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Beam-tests of prototype modules for the CMS High Granularity Calorimeter at CERN

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Abstract

As part of its HL-LHC upgrade program, CMS 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 16 layers combining both silicon+scintillator detectors interspersed with metal absorber plates. Starting from 2016, prototype modules, based on 6-inch hexagonal silicon pad sensors with pad areas of 1.0 cm², have been constructed. In 2017 and 2018, beam tests of different sampling configurations made from these modules have been conducted at CERN's SPS using beams of charged hadrons and electrons with momenta from 20 to 350 GeV/c. The setup was complemented with CALICE's AHCAL prototype, a scintillator-based sampling calorimeter, mimicking the proposed design of the HGCAL's scintillator part. Most importantly, the new Skiroc2-CMS readout ASIC has been used in the silicon modules, facilitating the study of its timing capabilities in practice. This talk summarises the test beam efforts in 2017 and 2018. In particular, the setups and the encountered challenges are discussed. Preliminary results, including gain characterisation, calibration with minimum ionising particles and energy reconstruction performance of electron- and hadron-induced showers are shown. Finally, a first impression on the timing capabilities is given.

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Beam-tests of prototype modules for the CMS High Granularity Calorimeter at CERN

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ABSTRACT: As part of its HL-LHC upgrade program, CMS 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 16 layers combining both silicon+scintillator detectors interspersed with metal absorber plates. Starting from 2016, prototype modules, based on 6-inch hexagonal silicon pad sensors with pad areas of 1.0 cm^2 , have been constructed. In 2017 and 2018, beam tests of different sampling configurations made from these modules have been conducted at CERN's SPS using beams of charged hadrons and electrons with momenta from 20 to 350 GeV/c. The setup was complemented with CALICE's AHCAL prototype, a scintillator-based sampling calorimeter, mimicking the proposed design of the HGCAL's scintillator part. Most importantly, the new Skiroc2-CMS readout ASIC has been used in the silicon modules, facilitating the study of its timing capabilities in practice. This talk summarises the test beam efforts in 2017 and 2018. Preliminary results, including gain characterisation, calibration with minimum ionising particles and energy reconstruction performance of electron induced showers are shown.

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1 Introduction

The High Luminosity phase of the HL-LHC, expected to start in 2026, will integrate 10 times more luminosity than the LHC. This increase of luminosity is a challenge for detector radiation tolerance and for the mitigation of the extreme pileup where up to 200 collisions per bunch crossing are expected. To sustain the radiation level and to keep the good performances of its detector, the CMS collaboration [1] has decided to replace its calorimeter endcaps. The key parameters for this new calorimeter are its capability to keep good performance after the expected HL-LHC luminosity (3000 fb^{-1}), a good timing resolution for the pileup mitigation and a tracking capability for the application of particle flow techniques. Among several options, the CMS collaboration chose the High Granularity Calorimeter [2].

The High Granularity Calorimeter Endcap (CE) consists of a sampling calorimeter with silicon and plastic scintillators in its active parts. Figure 1 shows a schematic view of the CE. The electromagnetic calorimeter (CE-E) will use lead, copper and copper-tungsten as absorber and hexagonal silicon sensors as active material. Silicon sensors will also be used in the highest radiation region of the hadronic calorimeter (CE-H). For the lower radiation region of the CE-H, plastic scintillator tiles readout by on-tile 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°C . This calorimeter design allows a high transverse and longitudinal readout and trigger granularity needed for the particle flow algorithms.

While the design of the CE is still being optimised, several beam tests have taken place in beams at CERN, Fermilab and DESY. The goals for these tests were to validate the basic design of the CE, to study calorimetric performance of a silicon-based calorimeter and to compare the GEANT4 simulation of such a calorimeter with experimental data. The first hexagonal modules were tested in beams at CERN and Fermilab in 2016, with up to 16 silicon modules. These modules were

Figure 1. Schematic view and its key parameters, of the design of the CMS high granularity Endcap Calorimeter (CE).

equipped with the Skiroc2 ASIC [3]. The results from these tests have been summarised in [4]. In addition, the timing performance of a set of non-irradiated and irradiated silicon diodes have been evaluated during a beam test in spring 2016. These results are also reported in the same paper [4]. At the end of 2016, it was decided to build a large-scale prototype with about 100 silicon modules equipped with the new Skiroc2-CMS ASIC [5]. This ASIC contains the Time Over Threshold (ToT) and the Time Of Arrival (ToA) measurements, which will be important features of the final ASIC of the CMS CE. The construction of this new prototype started in 2017, and was achieved in fall 2018. Smaller versions of the prototype were regularly tested with beams of electrons, pions and muons at CERN and DESY. Section 2 describes this new prototype and its construction. Section 3 presents preliminary results from the combined beam test with the CALICE AHCAL prototype in October 2018.

