FUTURE CIRCULAR COLLIDER

STATUS AND PERSPECTIVES FOR FCC-EE DETECTOR BACKGROUND STUDIES

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on behalf of the FCC-ee MDI group

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INFN LNF Istituto Nazionale di Fisica Nucleare

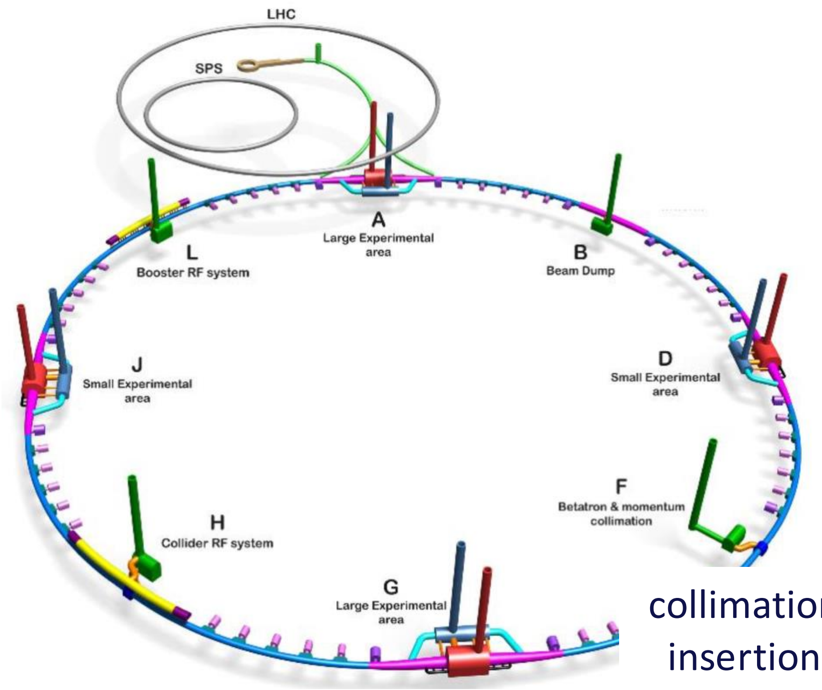
CERN

Summary

- Introduction: FCC-ee and Machine-Detector-Interface
- Beam-related background sources and simulation workflow
- Status of background simulations
- Outlook

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

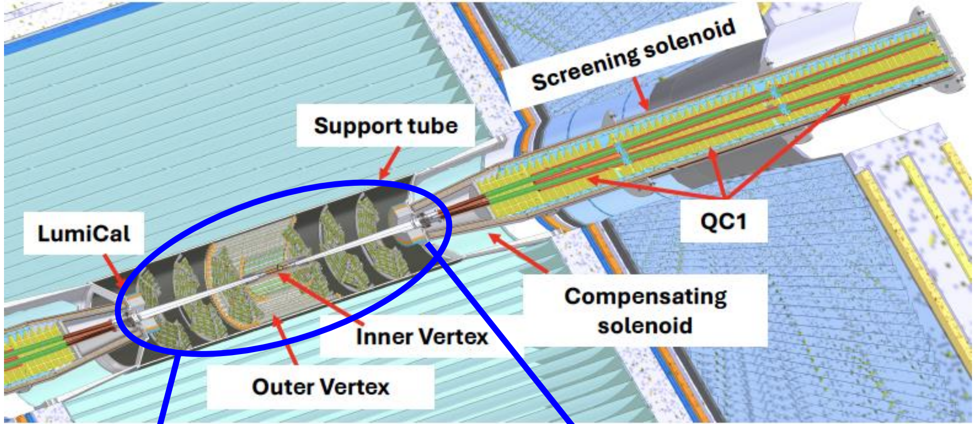
High Luminosity with **crab-waist** collision optics

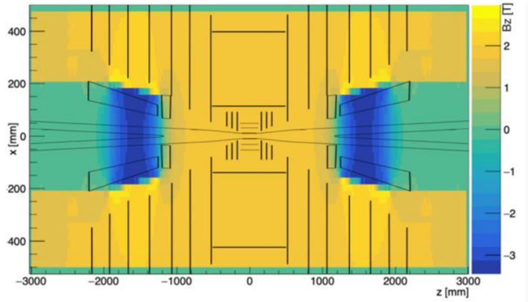
- Beam crossing angle of 30 mrad in x-z
  - Allows to reach high luminosity
  - Determines the luminous region size in x and z
- Final focus quadrupoles inside the detector (L*=2.2 m)
  - Determines the luminosity and the beam size in y

Interaction region layout

IR magnet system inside the detector

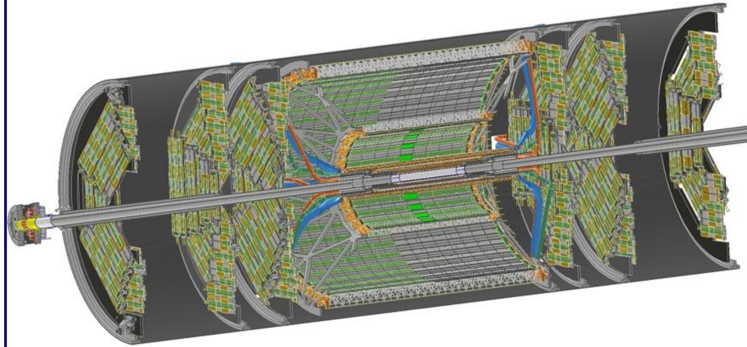
- Compensating solenoid (-5 Tesla)
- Final focus quadrupole QC1 (~100 T/m)
- Screening solenoid (-2 Tesla)



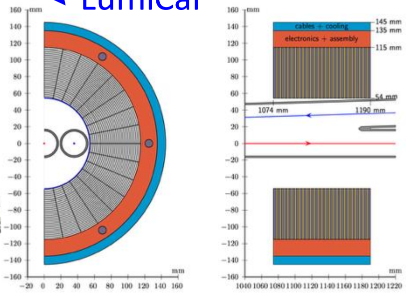


Field map of the screening and compensating solenoid including fringing fields. Important for the beam particle trajectories

zoom: vertex and beam pipe supported by "support tube"



LumiCal



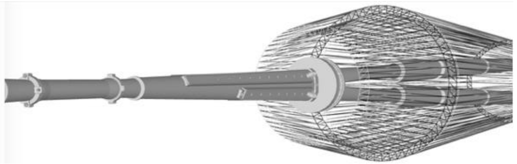
Goal: absolute luminosity measurement 10^{-4} at the Z.
Bhabha cross section 12 nb
acceptance **62-88 mrad** wrt the outgoing pipe

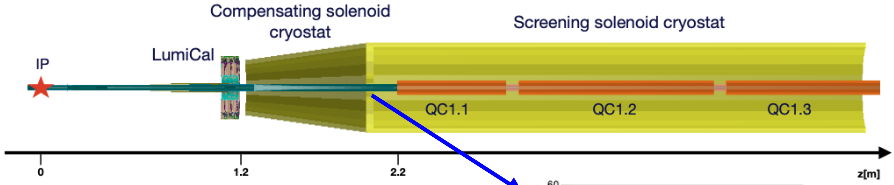
IR modelisation

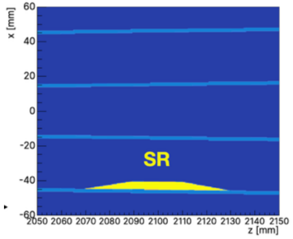
Key4hep

Engineered CAD model imported in Key4hep:

