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Calibration of TEPC for CubeSat Experiment to Measure Space Radiation

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A newly designed Tissue Equivalent Proportional Counter (TEPC) has been developed for the CubeSat mission, SIGMA (Scientific cubesat with Instruments for Global Magnetic field and rAdiation) to investigate space radiation. In order to test the performance of the TEPC, we have performed heavy ion beam experiments with the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. In space, human cells can be exposed to complex radiation sources, such as X-ray, Gamma ray, energetic electrons, protons, neutrons and heavy charged particles in a huge range of energies. These generate much a larger range of Linear Energy Transfer (LET) than on the ground and cause unexpected effects on human cells. In order to measure a large range of LET, from 0.3 to 1,000 keV/μm, we developed a compact TEPC which measures ionized particles produced by collisions between radiation sources and tissue equivalent materials in the detector. By measuring LET spectra, we can easily derive the equivalent dose from the complicated space radiation field. In this HIMAC experiment, we successfully obtained the linearity response for the TEPC with Fe 500 MeV/u and C 290 MeV/u beams and demonstrated the performance of the active radiation detector.

Keywords: space radiation, tissue equivalent proportional counter, galactic cosmic ray, linear energy transfer

1. INTRODUCTION

CubeSat, beginning in 1999, has been providing students opportunities to carry out real satellite projects from design phase through test and into real operation (Heidt et al. 2000). SIGMA (Scientific cubesat with Instruments for Global Magnetic field and rAdiation) developed jointly by Kyunghee University and Korea Astronomy and Space science Institute, is one of the CubeSat projects scheduled to be launched in 2015 to investigate the Earth's magnetic field, and space radiation at the altitude of about 750 km. Meanwhile, the TEPC (Tissue Equivalent Proportional Counter), the main payload of CubeSat, has been developed and characterized for monitoring radiation in the International Space Station (Nam et al. 2013). In this paper, we describe the design of the main payload, TEPC and show the calibration results.

At the low earth orbit, satellites are exposed to an intensive radiation environment by trapped high energy particles and Galactic Cosmic Rays (GCR) (Hastings & Garrett 2004). The particles trapped by the geomagnetic field form Earth's radiation belts. The intensity of space radiation formed by trapped particles dramatically increases between 500 km to 1,500 km altitude, as shown in Fig. 1. The equivalent dose is calculated with Geant4 simulation based on the measurements of the Van Allen Probes mission. The GCRs are high energy particles that originated from outside

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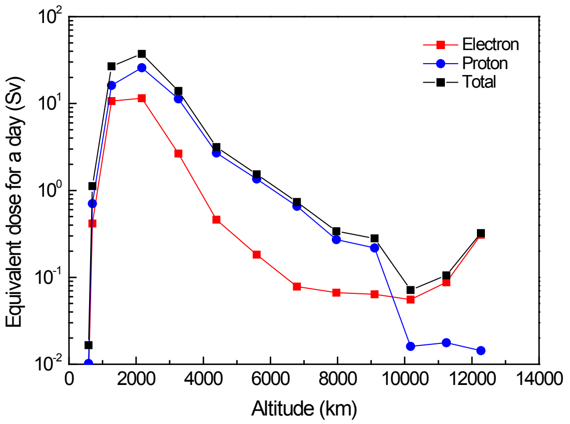

Fig. 1. Ambient equivalent dose derived from the measurements of the Van Allen Probes mission.

our solar system. About 99% of GCRs are composed of a proton and helium atom and just 1% are heavy nuclei (HZE, High-atomic-number and high energy) ions (O'Neill 2006). Due to the high charge and heavy nature of HZE ions, their contribution to an astronaut's radiation dose in space is significant even though they are relatively scarce. In order to measure the radiation dose contributed by the HZE ions and investigate the time variation of trapped particles, a specific radiation detector is required. The TEPC is known to be the best instrument for measuring the unknown complex radiation sources in small size volume (Rossi & Zaider 1996).

