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CALICE scintillator HCAL commissioning experience and test beam program

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Abstract. The active modules of the CALICE scintillator HCAL (or AHCAL for analog hadronic calorimeter) prototype are being commissioned using cosmic muons and the DESY electron test beam. These first data allow to check the functionality of the photo-detectors, the readout chain and the calibration electronics; and to test the performance of the entire system. This proceeding will discuss first operational experience, calibration and correction procedures, data analysis and results. The status of preparations for the first hadron beam measurements to start in summer 2006, and the data taking plans are also presented.

Keywords: silicon photomultiplier, scintillator, calorimeter
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INTRODUCTION

The calorimeter for experiments at the future ILC must be realized as a dense and hermetic sampling calorimeter with very high granularity to allow the separation of the various particles in a jet and to use the best suited detector component to measure their four-momentum. The goal is to reach a jet energy resolution of $\sigma/E \sim 0.3/\sqrt{E}$. The success of this approach will originate more from the higher segmentation (both lateral and longitudinal) than from the stochastic and constant term in the energy resolution, both of which can be moderate. One possible realization of the calorimeter is proposed for the LDC detector and described in [1]. This contribution concentrates on the progresses in the prototype development of the scintillator-steel hadron calorimeter (AHCAL)[1] readout by pixilated avalanche photo-diode operated in Geiger mode, the Silicon-Photomultiplier (SiPM, [2, 3, 4]).
The 38 prototype layers covering about 4.5 interaction lengths consist each of a matrix of 216 scintillator tiles with on-tile SiPM readout via coaxial cables routing the analog signal to the Very Front-End (VFE) electronics. One such a layer will be referred to as module. A dedicated ASIC chip [5], developed by LAL (Orsay), is used for multiplexed readout of 18 SiPM. This chip offers various combinations of preamplifier gain and shaping time to best match the SiPM readout and calibration. A more detailed description of the AHCAL prototype structure, and commissioning status is given in [6].

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[1] The institutes participating to this project are: DESY, Hamburg U, ICL (London), ITEP (Moscow), LAL (Orsay), LPI (Moscow), MEPHI (Moscow), Northern Illinois U., RAL, UCL (London).

This contribution focuses on a series of tests made during the commissioning phase of the first half of the modules. The aim of the studies was to establish the readout of a large sample of channels; to develop a calibration procedure applicable to the ∼8000 SiPM used to read out the AHCAL; and to test the monitoring of the SiPM responses in time.

The calibration of each tile is based on minimum ionizing particle signals such as cosmic muons or high energetic electrons from the DESY test beam facility. The full calibration of a calorimeter cell, though, requires to account for the non-linearity introduced by the finite number of pixels (1156/mm^2) in the SiPM. For this purpose a versatile UV-LED light distribution system was adopted, capable of delivering light to all tiles with intensity from few photo-electrons to the saturation of SiPM.

Furthermore, the LED system allows to monitor the variations of SiPM gain and signal amplitude; the latter being the product of gain and photo-detection efficiency, both sensitive to temperature and voltage fluctuations. The monitoring system ensures the applicability of calibration factors extracted in dedicated runs at the beginning and end of a data taking period of several days.

CALIBRATION OF CALORIMETER CELLS

Tests with fully equipped modules of AHCAL were performed with cosmic muons and electron test beam at DESY and with UV light from the LED monitoring system. Up to 4 modules (∼900 channels) at a time were read out via the VME DAQ. The procedure to calibrate all calorimeter channels was tested, which requires to account for the signal non-linearity introduced by the limited dynamic range of SiPM.

The charge collected by a SiPM is a multiple of the Geiger mode gain corresponding to the number of pixels fired. To extract the information of light intensity (proportional to the energy deposited in the tile) the number of fired pixels is converted into number of photo-electrons using a measurable response function

$$f_{resp} : N_{ph.e} = f_{resp}(N_{pixel}), \tag{1}$$

Fig.1 shows an example of the SiPM response curve from which f_{resp} is obtained. The horizontal axis of the function can be expressed in number of MIP given the light yield (LY) relation for each tile, i.e. the amplitude of a MIP signal expressed in number of pixels fired. The measured LY in the first AHCAL module is in average 15 pixels/MIP with a spread (RMS) of ∼20%. This variation is too large to assume the LY value equal for all tiles therefore, the slope of the saturation curve has to be calibrated for each *i*-th tile individually according to the equation

$$E_i[MIP] = f_{resp}\left(A_i[MIP] \cdot LY_i \left[\frac{pixel}{MIP}\right]\right) \cdot \frac{1}{LY_i'} \tag{2}$$

where $LY_i'[ph.e./MIP] = f_{resp}(LY_i[pixel/MIP])$, and $A_i[MIP] = \frac{A_i[ADC]}{A^i_{MIP}}$ is the recorded signal amplitude on the *i*-th tile expressed in units of MIP amplitude A^i_{MIP}.

