Development of a High Dynamic Range Front-End Electronics for the Total Absorption Calorimeter of CALET

Yusaku Katayose[*], Makio Shibata[*], Takayuki Asai[*], Masaki Go[*], Shoji Torii[†], Shunsuke Oazwa[†], Tadahisa Tamura[‡], Kinya Hibino[‡], Shoji Okuno[‡], Hiroyuki Murakami[§], Yukio Uchihori[¶], Hisashi Kitamura[¶], Kenji Yoshida[‖] and Shin Kubo[**]

[*]*Department of Physics, Yokohama National Univ., Yokohama, Kanagawa 240-8501, Japan*
[†]*Research Institute for Science and Engineering, Waseda Univ., Tokyo, 169-8555, Japan*
[‡]*Faculty of Engineering, Kanagawa Univ., Yokohama, Kanagawa 221-8686, Japan*
[§]*Department of Physics, Rikkyo Univ., Tokyo, 171-8501, Japan*
[¶]*National Institute of Radiological Sciences, Chiba, Chiba 263-8555, Japan*
[‖]*Department of Electronic Information Systems, Shibaura Institute of Technology, Saitama, Saitama 337-9570, Japan*
[**]*Clear Pulse Co. Ltd., Tokyo, 143-0024, Japan*

***Abstract*. Read-out systems using Si photodiodes and front-end circuits(FEC) were studied in order to measure the energy deposit with a dynamic range from 1MIP(minimum ionization particle) to 10^6 MIPs in a crystal scintillator bar of the total absorption calorimeter (TASC) of the CALET (CALorimetric Electron Telescope) instrument. Four types of FEC were investigated for the photodiode read out. Two of them were A225(AMP-TEK), which consisted of a hybrid charge sensitive preamplifier and a shaping amplifier, and MPX-08 (NOVA), which is a charge-integrating chip. It was confirmed that the A225 had a resolution of approximately 0.31 fC and a maximum range of approximately 2 pC. A new hybrid integrated circuit(IC) is being developed to measure the light yield of a scintillator with a dynamic range of seven orders by using two photodiodes. This FEC consists of two preamplifiers that have a different gain. The performance of a high-gain preamplifier was evaluated. The resolution is approximately 0.5 fC and the maximum range is more than 25 pC. A new application specified integrated circuit(ASIC), which has a high dynamic range of four orders, is being developed. This ASIC consists of one preamplifier circuit and two shaping circuits that have a different gain. The prototype IC was designed using the 0.5-μm BiCMOS process. The outline of read-out systems using each type of FEC and the state of the development of each system are described below.**

***Keywords*: CALET, Total absorption calorimeter, Front-end circuit**

I. Introduction

It is proposed that CALET will be launched on the Japanese Experiment Module (JEM), Exposed Facility (EF) of the International Space Station(ISS) [1], [2]. The calorimeter of CALET consists of an imaging calorimeter(IMC) and a total absorption calorimeter [3], [4], [5] . The TASC is an active detector with no dead volume located under the IMC. The signals from shower particles that penetrate the IMC are segmented in the TASC so as to obtain a lateral structure, and the total energy is determined by the sum of the light yield. The TASC performs particle identification, especially for the high energy primaries, through the difference in the development of electromagnetic showers and hadronic showers. We are examining two candidates of TASC: the BGO type and the $PbWO_4$ type. As for the former, the TASC consists of 12 layers, each of which is made up of 48 BGO bars of unit volume $25 \times 25 \times 300\text{mm}^3$ to have $600 \times 600\text{mm}^2$ in area and 26.8 r.l in total thickness. Each BGO in the upper layer (48 bars) is read out by the PMT to generate a trigger signal. A Si PIN-photodiode assembly consisting of photodiodes of two or three different active areas is used to read out other BGO bars. As for the latter, $PbWO_4$ is used instead of BGO to make the TASC light and compact. $PbWO_4$ has the advantages of a shorter radiation length and a bigger density in comparison with BGO although its the light yield of $PbWO_4$is smaller than that of BGO. A Si avalanche photodiode is used in addition to Si PIN-photodiode so as to measure the lower light yield of $PbWO_4$.

