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IDEA detector concept for FCC-ee

M. AL-THAKEEL(*) on behalf of the IDEA COLLABORATION
Dipartimento di Fisica e Astronomia "Augusto Righi", Università di Bologna and INFN, Sezione di Bologna - Bologna, Italy

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Summary. — IDEA (the Innovative Detector for Electron-positron Accelerator) is a detector concept optimized for future circular lepton colliders. In particular,the proposed sub-detector technologies for the IDEA concept are discussed, along with their expected performance.

1. – Introduction

The Future Circular Electron-Positron Collider (FCC-ee) [1] is proposed as the LHC's successor to advance energy and intensity frontiers of particle colliders, operating across a wide range of center-of-mass energies: the Z pole at 91 GeV, the WW threshold at 161 GeV, the Higgsstrahlung peak at about 240 GeV, and the $t\bar{t}$ threshold from 340 to 365 GeV. It aims to deliver precise measurements of Standard Model processes and explore potential new physics phenomena. The physics program includes detailed studies of Higgs boson properties, precision measurements of electroweak observables, flavour physics and searches for rare decays and new physics. These objectives are supported by the collection of extensive datasets, consisting of 5×10^{12} Z bosons, 10^8 W boson pairs, 10^6 Higgs bosons, and 10^6 top quark pairs. Achieving these ambitious goals requires exceptional detector performance across a wide range of energy scales and physics signatures.

2. – IDEA concept layout

The IDEA detector employs both established technologies refined through extensive R&D, as well as newer technologies with ongoing efforts to optimize their design. It consists of a silicon pixel vertex detector, a lightweight drift chamber, a silicon wrapper, a low-mass superconducting solenoid, a dual-readout fiber calorimeter, and muon chambers in the magnet return yoke. A new layout replaces the pre-shower with a high-resolution homogeneous crystal ECAL inside the solenoid, using dual-readout. Figure 1 compares both designs, while the following sections detail the sub-detectors.

(*) E-mail: `m.ali@unibo.it`, `mahmoud.ali@bo.infn.it`

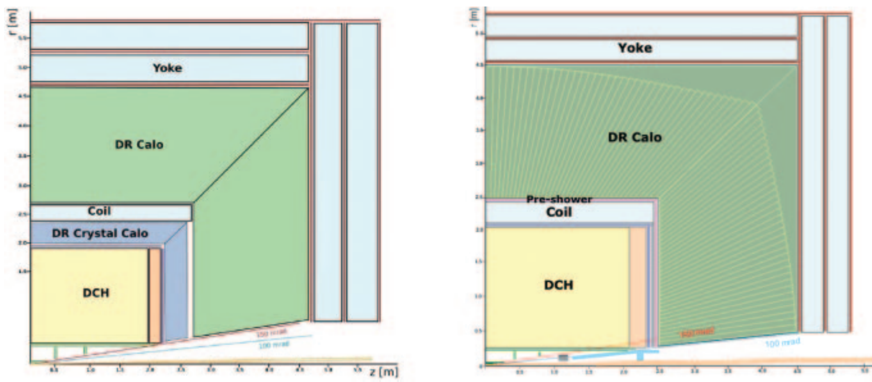

Fig. 1. – Layouts of the IDEA detector for FCC-ee: the new layout (left) includes a dual-readout crystal calorimeter, while the previous layout (right) features a pre-shower layer.

2·1. *Vertex detector*. – The silicon pixel vertex detector, inspired by the ALICE ITS [2] and based on monolithic active pixel sensors (MAPS) technology, incorporates advanced designs from the ARCADIA R&D program for the inner tracker and ATLASPix3 for the outer tracker. The inner vertex tracker consists of modules with a pixel size of $25 \times 25\,\mu\text{m}^2$, arranged in three air-cooled barrel layers, while the outer vertex tracker uses modules with a pixel size of $50 \times 150\,\mu\text{m}^2$, configured in two liquid-cooled barrel layers and six disks. The detector is designed with a lightweight mechanical structure to minimize multiple scattering, with the inner layers having a material budget of $0.3\%\,X_0$ per layer and the outer layers $1\%\,X_0$ per layer, and total material budget showed in fig. 2. It achieves a point resolution of approximately $3\,\mu$m and an efficiency close to 100%, making it highly suitable for precise vertex tracking in the FCC-ee environment.

