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Silicon Calorimeters

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Abstract
We review the development of silicon-based calorimeters from the very first applications of small calorimeters used in collider experiments to the large-scale systems that are being designed today. We discuss silicon-based electromagnetic calorimeters for future $e^+e^-$ colliders and for the upgrade of the CMS experiment’s endcap calorimeter to be used in the high-luminosity phase of the LHC. We present the intrinsic advantages of silicon as an active detector material and highlight the enabling technologies that have made calorimeters with very high channel densities feasible. We end by discussing the outlook for further extensions to the silicon calorimeter concept, such as calorimeters with fine-pitched pixel detectors.
1. INTRODUCTION

1.1. A New Paradigm in Calorimeter Design

With the discovery of the $W$ and $Z$ bosons in the 1980s a new era in the study of electroweak (EW) phenomena began. Because the Higgs, $W$, and $Z$ bosons decay predominantly into jets, in order to study these bosons in detail it is important for an experiment to be able to measure jets accurately.

Concurrently with these discoveries, theoretical developments in physics beyond the Standard Model (BSM) predicted that massive noninteracting particles would be produced at the highest energies. Accordingly, jet reconstruction and the ability to accurately measure transverse energy ($E_T$) became important tools for particle physics at the energy frontier. Initially, calorimeters were the main tools used in these studies. They consisted of an electromagnetic calorimeter (ECAL) in front, optimized for the measurement of electromagnetic (EM) interactions, and a hadronic calorimeter (HCAL) behind, to measure the hadronic energy. Jets were reconstructed as clusters of energy depositions in a two-dimensional grid in the azimuthal and polar angles. When signals from the calorimeters are combined, the jet energy resolution (JER) follows approximately a stochastic law of the form

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E} \text{(GeV)}} \oplus b, \quad 1.$$ 

where $a$ is the stochastic term reflecting the statistical fluctuations in the shower’s evolution and $b$ is the constant term needed to account for the calorimeter’s nonuniformity of response, incomplete energy containment, and stability over time. Typical values for $a$ are in the range 50–100%, whereas $b$ is a few percent. This method, however, suffers from limitations. First, most of the jet energy (~75%) is carried by hadrons (charged or neutral) (1), and the measurement thus inherits
the intrinsically poor performance of a traditional HCAL. Second, in a hadronic shower there are intrinsic fluctuations between the EM and hadronic components of the energy deposition that lead to a degradation in the JER. Improvements in the reconstruction of jets and in the precision on $E_T$ can be achieved by improving the measurement of photons and hadrons. However, measuring the energy of hadrons through their energy loss in matter suffers from several intrinsic limitations. Any design that achieves high precision in photon and hadron energy measurements simultaneously will be sensitive to fluctuations in the EM and hadronic components of a shower. A technique known as compensation has been proposed to address this problem. In a compensating calorimeter, the EM ($\gamma$) and hadronic ($\pi$) responses are matched, so that $\gamma\pi = 1$. However, most calorimeters are designed to measure electrons and photons well, as they are important for the physics. As a consequence, the EM response differs from the hadronic response [i.e., $\gamma\pi \neq 1$ (2)], leading to complexities in calibrating the calorimeter’s response to different types of particles. In addition, since the EM fraction increases with energy (3), the hadron response becomes nonlinear.

Hadronic showers contain additional fluctuations due, in particular, to the loss of invisible particles, energy lost to neutrons and to nonionizing nuclear interactions, which can further degrade the energy resolution. Any improvement in the design of a calorimeter, in which the precise measurement of jet energy and missing transverse energy is a requirement, needs to contend with these fundamental problems. Initially, due to practical limitations in the available readout technology, calorimeter cell sizes were relatively large, typically the size of the Molière radius or larger for ECALs, and even larger and usually about one interaction length for HCALs.

By the start of the new century and the end of operation of the Large Electron–Positron Collider (LEP), good progress had been made in the design of accelerating cavities, enabling new designs of $e^+e^-$ colliders with a higher center-of-mass energy. Several designs with energies ranging from the Z pole up to 3 TeV were considered, including the International Linear Collider (ILC) and the Compact Linear Collider at CERN (CLIC). In addition, when the Higgs boson was discovered with a mass of 125 GeV, two other circular $e^+e^-$ colliders were proposed, one in China (CEPC) and another at CERN (FCC-ee), which have center-of-mass energies of 250 and 350 GeV, respectively.

One of the main physics objectives of all these projects is the high-statistics measurement of events with two or more bosons ($ZZ, WW, ZH$, etc.). Therefore, accurate identification of the different bosons in their multijet final states is essential for the physics programs of these machines. As a result, one of the main requirements for the detectors at these machines is the ability to measure jets with sufficient accuracy to separate $W$ from $Z$ bosons, which have a mass difference of approximately 10 GeV, by the invariant mass of the dijet decay products. The required jet energy precision can thus be estimated from the dijet invariant mass, $M^2 \approx 2 E_1 E_2 (1 - \cos \theta_{12})$, where $E_{1,2}$ are the energies of the jets and $\theta_{12}$ is the angle between them. With a JER of $\sigma_E/E$, this translates into a mass resolution of $\sigma_M/M = (1/\sqrt{2})\sigma_E/E$, if the uncertainty in $\theta$ is neglected. If we take the natural width of the $W$ and $Z$ bosons of $\sim 2.7\%$ into account, a $3\sigma$ separation leads to the requirement of a JER of 3–4%.

This requirement cannot be met with measurements only from calorimeters. It falls short by a factor of two or more, for the reasons discussed above. To overcome this limitation, the H1 and LEP Collaborations developed a new method called energy flow. This method combines information from both calorimeters and the charged tracks to estimate the jet energy. The principal idea is to determine the energy difference between the energy of a cluster in the calorimeter and the sum of the momenta for charged tracks associated with that cluster. When there is an excess of cluster energy, a neutral object is created with an energy corresponding to the excess and located at the center of the excess. This technique is currently being used by the CMS Collaboration in its physics analyses at the Large Hadron Collider (LHC), with the ECAL and HCAL being used separately to identify the type of neutral particle. The results have been excellent and have, for
example, improved the precision of the measurement of $E_T$. Nevertheless, the gains obtained with this method do not reduce the JER by a factor of two.

