Performance of the Scintillator-Strip Electromagnetic Calorimeter Prototype for the Linear Collider Experiment

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Abstract. The scintillator-strip electromagnetic calorimeter (ScECAL) is one of fine granular calorimeters proposed to realize Particle Flow Algorithm for the International Linear Collider experiment. The ScECAL is a sandwich calorimeter with tungsten and scintillator layers, where the scintillator layer consists of plastic scintillator strips which size of 1 cm × 4.5 cm × 0.2 cm with a small photo-sensor (MPPC) attached at its edge. In alternate scintillator layers, strips are orthogonally aligned to make a virtual 1 × 1 cm² cell with its crossing area. To establish the ScECAL technology, we have built a prototype of the ScECAL which consists of 30 layers of tungsten and scintillator layers with 2160 scintillator strips in total. In 2008 and 2009 the beam test has been performed at Fermilab meson test beam line to evaluate performance of the ScECAL prototype with various types of beams ranging 1 to 32 GeV. As a preliminary result of the beam test in 2008, we have obtained linearity of energy measurement less than 6% from the perfect linear response. Energy resolution is measured to be $\sigma/E = (15.15\pm0.03)/\sqrt{E} \oplus (1.44\pm0.02)%$. Although detailed analyses are still ongoing, those results already establishes feasibility of the ScECAL as the fine granular calorimeter. However as the next step to precisely measure even higher energy jets, we will proceed to even more finely segmented calorimeter with 5 mm width scintillator strips.

1. Introduction
At the future international linear collider (ILC) experiment[1], precise jet energy measurement is crucial for many important physics studies which take advantage of the clean $e^+e^-$ collision. Practical goal of the jet energy resolution at the ILC is set to $\sigma/\sqrt{E} = 30\%$. To achieve this high performance, Particle Flow Algorithm (PFA) [2] is considered as the most powerful jet energy reconstruction method. In the PFA, particles in a jet are categorized into charged or neutral particles. Then momenta of the charged particles are measured by tracking chamber to obtain higher resolution of the momentum than the energy resolution by calorimeter. However to realize the PFA, charged and neutral particles in a jet have to be separated with each other in the calorimeter to avoid possible over-counting. This fact results in a requirement of fine granularity for the calorimeter with very small cell size, which is 0.5-1 cm for the jet energy measurement up to $E_{jet} \sim 200$ GeV. In the CALICE collaboration[3], there are several technologies suggested to approach the fine granular calorimeter. The Scintillator-tungsten electromagnetic calorimeter (ScECAL) is one of those which adopts plastic scintillator strip technology.

Figure 1 shows structure of the ILD, which is one of the collider detector concepts proposed for the ILC, and the schematic design of the ScECAL in the ILD. The ScECAL is a sandwich...
calorimeter composed of 3 mm thick tungsten and 2 mm thick scintillator layers. The scintillator layer consists of small plastic scintillator strips which size of 1 cm × 4 cm × 0.2 cm. In alternate scintillator layers, strips are aligned to orthogonal directions as shown in the Figure 1. Light signal of each scintillator strip is read by Multi-Pixel Photon Counter (MPPC [4][5]) attached at a longitudinal edge of the strip. Since this type of calorimeter with the plastic scintillator strips is the world’s first challenge, we have built a prototype of the ScECAL and performed beam tests to establish its feasibility. In this manuscript we will report a preliminary result of the beam test of the ScECAL prototype performed in September 2008 at Fermilab.

2. The Scintillator-ECAL Second Prototype
Test of the first ScECAL prototype has been done in March 2007 at DESY with 1-6 GeV e⁺ beams. Its result is reported elsewhere[6]. According to the result of the first test, the ScECAL second prototype has been built in 2008 with several improvements. In Figure 2 left side, structure and picture of the prototype are shown. It consists of 30 pairs of 3 mm thick tungsten and 2 mm thick scintillator layers. Each scintillator layer consists of 72 pieces of scintillator strips which size of 1 cm × 4 cm × 0.3 cm. In alternate scintillator layers, strips are aligned to orthogonal directions. Transverse size of the prototype is 18 cm×18 cm, and the total thickness is 26.1 cm which corresponds to about 28 radiation lengths.

Structure of each scintillator strip is also shown in right side of Figure 2. For the production of the scintillator, the plastic extrusion method is adopted [7] to reduce production cost while keeping its performance. Scintillation light signal is absorbed and re-emitted by 1 mmφ wavelength shifting fiber (Y11) and guided by the MPPC. Response uniformity of the scintillator strip is tested both by bench test system with beta-ray and the Minimum Ionizing Particle (MIP) beams at the Fermilab beam test. The Response uniformity observed with the MIP beam is also shown in Figure 2 right side. Attenuation of the response at the far side from the MPPC is 10-15%. Effect of this non-uniformity to the calorimetry performance will be discussed in the next section. Signal from the MPPCs are read by SPIROC chip [8][9], which is developed in the CALICE collaboration for SiPM/MPPC signal readout, and converted to digital value in unit of ADC counts. Since the MPPC response is not linear to the amount of input light, response correction is done with a response function which is measured in advance.

