*Proceedings of the 30th International Cosmic Ray Conference*
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 2 (OG part 1), pages 437–440



30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

# Development of High Dynamic Range Read-out System Using Multi-photodiode for the Total Absorption Calorimeter of CALET

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**Abstract:** We are developing a total absorption calorimeter (TASC) of the CALET (CALorimetric Electron Telescope) instrument for observing high energy electrons and gamma rays on the ISS (International Space Station). A read-out system using a multi-photodiode and a front-end circuit including analog ASIC, 16 bit ADC and FPGA has been developed to measure the energy deposit with the dynamic range from 1MIPs(Minimum Ionization Particle) up to $10^6$MIPs in a BGO bar of TASC. The output signal of 1 MIP was calibrated by cosmic-ray muon. The ADC count of light yield of BGO by a cosmic-ray muon was 10.8fC on average. The dynamic range of the read-out system was confirmed from 1MIPs to about 2400 MIPs with both of LED pulse and heavy ions beam.

## Introduction

CALET is proposed to be launched on the Japanese Experiment Module (JEM), Exposed Facility (EF) of the ISS. CALET consists of an imaging calorimeter(IMC) and a total absorption calorimeter(TASC) [1] [2]. The role of IMC is identification of the incident particle by imaging the shower tracks with scintillating fibers[3] [4]. TASC is used for observing the total development of shower particles with a stack of BGO scintillators. By the previous research[5][6], as a candidate of scintillators used in TASC, we examined in detail characteristics of both BGO and $PbWO_4$. As a result, we have selected BGO as the most suitable material of TASC in following points: light yield and that temperature dependence [5]. We made a small model of CALET with a size of 2/3 in thickness for the experimental tests using beams available at CERN-SPS [6]. The energy resolution and the proton rejection power were investigated by using both the accelerator beam and Monte Carlo simulation. We confirmed good consistency between the simulation and the beam test. A new read-out system using multi-photodiode and a front-end circuit with VLSI chip was employed for the development of TASC.

## Required Performance of TASC

In the CALET project, the observation of TeV electrons is main subject. To observe electrons in TeV energy region, the instrument requires a high rejection power of the background protons, because those flux's decrease with the energy and the background protons increase relatively. It is necessary to achieve a proton-rejection power of better than $10^5$ for observing electrons up to 10 TeV[7]. From simulation study, we found that TASC which consists of BGO with the thickness of 28r.l. can realize such a high rejection power in support of IMC. Therefore, the TASC structure is composed

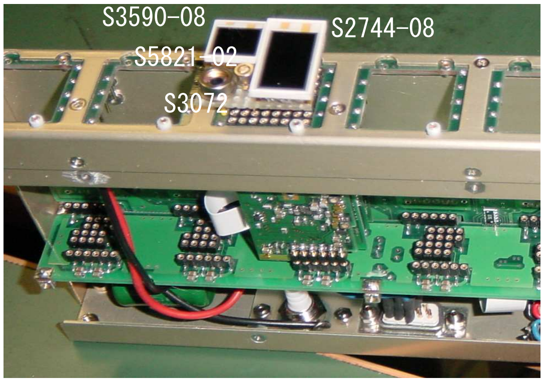


Figure 1: Front-end module installed with V32_HDR14 for a test of basic performance of the read-out system. and an arrangement of 4 photodiodes

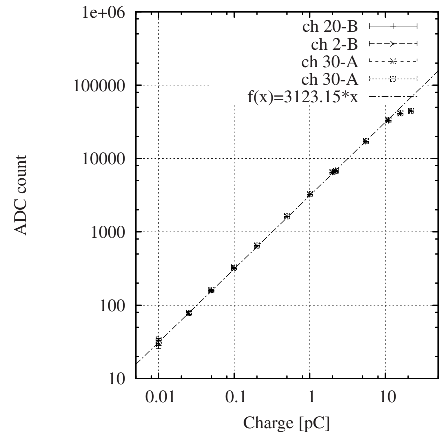


Figure 2: Linearity of the front-end module measured by the LED pulse.

of several hundreds of BGO bar with a volume of $25 \times 25 \times 300\,\mathrm{mm}^3$ for each. The proton rejection power depends on the threshold of light yield in BGO. It increases with decreasing threshold of light yield, and it reach to $5 \times 10^5$ for the threshold of 0.5MIPs[7]. On the other hand, we have found that the highest number of MIPs in one bar is about $10^5$ and $10^6$ MIPs for the highest energy of electron (10 TeV) and of proton (1000 TeV), respectively. Therefore, we need to confirm the read-out for TASC should have the dynamic range from 0.5 to $10^6$ MIPs.

