High-dynamic range readout system using dual APD/PD for the CALET-TASC

DAIJIRO ITO[1], YUSAKU KATAYOSE[2], KUNISHIRO MORI[1], HIROYUKI MURAKAMI[1], SHUNSUKE OZAWA[1], YUKI SHIMIZU[3], SHOJI TORII[1], YOSHITAKA UEYAMA[1], RYOSUKE FUNAHASHI[1]
[1]*Wise, Waseda University, Tokyo, Japan*
[2]*Yokohama National University, Kanagawa, Japan*
[3]*Japan Aerospace Exploration Agency, Ibaraki, Japan*

daijiro-ito@fuji.waseda.jp

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Abstract: The CALET (CALorimetric Electron Telescope) instrument is under development to observe cosmic-ray electrons, gamma-rays, and nuclei on the International Space Station (ISS). Total absorption calorimeter (TASC) of the CALET is adopted to image the development of shower particles with a stack of lead tungstenate (PWO) scintillators. Since it is necessary to measure in very high dynamic range, from a minimum ionization particle (MIP) to 10^6 shower particles, we developed a front-end circuit (FEC) which has a dynamic range of 7 orders of magnitude. Scintillation photons from PWO are read out by hybrid packages of Si avalanche photodiode and Si photo diodes (Dual APD/PD). Signals from each photodiode are amplified by a charge sensitive amplifier (CSA) with a high dynamic range of 4 orders of magnitude. Two amplifier circuits with different gains are provided for signal processing with each CSA. We will report on the basic performance of the FEC of CALET-TASC, especially the Dual APD/PD, hybrid integrated circuit (HIC) for the CSA, and the pulse shaping and main amplifier.

Keywords: Total Absorption Calorimeter, FEC, Large Dynamic Range, ISS.

1 Introduction

It is proposed that the CALorimetric Electron Telescope (CALET) instrument will be placed on the Japanese Experiment Module (JEM), Exposed Facility (EF) of the International Space Station (ISS) for observing cosmic-ray electrons (1 GeV-20 TeV), gamma-rays (10 GeV-10 TeV), and nuclei (10 GeV-1000 TeV) [1, 2]. CALET consists of a charge detector (CHD), an imaging calorimeter (IMC), and a total absorption calorimeter (TASC). CHD is used to measure particle charge. The role of IMC is identification of the incident particle by imaging the shower tracks with scintillating fibers.

TASC is an active detector located under the IMC. TASC consists of 12 layers of lead tungstenate (PWO) scintillators, each layer has 16 PWO bars of unit volume 20 mm$\times$19 mm$\times$326 mm to have 326 mm$\times$326 mm in surface area and 27 r.l. in total thickness. The signals from shower particles that penetrate IMC are segmented in TASC so as to obtain a lateral structure, and the total energy is determined by the sum of the light yields in each PWO. TASC performs particle identification, especially for the high energy primaries, through the difference in the development of electromagnetic showers and hadronic showers. Each PWO in the upper layer (16 bars) is read out by a photomultiplier tube (PMT) to generate a trigger signal. Hybrid packages of Si avalanche photodiode and Si photo diode (Dual APD/PD) is used to readout the remaining PWO bars. The APD and PD have different active area. The readout system of TASC is based on Dual APD/PD with Charge Sensitive Amplifier (CSA) and pulse shaping amplifier with dual gain for processing the signal from the PWO.

2 Required Performance of TASC

In the CALET project, the observation of TeV electrons is the main subject. To observe electrons in the TeV energy region, the instrument requires a high rejection power of background protons because the flux of electrons decreases rapidly with the increasing energy, and the background protons increase relative to the electrons. It is necessary to achieve a proton-rejection power better than 10^5 for observing electrons up to 10 TeV [3]. From simulation studies, we have found such a high rejection power can be realized by adopting TASC with a thickness of 27 r.l. in support of IMC. The proton rejection power depends on the threshold of light yield in a scintillator bar of TASC. It increases with the decreasing threshold of light yield, and it reaches 5×10^5 for the threshold of 0.5 MIPs [3]. On the other hand, the highest number of MIP in one bar is in the

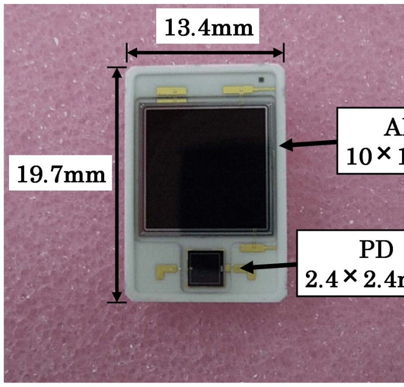

Figure 1: Dual APD/PD package used in CALET.

