Monitoring and Correcting for Response Changes in the CMS Lead-tungstate Electromagnetic Calorimeter

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Abstract. The CMS Electromagnetic Calorimeter (ECAL) comprises 75848 lead-tungstate scintillating crystals. Changes in the ECAL response, due to crystal radiation damage or changes in photo-detector output, are monitored in real time with a sophisticated system of lasers to allow corrections to the energy measurements to be calculated and used. The excellent intrinsic resolution of the CMS ECAL requires the monitoring system itself to be calibrated to a high precision and its stability to be controlled and understood. The components of the CMS ECAL monitoring system, and how it has evolved to include modern solid-state lasers, are described. Several physics channels are exploited to normalise the ECAL response to the changes measured by the monitoring system. These include low energy diphoton resonances, electrons from W and Z decays (using shower energy versus track momentum measurements), and the azimuthal symmetry of low energy deposits in minimum bias events. This paper describes how the monitoring system is operated, how the corrections are obtained, and the resulting ECAL performance.

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 pixel and strip tracker surrounded by a crystal electromagnetic calorimeter (ECAL) and a brass/scintillator sampling hadron calorimeter (HCAL), all in an axial 3.8 T magnetic field provided by a superconducting solenoid of 6 m internal diameter. The muon system is composed of gas-ionization detectors embedded in the steel return yoke of the magnet. In addition to the barrel and endcap detectors, CMS has an extensive forward calorimetry system.

The conception of the electromagnetic calorimeter has been driven by the search for the Higgs boson via its electromagnetic decay $H \rightarrow \gamma\gamma$, appearing as a very narrow resonance on a large background of events with a pair of photon candidates, coming mainly from QCD processes. The electromagnetic calorimeter consists of 75848 lead tungstate (PbWO$_4$) crystals. It is divided into a central part (barrel) covering the region $|\eta| < 1.48$ and forward parts (endcaps) extending the coverage up to $|\eta| < 3$ for a particle originating from the nominal interaction point. The crystals are arranged in a projective geometry with a granularity of 0.0174 in both the $\eta$ and $\phi$ directions.

$^1$ In the CMS coordinate system, $\theta$ designate the azimuthal angle with respect to the counterclockwise beam direction, and the pseudorapidity is defined as $\eta = -\ln \left[ \tan \frac{\theta}{2} \right]$. 

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in the barrel, and increasing with $|\eta|$ from 0.021 to 0.050 in the endcaps. The scintillation light is read out by avalanche photo-diodes (APDs) in the barrel and vacuum photo-triodes (VPTs) in the endcaps.

A preshower detector, consisting of two planes of silicon sensors interleaved with 3 radiation lengths of lead, is placed in front of the endcaps to cover the pseudorapidity region $1.65 < |\eta| < 2.6$.

The factors impacting the ECAL energy resolution are multiple. First of all the uniformity of the response and its time-stability, both monitored via a laser-based system. Secondly the channel-to-channel calibration, ultimately based on physics events such as $\pi^0/\eta \rightarrow \gamma\gamma$, $W \rightarrow e\nu$, $Z \rightarrow ee$, and on the azimuthal symmetry of the energy distribution in minimum bias events [2]. Finally the energy scale and linearity of the response to electrons and photons, both depending on effects such as bremsstrahlung and electron-positron pair production taking place in the tracker material in front of the calorimeter, determined with physics events such as $Z \rightarrow ee$ and $Z \rightarrow \mu\mu\gamma$.

We focus here on the first of these aspects, describing how a laser system is used to monitor and correct for changes in the ECAL response, mainly induced by radiation-dependent effects. For an overview of the calibration of the electromagnetic calorimeter and of the overall impact of its performance on the search for the Higgs boson see Ref. [3].

2. Changes to the ECAL response

There are three mains sources of change to the ECAL response: radiation due to the particles produced during collisions, which affect the crystal transparency via a dose-rate dependent effect and the response of the VPTs via the cumulated charge at the cathode [4]; temperature variations, affecting the light yield as $\Delta T / T \sim -2\%/\degree C$ at 18 $\degree C$ and the gain of the APDs as $\Delta G / G \sim -2\%/\degree C$; variations in the high-voltage bias applied to the APDs, as $\Delta G / G \sim 3\%/V$.

The last two of these three sources as well as others minor contributions from, for example, the low voltage system and the readout electronics, are controlled to a very precise level and are very well within specifications [5].

The radiation-induced effects, on the other hand, are continuously evolving thus requiring a continuous monitoring and prompt deployment of corrections to compensate for any changes. A precision of better than 0.3% in the correction to the response is required in order to be negligible compared to other contributions to the energy resolution and achieve the best ECAL potential.