To further improve the JER, another new technique, known as the particle flow algorithm (PFA), was proposed (4, p. 160; 5) on the basis of the idea of separately measuring the energy deposited by each particle in a jet. This method begins by associating tracks with energy clusters in the calorimeters, and the high-precision momentum measurement of charged particles is kept, while any energy depositions associated with the tracks are ignored. Next, the unassociated clusters in the ECAL, which generally are photons from neutral-pion decays, and any unassociated energy depositions in the HCAL, which generally come from neutral hadrons, are added to obtain the jet energy. Since the average distribution of the energy carried by the particles in a jet is 65% for the tracks, 25% for photons, and 10% for neutral hadrons, and since 90% of the jet’s energy is measured with high precision and only the 10% neutral-hadron component is measured with low precision, this approach significantly improves the JER relative to calorimetric measurements alone.

In the application of the PFA it is assumed that all the tracks can be accurately associated with energy deposits without confusion between particles, placing a significant constraint on the calorimeter design. This change in the way that energy is measured in collisions has led to a new paradigm of the design of detectors and, in particular, calorimeters. Calorimeters are no longer defined simply by their single-particle energy resolution but rather by their ability to associate individual showers with tracks and to track showers as they develop inside the calorimeter. It is this capability to construct a three-dimensional image of a shower as it progresses through the calorimeter that drives the performance of a PFA calorimeter and has led to calorimeter designs with a silicon active medium.

We note that, intrinsically, the PFA method includes a natural reconstruction of the decays of tau leptons, which is important for polarimetry analysis. This is linked to the fact that each individual particle is identified, leading to a possible identification and measurement of tau decays (6).

The first investigations of the PFA method were performed in the framework of the TESLA project. A GEANT4 simulation of jet events in $e^+e^-$ collisions at the Z pole showed that the necessary factor-of-two reduction in JER could be obtained. This finding was confirmed with more detailed detector simulations using more refined algorithms (7), which showed that the required precision can be reached for jet energies up to approximately 250 GeV, and that above that range significant improvement can still be obtained. Studies in the framework of the CLIC project, where the background conditions are more demanding, because of the short bunch crossing interval of 0.2 ns, and the high intensity of hadronic $\gamma\gamma$ interactions from beam-strahlung, have shown that the PFA method still significantly enhances performance and that high granularity, combined with timing information, is instrumental for pileup rejection (8).

### 1.2. The Choice of Silicon

As described in the preceding section, an essential component of the PFA method is a calorimeter that can accurately assign a track to a cluster. This requires three-dimensional imaging capability and fine granularity throughout the calorimeter’s depth, with small pixel sizes and a sampling frequency in depth that is as fine as is technically (and financially) feasible. The active material must be able to both detect minimum ionizing particles (MIPs) efficiently and measure the energy depositions on a scale of 1,000 MIPs. It must be a linear material that can be readily segmented, and in the case of the LHC (discussed below) it must also be radiation hard. The material has to be thin to keep the Molière radius of the EM calorimeter small, and it should not be expensive or exotic. Only two technologies come close to meeting these requirements: liquid argon and silicon. Although it is possible to finely segment multiple layers in a liquid argon calorimeter, it is difficult...
to efficiently integrate the readout into a thin detector layer, and the operation of high-density electronics at the low temperature of liquid argon is problematic. By contrast, silicon is a very well understood industrial material that can be readily patterned to suit the design requirements with lithography. The signal is short (∼10 ns), and the typical detectors are only 0.3 mm thick. Moreover, the well-understood radiation tolerance of silicon is a point in its favor for applications at hadron colliders.

For the high-luminosity phase of the LHC (HL-LHC), the radiation tolerance of silicon and the feasibility of building a compact finely segmented calorimeter with excellent time resolution have made silicon the natural choice for the active material of a new calorimeter. The new calorimeter will be an upgrade of the CMS endcap calorimeter and will be installed at the HL-LHC in 2025; for the HL-LHC, in addition to the need to resolve jet components, efficient rejection of background interactions from the same bunch crossing will be required. This calorimeter, the design of which is discussed below, will use layers of silicon sensors in both the EM and hadronic sections. It will have a total active silicon area of 580 m² and will be the first large-scale imaging silicon calorimeter to deliver physics data (9).

2. ENABLING TECHNOLOGIES

Silicon calorimeters are sampling calorimeters composed of layers of silicon detectors interspersed with absorber plates. Most silicon calorimeters built to date have been devised for the detection and measurement of EM showers caused by electrons and photons, covering a limited geometrical acceptance, principally for reasons of cost. As silicon fabrication techniques have advanced, this limitation has become less important.

As described above, silicon is an attractive choice for the active medium for a calorimeter because it can segment sensors into shapes that are convenient for application, signal duration from the passage of an ionizing particle is on the order of a few nanoseconds, and the sensors are thin, allowing for high-density construction of calorimeters with a small Molière radius. In addition, the response of silicon is intrinsically stable with respect to environmental conditions, such as temperature, thereby simplifying detector calibration.

Apart from cost, there are many technical difficulties that need to be considered when designing a silicon calorimeter. In particular, for a finely segmented calorimeter, the channel density can rapidly become very high. Consequently, the readout electronics needs to be integrated into the active layers of the calorimeter to collect and concentrate signals early on, so as to keep the signal pathways off-detector at a manageable level. The removal of the heat generated by the electronics, the extraction of signals to the periphery of the detector, and the delivery of power to the electronics also need to be taken into account.

