PROCEEDINGS OF SCIENCE

Design of the CMS High Granularity Calorimeter trigger primitive generator system

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The CMS collaboration has chosen a novel high granularity calorimeter (HGCAL) to instrument the endcap regions as part of its upgrade for the high luminosity LHC. The HGCAL will have fine segmentation in both the transverse and longitudinal directions and will be the first such calorimeter specifically optimised for particle flow reconstruction to operate at a colliding-beam experiment. The calorimeter data will be part of the Level 1 trigger of the CMS experiment and, together with tracking information, will allow particle-flow techniques to be used in this first level trigger. The Level 1 trigger has tight constraints on latency and rate and will be implemented in hardware. The high granularity leads to about six million readout channels in total, that are concentrated in one million trigger cells, sampled at 40 MHz for the Level 1 trigger. This presents a significant challenge in terms of data manipulation and data processing for the trigger system as the trigger data volumes will be an order of magnitude above those currently handled in CMS. In addition, the high luminosity will result in an average of up to 200 interactions per bunch crossing that yield a huge background rate in the forward region that will need to be efficiently rejected by the trigger algorithms. Furthermore, reconstruction of the three-dimensional particle clusters to be used for particle flow in events with high hit rates is also a complex computational problem for the trigger. The status of the HGCAL trigger architecture and design, as well as the various challenges encountered and the methodologies developed to improve these major aspects, will be presented.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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https://pos.sissa.it/

PoS(EPS-HEP2023)593

Introduction

The Compact Muon Solenoid (CMS) experiment focuses on studying proton-proton and Pb-Pb collisions generated by the Large Hadron Collider (LHC) at CERN. Its main goals include characterizing the Higgs boson, exploring physics beyond the Standard Model (BSM), and precise measurements of Standard Model quantities. To achieve these, after the completion of Run 3 (expected at the end of 2025), the LHC will undergo its High-Luminosity upgrade (HL-LHC), which should provide, by 2029, proton-proton collisions with an instantaneous luminosity of L = $(5-7.5) \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This luminosity is approximately four times greater than that achieved in previous runs. Moreover, considering the whole activity period of the future accelerator, the HL-LC will provide an integrated luminosity of $3000\mathrm{fb}^{-1}$, accompanied by an increased pile-up of up to 200 interactions. This upgrade presents significant technical challenges for the experiments, demanding several detector enhancements to address higher radiation, detector occupancies, and collision rates. Specifically, the existing CMS endcap calorimeters will be replaced. A new 5-D imaging calorimeter, providing energy, position and timing, is expected to be installed in CMS and to resolve the details of particle showers in an large-pileup environment, thus enabling precise particle flow reconstruction both online and offline.

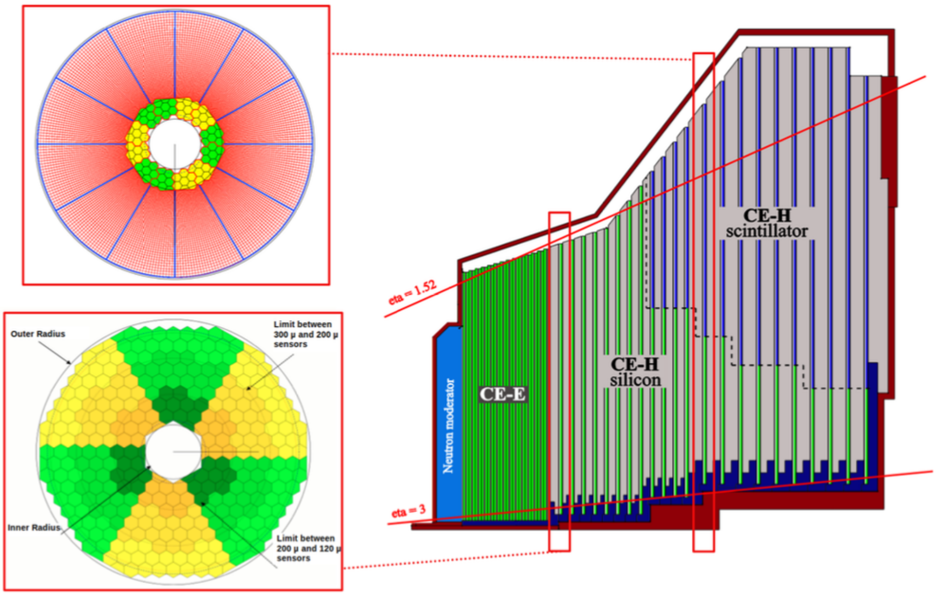

Figure 1: Schematic view of one HGCAL endcap slice (right), a mixed silicon and scintillators layer (top left), and a full silicon layer (bottom left). The majority of the HGCAL will be based on hexagonal silicon sensors with approximately $1\mathrm{cm}^2$ or $0.5\mathrm{cm}^2$ hexagonal cell sizes. The final HCAL interaction lengths in the low η region will be based on plastic scintillator with SiPM readout.