2 CMS-HGCal prototype

2.1 Silicon module description

The silicon modules are made of a glued stack of hexagonal base plate, a KaptonTM foil with a gold layer for applying the bias voltage to the back side of a hexagonal 6-inch silicon n-type sensor and a printed circuit board (PCB) holding 4 front-end Skiroc2-CMS ASICs and a MAX10 FPGA. Figure 2 shows a picture of a copper base plate and another base plate with its KaptonTM foil, a hexagonal silicon sensor and an assembled module attached to its copper cooling plate (see section 2.3). In the electromagnetic calorimeter part, the base plates are made of copper-tungsten (25%/75%) while copper is used in the hadronic part. The silicon sensors are manufactured by HPK¹ and most of

¹Hamamatsu Photonics, Hamamatsu, Japan

Figure 2. Top left: Two hexagonal copper base plates. A Kapton™ foil with a gold layer is glued on the bottom base plate. Top right: 6-inch hexagonal silicon sensor. Bottom: An assembled module on its copper plate.

them have a depletion thickness of $300\ \mu\text{m}$ (4 sensors have a depletion thickness of $200\ \mu\text{m}$). These sensors have 134 individual hexagonal silicon pads with an area of $1.1\ \text{cm}^2$ for the full cells. Among these cells, two are called "calibration pads" with about 1/9th of the area of a full cell. These two pads are aimed to keep good signal over noise ratio for MIP, after irradiation from the HL-LHC.

2.2 Front-end ASIC

The front-end ASIC is the Skiroc2-CMS chip. This chip is derived from the Skiroc2 ASIC [3] which was developed for the CALICE ECAL [6]. The Skiroc2-CMS ASIC provides 64 channels (32 are actually connected to a silicon pad) with a low noise pre-amplifier followed by high and low gain slow shapers. The signals from the shapers are sampled with a 13-deep 40 MHz memory and 12 bit ADCs. To measure large signals, a Time Over Threshold (ToT) measurement is also used after the pre-amplifier. Combining the two gains and the ToT, gives a large dynamic range going from the MIP (1-3 fC) up to 10 pC. The Time Of Arrival (ToA) measurement is obtained after a fast shaper, a discriminator and a TDC with 25 ps time bin. With the ToA, a time resolution of 50 ps is foreseen for large signals. More details about the Skiroc2-CMS ASIC can be found in [5].

2.3 Prototype construction

Figure 3. Left: Example of a cassette of the electromagnetic calorimeter. Right: Example of a layer of the silicon CE-H prototype with 7 silicon modules.

The CE-E part of the prototype is made of 14 cassettes as shown in Figure 3. These cassettes consist of a 4 mm thick lead plate, and a 6 mm thick copper cooling plate holding 2 silicon modules on its 2 faces. The cassettes are closed with an aluminium frame and a mylar foil. The cooling plate contains a groove where copper cooling pipes are inserted. During beam test operations, water at 28 °C is circulating in these pipes. The goal is to keep constant temperature because the ToT and ToA vary with temperature. The total depth of the CE-E section is about $24 X_0$ ($\approx 1\lambda_I$).

The 12 layers in the silicon hadronic section comprise a 6 mm copper cooling plate on which up to 7 silicon modules are attached as shown in Figure 3. A copper cooling pipe is attached on the back side of the plate. These layers are separated with 4 cm thick steel absorber plates. The total depth of the hadronic section is $3.5 \lambda_I$. In total the CE prototype contains 94 silicon modules (3 hadronic layers contain only one module) for about 12000 silicon pads. Figure 4 shows the full set-up of the combined beam test of October 2018 at the H2 beam line of the CERN SPS. On the upstream part (left of the picture), one can see a scintillator used for the trigger. It is followed by two micro channel plate detectors, which were used as time references. Then the silicon electromagnetic calorimeter prototype was followed by the silicon hadronic calorimeter prototype. In the back, there is the CALICE Analog Hadronic Calorimeter (AHCAL) prototype. This prototype is made of 39 active layers using scintillator tiles (tile size : $3 \times 3 \text{ cm}^2$) readout by silicon photo multiplier (SiPM). These layers are separated by 1.75 cm thick steel absorber plates. The total depth of the CALICE AHCAL prototype is $4\lambda_I$. The full set-up has been described and simulated using the GEANT4 framework.

Figure 4. Full set-up with the CE-E, the silicon CE-H and the CALICE AHCAL prototypes. The beam enters from the left and first crosses the CE-E prototype.

3 Preliminary results

During the 2 weeks of the beam tests in October 2018, the set-up was exposed to beams of electrons, muons and pions. This paper presents preliminary results from the electron and muon runs.

