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An overview of the CMS High Granularity Calorimeter

Bora Akgun for the CMS Collaboration

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Calorimetry at the High Luminosity LHC (HL-LHC) faces many challenges, particularly in the forward direction such as, radiation tolerance and large 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 compartments, with 5D information (space-time-energy) read out. The proposed design uses silicon sensors for the electromagnetic section (with fluences above 10^{16} n_{eq}/cm^2) and high-irradiation regions (with fluences above 10^{14} n_{eq}/cm^2) 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. Full HGCAL will have approximately 6 million silicon sensor channels and about 280 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. In this talk we present the ideas behind HGCAL, the current status of the project, the lessons learnt, in particular from beam tests as well as the design and operation of vertical test systems and the challenges that lie ahead.

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Article

An overview of the CMS High Granularity Calorimeter

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Abstract: Calorimetry at the High Luminosity LHC (HL-LHC) faces many challenges, particularly in the forward direction such as, radiation tolerance and large 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 compartments, with 5D information (space-time-energy) read out. The proposed design uses silicon sensors for the electromagnetic section (with fluences above 10^{16} n_{eq}/cm^2) and high-irradiation regions (with fluences above 10^{14} n_{eq}/cm^2) 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. Full HGCAL will have approximately 6 million silicon sensor channels and about 280 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. In this talk we present the ideas behind HGCAL, the current status of the project, the lessons learnt, in particular from beam tests as well as the design and operation of vertical test systems and the challenges that lie ahead.

Keywords: Front-end electronics for detector readout; Radiation-hard electronics; Silicon Detectors; Performance of High Energy Physics Detectors; Data Acquisition Systems

1. Introduction

The HL-LHC at CERN will operate at an instantaneous luminosity of 5×10^{34} $cm^{-2}s^{-1}$ or higher and is expected to record ten times more data than the LHC. This increase of luminosity will cause detector components to be exposed to extreme radiation levels. Moreover, due to the increased luminosity, we expect up to 200 collisions per bunch crossing, which presents a significant challenge for mitigating overlapping events (pile-up). To address this, the CMS experiment [1,2] will upgrade several components of its detector, including the introduction of a new High-Granularity Calorimeter (HGCAL). HGCAL will replace the current endcap calorimeters. HGCAL must achieve a $\sim$30 ps timing resolution to mitigate pile-up and maintain robust physics performance after an integrated luminosity of 3,000 fb^{-1} where in the innermost region the total ionizing dose will reach 2 MGy and the total neutron fluence will be 10^{16} n_{eq}/cm^2.

HGCAL is a high-precision sampling calorimeter composed of silicon and scintillator modules, arranged across 47 active layers with over 6 million channels. In the electromagnetic section, the silicon modules are interleaved with copper, copper-tungsten, and lead absorbers. The silicon sensors are segmented into hexagonal cells, with a cell size of 0.5 cm^2 in the innermost region and 1.2 cm^2 in the outer regions. The hadronic section features silicon sensors in high-radiation areas, while plastic scintillator tiles are used in regions of lower radiation. The hadronic calorimeter is equipped with steel absorbers. To minimize leakage currents in the silicon sensors and SiPMs, the entire calorimeter is maintained at -35°C. This highly-segmented design enables detailed measurements of both the transverse and longitudinal shower profiles, as well as precise timing information, aiding in pile-up mitigation and enhancing the event reconstruction performance.

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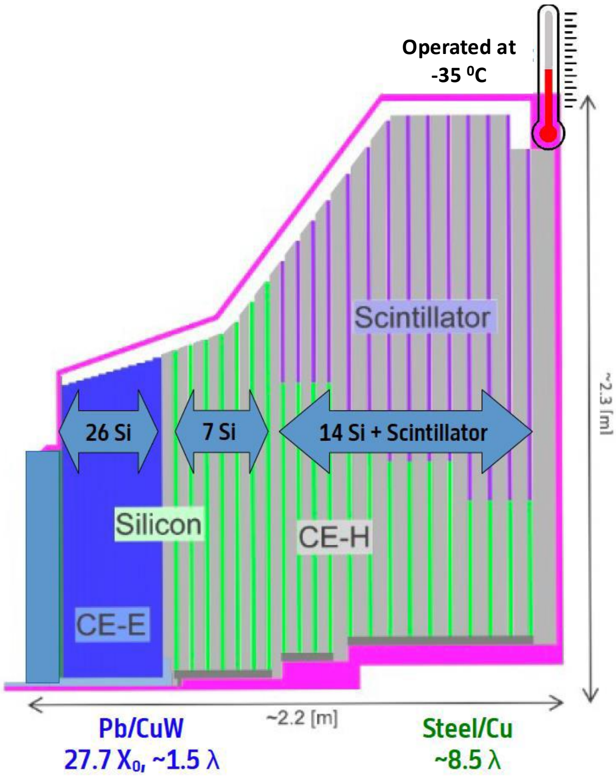

