CMS Conference Report

6 September 2004

Energy and impact point reconstruction in the CMS ECAL (Testbeam results from 2003)

I. van Vulpen

CERN, Geneva, Switzerland

Abstract

The Electromagnetic Calorimeter of the CMS detector at the LHC will consist of approximately 75,000 PbWO₄ crystals and is designed to provide a very precise energy measurement in a high radiation environment. During a testbeam campaign in 2003, an electron beam was used to test the performance of a system consisting of two super modules (a total of 100 crystals). In this talk an overview of the various issues related to the reconstruction of the energy deposition in single crystals and the resolution on the impact position of incident particles is presented. The final energy resolution, using a proto-type of the final electronics meets the target specification.

Presented at *the XI International Conference on Calorimetry in High Energy Physics - CALOR2004*,
Perugia - Italy, March 29 - April 2, 2004

1 Introduction and testbeam operation

Incident electrons and photons create an electromagnetic shower in the PbWO₄ crystals. The scintillation light produced in these showers is collected by photo-detectors on the rear surface of each crystal, pre-amplified and digitized at 40 MHz using a 12 bits ADC and multiple gain pre-amplifiers. Testbeam data was taken in 2003 using both the old (FPPA) and final proto-type (MGPA) of the front-end electronics. Electron energies ranged from 20 to 200 GeV.

2 Pulse amplitude (energy) reconstruction

The amplitude of the reconstructed pulse is a measure for the energy deposited in the crystal; in this section the algorithm that has been developed to provide an unbiased and precise estimate of this amplitude, over the full energy range expected at the LHC, is presented.

2.1 The weights method

The algorithm used to reconstruct the amplitude from the individual time samples (the pulse shape is digitized every 25 ns) is based on the widely used technique of digital filtering. An estimate of the amplitude is given by a linear weighting of the time samples:

$$A = \sum_i w_i S_i ,$$

where $\tilde{A}$ is the estimate for the amplitude, the S_i are the individual digitized samples (signal + noise) and the w_i are the corresponding weights at time t_i (a multiple of 25 ns). The expected variance is estimated using a χ^2 from the expected and observed pulse (samples):

$$\chi^2 = (\vec{S} - A \times \vec{F})^T V^{-1} (\vec{S} - A \times \vec{F}) ,$$

where $\vec{S}(\vec{F})$ is the set of measured(expected) time samples, A is the amplitude to be extracted and the correlations between the samples are described by V . The set of optimal weights (resulting in an unbiased and most precise amplitude estimation) is obtained by minimizing the expected variance. In the most simple case when there is no remaining base-line or pedestal and no correlated noise between the samples, the weights are given by:

$$w_i = \frac{f_i}{\sum_i f_i^2} ,$$

where f_i is the expected pulse height for sample i . If the base-line is also left free the expression for the weights is more complicated[1].

The expected pulse shapes are obtained from the data and described by an analytic function. The effect on the energy resolution from a shift between the expected and true time of the pulse-maximum is shown in the left plot of Figure 1. During LHC operation the time jitter is expected to be well below 1 ns.

2.2 Optimization and results on real data

During testbeam operation an optimization was performed by varying the range (and number) of samples used in the fit. The best resolution is obtained when using 5 samples: from 1 sample before the expected maximum up to 3 samples after. Using such a small number of samples reduces the contamination from pile-up events, reduces the data-volume and increases the reconstruction speed, all relevant issues when related to CMS operation.

The distribution of the reconstructed energy in a crystal far away from the crystal that was hit by the incident electron shows that there is no bias down to very small (zero) amplitudes and that the noise from a single channel is close to 50 MeV. In the right plot of Figure 1 the obtained energy resolution is shown for events within a window (4x4 mm) of impact positions relative to the centre of the crystal.

The resolution can be parametrized as a function of the energy as [2]:

$$\frac{\sigma(E)}{E} = \frac{2.4\%}{\sqrt{E}} \oplus \frac{142 \text{ MeV}}{E} \oplus 0.44\%.$$

Figure 1: The left plot shows the dependence of the energy resolution on a timing mismatch. The right plot shows the distribution of the energy resolution as a function of the energy. Both plots correspond to MGPA as front-end electronics.

