Performance of the CALET Prototype: CERN Beam Test

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Abstract: We are developing the CALET mission to observe high energy cosmic rays at the Japanese Experiment Module/Exposed Facility (JEM/EF) on the International Space Station. The instrument will be flown in 2013, and will be used for 5 years. The primary scientific purpose of CALET is to search for nearby cosmic ray sources and dark matter. We carried out an accelerator beam test with high energy particles with the CALET prototype at the CERN-SPS. The purpose of this test was to assess the detector performance as well as to study the accuracy of the Monte Carlo simulation method. The prototype detector consists of an imaging calorimeter with 256 scintillating fibers and a total absorption calorimeter consisting of 16 PWO logs. The longitudinal structure is similar with the CALET instrument. We used positron and proton beams in the energy region from 6 to 200 GeV, and from 30 to 150 GeV, respectively. Comparing the experimental data with the simulation results, we have measured the energy deposition in each component, the energy resolution, the lateral shower spread and the e/p separation capability.

Keywords: Beam Test, Monte Carlo Simulation, Calorimeter, CERN-SPS

1 Introduction

The CALorimetric Electron Telescope (CALET) is being developed as an instrument to observe high energy cosmic rays. The detector is intended to be placed on the Japanese Experiment Module of the International Space Station in 2013. The objective of the CALET mission is to reveal high energy phenomena in the universe by space-based observation of the high energy cosmic rays [1]. We have developed elemental components of CALET such as PWO scintillator, scintillating fiber and readout electronics for them. For verification of the observation capability, an accelerator experiment with a prototype of CALET was carried out, and results of the beam test are reported in this paper.

2 CERN-SPS Beam Test

2.1 Experimental Outline

The accelerator experiment was carried out at the European Organization for Nuclear Research (CERN) in September, 2010, using the Super Proton Synchrotron (SPS). The purpose of this experiment is to evaluate the detector performance and to investigate the accuracy of the Monte Carlo simulation method. We used positron and proton beams in the energy region from 6 to 200 GeV, and from 30 to 150 GeV, respectively, and 150 GeV muon beams for calibration.

2.2 Prototype Detector

The CALET instrument consists of a charge detector (CHD), an imaging calorimeter (IMC), and a total absorption calorimeter (TASC). A structure of the CALET prototype used for the beam test is similar in longitudinal structure with CALET instrument.
IMC is composed of 8 layers of scintillating fiber (SciFi) belts for detecting the beginning of the shower. One set of IMC component consists of one thin tungsten plate and a SciFi belt. Each belt is composed of 32 fibers, and each single SciFi has a dimension of 1 mm$\times$ 1 mm$\times$ 448 mm. The total thickness of tungsten plates is $\sim$3 X_0. IMC is used for the particle identification and the estimation of the incident direction.
TASC has 8 layers of PWO logs each of which has a dimension of 20 mm$\times$ 19 mm$\times$ 326 mm. Each layer consists of 2 PWO logs. The total thickness of TASC is $\sim$18 X_0. TASC is used for the measurement of the shower development to determine the energy of the incident particle.

2.3 Detector Setup

Figure 1 shows the detector setup of this experiment. Two trigger scintillators, S1 and S2 (10 mm × 10 mm × 2 mm), are placed in front of CHD. Signals of each SciFi are detected by 64ch multi-anode PMTs. To measure PWO signals, two PMTs are used for the top layer, and an avalanche photodiode and a photodiode are attached to each log in another layer. In this experiment, the detector is moved to horizontal position $(0, \pm 50, \pm 100, \pm 150, \pm 200$ mm) and vertical position $(0, \pm 10$ mm). Not only vertically-directed but also angled events $(0°, 30°, 45°)$ are acquired. An example of the event view is shown in Fig. 2.

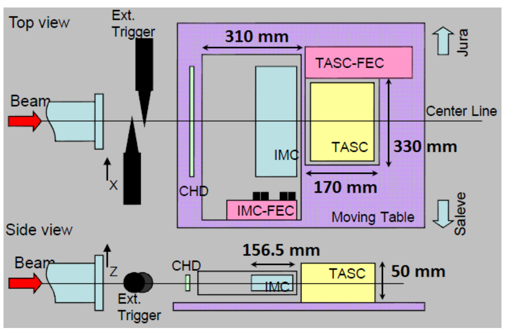

Figure 1: Detector setup of the beam test.

