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

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An overview of the CMS High-Granularity Calorimeter

Chiara Amendola for the CMS Collaboration

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An overview of the CMS High-Granularity Calorimeter

Chiara Amendola on behalf of the CMS Collaboration

CERN,
Esplanade des Particules 1, 1211 Geneva, Switzerland

E-mail: chiara.amendola@cern.ch

Abstract: Calorimetry at the High-Luminosity LHC (HL-LHC) faces two enormous challenges, particularly in the forward direction: radiation tolerance and unprecedented in-time event pileup. To meet these challenges, the CMS Collaboration is preparing to replace its current endcap calorimeters for the HL-LHC era with a high-granularity calorimeter (HGCAL), featuring an unprecedented transverse and longitudinal segmentation, for both the electromagnetic and hadronic sectors, with 5D information (space-time-energy) read out. The proposed design uses silicon sensors for the electromagnetic section and high-irradiation regions of the hadronic section, while in the low-irradiation regions of the hadronic section plastic scintillator tiles equipped with on-tile silicon photomultipliers (SiPMs) are used. The full HGCAL will have approximately 6 million silicon sensor channels and about 240 thousand channels of scintillator tiles. This will facilitate particle-flow-type calorimetry, where the fine structure of showers can be measured and used to enhance particle identification, energy resolution and pileup rejection.

Keywords: Front-end electronics for detector readout; Digital electronic circuits; Radiation-hard electronics; Performance of High Energy Physics Detectors

1 Introduction

The Compact Muon Solenoid (CMS) [1, 2], operating at the CERN Large Hadron Collider (LHC), is a multipurpose experiment featuring several subdetectors nested around the collision point, used to identify and measure the properties of different kinds of particles produced in high-energy collisions. The trajectories of charged particles are bent by a 3.8 T magnetic field, allowing for precise momentum measurements. The nature, energy, and direction of stable particles are determined through the combined information from all subdetectors, and more complex objects are built up from the detected particles.

As the LHC moves towards its High-Luminosity (HL-LHC) phase, the CMS experiment will undergo extensive upgrades to address the new challenges. The significant increase in luminosity, up to 7.5× higher than the original design value of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, will expose the detector's components to extreme radiation levels. This calls for upgrades or replacement of the active materials, readout sensors, and electronics in the regions most exposed to radiation, so that the experiment can collect high-quality data over the lifetime of the HL-LHC, expected to exceed 10 years. Additionally, the increased luminosity will result in up to 200 simultaneous interactions (pileup), which affects the reconstruction of vertices and objects at both the offline and trigger levels. For comparison, the busiest LHC operations have pileup of about 65.

The existing endcap regions of the CMS detector, currently equipped with a lead tungstate ($PbWO_4$) electromagnetic calorimeter and a plastic scintillator hadronic calorimeter, were originally designed to operate over an integrated luminosity of $500\,\mathrm{fb}^{-1}$. These detectors will be replaced to ensure operational efficiency and robust physics performance in the long term, up to $3000\,\mathrm{fb}^{-1}$. The new endcap calorimeter must be radiation-hard and tolerate fluences up to 10^{16} neq/cm^2 and absorbed doses of up to 2 MGy.

These proceedings present a description of the new High-Granularity Calorimeter (HGCAL), an overview of the challenges driving the design of its readout system, and highlights from the system validation results.

2 The High-Granularity Calorimeter design

The HGCAL [3] is a sampling calorimeter that combines a silicon-based electromagnetic section (CE-E) with a hadronic section (CE-H) that incorporates both silicon- and scintillator-based detectors. Silicon sensors can operate in regions with fluences of up to approximately $1.5{\times}10^{16}$ neq/cm^2, thus they are deployed in the most irradiated regions. Their usage in HGCAL provides the additional benefit of the intrinsic precision timing. Plastic scintillator tiles, read out by silicon photomultipliers (SiPMs), will be deployed in regions where the fluence is less than $4{\times}10^{13}$ neq/cm^2. One of the key features of the HGCAL is its unprecedented readout segmentation, both transversely and longitudinally. Overall, 6 million silicon pads and 240,000 plastic scintillator tiles will be deployed across 47 layers interleaved with absorber material (Pb and CuW in CE-E, steel and Cu in CE-H). A schematic view of the HGCAL design is shown in Fig 1.