2·2. *Drift chamber*. – The large-volume drift wire chamber, inspired by the detectors built for the KLOE [3] and MEG2 [4] experiments, is designed as a full-stereo unique volume coaxial with the 2T solenoidal field. This design combines high granularity, low mass, and short drift paths. A key feature of this detector is its exceptional transparency in terms of radiation lengths. The total material in the radial direction amounts to approximately $1.6\%\,X_0$, reaching about $5\%\,X_0$ in the forward regions. The chosen gas mixture for operating the chamber is 90% helium (He) and 10% isobutane (iC_4H_{10}), selected for its low radiation length. This mixture ensures a fast average drift velocity of approximately $2\,\text{cm}/\mu\text{s}$, corresponding to a maximum drift time of less than 400 ns, with an excellent spatial resolution of around $110\,\mu$m. Additionally, the number of ionization clusters generated by a minimum ionizing particle in this gas mixture is about $12.5\,\text{cm}^{-1}$, ensuring reliable tracking performance.

2·3. *Silicon wrapper around the central tracker*. – A precision silicon layer surrounding the central tracker is designed to enhance tracking performance by improving momentum resolution and extending coverage in the forward region, providing an additional measurement point for particles with limited interactions in the drift chamber. Several candidate designs have been considered, including two layers of silicon micro-strip detectors, a single double-sided micro-strip layer, or a single layer based on DMAPS technology, which offers high resolution in both coordinates.

2·4. *Dual readout crystal calorimeter*. – The new baseline version of the IDEA detector introduces a dual readout crystal calorimeter for precise reconstruction of electromag-

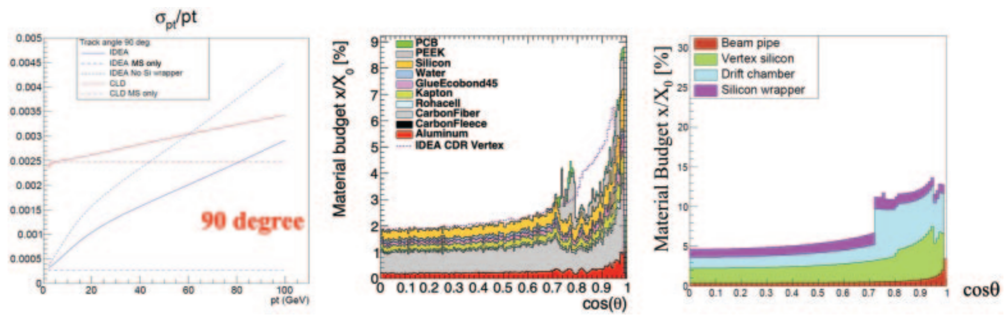

Fig. 2. – The performance of the IDEA tracker (left), the material budget of the vertex detector (middle), and the material budget of the tracker (right).

netic showers. In this version, the drift chamber remains unchanged, while the fiber-based dual-readout calorimeter is pushed after the magnet to place the DR crystal calorimeter inside the solenoid. This new design offers superior electromagnetic (EM) resolution compared to the fiber-based system, as well as enhanced longitudinal segmentation [5]. The proposed SCEPCal calorimeter design, based on $PbWO_4$ crystals, achieves the following energy resolution (1) for EM particles:

$$\frac{\sigma}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.2\%}{E} \oplus 0.5\%. \tag{1}$$

The calorimeter includes a LYSO timing layer and consists of 1.12 million barrel, 400000 endcap, and 30000 timing crystals, each $1 \times 1\,\mathrm{cm}$ and 22% X_0 thick, which significantly improves energy resolution and timing performance for EM particle detection.

2.5. *Fiber sampling dual-readout calorimeter*. – One major challenge in measuring hadronic shower energy is the fluctuation of the electromagnetic (EM) fraction, f_{EM}, which introduces uncertainty in the energy measurement. However, excellent hadronic energy resolution can be achieved by using two independent channels with different hadronic-to-electromagnetic (h/e) responses, improving the separation and measurement of energy contributions from both components [6] as shown in fig. 3.