With around six million readout cells, the HGCAL detector will be the first imaging calorimeter to be implemented in High-Energy Physics. It is a 47 layer sampling calorimeter, featuring unprecedented transverse and longitudinal readout and trigger segmentation for both electromagnetic (CE-E) and hadronic (CE-H) compartments [1]. These technical aspects will allow precise measurements of the particle shower structure and resulting in an improved pileup rejection, and particle identification. The CE-E section and a significant portion of CE-H will employ hexagonal silicon sensors as the active detection material. The sections exposed to lower radiation will feature scintillator tiles equipped with on-tile SiPM readout technology. The HGCAL layout is illustrated in Figure 1.

1. The HGCAL Trigger Primitive Generation System

The particularly precise information provided by the HGCAL will be used by the new trigger system to select potentially interesting collision events among the 40 millions produced by the LHC each second. Building such a system is challenging, since it has to maintain the trigger efficiencies and thresholds achieved in Run 2 and Run 3 to preserve the physics performance, and work in the harsher HL-LHC environment. The HGCAL will contribute to the upgraded Level 1 Trigger (L1T) system through the generation of trigger primitives (TP), composed of the reconstructed 3D clusters and trigger towers. In the following, the HGCAL trigger primitive generation (TPG) system is presented [2].

Front-end electronics The calorimeter information is firstly processed by the front-end (FE) electronics. Each HGCAL module is equipped with HGCROC readout chips, which measure the individual cell charges and group them into 48 trigger cells (TCs). Subsequently, TCs are processed by concentrator chips known as ECON-Ts, which each cover one full module and execute an initial TC pre-selection using one of the following algorithms: the Threshold algorithm, which eliminates any TCs falling below a designated energy threshold, the Best-Choice algorithm, that selects a fixed number of the most energetic TCs, or the Super-Trigger-Cell algorithm, that groups TCs into coarser objects called Super TCs. Alongside these functions, the ECON-T computes energy module sums without applying any threshold. Then data flowing from different modules converge into the same motherboard where they are transmitted to the back-end (BE) electronics through low-power GigaBit Transceiver (lpGBT) links at a rate of 10 Gbps.

Back-end electronics The BE electronics comprises two stages, both implemented on dedicated Serenity ATCA boards equipped with Xilinx VU13P FPGAs. The first stage (Stage 1) implements a data aligner and unpacker to receive and group data from the FE per bunch crossing. Its main function is to perform a TCs sorting in ϕ bins. Each Stage 1 FPGA is also responsible for constructing both CE-E and CE-H partial towers by utilizing module sum energy information. Subsequently, data streams are generated and transmitted through time-multiplexing to Stage 2, where the primary reconstruction takes place.

At Stage 2, distinct blocks are implemented, including a data unpacker and packer, responsible for formatting the information received from Stage 1 and sending TPs to the L1T, respectively. Unpacked data follow one of two paths depending on their nature. Trigger tower maps are created in the (η,ϕ) plane starting from partial towers data, while 3D clusters are formed using the sorted TC collections through the following steps. First, the TCs are sorted into fine bins in the r/z (where r is the distance between each TC and the beam pipe) and ϕ plane, in three partially overlapping 180° sectors for each endcap. The resulting histogram is then smeared both in the r/z and ϕ directions, reducing the impact of fluctuations. Local energy maxima (seeds) are then identified and used to built 3D clusters by aggregating all the TCs within a layer-dependent distance ΔR from

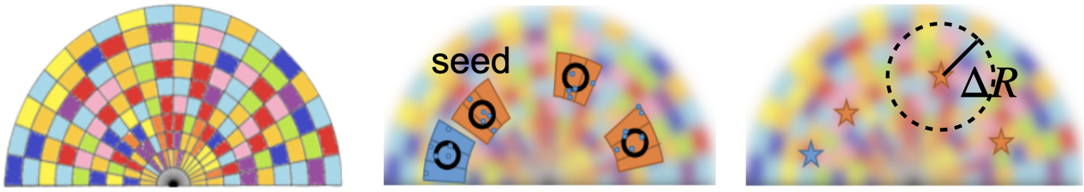

Figure 2: Schematic representation of the clustering steps at Stage 2. In the histogramming step (left), TCs are sorted into 42×108 fine bins in the $(r/z, \phi)$ projective plane. Then a smearing kernel, represented here with blurred background, is applied and the cluster seeds can be found (center). TCs are associated to a specific seed based on a geometrical matching (right).

each seed, in the $(x/z, y/z)$ plane. In cases where multiple nearby seeds exist, the allocation of TCs to a specific cluster is determined by either selecting the one with the shortest distance to the seed or by prioritizing the seed with the highest energy. Finally, the cluster's kinematic and shape characteristics are assessed and optimally encoded to form TPs before being sent to the L1T. Specifically, TPs are transmitted to both the Global Calorimeter Trigger, which gathers information from the barrel and endcap calorimeters, and the Correlator Trigger, whose primary role is to combine TPs from the muon, tracker, and calorimeter subsystems for particle-flow analysis. The most significant cluster reconstruction steps have been illustrated in Figure 2.

