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Test beam measurements of the CMS High Granularity Calorimeter

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Abstract: As part of the High Luminosity LHC detector upgrade programme, the CMS experiment is developing a High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeters. The HGCAL will be realised as a sampling calorimeter, including 36 layers of silicon pads and 14 layers combining both silicon and scintillator detectors interspersed with metal absorber plates. Prototype modules based on 6-inch hexagonal silicon pad sensors with pad areas of 1.0 cm^2 have been constructed. Beam tests of different sampling configurations made from these modules have been conducted at the CERN SPS using beams of charged hadrons and electrons with momenta ranging from 20 to 300 GeV/c. The setup was complemented with a CALICE Analog Hadronic Calorimeter (AHCAL) prototype, a scintillator-based sampling calorimeter, mimicking the proposed design of the HGCAL scintillator part. Test beam measurements at CERN in October 2018 are presented, including measurements of pedestal and noise, calibration with single charged particles and energy reconstruction performance of electron and hadron induced showers. Measurements of the timing capabilities of this prototype system are also reported.

Keywords: Calorimeters; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Performance of High Energy Physics Detectors; Si microstrip and pad detectors

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1 Introduction

The High Granularity Calorimeter Endcap (CE) [1] project at the CMS experiment [2] aims to build a highly segmented sampling calorimeter with 50 active layers and more than 6 million silicon channels. The electromagnetic section (CE-E) of the calorimeter will contain hexagonal silicon sensors as active material and lead, copper and copper-tungsten as absorber. The silicon sensors will be segmented into hexagonal pads of about 1 cm^2 and 0.5 cm^2 in the innermost region where the radiation dose will be more significant. The hadronic section (CE-H) will also use silicon sensors for the active part in its higher radiation region. In the lower radiation region of CE-H, plastic scintillator tiles read out by silicon photomultipliers (SiPM) will be used. The hadronic calorimeter will use steel as absorber. The full calorimeter will be inserted in the same cold volume at -30^{o}C to keep low dark current in the silicon sensors and in the SiPMs. This calorimeter design allows a high transverse and longitudinal readout and trigger granularity. Beam tests have been performed of the High Granularity Calorimeter (HGCAL) prototype modules at CERN. The primary objectives of the beam test are technological prototyping of the detector, evaluation of the first experience under beam conditions of silicon modules equipped with a new front-end (FE) Skiroc2-CMS ASIC [3] with the same functionality as the ultimate (HGCAL) read-out chip (HGCROC) with Time over Threshold (ToT) and Time of Arrival (ToA) information, studying the physics performance of the CE-E and CE-H silicon/scintillator parts, and check agreement of the experimental data with simulation. This is the first large-scale beam test with 94 HGCAL modules which took place in October 2018 at CERN. A large data set of electrons, pions and muons in a wide range of momenta (20 to 300 GeV/c) has been collected for the test beam performance studies of the HGCAL prototypes.

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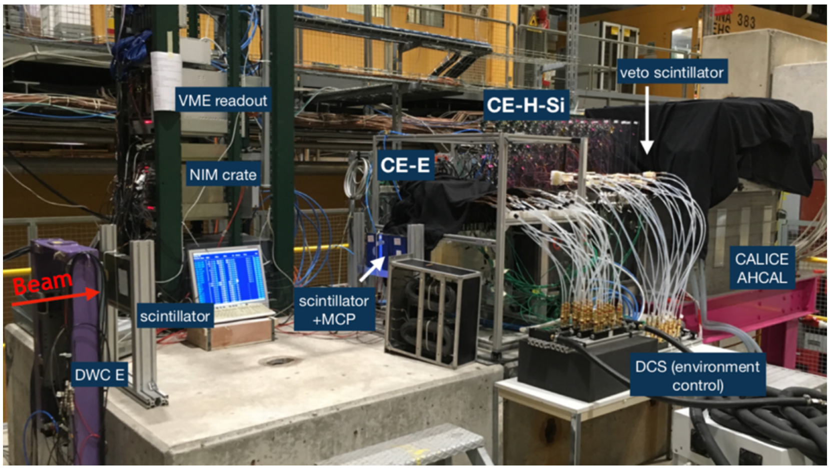

Figure 1. The October 2018 HGCAL test beam setup at CERN.

