Detector IDEA (Innovative Detector for Electron-positron Accelerators) designed for future accelerators e^+e^-

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Summary. — The Innovative Detector for Electron-positron Accelerators (IDEA) is designed for future e^+e^- colliders like the FCC-ee. This detector leverages advanced technologies to achieve high precision in measuring Standard Model particles. This paper provides an overview of the FCC-ee's capabilities at various center-of-mass energies and details the IDEA detector's design and features, highlighting its potential for groundbreaking discoveries in high-energy physics.

1. – Introduction

The first phase of the LHC physics programme has left a significant legacy, with one of the highlights being the discovery of the Higgs boson. This milestone initiated an in-depth exploration of this particle's properties to unravel the fundamental origins of electroweak symmetry breaking. Additionally, the outcomes indicate that signals of new physics around the TeV scale remain elusive, prompting a heightened focus on precision measurements across various sectors, including the Higgs and flavour sectors.
The success of the LHC owes much to the remarkable achievements of both the accelerator and detectors, surpassing expectations. Building on this legacy and drawing from the experiences of previous circular colliders like LEP, HERA, and the Tevatron, the Future Circular Collider (FCC) is envisioned within a 90.7 km tunnel at CERN.

The future of high-energy physics in the 21st century hinges on designing and building colliders capable of pushing the energy and intensity frontiers by an order of magnitude beyond the present values.

The resurging global interest for e^+e^- physics, particularly fueled by the momentous discovery of the Higgs boson at the LHC, has led to a collective endeavor in this scientific pursuit. With no compelling indications of physics beyond the Standard Model (BSM) in the LHC data thus far, the landscape has markedly changed since 2013. Consequently, there are at the present day four distinct e^+e^- collider designs under consideration, all poised to meticulously investigate the characteristics of the Higgs boson and other Standard Model (SM) particles with an unprecedented precision:

- The International Linear Collider (ILC) project, in Japan, initially designed with a focus on the Higgs boson at a center-of-mass energy of 250 GeV (upgradable to 500 GeV and possibly to 1 TeV), has become a dedicated platform for the in-depth exploration of Higgs boson properties.

- The Compact Linear Collider (CLIC), at CERN, originally conceived for a lowest center-of-mass energy of 500 GeV, has recalibrated its objectives, reducing the energy to 380 GeV to enhance studies on the Higgs boson and the top quark.

- The Circular Electron Positron Collider (CEPC), situated in a 100 km tunnel in China, aims to investigate the Z, W, and Higgs bosons across center-of-mass energies ranging from 90 to 250 GeV.

- The Future e^+e^- Circular Collider (FCC-ee), proposed at CERN in a new $\approx 100km$ tunnel, presents a comprehensive capability to explore the entire electroweak (EW) sector, covering Z and W bosons, the Higgs boson, and the top quark, with center-of-mass energies spanning from 88 to 365 GeV.

2. – FCC

The goal of the FCC [1] is to push the energy and intensity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV, in the search for new physics.

The new tunnel would initially host an electron–positron collider (FCC-ee) allowing precise measurement of the properties of the Higgs boson and other SM particles. The second step, would be an energy frontier proton collider (FCC-hh), offering collision energies of 100 TeV or higher, i.e. 8 times the energy of the LHC, following developments in the superconducting and magnet technologies.

The FCC examines scenarios for three different types of particle collisions:

- FCC-ee: Electron-positron collisions, will function across a range of center-of-mass energies, generating a significant abundance of Z and W vector bosons, Higgs bosons (H), and top quark-antiquark pairs $(t\bar{t})$. This setup holds promise for exploring phenomena BSM and conducting precise measurements related to the properties of the Higgs boson, in the following we will focus on this scenario.

- FCC-hh: Hadronic collisions, protons or ions will collide, enabling the direct detection of masses on the order of tens of TeV if they exist. The goal will be to study the potential of the Higgs field, focusing on the rare decays of the corresponding boson, searching for new physics BSM, and providing new insights into the theory of Grand Unified Theory.