2. Ongoing back-end improvements

The back-end electronics of the HGCAL and its reconstruction algorithms are currently under development, requiring ongoing improvements and testing. Specifically, identified issues or weaknesses are being addressed. One of the major critical points to be taken into account is the non-trivial data flow between the FE and the BE electronics. Indeed, as the expected occupancy rate exhibits significant variability within the layers and the η coordinate, the module to motherboard mapping must adapt and vary considerably across different regions of the detector. Moreover, since Stage 2 FPGAs make use of projective coordinates during the clusters' reconstruction, special techniques have been developed to efficiently handle the variable event-by-event data flow within the same $(r/z,\phi)$ bin. For instance, a dedicated TCs sorting algorithm has been introduced at Stage 1.

Several proposals to improve the cluster algorithm are currently under investigation. Indeed, the algorithm employs projective coordinates $(r/z, \phi)$ to generate energy histograms from FE data, resulting in significant variability in the number of TCs per bin depending on their location in the HGCAL detector. In some cases, especially at high η, the bin dimension is smaller than the TC size and leads to nonphysical cluster splitting [3]. An example is shown in Figure 3. On the contrary, at low η, given that the dimension of the bin is much larger than the TCs size, the current algorithm can experience difficulty in separating nearby particle showers.

To address these challenges and to reduce the occurrences of cluster splitting in the current TPG system, various strategies are being explored. A promising method focuses on reducing the variance in the number of TCs per bins along ϕ, the direction along which the cluster splitting is most prevalent. To achieve this, an offline iterative algorithm has been developed to artificially modify the ϕ bin index to which a TC is assigned. Other methods include extending the detector region

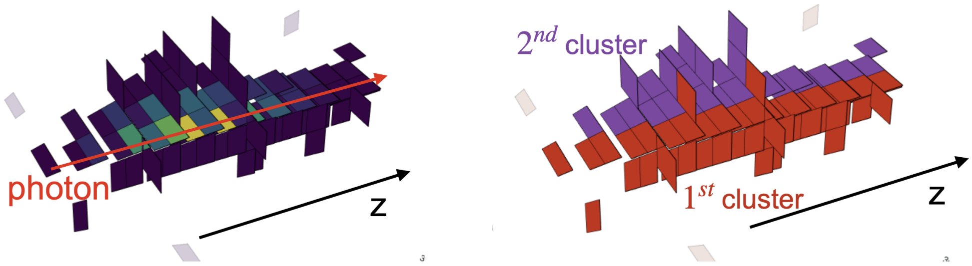

Figure 3: Cluster splitting in a simulated unconverted photon event in the HGCAL, produced using a 0 pileup sample. TCs coloured based on the energy (left), and on the cluster seed index (right).

along ϕ to identify energy local maxima, or adjusting the current smoothing kernel along ϕ before the seeding step, to reduce the number of non-physical local maxima in the 2D energy histograms. Differently from the previous methods, a different seeding algorithm based on natural detector coordinates rather than $(r/z, \phi)$ is being investigated.

3. Conclusions

The CMS collaboration has chosen a novel high granularity calorimeter (HGCAL) to instrument the endcap regions as part of its upgrade for the HL-LHC phase. The calorimeter will contribute to the generation of trigger primitives, which will significantly impact the L1T for both electromagnetic and hadronic objects. Furthermore, when combined with tracking data, they will extend the trigger's capability to high pseudorapidities with excellent performance, and enabling particle-flow techniques.
The HGCAL is comprised of one million TCs, sampled at 40 MHz, and this poses a major data manipulation challenge due to trigger data volumes. Additionally, reconstructing 3D clusters for particle flow in high hit-rate events is a complex computational task. The HGCAL trigger's architecture, design status, and the algorithms developed to address these challenges have been presented. Currently, firmware implementation and hardware testing are ongoing for both HGCAL TPG and L1T electronics, together with the efforts toward further optimizations and the exploration of improved algorithms.

References

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[2] Portales, L. L1 Triggering on High-Granularity Information at the HL-LHC. Instruments 2022, 6(4), 71.

[3] Alves, B. Cluster reconstruction in the HGCAL at the Level 1 trigger. *CHEP*. (2023).