The Compact Muon Solenoid Experiment
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Commissioning and Operation of the CMS Electromagnetic Calorimeter

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Abstract

The operation and general performance of the CMS electromagnetic calorimeter using cosmic-ray muons recorded after the closure of CMS in late 2008 are described. The overall status of the 75,848 channels corresponding to the crystal barrel and endcap detectors is reported. The stability of crucial operational parameters, such as high voltage, temperature and electronic noise, is summarised and the performance of the light monitoring system is presented. The status of the barrel, endcap and preshower detectors following additional cosmic-ray muon tests in 2009 is also summarised.

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Index Terms—IEEEtran, CMS, ECAL, electromagnetic calorimeter, performance.

I. INTRODUCTION

THE primary goal of the Compact Muon Solenoid (CMS) experiment [1] is to explore physics at the TeV energy scale, exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) [2]. The main component of the CMS detector to identify and measure photons and electrons is the electromagnetic calorimeter (ECAL) [1], [3].

The CMS ECAL is a fine grained crystal calorimeter using lead tungstate (PbWO_4) crystals, designed with stringent requirements on energy resolution, in order to be sensitive to the decay of a Higgs boson into two photons. It consists of a barrel region, providing coverage to $|\eta| = 1.48$, and two endcaps, which extend coverage to $|\eta| = 3.0$, where $\eta = -\ln(\tan \theta/2)$ is the pseudo-rapidity. In addition, silicon preshower detectors are installed in front of the crystal endcaps in order to improve the discrimination between single unconverted photons and photons from π^0 decays.

In order to achieve the desired energy resolution of the ECAL it is necessary to maintain the stability of the per-channel energy calibration over time. This places stringent requirements on the stability of the temperature of the ECAL and of the high voltage applied to the Avalanche Photodiodes (APDs) used in the ECAL barrel. This is due to the temperature dependence of the crystal light yield, as well as the sensitivity of the APD gains to variations in both temperature and high voltage. In addition, changes in lead tungstate crystal transparency under irradiation must be monitored during beam operation and corrected for in the calorimeter output.

During October-November 2008 the CMS Collaboration conducted a month-long data taking exercise known as Cosmic Run At Four Tesla (CRAFT) [4]. With all installed detector systems participating, CMS recorded 270 million cosmic-ray

muon events with the solenoid at its nominal axial magnetic field strength of 3.8 T. These tests were the first opportunity to exercise over an extended period of time the electromagnetic calorimeter as installed within CMS. Performance results from the ECAL during these tests are reported in this paper.

II. DETECTOR DESIGN

The ECAL barrel (EB) consists of 36 individual supermodules. Each supermodule is composed of 1700 tapered PbWO_4 crystals with a frontal area of approximately $2.2 \times 2.2 \text{ cm}^2$ and a length of 23 cm (corresponding to 25.8 radiation lengths). The crystal axes are inclined at an angle of 3° relative to the direction of the nominal interaction point, in both the azimuthal (ϕ) and η projections. Scintillation light from the crystals is detected by two Hamamatsu S8148 $5 \times 5 \text{ mm}^2$ APDs which were specially developed for CMS and operate at a gain of 50.

The two ECAL endcaps (EE) are constructed from four half-disk ‘dees’, each consisting of 3662 tapered crystals, with a frontal area of $2.68 \times 2.68 \text{ cm}^2$ and a length of 22 cm (corresponding to 24.7 radiation lengths), arranged in a quasi-projective geometry. The crystals are focussed at a point 1.3 m farther than the nominal interaction point along the beam line, with off-pointing angles between 2° and 8° . Scintillation light is detected by Vacuum Phototriodes (VPTs) produced by NRIE (type PMT188). These have an active area of 280 mm^2 , operate at gains of 8–10 in the 4 T magnetic field of CMS, and are are glued to the rear face of the crystals.

The signals from the APDs and VPTs are pre-amplified and shaped by Multiple Gain Pre-Amplifier (MGPA) ASICs located on the VFE boards, which consist of three parallel amplification stages (gains 1, 6 and 12) [5]. The output is digitised by a 12-bit ADC running at 40 MHz, which samples the pulse ten times for each channel and selects the gain with the highest non-saturated signal. The data from five VFE cards are transferred to a single front-end card, which generates the trigger primitive data [6], and transmits it to the dedicated off-detector trigger electronics.

