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# Monitoring the stability of the CMS electromagnetic calorimeter

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**Abstract.** The lead tungstate electromagnetic calorimeter of the CMS experiment has been proved to achieve an excellent energy resolution during the commissioning phase of the detector. The uniformity of the relative response of individual channels and the energy scale for electrons and photons are constrained by the several calibration procedures. The stability of the detector in time is constantly monitored throughout the LHC operation by means of dedicated runs and data taken at 100 Hz in the 3 $\mu$s abort gap at the end of each 89 $\mu$s beam cycle. A laser monitoring system is used to track the single channel response variations with time, as changes of the crystal transparency caused by irradiation. The stability of crucial detector parameters such as high voltage, temperature and electronic noise and the performance of the operation of the light monitoring system are shown to fulfill the requirements needed to achieve the target resolution of 0.5% at high energies.

## 1. Introduction

The Compact Muon Solenoid (CMS) detector [1] is a general purpose detector installed at the CERN Large Hadron Collider (LHC). It consists of a silicon central tracking device surrounded by the electromagnetic and hadron calorimetry, all immersed in a magnetic field of about 4 T, and by a muon detector placed in the return yoke of the magnet. The Electromagnetic Calorimeter (ECAL) of CMS [2] is a hermetic homogeneous calorimeter made of about 76000 lead tungstate ($PbWO_4$) crystals, equipped with avalanche photo-diodes (APDs) in the “barrel” part and vacuum photo-triodes (VPTs) in the end-caps for the collection of the scintillation light. The barrel calorimeter is divided into 36 super-modules, each containing 1700 crystal arranged in four modules, and covers a pseudo-rapidity ($\eta$) region up to $|\eta| < 1.48$. It is closed at each end by an end-cap consisting of two *dees* of 3662 crystal each and extending the pseudo-rapidity coverage up to $|\eta| < 3$. The design of ECAL has been optimized for the search of the Higgs boson via its electromagnetic decay $H \to \gamma\gamma$. To fully exploit its discovery potential, the electromagnetic calorimeter must achieve and maintain the target resolution of 0.5% at high energies. The resolution is affected by the uniformity of the detector response, determined by the accuracy of the channel-to-channel calibration, whose ultimate precision will be reached *in-situ* using events from the LHC collisions. Collision events also allow to determine the energy scale and linearity of the ECAL response to electromagnetic particles. In fact, in the Tracker material in front of ECAL electrons may loose energy through bremsstrahlung and photons may be converted into

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electron pairs. These effects may affect the energy measurement and resolution, thus they also need to be calibrated.

An essential part of the calibration procedure is the time stability of the calorimeter response. The main sources of variation in the ECAL response are due to the dependence of the crystal transparency on the absorbed radiation dose-rate, to the temperature dependence of the scintillation process, and to the temperature and high-voltage dependence of the APD gain. The electronic noise is also playing an important role, as it affects directly the energy resolution, though it becomes negligible at high energies.

The following sections will give an overview of the stability of the main parameters affecting the operation of the electromagnetic calorimeter. More detail can be found e.g. in [3].

## 2. ECAL readout and monitoring procedures

The signals from the scintillation light of the lead tungstate crystals are pre-amplified and shaped, and then amplified by three amplifiers with nominal gains of 1, 6 and 12. The signals are then digitized into 10 samples by a 40 MHz, 12-bit ADC. An integrated logic provides for each sample the highest non-saturated value among the three available gains. The readout phase of the detector is adjusted so to have the sixth sample on the maximum of the electronic signal, with the first three samples providing a measurement of the baseline. Digital filtering techniques are applied to reconstruct the amplitude and the time of the signal maximum with respect to the readout phase.

In order to monitor the main parameters affecting the ECAL operations, a so called "calibration sequence" run continuously during the data taking using $\mathcal{O}(1\%)$ of the LHC beam abort gaps, a period of 3 $\mu$s at the end of each 89 $\mu$s of beam cycle. This allows to monitor the crystal transparency via the laser system described in the following sections, the electronic noise via pedestals, and the electronic response stability via a fixed charged injection in the readout chain (Test Pulse). In addition to that, the on-board electronics gives a continuous readout of parameters such as the temperature of the thermistors, high voltage, low voltage, APD dark currents. Finally, dedicated runs can be taken to monitor specific quantities.