2 Test beam setup

The comprehensive experiment in the 2018 CERN test beam utilised three different depth configurations optimised either for electromagnetic or hadronic showers. The configuration optimised for electromagnetic showers consisted of a 28-layer CE-E (one silicon module per layer), followed by a 12-layer silicon CE-H (nine layers with seven modules per layer followed by three single-module layers). The modules were assembled as glued stack of baseplate, Kapton, 6-inch Si sensor and readout electronics. Different baseplate materials (copper-tungsten, copper, PCB) and two different sensor thickness for the modules, as well as different grounding schemes were tested. A 40 mm thick stainless steel absorber was placed between each layer as the passive material for the CE-H (Si), and lead, copper-tungsten and copper acted as passive material for the CE-E part. A hanging file design was employed for flexible insertion. Behind the silicon layers was a 39-layer scintillator+SiPM hadronic sampling calorimeter prototype provided by the CALICE collaboration [4], mimicking somewhat the proposed design of HGCAL back part. The October 2018 CERN test beam setup is shown in figure 1. The H2 beam line [6] provides several detectors to monitor the beam. Delay Wire Chambers (DWC) for particle tracking, Micro-Channel Plate detectors (MCP) for time reference measurement and Threshold Cherenkov Counters for hadron identification were integrated in the data-taking. Four DWC located at 40, 35, 2 and 1.5 m upstream from the electromagnetic calorimeter prototype allow the reconstruction of the trajectory of the incoming particles. They are used for event selection, alignment of all sub-detectors, and analysis of the muon data. In front of the CE-E prototype, two plastic scintillators tiles read out by fast photomultiplier have been used to trigger the readout of the sub-detectors with a trigger acceptance of $2{\times}\mathrm{cm}^2$. Between the two scintillators, two MCP detectors with an active area of $1{\times}\mathrm{cm}^2$ and 20 ps time resolution were installed to provide a precise time reference. The timing information is embedded in the readout Skiroc2-CMS, which is based on the CALICE Skiroc2 [5]. It shapes, amplifies and digitises signals from the silicon sensors. The Skiroc2-CMS has 64 channels and 13 switched-capacitor array (SCA) rolling analog memory sampled at 40 MHz. It overwrites every $13{\times}25$ ns. The charge is measured with 2 (so-called Low and High) gains. Large charges exceeding the ADC range are measured with

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a Time Over Threshold. Four quantities are read out: Low and High Gain, Time over Threshold (ToT) and Time of Arrival (ToA). A cooling system using water at 28°C was used to keep the silicon modules at a constant temperature.

