Results of the CALICE Scintillator ECAL beamtest at DESY

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Abstract. A prototype ILC scintillator-Tungsten electromagnetic calorimeter was constructed, with active layers consisting of scintillator strips, individually read out by MPPC devices. This prototype was exposed to positron beams at DESY in March 2007. Preliminary results of the analysis of the collected data are presented.

1. Introduction
A future detector at the ILC requires excellent jet energy reconstruction to maximise the physics output of the accelerator. The ability to distinguish the hadronic decays of Z and W bosons is one of the most stringent requirements, leading to a required relative jet energy resolution of around 3%. One way to achieve this resolution is by means of a particle flow approach, which uses the tracking system to estimate the charged jet energy, and the calorimeter to measure only the neutral energy component. The success of this approach depends on the ability to distinguish the energy deposited in the calorimeter by individual particles within a jet, allowing neutral energy deposits to be reliably identified. This leads to the requirement of a calorimeter with small Molière radius to reduce the overlapping of showers, and a calorimeter with finely segmented readout.

In this paper we describe a prototype of an ECAL designed to satisfy these requirements. A small sampling calorimeter was constructed, with active layers consisting of small scintillator strips, individually read out by photon detectors, and absorber layers of tungsten, respectively giving the required high granularity and small Molière radius.

This prototype was exposed to positron beams with momenta between 1 and 6 GeV/c at the DESY-II electron synchrotron. The preliminary results of the analysis of the collected data are presented in this paper.

2. Scintillator ECAL prototype detector
The ECAL prototype consisted of 26 layers of scintillator and tungsten, as shown in figure 1. Each active layer consisted of 18 1 × 4.5 cm² strips of 3mm thick scintillator, arranged in two rows, giving a total cross-section of 9 × 9 cm². A photon detector was attached to the end of each strip to read out the produced light. The photon detector used was the Multi Pixel Photon Counter (MPPC) produced by Hamamatsu Photonics [1]. This has a high photon detection efficiency, very compact size, and a reasonable cost, making it a suitable candidate for such a
calorimeter at the ILC. The strips were orientated to be perpendicular in adjacent layers, giving an effective granularity close to $1 \times 1 \text{ cm}^2$.

The tungsten absorber layers had a thickness of 3.5 mm, and a gap of around 1 mm was used to route the cables to extract the MPPC signals.

Three types of scintillator strip were tested. Two types were based on a “megastrip”: a $9 \times 4.5 \times 0.3 \text{ cm}^3$ tile of Kuraray scintillator, as shown in figure 2. The tile was machined with eight pairs of thin grooves, into which white PET film was placed, giving a total of nine strips with reasonable optical isolation. One type of megastrip also had a 1mm hole drilled along the length of the strip, into which a wavelength–shifting fibre (WLSF) was inserted. The megastrip tiles were covered with 3M reflector film.

Scintillator strips manufactured by an extrusion method were also tested. These were produced by the Misung Chemical Company (Korea) in association with Kyungpook National University. These strips had dimensions of $4.5 \times 1 \times 0.3 \text{ cm}^3$, and were produced with a co–extruded coating of TiO$_2$ (for light shielding) and a central hole with 1mm diameter (into which a WLSF was placed). A photograph is shown in figure 3. The cost of producing such extruded strips is significantly less than that of the megastrip tiles.

Three half–detectors of 13 layers were constructed, each using a different type of scintillator. Different arrangements of these half–detectors were tested: WLSF readout megastrip upstream of direct readout megastrip; direct readout megastrip upstream of WLSF readout megastrip; and extruded scintillator upstream of WLSF readout megastrip. Since the maximum of EM showers occurs at around layer 6 or 7 in this detector, the upstream half–detector measures most of the deposited energy.

The MPPC signals were read out using the CALICE readout electronics and DAQ developed by our CALICE colleagues at DESY, LAL–Orsay, and in the UK. They are essentially the same as those used by the CALICE Analogue–HCAL group.

3. Beamtest

This detector prototype was exposed to beams of positrons at the DESY laboratory in March/April 2007. Positron beams with a tunable momentum between 1 and 6 GeV/c were...
Figure 2. Photograph of megastrip tile made of Kuraray scintillator, showing the machined grooves for optical isolation, and central holes for the WLSF.

Figure 3. Photograph of a Misung C.C. extruded scintillator strip, with inserted WLS fibre.

provided by the DESY-II electron synchrotron. The beamline was instrumented with four drift chambers to precisely measure the beam position on an event-by-event basis, and various scintillator trigger and veto counters were used to trigger on and select interesting events. The detector prototype was placed on a movable stage, allowing the beam to be scanned over the front face of the detector.