## 3. Noise stability

During the Cosmic Run At Four Tesla (CRAFT), a one month period of extensive cosmic rays data taking that took place in October-November 2008 [3], the electronic noise has been monitored via dedicated pedestal runs. The electronic noise, defined as the r.m.s. of the reconstructed signal amplitude, has been evaluated to be for the barrel (end-caps) 1.06 (1.96) ADC count with less than 0.1% of the barrel (end-caps) channels with a noise greater than 2 (3) ADC count[2]. These values are consistent with those measured during the test beam campaigns (see e.g. [5]) and with the specification of the readout electronics [6].

## 4. High voltage stability

High voltage is supplied to the barrel APDs and end-cap VPTs via custom power supplies developed in collaboration with CAEN (model SY1527).

The APD gain $\mathcal{G}$ (nominal value of 50) is very sensitive to the bias voltage, showing a variation of $1/\mathcal{G}(\partial\mathcal{G}/\partial V) \approx 3\%/\mathrm{V}$. The nominal operating voltage, which is between 340 and 430 V, has to be kept stable to better than 60 mV in order to provide a negligible contribution to the energy resolution of the calorimeter. During CRAFT all the channels have been proved to be stable to better than 10 mV with an average fluctuation of about 2.1 mV (r.m.s.) and 97% of the channels below 5 mV. It is worth mentioning that the measurements performed during the CRAFT data taking showed APD dark currents below the measurable threshold for all the

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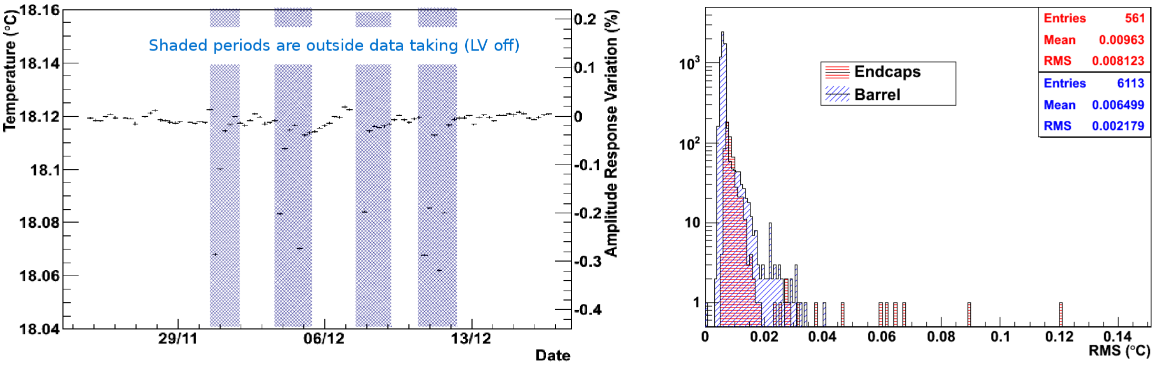
[2] The average energy equivalent noise can be evaluated to be roughly 40 (140) MeV for the barrel (end-caps) .



(a) (b)

**Figure 1.** (a) Average temperature of the ECAL barrel over a period of one month of data taking at the start of the LHC operations in 2009. The shaded regions correspond to periods outside the data taking in which the Low Voltage (LV) was off. (b) Histogram of the corresponding temperature stability measured by each single thermistor for the barrel (blue diagonal lines) and the two end-caps (red horizontal lines).

channels but 11 (0.02%).

At the operating bias used in CMS, the VPT gain is close to saturation. Therefore, the voltages for the end-caps do not need to be controlled very precisely, as the gain dependence on high voltage is less than 0.1%/V [7].

## 5. Temperature stability

Fluctuations in the temperature of ECAL directly affects the scintillation process (the temperature light yield of the crystals is approximately -2%/°C) and the gain $\mathcal{G}$ of the APDs as $1/\mathcal{G}(\partial\mathcal{G}/\partial T) \approx -2.3\%/^{\circ}\mathrm{C}$ [8]. In the end-caps, the temperature variation of the VPT relative response is assumed to be negligible with respect to the temperature sensitivity of the crystal light yield [9, 10]. According to these considerations, to provide a negligible contribution to the energy resolution the temperature of the ECAL barrel is required to be stable within 0.05 °C, while a less stringent requirement of 0.1 °C is assumed for the end-caps.

The nominal operating temperature of ECAL is 18 °C. A cooling system utilising water flow [4, 2] is used to regulate the temperature of the barrel and end-cap crystals. As a figure of merit, the power dissipated by the electronics of 400 crystals is of about 5 kW.

