

FUTURE
CIRCULAR
COLLIDER

Collimation of High Intensity Electron Beams

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Workshop on Injectors and Beam Physics for Future Accelerators, SLAC, 14/09/2026

Acknowledgements:

I. Drebot, M. Hofer, G. Nigrelli

Outline

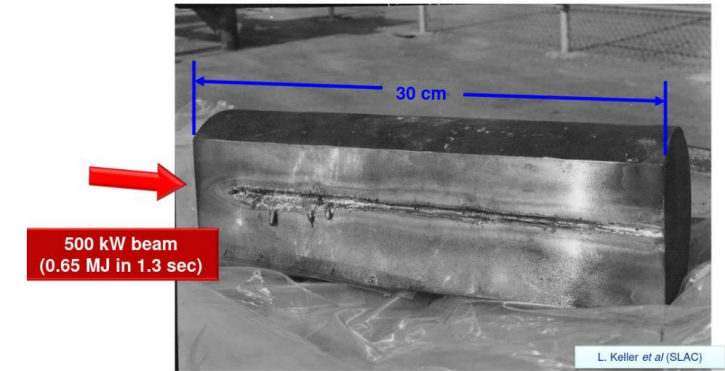
- **Introduction**
 - o Challenges of collimating high intensity electron beams in colliders
- **Proposed methods for the FCC-ee case**
 - o FCC-ee baseline collimation system
 - o Alternative collimation schemes: new R&D directions
- **Collimation simulations tools**
- **Laser collimation at FCC-ee**
- **Outlook**

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Introduction

- Collimation of high-energy beams is an increasingly critical challenge for modern and future high-luminosity colliders
- High luminosity requires **high beam intensity** and **small beam sizes**
 - High energy densities in the stored beams
 - **Highly destructive beams**
- **The FCC-ee example**
 - Up to **17.7 MJ stored beam energy** — the kinetic energy of a 20-tonne truck at 150 km/h
 - Typical FCC-ee beam sizes: $\sigma_x \sim 200\text{--}300\text{ }\mu\text{m}$, $\sigma_y \sim 10\text{ }\mu\text{m}$
 - That's 17.7 MJ concentrated into a spot of $\sim 0.002\text{ mm}^2$
 - **Energy densities up to several thousands of MJ/mm²**
- **Beam collimation no longer just about suppressing backgrounds in the experiments — now equally about protecting the machine from unavoidable beam losses**



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)

[A.Lechner, talk](#)

Collimator design challenges

- **Collimator design should ideally simultaneously satisfy**
 - o robustness to direct beam impacts
 - o low impedance
 - o efficient absorption of shower debris
- These requirements are fundamentally in tension

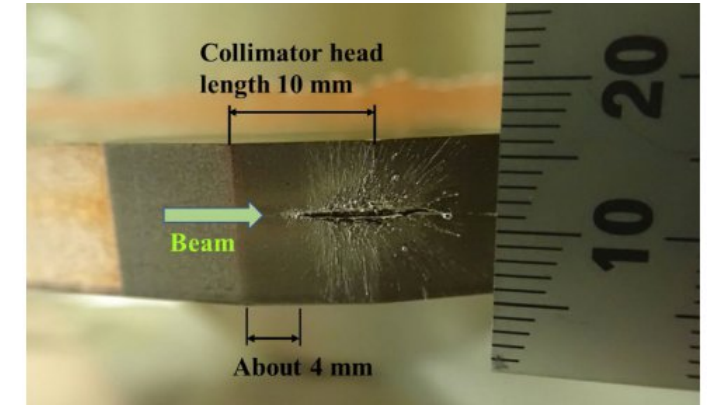
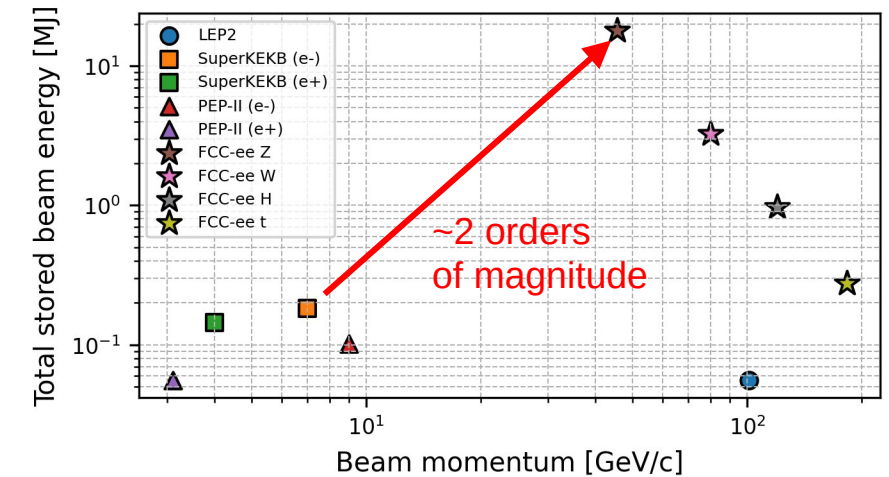


