The cell geometry is adapted to the manufacturing process. One side of the cell carries all the features required for the RF, whereas the other side is flat for bonding (Fig. 12.11). The cells are diamond machined, joined by diffusion bonding under hydrogen at about 1000°C and vacuum baked at 650°C. With exacting machining tolerances, typically in the 1 µm range, the tuning of the final structure is avoided.

A number of test facilities is in operation worldwide including those at CERN which houses the only facility modelling the two-beam scheme in addition to a number of test stands powered by klystrons for high turn-around of testing structure variants. Nominal accelerating gradients of 100 MV/m have been achieved in the accelerating structures under development in a worldwide collaboration with the required low break-down rate while the PETs have been tested at the nominal output power of 150 MW. However, more variants of these two structures have to be built and examined to address HOM damping, lifetime, breakdown statistics, industrial-scale fabrication, and better understanding of the break-down mechanisms.

12.5 The Next Energy Frontier e⁺e⁻ Collider: Innovation in Detectors

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Throughout the history of particle physics, both protons and electrons, with their respective antiparticles, have been used extensively for high energy colliders [Box 4.1]. The merits and difficulties of physics research with high luminosity proton–proton colliders are briefly described in the Box 8.3.

Electrons, in contrast to protons, are genuine elementary particles. Apart from initial-state radiation and beamstrahlung effects (see below), they provide very good knowledge of the initial state of the collision. The e⁺e⁻ annihilation cross section (Fig. 12.12) decreases as $E^{-2}$ and, at TeV energies, cross sections for most processes are small, typically of order $10^{-37}$ cm² or lower, and at a similar level as the interesting events in proton–proton collisions. However, the absence of the large physics background that plagues hadron colliders allows for much easier signal selection. If they can deliver sufficiently high luminosity ($>10^{34}$ cm⁻²s⁻¹), future e⁺e⁻ colliders are therefore the tool of choice for precision measurements.

Two design studies of high energy, high luminosity e⁺e⁻ colliders are currently hosted by CERN. The Compact Linear Collider (CLIC) is designed to cover a centre-of-mass energy range from ~350 GeV to 3 TeV, while the e⁺e⁻ option of the large circular collider, FCC-ee, is foreseen to cover energies from the Z-pole
at ~91 GeV up to the top pair production threshold near 350 GeV. CERN also participates in the International Linear Collider (ILC) study, a 250–500 GeV collider, upgradable to 1 TeV, which could be realized in Japan.

Beyond their respective physics discovery potential, all three machines will allow high-precision measurement of processes involving known particles. Besides a deeper understanding of the underlying processes these studies could provide insight into the nature of new physics at very high energy scales. In this context the most prominent examples are the accurate measurement of the Higgs boson and its couplings to mass, as well as the mass and production characteristics of the top quark. In the case of FCC-ee this is complemented by measurement of W and Z bosons with very high statistics. The centre-of-mass energy at CLIC will give access to the discovery and accurate measurement of pair-produced particles with a mass of up to 1.5 TeV, or single particles up to 3 TeV. In this context new electroweak particles or dark matter candidates are of special interest, as they may escape detection at the LHC. In addition, CLIC energies will give optimal access to double Higgs production, governed by the Higgs potential.

Spin plays a key role in research at an e+e− collider. In particular, beam polarization gives access to the spin dependence of the production processes. A polarized e− beam at a linear collider would be useful for testing the Standard Model (Chapter 7) and “feeling” new physics. While waiting for a broader view on the physics case after LHC, the CLIC baseline design foresees e− polarization, and reserves space in the design for the more challenging e+ polarization option.
The superb accuracy potential offered by $e^+e^-$ collisions drives the detector requirements [34–36]. Several “must-do” physics measurements, serving as benchmarks, determine specifications for the momentum resolution, energy measurement and quark flavour tagging of the detectors. The vertex and tracking systems have to be significantly more accurate (a factor 3 to 5) than the current state-of-the-art LHC systems, while highly granular calorimeters are needed to obtain the anticipated improvement of a factor 1.5 to 2 in jet energy resolution. In order to achieve this performance, the tracking and calorimeter systems will be located inside a powerful superconducting solenoid (Fig. 12.13).

