IL NUOVO CIMENTO **43 C** (2020) 27
DOI 10.1393/ncc/i2020-20027-2

Colloquia: IFAE 2019

IDEA: A detector concept for future leptonic colliders

M. Antonello on behalf of the RD-FA Collaboration
INFN, Sezione di Milano - Milano, Italy

received 8 June 2020

Summary. — The Innovative Detector for Electron-positron Accelerator (IDEA) concept, specifically designed for operation at future leptonic circular colliders, is presented. The detector layout has been studied to match all the requirements set by these machines and it is based on innovative, but proven, detector technologies developed over years of R&D.

1. – Introduction

The Higgs boson (H) discovery at the Large Hadron Collider (LHC) of CERN was a groundbreaking moment for high energy physics. This particle is the cornerstone of the Standard Model (SM) and it is assumed to be related to the key questions of modern particle physics like the nature of the electroweak (EW) phase transition, the origin of the Electroweak Symmetry Breaking (EWSB) or the "Hierarchy Problem" between the Planck and weak scales. Thanks to its relatively low mass, the Higgs boson can be copiously produced at a future high-luminosity e^+e^- collider in a very clean environment. Precise measurements of its properties, as well as those of the Z and W bosons, will provide important tests of the SM and will be essential for searches of physics Beyond the Standard Model (BSM). Moreover, the high statistics measurement programme goes far beyond precision Higgs coupling determination: for instance, the observation of lepton-flavour violating decays, or the precise measurements of the H and Z invisible decay widths, or the direct observation of particles with extremely weak couplings, are expected to provide signals of new physics. This programme will be one of the most important topics of the particle physics road map in the coming decades.

Presently there are 4 different leptonic collider designs proposed to perform this program: i) the International Linear Collider (ILC), in Japan, with a 250 GeV centre-of-mass energy (upgradable to 500 GeV and possibly to 1 TeV) and a dimension of 20.5 km [1]; ii) the Compact Linear Collider (CLIC), at CERN, that could operate at three energy stages: 380 GeV, 1.5 TeV and 3 TeV, for a dimension ranging from 11 up to 50 km [2]; iii) the Circular Electron Positron Collider (CEPC), in China, with a centre-of-mass energy range from 90 up to 250 GeV and a circumference of 100 km [3]; iv) the Future

Circular Collider (FCC-ee), at CERN, with $\sqrt{s}$ values between 88 and 365 GeV and a similar circumference of 97.75 km [4]. Most detector studies done so far for FCC-ee and CEPC are based on previous work on the ILC and CLIC and assume similar detector requirements. Nevertheless, there are some notable differences that will be presented in the next section.

2. – Detector constraints

The precision physics program sets stringent requirements on the detector performance. Among these, very large solid angle coverage, excellent particle ID, very good energy and momentum resolution, efficient vertex reconstruction are critical. Indeed, as Higgs, W and Z boson factories, detectors at the future e^+e^- colliders have to reconstruct and identify their decay products with high efficiency, purity and precision. The most important detector requirements are listed below.

Tracking performance: the typical luminosity expected at circular colliders, especially at the Z pole, will be orders of magnitude larger than at linear colliders, with a much shorter bunch spacing and without large time gaps in the beam structure [4]. This places severe constraints on the tracking system: an intrinsically fast main tracker is needed to fully exploit the cleanliness of the e^+e^- environment and a very low power dissipation vertex detector is required (since power pulsing is not allowed by the bunch spacing). Moreover, due to the scalar nature of the Higgs boson, its decay products are uniformly distributed over the full solid angle while the cross sections of the background processes are peaked in the forward region: a large solid angle coverage ($|\cos(\theta)|<0.99$) is needed in order to have a large signal acceptance and separate the different physics channels.

Magnetic field: additional issues of emittance preservation, typical of circular machines, set limits on the maximum magnetic field usable for the tracker solenoid to 2 Tesla (especially when running at the Z pole). This could be a problem for a large volume TPC, due to the resolution degradation, and also for a silicon tracker, since it would require more layers at large radii, thus significantly increasing the cost.

