Integration concepts for highly granular scintillator-based calorimeters

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The Analog Hadron Calorimeter is an option for the hadronic calorimeter of a future linear collider detector, based on scintillator tiles read out by silicon photomultipliers. The high channel density compared to current collider detectors requires an integration of the readout electronics into the active detector layers. The electronics developed by the CALICE Collaboration is very flexible, and its use in the Analog Hadron Calorimeter engineering prototype as well as options for different silicon photomultipliers and different scintillator geometries are discussed.

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1. Introduction

Within the CALICE collaboration, several options for the hadronic calorimeter of a future linear collider detector are studied. After having demonstrated the capabilities of the measurement methods in "physics prototypes", the focus now lies on improving their implementation in "engineering prototypes", that are scalable to the full linear collider detector. The calorimeters are designed for the application of particle flow algorithms to reconstruct particle energies, which require a compact calorimeter layout contained within the magnet coil and a fine detector granularity.

The Analog Hadron Calorimeter (AHCAL) concept is a sampling calorimeter of tungsten or steel absorber plates and plastic scintillator tiles read out by Silicon Photomultipliers (SiPMs, also called Multi-Pixel Photon Counters, MPPCs) as active material. In the AHCAL engineering prototype, the readout electronics is fully integrated into the active layers. Since the design of a future linear collider detector is still being optimized, the AHCAL readout electronics is very versatile, allowing for an easy adaptation to various scintillator tile designs, tile sizes and SiPM types. The readout for the scintillator option for the electromagnetic calorimeter of a future linear collider detector has been derived from the AHCAL design.

2. AHCAL Engineering Prototype

The AHCAL Engineering Prototype is based on 3*3*0.3 cm$^3$ tiles of plastic scintillator. The scintillation light is coupled into the SiPM via a wavelength shifting (WLS) fiber in the middle of the tile (figure 1). The WLS fiber also improves the uniformity of the signal over the tile area. The edges of the tile are matted to improve reflection of light within the tile and to reduce the cross talk to neighbouring tiles. The SiPMs have 796 pixels and are operated at typical bias voltages of 35 – 45 V and a gain of 0.5 – 1.5 * 10$^6$, with considerable spread within the used SiPM sample.

![Figure 1: AHCAL tile design.](image)

The layout of the AHCAL for the International Linear collider Detector (ILD) [1] is planned to consist of two endcaps and a barrel, which is segmented into two rings along the beam direction. Each of the half-barrels is further segmented into 16 half-octants with a thickness of 40 to 48 layers (figure 2). The layers in turn are segmented into 18 HCAL Base Units (HBUs) arranged into 3 slabs with a length of 6 HBUs each.

2.1 Integrated Electronics

The HBUs are the base unit for the integrated readout electronics, consisting of a PCB of 36*36 cm$^2$ with 4 SPIROC readout ASICs [2] on one side and 144 scintillator tiles on the other
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Figure 2: (left) ILD AHCAL barrel layout. (right) Layer structure of an AHCAL barrel half-octant.

Figure 3: (left) HBU connected to a Central Interface Board. (right) Schematic side view of one AHCAL layer.

Since the calorimeter has to be compact, the layers are designed for minimal thickness and the SPIROCs are lowered into cut-outs of the PCB to reach 5.4 mm total thickness of the active layers, including the 3 mm for the scintillator. The SPIROC is a highly integrated specific chip for SiPM readout. It provides individually adjustable bias voltages, amplification gains and trigger thresholds for 36 channels. This allows an equalization of channel differences caused by varying SiPMs as well as an easy adaptation to different SiPM types. In order to allow operation without active cooling, the power consumption of the readout ASICs is limited to 25 µW per channel, which can only be realized by switching off parts of the chip that are not needed during some data taking phases (power-pulsing). Each AHCAL layer is connected to one Central Interface Board that provides the power, DAQ interface and calibration signals for the whole layer.

2.2 LED Calibration System

For a highly granular scintillator-based calorimeter, calibration and monitoring of the large number of channels is very important. Two solutions for a calibration system based on LEDs have been developed for the AHCAL: either one LED per channel is integrated into the HBU, or
as an alternative the light of one LED is distributed by optical fibers to 72 channels (figure 4). Both systems allow a determination of the gain of each channel in Single Pixel Spectra (SPS), where at low LED intensities single photons cause discharges of single pixels in a SiPM, as well as measurements of the saturation behaviour of the SiPMs at high intensities. An example of an SPS measured with the fiber distribution LED system is shown in figure 5. It was measured in a slab of six HBUs, corresponding to the full slab length foreseen for ILD, demonstrating the quality of the light distribution as well as the signal readout over 2.2 m.

