Engineering prototype of the CALICE analog hadron calorimeter

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Abstract. A new prototype of a tile hadron calorimeter (AHCAL) for the International Linear Collider detector is currently developed within the CALICE collaboration. The aim is to improve the energy resolution by measuring details of the shower development and combining them with the data of the tracking chamber (particle flow). The prototype is based on scintillating tiles that are read out by novel Silicon-Photomultiplier (SiPM). This new prototype will take into account all design aspects that are demanded by the intended operation at the ILC. It will contain about 2500 detector channels. This is the first calorimeter design which makes full use of the high integration potential of the novel photo-sensor technology.

Main focus of this contribution is the mechanical and electrical integration of the front-end electronics into the calorimeter absorber structure, with the aim of maintaining high-density calorimeter. Integration aspects and scalability to an ILC detector are discussed.

For the analog calorimeter the proposal of an integrated light-calibration system for calibration and gain monitoring are presented, addressing temperature and bias dependence of the SiPM gain.

First results from the measurements with one prototype module at the DESY test beam are presented, which demonstrate the quality of the readout system, and of the light-calibration system.

1. Introduction

The CALICE collaboration [1] is developing calorimeters with the specific aim to fulfill the hardware and physics demands of the International Linear Collider (ILC [2]) physics program [3]. The ambitious required jet energy resolution \(0.3/\sqrt{E[\text{GeV}]}\) could be achieved with extremely segmented calorimeters using the particle flow approach (PFLOW, [4]). For the Analogue Hadron Calorimeter (AHCAL) option for the ILC a physics prototype was successfully built and commissioned in test-beam campaigns at DESY, CERN and FNAL in the years 2006-09. The prototype has operated together with prototypes of an electromagnetic calorimeter, and of a tail-catcher and muon tracker. This first physics prototype [5] consisted in total of 7608 scintillator tiles with individual readout via a SiPM. The aims of this development is to establish the innovative design of highly granular sampling calorimeters; and exploit them to study hadronic showers with a new degree of accuracy to validate Monte Carlo models of hadronic physics. In addition, it is intended to show with this prototype that the requirements for particle flow applications are fulfilled, in terms of showers separability and energy resolution in a multi-particle environment.
More recently, a new prototype for the AHCAL is being developed and commissioned to
demonstrate the feasibility to build a calorimeter with fully integrated electronics meeting the
constraints of a real detector. In order to cope with the expected channel number of the AHCAL
barrel of about four millions, reliable assembly and production procedures have to be developed.
A new engineering prototype with about 2500 detector channels is currently under development
in order to test all assembly and integration issues. This prototype corresponds to one layer of
the next generation analog hadronic calorimeter for the ILC.

![Figure 1. Drawing of an AHCAL wedge (half of a barrel octant), with integrated
electronics covering one of the active
layers. The detector interface electronics
and the cable path are at the edge of
the barrel in the gap before the end-cap
detector.](image1)

![Figure 2. Mechanical structure of
an AHCAL wedge. Steel plates 2 cm
thick are held together by a 0.5 cm
panel, without spacers between the layers.
The 1 cm thick cracks between wedges,
resulting from two adjacent panels are
pointing to the beam axis.](image2)

2. Technological prototype concept and realization
One design option for the hadronic barrel calorimeter for the ILC is to subdivide the octagonal
shaped detector in 16 equivalent wedges segmented in two parts in the longitudinal direction
(i.e. along the beam direction). Each resulting wedge would have the structure shown in Fig. 1.
A wedge is divided in 48 layers of 2 cm-thick steel, with gaps to host the active detector layers.
Each active layer is obtained connecting single detector cassettes of a size of 36×36 cm². Six
rows and three columns of cassettes will make up one layer. The cassettes carry the active part
of the calorimeter: scintillator tiles (3×3×0.3 cm³ in size) read out via a SiPM, and the readout
electronics which allows signal processing and digitization. Communication to the electronics
as well as bias voltage for the photo-detectors and calibration pulses are provided by dedicated
cards located at the edge of the detector, in the gap between barrel and end-cap. The control
signals, for the electronics as well as the data, need to be transmitted over the 2.2 m long
interconnected cassettes and back to the detector interface electronic cards.

2.1. Mechanical structure
The AHCAL mechanical structure for one wedge is a self-supporting sandwich of 48 2 cm-thick
stainless-steel absorber plates. The plates are held together by a 0.5 cm steel panel and require
no additional spacers between the layers. The 1 cm thick cracks between wedges, resulting from
two adjacent panels are pointing to the beam axis. This satisfies the challenging requirements
on minimum dead material in the wedge itself and in between adjacent wedges in the barrel.
Studies based on particle flow reconstruction, demonstrated that this amount of material does not effect jet energy resolution in a typical ILC jet energy range.

For the mechanical aspect, the flatness of the plates below 1 mm is essential for the insertion of the active layers and is obtained by a roller leveling procedure. The picture of the first AHCAL mechanical structure prototype, standing in its vertical position, is shown in Fig. 2.

2.2. AHCAL cassette
Each calorimeter active layer is built interconnecting several AHCAL cassettes. One cassette (see Fig. 3) can be seen as an independent piece of calorimeter hosting 144 scintillator tiles with SiPM readout. The tiles are like LEGO pieces fixed on the electronics PCB as in a puzzle. Four SPIROC chips [6] are reading out all the channels of one cassette. This chip has been designed for the readout of a large number of SiPMs with minimum power consumption, for special application in the integrated electronics. Fig. 4 is a vertical section of the AHCAL cassette showing the active layer with embedded electronics sandwiched between two steel layers. The overall thickness of the cassette, including the PCB board carrying the SPIROC chips, is 6.5 mm. On the edge of the AHCAL wedge, in the gap between barrel and end-cap, sits the detector interface electronics, with a maximum thickness below 18 mm.