Since the first silicon calorimeters were proposed in the early 1980s, several technological advances have made the design of large-scale finely segmented silicon calorimeters feasible. One of the most important advances is the significant progress made in the design of fast, large-dynamic-range electronics, and in the very large scale integration of microelectronics, which has enabled the creation of analog–digital mixed-circuitry system-on-chip architectures. The signal from a MIP traversing a 300-µm silicon wafer is approximately 3.8 fC, whereas for a 100-GeV EM shower signals of order ∼1,000 MIPs cm⁻² are typical at the shower maximum. The calorimeters used to measure the luminosity for the LEP experiments ALEPH and OPAL used application-specific integrated circuits (ASICs) designed with 3-µm technology, while the CMS High Granularity Calorimeter group is designing its electronics using radiation-hard 130-nm technology. With the reduction in feature size there is a corresponding reduction in power consumption and a corresponding increase in the number of channels that it is feasible to read out.
Another major development that has been particularly relevant for applications at hadron colliders is in the area of signal transmission. Modern radiation-tolerant optical links operate reliably at speeds of up to 10 Gb s\(^{-1}\), enabling extraction of the huge volumes of data generated in an imaging calorimeter.

Furthermore, the average power consumed by the electronics can be reduced by power pulsing the electronics between collision events. Such a technique could be applied to the calorimeters proposed for the linear electron colliders, in which the interval between bunch trains is long. In the case of the calorimeters at the LHC, where this approach is not possible, the use of large-scale biphase \(\text{CO}_2\) cooling systems to remove the heat generated from the electronics is now feasible. As the difference in enthalpy between liquid and vapor states is large (~2,300 kJ kg\(^{-1}\)) at temperatures below \(-20^\circ\text{C}\), this is an excellent method to extract heat without the need for large cross-section piping, as would be the case if water, or another liquid, were used to cool the electronics.

3. EARLY DEVELOPMENTS

To our knowledge, the benefit of using silicon in a calorimeter was first discussed in 1980 by Nakamoto et al. (10) with regard to an application where a single layer of silicon was used to measure the location of EM showers in cosmic rays. Subsequently, Nakamoto et al. (11) described a silicon sampling calorimeter with a lead absorber, and Barbiellini et al. (12, 13) became the first to propose the use of tungsten and uranium as absorbers to minimize the length of the calorimeter for the detection of high-energy showers. Bormann et al. (14) constructed a small (3.2-cm-diameter) test calorimeter for applications at HERA. This calorimeter had 12 layers of sensors separated by 1\(X_0\) lead plates; the authors reported a resolution consistent with Equation 2 for electron energies up to 5 GeV.

In these early applications, the detectors’ lateral dimensions were limited by the size of the silicon wafers then available. The silicon–lead detector proposed by Nakamoto et al. was built with 11 layers of lithium-drifted silicon sensors, with a diameter of 70 mm, interspersed with 5-mm lead sheets. With this detector, the authors achieved an energy resolution of \(\Delta E/E = (16.5 \pm 0.5)/\sqrt{E} (\text{GeV})\) with electron beams of up to 750 MeV. The detector proposed by Barbiellini et al. contained sensors with an area of 25 cm\(^2\) arranged in a 24\(X_0\) stack of 2\(X_0\)-thick plates of tungsten or uranium, and was exposed to electrons with energies up to 100 GeV. With this detector, Barbiellini et al. demonstrated excellent linearity and measured the shower development with the depth of the calorimeter. The resolution of both calorimeters agreed well with the expectation given by

\[
\frac{\Delta E}{E} \sim (20\% \sqrt{X_S}/\sqrt{E}),
\]

where \(X_S\) is the sampling fraction in radiation lengths and \(E\) is expressed in GeV. In both calorimeters, the silicon sensor was a single large-area diode with a depletion depth on the order of 200 \(\mu\)m with a capacitance of \(
\sim 1 \text{nF},\)
placing significant constraints on the design of the preamplifier (15).

These developments paved the way for the use of silicon detectors in H1 at HERA and in the luminometers at the \(e^+e^-\) colliders SLC (SLAC Linac Collider) and LEP, which began operation in the 1990s.

3.1. Forward Calorimetry and Luminometers

The first application of silicon calorimetry in an experiment was the H1-PLUG detector at the HERA \(e^p\) collider (16, 17). The detector filled the gap between the beam pipe and the forward liquid argon calorimeter and was used to measure hadronic energy in the very forward region.
H1 to ensure hermeticity of the detector and to tag rapidity gap events. The silicon sensors were mostly $5 \times 5$ cm$^2$, with smaller sensors for the edges of the detector. In all, there were 672 sensors combined into 336 readout channels. The absorbed dose during operation was 300 Gy for the innermost detector, and as a consequence, approximately 10% of the detectors were irreversibly damaged (18).

At $e^+e^-$ colliders, luminosity is monitored through the measurement of Bhabha scattering at small angles. Since the cross section of this process decreases with the cube of the production angle, the precision of the position of the shower as measured in the calorimeter is crucial. Segmented silicon calorimeters were used by the CERN LEP experiments and at the SLC. These so-called luminometers were the first calorimeters to use highly segmented silicon sensors for precision measurements of the energy and position of EM showers. This innovation was made possible by the many advances in semiconductor processing technology that occurred in the 1990s.

For the SLAC Large Detector (SLD), whose total integrated luminosity was relatively small, the required precision on the luminosity was 3%, whereas for the LEP experiments it was 0.1%. The SLD luminosity monitor was divided into two distinct calorimeters, the luminosity and small-angle tagger (LMSAT) and the medium-angle silicon calorimeter (MASC), using a total of $\sim 2$ m$^2$ of silicon sensors. The sensors were $n$-type with a 300-$\mu$m depletion thickness. They were subdivided into pixels that had an area of approximately 1 cm$^2$. The calorimeters were built with 23 layers of $0.86X_0$ (LMSAT) and 10 layers of $1.74X_0$ (MASC) tungsten absorber plates, with the sensors glued directly to the plates. The readout of these calorimeters employed a 32-channel preamplifier ASIC, adapted from the preamplifier used in the SLD liquid argon calorimeter. This design demonstrates one of the major benefits of a highly pixelated ECAL, which is the lack of correlation between the locations of the energy depositions in each layer, leading to a precise measurement of the shower’s location and direction. In a test beam with electrons, an energy resolution $\sigma_E \sim 25\%/\sqrt{E}$ and a position resolution of 1–1.5 mm at 4 GeV were achieved.