The detectors also have to meet requirements driven by the beam conditions. In a linear collider the transverse size of the bunch is very small — indispensable for achieving high luminosity (12.1 and 12.4). As a result, the electron and positron beams produce strong electromagnetic radiation (beamstrahlung) in the high field of the opposite beam. Such radiative effects change the centre-of-mass energy distribution of the $e^+e^-$ collisions: the electron or positron may radiate a high-energy photon before the collision, resulting in a centre-of-mass energy below the nominal value. As a result, the spectrum of centre-of-mass energies shows a sharp peak at the nominal value and a long tail towards lower energies. This so-called luminosity spectrum can be measured in situ from Bhabha scattering, and subsequently used in the interpretation of the physics results. In principle the tail allows for a crude exploration of the physics which lies below the nominal energy, but with much reduced luminosity.

![Fig. 12.13. Artist view of a possible CLIC detector.](Image)
Beamstrahlung is also a source of additional background in the detectors, which is strongest at CLIC due to its high beam energy and smaller beam size. Background $e^+e^-$ pairs are produced at high rates and very close to the beam direction, while background hadrons with transverse momenta up to $\sim 5$ GeV/c reach out to larger polar angles. At 3 TeV the pile-up of beamstrahlung over the entire 156 ns bunch train amounts to $\sim 5000$ charged particles and $\sim 19$ TeV of energy deposited in the central detector volume. For comparison, at most one hard $e^+e^-$ physics event is produced per bunch train at 3 TeV. Provided the CLIC detectors produce timing information for all hits, with an accuracy of 10 ns for the tracking detectors and 1 ns for calorimeter hits, these beam-induced backgrounds can be suppressed efficiently in the data. At the ILC, beam-induced backgrounds will be less pronounced, due to the lower centre-of-mass energy and larger bunch sizes. Moreover, individual bunch crossings will be separated by several hundred ns. Therefore, the ILC detectors do not need to provide such accurate time information. Reduced occupancies in the inner ILC detector regions will allow the most inner vertex layer to be placed at a radius of 15 mm, as compared to 31 mm for the 3 TeV CLIC. At FCC-ee the dominant backgrounds originate from synchrotron radiation in the bending magnets closest to the experiment. The extent of this background and the resulting demands on the detector are under study.

Given the small $e^+e^-$ interaction cross sections the radiation levels are low. For example, at CLIC they will be typically a factor $10^4$ lower than at LHC. Only the small very-forward calorimeter systems will experience LHC-like radiation levels.

In the domain of vertex and tracking detectors, semiconductor devices provide the best accuracy. Silicon detectors are extensively used at the LHC and many interesting developments are on-going for the upgrades of the LHC experiments, with special emphasis on reducing the mass of the detectors and increasing their granularity, position accuracy and radiation hardness. Requirements for CLIC push the demands on position accuracy, cell size and low mass even further. For example, at CLIC each layer of the vertex detector should feature a position resolution of 3 $\mu$m and a time resolution of 10 ns for a material thickness corresponding to 0.2% of a radiation length $X_0$. Cell sizes need to be smaller than $25 \times 25$ $\mu$m$^2$ to limit occupancies due to beam-induced background particles. Assuming a minimal amount of material required for supports and services, the design allows for 50 $\mu$m sensor thickness and 50 $\mu$m readout ASIC thickness. To reduce heat dissipation, the electrical power to electronics will be turned off during most of the 20 ms interval between 156 ns bunch trains. This allows for air cooling, thereby avoiding the material otherwise needed for cooling tubes and liquids.

The semiconductor industry progresses fast, thanks to societal applications such as personal computers, mobile phones, sensors and cameras. Even though
particle physics has often quite specific detector requirements, innovations in the wider realm of semiconductors provides many opportunities for our field to progress. An example is the decreasing CMOS feature size with the associated increase in density of readout electronics. Industrial sensor and camera R&D involves integrated (high-resistivity) sensor materials, nanostructures and compact interconnect features, which are also interesting for particle detectors. The current readout ASIC for CLIC is based on 65 nm CMOS technology. Compared to the 0.25 µm CMOS circuits commonly used at LHC, this technology can accommodate about 25 times more logic cells per mm², which is very similar to the ratio of LHC to CLIC pixel sizes in the vertex detector. The 65 nm technology has the added advantage of reduced power consumption, with reduced detector mass as a further bonus.

