CMS Electromagnetic Trigger commissioning and first operation experiences

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Abstract. The CMS electromagnetic calorimeter (ECAL) is a high-resolution calorimeter made of 75848 lead tungstate crystals and optimized for the discovery of the Higgs boson in its two photon decay mode. In view of the high raw event rate at the Large Hadron Collider, the ECAL Trigger will play a major role. This paper reviews the strategy and the tests completed to ensure that the ECAL Trigger reaches the required specifications. The results from the commissioning and the first experiences with cosmic ray data are presented.

1. Introduction

The Compact Muon Solenoid (CMS) [1] is a general-purpose detector that operates at the Large Hadron Collider (LHC). This proton-proton collider will reach an energy of 14 TeV in the centre of mass and a high luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ with a bunch-crossing rate of 40 MHz. The CMS trigger system has the formidable task of reducing the input data rate by a factor of $O(4.10^5)$. This reduction is made in 2 stages. The CMS data acquisition system is designed to accept an input rate of 100 kHz, with event size of the order of 1.5 MB. In the first stage, the trigger system uses a custom Level-1 [2] processor to select these 100 kHz of events from the input bunch crossing rate. This selection is based on coarsely segmented data from the calorimeters (electromagnetic and hadronic) and the muon detector systems. During the 3.2 μs latency of the Level-1 trigger, the event data are stored in front-end pipelines. The second stage of the event rate reduction, the High Level Trigger, is made in a farm of standard commercial processors that achieve an output rate of $O(10^2)$ Hz which will be written to permanent storage.

The CMS electromagnetic calorimeter (ECAL) is one of the 3 subdetectors involved in the Level-1 trigger decision. It is a high-resolution calorimeter made of 75848 lead tungstate (PbWO$_4$) crystals and optimized for the discovery of the Higgs boson in its two photon decay mode. Avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps. The ECAL barrel crystals are slightly tapered with front-face dimensions of $2.2 \times 2.2$ cm$^2$ and a crystal length of 23 cm ($25.8 X_0$). The barrel covers a range $|\eta| < 1.48$ and consists of 36 supermodules each containing 1700 crystals. The 2 endcaps extend the coverage up to $|\eta| < 3$. A trigger tower in the ECAL barrel is made up of $5 \times 5$ PbWO$_4$ crystals, following the HCAL segmentation $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$, whereas in the end-cap, the size of the trigger tower varies with the pseudorapidity in order to follow approximately a projective geometry.

This paper is organized as follow: in the next section, the calorimeter trigger system is described with an emphasis on the ECAL trigger primitives. The section 3 reviews the different
steps of ECAL trigger commissioning. Finally, the last section is devoted to the first operation experiences with cosmic ray events.

2. The Level-1 calorimeter trigger

The Level-1 calorimeter trigger is able to define up to 4 isolated or non-isolated electromagnetic objects (electron or photon), 4 tau-jets, 4 central or forward jets, the total transverse energy and the missing transverse energy.

2.1. Algorithm of the electron/photon Level-1 trigger

The electron/photon Level-1 trigger algorithm [2] displayed on figure 1 uses a $3 \times 3$ trigger towers sliding window. The transverse energy of an electron/photon candidate is defined by the transverse energy deposit in the central tower of the sliding window summed with the largest deposit in one of its 4 neighbor towers adjacent by side (see figure 1). Electromagnetic showers being characterized by a compact lateral extension, only candidates with a central tower containing 2 adjacent strips (5 crystals in $\phi$ are called a strip) with a significant fraction of the tower energy (typically 90%) are kept. This criterion characterized by 1 bit is called the Fine Grain (FG) veto bit. Moreover, the associated HCAL energy contribution is required to be below a threshold (typically H over E $<$ 5%). Non-isolated electron/photon candidates require passing the previous criteria (FG and H over E). In addition, the isolated candidates must have a quiet neighborhood characterized by at least five adjacent trigger towers among the 8 nearest ones with their transverse energy below a threshold.

![Figure 1. The L1 trigger algorithm of calorimeters](image)

2.2. The ECAL trigger primitives

The trigger primitives of the electromagnetic calorimeter are basic quantities allowing the identification of electromagnetic showers by the Level-1 calorimeter trigger. They are computed for each bunch crossing and for all trigger towers. The trigger primitives are generated by two different sub-systems located on the On-Detector electronics and the Off-Detector electronics. The On-Detector electronics is composed of radiation resistant circuits located just behind the PbWO$_4$ crystals and the trigger primitives are generated by the Front-End (FE) boards. The
trigger primitives are then completed by a dedicated 9U VME board called Trigger Concentrator Card (TCC) [3] belonging to the Off-Detector sub-systems located in the electronics cavern. The two sub-systems are connected by about 70 m serial optical links working at 800 Mbits/s. 3072 Front-End boards and 108 TCC boards are necessary to manage the trigger flow of the whole calorimeter.