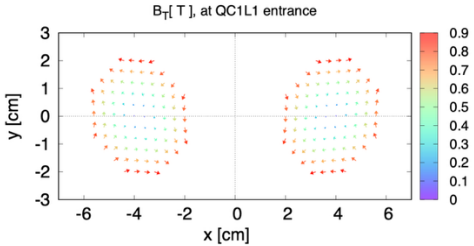
- IR beam pipe
- IR magnets simple equivalent material model
- Cryostat simple guess
- Synchrotron radiation (SR) mask at 2.1 m from IP



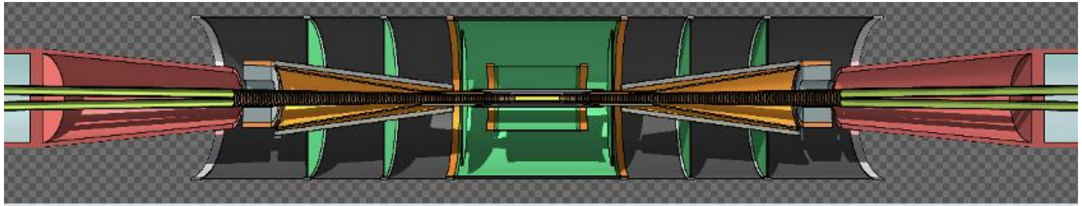


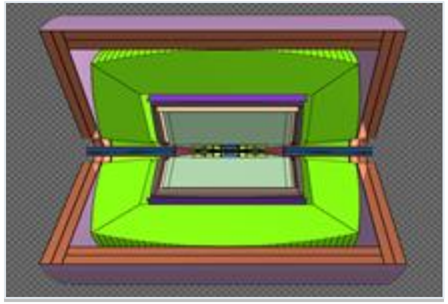


Final focus quadrupole QC1 implemented



Fluka





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

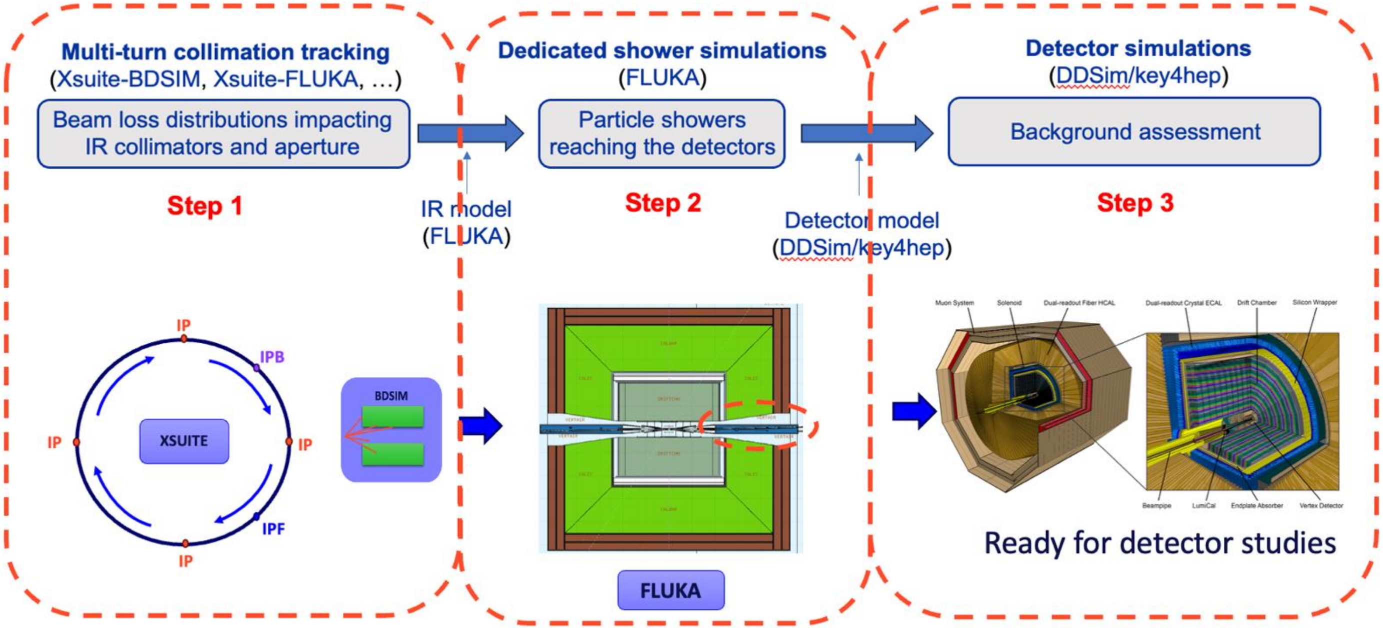
Single Beam effects

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 tracked into detectors for occupancy and data rates.

Background simulation workflow



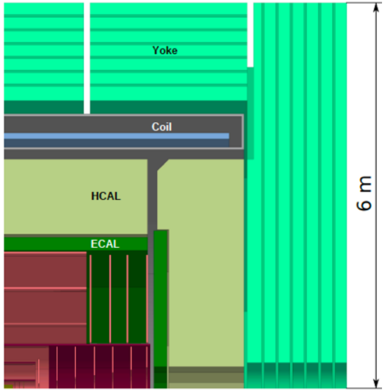
Fluka tracks particles up to the interface plane, defined as:

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

Data format for detector backgrounds studies has been defined: HEPEVT

Detectors for FCC-ee

CLD

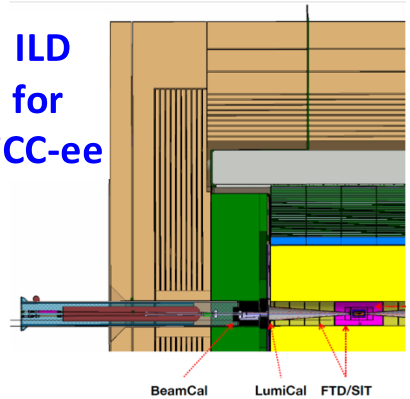


- VTX MAPS
- Main Tracker: Silicon
- Very high granularity (CALICE) inside the Solenoid
  - ECAL Si+W
  - HCAL Fe+scintillator
- PID: RICH and TOF
- Muons ID with RPC

ALLEGRO

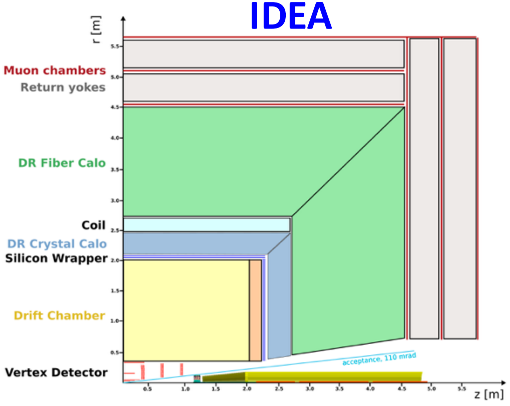
- VTX MAPS
- Main Tracker:
  - Drift Chamber/Straw/Si
- Si/LGAD wrapper (TOF)
- ECAL: Pb+L-Ar/W-L-Kr
- HCAL: Fe+scintillator outside the Solenoid
- PID: RICH (in case of Silicon main tracker)
- Muons with RPC

ILD for FCC-ee



- VTX MAPS
- Main Tracker: TPC
- Very high granularity (CALICE) inside the Solenoid
  - HCAL Fe+scintillator
  - ECAL Si-W
- Muons with scintillator

IDEA



- VTX MAPS
- Main Tracker:
  - He+Isob drift chamber
- Si/LGAD wrapper (TOF)
- DR calorimetry (fibres):
  - ECAL: Crystals
  - HCAL: Iron **outside** the Solenoid
- HTS Solenoid (up to 3T)
- Muon ID: μ-RWELL