Particle identification: specific requirements on a detector for circular colliders come from precision physics at the Z pole, where the statistical accuracy on various EW parameters is expected to be more than an order of magnitude better than at the LEP. This requires a very tight control of the systematic error on the acceptance (with boundaries at the level of a few μm) and a very good e-γ-π^0 discrimination to identify τ leptons efficiently and measure their polarization. Moreover, a high identification efficiency for charged kaons is required for the flavour physics program (kaon identification allows for jet flavour tagging) [3].

Energy resolution: the photon energy resolution is a key element for the $H \to \gamma\gamma$ measurement and for the jet energy reconstruction. To fully explore the Z, W and H hadronic decays and to clearly discriminate the $H \to ZZ^* \to 4j$ and $H \to WW^* \to 4j$ final states, the jet energy resolution needs to be $\sim$30–40%$/\sqrt{E}$. This requirement (a factor two better than the calorimeters operating at the LHC) would optimise the separation of the W and Z hadronic decay peaks.

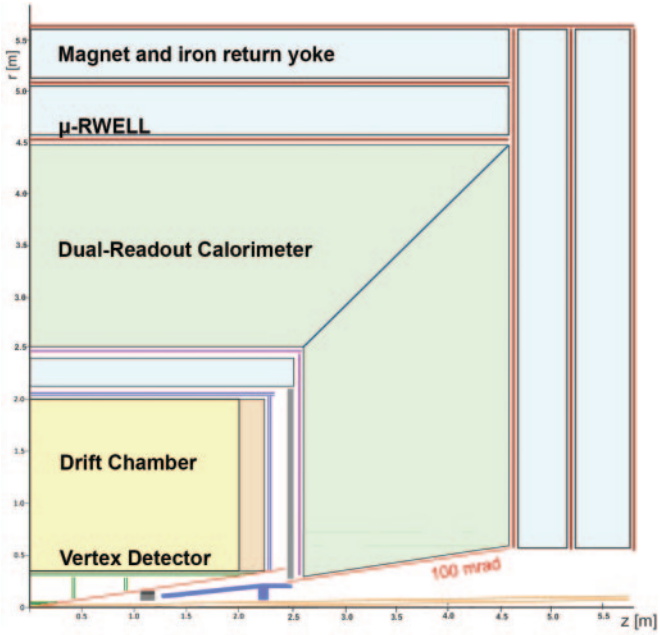

Fig. 1. – The structure of the IDEA detector and its overall dimensions.

To properly address all these requirements, many R&D and simulation studies were carried out and several international collaborations proposed different detector concepts. Among these, IDEA is one of the two baseline detector concepts of FCC-ee and a viable solution at CEPC.

3. – IDEA layout and characteristics

The structure of IDEA is outlined in fig. 1 and the key detector parameters are listed in table I. The detector consists of a silicon pixel detector, an extremely light, large volume, drift chamber surrounded by a layer of silicon micro-strip detectors, a solenoidal magnet, a preshower detector, a dual-readout calorimeter and a muon spectrometer within the magnet return yoke.

A key element is an ultra-thin (∼30 cm thick) and low mass (∼0.7 X_0 and ∼0.16 λ_{int}) solenoidal coil with a magnetic field of 2 T, located between the tracking and the calorimeter volume. The low-magnetic field minimises the impact on emittance growth and allows for manageable fields in the compensating solenoids [5]. Moreover, by positioning the coil inside the calorimeter volume, the stored energy is reduced by a factor four and the cost can be halved [6].

Vertex detector: the innermost detector, surrounding the 1.5 cm beam pipe, is a silicon pixel detector (based on monolithic active pixel sensors) for the precise determination of the impact parameter of charged particle tracks. Technologies relying on fully depleted high-resistivity substrates [7] are being considered, together with architectures implementing on-pixel sparsification and data-driven, time-stamped readout schemes. The ongoing activities are targeting resolutions at a few μm level,