2. INSTRUMENT

Fig. 2 shows the assembled SIGMA structure. The SIGMA is a 3U CubeSat 100 mm × 100 mm × 340.5 mm in size and consists of satellite structures, an avionics bus and two payloads, the TEPC and a magnetometer to investigate space environments.

The TEPC was first developed by Rossi & Rosenzweig (1955) to simulate the measurement of energy deposition in volumes of tissue with dimensions similar to the nucleus of a mammalian cell. TEPC has a rigid wall made of tissue-equivalent plastic, surrounding a gas-filled cavity. An anode wire extends through the center of this gas cavity. Simulation of energy deposition in volumes with dimensions of a few micrometers is accomplished by operating the TEPC at a low pressure (Taddei et al. 2006).

Fig. 3 shows the TEPC chamber and detector electronics boards, such as a voltage divider, preamp and connector PCBs developed for the SIGMA mission. In particular, in order to minimize the detector electronic noise, the preamp board is located in the TEPC chamber.

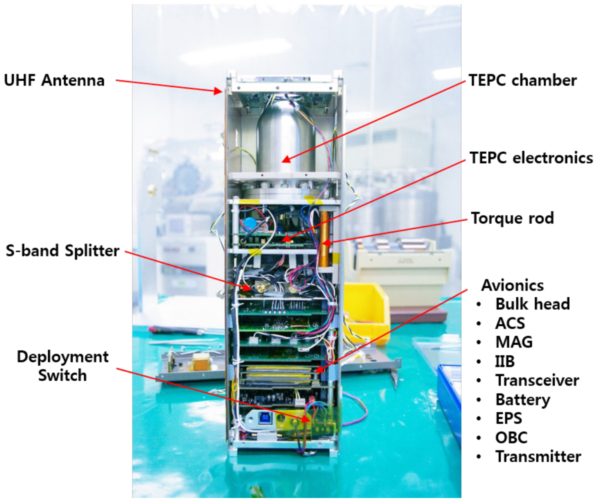

Fig. 2. The assembled CubeSat SIGMA. SIGMA consists of avionics, UFH antenna, DC-DC Converters, S-band splitter and a torque rod including TEPC as a main payload.

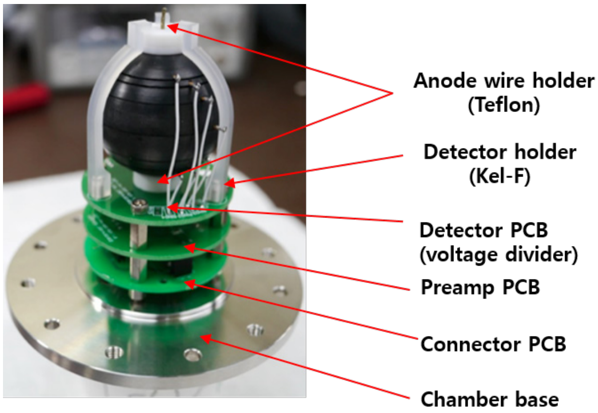

Fig. 3. The assembled TEPC showing the inside structure of the detector chamber.

The spherical type detector is made of tissue equivalent plastic, A-150 with an outer diameter of 40 mm, and an inner diameter of 30 mm. We adopted a segmented TEPC sphere in which 5% voltage increments are applied on the segmented tissue equivalent sphere, which is comprised of 7 isolated cathode rings, in order to make uniform electric field. The TEPC is housed in a 1.5 mm wall thickness stainless chamber filled with pure propane (C_3H_8) at 27.7 Torr pressure to simulate a 2 μm site size. In addition, a digital pulse processor (DPP) algorithm was applied to the new version of the TEPC to improve the noise to signal ratio and to reduce power consumption. Also a two gain mode was adopted to obtain a wide measurement range with a single detector, from 0.3 to 1,000 keV/μm.