Detectors for FCC-ee

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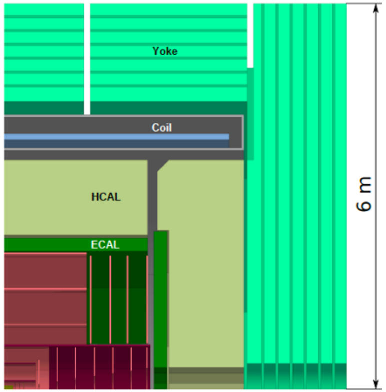

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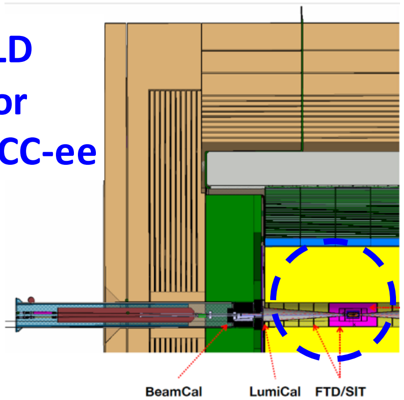

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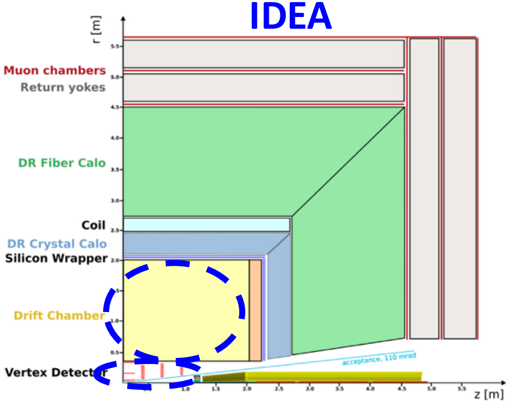

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- Main Tracker:
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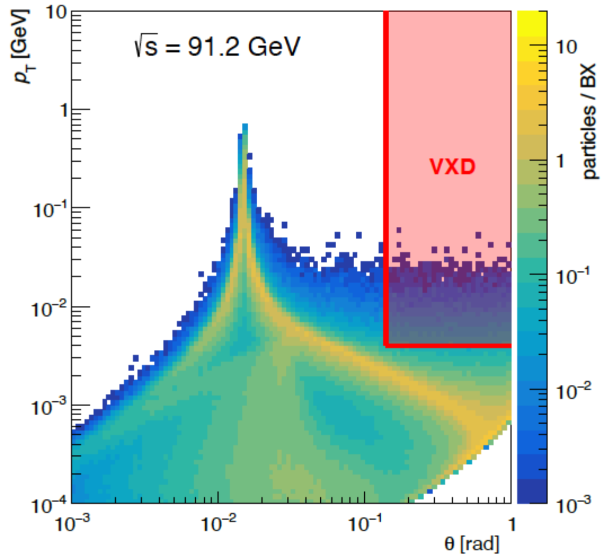
Beam-related backgrounds in the detectors

- **IPC: Incoherent pair creation dominant**

  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

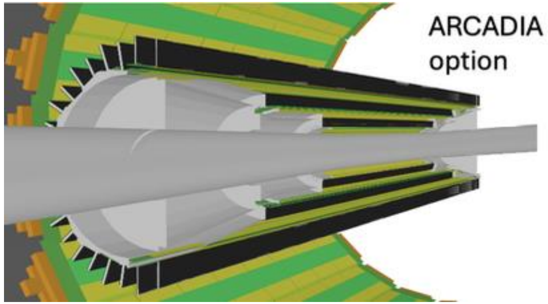


see talk by F. Palla

IPC for the IDEA Vertex Detector

Two sensor technology options under investigation:

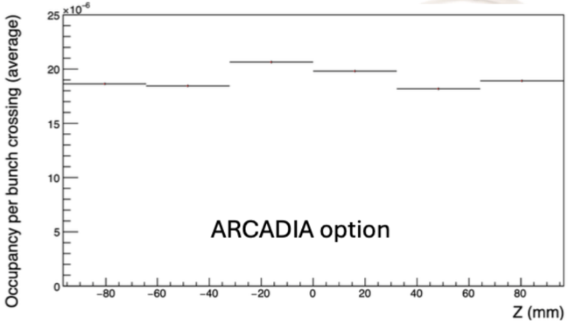
- ARCADIA sensor staves
- ultralight ALICE ITS3 bent sensors



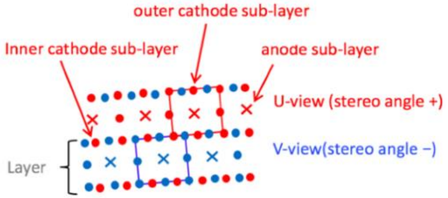
- **Occupancy for the vertex innermost layer** (r=13.7 mm)
  - Cluster size of 5, safety factor of 3, 25 μm pitch pixels
  - Cut at 1.8 keV of deposited energy (500 e^-)

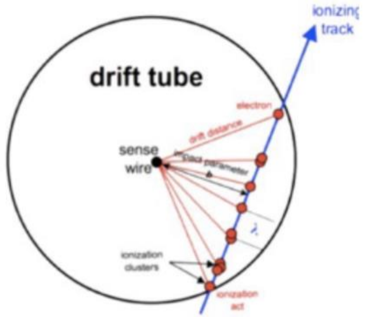
challenging for readout ~**100 Gb/s per ladder**

	ARCADIA	ALICE ITS3
Occupancy	$\sim 20\times10^{-6}$	$\sim 30\times10^{-6}$
Hit rate	$170\ MHz/cm^2$	$250\ MHz/cm^2$
	flat layout	curved layout



IPC for the Drift Chamber

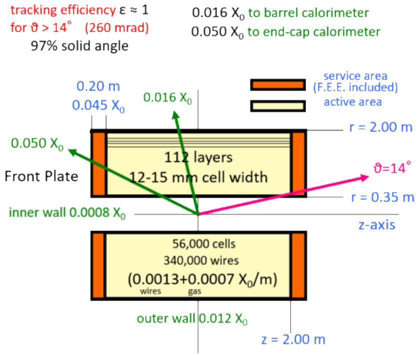


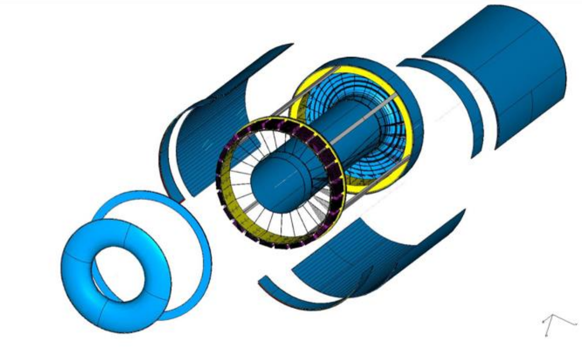


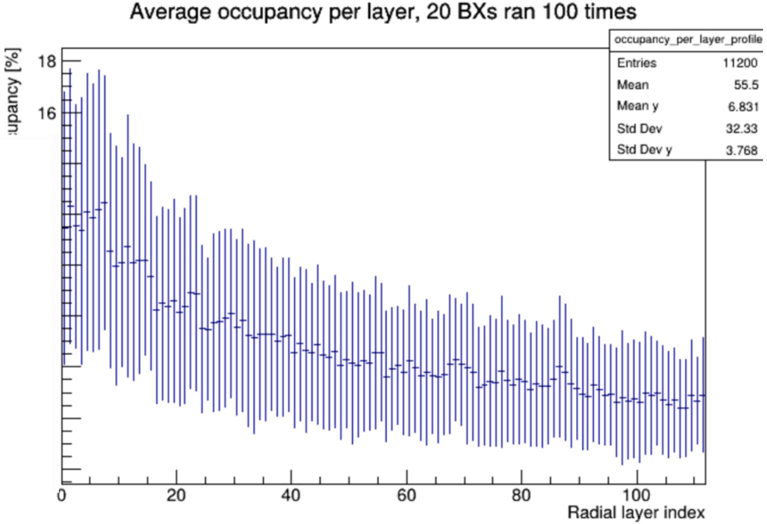
Occupancy in the drift chamber at **SIM hit level** from IPC.

