The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

17 January 2020 (v4, 16 June 2020)

Performance of CMS high granularity calorimeter prototypes in testbeam experiments

Artur Lobanov for the CMS Collaboration

Abstract

The present electromagnetic and hadronic calorimeters of the CMS experiment will be upgraded to cope with the harsh radiation environment and pileup conditions posed by the high luminosity operations of the LHC (HL-LHC) expected to start in 2027. CMS has opted for a sampling calorimeter, based on silicon and scintillator technologies, with unprecedented transverse and longitudinal segmentation to facilitate particle identification, particle-flow reconstruction and pileup rejection. As part of the ongoing development and testing phase of this High Granularity Calorimeter (HGCAL), prototypes of both the silicon and scintillator based calorimeter sections have been tested in 2018 in beams at CERN. We report on the performance of the prototype detectors in terms of stability of noise and pedestals, calibration with minimum-ionizing-particles (MIPs), and energy linearity and resolution for electrons and pions. We compare the measurements with a detailed GEANT4-based simulation.

Presented at *CHEF2019 Calorimetry for the High Energy Frontier 2019*

PREPARED FOR SUBMISSION TO JINST

CHEF2019: CALORIMETRY FOR HIGH ENERGY FRONTIER
25-29 NOVEMBER 2019
CENTENNIAL HALL, KYUSHU UNIVERSITY, FUKUOKA, JAPAN

Performance of CMS High Granularity Calorimeter prototypes in beam test experiments

S. Pandey,^a S. Sharma,^a A. Lobanov^b on behalf of the CMS collaboration

^a*Indian Institute of Science Education and Research (IISER), Pune, India*

^b*Laboratoire Leprince-Ringuet (LLR), 91128 Palaiseau, France*

E-mail: shubham.pandey@cern.ch

ABSTRACT: The present electromagnetic and hadronic calorimeters of the CMS experiment will be upgraded to cope with the harsh radiation environment and pileup conditions posed by the high luminosity operations of the LHC (HL-LHC) expected to start in 2027. The CMS collaboration has opted for a sampling calorimeter in the endcap sections of the detector, based on silicon and scintillator technologies, with unprecedented transverse and longitudinal segmentation to facilitate particle identification, particle-flow reconstruction and pileup rejection. As part of the ongoing development and testing phase of this High Granularity Calorimeter (HGCAL), prototypes of both the silicon and scintillator based calorimeter sections have been tested in 2018 in beams at CERN. We report on the performance of the prototype detectors in terms of stability of noise and pedestals, calibration with minimum-ionizing-particles (MIPs), and energy linearity and resolution for electrons and pions. We compare the measurements with a detailed GEANT4-based simulation.

KEYWORDS: Calorimeter methods; Calorimeters; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Radiation-hard detectors

Contents

1	Introduction	1
2	Calibration and energy reconstruction	2
3	Performance with positrons and charged pions	4
3.1	Electromagnetic showers	4
3.2	Hadronic showers	5
4	Summary	6

1 Introduction

The endcap calorimeter detectors ($1.5 < |\eta| < 3.0$) of the CMS experiment will be replaced by a High Granularity Calorimeter (HGCAL) [1] to be able to withstand high radiation exposure as well as to allow efficient particle reconstruction in high pileup conditions expected in high luminosity operations of the LHC (HL-LHC). The HGCAL is a sampling calorimeter based on silicon and lead for electromagnetic compartment (CE-E) followed by a hadronic compartment (CE-H) made of a combination of silicon and scintillator for the active part and steel for the absorber. Figure 1 (left) shows a cross sectional view of HGCAL. Prototypes of CE-E and CE-H sections in a hanging file setup, as shown in Figure 1 (right), were exposed to single particle beams of muons (μ), positrons (e^+), and charged pions (π^-) at the CERN SPS H2 beamline in October 2018.

Figure 1. A cross-sectional view of the HGCAL detector showing CE-E and CE-H compartments (left), and beam test setup of the prototype detectors (right).

