FUTURE CIRCULAR COLLIDER

FCC-EE BEAM-INDUCED BACKGROUNDS

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for the MDI group

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FCC-ee Vertex Detector Workshop
Pisa

INFN LNF Istituto Nazionale di Fisica Nucleare

CERN

Outline

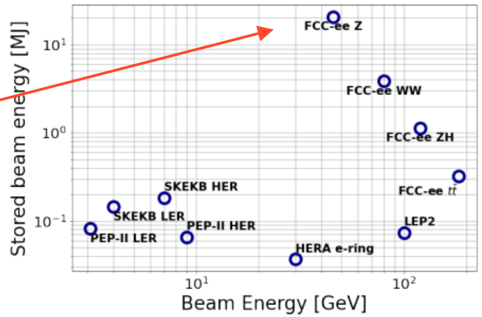
More details in EPJ Techn Instrum (2025) 12:4,
“Status of the FCC-ee interaction region design”
https://doi.org/10.1140/epjti/s40485-025-00117-3

- Beam-induced background sources
- Background simulation workflow
- Status of background simulations
- Dataset for background studies
- Outlook

FCC-ee collimation overview

FCC-ee presents unique challenges:

- At Z pole 17.5 MJ of stored beam energy (two orders of magnitude bigger than any other lepton collider)
- Beams are highly destructive

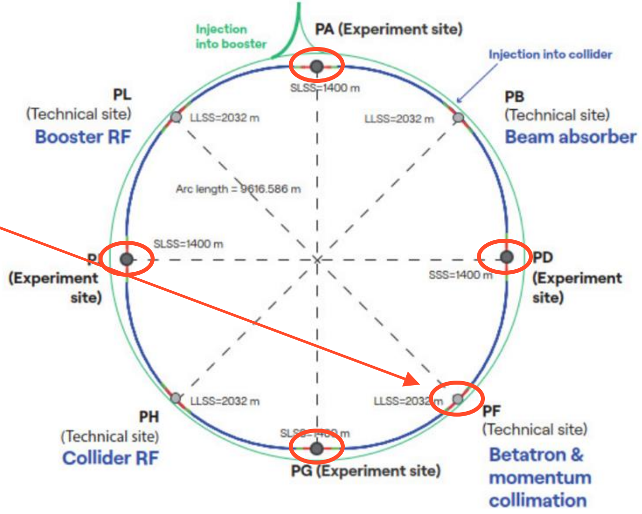


Collimation system must:

- Protect the machine and the detectors from unavoidable beam losses
- **Minimize background for the experiments**

Collimation set-up:

- Global system in **PF**: 2 stage betatron + momentum
- **Experimental IRs**: SR collimators and mask + robust tertiary collimator
- Local protection for injection, extraction
- **Secondary particle shower absorber**



Beam-induced backgrounds in detectors

Ongoing studies using simulation tools validated with SuperKEKB data

Two classes of backgrounds: single beam and colliding beams

Single beam:

- ✓ Beam halo losses datasets ready to be tracked in detectors
- ✓ Beam-gas: Coulomb and Bremsstrahlung datasets ready to be tracked in detectors
- ✓ Synchrotron radiation caused by deviation to the zero-orbit and beam tails to be tracked in detectors (*caveat* on the SR masks in the MDI model)
- ✓ Touschek scattering losses
- ✓ Injection background ongoing – first datasets ready
- ✓ Fast instability – first datasets ready
- Thermal photons planned

- **Colliding beams:**
  - ✓ Incoherent Pair Creation (IPC) dominant – datasets ready and being tracked in detectors
  - ✓ Radiative Bhabha $e^+e^- \rightarrow e^+e^-\gamma$
  - ✓ Beam-beam
- Fluences and Ionization doses studies extending at larger radii

FCC-ee beam-induced background sources

Currently **the focus is on the Z mode**

Beam losses have been studied from:

- **Generic beam halo**
- **Interactions with residual gas**
- **Beam-beam interactions**
- **Fast instabilities**
- **Top-up injection**
- **Touschek scattering**

} **First iteration at tracking level done**
Ready to be tracked in detectors

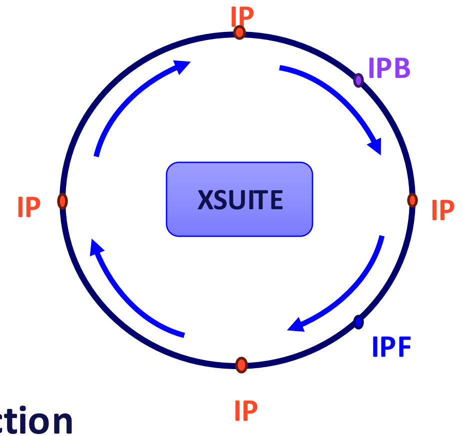
- SuperKEKB-like sudden beam loss events
- Injection failure

} **Work in progress**

- Interactions with thermal photons
- Extraction failure
- Other failures: power supplies, RF, missing beam-beam, feedback

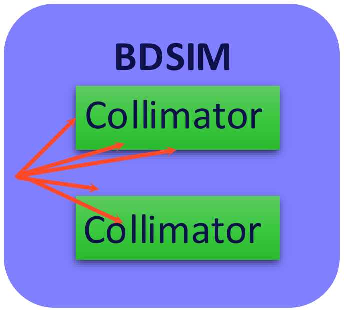
} **Not started**

Workflow - step 1-2

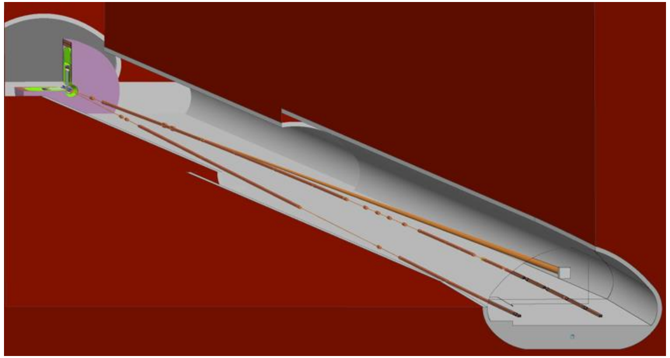


- Multi-turn simulation with full lattice, which includes:
  Synchrotron Radiation
  Beam-beam
  Full aperture model & collimation system.
  Selection of background source to study

- When particles touch the collimators, **the particle-matter interaction is handled by BDSIM:**
  - The 6D coordinates ($\bar{x}, \bar{p}$) of the particle touching the collimator are propagated in the collimator geometry using GEANT4.
  - If the particle is not stopped, it is tracked for the next turn.
  - Any stable charged secondary particle produced in the beam-collimator interaction is tracked as well.
  - Every impact with a collimator is registered.