2.3. SPIROC chip
The readout chip for the AHCAL has to be embedded in the calorimeter structure. A maximum power consumption of 25µW per channel is allowed. In order to achieve this the chip is operated in power pulsed mode (according to the ILD bunch structure) with an on-time of about 1/200th. The chip offers the possibility to individually adjust the bias voltage to the SiPM. After the variable preamplifier and shaping stage, an analog memory array of 16 capacitors stores the signals to be converted by an integrated ADC. The chip features a time stamp capability, O(1 ns). Data are collected using the auto-trigger option of each channel individually. An overview of characterization studies on the SPIROC chip is given in [7].
2.4. **Tile-SiPM system**

Each calorimeter channel consists of a scintillators tile, $3 \times 3 \times 0.3 \text{ cm}^3$ in size, with embedded wavelength shifter fiber and photo-detector (see Fig. 5). The tiles size has been optimized with PFLOW studies using the PANDORA PFA code [8]. No clear advantage is seen in choosing smaller tiles, while the option of larger calorimeter channels would lead to a deterioration of the jet energy resolution for jet energies above 100 GeV.

As photo-detector the CPTA SiPM [9] is used. The photo-detector main characteristics are:

- gain: $0.5-1 \times 10^6$,
- inter-pixel crosstalk: <10%,
- average dark noise (above 0.5 p.e. threshold): $\sim 1.5 \text{ MHz}$,
- typical current: $0.2-0.3 \, \mu\text{A}$,
- dark noise frequency (above 0.5 MIP threshold): <150 Hz.

This last point makes the photo-detector particularly suitable for calorimetry applications.

![Figure 5. Single AHCAL channel: a scintillator tile readout via a wavelength shifter fiber and a SiPM (CPTA).](image)

![Figure 6. Tile size optimization studies performed with the PANDORA PFA code. The jet energy resolution for jets from $Z \rightarrow uds$, as a function of the AHCAL cell size.](image)

2.5. **LED monitoring system**

The LED calibration and monitoring system for the technological AHCAL prototype needs to be a scalable system, addressing the needs determined during operation and analysis of the AHCAL physics prototype. The main tasks of the system are:

- calibration of the SiPM gain using single photo-electron (p.e.) peak spectra, which requires light in the order of 1-2 p.e.,
- monitoring of the long term stability of the detector using medium power light, in the order of 20-100 p.e.,
- measurement of the SiPM saturation level, with light corresponding to approximately 2000 p.e.

For each of these tasks a channel-to-channel pulse spread from the LED system as small as possible, not worse than a factor of two, is required.
Two approaches are being followed for this system, one based on a central driver and optical signal distribution (Fig. 7), one based on electrical signal distribution and an individual LED per tile (Fig. 8). The latter is already integrated in the AHCAL cassette, but not yet fully optimized. The aim is to equalize the light intensity and maximize its dynamic range.

Figure 7. One option for the AHCAL LED system based on central driver and optical signal distribution [11].

Figure 8. Another option for the AHCAL LED system based on electrical signal distribution and an individual SMD-LED per tile [10].

Results obtained with the quasi-resonant LED driver and light distribution via optical fibers are reported in [11]. A six channels UV LED driver, which meets the basic requirements for SiPM calibration, has been realized and tested. The prototype is complemented by the optical system that distributes light from the LED via a single notched fiber to a row of scintillator tiles. The uniformity of the light radiated by the notches is constant within ±20%.

Preliminary results [10] using this system show that it is possible to obtain single photo-electron peak spectra from the SiPM on tile, i.e. to extract SiPM gain, using the light injected on the tile by the SMD-type LED integrated on the PCB board. A histogram for a single SPIROC2 channel at low LED light intensity is shown in Fig. 9.

3. First test beam results
One fully equipped AHCAL cassette, described in the previous section, has been tested at the DESY test beam facility. It has been exposed to 3 GeV electron beam without absorber material in front of the cassette. The beam penetrates the thin cassette cover and leaves a MIP-like signal in the scintillator tiles. Fig. 10 shows an example of a one channel MIP calibration spectrum. A pedestal peak is visible on the left due to false trigger coincidences. The most probable value of the MIP distribution gives a light yield of 9 pixels/MIP, as expected for this system. The single photo-electron peak structure is clearly visible in the spectrum, which is a very advantageous feature of the low noise readout electronics. A signal-to-noise ratio of 5.5 is obtained for single photo-electron measurements, while the most probable value of a MIP energy distribution has a signal-to-noise ratio of 45.

4. Conclusions and outlook
A technological solution for a scintillator-based HCAL for the ILC is presented. This prototype addresses electronics integration and power pulsing issues as well as the mechanics integration and scalability.
A complex readout chip for SiPM, including signal digitization is under commissioning and the
first calibration measurements taken at the DESY test beam have been presented. Results are very encouraging.

In the future, CALICE will proceed towards the full commissioning of a calorimeter module. A 2.2 m long full calorimeter layer has to be assembled to check signal distributions and interconnectivity of cassettes. To test multi-layer operation a tower of cassettes will be equipped. In view of this test, the re-design of the detector interface is under way.

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