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Upgrade: Calorimetry Towards High-Granularity

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The increase of the instantaneous luminosity at the High-Luminosity LHC (HL-LHC, phase 2) places stringent requirements on the detectors. New proposed calorimeters have to be 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. The LHC experiments have proposed various high-granularity calorimetric solutions. In this talk, I focus on the new CMS high-granularity calorimeter (HGCAL), a highly granular sampling calorimeter with approximately six million silicon sensor channels ($\simeq 0.5$ cm^2 and 1.1 cm^2 cells) and about four hundred thousand scintillator tiles read out by on-tile silicon photomultipliers. The HGCAL electronics, besides measuring energy and position of the energy deposits, are also designed to measure the time of particle arrival with a precision of about 50 ps. In HGCAL, we have developed a reconstruction approach that fully exploits the granularity to achieve optimal electron, photon and hadron identification, as well as good energy resolution in the presence of pileup.

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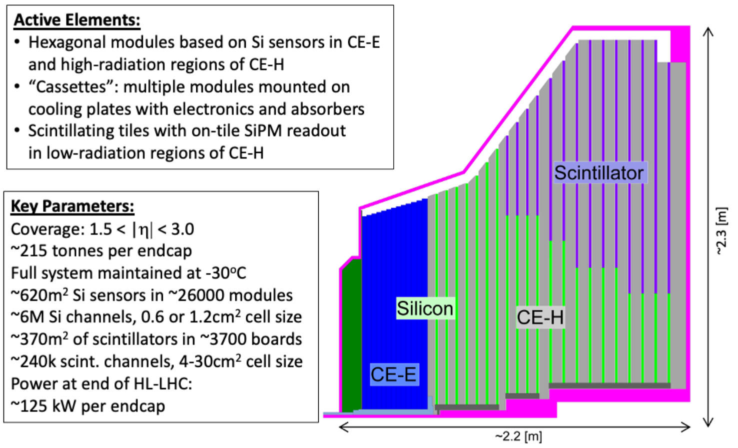
The upgraded LHC (HL-LHC) is planned to operate at a levelled peak luminosity of 5×10^{34} cm^{-2} s^{-1} [1, 2]. The mean number of events per bunch crossing (pileup) will increase from the current value of around 40 to 140 - 200. To cope with the higher event rates and the higher levels of radiation, the LHC experiments have proposed upgrades to their calorimetric subdetectors. The common characteristic of these new calorimeters is high granularity. Examples of such upgrades are, the ALICE FoCal-E high granularity ECal [3], the scintillating ECAL for LHCb (SPACAL Si-W calorimeter) [4], and the CMS HGCAL [5]. In addition, ATLAS and CMS have proposed to build high-granularity timing detectors: the High Granularity Timing Detector [6, 7] and the MIP Timing Detector [8], respectively. These are covered in R.E. Geertema's talk.

The CMS experiment [9] is undergoing an extensive upgrade program [10]. Due to the high levels of radiation expected during HL-LHC operation, the EM and HAD endcap calorimeters have to be replaced. The maximum fluence expected at the position of the endcaps is about $1.5{\times}10^{16}$ neq/cm^2 at the end of LHC operation. To maintain good energy resolution and cope with the increased pileup, the detector will feature high granularity and measure the time of arrival of incident particles [11]. In particular, in the endcap region a high granularity calorimeter was the chosen technology not only for mitigating pileup, but also for improving particle flow reconstruction. The HGCAL shown in Fig. 1 is a pair of sampling calorimeters, covering a pseudorapidity range from 1.5 to 3. In the high-radiation region, Si sensors will be used as active material. The whole EM section (CE-E) will be built from Si sensors. In the HAD compartment (CE-H), at larger radii, scintillator tiles read out by Si-photomultipliers (SiPM) will be used. The detectors will be mounted on disks which will be separated by absorber material, copper and lead in the EM section and steel in the HAD section. To cope with the increased silicon 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.


Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Figure 1: Schematic of the CMS High Granularity Calorimeter.

The high-radiation and high-occupancy region where Si sensors are employed includes the full EM and the inner HAD compartment ($|\eta| > 2.4$) [12, 13]. The sensors are expected to be exposed to a total radiation fluence ranging from $2{\times}10^{14}$ neq/cm^2 to $1{\times}10^{16}$ neq/cm^2. They are produced in a hexagonal shape on 8″ wafers, thus maximizing the sensor area per wafer. These are planar, DC-coupled, p-type sensors produced by Hamamatsu. Depending on their respective location in the detector, the shape 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.

The heart of the Si sections of the HGCAL are the modules. The Si modules are assemblies of a sensor PCB (the hexaboard) glued directly onto the silicon sensor. On the PCB the readout 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 either a Cu-W, or PCB baseplate, depending on the location of the module. About 27,000 of such modules will be produced in six sites located in the US and in Asia. In the CE-E, 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 CE-H, only a single layer of silicon per disk will be used, mounted between steel absorbers. Two versions of hexaboards will be used, one for the high density region, featuring six readout chips and a low density version with three chips. 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 utilize optical links to transmit the data to the off-detector electronics.

