



The Compact Muon Solenoid Experiment
Conference Report

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



19 February 2018 (v3, 15 March 2018)

Construction and beam-tests of silicon-tungsten and scintillator-SiPM modules for the CMS High Granularity Calorimeter for HL-LHC

Yung-Wei Chang for the CMS Collaboration

Abstract

A High Granularity Calorimeter (HGCAL) is being designed to replace the existing endcap calorimeters in CMS for the HL-LHC era. It features unprecedented transverse and longitudinal segmentation for both electromagnetic (ECAL) and hadronic (HCAL) compartments, with silicon sensors being chosen for the high-pseudorapidity regions due to their radiation tolerance. The remainder of the HGCAL, in the lower radiation environment, will use plastic scintillator with on-tile SiPM readout. Prototype hexagonal silicon modules, featuring a new Skiroc2-CMS front-end chip, together with a modified version of the scintillator-SiPM CALICE AHCAL, have been built and tested in beams at CERN in 2017. In this poster, we present measurements of noise, calibration, shower shapes and performance with electrons, pions and muons.

Presented at *HSTD11 11th International Hiroshima Symposium on the Development and Application of Semiconductor Tracking Detectors*

Construction and beam-tests of silicon and scintillator-SiPM modules for the CMS High Granularity Calorimeter for HL-LHC[☆]

Yung-Wei Chang^{a,1}, on behalf of the CMS collaboration

^aNational Central University, Department of Physics, Chungli, Taiwan

Abstract

A High Granularity Calorimeter (HGCAL) is being designed to replace the existing endcap calorimeters in CMS for the HL-LHC [1] era. It features unprecedented transverse and longitudinal segmentation for both electromagnetic (CE-E) and hadronic (CE-H) compartments, with silicon sensors being chosen for the high-pseudorapidity regions due to their radiation tolerance. The remainder of the HGCAL, in the lower radiation environment, will use plastic scintillator with on-tile SiPM readout. Prototype hexagonal silicon modules, featuring a new Skiroc2-CMS front-end chip, together with a modified version of the scintillator-SiPM CALICE AHCAL, have been built and tested in beams at CERN in 2017. In this paper, we present measurements of noise, calibration, shower shapes and performance with electrons, pions and muons.

Keywords: CMS HGCal

1. The CMS HGCal upgrade for HL-LHC

The instantaneous luminosity of the LHC will be increased to $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for the high-luminosity (HL-LHC) phase, after about 2026. It is expected to result in a radiation and pileup environment that cannot be sustained by the present endcap calorimeters of CMS. Indeed the existing CMS calorimeters were designed for an integrated luminosity of 500 fb^{-1} , a factor 6 lower than expected at the end of HL-LHC. The endcap calorimeters, comprising the preshower (ES), endcap electromagnetic calorimeter (EE), and endcap hadronic calorimeter (HE) must be replaced during long shutdown 3 of the LHC, a two-year period starting in 2024. The CMS collaboration [2] is designing a High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeters. The HGCAL will feature unprecedented spatial resolution for both electromagnetic and hadronic compartments. Figure 1 illustrates the longitudinal cross section of the upper half of HGCal. The fluence simulation using the *FLUKA* program [3] in HL-LHC conditions is shown in Figure 2. It can be seen that the fluence changes rapidly with position, leading to the possibility of different sensor technologies in different regions.

The electromagnetic compartment of HGCAL (known as CE-E) will comprise 28 sampling layers of hexagonal silicon sensors interspersed with Cu, CuW (Cu: 25%/W: 75%) and Pb absorbers, leading to an approximate depth of about $26X_0$ (about $1.7\lambda_0$). This is followed by the hadronic section (CE-H) with 24 samplings incorporating both silicon modules and scintillator+SiPM modules, using stainless steel as the absorber, resulting in an interaction length of about $9\lambda_0$. All active layers of HGCal are readout for energy reconstruction, with alternate layers also providing trigger information. Silicon modules are used for all of CE-E and the high-radiation regions of CE-H; scintillating tiles with on-tile SiPM readout is used in the low-radiation regions of CE-H. The full system has to be maintained at around $-30 \text{ }^\circ\text{C}$, cooled by a dual-phase CO_2 system in order to keep electronics noise and leakage currents sufficiently low to survive the full expected fluence and dose and still operate efficiently. The HGCAL has a total area of approximately 600 m^2 of silicon sensors (about 27000 Si modules) and 500 m^2 of scintillator tiles (about 4000 tileboards). It will comprise about 6 million silicon channels and 0.4 million SiPM channels. The silicon sensors will be divided into hexagonal pads with active area of 0.5 or 1.2 cm^2 (smaller cells at higher pseudorapidity).