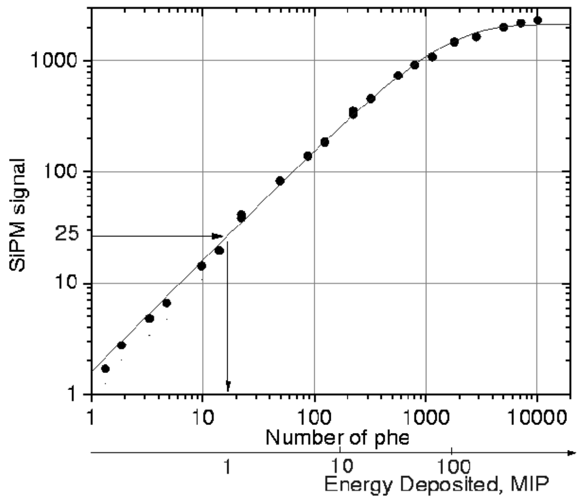

FIGURE 1. Response to increasing intensity LED light of a 1156-pixels/mm^2 SiPM.

The LY is determined using the SiPM gain (G_{pixel}) extracted from single photo-electron peak spectra. Such spectra are simultaneously obtained for all SiPM by fleshing low intensity LED light to each tile. For this measurement the VFE electronics is operated with the highest possible preamplifier gain ($\sim$90 mV/pC). The shortest shaping time of the ASIC chip is selected ($\sim$40 ns) to minimize integration of SiPM dark-rate and optimize single photo-electron peak separation.
Though more favorable from the noise point of view, a 40 ns shaping time is not sufficient to provide the required trigger latency which in the test beam setup is typically of 150 ns (mainly driven by the DAQ logic and trigger distribution). A shaping time of $\sim$200 ns is used when collecting physics data, in combination with a medium gain ($\sim$8 mV/pC) to match the range of energy deposited in one tile to that of the 16-bit ADC.
When extracting the LY ratio, between MIP and SiPM gain, it is necessary to account for the different ASIC gains in these two modes of operation of the VFE electronics. For this purpose, an inter-calibration factor (I^{calib}_{phys}) is extracted for each channel as the ratio of SiPM response to medium-intensity LED light when operating the ASIC chip in the two modes (*phys* and *calib*). Including this correction the LY of each individual tile is expressed by the equation

$$LY_i = \frac{A^i_{MIP}}{G^i_{pixel}} \cdot (I^{calib}_{phys})_i. \tag{3}$$

MIP CALIBRATION

All produced AHCAL modules have been commissioned at the DESY electron test beam and, a sub-sample of 4 modules, also in a dedicated cosmic muons test bench. The scan performed with the e^- beam through the module surface proves to be faster than accumulating the required statistics with cosmic muons. The comparison of the extracted

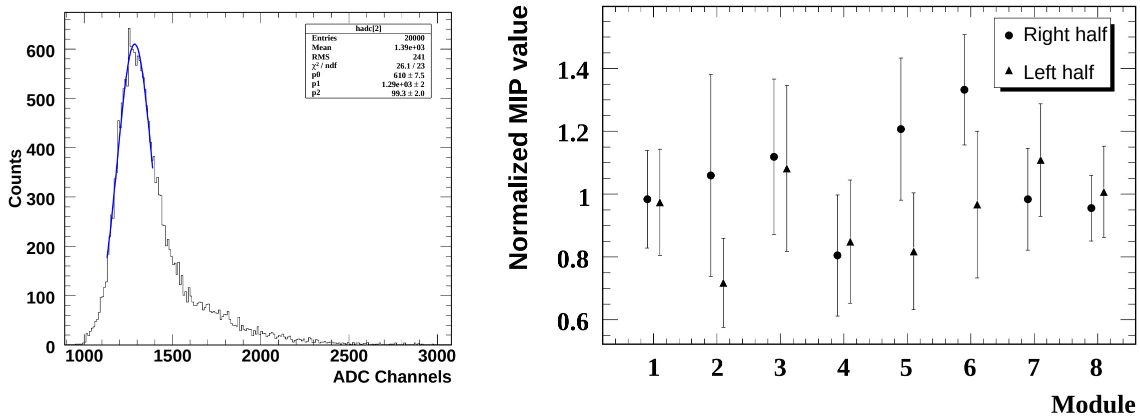

FIGURE 2. Left) A typical MIP spectrum from one AHCAL tile with SiPM readout. Right) Comparison of MIP calibration values for 15 modules. The error bars represent the RMS of 108 tiles per half module.

