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Development of readout system for the CALET scintillating fiber detector

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Abstract.
We have a plan to make observations of high energy electrons and gamma rays with the Japanese Experiment Module (JEM) on the International Space Station (ISS). We are carrying out a R&D for the detector, CALET (CALorimetric Electron Telescope). It consists of an imaging calorimeter (IC) and a total absorption calorimeter (TASC). We will utilize a few hundred-thousands scintillating fibers (SCIFI) for the IC part to visualize cascade showers. We have two options for readout of such amount of SCIFI. First, we have developed a new image intensifier coupled to CCD camera (II-CCD), which is based on the technology utilized and established in the balloon observations with BETS (Balloon-borne Electron Telescope with Scintillating fibers). Although the data acquisition rate will be limited to a few 10 Hz, a lot of SCIFI can be read relatively easily with the readout system of the II-CCD. Second, we are developing a readout system with multi-anode photo multipliers (MA-PMT) and front-end chips (VA32_hdr32; one of the Viking family). The readout system with the MA-PMT will enable us to make data acquisition at high frequency of over one thousand Hz.

1 Introduction

High energy electrons ranging from GeV to 10 TeV are very important to know the origin, acceleration and propagation. Super nova remnants are most likely candidates for the source of the high energy electrons. The possible sources of electrons with the energy beyond TeV are limited to only a few super nova remnants. As a result, if we will observe the electrons over TeV , the contribution from each source will appear on the energy spectrum and on the anisotropy of arrival directions, as pointed by the authors(Kobayashi et al. , 1999). However, the measurement is very difficult since the flux of electrons are very small and the proton backgrounds are as much as over 1000 in the TeV region. Therefore, we need a high performance detector in the proton rejection power which can be used for a long term observation in space. From our experience of balloon experiments using the BETS, Balloon-borne Electron Telescope with Scintillating fibers SCIFIs(Torii et al. , 2000a), the imaging calorimeter composed of scintillating fibers (SCIFIs) is very efficient in such an electron observation.

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Table 1. Comparison of the readout systems for 30000 SCIFIs

	I.I.+CCD	MA-PMT+VA32_hdr2	
Quantity	4∼5 sets	469 PMTs	938 chips
Power Consumption	< 50 W	5 W	45 W
Weight	~ 30 kg	15 kg	< 1 kg
DAQ Rate	a few 10 Hz	≥ 1 kHz	

By using the BETS, we have successfully carried out observations of the electrons in the energy range from 10 GeV to 100 GeV(Torii et al. , 2001). The performance of the BETS detector has been already confirmed with electron and proton beams at CERN(Tamura et al. , 2000). We can effectively decrease the background protons by imaging the shower profiles with a high granulation. The imaging calorimeter with SCIFIs was also able to be applied to the detection of gamma rays in the GeV region without any serious modification(Torii et al. , 2000b).

We are planning to make a space observation on the International Space Station (ISS) to observe the electrons from a few GeV to 10 TeV and the gamma-rays from 0.1 GeV to 1 TeV. We are developing a new detector, CALET (CALorimetric Electron Telescope), and proposed it for ISS observation(Torii et al. , 1999a,b, 2000c). The detector will have a total of a few hundred-thousands of 1 mm square SCIFIs. We have two options for the readout of such a lot of SCIFIs. Characteristics of two options are summarized in Table 1 by supposing that thirty thousand SCIFIs will be used.

In one option, which has been used for BETS, scintillation photons from the SCIFIs are amplified with image intensifiers (I.I.) and the amplified images are taken with CCD cameras coupled to the I.I. which has a large input window of 10 cm diameter (Fig. 1). At least 5000 SCIFIs can be dealt with by one pair of I.I. and CCD camera. Although the rate of data acquisition will be limited to at most a few 10 Hz due to the readout of the CCD camera, a lot of SCIFIs can be read relatively easily.

