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Development of highly granular calorimeters in CALICE

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The design of calorimeter systems for a detector at a future e^+e^- Linear Collider (ILC, CLIC) is largely driven by the requirements of jet reconstruction. The particle flow technique has been shown to be capable of achieving an energy resolution $\sim 30\% / \sqrt{E}$, permitting the discrimination of W and Z bosons in their hadronic decays. Such performance requires the separation of neutral and charged energy deposits in the calorimeters, which in turn demands that they have high spatial granularity both transversely and longitudinally, and be placed within the magnet coil. The CALICE collaboration has been developing prototype calorimeters to meet these requirements. The electromagnetic calorimeter is based on tungsten absorbers and active layers of silicon pads of $\sim 5\times5\,\mathrm{mm}^2$ and/or crossed short scintillator strips of $\sim 5\times45\,\mathrm{mm}^2$. The hadronic calorimeter could use iron or tungsten absorbers, sampled using either scintillator tiles of $\sim 3\times3\,\mathrm{cm}^2$ or gaseous detectors with $\sim 1\times1\,\mathrm{cm}^2$ readout. The scintillator option uses an analogue readout, while the gas detectors (RPCs, Micromegas or GEMs) use either digital (1 bit) or semi-digital (2 bit) readout. All these options are being pursued in CALICE. Key issues include: extreme compactness, hermeticity and scalability, power cycling and precise timing. We report on recent R&D and test beam activities from CALICE which address all these key questions.

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1. Motivations for Particle Flow calorimetry

The recent discovery at LHC of a new particle compatible with the Standard Model (SM) Higgs boson has enhanced the physics case of a e^+e^- linear collider [1, 2]. With a mass of 125 GeV, this particle can be produced at an ILC or CLIC and its properties studied with great precision thanks to the unique environment of these machines. The low expected backgrounds at a linear collider and its specific bunch structure gives the possibility to record all the particles produced in the acceptance of the detector. Event selection and reconstruction are performed offline and most Higgs decay channels (mostly hadronic) can be studied provided an excellent energy resolution of 3–4 % for 40–500 GeV jets. This resolution allows the separation of W and Z bosons in their hadronic decays and would benefit to many searches for physics beyond the SM [3, 4]. It can not be achieved with current calorimeter systems whose precision is limited by the modest performance of the hadronic section. Therefore a new approach is needed.

In order to reduce the impact of calorimeter resolution on the jet resolution, it has been proposed to measure only neutral particles inside jets with the calorimeters. The charged particles are measured with much better precision with the tracking system. This approach called Particle Flow (or PFA) [5] relies on the ability to identify individual showers inside jets by means of highly granular sampling calorimeters placed inside the solenoid magnet and a precise tracking system. It also relies on software tools as this identification is done by sophisticated algorithms.

2. Technical challenges and calorimeter design

The merits of Particle Flow are evaluated by the CALICE collaboration by means of simulation tools, detector R&D and testbeam of real-scale calorimeter prototypes [6]. Detailed simulation studies have shown that Particle Flow performance is very sensitive to the transversal and longitudinal segmentation of the calorimeters as they determine the ability to distinguish photons from electrons in the ECAL and neutral from charged hadrons in the HCAL [7]. In order to minimise the level of mistakes when reconstructing individual showers (so-called confusion), cell sizes of 25–100 mm^2 and 1–10 cm^2 are necessary in the ECAL and HCAL respectively. This has profound implications on the design of the calorimeters. First of all, the digitisation of cell signals should be performed inside the active layers by self-triggered ASICs mounted as close as possible to the sensors. Secondly, ASICs should be powered synchronously to the accelerator clock (1 ms bunch trains crossing every 200 ms at ILC) so heat dissipation is minimal and no active cooling is required.