Fig. 4 shows the electronics configuration of the digital pulse processor for the TEPC experiments. Signals from the anode wire of the TEPC are fed into the two-gain

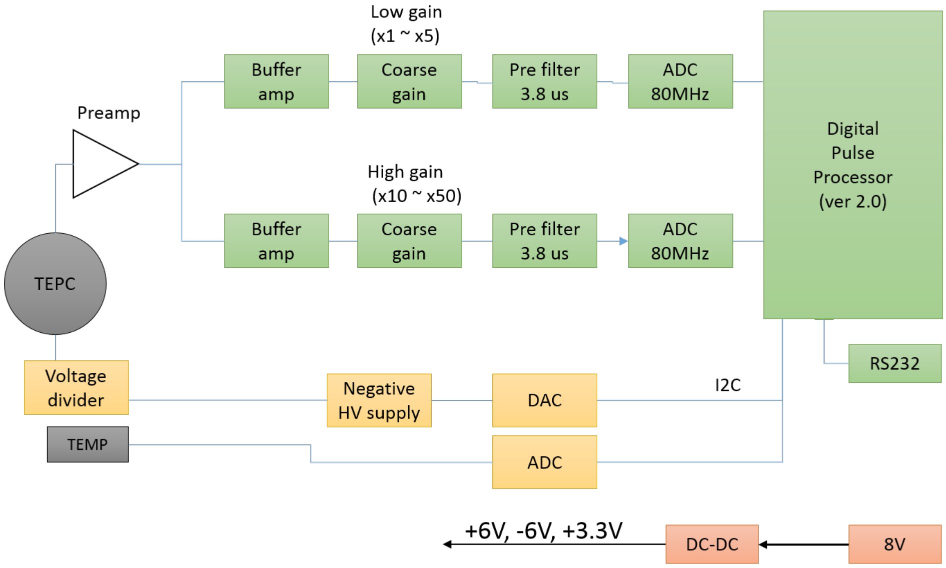

Fig. 4. The TEPC electronics configuration.

(Low and High gain) electronics, which consist of buffers, coarse gain amps, pre-filters and 14-bit, 80 MHz sampling Analog-to-Digital converters. The new version of the digital pulse processor utilizes trapezoidal digital pulse shaping (Jordanov et al. 1994) which makes it possible to process the radiation signals fast, effectively reducing power consumption to less than 3 watts and improving the signal to noise ratio even with a small size electronics board.

All of the functions for the digital pulse processing and the pulse height analyzer are implemented in a FPGA (field-programmable gate array), Xilinx Spartan 6 - XC6SLX45. Also the housekeeping circuits consist of a high voltage supply and a temperature sensor reader to monitor the temperature inside the chamber. The negative high voltages for the TEPC are controlled remotely up to -1,000 volts. The control commands and energy histograms are transferred to the CubeSat using RS232 communication.

3. EXPERIMENT

In order to test and calibrate the TEPC, several experiments have been performed with HIMAC (Heavy Ion Medical Accelerator in Chiba) at NIRS (National Institute of Radiology Science) in Japan (Nam et al. 2014). While the HIMAC is a facility for radiotherapy, the heavy ion beams are assigned to scientific research for nighttime and weekends (Hirao et al. 1992).

Fig. 5 shows the experimental setup of the TEPC for the HIMAC beam exposure in the BIO room. Table 1 summarizes the HIMAC experiments performed from 2013 to 2014. In 2014, two experiment runs were performed. On 1st February 2014, our first experiment was performed with He (150 MeV/u) and on 5th February 2014 the second experiment was conducted with C (135 MeV/u). The goal

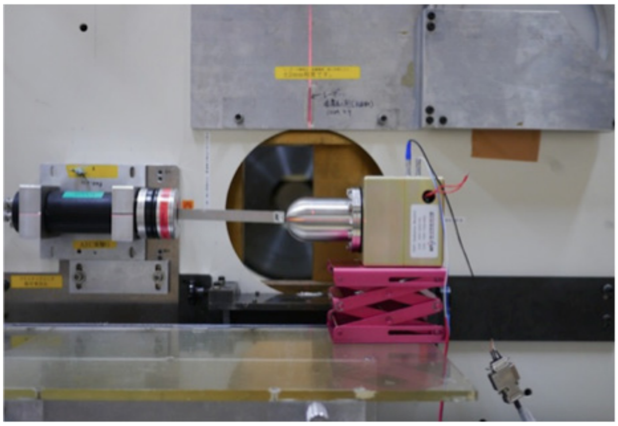

Fig. 5. Setup of the prototype of the Tissue Equivalent Proportional Counter (TEPC) calibration in the HIMAC BIO room.