## Read-out System

In space experiment, as well known, electric power consumption is severely restricted for data acquisition circuit as well as detector. Because TASC is composed of 576 BGO bars, the whole electric power consumption of TASC is restrained within about 60W and the electric power consumption in each BGO bar about 100mW. A read-out system of the Viking chip(VA32_HDR14) and multi-photodiode were made to evaluate the performance.

**Front-end module and multi-photodiodes**
Pre-amplifier, shaping amplifier, sample-hold circuit and analog-multiplexer are built in the VA32_HDR14 with the size of 3.4mm$\times$ 3.6mm. A front-end module which has VA32_HDR14 , 16bits ADC and FPGA was developed (Fig.1). The standard deviation of the pedestal distribution of the ADC is 1.4fC approximately. A charge resolution of the system is about 0.32fC/count and that linearity is about 11pC ($<$5% deviation) as shown in Fig.2. To measure energy loss of six-digit range in one BGO bar, a multi-photodiodes assembly which consists of more than one PD of the different size is indispensable. The existent PDs were tested to find the combination of the suitable PD size. Four PDs Hamamatsu, S2744-08(10mm$\times$20mm), S3509-08(10mm$\times$10mm), S3072($\phi$7mm) and S5821-02($\phi$1.1mm), that have different active area were installed on the side of BGO by an arrangement as shown in Fig.1, and a read-out test was done using this module.

**Dynamic range**
The range for each photodiode was examined using a LED pulse(NICHIA NSPE590S) and an optical filter. The ratio of the output ADC value from each photodiode is almost proportional, until it is saturated by the maximum value(a dotted line in the figure) of ADC as shown in Fig.3. The noise level of S2744-08 which has a maximum area is approximately ten counts ($\sim$3.2fC) in ADC. The ADC distribution of the cosmic-ray muon was measured by S2744-08 to find 1MIP value. The peak of the ADC distribution by the cosmic-ray muon is approximately 10.8fC as shown in Fig.4. On the

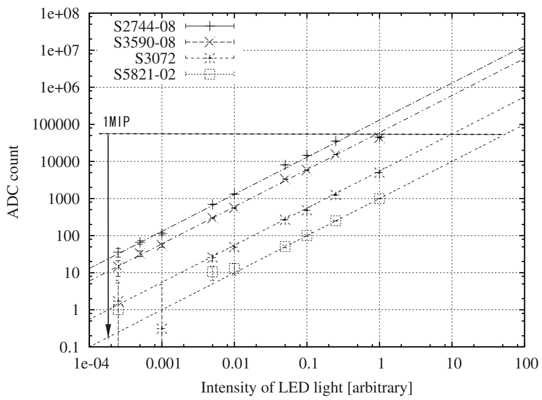


Figure 3: The intensity of LED light and ADC value measured by each photodiode.

other hand, The ADC value of S2744-08 is saturated at about 65000 counts, that linearity is kept to about 0.2 in the intensity of LED light as shown in Fig.3. In other words, it is understood that we can measure up to several 1000 MIPs. When the intensity of LED light are increased more, as for the ADC value of S5821-02, it is expected that the linearity is kept until it becomes more than 10 in the intensity of LED light. From these results, it was found that these two photodiodes can measure from 1MIP to $10^5$MIPs approximately. If the optical filters with an attenuation of 1/10 are installed on S5821-02 or smaller photodiode (for example, Hamamatsu S5973-02 $\phi$ is 0.4mm) is used, measurement beyond $10^6$MIPs becomes possible using three photodiodes.

## Beam Test

The performance of the read-out system was evaluated using the accelerator beam. Four kind of heavy ion beam (He:230MeV/u,C:430MeV/u, Si:800MeV/u and Xe:400MeV/u) were irradiated to BGO with the HIMAC of the National Institute of Radiological Sciences in Japan.

**Uniformity of Light yield**

To check the difference of light yields by the beam position on BGO , the photon number was measured at nine positions as shown in Fig.5 using multi-anode PMT(Hamamatsu H6568). At first, it is confirmed that there was no position dependence of light yield by measuring a cosmic-ray muon from the uniform direction. Then, Si beams are irradiated at the center of the top of BGO in parallel and at three different positions in vertical; they are the positions of $\pm$10cm from the center of BGO and the center on the side. The difference in light yield between central channel No.7 defined in Fig.5 and other channels is within $\pm 5\%$ approximately. No dependences for light yield were found both on the direction and the position.