The ECAL trigger primitive algorithm is displayed on figure 2 and 3. The 5 digital signals from the crystals of a strip are first linearized (see figure 2). The linearization process takes into account the gain used in the readout electronics and corrects the ADC counts by the calibration coefficients. A multiplicative factor is applied to get linearized ADC counts proportional to the transverse energy deposit in the crystal. The 5 linearized signals of the crystal are then summed up to produce the strip signal. An amplitude filter is applied to measure the amplitude of the strip pulse. The filter is based on linear weighted sums where the weights take into account the expected shape of the signal and subtract dynamically a possible residual pedestal. The output of the amplitude filter is then filtered by a peak finder stage that keeps only the maximum as a measure of the transverse energy contained in the strip.

![Figure 2. The ECAL trigger primitive algorithm: from the crystals to the strip.](image)

The signals of the 5 strips of a tower are finally summed up to provide a measurement of the total transverse energy of the trigger tower (see figure 3). The dynamic range of the transverse energy must then be reduced from 10 bits to 8 bits. Look-up tables are used for this purpose. The look-up tables are chosen so that the loss of resolution due to the compression follows approximately the intrinsic ECAL resolution. In parallel, the signals of the strips are combined in a Fine Grain filter producing 1 bit, the fine grain veto bit, indicating the transverse extent of the electromagnetic energy deposit.

In summary, the ECAL trigger primitives are made of the total transverse energy of the trigger tower uncoded on 8 bits, accompanied by the fine grain bit. They are computed for all trigger towers and for each bunch crossing.

2.3. The Level-1 ECAL trigger path

The trigger primitives from both electromagnetic and hadronic calorimeters are sent to the Regional Calorimeter Trigger (RCT). One RCT crate covers a region of the calorimeters of 40°
Figure 3. The ECAL trigger primitive algorithm: from the strips to the tower

in $\phi$ (equivalent to 2 ECAL supermodules) and up to $|\eta| < 5$. RCT applies the algorithm described in section 2.1 to produce isolated and non-isolated electron/photon candidates. The 4 candidates of each region with the highest energy are sent to the Global Calorimeter Trigger (GCT) that sorts out all candidates according to their energy. Only the 4 most energetic are sent to the Global Trigger. The decision to issue a Level-1 accept signal is thus based on these candidates for what concerns the ECAL trigger.

3. Commissioning of the electromagnetic calorimeter trigger

The commissioning of the electromagnetic calorimeter trigger is divided in two parts: the commissioning of the electronics components, boards and links, and the commissioning of the ECAL trigger primitives.

3.1. Commissioning of the electronics cards

There are 3 kinds of ECAL electronics cards involved in the ECAL trigger:

- the Front-End (FE) boards performing the pre-trigger primitives calculation per trigger towers,
- the Trigger Concentrator Cards (TCC) finalizing the trigger primitives calculation for a whole supermodule (barrel) or $20^\circ$ sector in $\phi$ (endcaps),
- the Synchro Link Boards (SLB), mezzanine cards plugged on the TCC, in charge of the synchronization (time alignment) of the trigger primitives.

For the barrel, it represents a total of 2448 FE boards, 36 TCC boards and 324 SLB cards. All cards were first tested after the production thanks to dedicated test-benches located in the different labs in charge of the production. See for example [3] and [4] for more details. In a second stage, when the boards were assembled, integration tests were performed. The FE boards were tested during the assembling of the supermodules in the integration center at CERN. For these tests, the FE boards were configured to send a word representing its ‘Id’. Prototypes of the TCC, configured in ‘spy mode’ (filling of input buffers allowing the capture of the data) were
used to receive and check the word content with respect to the expectation. The TCC and SLB boards were tested during the assembling of the ECAL Off-detector crates in the electronics integration center at CERN. For this purpose, a tester module able to emulate the front-end was used: patterns were loaded in its memory and sent after serialization to the TCC and SLB. The data received by the TCC and SLB were then captured and analyzed quasi on-line. Once the supermodules and the Off-detector crates had been installed in the experimental and service caverns, the previous integration tests were reproduced.

3.2. Commissioning of the links between ECAL and the Regional Calorimeter Trigger

The previous tests involve only ECAL components. However, the testing of the links between ECAL and the Regional Calorimeter Trigger (RCT) is also important. These tests, also known as pattern tests, use the TCC boards as a pattern generator. Indeed, patterns were loaded (though VME) in dedicated memories of the TCC. In this mode, the TCC doesn’t process the data from its optical inputs but the ones from its memory. The patterns were chosen to allow to activate an individual output channel per clock. On the RCT side, the data were received and compared on-line to the expectation. These simple tests revealed among other things few errors in the cabling. It is foreseen to apply this procedure regularly to check the quality of the signals between ECAL and RCT, in particular the stability of the phase of the signals.