At LEP, two silicon calorimeters were installed in the ALEPH (19) and OPAL (20) detectors to measure luminosity. The ALEPH tungsten–silicon luminometer (SICAL) was constructed with 300-$\mu$m $n$-type silicon assembled from tungsten–silicon–tungsten modules. Each calorimeter was built in two C-shaped halves containing 12 tungsten–silicon–tungsten modules. Each wedge-shaped silicon sensor was made from 10-cm silicon wafers and divided into 32 pads that increased in size radially from 0.6 to 1.45 cm$^2$. The number of channels in both calorimeters was 12,288; readout was a modified version of the AMPLEX ASIC (21) low-power multiplexed 16-channel preamplifier (12.5 mW per channel) made with 3-$\mu$m complementary metal–oxide semiconductor (CMOS).

The OPAL luminimeter consisted of a stack of 19 silicon sampling layers interspersed with tungsten plates. The first 14 plates were $1X_0$, whereas the last 4 plates were $2X_0$. Figure 1 depicts the layout of the sensors used in the OPAL luminometer.

The $\sim 39,000$ channels for the two OPAL luminometers were read out with the AMPLEX ASIC. Because the main purpose of these calorimeters was to measure the luminosity, the accuracy of the measurement of the location of EM showers and a complete understanding of the detector acceptance were paramount. In the OPAL detector, the shower location was measured to $130 \mu$m and $170 \mu$m at the pad boundaries and pad centers, respectively. The energy resolution achieved with these detectors was consistent with the expectation provided by Equation 3. The operational experience was excellent, with 99.4% of the detector channels in the OPAL luminimeter functioning at the end of LEP operation.

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1The AMPLEX chip was originally developed for the UA2 silicon tracker and adopted by the OPAL group, demonstrating the synergy between the development of silicon trackers and the development of silicon calorimeters.
Silicon continues to be the first choice for the active material of calorimeters to be located close to the beam line. Research and development (R&D) are under way toward optimizing these detectors for the higher demands of future experiments in terms of precision, rate capability, and radiation tolerance. At the same time, novel materials such as diamond, sapphire, and gallium arsenide are also being explored. In the remainder of this review, we concentrate on the establishment of silicon calorimetry in large collider detector systems.

3.2. Preshower Detectors

In the initial applications of silicon detectors in large-scale calorimeters, the instrumentation of the first few radiation lengths of the calorimeter was used to separate hadrons from electrons and...
photons and to localize EM showers. Early in the development of a high-energy EM shower, the ionization is predominantly in the forward direction, so the signals are large and narrow, whereas for a hadron they are typically at the MIP level. The first example of a silicon preshower detector was the ZEUS hadron–electron separator (HES) (22, 23), which was an upgrade of the ZEUS calorimeters. The HES contained two detectors mounted on the two front faces of the forward and rear uranium/scintillator calorimeters. The total area of active silicon in the two HES detectors was 20 m² (a factor of 10 larger than the area of either of the LEP luminometers) with 20,518 readout channels. It was built in 4.6-m-long modules that were inserted through a 16.3 × 1.5 cm² slot. The silicon diodes were 3.47 × 3.07 cm², with an inactive region approximately 1 mm wide on the periphery. The diodes were mounted along with the preamplifiers on 4.6-m-long, 18-layer printed circuit boards (PCBs), with two back-to-back instrumented layers forming a 224-channel detection layer. The position resolution achieved for the EM showers was 5 mm², and the misidentification rate for hadrons was ∼3.5% with an electron efficiency of 90%.

In the CMS detector, the two crystal endcap calorimeters were supplemented with a 3X₀ preshower detector. The purpose of this detector was to distinguish neutral pions from photons. This goal was motivated by the need to minimize the background from coalescing neutral pions in the search for the Higgs boson in the two-photon decay. Because the preshower detector was to be installed following insertion of the beam pipe into the main detector, it was constructed in two D-shaped halves. The sensors were 300-µm-thick squares, 63 mm on each side, divided into 32 strips. The detector was built with two orthogonal layers, one at 2X₀ and the other at 3X₀. The temperature of the preshower was kept at −10°C in order to maintain sensitivity to MIPs after the expected radiation dose in the detector.

The experience gained from operation of the luminometers at LEP and the preshower detectors discussed above, as well as from construction of the very large area silicon tracker at CMS, led the high-energy physics community to choose calorimeters made of highly granular silicon for use in the detectors planned for the next generation of e⁺e⁻ colliders, and for the replacement of the CMS endcap calorimeters at the HL-LHC. These calorimeters are discussed below.

4. SILICON CALORIMETRY FOR e⁺e⁻ COLLIDERS

In the past 20 years, plans for machines to explore the EW sector with high-luminosity and high-energy e⁺e⁻ colliders at high precision have been developed, and technical progress in accelerator design has made such machines feasible. The designs of all the different detectors include silicon trackers with imaging silicon calorimeters, and the PFA has been used to demonstrate the physics reach.

