

# Installation, Commissioning and Performance of the CMS Electromagnetic Calorimeter Electronics

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## Abstract

This contribution reviews the CMS high resolution electromagnetic calorimeter (ECAL) and its commissioning within CMS in situ.

## I. CMS: A DETECTOR FOR LHC

The Compact Muon Solenoid (CMS) detector is a multi purpose apparatus due to operate at the Large Hadron Collider (LHC) at CERN. LHC will yield head on collisions of two proton (ion) beams of 7 TeV (2.75 TeV per nucleon) each, with a design luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  ( $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ ).

A complete description of the CMS detector can be found in [1]. Here we report a short summary.

The overall layout of CMS is shown in Fig. 1. At the heart of CMS sits a 13 m long, 6 m inner diameter, 4 T superconducting solenoid providing a large bending power (12 Tm) before the muon bending angle is measured by the muon system. The return field is large enough to saturate 1.5 m of iron, allowing 4 muon stations to be integrated to ensure robustness and full geometric coverage. Each muon station consists of several layers of aluminium drift tubes (DT) in the barrel region and cathode strip chambers (CSC) in the endcap region, complemented by resistive plate chambers (RPC).

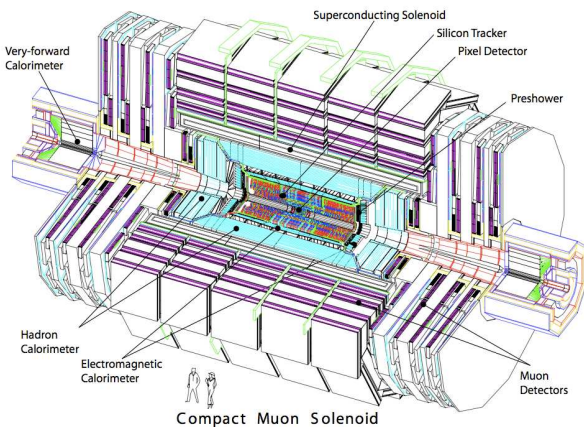


Figure 1: The CMS detector

The bore of the magnet coil is large enough to accomo-

date the inner tracker and the calorimetry inside. The tracking volume is given by a cylinder of 5.8 m length and 2.6 m diameter. In order to deal with high track multiplicities, CMS employs 10 layers of silicon microstrip detectors, which provide the required granularity and precision. In addition, 3 layers of silicon pixel detectors are placed close to the interaction region to improve the measurement of the impact parameter of charged particle tracks, as well as the position of secondary vertices. The electromagnetic calorimeter (ECAL) uses lead tungstate ( $\text{PbWO}_4$ ) crystals with coverage in pseudorapidity up to  $|\eta| < 3.0$ ; ECAL is surrounded by a brass/scintillator sampling hadron calorimeter (HCAL) with the same coverage. HCAL is extended by an hadron forward calorimeter (HF) to cover up to  $|\eta| < 5.2$ .

## II. THE CMS ELECTROMAGNETIC CALORIMETER

The geometrical structure of ECAL is shown in Fig. 2. The barrel part of ECAL (EB) covers the pseudorapidity range  $|\eta| < 1.479$ . The barrel granularity is 360 fold in  $\phi$  and (285) fold in  $\eta$ , resulting in a total of 61 200 crystals. The crystals have a tapered shape, slightly varying with position in  $\eta$ . They are mounted in a quasi projective geometry to avoid cracks aligned with particle trajectories, so that their axes make a small angle ( $3^\circ$ ) with respect to the vector from the nominal interaction vertex, in both the  $\phi$  and  $\eta$  projections. The crystal length is 230 mm corresponding to 25.8 radiation length. The barrel crystal volume is  $8.14 \text{ m}^3$  and the weight is 67.4 t.

The full barrel calorimeter is divided into 2 equal cylinders of radius 1.29 m. Each cylinder is made of 18 supermodules. A supermodule (SM), 1700 crystal, is divided along  $\eta$  into 4 different modules, each containing 400 or 500 crystals. Four modules, separated by aluminium conical webs 4 mm thick, are assembled in a SM.