MIP calibration indicates good correlation between the two methods therefore, the faster one has been adopted for the mass test of all modules.

The MIP calibration for each tile is extracted from a fit to the ADC spectrum. Various fitting functions have been tested, for this results a Gaussian fit in the range of $-1.5/+1\sigma$ has been chosen. The fit result for a typical channel is shown in the left panel of Fig.2. The average signal to noise separation for MIP signals is 4.

The right panel of Fig.2 is a compilation of all MIP calibrations for the first 8 commissioned AHCAL modules. The results are presented as average over each half module since in general the two halves can be made out of SiPM from different production batches, powered via an independent bias voltage line. The averages are normalized to the mean value of all modules. The error bars represent the RMS of 108 tiles. The error on each MIP calibration is below 2% including the systematic of the fit. The spread of about 25% in MIP calibration for various tiles reflects both the SiPM gain and the LY spread.

UNIVERSALITY OF SIPM RESPONSE FUNCTION

Detailed studies on SiPM saturation correction have been carried out on the first produced AHCAL module in a dedicated setup, which allows to measure energies up to $\sim$40 MIPs per tile and compare the SiPM response with that of a linear photo-multiplier tube (PMT). As shown in Fig.3, a lead absorber plate of variable thickness is positioned on the beam line to initiate an electromagnetic shower. Fig.4 shows the correlation between the energy collected by the scintillator behind the lead plate (PMT2) and the SiPM tile behind it. Data (closed symbol) from a 5 GeV e^- beam showering on 5 X_0 lead are compared to the GEANT3 simulation of the setup (open symbol). Above 40 MIP amplitude the low statistics does not allow to extract sensible information from the data and the simulation was not performed. A clear deviation of the data from simulation

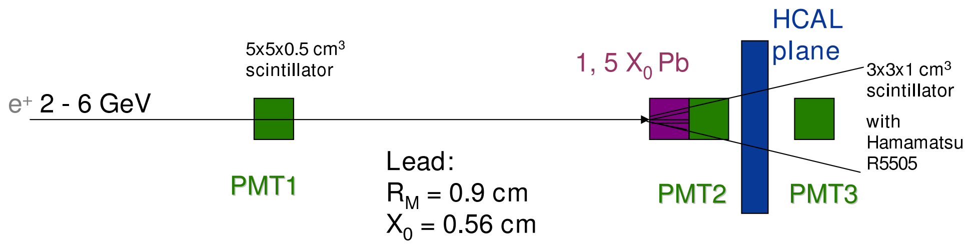

FIGURE 3. Sketch of the setup used for studies of SiPM saturation correction.