The ECAL preshower (ES) is a two-layer sampling calorimeter, consisting of lead radiators, which produce electromagnetic showers from incident electrons and photons, and silicon strip sensors, with dimensions $1.6 \times 61 \text{ mm}^2$, which record the deposited energy and transverse shower profiles. The material thickness of the preshower at $\eta = 1.65$ prior to the second sensor plane is $3X_0$ - hence 95% of incident photons will begin showering before the second sensor plane. The preshower consists of four half-disk dees, with the same

orientation as the endcap dees, and covers the pseudo-rapidity range $1.65 < |\eta| < 2.6$. A total of 137216 silicon strips are read-out by on-detector front-end ASICs which, on receipt of a Level-1 trigger, read out three consecutive 25 ns time samples for all 32 strips of a single silicon sensor. The ASICs have two gain settings: low gain (for LHC beam operation) and high gain (for MIP calibration purposes).

III. DETECTOR INSTALLATION AND COMMISSIONING

The ECAL barrel was installed in CMS during 2007. Prior to this, all supermodules were fully tested in the laboratory after construction and were exposed to cosmic-ray muons for a period of ten days, to obtain relative channel-to-channel inter-calibration constants. Nine of the 36 supermodules were also exposed to test beam electrons to provide absolute energy calibrations. The endcap dees were constructed and commissioned at CERN during early 2008 and were installed in CMS during July 2008. The entire barrel and endcap calorimeter was commissioned prior to the closure of CMS in late August, in preparation for first LHC beam. The silicon preshower detectors were not included in CMS for the 2008 run. They were installed during early 2009 and have been fully commissioned using cosmic-ray muons prior to the resumption of LHC beam operation in November 2009.

During the cosmic-ray tests in October-November 2008, the fraction of channels that were operational was 98.33% in EB (60177/61200) and 99.66% in EE (14598/14648). For the barrel, 1.14% of channels were turned off due to low voltage supply problems, which were repaired after CRAFT. The read-out of 0.45% of the barrel channels was suppressed due to data integrity problems and a total of 48 channels (0.08%) were classified as inoperable, based on pedestal, charge injection and laser calibration measurements. For the endcaps, data from 50/14648 channels (0.34%) were suppressed due to a broken data optical fibre (25 channels) and a faulty low voltage connection (25 channels).

The data taken during CRAFT was used to assess the stability of ECAL over an extended operating period. The results are summarised in this paper, and a detailed description of the results is given in Ref. [7]. Cosmic ray muons were recorded with two settings of the barrel APD gain: the nominal gain 50 to study the signatures of minimum ionising particles (MIPs), and to exercise the ECAL trigger algorithms at the settings that will be used for LHC beam operation; and at a higher gain of 200 to study MIP signals with higher signal to noise. The latter were used to provide a measurement of the muon stopping power in lead tungstate [8], which validated the overall energy scale calibration of ECAL, and to validate the existing channel-to-channel inter-calibration constants [7]. In addition, cosmic-ray muons and beam-induced muons (the latter from LHC beam commissioning tests in September 2008) were used to provide the time synchronisation of barrel and endcap channels prior to LHC startup [9].

IV. PERFORMANCE REQUIREMENTS

The electromagnetic (EM) energy resolution of ECAL can be parameterised as a function of the incident electron/photon energy, E (in GeV), as

Fig. 1. Average electronic noise in the barrel (open circles) and endcaps (filled circles) expressed in ADC counts versus time for pedestal data taken during CRAFT. The dashed lines represent the average noise levels in the barrel and endcaps, over the time period shown.

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (1)$$

where a represents the stochastic term, which depends on event to event fluctuations in lateral shower containment, photo-statistics and photodetector gain; b represents the noise term, which depends on the level of electronic noise and event pile-up (additional particles causing signals that overlap in time); and c represents the constant term, which depends on non-uniformity of the longitudinal light collection, leakage of energy from the rear face of the crystal and the accuracy of the detector inter-calibration constants. The target value for the constant term, which dominates the resolution at high energies, is 0.5% for both the barrel and the endcaps [3].

Previous measurements taken with test beam electrons with energies between 20 and 250 GeV have shown that the EM energy resolution and noise performance of the ECAL barrel meets the design goals for the detector [10]. One of the main goals of the cosmic-ray tests during 2008 was to show that the operating conditions during an extended running period can meet the ECAL goals on detector stability, and that the observed high voltage and temperature fluctuations provide a negligible contribution to the constant term of the EM energy resolution.

V. STABILITY MEASUREMENTS

A. Electronic noise

The electronic noise of the ECAL barrel and endcap detectors was monitored during CRAFT from dedicated pedestal runs, which measure the noise in all three gains of the MGPA in the absence of signal pulses. Figure 1 shows the stability in EB and EE of the per-channel noise level (expressed in ADC counts) for the highest MGPA gain, which is the most sensitive to electronic noise.

