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Design and Performance of the IDEA Vertex Detector at FCC-ee in Full Simulation

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The FCC-ee is a proposed future e^+e^- collider aimed at producing an unparalleled number of Higgs, Z, and W bosons, as well as of top quarks, in very clean experimental conditions. Numerous measurements at the FCC-ee rely on a precise and accurate measurement of the location of the primary and secondary vertices.
This work presents the implementation of the IDEA vertex detector in full simulation using the Key4hep and DD4hep frameworks widely used by the future collider communities. The IDEA vertex detector is represented in DD4hep in great detail, using the correct stack of materials for the support, cooling and readout structures. The silicon sensors are described as multiple sensitive and insensitive volumes, properly representing the sensor layout. The material budget is evaluated to be $\approx 1/3\%$ X_0 per inner vertex layer at normal impact, which aligns with the assumed material budget in the FCC conceptual design report. Soon, the complete IDEA detector will be available in full simulation, allowing the evaluation of the detector concept realistically.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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Introduction

The FCC-ee [1] is a 90.7 km circumference e^+e^- collider producing intense collisions at energies of 90–365 GeV, making it a Higgs, electroweak (EW), top and flavour factory.

With $2 \cdot 10^6$ Higgs bosons, $2.4 \cdot 10^8$ WW pairs and $6 \cdot 10^{12}$ Z bosons produced, the FCC-ee will significantly improve our knowledge of EW physics. An improvement of 1–2 orders of magnitude is estimated for EW precision observables providing indirect sensitivity to new particles of 10–70 TeV [1]. The vast Z sample in clean collisions leads to tiny statistical uncertainties, challenging the detectors to match with systematic uncertainties down to 10^{-4}–10^{-5} to exploit the FCC-ee fully.

1. FCC-ee vertexing requirements

At the FCC-ee experiments, a dedicated *vertex detector* is used in conjunction with the tracker to determine the spatial locations of vertices. This is crucial for efficient flavour tagging, precise flight distance measurements and the reconstruction of complex decay chains, e.g. in flavour physics and to measure for the first time the Higgs couplings to second generation quarks. The vertexing performance mainly depends on three items: The radius of the first layer, the spatial resolution of the sensors and the amount of material in the detector (*material budget*).

Minimising the vertex detector material budget is also crucial for the tracker and the calorimeter, as high material budge dilutes the resolution of the particle momentum and energy.

2. The IDEA detector concept

The IDEA (Innovative Detector for e^+e^- Accelerators [2]) detector concept depicted in Figure 1 foresees a light drift chamber using cluster counting and an outer silicon wrapper as the tracker. A time resolution of the wrapper of $O(30\,\text{ps})$ would enable supreme particle identification over large ranges of momenta. Outside of the tracker, there is the ultra-light solenoid coil and a dual-readout calorimeter with preshower. The muon system is located in the return yoke of the solenoid.

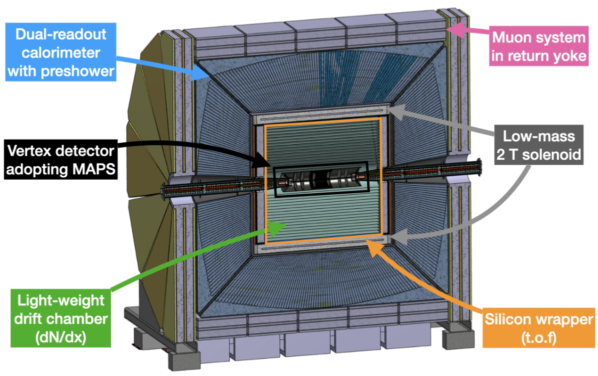

Figure 1: The IDEA detector concept for FCC-ee.

The vertex detector sits at the centre of IDEA, starting just outside of the beam pipe at a radius of 13.7 mm. The goal for the vertexing performance in IDEA is described by an impact parameter resolution in the transverse plane of $\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$ with $a \approx 5\,\mu$m and $b \approx 15\,\mu$ GeV [1], where b is the contribution from the material budget. The IDEA vertex detector is designed [3] using the ARCADIA monolithic active pixel sensors (MAPS) with pixels of $25 \times 25\,\mu\text{m}^2$ for the *inner vertex barrel* while the *outer vertex barrel* and *outer vertex disks* use ATLASPix3 quad sensors.

3. The IDEA vertex detector in Key4hep

The IDEA vertex detector is implemented in DD4hep to enable the estimation of the vertexing performance. DD4hep enables plug-and-play functionality so that parts of the detector can easily be rescaled or replaced by subdetectors from other detector concepts, for example. DD4hep is part of the *Key4hep* ecosystem, widely adopted by the future collider initiatives. It enables to perform all steps from MC generation to physics analysis in one coherent framework.

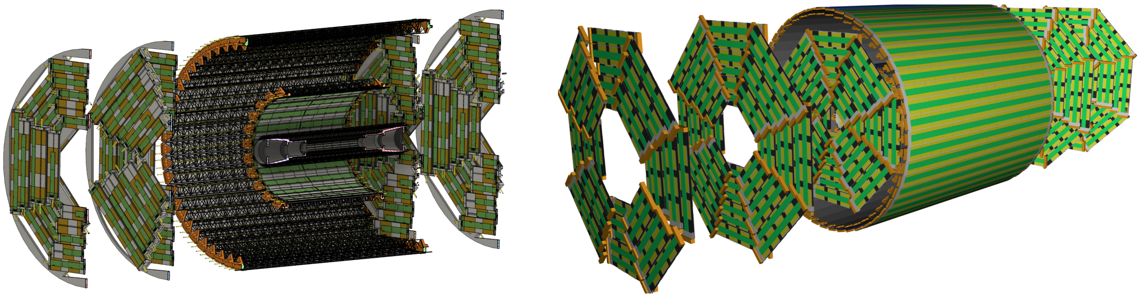

Figure 2: CAD model (left [3]) and DD4hep implementation (right) of the IDEA vertex detector.

