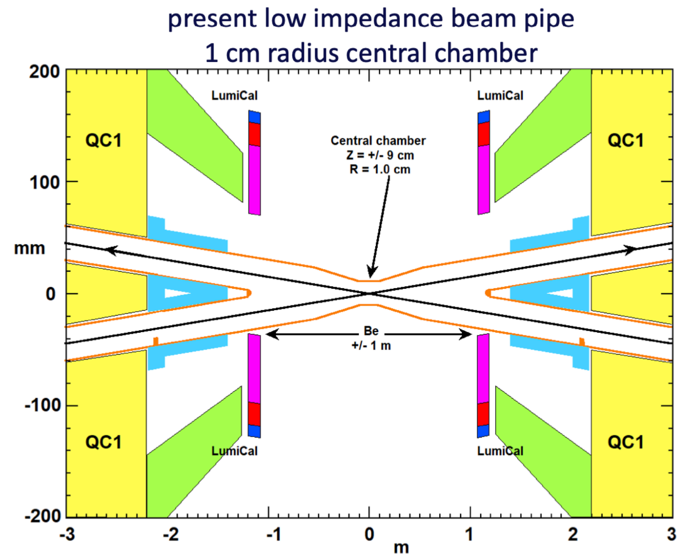
FCC-ee INTERACTION REGION DESIGN

A. Ciarma
on behalf of the FCC-ee MDI group

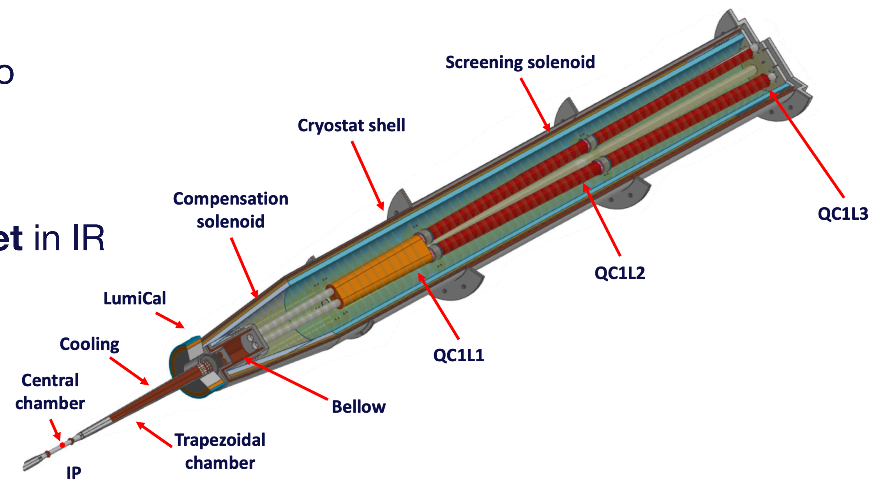
This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

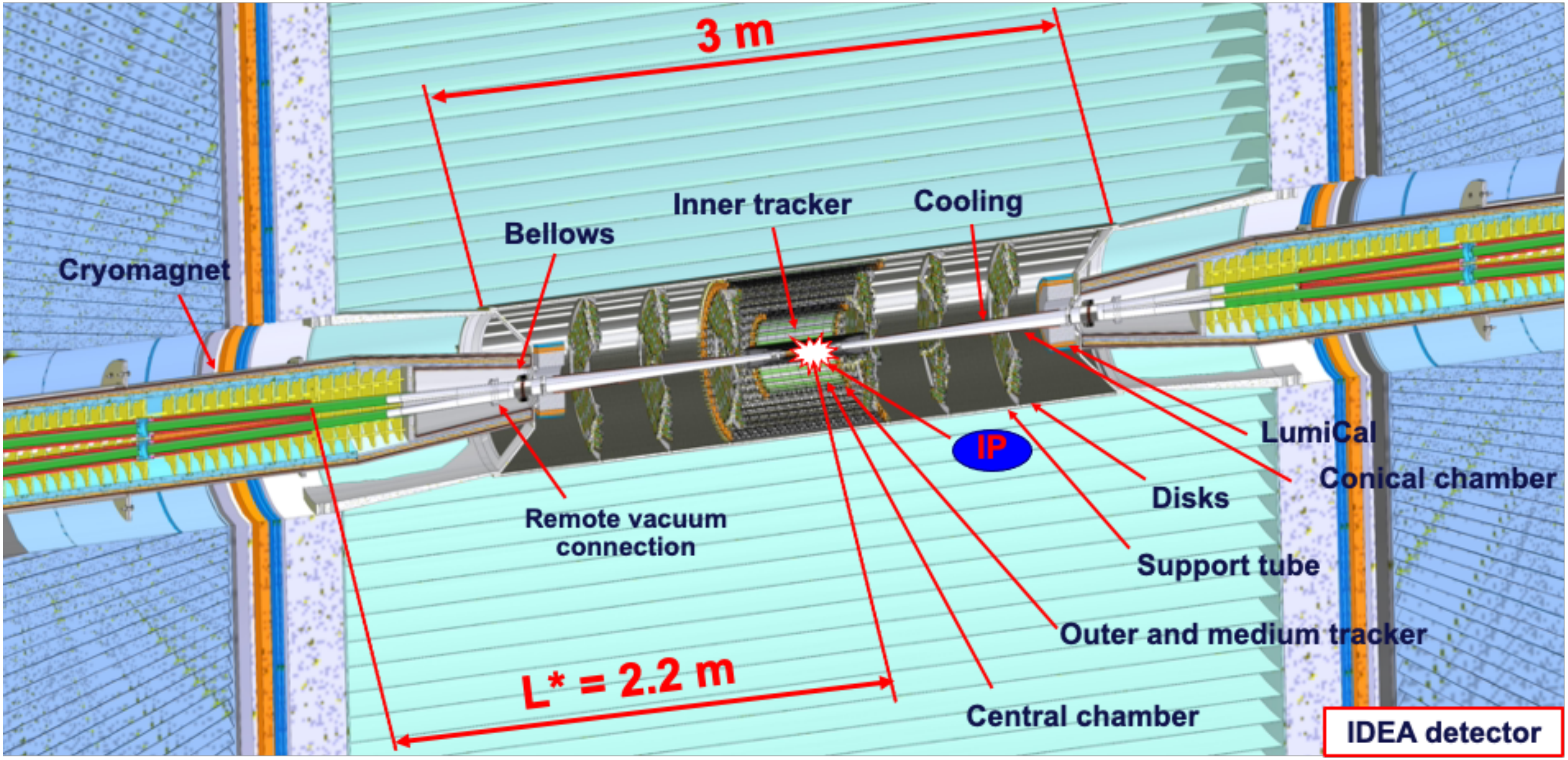
FCC-ee Interaction Region and Machine Detector Interface



- Luminosity of O(10^{36} $cm^{-2}s^{-1}$) achieved via **crab waist scheme**
- Large Piwinski angle $\phi = \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}$ requires **compact IR** and limits **detector solenoid field**

  ➡ $L^* = 2.2m \quad B_{det} = 2T$
- **Common IR design** for all 4 working points
- Detector angular acceptance $100mrad$, beam pipe separation at $\sim 1m$
- First Final Focus Quadrupole **inside the detector**, requires **screening solenoid** to shield from detector magnet
- Solenoid compensation achieved locally via **-5T compensation solenoid**
- Low angle Bhabha luminosity monitor **LumiCal** requires **very low material budget** in IR vacuum chamber




3 m
Inner tracker
Cooling
Bellows
Cryomagnet
IP
LumiCal
Conical chamber
Disks
Remote vacuum
connection
Support tube
Outer and medium tracker
L* = 2.2 m
Central chamber
IDEA detector

FCC-ee MDI activities

IR Mechanical Model

- engineered design of beam pipe, cooling system and support
- heat load distribution from wakefield and SR
- integration in the MDI region and assembly strategy of LumiCal and vertex detector

Background Simulations

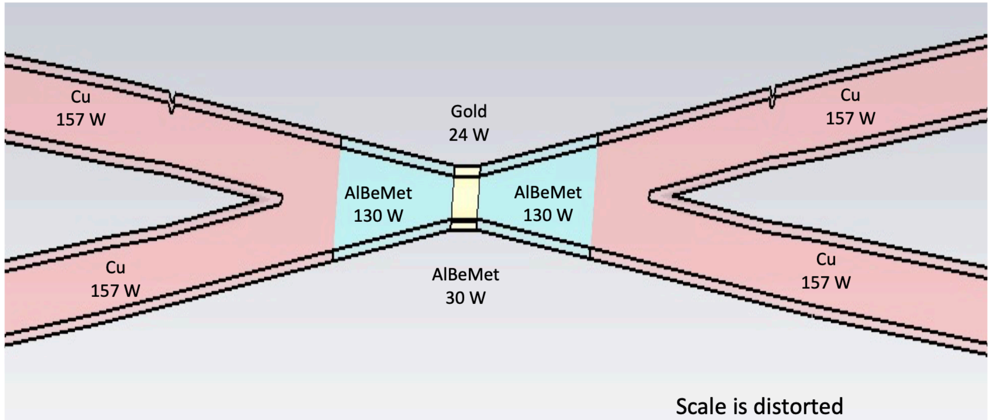
- estimation of beam losses in the MDI region and halo collimation scheme
- development of SR maskings
- tracking of unwanted particles in the detector for occupancy calculation

