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An Overview of the CMS High Granularity Calorimeter

Gabriele Milella[a,*] **on behalf of the CMS collaboration**

[a] *DESY, Hamburg, Germany*

E-mail: gabriele.milella@cern.ch

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 a previously unrealized 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 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. 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. In this talk we present the ideas behind the HGCAL, the current status of the project, the lessons that have been 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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*Speaker

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1. The Upgrade of the CMS Endcap Calorimeter

After collecting 25 fb^{-1} during Run 1 (2010–2012) at 7 and 8 TeV, 138 fb^{-1} in Run 2 (2016-2018) at 13 TeV and some 300 fb^{-1} by the end of Run 3 (2025) at 13.6 TeV, the CMS collaboration will face a period of major upgrades in order to cope with requirements of the High Luminosity Phase of LHC (HL-LHC). A total integrated luminosity of up to 4000 fb^{-1} is envisaged for HL-LHC over 10 years, exceeding the LHC design value by one order of magnitude and the corresponding mean number of collisions (pileup) per bunch crossing will be 140. This poses challenges, especially for calorimetry in the forward regions. In these regions, the radiation levels are expected to be equivalent as in the region of the inner pixel trackers, with the highest fluence of 10^{16} n$_{eq}$/cm^2 (2 MGy) after 3000 fb^{-1} [1]. The existing forward calorimeters, the PbWO$_4$-based electromagnetic calorimeter (EE) were designed for a total integrated luminosity of 500 fb^{-1}, therefore leading to unacceptable performance loss beyond this value.
The CMS collaboration has proposed the High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeter. The HGCAL must maintain its performance throughout its entire operational lifespan, necessitating the use of radiation-resistant technologies. Due to the anticipated exceptionally high number of collisions and the necessity for pileup mitigation, the HGCAL will contribute to the level-1 (L1) trigger decision of the CMS, targeting a resolution per channel of 20 ps, independent from detector aging. Moreover, the engineering challenges for the HGCAL are significant, as it is designed to be a compact, dense calorimeter within tight space constraints while providing fine 3D lateral and longitudinal granularity and the possibility to measure the energy spanning the range from single Minimum Ionizing Particle (MIP) to electromagnetic and hadronic showers. To meet these requirements, the HGCAL project involves using silicon sensors and plastic scintillator tiles as active materials, comprising two distinct sections within a single detector, as shown in figure 1.

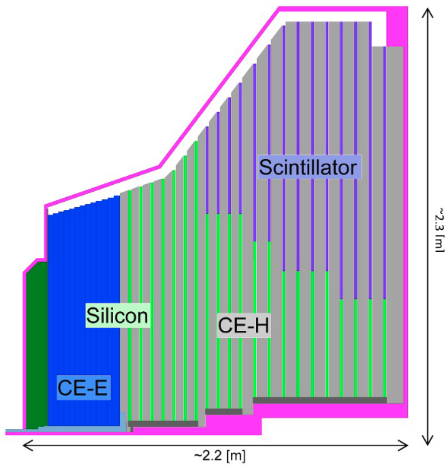


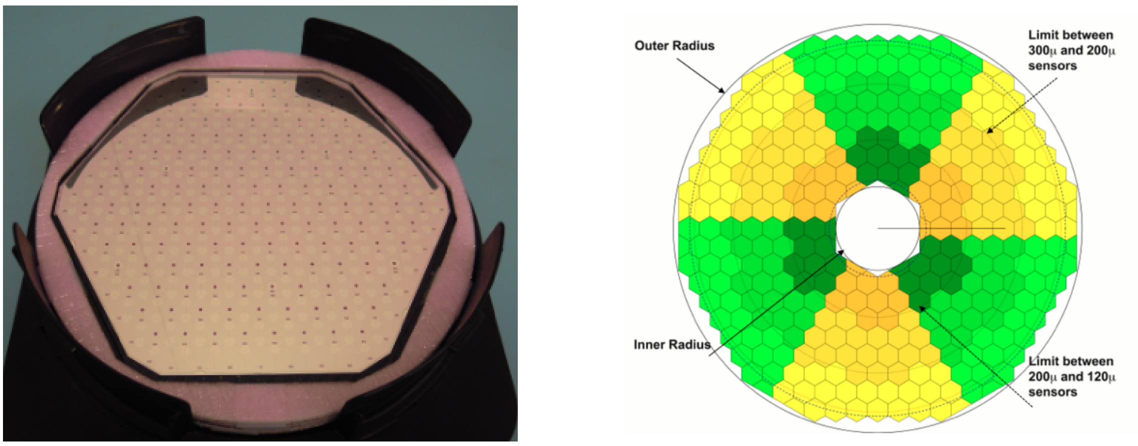
Figure 1: Cross-sectional longitudinal view of one endcap proposed for the CMS HGCAL.