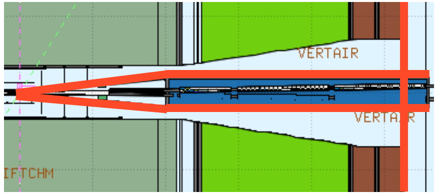


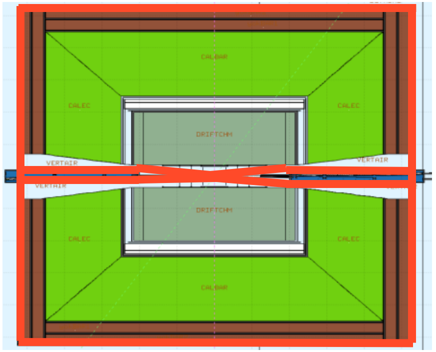
Workflow - step 3



- For background studies the **relevant impacts** are the one **in the tertiary collimators**, placed **upstream the IR**.

- Each primary electron is **propagated in FLUKA from the collimators up to the Machine-Detector Interface surface (in red)**, *i.e.:*





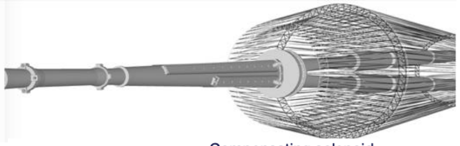
- the internal beam pipe for losses inside the detector
- external boundary of detector for showers coming from outside the detector

- The **particles reaching the MDI are saved and then converted into HEPEvt format**, ready to be used in detector simulation.

MDI modelisation

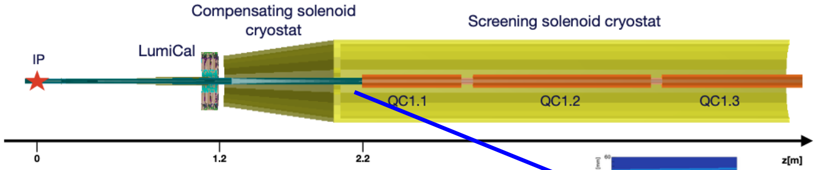
Very relevant for the detector BIB simulations, two options:

- **shaped-based model**: two cylinders at one point become one, very unrealistic
- **CAD-based model**: real beam pipe profile, but at the moment default has air instead of vacuum, needs a switch to activate vacuum *CAVEAT!*

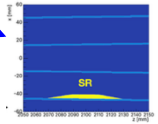


Key4hep

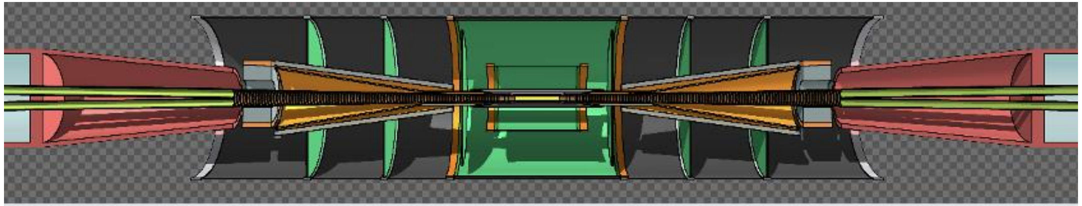
Engineered CAD model imported in Key4hep:

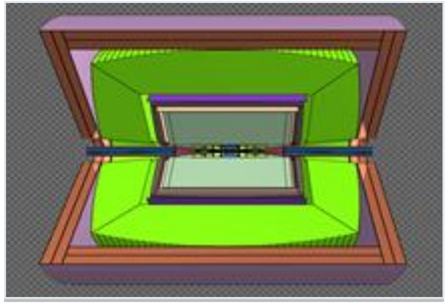


- IR beam pipe
- IR magnets simple equivalent material model
- Cryostat simple guess
- Synchrotron radiation (SR) mask at 2.1 m from IP → presently only on one side of the pipe, not enough (see later)



Fluka





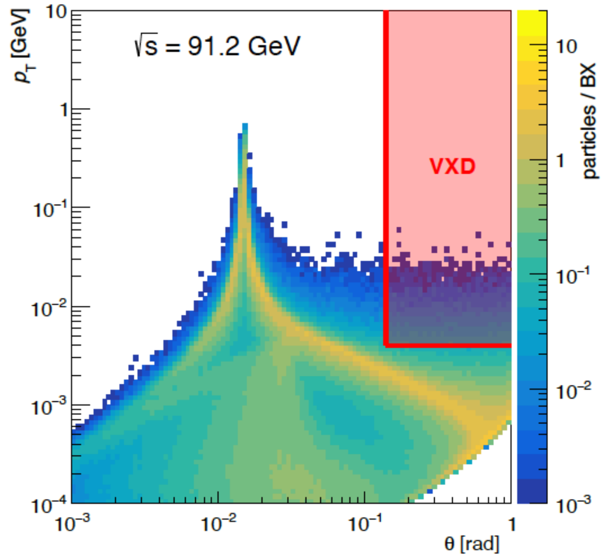
IPC

Dominant effect

Secondary e+e- pairs produced during bunch crossing via the interaction of beamstrahlung photons with real or virtual photons.

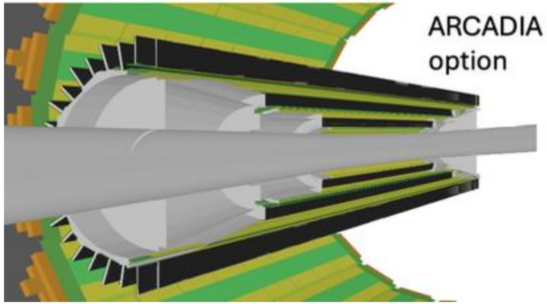
Beamstrahlung limits the beam pipe size and determines occupancy in vertex detector

Lot of low p_T (few MeV) particles hitting the detectors directly or backscattering



Preliminary results

IPC for the IDEA Vertex Detector



Two sensor technology options under investigation:

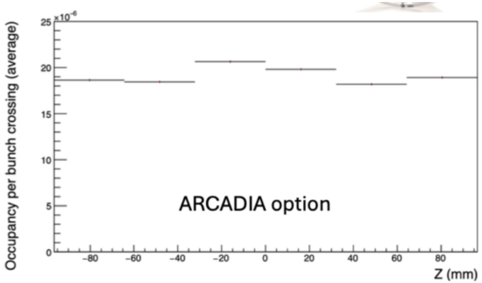
- ARCADIA sensor staves
- ultralight ALICE ITS3 bent sensors

- **Occupancy for the vertex innermost layer** (r=13.7 mm)
  - Cluster size of 5, safety factor of 3, 25 μm pitch pixels
  - Cut at 1.8 keV of deposited energy (500 e^-)

challenging for readout ~**100 Gb/s per ladder**

	ARCADIA	ALICE ITS3
Occupancy	$\sim 20\times10^{-6}$	$\sim 30\times10^{-6}$
Hit rate	90 MHz/cm^2	132 MHz/cm^2
	flat layout	curved layout

Caveat!
Beam pipe filled with air!