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Collimation for the FCC-ee

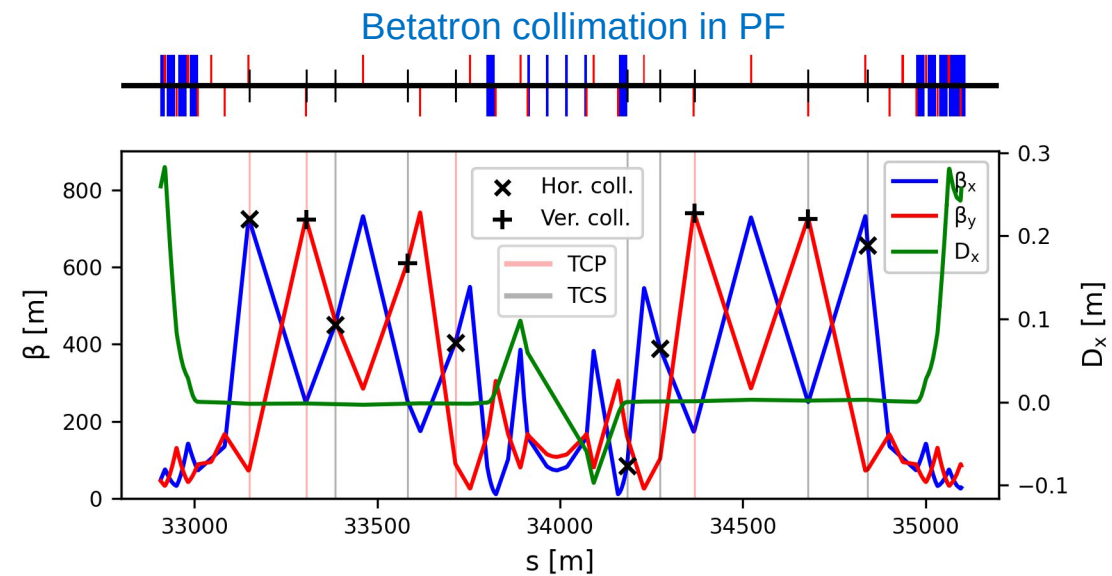
- **FCC-ee presents unique collimation challenges**
 - Unprecedented stored beam energy for a lepton collider
 - **17.7 MJ** in the **Z** operation mode (**45.6 GeV** beam energy)
 - New regime for e+e- colliders
 - Highly destructive beams: **collimation system indispensable**
 - The main roles of the collimation system are:
 - Reduce background in the experiments
 - Protect the machine from unavoidable beam losses
- **Collimation strategy for the FCC-ee:** present baseline relies on conventional, amorphous-material collimators
 - Beam-halo (global) collimation: betatron and momentum
 - + local protection collimation
 - Secondary particle shower absorbers
 - Synchrotron radiation (SR) collimation – upstream of the IPs
- New R&D directions for beam collimation at FCC-ee are being considered



Damaged Cu coated Ta collimator in SuperKEKB (LER) due to sudden beam loss. Courtesy of T. Ishibashi and S. Terui.

FCC-ee betatron collimation

- **Aperture bottlenecks at Z mode**
 - o $15\sigma_x$ at QF1BR — $90\sigma_y$ at QD0BR*
 - o $\epsilon_x = 0.72$ nm — $\epsilon_y = 1.43$ pm (2‰ coupling)
- **Double-phase (two-stage) betatron collimation**
 - o Two primary collimators installed 90° apart in phase
 - o Proven highly effective against fast losses
- **Betatron collimator settings**
 - o $9\sigma_x$ (TCP) — $11\sigma_x$ (TCS)
 - o $60\sigma_y$ (TCP) — $75\sigma_y$ (TCS)
- o **Secondary particle shower absorbers** in between primary and secondary collimators to reduce the fraction of beam power lost to the beam pipe, tunnel, and surrounding environment



