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Concepts and design of the CMS High Granularity Calorimeter Level 1 Trigger

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Abstract

The CMS collaboration has chosen a novel high granularity calorimeter for the endcap regions as part of its planned upgrade for the high luminosity LHC. The calorimeter 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 form part of the Level 1 trigger of the CMS experiment and, together with tracking information that will also be available at this level, should allow particle-flow techniques to be used as part of this trigger. The trigger has tight contraints on latency and rate, and will need to be implemented in hardware. The high granularity results in around six million readout channels in total, a million of which are also used as part of the Level 1 trigger, presenting a significant challenge in terms of data manipulation and processing for the trigger system. The trigger data volumes will be an order of magnitude above those currently handled at CMS. In addition, the high luminosity will result in an average of 140 (or more) interactions per bunch crossing that give a huge background rate in the forward region and these will need to be efficiently rejected by the trigger algorithms. Furthermore, reconstruction of the 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 trigger architecture and design, as well as the concepts for the algorithms needed in order to tackle these major issues, will be presented.

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Concepts and design of the CMS high granularity calorimeter Level 1 trigger

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Abstract: The CMS collaboration has chosen a novel high granularity calorimeter for the endcap regions as part of its planned upgrade for the high luminosity LHC. The calorimeter 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 form part of the Level 1 trigger of the CMS experiment and, together with tracking information that will also be available at this level, should allow particle-flow techniques to be used as part of this trigger. The trigger has tight contraints on latency and rate, and will need to be implemented in hardware. The high granularity results in around six million readout channels in total, a million of which are also used as part of the Level 1 trigger, presenting a significant challenge in terms of data manipulation and processing for the trigger system. The trigger data volumes will be an order of magnitude above those currently handled at CMS. In addition, the high luminosity will result in an average of 140 (or more) interactions per bunch crossing that give a huge background rate in the forward region and these will need to be efficiently rejected by the trigger algorithms. Furthermore, reconstruction of the 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 trigger architecture and design, as well as the concepts for the algorithms needed in order to tackle these major issues, will be presented.

Keywords: Front-end electronics for detector readout; Radiation-hard electronics; Trigger algorithms; Trigger concepts and systems (hardware and software)

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Contents

1 Introduction

The Large Hadron Collider (LHC) has already delivered over 160 fb^{-1} of proton-proton collision data (Run 2) at the center-of-mass energy of $\sqrt{s} = 13$ TeV and with an instantaneous luminosity which is already exceeding the design value of the LHC. However, it is intended to deliver 300 fb^{-1} more by the end of Run 3 (2024). The High Luminosity phase of the LHC (HL-LHC) is planned to begin in 2027. The HL-LHC is planned to operate at an instantaneous luminosity of $5 \times 10^{34}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ and should accumulate around 3000 fb^{-1} by the mid-2030s. The most significant discovery from Run 1 of the LHC was the discovery of the Higgs boson. The current physics program covers a vast physics program consisting of extensive studies of the Higgs boson, Standard Model (SM) measurements, as well as searches of phenomena beyond the SM. The estimated mean number of collisions (pileup) per bunch crossing (BX) at the HL-LHC is of the order of 140–200. The HL-LHC detectors will need to face significant challenges in terms of radiation tolerance and event pileup. The Compact Muon Solenoid (CMS) collaboration [1] is planning an upgrade of its detector systems and infrastructure to deal with the challenging environment of the HL-LHC. The current calorimeters were designed to work efficiently only up to an intergrated luminosity of 500 fb^{-1}. Thus, they would need to be replaced in order to maintain the physics potential of the LHC. The CMS collaboration [1] is proposing to build a High Granularity Calorimeter (HGCAL) [2] with radiation hard technologies to replace the current endcap calorimeters. In order to achieve the physics goals of the HL-LHC, the triggering and reconstruction of physics objects are very important and hold the key to unravel the true physics potential of the HL-LHC.