More details about active elements are presented in

[☆]This document is a collaborative effort.

Email address: willychang20@gmail.com (Yung-Wei Chang)

Section 2. The HGCAL Technical Design Report [5] was published at the end of 2017 and contains detailed information about the project realization in the past two years and for the future. This paper summarizes some of the latest results of several beam tests at CERN, to verify the design concept.

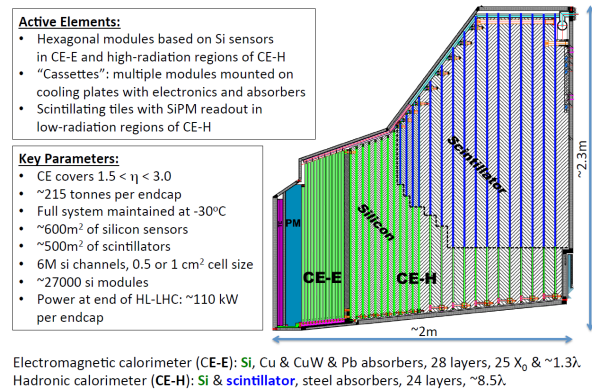


Figure 1: Active elements and key parameters of HG-CAL are shown. Longitudinal structure of the upper half endcap in the pseudorapidity region $1.5 < |\eta| < 3.0$, green region to the lower left contains CE-E and CE-H silicon sensors; blue region to the upper right the scintillator+SiPM modules.

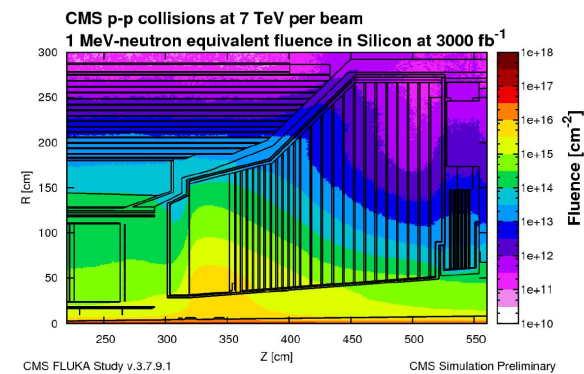


Figure 2: Fluence simulation in the CMS endcap along coordinates R and Z ; the fluence of 1 MeV equivalent neutrons in HGCAL is shown after an integrated luminosity of 3000 fb^{-1} .

2. Testbeam module construction

2.1. Silicon modules

Each silicon module comprises a 6” n-type silicon hexagonal wafer from Hamamatsu [7]. They are subdivided into 128 cells, mostly hexagonal with an area of 1.1 cm^2 each. The depletion thickness for 2017 sensors was $300 \mu\text{m}$ ($200 \mu\text{m}$ in 2016). The bias voltage was applied with positive on the sensor’s backside contact (n-bulk) and negative (ground) on the p-side. Signals are returned from the p-side to the corresponding front-end readout channel. The sensor is glued to a PCB “hexaboard”, including four front-end readout ASICs and one MAX10 FPGA for clock/trigger distribution and digitized data transfer off-detector. The 64-channel Skiroc2-CMS ASIC [6] is matched to the CMS specific needs with 40 ns shaping time, two gain stages as well as ToT (Time-over-Threshold) and ToA (Time-of-Arrival) information. Each channel has a 13-depth memory SCA (Switched Capacitor Array). For each readout chip, only 32 of the 64 channels were connected to the PCB and wire-bonded through a stepped hole to the sensor cells below. Wire-bonds for three sensor pads at a stepped hole to three Au bonding pads on the hexaboard are shown in Figure 3.