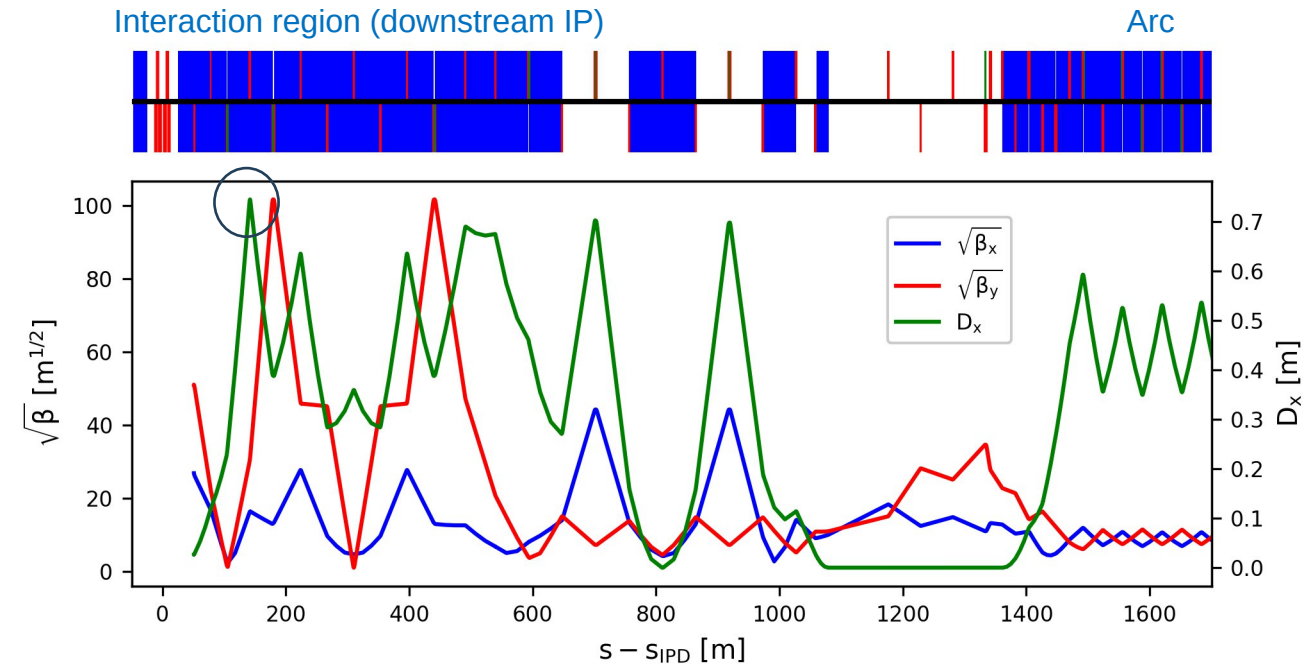
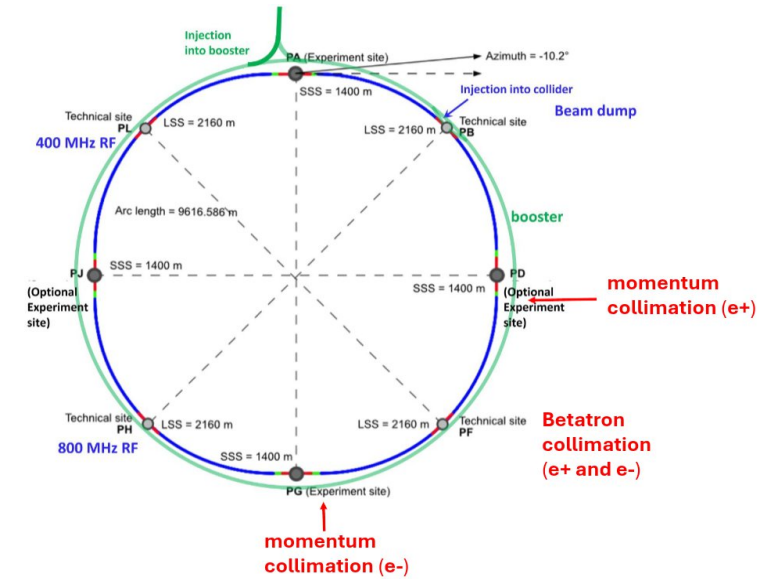
FCC-ee betatron collimator parameters and settings (Z mode)

Name	Plane	Material	Length [cm]	Half-gap [σ]	Half-Gap [mm]	δ_{cut} [%]
TCP.H.B1	H	C-based	10	9.0	6.5	-
TCS.H1.B1	H	Mo-based	30	11.0	6.3	-
TCS.H2.B1	H	Mo-based	30	11.0	5.8	-
TCP.V.B1	V	C-based	10	60	1.9	-
TCS.V1.B1	V	Mo-based	30	75	2.2	-
TCP.HH.B1	H	C-based	10	9.0	4.9	-
TCS.HH1.B1	H	Mo-based	30	11.0	2.7	-
TCS.HH2.B1	H	Mo-based	30	11.0	7.6	-
TCP.VV.B1	V	C-based	10	60	1.9	-
TCS.VV1.B1	V	Mo-based	30	75	2.4	-