Figure 1. Schematic layout with key parameters of HGCAL design in the longitudinal cross section of the upper half of one endcap.

The total power required for the front-end (FE) electronics is approximately 110 kW per endcap. The FE electronics requires 1.2 V for analog and digital, and 2.5 V for optical transmission electronics. The power is fed to the silicon and scintillator modules through FE printed circuit boards (PCBs) that also host HGCAL application specific integrated circuits (ASICs). DC-DC converters are planned for the powering scheme.

Section 2 describes the active elements. Sec. 3 gives an overview of the electronics systems and Sec. 4 outlines the results of the tests, performed in the laboratory and with particle beams, and the status of the reconstruction software development.

2. Active Elements

HGCAL is instrumented with two types of active elements: silicon sensors covering an area of 620 m^2 and small plastic scintillator tiles covering an area of 370 m^2.

2.1. Silicon Sensors and Silicon Modules

The HGCAL silicon sensors are fabricated on 8-inch wafers. They are hexagonal in shape. The choice of the hexagonal geometry motivated to maximize the use of the circular wafer area. There are three different active silicon sensor thicknesses (120, 200, and 300 μm) optimized for regions of different radiation levels. Sensors are segmented into cells and read out individually. The 200 and 300 μm thick sensors contain 192 cells each with 1.2 cm^2/cell, while the 120-μm thick sensors contain 432 cells with 0.5 cm^2/cell. The physically thinned p-type float zone silicon wafers are the line substrate material for the 200 and 300 μm thick sensors, while P-type epitaxial wafer is the line substrate material for the 120-μm sensors. A comprehensive irradiation campaign was performed to converge on optimal sensor design choices and parameters [4–9].

There are four components to a silicon module; a PCB with embedded electronics, a silicon sensor, a kapton isolating foil and a baseplate for mechanical support. HGCAL will have about 26,000 silicon modules. Six module assembly centres (MACs) will be responsible for their assembly. Each MAC will be able to produce up to 24 modules per day. The assembly and testing procedures are being established at the MACs [10].

2.2. Scintillators and Scintillator Tile-modules

Two types of scintillator material are considered for the hadronic section: polyvinyltoluene-based (PVT) and polystrene-based (PS). Based on cost, performance, and ease of assembly, the cast and machined PVT-based scintillators will be used in the front, and injection molded PS-based scintillators will be used for the rest of the hadronic section.

The SiPM-on-tile technology, pioneered by the CALICE Collaboration [11,12], is identified as the most cost-effective solution. This technology utilizes direct detection of light from the scintillator tile by a SiPM that collects the light through a dimple in the surface of the tile. The dimple equalizes the response across the tile, and reflective wrapping maximizes light collection. The hadronic section contains 280,000 channels with tile sizes from 4 to 30 cm^2, and the SiPM area ranges from 2 to 4 mm^2.

3. Electronics Overview

The HGCAL readout, trigger, and control system uses a combination of custom and commercial parts. Some of the custom parts are specific to HGCAL, and some are common with other CERN projects.