Beamstrahlung Photon Dump

- characterization of beamstrahlung radiation and first FLUKA studies on dump
- integration of extraction line with civil engineering of downstream tunnel and magnet aperture design

Non-local Solenoid Compensation Scheme

- first studies on alternative solenoid compensation scheme without the -5T compensating solenoid in IR



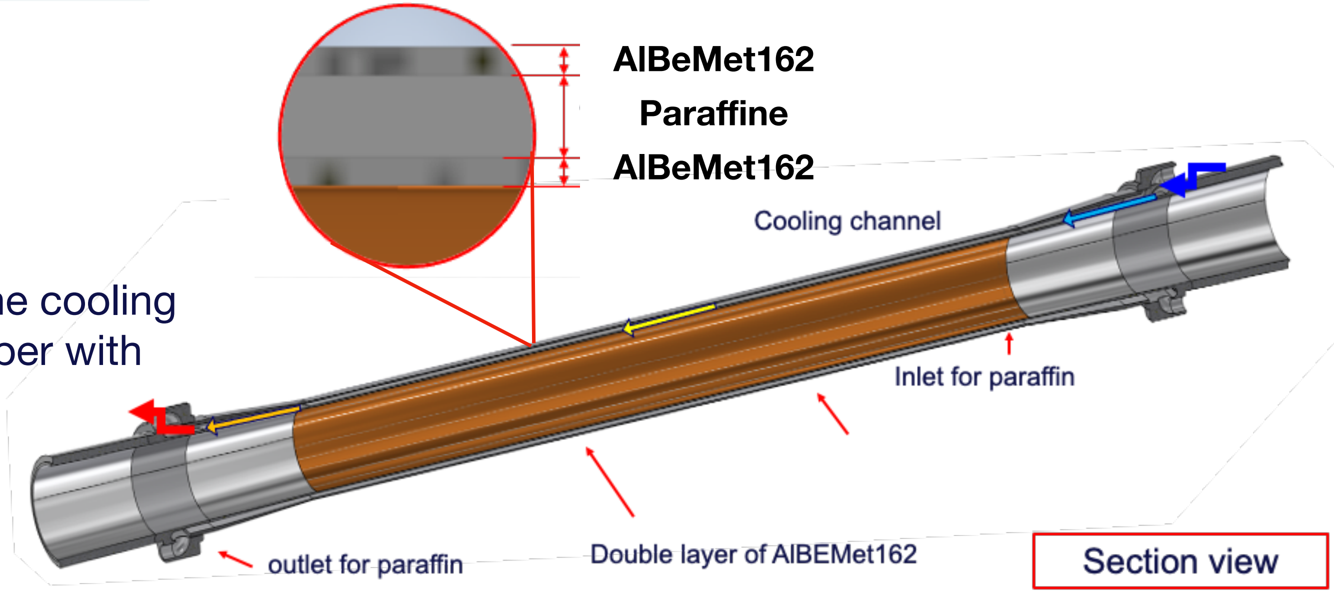
Low impedance beam pipe

Beam pipe design optimized for low impedance using **CST wakefield evaluations**.

Heat load estimates used in ANSYS simulations for **cooling system dimensioning** and structural analysis.

Central Chamber

- Extending ±90mm from the IP
- Double AlBeMet162 layer to contain Paraffine cooling
- Geometry studied to integrate central chamber with vertex detector



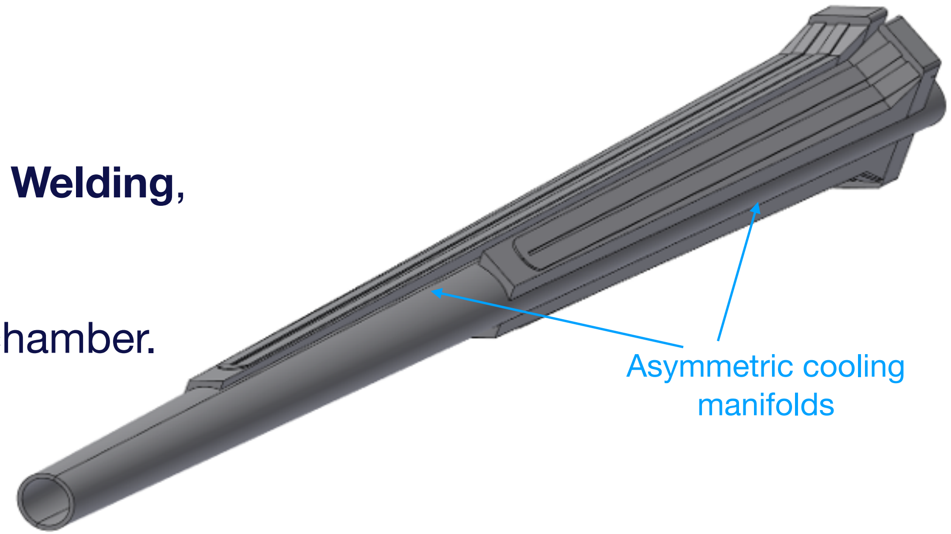
A. Novokhatski, F. Fransesini, et al. “Estimated heat load and proposed cooling system in the FCC-ee IR beam pipe”, IPAC23

Elliptoconical Chambers

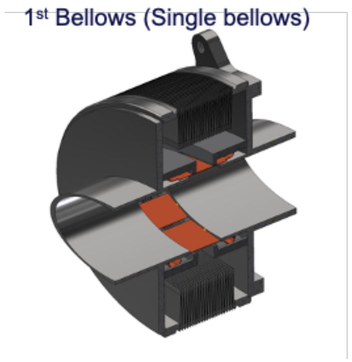
Two AlBeMet162 chambers assembled using **Electron-Beam Welding**, 90mm to 190mm from IP.

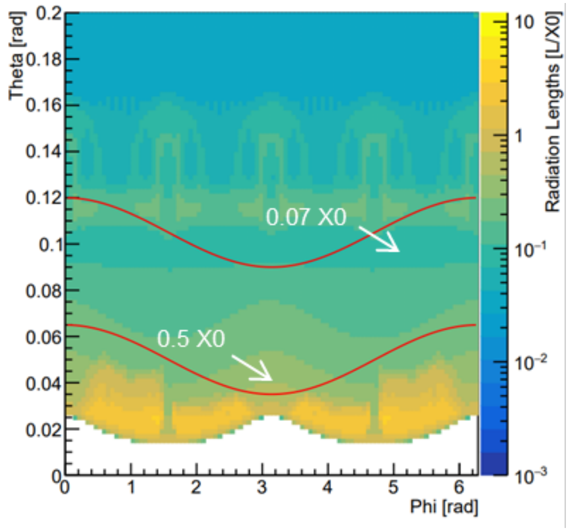
Cooling channels for water recirculation machined over the chamber.

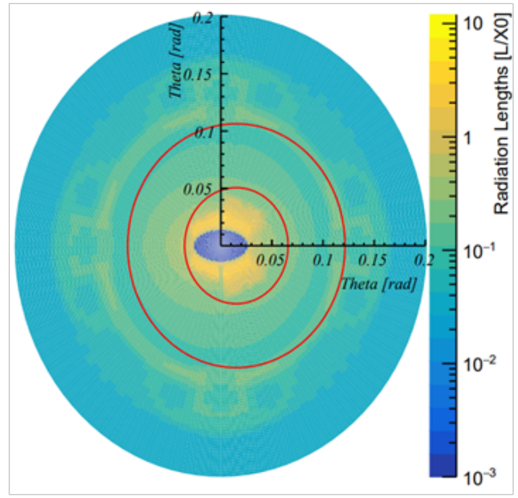
Asymmetric cooling manifolds to **minimise material budget** in the LumiCal angular acceptance.



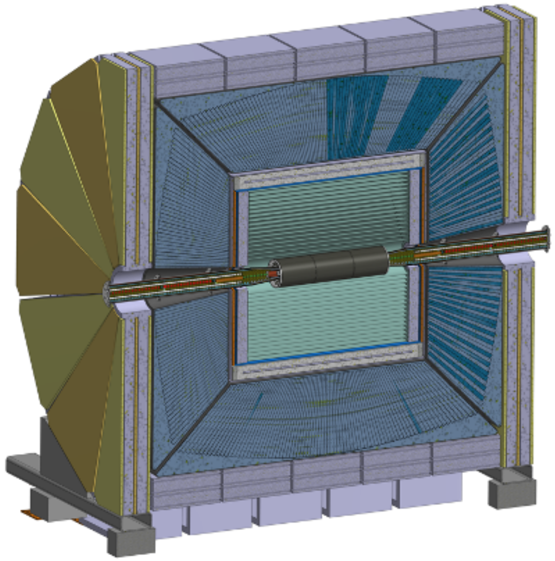
Dedicated bellows based on the **DAFNE** and **ESRF** design will support the central and the two elliptoconical chambers.