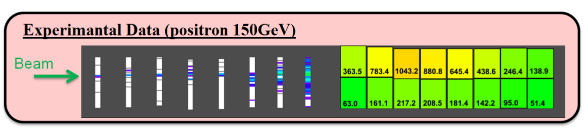

Figure 2: Example of event view by 150 GeV positron. The track in IMC and energy deposit in PWO are shown. The number in PWO denotes the number of MIP.

3 Data Analysis

3.1 Analysis Procedure

The analysis procedure of experimental data and simulated events is shown in Fig. 3. To make an appropriate comparison, by using muon track, exact coordinates of SciFi in IMC and the position of TASC are corrected, and beam profiles in the experiment are introduced in the simulation. Expected effects in the experiment, such as crosstalk, fluctuations from the detector and dead channels are also introduced in the simulation. We compare the result of the experiment with simulation, under the condition of shower trigger and contamination rejection cut which are described below.

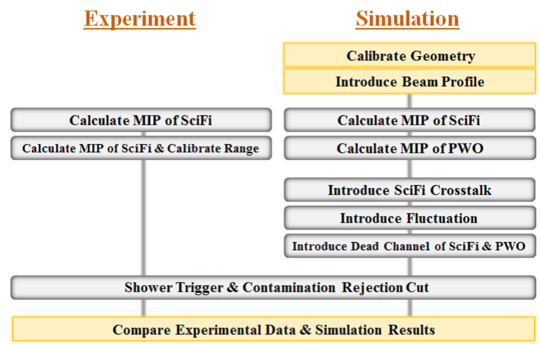

Figure 3: Comparison of data analysis procedure of experiment and simulation.

3.2 Shower Trigger and Quality Cut

CALET has three event trigger modes, and event selection is dependent on them [2, 3]. For electron or gamma ray observation, most of background protons are rejected without serious loss of objective particles. The trigger mode is classified into three categories according to particles of different energy and types. This time, we apply the high energy shower trigger to data analysis of the CALET prototype. This mode uses the energy threshold at the top PWO layer which is determined to detect 95 % of the 10 GeV electrons, and at two SciFi layers at the bottom to detect 98 % of the 10 GeV gamma rays. The condition of this trigger is as follows:

- IMC : Sum of energy deposit in two SciFi belts at the bottom ≥ 15 MIP
- TASC : Energy deposit in two PWOs in top layer ≥ 52 MIP

Since there is the possibility of contamination in the accelerator beam, we need to select particle by simulation, so quality cut defined by simulation is used. The main contamination in the positron beam might be muons or pions. Since contamination particles might be distributed in lower region, quality cut is applied as Fig. 4, and 99 % of positrons are left by this selection.

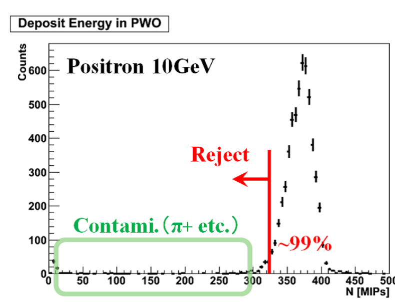

Figure 4: Quality cut of contamination particles by using energy deposit in TASC.

4 Comparison of Experimental Data with Simulation

4.1 Simulation Conditions

For simulation code, Geant4 (ver. 9.4.p01) and EPICS (ver. 9.08) [4] are used, and QGSP-BERT and DPMJET-III are adopted as hadronic interaction models, respectively. Figure 5 shows a geometry of the CALET prototype detector which consists of CHD, IMC and TASC. An example of shower profile in Fig. 5 is 10 GeV positron. In these simulations, positron (10, 15, 25, 50, 75, 150 GeV) is vertically entered into the detector surface, and the same trigger conditions as in the experiment are used.

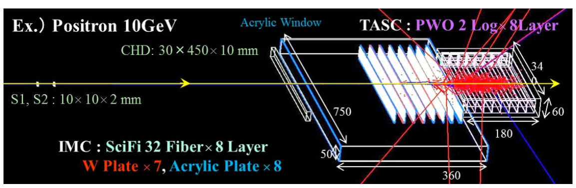

Figure 5: Overview of CALET prototype detector and shower of 10 GeV positron drawing by Geant4 simulation.

