Combined talk: Digitization for tracker/vertexing full simulation. Tracking performance tools & Beam-induced backgrounds

5th FCC / DRD France Workshop, Paris (Nov. 26–28, 2025)

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Work also from Jérémy Andrea, Anita Sadowski – IPHC Strasbourg
J. Eyseman et al. (MIT)

Context and motivation

High-precision tracking and vertexing are central to the FCC-ee physics programme. Realistic detector performance studies require detailed full simulation, including detector response and background conditions.

Digitization bridges the gap between Geant4 energy deposits and reconstructed hits. Tracking studies and beam-induced background simulations then guide detector optimisation and electronics requirements.

Objective: establish a coherent chain from beam conditions to detector response, reconstructed objects and performance.

Simulation and detector R&D

A detailed detector simulation at all stages is essential to guide design and optimisation.

From physics goals to detector concepts:
- In the early phase, simple and fast simulations are sufficient to estimate the required performance.
- In the concept phase, full and detailed simulations are needed to demonstrate physics reach.

R&D and demonstrators:
- Beam tests and prototypes feed back into the simulation, making it progressively more realistic.
- Algorithms for calibration, reconstruction and analysis are developed and validated together with the simulation.

Full simulation chain

A realistic detector description enters at each step of the full simulation chain:

1. Event generation: physics generators provide the processes of interest.
2. Geant4: particle–detector interactions and energy deposition.
3. Digitization: conversion of deposited charge into realistic detector signals.
4. Reconstruction: building tracks and physics objects from hits.

In this talk the emphasis is on digitization for the silicon tracker and vertex detector as a key element for performance realism.

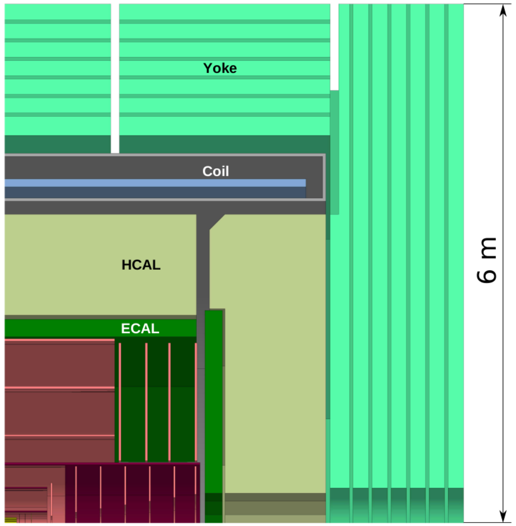
CLD detector concept

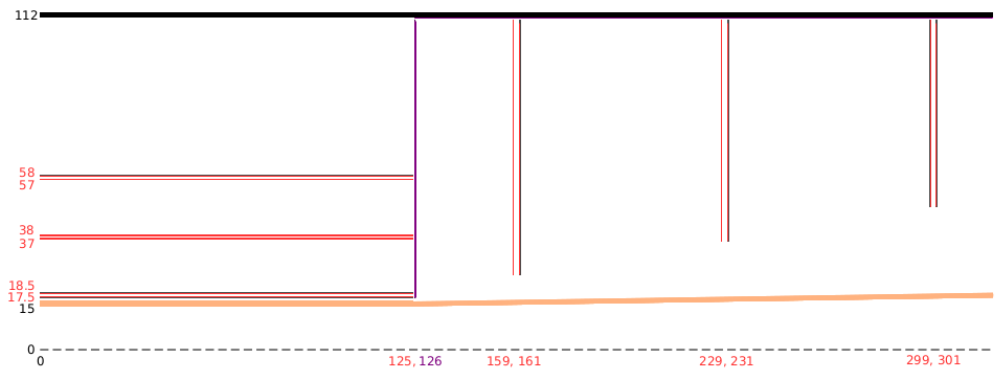
CLD is a CLIC-like detector concept featuring an all-silicon tracker in a 2 T solenoid.

Vertex detector:
- 3 barrel double layers and 3 endcap double layers.
- 20×20 μm² MAPS pixels, 50 μm thick sensors.