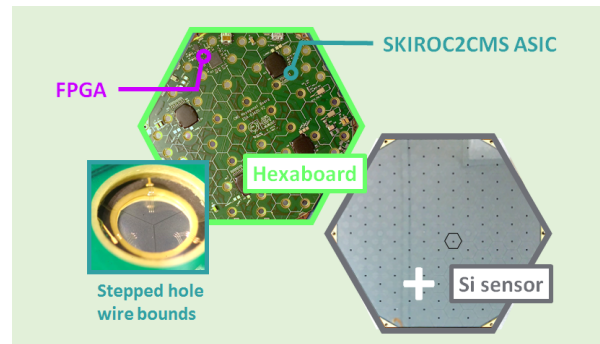


Figure 3: CMS HGCal silicon module assembly, used for the beam tests in 2017.

For the biasing of sensor’s backside plane, we used a thin ($105 \mu\text{m}$) polyimide foil coated with gold, glued to a metallic baseplate. The baseplate provides mechanical support and a conductive cooling path. The baseplate had a uniform thickness of $1.4 \pm 0.03 \text{ mm}$. Copper-tungsten is used for the baseplate material in the CE-E while pure copper is used in CE-H. In short, a full silicon module assembly starts from the CuW (Cu) baseplate, Kapton-Au sheet, then the sensor, then the Hexaboard on top. These four elements are glued together to form a single silicon module. Figure 3 also illustrates the 6” silicon module for HGCal beam tests.

2.2. Scintillator tile-modules

As mentioned, plastic scintillator tiles and on-tile SiPM photodetection will be used in the low-radiation regions of CE-H. In 2017 we used the CALICE AHCAL prototype [8]: 12 layers of steel absorber interspersed with layers of scintillator tiles. Each $3\text{ cm} \times 3\text{ cm} \times 3\text{ mm}$ tile sandwiches the SiPM SMD on the backside of a large “tile-board” PCB, shown in Figure 4. The board includes 4 SPIROC2B ASICs on the front side and 144 scintillator tiles on the backside. The square geometry was made for CALICE; for the CE-H the tiles will be arranged in an approximate $R - \phi$ grid. Different designs and techniques are still under consideration. For further information about the scintillator-tile modules, please refer to the active elements section of the HGCAL TDR [5].

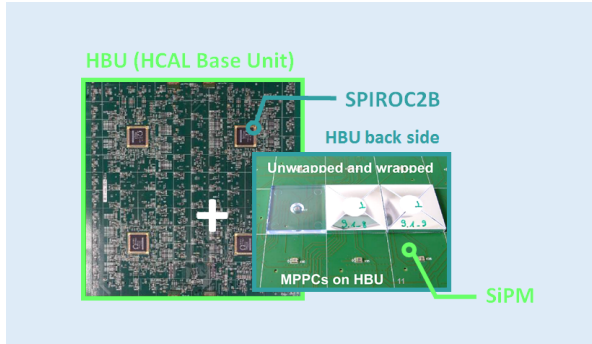


Figure 4: CALICE AHCAL scintillator SiPM-module assembly, used for the beam tests in 2017.

3. Test beam setup with CALICE AHCAL at CERN

At the beginning of 2017 we aimed at building a large-scale system, comprising 28 layers with a single silicon module (each layer) in the CE-E region, 12 layers of 7 silicon modules as a honeycomb structure and 12 layers of CALICE AHCAL SiPM modules in the CE-H region. However, a bottleneck in hexagonally-shaped PCB production resulted in more modest configurations being possible, evolving through the year. The first configuration comprised just 2 modules in the CE-E part, and 4 layers of modules in the CE-H. The first two of these layers comprised one module each, with 3 modules in layers 3 and 4 of CE-H. Lead absorbers were used in the CE-E, and steel in the CE-H. The AHCAL was used in its entirety. The above experimental setup was used at CERN’s SPS H2 beam line in July 2017.

Figure 5 illustrates the full structure for beam tests of HGCAL prototype system at CERN.

