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Moritz Wiehe for the CMS Collaboration

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The CMS High Granularity Calorimeter for the High Luminosity LHC

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Abstract

The CMS Collaboration is preparing to build replacement endcap calorimeters for the High Luminosity LHC (HL-LHC) era. The new high-granularity calorimeter (HGCAL) is, as the name implies, a highly granular sampling calorimeter with approximately six million silicon sensor channels ($\approx$ 1.1 cm^2 or 0.5 cm^2 cells) and about four hundred thousand scintillator tiles readout with on-tile silicon-photomultipliers. The calorimeter is designed to operate in the harsh radiation environment at the HL-LHC, where the average number of interactions per bunch crossing is expected to exceed 140. Besides measuring energy and position of the energy deposits the electronics is also designed to measure the time of their arrival with a precision on the order of 50 ps. In addition to the hardware of the HGCAL, developing a reconstruction sequence that fully exploits the granularity to achieve optimal electromagnetic and hadron identification, as well as a good energy resolution in the presence of pileup, is a challenging task.

1. Introduction

The LHC will be upgraded to the High Luminosity LHC (HL-LHC) [1, 2], which is planned to operate at a levelled peak luminosity of 5×10^{34} cm^{-2}s^{-1}. The mean number of events per bunch crossing (pile-up) will increase from the current value of around 40 to a value of 140 - 200. To cope with the higher event rates and the higher level of radiation, the CMS experiment [3] is undergoing an extensive upgrade program [4]. For example, the granularity of the outer tracker and the pixel system will be improved. In addition, for the first time, tracking information will be used for the level 1 trigger decision. A dedicated timing layer (MIP timing detector) with hermetic coverage will be inserted to measure minimum ionizing particles with a time resolution of up to 30 ps. The muon systems will be upgraded with new electronics and additional GEM and RPC chambers will be installed to maintain the Level 1 trigger acceptance. The calorimeter endcaps have to be replaced because the current detector could not withstand the high radiation expected during HL-LHC operation. The maximum fluence expected at the position of the endcaps is about 1.5×10^{16} $\mathrm{n_{eq}/cm^2}$ at the end of LHC operation. The highest radiation levels are expected closest to the interaction point. To maintain the good energy resolution and to make it possible to cope with the increased pile-up, the detector will feature higher granularity and measure the time of arrival of incident particles [5]. The combination of calorimeter timing information with the data from the MIP timing detector will be beneficial for the identification of the primary vertex. A strong motivation for constructing a highly granular calorimeter is not only the mitigation of pile-up but also the possibility to improve particle flow reconstruction. The general idea behind particle flow algorithms is that energy deposits are not clustered together within the electromagnetic and hadronic calorimeters separately but are associated to individual particles, also using information from the tracker. For example, the energy of charged hadrons is calculated as the weighted average of the tracker momentum and calorimeter energy measurement, and is therefore reconstructed with the best possible energy resolution. The use of particle flow results in a much improved energy resolution compared to traditional algorithms, especially for low p_t jets. The HGCAL [6] is a sampling calorimeter, covering a pseudorapidity range from 1.5 to 3 (fig. 1). In the region of high radiation levels and high track density, silicon sensors will be used as active material. The whole electro-magnetic section (CE-E) will be built from silicon sensors. In the hadronic compartment (CE-H), at larger radii, scintillator tiles read out by silicon-photomultipliers will be used. The detectors will be mounted on disks which will be separated by absorber material, copper and lead in the electromagnetic section and steel in the hadronic section. The two HGCAL endcaps will be built of 620 m^2 of silicon and 400 m^2 of scintillator material, featuring more than 6 million read-out channels. To cope with the increased sensor leakage current after irradiation, the entire HGCAL will be operated at a temperature of -30° C, which will be achieved by CO_2-cooling.