II. Performance Requirement 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 in line with the energy, and the background protons increase relatively. It is necessary to achieve a proton-rejection power better than 10^6 for observing electrons up to 10 TeV [3]. From a simulation study, we found that the TASC of a thickness of 28 r.l. can realize such a high rejection power in support of the IMC. The proton rejection power depends on the threshold of light yield in a scintillator bar of the

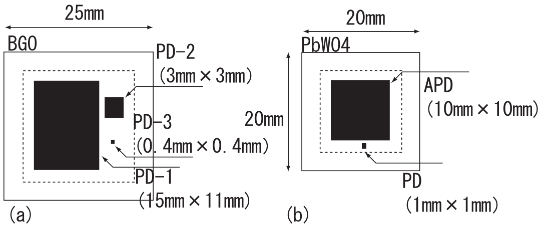

Fig. 1. Design example of photodiode assembly. (a) A three Si PIN-PDs assembly installed on the side of a BGO and (b) an assembly consisting of Si PIN-PD and Si APD installed on a $PbWO_4$.

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, we have found that the highest number of MIP in one bar is approximately 10^5 and 10^6 MIPs for electrons of 10 TeV and protons of 1000 TeV, respectively. Therefore, we need a read-out system for TASC that should have a dynamic range from 0.5 to 10^6 MIPs.

III. Read-out system

A. Multiple Si Photodiode Assembly

To measure the energy deposit in the range with six orders of magnitude at one BGO bar or one $PbWO_4$ bar, it is also demanded that read-out electronics has a dynamic range higher than six orders. Generally, it is difficult to read out a signal in the wide range of six orders by using only one front-end circuit. Multiple Si photodiodes assemblies that have two or three different active areas are indispensable for one scintillator bar. In a previous study, existent photodiodes were tested to find a combination of the most suitable size photodiodes by simulation and experiment [6], [7]. It was found that the most suitable size-ratio of the largest photodiode to the smallest one was approximately 1000, and the energy measurement with a range of six orders of magnitude was made possible by means of a set of two or three photodiodes [6]. Fig.1(a) shows an example of the photodiode assembly to be installed on a BGO. The output charge of the largest Si PIN-photodiode and the smallest one is approximately 12 fC/ MIP and approximately 1.2×10^{-3} fC /MIP, respectively. Therefore, the energy deposit from 0.1 MIPs to 8 $\times10^6$ MIPs can be measured by using multiple Si PIN-photodiode when the charge signal are read out by the FEC having the range from 1 fC to 10 pC . On the other hand, as for $PbWO_4$, the Si avalanche photodiode, which has the gain of 50 $\sim$ 100, must be used instead of the largest Si PIN-photodiode because light yield of $PbWO_4$ is almost one-tenth of that of the BGO, as shown in Fig.1(b).

B. Front-End Circuit

In a space experiment, as is well known, the amount of electrical power is severely restricted for data acquisition circuits and detectors. Since the power consumption of TASC, which consists of 576 BGO bars, is restricted to 60 W due to the power limitation of ISS, the power

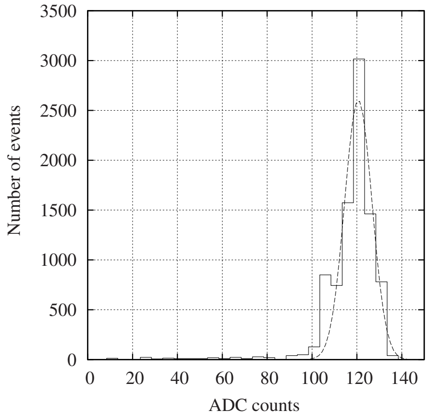

Fig. 2. Energy distribution of 59.5 KeV gamma ray measured with an A225 and a Si-PIN photodiode (Hamamatsu S3589)