In the other option, the SCIFIs are to be attached to compact multi-anode photo multiplier tube (MA-PMT). It has 64 anodes of regular squares of 2 mm which are arranged in a matrix of 8×8. It is assembled with a breeder network into a small box of 30×30×45 mm^3. We can individually get 64 anode signals. This option is a new method which we should confirm whether we can implement it for an actual detector of cosmic-ray observations. Since one SCIFI is to correspond to one anode of the MA-PMT, we need the same number of channels for the readout circuit. It must be compact and should contain a function of signal delay or holding because the trigger signal can be delayed a few hundred nano-seconds. The Viking chips (IDE AS) which are developed for the readout of Si strip detectors(Nygård et al. , 1991; Toker et al. , 1994), have capability of shaping analog signal with a certain peaking time and of holding the shaped signal at the peak. These capabilities fit to the function required for the MA-PMT readout. It enables us to make data acquisition with the MA-PMT at very high rate.

2 Required Dynamic Range

By simulations for CALET, we have estimated the average maximum number of particles traversing one SCIFI to be about 500 for an incident electron of energy 100 GeV. The number becomes $\sim$ 3,300 particles for 1 TeV and $\sim$ 20,000 particles for 10 TeV. In Table 2, we show the estimated values of average number of SCIFI with signal and that of saturated one for each incident energy of electron.

Among the SCIFIs with signal, those of 1.1 % will be saturated with the dynamic range of 210, which is typical in the VA32_hdr2 (see § 4), in case of 100 GeV. The rate of number of saturated SCIFI becomes about 5 % above 1 TeV. We have also estimated saturation of deposited energy, as presented in Table 3. The rate of saturated energy become serious with the dynamic range of 210 above 1 TeV. Should the dynamic range be improved to 2000, we can use the readout system up to several TeV. It is difficult to cover all the dynamic range over 20000 with only one sensor. We are considering to attach the readout systems of different gain at the both ends of the SCIFI.

Table 2. Estimated average number of SCIFI to be saturated

Energy [GeV]	Av. # of Fiber with Signal	Number of Saturated Fiber D.R.: 210	D.R.: 2000
100	1.3×10^3	14 (1.1%)	0 (0%)
1000	2.8×10^3	142 (5.0%)	9 (0.3%)
10000	5.8×10^3	277 (4.8%)	73 (1.3%)

Table 3. Estimation of average energy deposition and saturation

Energy [GeV]	Av. Energy Dep. [MIP*]	Saturated Energy Dep. [MIP*] D.R.: 210	D.R.: 2000
100	2.1×10^4	1.1×10^3 (5.2%)	0 (0%)
1000	1.4×10^5	7.8×10^4 (55%)	2.1×10^4 (15%)
10000	6.8×10^5	5.6×10^5 (83%)	4.7×10^5 (69%)

∗Deposit energies were converted to numbers of MIP.

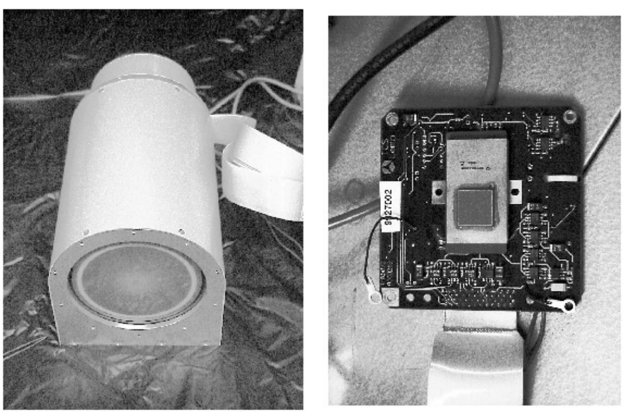

Fig. 1. I.I. and CCD Camera

3 I.I. and CCD

We have developed a new image-intensifier system for using in the space observation on ISS. Especially, there were many improvements in the image reducer. In order to withstand against vibration in launching, some parts made of glass were replaced with those of metal, and the structure of electrodes were simplified and strengthened. We reduced its volume to half in comparison with those implemented for BETS, while its input window remains a diameter of 10 cm.

Images amplified and reduced by the image reducer are to be amplified again with two MCPs. We replaced the MCPs of inventor type with those of proximity type. Thus the total volume of I.I. was reduced significantly as shown in Fig. 1.

For the read-out of image, we adopted a CCD (Thomson TH7888A) which has 1024×1024 pixels. The dimension of each pixel is a square of 14 μm. We can obtain up to 30 images per second with the readout frequency of 40 MHz. It has anti-blooming structure providing a capability of electronic shutter. Its S/N ratio of 70 dB is much better than that of 54 dB of CCD used for BETS. The dynamic range of CCD becomes larger by a factor of 6.3. Since the sensitive area of the new CCD is larger, the overall dynamic range of CCD for one fiber can increase by about two orders of magnitude. Finally, the dynamic range might reach over 3000 with the CCD.