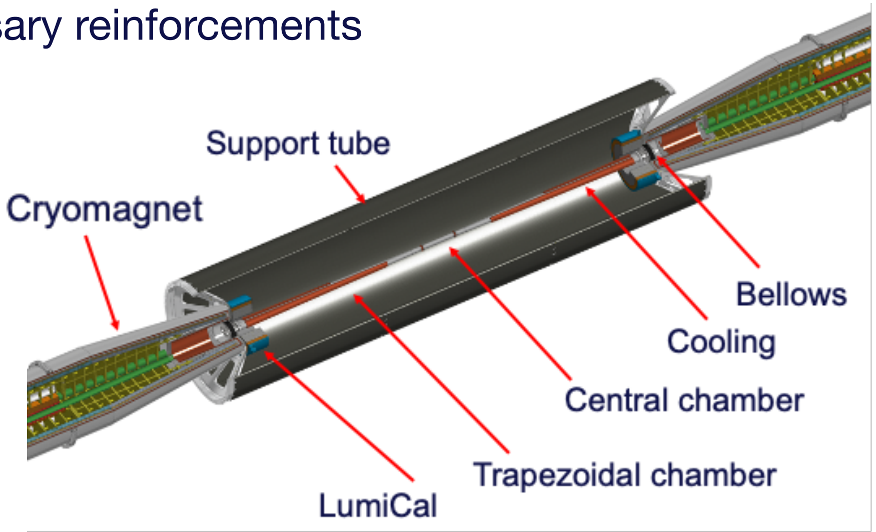
Support Tube for Vertex Detector and LumiCal Integration

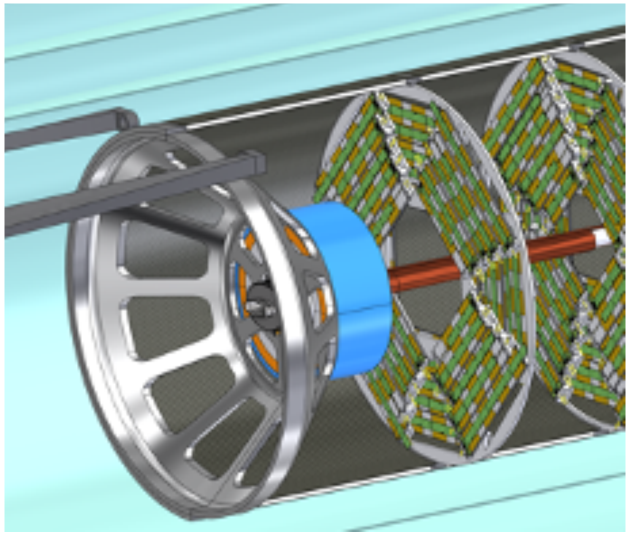


Carbon Fibre support tube with Aluminum endcaps for IR integration

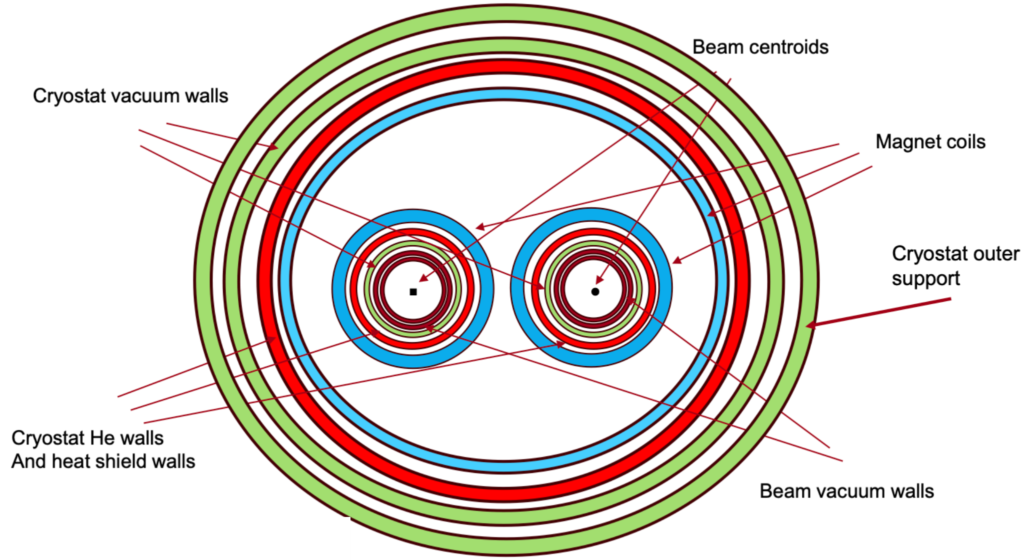
- **Cantilevered support** for the beam pipe
- Ease **assembly procedure** for thin-walled central chamber
- Provide support for LumiCal and Vertex Detector

ANSYS structural analysis performed to optimise thickness and necessary reinforcements





Cryostats for Final Focus

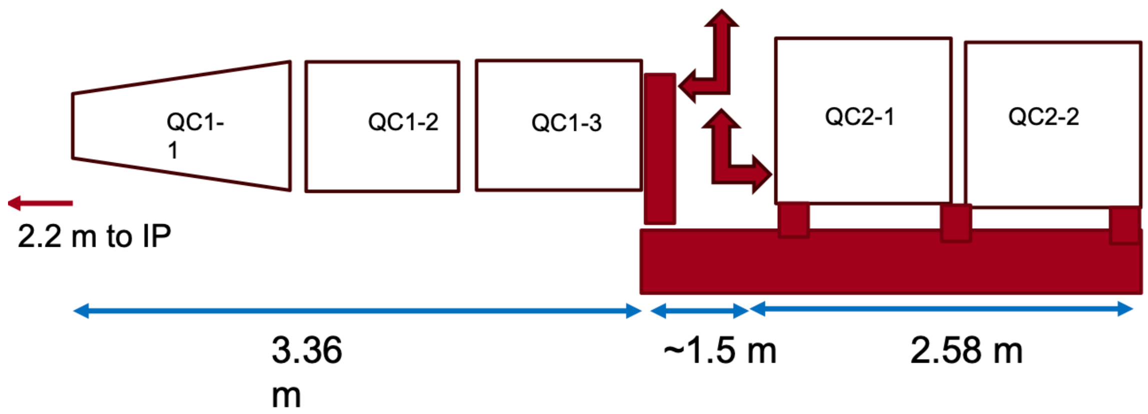


Main challenges for Final Focus cryostat design:

- Tight space inside the detector
- **Common He space** for antisolenoids and superconductive Final Focus Quadrupoles
- Thermal insulation for **warm beam pipe**
- SuperKEKB experience -> reserve some space for additional **shielding material** inside cryostat

Proposal to have two **separate cryostats** for QC1 and QC2 on the same raft.

- Reduced stress on cantilevered support
- Required space between the two FF quads

