The SCintillator-ECAL Beam Test
at DESY, 2007
— Update 3 —

The CALICE collaboration

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Abstract

A beam test of the SCECAL prototype module was performed in the period Feb 26 - Mar 28 2007 using 1-6 GeV positron beams at the DESY-II electron synchrotron.

This note describes an update of the analysis presented in previous notes [1] [2] [3]. Changes with respect to previous notes include the correction for the effect of MPPC saturation, and the measurement of the longitudinal and transverse shape of positron showers.

These results are to be presented at the ECFA 2008 meeting at Warsaw.
1 Introduction

This note should be read in conjunction with [1], [2] and [3]. It describes further progress in the analysis of the data collected at the SCECAL testbeam at DESY in 2007.

A correction for MPPC saturation was developed and applied to electron shower data. The longitudinal and transverse shower shapes were measured.

2 MPPC Saturation Correction

Since the MPPC has a finite number of pixels and one pixel can count only one photon at a time, the response of the MPPC is not a linear function of the amount of input light. To achieve a precise energy measurement, correction of non-linear response is necessary, especially for the measurement of high energy particles. The response function of the MPPC (or SiPM) can be theoretically calculated as (neglecting cross-talk effects):

\[
N_{\text{fired}} = N_{\text{pix}} \left(1 - e^{-N_{\text{p.e.}}/N_{\text{pix}}}\right),
\]

where \(N_{\text{pix}}\) and \(N_{\text{fired}}\) denote the number of pixels on a sensor and number of pixels which fire a signal, \(N_{\text{p.e.}}\) is the number of photoelectrons injected, which is the product of the number of injected photons and the photon detection efficiency of the MPPC. This function can be approximated as a linear function if \(N_{\text{p.e.}} \ll N_{\text{fired}}\), but above this region the MPPC output starts to saturate, and eventually the response becomes completely flat at \(N_{\text{fired}} \sim N_{\text{pix}}\). We use sensors with \(N_{\text{pix}} = 1600\), however it is also known that the dynamic range of the MPPC can be enhanced with longer light input thanks to the short recovery time of the MPPC (\(\sim 4\) ns for 1600-pixel MPPC). This effect appears as an enhancement of \(N_{\text{pix}}\) in the above response function. We perform the saturation correction by measuring the response curve of the 1600-pixel MPPC. The procedure of the correction is as follows:

1. Measure response curves of the MPPC with three different types of scintillator.

2. Measure the ADC signal corresponding to a single fired pixel (\(d\)-value) of the MPPCs to translate MPPC output in the beam data from ADC counts to the number of fired pixels.

3. Translate the MPPC output from ADC counts to the number of fired pixels, and correct it to number of photoelectrons using the correction function.

This corrected number of photoelectrons gives the light signal after the saturation correction. In this section we describe above steps in detail. Then, we finally show the performance of the calorimeter prototype after the saturation correction.
2.1 MPPC Response-curve Measurement

We have measured the response curves of the 1600-pixel MPPC. The setup of the measurement is shown in Figure 1.

![Figure 1: Setup of the response curve measurement. Baseboard is the readout electronics provided from AHCAL group and used for the scintillator-ECAL beam test.](image)

From a UV LED installed on top of the system, light pulses are injected into the scintillator strip to generate scintillation light. This scintillation light is guided into both a photomultiplier and the MPPC, and signals from these two sensors are read by readout electronics. The signal from the photomultiplier is used to measure the amount of input light to the MPPC. By comparing the signal of the photomultiplier and MPPC, we can obtain the response curve of the MPPC.

We measured the response curves with three different types of scintillator strips: Kuraray fiber readout, direct readout and extruded strips. These strips have almost the same structure as the ones used in the scintillator-ECAL prototype, however they don’t have the mega-strip structure. By changing the amount of input light, the responses from both the photomultiplier and the MPPC are measured and compared. A typical “raw” response curve, where both responses from MPPC and photomultiplier are given in unit of ADC counts, is shown in Figure 2 left plot. Then MPPC output is translated to number of fired pixels as,

\[ N_{\text{fired}} = \frac{\text{ADC}_{\text{MPPC}}}{d_{\text{MPPC}}}, \]

where \( d_{\text{MPPC}} \) is the signal in ADC counts corresponding to the signal of one fired pixel. This value is measured before the response curve measurement. Then the raw response curve is fitted with following function to extract the “effective” number of pixels \( N_{\text{eff pix}} \), including the effect of dynamic-range enhancement due to the quick recovery of the MPPC:

\[
N_{\text{fired}} = N_{\text{eff pix}} (1 - e^{-N_{\text{p.e.}}/N_{\text{eff pix}}}) \\
= N_{\text{eff pix}} (1 - e^{-s(\text{ADC}_{\text{PMT}}-\Delta_{\text{PMT-ped}})/N_{\text{eff pix}}}),
\]
Figure 2: A typical “raw” response curve. Left plot is before any scaling, both axis are given in ADC counts. Right plot is after translating the units of the MPPC output from ADC counts to number of fired pixels.

where $\text{ADC}_{\text{PMT}}$ is the photomultiplier response in ADC counts, $s$ is a fit parameter which scales $\text{ADC}_{\text{PMT}}$ to $N_{\text{p.e.}}$. A pedestal shift $\Delta_{\text{PMT-ped}}$ is introduced as a fitting parameter to correct shifting pedestal due to pickup noise from the LED driving pulse.

Figure 3 shows the response curves measured with three types of scintillators at different MPPC bias voltages. The number of fired pixels obtained from the fit are summarized in Table 1. The Kuraray fiber readout strip shows larger enhancement of $N_{\text{eff pix}}$ than Kuraray direct readout strip, possibly due to an effect of the time smearing of the scintillation light by the WLS fiber. The extruded scintillator shows even more enhancement of $N_{\text{eff pix}}$, this may be explained by difference of scintillator material with Kuraray, which can give different amount of time smearing. On the other hand no strong dependency on applied bias voltage is observed in any scintillator type. Therefore for each strip type we take average of $N_{\text{eff pix}}$ among results of different bias voltages as:

$$N_{\text{eff pix}} = \begin{cases} 2072.8 & \text{for Kuraray fiber readout strips,} \\ 1677.2 & \text{for Kuraray direct readout strips,} \\ 2270.5 & \text{for extruded strips,} \end{cases}$$

and use those values for the actual saturation correction applied to the beam data. The statistical uncertainties on $N_{\text{eff pix}}$ are less than 10 pixels, which is negligible compared to the uncertainty on the electronics gain inter-calibration (explained later in this subsection).
Figure 3: Response curves measured with different types of scintillator strips and bias voltages. The horizontal axis has been translated to $N_{\text{p.e.}}$ using the scale factor obtained from the fit with function (2).

<table>
<thead>
<tr>
<th>Strip type</th>
<th>Bias voltage (V)</th>
<th>Effective number of pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuraray Fiber readout</td>
<td>76.75</td>
<td>2053.4 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>77.25</td>
<td>2089.0 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>78.25</td>
<td>2076.0 ± 4.7</td>
</tr>
<tr>
<td>Kuraray direct readout</td>
<td>77.25</td>
<td>1670.2 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>78.25</td>
<td>1684.1 ± 2.2</td>
</tr>
<tr>
<td>Extruded</td>
<td>77.25</td>
<td>2263.3 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>78.25</td>
<td>2277.6 ± 9.7</td>
</tr>
</tbody>
</table>

Table 1: Effective numbers of pixels obtained from the fit to the response curves. Errors are statistical only.
2.2 Measurement of $d$-values

To apply the saturation correction to the beam data, the MPPC output needs to be converted from ADC counts to the number of fired pixels. To do this we need to measure the “$d$-value”, which is the ADC signal corresponding to one fired MPPC pixel. To measure the $d$-value, we have installed a LED gain monitoring system into several strips used in the calorimeter prototype. This system provides light pulses, corresponding to a few photoelectrons, into the MPPCs to see MPPC output spectra with the pedestal and a couple of photoelectron peaks. Typical distributions with the gain monitoring system can be found in Figure 4. These spectra are fitted with sum of 4 Gaussian functions with some constraints:

$$f(x) = \sum_{i=0}^{3} A_i e^{-\frac{(x-\mu_{\text{ped}}-i\cdot d)^2}{2\sigma^2}},$$

where the Gaussian with index $i$ corresponds to the $i$ photoelectron peak. In the fit, $A_i$, $\mu_{\text{ped}}$, $d$ and $\sigma$ are treated as free parameters and eventually the $d$-value is obtained. Fitting results are also shown in Figure 4. In the plots $d$ corresponds to the distance between adjacent peaks.