3.1. Front-end Electronics

The FE electronics digitizes either the silicon sensor or SiPM signal, provides a high-precision time-of-arrival measurement, and transmits the digitized data to the back-end (BE) electronics. It also computes, for every bunch crossing, the digital sums of neighbouring cells (2×2 cells in the case of the 1.2 cm^2 silicon pads and 3×3 cells in the case of the 0.5 cm^2 silicon pads) to build trigger primitives. The custom HGCAL Readout Chip (HGCROC) measures the charge and the time-of-arrival at 40 MHz. The HGCROC requirements are extremely challenging: a high dynamic range from a few fC to 10 pC, low noise of about 2,000 electrons, high precision timing information for pileup mitigation, and low power consumption of 15 mW/channel. The HGCROC will also face a harsh radiation environment, up to 300 MRad. The HGCROC has 72 channels of analog low noise and high gain preamplifier and shapers, and a 10-bit 40 MHz successive-approximation analog-to-digital converter (SAR ADC), which provides the charge measurement over the linear range of the preamplifier. In the saturation range of the preamplifier, a discriminator and time-to-digital converter (TDC) provide the charge information over a 200 ns dynamic range using 50 ps binning. A fast discriminator and TDC provide timing information to 25 ps precision. Both charge and timing information are kept in a memory waiting for a Level1-accept (L1A). At a bunch crossing rate of 40 MHz, data corresponding to (4 or 9) adjacent channels are sent out to participate in the generation of the trigger primitives. As part of the ongoing development and testing of the HGCAL electronics, the performance of the HGCROC prototype in terms of signal-over-noise ratio, charge, and timing, as well as radiation qualification with total ionizing dose, and single-event effects, has been studied [13]. The data are transmitted to the custom concentrator ASIC, ECON-D via 1.28 Gb/s electrical links where they are suppressed. Digital sums of 4 or 9 adjacent channels (depending on the sensor granularity) are computed by HGCROC. These sums are transmitted for every bunch crossing from the HGCROC to a different custom concentrator ASIC, ECON-T, via separate 1.28 Gb/s electrical links to be used for the formation of trigger primitives. The ECON-D aggregates, formats, and serialises the data at the L1 average frequency of up to 750 kHz. For the trigger path, the ECON-T selects the trigger sums of interest, aggregates and formats their data in packets, and stores them in a First-in-First-out (FIFO) buffer. These data are sent within a defined latency to the trigger primitive generator (TPG) electronics, using separate optical links. The ECON-D and ECON-T act therefore as hubs, receiving up to twelve 1.28 Gb/s electrical links from the HGCROCs and serialising the corresponding data, trigger and L1A readout, and outputs at the same rate. They are connected to the BE electronics via a bi-directional link using low-power gigabit transceivers (lpGBTs) and are coupled to a slow control adapter ASIC (SCA) [14] and versatile transceiver plus (VTRx+) [15], all three developed for HEP experiments. The fast control links will run at 320 Mb/s and the slow control links will use I^2C protocol at 1 Mb/s. The optical transmission is performed through the VTRx+ optoelectronics transceivers.

The PCB layouts for the FE electronics optimize the board shapes and the number of optical links, as required by the data rates. For high-density silicon modules ECONs are mounted directly on one PCB, Wagon board, and lpGBTs and VTRx+ are located on a different PCB, Engine board. In contrast, for silicon low-density modules, ECONs are mounted on mezzanine boards, separate from the Wagon boards. For scintillator modules ECONs, lpGBT, and VTRx+ components are all mounted on the same motherboard. The Wagon boards are connected to Engine boards with miniature connectors [16,17]. The lpGBTs use the forward error correction (FEC5) protocol [18] for the data path. The total average data volume for the whole HGCAL is around 2.5 MByte per event, which scales approximately linearly with the average pileup. At an L1A rate of 750 kHz, this corresponds to an average data rate from the FE electronics of 15 Tb/s. For the trigger path, the total average rate of trigger cell data will be 1.25 Mbit per bunch crossing, or 50 Tb/s. The total number of 10.24 Gb/s lpGBT links from FE electronics is about 10,000 for both DAQ, and TPG BE electronics. A schematic representation of HGCAL FE readout, trigger and control chain is shown in Figure 2.

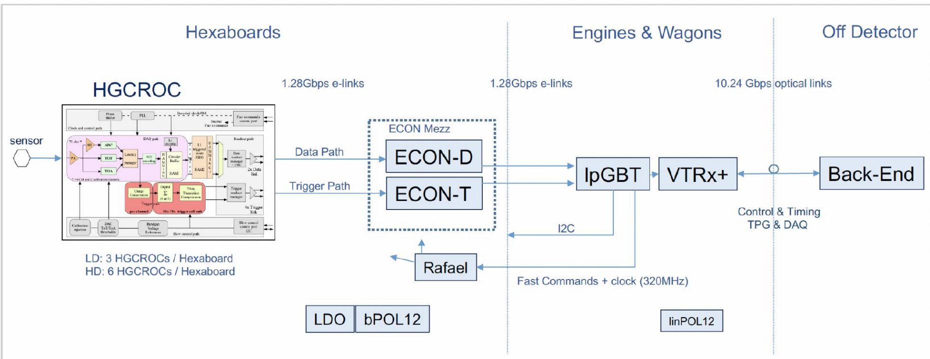

Figure 2. Schematic representation and key components of the CMS HGCAL FE readout, trigger and control chain.