Table 1. Summary of HIMAC experiments

	Date	Beam	Active Detector	Goal
2013	Feb. 1st, 2014	He (150 MeV/u)	Prototype TEPC	LET spectrum measurement
	Feb. 5th, 2014	C (135 MeV/u)		
2014	April 4th, 2014	Fe (500 MeV/u)	Segmented TEPC + DPP	Calibration of TEPC with DPP electronics.
	Feb. 6th, 2015	Fe (500 MeV/u)	Segmented TEPC + DPP (2 gain mode)	Calibration of TEPC with new revision of DPP electronics.
	Feb. 9th, 2015	C (290 MeV/u)		

of these experiments was to demonstrate the performance of the prototype TEPC, which is our first version of the active detector designed for the International Space Station operation. From these experiments, while the results are preliminary, we successfully measured the Linear Energy Transfer (LET) spectra for several bias voltages and measured the response functions for the different beam angles.

In 2014/15, the HIMAC experiment was performed three times, on April 4th, 2014, Feb. 6th, 2015 and Feb. 9th, 2015 with Fe (500 MeV/u) and C (290 MeV/u) beams. For these campaigns, we modified the TEPC design and applied new technology for the SIGMA mission. While the 2013 experiment was focused on testing the prototype detector, the 2014/15 experiments were designed to calibrate the new TEPC. In these experiments, we obtained LET spectra for the different beam filter thicknesses and beam directions.

4. RESULTS

Before the HIMAC experiments, the LET response of the TEPC was calibrated with the ^{252}Cf neutron source at KRISS (Korea Research Institute Standards and Science). Here, the fluence and dose rate of the neutron source were 4,200 n/cm^2/s and 5.93 mSv/h respectively. When the neutrons interact with the tissue equivalent material, A-150 of the TEPC, it produces protons that deposit energy in the cavity of the detector. By measuring the drop point of the deposited energy, we can obtain calibration factors. From Geant4 code simulation, the proton's energy of drop point should be 225 keV and considering a site diameter of 2 μm, the drop point of LET can be calculated with the following equation.

$$\mathrm{LET} = \frac{E}{l} = \frac{E}{\frac{2}{3}d} = \frac{225\ keV}{\frac{2}{3}2\ \mu m} = 168.8\ keV/\mu m \qquad (1)$$

Here, E, l and d are the drop point energy, mean chord length and site diameter respectively. Fig. 6 shows the pulse height spectrum obtained from the ^{252}Cf experiment. Here, the energy channel corresponding to the drop point of 168.8 keV/μm is 93 ch and the LET for one channel is 1.81 keV/μm/ch.

In order to measure the LET generated from HZE ions in space, the TEPC is required to have good linearity over a wide LET range. The TEPC for the SIGMA mission is designed to measure the LET in the range of 0.3 ~ 1,000 keV/μm. To confirm the LET range, we performed a HIMAC experiment with C (290 MeV/u) and Fe (500 MeV/u) beams whose beam size were 10×10 cm^2. The beam flux was 100 particles/cm^2-spill and pulse duration was 1.7 second with a period of 3.3 seconds.

