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Construction and response of a highly granular scintillator-based electromagnetic calorimeter

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ABSTRACT

A highly granular electromagnetic calorimeter with scintillator strip readout is being developed for future linear collider experiments. A prototype of 21.5 X_0 depth and 180×180 mm^2 transverse dimensions was constructed, consisting of 2160 individually read out $10 \times 45 \times 3$ mm^3 scintillator strips. This prototype was tested using electrons of 2–32 GeV at the Fermilab Test Beam Facility in 2009. Deviations from linear energy response were less than 1.1%, and the intrinsic energy resolution was determined to be $(12.5 \pm 0.1(\mathrm{stat.}) \pm 0.4(\mathrm{syst.}))\%/\sqrt{E[\mathrm{GeV}]} \oplus (1.2 \pm 0.1(\mathrm{stat.})^{+0.6}_{-0.7}(\mathrm{syst.}))\%$, where the uncertainties correspond to statistical and systematic sources, respectively.

1. Introduction

Detectors for the International Linear Collider (ILC) are designed to perform high precision measurements, taking advantage of the well-defined initial conditions of electron–positron collisions [1]. To characterise final states that are dominated by the production and decay of quarks, gauge bosons and/or Higgs bosons, the accurate reconstruction of jets of hadrons is mandatory. One way to achieve this is by measuring each particle within a jet individually, and combining information from calorimeters and tracking detectors. This method, known as the particle flow approach (PFA) [2,3], requires highly granular sampling calorimeters. To achieve this single particle separation the electromagnetic calorimeter (ECAL) must have longitudinal sampling at least every X_0, and a lateral segmentation better than the Molière radius of the absorber (*e.g.* 9.3 mm for Tungsten). Because we require more than 20 X_0 for the total thickness of ECAL to prevent energy leakage, the ECAL must therefore have at least 20–30 layers. At the ILC, an ideal value for the intrinsic energy resolution of the ECAL is required to be less than $15\%/\sqrt{E[\mathrm{GeV}]}$ by PFA [3]. Emerging designs for scintillator-based sampling calorimeters now have the potential to realise these design criteria.

The previous limiting factors for the segmentation of a scintillator-based calorimeter were the size and sensitivity of the readout technology. This situation changed drastically with the introduction of the silicon photomultiplier (SiPM) [4–8]. Small scintillator elements can be read out individually using SiPMs without introducing large dead volumes for the readout systems. This technology is used in the scintillator strip electromagnetic calorimeter (ScECAL) being developed by the CALICE Collaboration. To reduce both the total number of readout channels and the overall insensitive volume associated with the readout SiPMs, strips of scintillator, each with a length of 45 mm and a width of between 5 and 10 mm, are used. Strips in successive layers have an orthogonal orientation relative to each other [1] and an algorithm has been developed to achieve fine effective segmentation from such a strip-based design. A study [9] of the invariant mass resolution of neutral pions, carried out using a full simulation of a detector for the ILC, showed that a 45×5 mm^2 ScECAL using this algorithm had almost the same performance as a 5×5 mm^2 ScECAL.

To achieve the required longitudinal segmentation, the ScECAL is designed as a sampling calorimeter using 25–30 tungsten layers of thickness of 2–4 mm, interleaved with scintillator strip sensor layers. The first CALICE ScECAL prototype [10] consisted of 26 sensor layers, interleaved with 3.5 mm thick tungsten carbide (WC) absorber layers, and had a transverse area of 90×90 mm^2.

The current prototype consists of 30 detector layers and has transverse dimensions of 180×180 mm^2 and a depth of 21.5 X_0 (266 mm), reducing the effect of lateral and longitudinal shower leakage relative to the previous prototype. The basic unit was a $45 \times 10 \times 3$ mm^3 scintillator strip with a central hole of 1.5 mm diameter running along its length, hermetically wrapped with reflective foil. A wavelength shifting (WLS) fibre inserted into the hole guides light to a SiPM placed at one of the ends of the scintillator strip. A LED-based gain monitoring system was implemented for each strip, an improvement on the first prototype in which only one LED was provided per layer. This prototype was tested in conjunction with the CALICE analogue hadron calorimeter (AHCAL) [7,11][11] and tail catcher muon tracker (TCMT) [12] prototypes.

This paper is organised as follows. Details of the prototype design including properties of applied SiPMs are given in Section 2. The test beam experiment at Fermilab is described in Section 3, and the analysis including detector calibration and results obtained using electron beams are given in Sections 4 and 5. Section 6 compares the analysis results with Monte Carlo simulations, Section 7 discusses the results and Section 8 draws conclusions.

2. Construction

2.1. Detector

The prototype, shown in Fig. 1 in front of the CALICE AHCAL, has a total thickness of 266 mm. It consists of 30 pairs of alternating 3.5 mm thick tungsten carbide absorber and scintillator layers, with the first layer being absorber. Fig. 2 shows the design of a scintillator layer, consisting of four rows of 18 scintillator strips, held in a rigid steel frame. Fig. 3 illustrates the design of a single polystyrene-based scintillator strip and shows the central hole for the WLS fibre, manufactured using an extrusion method [13] and cut into strips. The polystyrene was doped using a mixture of 1% 2,5–diphenyloxazole and 0.1% 2,2'–(*p*–phenylene)bis(5-phenyloxazole) for fluorescence. A notch with a depth of 1.40 ± 0.05 mm and a width of 4.46 ± 0.03 mm was cut mechanically to accommodate the SiPM. The specific SiPM used was a multi-pixel photon counter (MPPC), from Hamamatsu K.K. [14]. The size of the MPPC package was $1.3 \times (4.2 \pm 0.2) \times (3.2 \pm 0.2)$ mm^3. The four long sides of each strip were polished to control precisely the strip size and to ensure reflection of the surfaces.

From a randomly chosen sample of 20 strips, the measured mean values and the sample standard deviations (SD) of the widths, lengths and thicknesses were 9.85 ± 0.01 mm, 44.71 ± 0.04 mm, and 3.02 ± 0.02 mm, respectively. A double clad 1 mm diameter Y-11 WLS fibre provided by KURARAY Co., Ltd. [15] with a length of 43.6 ± 0.1 mm was inserted into the hole of each strip. Each strip was wrapped with a 57 μm-thick reflective foil provided by KIMOTO Co., Ltd [16]. This foil consists of layers of silver and aluminium, deposited by evaporation

[11] Electromagnetic response of AHCAL is also available.