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Simulation and tools for the IDEA detector concept(*)

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Summary. — IDEA (Innovative Detector for an Electron-positron Accelerator) is an innovative general-purpose detector concept, designed to study electron-positron collisions at future e^+e^- circular colliders (*i.e.*, FCC-ee). The IDEA detector consists of a silicon vertex detector, a very large and very light drift chamber surrounded by a layer of silicon detectors, a super-thin low-mass superconducting magnet, a preshower detector, a dual-readout calorimeter, and muon chambers inside the return joke of the magnet. The research and development conducted in the laboratory and the data taken from the various test beams to measure the performance of the prototypes of the various subdetectors must be accompanied by a verification that these performances are adequate to satisfy the extensive physics program of FCC-ee. The IDEA description was then implemented in a detailed simulation with Geant4 but also in a quick simulation with Delphes. This report describes the state of the simulations and the results of studies obtained in the context of physics analyses for FCC-ee. New algorithms for τ identification and electron energy regression in the calorimeter are also being developed with innovative machine learning methods which will be included in the global reconstruction of the particle flow event.

1. – Introduction

IDEA [1] is one of the most promising detector concepts proposed for installation at future e^+e^- circular colliders (FCC-ee [2] and CEPC [3]). In order to perform its challenging physics programme, spanning from Standard Model precision measurements to new physics searches, IDEA will rely on breakthrough technologies and efficient algorithms for particle identification and reconstruction. IDEA is currently under design and optimization, with dedicated full-simulation investigations.

Feasibility studies are being now carried out, using benchmark physics processes to determine, via appropriate simulations, the requirements on the detector performance which can guarantee that the systematic uncertainties of the measurements will be lowered as far as possible. Additionally, the potential for discovering very weakly coupled new particles, in decays of Z or Higgs bosons, motivates dedicated detector designs that would increase the efficiency for reconstructing the unusual signatures of such processes.

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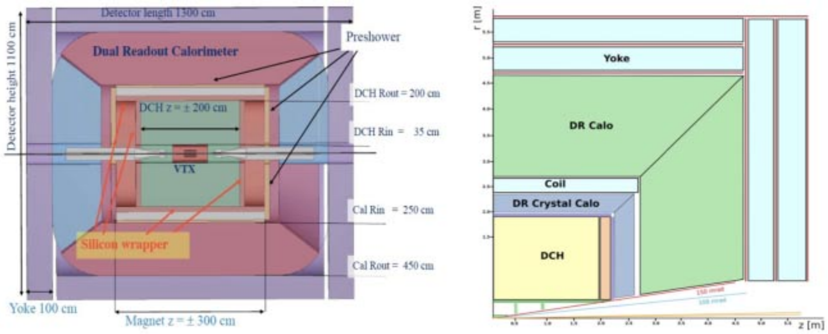

Fig. 1. – Left: a sketch of the IDEA detector concept. Right: a transversal view of the IDEA detector concept, including a crystal section with dual readout technology, in front of the hadronic calorimeter.

2. – The IDEA detector concept at FCCee

The Future Circular Collider (FCC) [4] at CERN is a project that integrates a circular leptonic collider FCC-ee, in a first stage, followed by a proton-proton collider FCC-hh [5], in a second stage. The data taking program of the FCC-ee collider foresees to deliver $5\,\text{ab}^{-1}$ of integrated luminosity in 3 years of operation at $\sqrt{s} = 240\,\text{GeV}$ and it will run at the Z mass peak and at the W^+W^- production threshold. Finally, the FCC-ee will be operated at the $t\bar{t}$ production threshold with an expected integrated luminosity of $1.5\,\text{ab}^{-1}$ delivered in 5 years. The data collected at these various center-of-mass energies make this machine the only one able to provide extremely high precision measurements of all the Standard Model features of interest and eventually provide hints of new physics.

IDEA is a detector concept based on innovative technologies, developed in recent years. It features a silicon inner tracker, surrounded by a ultra-light drift chamber and a silicon wrapper. The Inner detector is immersed in a 2 T B-field, generated by a very thin superconducting solenoid. A dual readout calorimeter is placed outside the magnet, and within the return joke of the magnet. In the outer part, a muon tracker, based on μ-Rwell technology, is interleaved with the return joke material. This same technology also provides a layer of preshower in front of the calorimeter.

A sketch and a transversal view of IDEA are shown in fig. 1.

3. – Overview of the IDEA detector simulation

Simulation is a crucial tool in the design, build, and commissioning of particle detectors employed in high-energy physics (HEP). Within this framework, simulation denotes a software procedure including a sequence of steps, starting with the production of particles and followed by the simulation of the passage of these particles through the detector material. Finally, electronic signals from the sensor components are simulated, mirroring the response to simulated physics interactions and outputting data in a format identical to the genuine detector system. The datasets produced via the above modelling procedure can be exploited by the same algorithms used to derive physical observations from genuine data. Thus, simulations are essential in shaping HEP experiments and they also play a fundamental role in the interpretation and validation procedures.