The data points shown in Fig. 1(a) come from several different runs, taken with the CMS magnetic field at 0 T or 3.8 T and in the barrel with APD gains G50 or G200. The fact that the noise level is constant over this period

Fig. 2. Monitored HV on a barrel sense wire during one week of CRAFT data taking when the APD gain was set to G50. Each data point is averaged over a three hour time period.

indicates that the electronic noise in the ECAL does not depend on the CMS magnetic field nor on the APD gain. For the highest MGPA gain, the average noise level per channel was 1.06 ADC counts in the barrel, and 1.96 ADC counts in the endcaps. The observed noise levels in EB and EE during CRAFT are consistent with the values measured during module construction (see, for comparison, Table 1 of Ref. [11] for EB noise measurements obtained with test beam data using the “3+5 weight” method), and meet the MGPA design specifications [5]. For the barrel, the average value of the noise in energy equivalent units corresponds to roughly 40 MeV/channel (APD G50).

B. High Voltage

High voltage (HV) is supplied to the barrel APDs via a custom HV power supply developed in collaboration with CAEN. A total of 18 CAEN SY1527 crates are used, and each crate contains eight A1520E boards, which carry up to 9 channels. A total of 1224 HV channels are used, and each channel can provide a bias voltage of 0–500 V to 50 APD pairs with a maximum current of 15 mA. Since the APD gain, G , is very sensitive to the bias voltage, $1/G (\partial G/\partial V) \approx 3\%/V$, the operating voltage must be kept stable to better than 65 mV to provide a negligible contribution to the constant term of the EM energy resolution. Since, at the operating bias used in CMS, the VPT gain is close to saturation, the voltages for the endcaps do not have to be controlled very precisely (the VPT gain dependence on high voltage is less than $0.1\%/V$).

For the measurement of high voltage stability in the barrel, a one-week period during CRAFT was been selected, when all channels were continuously operated at APD G50. Figure 2 shows the monitored voltage on one HV sense wire, as recorded by the CAEN crate. All the points are compatible with a constant value within the measurement errors, and the line represents the average over this period. The average fluctuation of the high voltage is 2.1 mV (RMS). More than 97% of the total number of channels have fluctuations below 5 mV and all were within 10 mV during the time period considered here.

Fig. 3. Mean temperatures recorded over eight-hour time bins for PTM sensors located in four different ECAL barrel supermodules. Three of the four sensors monitored the temperature close to the rear face of the crystals, and one sensor recorded the input water temperature in one of the cooling circuits.

C. Temperature stability

Fluctuations in temperature directly affect the light yield of the crystals (the temperature dependence of the light yield is approximately -2% per $^{\circ}\text{C}$) and the gain of the APDs in the ECAL barrel, $1/G (\partial G/\partial T) \approx -2.4\%/^{\circ}\text{C}$ [12]. The temperature of the ECAL barrel is therefore required to be stable within 0.05°C , which ensures that temperature fluctuations provide a negligible contribution to the constant term of the EM energy resolution. In the endcaps, the temperature dependence of the VPT response is assumed to be negligible relative to the temperature sensitivity of the crystal light yield [13], [14]. Accordingly, a less stringent temperature stability requirement of 0.1°C is assumed for the endcap dees.

Temperature readings are provided by two independent groups of sensors. Precision Temperature Monitor (PTM) devices (10 per supermodule, 24 per endcap dee) measure the temperatures on each side of the crystal volume and the incoming and outgoing cooling water, with a relative accuracy of $\approx 0.01^{\circ}\text{C}$. In addition, thermistors are fixed to the back of each 5×2 crystal matrix (170 per supermodule) in the barrel and to each supercrystal in the endcaps. The thermistors were calibrated in the laboratory prior to installation.

Figure 3 shows the temperature history during CRAFT for three representative PTM sensors in the barrel, monitoring the temperature close to the rear face of the crystals of three different supermodules. Measurements from an additional sensor, monitoring the input cooling water temperature of another supermodule, are also shown.

During CRAFT, the barrel temperature readings were stable to better than 0.01°C , and the endcap readings were stable within $\pm 0.02^{\circ}\text{C}$, after an initial period of temperature stabilization at the beginning of CRAFT. These measurements are well within the desired stability targets. The mean temperature measured in the ECAL barrel during CRAFT was $18.10 \pm 0.02^{\circ}\text{C}$ by the PTM sensors and $18.12 \pm 0.04^{\circ}\text{C}$ by the APD capsule thermistors. The mean temperature measured by the PTM sensors in the endcaps during CRAFT was $18.56 \pm 0.06^{\circ}\text{C}$.