4.1. Silicon Electromagnetic Calorimeter Designs for an e⁺e⁻ Linear Collider at √s = 250 GeV

As both ECAL and HCAL calorimeters have to absorb all the energy of a shower, the difference between radiation and interaction lengths leads to a significant difference in their thicknesses. To limit overlaps between showers, the ECAL’s depth in the particle direction must be as thin as possible. This requirement, along with the need for clear particle separation, led to the choice of a sampling calorimeter with a tungsten radiator (radiation length X₀ = 3.5 mm, Molière radius R₉ = 9 mm, and interaction length λ = 99 mm), resulting in a compact design with a depth of roughly 24X₀ within 20 cm and an optimal separation of close EM showers because of the smaller Molière radius. Regarding the HCAL, this design yielded a better average longitudinal separation of hadronic versus EM showers due to the larger ratio of λ to X₀, compared with alternative materials such as lead or steel.
Studies of the PFA performance were performed for the TESLA project (4) and have continued for the ILC project (24), whose ECAL will have a longitudinal segmentation of 20 to 30 layers and, possibly, tungsten thicknesses that vary with depth. The final choice of the number of layers in the ILC design will be dictated by the trade-off between cost and performance, although the cost of the calorimeter, when compared with the expected running cost of the ILC itself, is low. Note, however, that the cost of the calorimeter, when compared with the expected running cost of the ILC itself, is low. Given the very large number of electronic channels in the system, power budget constraints have led to the requirement that the power of each channel of the very front end (VFE) be kept at or below 25 $\mu$W. In order to achieve this value, the readout electronics are power pulsed between bunch crossings, yielding a duty cycle of 1%—a solution that benefits from the ILC beam structure. As a result, with only passive cooling, the number of channels can be very high and the pixel sizes can be as small as few square millimeters.

Two separate collaborations are currently working on the design of a detector (25) for the ILC. These are the ILD Collaboration, with a design based on CALICE R&D, and the SiD Collaboration.

4.2. Geometrical Design and Internal Structure of the ILD Detector

A critical component of a silicon calorimeter, as with other calorimeters, is its mechanical design. Cost, assembly, and operational constraints need to be taken into account simultaneously. The calorimeter for the ILD detector will be placed inside a large cylindrical solenoid, and its geometry is designed to have the best possible coverage. It will have three angular regions: the central or barrel region, the forward region consisting of two endcaps, and the intermediate region between the barrel and forward regions.

Four locations pose particular problems for the mechanical design: the boundaries between mechanical modules, the overlap between barrel and endcap, the small-angle region near the beam, and the connection to the luminosity monitor. Large modules with nonpointing intermodule boundaries are preferable, as they minimize the number and effects of cracks in the barrel. The cylindrical symmetry of the solenoid is reflected by an eightfold symmetry in the calorimeter, and the modules are designed such that the gaps between octants (known as staves) are at a large angle with respect to the radial direction. Each stave is subdivided into five modules, and the whole assembly is fastened to the front face of the HCAL by rails for ease of insertion (and any necessary maintenance), with space between the ECAL and the HCAL for services such as cooling, electrical power, and signal distribution. The ECAL endcaps are attached to the front face of the hadronic endcap calorimeters using a similar rail system.

The barrel ECAL is made of 40 identical modules. The absorber structure of each module consists of a tungsten and carbon fiber with slots for insertion of the active layers. The endcap calorimeter is constructed similarly. The mechanical design of the modules has been built and tested under real conditions in several test beam experiments.

The detector slabs, which are up to 2 m long in the endcap calorimeter, are built around an H-shaped supporting structure incorporating a layer of tungsten absorber. An active layer is placed on each side of the H. This active layer consists of a chain of identical active sensor units (ASUs), which consist of a PCB, the silicon sensors, the front-end electronics, and electrical infrastructure (Figure 2). The ASUs are designed to be able to operate as a stand-alone unit, enabling their testing at different stages during assembly.

Each 9 $\times$ 9 cm$^2$ silicon sensor is made from 6-inch wafers. The readout pixel size in a recent CALICE prototype was 5 $\times$ 5 mm$^2$, which is the lower limit for the use of small conductive glue dots connecting the pixels and the PCB. Standard glue (EPO-TEK) is applied to the PCB by a robotic gluing machine; the robot then places the matrix with precision on the order of 100 $\mu$m.
No problems arising from the gluing technique have been observed over a period of approximately 10 years.

With such a large number of channels, it is essential to maintain a good signal-to-noise ratio; therefore, the sensors are based on high-resistivity (5 KΩ cm) silicon. The thickness of the silicon detector, 330 µm, is the same as that used in earlier silicon tracker applications. Discussions with silicon producers have led to the possibility of using thicker wafers, which would improve single-photon energy resolution at a reasonable cost. The ILD Collaboration is currently testing 650-µm-thick sensors for inclusion in future detector layers to be tested by the CALICE Collaboration.

Note that the present choice of wafer size is dictated by the silicon producers. It is expected that 8-inch wafers will become available in the near future, which would change the size of the square matrices. In addition, the potential use of small rectangles between the matrix and the physical edge of the wafers would optimize the use of the high-resistivity ingot.

4.3. Status of CALICE Research and Development

In several beam test campaigns between 2005 and 2011, the CALICE Collaboration has studied the performance of the ILD silicon–tungsten ECAL by using a physical prototype (26). The prototype was made of 30 layers of 1 × 1 cm² pixels for a total of approximately 10,000 channels. The VFE ASIC contains the analog part but did not include any on-detector digitization of the signal or power pulsing. Consequently, much of the electronics readout was located outside the detector.

Several test beam campaigns were carried out for this prototype to demonstrate the detector’s performance (results from these tests can be found in Reference 27). The energy resolution is $(16.6 \pm 0.1)/\sqrt{E(\text{GeV})} \oplus (1.1 \pm 0.1)\%$ with a MIP signal-to-noise ratio of ~7.5.

A second generation of prototypes has recently been built to further advance the ECAL design for the ILC. Their design is very similar to that of the final ILC detector modules. These
second-generation prototypes will address issues relevant for a full-size detector at an $e^+e^-$ collider: the high level of integration for the VFE located between layers, operation with power-pulsing mode in a high magnetic field, a pixel size of $5 \times 5 \text{ mm}^2$, and a thin PCB with packaged or embedded chip-on-board ASIC on the top and silicon matrices glued on the bottom.

The 64-channel VFE ASIC, SKIROC, was designed by the Omega Group (see https://portail.polytechnique.edu/omega/en) at the École Polytechnique, France. It has an internal analog-to-digital converter and two paths, one for triggering and one for precision readout. Additionally, it can be power pulsed and self-triggered.

