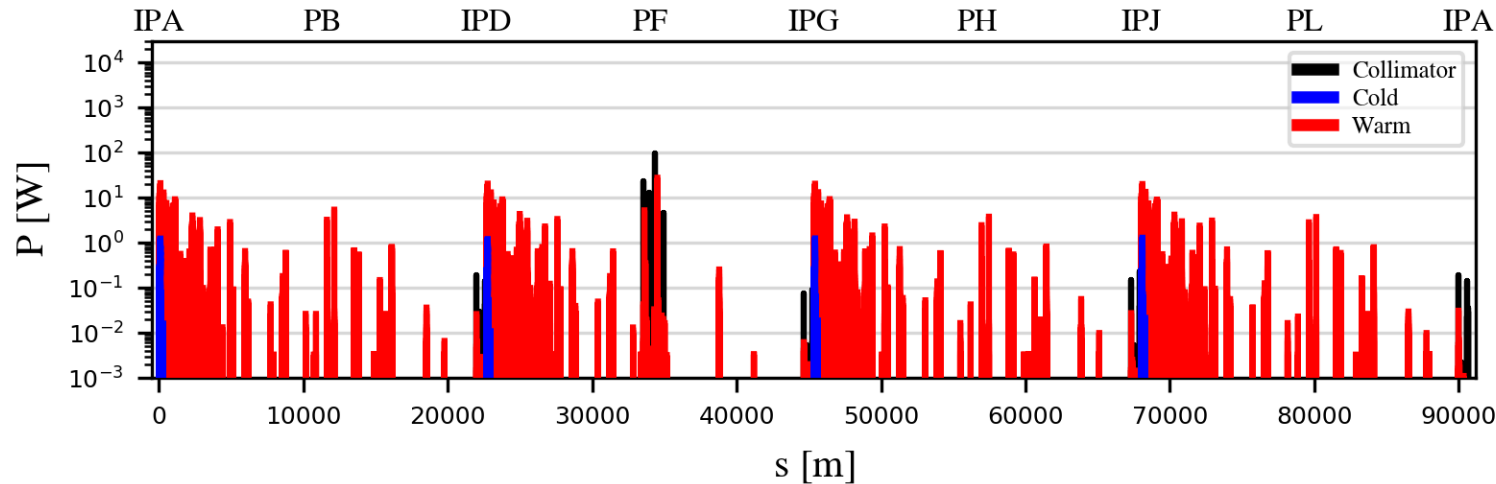
- **Vertical DA in the FCC-ee Z-mode lattice is limited to $\sim 25\sigma$**
 - Beam is highly sensitive to vertical angular kicks
 - Typical vertical divergence (arcs): $\sigma_{pY} \approx 0.3 \mu\text{rad}$
 - A $10 \mu\text{rad}$ vertical kick $\rightarrow >25 \sigma_{pY} \rightarrow$ **particle loss**
- **Sensitivity increases near IPs**
 - β_Y reaches several km $\rightarrow \sigma_{pY}$ further reduced
 - Even smaller kicks can cause losses
- **Horizontal sensitivity is lower**
 - $\sigma_{pX} \gg \sigma_{pY}$ (due to much larger ϵ_x and lower IR- β_x)
 - Same kick $\rightarrow$ smaller normalized deflection
 - Horizontal DA $\approx$ vertical DA
- **Bremsstrahlung losses more sensitive to momentum acceptance**
 - Caused by photon emission $\rightarrow$ off-momentum particles
- **Despite this, beam-residual gas interactions have not been identified as a performance limitation for the FCC-ee, and the FCC-ee collimation system has proven effective in mitigating related beam losses**



The **Dynamic Aperture (DA)** defines the region in phase space where particle motion remains stable and can be well described by linear optics.

Beam-beam losses for the Z mode

- Improved statistical sampling of radiative Bhabha scattering losses
 - Artificially increased RBS rate: large sample of post-RBS trajectories



- Resulting beam loss pattern normalized to RBS lifetime (22 min – total power loss 13 kW)

- RBS losses localized in the PF collimation insertion and downstream of the IPs
 - Horizontal betatron and off-momentum TCPs intercept surviving RBS debris
- Unavoidable local losses on downstream final-focus quads & crab sextupoles
 - Tungsten shielding (few-mm) in SC quads: already proposed by CERN SY-STI group [30]
 - Additional collision debris collimators to be studied in the future

