Response of the CALICE Si-W ECAL Physics Prototype to Electrons

Djamel BOUMEDIENE on behalf of the CALICE Collaboration
Laboratoire de Physique Corpusculaire, CNRS/IN2P3, Univ. B. Pascal
24 Av. des Landais, F-63177 Aubière Cedex - France
E-mail: Djamel.Boumediene@cern.ch

Abstract. The CALICE [1] Si-W electromagnetic calorimeter [2] has been tested with low energy electron beams at DESY (1 to 6 GeV) in May 2006, as well as higher energy electrons (6 to 45 GeV) at CERN in August and October 2006. The large amount of high quality data allows the characterisation the ECAL physics performance.

1. Introduction
In the frame of Particle Flow Analysis and in a high particle multiplicity environment, the jet measurements require efficient single particle reconstructions. A way of achieving it is by building high granularity calorimeters as proposed for ILC [3] by the CALICE collaboration.

The ECAL prototype developed by the collaboration is a highly segmented, sampling Si-W calorimeter. It has 30 layers, each with 216 $1 \times 1 \text{ cm}^2$ detection pads distributed on six wafers leading to a total of 6480 channels. Around the pads in each wafer, a non-active region of 1.8 mm width was used for a grounded guard ring structure.

The prototype was tested during two test beam campaigns at DESY and CERN. Four drift chambers were used to monitor the beam. Čerenkov detectors were also available for $e/\pi$ discrimination. The large sample of collected data was used to characterise the ECAL physics performance in terms of energy resolution, linearity of the response, spatial resolution as well as the longitudinal and radial development of the electromagnetic showers. The spatial homogeneity of the detector was also addressed.

Some comparisons are performed between data and Monte Carlo simulations based on Geant4 [4] [5].

2. Electron selection
The total energy recorded in the ECAL, $E_{\text{raw}}$, is defined as follows:

$$E_{\text{raw}} = \sum_{i=0}^{i=9} E_i + 2 \sum_{i=10}^{i=19} E_i + 3 \sum_{i=20}^{i=29} E_i,$$

where the three stacks are weighted in the ratio 1:2:3 according to the tungsten thickness in each of them.

The selection of single electrons is performed in three steps:
an energy window, scaled to the beam energy, is applied on $E_{\text{raw}}$:

$$125 < \frac{E_{\text{raw}}(\text{MIP})}{E_{\text{beam}}(\text{GeV})} < 375$$

This cut rejects the low energy peaks due to muons and pions;

- rejection of pions is obtained by requesting higher then threshold signals from the Čerenkov counter;
- the beam halo which contains low energy electrons is rejected on a run-per-run basis.

![Figure 1. Distribution of $E_{\text{raw}}$ for a 20 GeV beam. The $E_{\text{raw}}$ selection window and the shaded area obtained by demanding a signal from the Čerenkov counter are shown. The low energy peak is due to MIP like particles (muons and pions).](image)

3. Interwafer gap effects

The guard-rings represent a non-active area of 2 mm width leading to energy loss when particle traverse them. They represent the dominant source of lateral inhomogeneity. This non-uniformity is studied as a function of the position of the shower barycentre. The shower barycentre is given by the mean position of the hits weighted by their energy:

$$(\bar{x}, \bar{y}) = \left( \sum_i E_i x_i, \sum_i E_i y_i \right) / \sum_i E_i$$

The effect of the guard rings on the uniformity of the ECAL energy response is illustrated in figure 2. The ECAL energy response, $f(x, y) = E_{\text{raw}}/E_{\text{beam}}$, is modeled by a Gaussian function:

$$f(\bar{x}, \bar{y}) = \left( 1 - a_x e^{-\frac{(\bar{x} - \text{gap})^2}{2\sigma_x^2}} \right) \left( 1 - a_y e^{-\frac{(\bar{y} - \text{gap})^2}{2\sigma_y^2}} \right)$$

$f(\bar{x}, \bar{y})$ is fitted to the data, as displayed on figure 3, to extract the values of its parameters, $a_x$, $a_y$, $\sigma_x$ and $\sigma_y$.