The passage of particles through a PbWO$_4$ crystal loses its transparency because of the formation of so called “colour centres”. When the crystal is not subject to irradiation, it spontaneously recovers some of its transparency due to thermal annealing of shallow colour centres. The characteristic timescales of these two antagonistic processes of loss and recovery are different but are of the order of hours in both cases. The effect of the LHC operations on the relative response of the crystals is shown in Fig. 2, as probed by the laser monitoring system described in the Section 3. Rapid loss and recovery of the optical transmission corresponding to LHC cycles are clearly visible, as well as steady recovery during LHC technical stops and the low-irradiation Heavy-Ion collision period towards the end of the 2011 run. The red curve corresponds to the average variation in the ECAL barrel, while the other colours refer to the average variations in different ranges of $|\eta|$. Due to the tracker coverage, electron and photon in CMS are not reconstructed beyond $|\eta| = 2.5$.

The losses are consistent with expectations and with the rejection at construction time of crystals experiencing a response loss of more than 6% at a dose rate of 0.15 Gy/h, which is not exceeded up to $|\eta| \sim 2$ with the 2011 LHC peak luminosity $(3.5 \cdot 10^{33}$ cm$^{-2}$s$^{-1})$.

For the regions of the ECAL endcaps, Fig. 2 is de facto showing the convolution of the
Figure 1. Relative response variation measured by the ECAL laser monitoring system in 2011. The red curve corresponds to the average variation in the ECAL barrel, while the other colours refer to the average variations in the ranges of $|\eta|$ listed in the legend. Technical stops without monitoring data are shaded. The LHC luminosity varied from $10^{33}$ cm$^{-2}$s$^{-1}$ in April to $3.5 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ in October. Heavy-Ion collisions took place in November.

transparency variations with the loss in response of the VPTs due to the accumulated charge on the cathode. Dedicated laboratory studies have been performed over six months on a limited number of VPTs immersed in a 3.8 T magnetic field. A load pulse has been used to induce an average current as expected at nominal LHC luminosity. Cycles corresponding to periods with/without beam of 8/4 and 16/20 hours have been simulated. By monitoring the VPT response with blue LED light it has been shown that the VPT average loss has been 12%, with a spread of 10% and a tendency towards a non-zero plateau after 5-20 mC of integrated charge, while in 2011 about 0.5 mC of charge have been integrated at $|\eta| = 2.1$. More precise assessments of these effects are ongoing. Currently it has not been possible to disentangle the VPT loss and transparency loss in situ.

3. The CMS ECAL monitoring system
The evolution of the crystal response is continuously measured with a dedicated laser system [6], operating at 100 Hz during about 1% of the LHC beam abort gaps, a period of 3 $\mu$s at the end of each 89 $\mu$s beam cycle. This mode of operation allows the monitoring of the response, along with other quantities such as the electronic noise and the electronic stability, without interfering with the normal data taking.

Laser pulses are injected via a system of optical fibres and diffusing spheres into each of the 75848 ECAL crystals in groups of a few hundred crystals (700 to 900, depending on the region). A relative response measurement is obtained by normalising the crystal response to reference silicon PN photo-diodes, which are associated to groups of 100 to 200 crystals and give the fraction of laser light received by the specific group. The laser signal is also sampled at 1 GHz at the source by a fast CAEN digitizer, model V1729.
Figure 2. Schema of the laser monitoring system. The light is sampled at 1 GHz at the output of the source and injected into the crystals via a two level distribution systems. At the output of the Level-1 fanout, PN photo-diodes provide a reference to measure relative response changes.

More than one laser can be operated, to ensure adequate redundancy in the system and the possibility to probe the transparency with different wavelengths.

Because of the different optical paths within a crystal, it has been determined at test-beams that the response to scintillation light from an electromagnetic shower is related to the response measured via the laser light by

$$\frac{S}{S_0} = \left( \frac{L}{L_0} \right)^\alpha$$

where $\frac{S}{S_0}$ is the relative response to scintillation light, and $\frac{L}{L_0}$ is the relative response to laser light. The empirical parameter $\alpha$ has been studied in Test-Beam campaigns [7] for a limited number of crystals, from different production batches and manufacturers. An average value of 1.52 (1.00) has been found for BC$$^2$$TP$^2$ (SIC$^3$) crystals, with a 10% rms spread within the crystals from the same manufacturer. A determination of the average $\alpha$ using physics events has tuned the value of BC$$^2$$TP crystals in EE to 1.16, which is also effectively correcting for the average VPT response variations not disentangled from the transparency changes by the current monitoring system. With the response variations measured in 2011, the spread of $\alpha$ is expected to contribute to the spread of the single crystal response by order of 0.1% in the barrel and 1% in the endcaps. Studies are ongoing to determine $\alpha$ on a crystal-by-crystal basis using physics events.

A transparency measurement for each of the ECAL crystal is performed in about 40

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minutes. Corrections to physics events are obtained by interpolating the response between each measurement and are delivered within 48h for prompt reconstruction of CMS data. The main laser used throughout the whole 2010 and 2011 data taking period was manufactured by Quantronix (Nd:YLF 527DQ-S Q-switched) and provides light at \( \lambda = 440 \text{ nm} \), close to the scintillation emission peak. Residual instabilities in the pulse width and timing of the light source as well as other second order effects such as non-linearities of the silicon PN photodiodes, ballistic deficit between the APD (VPT) and the PN photo-diodes are corrected for. In particular, at the beginning of the 2011 data taking the whole monitoring chain was recalibrated with dedicated measurements spanning the range of laser parameters, and the single pulse response of each individual channel has been re-measured to optimise the quality of the corrections. To ease the maintenance and operation, an upgrade of the main laser was foreseen and took place at the beginning of 2012 [8].