3.3. Commissioning of the trigger primitives

The commissioning of the trigger primitives constitutes a severe test of the ECAL trigger. It is based on the comparison to emulated trigger primitives. The emulator is software that reproduces at the bit level the hardware response. It is therefore used to monitor the hardware and was initially tuned and checked with test beam data. All the operations described in section 2.2 are performed by the emulator taking into account the number of bits used for each calculation. The principle of the test with the emulator is the following: for each trigger tower, there are 2 streams of data sent to the DAQ when a level-1 accept signal is issued: the 10 consecutive ADC samples of the 25 individual crystals and the trigger primitive. The emulator uses the crystal data to reproduce the trigger primitives pipeline. However from the 10 samples of crystal data, only 5 trigger primitives can be computed (the amplitude filter needs 5 samples). The trigger primitive stored in the event is then compared to the 5 emulated trigger primitives. If none of them matches the real data, it indicates a problem in the hardware. Moreover, if the data are properly timed-in with respect to the level-1 trigger signal, the same emulated trigger primitive should match the data for all trigger towers. The procedure previously described has been regularly applied during runs and was found to be very useful to properly time-in the ECAL trigger with the detector.

4. First operation experiences with cosmic ray events

Since May 2007, the CMS collaboration organizes regularly global runs lasting several days. These global runs constitute a coherent exercise of CMS data taking in preparation for LHC collisions. The level of complexity is increased for each new global run, more and more subsytems becoming involved. In 2007, the electromagnetic calorimeter participated several times in global runs. However, only the readout of ECAL data was tested. In 2008, for the first time, ECAL participated in the global runs as a component of the trigger system trying to trigger on cosmic ray signals deposits in the crystals. However, a muon crossing longitudinally a PbWO₄ crystal loses about 250 MeV as a minimum ionizing particle. Since the noise level per channel is equivalent to about 40 MeV, it is too large with respect to mips signal to provide an efficient trigger. Therefore, a special setting of ECAL is used to increase the signal to noise ratio: the bias voltage applied to the APD is increased to multiply the nominal APD gain by a factor 4, the noise level being then equivalent to 10 MeV. In addition, a threshold is applied at the ECAL
trigger tower level: trigger primitives below about 200 MeV are zeroed. The mips signal being mainly contained in a single trigger tower, this threshold decreases the noise contribution due to the second tower used by the Level-1 calorimeter trigger algorithm (see 2.1). Finally to keep the trigger rate under control, the double electron stream is used requiring a coincidence between the top and bottom sectors of ECAL.

Many events have been taken with the configuration 'mip trigger' described before, where the whole barrel was readout and the 8 supermodules located in the top-bottom region were involved in the trigger decision. Given the small amplitude of the mips signal, any problematic channel can pollute the signal and may pass the very low threshold applied. ECAL trigger is thus a perfect tool to reveal noisy channels. A systematic scan of all supermodules has been performed and about 2% of the ECAL trigger towers have been declared as noisy for mips trigger conditions. However, as soon as the threshold will be increased for beam collision (the typical trigger threshold will be of the order of 20 GeV) only very few towers will remain classified as noisy. The measurement of the noise rate as function of the threshold for all towers of the whole barrel is still an on-going activity.

During the global run of May 08, more than 23 million events were recorded by ECAL. ECAL mips trigger and usual muon subdetectors triggers were active. An analysis searching for cosmic events, requiring at least 1 crystal with an energy greater than 135 MeV or 2 adjacent crystals with each containing more that 45 MeV has shown that more than 2.2% of the events passing the cosmic selection were triggered by ECAL, the muon detector trigger bits (mainly from Drift Tubes) being also fired in a large fraction of these events. An example of such an event is shown in figure 4. The tracks in the muon chambers are clearly seen in both top and bottom sectors. The energy deposit in the top cluster of ECAL is 15 GeV shared by 17 crystals, so clearly not a muon at minimum ionization but rather an energy loss by bremsstrahlung. The energy deposit of the bottom cluster is 1.15 GeV. Both top-bottom clusters and muon tracks are compatible with a muon crossing the CMS detector.

5. conclusion
The commissioning of the ECAL barrel trigger has been presented. The ECAL trigger has been successfully commissioned with all the other subsystems of the CMS trigger chain, starting from the front-end of ECAL up to the Global Trigger system. It has been operated successfully and a large number of cosmic ray events have been recorded during the global runs.

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Figure 4. A cosmic ray event triggered by ECAL detector and seen in muon chambers and ECAL.