A fast simulation of the IDEA detector is fully operational in Delphes [7]. The Delphes software is designed to simulate the response of a simplified and generic collider detector composed of an inner tracker, electromagnetic and hadron calorimeters, and a muon system. It is mostly used for phenomenological studies for which a parameterized detector response is good enough. All sub-detectors are cylinders organized concentrically around the beam axis. As an advantage, this approach is versatile and extremely fast.

On the other hand, the IDEA collaboration adopted the Geant4 [8] software toolkit as its full-simulation framework, and the expected performances for the calorimetric and tracker systems are in line with the IDEA requirements.

Moreover, there are two options for the detector geometry description:

1) a classic Geant4 approach, whose standalone simulation is fully interfaced to the new software ecosystem designed for experiments at future colliders, called key4hep [9];

2) recently, DD4hep [10] has emerged as a commonly used detector geometry description tool. It is natively part of key4hep and it allows to plug and play different detector configurations in a simple way: DD4hep provides a conversion path for complex surfaces into tessellated bodies usable directly in simulation. This facilitates the design optimisation cycle, the handling of multiple geometry versions, and the integration of important detector conditions such as alignment.

From the software point of view, one of the main goals in the next future is to port the simulation and the algorithms to a common FCC framework to develop studies, physics analysis and algorithms in the standard/final environment, using EDM4hep [11] as a common event data model that can be used by all communities in the key4hep project.

This report describes the current IDEA simulations, focussing on the inner detector and calorimeters system state of the art.

4. – Inner detector

Due to the fact that most of the tracks have rather low momenta ($p_T \leq 50\,\mathrm{GeV}$), detector transparency is more relevant than asymptotic momentum resolution for this type of experiment. For this reason, the Inner detector is optimized to feature as low a material budget as possible. The core of the tracker is a Drift Chamber, which inherits the technology from both KLOE and MEG II experiments. It features only 1.6% of X_0 at 90°, mainly due to the Tungsten wires in the chamber. It will be operated with a gas mixture of 90% He and 10% iC4H10. The detector will also provide particle identification capability, based on the cluster counting technique (dNc/dx) which shows a better resolution with respect to the dE/dx method. The drift chamber will be assisted by a Silicon layer which will allow to increase the momentum resolution and extend the tracking coverage on the forward/backward region. Two technologies are at the moment under evaluation: silicon microstrips and DMAPS. This last technology has been also proposed for the vertex detector. The proposed inner tracker features a low material budget (15% of X_0), an excellent spatial resolution (3 μm), and a very low power consumption (20 mW/cm^2). Current development is based on 110 nm CMOS CIS technology, with 25 × 25 μm^2 pixel size.

The tracking system simulation is available in Geant4.

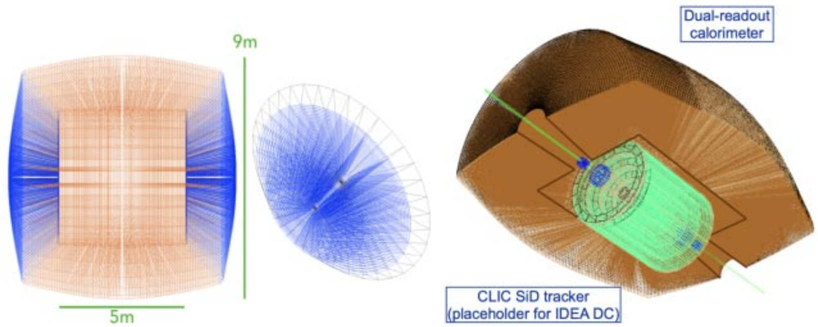

Fig. 2. – Left: a simulation of the IDEA dual readout calorimeter in Geant4. Right: a simulation of the IDEA dual readout calorimeter using DD4hep.

5. – Dual readout calorimeter

The IDEA calorimeter is based on the dual readout technique. This concept allows to obtain a superior hadronic energy resolution, thanks to the capability to measure the electromagnetic fraction on an event-by-event basis and remove the relative fluctuations in the hadronic shower. This can be achieved by measuring the same shower with two different technologies, one sensitive to the deposited energy (scintillation light) and one sensitive only to the electromagnetic component of the hadronic shower, namely electrons and positrons, which produce Cherenkov light. The dual readout calorimeter for the IDEA detector is composed of an unsegmented fiber calorimeter which acts as both electromagnetic and hadronic calorimeter. The achievable energy resolution is compatible with the 3% resolution required to distinguish jets coming from W, Z and Higgs boson decays, and with a 10-20%$/\sqrt{E}$ resolution for the measurement of the Higgs $\rightarrow \gamma\gamma$ decay channel. The design of the calorimeter is based on a very fine granularity, with a fiber-to-fiber pitch of the order of 2 mm. This also brings an excellent position and angular resolution, A better resolution for the electromagnetic performance may be needed for the heavy flavour physics. This should require an electromagnetic energy resolution around 3-4%/ $\sqrt{E}$, which may be achieved by a crystal section, again based on dual readout technique, in addition to the fiber calorimeter (see fig. 1 right).