Results from tests of the first three-layer prototype, made with a single ASU per layer, agreed with predictions from simulations (28); the signal-to-noise ratio at the MIP was typically in the range of 15–18. In 2017, four additional layers were produced, also with a single ASU per layer but with improved shielding and grounding; only 2% of the channels showed noise problems or VFE bad responses. Figure 3 depicts the MIP dispersion and the signal-to-noise ratio. In addition to these tests, the detector’s operation in a magnetic field was examined. The detector was rotated vertically and placed inside a magnetic field of up to 1 T. When data were taken with a 3-GeV positron beam and with muons, the only observed change in performance was a 3% shift in the MIP signal arising from the longer muon trajectory. The good results obtained with this prototype have led the CALICE Collaboration to expect that the final design of the ILD ECAL will be settled by 2019.

4.4. The Electromagnetic Calorimeter in the SiD Detector

Whereas the technical choices made for the CALICE ECAL design are guided by current industrial capabilities and cost, the design of the SiD ECAL has pursued a more aggressive integration concept without PCBs and direct bonding of chips to hexagonal wafers (Figure 4). As a result, there is an active gap of 1.25 mm between absorber plates, a cell size of 13 mm$^2$, and an effective Molière radius of 14 mm. The readout chip, KPIX (29), was developed by SLAC to manage all the channels (approximately 1,000) of a hexagonal sensor made in a 6-inch wafer process. The ASIC is a common design that will be used for both the silicon calorimeter and the silicon tracker readouts.
Two Kapton layers are used to connect the sensor to the ASIC, one on the bottom of the hexagon to provide the bias voltage and the other one on the top to extract the signal and allow access to the slow control of the chip. The baseline configuration of the ECAL has 30 layers of tungsten that progressively increase in thickness and are stacked in a self-supporting structure. The signals and services of the barrel are routed parallel to the beam axis to the end face. The heat dissipated by the sensors and electronics is extracted by a tungsten radiator.

In order to demonstrate the feasibility of its concept, the SiD Collaboration (30) built a prototype of nine layers representing a total of 6X0. It was exposed to a pulsed test beam at SLAC with 12-GeV electrons, with only a few particles per pulse, enabling measurements of overlapping showers. Figure 4 compares the distribution of the total charge signal with GEANT4-based simulations. The efficiency of the separation of nearby showers is close to 100% when they are separated by 10 mm.

The beam test also exhibited cross talk from capacitive coupling between pixels. A new version of the silicon hexagon with improved shielding is under development. To minimize this effect, the SiD Collaboration is also considering the option of a so-called digital ECAL based on monolithic active sensors with 50-µm square pixels read out in binary mode (see Section 6).

4.5. Other $e^+e^-$ Colliders

For the detector at the CEPC, which is expected to run only at $\sqrt{s} = 250$ GeV, a silicon–tungsten sampling ECAL is one of the options under consideration. In contrast to the ILC, active cooling is anticipated because the time structure does not allow for power pulsing of the electronics. This has led to an interesting study of the effect of increasing the pixel size in PFA applications. Large pixels would mean fewer readout channels and hence less heat to remove. So far, results have suggested that pixels as large as $2 \times 2$ cm$^2$ could be used without significantly degrading the PFA performance (31). However, without active cooling the pixel size would need to be $5 \times 5$ cm$^2$, and studies have shown that such large pixels would significantly degrade both the PFA performance and the signal-to-noise ratio.

Figure 4

(a) Cross section of an electromagnetic calorimeter layer in the SiD design. (b) Distribution of total measured charge in prototype runs for data and a GEANT4 simulation, assuming a Poisson distribution of beam particles with an average of 0.8 electrons per beam bunch.
The design of the CLIC detector is optimized for higher energies. The ECAL has 40 layers of silicon diodes sandwiched between tungsten plates of equal thickness to ensure longitudinal containment for the higher center-of-mass energies at CLIC to achieve good resolution at higher energies.

5. THE CMS ENDCAP CALORIMETER

With CERN’s decision to proceed with the upgrade of the LHC to the HL-LHC, which is expected to deliver an integrated luminosity of 3,000 fb$^{-1}$ or more, it became clear that the endcap calorimeters in the CMS detector would need to be replaced. The CMS endcap calorimeters cover the pseudorapidity ($\eta$) region from 1.47 to 3.00 at both ends of the detector. At the HL-LHC, the instantaneous luminosity is expected to be $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$. At these values, the average number of $pp$ collisions per bunch crossing is 140, distributed over an $\sim 10$-cm region along the beam direction. As a consequence of the high luminosity, after 10 years of operation the radiation levels and neutron fluence will reach unprecedented levels inside the calorimeters—in excess of $10^{16}$ neutrons cm$^{-2}$ and 1 MGy at high $\eta$—which are levels that few detector materials are capable of sustaining.

Since neither the lead tungstate crystals of the ECAL nor the plastic scintillator of the HCAL in the calorimeters presently installed in the CMS detector can sustain such levels, the collaboration chose to replace the endcap calorimeters with a high-granularity calorimeter containing an EM section. This calorimeter will be entirely instrumented with silicon, and the hadronic section behind will be built from a mixture of silicon and scintillation sensors. Figure 5 depicts the layout of the calorimeter.

**Figure 5**
The layout of the CMS endcap calorimeter to be installed for operations at the High-Luminosity LHC (HL-LHC). The front (electromagnetic) section of the calorimeter is equipped entirely with silicon, whereas the back section is equipped with silicon in the regions of highest radiation and with scintillators, such that the radiation levels will not significantly degrade the scintillators or the silicon photomultipliers used in their readout.
5.1. The Choice of Silicon

The primary reason for the choice of silicon is its ability to continue providing a sufficient signal even after the expected very high levels of radiation. This choice was made following a detailed investigation of the performance of silicon after exposure to significant levels of radiation by the CERN RD51 Collaboration, R&D carried out by the CMS tracker group in preparation for the upgrade of the CMS tracker for HL-LHC operations, and specific tests performed by the CMS endcap calorimeter group (9, pp. 120–4). A major difference between an endcap calorimeter and a silicon tracker is that in the former the cell size is of order 1 cm\(^2\), whereas for the latter the strips are of order 100 \(\mu\)m wide. Moreover, the fluence for the tracker will consist predominantly of charged hadrons, while the fluence in the endcap calorimeter will be mostly from neutrons.