Assuming a conservative 400 ns maximum drift time:

- Integrate IPC for 20 bunch crossings (at Z pole bunch spacing is 20 ns)
- With no cuts, and no digitisation (**upper limit**) → about **7%**
- Digitisation in progress

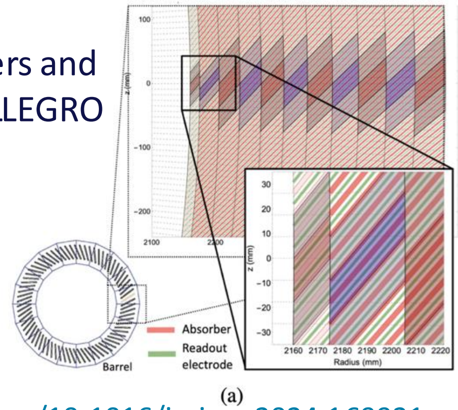






IPC for the ALLEGRO ECAL

Layered structure of absorbers and readout electrodes of the ALLEGRO ECAL barrel concept

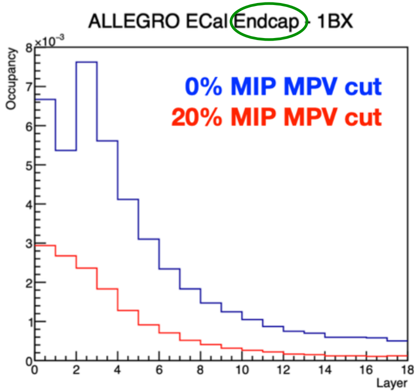


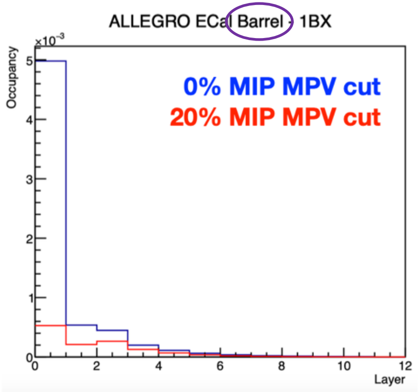
https://doi.org/10.1016/j.nima.2024.169921

Average occupancy per BX (4000BXs):

	No cuts	20% MPV cut
Endcap	0.1% ~ 0.8%	0.02% ~ 0.3%
Barrel	<0.5%	<0.05%

O(0.1%) occupancy/BX may grow quickly if the **readout integration time** is larger than a few BXs ($\Delta t \sim 20ns$ at Z-pole)





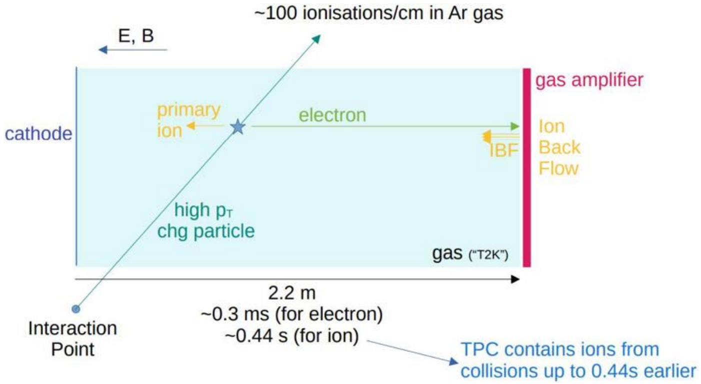
IPC in the TPC

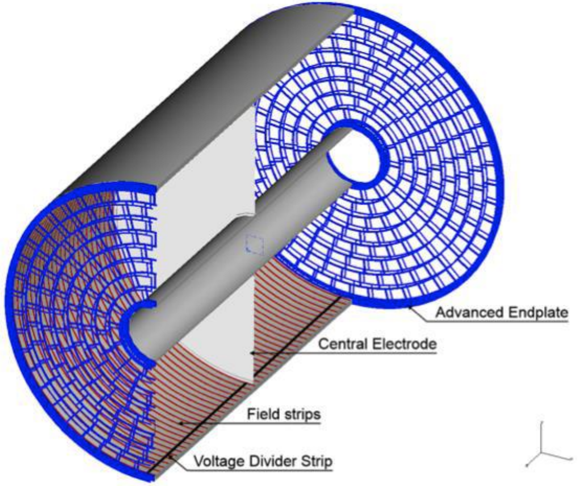
- **TPC is particularly affected by large #ions produced, with distortions up to ~1 cm at FCC-ee**

- Order of 2k photons/BX entering outer tracker region
- ~ MeV typical energy

- Study ongoing to mitigate this effect by
  - adding Bx magnetic field component to deviate IPC
  - adding masking and shielding around the TPC, W and C

  - ~25% reduction could be obtained
    but these remedies affect the IR layout with a nontrivial implementation

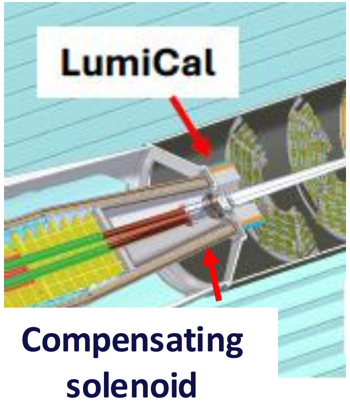


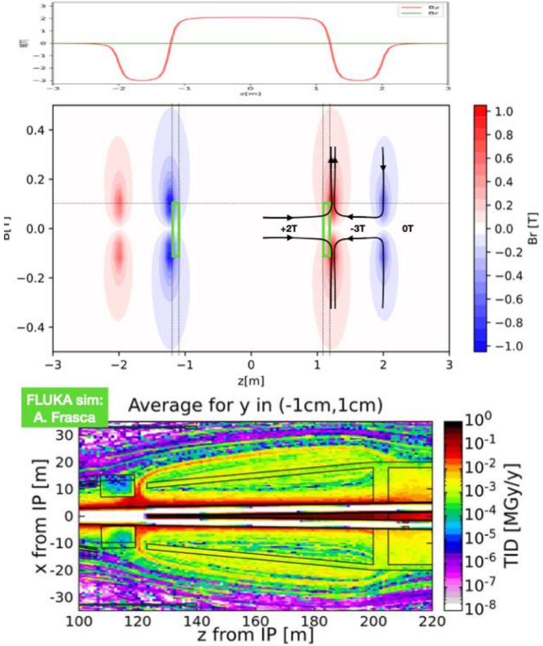


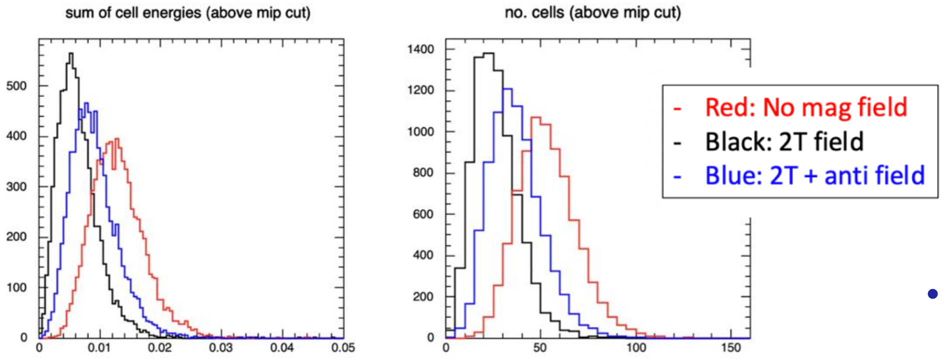
IPC in the LumiCal for Z pole

The LumiCal is in the fringing field region of the -5 Tesla compensating solenoid.