*250 um maximum closed-orbit-distortion – 20% max. beta-beating

FCC-ee momentum collimation

- **Single-stage momentum collimation system** downstream of the IP — just upstream of the betatron collimation section
 - o **High $D_x/\sqrt{\beta_x}$**
 - o Large dispersion at this location is already required for chromaticity correction — contributing to the **lattice equilibrium emittance**
 - o Momentum collimation makes **dual use of this high-dispersion region**

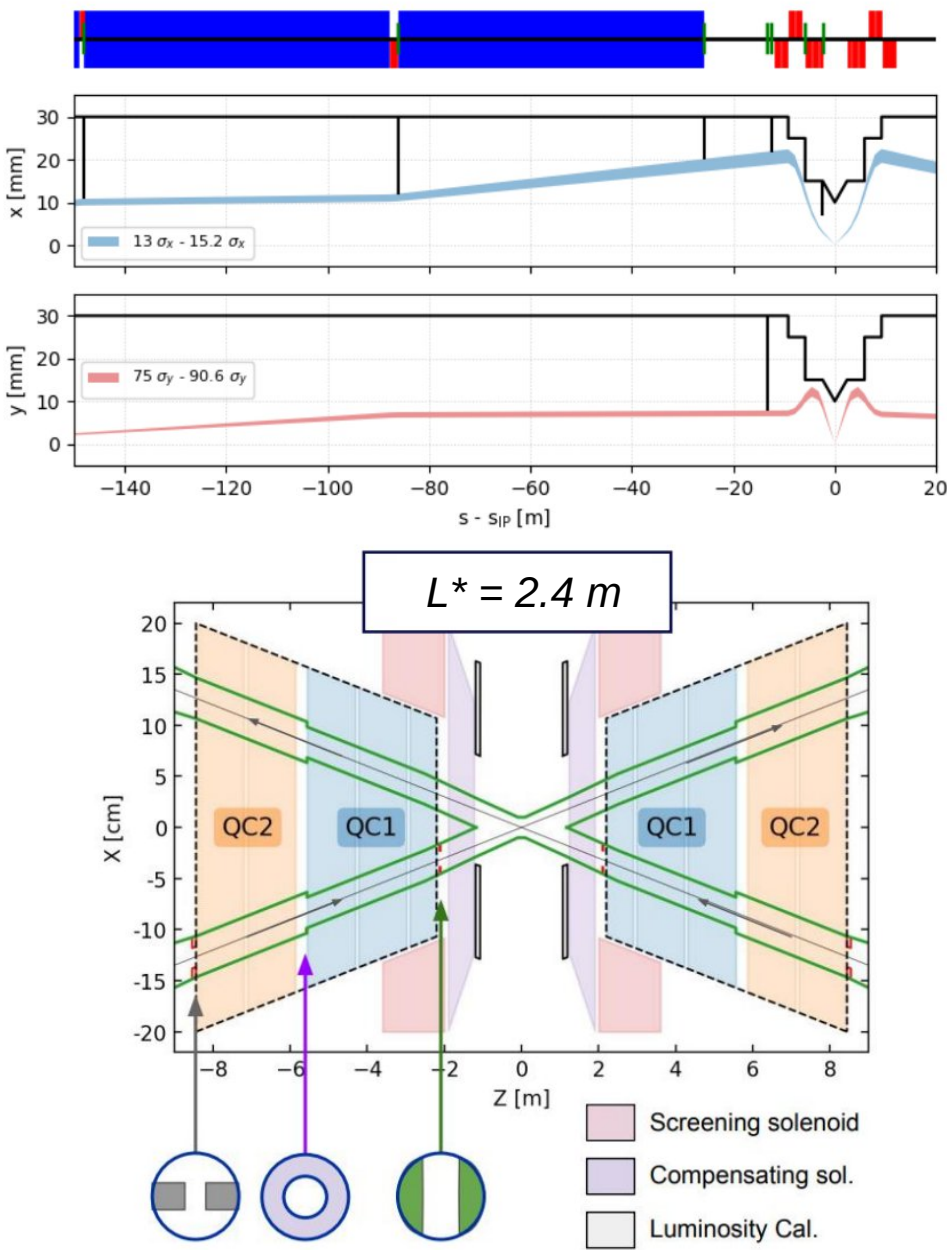


FCC-ee SR collimation

- 5 movable W-based collimators and 2 fixed masks upstream of each IP
 - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses
 - Details in [G. Nigrelli, FCC week 2026 talk](#)