2. Silicon sensors

Silicon sensors will be used in the region where radiation and occupancy levels are high, this means in the full electromagnetic and in the inner hadronic compartment ($|\eta| > 2.4$) [7, 8]. The silicon sensors of the HGCAL will be exposed to a total radiation fluence ranging from 2×10^{14} $\mathrm{n_{eq}/cm^2}$ to 1×10^{16} $\mathrm{n_{eq}/cm^2}$. The sensors are produced in a hexagonal shape on 8" wafers, which maximizes the sensor area per wafer and facilitates tiling the sensors for full coverage. The sensors are planar, p-type sensors produced by Hamamatsu,

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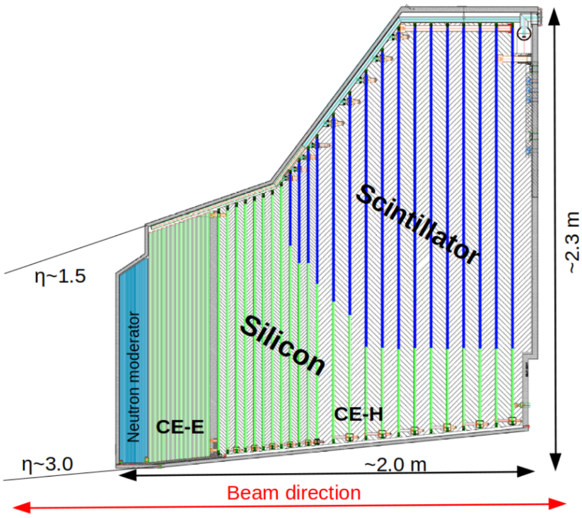

Figure 1: Layout of the HGCAL. Shown is the upper half of one endcap. The interaction point is located to the left.

which are DC-coupled to the read-out. Depending on their respective location in the detector the layout and thickness of the sensors change. Within a radius around the beam axis of approximately 70 cm, thin sensors with an active thickness of 120 μm will be used on all-silicon disks. Those sensors feature a high density layout with over 400 individual cells with a size of 0.5 cm^2 each. Further away from the beam ($r > 70$ cm), the sensor active thickness increases to 200 and 300 μm and the number of individual cells is about 200. 200 and 300 μm sensors are produced from physically thinned FZ material, while 120 μm sensors are epitaxial with a thick handle wafer. Sensor development and testing is well advanced and most design parameters are final. Irradiation tests of 8" sensors are carried out at the Rhode Island Nuclear Science Center (RINSC) irradiation facility. The quality of the sensor production is assessed with dedicated process quality control structures located on the periphery of the wafer. Custom probe- and switch-cards were developed for full sensor tests, with which it is possible to test individual cells while biasing the full sensor. During sensor production every sensor will be tested by the manufacturer and a fraction of those is tested again by the CMS groups. Sensor tests after irradiation are shown in fig. 2.

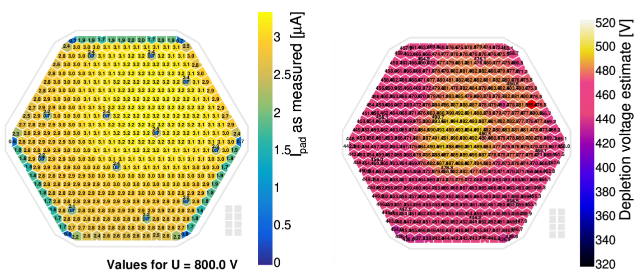

Figure 2: Pad current at 800 V (left) and depletion voltage, obtained from a CV-measurement (right). Some inhomogeneities of the leakage current and the depletion voltage are a result of inhomogeneous irradiation.

The leakage current and depletion voltage of sensor cells of a 120 μm sensor which has been irradiated to a total fluence of 1×10^{16} n_{eq}/cm^2 was measured for each cell individually. Some variation in the values obtained can be observed, which are mostly attributed to inhomogeneities in the delivered fluence during irradiation. The pad leakage current is in the order of 3 μA at 800 V and the depletion voltage varies between 420 and 500 V. With full-sensor tests and studies on mini-sensors it was possible to identify the best production process and to prove that these sensors can withstand the expected radiation levels. Electrical tests, as well as charge collection studies on different sensor types (fig. 3) show good performance and are in-line with the expectations stated in the technical design report [6]. Pre-series sensors of the latest prototype version will arrive in spring 2022. Pre-production is planned to start later this year.