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IPC backgrounds

Discussion at the #69 MDI meeting, 8 Sept. 2025
https://indico.cern.ch/event/1582772/

Simulation of the IR

- ❑ Use a detailed CAD geometry of all IR elements including beam pipes,magnetic field, LumiCal etc
- ❑ Use GEANT interaction of e+e- pairs with all elements of the IR, as well as all the detector, including backsplashes
- ❑ At the time of writing the FSR the effect of some processes (Auger and fluorescence) have not been switched on by default in GEANT4, as well as the thresholds for tracking were at 1keV.
  - Once switched on and lowered to 0 keV the thresholds**, the effect is of the order of an increase of less than 10%** in the number of hits in the VTX for low energy release (at around 1 keV)

Effort from MIT to improve on GuineaPig

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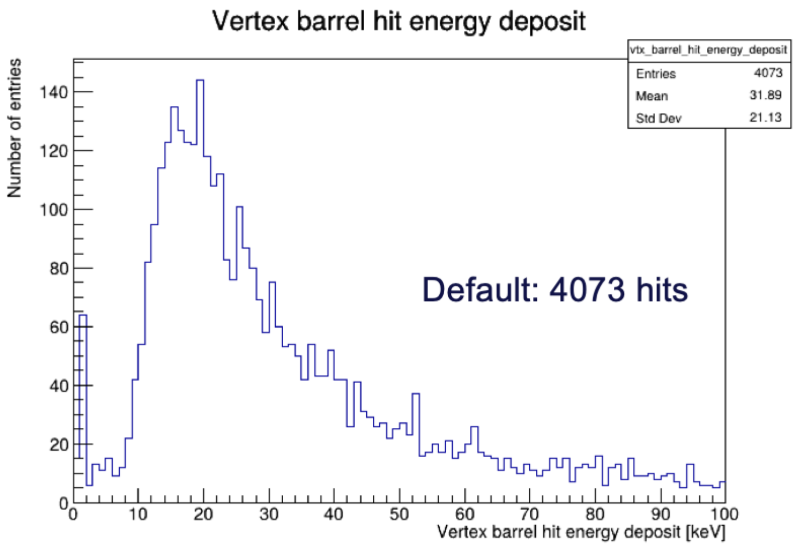
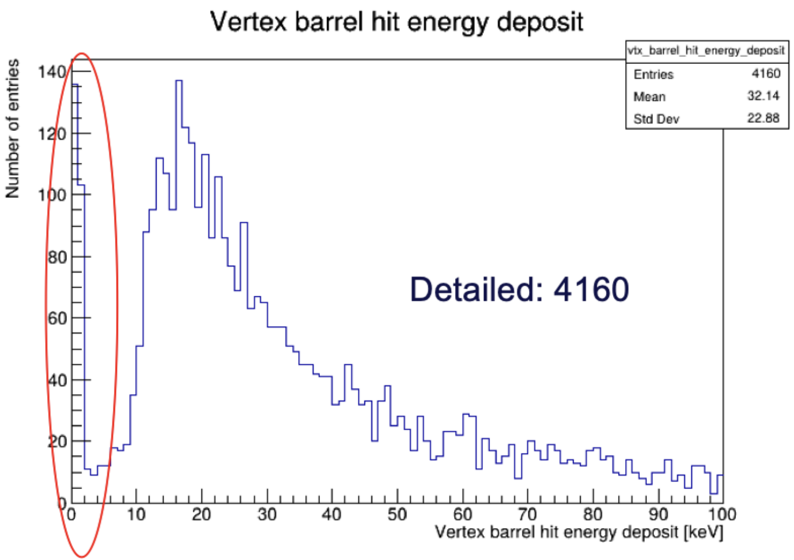
From GEANT simulation

Switching on the **fluorescent processes and Auger electrons**, and **lowering the thresholds of the simhits to ~0 eV**, we get a peak below 1 keV





FCC-ee vs SLC (answering feedbacks from SLD vertex detector)

Difference due to the beam profile

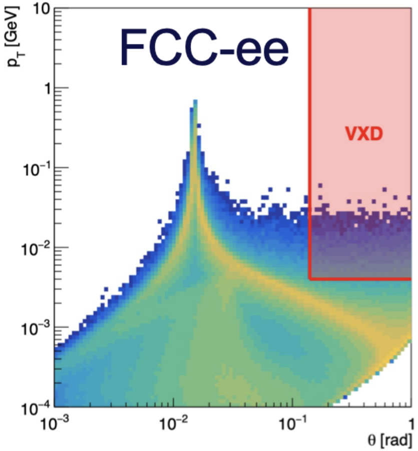
SLC had **head-on collisions, smaller current and different beam sizes**

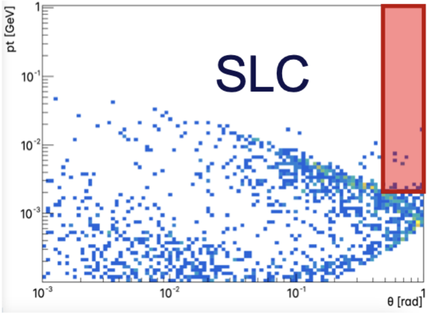
We ran GuineaPig with SLC parameters: **Obtained 1700 particles/BX**

FCC-ee: **1350 particles/BX, but completely different shape because of 30 mrad crossing angle**

Number of particles in the vertex detector:
in SLD (0.9%→ 16/BX) FCC-ee (0.7%→ 10/BX)

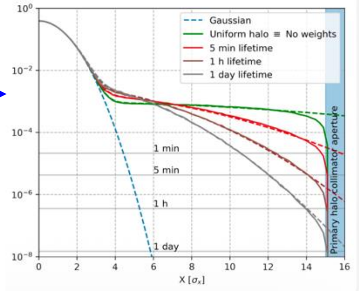
- run SLC with the same current of FCC-ee (x5) we get: ~50,000 particles (a factor 30 more!)
- run SLC with the same crossing angle of FCC-ee (30 mrad) we get: 40 particles (a factor 40 less!)



