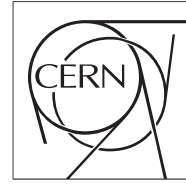


The Compact Muon Solenoid Experiment  
**Conference Report**

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# Studies of the CMS Electromagnetic Calorimeter performance in the electron test beam

Roberta Arcidiacono, on behalf of the CMS ECAL Group

## Abstract

The Compact Muon Solenoid (CMS) is a general purpose detector for LHC. The electromagnetic calorimeter (ECAL), comprising about 76,000  $\text{PbWO}_4$  scintillating crystals, will allow a very accurate energy measurement of electrons and photons. The 36 supermodules (units of 1700 crystals) of the barrel have been successfully integrated inside the CMS solenoid. In 2006 nine supermodules with the final mechanics, cooling and electronics were exposed to electron test beams in order to perform precise inter-calibration and comprehensive studies of the detector response. A survey of results from these tests are here presented, with emphasis given to the energy resolution and linearity achieved.

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# Studies of the CMS Electromagnetic Calorimeter performance in the electron test beam

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**Abstract.** The Compact Muon Solenoid (CMS) is a general purpose detector for LHC. The electromagnetic calorimeter (ECAL), comprising about 76,000  $\text{PbWO}_4$  scintillating crystals, will allow a very accurate energy measurement of electrons and photons. The 36 supermodules (units of 1700 crystals) of the barrel have been successfully integrated inside the CMS solenoid. In 2006 nine supermodules with the final mechanics, cooling and electronics were exposed to electron test beams in order to perform precise inter-calibration and comprehensive studies of the detector response. A survey of results from these tests are here presented, with emphasis given to the energy resolution and linearity achieved.

## 1. Introduction

The CMS (Compact Muon Solenoid) [1] is one of the two multi-purpose experiments that will take data at the LHC proton-proton collider. The main physics goals of the CMS experiment are the discovery of the Higgs boson and the search for new physics phenomena, in particular the search for supersymmetric particles. For a mass lower than 150 GeV, the Higgs decay in two photons is the cleanest channel for the discovery. In this mass range, the very narrow Higgs signal will lie above an irreducible background: this led to the choice of a high resolution electromagnetic calorimeter.

## 2. The CMS electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) [2] is an hermetic homogeneous calorimeter consisting of about 76,000 lead tungstate ( $\text{PbWO}_4$ ) scintillating crystals. It covers the pseudo-rapidity ( $\eta$ ) range from 0 to 3.0 by means of a barrel part ( $0 < |\eta| < 1.48$ ) and two endcaps ( $1.48 < |\eta| < 3$ ). ECAL is organized in 36 supermodules (SM), each containing 1700 crystals, in the barrel, and in 4 dees, each consisting of 3662 crystals, in the endcaps. The ECAL detector is mounted inside the CMS superconducting solenoid (4 Tesla). The target value of the energy resolution of the calorimeter at high energies is less than 0.5%.

The choice of lead tungstate [3], very dense material ( $\rho = 8.28 \text{ g/cm}^3$ ) with short radiation length (0.89 cm) and a small Moliere radius (2.2 cm), led to a very compact high granularity calorimeter design. The  $\text{PbWO}_4$  produces fast signals (80% of light is emitted within the 25 ns LHC bunch crossing time) and is radiation resistant. Nevertheless this material presents major drawbacks: a low light yield ( $\sim 100$  photons/MeV, 0.2% with respect to NaI:Tl) which imposes a photodetector read-out with internal gain; a strong light yield dependence on temperature ( $-2\%/^\circ\text{C}$  around  $18^\circ\text{C}$ ), imposing a high precision cooling system to stabilize crystals temperature

to  $\pm 0.05^\circ\text{C}$ ; high refractive index (2.29 at peak emission wavelength = 420 nm) which makes the light extraction difficult.