Low-p_T particles can spiralize due to this fringing field and hit the LumiCal causing backgrounds.







For full field (blue):

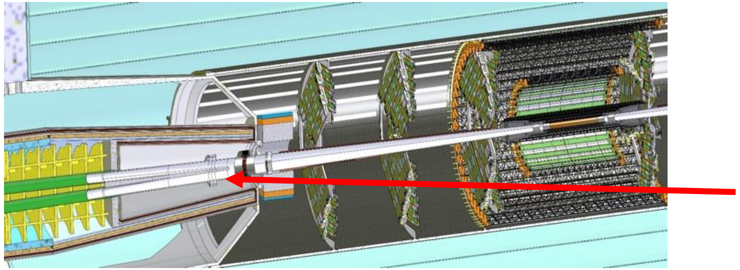
Avg. = 9.0 MeV
1.7% of 510 MeV (45.6 GeV electrons)

Avg. = 36 cells
5.3% of 680 (45.6 GeV electrons)

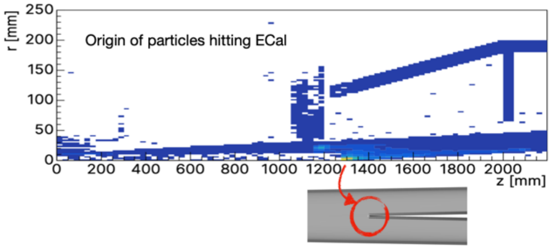
- Dedicated shielding might be needed
  not trivial to find space required
- Non-local solenoid scheme that removes this antisolenoid (it goes at ~10 m from the IP, outside the detector) would be the cleanest solution.

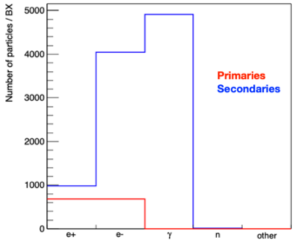
Non-negligible effect for the required energy resolution at < % level

IPC hit the Y-beam pipe

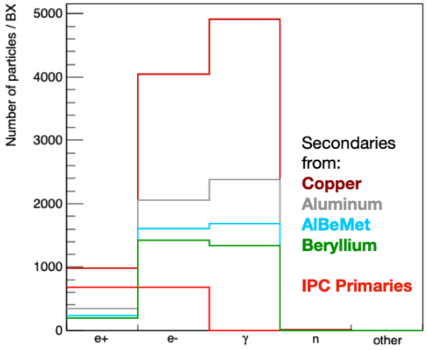


A large contribution of backgrounds come from secondaries generated by low-P_T particles hitting the beam pipe separation region.





Large production of electrons and photons from copper beam pipe material.

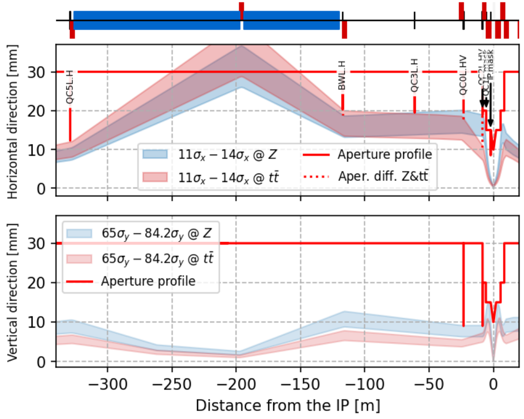


Different Y-pipe material (with respect to copper) reduces secondaries, equivalent to the effect of a 2 cm of tungsten shielding (and much lighter!)

Synchrotron Radiation (SR) backgrounds

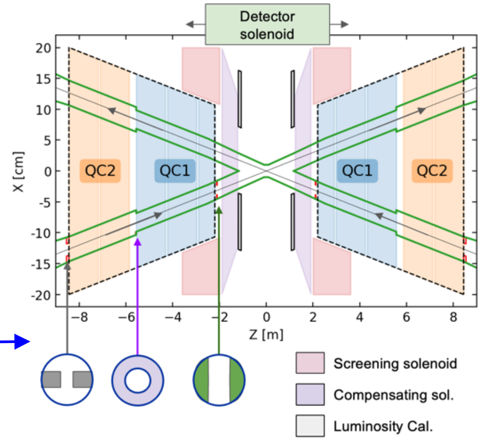
- Simulations with BDSIM (GEANT4 toolkit)
- SR evaluated for
  - **beam core** with non-zero closed orbits for considering optics imperfections
  - **transverse beam tails**

bulk of SR produced upstream the IR is stopped by collimators



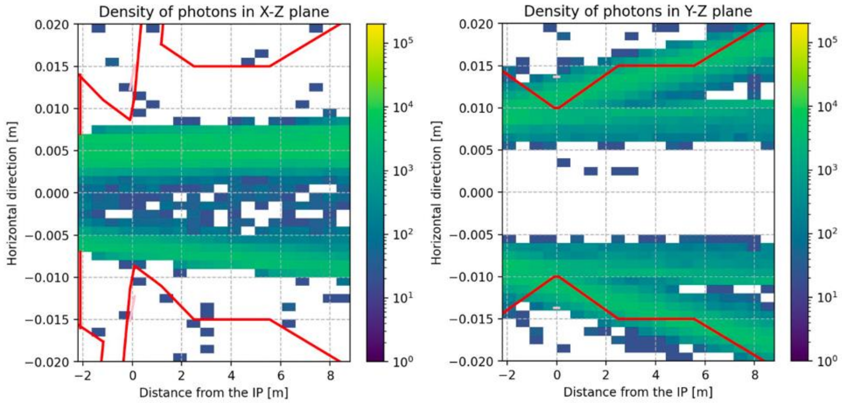
- **All beam energies studied.**

- **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**

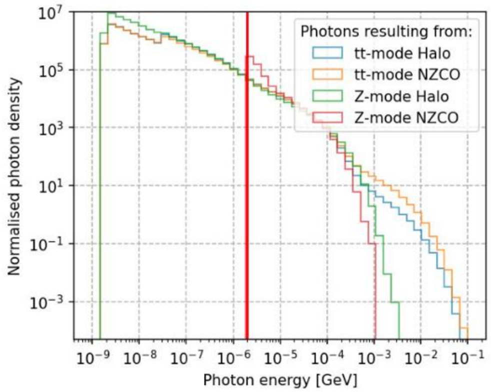


Synchrotron Radiation background

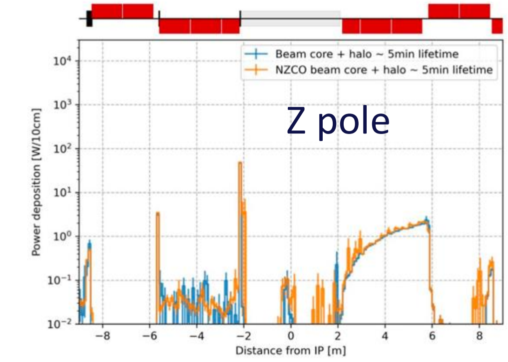
Photons ready to be tracked in the detectors



Photons passing through the horizontal SR mask



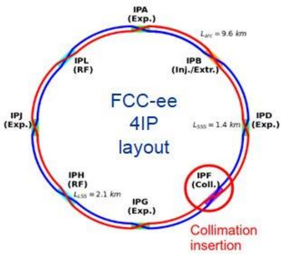
accept > 2 keV



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.