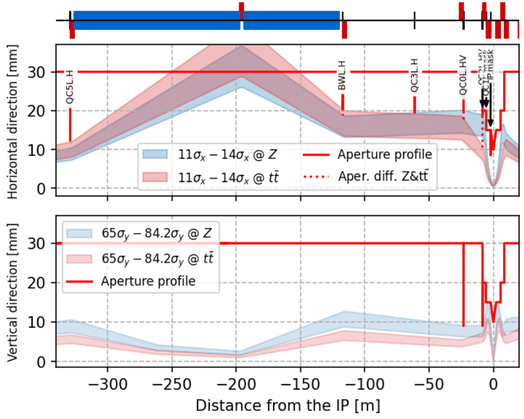


Synchrotron Radiation (SR) backgrounds

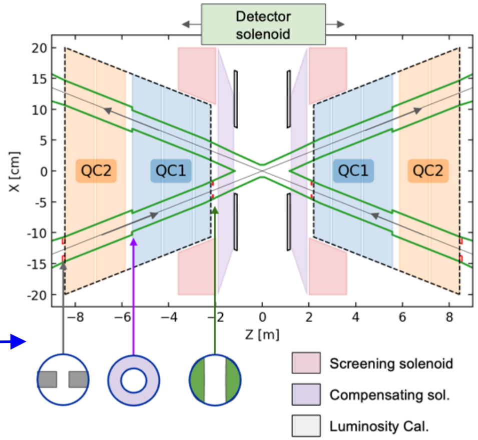
- Simulations with BDSIM (GEANT4 toolkit)
- SR evaluated for
  - **beam core** with non-zero closed orbits for considering optics imperfections
  - **transverse beam tails,** pessimistic weighted halo model used:



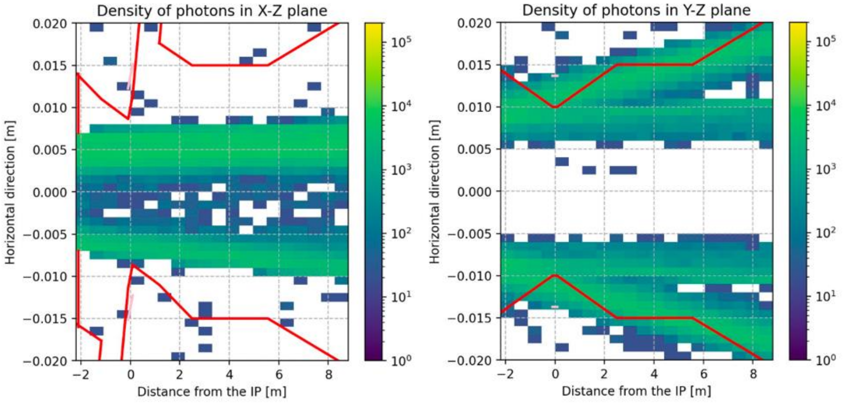
bulk of SR produced upstream the IR is stopped by collimators



- **SR produced in the IR** by **IR quads and solenoids:**
  - bulk of SR is collinear with the beam and will hit the beam pipe at the first dipole after the IP → no direct hits in the detectors
  - Transverse tails in the fringing field of the final quads produce SR that may hit the detector: **masks at the exit of QC1 and QC2**

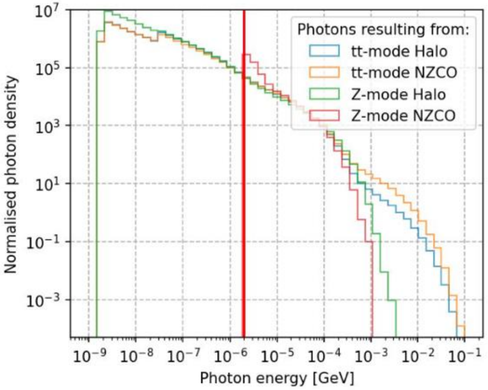


Synchrotron Radiation backgrounds

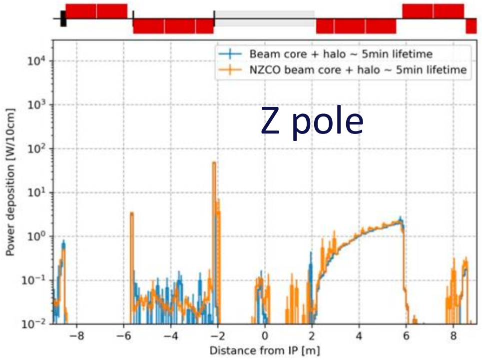


Photons passing through the horizontal SR mask

First studies on hits and occupancies are being performed.
Looks like we need an optimisation of the SR masks, as trade-off of impedance and efficiency. Help needed.



accept > 2 keV



GHC - SR power deposition summary
1% of the particles in the tails, with beam lifetime equivalent to 5 min, and 100 um X&Y and 6 urad PX&PY applied to the NZCO beam core.

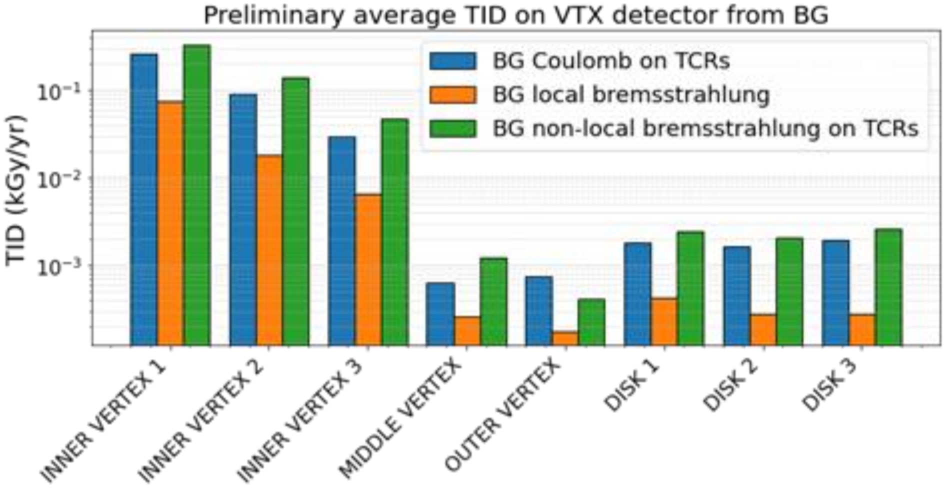
Power deposition on the beam pipe and masks ± 8 m from IP

Beam-gas interaction contribution to detector

local: upstream the MDI, single pass
non-local: generated far from IP and multiturn

Beam-gas bremsstrahlung

- contribution from TCTs negligible
- contribution from hits on TCRs non-local, higher than local BG bremsstrahlung



Beam-gas Coulomb scattering

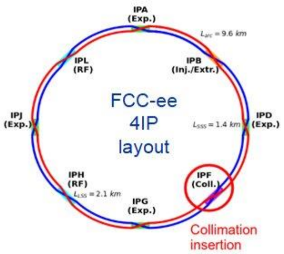
- contribution from TCTH negligible
- contribution from hits on TCRs comparable to BG bremsstrahlung hits
- contribution from TCTV difficult to estimate

Doses are proportional to backgrounds, subleading wrt IPC

Detector backgrounds

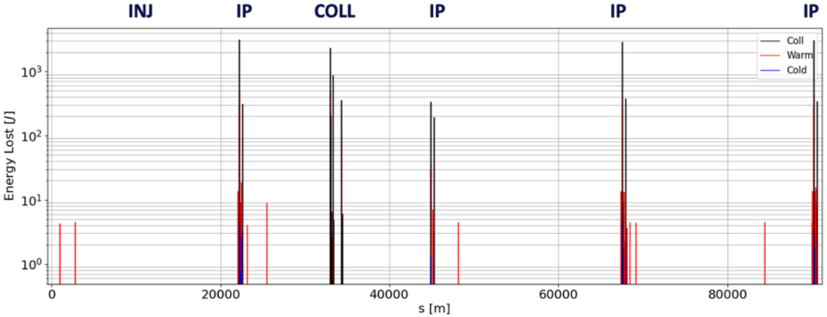
- workflow established to evaluate detector background from FLUKA simulations