A Particle Flow calorimeter is divided into two sections, each optimised for the measurement of electrons and photons on one hand and of hadrons on the other hand. It should be compact and contain high energy showers (small X_0 and λ_{int}), allow the separation of electrons and photons in the ECAL (small R_{M}) and a high discrimination between electrons and hadrons in the ECAL (high $\lambda_{\mathrm{int}}/X_0$ ratio). These requirements make tungsten ideal for the ECAL absorbers. Steel is suitable for the HCAL at a 500 GeV ILC but not dense enough at a 3 TeV CLIC due to the higher jet energies. In the latter case, tungsten absorbers are also foreseen for the HCAL. The choice of detectors for the active layers of the ECAL and HCAL is less constrained. Various options based on silicon, scintillators and gaseous detectors are studied within the CALICE collaboration. They are described in this contribution.

3. Electromagnetic calorimeters

Silicon In a Si/W ECAL with thin Si layers ($\sim 500\,\mu$m), electromagnetic showers develop with little transversal spread and the overall calorimeter thickness is minimal. Si is not sensitive to ambient changes and cell-to-cell calibration is stable with time. The performance of a Si/W ECAL was assessed by means of a prototype equipped with external front-end electronics and consisting of 3 sections. Composed of 30 layers of W absorbers and 525 μm thin Si wafers segmented into $1\times1\,\text{cm}^2$ PIN diodes, the prototype achieved an energy resolution to 6–45 GeV electrons of $16.5\%/\sqrt{E} + 1.1\%$ with a non-linearity at the 1% level [8]. Subsequent tests were conducted to study in details hadron shower development in tungsten and to refine Monte Carlo (MC) programs like Geant4 [9] (Fig. 1 left). Pad boards with integrated front-end electronics were then constructed. Assembled with Si wafers they will form the unit layer of a realistic ECAL module intended to house up to ~ 2 m long layers of such boards. The ASIC (SKIROC) features power-pulsing and self-triggering capability. A stack of a few boards is currently undergoing technical test to validate the design and consolidate the data acquisition system before incorporating more layers.

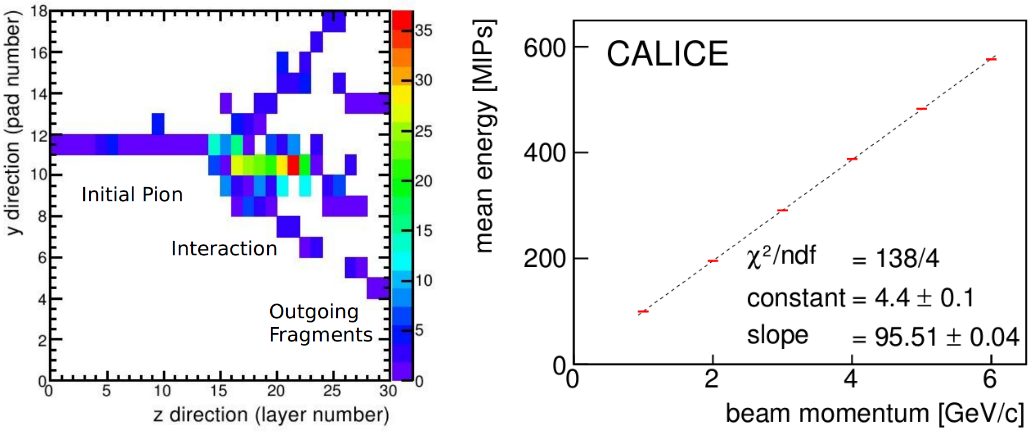

Figure 1: (*left*) Pion interaction in the SiW-ECAL. (*right*) Electron response of the ScW-ECAL.

