Results of the CALICE SDHCAL technological prototype

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Abstract. The SDHCAL prototype was completed in 2012, and exposed to beams of pions, electrons of different energies at the SPS of CERN for a total time period of 5 weeks. The data are being analyzed within the CALICE Collaboration. Preliminary results indicate that a highly granular hadronic calorimeter conceived for PFA application is also a powerful tool to measure hadronic particle energy. In addition it was found to discriminate efficiently pions from electrons. The use of multi-threshold readout mode shows a clear improvement of the resolution at energies exceeding 30 GeV with respect to the binary readout mode. New ideas to improve on the energy resolution using the topology of hadronic showers such as the Hough Transform technique are studied.

1. Introduction

The CALICE Semi-Digital Hadronic CALorimeter (SDHCAL) prototype achieved in 2012, was built for several purposes and it is one of the hadronic calorimeter candidate for the International Large Detector (ILD) of the future International Linear Collider (ILC). The main goal of the SDHCAL prototype is to show that highly granular gaseous calorimeters can provide a powerful detector for the hadron energy measurement and for the application of the Particle Flow Algorithm (PFA). First studies using Hough Transform methods tends to confirm that the tracking capability of such detectors will be a useful tool for the PFA and for the estimation of the detector behaviour in situ. Another motivation for the SDHCAL was to build a detector compatible with the future linear collider requirements in terms of efficiency, low power consumption and compactness. In this paper, a brief description of the SDHCAL prototype and the experimental set-up during test beams will be presented. Then, in section 2, the event building procedure will be introduced and detector behaviour presented. In section 3, the methods for the particle selection and the results for the energy resolution will be discussed. In the last section, a tracking method within hadronic showers using Hough Transform technique will be presented.

1.1. The SDHCAL prototype

The SDHCAL prototype is a sampling calorimeter composed by 48 Glass Resistive Plate Chambers (GRPC) as active layers [1]. The absorber layers are stainless-steel plates with a thickness of 2 cm. The total depth of the prototype represents 6λI. Each GRPC has a transverse size of 1 m². The cathode and the anode are glass plates with a thickness of 1.1 and 0.7 mm respectively. The gas gap between these electrodes is 1.2 mm. The readout of each chamber
is done by 9216 pads of 1 cm$^2$. This represents a total number of electronic channels of more than 440000 for the whole prototype. Readout signal from those pads is digitized and recorded in 2-bit format within HARDROC2 ASIC [2]. The aim of the thresholds is to have additional information of the number of particles which cross the pad and improve the energy resolution [3].

1.2. Test beam and set-up
The SDHCAL prototype has been exposed to muons, pions and electrons during test beam campaigns. In the following, only data collected in August 2012 at CERN H6 beam line of the SPS are considered. The gas mixture was 93% of TetraFluoroEthane(TFE), 5% of $CO_2$ and 2% of $SF_6$. The high voltage applied on the glass electrodes was 6.9 kV. The threshold values were set at 114 fC, 5 pC and 15 pC (0.1, 4, 12.5 MIP). The data acquisition was performed using the trigger-less mode. In this mode, all hits are recorded in the internal ASIC memory until one of them is full. Then a RamFull signal is sent and all the ASICs stop their acquisition to allow the readout of the data collected by all ASICs. After the data transfer, the acquisition restarts automatically. Because of the use of the trigger-less mode an event building procedure (see section 2.1) and an event selection (see section 3.1) are needed. Moreover no Cherenkov counter was used to discriminate particles. To reduce the noise and the energy consumption, the power-pulsed mode was used. In this mode the detector electronics are switched off during the time period separating two beam spills. The spill duration at SPS is about 9 seconds within a cycle of 45 seconds.

2. Event Building and detector behaviour
2.1. Event building
The event building procedure is based on a time clustering method. The time is recorded through the ASIC internal time counter with a step of 200 ns. To build physical events (cosmic and beam particles) a histogram of hit time is done (Fig. 1.a). A physical event candidate is found if the number of hits in one time slot exceeds 7. A time clusterisation is then applied by gathering all hits in the two adjacent time slots. Rejected bins are used to estimate the electronic noise per time slot. From the noise distribution, shown in Fig. 1.b, the contribution of the noise on the total number of hit per physical event should not be larger than one.