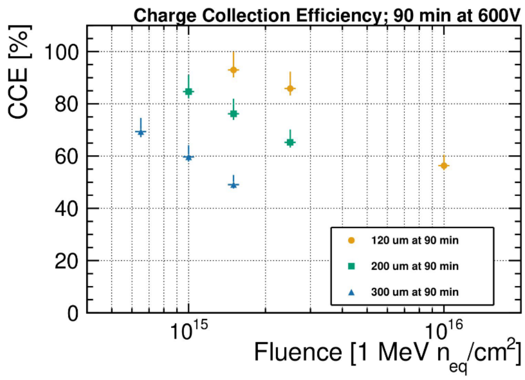

Figure 3: Charge collection efficiency measured at 600 V as a function of irradiation fluence. The sensors (test diodes) were annealed for 90 minutes at 60° C. IR-laser light was used for charge injection.

3. Silicon modules

To build a finished silicon module, sensor PCBs, the so-called hexaboards, are glued directly onto the silicon sensor. On the PCB the read-out chips are placed with the input channels wire-bonded to the sensor cells via holes in the PCB. Bias voltage is supplied to the sensor on the sensor backside. These components are mounted on a copper-tungsten or PCB baseplate, depending on the location of the module. About 27,000 of such modules will have to be produced. In the electro-magnetic section, the finished modules will be mounted on both sides of a copper cooling-plate. These double-sided layers are then sandwiched between lead absorbers. In the hadronic compartment only a single layer of silicon per disk will be used, mounted between steel absorbers. Two versions of the hexaboard will be used, one for the high density region, featuring six read-out chips, and a low density version with three chips. Besides the read-out chips, the hexaboards feature LDOs for power supply and connectors to the motherboard. The modules are mounted on cassettes for mechanical integration. The various modules on a cassette are connected via so called wagon boards, which are connected to engine boards. The wagon boards are purely passive and come in different shapes, depending on their location. They transmit power to the modules and data from the modules to the active engine boards which feature optical links to transmit the data to the off-detector electronics.

4. Scintillator and SiPM modules

With the requirement of a minimum signal-to-noise ratio ratio for MIPs of about 3 at the end of HL-LHC operation, scintillating tiles can be used in a region where the radiation level is comparably low (< 3 kGy and 8×10^{13} n_{eq}/cm^2). Individual scintillator tiles are wrapped in reflective foil and mounted on top of a silicon photomultiplier (SiPM) on a PCB to produce a so called tilemodule. The scintillator compartment features a radial design. The motherboards which are connected to the tileboards are located on the outside of the respective disk. The size of the scintillator tiles decreases with decreasing radial distance to the beam axis (32 cm^2 to 4 cm^2). This is beneficial to keep the occupancy at a manageable level and smaller tiles also increase the signal amplitude. The performance of individual components and full systems is continuously monitored [9]. Latest measurements were carried out at beam tests at Fermilab and DESY in 2020 and 2021 using different tileboards. An image of a tilemodule, partly equipped with wrapped scintillator tiles is shown in fig. 4 (left). As an example, the plot on the right shows the light yield of different tile geometries, obtained during test-beam measurements. These tests give a good performance estimate under realistic conditions as all components, including the read-out, are in a close-to-final state and since these modules were produced using automated tile-production and assembly procedures.

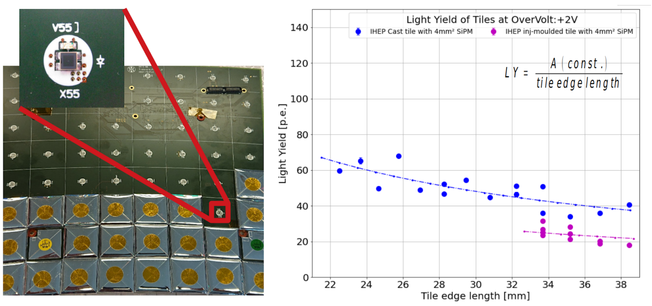

Figure 4: Left: Image of a partly equipped tileboard: Wrapped scintillator tiles are mounted on top of silicon-photomultipliers. Right: Light yield as a function of scintillator tile size, measured with beam-electrons.