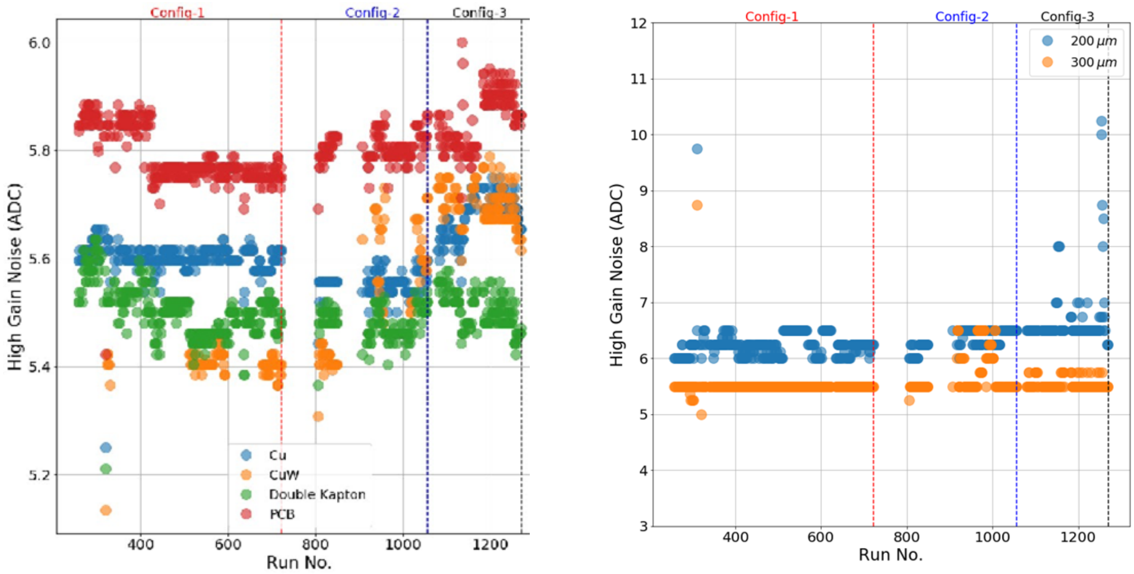

Figure 2. Noise stability distribution for HGCAL modules with different baseplate material (left), and with different sensor thickness (right).

3 Pedestal and noise stability

The first time-sample of every recorded event does not contain any signal yet and can therefore be used to calculate the pedestal and the noise in a specific run. The mean of the ADC-counts distributions defined the pedestal values, while the RMS of these distributions gave an estimate of the total noise for each channel. To completely avoid having any substantial signal leaking into the first time-sample used for pedestal contamination, only the muon runs were used to calculate the pedestal values that will be used in the pedestal subtraction. The total noise, σ_{total} is the quadratic sum of the intrinsic noise of the cell, $\sigma_{\text{intrinsic}}$, and any common-mode noise, σ_{CM} that may be present in the system. The common-mode noise comes from electronic effects in the Data Acquisition (DAQ) chain and disturbances on the bias-voltage lines. The common-mode is evaluated in every event per time-sample. Detailed studies of the common-mode correlation between different chips showed that it can be estimated per module. This has the advantage, that in high energy pion showers most of the cells of a single chip can contain signal, while this is not the case for the full module. So the median of the ADC counts over all cells in a signal module is taken as the common-mode for that module. After subtracting the common-mode, the noise is re-evaluated and the intrinsic noise of the cell, $\sigma_{\text{intrinsic}}$, is obtained. The intrinsic high-gain noise of around 5.5 ADC counts is substantially lower compared to the total noise, which is around 7-9 ADC counts. The intrinsic noise for different baseplate materials shows negligible run-by-run variations as seen in figure 2 (left). Also, the pedestal values are observed to be stable during the full run period. Comparing

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the different thickness of the sensors for modules with the new hexaboard design, we can see in figure 2 (right) that the noise is slightly lower for the thicker sensor, as expected. The high-gain noise labelled in the coloured axis is shown in figure 3 versus the temperature on vertical axis and the run number (data-taking period) in the horizontal axis. It shows no dependency over the marginal variations of temperature with time.

