A prototype module of fine granular electromagnetic calorimeter has been constructed by the CALICE collaboration and tested in the period Aug - Sep 2008 at FNAL meson beam test facility. The calorimeter is one of the proposed concepts for a highly granular electromagnetic calorimeter for the International Linear Collider (ILC) Experiment, which is designed to have an effective 10 mm x 10 mm lateral segmentation using 10 mm x 45 mm scintillator strips. The strips in 15 odd layers are orthogonal with respect to those in the 15 even layers. A total of 2160 strip scintillators are individually readout using Pixelated Photon Detector (PPD) of MPPC. As a preliminary result of the first stage analysis, we obtain a relative energy resolution for single electrons of $\frac{\sigma_{E}}{E} = (15.15 \pm 0.03)/\sqrt{E_{\text{beam}}(\text{GeV})} \% \oplus (1.44 \pm 0.02)\%$, with the quoted uncertainties purely statistical.

**Key words:** ILC, Electromagnetic calorimeter, Scintillator strip, PPD, MPPC

### 1. Introduction

The International Linear Collider (ILC) experiments are designed to perform high precision measurements using the clear initial states of the electron-positron collisions and well reconstructed final states. To characterize final states dominated by gauge bosons and heavy quarks, the reconstruction of jets is one of the key issues. One of the ways to precisely reconstruct jets is to measure individual particles within jets, by combining calorimetry and tracking. This method, called particle flow approach (PFA) requires highly granular calorimeters; finer than 10 mm x 10 mm lateral segmentation for the electromagnetic calorimeter (ECAL) [1].

The Scintillator ECAL (ScECAL) is one of the proposed concepts for a highly granular ECAL for the ILC, which is designed to have an effective 10 mm x 10 mm lateral segmentation using 10 mm x 45 mm scintillator strips. In order to achieve the required 10 mm x 10 mm lateral segmentation, the strips in odd layers are orthogonal with respect to those in the even layers. The proposed detector is a sampling calorimeter, with sensitive layers made of 2 mm thick plastic scintillator and 3 mm thick absorber layers. The scintillation photons are collected by a wavelength shifting (WLS) fiber, inserted centrally, along the longitudinal direction of each scintillator strip and are read out with a Pixelated Photon Detector (PPD).

A first ScECAL prototype had a transverse area of 90 mm x 90 mm and 26 scintillator layers in between 3.5 mm thick tungsten-cobalt absorber layers [2]. The radiation length of the whole detector was totally 18.5 $X_0$. This first prototype of the ScECAL was tested using 1 - 6 GeV/c positron beams at DESY in March 2007. The deviation compared with the linear behavior of energy response is less than 1% indicating the good linearity in this energy range. The stochastic term of the energy resolution curve, 14%, shows good energy resolution. However, the constant term of the energy resolution curve is found to be 3%. The large constant term is understood because of the shower leakage and non-uniformities in the response of strips.

The second prototype was build, transversally twice as large as the first prototype, 180 mm x 180 mm. The number of layers has also increased to 30 in 266 mm, leading to a total radiation length of 21.3 $X_0$. Hereafter “the ScECAL prototype” denotes the second prototype. In the period August - September 2008 and April - May 2009 at FNAL, the ScECAL prototype was exposed to electron and hadronic beams up to 32 GeV/c together with the analog scintillator hadron calorimeter [3] and the Tail Catcher [4] to evaluate their combined performance in the CALICE test beam activities.

These proceedings explain the analysis to evaluate the linearity and resolution of the energy measurement by the second ScECAL prototype using electron beams data and muon beams data taken in August - September 2008. The results in these proceedings are very preliminary, because they are estimated without any systematic uncertainty. More detailed analysis results will follow in near future.

### 2. Construction of The second ScECAL prototype

The layered structure of the ScECAL prototype is visible in Fig. 1, top: it has 30 pairs of scintillator and absorber layers with thickness of 3.0 mm and 3.5 mm respectively. The absorber is made of 88% tungsten, 12% cobalt and 0.5% carbon. Each scintillator layer as shown in Fig. 1, bottom has 18 x 4 scintillator strips of size of 45 mm x 10 mm, made by extrusion method at Kyungpook National University (KNU). Each scintillator strip is hermetically covered with the reflecting film made by Kimoto Co., Ltd. In successive scintillator layers, the strips are alternately aligned vertically ("X" layers) and horizontally ("Y" layers). The coordinate system used in these
proceedings is right handed and the $z$ direction given by the beam direction. The WLS fibers placed in the center of each strip to collect the scintillation photons are Kuraray Co., Ltd. Y-11 double clad type. They are read out with PPDs made by Hamamatsu Photonics KK, the "1600-pixel MPPCs". We measured the gain, capacitance, dark noise and breakdown voltage for each MPPC. The MPPCs were then soldered on a flat cable, and mounted in a housing at the end of each scintillator strip. To improve the longitudinal uniformity of response of scintillator, a shade of reflector film with hole for WLS fiber was interleaved between the MPPC package and the scintillator to prevent the photons near the sensor but not coming through the WLS fiber.