Injection backgrounds



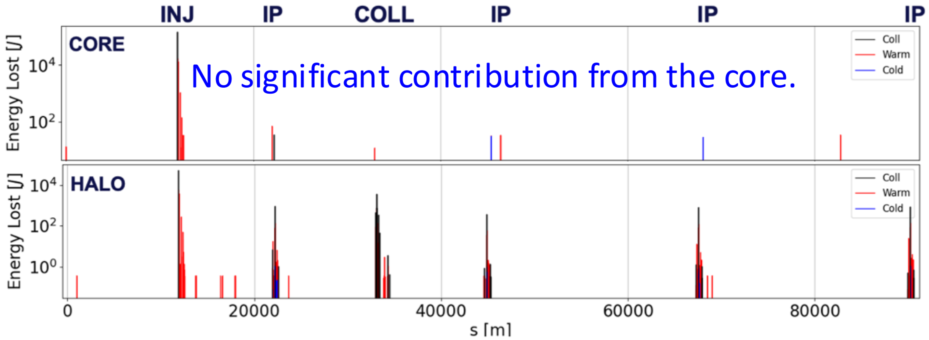
Top-up injection required, on-axis & off-energy current baseline scheme.
Injection efficiency is assed at 88% for lattice V25.1_GHC.

injected beam



The 12% of the injected beam is lost, and losses are distributed along the whole ring.

circulating beam



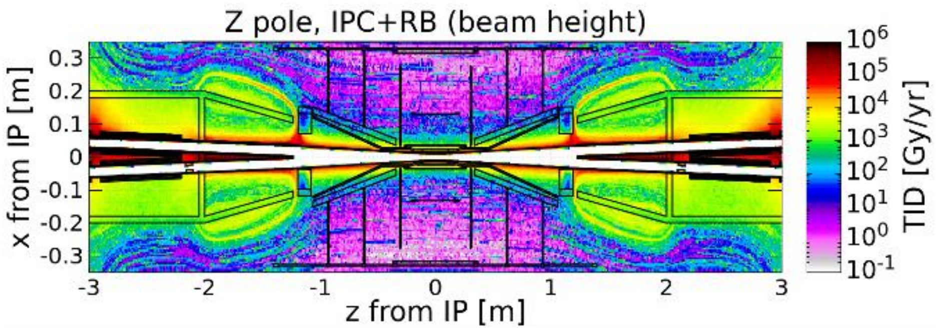
The study on the leakage to experiments is starting.

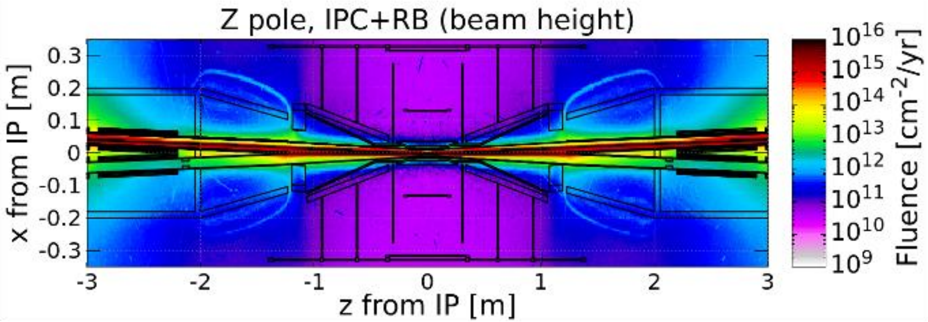
Beam losses due to injection that may impact the detector are tracked up to the detectors in Fluka with the "Step 2".
Next step is to evaluate occupancy and data rate.

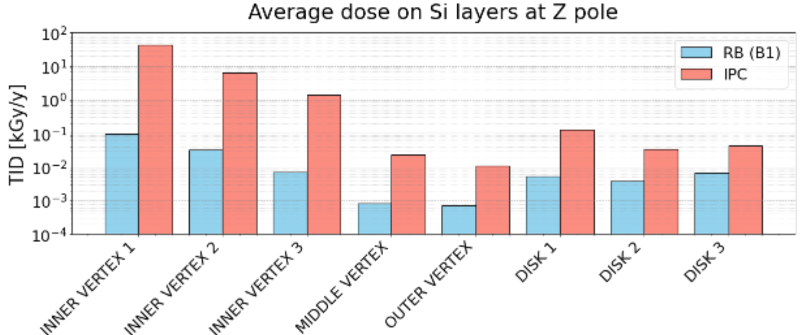
Vertex detector radiation levels

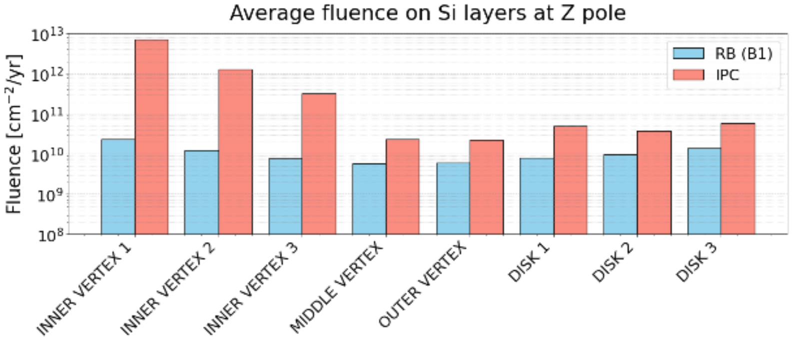
IPC dominant source

- Innermost layer (at ~1.3 cm) TID and fluence are one order of magnitude higher than second layer.
- Current MAPS technologies are OK
  - At 15 cm distance, dose and fluence are about 3 orders of magnitude smaller than innermost layer









Datasets for detector backgrounds studies

Data format for detector backgrounds studies has been defined to be HEPEVT

The HEPEvt files are here

Number of particles at interface surface per bunch crossing (BX) in 25 ns window

	Beam-gas	Injected beam
Average number of particles lost at surface/BX in 25 ns window	~ 0.2	~ 7
Maximum number of particles lost at surface/BX in 25 ns window		~ 30

Outlook

Great effort done on the beam-induced sources to provide datasets of particle losses up to the MDI surface