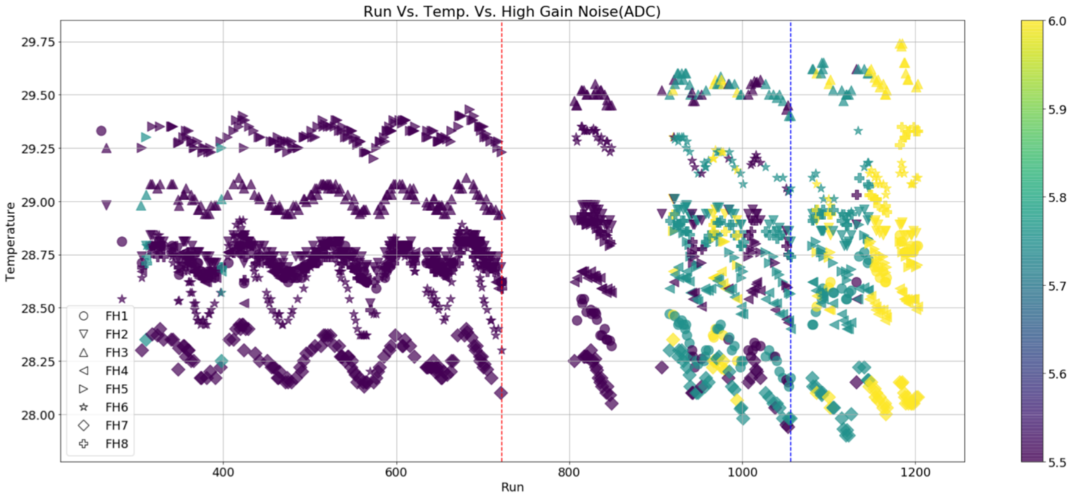

Figure 3. Noise stability distribution over temperature variation for the entire data-taking period.

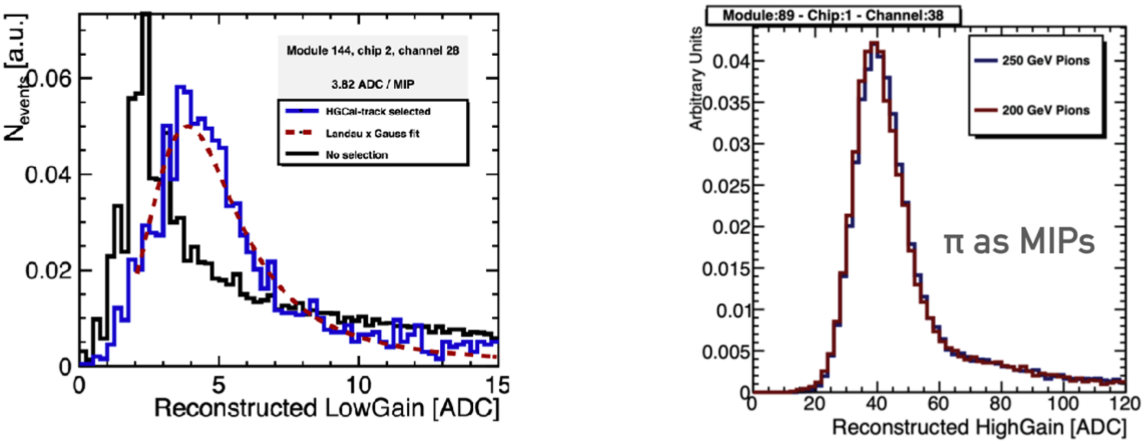

Figure 4. Energy deposition and MIP spectrum in low gain for tracks reconstructed in the calorimeter for an example module 144 having a sensor thickness of 200 μm (left). Energy deposition in high gain for cells of the electromagnetic section, using non-showering pions (right).

4 MIP calibration

The calibration of the calorimeter relies on the identification and selection of Minimum Ionising Particles (MIP). Muon beams are best used for this calibration. However, due to the limited spread

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of the muon beam, only a fraction of the cells could be calibrated with muons. For the other cells, the calibration made use of a so-called “parasitic” beam coming from another experiment located upstream. An example of such calibration, using the low gain ADC, is shown in figure 4 (left). Pion tracks can also be used before their interaction in the calorimeter. Figure 4 (right) shows the MIP reconstruction in the silicon electromagnetic prototype in high gain for non-showering pions. Modules equipped with 300 μm thick sensors reach a signal-to-noise (S/N) ratio of 7-8 in high gain and 4-5 in low gain. By comparison, a S/N of 5 and 3 is measured for 200 μm thick sensors in high and low gain respectively.