4. Detector calibration
To calibrate the detector, the Tungsten absorber plates were removed from the calorimeter, and data were taken with a 3 GeV/c positron beam. The signals on the trigger and veto counters and the drift chambers were required to be consistent with the passage, without showering, of a single positron along the beamline. Events in which the positron had passed through a particular strip were selected by considering the signals on the scintillating strips in the two up- and down-stream layers with the same strip orientation, and requiring them to be consistent with a single positron passing through the strip, parallel to the beamline. Such a calibration sample was defined for each of the strips in the detector. An example of the MPPC signal, after pedestal subtraction, in one of these samples is shown in figure 4. The distribution is well fitted by a Gaussian-convoluted Landau function. These signal distributions were used to extract the calibration constant for each of the scintillator strips.

Since the MPPC properties vary significantly with temperature, the dependence of these calibration constants on temperature was measured. Several calibration runs were taken during data-taking, allowing their dependence on the detector temperature to be extracted. All readout channels showed a similar temperature dependence of their calibration constant of around $-2\%$ per Kelvin.

The uniformity of the MIP response along the length of the scintillator strip was also measured. The beam was scanned over the entire front face of the detector, illuminating all regions of the strips. The drift chambers were used to determine the precise position at which the positron intersected the strips. The response to single positrons was measured as a function of the distance along the strip axis (i.e. the distance from the MPPC position); the results for a number of strips are shown in figure 5. The most uniform (and also the largest) light yield was shown by the WLSF read out megastrip, with a variation of around 80-90% along the strip length. The direct read out megastrips showed a slightly larger non-uniformity, of around 70-80%, due to light attenuation inside the scintillator. The extruded strips showed a significantly larger non-uniformity, of around 40-50%.

The reasons for the non-uniformity of the extruded strips was investigated in a separate
beamtest. Non-perfect matching between the WLSF and the MPPC, and scintillator with a relatively short attenuation length were identified as the major causes. Improved samples of scintillator are under development and will be used in the next prototype.

\[\chi^2 / \text{ndf} = 329.6 / 271\]
\[\text{Width} = 26.37 \pm 1.06\]
\[\text{MP} = 161.5 \pm 1.5\]
\[\text{Area} = 2.148 \times 10^4 \pm 273\]
\[\text{GSigma} = 59.1 \pm 2.5\]

**Figure 4.** An example of the measured MIP signal in a single scintillator strip, used to calibrate the detector response. The measured distribution (black histogram) is fitted by a Landau distribution convoluted with a Gaussian (red curve).

**Figure 5.** Relative MIP response along the strip length for three scintillator strip types: direct readout megastrip, WLSF readout megastrip, and the extruded strips. The MPPC position is at the right hand side of the x axis (at 45 mm). Different colours are for different strip samples. The WLSF readout strips show good uniformity, while the extruded strips show non-uniformity of \(\sim 50\%\) along the strip length.

The same events used for the calibration were also used to measure the optical cross-talk across the boundaries between adjacent strips. The average signal recorded when a positron passed through the neighboring strip was compared with the signal when the strip itself was hit. Examples of these distributions in the megastrips and extruded strips are shown in figures 7. The measured cross-talk in the “megastrip” layers was around 10% in the transverse direction.
(perpendicular to the strip axis), and rather smaller (∼1%) in the longitudinal direction (i.e. between the two megastrip plates in the same layer). The cross-talk in the extruded strips was much smaller in the transverse direction (∼1%). The system of grooves in the megastrip tile does not achieve perfect optical isolation, while the white co–extruded covering of the extruded strips does achieve good isolation. A method to correct for the cross-talk was developed, and was applied in the analysis of the EM shower data.

5. Energy linearity and resolution
The response of the calorimeter was measured using runs in which the Tungsten absorber plates were inserted. The response of the calorimeter to positrons in the momentum range $1 \rightarrow 6$ GeV/c was measured. The measured signals from the MPPCs were calibrated using the measured calibration constants, and corrected for the effects of temperature variation and optical cross-talk.

The detector performance was measured in two regions of the detector. “Central” events was defined as those in which the positron was measured (by the drift chambers) to have hit the front face of the calorimeter in the central $1 \times 1$ cm$^2$ region of the detector. In this region the lateral leakage of showers is minimised. However, in the central region the shower energy
is mostly deposited at the ends of the scintillating strips, either close to or far from the MPPC position. The effects of any response non-uniformity along the strip are therefore maximised in this central region.

To investigate these effects, events in the “quarter” regions were also considered. These quarter regions are defined as the four $1 \times 1 \text{ cm}^2$ regions whose centres are at $x, y = \pm 22.5 \text{ mm}$ with respect to the detector centre, as shown in figure 8. In these events, most of the energy is deposited close to the centre of the scintillating strips, minimising the effects of any non-uniform response along the strip length. However, the lateral shower leakage out of the calorimeter module is somewhat larger than for events in the central region.