In the beam test setup, each of the active layers consists of a single prototype 6" silicon sensor module or seven such modules arranged in a daisy structure (Figure 2 (left)). A detailed layout of a silicon module is shown in Figure 2 (right). At the bottom-most layer, Cu/CuW is used as a

baseplate which provides mechanical strength to the whole module. A gold-plated KaptonTM layer is then glued on top of the baseplate which provides a common bias voltage contact to the sensors. A Si sensor is glued carefully on top of KaptonTM layer. Finally, a PCB, which contains the required electronics for data acquisition, is glued on top of the Si layer. These sensors have depletion widths of 200 μm or 300 μm . This was the first large scale test where 94 such modules were used. The 6" modules have 128 cells of $\sim 1.1 \text{ cm}^2$, each of which is independently read out.

The CE-E prototype is made of 28 sampling layers with one Si sensor module per layer. It is constructed in 14 double sided cassettes, where each of the cassette consists of the arrangement shown in Figure 2 (left) mirrored on both sides of the baseplate, interspersed between 4.9 mm thick Pb absorbing layers. The CE-H prototype is composed of 12 sampling layers with seven Si modules each sandwiched between 40 mm thick steel absorbing layers. The full depth of CE-E is 28 radiation length (X_0) and 1.4 nuclear interaction length (λ_I), and that of the CE-H is $3.4 \lambda_I$. The CE-H is followed by a $4.4 \lambda_I$ thick prototype of the CALICE [2] Analogue Hadronic Calorimeter (AHCAL) made of 39 sampling layers based on SiPM-on-scintillator-tile active layers interspersed between steel absorbers. However, the data collected using AHCAL is not used in the results presented in this report.

Figure 2. Arrangement of sensor modules in CE-E and CE-H layers (left), and its detailed layout (right).

2 Calibration and energy reconstruction

The charge produced by particles traversing through the Si sensors is collected and digitised by SKIROC2-CMS [3] readout chips. Average pedestal values, that is charge collected due to inherent noise in the absence of a real particle, is found to be stable within uncertainties for both the CE-E and the CE-H readout channels over the course of the beam test experiment. Figure 3 shows the variation of the average pedestal counts of a typical CE-E and a CE-H module as a function of run number during the 2018 beam test experiment.

The SKIROC2-CMS ASIC provides different gain stages to provide a large dynamic range, ensuring the precise measurement of small signals deposited by minimum ionizing particles (MIPs). The high gain (HG) and low gain (LG) modes are used for energy deposited up to 50 and 200 MIPs respectively. On an average, approximately 40 HG ADC counts corresponds to a MIP signal. A time-over-threshold (ToT) measurement is used for higher energy deposits. Gain intercalibration coefficients are determined from the correlations between HG and LG, and LG and ToT ADC

Figure 3. Average pedestal ADC counts for representative CE-E and CE-H modules as a function of run numbers during the 2018 beam test experiment.

measurements, and fitting the linear regions as shown in Figure 4. This intercalibration procedure is important to identify saturation cross-over points of different gains, and to ensure a linear response over the full energy range.

Figure 4. Correlation of HG and LG ADC counts (left), and LG and ToT ADC counts (right).

The intercalibration of Si cells to equalize their response is performed using 200 GeV/c muons, referred to as MIPs in this context. The actual energy deposited by muons of 200 GeV/c momenta is higher than minimum ionizing particles. However, these serve as a robust tool for the detector calibration. A typical distribution of HG ADC counts measured for a signal generated by muons in a 300 μm cell is presented in Figure 5 (left). The MIP calibration constants are obtained as the most probable value of the energy spectrum by fitting it with a Landau distribution convoluted with a Gaussian distribution. Overall, 85% of the channels from the CE-E and CE-H prototypes are calibrated using the muon data.

In order to quantify the level of separation between the MIP signal and inherent noise, signal to noise ratio (SNR) is obtained for all the calibrated channels. Figure 5 (right) shows the SNR for

all the cells of a CE-E module used in Layer-2 that have been calibrated using muons. The SNR is measured to be ~ 7 for most of the calibrated $300\mu\text{m}$ Si cells. The energy is finally reconstructed in terms of MIPs using the gain intercalibrations and muon intercalibrations.

Figure 5. Distribution of ADC counts for energy deposited by muons in a $300\mu\text{m}$ cell (left), and signal-to-noise ratio (right).