3 Impact position reconstruction

Providing an accurate impact position of incident electrons and photons is important when computing invariant masses and is crucial in position matching of ECAL objects to tracks or pixel hits in the CMS triggers.

In the testbeam set-up a hodoscope system was used to estimate the ('true') impact point of electrons on the front-face of the crystal with a precision of up to $250 \mu\text{m}$ in both orientations (X and Y) and to select an event sample consisting of high quality tracks parallel to the beam axis.

3.1 General idea of position reconstruction

The (known) lateral development of an electromagnetic shower inside a PbWO_4 crystal defines the distribution of the energy deposition in a cluster of 3x3 crystals around the impact point. An estimate of the impact point can therefore be obtained using a centre-of-gravity technique in which the energy deposited in each crystal is weighted with its characteristic position[3]:

$$\tilde{X} = \frac{\sum_i w_i \cdot x_i}{\sum_i w_i}, \quad (1)$$

with a similar expression for $\tilde{Y}$. The position in x that represents best the average position of the energy deposited in each crystal is taken as the position of the shower maximum projected on the front-face of the crystal. The average shower depth as a function of the particle's energy is given by:

$$\text{shower depth} = X_0 (\log(E) + A_0), \quad (2)$$

where X_0 represents the radiation length for PbWO_4 (0.89 cm). Due to the non-pointing geometry of the crystals, the position of the shower maximum differs significantly from the centre of the front-face of the crystal. To avoid a complicated set of correction functions to obtain a bias free estimate, the expected shower shape should be considered when computing the weights used in equation (1). Since to first order the transverse shower profile is close to an exponential, a good set of weights is given by:

$$w_i = w_0 + \log\left(\frac{E_i}{E_{\text{tot}}}\right).$$

In this expression E_{tot} represents the total shower energy as collected in the 3x3 crystal matrix around the central crystal and since the weights are required to be positive, w_0 controls the smallest fractional energy in the crystal that will be used when reconstructing the centre-of-gravity.

3.2 Optimization and results on real data

After an alignment, the remaining bias on the impact point is controlled by A_0 from equation (2) and the resolution by w_0 . In the left plot of Figure 2 the resolution on the impact position in X is shown as a function of w_0 for incident electrons with an energy of 50 GeV. The optimal resolution is obtained when using a (almost energy independent) value of w_0 of 3.85 which corresponds to using a fractional energy threshold of 2.1%. After correcting for the non-uniform beam profile and the uncertainty on the true impact position, the average resolution on the impact position in X as a function of the beam energy is shown in the right plot of Figure 2.

Figure 2: The left plot shows the resolution on the impact position in X for 50 GeV electrons as a function of w_0 . The right plot shows the resolution on the impact position in X (averaged over the full front-face of the crystal) as a function of the beam energy.

The resolution as a function of the energy can be parametrized as:

$$\sigma_x(\mu\text{m}) = 550 \oplus \frac{5020}{\sqrt{E}} \quad \text{and} \quad \sigma_y(\mu\text{m}) = 430 \oplus \frac{5040}{\sqrt{E}}$$

4 Conclusions

The performances and characteristics of methods to reconstruct both the energy deposited in a single crystal and the impact point of incident particles have been evaluated using the data collected during the 2003 testbeam campaign. The energy estimation is unbiased down to small energies and reaches the target energy resolution as presented in the Technical Design Report and the logarithmic weighting method for the impact position reconstruction requires no (sets of) correction curves, but reaches a precision of better than 1 mm above 30 GeV.

Acknowledgments

I would like to give my thanks and acknowledge my indebtedness to the many collaborators on the ECAL project whose work on the preparation of the super-module, and its operation and data-taking in the testbeam, made the obtaining of these results possible. Also to the colleagues working on the software and analysis, and whose tools and ideas I have freely used. In particular I want to thank G. Daskalakis, M. Dejardin, P. Jarry, P. Paganini, C. Seez and Y. Sirois for their suggestions when preparing this talk.

References

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