4.2 Pulse-height Calibration by Muons

By fitting pulse-height of muon signals, one MIP is defined. To calibrate one MIP signal of experimental data, Gauss-convoluted Landau function are used. As a result, muon signals of the experiment and fitting function are well consistent, then one MIP is defined by peak of fitting function. By using this unit of one MIP, the energy deposit of shower events are calculated in both experiment and simulation.

4.3 Energy Deposit in Each Detector

Total energy deposit in SciFi of experimental results compared with simulation is shown in Fig. 6. A similar comparison of PWO is shown in Fig. 7. In these figures, 10 GeV positrons are taken as an example. Not only total energy deposit but also energy deposit in each Scifi and PWO layer are shown in Fig. 8, 9. The horizontal axis (partly logarithmic scale) is number of particles and the vertical axis is event count normalized with experimental data. From these, a consistency of Geant4, EPICS and experiment is found. In other words, consistency of two electromagnetic interaction models of simulation is verified. In Fig. 6, difference of averages evaluated on the basis of experimental results are Geant4: 1.2 %, EPICS: 0.85 %. In Fig. 7, difference of averages are Geant4: 0.46 %, EPICS: 0.16 %. In Fig. 8, the first interaction point of shower development can be confirmed by identification of single event and shower event.

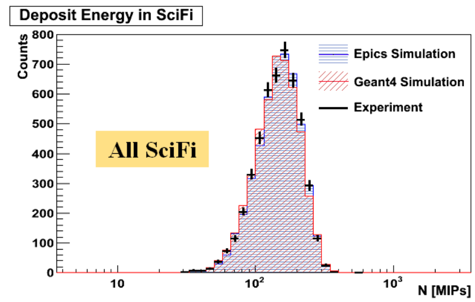

Figure 6: Experimental result of energy deposit in all SciFi's by 10 GeV e+, in comparison with Geant4 and EPICS.

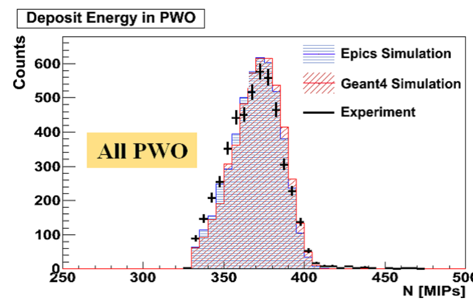

Figure 7: Experimental result of energy deposit in all PWO logs by 10 GeV e+, in comparison with Geant4 and EPICS.

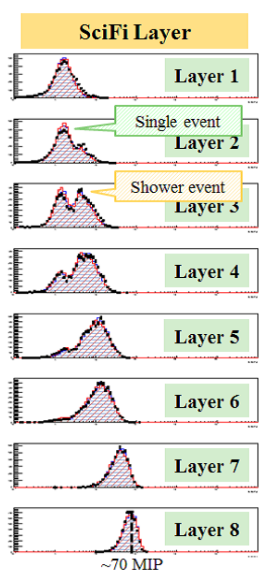

Figure 8: Energy deposit in each SciFi layer, in which the shower starting point is clearly seen.

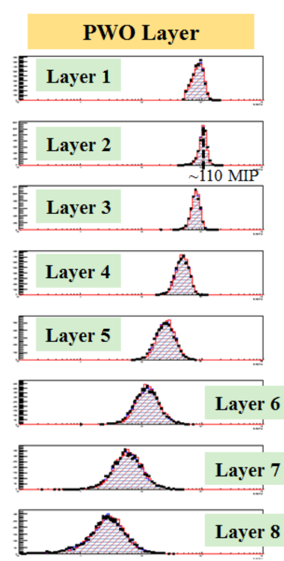

Figure 9: Energy deposit in each PWO layer.

4.4 Energy Resolution

The energy resolution of TASC is shown in Fig. 10. The horizontal axis is incident positron energy and the vertical axis is energy resolution. We define energy resolution as σ_{TASC} / $\langle E_{\mathrm{TASC}} \rangle$. Comparing experiment with simulations, a consistency of them is found. In the high energy region, shower leakage affects resolution degradation. In the whole energy region, resolution of experimental data is lower. This is attributed to effects such as contaminant particles and multi-hit events.