The principal radiation damage mechanism in crystalline silicon is the creation of interstitials or vacancies in the crystal lattice, which act both as carrier traps that reduce the carrier lifetime and as sources of thermal electrons that increase the dark current. Thus, with irradiation the charge-collection efficiency decreases while the dark current increases. The reduction in charge-collection efficiency occurs because the lifetime of the carriers liberated by ionizing radiation, and hence the magnitude of the current pulse (the signal), is decreased. This drawback can be compensated for in part by increasing the electric field in the diode (by increasing the applied voltage), thereby increasing the carrier velocity, but this is limited by breakdown and the power consumed. Consequently, whereas the signal for a typical 300-\(\mu\)m diode is larger than that for a thinner diode, after irradiation the signals are similar while the power consumption is larger. Figure 6 depicts the signal for different diode thicknesses for different levels of irradiation. For the very highest levels of irradiation, a 100-\(\mu\)m sensor has a signal similar to that of a thicker diode and is therefore preferable, as the dark current, which is proportional to the volume of the diode, is lower in the thinner diode.

Additionally, the production costs of large-area silicon diodes have decreased significantly since the SLD and LEP luminometers were built. These changes have made it feasible to design...
and build a large-scale silicon calorimeter to replace the endcaps of the CMS detector for the HL-LHC.

### 5.2. The Endcap Calorimeter Design

The design of the endcap calorimeter is discussed in detail in Reference 9. The front face of each endcap will be 3.19 m from the interaction point, and the area of the front face of the calorimeter will be nearly 8 m², increasing progressively with depth. In order to achieve the desired resolution \( \sigma_E/E < 25\% / \sqrt{E} \), the EM section of the calorimeter (EC-E) will be equipped with 28 layers of silicon. To keep costs down, the hadron calorimeter section (EC-H) will be composed of 8 layers equipped with only silicon and 16 layers equipped with both silicon and scintillator. At larger radii, where the radiation levels are lower, the calorimeter will be equipped with 300-µm sensors; closer to the beam, the detector thickness will be reduced to 200 µm; and at the highest radii, the sensors will measure 100 µm. These thicknesses were selected to match the reduction in charge-collection efficiency with radiation.

An important aspect of the detector design is its ability to calibrate the response of an individual cell with MIPs. For detectors with a sensor thickness of 300 µm, the signal is \( \sim 24,000 \) electrons, or \( 3.8 \) fC. In order to detect this signal with a short shaping-time preamplifier (<25 ns), the detector capacitance needs to be of order 65 pF. Consequently, the dimensions of an individual detector cell must be approximately 1 cm² for 300-µm sensors and approximately 0.5 cm² for 100-µm sensors. In addition, the dark current in the detectors after the expected radiation levels must be minimized by cooling the entire detector—EC-E and EC-H—to \(-30^\circ C\) so as to detect the MIP signal even at the end of operation.

The total area of the detector instrumented with silicon will be nearly 600 m², and the number of channels will be close to six million. At the back of the calorimeter there will be an additional 487 m² of scintillator tiles instrumented with nearly 400,000 silicon photomultipliers. Therefore, the upgraded endcap calorimeter for CMS will be an imaging calorimeter that can track the showers as they develop inside it. When combined with the silicon tracker upstream, it will be better suited for analyses based on PFAs.

In order to keep costs low, the silicon sensors of the detector cells will be hexagonal. This choice increases by \( \sim 20\% \) the surface area of active detector that can be made from a circular silicon wafer, compared with rectangular cells.

The instrumentation of such a large number of channels takes a considerable amount of power. With an estimated power consumption of 20 mW per channel by the front-end electronics, along with additional losses such as current drawn in the silicon and heat loss, the total power consumption per endcap is on the order of 100 kW. The calorimeter will be cooled with biphase CO₂, which was first used in a high-energy physics experiment to cool the LHCb Velo detector (32).

The readout of the detector is particularly challenging. The need to detect both the MIP signal (1 fC in the 100-µm sensors) for calibration and the signal expected from a 1.5-TeV electron (10 pC at shower maximum) places stringent demands on the design of the electronics. The solution adopted by the CMS experiment involves measuring the small signals in a linear analog-to-digital converter while using a time-over-threshold technique above 100 fC. Furthermore, the electronics design provides for a measurement of the time of arrival of the signals with a precision of 50 ps. The information derived from the calorimeter consists of both the energy deposited and the arrival time—information that, in the harsh environment of the HL-LHC, will be very useful to disentangle the complex events.

**Figure 7a** shows the energy resolution predicted by simulations of EM showers in the calorimeter with sensors of different thicknesses. In order to reduce the overlap of showers with pileup...
Figure 7

GEANT4 simulations of the CMS endcap calorimeter. (a) The energy resolution for different energies and different silicon thicknesses. (b) The lateral growth of electromagnetic showers with two different gap thicknesses (2 mm and 4 mm) for the detector services.

The expected EM energy resolution of $25%/\sqrt{E}$ was achieved in test beams. Like other properties, the energy resolution has been well matched by GEANT4 simulations (33).

Simulations have also shown that there is a significant advantage to having access to the detailed information that an imaging calorimeter provides. In particular, knowing the point where the shower starts, and how the shower grows with depth, significantly aids the separation of high-energy showers from the combination of several overlapping background events. Knowledge of the detailed structure of hadronic showers has enabled the development of algorithms that correct for EM fluctuations in these showers, and thus provide corrections for the fluctuations in energy response to hadrons.