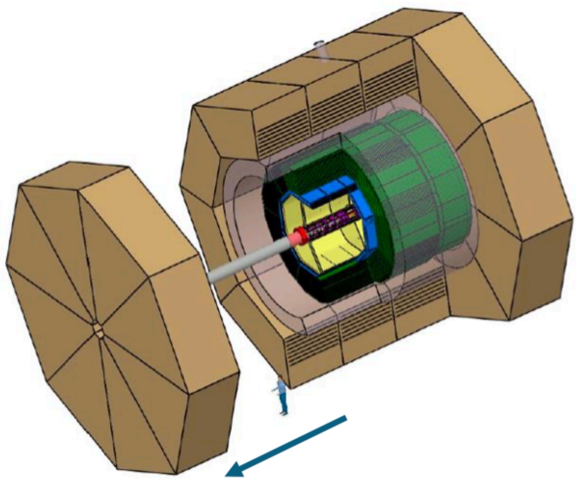


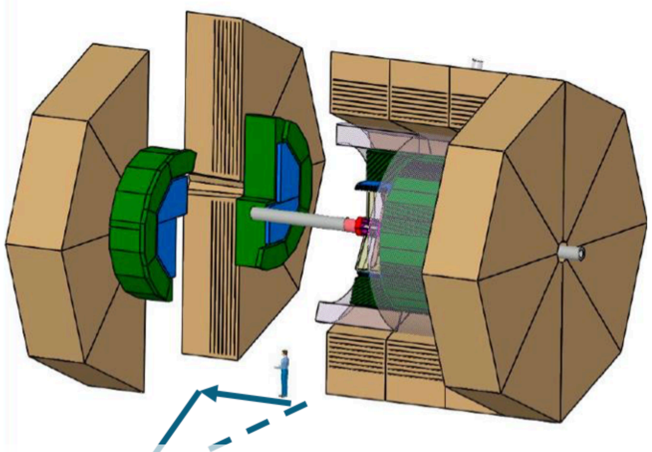
Detector Integration

MDI design should be compliant with detector integration strategy

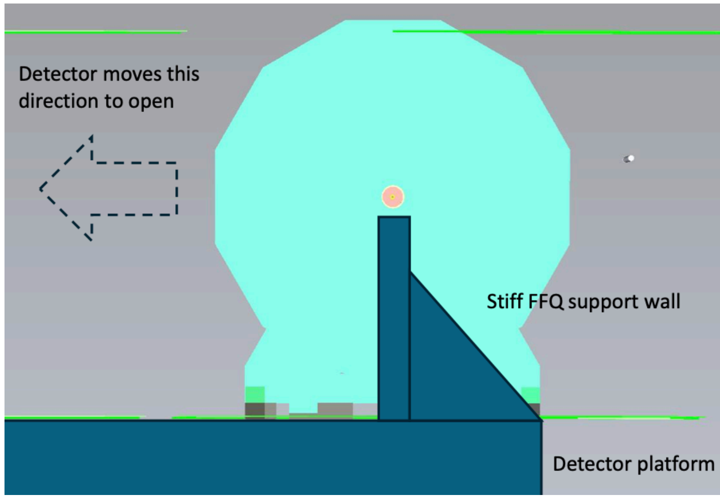
- Ensure **stability** of Final Focus Quadrupoles preserve **beam pipe vacuum**
- Reliable **alignment system**
- Allow **easy detector opening** sequence and simple **access during short shutdowns**

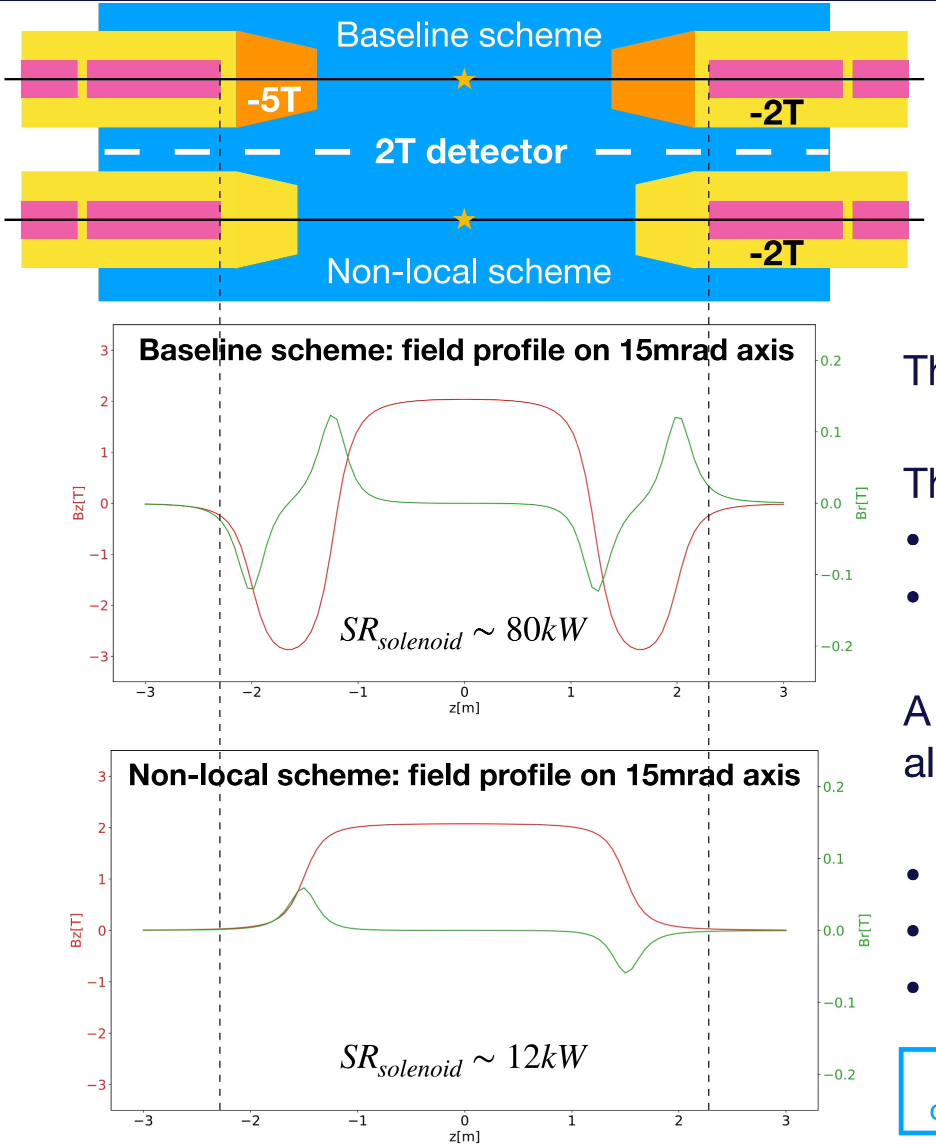
Final Focus and Cryogeny systems **cantilevered support** strictly connected to the detector **opening scenario.**





Three possible detector opening scenarios





Coupling Correction Scheme at FCC-ee

The **2T detector solenoids** induce coupling in the FCCee lattice.

The current correction scheme uses:

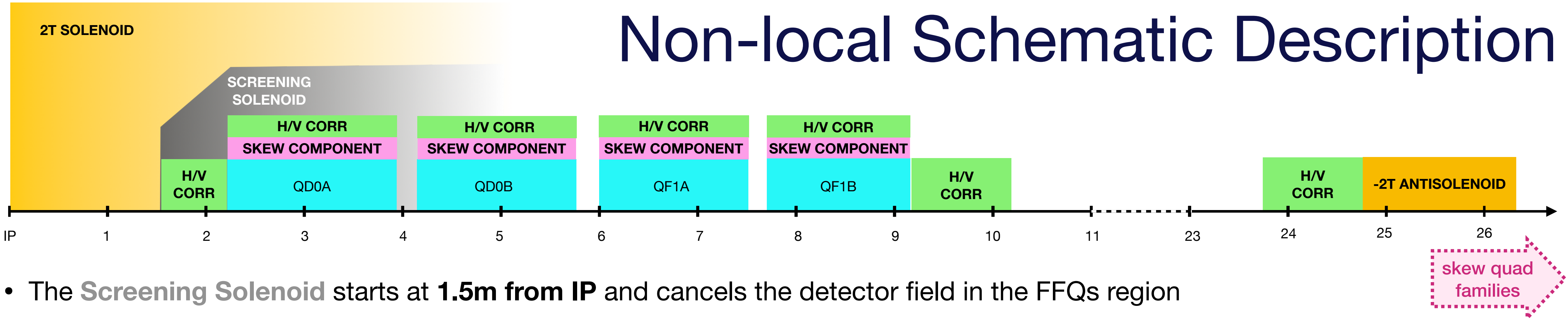
- **-5T compensating solenoids** to cancel the magnetic field integral
- **-2T screening solenoids** to shield the **FFQs** from the detector field

A **non-local correction scheme** proposed by P. Raimondi would allow to move the **compensating solenoids** outside the IR.

- relaxed mechanical constraints in the IR
- technical R&D of a -5T compact magnet
- **Synchrotron Radiation** from B-field transition region (~80kW).

IPAC proceeding: A. Ciarma, M. Boscolo, H. Burkhardt, P. Raimondi, "Alternative solenoid compensation scheme for the FCC-ee interaction region" - 10.18429/JACoW-IPAC2024-TUPC68

Non-local Schematic Description



- The Screening Solenoid starts at **1.5m from IP** and cancels the detector field in the FFQs region
  - may be **conical or cylindrical** according to detector angular acceptance and magnet radius
  - **starting point** can be varied for mechanical constraints
  - outer part will be **tapered** to match main solenoid fringe fields
- The antisolenoid moved outside the IR (before the first dipole) to cancel $\int B_z ds = 6.25\, Tm$ => **longer, weaker magnet**
- Skew components winded around the FFQs correct coupling due to beam rotation under Bs $K_{1s} = K_1\ sin(2\theta) \sim 0.02 K_1$
- 3 **H/V correctors** (COR1, COR2, COR3) are used to close the orbit bumps due to tilted solenoid Bx
  - Orbit correctors are **needed regardless of correction scheme**, these are not additional elements
- 3 **families of skew quadrupoles** placed at several hundred meters from IP to match vertical dispersion and coupling
- **Bx components** are winded around QD0A and QF1A to control emittance growth, orbit bump and dispersion bump