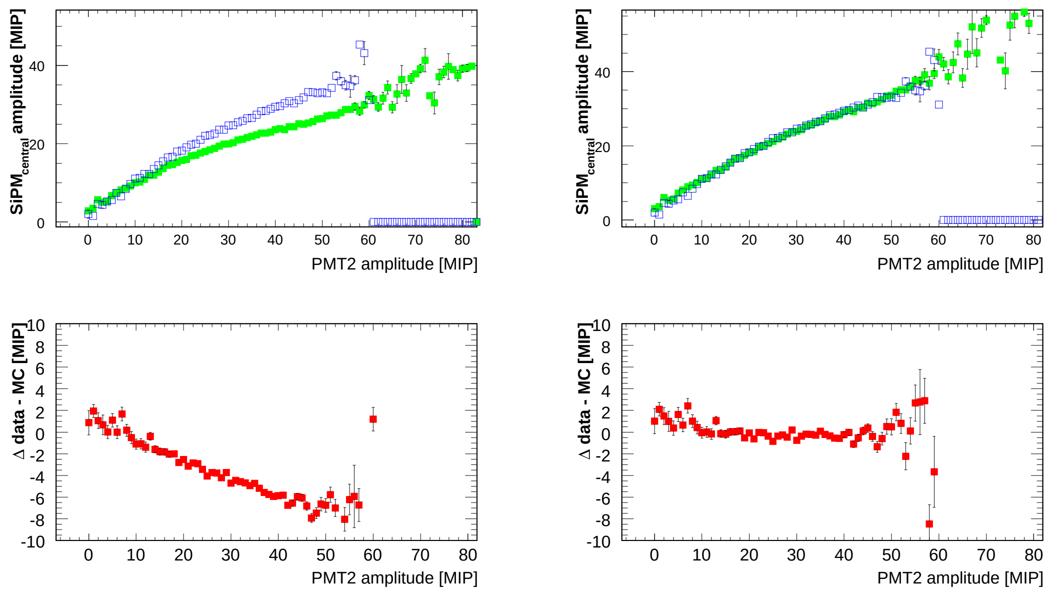

FIGURE 4. Comparison of SiPM and PMT amplitude for a 5 GeV e^- beam showering on 5 X_0 lead. Left) raw SiPM amplitude. Right) SiPM corrected for non-linear response. In the top two panels the data are closed symbol, while the open symbol are a GEANT3 simulation. The bottom two panels show the difference of data and simulation.

is observed already above 15 MIP amplitude (>200 pixels). The largest fraction of the shower maximum, generated after 5 X_0 is in the range between 15 and 35 MIP. For this amplitude the deviation from simulation is ~10-25%. After correcting on an event by event basis the SiPM amplitude according to Eq.3 the data is in very good agreement with the simulation, as it can be seen in the right upper panel of Fig.4.
To study the applicability of a unique SiPM response function to many channels the same test was repeated for a sample of 25 tiles in the core of the first AHCAL module. The average shower maximum in each tile normalized to the simulation prediction is presented in Fig.5, without (left) and with (right) non-linearity correction. The mean of the distribution for the tested tiles differ from simulation of ~20% when no correction is applied. After correcting each tile response with the same SiPM response function

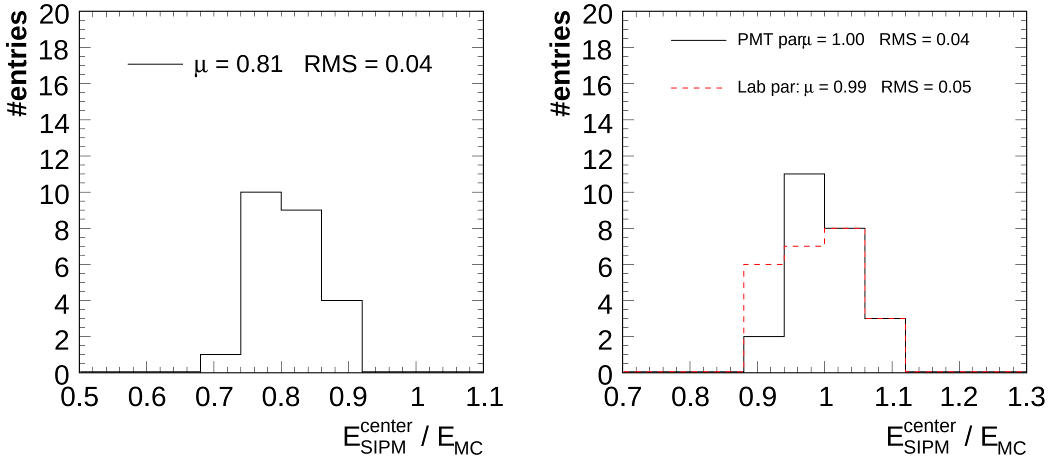

FIGURE 5. Average energy deposited in one AHCAL tile by a 5 GeV e^- beam showering on 5 X_0 lead, normalized to MC expectation, for a sample of 25 tiles. Left) raw SiPM amplitude. Right) SiPM corrected for non-linear response with two functions described in the text.

calibrated with the appropriate LY, data and simulation agree very well.

The spread of 5% between tiles reflects the present uncertainty on all the calibration factors, and the fact that no temperature correction has yet been applied to account for the variations during the data taking period.

To correct the non-linearity of SiPM two methods have been used. The parameterization of the response function in Fig.1, measured in a laboratory setup; and a model function inspired by the linearization often applied to PMT ("PMT par"). The model is the first order expansion of the saturation function

$$f_{PMT\,par} : N_{ph.e} = -N_0 \cdot \left(1 - ln\left(1 - \frac{N_{pixel}}{N_0}\right)\right) \sim \frac{N_{pixel}}{1 - \frac{N_{pixel}}{N_0}}, \qquad (4)$$

with effective number of fired pixels N_0 ~1500. In both cases the corrected amplitude agrees with the simulation expectations. The simplified model description works as well as the parameterization of the response function at the moderate amplitudes reached in this test. This observation needs to be corroborated by larger statistics and by measurements at higher amplitude.