The first section consists of an electromagnetic compartment (CE-E) equipped with silicon sensors, followed by a hadronic compartment (CE-H) with a mixed design of silicon sensors in the innermost region and plastic scintillators in the region towards the rear, whose scintillating light is read out by Silicon photomultipliers (SiPM). The active layers of material in the HGCAL are alternated with passive ones, consisting of lead absorber plates, CuW baseplates, and copper cooling plates for a total weight of 225 T. In order to keep the radiation-induced energy equivalent of electronics noise sufficiently low, HGCAL will be operated at -30 °C.

2. Detector Design

2.1 Silicon Sensors

In the silicon segments of the detector, the active components are 8-inch hexagonal wafers. These wafers host silicon cells of three distinct thicknesses—300 µm, 200 µm, and 100 µm— in regions of increasing fluence. The cell sizes vary—1.2 and 0.5 cm^2—taking into account the different lateral spread of electromagnetic and hadronic showers, resulting in wafers with varying densities, classified as low or high, depending on their proximity to the beam axis. Figure 2 shows a low-density sensor and the layout of one CE-E layer. The wafers are stacked with the CuW baseplate for rigidity, the Kapton-gold sheet to provide bias voltage to the sensors, and the printed circuit board (PCB), labeled the hexaboard, with front-end electronics to form the silicon *modules*. The modules in each layer of the HGCAL are grouped into 30° or 60° wedges called cassettes which host all the ancillary components. To ensure the endcap circular geometry, partial modules are also designed.



(a) The low-density hexagonal wafers, hosting 192 silicon cells.

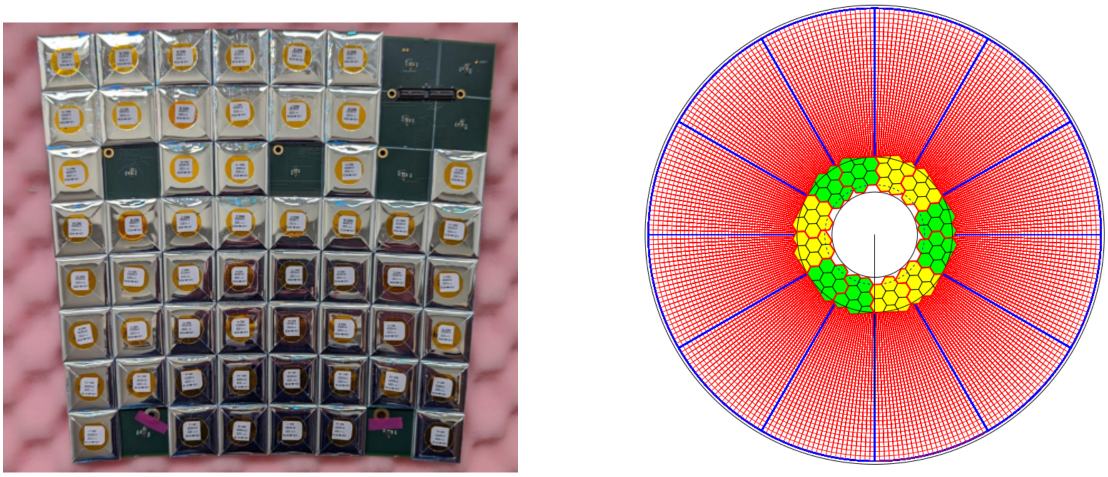
(b) Transverse plan of one layer of the CE-E section of HGCAL.

Figure 2: Elements of the silicon section of HGCAL.

2.2 SiPM-on-tile

The plastic scintillator tiles are arranged in different sizes, from 4 to 30 cm^2, in regions of increasing radial distance from the beam axis. Each tile, wrapped in a scintillating material, is optically coupled to a SiPM via a central dimple. The SiPMs and tiles are mounted on the *tileboard* module which hosts also the front-end electronics and the associated driving circuitry. 8 geometries of 10° tileboards are deployed and up to 5 tileboards are placed next to each other, forming a basic

10° detector unit. The tileboard modules are integrated with the silicon modules in mixed 60° cassettes in the CE-H section [2]. Figure 3 shows one geometry prototype of tileboard module and the mixed layout of one CE-H layer.