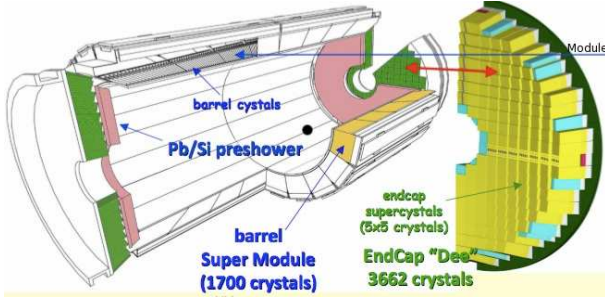


Figure 2: Geometrical structure of the ECAL calorimeter

The endcaps (EE) cover the rapidity range  $1.479 < |\eta| < 3.0$ . The longitudinal distance between the interaction point and the endcap envelope is 315.4 cm; the endcap consists of identically shaped crystals grouped in mechanical units of 55 crystals (supercrystals, or SCs). Each endcap is divided into 2 halves, or Dees which holds 3662 crystals. The crystals and SCs are arranged in a rectangular  $x - y$  grid, Fig. 3, with the crystals pointing at a focus 1300 mm beyond the interaction point, giving off pointing angles ranging from 2 to 8 degrees. The endcaps crystal volume is  $2.90 \text{ m}^3$  and the weight is 24.0 t.

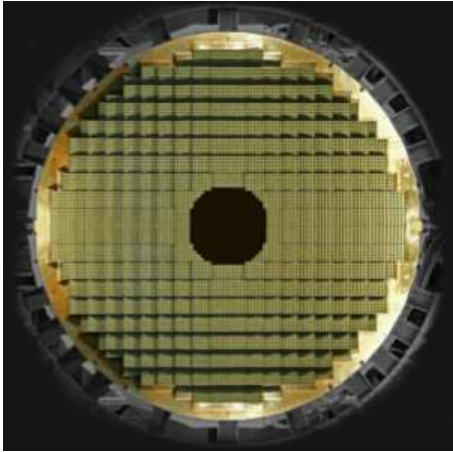


Figure 3: The crystals of the endcap calorimeter

### III. ECAL CONSTRUCTION AND INSTALLATION

The *ECAL project* spans many years and several hundreds collaborators. In September 2008 ECAL comprises about 200 PhD physicists.

The decision to use  $PbWO_4$  (instead of Cerium Fluoride) has been taken around the middle of September of 1994: TWEPP2008 marks almost exactly the 14th anniversary of that day. When the calorimeter material was finalized CMS was not yet officially existent: CMS had been proposed (Oct. 1992) but not approved yet (it happened on 31 Jan. 1996). The ECAL hardware procurement and construction phases lasted about 10 years. Crystals had been produced mostly in Russia, with a

contribution of 1531 barrel crystals and 2593 endcap crystals from China; the a production rate has been about 10,000 crystals/year. Modules have been built in two construction sites, Casaccia INFN laboratories near Rome and CERN, and then assembled in SMs at CERN: the first SM (without electronics) was completed in 2002 and the last in 2007. Endcaps Dees had been built in 2007 and 2008.

### IV. ANCILLARY SYSTEMS

The installation of a large system such as ECAL has as a *pre-requisite* several ancillary subsystems such as cooling, ECAL safety system and the the detector control system (DCS).

The cooling system has a double duty: the first and most obvious one is to remove the heat produced by the electronics, estimated to be 180kW while the second task is to ensure temperature stability to the photodetectors (especially the APD in the barrel) and crystals since the number of scintillation photons emitted by the crystals and the amplification of the APD are both temperature dependent. In the barrel the total water flow has been set at  $50 \text{ l/s}$  (each SM has a flow of  $1.39 \text{ l/s}$ ). A major task for the ECAL DCS is the monitoring of the crystals and APDs temperature and the verification that the required stability of  $\pm 0.05^\circ\text{C}$  of the is achieved.

The purpose of the ECAL Safety System (ESS) is to monitor the air temperature of the front end environment (expected to be around  $25 \text{ }^\circ\text{C}$ ), the water leakage detection cable, which is routed inside the the detector and the proper functioning of the cooling system. ESS automatically perform pre defined safety actions and generate interlocks in case of any alarm situation. The read out system, with full built in redundancy, is independent of the DAQ and control links and based on a Programmable Logic Controller (PLC). In case of any critical reading hard-wired interlock signals are routed to the relevant crates in order to switch off the high voltage (HV) and low voltage (LV) and/or the cooling PLC in order to stop the water flow on a certain cooling line.

The commissioning of these subsystems has been done in parallel with the installation of the first ECAL SMs. This is of course not an ideal situation since the requirements needed for SMs installation, mostly stable conditions, are in opposition to the needs of debugging these ancillary subsystems (possibility to change temperature conditions, turning on and off the electronics, generation of interlocks).