3.2. Back-end Electronics

The BE electronics consists of the DAQ and TPG systems. The DAQ and TPG systems are implemented in advanced telecommunications computing architecture (ATCA) [19] format. The systems consist of CMS common 'Serenity' boards [20] housed in ATCA crates, with DAQ and timing hub (DTH) ATCA boards [21] also in these crates to provide the central DAQ and timing systems interface. The DAQ system consists of ATCA boards containing one high-end Field Programmable Gate Array (FPGA) with sufficient bandwidth to drive 108 links in both directions to and from the FE electronics, and a further 12 optical links to and from a DTH in the same crate. The links from and to the FE electronics will run at 10.24 Gb/s and 2.56 Gb/s, respectively. The links to the DTH board will run at 25 Gb/s. The FPGA on these boards will handle and process the data, with the required buffering, event building, front-end emulation, and monitoring implemented in firmware. The TPG system has two tasks: to form 3D clusters from trigger cells, and to form the overall energy map from the coarse granularity HGCROC energy sums.

3.3. Control and Safety Systems

The HGCAL detector control system (DCS) is the main interface to turn HGCAL on and off in a safe and controlled fashion and provides all status information (power system, cooling system, gas system, temperature, etc.). It is based on the supervisory control and data acquisition chosen at the LHC. The HGCAL detector safety system (DSS) is based on industrial programmable logical controllers (PLCs) [22]. The HGCAL DSS will constantly monitor the temperature and humidity inside the HGCAL volume, including the interfaces, and will have access to all status information of the CO_2 cooling and dry gas system. Passive temperature sensors inside the HGCAL cryostat will be directly connected to the PLCs. A dedicated sniffer system will pump gas from the volumes via several pipes towards the service cavern, where the gas is analysed by commercial high-precision dew-point meters.

4. The Beam Tests Results and System Validation

The validation of HGCAL system has been ongoing with measurements in the laboratories with particle beams. Major test campaigns took place since 2018. 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 were used in 2018. In 2021 prototype 8-inch modules were tested for the first time. In 2023, the full readout chain was implemented with a small system. All campaigns carried out at beamline facilities at CERN with high-purity electron and pion beams of energy ranging from 20 to 300 GeV.

The 2018 campaign focused on the performance of the prototype electronics in terms of stability of noise and pedestals, calibration with MIPs, timing, and energy linearity and resolution for electrons and pions were examined. The energy response of the electromagnetic section was found to be linear within $\pm 1.5\%$ for electron beam above 50 GeV, and its resolution is within physics target. The timing resolution measured with electromagnetic showers is within 30 ps and improves to 16 ps at higher energies. The performance of the hadronic section also meets the physics target. The description of the systems and results of the tests with particle beams can be found in [10,23–28].

The 2023 campaign focused on validation of data transmission, quality, and system stability over near final readout chain elements. Both trigger and DAQ paths were employed at 100kHz for days, and data-quality has been monitored. This represents a major milestone since this was the first full vertical system integration in a test beam.

5. Conclusion

The CMS endcap calorimeters will be replaced with a high-granularity calorimeter equipped with silicon sensors and highly-segmented scintillators. The readout, trigger, and control chains use state-of-art electronics developed for HGCAL and other CMS upgrade projects. The HGCAL electronics design has been evolving with feedback from benchtop and beam tests. A reconstruction framework is being developed to fully exploit the exceptional granularity and precision timing. System integration and validation are progressing, and the readout chain will be further exercised in upcoming test beam campaigns. Mass production of cassettes and modules is planned for 2025, representing a crutial step towards full deployment.