The RMS deviation of temperature histories was also calcu-

lated for the 6009 barrel thermistors and 548 endcap thermistors that were read out during CRAFT. The average stability was 0.009°C in the barrel, with all measurements within the ECAL specification of 0.05°C . The average stability in the endcaps was measured to be 0.017°C , using data from 15th October onwards.

D. Light monitoring stability

The purpose of the ECAL laser monitoring (LM) system [15] is to accurately measure and to correct for changes in the lead tungstate crystal transparency, which will decrease during irradiation at the LHC due to the formation of colour centres. The crystals will slowly recover transparency through annealing when the LHC beams are off.

The LM system consists of two different lasers: a blue laser ($\lambda = 440\text{ nm}$) close to the emission peak of scintillation light from PbWO_4 , and an infra-red laser ($\lambda = 796\text{ nm}$) for which crystal transparency is stable under irradiation. The blue laser is used to monitor crystal transparency to scintillation light whereas the infra-red laser is used to disentangle effects due to irradiation from other possible effects such as gain variations. The light output of the lasers are independently monitored by radiation-hard PN diodes in order to remove pulse-to-pulse amplitude variations.

The LM system is required to monitor transparency changes for each crystal at the 0.2% level, with one measurement every 20 to 30 minutes. During CRAFT, a total of approximately 500 sequences of laser monitoring data were taken within the ECAL calibration sequence, which periodically injected pedestal, charge injection and laser events into the data stream during the simulated LHC abort gap ($3\text{ }\mu\text{s}$ gap at the end of each $89\text{ }\mu\text{s}$ beam cycle). The laser typically ran at 100 Hz, resulting in the injection of laser light into $\mathcal{O}(1\%)$ of the available gaps.

The average over 600 events of the APD(VPT) response was monitored, to follow variations of channel response to blue laser light. Because of problems in reading out the PN diode data during the calibration sequence (which were solved after the CRAFT run), two reference APDs(VPTs) were instead chosen in each light monitoring region (approximately 200 crystals). The reconstructed laser amplitudes in the other APDs(VPTs) were normalised relative to these reference channels, in order to correct for pulse-to-pulse variations in the laser output. Here it is assumed that the reference APDs(VPTs) are stable reference points in the data taking conditions of CRAFT, where no crystal transparency changes are expected to have occurred.

The stability of the light monitoring system was assessed in EB and EE over a 200 hour long period within CRAFT, when nominal data quality conditions were met. In EB, 99.8% of the monitored channels exhibited an $\langle\text{APD}/\text{APD}_{\text{ref}}\rangle$ stability better than the ECAL requirement of 0.2% (see Fig. 4). For EE, 98.3% of the monitored endcap channels showed a stability better than 0.2% during the same period.

VI. VPT PERFORMANCE AT 3.8 TESLA

Measurements taken during 2008 with the ECAL laser and LED monitoring systems in the CMS underground cavern, in

Fig. 4. Stability of the ECAL laser monitoring system during CRAFT. RMS deviation of the quantity $\langle\text{APD}/\text{APD}_{\text{ref}}\rangle$ for EB channels with nominal data quality cuts applied. The most stable of the two reference APDs was used in each light monitoring region. The small secondary peak at 0.2% from 150 neighbouring channels is shown by the grey histogram.

an operating field of 3.8 T, were used to study the performance of the 14 648 installed VPTs. They confirmed the operability of these devices in a high field and permitted studies of the effects of magnetic field and pulsing rate on the VPT anode sensitivity.

A. VPT response as a function of orientation to magnetic field axis

Over the range of angles between the endcap VPT tube axes and the magnetic field direction (4 to 18 degrees), the VPT anode sensitivity changes by a value between 5 and 30%, relative to the response at 0 T. The response varies as a function of the angle θ between the axis of the device and the magnetic field direction, and as a function of the orientation ϕ of the device about its axis. In CMS, the ϕ orientation of the VPTs was randomised during dee construction, so the effect of ϕ orientation on VPT response will be averaged out for a fixed value of θ .