Sources of Background in the MDI area

Luminosity backgrounds

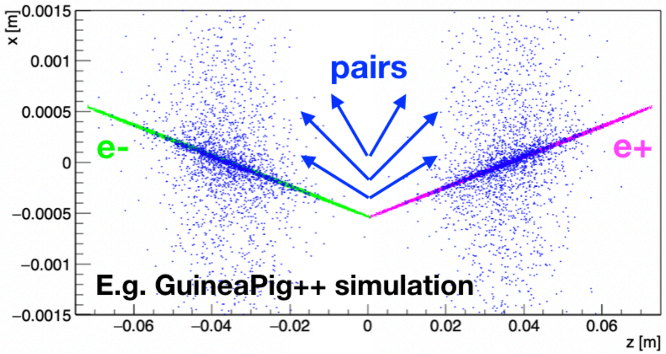
- **Incoherent Pairs Creation (IPC)**: Secondary e^-e^+ pairs produced via the interaction of the beamstrahlung photons with real or virtual photons during bunch crossing.
- **Radiative Bhabha:** beam particles which lose energy at bunch crossing and exit the dynamic aperture

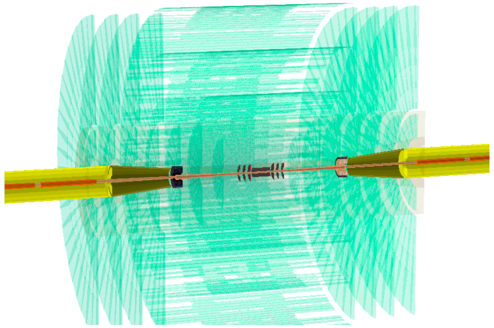
Single beam induced backgrounds:

- **Beam losses from failure scenarios:** high rate of beam losses in the IR coming from halo (transverse or longitudinal) being diffused by the collimators after lifetime drop
- **Synchrotron Radiation:** photons escaping the tip of the upstream SR mask at large angles
- **Beam-gas** (elastic, inelastic), Compton scattering on **thermal photons**: preliminary studies exist, needs to be replicated for new beam parameters

Background assessment: workflow with Key4hep

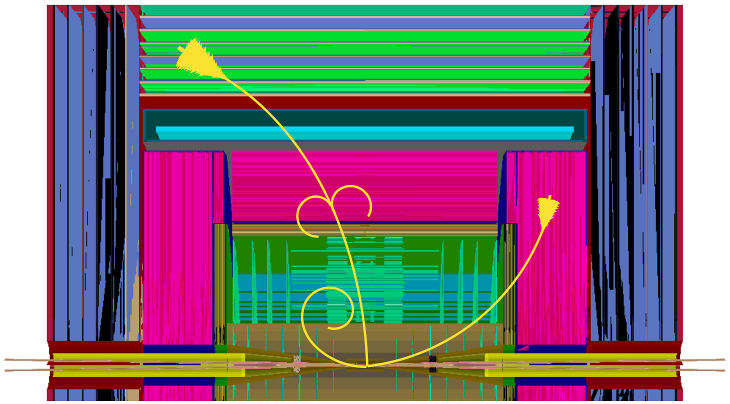
Primaries produced by **external generators** (GuineaPig++, BDSim, Xtrack, …)



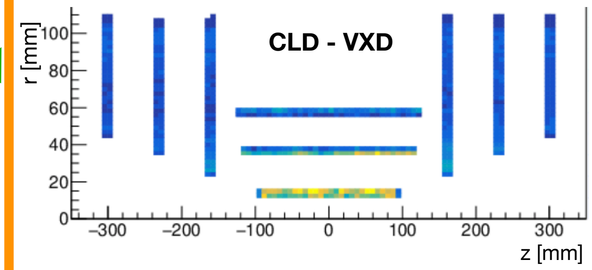


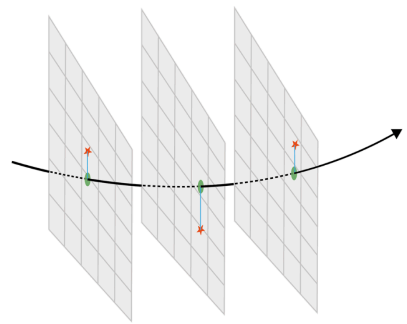
Detector and MDI geometry description in **DD4hep:** public common git repo

Tracking particles in the detector performed by **turnkey software Key4hep** - Geant4 physics libraries, DD4hep implementation, magnetic field map, …



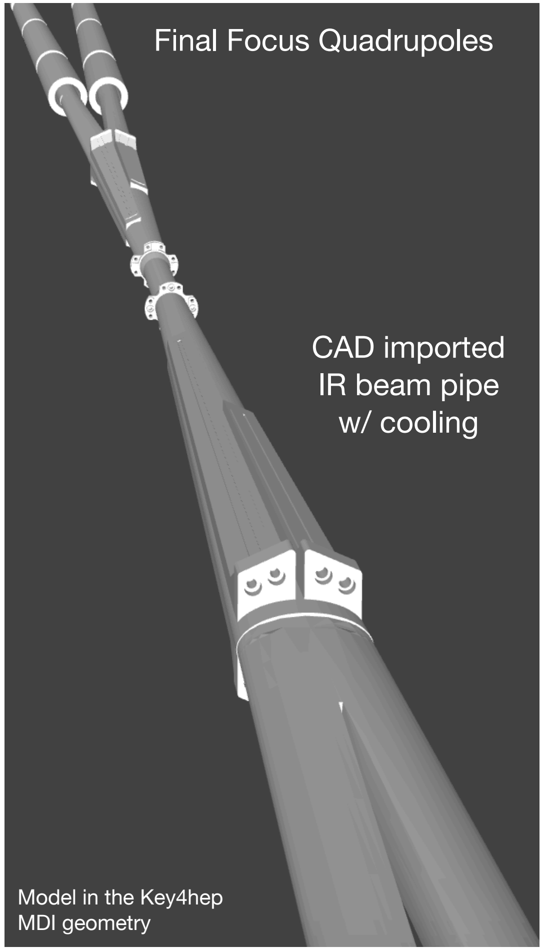
Hits collected for analysis and occupancy determination





Signal **reconstruction**

Key4hep MDI modelization



Engineered CAD model of AlBeMet162 beam pipe imported in **Key4hep**.

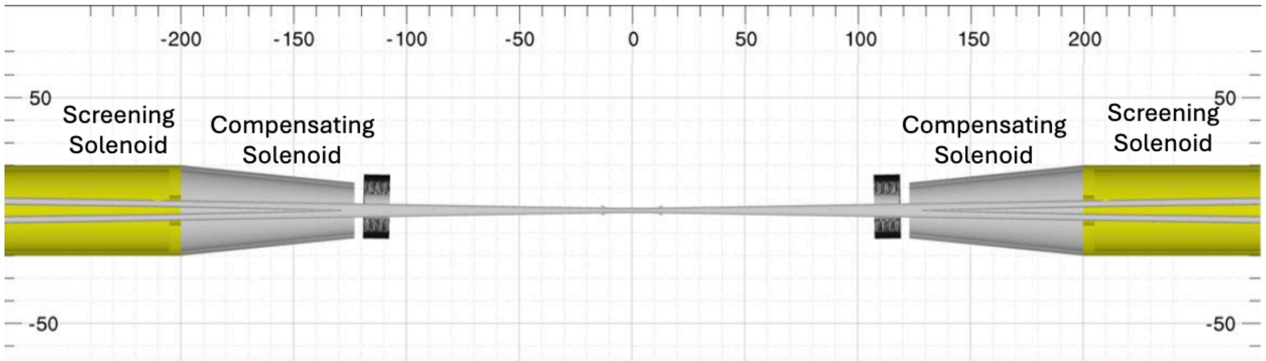
- Double-layered central section for paraffine cooling
- **Cooling manifolds** for ellipto-conical chambers implemented
- Beam pipe **separation region** profile congruent to impedance studies

Compensating and Screening solenoid cryostats

Final Focus Quadrupoles simple equivalent material model

<u>Future upgrades</u>:

- realistic **bellows** to be placed before beam pipe separation, currently under development
- IR carbon fiber **support tube**