Tracker:
- Silicon strips with 50 μm pitch and 300 μm length.
- Additional inner pixel disk with 50×50 μm² pixels.

The material budget is kept between about 1.1% and 2.2% X0 per layer to achieve excellent impact-parameter resolution at FCC-ee luminosities.



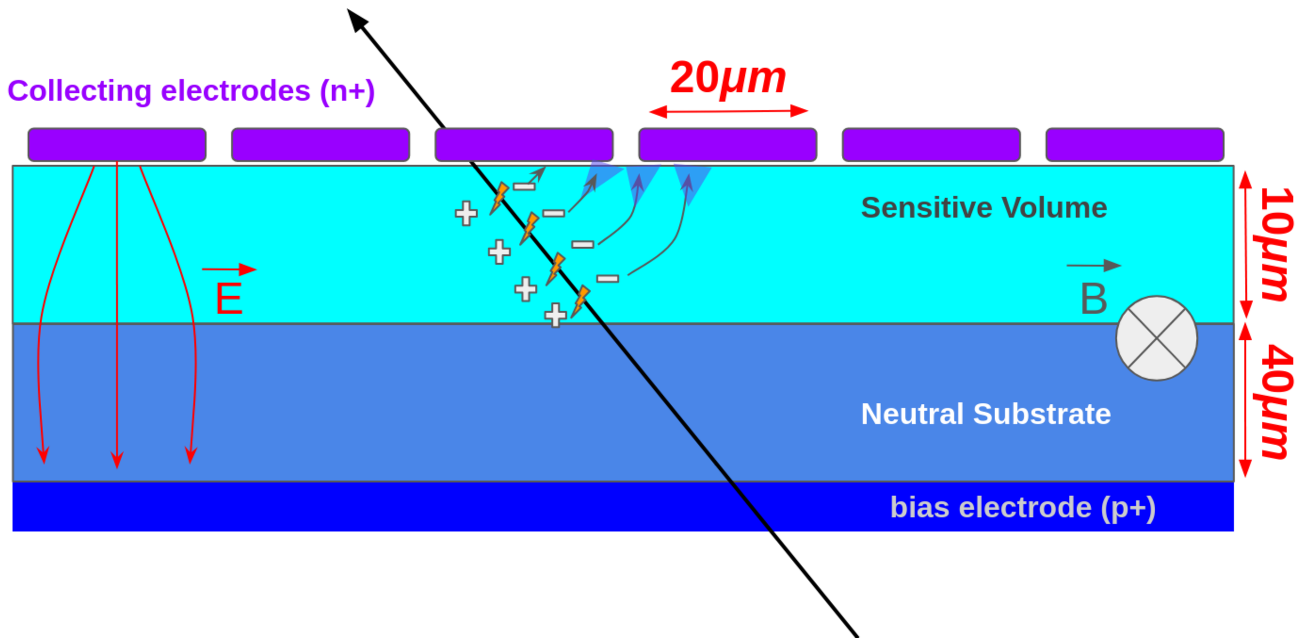


Digitizer: charge creation and transport

Input to the digitizer: SimTrackerHits from Geant4 with position, time and deposited energy (key4hep).

Along the particle path through the sensitive volume:
- The step is segmented and the energy loss converted into ionisation charge.
- Charge carriers are drifted in the depletion region with an assumed uniform electric field.
- The Lorentz angle is included (~0.1 rad per Tesla, inspired by CMS studies).
- Thermal diffusion is modelled as a Gaussian charge cloud with $\sigma \approx 1.5$ µm for a 50 µm path.

The result is a realistic spatial distribution of charge approaching the pixel plane.