The full simulation of the dual readout calorimeter is available in Geant4 (see fig. 2 left). Recently, a dual readout calorimeter description was implemented in DD4hep, as shown in fig. 2 right, to be coupled with a DD4hep description of the IDEA Drift Chamber.

5˙1. *Machine learning-based reconstruction algorithms.* – Machine learning (ML) is used for particle reconstruction and identification profiting of the high granularity of the fiber-based dual-readout calorimeter.

Two examples of ML tools for particle reconstruction and identification are considered:

- classification of τ leptons decays and separation from QCD jets based on Dynamic Graph Neural Networks (DGCNN)

- particle flow algorithm for dual readout calorimeter, based on deep neural networks

Although an excellent τ identification (above 90% accuracy) is currently achieved, this report will focus on the particle flow algorithm for dual readout calorimeter because the author is one of its main developer.

5˙1.1. Particle flow algorithm for dual readout calorimeter. Precision measurements of Z, W, and Higgs boson decays at the next generation of circular lepton colliders will require excellent energy resolution for both electromagnetic and hadronic showers. The resolution is limited by event-to-event fluctuations in the shower development, especially in the hadronic system. Compensating for this effect can greatly improve the achievable energy resolution.

Particle flow algorithms (PFAs) have become the paradigm of detector design for the high energy frontier. Since PFAs are designed to reconstruct every final state particle in the most suited sub-detectors, they require highly-granular calorimeters.

The approach of dual-readout calorimetry has emerged as a candidate to fullfill both of these requirements by allowing to reconstruct the fluctuations in the shower development event-by-event and offering a high transverse granularity.

The most promising strategy for achieving the desired IDEA jet energy resolution is the Particle Flow approach, using a highly granular detector. This approach requires the reconstruction of the four-vectors of all visible particles in an event: the reconstructed jet energy is the sum of the energies of the individual particles. Charged particles momenta are measured in the tracking detectors, while the measurement of the energy of photons and neutral hadrons are obtained from the calorimeters. The workflow is the following: starting from the full simulation of the particles in the IDEA detector, it is possible to extract both the truth particle information (position, momentum, particle type) and calorimeter information (fibre position, fibre type, collected light by the fibre) at the impinging layer, and exploit a NN based algorithm for particle identification and energy regression. A Geant-based [8] description is currently used and the code is developed on the EDM4hep [11] output format. Focusing on the details of the software implementation, this project aims at interfacing Pandora [12] with KEY4HEP [9] using the EDM4HEP data format. Algorithms have been implemented in KEY4HEP-Pandora and NNs have been trained against the energy resolution of the candite electron, exploiting mono-energetic electrons or electrons with a uniform distribution in energy (in the range $[0, 125]$ GeV) and θ and ϕ coordinates. In this study, the DNN input nodes are the energy and position of each hit in the electromagnetic shower generated by the impinging electron and recorded in both scintillating and Cherenkov fibres. 6 kinematic variables (E, x, y, z, t, fibre-type) are considered, multiplied by the average hit multiplicity per electron per event, resulting in around 60k information per event. A zero padding approach is adopted, meaning that if the number of hits in the event is less than the average hit multiplicity, the remaining positions in the array are set to zero to reduce the complexity of the problem. The model loss adopted is *MeanSquaredError()* ([1]), optimised with respect to the simulated energy of the incoming electrons. A stochastic optimiser, Adam [13], is used to minimise the loss. A Gaussian fit is performed to the residuals between the truth simulated electron energy and the energy estimated by the DNN outcome, split into 10 truth electron energy slices. The resolution of each Gaussian fit and its uncertainty, divided by the truth electron energy, is plotted as a function of the truth energy slice, as shown in fig. 3. The red line shows the fit typically used to

([1]) $\frac{1}{n}\sum_{i=1}^{n}(y_{\text{true}} - y_{\text{pred}})^2$

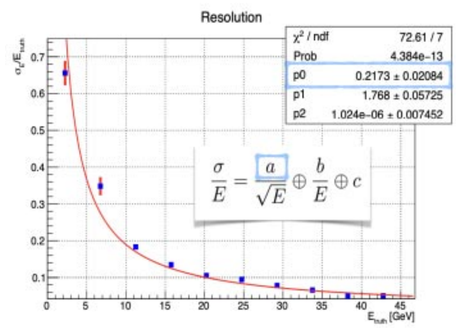

Fig. 3. – Electron energy resolution, the red line shows the fit typically used to evaluate the energy resolution: $\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$.

evaluate the energy resolution of the form: $\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$, where the parameter of interest for this study is the noise term a ($p0$ in the fit panel). The noise term extracted from this fit is higher than expected (it is $\sim 21\%$) and the NN configurations might be under-performing because a too easy architecture is used as first attempt.

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