- FCC-he: Proton electron collisions to conduct high-precision measurements of the properties of the Higgs boson, investigate deep inelastic scattering of the top quark, explore phenomena like quark-gluon plasma, and search for leptoquarks.

3. – FCC-ee

The FCC-ee [2] delivers the highest rates in a clean, well-defined, and precisely predictable environment and, operating at multiple center-of-mass energies ($\sqrt{s}$), is poised to produce substantial quantities of particles, including $5 \cdot 10^{12}$ Z bosons ($\sqrt{s} \approx 91GeV$), 10^8 WW pairs ($\sqrt{s} \approx 160GeV$), over 10^6 Higgs bosons ($\sqrt{s} \approx 240GeV$), and over 10^6 top quark-antiquark pairs $t\bar{t}$ ($\sqrt{s} \approx 340 - 365GeV$). Furthermore, the design ensures high-precision center-of-mass energy calibration at the Z and WW energies, reaching an unprecedented level of 100 keV, a distinctive feature exclusive to circular colliders.

Therefore, the FCC-ee is ideally positioned to provide high statistical precision and experimental accuracy for measuring the properties of SM particles. It also creates avenues for detecting rare new processes and offers opportunities to observe minute deviations from established symmetries.

The identification of the 125 GeV Higgs boson marks the culmination of the particle and interaction framework forming the bedrock of the SM for numerous decades. The SM has successfully described all phenomena observable through collider experiments. Simultaneously, the need for an extension to the SM has become apparent, driven by experimental observations such as the matter-antimatter asymmetry, dark matter indications, and the existence of non-zero neutrino masses. Theoretical challenges demanding attention encompass the hierarchy problem, the Universe's neutrality, the Higgs boson mass stability under quantum corrections, and the strong CP problem.

Consequently, the upcoming accelerator project must facilitate the broadest possible range of research, a criterion met by the FCC. Initially, the FCC-ee will extensively measure the properties of Z, W, Higgs bosons, and top quarks in e^+e^- collisions, achieving precision enhancements of orders of magnitude. This opens avenues to explore much higher scales or much smaller couplings. The FCC-ee outlines a comprehensive and diverse exploration aimed at:

- conduct high-precision measurements of a comprehensive set of electroweak and Higgs observables,
- rigorously constrain numerous parameters of the SM,
- identify subtle yet significant deviations from SM predictions,
- observe rare new processes or particles that go beyond SM expectations,

thus maximizing the potential for groundbreaking fundamental discoveries.

4. – IDEA detector concept

The IDEA detector concept, tailored specifically for FCC-ee, draws upon well-established technologies honed through extensive research and development efforts spanning years. However, further refinement and optimization are necessary to finalize the design. The schematic representation of the IDEA detector structure is presented in Figure 1. This detector configuration encompasses a silicon pixel vertex detector, an expansive yet lightweight short-drift wire chamber encased in a layer of silicon micro-strip detectors, a slender superconducting solenoid coil with minimal mass, a pre-shower detector, a dual-readout calorimeter, and muon chambers

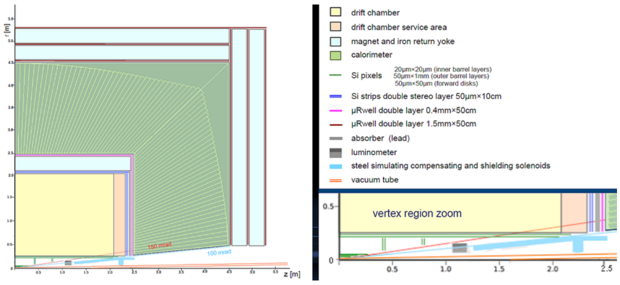

Fig. 1. – Schematic layout of the IDEA detector.

strategically positioned within the magnetic return yoke.

