Particle Beam Tests of the Calorimetric Electron Telescope

TADAHISA TAMURA[1], FOR THE CALET COLLABORATION.

[1] *Institute of Physics, Faculty of Engineering, Kanagawa university, Yokohama 221-8686 Japan*

ttamura@kanagawa-u.ac.jp

Abstract: The Calorimetric Electron Telescope (CALET) is a new mission addressing outstanding astrophysics questions including the nature of dark matter, the sources of high-energy particles and photons, and the details of particle acceleration and transport in the galaxy by measuring the high-energy spectra of electrons, nuclei, and gamma-rays. It will launch on HTV-5 (H-II Transfer Vehicle 5) in 2014 for installation on the Japanese Experiment Module–Exposed Facility (JEM-EF) of the International Space Station. The CALET collaboration is led by JAXA and includes researchers from Japan, the U.S. and Italy. The CALET Main Telescope uses a plastic scintillator charge detector followed by a 30 radiation-length (X_0) deep particle calorimeter divided into a 3 X_0 imaging calorimeter, with scintillating optical fibers interleaved with thin tungsten sheets, and a 27 X_0 fully-active total-absorption calorimeter made of lead tungstate scintillators. CALET prototypes were tested at the CERN (European Laboratory for Particle Physics) Super Proton Synchrotron (SPS) in 2010 and 2011 using electrons to 290 GeV and protons to 350 GeV. In 2012 the CALET BEAM-TEST Model (BTM) was tested at the SPS with electrons to 300 GeV and protons to 400 GeV. The flight charge detectors were tested in 2013 at the SPS in heavy-ion beams from fragmented lead at 13 and 30 GeV/nucleon. Here, the CALET beam tests and the results of those tests will be presented and implications for the mission measurement goals will be discussed.

Keywords: ISS, CALET, electron, gamma-ray, nuclei, dark matter

1 Introduction

We have been developing the Calorimetric Electron Telescope (CALET) to study the origin of high-energy particles and their propagation in the galaxy [1]. We are aiming at observations of electrons, gamma-rays, and nuclei with the CALET to obtain their precise energy spectra [2, 3, 4, 5]. We might find some signs of dark matter in the energy spectrum of electrons or gamma-rays [6]. It will launch on HTV-5 (H-II Transfer Vehicle 5) to the International Space Station in 2014. It will be installed to the Japanese Experiment Module–Exposed Facility (JEM-EF). The CALET collaboration is led by JAXA and includes more than 80 researchers from Japan, the U.S. and Italy. We have designed it and have evaluated its performance with MC simulations. Therefore we needed to make beam tests to verify the simulations. A testing team of the CALET collaboration carried out beam tests with CALET prototypes at the CERN (European laboratory for Particle Physics) Super Proton Synchrotron (SPS) from 2010 to 2013.

2 Instrumentation

In order to detect high-energy particles, the CALET Main Telescope consists of the Charge Detector (CHD), the Imaging Calorimeter (IMC), and the Total Absorption Calorimeter (TASC) as shown in figure 1. It has been improved for the higher energy observation on the basis of the previous balloon-borne observations carried out with the BETS [7] and the PPB-BETS [8].

The CHD at the top of the main telescope is composed of 28 plastic scintillator bars of 10 mm thickness, 32 mm width, and 448 mm length. It has 2 layers of X and Y, and 14 scintillator bars in each layer. Each scintillator bar is read out at one end through a light guide with one photo multiplier tube (PMT). It detects charged particles to Z=40 with an expected charge resolution of 0.15[e] for B and C and ∼0.3[e] for Fe [4].