3 Performance with positrons and charged pions

3.1 Electromagnetic showers

Performance of CE-E is measured by using positron beams of momenta 20-300 GeV/c. The energy response of the calorimeter to positrons is linear within a percent. Both the response and resolution measured as function of beam energy are shown in Figure 6. These measurement are also compared with those predicted by simulation based on the FTFP_BERT_EMN physics list of the GEANT4 [4] package, and are found to be in good agreement.

Figure 6. Energy response (left), and resolution (right) as a function of e^+ beam energy.

Longitudinal and transverse developments of electromagnetic showers in CE-E are studied using various shower shape variables. Figure 7 (left) shows the longitudinal shower profile measured from the average energy deposited as a function of shower depth for positrons of momenta 20, 100 and 300 GeV/c in data and simulation. Figure 7 (right) shows the center of gravity of the shower, which is defined as the energy weighted shower depth ($\sum_i E_i z_i / \sum_i E_i$). The simulation closely

models the longitudinal shower shapes measured in data. Similar observations are also made for the transverse shower shape variables.

Figure 7. Average energy deposited in each CE-E layer as a function of shower depth (left), and energy weighted shower depth or center of gravity of e^+ shower (right).

3.2 Hadronic showers

The performance of the CE-E and CE-H combined system with charged hadrons is studied using π^- beams with momenta ranging from 20 to 300 GeV/c. An algorithm based on hit multiplicity in consecutive layers is implemented to identify the detector depth of the first hadronic or nuclear interaction of the π^- , called the shower start point. This is an important input needed to reconstruct the combined energies deposited in different types of absorber layers. Figure 8 (left) shows the number of pions surviving without a hadronic interaction as a function of depth in the calorimeter. As expected the number of pions surviving without a hadron interaction falls exponentially as a function of pion interaction length as depicted by the exponential fit to the distribution.

Figure 8. The number of π^- (normalized to the interaction length) surviving without hadronic interaction as a function of λ_I (left), and comparison of energy deposited by π^- in the CE-E prototype with different physics simulations available in GEANT4 (right).

The inherent complexity of the hadronic showers requires a detailed study of energy sharing among compartments with different absorber materials to get the best resolution and to measure longitudinal shower profiles. Simulation samples with different physics lists for pions are compared with data in service of this goal. A comparison of out-of-the-box energies measured in terms of number of MIPs by various GEANT4 hadron physics lists with data is shown in Figure 8 (right). While the bulk of the distribution is closely modeled by simulation, the observed discrepancies are under study to make a realistic choice of physics list for modeling hadron showers in HGCAL.

The energy of pions is reconstructed by combining energies measured in CE-E and CE-H using a software compensation technique, which minimizes the resolution for different pion energies. The AHCAL measurements are not used in the results presented here. Figure 9 shows the average energy response (left) and resolution (right) as a function of beam energy. The average response and resolution measured in data are well described by GEANT4 simulation based on the FTFP_BERT_EMM list.

Figure 9. Energy response and resolution of pions measured in data and simulation. The AHCAL is not included in these results.

4 Summary

The CMS HGCAL community has successfully tested the silicon-based prototype of the electromagnetic and hadronic sections of the HGCAL in beam test experiments. Preliminary results presented here using the energies reconstructed with muons, positrons and charged pions show good agreement with those expected in GEANT4-based simulation. The detailed studies are ongoing to make a realistic choice of simulation for electromagnetic and hadronic showers.

References

- [1] CMS Collaboration, *The Phase-2 Upgrade of the CMS Endcap Calorimeter*, CERN-LHCC-2017-023; CMS-TDR-019 (2017).
- [2] Felix Sefkow et al., *A highly granular SiPM-on-tile calorimeter prototype*, 2019 *J. Phys.: Conf. Ser.* 1162 012012.
- [3] J. Borg et al., *Skiroc : Skiroc2-CMS an ASIC for testing CMS HGCAL*, 2017 *JINST* 12 C02019.
- [4] S. Agostinelli et al., *GEANT4 - a simulation toolkit*, 2003 *NIMA Volume 506, Issue 3, Pages 250-303*. [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).