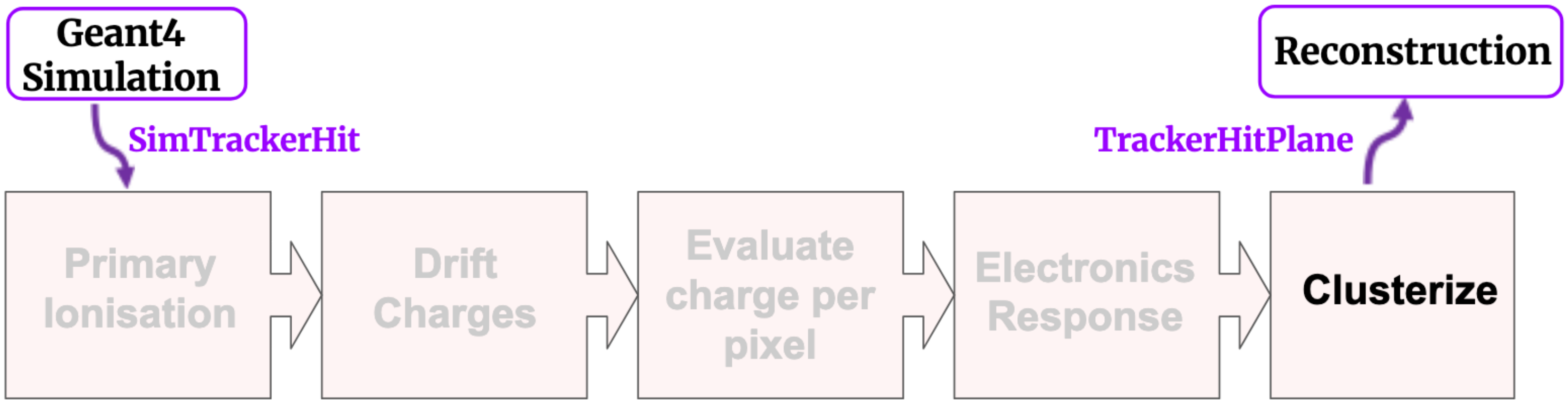
Digitizer: pixelisation and clustering

For each pixel or strip, the collected charge is obtained by integrating the charge cloud over the sensor segmentation.

A threshold of 100 e^- is applied to emulate the response of the front-end electronics. Planned extensions include electronic noise, and realistic pulse shapes.

Clusters are built from neighbouring pixels:
- The cluster position is computed as a charge-weighted centroid.
- The total collected charge is converted back to an energy estimate.

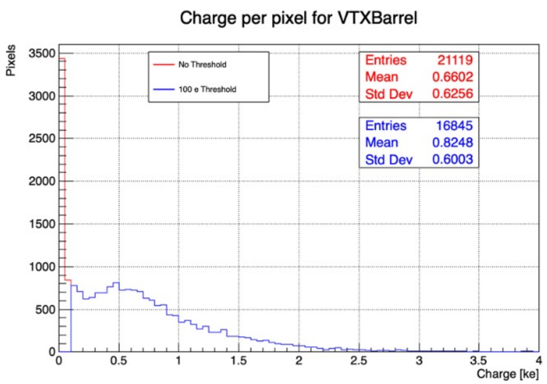
The digitizer outputs TrackerHitPlane objects used by the reconstruction, with position, uncertainties, time and energy.