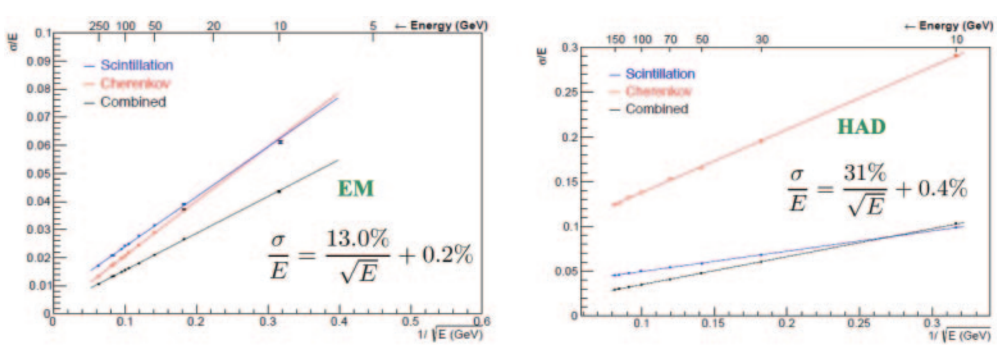

Fig. 3. – IDEA dual-readout calorimeter electromagnetic energy resolution (left), π^- energy resolution from 10 to 150 GeV (right) [6].

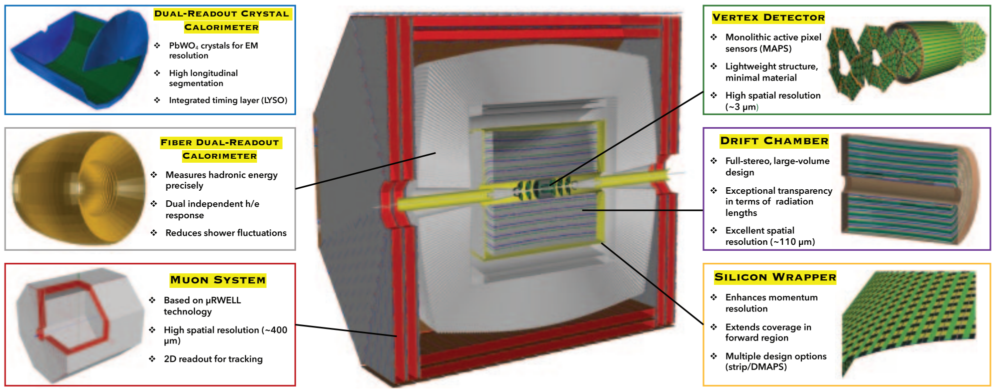

Fig. 4. – Overview of the IDEA detector sub-systems and their key features. The drawings of the sub-detectors are generated from full simulation using DD4hep [8].

2˙6. *Muon-system and pre-shower*. – The proposed muon-system and pre-shower of IDEA are based on the μRWELL technology [7], a MicroPattern Gaseous Detector (MPGD) composed of a WELL-patterned kapton foil for amplification, a resistive DLC (Diamond-Like Carbon) layer for discharge suppression with surface resistivity of $\sim$50–100 M$\Omega/\square$, and a readout layer. The muon system consists of three sensitive stations, each constituted by a large mosaic of μRWELL detectors, with $50 \times 50\,\text{cm}^2$ active tiles placed between the iron yoke layers, featuring a strip pitch of $\sim$1.2 mm and a spatial resolution of $\sim$400 μm, while the pre-shower system, designed as a single-layer μRWELL, has a finer strip pitch of 400 μm and a superior spatial resolution of $\sim 100\,\mu$m, and both has a 2D readout system, in which two orthogonal strip layers allow reconstruction of the second coordinate, enhancing spatial granularity in both dimensions.

3. – Conclusion

The IDEA Collaboration is actively engaged in ongoing R&D to optimize the detector for the future leptonic collider. Figure 4 shows the key features of the IDEA sub-detectors. A continuous effort is being made to refine various aspects of the detector, including the sub-detector technologies. Through rigorous simulation studies, the collaboration aims to enhance the detector's performance. Key decisions regarding detector parameters and sub-detector configurations will continue to evolve based on the results of these studies and ongoing R&D work, positioning IDEA as a key component of the FCC-ee program.

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