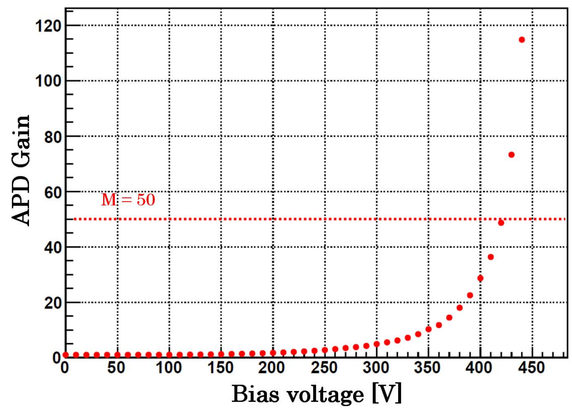

Figure 2: Example of APD gain dependence on the bias voltage. In this case, required bias voltage ($M = 50$) is approximately 420V.

range of 10^6 MIPs for observing protons of up to 1,000 TeV. Therefore, a readout system for TASC is required to have a dynamic range from 0.5 to 10^6 MIPs.

3 Readout System

3.1 Dual APD/PD Assembly

To measure the energy deposit in the range with 6 orders of magnitude at one PWO bar, it is also required that readout electronics has such a dynamic range. It is generally difficult to read out a signal in the wide range of 6 orders by using only one front-end circuit. Hybrid packages of Si avalanche photodiode and Si photodiode that have two different active areas are indispensable for one scintillator bar. The Dual APD/PD designed for CALET is shown in Fig. 1. The APD used in dual package is Hamamatsu S8664-1010, and PD is S1227-33 [4]. APD has an active area of 10 mm×10 mm, and PD has 2.4 mm×2.4 mm, thus an area ratio is 17.4:1. For having a total gain ratio of 870:1, the gain of APD is precisely set by high voltage bias controllers for a nominal gain of $M = 50$. The voltage to give the nominal gain is determined for APD by changing bias voltage, as shown in Fig. 2.

3.2 Front-End Circuit

3.2.1 Charge Sensitive Amplifier

The detector-coupled charge sensitive amplifier (CSA) is the first stage of readout electronics. The action of a CSA is to provide integration with a trailing edge returning to the baseline with time constant $\tau_{csa} = R_f C_f$, where R_f and C_f are the feedback resistance and capacitance, respectively. The output voltage amplitude is proportional to the charge received Q_{in} at the amplifier input, as $V_{out} = -Q_{in}/C_f$. The performance for CSA of TASC requires: a minimum detectable charge of 0.5 fC and an input dynamic range in 0.5 fC-15 pC. The required amplifier to achieve such performances is necessary to be operated with a large detector capacitance at its input: 220 pF for PD and 270 pF for APD. However, such large capacitance of the detector may lead to degradation of the noise performance.

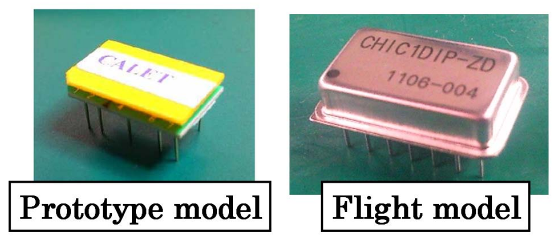

Figure 3: Picture of prototype (Left) / Flight (Right) models of HIC for charge sensitive amplifier

We have newly developed a hybrid integrated circuit (HIC) for CSA so as to achieve the required performance. The picture in Fig. 3 depicts a prototype version for testing and a flight model of HIC. Fig. 4 shows HIC readout linearity over dynamic range obtained by using 4417 spectroscopy amplifier (Clear Pulse Co., Ltd.) of type CR-4RC (shaping time constant: 2 μs) and MCA8000A multi-channel pulse height analyzer (Amptek Co., Ltd.). The equivalent noise charge (ENC) at the output of the spectroscopy amplifier depends on the input capacitance (detector capacitance) and the auto-discharge time constant τ_{csa}, as shown in Fig. 5.

3.2.2 Pulse Shaping Amplifier

Pulse shaping amplifier is a bandpass filter for the voltage step signal of CSA. It performs three functions: First, it provides an output pulse having a faster baseline restoration than CSA output pulse. This is especially important

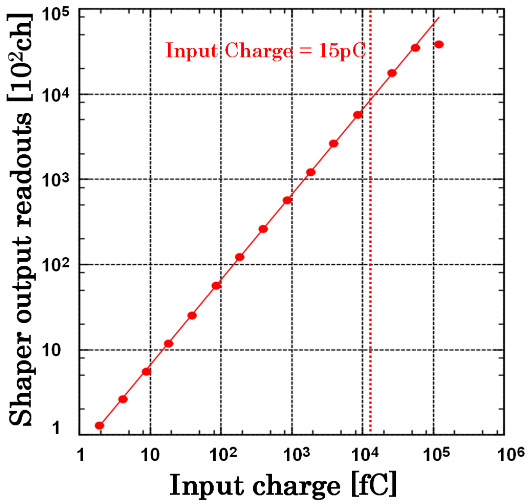

Figure 4: CSA linearity over dynamic range obtained by using 4417 spectroscopy amplifer (Clear Pulse Co., Ltd.) and MCA8000A multi-channel pulse height analyzer (Amptek Co., Ltd.).