### V. ECAL COMMISSIONING

*ECAL commissioning* is a very broad term that indicates all necessary actions needed to make ECAL work. It is a job that proceeds in parallel with the installation phase and terminates much later, when all ECAL parts are ready to take data. The first SM was installed in CMS during the first quarter of 2007 and the endcaps were installed and commissioned in Summer-Fall 2008. ECAL commissioning can be divided into two large groups:

- Hardware Commissioning: on- and off- detector electronics, HV and LV systems, laser monitoring and fiber optics

links

- DAQ: necessary software to run ECAL

### A. Hardware Commissioning

Fig. 4 shows a block diagram of the ECAL electronics. We indicate with the term *on-detector* electronics all components that are physically placed in the detector while the *off-detector* electronics is placed in the service cavern. On- and off- detector electronics are linked by a system of fiber optics with data and trigger information sent on different fibers:

- Data: 1 link per trigger tower
- Trigger: 1 link per trigger tower in the barrel and 5 links per trigger tower in the endcaps

The total capacity of the system is around 640Mb/s.

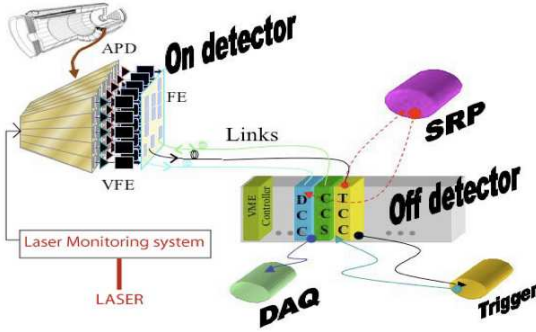


Figure 4: Block diagram of ECAL electronics.

The on-detector electronics chain starts with a photodetectors (the case of the APD is shown) whose signal is shaped by a Multi Gain Pre Amplifier and digitized by 40 MHz ADC. To meet the dynamic range and precision requirements the MGPA has 3 gains (1, 6 and 12) and the ADC has 12 bits. Data are pipelined in the FE card where trigger primitives generation is performed. FE sends trigger words at 25 ns rate while data are transmitted on receipt of a Level 1 trigger. Overall the on-detector electronics comprises approximately 21,000 custom made boards, with an average power consumption of 2.3 W/ch for a total consumption of 180 kW.

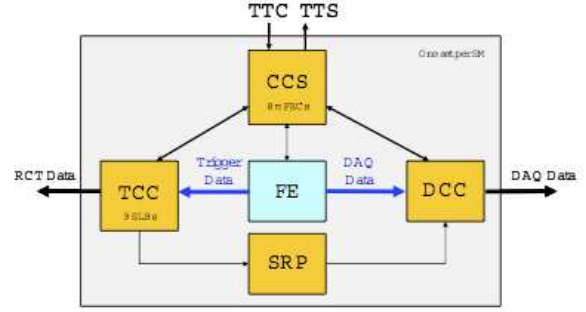


Figure 5: Block diagram of the off-detector electronics.

The logic of the off-detector electronics is shown in Fig. 5. Four boards are needed to configure the electronics, read out the appropriate data and generate the trigger. The clock and control system (CCS) board distributes the clock, trigger and broadcast commands, the trigger concentration card (TCC) generates the trigger primitives and transmit them at each bunch crossing, the data concentration card (DCC) is responsible for collecting crystal data while the selective read out protocol (SRP) selects which trigger tower should be read out. Overall the off-detector electronics comprises 18 VME 9U and 1 VME 6U crates controlled by 28 crate mounted PCs. The commissioning of both on- and off- detector electronics is completed with only two voltage regulators non functioning correctly.

The HV and LV systems provide the necessary voltages to the photodetectors (APD in the barrel and VPT in the Endcap) and on-detector electronics. The HV system has a total of 1224 independent channels in the barrel and 8 independent channels in the endcaps; the LV system comprises a total of about 680 LV channels in the Barrel and about 150 LV channels for the Endcaps. The commissioning of these systems is also completed

One of the most important issue for ECAL is how well we can track changes in crystal transparencies. Crystal transparency is affected by radiation damage in a way that depends on the dose-rate. It's estimated that transparency will decrease by 1 or 2 per cent at low luminosity while at nominal luminosity it can oscillate as much as 10% within an LHC cycle at  $\eta = 2.5$ . The first laser monitoring system has been used in a 2001 test beam and since then it has been used successfully in many other test beams achieving a stability of 0.068%. The full system is now installed in CMS and tested.

### B. DAQ Commissioning

DAQ commissioning deals with all aspects needed to run together the various sub parts of ECAL: trigger, selective readout protocol, laser, detector control units, condition and configuration databases, non event monitoring, run control, data quality monitor. In the following I will describe 3 examples: trigger, selective read out and laser.