1.1 High granularity calorimeter

HGCAL is a sampling calorimeter consisting of an electromagnetic (CE-E) part and a hadronic (CE-H) one with 28 and 22 layers respectively. The high transverse and longitudinal segmentation of HGCAL enables efficient particle-flow calorimetry and helps in triggering, pileup rejection and particle identification. The electromagnetic calorimeter and those parts of the hadronic calorimeter

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in a high radiation environment are comprised of hexagonal silicon cells of size (0.5–1.0 cm^2) and with an active thickness of 300, 200 or 120 µm depending on the region of the detector. These cell parameters are selected in order to keep the signal-over-noise ratio high enough for the measurement of MIP signals over the full lifetime of the HGCAL. The remainder of hadronic part is composed of highly-segmented plastic scintillators (4–30 cm^2) read out thanks to silicon photomultiplier (SiPM). Figure 1 shows the longitudinal cross-section of the HGCAL (left) along with the layout of a layer of CE-E (middle) and CE-H (right), respectively. The high-precision timing capabilities of the silicon sensors will be used as an extra dimension in event reconstruction. In addition, the high radiation tolerance of the HGCAL will help in efficient running of the detector even beyond 3000 fb^{-1}. The complete set of details about the HGCAL project can be found in [2].

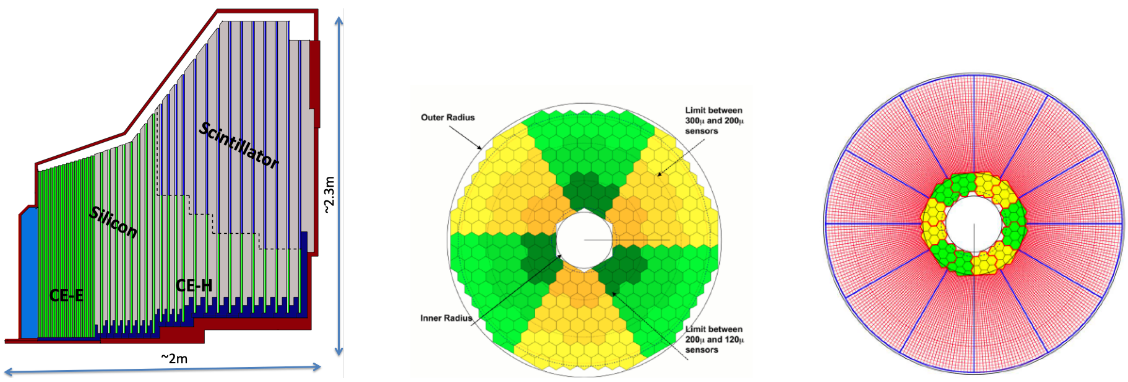

Figure 1. Cross-section of the upper half of one endcap calorimeter (left), layout of a layer of CE-E (middle) and a layer of CE-H (right).

2 HGCAL trigger (electronics and its challenges)

The harsh HL-LHC environment and the high granularity of the HGCAL, with six million silicon readout channels, pose significant challenges for the electronics and trigger requirements of the HGCAL detector. The high dosage of radiation requires the electronics to be radiation hard up to 2 MGy.

2.1 On detector electronics

The Front-End (FE) electronics measures and digitizes the charge deposited in the silicon sensor pads or generated in the SiPMs, provides a high precision measurement of the time of arrival (ToA) of the pulses, and transmits the digitized data to the Back-End (BE) electronics located in the service cavern. It also computes, at every bunch crossing, digital sums of neighbouring cells (2×2 cells in the case of the 1 cm^2 pads silicon sensors, 3×3 cells in the case of the 0.5 cm^2 sensors, and 2×2 cells in the case of scintillator tiles) that are transmitted to the trigger BE electronics to build trigger primitives.