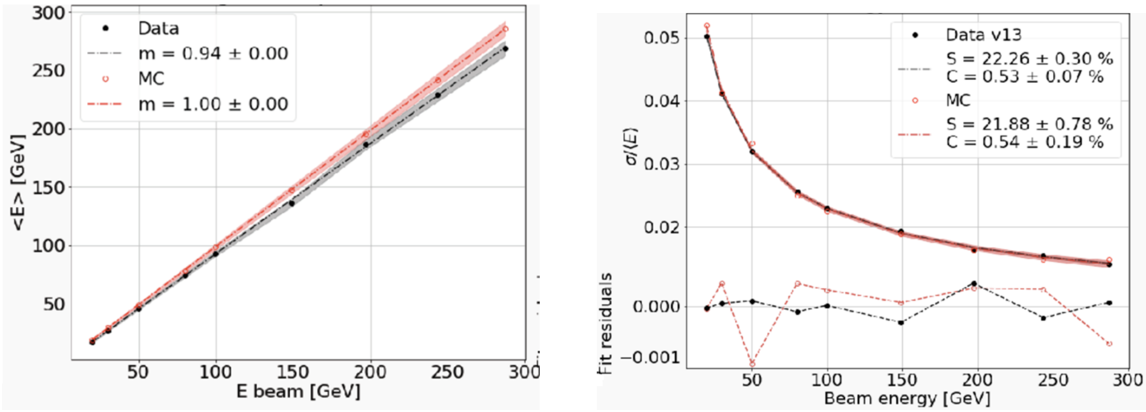

Figure 5. The energy reconstruction (left) and resolution (right) of the HGCAL prototype modules in response to electrons showing the comparison between data and simulation. The stochastic (S) and constant (C) terms have been specified.

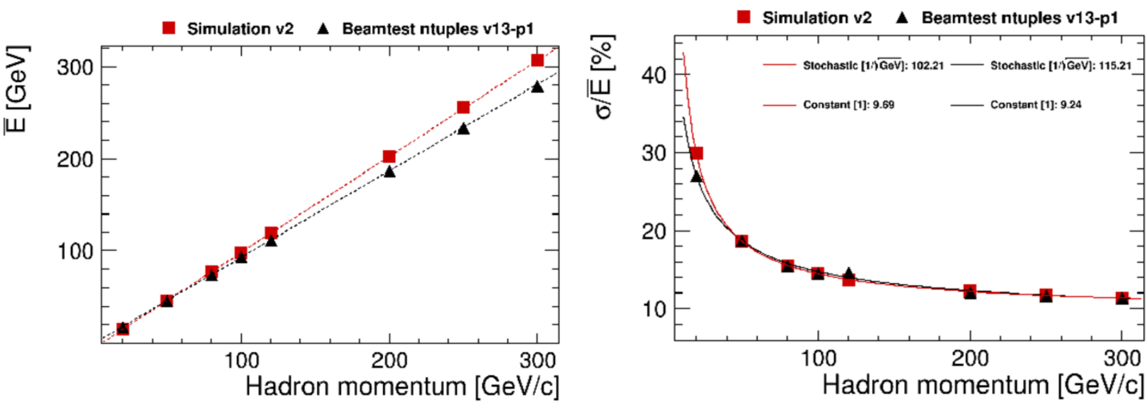

Figure 6. The energy reconstruction (left) and resolution (right) of the HGCAL prototype modules in response to pions showing the comparison between data and simulation. The stochastic and constant terms have been specified.

5 Electron and pion performance

Reconstructed hits were selected if their energy deposition exceeded a threshold of 0.5 MIPs. The energy deposited in each active layer was obtained by summing the number of MIPs measured by all the selected reconstructed hits, with the only exception being those in the non-hexagonal cells along the edge of the sensor, which exhibited larger noise occasionally and were excluded from the analysis. The setup tested at CERN had active layers of silicon interspersed with absorbers of different thickness. In these configurations, to estimate the total energy deposited in the detector, the energy deposited in the silicon layers is considered as a measurement of the energy loss (dominantly through ionisation) in the upstream absorber plate. To estimate the energy lost in the absorber layers, the reconstructed hits are therefore weighted by sampling factors reflecting the dE/dX for MIPs in the preceeding absorber plate. The HGCAL beam test simulation takes into consideration detector tuning, beamline properties and beam spot. The energy response and resolution for electrons and pions are shown in figure 5 and figure 6 respectively. The measured energy resolution as a function of energy is compared to simulation, showing a good initial understanding of the detector. The stochastic and constant terms are found to be in agreement with expectations.