Scintillators Providing high sampling fraction and shape flexibility, scintillators have long been sensors of choice for calorimetry. Because of the large number and small size of scintillators required for a PF-calorimeter, a traditional readout with photomultiplier tubes is prohibited. Thanks to their small size, SiPMs are well suited and can be mounted on scintillating tiles. A SiPM is a matrix of pixel-size avalanche photodiodes. Above a certain number of single photons incoming on the matrix, the response (or number of fired pixels) saturates which needs to be taken into account when inferring the energy deposited in the tile. In addition, the gain of avalanche photodiodes is strongly sensitive to temperature. Therefore, calibration and monitoring is crucial in a scintillating calorimeter with SiPM-based readout. The use of several thousands of SiPM for calorimetry was first demonstrated with $3\times3\,\text{cm}^2$ scintillating tiles in the hadron calorimeter (section 4). Later on, this technology was adapted to an ECAL prototype with scintillating strips of $4.5\times1\,\text{cm}^2$ and 3 mm thickness. The Sc/W ECAL is a sandwich of 30 layers of 72 strips and W plates. The orientation of strips in consecutive layers is orthogonal so an effective granularity of $1\times1\,\text{cm}^2$ is achieved. Each strip is viewed by a SiPM read out through a flexible cable to external electronics. Exposed to electrons of 2–32 GeV, the achieved energy resolution is $12.9\%/\sqrt{E} + 1.2\%$ with a linearity better than 2 % [10] (Fig. 1 right). More recently, 144 strips were mounted on a board with integrated electronics developed by the scintillator-HCAL group, forming an active layer of $18\times18\,\text{cm}^2$. Tests with radioactive sources and in a beam were conducted in 2012.

4. Hadronic calorimeters

Scintillators The operation of a ~8000 SiPM system was first demonstrated by the scintillator HCAL prototype [11]. The latter a sandwich of ~40 layers of absorber plates and 5 mm thick scintillating tiles read out by SiPMs. The SiPM output is digitised with 16 bit resolution outside the calorimeter by the SPIROC chip, hence the name: analogue HCAL or AHCAL. The size of the tiles in a layer varies from centre ($3\times3\,\text{cm}^2$) to periphery ($12\times12\,\text{cm}^2$). From 2006 to 2012, the AHCAL underwent several testbeams to measure in great details the characteristics of hadron (proton, pion, kaon) and electron showers in steel and subsequently in tungsten over a wide range of energies (1–300 GeV). Thanks to its high granularity and signal resolution, the AHCAL provided several observables (*e.g.* local energy distribution, shower substructure) to refine MC simulation programs [12] whose improved reliability benefits to the whole calorimeter physics community.

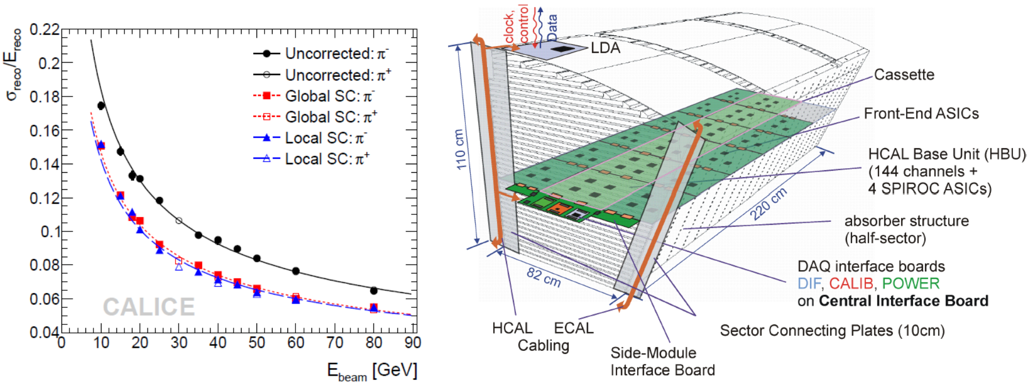

Figure 2: (*left*) Energy resolution to pions of the Sc-Fe AHCAL (*right*) Drawing of an ILD AHCAL module.