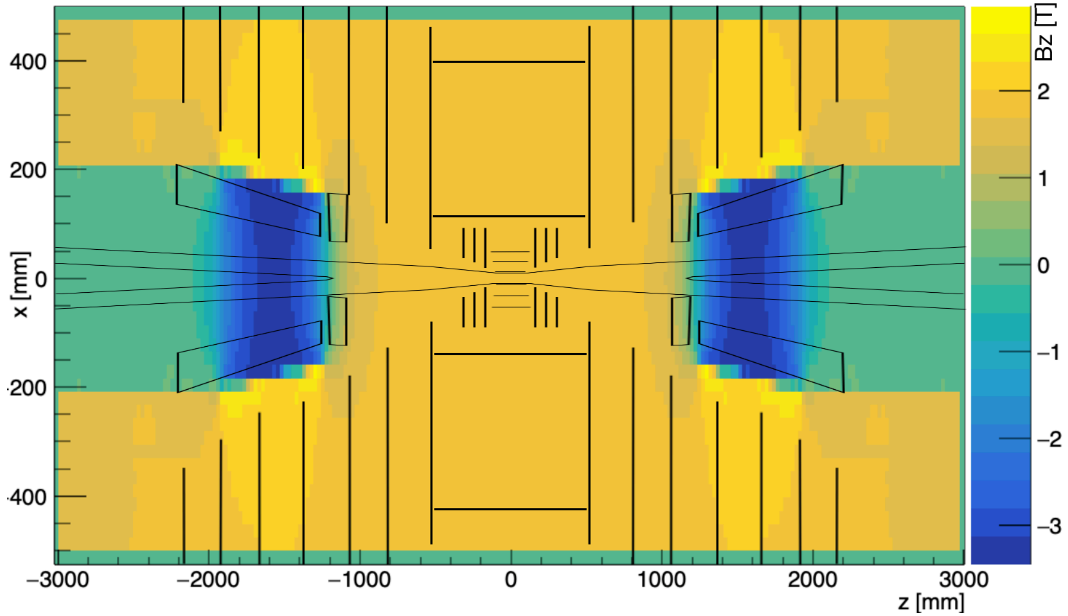


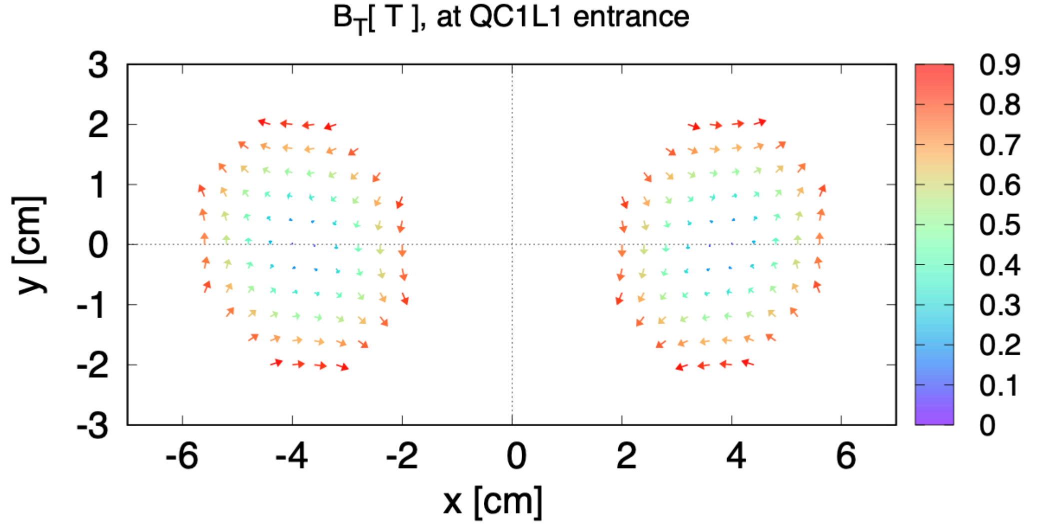
Magnetic Fields in the IR

In addition to the 2T solenoidal field of the experiment, allow for correct tracking of charged background particles, in particular those generated in the separated beam pipe region of the MDI area.

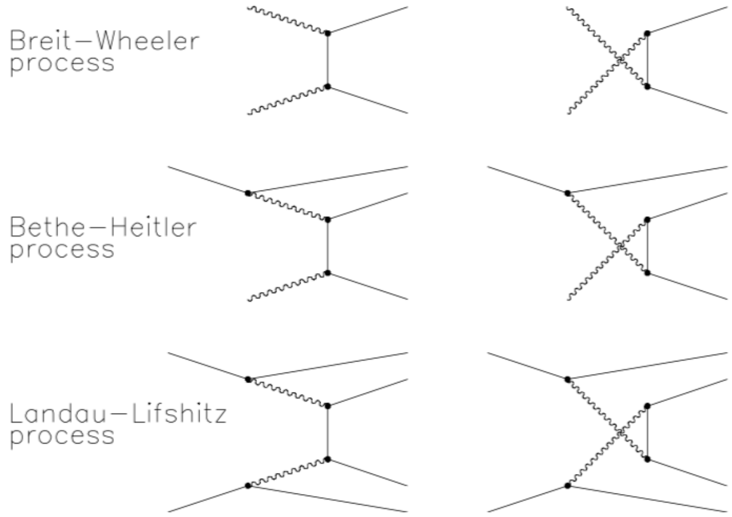
- Field coming from the **anti-solenoids** (screening-S, compensating-S) imported via **field map** to account for fringe effects

- Implementation of **FF quadrupole fields** in the Key4hep geometry



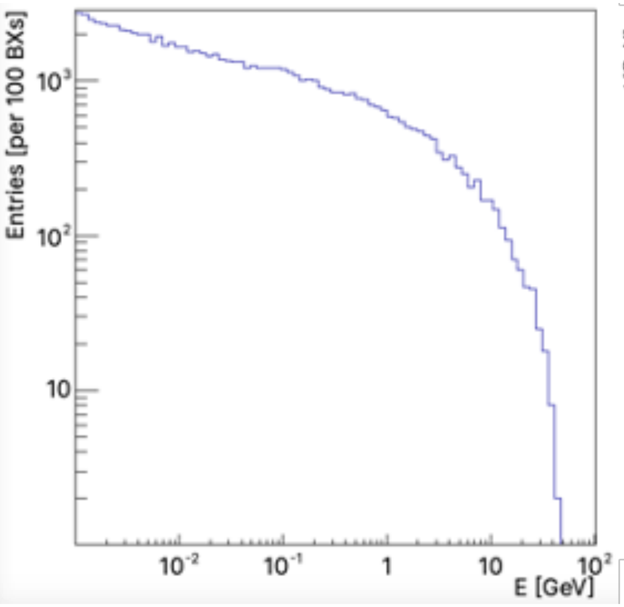


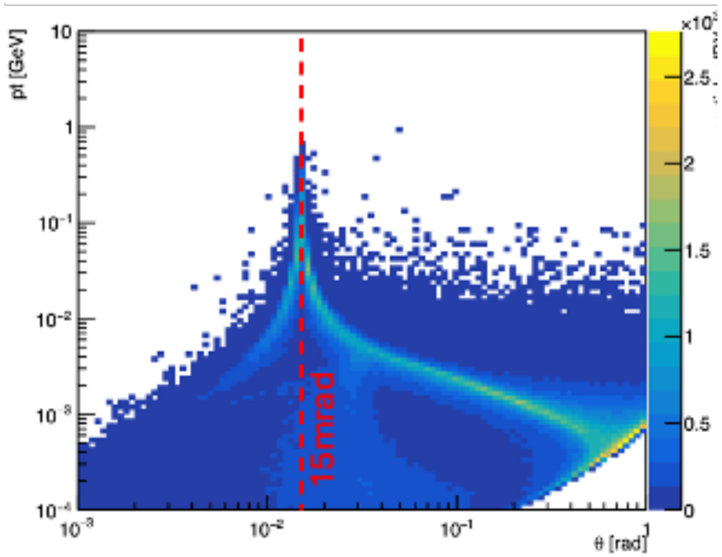
Incoherent Pairs Creation (IPC)



This process has been simulated using the generator **GuineaPig++.**

First occupancy calculations @Z-pole performed for CLD vertex/tracker, IDEA vertex/DC, and ALLEGRO ECal (see A. Ciarma FCCWeek24) show low background levels or possible background suppression strategies.





Beam parameters for V23 (06/05/2023)

β_x, β_y [mm]	110/0.7
σ_x, σ_y [μm]	8.837/0.031
σ_z [μm]	12700
N_e [10^{11}]	15.1
N_{IPC} per BX	~900

Number and kinematics of IPCs change with the evolution of the beam parameters!

Radiative Bhabha: beam losses in IR

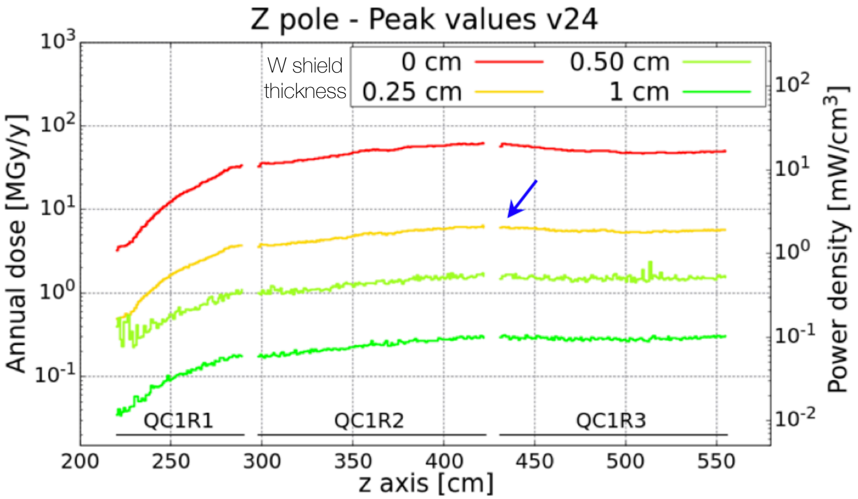
During bunch crossing beam particles can **lose energy** via photon emission, and exit the lattice **energy acceptance**.