The IMC follows the CHD. Its basic technology had been developed and established through the electron observations by the BETS and the PPB-BETS [9]. Shower particles are detected by scintillating fibers of 1 mm square and 448 mm length. 448 scintillating fibers are assembled into one belt and read out with 64ch multi-anode photo multiplier tubes (MaPMT's). The IMC is composed of 8 layers of scintillating fiber belts. One layer is made up of two belts for two directions (X and Y). The scintillating fiber belt layers are interleaved with 7 thin tungsten plates of 3 radiation length (X_0) in total. Each of 5 tungsten plates in upper part is 0.2 X_0, and each of 2 plates in lower part is 1 X_0. The IMC can take images of early stage of shower development with a total of 7168 scintillating fibers. Each scintillating fiber corresponds to each anode of MaPMT and is read out one by one. Starting points of showers and directions of incident particles can be derived from the shower images.

In order to observe higher energy particles, the TASC of 27 X_0 is added to the IMC. The thick calorimeter enables to achieve not only good energy resolution of 3 % over 100 GeV but also excellent separation power of electrons against protons. The TASC is a fully-active total absorption calorimeter made up of PWO (lead tungstate: $PbWO_4$) scintillators assembled into hodoscope arrangement. The dimensions of each PWO crystal are 19 mm (W) × 20 mm (H) × 326 mm (L). There are 16 PWO crystals in one layer and 12 layers are piled up. Thus, the TASC consists of 192 PWO crystals in total. Each PWO crystal is read out at one end by a set of PD (photo diode) and APD (Avalanche PD). Because an effective area of the APD is 20 times larger than that of the PD and the APD has a gain of 50, the output signal of the APD is about one thousand times larger than

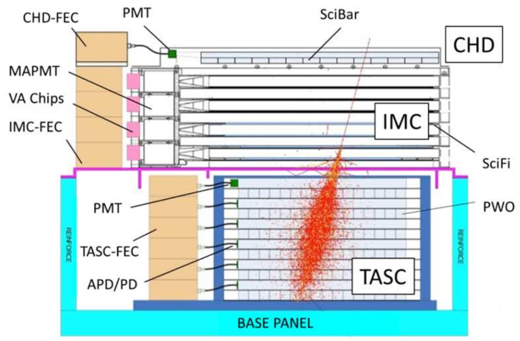

Figure 1: CALET main telescope.

that of the PD. Consequently, they cover different ranges for the readout of PWO.

The TASC can discriminate showers of electrons and protons by their vertical developments and lateral spread. It requires a dynamic range of 10^6 for readout of the PWO. Therefore, each of the signals from the APD and the PD is amplified by two front end circuits of different gains. The TASC has an excellent rejection power of 10^5 to 10 TeV for electron detection against proton background.

3 Development of CALET

Development of the CALET began in March 2010 after it was approved as an experiment utilizing the Japanese Experiment Module–Exposed Facility (JEM-EF) on the International Space Station (ISS) by JAXA. First of all, Bread Board Models (BBM) were made tentatively for electronics and detector structures as shown in figure 2.

Front end circuits (FEC) of limited channels for the IMC and the TASC were made as BBM to verify designs of electronics. The BBM FECs were checked including frequency response, amplifier gains, noise levels, dynamic range, and power consumption.

As for detector structures of the IMC and the TASC, one fourth of them were also made as BBM to establish assembling methods of detectors and to make vibration tests of them. After considering results obtained from BBM, Structure Thermal Models (STM) of the CHD/IMC and the TASC were made to verify design of structure and temperature in view of material, mass, heat, strength, and so on.

After various tests with BBM and STM, a Proto-Flight Model (PFM) of the CALET which will become a Flight Model (FM) has been developed since 2012. Engineering Model (EM) to confirm mechanical and electrical functions has not been made for the CALET as is typical these days to reduce costs. After Acceptance Tests (AT) of the PFM to verify its overall functions and performance, it will be launched as the CALET FM.

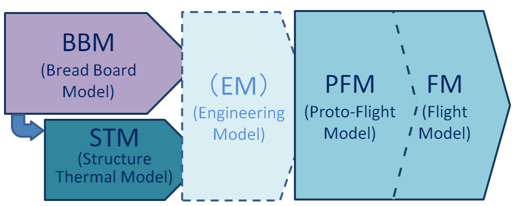

Figure 2: Procedure to develop the CALET.