Fig. 6 schematically shows a very powerful method used to commission the trigger system: the off line emulation of on line trigger decisions. During a global run, when the ECAL trigger



is active and its decisions are used to trigger CMS, the values used to calculate the trigger decisions are also recorded. Offline the trigger decisions are recalculated and compared with what was decided on line.

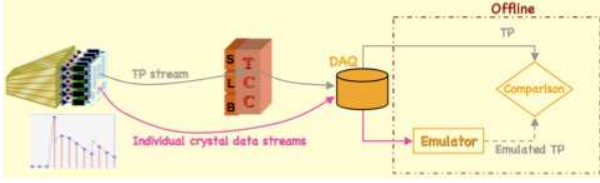


Figure 6: Trigger generation and emulation.

This method proved to be very important to spot hardware related problems (for example wrong cabling) and to tune trigger algorithms.

An important aspect of DAQ commissioning has been the implementation of the Selective Readout Protocol (SRP): when a trigger tower has energy over a given threshold (the actual value is programmable, we used values of the order of 0.5-1 GeV) the SRP flags for complete read out all towers around it, Fig. 7. This solution allows high interest regions to be read out without zero suppression.

Each colored square represents a trigger tower (TT) that has been read out and the color indicates the number of crystals read in that TT (red = 25 crystals, all of them).

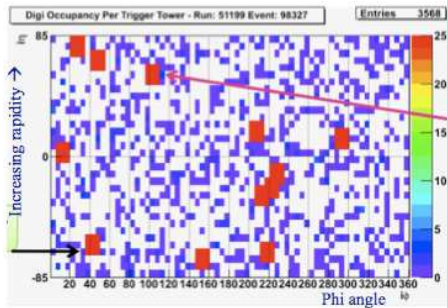


Figure 7: A single event read out using the Selective Read out Protocol: groups of 3x3 trigger towers are read completely around the seed tower. The arrows point to two different high interest regions.

Another important milestone in ECAL commissioning has been the start up of the monitoring system. During normal operation ECAL acquires 3 types of non physics events: pedestal, test pulse for the electronics and laser shots. These monitoring events are acquired during the LHC abort gaps: the LHC filling scheme has an interval of 118 bunch crossing ( $118 * 25 \text{ ns} = 2.95 \mu\text{s}$ ) where there are no particles, the so called *abort gap* (which might be used to dump the beam). ECAL uses these gaps to take calibration data and it takes 35 minutes to run the full calibration sequence.

The calibration sequence is routinely used in CMS and cali-

bration events are packed in special data streams which are then used to perform daily checks. The system works quite well even though not yet at the level required to handle such a high volume of data (40 Gb of laser data a day) over an extended period of time.

## VI. ECAL STATUS

The electromagnetic calorimeter is now fully installed in CMS. Overall the system performs as expected, with noise levels compatible with expectations both in the barrel (pedestal RMS = 1.0 ADC count) and the endcaps (RMS = 1.9 ADC counts). We noticed that noise conditions are dependent upon the CMS geometrical configuration, with the minimum noise reached when CSM is fully closed

The number of dead or problematic channels varies on a daily basis, some appear and some are fixed. It is difficult to provide a list which is valid beyond a couple of weeks; the most common problems are dead photodetectors, bad connections, broken front end electronics, some LV connections and some clock problems.

Overall we did not have time to deal in full with the list of problematic channels, more studies are needed which can be done only during the winter shutdown. It's difficult to assess exactly the situation however it's very exciting to see that less than 1% of the calorimeter has problems.

## VII. RUNNING MODE

In the period when ECAL was commissioned not only all other CMS sub detectors were also facing similar challenges but CMS as a single experiment was commissioned. All these activities competed for resources and manpower so it was agreed to divide the week into local runs, where sub detectors were allowed to advance in their preparation, and global runs, when all sub detectors were supposed to join together in global runs.

### A. CMS global runs

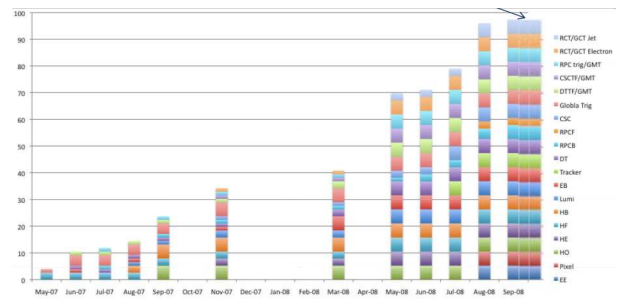


Figure 8: Evolution of CMS global run. 100 on the vertical scale mean total completion

Global runs started early in 2007, first with only the data acquisition system itself, and then grew to include almost all CMS at the end of August 2008; Fig. 8 shows this evolution.