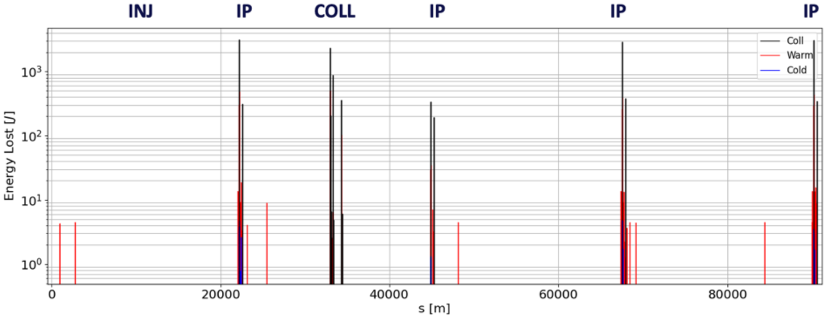
Power deposition on the beam pipe and masks ± 8 m from IP

Injection backgrounds



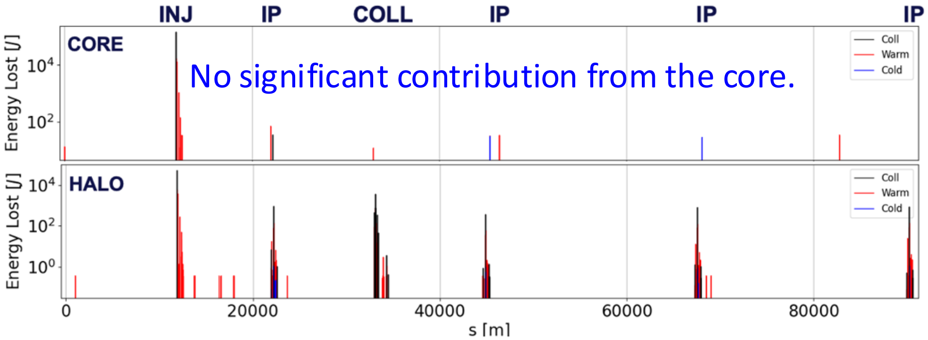
Top-up injection required, on-axis & off-energy current baseline scheme.
Injection efficiency is assed at 88% for lattice V25.1_GHC.

injected beam



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

circulating beam



The leakage to experiments will be studied as next step.

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.

Beam-gas backgrounds

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

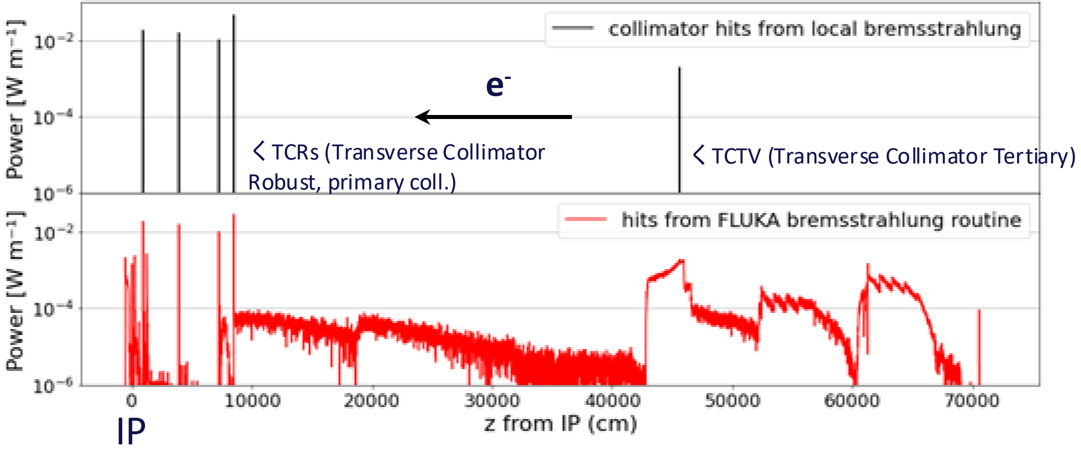
- Hits in the MDI (±5 m from IP) do not come from events further than ~250m upstream
- These non-local BG bremsstrahlung is mainly stopped by the collimators

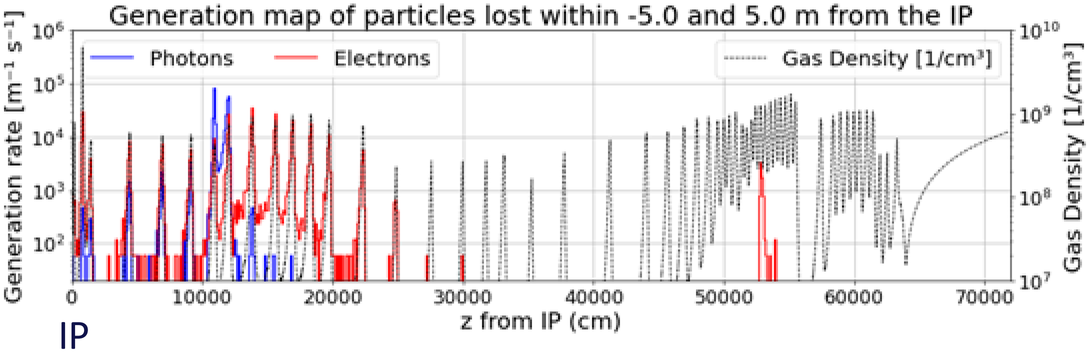
Detector backgrounds to be estimated from secondary showers produced by

- collimator hits
- and by particles lost after tertiary collimators

*only electron hits on the collimators are plotted

Beam-gas bremstrahlung





Beam-gas interaction contribution to detector

Beam-gas bremsstrahlung

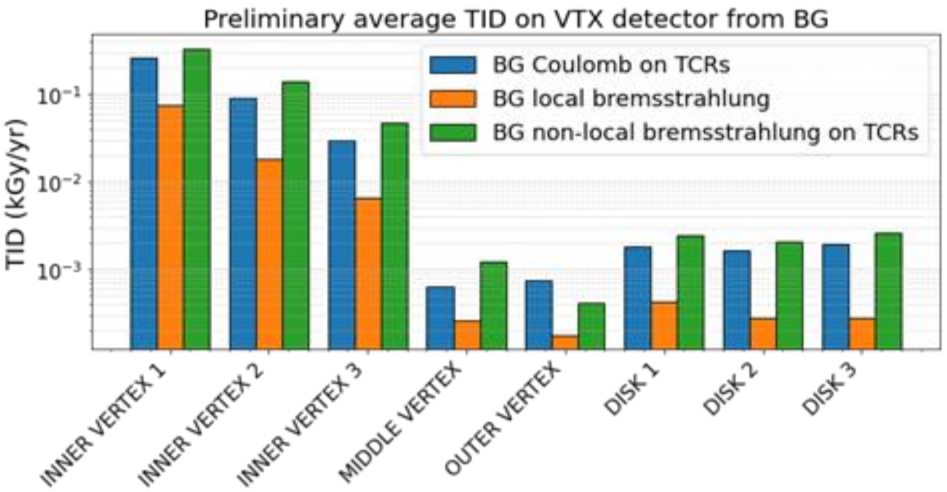
- contribution from TCTs negligible
- contribution from hits on TCRs non-local, higher than local BG bremsstrahlung