4 Beam tests at CERN

4.1 Prototype tests in 2010 and 2011

We had made preliminary beam tests for R&D of readouts of scintillating fibers and scintillator crystals (BGO, PWO) before 2010. After the CALET was approved as an experiment utilizing the Japanese Experiment Module–Exposed Facility (JEM-EF) by JAXA in 2010, configuration of the CALET was almost fixed. Therefore, we carried out beam tests with CALET prototypes in 2010 and 2011.

The CALET prototype I developed in 2010 had a limited lateral width (perpendicular direction to beams) and only one (X) direction, while it had a full depth (parallel direction to beams) of the IMC and two third depth of the TASC. Scintillating fiber belts of 32 mm width which were equivalent to the CALET FM were assembled as a prototype IMC. They are arranged into X direction and into 8 layers interleaved with tungsten sheets. Top (upstream of beams) three tungsten sheets were 448 mm length and 0.2 X_0, middle two were 384 mm length and 0.2 X_0, and bottom two were 320 mm length and 1 X_0. The widths of all tungsten sheets were equally 50 mm. Two PWO crystals were used in one layer and 8 layers were assembled in X direction as a prototype TASC. One plastic scintillator bar of 32 mm width and 450 mm length was set ahead of the prototype IMC as a prototype CHD.

The scintillating fibers of 256 channels were read out with 4 MaPMT, and each of the top two PWO crystals was read out with a PMT and each of the other 14 PWO crystals was read out with a set of PD/APD. The scintillator bar was read out by a PMT. Front end circuits developed for a balloon-borne experiment, bCALET-2 [10], to verify the conceptual design of the CALET were used for the readout. A data acquisition (DAQ) system was made up by utilizing general-purpose NIM and CAMAC modules, and a VME computer. Trigger logics were set up with the NIM modules. The DAQ was controlled by a VME computer which included general-purpose modules, a CAMAC controller, and dedicated interface modules for the balloon-FEC.

In 2011, the CALET prototype I for beam tests was im-

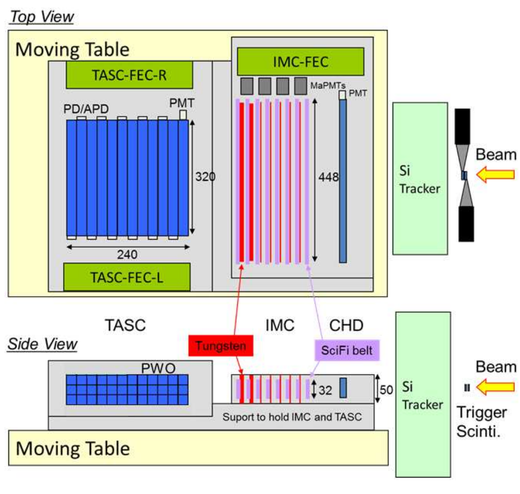

Figure 3: Configuration of the CALET prototype II for the beam test at CERN-SPS in 2011.

proved by increasing the number of PWO crystals of the TASC and replacing some parts of FEC with test circuits for the CALET FM. Figure 3 shows a configuration of the CALET prototype II for beam tests in 2011. One PWO crystal was added to each layer, and the number of layers was increased from 8 to 12. Thus, the CALET prototype for the beam test became equivalent to the CALET FM with regard to the total depth of the IMC and the TASC. As for improvements of electronics, charge sensitive amplifiers of the TASC PMT-FEC were replaced with a tentative hybrid IC developed for the CALET TASC-FEC, and outputs of shaping amplifiers of the TASC PMT were changed from unipolar to bipolar adopted to the CALET FM TASC-FEC.

The beam tests were carried out at the H4 beam line in the north area of the CERN SPS for one week both in 2010 and 2011. We took data with muons of 150 GeV to calibrate the CHD, the IMC, and the TASC with peaks of Minimum Ionizing Particle (MIP). Electrons to 290 GeV and protons to 350 GeV were available. We took data with electrons and protons by changing beam energies, 10, 30, 100, 150, 290 GeV for electrons and 10, 100, 350 GeV for protons. We also took data with different incident positions. In total we obtained 1950 thousand proton events, 381 thousand electron events, and 230 thousand muon events.