Fig. 2 shows a sample of image of photons from one SCIFI irradiated by ^{90}Sr taken with the I.I. One short SCIFI of 1 mm

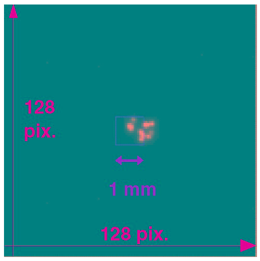

Fig. 2. A sample image of detection of β particle with one fiber. A part of whole CCD image was extracted.

square was attached to the I.I. The size of the SCIFI on the CCD was indicated with a red square in the center. It is not the actual position of the SCIFI. As clearly seen in the figure, it is possible to discriminate each photoelectron (p.e.) image.

4 MA-PMT and VA32_hdr2

Since we need a dynamic range as high as possible for the detection of the cascade shower, the VA32_hdr2 has been chosen for the test. It has the highest dynamic range of 230 minimum ionizing particles (MIPs) for Si detectors. Here, the number of electrons yielded by the Si detector is defined to be 22400 for 1 MIP. It follows that the VA32_hdr2 can deal with the maximum input charge of 5×10^6 electrons. The VA32_hdr2 is such compact that it contains 32 channels of preamplifier, shaping amplifier, and sample hold circuit within the chip size of 3.642×3.355 mm^2 (Fig. 3) and its power consumption is as low as 1.5 mW/channel.

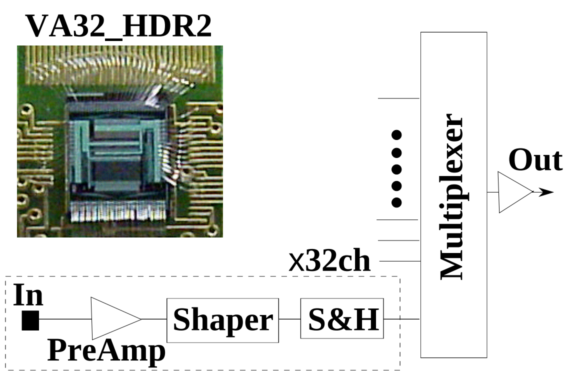

Fig. 3. VA32_hdr2 consists of 32 channels of preamplifier, shaper amplifier, and sample hold circuit.

We estimated the number of p.e. detected to be about 4 or 5 for the SCIFI of 1 mm square (Kuraray SCSF-38 Single-Cladding) from our beam test results(Gorine et al. , 1999) which gave 8 p.e for the 2mm square SCIFI. The photoelectrons should be multiplied up to around 22400 electrons; thus an optimum gain factor of the MA-PMT is supposed to be a few thousands. The MA-PMT composed of 12 stage dynodes (Hamamatsu R5900-00-M64) has a gain factor of 3.0×10^5 at the supplied high voltage of -800 V, which is apparently too high for the VA32_hdr2. Therefore we prepared the MA-PMT composed of 8 stage dynodes (Hamamatsu R7600X-00-M64) in order to reduce the gain factor by two orders of magnitude. The gain of the MA-PMT of 8 dynodes is 2.0×10^3 at the voltage of -500 V.

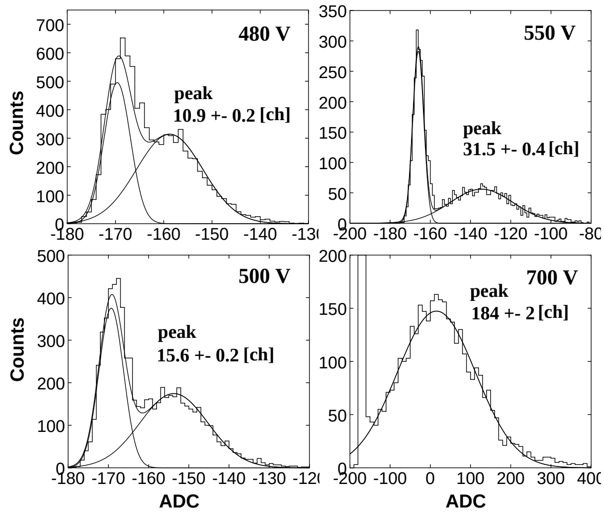

Fig. 4. Examples of ADC distributions for beta particle with the various supplied high voltages to the MA-PMT of 8 dynodes. The SCIFI of 1 mm was attached to the MA-PMT.