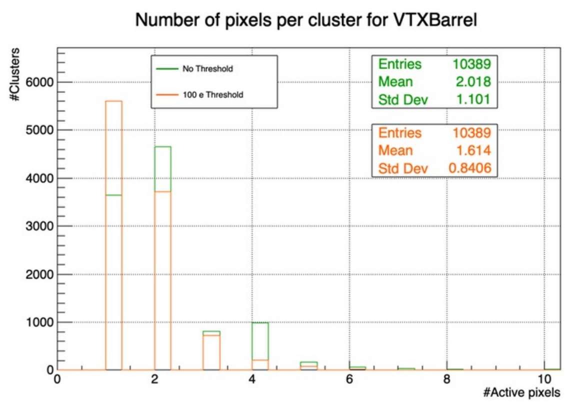


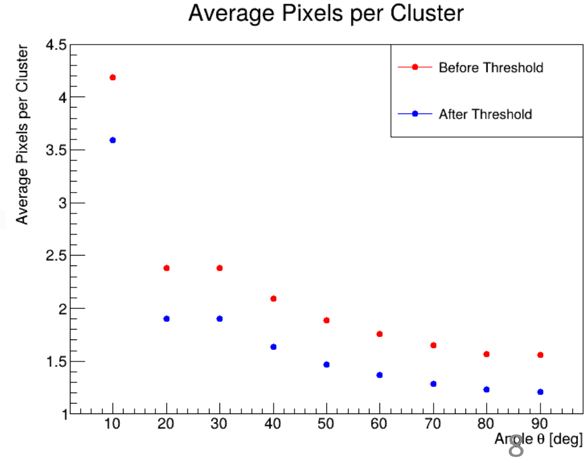
First results: pixels and clusters

Full results presented by Jessy Daniel in [Pisa FCC-ee vertex detector R&D workshop]()
A first validation sample uses 2000 muons with 10 GeV crossing the vertex barrel.

Main observations:
- The average ionisation of ~66 e⁻ per µm is consistent with expectations.
- Applying the 100 e⁻ threshold reduces the number of fired pixels by about 20%, while the number of clusters remains almost unchanged.
- The average cluster size decreases with increasing incident angle, as expected from the changing path length and charge sharing.







Spatial resolution

The single-hit resolution is extracted from the distance between true and digitized hit positions.

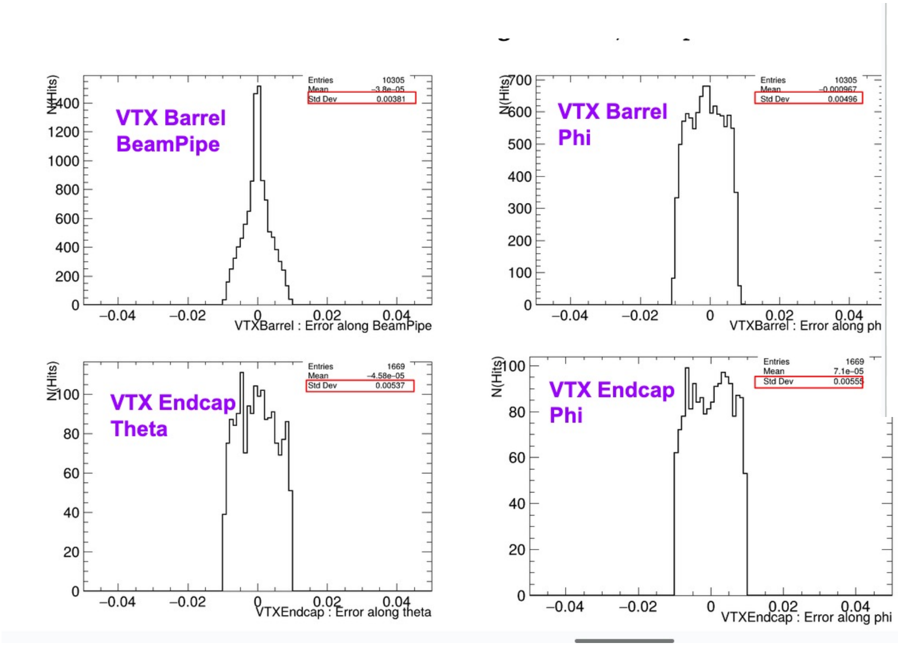
Vertex barrel:

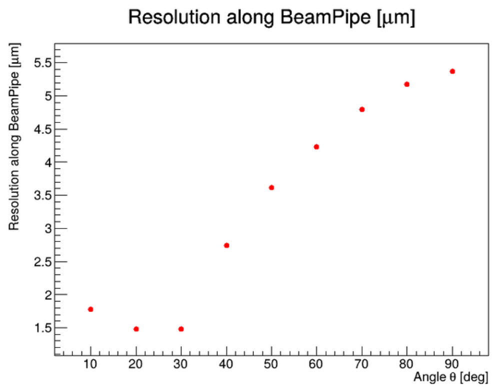
- Around 3.8 µm along the beam axis (z) and about 5.0 µm in the transverse direction (ϕ).