![Figure 1](image1.png)

Figure 1. (a): Hit time spectrum. Each bin corresponds to 200 ns. Bins in green ($#hit > 7$) are the candidates to build a physical events. (b): Distribution of the number of noise hits in a time slot of 200 ns for the whole detector.
2.2. Detector performance

The SDHCAL performance is studied using the detector response to muons. The efficiency and the pad multiplicity of one layer are estimated using reconstructed tracks from other layers. A muon selection is needed because of the trigger-less mode. To select those particles, hits of one layer are grouped into clusters if they share an edge. Then a linear fit is applied to determine the expected track impact. The layer is counted as efficient if one cluster is found at a transverse distance lower than 2.5 cm to the expected track impact. The multiplicity is the number of hits of the closest cluster if any. The efficiency and the multiplicity per layer are shown in Fig. 2.

![Figure 2](image_url)

Figure 2. (a): Efficiency per layer. The red line represents the average efficiency ($\simeq 95\%$). (b): multiplicity per layer. The red line represents the average multiplicity ($\simeq 1.73$).

3. SDHCAL prototype results

3.1. Particle identification

At SPS, the pion beam is contaminated by different kind of particles. There is a contamination by electrons, muons and protons [4]. Cosmic muons are also recorded in data samples. Because of the absence of Cherenkov counter, the pion selection is done using topological variables and in the following protons will be treated as pions. To eliminate the muons, it is requested that the ratio between the total number of hits and the number of fired layers is higher than 2.2. In addition, radiative muons are rejected by requesting that the ratio between the number of layers in which the hit dispersion is higher than 5 cm and the total number of fired layers is greater than 20%. The electron contamination could be quite high, especially at low energy, even though the presence of a 4 mm thick lead absorber is supposed to eliminate most of them. To remove those particles, the fact that electrons start their shower in the first plates is used ($X_0=1.75$ cm) by requesting that the shower is starting after the fifth layer. The first interaction plane (FIP) is defined as the first layer with at least 4 hits and with the three following layers containing at least 4 hits. To avoid the rejection of many hadronic showers, the previous criterion ($FIP \geq 5$) is applied only if the number of fired layers is lower than 30. Indeed, electromagnetic showers are well contained in 30 layers even at high energy as it can be seen in Fig. 3.a. With this selection, at low energy the part of rejected hadronic shower is not negligible but the effect is only statistical and the energy resolution is not affected. The power of this selection has been tested on electromagnetic showers and can be seen in Fig. 3.b. Additional criteria are used to eliminate neutral and multi-particles. Multi-particle events are rejected if the hit dispersion in the first five layers is greater than 5 cm. Neutral particle events are dropped by requesting that the number of hits in the first five layers is exceeding 4. Fig. 3.c shows the distribution of number of hits for a 50 GeV pion run before and after applying the selection criterions.
3.2. Energy resolution

The hadronic showers reconstructed energy (Eq. 1) is calculated after the previous selection using the number of hits per threshold ($N_i$).

$$E_{\text{reco}} = \alpha(N_{\text{hit}})N_1 + \beta(N_{\text{hit}})N_2 + \gamma(N_{\text{hit}})N_3$$  

(1)

The coefficients $\alpha$, $\beta$ and $\gamma$ are quadratic functions of total number of hits and they are determined using a $\chi^2$ minimisation (Eq. 2). The choice of such a parametrization comes from a previous study [3] which shows that this parametrization is needed to restore linearity at high energy.

$$\chi^2 = \sum_{i=1}^{N} \frac{(E_{\text{beam}} - E_{\text{reco}})^2}{E_{\text{beam}}}$$  

(2)

In Fig. 4.a the evolution of these parameters with the total number of hits is shown. These coefficients are then used to estimate the reconstructed energy of incoming particles. Reconstructed energy distributions are fitted with a Crystal Ball function defined in [3] to take into account the tail on the left part of those distributions (Fig. 4.b). A Gaussian fit is also performed and used for estimation of systematic uncertainties. The mean reconstructed energy for pion showers and the relative deviation of the pion mean reconstructed energy with respect to the beam energy are shown in Fig. 5.a. The relative deviation of the pion mean reconstructed energy with respect to the beam energy is lower than 5% on a large energy scale ([7.5-80] GeV). Figure 5.b shows the hadronic energy resolution of the SDHCAL prototype which reaches 9% at 80 GeV. Since no gain correction was applied, this results are very encouraging.