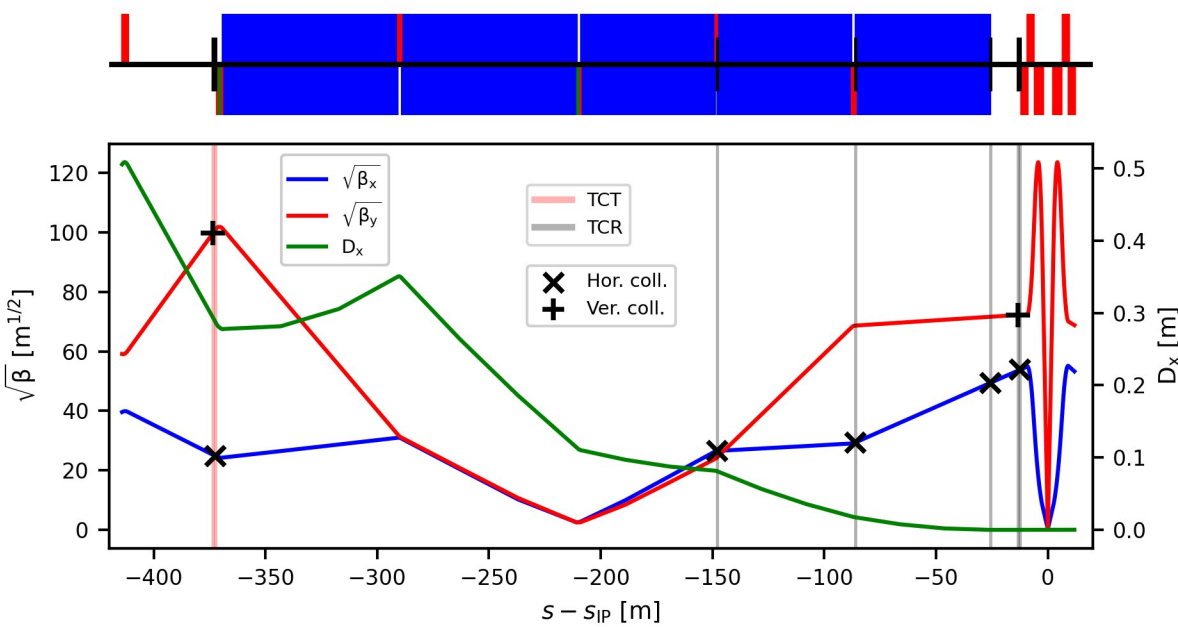
FCC-ee SR collimator parameters and settings (Z mode)

Name	Plane	Material	Length [cm]	Half-gap [σ]	Half-gap [mm]	δ_{cut} [%]
TCR.H3.B1	H	W-based	10	15.0	10.7	--
TCR.H2.B1	H	W-based	10	15.0	11.8	--
TCR.H1.B1	H	W-based	10	15.0	19.9	--
TCR.V.C2.B1	V	W-based	10	90.0	7.8	--
TCR.H.C2.B1	H	W-based	10	15.0	21.7	--



FCC-ee IR local protection collimation

- 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**
 - Placed **upstream** of each IP
 - Position optimized for optimal phase-advance (multiple of π) with respect to:
 - **SR collimators**
 - **Aperture bottlenecks**
- **IR collimator losses must be minimized during regular operation to reduce detector backgrounds**
 - Addition of shower absorbers once **radiation & shielding requirements** quantified



FCC-ee tertiary collimator parameters and settings (Z mode)

Name	Plane	Material	Length [cm]	Half-gap [σ]	Half-gap [mm]	δ_{cut} [%]
TCT.V.B1	V	C-based	25	75.0	9.0	-
TCT.H.B1	H	C-based	25	13.0	8.7	3.0

Alternative collimation schemes for FCC-ee

- **Crystal collimation**

- o First exploratory studies identify crystal collimation as a potentially attractive solution for the FCC-ee
- o [G. Broggi et al., Nucl. Instrum. Methods A](#); [G. Broggi, PhD thesis, 2026](#)

- **Nonlinear collimation**

- o Not yet extensively studied for the FCC-ee
- o Operational experience at SuperKEKB has demonstrated its potential, motivating consideration for FCC-ee

