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DESIGN CHALLENGES OF THE CMS HIGH GRANULAR CALORIMETER LEVEL 1 TRIGGER

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The high luminosity (HL) LHC will pose significant detector challenges for radiation tolerance and event pile-up, especially for forward calorimetry. This will provide a benchmark for future hadron colliders. The CMS experiment has chosen a novel high granularity calorimeter (HGCAL) for the forward region as part of its planned Phase 2 upgrade for the HL-LHC. Based largely on silicon sensors, the HGCAL features unprecedented transverse and longitudinal readout segmentation which will be exploited in the upgraded Level 1 (L1) trigger system. The high channel granularity results in around one million trigger channels in total, to be compared with the 2000 trigger channels in the endcaps of the current detector. This presents a significant challenge in terms of data manipulation and processing for the trigger. The high luminosity will result in an average of 140 interactions per bunch crossing and along with it a higher rate of background in the endcap for trigger algorithms to mitigate. Three-dimensional reconstruction of the HGCAL clusters in events with high hit rates is also a more complex computational problem for the trigger than the two-dimensional reconstruction in the current CMS calorimeter 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 and their impact on trigger object performance, will be presented.

Keywords: HL-LHC, HGCAL, Trigger, CMS.

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1. Introduction

With the end of the large hadron collider (LHC) Phase-1 in 2023, the accelerator will undergo an upgrade in luminosity (high luminosity LHC or HL-LHC) [1]. The Phase-2 of the physics program will see an increase of pile-up from ~50 to 140-200 interactions per bunch crossing, reflecting the luminosity increase from $\sim 2\times10^{34}$ to $5\text{-}7\times10^{34}$ cm^{-2} s^{-1}. The current CMS detector [2] is not designed to withstand these levels of radiation and pile-up. For this reason, a significant detector upgrade is also foreseen. In particular, the radiation dose in the endcap regions has imposed a complete redesign of the endcap calorimeters. The high-granular calorimeter (HGCAL) has been chosen as the solution for the Phase-2 upgrade of CMS.

2. The high-granular calorimeter

The HGCAL [3] will include both electromagnetic (CE-E) and hadronic (CE-H) calorimeters in one. It is a sampling calorimeter whose active layers will adopt a fully silicon technology for the CE-E and a hybrid silicon-scintillator for CE-H. The silicon is needed in order to achieve high radiation tolerance (up to 10 MGy at 3 pb^{-1} see Fig. 1) and the scintillator to reduce costs where possible. The detector's high granularity (cell size of 0.5 and 1.2 cm^2 depending on θ position, where θ is the azimuthal angle and φ is the inclination) requirement will improve jets separation at low angles. Each detector endcap will be formed by 28 layers (CuW+Cu+Pb absorber and 25 X_0 + 1.3 λ_0) in the CE-E region and 22 layers (stainless steel absorber and 8 λ_0) in the CE-H region (Fig. 1).