Crystals in the barrel are read-out by Avalanche PhotoDiodes (APD), while in the endcaps the scintillating light is detected by Vacuum Photo Triodes (VPT).

The front-end electronics [4] and the trigger primitive generation are located on the detector with the advantage of minimizing external noise contribution and reducing the number of optical links to the off-detector read-out. Crystal signals are digitized sending the signal in parallel to the three amplifiers (gain 1, 6, 12) of the MGPA chip, choosing the highest not saturated gain, and sampled at 40 MHz. A time window of 10 samples is read-out for every L1 trigger.

In the following, test beam data results related to the ECAL barrel are described.

### 3. Test beam data taking in 2006

Two test beam campaigns, on the H4 and H2 beam lines of the CERN North Area, have been carried on during summer 2006.

In H4, where electrons in the 15-250 GeV range were delivered, detailed performance studies and precise inter-calibration of 9 SMs have been done. The final version of the read-out electronics, data acquisition and of all services have been tested. The supermodules were mounted on a rotating frame reproducing the same almost pointing geometry of CMS. Four planes of hodoscopes were used to reconstruct the trajectories of the electrons impinging on the crystals.

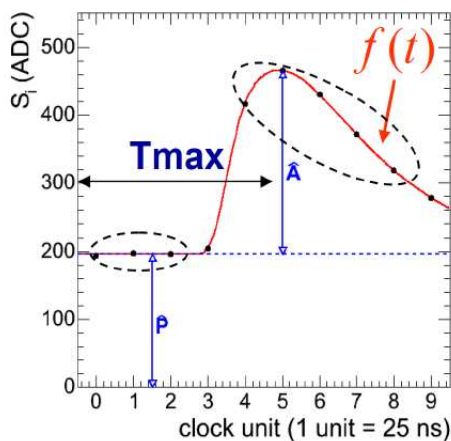
In H2, electrons/positrons in the 2-100 GeV range or pions were available for the combined test of the electromagnetic and hadronic calorimeters. ECAL response to low energy particles has been studied.

In parallel, each of the 36 ECAL barrel SMs has been tested for inter-calibration purpose with cosmic muons.

## 4. Performance studies

### 4.1. Detector response

The amplitude of the signal collected in each crystal is reconstructed using a digital filtering technique. A weighted linear combination of the time samples  $S_i$ ,  $A = \sum_i w_i S_i$ , is performed, to minimize the contribution of electronics noise. The determination of the optimal set of weights makes use of a representation  $f(t)$  of the time development of the signal pulse, as shown in figure 1.



**Figure 1.** Signal amplitude reconstruction with digital filtering technique: time samples in the read-out window with superimposed the analytical representation  $f(t)$  of the pulse shape time development.

Real data are affected by (high frequency) noise correlations between time samples, while any low frequency (e.g. pick-up) noise is taken away by pedestal measurements and subtraction. The best results for test beam data have been obtained with the “pedestal subtracting” or “3 + 5” weights scheme, where weights for samples on the rising edge of the signal pulse are set to zero, leaving 3 pedestal samples before the pulse and 5 samples during the pulse.

The measurement of the electronics noise is made by applying the amplitude reconstruction procedure to data taken with a random trigger. The distribution of such noise measurements for a large number of individual channels gives a mean width  $\sigma_{1 \times 1}$  of 35.7 MeV with a rms dispersion of 3.3 MeV. The shower energy is measured by summing the energy deposits in matrices of either 3x3 or 5x5 crystals centered on the crystal with the largest energy deposit, with crystal channels inter-calibrated at gain 12 using 120 GeV electrons.

The noise distribution in the two clustering matrices has a width  $\sigma_{3 \times 3} = 107$  MeV and  $\sigma_{5 \times 5} = 179$  MeV respectively. This corresponds to about 3 and 5 times the single channel noise, as expected in absence of channel-to-channel correlated noise.