4. Tracking within hadronic showers using Hough Transform

Hadronic showers can contain many tracks generated by Minimum Ionising Particles (MIP) which can cross several layers before being stopped. Imaging calorimeters like the SDHCAL prototype can reconstruct the path of such tracks and use them to monitor the detector efficiency. Tracks reconstruction may be also helpful for the estimation of the reconstructed energy and for the application of the Particle Flow Algorithm. The Hough Transform technique is particularly interesting for the track detection within a dense environment like hadronic shower [5].
Figure 4. (a): α (green line), β (blue line) and γ (red line) evolution in terms of the total number of hits. (b): Reconstructed energy distribution for a 60 GeV pion runs.

Figure 5. (a): Mean reconstructed energy for pion showers and relative deviation of the pion mean reconstructed energy with respect to the beam energy as a function of the beam energy. (b): σ\(\frac{E}{E}\) of the reconstructed pion energy \(E\) as a function of the beam energy

4.1. Hough Transform method
Hough Transform is a simple method that allows to distinguish aligned points from others. The principle is to replace the point coordinates \((x,z)\) by curves \((\rho,\theta)\) using the following transformation :

\[
\rho(\theta) = z \cos \theta + x \sin \theta
\]

The aligned points have their curves intersecting in the same point \((\rho_0,\theta_0)\) in the \((\rho,\theta)\) plan. The point coordinates \((\rho_0,\theta_0)\) determine the distance from the origin to the track and the angle between the ordinate axis and the track. The previous method can not be applied directly to hadronic showers recorded in the SDHCAL. The spatial resolution and the Multiple Coulomb Scattering require an adaptation of the method. The \((\rho,\theta)\) plan is discretized into a histogram. The bins of this histogram are incremented when they are crossed by a curve associated to one point in \((x,z)\) plan.

4.2. Hough Transform within hadronic showers in the SDHCAL
To apply the Hough Transform method to the SDHCAL data samples the hits are grouped into clusters if they share an edge. Then the clusters in the dense part of the shower are rejected if
two other clusters are found in an area of $10 \times 10 \text{ cm}^2$ around (in the same layer) or if one other cluster composed by more than 5 hits is found in this area. Hough Transform is then applied to the remaining clusters where the cluster coordinates are the geometrical barycenter of its hits. At first, the Hough Transform is applied using one projection of the cluster coordinates (for example $(z,x)$). The distance $\rho$ is calculated for 100 values of $\theta$ covering the range $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ and used to fill the $(\rho,\theta)$ histogram. The bins with more than 6 entries are selected. With the clusters belonging to the selected bins, the procedure is performed again using the other projection to avoid accidentally aligned clusters in one 2D projection. The selected clusters are used to build tracks. Fig. 6.a shows one event display of a 80 GeV hadronic shower with the Hough Transform selected hits. The detector efficiency has been estimated using the same method described in section 2.2 but with the reconstructed tracks from the Hough Transform method. This efficiency was found to be in good agreement with the previous study (Fig. 6.b).

Figure 6. (a) 80 GeV hadronic shower with hits belonging to tracks in red. (b): Efficiency per layer estimated with tracks reconstructed with Hough Transform technique.

5. Conclusion
The SDHCAL prototype achieved in 2012 was successfully tested at the SPS in CERN using trigger-less and power-pulsed modes. It has been exposed to beams of pions, electrons and muons on a large energy range (5-80 GeV). Encouraging results on the energy reconstruction and resolution have been reached without any gain correction. New algorithms to linearize the pion response have been developed. They allow to obtain a satisfactory linearity on the energy reconstruction and a good energy resolution which reaches 9% at 80 GeV. The Hough Transform technique has been applied successfully and it was found to be a powerful tool for the track detection.

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