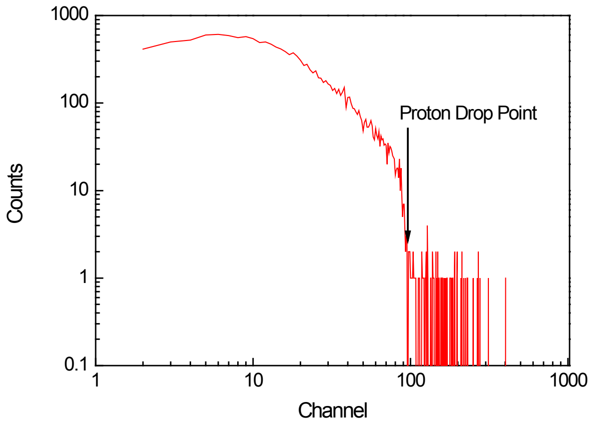

Fig. 6. The pulse height spectrum obtained from the ^{252}Cf experiment at KRISS.

When ionizing radiation travels through matter, the energy loss plots a Bragg curve. Generally a peak occurs immediately before the particles come to rest. In this HIMAC experiment, the Fe (500 MeV/u) ions got through binary filters of 0 mm, 30.05 mm, 46.99 mm, and 56.70 mm thickness. Fig. 7 shows the LET spectra measured by TEPC for the Fe (500 MeV/u) ion beams with changing beam binary filters. Without the beam binary filter, the LET peak was measured at 297 keV/μm and for the 56.70 mm binary filter, the LET was measured at 957 keV/μm. Note the LET peak shifted to high energy channels and the count rate decreased according to the increase in the thickness of the beam binary filters.

In Fig. 8, the LET obtained from the HIMAC experiment and from neutron (^{252}Cf) sources in KRISS are plotted together. In this figure, it should be noted that the LET

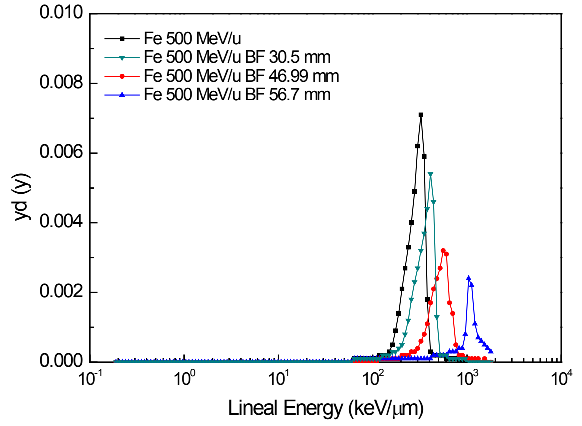

Fig. 7. Linear energy spectra measured by TEPC with Fe (500 MeV/u) for the different thicknesses of beam binary filters.

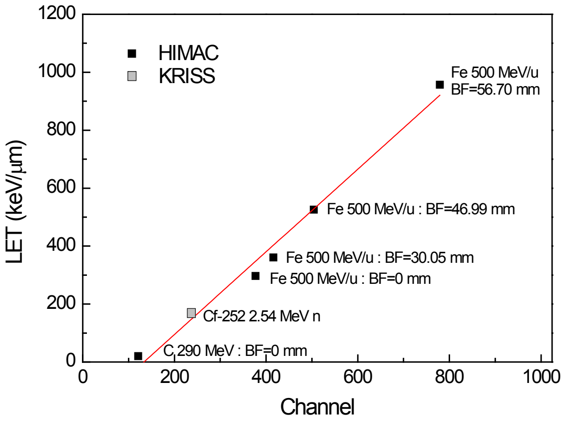

Fig. 8. Linearity of the TEPC response in LET obtained from three sources, C (290 MeV/u, Fe (500 MeV/u), and neutron (^{252}Cf).

points are fitted well with a linear function and this means our instrument has good linearity from low to high LET.

5. CONCLUSION

In this paper, we describe the results of linearity responses of the TEPC obtained with HIMAC heavy ion beams. The design goal of our instrument is to measure the LET of space radiation in the wide range of 0.3 ~ 1,000 keV/μm, and so the device needs to be calibrated with known energy radiation sources. While low LET could be calibrated with gamma, proton and neutron beams in Korea, to confirm the high LET, heavy ion beam experiments are absolutely required. In the experiments reported here, we successfully obtained high LET spectra that will be used to design a flight model for the SIGMA mission that will be launched in late 2015.

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