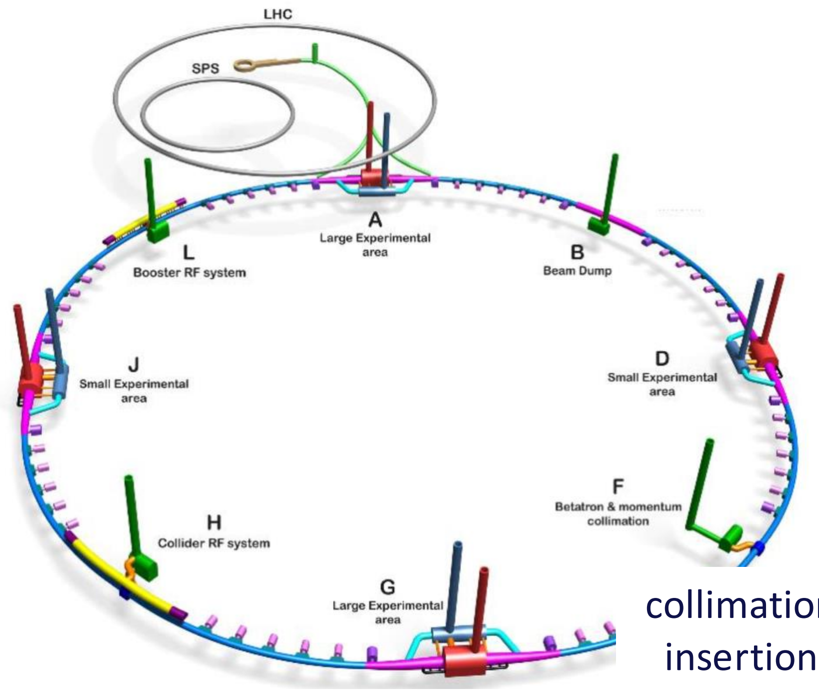
→ Next step is to track them in each subdetector !

- IPC:
  - dominant effect, need iteration on first results
- SR backgrounds
  - need first evaluations for VXD, most likely we will need to modify the SR masks design
- Injection backgrounds
  - first datasets are ready to be tracked in subdetectors
- Doses and fluences evaluated

Additional Material

FCC-ee high-level layout

- Double ring e+e- collider with 91 km circ.
- Common footprint with FCC-hh, except around IPs
- Synchrotron radiation power 50 MW/beam at all beam energies
  - determines maximum beam current per each c.o.m. energy and therefore limits the available instantaneous luminosity
  - In turn determines the no. of bunches → interaction frequency
  - Also determines the size of the beam in z together with the beamstrahlung
- Top-up injection scheme for high luminosity



collimation insertion

High Luminosity with crab-waist collision optics

- Beam crossing angle of 30 mrad in x-z
  - Allows to reach high luminosity
  - Determines the luminous region size in x and z
- Final focus quadrupoles inside the detector (L*=2.2 m)
  - Determines the luminosity and the beam size in y

FCC-ee Interaction Region rationale: crab-waist

Crab-waist scheme, based on two ingredients:

- concept of **nano-beam scheme:**
  - vertical squeeze of the beam at IP and large horizontal crossing angle
  - large ratio σ_z/σ_x reducing the instantanous overlap area, allowing for a lower β_y^*
- concept of **crab-waist sextupoles:**
  - placed at a proper phase advance they suppress the hourglass effect by inducing a constant β_y along the larger coordinate of the beams overlap.

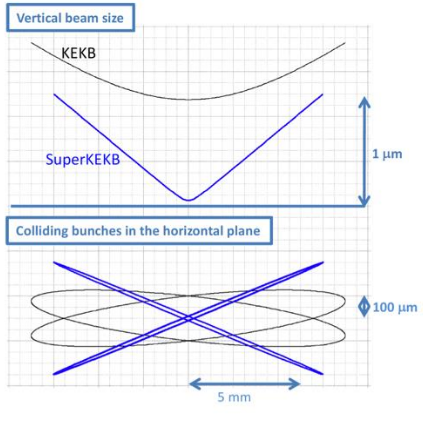
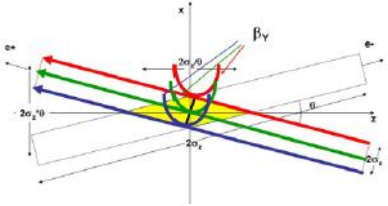
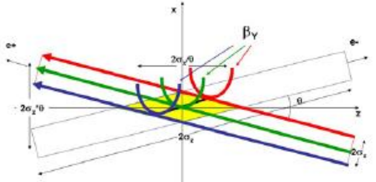


Figure 2: Schematic view of the nanobeam collision scheme.

SuperKEKB https://arxiv.org/pdf/1809.01958.pdf

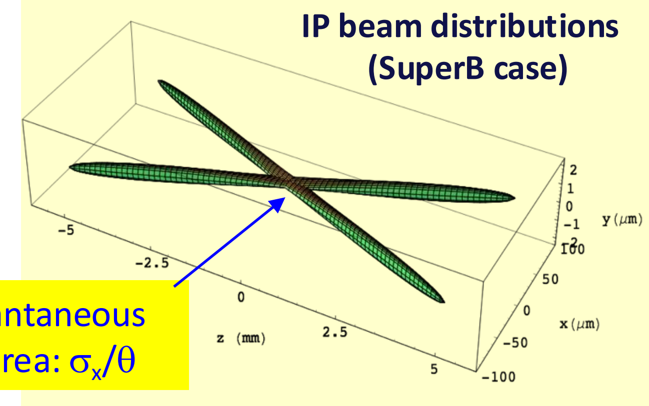


crab sextupoles off



crab sextupoles on

DAFNE, PRL 104, 174801 (2010)



Small instantaneous collision area: σ_x/θ

Beam-induced Backgrounds

Luminosity backgrounds

Beamstrahlung: photons and spent beam

- Incoherent e^+e^- Pair Creation (**IPC**) ← **dominant**
- Coherent e^+e^- Pair Creation
- $\gamma\gamma$ to hadrons

Radiative Bhabha

Synchronous with the interaction, can be discriminated at trigger level

Single Beam effects

Synchrotron Radiation

Beam-gas

Thermal photons

Touschek

Injection backgrounds

Beam halo losses

Mostly can be mitigated with collimators & shielding, except for those produced just in the IR.

A collimation insertion intercepts most the beam losses. Tertiary collimators upstream MDI area protect the experiments. Residual losses produce BIB and need to be tracked into detectors for occupancy and data rates.