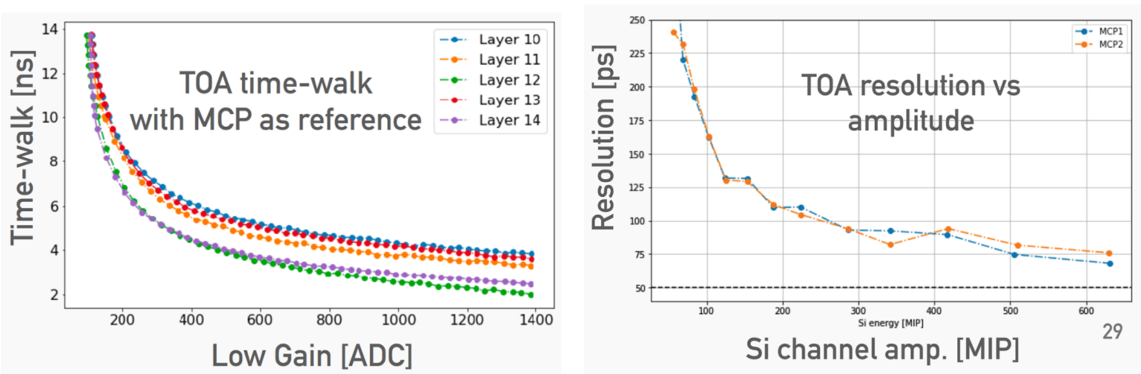

Figure 7. ToA time-walk with MCP as reference (left) and ToA resolution versus amplitude (right).

6 Timing performance

An important consideration for all detectors for the HL-LHC operation is their intrinsic evaluation of the timing of signals, due to the need to mitigate the effects of in-time event pileup. The HGCAL should be able to provide an estimation of the timing of electromagnetic and hadronic showers, with a precision of better than 50 ps. This information will be complementary to that provided by dedicated timing detectors sensitive to minimum ionising particles, planned to be placed in front of both the barrel and endcap calorimeters in CMS. The time of the MCP signal is extracted from an interpolation of the rising edge, at half of the maximum amplitude computed via constant fraction method. Timing performance is measured with ToA. The ToA calibration is done using data from asynchronous beam. Time-walk is derived with MCP time reference. At high charges, the ToA resolution is observed close to Skiroc2-CMS specification of 50 ps as shown in figure 7.

7 Summary

The CMS High Granularity Calorimeter is a very challenging detector for the high luminosity phase of the LHC. It is designed for harsh radiation environment, high pileup and occupancy rate.

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The detector has 5D (3D position + energy + time) measurement capability of showers which provides unique opportunities for particle identification and pileup mitigation. The HGCAL beam tests in October 2018 at CERN are the first large-scale tests performed by using of the order of 100 modules. The tests were performed using electronics providing the same functionalities as the final HGCROC readout ASIC, currently under design. Noise and pedestal values were stable over the 2-week data-taking period in the October 2018 CERN test beam. The variation of the energy calibration constants with MIP as well as the signal-over-noise ratio has been found consistent with the targeted HGCAL design values. Electron and pion performance has been studied in terms of energy resolution and linearity and found consistent with expectations. The timing performance has also been studied and excellent time resolution close to the design specification is observed.

References

[1] CMS collaboration, *The phase-2 upgrade of the CMS endcap calorimeter*, CERN-LHCC-2017-023, CERN, Geneva, Switzerland (2017) [CMS-TDR-019].

[2] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004.

[3] J. Borg et al., *SKIROC2_CMS an ASIC for testing CMS HGCAL*, 2017 *JINST* **12** C02019.

[4] CALICE collaboration, *Design and electronics commissioning of the physics prototype of a Si-W electromagnetic calorimeter for the International Linear Collider*, 2008 *JINST* **3** P08001 [arXiv:0805.4833].

[5] S. Callier, F. Dulucq, C. de La Taille, G. Martin-Chassard and N. Seguin-Moreau, *SKIROC2, front end chip designed to readout the Electromagnetic CALorimeter at the ILC*, 2011 *JINST* **6** C12040.

[6] *H2 beam line webpage*, http://sba.web.cern.ch/sba/BeamsAndAreas/h2/H2manual.html.