The energy loss in the interwafer gaps can be corrected by applying a $1/f$ correction factor to the reconstructed energy of each shower. Since this method relies on calorimetric informations only, it can be applied on photons as well as on electrons.

As shown on figure 4, the correction improves the detector uniformity to the percent level. It also improves the shape of the energy distribution, which becomes more Gaussian as shown on figure 5.
Figure 2. Mean values of $E_{raw}$ for a 15 GeV $e^-$ beam as function of the barycentre coordinates. The square pattern corresponds to the effect of the guard rings on the reconstructed energy.

Figure 3. $f(\bar{x},\bar{y})$ function of the shower barycentre coordinates, for a combined sample of 10, 15 and 20 GeV electrons. To characterise the $x$ ($y$) response, the events were requested to be outside the interwafer gap in $y$ ($x$).

4. Performance studies

4.1. Spatial and angular resolution

The spatial and angular resolution of the ECAL are studied with the DESY data at normal incidence. The shower direction and position at the ECAL front face are constructed on an event-by-event basis using a linear two-parameter chi-square fit to the shower barycentre positions in each layer for the $x$ and $y$ coordinates separately. The correlation matrix is determined from simulations for each beam energy.

The fit results are compared with the position and angle measured by the tracking system. The expected $e^-$ position and direction at ECAL front face is obtained from a linear fit of the drift chambers. Sources of systematic uncertainties as residual misalignment, material modeling,
Figure 4. Mean $E_{\text{raw}}$ function of the shower barycentre coordinates for 20 GeV electrons, before (black triangles) and after the corrections (blue circles) were applied on $E_{\text{raw}}$.

Figure 5. Energy distribution for 20 GeV electrons in case of events outside the interwafer gaps (red histogram), all events without corrections (black histogram) and all events with corrections (blue circles). The histograms are normalised to the same number of entries.

and background rate are estimated for the extrapolation to the ECAL front face.

The ECAL resolution, deconvoluted from the tracking errors, is displayed in figure 6.

4.2. Selection of showers well contained in the ECAL
A fiducial volume selects the showers well contained in the ECAL module and in the wafers. A first cut is applied to the distance between the barycentre of the electron shower and the borders of the ECAL in order to minimise the effect of the lateral leakage, while a second cut is applied on the distance between the electron track and the wafer borders in order to disentangle the effect of the guard rings. A summary of the selected electron and positron data is shown in table 1.
Figure 6. Resolutions in position (left) and angle (right) as a function of the beam energy. The data are shown as points with error bars. The expectation from simulation is shown by the continuous line.

Table 1. Number of selected electron events used to characterise the response of the calorimeter.

| Beam energy (GeV) | Particle | Sample size (kevts) |
|------------------|----------|---------------------|
| 6                | $e^+$, $e^-$ | 10.6               |
| 10               | $e^+$, $e^-$ | 55.9               |
| 12               | $e^+$, $e^-$ | 32.1               |
| 15               | $e^+$, $e^-$ | 60.4               |
| 20               | $e^+$, $e^-$ | 76.9               |
| 30               | $e^+$, $e^-$ | 43                 |
| 40               | $e^-$       | 27                 |
| 45               | $e^-$       | 129.3              |

4.3. Linearity and energy resolution

The total energy response of the calorimeter is calculated as

$$ E_{\text{rec}} = \sum_{i=0}^{i=29} w_i E_i $$

where $w_i$ is the sampling fraction of the layer $i$. This weight takes into account the tungsten thickness as well as the contribution of the passive materials of the calorimeter: PCB, aluminum, glue, etc. The distribution of $E_{\text{rec}}$ for 20 GeV electrons is shown on figure 7. A Gaussian fit is performed in the range $[-\sigma, +2\sigma]$ in order to extract the mean energy response and the dispersion. The sensitivity to the pion background and the influence of the inter-wafer gaps are reduced by the asymmetry of the range.