3. Beam Test at Fermilab and the Preliminary Result
The performance of the ScECAL second prototype is evaluated at the Fermilab Meson test beam facility in 2008, using electron, pion and muon beams with its energy of 1-32 GeV. Major goals...
of the beam test includes evaluation of energy resolution, linearity, and combined performance with the Analog hadron calorimeter (AHCAL) [10]. Although several detailed analyses on the data of the beam test are currently ongoing, we report some preliminary results of the beam test in this section. Setup of the beamline is shown in Figure 3. The data taking is done with trigger signal from scintillation trigger counters. Čerenkov counters located upstream of the beamline give additional information to trigger electron or pion events.

At first response calibration among individual strips is done using 32 GeV muon beam which passes through the detectors as MIPs with constant amount of energy deposition. Shape of the typical MIP events on the ScECAL is shown in Figure 4. From the ADC distribution of the MIP events, mean response for the MIP is obtained for each individual channel as “MIP calibration constant”. The MIP calibration constant is used for the response calibration of the ScECAL.

After calibrating all the channels, energies of electron beams are measured to examine the linearity and resolution of the electron energy measurement. Energy spectra for all the electron-triggered data sets at each energy points are shown in Figure 5 left side. Although electron events are taken with Čerenkov counters trigger, the electron data are still contaminated by pion and muon events. To obtain pure electron sample, offline event selection is done as follows based on various detector signal:
Figure 4. An event display (left) and the ADC distribution (right) of a typical MIP events after the MIP event selection.

- Signal on the AHCAL is required to be consistent with zero,
- Longitudinal and lateral shower profiles in the ScECAL are consistent with electromagnetic event.

In Figure 5 right side, measured energy spectra with different step of the event selections are shown. After all the cuts, energy spectra with clear Gaussian shape are obtained.

Figure 5. The energy spectra for all the electron-triggered events with various energies (right), and the measured energy spectra for 25 GeV electron events with each step of electron event selection (right).

From the measured energy spectra of the selected electron events, linearity and resolution of the electron energy measurement are evaluated. For those evaluations, the selected events are classified into two regions according to injecting position on the ScECAL surface, which are named “central” and “uniform” regions. The central region is defined as the center of the ScECAL and corresponds to the longitudinal edge of the scintillator strips, while the uniform region corresponds to ±2.25 cm away from the ScECAL center to both vertical and horizontal
directions. In the uniform region, effect of the strip response non-uniformity is expected to be small because core of the electromagnetic shower always hits around the center of the strip in every layer. Therefore if the strip response non-uniformity affects to the calorimeter performance, it should appear as larger effect in the central region, but would be smaller in the uniform region. The linearity and resolution are measured for those two regions and as a sum of those two regions. Results are shown also in Figure 6. As the preliminary result, we have obtained the linearity of the energy measurement less than 6% in terms of deviation from the perfectly linear response. This value is rather larger than expected, however ongoing detailed analyses including more precise corrections (temperature change, MPPC response curve) are expected to improve the linearity. Energy resolution is obtained to be $\sigma/E = (15.15 \pm 0.03)/\sqrt{E} \oplus (1.44 \pm 0.02)\%$ where $E$ is the electron energy in GeV, and uncertainties are statistical only. This value is close to the expectation by GEANT4 simulation. Reason of non-zero constant term might be a leakage of shower from the ScECAL in addition to the same reason with the 6% of non-linearity. There is no significant difference among results in central, uniform and combined regions. It indicates the effect of strip response non-uniformity to the calorimeter performance is negligibly small.

**Figure 6.** Definition of the center and uniform region, and the performances of the ScECAL second prototype as the preliminary result of the beam test.

4. Summary and Outlook
We have built the performance of the ScECAL second prototype. The prototype is tested by 1 to 32 GeV of electron beams at the Fermilab meson test beam line in 2008. Although detailed analyses are underway, preliminary result of the beam test shows feasibility of the ScECAL as the fine granular calorimeter with virtual cell size of $1 \times 1$ cm$^2$.

However recent study with Monte Carlo and PFA indicates that even smaller cell size is desirable to measure higher energy jets. Figure 7 left plot taken from reference [11] shows jet energy resolution for various energy jets, as a function of the ECAL cell size. According to this study, ECAL cell size of $1 \times 1$ cm$^2$ works for jets up to 100 GeV, however to measure higher energy jets, $0.5 \times 0.5$ cm$^2$ is desirable. To improve the granularity from 1 to 0.5 cm, we are developing new version of the scintillator strip with 5 mm width without wavelength shifting fiber for the light readout. First result of response measurement with beta-ray source is sufficiently uniform as shown in Figure 7, which encourages to proceed to the future ScECAL prototype with the 5 mm segmentation.

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Figure 7. Jet energy resolution with various jet energies as a function of ECAL cell size, and design of the version of the scintillator strip for 5 mm granularity. Result of the response uniformity measurement is also shown.

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