In order to measure this effect, a series of laser runs were taken in both endcaps at zero and 3.8 T magnetic field. The measured dependence of VPT response as a function of the tilt angle θ of the endcap VPTs with respect to the magnetic field direction is shown in Fig. 5. The ratio of VPT response for two laser runs taken at 3.8 T ($Y_{3.8}$) and 0 T (Y_0) during CRAFT is shown, for the angular range between 4 and 18 degrees. Among the endcap VPTs, more than 75% of the tubes exhibit tilt angles between 10 and 18 degrees, and the measured value of the ratio $Y_{3.8}/Y_0$ averaged over all tubes is 88.9%. The RMS spread of the data points, indicated by the dashed lines in Fig. 5(b), is 4% and shows the effect of averaging over the ϕ angle in CMS.

The solid line in Fig. 5 shows the result of an empirical fit to this data. Since the pre-calibration constants for the endcaps discussed in the previous section and the energy scale derived from test beam measurements were all obtained at zero magnetic field, this fit was used to provide θ -dependent correction factors, which were used to translate the pre-calibration constants to 3.8 T.

Fig. 5. Normalised ratio of VPT response $Y_{3.8}/Y_0$ as a function of the tilt angle θ for EE laser runs taken with a magnetic field of 3.8 T and 0 T. The band between the two dashed lines represents the RMS spread of the quantity $Y_{3.8}/Y_0$ for all VPTs at a given θ angle. The solid line shows the result of a fit to the data using a sinusoidal function.

B. VPT rate sensitivity

The VPTs used in CMS are designed to operate in a high magnetic field. Since they do not have electrostatic focussing, they require the presence of a strong quasi-axial magnetic field for stable operation. Variations of 5 to 20% in VPT response at zero magnetic field, induced by sudden changes in the illuminating light pulse rate, have been observed in both laboratory and test beam measurements. These variations were found to be strongly suppressed in the laboratory at 1.8 T and 4 T, and also suppressed in the presence of a constant background illumination. A LED pulser system provides a constant background rate to each VPT, in order to keep them active in the absence of LHC collisions and reduce their rate sensitivity.

Figure 6 shows the normalised VPT response, averaged over 200 channels, as a function of time, during two tests, performed with a magnetic field of 0 T and 3.8 T. In both cases, the LED pulsing at high rate, equivalent to the expected average VPT load during LHC running at a luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, was turned off at time $T = 0$ hours. The response of each VPT was continuously monitored throughout the entire period via dedicated LED runs (approximately 500 pulses taken at 100 Hz). The average variation of VPT response when the high rate pulsing was turned off was measured to be 5% with the CMS magnet at 0 T. When the same test was performed with the CMS magnet at 3.8 T, the average variation of VPT response was measured to be less than 0.2%, as expected.

VII. SUMMARY

The cosmic-ray data taking period in October and November 2008 was the first opportunity to operate the crystal ECAL for an extended period of time, with CMS in its final configuration. Both the barrel and endcap detectors operated stably during this period, with more than 98.5% of channels active. The stability of electronic noise, high voltage and temperature are found to satisfy the ECAL performance targets

Fig. 6. Normalised VPT response (averaged over 200 tubes) for two high rate LED pulsing tests at 0 T (open circles) and 3.8 T (filled circles) during CRAFT. In both tests, LED pulsing with a rate of 10 kHz was performed for a period of 17 hours and turned off at time $T = 0$ hours. The VPT response was normalised to the value at time $T = -10$ hours in both tests.

and therefore do not provide significant contributions to the constant term of the EM energy resolution.

The ECAL light monitoring system will track changes in crystal transparency during LHC operation and will provide correction factors to be applied to the calorimeter output. The laser calibration data taken during the cosmic-ray tests were used to evaluate the stability of the light monitoring system in a 200 hour period only using the channels for which nominal data quality criteria were met. A total of 99.8% of the monitored barrel channels and 98.3% of the monitored endcap channels showed a normalised laser amplitude stability better than 0.2% (RMS).

The 14 648 VPT photodetectors, which are used in the endcaps, were shown to operate stably at 3.8 T. The dependence of VPT response on the angle of the tube axes with respect to the magnetic field direction was measured, and was used to update the existing calibration constants that were obtained at 0 T. The endcap LED system was used to measure the sensitivity of the VPT anode (averaged over 200 tubes) to sudden changes in rate. This sensitivity was found to be less than 0.2% in the high magnetic field of CMS.

Additional cosmic-ray muon tests were performed during 2009 prior to the resumption of LHC beam operation. During this period, the preshower detectors were installed and commissioned. Of the 137 216 preshower channels, 99.9% are operational for LHC physics. The trigger electronics for the crystal endcap detectors was installed and commissioned during 2009. The status of the barrel and endcap channels was continuously monitored during these cosmic-ray tests, and greater than 99.4% of the crystal ECAL channels are operational for LHC physics.

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