- **LASER collimation**

- o Attractive scheme: a "laser collimator" removes halo particles the way a conventional collimator does — without adding to the machine's impedance budget
- o Could be a strong candidate for combined operation alongside conventional collimators
- o **Specific FCC-ee use case: reducing beam halo scraped at the injection septum**
- o Possible experimental demonstration at FACET-II

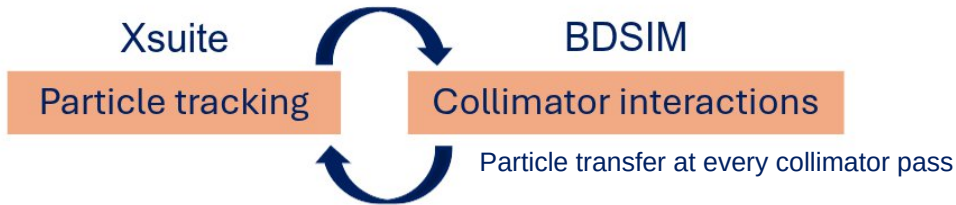
Focus of today's talk

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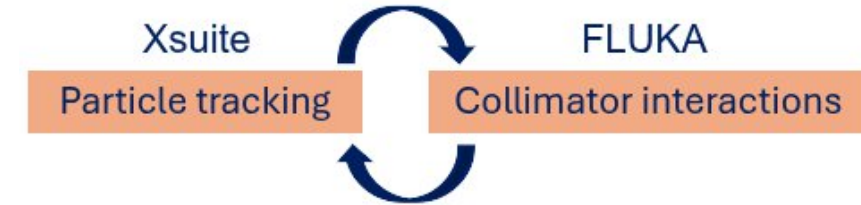
Collimation simulations

Xsuite-BDSIM



- **Originally developed for FCC collimation studies**
 - Accounts for all relevant effects: synchrotron radiation, tapering, detailed aperture and collimator modeling, and electron/positron particle-matter interactions
- **Benchmarked against**
 - Other codes: [pyAT-BDSIM](#), [Sixtrack-FLUKA](#)
 - Measured data from:
 - SPS
 - LHC
 - [SuperKEKB](#)

Xsuite-FLUKA

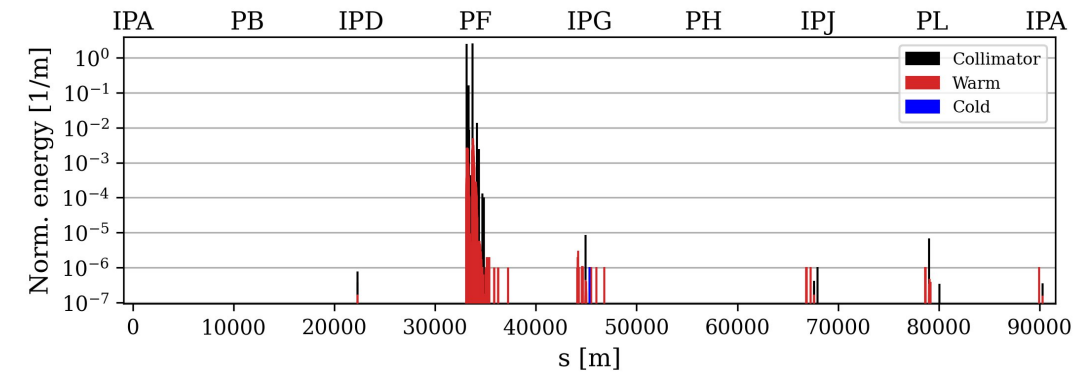


- Recent development for e+e- beam collimation studies
- Same coupling concept as Xsuite-BDSIM, using **FLUKA** for particle-matter interactions in collimators
 - Builds on the well-established FLUKA coupling developed for LHC collimation studies
 - Benchmarked against Xsuite-BDSIM for FCC-ee collimation studies ([G. Broggi, talk](#))