(a) Tileboard modules equipped with wrapped scintillator tiles. Naked SiPMs are also visible.

(b) Transverse plan of one layer of the CE-H section of HGCAL.

Figure 3: Elements of the scintillator section of HGCAL.

2.3 Electronic System

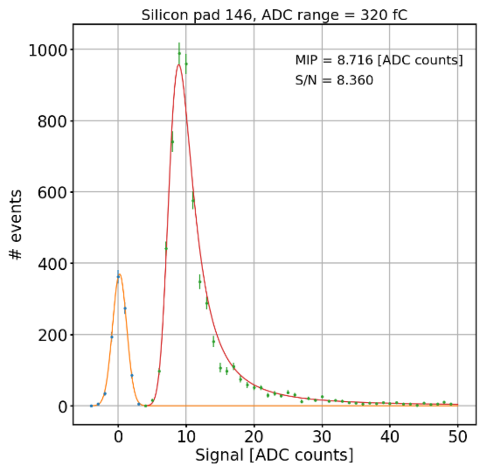
The front-end ASIC readout employed for HGCAL (HGROC) provides for both charge and time measurements. This chip features a similar design for the silicon and scintillator sections of the HGCAL. In terms of distribution, the low-density silicon module accommodates three HGROCs, the high-density version supports six, while each tileboard is equipped with a single HGROC. The dynamic range required for energy measurements is ensured by employing the 10-bit 40 MHz ADC, for Minimum Ionizing Particle (MIP) measurements, and the 12-bit TOT for shower detections. The time information is collected by the 10-bit (25 ps LSB) TOA. Energy and time data are then transmitted through the Data Acquisition (DAQ) path, which activates upon receiving the level-1 trigger, and the trigger path after a summation process of 4 or 9 channels, and the resultant data is sent via 1.28 Gb/s outputs [3][4]. The comprehensive readout chain of the HGCAL also includes concentrator chips: the ECON-T chip designed to select and compress trigger data transmitting it at a rate of 40 MHz and the ECON-D chip to process the full resolution data after trigger, to perform zero suppression and to transmit them at 750 kHz. Key components within these chains, known as *engines* and *wagons*, active and passive elements, are employed for the transmission to the DAQ back-end, for clock distribution and fast commands and configuration. Further details regarding the testing of the first fully assembled readout chain are provided in 3.2.

3. System validation and status of the project

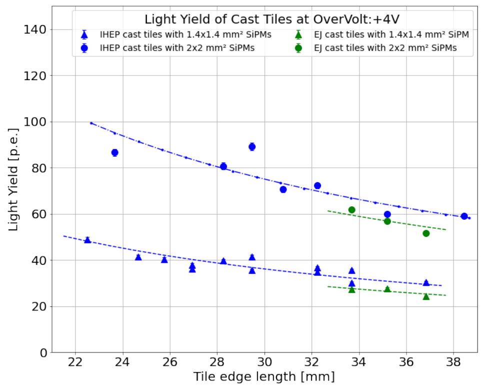
The first module prototypes have been tested extensively in laboratories and in test-beam campaigns at test-beam facilities at CERN, DESY, and Fermilab. The manufacturing of the modules, cassettes, and mechanical components is distributed across various production sites globally.

3.1 Silicon and SiPM-on-tile modules

Dedicated test-beam campaigns were carried out at CERN to test and validate low-density silicon modules. The outcome of one of these tests is shown in figure 4a, where the MIP signal was measured in ADC counts by a single silicon pad.
The first high-density module was assembled and tested in December 2022, showing performance similar to the low-density modules. Figure 6a shows the module.
Tiles produced through various mechanisms and SiPMs of different sizes were tested at the DESY electron test-beam facility. The MIP signal from electrons was reconstructed for these different tile productions and SiPM. The measured light yield for tiles of various areas is presented in Figure 4b, demonstrating the outcome of one such test-beam campaign. To optimize the performance of the detectors, studies on scintillator material, tile wrapping, and SiPM parameters are still ongoing.



(a) MIP signal in ADC counts measured by a single silicon pad during a test-beam campaign.