3. Beams and the experimental setup

The beam test has been performed at the MT6 experimental area in the Meson Test Beam Facility (MTBF) of FNAL. The electron and the charged pion beams with an momentum between 1 GeV/c to 32 GeV/c were used. The muon beams at 32 GeV/c were also provided for the calibration with MIP.

The electron beam momentum was tuned at 1, 3, 6, 12, 16, 25, 32 GeV/c.

4. Analysis

4.1. Detector calibration with MIP particles

The first step in the analysis is the calibration of the strips using muons in order to measure the energy deposit by the Minimum Ionizing Particles (MIPs). This analysis gives the converting factor between the ADC counts and the number of MIPs. The muon-tuned beam contains almost no electrons nor pions because of the iron dumper put in the beam line upstream of our experiment site. Therefore, the MIP events are required only to have the same X and Y "hit" positions at least in 10 different X and Y layers, respectively, and are not required to be isolated. A "hit" is defined as a signal larger than the mean value of the pedestal by at least three standard deviations of the pedestal.

For each channel, the MIP response is obtained by fitting the distribution of the charge deposited by the MIP events, in ADC counts, with a Landau function convoluted with a Gaussian function. The MIP calibration factor is the most probable value (MPV) of the distribution. The average and the RMS of the MIP calibration factors over the 2160 channels are 160.3 and 31 ADC counts, respectively. The average is significantly larger than the corresponding standard deviation of the pedestal which is 15 ADC counts.

4.2. The correction of the MPPC saturation

The MPPC response has a saturation behavior according to its intrinsic property. Prior to the FNAL beam test, the MPPC saturation was measured on a test-bench. A scintillator strip of the ScECAL prototype was illuminated with a blue laser sending pico-second pulses. The photons which came through one of the two cross sections of the WLS fiber in the strip were read out by a MPPC and the photons which came through the cross section on the other side, were read out by a PMT.

Figure 2: The response of the PPD as a function of the PMT in ADC counts. The red line shows the result of a fit using Eq. (1)
where \( N_{\text{filled}} \) is the number of photons detected with MPPC, \( N_{\text{pix}} \) is the effective number of pixels on the MPPC, \( \epsilon \) is the photon detection efficiency and \( N_{\text{in}} \) is the number of photons come into the MPPC sensitive area. By fitting Eq. (1) to the MPPC vs PMT curve in Fig. 2, the fitting parameter \( N_{\text{pix}} \) is determined to be 2424 \( \pm \) 3. The actual number of pixels is 1600. We think this result shows that the photon generation in the scintillator has a time duration which allows some pixels to be active again in the allocated time window, hence allowing to be hit more than once in an event. In order to apply the correction for each channel, we use the inverse function of the Eq. (1). The input of the function, \( N_{\text{filled}} \) should be the number of photons detected with the MPPC of the relevant channel. Therefore, the ADC counts of the output signals of the strip should be converted to the number of photons. To convert the ADC counts to the number of photons, the ratio of the ADC counts per photon for each channel has to be known. An LED calibration system [5] to get such ADC-photon ratio was embedded in the ScEAL prototype and the LED calibration data taking were carried out. For nearly 30% of all channels, the LED calibration system had problems. Therefore, the average of the ADC-photon ratios of all available channels are used for such channels.

4.3. Energy spectra

Using the set of calibration factors obtained in Section 4.1, the deposited energy is obtained in MIP units by summing the calibrated response over all strips:

\[
E_{\text{total}} = \sum_{l=1}^{30} \sum_{s=1}^{72} E'_{ls} / c_{ls}, \tag{2}
\]

where \( l \) and \( s \) are the layer and strip indices, \( E'_{ls} \) is the measured energy corrected for MPPC saturation and \( c_{ls} \) is the calibration factor on the corresponding strip. The corrected value of the measured energy, \( E_{ls} \) is obtained as the following:

\[
E_{ls} = -n_{\text{pix}} R_{\text{ADC-photon,ls}} \log \left( 1 - \frac{N_{\text{ADC,ls}} / R_{\text{ADC-photon,ls}}}{n_{\text{pix}}} \right), \tag{3}
\]

where \( n_{\text{pix}} \) is the effective number of pixels and \( R_{\text{ADC-photon}} \) is the ratio of ADC counts to the number of detected photons for each strip, both \( n_{\text{pix}} \) and \( R_{\text{ADC-photon}} \) were obtained in the Section 4.2, and \( N_{\text{ADC,ls}} \) is the number of ADC counts as the response of each strip.