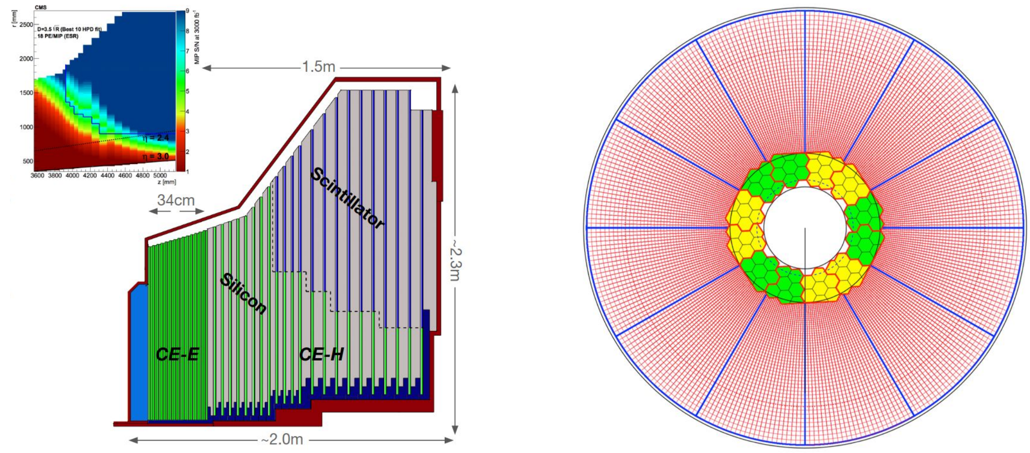


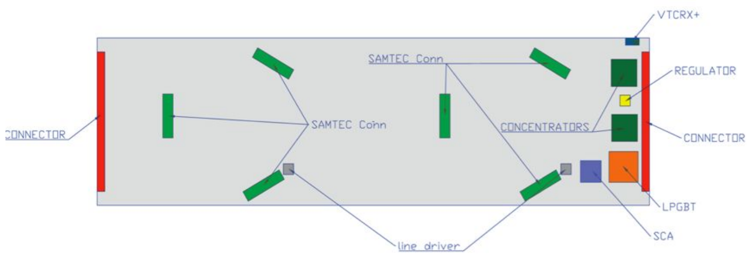
Figure 1. Left-Top: signal/noise ratio for one MIP in scintillator at the end of the HGCAL life span. Left-Bottom: the HGCAL lateral view. Right: an HGCAL hybrid layer, in red the scintillator tiles and in green-yellow the silicon modules

An HGCAL active layer is reported in Fig. 1. One of the main challenges, while designing the detector, has been the one-order-of-magnitude variability of bandwidth across the detector. In order to adapt to this variability, each detector element is mounted on motherboards of variable size (see Fig. 2).

3. The trigger primitive generator

The capability to trigger on complex objects in the forward region will be a key feature of the CMS detector during the HL-LHC. One compelling physics signature to study is weak vector boson fusion production of both standard model vector boson and new physics, which often produces two jets in the endcaps. One of the key points has been to reduce the bandwidth while balancing the reduction in physics performance. To achieve this goal, several key design choices have been studied and implemented into simulations:

- Trigger data are readout with a coarser granularity: 1/4 or 1/9 of the full granularity (depending on the θ region),
- electromagnetic section CE-E contributes to the trigger using every other layer,
- time information are not transmitted to the trigger processor,
- trigger cells data are not sent to the backend if a programmable energy threshold is not reached,
- in case of buffer overflows the system is designed to drop data outside the latency window.



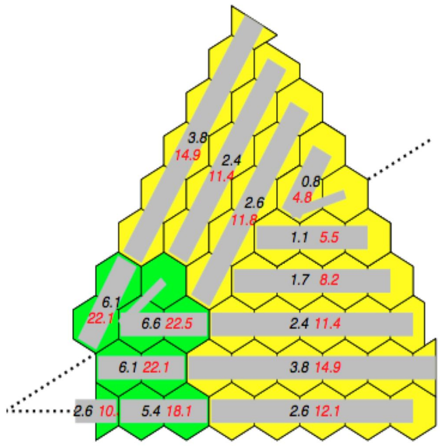


Figure 2. Left: Example of a motherboard. Right: silicon modules grouped into motherboards (grey boxes), bandwidth in Gbps is reported for both data (black) and trigger (red)

The trigger primitive generator will implement its algorithms over the Serenity platform [4]. This is a flexible ATCA blade able to host different Xilinx FPGAs. This flexibility allows the collaboration to optimize the hardware resources to the specific sub-system. Moreover, the Serenity community provides all the common infrastructure letting the HGCAL developers focusing on detector-specific firmware development. The trigger primitive will be a collection of three-dimensional clusters that the Central Level 1 trigger processor will use to implement particle flow algorithms [5] in firmware.

The general overview of the HGCAL trigger primitive generator is presented in Fig. 3. It consists of 2 stages. It is based on a time multiplex (TMUX) architecture (see Fig. 3) [6], a fundamental choice that reduces the intr-FPGA data sharing hence bandwidth, and concentrate the data from the same bunch crossing and an entire region of the detector (in the HGCAL case a 120º sector) in a single processor unit.

The detector upgrade will increase also the total allowed latency for the trigger path, from the current 4 μs to 12.5 μs. This will include the central trigger processor latency and all the hardware contributions. The total latency allocated to the HGCAL tigger primitive generator (TPG) is 5 μs. This latency is the sum of the fixed contributions from upstream electronics (e.g. front-end, concentrator ASIC, SerDes and TMUX) and contribution from data processing int the trigger firmware. The fixed latency from upstream electronics amounts to 2.2 μs, leaving ca. 2.8 μs for TPG algorithm development.