#### 4.2. Position resolution

The distribution of the energy which is deposited by an electron in a NxN matrix depends on the electron impact point on the face of the central crystal. The impact position measured by the ECAL detector is reconstructed as a weighted average of the positions of the crystals in the matrix,  $X = \sum_i w_i x_i / \sum_i w_i$ . The  $x_i$  is the shower center of gravity projected on the  $i$ -crystal front face, which depends on the shower maximum depth, given the quasi-projective crystals geometry. The weights  $w_i = w_0 + \ln(E_i/E_{tot})$ , have a logarithmic dependence on the fraction of shower energy of the crystal to take into account the dependence of the shower density with the distance from the shower axis. The  $w_0$  parameter controls the smallest energy fraction a crystal can have to be considered in the sum, and it has been selected to optimize the position resolution ( $w_0 = 5$ ).

Dedicated large statistics samples collected at different energies on SM16 and SM6 are used for this study. The amplitude in the crystal is evaluated using the weight method with optimized weights calculated from a shape profile specific for each crystal. Inter-calibration coefficients calculated at 120 GeV are used.

The ECAL shower coordinates are compared to the coordinates measured by the hodoscope system positioned along the electron beam line (150  $\mu$ s resolution), which are referred as “true”.

Figure 2 shows the obtained resolution as a function of the beam energy for the X and Y coordinate (average of the 25 analyzed crystals of SM16). The hodoscope resolution has been subtracted. The plot shows results related to the 3x3 and 5x5 clustering algorithms, the second being slightly better.

#### 4.3. Energy resolution

A uniform energy measurement response of ECAL is essential for precision physics. As already mentioned, the shower energy is reconstructed by summing signals in a 3x3 or 5x5 matrix centered on the crystal with the largest energy deposit. The variation of energy contained inside the clustering matrix, due to the electron impact position, leads to a degradation of the energy measurement. To achieve the desired energy resolution and uniformity of response when the incident electrons are distributed over the full crystal front face, a correction must be applied on event-by-event basis.

To study the calorimeter energy resolution decoupled from the shower containment correction, only electrons with central beam incidence, defined within an area of  $4 \times 4$  mm<sup>2</sup> around the point of maximum shower containment, are considered. For such a small central area of incidence, there is no observable dependence on the incident position.

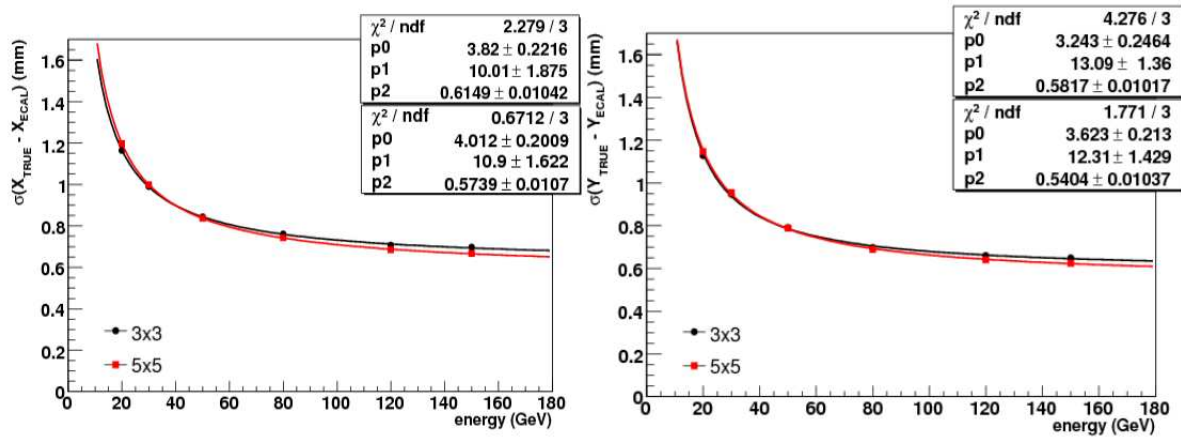
High statistics samples have been taken at 20, 30, 50, 80, 120, 180 and 250 GeV. The energy resolution versus energy is fitted by the following functional form:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2 \quad (E \text{ in GeV})$$