The spectra of the deposited energy for several beam momenta include some contamination from pions and muons. After implementing certain criteria to purify the electron events, the spectrum of each run is fitted with a Gaussian function.

Figure 3 shows the shape of the spectrum after all cuts for one of the 25 GeV/c runs. The spectrum is fitted well in the range including 90% of the function area, i.e. between \( \pm 1.65 \sigma \). On the other hand, the similar distributions for the 1 GeV/c runs show a residual contamination with pions in lower energy region of the electron peak. We discuss this issue more in Section 5.

The deposited energy and its resolution are determined as the mean value and the standard deviation of the fitted Gaussian function, respectively.

For every selection cut, we investigate the variations of the deposited energy in the ScEAL prototype and its resolution when changing the cut values. It was checked that for any of the applied selection criteria and for all beam momenta, the stability of the deposited energy is better than 0.1% and the resolution stability better than 1%.

The temperature monitoring was implemented during the data taking, and the overall effect of temperature variation on each channel was investigated in May 2009 beam test. It changes the MIP calibration factors by 3.5% per one Kelvin. Unfortunately, the temperature monitoring in September 2008 was not very reliable, sometimes leading to noisy or missing data. Although we are still trying to recover the temperature data, the deposited energy and the energy resolution for each beam momentum are calculated as the weighted average of runs in order to avoid the effect of temperature differences between runs.

5. Results and discussions

5.1. Linearity of the energy response

Figure 4 shows the deposited energy in the ScEAL prototype as a function of beam momentum. The lines are the results of a fit with a linear function passing through the origin. Although Fig. 4 shows the good linearity, the deviations from the linear behavior is better than 6%.

The MPPC saturation correction is applied according to Eq. (3) which has only one parameter; the number of the effective pixels, \( n_{\text{pix}} = 2424 \). This number is larger than the actual number of pixels, 1600, because the timing structure of incoming photons allows some pixels to become active again during the event. Since there is a possibility that the timing structure is depending on the deposited energy and the incident particle species, the behavior of MPPC saturation should be studied in
more detail and the systematic uncertainty from MPPC correction should be estimated. Additionally, there is a possibility that a part of the fluctuation of MIP calibration factors discussed in Section 4.1 is from the MPPC/Fiber mismatch. In that case, some of pixels are not covered with WLS fiber, then $n_{\text{pix}}$ decreases. The effect of correction for such case should increase the size of MPPC saturation correction. Another possible origin of the deviation is some transverse or longitudinal leakage. We will investigate in detail of the MPPC saturation correction and the leakage effects in the near future.

5.2. Resolution of the energy response

Figure 5 shows the resolution of the deposited energy in the ScECAL prototype as a function of the beam momentum. The line is the results of a fit with the quadratic parameterization of the resolution:

$$\frac{\sigma}{E} = \sigma_{\text{constant}} + \sigma_{\text{stochastic}} \frac{1}{\sqrt{E_{\text{beam}}(\text{GeV})}}$$

where, $E$ is the deposited energy in the ScECAL, $\sigma$ the energy resolution, $E_{\text{beam}}$ the beam energy and $\sigma_{\text{constant}}$ and $\sigma_{\text{stochastic}}$ the constant and stochastic terms of the energy-resolution parameterization, respectively. The stochastic and constant terms of the energy resolution parameterization are $15.15 \pm 0.03\%$ and $1.44 \pm 0.02\%$, where the uncertainties are only statistical uncertainties. Deviations from linear behavior of the energy measurement are found to be less than 6%. These results are very preliminary because they are estimated without any systematic uncertainties. Further analysis including the temperature correction, the MPPC saturation correction, the energy leakage and the effect of the pion contamination is ongoing.

6. Summary

The ScECAL beam test has been performed using an electron beam in the momentum range 1 - 32 GeV/c. As a result of this preliminary analysis, the stochastic and constant terms of the energy resolution parameterization are $15.15 \pm 0.03\%$ and $1.44 \pm 0.02\%$, where the uncertainties are only statistical uncertainties. Deviations from linear behavior of the energy measurement are found to be less than 6%. These results are very preliminary because they are estimated without any systematic uncertainties. Further analysis including the temperature correction, the MPPC saturation correction, the energy leakage and the effect of the pion contamination is ongoing.

References