The CMS endcap calorimeter group has also demonstrated that precise timing information can be obtained from the showers (34). By comparing the time of arrival of the signal from two sensors in an EM shower, or by comparing the signal to a time signal extracted from a microchannel plate detector, one can obtain a timing resolution of less than 20 ps for signals of 20 MIPs or more. Figure 8 shows the precision of the timing signal achieved with different thicknesses of silicon.

This high level of precision was achieved using specialized electronics; the readout electronics for the CMS endcap calorimeter is being designed to achieve a timing precision of 50 ps or better. This will permit the localization of energy depositions for each cell in both space and time, which will be a great advantage in the very hostile environment expected at the HL-LHC.
Collaboration is investigating the possibility of using precision timing in hadronic showers to correct for the $e/h$ fluctuations in a hadronic shower.

6. FUTURE APPLICATIONS OF SILICON CALORIMETERS

The power to separate nearby showers is ultimately limited by granularity, since in the early stages of a shower’s development its lateral extension is considerably smaller than the Molière radius. Extreme granularities can be achieved by using technologies that were originally developed for vertex detectors, such as monolithic active pixel sensors. Such sensors can be manufactured from standard wafers in a commercial CMOS process, making them relatively low cost and competitive with high-resistivity silicon pad diodes. The small pixel size of 50–100 $\mu$m enables the use of digital calorimetry (as opposed to analog calorimetry) for EM showers. In digital calorimetry, one measures the energy by counting the particles traversing the active layers. This technique, first explored in the linear collider framework (35), is now being studied for the forward calorimeter upgrade of the ALICE detector. The feasibility of using such a calorimeter has been demonstrated with a prototype containing 39 million pixels tested in particle beams (36).

The prototype (Figure 9) has 24 layers of tungsten, each corresponding to 0.97 $X_0$. The active layers are based on the PHASE2/MIMOSA23 chip, with matrices of $640 \times 640$ pixels measuring 30 $\mu$m. Although the active sensors produce more heat ($\sim 0.1$ W cm$^{-2}$) than conventional sensors do, passive cooling via the tungsten structure is sufficient, and keeps the structure compact, with a Molière radius of 11 mm. The prototype was tested with electron beams over a wide energy range (2–244 GeV); Figure 9 shows an event display. The energy resolution exhibits stochastic, constant, and noise terms of $30\% \sqrt{E}$ (GeV), 2.8\%, and 0.063 GeV, respectively, which agree reasonably well with simulations. Future R&D would improve the modest area ratio (active/electronics auxiliary) and the relatively small size of the MIMOSA chip.
7. CONCLUSION
Advances in high-energy physics have always arisen from changes and innovations in technology. The adoption of silicon calorimeters as one of the standard tools of the field is just such a result of technological advances. The progress from the early test structures to the large-scale devices planned for future colliders has followed developments in silicon sensor fabrication methods, high-speed data links, ASIC design, and novel cooling techniques. The paradigm shift from the use of calorimeters simply to measure energy to the use of PFAs to accurately measure the energy of jets has motivated intense research on designing, building, and testing silicon calorimeters capable of imaging showers in detail. Taking advantage of the synergy between fine-grained trackers and imaging calorimeters will have a significant impact on this field in the years ahead. Furthermore, novel methods currently under evaluation, such as precision timing in EM and hadronic showers and the use of ultrafine-grained silicon detectors, may lead to new methods and techniques that can be used in future experiments to shed light on important questions in this field.

DISCLOSURE STATEMENT
R.R. was one of the original proponents of the use of silicon calorimeters for the CMS detector. The other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Contents

Guido Altarelli
   Luciano Maiani and Guido Martinelli .................................................. 1

Multiquark States
   Marek Karliner, Jonathan L. Rosner, and Tomasz Skwarnicki ....................... 17

Penning-Trap Mass Measurements in Atomic and Nuclear Physics
   Jens Dilling, Klaus Blaum, Maxime Brodeur, and Sergey Eliseev ................... 45

Dispersion Theory in Electromagnetic Interactions
   Barbara Pasquini and Marc Vanderhaeghen ........................................... 75

Progress in Measurements of 0.1–10 GeV Neutrino–Nucleus Scattering and Anticipated Results from Future Experiments
   Kendall Mabn, Chris Marshall, and Callum Wilkinson ................................ 105

Structure of $S = -2$ Hypernuclei and Hyperon–Hyperon Interactions
   Emiko Hiyama and Kazuma Nakazawa .................................................... 131

Deep Learning and Its Application to LHC Physics
   Dan Guest, Kyle Cranmer, and Daniel Whiteson ...................................... 161

The Construction of ATLAS and CMS
   Michel Della Negra, Peter Jenni, and Tejinder S. Virdee ......................... 183

Small System Collectivity in Relativistic Hadronic and Nuclear Collisions
   James L. Nagle and William A. Zajc .................................................... 211

From Nuclei to the Cosmos: Tracing Heavy-Element Production with the Oldest Stars
   Anna Frebel .............................................................................................. 237

Silicon Calorimeters
   J.-C. Brient, R. Rusack, and F. Sefkow .................................................... 271

Automatic Computation of One-Loop Amplitudes
   Celine Degrande, Valentin Hirschi, and Oliver Mattelaer .......................... 291

On the Properties of Neutrinos
   A. Baha Balantekin and Boris Kayser .................................................... 313
Heavy Ion Collisions: The Big Picture and the Big Questions
   Wit Busza, Krishna Rajagopal, and Wilke van der Schee ......................... 339

Particle Acceleration by Supernova Shocks and Spallogenic
   Nucleosynthesis of Light Elements
   Vincent Tatischeff and Stefano Gabici .............................................. 377

Jefferson Lab at 12 GeV: The Science Program
   Volker D. Burkert ............................................................................. 405

Dark Matter Searches at Colliders
   Antonio Boveia and Caterina Doglioni ................................................. 429

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