Hadronic shower properties in highly granular calorimeters with different absorbers

Marina Chadeeva\textsuperscript{1,2} for the CALICE collaboration

\textsuperscript{1} P. N. Lebedev Physical Institute of the RAS, Moscow, Russia

E-mail: chadeeva@lebedev.ru

Abstract. The CALICE collaboration develops and tests highly granular calorimeter prototypes for future collider experiments. The scintillator-SiPM-based prototypes of hadron calorimeters with steel and tungsten absorbers were exposed to test beams from the CERN SPS in 2007–2011. The paper presents a comparison of hadronic shower properties observed in the test beam data. The application of software compensation technique is discussed for the energy reconstruction in calorimeters with different level of compensation. It was observed from the experimental data that the achieved improvement of relative energy resolution is about 20\% for the noncompensating calorimeter, while it is less than 5\% for the compensating one.

1. Introduction

The modern trend in detector development for future experiments in the field of high energy and particle physics is the implementation of high-granular systems for the particle-flow-based reconstruction \cite{1}. The sampling highly granular calorimeters are proposed for the ILD experiment at the ILC and CLIC \cite{2, 3} and for the upgrade of the CMS endcap hadron calorimeters at the HL-LHC \cite{4}. The overwhelming majority of detector subsystems are involved in the particle flow reconstruction, which performance depends in a large extent on the ability to separate nearby particle showers in the calorimeter. Therefore, the level of longitudinal and transverse granularity as well as the absorber material properties of a calorimeter system are important for the particle flow algorithms. Though stainless steel is cheaper than tungsten, the option with tungsten as absorber can be also considered for a hadron calorimeter. The use of denser absorber material in a calorimeter results in more compact size of the whole detector system and smaller dimensions of the superconducting solenoid and yoke.

The CALICE collaboration works on the R&D of highly granular electromagnetic and hadron calorimeters for HEP experiments. During the last decade, many calorimeter systems have been developed and tested with different readout technologies (analog, semi-digital, digital), active materials (silicon, scintillator-SiPM, RPC) and absorber materials (stainless steel, tungsten).

The main goals of these efforts were the investigation of performance with test beams, study of the energy resolution, reconstruction schemas, shower development and shower substructure as well as validation of Geant4 simulations. Figure 1 shows two artificially overlaid hadronic showers from CALICE test beam data. Two overlapped showers from 10 GeV and 30 GeV hadrons with 15 cm between shower axes can be separated due to the unprecedented granularity. This paper

\textsuperscript{2} Also at National Research Nuclear University MEPhI, Moscow, Russia
focuses on the comparison of shower characteristics observed in the scintillator-SiPM hadron calorimeters with different absorbers exposed to test beams of single particles in the energy range 10–80 GeV.

2. Experimental setups and test beams

The first-generation prototype of the CALICE scintillator-SiPM analogue hadron calorimeter (AHCAL) is assembled from 5 mm thick scintillator tiles with transverse sizes $3 \times 3 \text{ cm}^2$ in the centre, $6 \times 6 \text{ cm}^2$ in the middle and $12 \times 12 \text{ cm}^2$ along the perimeter of active plane. The overall transverse size is $90 \times 90 \text{ cm}^2$. The prototype was tested with two absorber materials: steel (Fe-AHCAL) and tungsten (W-AHCAL). In both sampling calorimeters the same active layers were interleaved with absorber plates from 2 cm steel in the Fe-AHCAL and 1 cm tungsten (+0.5 mm steel support) in the W-AHCAL. The parameters of the prototypes are presented in table 1, where $\lambda_1$ and $X_0$ denote nuclear interaction length and radiation length, respectively. The details on commissioning, calibration and test beam studies can be found in refs. [5, 6].