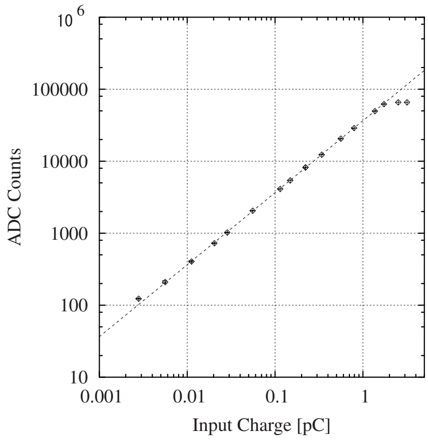

Fig. 3. Linearity of A225 measured by a test pulse. The A225 was operated using a power supply of +12 V.

consumption in each BGO bar is restricted to approximately 100 mW. Therefore, read-out electronics that have a low power consumption and a wide dynamic range are indispensable. As for the FEC, which is the most important part of the read-out electronics, it is necessary that one channel of the FEC has a large dynamic range with at least three orders of magnitude. Four types of FEC are tested for the read out system. The concept of each system and its basic performance are described in the following subsections.

1) A225: A225 is a thin film hybrid-charge-sensitive preamplifier and shaping amplifier. Because the power consumption of A225 is only 10 mW/ch, it is possible that the total power consumption for the 576 BGOs can be restrained to approximately 17 W, even if three A225s were used per BGO. To examine the resolution of the FEC, the 59.5 KeV gamma ray line from a radiation source of ^{241}Am was measured by a Si-PIN photodiode (Hamamatsu S3590) and an A225. Fig. 2 shows the ADC distribution of the 59.5 KeV gamma line. The average and the standard deviation were 120.1 counts and 6.1 counts, respectively. In other words, the energy resolution was approximately 7.1 keV in the FWHM.

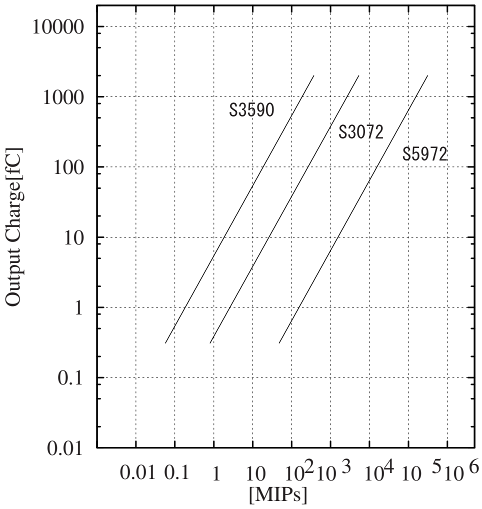

Fig. 4. The expected dynamic range with triple photodiodes and an A225.

It is approximately 0.31 fC in the FWHM, when the ADC value is converted into charge. As for the dynamic range of A225, linearity up to approximately 2 pC, could be confirmed as a result of examining the range by the test pulse as shown in Fig. 3. Because 1 MIP of the BGO measured by the S3590 will be 5.4 fC [6], S3590 and A225 can be used for the measurement from approximately 5.7×10^{-2} MIPs to 3.7×10^{2} MIPs. Fig. 4 shows the dynamic range that can be measured by the three photodiodes: Hamamatsu S3590, S3072, and S5972. The maximum range is approximately 3.1×10^{5} MIPs in this case. If the measured light yield of BGO is attenuated, a dynamic range of 10^{6} can be realized with A225 and three photodiodes of different sizes.

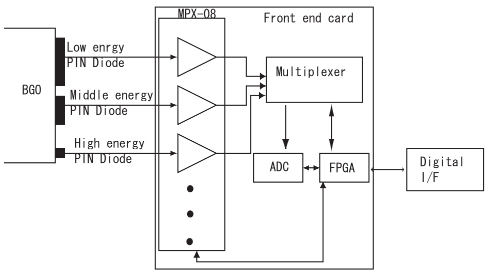

Fig. 5. Block diagram of a read-out system with MPX-08.