4.2 BTM test in 2012

In 2012, the CALET BBM of electronics and STM of the CHD/IMC and the TASC were available for a beam test because the development and manufacturing of the PFM already started at that time. Therefore, we decided to assemble a CALET Beam-Test Model (BTM) as shown in figure 4 for the 2012 beam test by making use of BBM and STM.

As for detector structures, the CHD/IMC STM and the TASC STM were available. In the CHD-STM structure, we set 6 plastic scintillator bars, 3 in each layer (X and Y), to which the PMTs were attached through light guides, and 22 dummy plastic bars without PMT. The IMC-STM structure contained all scintillating fibers in it. We used central 256 of 448 scintillating fibers in one layer for the beam test and 64 MaPMTs were attached in total to read out 4096 scintillating fibers. In the TASC-STM structure, we put 36 PWO crystals, 3 in each layer, into slots of the central PWO holder made of CFRP (Carbon Fiber Reinforced Plastic). PMTs were attached to the 3 PWO crystals in the top layer and 33 sets of APD/PD were attached to the other PWO crystals. Brass bars made as mass dummies for STM tests were put into the other 156 slots.

As for electronics, the BBM IMC-FEC for 2 layers in one direction, the BBM TASC-PMT-FEC for one layer, and the BBM TASC-APD/PD-FEC for one layer were available. We used the BBM IMC-FEC for the bottom 2 layers of the IMC because they are important to generate trigger signals, The other part of IMC were read out with the balloon-FEC's used also for the CALET prototype I and II.

The TASC top layer was read out with the BBM TASC-PMT-FEC. We used the BBM TASC-APD/PD-FEC for the readout of the second layer. The other layers were read out with the balloon-FEC's. Tentative circuits for the readout of the STM CHD were used. They were made as equivalent as possible to the design of PFM circuits.

In order to control these BBM FEC's and to gather data from them, we used a VME module as an interface in which we could build programmable functions. It had FPGA and LVDS interface on it. We programmed protocols on the interface module to communicate with the BBM FEC's through LVDS lines. We utilized general-purpose NIM, CAMAC, and VME modules for the DAQ of the CALET BTM. High voltages for the CALET BTM were also supplied by general high voltage power supplies. Figure 5 shows the CALET BTM installed at H8.

Normally an experiment is allowed one week machine time in a year, however we had 3 weeks machine time in total in 2012. That is because CALET has been approved as a recognized experiment (RE-25) since February 2012. One of our machine times was assigned to ion beam tests at H8 for 2 weeks, and the other was continuously assigned to electron/proton beam tests at H4 for one week. Unfortunately, all ion runs at the SPS were postponed and we carried out electron/proton beam tests also at H8. Collected

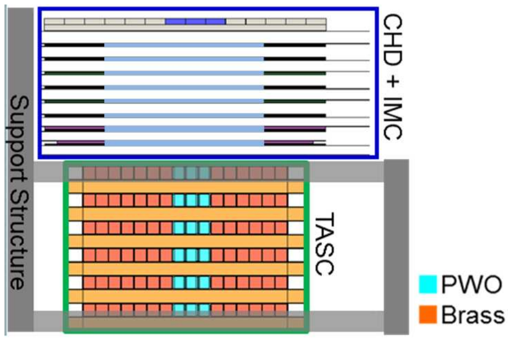

Figure 4: Configuration of the CALET BTM for the beam test at CERN-SPS in 2012.