The basic architecture of the FE (on-detector) electronics can be seen in figure 2. The pads of the silicon sensors or the SiPMs are connected to the input of the HGCAL FE ASIC. This chip is called the high granularity readout chip, HGCROC, and it measures the charge and the time of arrival

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at a frequency of 40 MHz. Sums of 4 or 9 adjacent channels (depending on the sensor granularity) are used to form energy sums, called trigger cells (TC). These sums are transmitted for every bunch crossing from the HGCROC to the concentrator ASIC, via separate 1.28 Gb/s electrical links. The trigger concentrator ASIC (ECON-T) performs the reduction of trigger cell data using two types of algorithms. The variable data format algorithm, produces a variable number of units of data per BX, transmits all TC that exceed a programmable threshold per BX ("Threshold" algorithm). The other type of algorithm produces a fixed number of units of data per BX. There are two possibilities for fixed format, "Best Choice", which selects a fixed (programmable) number of TC per BX according to TC charge, and Super Trigger Cells ("STC"), which involves reading out large areas of trigger cells (super trigger cells) with reduced transverse granularity. This compressed set of trigger data is sent to detector Back-End for further processing and clustering to build HGCAL trigger primitives.

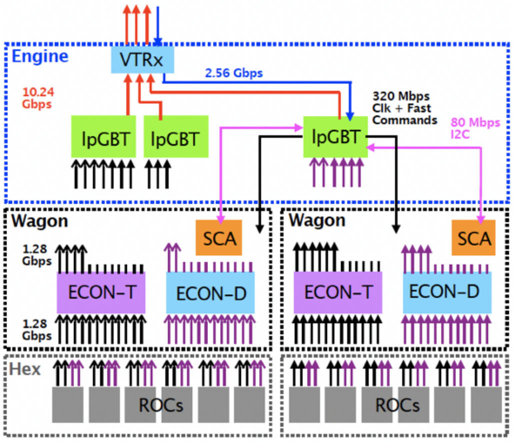

Figure 2. Basic architecture of the FE system consisting of Hexaboards (Hex), housing the HGCROC, and two types of motherboards (wagon and engine) which house the concentrator ASICs for both the trigger (ECON-T) and the data aquisition system (ECON-D) of the detector.

2.2 Off detector electronics

The HGCAL off-detector trigger primitive generator (TPG) system receives FE data and creates trigger primitives and pass them to the CMS central Level-1 Trigger (L1T) system as information to be used for making trigger decisions. The TPG receives FE HGCAL data delivered on radiation-hard low power gigabit transceiver (lpGBT) links. This raw data mainly consist of selected trigger cells and energy sums of the unselected trigger cell energies. The BE electronic boards are based on the CMS common "Serenity" development [3]. This family of ATCA boards will be used in several systems of CMS. The fundamental aim of the Serenity board family is to have a structure that allows a significant number of optical links and up to two large FPGAs per ATCA board. The TPG is implemented in two stages, Stage 1 and Stage 2. Each of the stages is implemented on an array of Serenity boards. Stage 1 receives the raw data links from the FE and does calibration, conversion to transverse energies, and rearrangement of the data. It also time multiplexes the data before transmission to stage 2. Stage 2 is where the clustering is performed to form trigger primitives.

The structure of the system can be seen in figure 3. This represents the system for one endcap only. The two endcaps are treated identically, and within each endcap, the 120° symmetry of the HGCAL TPG is used to process data in terms of three identical sectors which run independently. Stage 1 is served by 72 Serenity boards, i.e. 36 per endcap and hence 12 per 120° sector. For stage 2, with a time multiplex factor of 18, each 120° sector is handled by 18 FPGAs mounted on 9 boards, with each FPGA processing data from a separate BX. This results in 54 boards in total or 27 per endcap. Stage 2 does the clustering of trigger data to produce 3D cluster objects. This is performed in two steps: a) Seeding — seeds the clusters from an energy weighted maxima obtained from a 2D histogram (binned in r/z, ϕ) with the seed defined above a certain threshold value; b) Clustering: associate all trigger cells to seeds within a maximum scaled distance (programmable), $\Delta\rho$. If more than one seed lie within the distance, then the trigger cell is associated to the cluster with the nearest seed. These associated trigger cells are further used to calculate the properties of each 3D cluster, i.e., position, energy and shape variables.