Vertex detector: the innermost detector, surrounding the beam pipe, takes the form of a silicon pixel detector. Recent experimentation with detectors designed for the ALICE ITS upgrade, employing the ALPIDE readout chip [3], has demonstrated outstanding characteristics, including a resolution of approximately 5 μm, high efficiency at low power consumption, and a low dark-noise rate [4]. Additionally, the vertex detector meets stringent requirements: fast readout of all signals from an event in less than $\Delta t \approx 85\mu s$. Low power consumption $< 20mW/cm^2$. Low material budget $0.15\% X_0$.
It is structured in 5 MAPS layers:

- R=1.7-2.3-3.1 cm
  Pixel size: 20x20 μm^2
- R=32-34 cm
  Pixel size: 50x100 μm^2

These exceptionally lightweight detectors, with a radiation length of $0.3\% X_0$ for the innermost layer and $1.0\% X_0$ for the outermost layer, serve as the foundation for the IDEA vertex detector.

The drift chamber (DCH) is designed to deliver precise tracking, accurate momentum measurement, and excellent particle identification through cluster counting. Notably, this chamber stands out due to its remarkable transparency in terms of radiation lengths, achieved through innovative wiring and assembly techniques. The overall material content in the radial direction towards the barrel calorimeter is approximately $1.6\% X_0$, while in the forward direction it reaches about $5.0\% X_0$, with 75% concentrated in the end plates equipped with front-end electronics.
The DCH stands as a distinctive, voluminous, high-resolution, all-stereo, lightweight, cylindrical, short-drift, wire chamber perfectly aligned with the 2 T solenoid field. Its spatial extension spans from an inner radius, $R_i n = 0.35m$, to an outer radius, $R_o ut = 2m$, covering a length, L = 4 m. Comprising 112 co-axial layers, featuring alternating-sign stereo angles and organized into 24 identical azimuthal sectors, this chamber boasts an approximately-square cell size ranging between 12.0 and 14.5 mm. The grand total of 56,448 drift cells is thoughtfully designed to tackle potential challenges associated with a considerable number of wires.
The operation of the chamber involves a remarkably lightweight gas mixture, specifically 90% helium (H_e) and 10% isobutane (iC_4H_{10}), resulting in a maximum drift time of approximately 400 ns. For a minimum ionizing particle (m.i.p.), around 12.5 ionization clusters are generated

per centimeter, enabling the utilization of cluster counting/timing techniques. This not only enhances spatial resolution $\sigma_x < 100\mu m$ but also improves particle identification $\sigma(dN_{cl}/dx/(dN_{cl}/dx) \approx 2\%$. The angular coverage spans down $\approx 13°$ and holds the potential for further extension by incorporating additional silicon disks between the DCH and the calorimeter end caps.

IDEA preshower detector: A pre-shower detector is positioned between the magnet and the calorimeter in the barrel region and between the drift chamber and the end-cap calorimeter in the forward region. In the barrel region, the magnet coil serves as an absorber of approximately $1X_0$ and is succeeded by one layer of Micro Pattern Gas Detector (MPGD) chambers, followed by a second layer of chambers after an additional $1X_0$ of lead. A similar arrangement is found in the forward region, but with both absorber layers made from lead.
The MPGD chambers layers offer a precise determination of the impact point for both charged particles and photons, thus defining the tracker acceptance volume with high precision and enhancing the tracking resolution. Furthermore, a significant portion of π_0 particles can be identified by detecting both photons resulting from their decay through the preshower. The optimization of the preshower system and the assessment of its performance are currently underway.

IDEA dual-readout calorimeter: The lead-fiber dual-readout calorimeter encompasses the second preshower layer, with a depth of 2 meters, equivalent to approximately $7\lambda_I$. For a realistic 4π detector, two configurations have been simulated, covering the entire volume down to 100 mrad of the z-axis without any inactive region. The first configuration consists of truncated rectangular-base pyramidal towers in 92 different sizes, while the second utilizes rectangular prisms coupled to pyramidal towers. Both configurations involve approximately 10^8 fibers.
This dual-readout calorimeter operates by detecting independent signals from scintillation light (S) and Cerenkov light (C) production, see figure 2. Consequently, it achieves outstanding energy resolution for both electromagnetic and hadron showers. The combination of these signals yields a resolution estimated from GEANT4 simulations, reaching close to $10\%/\sqrt{E}$ for isolated electrons and $30\%/\sqrt{E}$ for isolated pions, with negligible constant terms. The dual-