We made several measurements to investigate a novel approach of reading the SCIFI based on the MA-PMT coupled with the VA32_hdr2. We optimized a setup based on existing hardware with small modification. Fig. 4 shows examples of ADC distributions for β particle obtained with MA-PMT of 8 dynodes coupled to the VA32_hdr2. The single beta particle corresponded to 8 p.e. which was somewhat larger than expected value for single MIP. We are, however, certain of capability to detect single MIP of 4 or 5 p.e. because even single p.e. had been detected.

The dynamic range turned out to reach to at least 210. It was consistent with the specification of the VA32_hdr2 for a Si detector. We got the conclusion that the MA-PMT of 8 dynodes is appropriate for the photo multiplier coupled to the VA32_hdr2. Further improvement in dynamic range can be obtained by a reduction of the noise and, most efficiently, by a simple modification of the VA32_hdr2.

We have developed a MA-PMT readout unit with the VA32_hdr2 as shown in Fig. 5. The unit consists of 16 pairs of VA32_hdr2 and TA32cg. Eight MA-PMTs are mounted on it and analog signals of 512 channels are to be processed with one ADC on a VME board. The picture of the unit are presented in Fig.6. Fig. 7 shows an example of the pulse heights of 512 channels taken with the readout system. It is seen in the figure, one channel has a signal of β particle from SCIFI, which exceeds the pedestal levels in other channels.

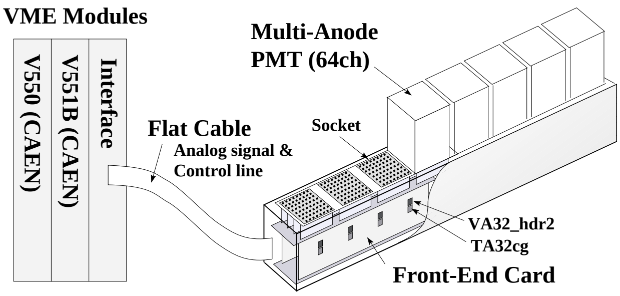

Fig. 5. Schematic drawing of the MA-PMT readout unit. Signals of 512 channels from MA-PMTs are read out with 16 chips of VA32_hdr2. These chips are controlled by a VME module and are processed with one ADC on a VME module.

In order to make more intensive study We have carried out a test of MA-PMT readout unit with Helium beams of 230 MeV/n. Several tests with other heavy ions is planned to confirm the capabilities and to improve the performance.

Fig. 6. Two units of MA-PMT readout system. The unit contains 16 pairs of VA32_hdr2 and TA32cg, and 512 SCIFIs can be read with one unit.

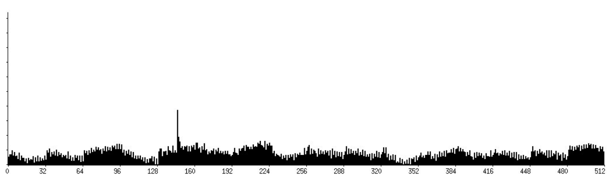

Fig. 7. An example of readout with MA-PMT readout unit. Horizontal axis shows the readout channels of 512 and vertical one shows ADC value. Pedestal values were not subtracted. One MA-PMT was mounted and signal of β particle detected with SCIFI was seen around ch.150.

5 Summary

We are proposing the CALET mission for the high-energy electron and gamma-ray observation on the ISS. The key technology of the CALET instrument is the read-out of SCIFI. As for an established technology, we have successfully developed a new I.I. system, in which the dynamic range could be more than 2000, which is useful for showers over 100 GeV. The MA-PMT has a very suitable performance for the read out. It is basically confirmed that the MA-PMT coupled to the VA32_hdr2 could satisfy our requirements in the dynamic range, the DAQ speed, the size, the power consumption, and so on. Further investigations are necessary in order to decide which options of the readout system we will adopt for CALET. It may be possible for us to utilize the both options by taking the advantage of each merit.

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