![Figure 8. Cartoon of the front face of the calorimeter prototype. The strip and MPPC positions in the X and Y layer orientations are shown in red and black. The four $1 \times 1 \text{ cm}^2$ quarter regions are shown as magenta squares.](image)

Figure 9 shows the reconstructed energy, in terms of MIP equivalents, at the six beam momenta of 1, 2, 3, 4, 5 and 6 GeV/c, for the first detector configuration (WLSF readout megastrip module upstream of the direct readout megastrip module). These energy distributions are well fitted by Gaussian distributions. The mean values of the fitted Gaussian functions are used to measure the detector’s energy response, and the fitted widths to estimate the energy resolution.

![Figure 9. The reconstructed energy in the first (fibre+direct) detector configuration. Only events in which the beam hit the “quarter regions” are included. The six histograms show the reconstructed energy for beam momenta between 1 and 6 GeV/c, and are fitted by Gaussian functions.](image)
The mean energy response for centrally injected events of the three detector configurations is shown in figure 10. The configurations have very similar response to EM showers, and the response is linear to within $\sim 4\%$ in this energy range.

![Figure 10](image)

**Figure 10.** The mean reconstructed energy as a function of beam momentum, for centrally injected events. The three lines show the results for the different detector configurations.

The measured energy resolution in the two detector regions are shown in figures 11 (for the quarter regions) and 12 (in the central region). In the quarter region, the energy resolution of the three configurations is rather similar, the “extruded+fibre” configuration having only slightly worse resolution than the others. In the central region, however, the energy resolution of the “extruded+fibre” configuration is significantly worse than that of the other two. This difference is due to the effects of the strip response non-uniformity, which is largest in the extruded strips, and whose effects are maximised in the central detector regions.

![Figure 11](image)

**Figure 11.** The measured energy resolution of the three detector configurations, in the quarter detector regions.

![Figure 12](image)

**Figure 12.** The measured energy resolution of the three detector configurations, in the central detector region.

A fit of the measured energy resolutions to the quadratic sum of a stochastic and constant term give the values shown in table 1. The stochastic term is similar in all configurations and regions, between 13.5 and 14.5%, however the constant term varies significantly between the
different configurations, particularly in the central region, again due to the non-uniformity of the strip response.

**Table 1.** Results of the fits of the measured energy resolutions to the quadratic sum of a stochastic and constant term. Results are shown for the central and quarter regions of the three detector configurations. Errors are statistical only.

|          | Quarter | Central |
|----------|---------|---------|
|          | stochastic | constant     | stochastic | constant     |
| fibre + direct | 13.98 ± 0.07 | 1.96 ± 0.12 | 13.39 ± 0.05 | 2.57 ± 0.07 |
| direct + fibre  | 13.83 ± 0.07 | 2.58 ± 0.09 | 13.70 ± 0.06 | 3.39 ± 0.05 |
| extruded + fibre | 14.61 ± 0.08 | 2.35 ± 0.12 | 14.52 ± 0.09 | 7.26 ± 0.05 |

6. Future plans
Now that several issues have been identified and resolved, a larger detector prototype is being constructed. It will have larger transverse size ($18 \times 18 \text{cm}^2$), and more longitudinal layers (30). Improved extruded scintillator strips will be used. This detector will be taken to Fermilab later in 2008, and exposed to beams of electrons with a significantly higher range of momenta and also to beams of other particle types. Data will be collected together with the CALICE Analogue-HCAL detector, which will be positioned downstream of the ECAL.

7. Summary
A sampling calorimeter prototype for an ILC detector was designed and constructed. Active layers consisted of scintillator strips individually read out by MPPC devices, while absorber layers were made of Tungsten, giving a calorimeter with small Molière radius and highly segmented readout, suitable for the particle flow approach to jet energy measurement. Three different types of scintillator strips were tested: cast scintillator “megastrips” with and without wavelength-shifting fibre readout, and extruded scintillator strips.

This detector was exposed to positron beams in the momentum range $1 \rightarrow 6 \text{ GeV/c}$ at the DESY-II synchrotron. Three detector configurations, using different types of scintillator strips, were tested. The detector was calibrated, and the non-uniformity of strips response to MIPs was measured, as was optical cross-talk between adjacent strips. The “megastrip” scintillators showed good uniformity, but also optical cross-talk between neighbouring strips of around 10%. The extruded strips showed significant non-uniformity of around 50% along the strip length, but good optical isolation.

The response of the detector to electromagnetic showers was measured in the two detector regions where the effects of strip non-uniformity were maximised and minimised. In the region where effects of non-uniformity are minimised, the three configurations showed similar performance: good linearity, and energy resolution with a stochastic term of around 14% and a constant term of around 2%. In the region with significant effects of non-uniformity, the constant term rose to around 7% for the detector configuration with largest non-uniformity.

A larger prototype is presently being designed and constructed. Improved samples of extruded scintillator will be used. This prototype will be tested at Fermilab in Fall ’08, in conjunction with other CALICE calorimeters.

References
[1] http://jp.hamamatsu.com/products/sensor-ssd/4010/index_en.html