5. Electronics

The HGCROC read-out chip [10, 11] was specifically developed for the HGCAL. Our application requires a high dynamic range, as it is necessary to be sensitive to single minimum ionizing particles and as well to high energy deposits (TeV-scale). Therefore the HGCROC features a dynamic range from 0.2 fC to 10 pC. This is achieved by combining a 10-bit ADC for the low energy range and a measurement of the time over threshold with a 12-bit TDC for charge deposits above approximately 50 fC. In addition the time-of-arrival is measured with a 10-bit TDC for any charge deposits above 12 fC, with a resolution ranging from 20 to 150 ps for a single cell. The data is stored at 40 MHz in a circular buffer, waiting for a trigger accept. At the same time, energy sums of neighboring cells are build and send to the trigger read-out. From the energy sums the HGCAL trigger logic builds three dimensional energy clusters, which are passed on to the global CMS Level-1 trigger. On a Level-1 trigger accept, the full data is send out to the back-end electronics. Data transmission from the HGCROC is realized via the ECON-D (data) and ECON-T (trigger) chips. In addition to the data processing, the chip has to satisfy stringent requirements on noise, power consumption (< 20 mW per channel) and radiation hardness. With slight modifications, the same chip is used for the silicon and scintillator read-out. The final version (V3) of the read-out chip is being tested. Good progress is also being made in terms of full-system tests of both the silicon and the scintillator read-out. Prototypes or emulators of all components were produced and tests of the full read-out chain from the respective sensor to the data-transmission to the back-end are on-going. On the scintillator side a version 3 system assembly is planned for this year. It is planned to test fully equipped version-3 silicon modules in the next months.

6. Beam tests

During the development phase, beam tests were carried out to validate the functionality of the components and also the general principle of using an imaging calorimeter [12, 13]. For an early setup for a test-beam in 2018 early 6" prototype silicon modules together with a scintillator and SiPM setup were used. The electronics were initially developed for the CALICE collaboration. The display of a 250 GeV/c-pion event (fig. 5) shows the resolution of the shower development. With the accurate time measurements it is also possible to resolve the development of a single shower in time. The latest test-beam using silicon modules was conducted in September and October 2021 at the CERN north area. The goal was to test the noise and MIP response in a realistic environment. In these tests also the latest version 3 ROC was used and the analysis is currently ongoing.

Figure 5: Display of a 250 GeV/c pion induced particle shower, recorded at a CERN test-beam in 2018. During this early campaign 6" silicon sensors for the CE-E and CE-H compartments were used.

7. Methods for reconstruction

For successful operation of the HGCAL, it is necessary to significantly improve the reconstruction capabilities [14]. One approach is the development of classical clustering and reconstruction algorithms, which can be run on GPUs to increase computational efficiency. Also machine learning approaches are being explored using convolutional and graph neural networks.

The main difficulty in the reconstruction of events is the large number of recorded hits. To reduce the required computational load, hits are combined in 2D, to form clusters of energy. The CLUstering of Energy (CLUE) algorithm [15] calculates the energy density in a given distance around individual hits and finds the next higher hit. Based on the calculated energy density and the distance to the nearest higher hit, seeds, followers, and outliers can be defined. Only the found energy clusters are then passed on to the next reconstruction step. This algorithm is designed to run on GPUs and is very efficient in suppressing noise. The algorithm is continuously validated in simulation and is also applied to testbeam data. It is found that CLUE nearly recovers all available reconstructable energy. The reconstructed 2D layer clusters from the CLUE algorithm are used as input to the so-called iterative clustering algorithm (TICL). Based on a search window and angular requirements, the 2D clusters are grouped together to form so-called tracksters, which represent particle showers. At this stage also information from the tracker and timing detectors can be used. The algorithm is iterative in the sense that simpler objects are reconstructed first, which are then masked before the algorithm moves on to reconstruct more complex objects.

8. Summary

The CMS collaboration is currently developing calorimeter endcaps for the phase-2 upgrade of the experiment for operation at the HL-LHC. The HGCAL is a sampling calorimeter, featuring silicon sensors with a single cell size of down to 0.5 cm^2 in the inner region and scintillators, read out by silicon-photomultipliers in the region further away from the interaction point. The HGCAL will allow for precise spatial and time measurements, which will make it possible to resolve the substructure of particle jets and improve the particle flow reconstruction capabilities. The development of silicon sensors, scintillators and silicon-photomultipliers is well advanced and pre-production will start in 2022 and 2023. A new readout chip (HGCROC) was developed specifically for the HGCAL. The chip is close to being finalized and is tested together with other components (PCBs, sensors) in full-system tests to test the read-out chain of the detector. In parallel to the development of hardware components, new reconstruction algorithms are being developed to fully exploit the high granularity of the detector, while keeping computational requirements at a manageable level.