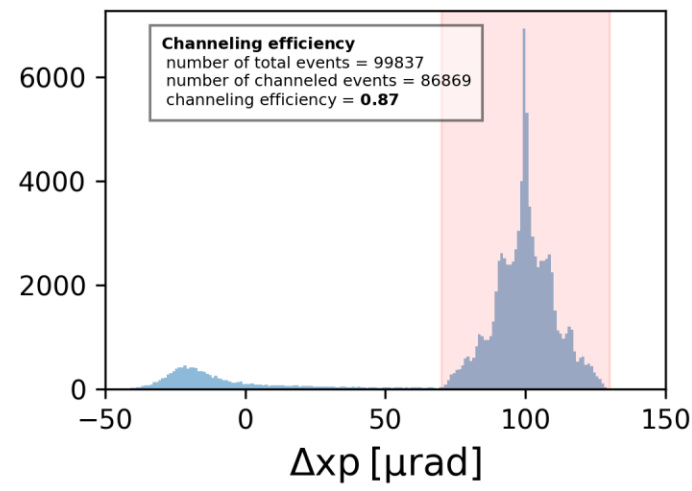
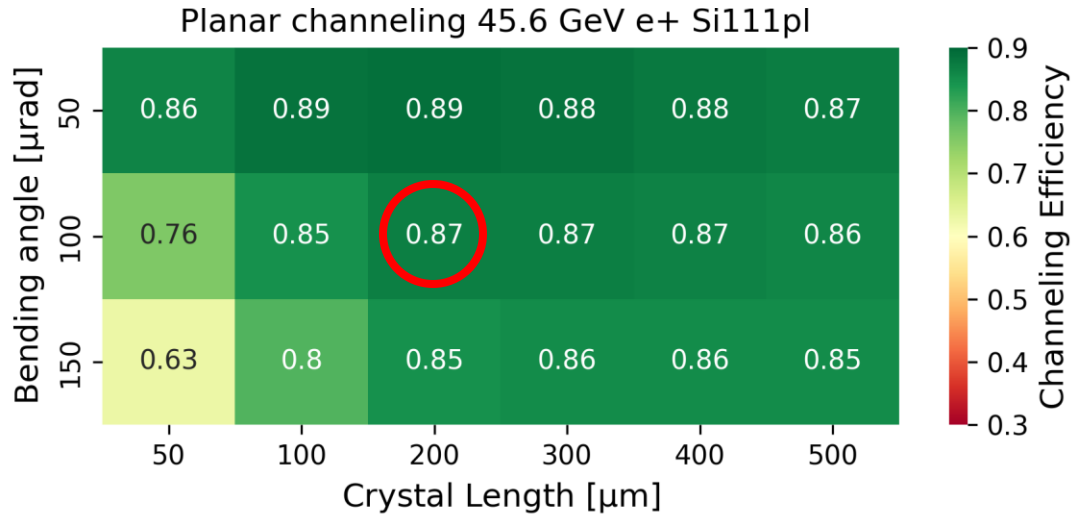
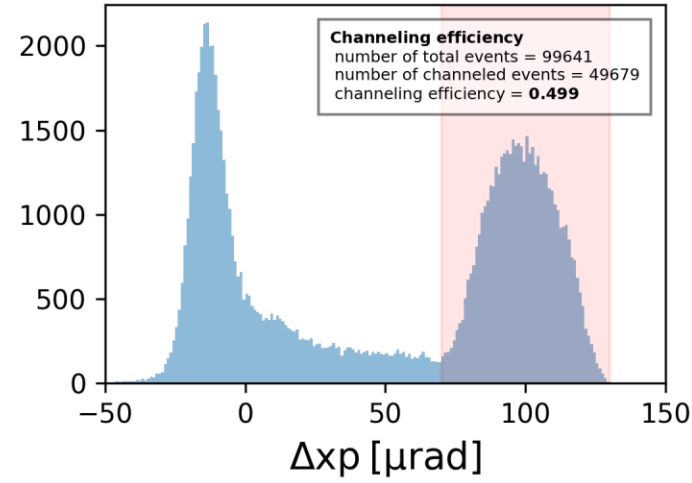
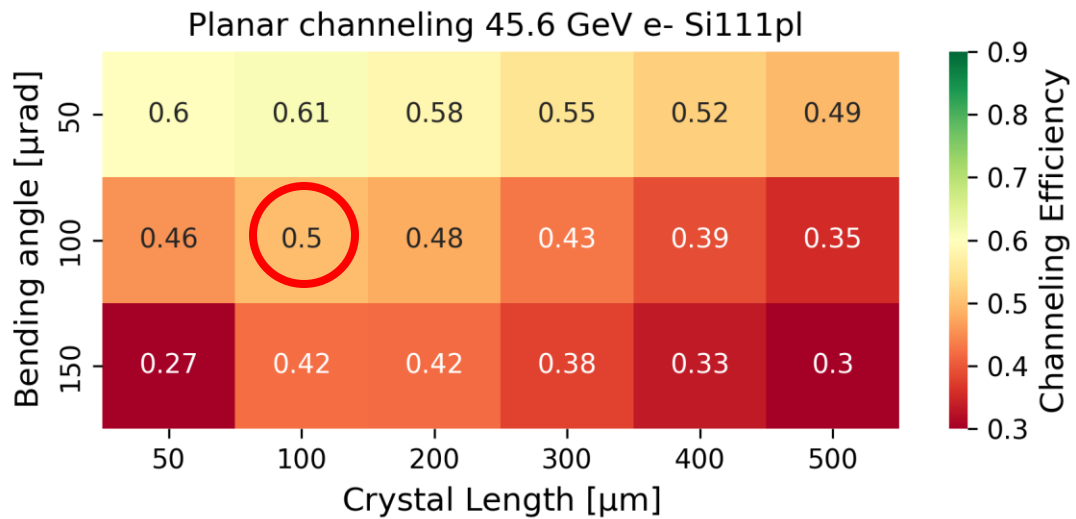
Channeling efficiency

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 μ rad of 45.6 GeV e- using the Si (111) planar potential of a 100 μ m long Si crystal.



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