One more thing we have to note is that the readout electronics have two modes with different gains, called the low and high gain modes. The low gain mode is used for actual beam run, but with this mode the gain of electronics is too low to observe the photoelectron peaks of the MPPC. Therefore we need high-gain mode for the $d$-value measurement or MPPC gain monitoring. However to apply the $d$-values measured in the high gain mode to the saturation correction for the beam data, we have to translate the $d$-value from high gain to low gain mode. This can be done by measuring ratio of gains in two different modes. The ratio is called the “(electronics gain) inter-calibration factor”. The procedure of the electronics gain inter-calibration is described later.

Since the available time to take data with LED gain monitoring system was limited during the beam run, we measured $d$-values for only a few channels of the entire calorimeter prototype (116 Kuraray fiber readout strips and 16 extruded strips). The measured $d$-values are plotted in Figure 5. From these distributions the $d$-value in high-gain mode for the Kuraray fiber readout and extruded strips are taken to be

$$d_{\text{high-gain fiber}} = 144.9 \pm 6.4 \text{ (ADC counts)} \text{ with } \Delta V_{\text{fiber}} = 2.9 \text{ V},$$

$$d_{\text{high-gain extruded}} = 182.8 \pm 5.1 \text{ (ADC counts)} \text{ with } \Delta V_{\text{extruded}} = 3.7 \text{ V}.$$  

Here $\Delta V$ is over-voltage which is uniformly set to all the MPPCs used in the same module. The over-voltage for the Kuraray direct readout and the extruded strips are set to slightly higher than the Kuraray fiber readout, because Kuraray direct and extruded strips give somewhat lower light yield and we need to gain more signal by increasing the photon detection efficiency of the MPPC by applying a higher over-voltage. Unfortunately we have no measurement of $d$-value for direct
readout strips due to some reasons. However as shown in following formula, the $d$-value depends only on the MPPC gain $G$.

$$d (\text{ADC counts}) = Ge = C \Delta V k$$

where $e$ is charge of the electron, $C$ is the pixel capacitance, $k$ denotes the scale factor to convert from Coulomb to ADC counts. Before the beam test we confirmed that the variation of pixel capacitance among all the MPPCs used to build the prototype was less than 4%. Therefore from the $d$-values (4) and (5) and value of $\Delta V$ set for the Kuraray direct readout strip (3.2 V), one can calculate the $d$-value for the direct readout strips as:

$$d_{\text{direct}}^{\text{high-gain}} = \frac{d_{\text{fiber}}^{\text{high-gain}} - d_{\text{extruded}}^{\text{high-gain}}}{\Delta V_{\text{fiber}} - \Delta V_{\text{extruded}}} \Delta V_{\text{direct}}$$

$$= 151.6 \pm 8.3 \text{ (ADC counts)} \text{ with } \Delta V_{\text{direct}} = 3.2 \text{ V.}$$

Now we have the $d$-values for all types of strips in the high-gain mode. As previously mentioned in this subsection, we have to translate those values to the low-gain mode by measuring the ratio of gains in the two different modes. This “gain inter-calibration” was done by injecting a certain amount of light signal (~150 photoelectrons) into the strips using the gain monitoring system, and measuring the output signal with both modes. Figure 6 shows typical ADC distributions of the LED light measured with high and low gain modes for the inter-calibration. By taking the ratio of mean values of these distributions, one
can obtain the inter-calibration factor $C_{\text{inter-calib}}$ as:

$$C_{\text{inter-calib}} = \frac{\langle \text{ADC}_{\text{high-gain}} \rangle}{\langle \text{ADC}_{\text{low-gain}} \rangle}.$$ 

We have measured the inter-calibration factor for 30 channels as shown in Figure 7. From this result, we determine

$$C_{\text{inter-calib}} = 10.08 \pm 0.95.$$ 

Now one can translate $d$-values from high-gain to low-gain mode

$$d_{\text{low-gain}} = \frac{d_{\text{high-gain}}}{C_{\text{inter-calib}}}.$$ 

Table 2 summarizes the obtained $d$-values in low-gain mode, for the three different types of scintillators.