| Absorber | Longitudinal depth per layer | Total |
|----------|-------------------------------|-------|
| Fe-AHCAL | stainless steel | $5.2 \lambda_1$ | $0.137 \lambda_1 (1.24 X_0)$ | noncompensating, $e/\pi \sim 1.2$
| W-AHCAL  | tungsten alloy | $4.9 \lambda_1$ | $0.129 \lambda_1 (2.80 X_0)$ | compensating, $e/\pi \sim 1$

In this study we present the analysis of test beam data obtained with mixed negative beams from the CERN SPS with momenta 10–80 GeV. The combined calorimeter setup during the 2007 test beam campaign contained silicon-tungsten electromagnetic calorimeter [7], Fe-AHCAL and tail catcher and muon tracker, TCMT [8]. The setup during the 2011 test beam campaign comprised the W-AHCAL and TCMT. Both setups were equipped by veto and Čerenkov counters for offline particle identification and sample cleaning.
The calibration of calorimeter starts from the equalisation of cell response to minimum ionising particles (MIP). The visible signal obtained in units of MIP is converted to an electromagnetic or hadronic energy scale using the corresponding factors. The ratios of electromagnetic to hadronic scale factor for both calorimeters are shown in table 1. Hereinafter, the cell signals above noise threshold (set on 0.5 MIP) are called hits. For the presented comparison of hadronic shower development in different absorber materials, the test beam events were selected where hadrons start showering in the first layers of the hadron calorimeter. For the combined setup with the electromagnetic calorimeter, track in the electromagnetic calorimeter is required. More details concerning event selection can be found in refs. [6, 9].

3. Hadron energy reconstruction

The energy resolution for hadrons is determined by a complex structure of hadron-induced showers. Hadronic showers typically contain some fraction of electromagnetic subshowers (electromagnetic component) from decays of $\pi^0$'s produced in the hadron-nucleus interactions. The visible energy measured in a calorimeter exhibits large event-by-event fluctuations due to fluctuations of released binding energy and a number of produced $\pi^0$'s. Such a behaviour results in degradation of the hadron energy resolution compared to that of electromagnetic showers. In highly granular calorimeters, additional observables can be extracted, which are assumed to be correlated with the electromagnetic fraction in hadronic shower. This approach is called "software compensation technique" and has been successfully applied to the energy reconstruction in the noncompensating Fe-AHCAL [9]. The main goal of the software compensation (SC) reconstruction is to improve the energy resolution by taking into account fluctuations of electromagnetic fraction on an event-by-event basis.

3.1. Standard reconstruction

In the standard reconstruction schema, the particle energy, $E_{\text{std}}^{\text{event}}$, in the combined setup from $M$ subdetectors is calculated as a sum of hit energies

$$E_{\text{std}}^{\text{event}} = C_{\text{trk}} \cdot \sum_{t=1}^{N_{\text{trk}}} e_t + \sum_{s=1}^{M} C_s \cdot \sum_{i=1}^{N_s} e_{is},$$

where $e_{is}$ is the amplitude in units of MIP of $i$-th hit in $s$-th subdetector (electromagnetic or hadron calorimeter) multiplied by the hadronic scale calibration factors $C_s$ in units of GeV/MIP, $N_s$ is the number of shower hits in $s$-th subdetector, The energy scale factor, $C_{\text{trk}}$, is applied to track hits with amplitudes $e_t$. The reconstructed energy, $E_{\text{reco}}$, and the absolute resolution, $\sigma_{\text{reco}}$, for a given beam momentum are obtained from the energy distribution using the two-step Gaussian fit within ±2 standard deviations. The relative resolution is defined as a ratio $\sigma_{\text{reco}}/E_{\text{reco}}$.

3.2. Software compensation reconstruction

Two software compensation techniques were developed for the Fe-AHCAL. Both techniques assume that the energy density is typically higher in the electromagnetic component of hadronic shower. As a result, the hits, which belong to the electromagnetic component, have typically higher amplitude than hits, which belong to the hadronic component.