TABLE I. – *The main parameters of the IDEA concept detector.*

Parameters	
vertex technology	silicon
vertex inner/outer radius (cm)	1.7/34
tracker technology	drift chamber and silicon wrapper
tracker half length (m)	2.0
tracker outer radius (m)	2.0
solenoid field (T)	2.0
solenoid bore radius/half length (m)	2.1/3.0
preshower absorber	lead
preshower R_{min}/R_{max} (m)	2.4/2.5
DR calorimeter absorber	copper
DR calorimeter R_{min}/R_{max} (m)	2.5/4.5
overall height/length (m)	11/13

thickness in the 0.15–0.30% X_0 range per layer and power dissipation not exceeding 20 mW/cm^2. In particular, recent beam test results on the detectors developed for the ALICE inner tracker upgrade (ITS) [8, 9] indicate an excellent resolution ($\sim$5 μm) and high efficiency at low power and dark noise rate [10]. This was identified as the state-of-the-art starting point for the IDEA vertex detector. This choice could significantly profit from the electronic and mechanical work for the ALICE ITS as well as from new ongoing developments, in the context of the INFN ARCADIA R&D project.

Drift chamber: the drift chamber, evolving from the detectors built for KLOE [11] and MEG2 experiments [12], is a full-stereo unique volume, co-axial with the 2 T solenoid field, with high granularity, low mass and short drift path. The special feature of this detector is its high transparency: the total amount of material in the radial direction is about 1.6% X_0, reaching about 5% X_0 in the most forward regions. The drift chamber is 400 cm long, with an inner (outer) radius of 35 (200) cm. The sensitive volume comprises 56448 squared drift cells with an edge ranging between 12 and 14.5 mm. The chamber is filled with a very light gas mixture (90% He and 10% iC_4H_{10}), and the maximum drift time is $\sim$400 ns. The number of ionization clusters generated by a MIP in this gas mixture is about 12.5 cm^{-1}, allowing for the exploitation of the cluster counting/timing techniques for improving both spatial resolution ($\sigma_x < 100$ μm) and particle ID capability ($\sigma(\mathrm{d}N_{cluster}/\mathrm{d}x)/(\mathrm{d}N_{cluster}/\mathrm{d}x) \approx 2\%$) [12]. A layer of silicon micro-strip detectors surrounds the chamber providing an additional accurate space point and defining precisely the tracking acceptance. A track momentum resolution of about 0.28% for 100 GeV tracks is expected when vertex detector and outer silicon information are included in the track fit.

Preshower: the preshower detector is based on the micro-Resistive WELL (μ-RWELL) technology [13]: a compact Micro-Pattern Gaseous Detector (MPGD), with a single, intrinsically spark protected, amplification stage. It is composed of only two elements: the drift cathode and the μ-RWELL PCB providing a micro-patterned matrix (WELL) as amplification stage, a resistive layer and a rigid readout electrode. In the barrel region the magnet coil works as an absorber of about 0.7 X_0 and is followed by a layer of μ-RWELL chambers. In the forward region a 1 X_0 lead absorber is placed in front of a layer of μ-RWELL chambers located immediately before the endcap calorimeter. This allows to tag about 30% of the π^0's by having both γ's from their decay identified by the preshower (additional identification power comes from the dual-readout calorimeter) and provides a good acceptance determination for photons given the high mechanical stability of the chambers. Both silicon and μ-RWELL chamber layers provide a very precise acceptance determination for charged particles, besides increasing the overall tracking resolution. The evaluation of the preshower performance and the optimisation of its thickness are still in progress.

Magnet system: a solenoidal magnet, 5 m long and with an inner diameter of 4.2 m, surrounds the tracking system. The 2 T field and the small dimensions have important implications on the overall magnet package thickness, that can be kept at the 30 cm level, and on the size of the flux return yoke, which scales linearly with the field and the square of the coil diameter. With the given dimensions a yoke thickness of less than 100 cm of iron is sufficient to completely contain the magnetic flux and provide adequate shielding and support for the muon chambers.