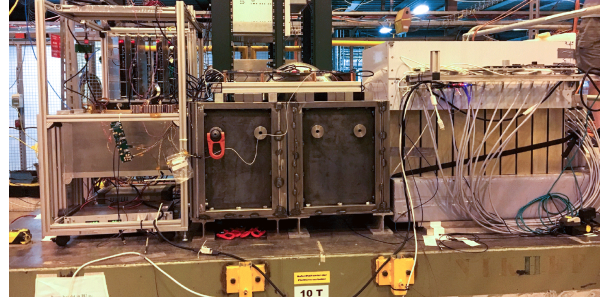


Figure 5: Testbeam setup, with CE-E (left), CE-H (centre), and CALICE AHCAL prototype (right) at CERN’s SPS H2 beam line. (from July to September)

Example HGCAL event displays with incident electrons and pions are shown in Figure 6.

At the end of September, another beam test of 2017 was performed. With more modules coming, the system featured 7 active layers in the CE-E section and 10 active layers in the CE-H section, each plane with one silicon module. The final beam test in October was performed at CERN’s H6 beam line, with up to 20 silicon modules. The CE-E section featured 5 active layers of single modules and 7 active layers (one with seven modules arranged in a honeycomb structure, another one with three modules) in the CE-H section. All setups included the CALICE AHCAL downstream of the silicon parts.

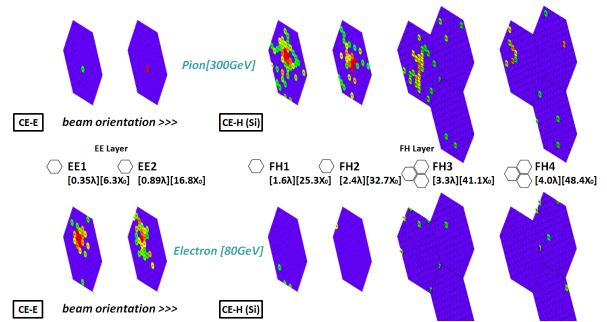


Figure 6: Event display, the silicon modules with 300 GeV pion beams (top) and 80 GeV electron beams (bottom) in July beam tests, 2017. The AHCAL is not shown in the same analysis framework.

4. The DAQ and analysis chain

The Skiroc2-CMS ASIC incorporates 12-bit analog to digital converters for digital readout. The output sig-

nal consists of three different gains and timing information, integrated through a MUX (multiplexer) in the on-board FPGA and transferred to the custom-designed readout board. In 2017, multiple modules were connected to readout boards, all controlled by a synchronization board (SYNC-board) with a common clock and trigger signal. This custom DAQ hardware was based largely around commercial components: FPGAs and Raspberry PI microcomputers. The IPbus protocol was used for data transfer. The EUDAQ [10] software framework integrated all hardware control, data taking and monitoring.

Data were reconstructed through a series of processes using a dedicated CMS HGCAL test beam analysis framework for preliminary analysis. The offline analyzer contains channel mapping information on each module, pedestal distributions, low/high gain ADC counts for each time sample, ToT information, and event display.

5. Results

The first results in 2017 mainly focused on noise analysis, MIP and gain calibration, shower profiles and reconstructed energy resolutions. After pedestal subtraction and common-mode noise subtraction (event by event), the test beam data were used to investigate the agreement with simulation using the CMS software (CMSSW) framework, based on GEANT4[11]. The FTFP_BERT_EMM physics list was used.

5.1. Pedestals and noise

A high level of common mode noise was present in the silicon modules, comparable to the intrinsic noise. This was evaluated on an event-by-event basis, for each channel, gain and SCA. After common-mode subtraction the pedestals were found to be very stable with time. The following results were all presented after common-mode and pedestal subtraction.

5.2. Calibrations

Single muons are effectively “minimum ionizing” particles (MIPs) and can be used for calibration purposes. Delay Wire Chambers (DWC) are used to provide information on the position of incidence of muons on the modules and reduce the impact of spurious triggers. Figure 7 shows a typical distribution (in units of ADC counts) of signals in a single silicon cell due to incident muons. Fitting this distribution with a Landau (for the signal) convoluted with a Gaussian (for the noise) provides a “most probable value” that is used to

define the calibration coefficient in units of ADC counts per MIP. This procedure is performed for all cells hit by muons, roughly a third of the total, due to the beam spread and the trigger area.