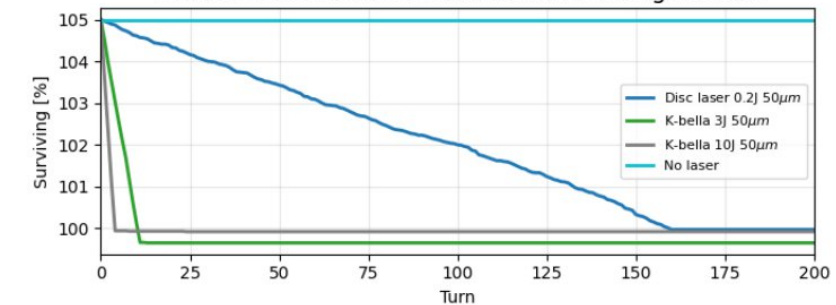
FCC-ee collimation simulations

- Xsuite-BDSIM / Xsuite-FLUKA simulations allow to evaluate the performance of the proposed FCC-ee collimation scheme under selected beam loss scenarios
- Example beam loss scenarios studied so far
 - o Generic betatron losses
 - o Generic off-momentum losses
 - o Radiative Bhabha scattering losses
 - o Fast impedance driven instability
 - o Top-up injection losses
 - o Beam-gas losses
 - o Touschek scattering losses
 - o Inverse Compton Scattering losses
 - ICS proposed as possible mitigation for 3D flip-flop instability
 - Integration of beam-LASER interaction during Xsuite tracking
 - Xsuite coupling to CAIN (M. Hofer and G. Broggi, XCain, <https://gitlab.cern.ch/gbroggi/xcain>),

Horizontal betatron collimation loss map (FCC-ee Z mode)



Beam evolution under different laser configurations



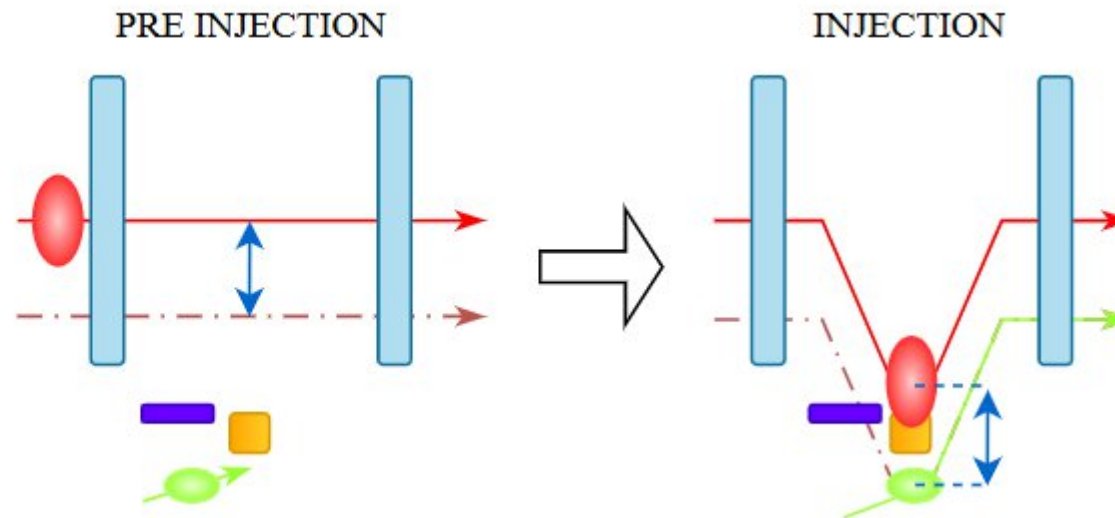
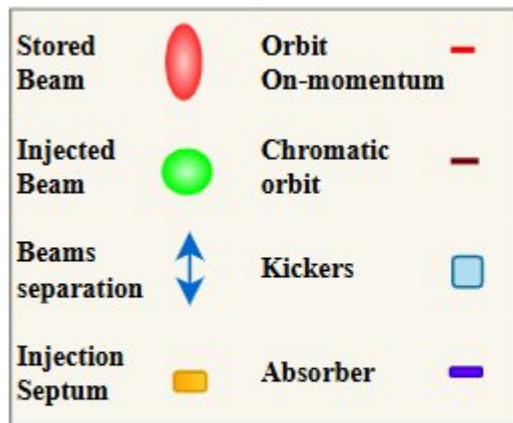
[I.Drebot et al., IPAC'26 paper](#)