CLIC R&D is also testing so-called integrated HV-CMOS sensors, which comprise a high resistivity sensor layer (for fast signal development) and the electronics circuit in the same thin device [37]. At the current stage of the R&D, the integrated sensor includes two amplification stages. As a result, the detected signal is large enough to be transmitted through a simple layer of non-conductive glue (AC coupling) to the readout ASIC (Fig. 12.14).

At a readout pitch of 25 µm this represents a significant production gain over the delicate traditional bump-bonding (DC coupling) between sensors and readout ASICs. The ALICE experiment is currently developing a related fully-integrated monolithic CMOS technology for their 10 m² inner tracker upgrade. It has supreme position resolution, albeit with limited signal speed [38]. In the coming years one can expect such trends in technology to evolve further, and tenacious particle physicists to cleverly exploit such features for their future detector systems. The CLIC R&D effort towards a fast and thin 100 m² e⁺e⁻ silicon tracker system with 7 micron single-point resolution and small readout cells will surely explore such opportunities.

For the calorimeter system CLIC will make use of the so-called Particle-Flow Analysis (PFA) approach, a development that was initiated at CERN by the ALEPH experiment at LEP and was successfully developed further for the CMS experiment at the LHC [39]. The approach will be exploited in future experiments thanks to newly available detector technologies.

Traditionally, the reconstruction of collision data proceeds mostly independently for the tracker system and the calorimeter. The production angle and momentum of charged particles are measured in the tracker, while the energy of nearly all outgoing particles (except neutrinos and muons) is measured independently in the calorimeter system. Particle showers in the calorimeter, in particular in the hadron calorimeter, develop over large volumes. This hampers the
matching between tracking and calorimeter information when particles are produced close in space. Quark and gluon jets are typically composed of many nearby particles, 60% of which are charged hadrons, 30% are photons (mostly from $\pi^0$ decays), and 10% are neutral hadrons. The charged hadrons are normally measured to high accuracy in the tracker (relative accuracy better than $10^{-4}$ $p_T$, with $p_T$ in GeV/c). The energy of photons is measured typically better than 15%/√$E$ (with $E$ in GeV) in the first layers of the calorimeter system. Neutral hadrons are not equally well measured, due to the much larger fluctuations in the hadronic shower development. Using the best information available for each of the individual particles in the jet, the jet energy resolution can be improved by a factor 1.5 to 2 compared to traditional calorimeter-only reconstruction techniques. This will allow to reach ~3.5% accuracy in jet energy measurements at high energies and to separate W, Z and Higgs decays reliably in multi-jet topologies.

This detailed PFA can be realized by combining fine-grained calorimetry with powerful event reconstruction software. In case calorimeter cells are small enough, one can assign energy deposits to individual particles in the event reconstruction. At the same time, PFA allows to identify individual particles originating from beamstrahlung and to reject them in the data analysis by using time information [40]. Figure 12.15 shows the PFA reconstruction of a simulated event in the CLIC detector model.

Cell sizes in the active layers are foreseen to be as small as $5 \times 5$ mm$^2$ in the electromagnetic section of the calorimeter and some $3 \times 3$ cm$^2$ in the hadronic section. The electromagnetic section is foreseen to have 30 layers in depth of one radiation length each, while the hadronic section will have ~60 layers for a total of 7.5 interaction lengths in order to fulfil the jet energy resolution goals up to 3 TeV centre-of-mass energy. Compared to the current ATLAS or CMS calorimeters this represents a factor 400 increase in the number of readout cells.
SiPMs are single photon counting devices composed of an array of avalanche photodiodes (APD) on a common silicon substrate. The miniature devices can host over 10 000 APDs per mm², and are insensitive to magnetic fields. Compared to traditional photomultipliers they offer a wealth of new possibilities for particle detection, including highly granular calorimetry.

Prototypes of highly granular calorimeters have been pioneered by the CALICE collaboration, initially targeting calorimetry for the ILC and subsequently also for CLIC and other facilities. Full-size fine-grained electromagnetic and hadronic calorimeters were built and successfully tested. Several options for the active layers and passive absorbers were explored [41]. Such fine-grained prototypes do not only demonstrate technical feasibility and performance capabilities, they also provide invaluable information on calorimetric shower development: a very welcome input for detector simulation tools, such as Geant4.

The demanding performance goals for future e⁺e⁻ collider experiments have motivated advanced detector R&D across the planet. The community is preparing to realize these experiments in a foreseeable future and to explore the physics discovery potential at these new machines.