(b) Light Yield measured for scintillator tiles of different sizes and productions. The light yield is proportional to $\frac{1}{\sqrt{A_{tile}}}$

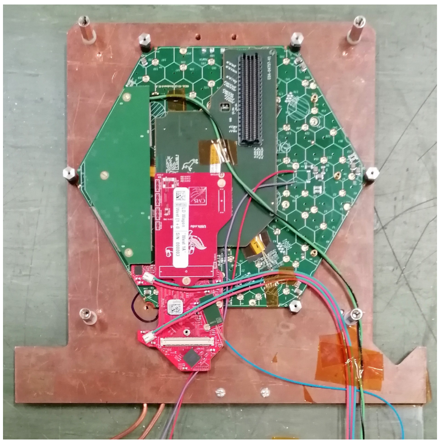
Figure 4: Results of different test-beam campaigns for the silicon and tileboard modules.

3.2 First test of the full readout chain

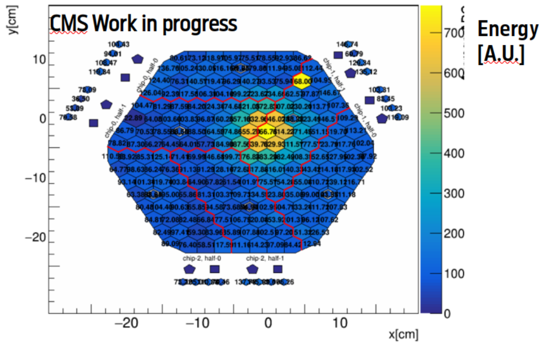
At the CERN test beam conducted from August 2nd to 9th, 2023, the first comprehensive test of the HGCAL readout chain was performed. Two low-density silicon modules, equipped with engines and wagons, were tested with electron, muon and pion beams and one module is shown in Figure 5a. Figure 5b presents a sample signal hit map from electromagnetic showers, as recorded by one of these silicon modules. For this particular test beam, the functionality of the ECON T/D chips was replicated using emulators. The complete integration, including the actual ECONs ASIC components, undergoes a test in the next test-beam session at CERN, planned for September.

3.3 Preparation for mass production

As of July 2023, the project's progress indicates that the design of most components is expected to be finalized by the end of the year, along with the qualification of manufacturers and



(a) One low-density module equipped with engines and wagons.



(b) The hit map readout by the module.

Figure 5: First test of the full HGCAL readout chain.

production processes. The components produced in these pre-series runs, while not intended for the final installation, are crucial to be ready for the pre-production phase. This phase, commencing in 2024, will account for 5% of the total production, with its components specifically designated for installation in the detector.

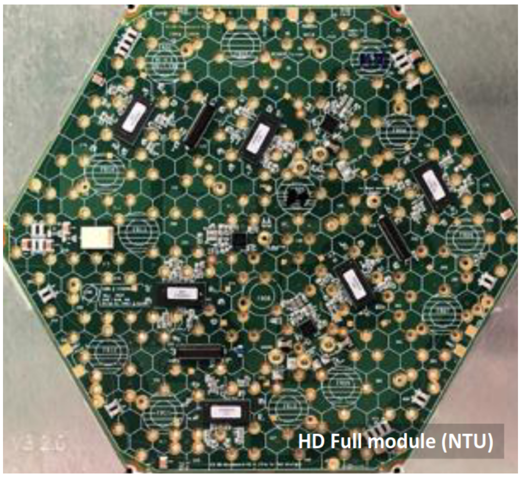
In preparation for mass production, a range of tasks has been distributed among CMS institutes to streamline the workflow. A total of 26,000 silicon modules are planned to be constructed and tested in five Module Assembly Centres (MACs). Figure 6a displays an example of a pre-series high-density module that has already been assembled.

Furthermore, the project anticipates the production of 240,000 SiPM and scintillator tiles, which will be used to equip and assemble a total of 3,744 tileboard modules. The assembly and testing of these components will be conducted in two Tilemodules Assembly Centres (TACs). The DESY assembly machine, which is utilized for accurately placing the scintillator tiles onto the tileboards, is illustrated in Figure 6b.

The organized workflow is in alignment with the planned integration and lowering of the components, which is targeted for the year 2027.

4. Conclusion

As the CMS collaboration prepares for HL-LHC, the HGCAL project has shown consistent progress in addressing the anticipated challenges for the increased collision rates and radiation levels. The successful testing of module prototypes and the recent implementation of the full readout chain show the project's readiness for the next stages. The pre-production phase, scheduled for 2024, marks a significant step towards the final detector assembly envisaged for 2027.



(a) One high-density full module recently assembled.

(b) The assembly machine for building tileboard modules at DESY.

Figure 6: Pre-series components

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