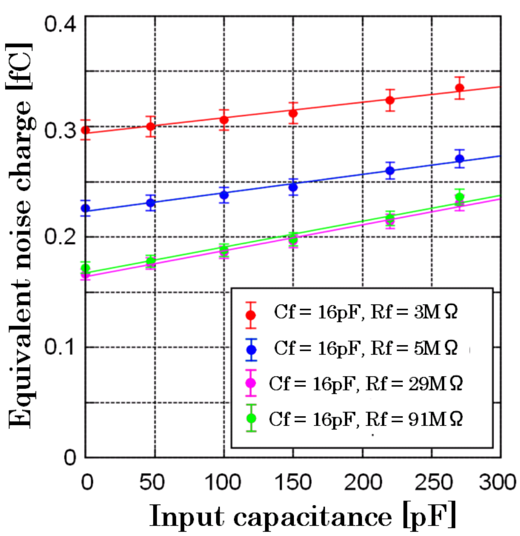

Figure 5: Equivalent noise charge of HIC dependence on the input capacitance. Comparison on equivalent noise charge between four patterns of auto-discharge time constant. Required minimum detectable charge is 0.5 fC.

at high count rates, where pulses from consecutive events can pile up. Secondly, It filters some of the noise from CSA output signal. Finally, It may also be used to provide extra gain to the signal, which may be very small at CSA output. Shaping amplifier for TASC consists of a series of 1st order high-pass filter (differentiator circuit, CR) with pole-zero cancellation tuned for the CSA, 2nd order low-pass filter (integrator circuit, RC), and 1st order

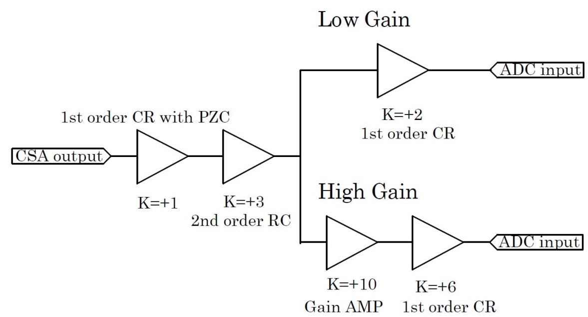

Figure 6: Dual-gain shaping amplifier of type CR-2RC-CR with pole-zero cancellation. The two sections have a gain ratio of 30:1.

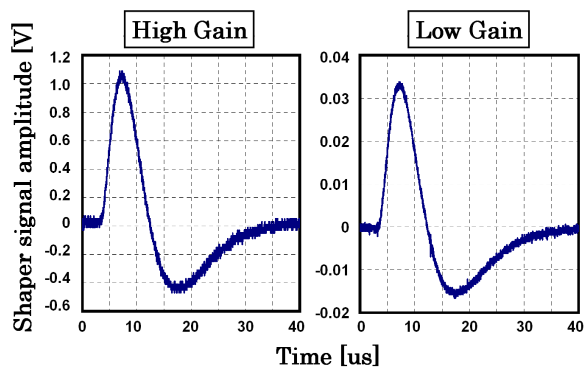

Figure 7: Oscilloscope pictures of shaping amplifier high (Left) and low (Right) gain channel of the same pulser iuput with expected gain ratio of 30:1. The measured gain ratio is 30.9:1.

high-pass filter which makes bi-polar signal outputs. Each high/low-pass filter has the same time constant of several μs. Fig. 6 shows the dual-gain shaping amplifier for TASC, which was developed for optimal noise performance with gain ratio of 30:1 for low-energy and high-energy ranges. The dual gain outputs for the same input signal are shown in Fig. 7. The measured gain ratio for pedestal-corrected amplitudes is 1.02/0.033 = 30.9.