Beam-gas Coulomb scattering

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

local: upstream the MDI, single pass

non-local: generated far from IP and multiturn



Doses are proportional to backgrounds, subleading wrt IPC

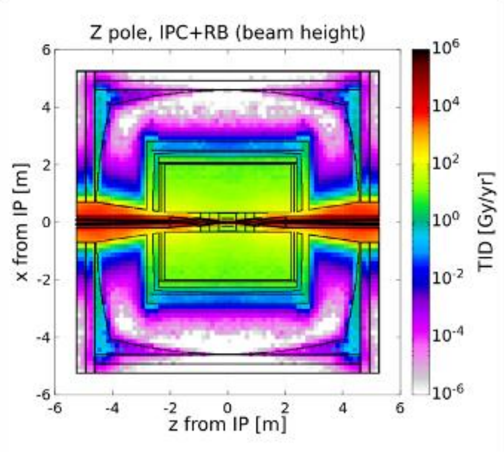
Detector backgrounds

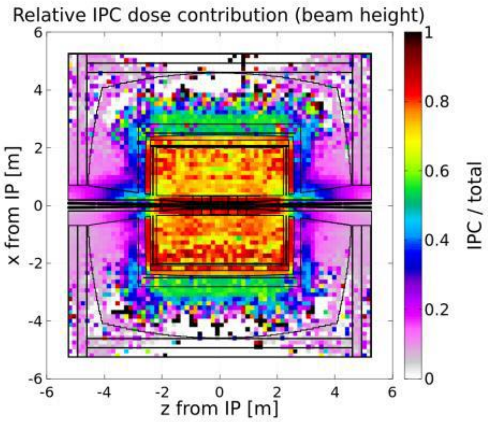
- workflow established to evaluate detector background from FLUKA simulations

Detector radiation levels

FCC-ee smaller radiation environment than LHC

- IPC dominant up to the drift chamber, centrally, whereas radiative Bhabha's ($e^+e^- \to e^+e^-\gamma$ (in forward direction (HCAL endcaps) and muon chambers
- Intense synchrotron radiation (SR) in the forward direction, outside of the detector. SR from the last dipole (~100 m from IP) is suitably shielded before the experiments
- Injection backgrounds (important at SuperKEKB) under study
- Beam losses tracked with Fluka up to an interface plane with the detector



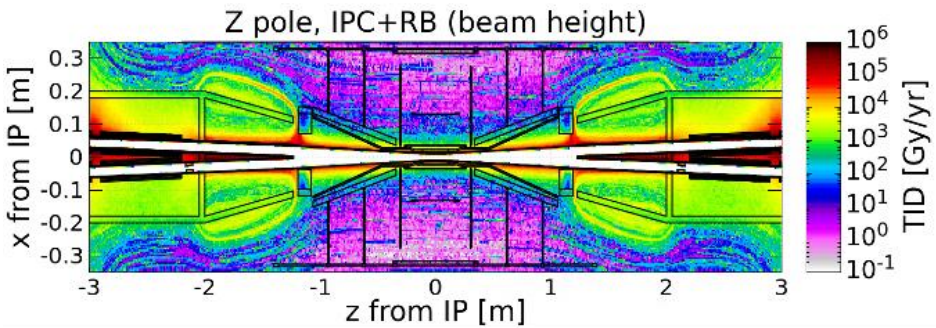


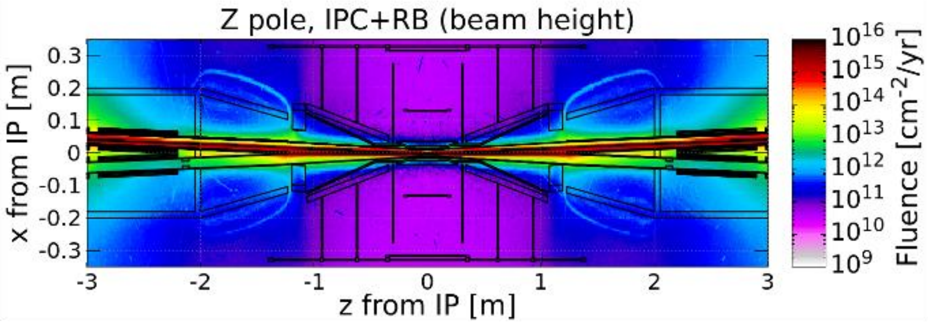
	TID [Gy/yr]	Fluence [cm^{-2}/yr]
Vertex	~40k	~10^{13}
Drift chamber	~10	~10^{11}
ECAL	~1	~10^{10}
HCAL	<1	<10^{10}
Lumical	~10k	~5 10^{12}

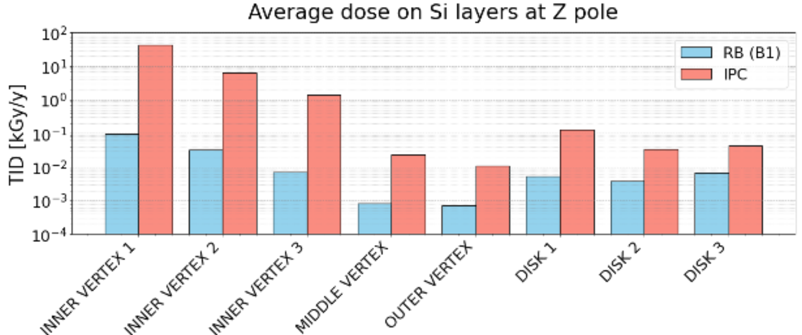
Vertex detector radiation levels

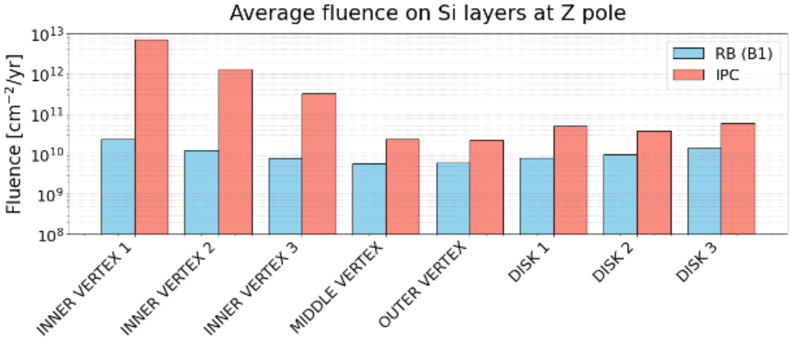
IPC dominant source

- 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









Next steps - Beam induced backgrounds

- Activity on the acceleration simulation level, great effort done, to be continued in the next months, to evaluate occupancy and data rates.

- Beam collimators implemented, also tertiary ones in the MDI area.
- IPC evaluated.
- Single beam effects studied, ready to be tracked in the detectors.
- SR backgrounds studied for different machine conditions, ready to be tracked in detectors.
- Injection backgrounds study started, ready to track first events in detectors
- Doses and fluences evaluated.
- Thermal photons background is planned.