<table>
<thead>
<tr>
<th>Strip type</th>
<th>$d$-value in low gain mode (ADC counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuraray fiber readout strip</td>
<td>14.4 ± 1.5</td>
</tr>
<tr>
<td>Kuraray direct readout strip</td>
<td>15.8 ± 1.7</td>
</tr>
<tr>
<td>Extruded strip</td>
<td>18.1 ± 1.8</td>
</tr>
</tbody>
</table>

Table 2: Obtained $d$-values in low gain mode. Uncertainties include errors of $d$-value in high gain mode and inter-calibration factor.

### 2.3 Energy resolution and linearity with the MPPC Saturation Correction

With the results obtained in the previous procedure, we have corrected the effect of MPPC saturation in the beam data. We use following correction function:

$$N_{j}^{\text{p.e.}} = -N_{\text{pix}}^{\text{eff}} \log \left( 1 - \frac{N_{j}^{\text{fired}}}{N_{\text{pix}}^{\text{eff}}} \right),$$

Figure 5: Distributions of the $d$-value in high gain mode. Left plot is for Kuraray fiber readout strips, right is for extruded strips.
Here we describe and compare the calorimeter performance before and after the MPPC saturation correction. The MIP calibration, temperature and optical cross-talk corrections are also applied.
At first we compare the linearity of the energy measurement, because it is most sensitive to the effect of the MPPC saturation. Figures 8 (central region) and 9 (quarter region) compare the deviation from linear response as a function of positron beam energy.

We fit the fitted mean measured energy response with a linear function. The saturation correction clearly improves the linearity of the calorimeter response.

Figure 8: Plots to show the linearity of the energy measurement in terms of deviation from linear response. The left plot is before the saturation correction, the right plot is after the correction.

Figure 9: Same as previous figure but for quarter region.

We have also compared the energy resolution before and after the saturation correction. The measured points were fitted by a function of form $\sigma_E/E =$
\(A/\sqrt{E} \oplus B\), where \(A\) and \(B\) are respectively the stochastic and constant contributions to the energy resolution. Results are shown in Figure 10 and summarized in Table 3. It is observed that constant term grows in all the configurations after the saturation correction. This is because the MPPC saturation skews the measured energy spectra, and with higher incident particle energies one gets unfairly sharper spectra, resulting in a small constant term which is clearly underestimated.

![Figure 10](CALICE.png)

Figure 10: Comparison of the energy resolution with and without the saturation correction. Left and right plots are for central and quarter region, respectively.

<table>
<thead>
<tr>
<th>Module type &amp; region</th>
<th>Stochastic term (%)</th>
<th>Constant term (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>before corr.</td>
<td>after corr.</td>
</tr>
<tr>
<td>1st config. central</td>
<td>13.38 ± 0.05</td>
<td>13.24 ± 0.05</td>
</tr>
<tr>
<td>2nd config. central</td>
<td>13.61 ± 0.06</td>
<td>13.43 ± 0.06</td>
</tr>
<tr>
<td>3rd config. central</td>
<td>14.82 ± 0.09</td>
<td>13.84 ± 0.10</td>
</tr>
<tr>
<td>1st config. quarter</td>
<td>13.98 ± 0.07</td>
<td>13.76 ± 0.07</td>
</tr>
<tr>
<td>2nd config. quarter</td>
<td>13.83 ± 0.07</td>
<td>13.73 ± 0.08</td>
</tr>
<tr>
<td>3rd config. quarter</td>
<td>14.61 ± 0.08</td>
<td>14.62 ± 0.08</td>
</tr>
</tbody>
</table>

Table 3: Table of the energy resolution before and after applying the saturation correction. Uncertainties are statistical only.
Figure 11: Final result of the energy resolution after all corrections.
3 Shower shapes

The shape of electromagnetic showers in the calorimeter were measured, in both the longitudinal and transverse directions. The first configuration detector was used, since the effects of strip response nonuniformity was minimised in this configuration. The MIP-equivalent energy deposited in each strip was calculated using temperature-corrected calibration constants, and corrected for the effects of optical cross-talk and MPPC saturation. For the measurement of shower shapes, a cut on the deposited energy per strip was applied at 0.5 MIP equivalents, removing most of the noise contribution to the low energy tails of the shower profile distributions. Applying this cut on individual strip energies has a negligible effect on the energy resolution of the whole detector.

3.1 Longitudinal shower shape

The longitudinal energy profiles showing the mean energy deposited per layer in electron showers at different beam momenta are shown in fig 12. The distributions were fitted by a function of the form \(E(t) = At^\alpha e^{-\beta t}\), where \(t\) is the longitudinal position (layer) inside the calorimeter. The maximum of this function occurs at \(\alpha/\beta\). The dependence of the shower maximum position on the beam energy is shown in fig 12, showing the expected logarithmic dependence.