4. Performance of the monitoring system

Tools are available in order to estimate the intrinsic precision of the monitoring system as well as the stability and precision in time of the response corrections. They make use of the response measurements themselves and of standard physics channels, and are briefly summarised in the following paragraphs.

4.1. Precision of the response measurement

It is possible to evaluate the precision of a single measurement of the response by using the data themselves, in periods subjected to low irradiation, thus having small response changes. In 2011 this has been the case during the Heavy-Ion period at the end of the data taking, Fig. 3-left. One can consider three consecutive response measurements \( p_{n-1}, p_n, \) and \( p_{n+1} \), taken at time \( t_{n-1}, t_n, \) and \( t_{n+1} \). The response, \( i(t_n) \), is the interpolation between \( (p, t)_{n-1} \) and \( (p, t)_{n+1} \) evaluated at time \( t_n \). The variance of the difference \( \delta_n = i(t_n) - p_n \) computed every two measurements in the considered period gives an estimate of the intrinsic precision on the single measurement. It is worth noting that the method would give correct results even in the case of quadratic drifts. Since the typical distribution of \( \delta_n \) for one channel is well described by a Gaussian curve, the precision has been estimated from the \( \sigma \) parameter of a fit to the distribution. The results of this analysis for the barrel and the two endcaps are shown in Fig. 3, and show a precision on the single response measurement of about \( 3 \cdot 10^{-4} \), very well within the requirements.

4.2. Performance of the response measurement

The invariant masses of \( \pi^0, \eta \) and \( Z \), reconstructed from their electromagnetic decays, give an absolute reference to evaluate the stability of the corrected response. In particular, \( \pi^0 \) and \( \eta \) are selected by CMS at the High Level Trigger level via a dedicated stream with a rate of a few kHz, allowing a fine grain monitoring of the correction with a few points per hour, as shown in Fig. 4.

In contrast, \( Z \) bosons require more time to accumulate enough data, but the clean signal also provides information about the resolution of the calorimeter, via the width of the invariant mass distribution (Fig. 5).

In addition to that, it is possible to use isolated electrons and positrons from the decays of \( W \) and \( Z \) bosons as additional probes of the correction quality. The ratio \( E/p \) between the energy measured by the ECAL and the momentum measured by the tracker gives an estimate of the stability of the response corrections, under the verified assumption that the error on \( p \) is negligible with respect to the precision on \( E \) (Fig. 6).

The overall picture is that the ECAL monitoring system tracks response changes in ECAL with a stability of about 0.12% in EB and 0.35% in EE. The resolution is stable throughout the
Figure 3. Left: example of a history plot for the relative response of one typical channel of EB at large $|\eta|$ during low irradiation period (Heavy-Ion run). Right: barrel and endcap distributions of the precision on the single response measurement estimated as explained in the text. The peaks at $3 \cdot 10^{-4}$ are much better than the required precision of $2 \cdot 10^{-3}$.

Figure 4. Stability of the energy response in 2011 as measured from the invariant diphoton mass from $\eta \rightarrow \gamma \gamma$ decays as a function of time in the barrel, before (red points) and after (green points) response corrections are applied. The right plot shows in greater detail the period of September 2011.

2011 data taking period in the barrel. In the endcaps, where the radiation-induced variations are larger and other effects such as pileup have a greater impact, a worsening of the resolution of about 1.5% in quadrature is observed. Refined measurements of crystal properties such as $\alpha$ at the single channel level and optimisation of the handling of additional effects such as the pile-up are being carried out, and can bring further improvements especially in the endcaps.

5. Conclusions
Operating the CMS electromagnetic calorimeter to its full potential in the LHC radiation environment is a very challenging exercise.

The excellent stability of environmental conditions has been such that response changes have depended to a large extent only on radiation-induced effect in the PbWO$_4$ crystals and in
Figure 5. Stability of the mass resolution estimated from $Z \rightarrow e^+e^-$ for the barrel (left) and the endcaps (right), before (red points) and after (green points) response corrections are applied.

Figure 6. Stability of the energy response of the barrel (left) and endcap (right) from the ratio of electron energy $E$, measured in the ECAL to the electron momentum $p$ measured in the tracker, before (red points) and after (green points) response corrections are applied.

the readout photo-detectors in the endcaps. The ECAL laser-based monitoring system has successfully operated during more than three years of LHC data taking campaigns. Along with a precise calibration of the calorimeter [2] this has put CMS in an excellent position to be able to observe or exclude the Standard Model Higgs boson through the $H \rightarrow \gamma\gamma$ decay [3]. At the time of writing these Proceedings, CMS has observed a new boson with a mass near 125 GeV using data samples of 5.1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV (2011) and of 5.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV (2012), with a local significance in the $H \rightarrow \gamma\gamma$ alone of 4.1 $\sigma$ [9].

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