The "local software compensation" technique (hit energy weighting) performs the reweighting of each hit depending on its energy. The hit energy spectrum of $s$-th subdetector is divided in $K_s$ bins with typical $K_s = 8$. Then the corrected energy can be calculated as

$$E_{\text{SClocal}}^{\text{event}} = C_{\text{trk}} \cdot \sum_{t=1}^{N_{\text{trk}}} e_t + \sum_{s=1}^{M} C_s \cdot \sum_{j=1}^{K_s} w_{js} (E_{\text{std}}^{\text{event}}) \cdot \sum_{i}^{N_{js}} e_{ij},$$

where $w_{js}$ is the weight factor for the $j$-th bin of the $s$-th subdetector.
Figure 2. Reconstructed energy distributions in the Fe-AHCAL for 80 GeV negative pions with standard (black circles), local SC (blue triangles) and global SC (red squares) reconstruction. The curves show fits with a Gaussian function. Figure 2b from [9].

where $E_{\text{event}}^{\text{std}}$ is from equation (1), $e_{ij}$ is the amplitude in units of MIP of $i$-th hit in $s$-th subdetector and $j$-th bin of hit energy spectrum. The hit amplitudes are multiplied by weights $w_{js}$. The energy dependence of weights is parametrised using test beam data. It should be noted that the local software compensation technique was implemented in the simulation of the ILD detector resulting in the improvement of jet energy resolution [10].

The ”global software compensation” technique (event energy weighting) extracts one weight from the shape of hit energy spectrum to calculate the corrected energy as

$$E_{\text{corr}}^{\text{global}} = C_{\text{trk}} \cdot \sum_{t=1}^{N_{\text{trk}}} e_t + E_{\text{corr}}^{\text{event}} \cdot P(a_G, E_{\text{corr}}^{\text{event}}),$$

$$E_{\text{corr}}^{\text{event}} = \sum_{s=1}^{M} C_s \cdot W_{\text{event}}^{s} \cdot \sum_{i}^{N_s} e_{is}$$

where the weights $W_{\text{event}}^{s}$ are obtained from the hit energy spectrum shape in a particular event and the coefficients $a_G$ of the second-order polynomial $P$ are estimated from test beam data. More details on the software compensation techniques can be found in [9].

Figure 2 shows the energy distributions for 80 GeV pions in the Fe-AHCAL obtained with standard and software compensation reconstruction. The software compensation reconstruction techniques allow energy correction on an event-by-event basis, do not require the knowledge of initial particle energy and do not distort the linearity of calorimeter response. The achieved improvement of relative resolution in the noncompensating Fe-AHCAL amounts up to 20%.

3.3. Comparison of noncompensating and compensating calorimeters

In this study, the global software compensation technique developed for the undercompensating Fe-AHCAL is applied for the energy reconstruction in the compensating W-AHCAL prototype to test a relationship between the observables used in the software compensation method...
Figure 4. Relative resolution for pions in the Fe-AHCAL for standard (black circles), local SC (blue triangles) and global SC (red squares) reconstruction. The error bars show overall uncertainties. Figure 4 from [9].

Figure 5. Relative resolution for negative pions in the W-AHCAL for standard (black circles) and global SC (red squares) reconstruction. The error bars (bands) show statistical (systematic) uncertainties.

and the electromagnetic fraction in a hadronic shower. The energy distributions in the W-AHCAL for 80 GeV negative pions are shown in figure 3 for both standard and global software compensation reconstruction. Figures 4 and 5 show the relative resolution for standard and software compensation reconstruction. The improvement of resolution in the compensating W-AHCAL does not exceed 5%, which is much smaller than the improvement at the level of 20% achieved for the noncompensating Fe-AHCAL. This result confirms our initial hypothesis that the software compensation technique corrects presumably for the fluctuations of electromagnetic fraction in hadronic showers.