![Figure 12: Longitudinal profiles for events in which the beam hit the centre of the 1st configuration detector. Left: measured longitudinal energy profiles for the different beam momenta, together with fitted functions. Right: the dependence of the fitted shower maximum on the incident beam momentum, and a linear fit to these points.](image)

3.2 Transverse shower shape

Transverse shower shapes were measured projected onto the X and Y axes (where X/Y are orientated along the strip axes). Since the calorimeter layers are alter-
natively orientated in the X and Y directions, half can be used to measure the X shower profile, and the other half to measure the Y profile.

In the following, we discuss a layer in which the long axis of the strips is in the Y direction.

In each layer, the mean energy deposited in the two Y neighbour strips was measured as a function of the X distance between their common central axis and the track impact position.

To minimise the effect of shower leakage in the Y direction (which is integrated over), only events in which the track hit the front face of the calorimeter within 5mm of the centre of the calorimeter in the Y direction were considered, as highlighted in fig 13.

![Diagram](image.png)

Figure 13: Diagram showing the region in which the track was required to hit the detector.

An example, for 3 GeV/c beam momentum, of the measured shower profiles in each layer is shown in fig 14. The shower becomes broader with increasing depth, as expected.

These distributions were integrated over X and Y layers separately to give total transverse profiles. An example of such an integrated profile, of the Y profile with a 3 GeV/c beam, is shown in fig 15. A function of the form

$$E = \frac{A}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} + Be^{-\frac{|x-\mu|}{\gamma}}$$

(a Gaussian with exponential tails) was used to fit these distributions. The function fits the distributions quite well, except far in the tails where an small, wider contribution is seen.

The integrated X and Y profiles for all beam momenta were fit to similar functions. The dependence of the fit parameters on the beam momentum is shown in fig 16.
The Gaussian component has contributions from the true shape of the central jet core, convoluted with the position resolution of the tracking, which has some energy dependence due to multiple scattering in the upstream material.

The reconstructed shape of showers gets slightly narrower as the incident beam energy increases. The shower shapes in the X and Y projections are similar, but show some small differences. The reasons for this are still under study. A possible cause is the different tracking resolution in the X and Y directions, due to a poorly functioning drift chamber measuring the Y coordinate, which will give different contributions mostly to the width of the Gaussian contribution.

A quantity related to the Molière radius was calculated by measuring the distance between the points beyond which 2.5% (5%) of the shower energy is deposited on each side of the shower centre. The “half–width” is defined as half this full width. Since most of the energy deposit is integrated over in one direction, this is somewhat larger than the true Molière radius. The dependence of this half–width is shown in fig 16, and shows good consistency between measurements in the X and Y directions, and no significant energy dependence.

4 Conclusions

A correction procedure for the effects of MPPC saturation was developed. Applying this correction significantly improves the linearity of the detector’s energy response. It also increases the constant contribution to the energy resolution, which is underestimated if the MPPC saturation is not taken into account.

The longitudinal and transverse shapes of electromagnetic showers in the calorimeter module were measured. The position of the shower maximum shows the expected logarithmic dependence on the incident beam energy. The dependence of the transverse beam shape on beam energy and calorimeter layer was measured.

References

[1] CALICE analysis note 005.
“The scintillator ECAL beam test at DESY, 2007 - First results”.
http://www.hep.phy.cam.ac.uk/~drw1/AnalysisNotes/CAN-004/CAN-004.pdf

“The scintillator ECAL beam test at DESY, 2007 - Update 1”.

“The scintillator ECAL beam test at DESY, 2007 - Update 2”.
http://www.hep.phy.cam.ac.uk/~drw1/AnalysisNotes/CAN-007/CAN-007.pdf
Figure 14: Transverse shower profile of 3 GeV/c positron showers in the first 25 calorimeter layers.
Figure 15: Y profile of 3 GeV/c positron showers, integrated over calorimeter layers.

Figure 16: Results of fits to the integrated X and Y transverse profiles. The dependence of the fit parameters on the beam momentum are shown: width of the fitted Gaussian and exponential contributions, and the energy fraction contained in the Gaussian part of the distribution. The lower right plot shows the half-width which contains 90% (95%) of the projected shower energy.