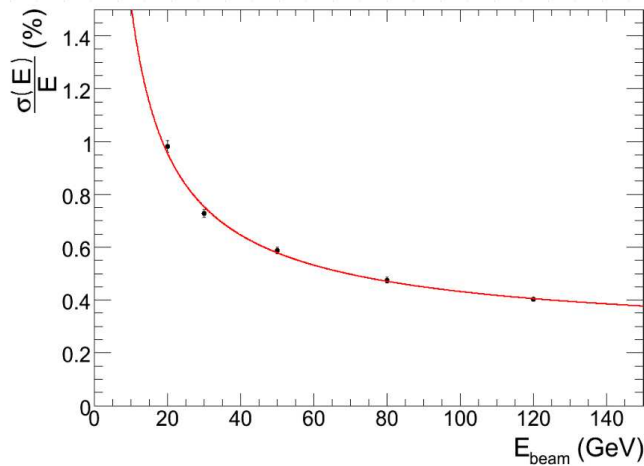
where  $S$  is the stochastic term,  $N$  the noise and  $C$  the constant term. The fit is performed with the noise term fixed for each crystal at the value measured in the pedestal runs.

Figure 3 shows the relative energy resolution  $\sigma/E$  measured for a crystal array of 5x5 crystals in the 20-120 GeV energy range, where optimized weights have been computed for all the crystals of the matrix. The noise term has been fixed to 0.107 GeV. The fit gives a stochastic term of 3.37% and a constant term of 0.25%, well in agreement with the designed values.

Compared to the results obtained for central incidence a slightly larger dispersion of the



**Figure 2.** Position resolution in the X (left) and the Y (right) coordinate as a function of the beam energy. The crystals belonging to a 3x3 or a 5x5 matrix around the crystal with maximum energy deposition are considered as possibly contributing



**Figure 3.** Energy resolution  $\sigma_E/E$ , as a function of the beam energy (average over 25 crystals of SM16), for central beam incidence. The energy is reconstructed using a 3x3 clustering matrix.

stochastic and constant terms is observed for uniform incidence. The resolution nevertheless remains better than 0.5% for electrons of energy greater than about 100 GeV.

#### 4.4. Energy linearity

During the 2006 test campaign the H4 beam line has been equipped to be able to measure the incident electron energy with high precision. The precision achieved is  $dE/E \sim 0.1\%$ .

Special runs, where the beamline parameters (collimators, bends) have been carefully configured, are used to study at best the ECAL non-linearity as a function of the beam energy. Only very central electrons, impinging within an area of  $2 \times 2 \text{ mm}^2$  around the point of maximum shower containment, are considered for this study.

The reconstructed energy is obtained fitting the  $5 \times 5$  array energy distribution (E25) with a Gaussian plus an exponential low energy tail (Crystal Ball function). Inter-calibration coefficients calculated at 120 GeV are applied.

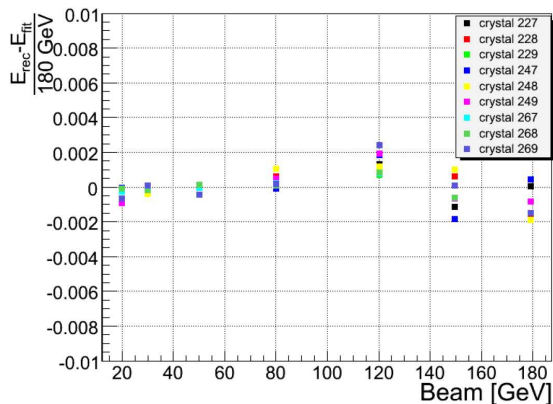
The preliminary differential non-linearity (deviations from a linear fit of reconstructed energy versus beam energy normalized to the measured energy range) is shown in figure 4. The beam and inter-calibration uncertainties have not been subtracted. The linearity of the Very Front-End (VFE) cards has also been measured in laboratory to be of the order of 0.1%.