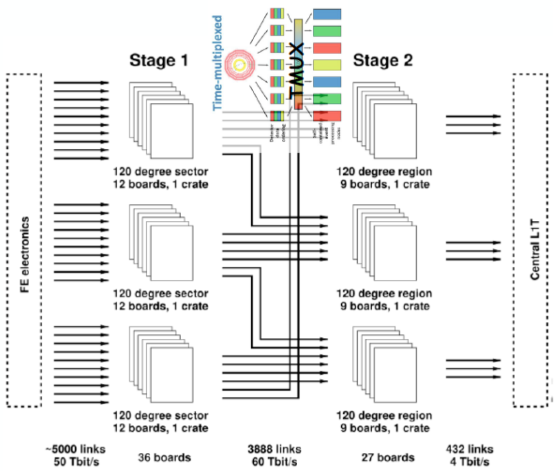

Figure 3. Basic architecture of the Back-End TPG system showing the layout of Stage 1 and Stage 2 boards for one endcap. The full TPG system consists of two identical and independent copies of this layout.

2.3 Physics object performance

The impact of the FE selection algorithms (described in 2.1) on the performance of physics objects has been studied. The 3D clustering parameters (for example — clustering radius ($\Delta\rho$)) were optimized for each FE algorithm option in order to obtain a fair comparison between the algorithm options. Figure 4 shows the performance of the jet resolution as a function of jet p_T (left) and the level-1 trigger rates obtained for the electron objects reconstructed using HGCAL information (right). It shows that the choice of FE algorithm affects jet resolution performance at higher values of p_T and the "Threshold" FE algorithm option gives the lowest electron rates at level-1 trigger with a pileup of around 200.

3 Summary

The CMS High Granularity Calorimeter trigger project is a very challenging venture for the HL-LHC upgrade, due to the high luminosity conditions, harsh radiation environment, high pileup and

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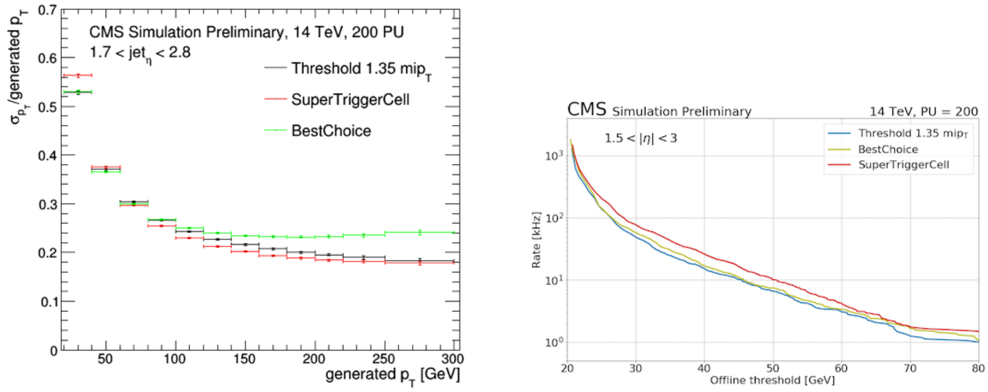

Figure 4. Impact of FE selection algorithms on the performance of physics objects.

the stringent requirements needed on its performance. There have been significant developments in the area of defining the Front-End and Back-End system architecture, hardware, and algorithms. Extensive studies are being performed to study the performance of the HGCAL trigger. Ongoing studies will balance performance and resource utilization, resulting in an optimal system.

Acknowledgments

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