The error on the beam energy, $\Delta E_{\text{beam}}$, is taken into account and evaluated using the dispersion of the mean value of $E_{\text{rec}}$, observed on different runs at the same energy:

$$ \frac{\Delta E_{\text{beam}}}{E_{\text{beam}}} = \frac{0.12}{E_{\text{beam}}(\text{GeV})} \oplus 0.1\% $$

The linearity of the response with respect to the beam energy is described by:
\[ E_{\text{mean}} = \beta E_{\text{beam}} - \alpha, \]

where \( \alpha \) and \( \beta \) are extracted from a fit to the data as shown on figure 8. The response of ECAL is linear at percent level as deduced from the residuals, displayed on figure 9, and the measured energy can be defined as \( E_{\text{meas}} = (E_{\text{mean}} + \alpha)/\beta \).

The relative energy resolution \( \Delta E_{\text{meas}}/E_{\text{meas}} \) can be parameterised by a quadrature sum of stochastic and constant term (figure 10):

\[ \frac{\Delta E_{\text{meas}}}{E_{\text{meas}}} = 16.69 \pm 0.13 \div (1.09 \pm 0.06)\% \]

from which the intrinsic momentum spread of the beam was subtracted.

4.4. Shower Development

Only events outside the interwafer gaps were used to characterise the longitudinal development of the shower. The mean energy distribution is well fitted by the standard parametrisation, \( \gamma(t) = c t^\alpha \exp(-\beta t) \), where \( t \) is the calorimeter depth, \( c \) is an overall normalisation, \( \alpha \) and \( \beta \) are constants (figure 11). The position of the shower maximum grows logarithmically with the beam energy (figure 12).

An important issue in the development of a calorimeter is to achieve the smallest possible effective Molière radius (\( R_M \)), in order to provide the best shower separation. It requires the use of an absorber with a small intrinsic Molière radius, but also the minimisation of the gaps between the absorber layers. \( R_M \) is often quoted as the radius of 90\% (95\%) of shower containment. With this definition our measurement values are 20 (28) mm. The results for the various energies studied are summarised in figure 13.

The geometry of the ECAL prototype, with 2.2 mm thick interlayer gaps leads to a \( R_M \) which is expected to be larger by a factor of about 2 with respect to the Molière radius of solid tungsten. The results from the test beam studies are therefore in agreement with expectations. R&D effort towards the use of Si pads with integrated readout is under way and will hopefully lead to a significant decrease of the interlayer gap and therefore of the \( R_M \) for ECAL.
Figure 8. Linearity of the energy response of ECAL with respect to the beam energy. All the runs around a nominal energy of the beam were combined in one entry for clarity of the plot.

Figure 9. Residuals of the energy response of ECAL with respect to the linear function.

Figure 10. Relative energy resolution ($\Delta E/E_{\text{meas}}$) function of the beam energy. For clarity sake, the 35 runs available were combined into 8 different beam energy points. For the parametrisation of the energy resolution each run was however treated individually.

5. Conclusion
The Si-W ECAL prototype operated successfully during 2006 in its first testbeam at DESY and at CERN. The response of the prototype was measured using the recorded electrons and its physics performances were presented.

Additional data were collected at CERN in summer 2007 and at Fermilab in summer 2008. Their analysis is ongoing.
Figure 11. Longitudinal shower profile for the data (points) and Monte Carlo simulation (histogram). The smooth curve is the used parametrisation of the shower profile.

Figure 12. Evolution of the shower maximum as a function of the beam energy.

Figure 13. Radii for 90% and 95% containment of $e^-$ as function of the beam energy.

References
[1] The CALICE collaboration : calorimeter studies for a future linear collider, 2002.
  http://www.ppd.clrc.ac.uk/AnnReps/2004/exp/Calice-317.pdf
[2] J. Repond et al, “Design and Commissioning of the Physics Prototype of a Si-W Electromagnetic Calorimeter for the International Linear Collider”, to be submitted to NIM.
[3] T. Behnke et al(ed.), Reference Design Report “Volume 4:Detectors”, available at http://lcdev.kek.jp/DR.
[4] “Mokka Geant4 Application for Linear Collider Detectors” described at
  http://polzope.in2p3.fr:8081/MOKKA
[5] S. Agostinelli et al, “Geant4 – A simulation Toolkit”, NIM A 506 (2003) 250-303.