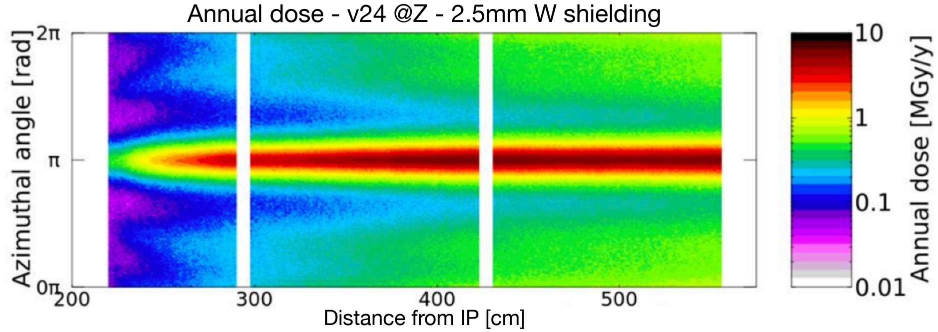
Particles produced using **BBBrem**[1] and **GuineaPig++**.

Off-energy particles are tracked downstream to estimate the **power deposited** on the SC final focus quadrupoles.

FLUKA simulations show that a **thin tungsten shielding** between the magnets and the pipe efficiently reduces the total dose below O(10MGy/y).

Integration of this shielding is an important part of the magnets final design.



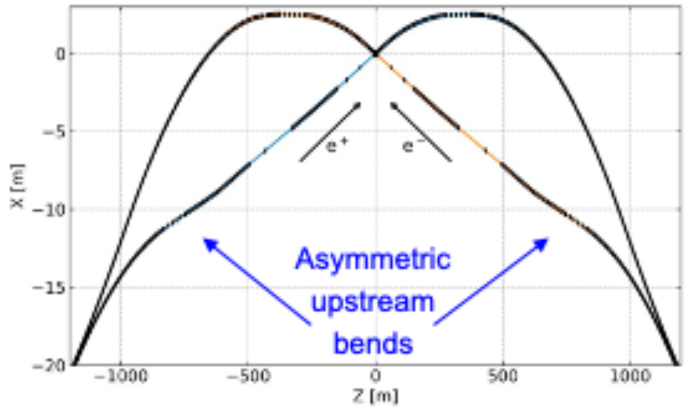


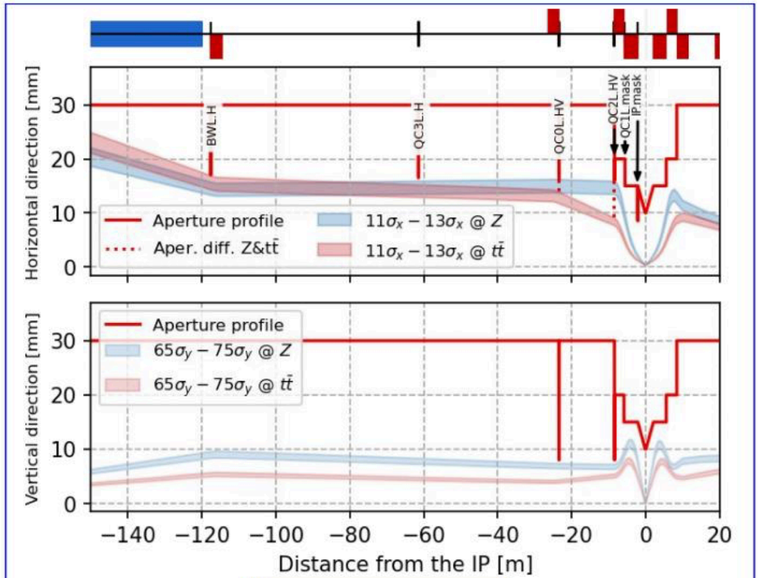
[1] BBBREM – Monte Carlo simulation of radiative Bhabha scattering in the very forward direction, R. Kleiss, H. Burkhardt

Synchrotron Radiation

SR is the **main driver** for FCC-ee MDI and lattice design

- **Asymmetric bend** to mitigate SR coming from upstream magnets
- Characterization of the radiation using **G4 based tool BDSim**
- Tungsten **SR collimators and masks** to protect the IR





GHC lattice

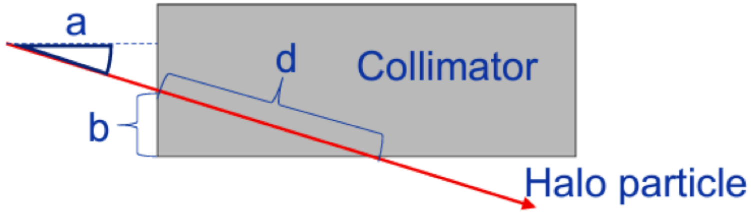
SR Background coming from the **beam core** particles is **shielded** thanks to the **tungsten masks**. Other contributions currently under study are:

- **beam halo** particles
- top-up **injection**

Characterization of background is essential for **dedicated shielding** design.

First tracking in key4hep ongoing for **occupancy calculation**.

Generic Halo Losses in the IR



a = angle of incidence
b = impact parameter
d = distance traversed

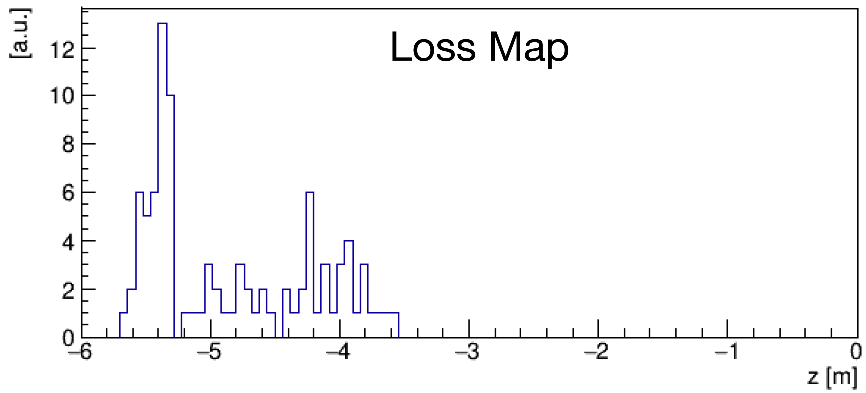
Following **beam lifetime reduction** due to a slow process, beam halo particles can be **lost in the MDI region** following the interaction with the **main collimators**.

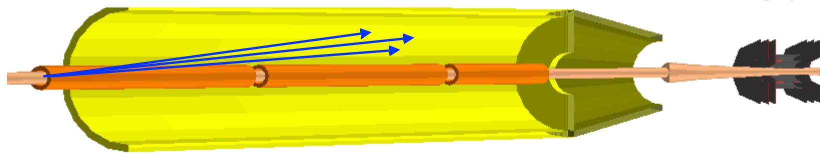
This study is independent on the loss process, particles are generated hitting the collimator with a given **impact parameter range** and tracked for 500 turns into the full lattice.

Tracking performed using **X-Suite**, interfacing with **BDSIM** for the collimator interaction.

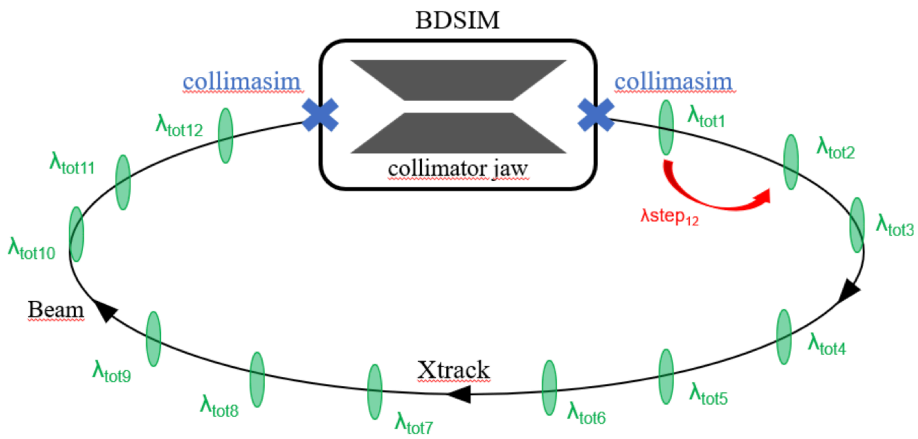
Particles hitting the beam pipe in the MDI region need to be tracked using **FLUKA / key4hep** to study the production of secondaries and the **induced backgrounds** in the detector.