Dual-readout calorimeter: a copper-based dual-readout fibre calorimeter surrounds the preshower. This technique has been extensively studied and demonstrated in over 15 years of R&D by the DREAM/RD52 Collaboration [14]. The total calorimeter depth is 2 m, corresponding to $\sim 8\ \lambda_{int}$. The energy resolution is expected to be about $11\%/\sqrt{E}$ for electrons and $33\%/\sqrt{E}$ for isolated pions with negligible constant terms, as obtained from extrapolations from test beam data (using GEANT4). With this technology the electromagnetic and hadronic calorimeters could come in a single package that plays both functions. This detector has very good intrinsic discrimination between muons, electrons/photons and hadrons for isolated particles (for example, with a multivariate analysis on 60 GeV e^-/π^- beams, an electron identification of 99.8% was obtained, with a pion mis-ID of 0.2%) [15]. Moreover, the intrinsic high transverse granularity, obtained coupling the fibres to Silicon-PhotoMultipliers [16], allows the separation of close, overlapping showers and makes it possible to achieve a high-resolution matching with track segments extrapolated from both the inner and the outer detector elements, making this calorimeter suitable for a particle-flow reconstruction. A longitudinal segmentation is required to disentangle signals produced by overlapping electromagnetic and hadronic showers. Different solutions for this segmentation (as an arrangement with fibres starting at different depths or the extended use of the signal timing information) are considered: the different advantages and drawbacks of each approach are under study (through both simulations and beam tests).

Muon detector system: similarly to the preshower detector, the choice of an MPGD technology such as the μ-RWELL, would perfectly match the specifications required for the IDEA muon detection system, providing good tracking efficiency and both precise space resolution on the coordinates of a muon track (about 200–300 μm) and good time resolution. This choice also leads to a significant reduction of the cost to equip extremely large surfaces with tracking chambers outside the calorimeter volume. The best option is using tiles of μ-RWELL detectors of $50 \times 50\,\text{cm}^2$ assembled into 3 detector stations, each one equipped with a layer of μ-RWELL detectors with bi-dimensional readout. This would make the whole muon system very modular with components which can be mass produced by industry. Recent developments in the industrialization of μ-RWELL-based large-area chambers, as planned for the CMS Phase II upgrade, are very promising examples.

4. – Conclusions

A different innovative concept for a detector at future circular leptonic colliders has been proposed. This detector is specifically designed for these machines and their specific running conditions and physics goals. In particular it is designed for minimising the interferences of the detector solenoidal field on the beam. Although additional R&D to optimize performance and come to a detailed engineered design is still necessary, the detector is based on technologies established after many years of R&D and whose feasibility has been largely assessed. Furthermore several choices are meant to simplify the detector structure and reduce the cost.

REFERENCES

[1] Bauer H. *et al.*, *The International Linear Collider Technical Design Report - Volume 2: Physics*, ILC-REPORT-2013-040 (2013) `http://arxiv.org/abs/1306.6352v1`.
[2] CLIC Collaboration, *Physics and Detectors at CLIC: CLIC Conceptual Design Report*, CERN-2012-003 (2012) `http://arxiv.org/abs/1202.5940v1`.
[3] CEPC Study Group, *CEPC Conceptual Design Report: Volume 2 - Physics & Detector*, IHEP-CEPC-DR-2018-02 (2018) `http://arxiv.org/abs/1811.10545v1`.
[4] Abada A. *et al.*, *Eur. Phys. J. ST*, **228** (2019) 261.
[5] Koratzinos M. *et al.*, *Progress in the FCC-ee Interaction Region Magnet Design,* in *IPAC2017* (2017) `http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/wepik034.pdf`.
[6] Ten Kate H. H. J., *Ultra-light 2T/4m bore Detector Solenoid for FCC-ee*, FCC Week presentation (2018) `https://indico.cern.ch/event/656491/contributions/2939122/attachments/1629705/2597192/20180409-TenKate_-_FCCee_IDEA_thin_2T_Solenoid.pdf`.
[7] Panati S., in *IEEE-NSS Conference record* (IEEE) 2017.
[8] Keil M., *JINST*, **10** (2015) C03012.
[9] ALICE Collaboration, *Nucl. Instrum. Methods A*, **824** (2016) 434.
[10] ALICE Collaboration, *Nucl. Instrum. Methods A*, **845** (2017) 583.
[11] KLOE Collaboration, *Nucl. Instrum. Methods A*, **367** (1995) 104.
[12] Baldini A. M. *et al.*, *JINST*, **11** (2016) P07011.
[13] Bencivenni G. *et al.*, *JINST*, **10** (2015) P02008.
[14] Lee S. *et al.*, *Rev. Mod. Phys.*, **90** (2018) 025002.
[15] Akchurin N. *et al.*, *Nucl. Instrum. Methods A*, **735** (2014) 120.
[16] Antonello M. *et al.*, *Nucl. Instrum. Methods A*, **899** (2018) 52.