3. Alternatives and Further Developments

3.1 New Tiles and New SiPMs

Since SiPMs are relatively new devices, the field is very active and new developments become available frequently. A new generation of SiPMs is sensitive to light in the blue to UV range such that the wavelength shifting fibre is not necessary any more to detect the light of the scintillator in the SiPM. In order to reach a uniform light detection over the full active area without a WLS fibre, the geometry of the tile has to be optimized [3]. At ITEP, a new tile optimized for fiberless coupling
has been produced by injection moulding, while Hamburg University has developed an optimized
design where the tile is machined from the scintillator (see figure 6). Both designs reach a good
signal uniformity. The Hamburg University design shows a slightly better uniformity, while the
ITEP tile has advantages in the mass production process. In addition to the better UV sensitivity,
the new SiPMs offer a larger number of pixels resulting in smaller saturation effects. It is planned
to study tiles of both designs with SiPMs of the new generation in upcoming beam tests.

![Figure 6: New tile designs without wavelength shifting fibre: (left) tile produced by ITEP using injection moulding; (right) tile produced by Hamburg University using machining.](image)

3.2 Surface Mount HBU

Another way to avoid the WLS fiber in the tile and to simplify the assembly of an HBU with
tiles is to place the SiPM not on the tile, but on the PCB of the HBU [4, 5]. In this design the
scintillator is produced in the form of a "mega-tile" covering several channels. Each of the sub-
tiles needs a concave cavity to improve the signal uniformity (figure 7). Two HBUs for surface
mounted SiPMs have been produced and are foreseen to be equipped with mega-tiles and studied
in beam tests.

![Figure 7: (left) Schematic sideview of the HBU layout for surface mounted SiPMs. (right) Surface mounted SiPM seen through the hole in the HBU.](image)
3.3 Scintillator ECAL

For an electromagnetic calorimeter [1], a smaller channel size is needed than planned for the AHCAL. For the ECAL Base Unit (EBU), the electronics has been adapted to a geometry of scintillator strips of $4.5 \times 0.5 \text{ cm}^2$ size (figure 8). The orientation of the strips in subsequent layers alternates between horizontal and vertical strips, such that reconstruction with a strip splitting algorithm leads to an effective lateral granularity of $0.5 \times 0.5 \text{ cm}^2$. The EBU layout is directly derived from the HBU layout, but due to the four times larger channel density a few strips have no LED for calibration. The scintillator ECAL uses Hamamatsu MPPCs with 1600 pixels, operated at bias voltages around 70 V and a gain of several $10^5$. Several vertical EBUs have been tested and calibrated in the lab as well as in electron beam tests.

![Figure 8: (left) EBU with vertical strip orientation. (right) Sketch of the EBU with horizontal strip orientation.](image)

3.4 Alternative Geometries

The strip design of the scintillator ECAL could easily be adapted to the cell size of the AHCAL, resulting in $9 \times 1 \text{ cm}^2$ large strips. Going the opposite way and reducing the size of square tiles, e.g. for a tile ECAL, is limited by the placement of LEDs for the calibration as well as the size of the SPIROC readout chips. A design with $2 \times 2 \text{ cm}^2$ square tiles would result in 9 SPIROCcs with 324 channels per HBU, corresponding to a more than a factor of two larger channel density. In this case, only a few channels would miss the calibration LED. Going to even larger channel densities with $1.5 \times 1.5 \text{ cm}^2$ tiles would require special solutions for the SPIROCcs, for example by a few enlarged $3 \times 1.5 \text{ cm}^2$ tiles underneath, or the SPIROCcs could be used without housing.

4. Conclusions and Outlook

The CALICE Collaboration has developed highly integrated electronics for a scintillator-based hadronic calorimeter scalable to a future linear collider detector. The AHCAL electronics allows
an equalization of the detector response and operation with a common single threshold, and its capabilities have been demonstrated in testbeam measurements. Due to its flexibility, it can be used with different types of SiPMs and can be adapted easily to different ECAL and HCAL scintillator geometries, opening up possibilities for cost optimization of the detector. In the future, system aspects like power distribution and data concentration will be addressed. New generations of scintillator tiles and SiPMs as well as detector configurations with several layers will be studied in forthcoming beam tests.

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References