2) MPX-08: The MPX-08 integrated circuit consists of eight-channels of a charge-integrating analog data acquisition system, which has a range from several fC to over 10 pC. It follows a 0.35-μm CMOS process; the radiation hardness is high and the power consumption is small at 454mW/ch. Fig. 5 shows the outline of a read-out system that uses MPX-08. Three types of photodiodes are installed on one BGO, and three signals are measured with each MPX-08. Two hundred and eighty eight MPXs are used in total when 1 MPX is used for two BGOs. The total power consumption is approximately 1 W. When three photodiodes(Hamamatsu 3590-08, S3072, and S5972) are installed on a BGO and they are read out using an MPX-08, one can measure the signal from 0.9MIPs to 1.5×10^{6}MIPs.

3) Development of new hybrid FEC: A new front-end circuit, which has a wider dynamic range of more than four orders of magnitude, is being developed. Fig. 6 shows the block diagram of a read-out system using this new FEC. This FEC has two preamplifiers: one is a high-gain preamplifier for a larger photodiode and the other is a low-gain preamplifier for a smaller photodiode. The output signal from each preamplifier is amplified again by the shaping circuit, which has a different gain. The signal out of the shaping circuit is digitized by a sample-hold ADC. When the Si-PIN photodiode (S3590, active area 100 mm^2) is used as the larger photodiode, and S5973 (active area 0.12 mm^2) is used as the smaller one, it is expected that each photodiode signal of the BGO will be read out by the range with four orders of magnitude, and the dynamic range of 10^7 will be realized by two photodiodes. The high-gain preamplifier in this FEC has already been developed. To examine the resolution of the preamplifier, a 59.5 KeV gamma ray from a radiation source of ^{241}Am was measured by an S3590 and the preamplifier. Fig. 7 shows the energy resolution of the measurement against each power supply. The average energy resolution was approximately 10 KeV in the FWHM and this signifies approximately 0.53 fC in FWHM. Linearity is examined by means of a test pulse. Fig. 8 shows the preamplifier output as a function of the input charge. The unit on the horizontal line is the energy loss of a gamma ray in a Si-PIN photodiode. It is approximately 22pC when 500 MeV(Si) is converted into the input charge.

4) Development of new front-end ASIC : A new front-end ASIC, which has a wide dynamic range of four orders of magnitude, is being developed using the BiCMOS process. This FEC is a dual-gain amplifier consisting of a preamplifier and two shaping circuits that have different gains as shown Fig. 9. A preamplifier circuit is the charge integrating circuit of an operational amplifier. The capacitance of the integrating capacitor is 12 pF and the time constant of integration is approximately 4 μs . The output signal from preamplifier is amplified again with two different gains in two shaping circuits. Each part consists of a pole zero cancellation(PZC) circuit and low-pass filter(LPF) circuit. The input signal is attenuated by low gain PZC by half and amplified by high gain PZC by two times. LPF is the multiple feedback low-pass filter, which has the cut off frequency of 30 MHz. The gains of the LPF are 1 and 4 for the low-gain and the high-gain, respectively. After all, the signal is attenuated by the low-gain part by half and amplified by the high-gain part by eight times. Internal circuits were designed by the 0.5-μm BiCMOS process and the parameter of each element such as resistance value and capacity was optimized by the simulation of SPICE. The linearity of each channel was checked by the simulation. Relations between the input charge and the output pulse

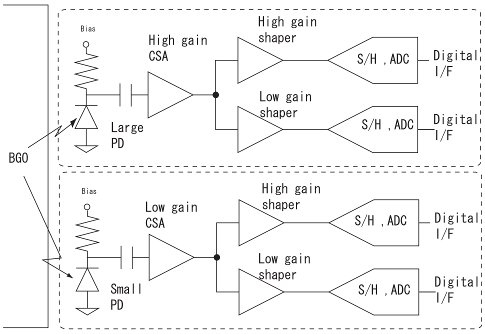

Fig. 6. Block diagram of read-out system using a new hybrid FEC.