UNIFORMITY STUDIES

A study of the uniformity of the calorimeter response has been performed using the same setup as presented in Fig.3 with 1 X_0 lead to initiate an electromagnetic shower. In this configuration the lateral extension of the shower is 99% contained in a matrix of 9 3 × 3 cm^2 tiles (90% is contained in the central tile). It is intended to study the homogeneity of one calorimeter layer by comparing the energy deposited in many such matrices, in a region of amplitude where the SiPM saturation is relatively small.

The energy collected in the 9 tiles is in average ∼7 MIP (∼100 pixels), for which the non-linearity correction is ∼10%. The spread between the 45 tile matrices is of the order of 5%, which is in the current uncertainty of these studies. At present this measurements are only indicative that the calorimeter uniformity must be better that 5%. Higher precision is expected when correcting for temperature variations, not yet possible when the data were collected.

MONITORING OF TEMPERATURE VARIATIONS

During the calorimeter operation possible variations in the system are detected by a threefold monitoring system. A slow control system reads the SiPM bias voltage and the temperature of each module with a 5 points interpolation. The SiPM gain is measured at the beginning of each run with low LED light intensity. The total temperature (T) and voltage (V) dependence of the SiPM gain at room temperature as measured by the manufacturer (MEPHI) is $\frac{dG}{dT} = -1.7\frac{\%}{°C}$ and $\frac{dG}{dV} = 2.5\frac{\%}{0.1V}$. Finally, the peak position of a medium amplitude LED signal is monitored. LED light fluctuations are corrected using the light amplitude read out by a photo-diode. Variations in the response to UV-LED light reflect the SiPM signal amplitude dependence on T and V. This dependence is expected to be larger than that of the gain given that the SiPM signal amplitude is the product of SiPM gain, quantum efficiency and Geiger efficiency; and that all three factors depend on T and V. According to the manufacturer the signal amplitude varies according to $\frac{dQ}{dT} = -4.5\frac{\%}{°C}$ and $\frac{dQ}{dV} = 7\frac{\%}{0.1V}$. The combined information from the monitoring system is used to correct the calorimeter response to an expected stability of 1-2%.

The measurements performed on one test AHCAL module over two weeks of continuous monitoring indicate a similar dependence on temperature variations. For this measurement the average of all monitored calorimeter tiles is taken assuming that they all undergo the same temperature fluctuation. Measurements of SiPM gain are repeated through out the day in dedicated low light-intensity runs. Otherwise the module is continuously fleshed with low-rate medium-intensity LED light to observe change in SiPM amplitude. The day-to-night temperature variation was within one degree, but the very high-precision temperature measurement and the low systematic error in the monitored values allow to extract the following results:

$$\frac{dG}{dT} = -1.7 \pm 0.1\frac{\%}{°C}\ ,\ \frac{dQ}{dT} = -3.7 \pm 0.2\frac{\%}{°C},$$

which are in quite good agreement with the expectation from the manufacturers. Voltage fluctuations are as crucial as temperature ones

CERN TEST BEAM PLANS

At the moment 15 commissioned AHCAL modules have been installed on the H6 test beam line of the SPS at CERN. Having equipped every other layer of the steel sandwich structure ∼80% of the total depth is equipped with half the foreseen longitudinal granu-

larity. The complete granularity coverage is expected latest for October.
Three data taking periods are planned in which the AHCAL prototype will be tested both as stand alone and with a prototype of the Si-W ECAL in front. The first two runs will have reduced longitudinal segmentation, while for the last run all 38 calorimeter active layers will be installed. For the last data taking period also a tail catcher and muon tagger should be fully equipped in the rear of the AHCAL, to ensure full hadronic shower containment.
The test program is quite rich, both electromagnetic and hadronic showers will be investigated at energies ranging between 6 and 200 GeV, and under various incident angles to the calorimeters. The beam can be varied between: $\mu, e^{\pm}, \pi^{\pm}, p$, or $\bar{p}$.
While electromagnetic showers are correctly modeled in simulation tools like GEANT3 or GEANT4, the unprecedented longitudinal and transverse granularity of the data collected with the AHCAL prototype will allow a deeper understanding of hadronic showers, and will serve to discriminate among the large variety of existing hadronic models. Furthermore, the operation of 8000 channels with SiPM readout will be a technological step toward establishing this new photo-detector for calorimetry applications

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