The temperature is measured by two independent group of sensors. Precision temperature thermistors manufactured by EPCOS (10 per supermodule, 24 per *dee*) monitor the temperature on each side of the crystal volume and on the incoming and outgoing cooling water. In addition, thermistors are fixed to the back of each $5\times2$ ($5\times5$) array of crystal in the barrel (end-cap). Figure 4(a) shows the average temperature of the ECAL barrel over one month of data taking at the start of the LHC operations in 2009. The histogram of the corresponding temperature stability measured by each single thermistor for barrel and end-cap is shown in figure 4(b) and for both barrel and end-caps has proven to be much better than the required 0.05 °C.

It is worth noting that eventual local in-homogeneities of the temperature are irrelevant, provided they are stable in time, as they are absorbed into the definition of the channel-to-channel calibration constants.

## 6. Crystal transparency monitoring

The lead tungstate crystals composing the calorimeter show a response variation dependent on the absorbed radiation dose-rate. This is due to the formation of colour centres which absorb a

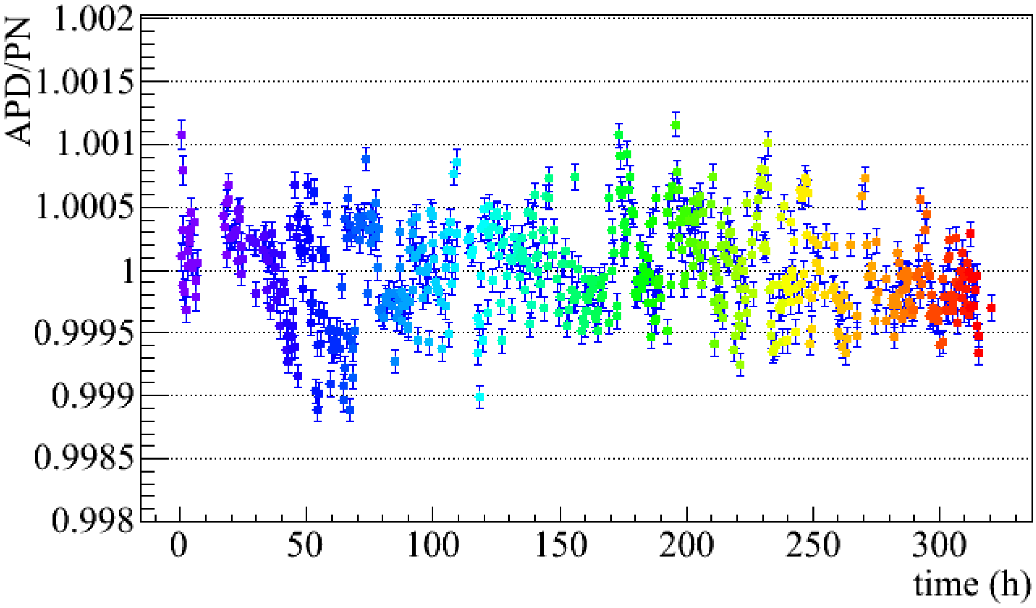


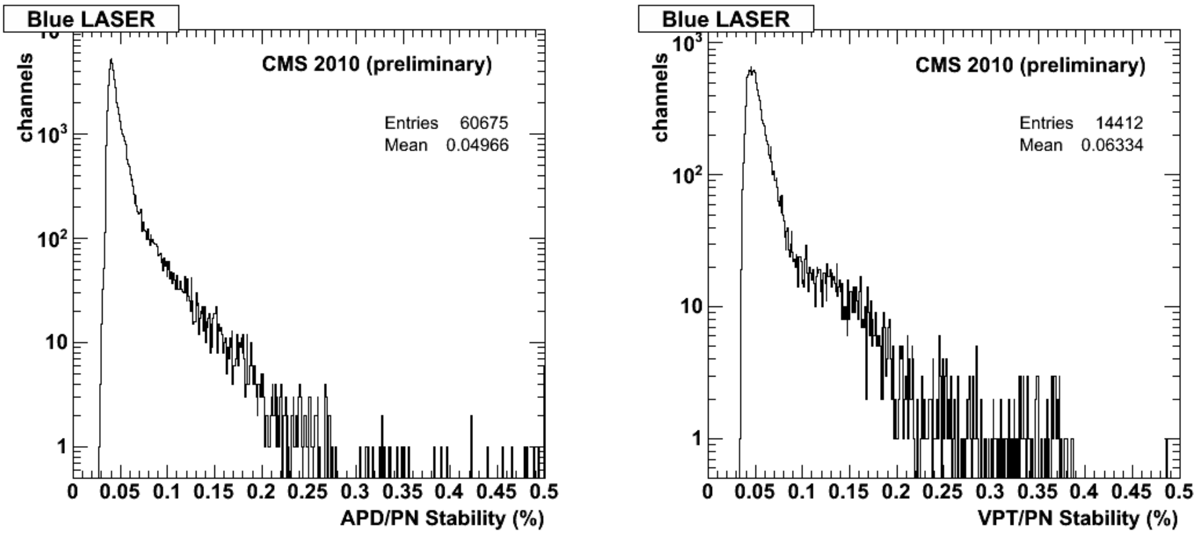
**Figure 2.** Typical channel stability, defined as the r.m.s of the amplitude measured by the APD normalised to the PN amplitude, after applying all the corrections mentioned in the text. The point colours (if visible) please the eye over the about 350 h of LHC data taking, which shows a stability better than 0.04% (to be compared with the required 0.2%).