Testbeam combining the AHCAL, a W-ECAL and a tail catcher were also conducted within CALICE. Off-line overlay of different events were used to assess key aspects of Particle Flow in a realistic detector configuration where hadron showers are measured in two different calorimeters [13]. Most importantly, the AHCAL validated procedures for channel calibration and monitoring that account for the non-linear and T-dependent response of SiPMs. Also, it demonstrated powerful compensation techniques based on the energy density to reduce the shower stochastic fluctuations from $58\%/\sqrt{E}$ to $45\%/\sqrt{E}$ [14] while keeping a constant term smaller than 2 % (Fig. 2 left). More recently, the AHCAL group elaborates solutions to integration issues posed the construction of a realistic module (Fig. 2 right). In this new design, $3\times3\,\text{cm}^2$ tiles are mounted directly on thin boards with cutouts for ASICs to minimise the active layer thickness to 5.4 mm. The ASICs are self-triggered with power-pulsing capability and time-stamping at the 1 ns level for improved background rejection at CLIC. A LED calibration system of the SiPM is implemented on board. Synchronisation and chaining of several boards is being validated on testbench and in testbeams.

4.1 Gaseous detectors

Digital calorimetry Gaseous detectors can be easily segmented and were proposed to increase the granularity of the HCAL (down to 1×1 cm^2) and thus its imaging capability. The very large number of channels and resulting cost are mitigated with a low-power simple-threshold electronics with 1 bit resolution, hence the name digital hadron calorimeter or DHCAL. As long as the average number of particles per cell is close to one, the shower energy can be reconstructed from the number of fired cells (or hits) with good accuracy. This counting approach is actually well justified in gas where the deposited energy is affected by large Landau fluctuations. Above a certain energy, however, the DHCAL response is expected to depart from linearity due to the increased number of particles per cell. Particle density is expected to be highest in the electromagnetic core of hadron showers. As a result of this strongly under-compensated response, techniques using detailed spatial information or additional readout thresholds (2 bits) are being developed to tag and weight electromagnetic clusters and eventually restore linearity and improve resolution.

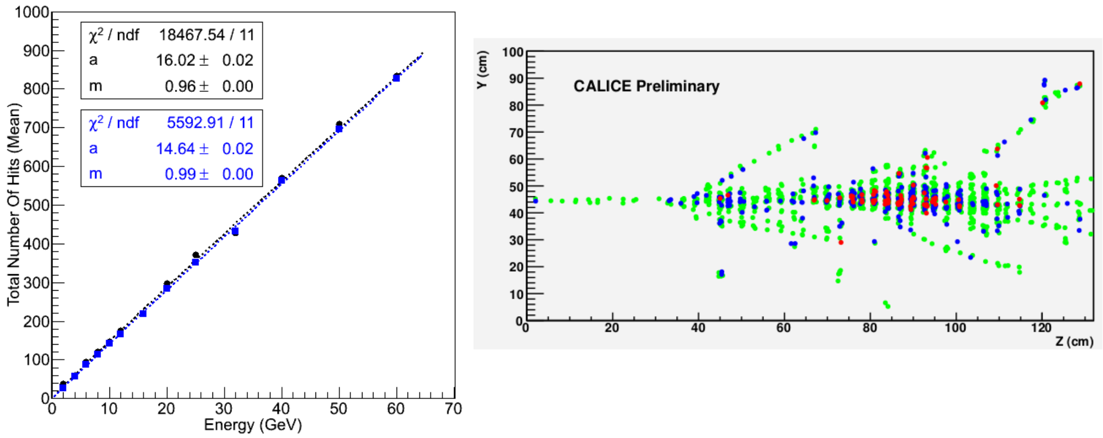

Figure 3: (*left*) Pion response of the Fe-RPC-DHCAL before (black dots) and after (blue dots) layer-to-layer calibration. (*right*) Pion shower in the Fe-RPC-SDCHAL, the hit colors correspond to different thresholds.