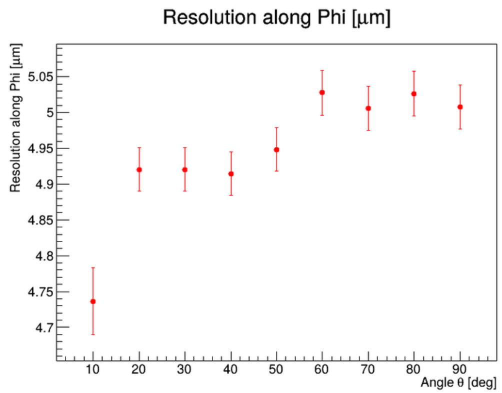
Vertex endcap:

- Single-hit resolution around 5.5 µm.

The resolution along z depends on the track pseudo-rapidity, while the transverse resolution remains nearly constant.







Digitization: summary

A detailed silicon digitizer has been implemented within the Key4HEP / FCCSW framework by IP2I.

Key features:
- Modular implementation, largely independent of the specific sensor geometry.
- Supports both pixel and strip technologies.
- Reproduces realistic cluster properties and single-hit resolutions for CLD.

Next steps:
- Add noise, ageing (? or defects) and timing effects in the electronics chain.
- Validate on alternative detector layouts (e.g. SEED) and more realistic event samples.
- Use the digitizer for full tracking performance and background studies.
    - Occupancy, realistic rates

From detector response to realistic operating conditions

Realistic tracking and vertexing performance predictions require combining:
- Detailed digitization of the detector response.
- Fast tools to explore tracking performance vs geometry and material.
- Realistic beam-induced backgrounds (BIB) to set occupancy and rate conditions.

So far, the focus has been on modelling the detector response itself.
The next step is to assess the impact of beam-induced backgrounds on occupancies, layout decisions and Electronics R&D strategies.

Next slides largely inspired from the daq presented at the last TDAQ workshop (Nov 25) :
Machine-detector interface: beam and detector simulation interface studies presented by J Eysermans et al. (MIT)

Beam-induced backgrounds: overview

Beam-induced backgrounds (BIB) are a key input to detector design at FCC-ee.

A consistent framework is required to address:
- Modelling and characterisation of BIB sources and generators.
- Occupancy studies in vertex, tracking and muon systems, both globally and locally.
- Detector layout and shielding optimisation to mitigate BIB.
- Impact of BIB on physics analyses and background rejection.

Here we focus on luminosity-induced backgrounds and their impact on the inner vertex regions.

beam and detector simulation interface studies presented by J Eysermans et al. (MIT)

Sources of beam-induced backgrounds

Beam-induced backgrounds can be grouped into two main categories:

1. Single-beam backgrounds (from one circulating beam):
   - Synchrotron radiation from final-focus and bending magnets.
   - Beam–gas scattering, beam halo losses, injection backgrounds and instabilities.

2. Luminosity-induced backgrounds:
   - Incoherent Pair Creation (IPC).
   - Radiative Bhabha scattering.
   - Beamstrahlung photons and two-photon processes.

At the Z pole, the combination of very high luminosity and bunch rates makes these backgrounds especially challenging.

beam and detector simulation interface studies presented by J Eysermans et al. (MIT)

Simulation of single-beam backgrounds

Single-beam backgrounds are modelled through a dedicated simulation chain:
- XSUITE and related tools describe accelerator and beam dynamics.
- BDIM / FLUKA simulate particle–matter interactions and transport up to the detector interface.
- Geant4-based detector simulation propagates particles through the detector volume.

This chain produces lists of background particles at the interface surface, to be used as input for full detector simulation and occupancy studies.

Several samples are already produced and will be evaluated in detail.

[beam and detector simulation interface studies presented by J Eysermans et al. (MIT)]

Luminosity backgrounds and Guinea-Pig

Luminosity-induced backgrounds are dominated by Incoherent Pair Creation (IPC) and radiative Bhabha processes.