Stage 1 receives data from the front-end electronics via low power gigabit transceiver links (lpGBT) [7]. This stage is implemented using Xilinx Kintex Ultrascale+ FPGAs (KU15P). Each FPGA collects data from 72 links and implements: trigger cell calibration, previous bunch crossing correction (large energy deposits have effects on several consecutive bunch crossings) and time multiplex.

Stage 2 implements the trigger primitive generation. It is planned to mount Xilinx Virtex Ultrascale+ FPGAs (VU7P). Each FPGA is collecting data for the full depth of a 120º sector. The current time multiplex period is set to 18 bunch crossing (450 ns). This is a clear design choice in order to keep the system flexible for future updates of the firmware.

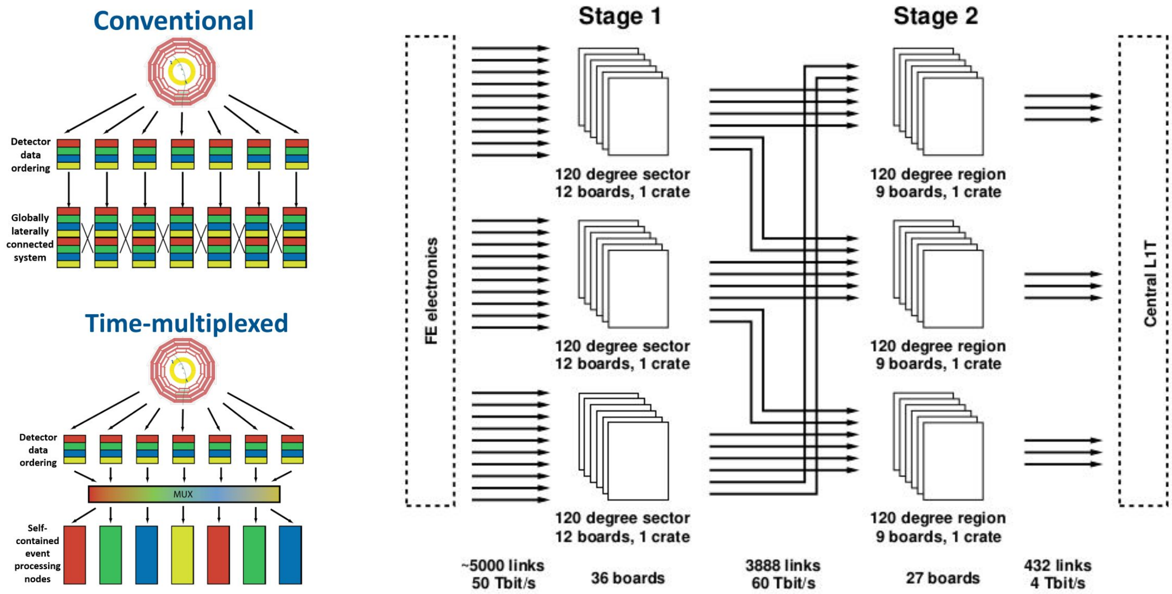


Figure 3. Left-top: conventional data flow in which each FPGA collects data from all bunch crossings. Left-bottom: TMUX architecture, each FPGA collects data from one bunch crossing. Right: HGCAL trigger primitive generator (TPG) architecture

Currently, the baseline for the Stage 2 algorithm adopts an imaging algorithm for the cluster reconstruction. The algorithm is split into two logically separated steps, the first one generates seeds to be passed to the second where the actual clusters are built.

The seeds are generated using a histogram. The histogram is built using the position and energy of all the Trigger cells projected to the (r/z, φ/z) plane (where z is the distance from the interaction point along the beam axis and r the transversal distance form the). Once all the trigger cells are collected into the histogram a Gaussian smearing function is applied over all the histogram bins. This is crucial to removing local fluctuations and identify the local maxima that are then used as seeds. An example of this procedure is illustrated in Fig. 5.