Acknowledgement

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References

[1] O. Brüning, P. Fessia, M. Lamont, L. Rossi, L. Tavian, M. Zerlauth, High-Luminosity Large Hadron Collider (HL-LHC) (2020).

[2] CERN, The HL-LHC project (2022).
URL `https://hilumilhc.web.cern.ch/`

[3] CMS Collaboration, S. Chatrchyan, G. Hmayakyan, V. Khachatryan, A. Sirunyan, W. Adam, T. Bauer, T. Bergauer, H. Bergauer, M. Dragicevic, et al., The CMS experiment at the CERN LHC, Journal of Instrumentation 3 (2008) S08004.

[4] D. Contardo, M. Klute, J. Mans, L. Silvestris, J. Butler, Technical Proposal for the Phase-II Upgrade of the CMS Detector, Tech. rep., Geneva, Upgrade Project Leader Deputies: Lucia Silvestris (INFN-Bari), Jeremy Mans (University of Minnesota) Additional contacts: Lucia.Silvestris@cern.ch, Jeremy.Mans@cern.ch (Jun 2015).
URL `https://cds.cern.ch/record/2020886`

[5] A. Lobanov, Precision timing calorimetry with the CMS HGCAL, Journal of Instrumentation 15 (07) (2020) C07003.

[6] The Phase-2 Upgrade of the CMS Endcap Calorimeter, Tech. rep., CERN, Geneva (Nov 2017).
URL `https://cds.cern.ch/record/2293646`

[7] P. Paulitsch, CMS Collaboration, The silicon sensors for the High Granularity Calorimeter of CMS, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 978 (2020) 164428.

[8] E. Brondolin, Silicon sensors for the CMS HGCAL upgrade: challenges, sensor design & electrical characterization, Journal of Instrumentation 15 (05) (2020) C05068.

[9] A. Belloni, Y. Chen, A. Dyshkant, T. Edberg, S. Eno, J. Freeman, M. Krohn, Y. Lai, D. Lincoln, S. Los, et al., Test beam study of SiPM-on-tile configurations, Journal of Instrumentation 16 (07) (2021) P07022.

[10] A. Lobanov, Electronics and triggering challenges for the CMS High Granularity Calorimeter, Journal of Instrumentation 13 (02) (2018) C02056.

[11] G. Bombardi, A. Marchioro, T. Vergine, F. Bouyjou, F. Guilloux, S. Callier, F. Dulucq, M. El Berni, C. de La Taille, L. Raux, et al., HGCROC-Si and HGCROC-SiPM: the front-end readout ASICs for the CMS HGCAL, in: 2020 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), IEEE, 2020, pp. 1–4.

[12] B. Acar, G. Adamov, C. Adloff, S. Afanasiev, N. Akchurin, B. Akgün, M. Alhusseini, J. Alison, G. Altopp, M. Alyari, et al., Construction and commissioning of CMS CE prototype silicon modules, Journal of Instrumentation 16 (04) (2021) T04002.

[13] B. Acar, G. Adamov, C. Adloff, S. Afanasiev, N. Akchurin, B. Akgün, F. A. Khan, M. Alhusseini, J. Alison, A. Alpana, et al., Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20-300 GeV positrons, arXiv preprint arXiv:2111.06855 (2021).

[14] A. Di Pilato, Z. Chen, F. Pantaleo, M. Rovere, Reconstruction in an imaging calorimeter for HL-LHC, Journal of Instrumentation 15 (06) (2020) C06023.

[15] M. Rovere, Z. Chen, A. Di Pilato, F. Pantaleo, C. Seez, CLUE: A Fast Parallel Clustering Algorithm for High Granularity Calorimeters in High-Energy Physics, Frontiers in Big Data 3 (2020).