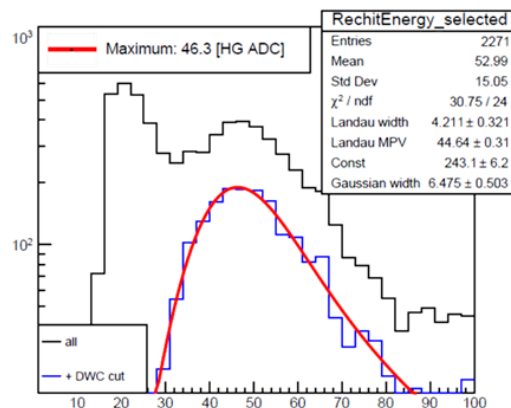


Figure 7: The MIP signal seen in a single silicon cell, before and after applying cuts using the DWCs.

Larger signals (from electrons or pions) are used to intercalibrate the preamplifier gains: High gain (HG) with a dynamic range of about 0-50 MIPs; Low gain (LG) with a range 0-150 MIPs). In Figure 8 we plot the HG ADC counts vs the LG ADC counts for the same event. Fitting the linear overlap region provides the LG-to-HG calibration factor, which is about a factor 9 and stable with energy for all the readout chips in all the modules.

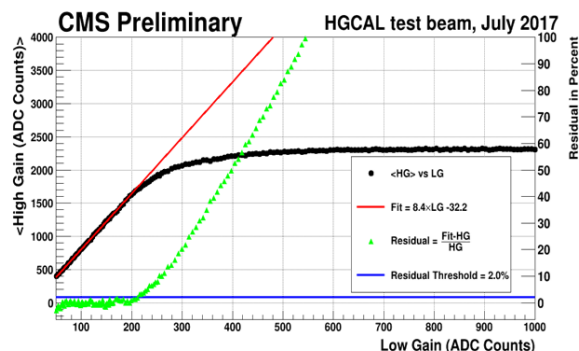


Figure 8: Low gain to high gain calibration: LG-HG calibration factor is about 9.

5.3. Shower profiles

Transverse and longitudinal shower profiles, both for electrons and pions, are good methods of evaluating the data-simulation correspondence. The longitudinal

shower depth barycentre for electrons is simply defined as:

$$t = (\sum_{i=1}^N X_{0_i} \cdot E_{layer_i}) / (\sum_{i=1}^N E_{layer_i}) \quad (1)$$

where N is the number of layers, X_{0_i} is the total radiation length up to sampling layer i and E_{layer_i} the total energy on layer i . Good agreement between data and simulation has been observed, as illustrated in Figure 9.

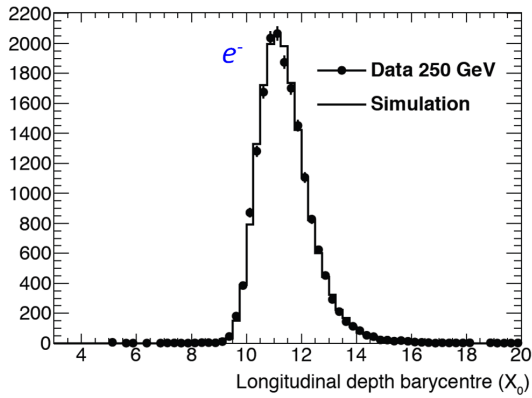


Figure 9: Longitudinal shower depth for 250 GeV electron beams at CERN: comparison between data and simulation.

The transverse shower spread was evaluated using ratios of energies in central cells and rings of their neighbours, which are defined as:

$$\begin{aligned} E1/E7 &= E_{Max} / (E_{Max} + Pri.ring); \\ E1/E19 &= E_{Max} / (E_{Max} + Pri. + Sec.ring); \\ E7/E19 &= (E1/E19) / (E1/E7) \end{aligned} \quad (2)$$

where E_{Max} , the most energetic cell, is surrounded by six cells, the *Pri.ring*. The secondary ring *Sec.ring* has twelve neighbouring cells surrounding the seven. The energy sums $E7$, and $E19$ are sums of energy in the maximum energy cell plus the primary ring, and the secondary ring respectively. Good agreement for electron and hadron beams can be seen in Figures 10 and 11.