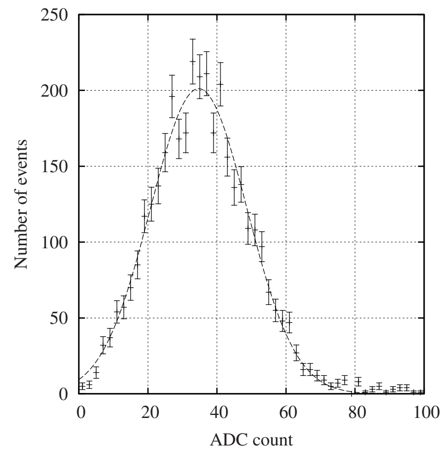


Figure 4: The ADC distribution of the cosmic-ray muon. Point are data and dotted line landau distribution with a peak of 34.7 and $\sigma$=14.0.

**Dynamic range**

The dynamic rang of the multi-photodiode readout system is was evaluated also by using heavy ion beams. The ADC value measured in each photodiode against the energy loss in BGO is presented in Fig.6. The ratio of the output from photodiodes is proportional to the ratio of those areas in the energy range up to about 50GeV, though the effect of quenching in BGO was seen. There was little cross talk between the channels in the front-end module. We could, therefore, confirm the performance in a range up to about 2400MIPs.

## Further Development

**Triple PIN Photodiode Assembly**

To use multi-photodiode in a space experiment, PIN photodiodes should be assembled on a ce-

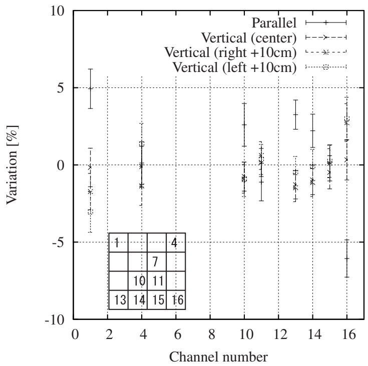


Figure 5: Uniformity of light yield in BGO. The light yield was measured at 9 positions. A Teflon reflection seat (NITTO DENKO No.95S) with the thickness of 300$\mu$m was wound on the side of BGO.

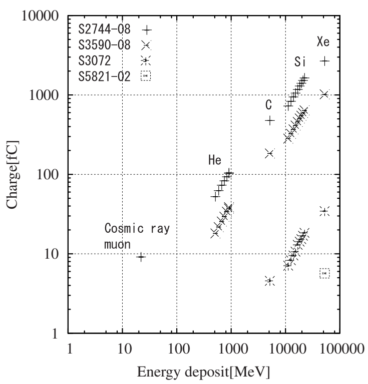


Figure 6: Output charge of each photodiode against the energy loss in BGO. To increase points of measurement, as for C and Si, beam intensities were attenuated by aluminum board.

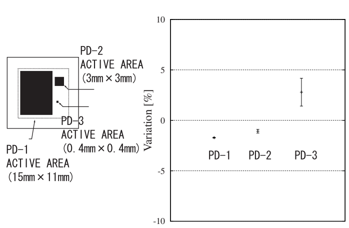


Figure 7: A design of triple PIN photodiode assembly and uniformity of light yield of BGO measured by 3 photodiodes. A vertical axis is a deviation to the average of the light yield measured in the unit area.

ramics base. A design of photodiode assembly has been studied in case of 3 photodiodes under condition that a suitable size ratio of the largest photodiode to the smallest one is 1000 approximately. We have designed a photodiode assembly as shown in Fig.7, to fulfill the condition. The uniformity of light yield measured by each photodiode was checked by a simulation using Geant4. The light yield was almost proportional to the each area of the photodiodes with the size of 15mm$\times$11mm(PD-1), 3mm$\times$3mm(PD-2) and 0.4mm$\times$0.4mm(PD-3) respectively , when muons of 1GeV passed vertically in the center of BGO from the side. The position dependence is within about $\pm$3% as shown in Fig.7.

## Summary

A multiple range read-out system has been developed by a low consumption of electric power, in which a multi-photodiode and a VLSI chip were used to measure the energy deposit in dynamic range from 1MIP up to $10^6$MIPs. The performance of the dynamic range was confirmed from 1MIP to about 2400 MIPs. A balloon test of a small model of CALET is planned in 2008 to verify the whole performance including the BGO read-out system.

This work is carried out as a part of Grants-in-Aid for Scientific Research C No. 17540239.

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