➡ optimization of collimation scheme and shielding design





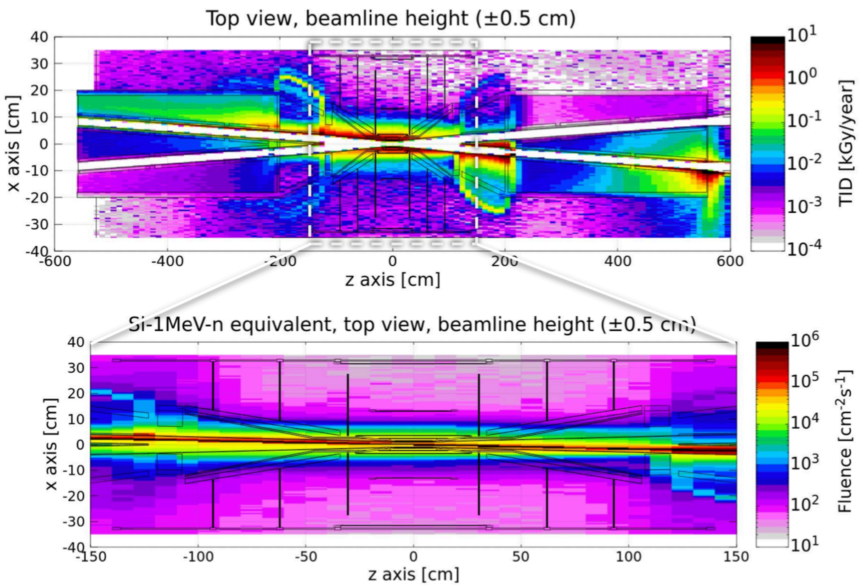
Beam-gas Losses from multi-turn



First multi-turn tracking in **X-Suite** using **beam-gas elements** based on lattice pressure profile.

Dominant contribution: **inelastic beam-gas** (Bremsstrahlung)

First loss maps produced, tracking in key4hep will follow.



Beam-gas Losses in IR

Local beam-gas losses in the IR studied also with FLUKA.

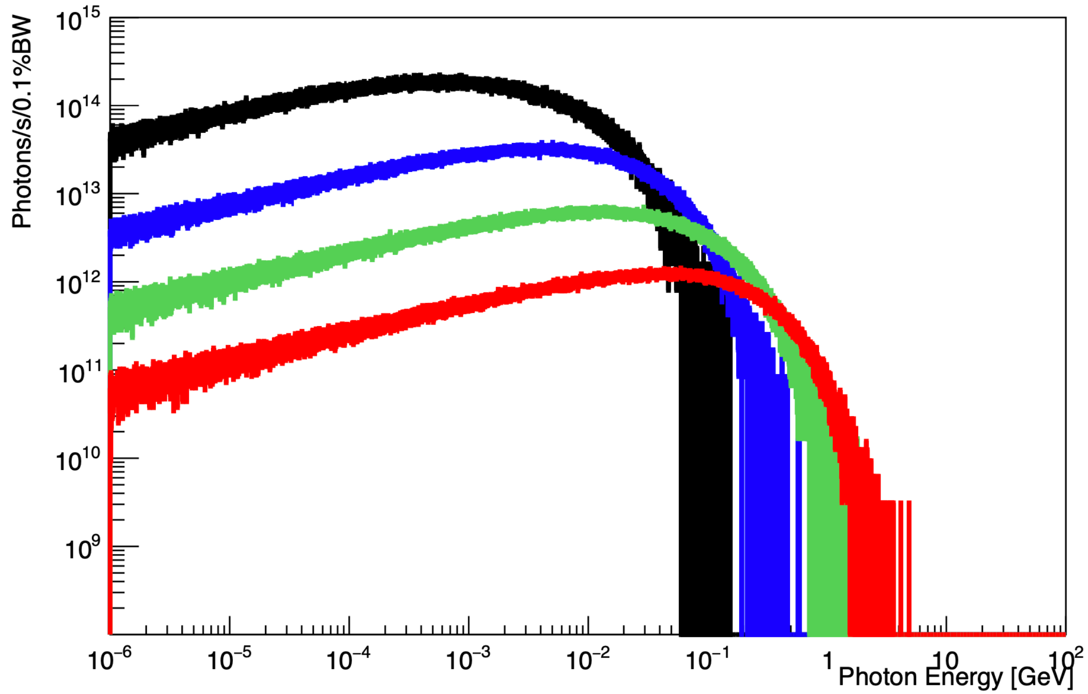
- Geometry includes both beam lines, SR masks and collimators, MDI elements, IDEA detector.
- particles generated from 500m upstream the IP
- first loss maps for e^- and photons
- Total Ionizing Dose below kGy/year

Beamstrahlung radiation Characterisation

The photons are emitted **collinear to the beam** with an angle proportional to the beam-beam kick.

This radiation is extremely intense **O(100kW)** and **hits the beam pipe** at the end of the first downstream dipole.

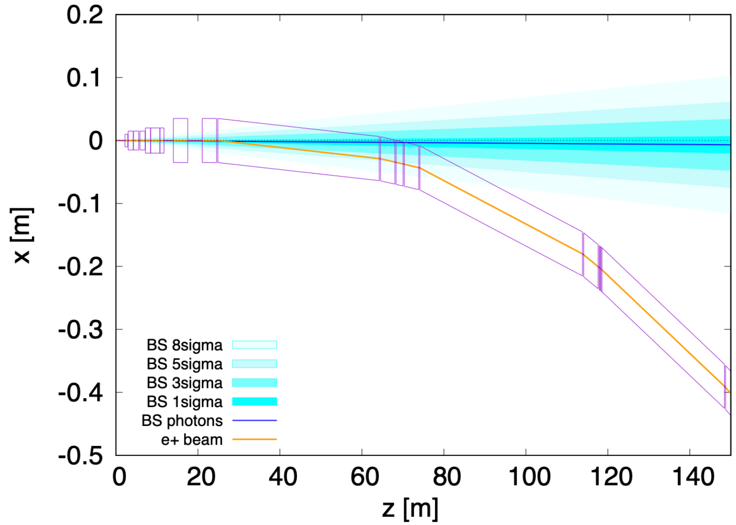
The generator for the beamstrahlung radiation is **GuineaPig++**



	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

M. Boscolo and A. Ciarma, "Characterization of the beamstrahlung radiation at the future high-energy circular collider" Phys. Rev. Accel. Beams **26**, 111002

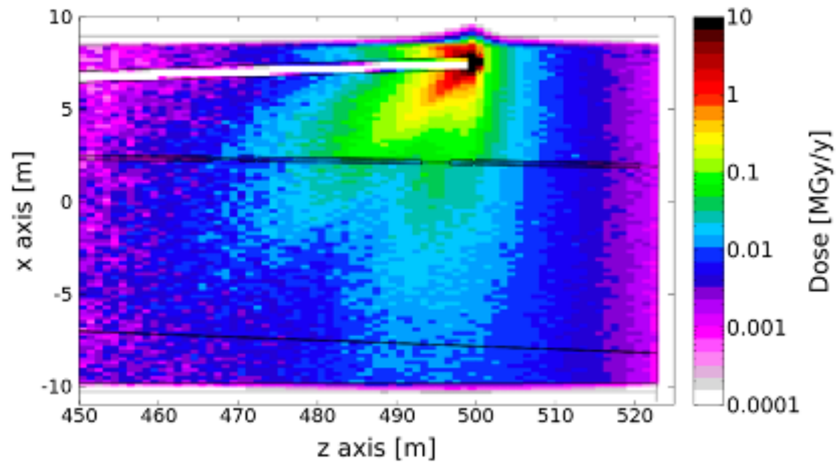
Beamstrahlung extraction line and beam dump



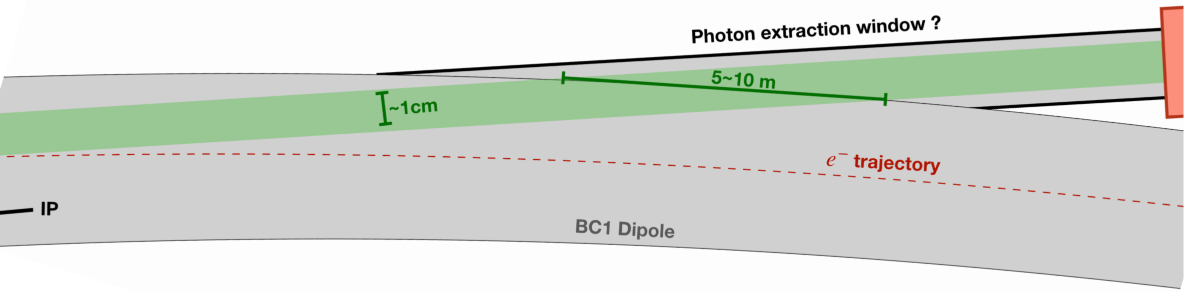
A **dedicated extraction line** is used to collect the intense radiation produced at the IP.

The downstream **magnets** need to be **redesigned** to allow the passage of the extraction line.

Integration with the tunnel show that a possible location of the beamstrahlung dump is **500m from the IP**.



First studies using FLUKA to determine **power absorption** in the dump and potential damages to main ring electronics are ongoing.



Summary

Significant progress on all key aspects of the FCC-ee MDI design:

- Engineered model of the low impedance beam pipe
- Cylindrical support tube for assembly and vertex detector and LumiCal integration
- Development of primary collimators to mitigate IR beam losses
- Synchrotron Radiation masks
- Detector background estimation
- Beamstrahlung photon dump
- Alternative solenoid compensation scheme