- Next steps necessitates to track those loss particles up to each subdetector
  to estimate detector hit occupancies and data rates → Iteration with acceleration

Thanks to inputs by:

K. Andrè, G. Broggi, A. Ciarma, M. Dam,

A. Frasca, D . Jeans, G. Nigrelli, F. Palla

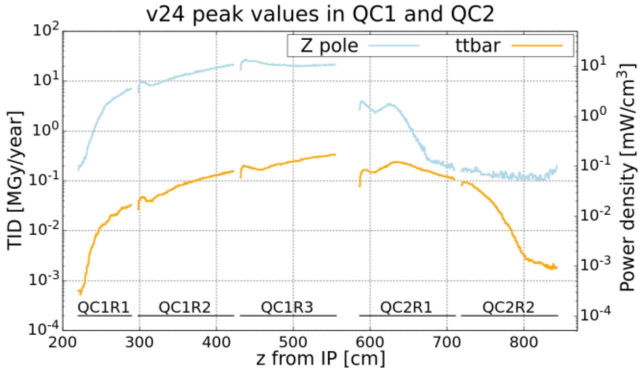
Radiative Bhabha scattering

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

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.

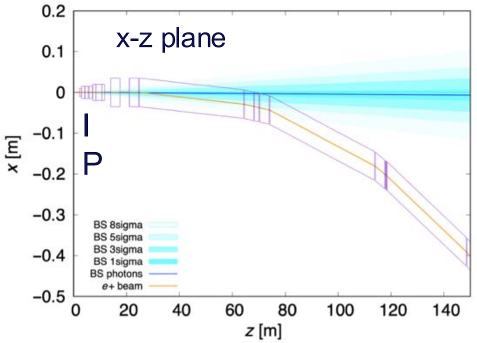


Off-energy particle may reach the LumiCal, even if negligible wrt IPC (~3%)

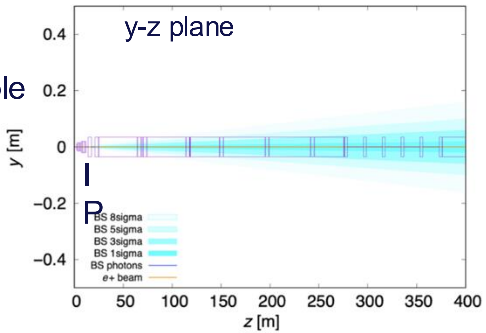
* BBBREM, Monte Carlo simulation of radiative Bhabha scattering in the very forward direction, R. Kleiss and H. Burkhardt

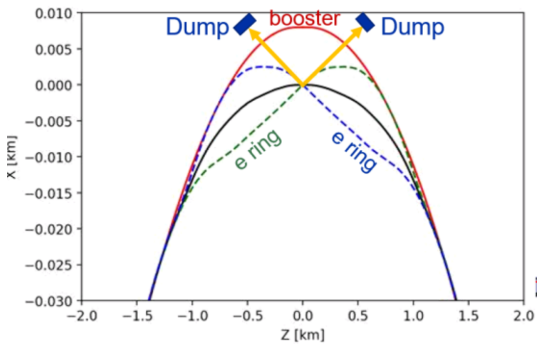
BS and SR Radiation produced at IR

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



Z-pole





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

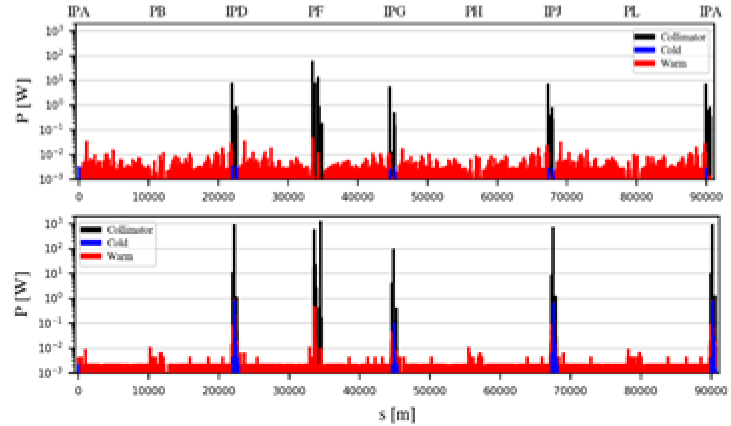
High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

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

Beam-driven radiation sources at Z pole: Beam-gas scattering

Beam-gas interactions (BG)

- high beam current (1.29 A) @Z pole→more important than at the other modes
  - BG bremsstrahlung→photons and off-momentum beam particles
  - BG Coulomb scattering→small angular deflection, high cross section + limited DA



Beam-gas bremsstrahlung

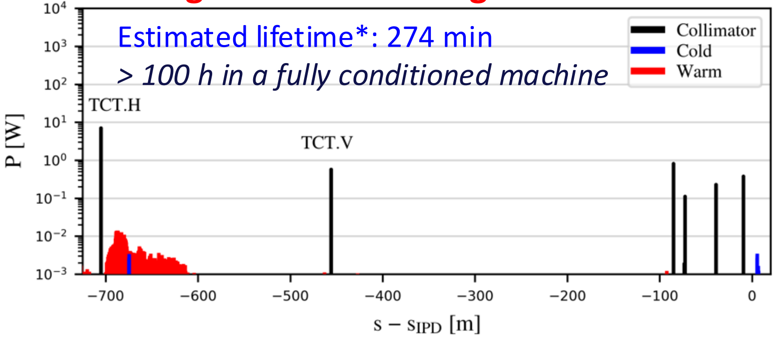
- Estimated lifetime after only 1h of beam conditioning*: **274 min**
- Expected to increase to > 100 h in a fully conditioned machine

Beam-gas Coulomb scattering

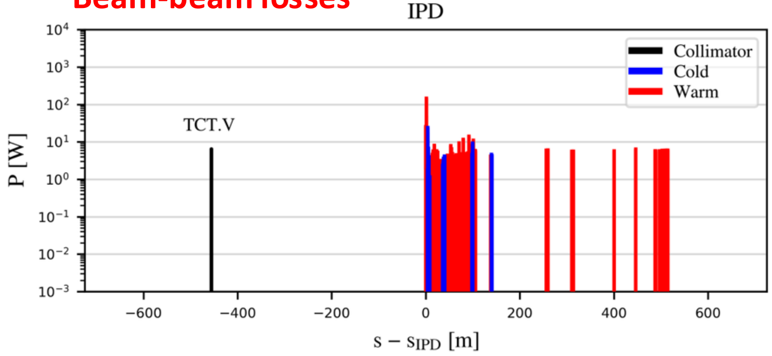
- Estimated lifetime after only 1h of beam conditioning*: **41 min**
- Expected to increase to > 10 h in a fully conditioned machine

IR beam losses and MDI collimators

Beam-gas bremsstrahlung



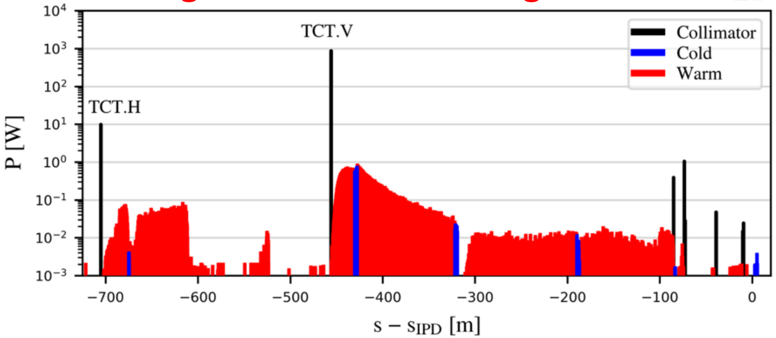
Beam-beam losses



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

Beam-gas Coulomb scattering



Estimated lifetime*: 41 min

> 10 h in a fully conditioned machine

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.