The Guinea-Pig (GP) code is used to simulate beam–beam interactions and corresponding BIB:
- Macro-particle representation of the colliding beams.
- Finite-element grid for the electromagnetic fields.
- Beams are sliced longitudinally and tracked through the interaction region.
- IPCs and other processes are generated on the grid and propagated in the beam fields.

The resulting particle kinematics are then passed to Geant4/ddsim for detector-level studies.

beam and detector simulation interface studies presented by J Eysermans et al. (MIT)

Improvements in Guinea-Pig modelling

Initial GP configurations exhibited two main issues:
- Some pairs propagated outside the field grid and even outside the beampipe.
- The detector magnetic field was not taken into account during propagation.

Recent improvements include:
- Stopping IPC propagation at the edge of a reduced grid fully contained in the beampipe.
- An option to use production kinematics without in-GP tracking in the beam fields ("noTracking").
- Implementation of a uniform Bz field, validated against analytic propagation.
- Studies of grid density, showing that a reduced mesh preserves relevant observables while lowering CPU time per event.

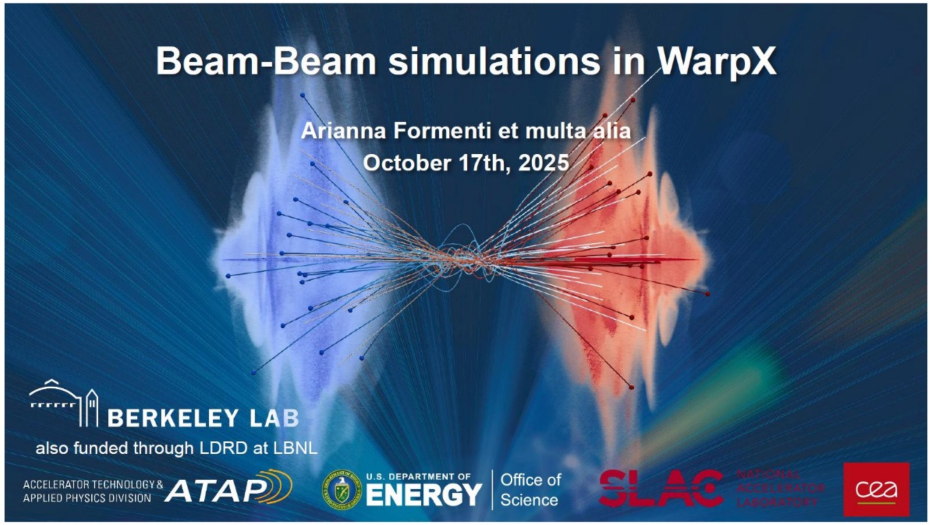
The improved GP configurations have a direct impact on simulated occupancies in the innermost vertex layers.
These ongoing studies help define realistic safety factors and support vertex layout choices.

beam and detector simulation interface studies presented by J Eysermans et al. (MIT)

From Paul Colas talk given during the morning session today

WarpX

- Modernize the software (Andrea Ciarma, DESY PhD student Victor Schwan,…)
- To replace the GuineaPig generator which is not maintained anymore.



Tracking studies and French efforts

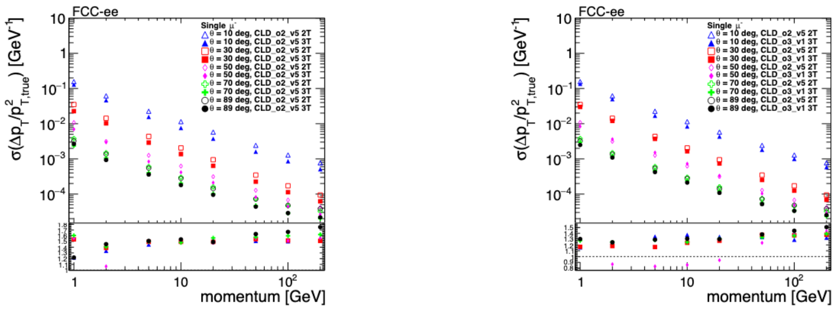
A dedicated tracking study effort started in France (IPHC Strasbourg)
A flexible tool has been developed to evaluate tracking resolution as key parameters vary:
- Detector geometry and beam-pipe material budget.
- Single-hit spatial resolution and particle identification hypotheses.
- Magnetic field strength and configuration.