3.3 Expected dynamic range

In space experiment, as is well known, the amount of electrical power is severely restricted for data acquisition circuits and detectors due to the limitation in power supply. Therefore, the readout electronics that have a low power consumption and a wide dynamic range are indispensable. As for FEC, which is the most important part of the readout electronics, it is necessary that one channel of FEC has a large dynamic range with at least 3 orders of magnitude. A new FEC for the CALET-TASC has been developed.
The FEC main task is to measure the particle energy very

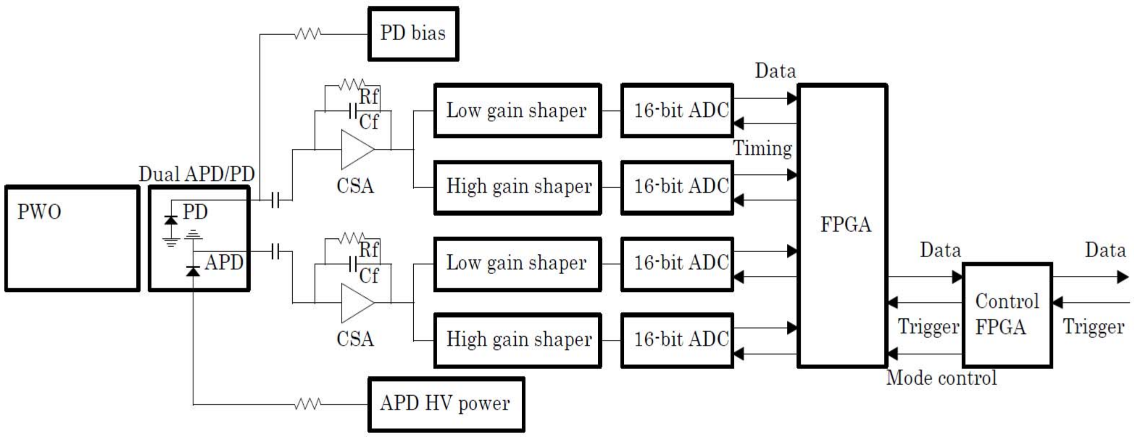

Figure 8: Block diagram: Front-end circuit for the CALET-TASC.

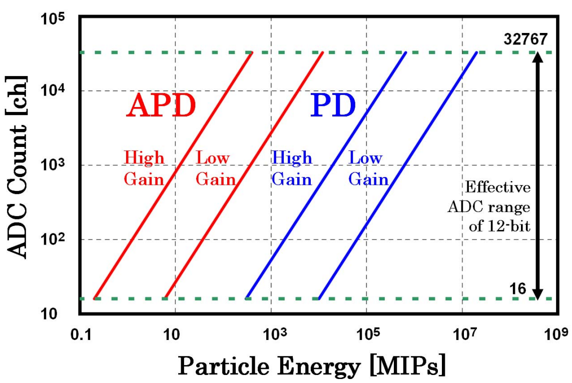

Figure 9: The expected dynamic range with dual-gain photosensors, high/low gain shaping amplifiers, and 16-bit A/D converter.

precisely over a dynamic range via dual gain photodiodes, CSA, and shaping amplifiers. The common electronics is shown as Fig. 8. The Dual APD/PD is glued to the end of the crystal, and the outputs are directly connected to CSA with a sensitivity of 63 mV/pC for APD and 72 μV/pC for PD, 50 ns rise time and 160 μs auto-discharge time, which produces an output voltage step proportional to the charge created in APD or PD. The step voltage produced by each CSA is connected to a CR-2RC-CR shaping amplifier and produces a bi-polar signal of approximately 4 μs peaking time. Each shaping amplifier has two sections for each input channel, and the two sections have a gain ratio of 30:1, each getting digitized by a 16-bit A/D Converter with a self-contained sample-hold.
The combination of dual-gain photosensors and high/low gain shaping amplifiers per each PWO channel corresponds to four ADC ranges: 0.2 - 400 MIPs, 6 - 1.2×10^4 MIPs, 300 - 7×10^5 MIPs, and 9×10^3 - 2×10^7 MIPs. Fig. 9 shows the expected dynamic ranges of these four ADC ranges.

4 Summary

Hybrid packages of APD and PD, hybrid integrated circuit for CSA, and dual-gain pulse shaping amplifier have been developed to achieve the high-dynamic range readout system for CALET-TASC.

1. As for the photosensor, since two photodiodes are necessary per scitillator bar of TASC to measure the energy deposit from 0.5 MIPs to 10^6 MIPs, we have developed Dual APD/PD which has a total gain ratio of 870:1 (an area ratio of 17.4:1, a gain ratio of 50:1).

2. A low-noise preamplifier for Dual APD/PD has already been developed, and a performance test of HIC was performed. The resolution is approximately 0.30$\pm$0.05 fC and the maximum range is approximately 50 pC.

3. The high-dynamic range front-end circuit was designed. The performance of the prototype of FEC is being evaluated at present. That is expected to have a dynamic range of 7 orders of magnitude (0.5 MIPs - 10^6 MIPs).

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