With the requirement of a minimum signal-to-noise 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} neq/cm^2). Individual scintillator tiles are wrapped in reflective foil and mounted on top of a 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 (from 32 cm^2 to 4 cm^2). This is beneficial to keep the occupancy at a manageable level. Smaller tiles also increase the signal amplitude. The performance of various SiPM on-tile configurations has been studied in beam tests [14].

The HGCROC chip [15, 16] is designed specifically for the HGCAL. The sensors need to be sensitive to minimum ionizing particles, as well as to high energy deposits (TeV-scale). To meet these requirements, 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 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 built and sent to the trigger readout. 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 sent out to the back-end electronics. Data and trigger data transmission from the HGCROC is realized via the ECON-D and ECON-T chips, respectively.

During the development phase, beam tests were carried out to validate the functionality of the components and the general principle of using an imaging calorimeter [17, 18]. The measured energy resolution for positron beams in the range 20 to 300 GeV is shown in Fig. 2.

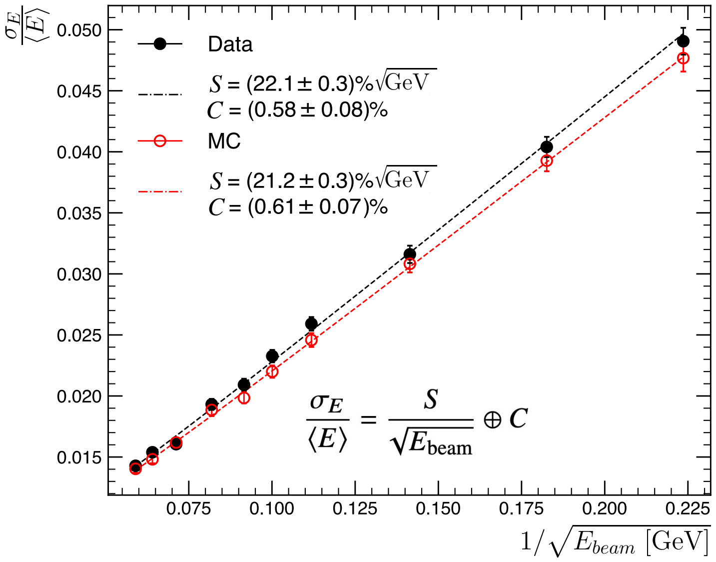


Figure 2: HGCAL prototype energy resolution measured in beam tests performed in 2018 [18].

For the successful operation of the HGCAL, it is necessary to fully optimize its reconstruction capability [19]. One approach is the development of classical clustering and reconstruction algorithms, which can be run on GPUs to increase computational efficiency. At the same time, 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 calculates the energy density in a given distance around individual hits and finds the next highest energy hit [20]. Based on the calculated energy density and the distance to the nearest highest energy 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 reconstructed 2D layer clusters from the CLUE algorithm are used as input to the so-called iterative clustering algorithm (TICL).

In summary, the CMS Collaboration is currently developing an endcap calorimeter for the phase-2 upgrade of the experiment for operation at the HL-LHC. The HGCAL is a hybrid 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 farther 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 CMS particle flow reconstruction capability. The development of silicon sensors, scintillators and silicon-photomultipliers is well advanced and pre-production has already started and will continue in 2023.

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References

[1] O. Brüning et al., The scientific potential and technological challenges of the High-Luminosity Large Hadron Collider program, Rept.Prog.Phys. 85 (2022) 4, 046201.

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

[3] ALICE Collaboration, Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment, CERN-LHCC-2020-009, LHCC-I-036. URL https://cds.cern.ch/record/2719928

[4] Yu. Guz for the LHCb and Crystal Clear Collaborations, The Phase 2 Upgrade of the LHCb Calorimeter system, JINST 15 (2020) 09, C09046.

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

[6] ATLAS Collaboration, Technical Proposal: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade, CERN-LHCC-2018-023, LHCC-P-012.

[7] ATLAS Collaboration, A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade: Technical Design Report, CERN-LHCC-2020-007, ATLAS-TDR-031.

[8] M. Ferrero for the CMS Collaboration, The CMS MTD Endcap Timing Layer: Precision timing with Low Gain Avalanche Diodes, Nucl.Instrum.Meth.A 1032 (2022) 166627.

[9] 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, JINST 3 (2008) S08004.

[10] 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 (INFNBari), Jeremy Mans (University of Minnesota) Additional contacts: Lucia. Silvestris@cern.ch, Jeremy.Mans@cern.ch (Jun 2015). URL https://cds.cern.ch/record/2020886

[11] A. Lobanov on behalf of the CMS Collaboration, Precision timing calorimetry with the CMS HGCAL, JINST 15 (07) (2020) C07003.

[12] P. Paulitsch on behalf of the 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.

[13] E. Brondolin on behalf of the CMS Collaboration, Silicon sensors for the CMS HGCAL upgrade: challenges, sensor design & electrical characterization, JINST 15 (05) (2020) C05068.

[14] 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-ontile configurations, JINST 16 (07) (2021) P07022.

[15] A. Lobanov, Electronics and triggering challenges for the CMS High Granularity Calorimeter, JINST 13 (02) (2018) C02056.

[16] 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.

[17] CMS HGCAL Collaboration, First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter, JINST 13 (2018) P10023.

[18] CMS HGCAL Collaboration, Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20-300 GeV positrons, JINST 17 (2022) P05022.

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

[20] 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).