4. Spatial development of hadronic showers
The unprecedented granularity of the CALICE calorimeter prototypes opens an opportunity to study spatial development of hadronic showers and perform detailed comparisons with simulations [11, 12]. Such comparisons are important for the optimisation and performance studies of the full-scale detector concepts. Both longitudinal and transverse energy density distributions can be investigated and compared for calorimeter prototypes with different absorbers.

The longitudinal shower development, which is important for estimation of leakage, is characterised by the longitudinal centre of gravity. This observable is calculated as an energy weighted sum of longitudinal hit distances from the identified shower start position. It is integrated over the transverse direction and is expressed in units of nuclear interaction length. The preliminary comparisons show that the longitudinal centre of gravity tend to be slightly deeper in the calorimeter with tungsten absorber compared to the steel one.

The majority of particle flow algorithms rely on the possibility to spatially resolve nearby particles. Therefore, the lateral energy density distribution in a calorimeter is important for the performance of the algorithms. To characterise the radial development, the shower radius is introduced. This observable is calculated as an energy weighted sum of radial hit distances from the shower axis. Our preliminary study shows that hadronic showers in the tungsten absorber tend to be narrower than in the calorimeter with steel absorber material, which is expected.
5. Conclusion
We have performed the analysis of experimental data obtained with the CALICE scintillator-SiPM analog hadron calorimeter prototypes with the same active layers but different absorber materials, steel or tungsten. The calorimeter with steel absorber is undercompensating, while that with tungsten absorber is almost compensating. The significantly larger improvement of the energy resolution achieved by the application of software compensation technique to the noncompensating calorimeter leads to the conclusion that the developed software compensation procedure accounts for the fluctuation of electromagnetic fraction in hadronic showers.

Acknowledgments
The work was supported by the grant of Ministry of Education and Science of Russian Federation 14.W03.31.0026.

References
[1] Thomson M A 2009 Particle flow calorimetry and the PandoraPFA algorithm Nucl. Instrum. Meth. A 611 25 (Preprint arXiv:0907.3577)
[2] Behnke T et al. 2013 The International Linear Collider technical design report - Volume 4: Detectors Preprint arXiv:1306.6329
[3] Simon F 2012 Detector systems at CLIC Physics Procedia 37 63 (Preprint arXiv:1109.3387)
[4] Magnan A M 2017 HGCal: a High-Granularity Calorimeter for the endcaps of CMS at HL-LHC JINST 12 C01042
[5] Adloff C et al. 2010 Construction and commissioning of the CALICE analog hadron calorimeter prototype JINST 5 P05004 (Preprint arXiv:1003.2662)
[6] Chefdeville M et al. 2015 Shower development of particles with momenta from 15 GeV to 150 GeV in the CALICE scintillator-tungsten hadronic calorimeter JINST 10 P12006 (Preprint arXiv:1509.00617)
[7] Adloff C et al. 2009 Response of the CALICE Si-W electromagnetic calorimeter physics prototype to electrons Nucl. Instrum. Meth. A 608 372 (Preprint arXiv:0811.2354)
[8] Adloff C et al. 2012 Construction and performance of a silicon photomultiplier/extruded scintillator tail-catcher and muon-tracker JINST 7 P04015 (Preprint arXiv:1201.1653)
[9] Adloff C et al. 2012 Hadronic energy resolution of a highly granular scintillator-steel calorimeter using software compensation techniques JINST 7 P09017 (Preprint arXiv:1207.4210)
[10] Tran H L, Krüger K, Sefkow F, Green S, Marshall J, Thomson M and Simon F 2017 Software compensation in particle flow reconstruction Eur. Phys. J. C 77 698 (Preprint arXiv:1705.10363)
[11] Bilki B et al. 2015 Testing hadronic interaction models using a highly granular silicon-tungsten calorimeter Nucl. Instr. Meth. A 794 240-254 (Preprint arXiv:1411.7215)
[12] Eigen G et al. 2016 Hadron shower decomposition in the highly granular CALICE analogue hadron calorimeter JINST 11 P06013 (Preprint arXiv:1602.08578)