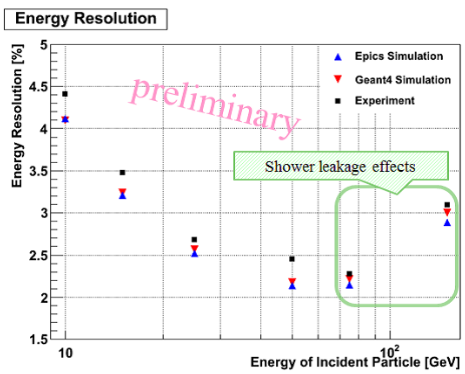

Figure 10: Energy resolution of TASC for positrons.

4.5 Lateral Shower Spread

The energy weighted spread in IMC of experiment compared with simulation is shown in Fig. 11. A similar comparison of TASC is shown in Fig. 12. Using lateral shower spread in each layer represented as R_i, the energy weighted spread R_E is defined as follows:

$$R_i = \sqrt{\frac{\sum_j \Delta E_{each_j} \times (x_j - x_c)^2}{\sum_j \Delta E_{each_j}}} \tag{1}$$

$$R_E = \sqrt{\frac{\sum_i (\Delta E_{layer_i} \times R_i^2)}{\sum_i \Delta E_{layer_i}}} \tag{2}$$

ΔE_{each_j} and ΔE_{layer_i} are the energy deposit in each scintillator in layer i, and in each layer i, respectively. x_j is the position of each scintillator, and x_c is the position of shower axis in each layer. We use this parameter for e/p separation [2]. For calculating R_E of IMC, events at least 1 mm from the edge of the bottom SciFi layer are used. Simulations and experimental results have similar distributions in both IMC and TASC. In Fig. 12, since only two PWO logs are arranged in each PWO layer, the shower spread is geometrically limited less than 1 cm. In Fig. 11, difference of averages evaluated on the basis of experimental results are Geant4: 3.8 %, EPICS: 4.1 %. In Fig. 12, difference of averages are Geant4: 1.9 %, EPICS: 1.9 %.

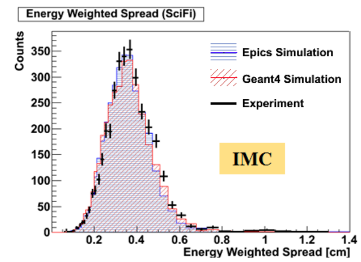

Figure 11: Energy weighted spread in IMC

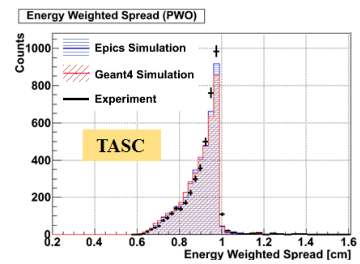

Figure 12: Energy weighted spread in TASC

5 Summary and Future Plans

We carried out the accelerator beam test with CALET prototype at the CERN-SPS, and investigated the accuracy of the Monte Carlo simulation method. Comparing the experimental data with the simulation results, consistencies of the energy deposition in each component, the energy resolution and the lateral shower spread are confirmed. Table 1 is tabulated results of percent difference (evaluated on the basis of experimental results) of averages. $\langle E_{\mathrm{IMC}} \rangle$ and $\langle E_{\mathrm{TASC}} \rangle$ are the mean values of the total energy deposit in SciFi and in PWO, respectively. $R_{E_{\mathrm{IMC}}}$ and $R_{E_{\mathrm{TASC}}}$ are the mean values of the energy weighted spread in IMC and in TASC, respectively. In this results, consistency among Geant4, EPICS and experiment is found. To evaluate the e/p separation capability, we are going to conduct the CERN-SPS beam test of CALET prototype in September, 2011.

Table 1: Percent difference of experimental results from EPICS and Geant4.

	$\langle E_{\mathrm{IMC}} \rangle$	$\langle E_{\mathrm{TASC}} \rangle$	$R_{E_{\mathrm{IMC}}}$	$R_{E_{\mathrm{TASC}}}$
10 GeV (EPICS)	0.85	0.16	4.1	1.9
10 GeV (Geant4)	1.2	0.46	3.8	1.9
150 GeV (EPICS)	1.7	0.99	3.0	2.1
150 GeV (Geant4)	6.9	1.1	0.71	2.3

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