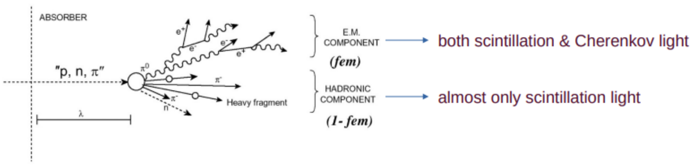

Fig. 2. – Schematic of development of hadronic shower with the scintillation and Cherenkov light component.

readout calorimeter offers effective intrinsic discrimination among muons, electrons/photons, and hadrons for isolated particles. Besides the C/S ratio, a few other variables, such as the lateral shower profile, the starting time of the signal, and the charge-to-amplitude ratio, can be utilized to enhance the intrinsic particle separation capability of the calorimeter.
Alongside its inherent particle identification capabilities, the dual-readout calorimeter, with its fine transverse granularity, enables the separation of closely located showers. It facilitates accurate matching with tracks in the inner preshower signals and muon tracks, establishing it as a promising candidate for efficient particle-flow reconstruction.

IDEA muon system: consists of layers of chambers embedded in the magnet return yoke.

The system utilizes $\mu - RWell$ technology, see also [5]. The key requirements include high-momentum muon identification with a spatial resolution of less than 400 μm and an efficiency greater than 98%. Additionally, cost-effectiveness is crucial due to the necessity of covering an area of several hundred square meters.
A suitable technology is the MicroPattern Gas Detectors (MPGD) , which operates with a pattern of Kapton sheets functioning as the amplification stage, a resistive stage that enables current flow and suppresses discharges, and a PCBoard pattern for signal readout. The system achieves muon momentum measurement with Vertex+DCH+Outer Silicon Layers, reaching a resolution of approximately 0.27% at 100 GeV, and provides excellent identification of isolated particles. For muon identification in jets, the system is positioned behind the calorimeter with an iron yoke thickness exceeding 50 cm and includes 3-4 stations, each with 2 layers of 50x50 cm^2 $\mu - RWell$, achieving a muon track position resolution of less than 60 μm.

5. – Conclusions

The IDEA detector concept represents a significant advancement in the field of high-energy particle physics, tailored to meet the demanding requirements of future e^+e^- colliders like the FCC-ee. By integrating well-established and innovative technologies, the IDEA detector promises to deliver high-precision measurements of Standard Model particles, facilitating the exploration of new physics beyond the current paradigm. The detailed design and simulation studies presented in this paper highlight the detector's potential to enhance our understanding of fundamental particles and forces. As the FCC-ee project progresses, the continued development and optimization of the IDEA detector will be crucial in maximizing its scientific impact. This detector will enable the exploration of Higgs, top quark-antiquark pairs $t\bar{t}$, and Z physics in multiple final states, projecting forward toward future discoveries in particle physics.

REFERENCES

[1] A. Abada et al. Fcc-hh: The hadron collider: Future circular collider conceptual design report volume 3. *The European Physical Journal Special Topics*, 228(4):755–1107, July 2019.

[2] Abada et al. Fcc-ee: The lepton collider: Future circular collider conceptual design report volume 2. *The European Physical Journal Special Topics*, 228(2):261–623, June 2019.

[3] M Mager, ALICE collaboration, et al. Alpide, the monolithic active pixel sensor for the alice its upgrade. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 824:434–438, 2016.

[4] Gianluca Aglieri Rinella, ALICE collaboration, et al. The alpide pixel sensor chip for the upgrade of the alice inner tracking system. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 845:583–587, 2017.

[5] G. Bencivenni, R. De Oliveira, G. Felici, M. Gatta, M. Giovannetti, G. Morello, and M. Poli Lener. The -rwell for high rate application. *Journal of Instrumentation*, 15(09):C09034, sep 2020.