6. Conclusion

CMS HGCAL prototypes, including CE-E part, CE-H (Si) part, and CALICE AHCAL (scintillator + SiPM), have been tested with electrons and pions at CERN in 2017. Preliminary analysis shows good MIP visibility and good agreement with Geant4 simulation for basic quantities after successful calibration. Analysis of

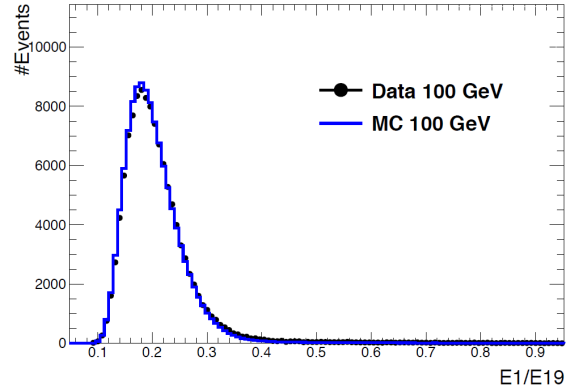


Figure 10: Transverse shower shapes. 100 GeV electrons at a depth of around $12 X_0$: comparison between data and simulation.

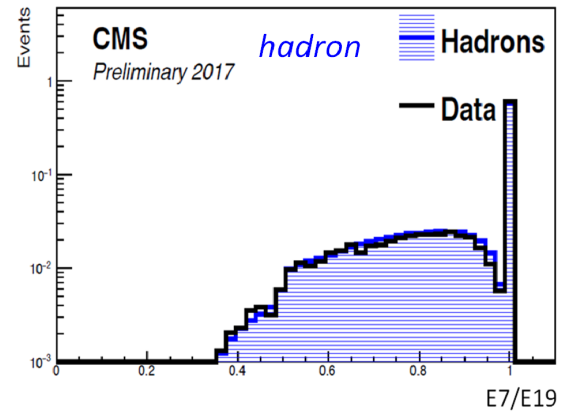


Figure 11: Transverse shower shapes. 200 GeV hadrons at a depth of $4.0 \lambda_0$ (20% pions and 80% protons).

higher-level quantities is ongoing, including energy reconstruction with the AHCAL data. Further tests are planned at FNAL, DESY, IHEP Beijing and CERN, with more modules and extensions, in 2018.

Reference

- [1] The CMS Collaboration, [High-Luminosity Large Hadron Collider](#), *Technical Design Report CERN-2015-005*. (December 2015)
- [2] The CMS Collaboration, [The CMS Experiment at the CERN LHC](#), *Journal of Instrumentation (Vol 3)*, page 1 - 3. DOI: 10.1088/1748-0221/3/08/S08004 (August 2008)
- [3] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, et al., [FLUKA: A multi-particle transport code](#), *CERN-2005-010*. (October 2005)

- [4] C. Graf for the CALICE Collaboration, [Performance of a Highly Granular Scintillator-SiPM Based Hadron Calorimeter Prototype in Strong Magnetic Fields](#). (November 2017)
- [5] The CMS collaboration, [CMS Endcap Calorimeter Technical Design Report](#), *Technical Design Report CERN-LHCC-2017-023*. (November 2017)
- [6] J. Borg, S. Callier, D. Coko, F. Dulucq, C. de La Taille, L. Raux, T. Sculac and D. Thienpont, [SKIROC2.CMS an ASIC for testing CMS HG-CAL](#), *Journal of Instrumentation*, Vol 12. (February 2017)
- [7] [Hamamatsu Photonics K.K \(HPK\)](#)
- [8] The CALICE collaboration, C Adloff, Y Karyotakis, J Repond, A Brandt, H Brown, K De, C Medina, J Smith, J Li, et al., [Construction and commissioning of the CALICE analog hadron calorimeter prototype](#), *Journal of Instrumentation*, Vol 5. page 25. DOI: 10.1088/1748-0221/5/05/P05004 (May 2010)
- [9] S. Callier, et al., [SKIROC2, front end chip designed to readout the Electromagnetic CALorimeter at the ILC](#), *Journal of Instrumentation (Vol 6)*. page 3. DOI: 10.1088/1748-0221/6/12/C12040 (December 2011)
- [10] E. Corring, [EUDAQ Software User Manual](#), *EUDET-Memo-2010-01*. (2010)
- [11] GEANT4 Collaboration, [GEANT4: A Simulation Toolkit](#), *Nuclear Instrumentation Methods. A506*. p 250-303. DOI: 10.1016/S0168-9002(03)01368-8. (August 2002)