The silicon modules are hexagon-shaped to efficiently cover the layers surface, tiled with hexagonal silicon pads (and partial pads at the edges) to maximize the active area on the 8-inch wafers. The modules feature variable pads size of 0.6 (High-Density or HD) or 1.2 cm^2 (Low-Density or LD),

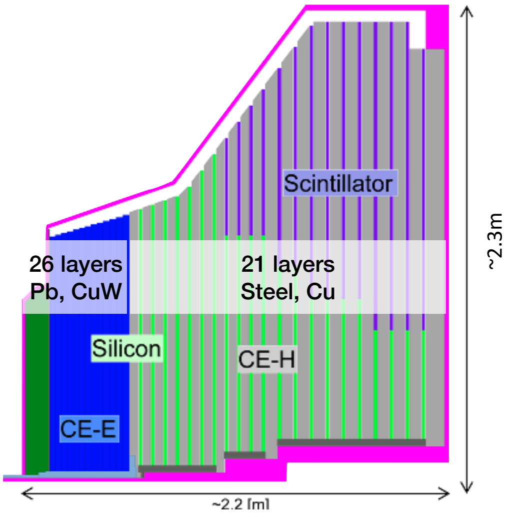


Figure 1: Schematic layout of the HGCAL design in the longitudinal cross section of the upper half of one endcap.

to match the granularity needed in different areas of the detector, and variable silicon thickness of 120, 200, and 300 μm, to minimize noise induced by radiation damage. The front-end readout is implemented through HGCROC custom ASICs, mounted on “Hexaboard” PCBs. The Hexaboard also provides the bias supply voltage and connects to the motherboard for data transfer. The module is supported by a copper-tungsten (CuW) baseplate, which also contributes to the calorimeter’s absorber material. A kapton sheet isolates the silicon layer from the baseplate.

In the scintillating tile modules, the tile sizes range from 4 to 30 cm^2 depending on the radial position. These tiles are wrapped in reflective foil to improve light yield and are coupled with 9 mm^2 Silicon Photomultipliers (SiPMs), which are placed within a dome to maximize light collection. Like the silicon modules, the SiPMs are read out by HGCROC custom ASICs and connected to the motherboard via a “Tileboard” PCB.

The modules will be mounted in assemblies (“cassettes”) over 30° or 60° wide cooling copper plate slices, which serve as the structural support. In the electromagnetic section, cassettes house modules on both sides. The combination of silicon modules of different density and thickness, variable-sized scintillator tiles, and variable coverage by silicon and scintillator modules across layers make the layout of most layers unique.

The HGCAL design presents several challenges. Both the mechanical design and the services infrastructure must accommodate its complex architecture. In addition, the design and operation of the front-end and back-end electronics must handle the high data rates and radiation environment without sacrificing performance. To fully exploit the HGCAL capabilities, new algorithms must be developed to integrate the 5D information – the 3D segmentation for spatial data, energy reconstruction, and precise timing. Finally, the preparation for data-taking operations includes the detailed characterization of the performance of HGCAL, the development of configuration and calibration routines, and the definition of data quality monitoring systems to ensure reliable operation.

3 The HGCAL readout system

The layout of the readout system is represented in Fig 2. The HGCROC is a radiation-hard ASIC designed to receive and digitize signals from both silicon and scintillator tile sensors, with only minor adaptations. Three or six HGCROCs are employed to read out each silicon module, depending on the channel density, and one is employed for each tile module. The ASIC provides three measurements: the charge (ADC) with a dynamic range of 0.2 fC to 10 pC; the preamplifier saturation time (ToT) with a dynamic range of 200 ns; and the time of arrival (ToA) with a precision of 25 ps. Data is transmitted over two paths through 1.28 Gb/s e-links: the standard data acquisition (DAQ) path, which includes ADC, ToA and ToT for each readout channel; and the trigger path, where signals from groups of 4 or 9 channels are summed, linearized, and compressed into 7-bit data for faster processing. The ECON mezzanines (T or D) act as data concentrator chips to reduce the number of links to the back-end. The ECON-T selects and compresses data to be tramsmitted at 40 MHz over the trigger path; the ECON-D processes the DAQ data for events that pass the trigger selection, applying zero-suppression and performing channel alignment, and transmits DAQ data at 750 kHz. Fast, radiation-hard link chips (lpGBTs), paired with VTRx+ transceivers, manage the data transmission and the distribution of clock, slow control, and fast control signals. Finally, the back-end system consists of ATCA-based boards that receive and buffer the data, as well as distributing clock and control signals. This system interfaces with the CMS DAQ and Timing Hub (DTH), ensuring proper synchronization and data collection across the entire calorimeter system and the global CMS system.