The maximum deviation observed over the 20-180 GeV range (where gain switching occurs around 150 GeV) is of the order of 0.2%.

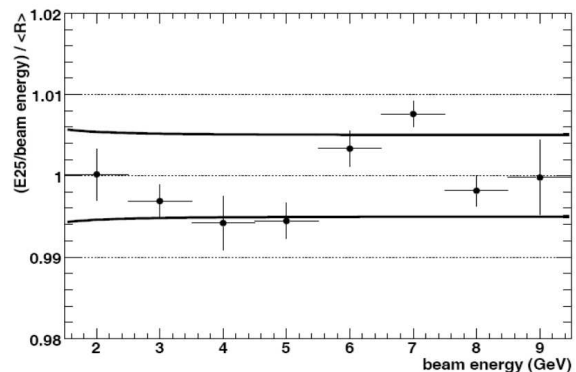
The linearity of ECAL response was also investigated at the ECAL-HCAL combined test beam in H2, using electrons (2-9 GeV) and positrons (9-100 GeV). The precision of the beam energy measurement in H2 was of the order of 0.5%.

The ratio  $E_{25\text{peak}}/E_{\text{beam}}$ , where  $E_{25\text{peak}}$  is the E25 fitted energy peak, is used to quantify the deviation from linearity of every energy point.

Several corrections have been applied on ECAL energy measurements, related to the temperature variation during the data taking, the energy loss along the H2 beam line, the energy leakage of the crystals, the beam energy scale variation and beam energy spread.



**Figure 4.** Preliminary differential non-linearity measurement in the 20-180 GeV range for 9 crystals - H4 beam line.



**Figure 5.** Profile of  $E_{25}/E_{\text{beam}}$  normalized to the weighted average  $\langle R \rangle$ , for 16 crystals - H2 beam line.

In figure 5 the results for the low energy electrons events are shown, averaged over the 16 studied crystals distributed along the SM.

The plot displays, for every beam energy, the  $E_{25\text{peak}}/E_{\text{beam}}$  rescaled by the  $\langle R \rangle$  factor, which is a weighted average of the  $R_j = E_{25\text{peak}}/E_{\text{beam}}$  ratios for the various energies. The

$\langle R \rangle$  factor is directly related to the inter-calibration constant of the crystal; the rescaling of  $E_{25\text{peak}}/E_{\text{beam}}$  removes the contribution of the inter-calibration uncertainty from the linearity study. The two curves represent the beam energy scale uncertainty.

The RMS of the points, which is 0.51%, gives an indication that, in 2-9 GeV energy range, no deviation from linearity is observed at level of 0.5%.

#### 4.5. Cosmic and Test-beam inter-calibration

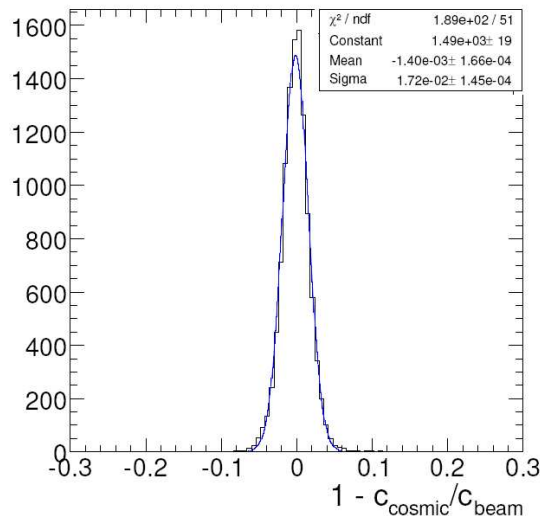
All ECAL barrel SMs have been inter-calibrated with cosmic events in the cosmic test bench prepared in the CERN North Area, while, due to time constraints, only 9 SMs have been inter-calibrated with high energy electron beam.