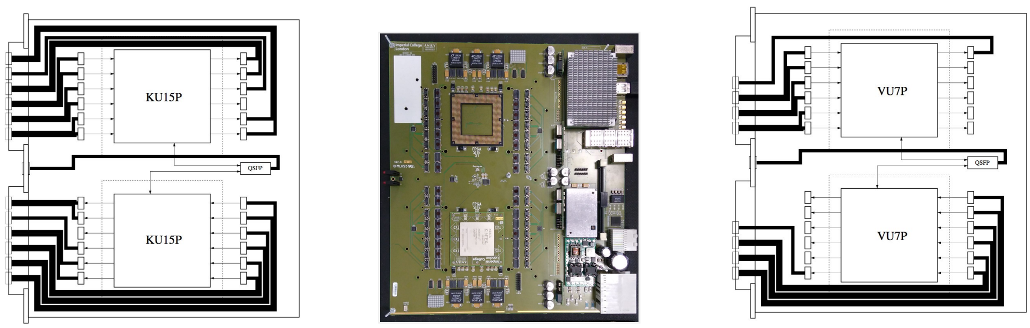


Figure 4: Left: Serenity board configuration for HGCAL Stage 1 TPG, black lines denotes physical links. The board will collect data form 144 lpGBT links (72 per FPGA) at 10 Gbps and transmit calibrated and time-multiplexed data to Stage 2 (Right) via 54 16 Gpbs links, 3 for each Stage 2 board. Centre: an example of Serenity ATCA board, clearly visible the interposer technology that

allow us to replace the FPGA (on the top half of the picture). The bottom half of the picture shows an FPGA mounted on the interposer. Right: Serenity board configuration for HGCAL Stage 2 TPG, which receives data from all the Stage 1 boards via 72 links at 16 Gpbs and transmits the primitives to the central correlator.

The second step consists in collecting the trigger cells around a seed and within a programmable radius (in the (r/z, φ/z) plane).

Finally the three-dimensional clusters are formed and relevant information are extracted (e.g. position, energy and shape).

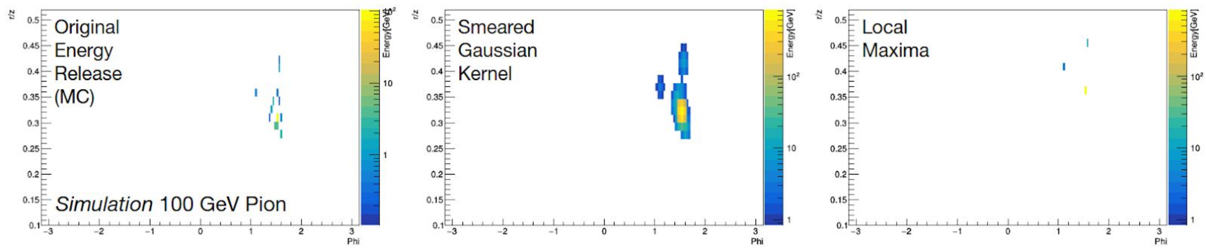


Figure 5: Example of seeding for the HGCAL three-dimensional clustering. Left: the histogram is filled with the trigger cells energy and position. Centre: Gaussian smearing is applied in order to remove local fluctuations. Right: seeds are selected as local maxima

4. Conclusions

The HGCAL and its trigger primitive generator designs are facing new challenges dictated by the unprecedented at LHC pile-up levels and radiation dose that the system must withstand. This note describes the main problems faced and proposed solutions found have been presented. A careful study of the trigger path and algorithms is underway in order to ensure the performance needed to fulfil the future challenges. An important role has been played by the implementation choice of adopting the Serenity platform, this has allowed the collaboration to tailor resource, hence costs, to the specific problem. The hardware tests and the firmware implementation has started.

References

[1] G. Apollinari, O. Bruening, T. Nakamoto, L. Rossi, "High Luminosity Large Hadron Collider HL-LHC", *CERN Yellow Report* CERN-2015-005, pp.1-19.

[2] The CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST 3* (2008) S08004.

[3] The CMS Collaboration, "The Phase-2 Upgrade of the CMS Endcap Calorimeter", *CERN-LHCC-2017-023*; *CMS-TDR-019*.

[4] G. Ardila al., "Serenity: An ATCA prototyping platform for CMS Phase-2", in proceedings of "Topical Workshop on Electronics for Particle Physics", *PoS(TWEPP2018)115*, DOI: https://doi.org/10.22323/1.343.0115.

[5] The CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST 12* (2017) P10003.

[6] R. Frazier at al., "A demonstration of a Time Multiplexed Trigger for the CMS experiment", *JINST 7* (2012) C01060.

[7] P. Moreira st al., "The LpGBT Status, in Common ATLAS CMS Electronics Workshop for SLHC", CERN/Geneva, Switzerland, March 2015.