The main goal of global runs is to exercise as many compo-

nents as possible and to establish protocols for stable running mode. CMS ran in global mode a few days each week and a full week every month to achieve particular milestones. In the period March-August CMS has logged more than 350 million cosmics triggers.

### B. ECAL performance in Global Runs

ECAL is designed to measure energy depositions up to 1.5 TeV therefore it's not optimized to detect the energy released by a cosmic ray (250 MeV). However, increasing the gain of the photodetectors (this is possible only in the barrel) from 50 to 200, it's possible to clearly see a signal. Note that since cosmic muons are reaching ECAL with all possible angles there is not a real signal 'peak' but more a continuous shoulder. Cosmic muons can also deposit quite high energy clusters via catastrophic bremsstrahlung photon emission.

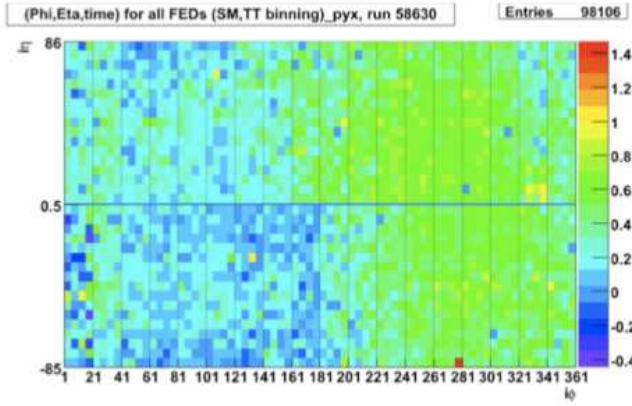


Figure 9: Time of arrival of cosmic muons in ECAL. Vertical axis is the rapidity index of the crystals while the horizontal axis is the unwrapped phi angle. The colors denote the time of arrival of the signal in clock unit (25 ns). The top part of the calorimeter is earlier than the bottom part by almost a full clock.

Cosmic muons have been used to commission many aspects of ECAL; in particular, since their signal is quite small, they represented a real challenge for the trigger. Fig. 9 shows the cosmic ray time of arrival in ECAL: even with very small signal we were able to measure quite well the time difference between the top and bottom part of ECAL. The occupancy of this plot is asymmetric along the y axis since low energy muons reach ECAL preferentially along the shaft used to lower CMS (which is near the negative rapidity part).

### C. Beam Run

On September 10, 2008, LHC injected beam in the accelerator and in the following days CMS saw clear beam related signals. In particular, during the ring commissioning, LHC dumped on purpose the beam (a low intensity version of the real beam,  $10^9$  protons at 450 GeV) several times on collimators placed 150 meters away from CMS creating a huge number of muons. We estimated that 2-300,000 muons reached ECAL at the same time dumping 300 TeV of energy: 98% of the crystals were lit up. Fig. 10 shows the energy deposition for one of these dumps.

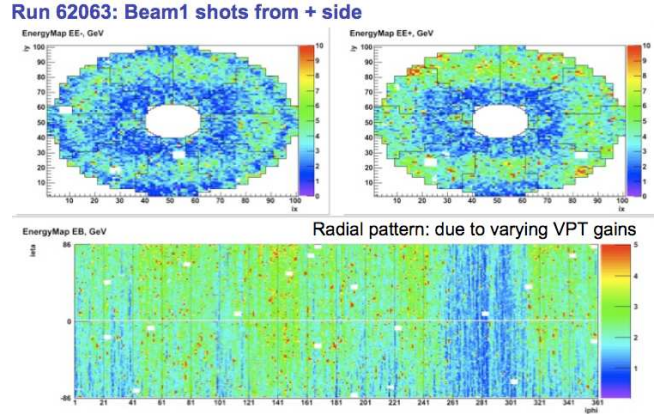


Figure 10: This set of plots shows the energy deposition in ECAL barrel and endcaps due to a beam dump 150 meters upstream. The positive side has more energies since the beam was coming from that direction, the bottom part of ECAL has less energy since it's shielded by the beam tunnel floor. The radial pattern visible in the endcaps is due to photodetectors with different light yield.

These beam dump events have been also extensively used to check the timing of the read out, especially for the endcaps, since all crystals are hit at the same time.

## VIII. CONCLUSIONS

It has been 14 years almost to the days of TWEPP2008 that the choice of  $PbWO_4$  was made. ECAL is now ready to take data and we are sure that the next 14 years will bring exciting new insights.

## REFERENCES

- [1] R. Adolphi *et al.* [CMS Collaboration], JINST **3**, S08004 (2008)