The reference signal for the calibration with cosmic rays is provided by the energy released by minimum ionizing particles (about 250 MeV) crossing the ECAL crystals all along their length. The APD read-out gain is increased by a factor four with respect to the nominal working point, to enhance the signal to noise ratio to about 25. The trigger, given by the coincidence of a layer of plastic scintillators placed under the supermodule and of a plastic scintillator placed in the focal point, helps the selection of muons directed along the crystal axis.

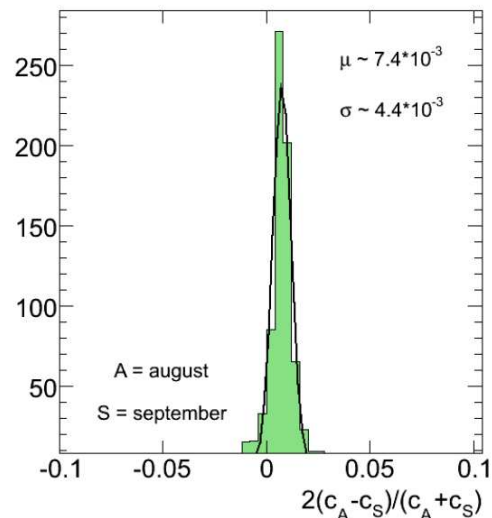
About 5 million triggers, typically collected in seven days of data taking, ensures a statistical accuracy ranging from 1% to 2.5% according to the crystal position along  $\eta$ .

The inter-calibrations are obtained equalizing the responses of the different crystals to the muons. A detailed comparison with the coefficients from the inter-calibration with an electron beam shows an agreement over the single whole supermodule at 1.5% level (figure 6). The calibration with cosmic guarantees that the large majority of the ECAL channels are equalized to 1.5% already at the beginning of the data taking.

The high energy electron beam inter-calibration has been carried on in H4. For this study, each crystal of the SMs has been irradiated with more than 3,000 electrons. The beam has been set to the energies of 120 GeV and 90 GeV, allowing the study of systematic effects on the inter-calibration related to the energy. Two techniques, based on the energy deposited in



**Figure 6.** Distribution of the fractional difference between the inter-calibration coefficients measured at the test beam and the ones measured with cosmic rays (S1 method).



**Figure 7.** Relative difference between August and September inter-calibration coefficients (S25 method) for supermodule 22 that was under beam twice

each single crystal (S1) and on the energy deposited in a 5x5 matrix of crystals (S25), have been used. In the first case, the coefficients are calculated by equalizing the maximal response of each crystal to a reference value. In the second case, which will be used during the data taking, the energy deposited in each crystals cluster is compared to the one of the electron beam. The two methods are in agreement at a level of 0.3%.

The reproducibility of the inter-calibration measurements has been tested by performing the procedure twice on the same supermodule, with a time interval of one month. Figure 7 shows the distribution of the relative difference of the two measures for all the crystals of a supermodule. The width of the distribution is 0.27%, corresponding to an error on the coefficients of about 0.2%. The distribution of the relative difference between the measurements performed at 90 GeV and 120 GeV has been built. The inter-calibration coefficients are reproducible at a level of 0.3%.

## 5. Conclusion

The ECAL barrel has been pre-calibrated during the test beam campaign, installed and commissioned inside the CMS solenoid in the P5 experimental cavern. Many other extensive test beam studies have been carried on during summer 2006 on part of the ECAL barrel to evaluate the detector performance. Results look very promising and indicates that CMS ECAL will meet its ambitious design goal for energy resolution, uniformity of the response and noise level.

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