Results have been presented in FCC detector concept meetings, LCWS2024 and ECFA workshops, providing guidance for vertex and tracking design choices.

Tracking resolution

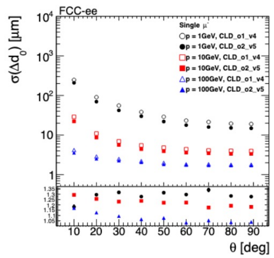
Effect of magnetic field

- Magnetic field of **2 T** is imposed for Z peak ($\sqrt{s} = 91$ GeV)
- **2 T** to **3 T** (without any consideration of whether it is possible)increase p_T resolution and compensate the loss of p_T resolution caused by the shrunk tracker



Effect of shortened vertex detector and Beam Pipe material budget

Beam Pipe and Vertex geometry



- Improvement of the d_0 resolution in the new geometry (o2_v05)
  - **Smaller vertex radius compensates fully for the increased material budget in beam pipe**

CLD_o1_v04 (nominal geometry)
- Beam Pipe **radius**: **15** mm
- Beam Pipe **material**: Beryllium
- Beam Pipe **thickness**: **1.2** mm + 5 µm gold
- **X/X0** = **0.45 %**

CLD_o2_v05
- Beam Pipe **radius**: **10** mm
- Beam Pipe **material**: AlBeMet 0.35 mm + paraffin 1 mm + AlBeMet 0.35 mm
- Beam Pipe **thickness**: **1.7** mm + 5 µm gold
- **X/X0** = **0.61 %** ⇒ **+ 33 % material budget**

Vertex Barrel [mm]	R_1	R_2	R_3	L
o1_v04	17.5	37	57	125
o2_v05	**13.0**	**35**	**57**	**109**

CLD_01_v04: BeamPipe material 100 % Be, BeamPipe radius = 15 mm
CLD_02_v05: BeamPipe material AlBeMet + paraffin, BeamPipe radius = 10 mm

Global view: from beams to physics

This talk connects three complementary ingredients needed for realistic FCC-ee tracking performance predictions:

- Digitization:
  Detailed simulation of the detector response, turning Geant4 energy deposits into reconstructed hits. This enables realistic modelling of clusters, resolutions and tracking performance.

- Tracking performance tools:
  Fast and flexible evaluation of tracking resolutions and efficiencies as geometry, material budget and magnetic field are varied. These tools guide detector design choices.

- Beam-induced backgrounds (BIB):
  Definition of realistic occupancies and data rates in the innermost layers, driving constraints on layout, readout architecture and TDAQ capabilities.

Together, they provide a consistent chain from beam parameters to reconstructed physics objects and detector optimisation.

Take-home messages

Digitization:
- A detailed, modular silicon digitizer is now available within Key4HEP / FCCSW (IP2I).
- First studies for CLD show realistic cluster behaviour and spatial resolutions.

Tracking tools:
- Dedicated tools developed at IPHC quantify the impact of geometry, material and B-field.
- They are crucial to navigate design trade-offs for vertex and tracking systems.

Beam-induced backgrounds:
- Improved Guinea-Pig modelling and full-simulation studies yield more reliable occupancy estimates.
- IPCs remain the dominant luminosity-induced background in the inner layers and set important constraints on detector and electronics design.

Overall:
- A coherent treatment of simulation, tracking performance and BIB is mandatory for robust FCC-ee detector performance predictions.
- The ongoing joint effort puts us in a good position for informed design decisions in the coming years.

material from
J. Eysermans (MIT) – presented at the last TDAQ meeting
G. Sadowski - Talk at LCWS 2024
J. Daniel – Talk at **FCC-ee vertex detector R&D workshop**