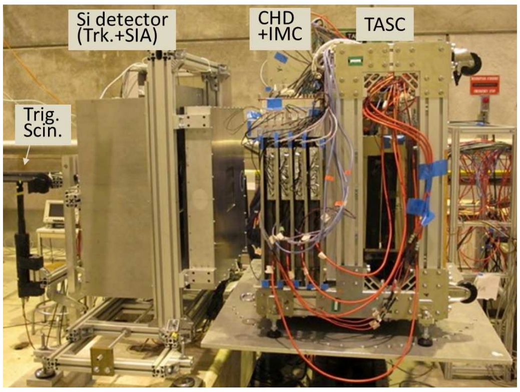

Figure 5: The CALET BTM was rotated by 90 degrees and set up on a moving table at H8 beam line of CERN-SPS.

	H8		H4	
	Events	Energy [GeV]	Events	Energy [GeV]
muon	898 k	180	575 k	150
electron	1318 k	10,20,30, 50,80,100, 150,200,	547 k	10,150, 200,250, 290
proton	2156 k	400	1297 k	30,100

Table 1: Data statistics collected at CERN-SPS in 2012

data at H8 and H4 by changing beam energies and incident positions and angles are summarized in Table 1.

4.3 CHD test in 2013

We requested machine time at the H8 beam line for an ion run in 2013 before the accelerator facility of CERN was closed for a long period more than one year. We tested readout of 2 plastic scintillator bars of CHD with the BBM TASC-PMT-FEC which was common for the readout of CHD-PMT and TASC-PMT. Primary lead beams of 30 GeV per nucleon were sent through a fixed target at the upper stream of the beam line and fragments from it could be selected by A over Z. Fragments with A/Z equal to about 2 were selected. We could distinguish the fragments species with the silicon detector set in front of the CHD scintillator bars. We gathered data of about 3.5 million events with different high voltages supplied to the PMT or different input channels of the BBM FEC. Detailed results are reported elsewhere in this proceedings [4].

5 Results

Pedestal data were taken when we changed data files at every 50 thousand events. The period of data taking for 50 thousand events depended on kinds of particles and their energies. For example, it took about one hour for electrons of 200 GeV at H8.

Overall gains of the CHD, IMC, and TASC were calibrated with MIP peaks obtained from the muon beams. After such calibration, ADC values were converted to numbers of particles in units of MIP and we could compare the experimental results with simulations. We could calibrate gain changes due to temperature of which daily variation was within 4 degrees during beam tests.

Positions of scintillating fibers were also calibrated with muon tracks. Then, shower axes were obtained by fitting lines to shower images taken by the IMC, and incident angles of particles were determined. Angular resolution was σ_x = 0°.10 by using X-layer images, and σ_y = 0°.11 by using Y-layer images for vertical electrons of 150 GeV. Three dimensional angular resolution was roughly obtained by $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$, then it became σ = 0°.15. Angular resolutions obtained with electron beams from 10 GeV to 290 GeV were consistent with simulated results.

Incident electron energies were determined with total numbers of particles in the units of MIP in the TASC. After temperature dependence of the TASC was calibrated, energy resolution was analyzed to verify consistency of results of the beam test and simulations. Detailed results are described elsewhere in this proceedings [11].

6 Summary and future prospect

We have obtained the beam test data needed to develop the CALET flight hardware. We confirmed validity of the simulation at the beam energies. Some detailed analyses, the discrimination between electrons and protons and so on, are continuing.

After the CALET is launched in 2014, we will need to verify CALET responses to some operations or to study its aging change of performance on the ground. Therefore, we have a plan to improve the CALET BTM as a ground-based unit. We will increase the number of the scintillator bars of CHD and that of the PWO crystals as many as possible. We also need more readout sensors like PMT, MaPMT, and APD/PD. The FEC's, the high voltage power supplies, and the mission data controller (MDC) should be replaced with ones equivalent to the CALET FM. Now, we have a spare of the high voltage power supply unit and an MDC which has functions equivalent to the FM and is being used for tests of flight electronics. After launch, we will be able to use them for the improved BTM. We will reproduce the FEC's. Commercial base parts can be used for them to reduce costs because we do not need to require space qualities for them.

CERN will resume its accelerator facilities before the end of 2014. We will request machine times to test the improved CALET BTM at CERN-SPS for a couple of years or more.

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