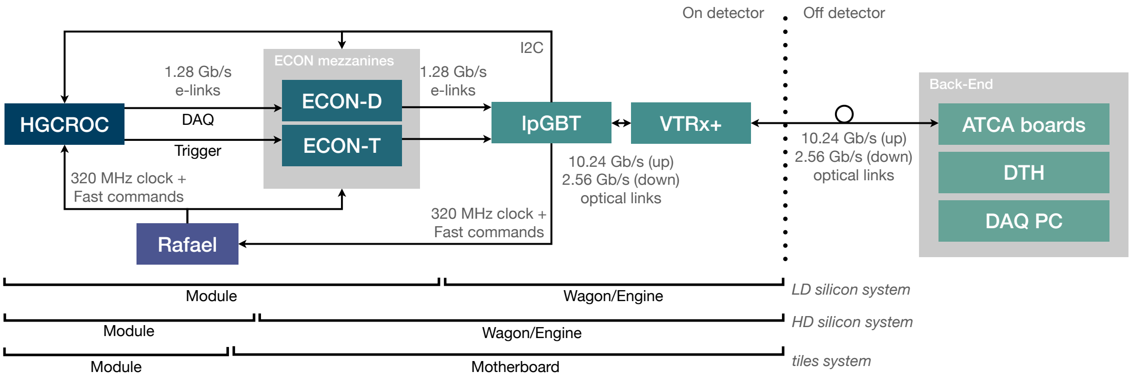
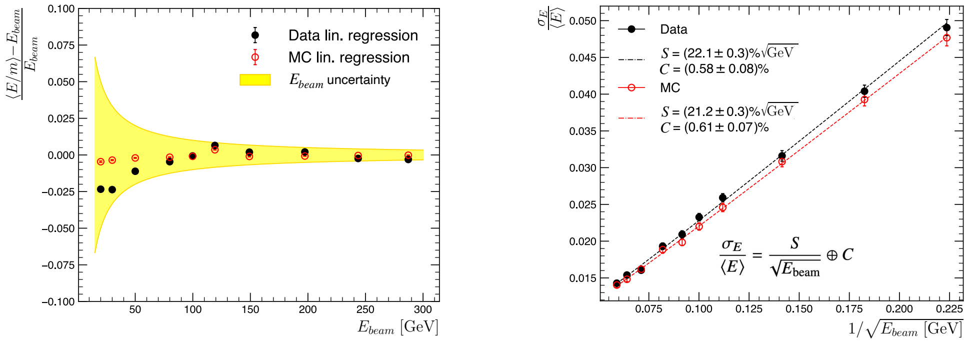


Figure 2: Schematic layout of the HGCAL readout system.

4 The system validation

The HGCAL system is being validated in test bench configuration and under test beam. Two highlights among the test beam campaigns are the one carried out in 2018, featuring a large system consisting of an electromagnetic and a hadronic section made of multiple layers of silicon modules equipped with HGCROC early prototypes, complemented by a section of SiPM-on-tile prototypes; and that of 2023, with a smaller system implementing the full readout chain. Both were carried out at beam lines branching from CERN SPS (Super Proton Synchrotron) which provide high-purity

electron and pion beams of energy ranging from 20 to 300 GeV.
The scope of the 2018 campaign was to probe the physics performance of the detector prototype.



(a) (b)

Figure 3: Energy linearity (a) and resolution (b) as a function of the incoming electron beam energy, measured with 2018 test beam data and simulated events. [4]

The linearity of the energy response with the incoming beam energy and the energy resolution for electromagnetic showers are shown in Fig 3, and compared to the performance observed in Monte Carlo events from a GEANT4-based simulation. To measure linearity, a linear fit to the mean energy response $\langle E\rangle$ as a function of the incoming electron beam energy E_{beam} is performed. The measured energy E is normalized by the resulting slope m, and the mean value $\langle E/m\rangle$ relative to E_{beam} is represented in Fig 3a. The energy response is found to be linear within ±1.5% for electron beam with energy above 50 GeV. The relative energy resolution $\sigma_E/\langle E\rangle$ is parametrized as a function of $1/\sqrt{E_{beam}}$ and fitted using the functional form

$$\frac{\sigma_E}{\langle E\rangle} = \frac{S}{E_{beam}} \oplus C,$$

where S is the stochastic term and C is the constant term. As shown in Fig 3b, the energy resolution measured in test beam data and simulation are in good agreement, and the constant term values 0.6%, which is within the physics performance target [4].

The timing resolution measured with electromagnetic showers is within 30 ps for energies above 50 GeV, and asymptotically improves to 16 ps at higher energies [5]. The hadronic performance also meets the physics target and is compatible with that of the current CMS detector [6].

The test beam data have also been used to validate the novel 3D clustering algorithm of the HGCAL particle reconstruction framework. The algorithm iterates from basic clustering towards higher complexity: first, the reconstructed hits are clustered into 2D objects based on energy density, using parallel GPUs to achieve fast operations (300 events/s); next, the longitudinal dimension is used to re-cluster into 3D objects or "tracksters" (processing over 200 events/s); finally, tracksters are geometrically linked, accounting for energy and time compatibility, and the resulting candidates are used to build showers and particles. The performance of the algorithm in test beam data was found to be well modelled by the simulation [7].

The 2023 campaign focused on validating data transmission, quality, and system stability over near-final elements of the readout chain. Both the DAQ and trigger paths were exercised at 100 kHz for several days, and the data-quality has been monitored through the integration in the CMS software. This effort marked first full vertical system integration in a test beam, and represents a milestone in the validation of the HGCAL readout.

5 Conclusion and outlook

The busy collision environment of the upcoming HL-LHC program requires a complete change of paradigm in detector technology. The HGCAL addresses this challenge with excellent capabilities in spatial, energy, and timing measurements. Novel reconstruction algorithms are designed to be fast and robust, ensuring accurate performance under high-luminosity conditions. System integration and validation are progressing swiftly, and the readout chain will be further exercised in upcoming campaigns under beam and magnetic field. Mass production of cassettes and modules is planned for 2025, representing a critical step towards full deployment.

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