The digital hadron calorimeter Two large scale gaseous hadron calorimeter prototypes of 40–50 layers of $\sim 1\times1$ m^2 have been constructed and tested in particle beams. They are using Resistive Plate Chambers (RPC) as active layers with 1×1 cm^2 readout segmentation. The first prototype constructed consists of 33×96 cm^2 RPCs read out by two ASIC-pad boards [15, 16]. The ASIC (called DCAL) records a digital information (1 bit) and 3 RPCs are housed in a case called a cassette. With almost 10^4 channels per layer, the DHCAL tackled the challenge of setting and operating a system with a very large number of channels ($\sim$ 350000 channels on the first testbeam and $\sim$ 500000 today). With steel absorbers, the pion response measured at Fermilab is linear up to at least 60 GeV and shows very little dependence on layer-to-layer calibration (Fig. 3 left). As expected, saturation was observed with electrons already at a few GeV [17]. A test program was also completed in the CLIC tungsten absorber structure at the CERN PS and SPS (tested energy range of 1–10 GeV and 12–300 GeV respectively). Electron and hadron data in tungsten show a more pronounced saturation effect than in steel due to a smaller R_{M}, indicating that smaller pads may be necessary in a W-DHCAL.

The semi-digital hadron calorimeter The second prototype has a slightly more advanced design. It uses RPCs of $\sim 1\times1\,\mathrm{m}^2$ size to reduce dead zones inside the calorimeter, smaller readout boards on one side only of the cassettes (thanks to flexible connections between ASIC boards) and self-triggered and power-pulsed front-end chips (HARDROC) [18]. With 2 bit resolution per channel to mitigate the effect of saturation, this prototype is called the semi-digital HCAL or SDHCAL. The SDHCAL, consisting of 50 RPC cassettes inserted inside a dedicated steel absorber structure, was tested at CERN in 2012. Power-pulsing of the ASICs was performed synchronously to the SPS cycle to maintain a low gas temperature in the RPCs and to achieve a low noise level of ~ 1 hit per event (for a total number of channels of ~ 450000). The SDHCAL functions without external trigger: the ASICs record signals above one of the three thresholds (from beam particles, cosmics, noise) and are read out when one ASIC memory is full. With a 127 event depth memory and at the typical values of cell occupancy and noise, the average time between two readouts is ~ 40 ms. This already complies with ILC specifications (1 ms long bunch trains) and demonstrates that noise rates can be kept to the required level. The physics program of the SDHCAL focused on electron and pion showers of 1–100 GeV (Fig. 3 right). So far, the data analysis efforts are concentrated on the particle identification capability of the SDCHAL and on the possible improvement of resolution from one to thee thresholds. In this latter case, a significant improvement of pion resolution was demonstrated at energies above 40 GeV [19].

Alternative technologies Micro Pattern Gaseous Detectors (MPGD) are studied in CALICE as an alternative to RPCs. Less mature than the well-established RPC technology, this new generation of detectors has a high potential for calorimetry. Thanks to a separation of the gas medium into two regions (for signal generation and multiplication), they operate at low gas gains (a few 10^3) in a non-saturated regime. The MPGD response is thus proportional to the energy deposited in the gas medium up to the breakdown limit (*i.e.* $\sim 10^4$ times the energy deposited by a minimum ionising particle). Three projects are currently focusing on double-GEM [20], thick-GEM [21] and Micromegas [22, 23]. The latter is most advanced and tightly related to the RPC-SDHCAL project with which it shares common detector specifications. Four Micromegas layers of $\sim 1\times1\,\mathrm{m}^2$ with $1\times1\,\mathrm{cm}^2$ segmentation and 2-bit self-triggered power-pulsed electronics (MICROROC chip) were constructed. Testbeam inside the SDHCAL were successfully conducted at CERN with a common DAQ. Thanks to the synchronisation with the RPCs, the pion shower shapes and the pion response in Micromegas was measured. Comparison of the results with MC predictions is on-going.

5. Conclusion

The CALICE collaboration is undertaking a vast program of R&D into calorimetry for a future linear collider. Driven by the need for very high granularity, the design of Particle Flow calorimeters raises technical issues which are addressed by CALICE through the construction and test of several prototypes of growing size and complexity. These prototypes are used to improve our knowledge of particle showers development in steel and tungsten and of the formation of resulting signals in scintillators, silicon and gaseous sensors. The expertise of the collaboration is broad and useful beyond the case of a linear collider, to upgrades of current collider experiments and refinement of simulation programs of particle interactions with matter.

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