3.1 Analysis procedure and calibration

As explained in Section 2.2, the Skiroc2-CMS ASIC contains 2 gains with a 13-deep 40 MHz analog memory and the ToT for each channel to measure the energy deposited by incoming particles. This requests a procedure to reconstruct the signal for the 2 gains and the ToT, signal equalisation among the different channels and gain inter-calibration. Following pedestal and common-mode noise subtraction, the signal is reconstructed by fitting these samples with the following function:

$$S(t) = E_{\max} \frac{1 - \frac{t - (t_{\max} - t_{\text{rise}})}{\tau}}{n_{\text{ord}} + 1} \left(\frac{t - (t_{\max} - t_{\text{rise}})}{\tau} \right)^{n_{\text{ord}}} e^{-\alpha \frac{t - (t_{\max} - t_{\text{rise}})}{\tau}} \quad (3.1)$$

where $t_{\max}$ corresponds at the time of the maximum of the amplitude and $E_{\max}$ the signal amplitude. The other parameters t_{rise} , n_{ord} , τ and α are constrained by lab data. Figure 5 shows one example of this shape reconstruction for the two gains.

The system is calibrated using muons. The high-gain signal amplitudes are used to fill histograms as shown in Figure 6. These histograms are fitted with a sum of convolutions of a Landau (signal) and a Gaussian (noise) functions. The peak of the first Landau defines the conversion factors from ADC counts to MIP equivalent. The second bump (around 80 ADC counts) is the 2-MIP peak. When the statistics are high enough (basically channels from CE-E and from the central modules of silicon hadronic section due to the trigger acceptance), one conversion

Figure 5. Example of sampled signal for both high gain (left) and low gain (right) for a 80 GeV electron induced shower. The reconstructed signal corresponds to about 15 MIP equivalent.

Figure 6. Example of a single particle signal amplitude spectrum for one channel of the silicon CE-H prototype.

factor is extracted per channel. For the other channels, the conversion factor is defined as the average factor from the channels of the same ASIC. The signal over noise ratio of single particle was found to be between 6 and 7 for most of the calibrated channels and between 8 and 10 for the calibration pads.

The gain inter-calibration for the CE-E modules is performed using data from high energy electromagnetic showers to ensure that most of the dynamic range is explored. The left plot of Figure 7 shows the high gain signal amplitude as a function of the low gain signal amplitude for one channel. A linear fit is performed up to the high gain saturation (≈ 2000 ADC counts on the vertical axis) and the slope gives the conversion factor between the low and the high gain. The

Figure 7. Left: High gain signal amplitude as a function of the low gain amplitude for one channel of the CE-E. Right: Low gain signal amplitude as a function of the ToT.

average slope was found to be around 8.2 while it was found to be around 10 for bare Skiroc2-CMS chip. The right plot of Figure 7 shows the low gain amplitude as a function of the ToT. As described in [5], the ToT starts after a given threshold and is not immediately linear. The short overlap region where both low gain and the ToT are linear is found using a spline interpolation and fitted with a straight line. The slope and offset are used to calibrate the ToT in term of low gain amplitude. The possibility of performing charge injection in these silicon modules will help to improve the calibration of the ToT in the future.

3.2 Electromagnetic shower energy resolution

The energy of each cell, in unit of MIP equivalent, is determined using the most adequate gain (high gain, low gain or ToT) and the conversion factors introduced in Section 3.1. The energy of electromagnetic showers is reconstructed with a linear sum of the cells energy from the CE-E prototype. Only cells with energy above a threshold of 0.5 MIP equivalent are used. The same method is applied for the simulation. Figure 8 shows an event display of a 300 GeV electromagnetic shower in the CE prototype.

Figure 8. Event display of a 300 GeV electromagnetic shower in the CE prototype. The colour of the cells scales with their energy.

At the H2 beam line of the SPS at CERN, the particle momentum is chosen thanks to bending

magnets. Therefore, the electrons suffer from synchrotron radiation and lose a fraction of their energy. The beam energy has been corrected to take this effect into account for the data. The particle incident energy will be corrected in future simulation production samples. Figure 9 shows

Figure 9. Left: Reconstructed energy as a function of the beam energy. Right: Relative energy resolution as a function of the beam energy.

the total energy and the energy resolution as a function of the beam energy for both data and the simulation. Both data and simulation show a good linearity although the simulation overestimates the deposited energy by about 10%. The beam test data have slightly worse energy resolution than the simulation but these very preliminary results are already satisfactory and will be improved in the future with better calibrations and reconstruction techniques.

4 Conclusion

A new high granularity calorimeter prototype has been built between 2017 and 2018 and regularly tested with beams of particles at CERN and DESY. It has been operated successfully together with the CALICE AHCAL prototype. The new prototype presents good performance in terms of MIP signal over noise ratio. Preliminary results for electromagnetic showers are encouraging and will be improved with better calibrations. Combined data analysis with the CALICE AHCAL prototype is being performed to study the hadronic shower performance of such a calorimeter.

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