Beam-gas backgrounds

Hits on the collimators from BG bremstrahlung* (two models, particle tracking and Fluka, excellent agreement)

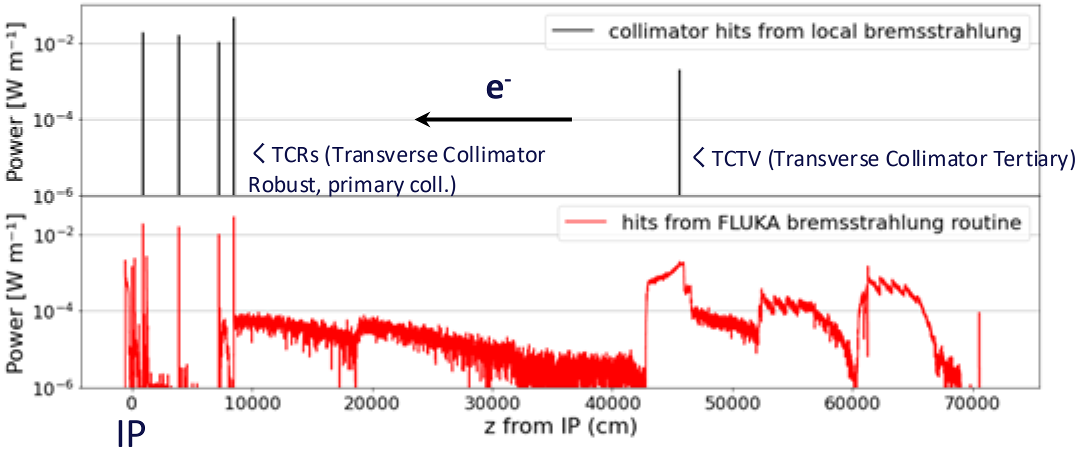
- Hits in the MDI (±5 m from IP) do not come from events further than ~250m upstream
- These non-local BG bremsstrahlung is mainly stopped by the collimators

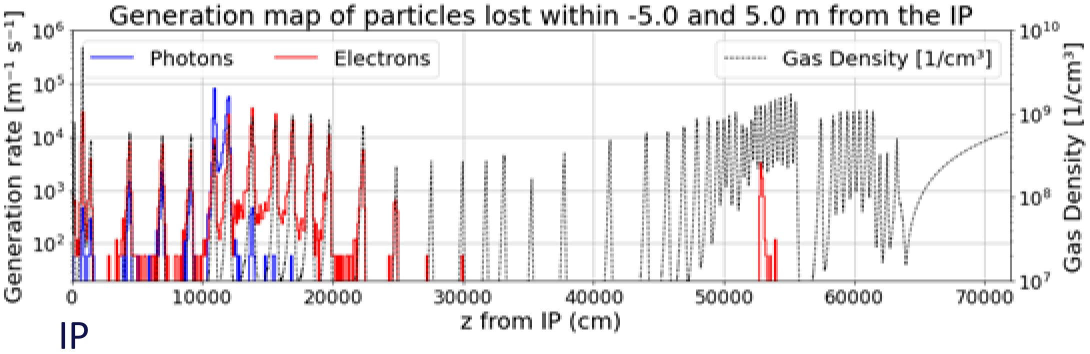
Detector backgrounds to be estimated from secondary showers produced by

- collimator hits
- and by particles lost after tertiary collimators

Beam-gas bremstrahlung

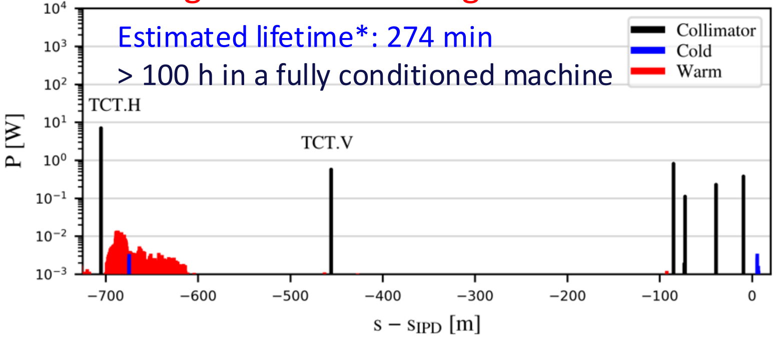
*only electron hits on the collimators are plotted





IR beam losses and MDI collimators

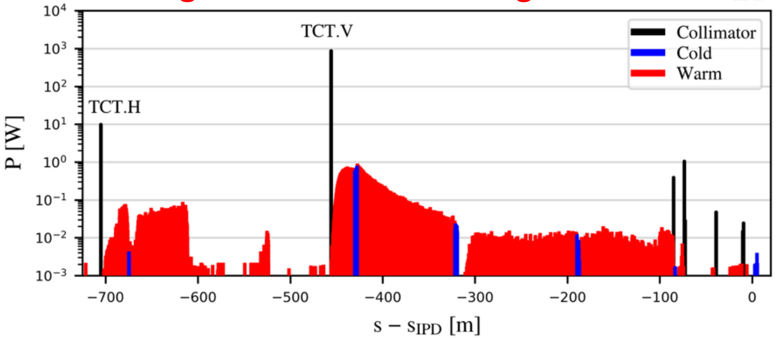
Beam-gas bremsstrahlung



Estimated lifetime*: 274 min

> 100 h in a fully conditioned machine

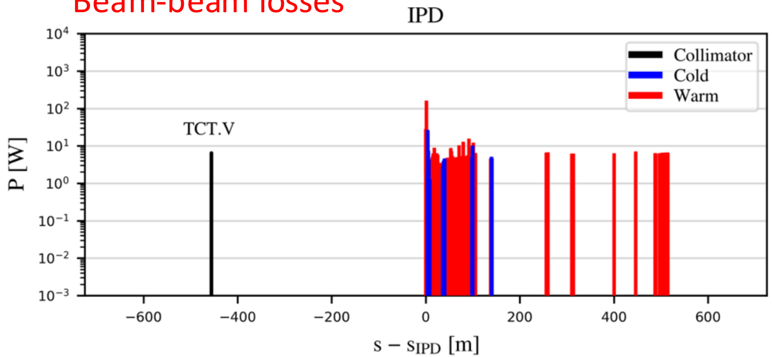
Beam-gas Coulomb scattering



Estimated lifetime*: 41 min

> 10 h in a fully conditioned machine

Beam-beam losses



Physics-debris-like collimators downstream of the IPs, to be studied after evaluation of detector impact

Beam-beam kicks, radiative Bhabha, beamstrahlung in 4 IPs + detailed aperture and collimator model

First tracking of Touschek effect:

Touschek lifetime in the FCC-ee (*Z*): 2069 min (~35 h)

- Lifetime from radiative Bhabha scattering: 22 min
- Lattice lifetime (q + BS + lattice): 83 min
- Beam-gas lifetime: 36 min (1h conditioning),
  >500 min (conditioned machine)

Benchmarking and experience with measurements at SuperKEKB.