fraction of the transmitted light, thus modifying the crystal transparency. At the ECAL working temperature of 18 °C, the colour centres anneal and the crystal progressively recover its initial properties. Given the nominal LHC operations, these changes take place on a time scale of hours and cause a transparency variation of a few percent at the design luminosity.

In order to measure the evolution of crystal transparency, laser pulses are injected into each single crystal via a system of optical fibres. The crystal response is normalised to the laser pulse magnitude, measured using silicon PN photo-diodes. Before being injected in the light distribution system, the laser signals are sampled at 1 GHz by a fast CAEN digitizer (model V1729).

Two lasers are used, both manufactured by Quantronix (Nd:YLF 527DQ-S Q-switched and Ti:Sapphire, custom made), to provide sources of two different wavelengths. A blue one ($\lambda$ = 440 nm), very close to the scintillation emission peak, probes the crystal transparency. A red one ($\lambda$ = 790 nm), far from the scintillation peak, is very little affected by the changes in transparency and is used to verify the stability of the elements in the system. The lasers are operated at 100 Hz and exploit the 3 $\mu$s of the LHC beam abort gaps in order not to interfere with the normal data taking. The transparency of each crystal is measured every 20 to 30 minutes. For more detail as well as for the complete technical specifications of the laser system see e.g. [11].

To reach the ECAL target resolution, the laser monitoring system is required to monitor the transparency changes of a single crystal with a precision of 0.2%. With such a target, several second order effects cannot be neglected. In particular, the non linearities of the silicon PN photodiodes are measured and corrected for via a highly precise charge injection system (PN Test Pulse). In addition to that, the difference in shaping time of APD (VPT) and PN is also taken into account, by using the APD (VPT) Single Pulse Response of each individual channel and PN, convoluted with the fast-digitized laser signal in order to improve the estimate of the



(a)

(b)

**Figure 3.** Stabilities for the whole ECAL barrel (a) and end-caps (b) over about 350 h of LHC data taking. The stability for the barrel (end-caps) is defined as the r.m.s of the amplitude measured by the APD (VPT) normalised to the PN amplitude, after applying all the corrections mentioned in the text. The shoulder visible in (b) that still meets the requirements is due to a region of crystals for which the PN system was temporarily not fully operational.

measured amplitudes.

The capability of this system to allow corrections for transparency changes was proved with test beam data [4]. With no significant irradiation for the ECAL crystals, the 2010 LHC data taking period has given the possibility to demonstrate the stability of the laser monitoring system for the whole ECAL over a much longer period of time and using the nominal procedures in the calibration sequence.

An example of a typical channel is given in figure 6 for a period of 350 h, and shows a stability better than 0.04%. Figure 6 shows the stability of the blue laser for the whole barrel (a) and end-caps (b) over the same 350 h of LHC data taking. The average stabilities of the whole ECAL barrel and end-caps are of about 0.05% and 0.06% respectively, and are much better than the required 0.2%.

## 7. Summary and conclusions

The operation of the CMS electromagnetic calorimeter is able to meet the stringent requirements imposed by reaching the target resolution of 0.5% at high energies. For the whole data taking period starting from the cosmic rays campaigns till the ongoing LHC collisions, all the detector parameters have been constantly monitored and proven to be extremely stable during the CMS operations. In particular, the temperature stability of the detector is much better than the requirements, and so is the stability of the ECAL laser monitoring system.

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