Figure 2 compares the CAD model and the DD4hep detector model of the IDEA vertex detector. The latter describes the vertex detector correctly as staves of sensors, support structures, cooling pipes and readout flexes, using the correct material stack for all components. It also faithfully describes the sensitive and insensitive parts of the sensors. Complex support structures are imported directly from CAD using the DDCAD feature of DD4hep or implemented using proxy volumes with the correct material budget.

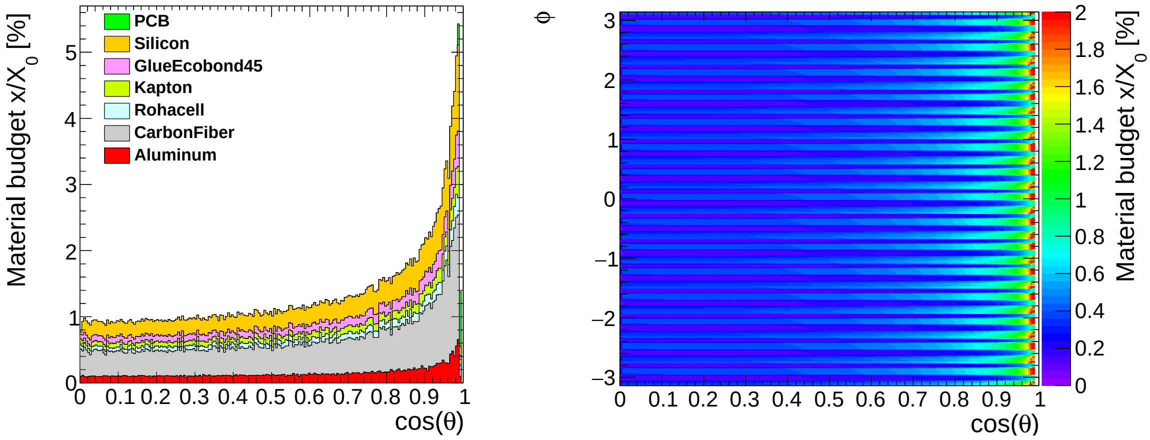

Figure 3: Material budget of the inner barrel (left) and its allocation for the full IDEA vertex detector (right).

The high level of detail enables a sophisticated material budget estimation, allows for checking for cracks in the detector coverage and assesses the vertexing performance realistically. Figure 3 shows the material budget by component in the vertex inner barrel and in the $\cos(\theta)$–ϕ plane for the innermost layer. The material budget shows good agreement with the value in Reference [1] of $3 \times 0.3\%$ x/X_0 for the three layers of the inner vertex detector. The consequences of the uneven distribution of the material budget along ϕ will have to be studied.

4. Curved wafer-scale MAPS for FCC-ee vertex detectors

As shown in Figure 3, the sensor itself (*silicon*) is only a small fraction of the total X_0. The tracking and vertexing performance could be further improved by reducing the material in the vertex

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detector to the bare minimum using wafer-scale curved MAPS as in the ALICE ITS3 project [4]. The power and data are transmitted in the silicon, and the power consumption is low enough to allow for air cooling. Thus, the detector almost only consists of the sensors, reducing the material budget to 0.05% X_0. Figure 4 shows a mechanical prototype of ITS3 and how much an ITS3-like vertex detector for FCC-ee would improve σ_{d_0}.

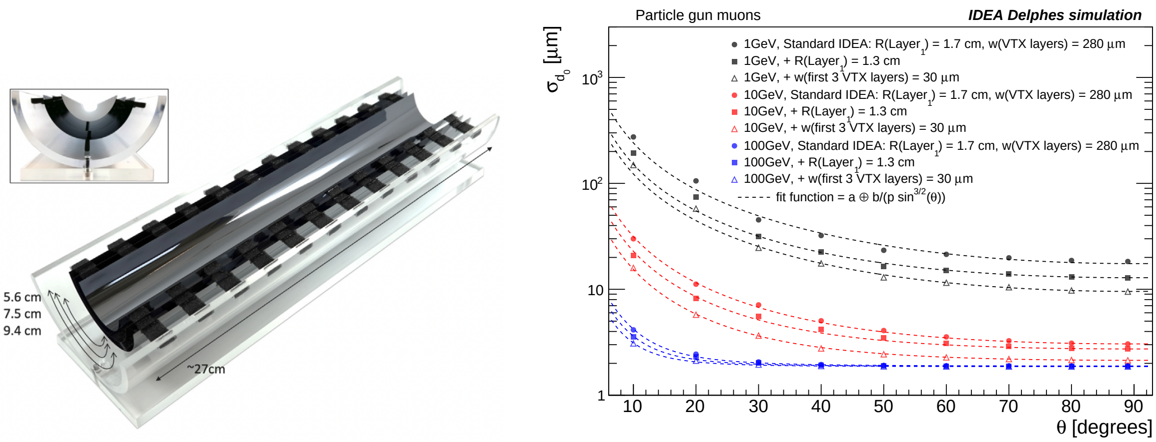

Figure 4: Mechanical prototype of the ALICE ITS3 detector [4] (left) and effect of reduced material budget on d_0 resolution in Delphes fast simulation (right, [5]).

Conclusions

This work presented the implementation of the IDEA vertex detector in DD4hep, showing good agreement with previous estimations of the material budget. Once all other subdetectors are also implemented, physics case studies can be performed using the IDEA detector concept in full simulation. The detector concepts will continue to adapt to new technologies in the next years.

References

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