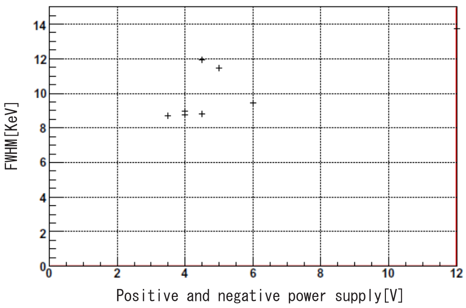

Fig. 7. Resolution of high-gain preamplifier. 59.5 KeV gamma ray was measured with a preamplifier and an S3590.

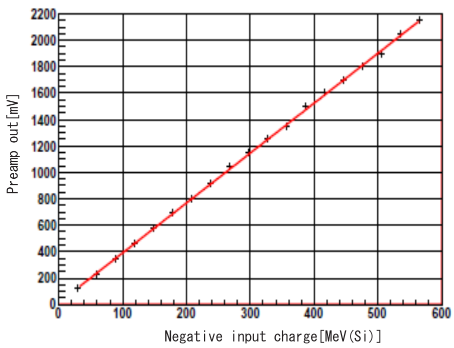

Fig. 8. Linearity of the preamplifier in the new hybrid FEC.

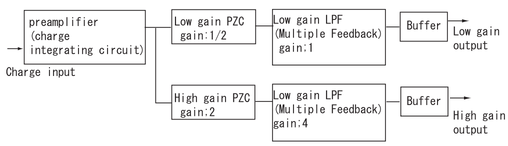

Fig. 9. Block diagram of the internal circuit in a front-end ASIC.

height are shown in Fig.10. The difference in gain between the low-gain and the high-gain is approximately sixteen times and the maximum range of each channel is approximately a few pC for high-gain channel and 30pC low-gain channel, respectively.

IV. Conclusions

A read-out system that used four types of FECs is studied for the TASC of CALET. As for the A225, the

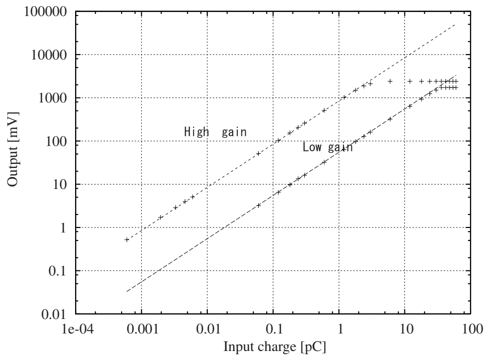

Fig. 10. Linearity of front-end ASIC obtained by SPICE simulation.

resolution is approximately 0.53 fC and the maximum range is approximately 2 pC. To measure the energy deposit from 1MIP to 10^6 MIPs by using an A225, three photodiodes are necessary per scintillator bar of TASC. A performance test of the MPX-08 is under study. If the expected performance is confirmed, the MPX-08 will make a wide range read-out with six orders of magnitude possible by using three types of photodiodes. We are developing a new hybrid FEC that has a dynamic range of four orders by one photodiode. Then, it is possible to cover the dynamic range of seven orders when two photodiodes are used. A high-gain preamplifier for a larger photodiode has already been developed. The resolution and maximum range is approximately 0.5 fC and 25 pC, respectively. The prototype of the front-end ASIC using the 0.5-μm BiCMOS process is designed. That is expected to have a range from less than 1fC to 30pC. The performance of the prototype is being evaluated at present. After the expected performance is confirmed, it will be improved in the 0.35-μm BiCMOS process to have high radiation hardness and low power consumption. On the basis of the appreciation of the four types of FEC, an accelerator beam test are planned to verify the overall performance of the read-out system, including the dynamic range , the energy resolution for each scintillator bar of TASC and effects of the shower particles which directly hit on a PD.

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