Synchrotron Radiation (SR) backgrounds

Minimization of the SR impacting on the IR

Optics design constraint:

- **weak bends upstream the IR** (and strong ones downstream, to produce the horizontal crossing angle), having an asymmetric optics wrt IP
- **critical energy below 100 keV** produced by the last bending magnets upstream the IR

Critical energy: $E_c = \frac{3}{2}\hbar c\,\frac{\gamma^3}{\rho}$

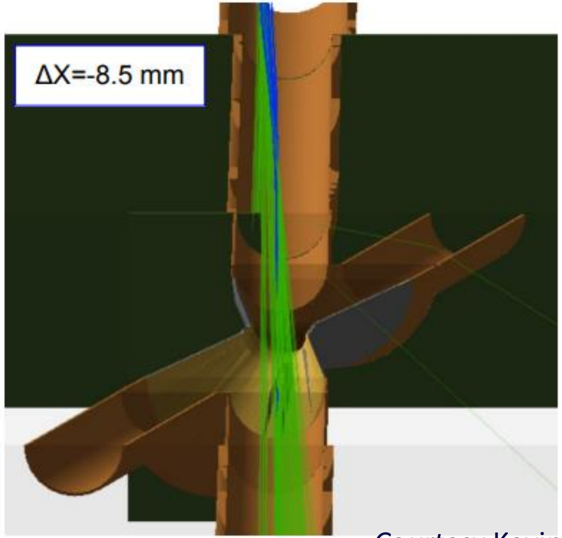
Half of the synchrotron radiation is radiated below, and the other half above the critical frequency.

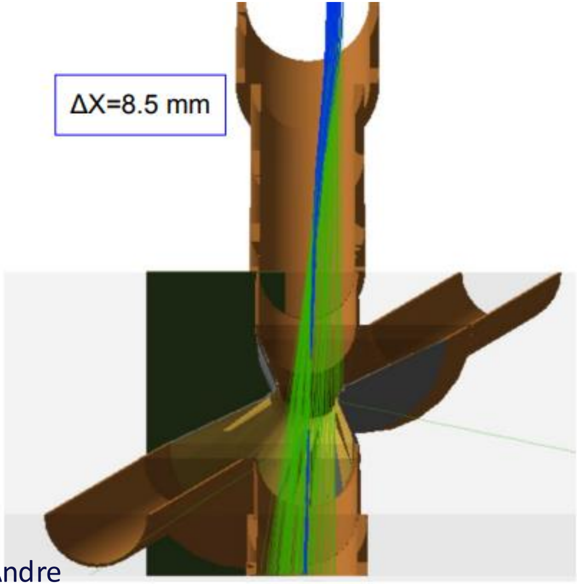
The mean photon energy is about 30% of the critical energy $< E_\gamma >= \frac{8}{15\sqrt{3}} E_c = \frac{4}{5\sqrt{3}}\hbar c\,\frac{\gamma^3}{\rho}$

Top-up injection

Required **with few percent of current drop** to keep a constant luminosity (lifetime is ~15 min).

Off-axis top-up injection challenging at Z due to large orbit excursion and slow damping.
SR intercepted by the last mask ~0.2mJ/Xing compared ~0.8μJ/Xing from colliding beam





Courtesy Kevin Andre

preference for longitudinal injection

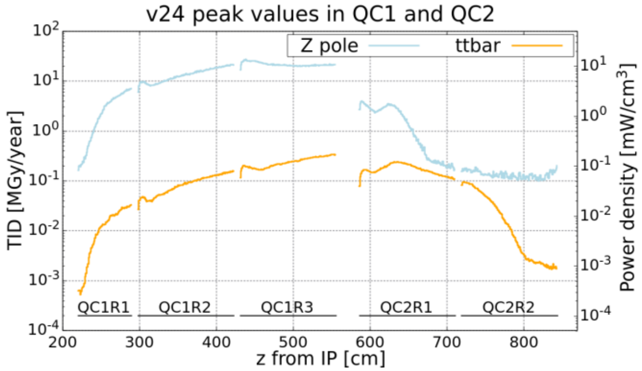
Radiative Bhabha scattering

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma$$

The emitted photon can carry a significant fraction of the energy of the incoming particles. BBBrem [*] + GuinaPig++ used to generate spent beam particles

Radiative Bhabha Total Cross Section [mbarn]				MINIMUM PHOTON ENERGY			LUMINOSITY PER IP
ENERGY	LATTICE	CUTOFF		0.01%	3%	50%	$cm^{-2}s^{-1}$
Z	v605 (V24.3)	1 sigmaY	36.5 nm	**332.6**	**112.7**	**18.3**	1.43E+36
T	v605 (V24.3)	1 sigmaY	43.6 nm	**337.1**	**114.3**	**18.6**	1.38E+34

Off-energy particles are tracked with FLUKA to evaluate the power deposition at the final focus quadrupoles. Shielding (tungsten, ~1 mm) is needed to reduce the total dose.

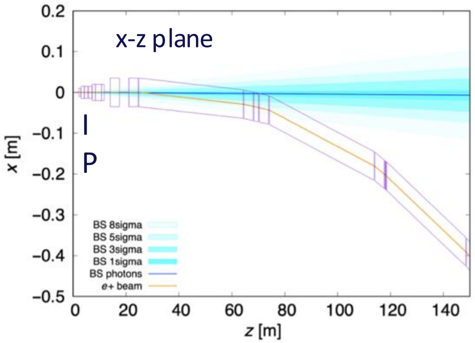


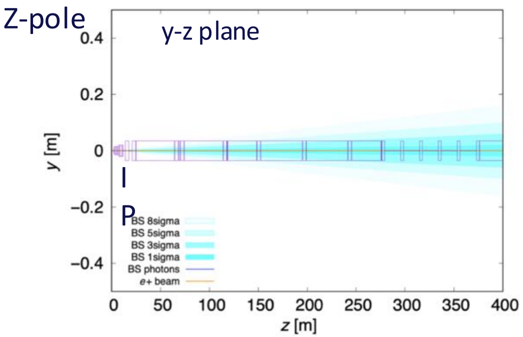
Off-energy particle may reach the LumiCal, even if negligible wrt IPC (~3%)

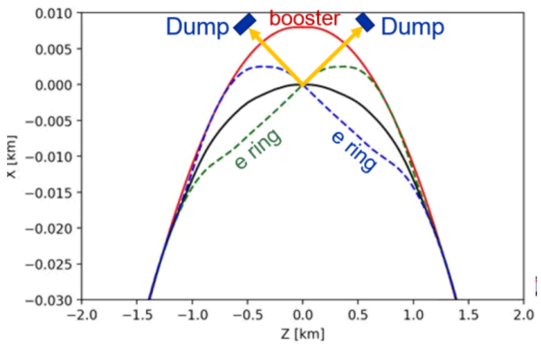
* BBBREM, Monte Carlo simulation of radiative Bhabha scattering in the very forward direction, R. Kleiss and H. Burkhardt

BS and SR Radiation produced at IR

Radiation from the colliding beams is very intense 400 kW at Z







Dump placed 500 m from IP in order to have enough separation from booster / collider (space for shielding)

MB and A. Ciarma, “Characterisation of the Beamstrahlung radiation at FCC-ee”, PRAB 26, 111002 (2023), link

High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

- Different targets as dump absorber material are under investigation
- Shielding needed for equipment and personnel protection for radiation environment