References

1. CMS Collaboration, The CMS experiment at the CERN LHC, *JINST* **2008**, *3*, S08004. [doi:10.1088/1748-0221/3/08/S08004].
2. CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3, *JINST* **2024**, *19*, P05064. [doi:10.1088/1748-0221/19/05/P05064].
3. CMS Collaboration, The Phase-2 Upgrade of the CMS Endcap Calorimeter. *CERN-LHCC-2017-023* **2017**, [doi:10.17181/CERN.IV8M.1JY2].
4. P. Almeida, *Versatile systems for characterization of large-area silicon pad sensors for highly-granular calorimetry*, 2020 *JINST* 15 C06050.
5. E. Brodolin, *Silicon sensors for the CMS HGCAL upgrade: Challenges, sensor design and electrical characterization*, 2020 *JINST* 15 C05068.

6. F. Pitters *et al.*, *ARRAY: An Open Source, Modular and Probe-Card based System with Integrated Switching Matrix for Characterization of Large Area Silicon Pad Sensors*, 2019 *Nucl.Instrum.Meth.A* 940 168-173.
7. N. Akchurin *et al.*, *Charge collection and electrical characterization of neutron irradiated silicon pad detectors for the CMS High Granularity Calorimeter* 2020 JINST 15 P09031.
8. CMS HGCAL Collaboration, *Neutron irradiation and electrical characterisation of the first 8" silicon pad sensor prototypes for the CMS calorimeter endcap upgrade* 2023 JINST 18 P08024.
9. Jan Kieseler *et al.*, *Isothermal annealing of radiation defects in silicon bulk material of diodes from 8" silicon wafers*, 2023 JINST 18 P09010.
10. CMS HGCAL Collaboration, *Construction and commissioning of CMS CE prototype silicon modules*, 2021 *JINST* 16 T04002.
11. CALICE Collaboration, *Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype*, 2010 *JINST* 5 P05004.
12. CALICE Collaboration, *A highly granular SiPM-on-tile calorimeter prototype*, 2019, *JoP: Conference Series* 1162 012012.
13. D. Thienpont and C. de La Taille, *Performance study of HGCROC-V2: the front-end electronics for the CMS High Granularity Calorimeter*, 2020 *JINST* 15 C04055.
14. A. Caratelli *et al.*, *The GBT-SCA, a radiation tolerant ASIC for detector control and monitoring applications in HEP experiments*, 2015 *JINST* 10 C03034.
15. C. Soos *et al.*, *Versatile Link PLUS transceiver development*, 2017 *JINST* 12 C03068.
16. https://www.hirose.com/product/series/FX11?lang=en .
17. https://www.molex.com/molex/products/part-detail/pcb_receptacles/5054730810 .
18. S. Luyi, *et al.*, *Forward Error Correction*, 2012 Fourth International Conference on Computational and Information Sciences, Chongqing, 2012, pp. 37-40, [doi: 10.1109/ICCIS.2012.158].
19. PICMG, 'R3.0 AdvancedTCA Base Specification', https://www.picmg.org/openstandards/advancedtca/.
20. A. Rose *et al.*, Serenity: An ATCA prototyping platform for CMS Phase-2, PoS TWEPP2018 (2019) 115. [doi: 10.22323/1.343.0115].
21. J. Hegeman *et al.*, First measurements with the CMS DAQ and Timing Hub prototype-1, PoS TWEPP2019 (2020) 111. [doi:10.22323/1.370.0111].
22. K. T. Erickson, *Programmable logic controllers*, in IEEE Potentials, vol. 15, no. 1, pp. 14-17, Feb.-March 1996, [doi: 10.1109/45.481370].
23. N. Akchurin *et al.*, *First beam tests of prototype silicon modules for the CMS High GranularityEndcap Calorimeter*, 2018 *JINST* 13 P10023.
24. CMS HGCAL Collaboration, *The DAQ system of the 12,000 Channel CMS High Granularity Calorimeter Prototype*, 2021 *JINST* 16 T04001.
25. A. Belloni *et al.*, *Test beam study of SiPM-on-tile configurations*, 2021 *JINST* 16 P07022.
26. CMS HGCAL Collaboration, *Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20-300 GeV positrons*, 2022 *JINST* 17 P05022.
27. CMS HGCAL Collaboration, *Performance of the CMS High Granularity Calorimeter prototype to charged pion beams of 20-300 GeV/c*, 2023 *JINST* 18 P08014.
28. CMS HGCAL Collaboration, *Timing performance of the CMS High Granularity Calorimeter prototype*, 2024 *JINST* 19 P04015.