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Laser collimation at FCC-ee

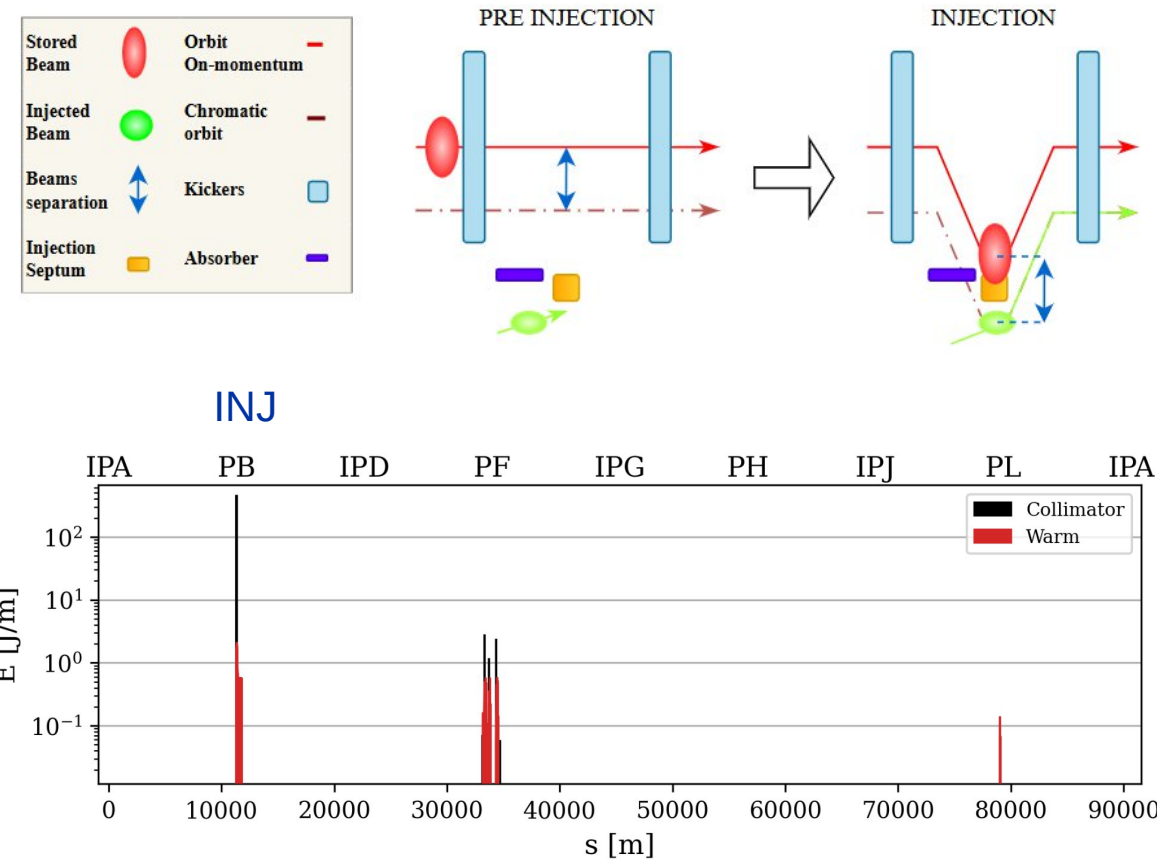
- **Laser collimation is unlikely to fully replace a conventional amorphous-collimator-based scheme at FCC-ee**
 - At FCC-ee, the collimation system must also serve as a passive machine protection system in the event of fast beam-loss or failure scenarios.
 - Laser collimation can instead be envisioned as an auxiliary system to the conventional scheme — for instance, reducing the load on conventional collimators during regular (non-accidental) beam loss
- One specific use case where laser collimation appears particularly attractive for FCC-ee is **reducing beam halo scraped at the injection septum**



Courtesy G. Nigrelli

Laser collimation at FCC-ee: use case

- Current baseline (top-up) injection scheme at FCC-ee foresees an orbit bump of the circulating beam at the injection septum location, where the top-up bunches are injected into the circulating beam.
- This orbit bump brings the circulating beam to within 5σ of the injection septum (absorber).
- During the bump, $\sim 5\sigma$ of beam halo is scraped at the injection septum (absorber).
- These bumps occur rather frequently (every few seconds), posing potential challenges for e.g., radiation levels and component survivability.
- Laser collimation can be applied before the orbit bump is switched on, to deplete the $\sim 5\sigma$ of beam halo that would otherwise be scraped by the septum (absorber).



Loss map for circulating beam halo scraped at injection point due to orbit bump

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Outlook

- **Collimation of high-energy beams is an increasingly critical challenge for modern and future high-luminosity colliders**
 - Beam collimation is no longer just about suppressing backgrounds in the experiments — it's now equally about protecting the machine from unavoidable beam losses
- **The FCC-ee is a clear example of this**
 - The FCC-ee's current baseline relies on conventional, amorphous-material collimators
 - But alternative schemes are also being explored
 - Crystal collimation
 - Nonlinear collimation
 - Laser collimation — possible experimental demonstration at FACET-II
- **Consolidated Xsuite-based simulation tools are now available for collimation studies**
 - Beam-laser interaction can already be simulated during Xsuite tracking, thanks to the Xsuite–CAIN coupling (Xcain) developed for laser-based ICS bunch intensity control studies at FCC-ee
- **Laser collimation can be an attractive solution for FCC-ee**
 - Some use cases — e.g., reducing beam halo scraped at the injection septum — appear to be ideal application candidates

Thank you!

Backup