Development of a New Space Dosimeter Based on LET Measurements for Heavy Charged Particles

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Abstract — Radiation effects on the human body are evaluated using dose equivalent *H*, defined as the product of the absorbed dose and the quality factor given as a function of LET. In space, there exist many kinds of radiation, such as galactic cosmic rays and geomagnetic trapped particles, where charged particles and neutrons are the main components contributing to radiation dose. Since the LET of these radiations is widely distributed, it is essential to measure LET directly to evaluate *H*. The standard space dosimeter has been the Tissue Equivalent Proportional Counter (TEPC), which is a simple gas counter made of tissue-equivalent materials. In TEPC, the lineal energy is measured instead of LET since no position information is given. Obviously, the lineal energy does not represent LET accurately. The dose obtained using TEPC is reported to be inconsistent with those measured with real LET spectrometers. We have developed a new dosimeter, the Position Sensitive Tissue Equivalent Chamber (PS-TEPC), based on a time projection chamber (TPC) using a Micro Pixel Chamber (μ-PIC) as a two-dimensional position-sensitive detector. In this study, we demonstrate the feasibility of PS-TEPC and complete a prototype of PS-TEPC that will be usable in space. Its performance was tested by using heavy-ion beams to examine its three-dimensional tracking and energy measurement capabilities.

1. Introduction

In radiation dosimetry, evaluation of radiation effects on the human body normally employs the dose equivalent *H* (Sv), which is defined as the product of the absorbed dose *D* (Gy) and the quality factor *Q* given as a function of linear energy transfer (LET). Many kinds of radiation (e.g., galactic cosmic rays (GCR), geomagnetic trapped particles, solar energetic particles (SEP), and their secondary particles) exist in space. Thus, workers in space (e.g., astronauts) face the risk of intense radiation exposure. The dose in space reaches up to 1mSv per day, which is compatible to that received in a year on the ground. The main components contributing to the doses in space are primary charged particles (protons and heavy ions) and secondary neutrons produced by the interaction between cosmic radiation and the spacecraft materials. The LET of these radiations distributes widely from 0.2 to 600keV/μm. Hence, direct measurement of the LET is essential for evaluating *H* in space.

NASA has used as a standard space dosimeter named the Tissue Equivalent Proportional Counter (TEPC) [1], which is a simple gas proportional counter made of tissue-equivalent plastics and filled with tissue-equivalent gas. Since no position information is given in TEPC, the assumption that LET is equal to the lineal energy (the deposited energy divided by the mean chord length of the detector) is normally used to achieve real-time measurement. However, since the lineal energy does not represent LET accurately, this assumption results in systematic errors of 51% [3]. A large discrepancy in dose data between TEPC and real LET spectrometers (e.g., RRMD-III), was observed in a flight experiment [2]. The RRMD-III, however, does not consist of tissue-equivalent materials, and it has a smaller detection view (<42%) and no neutron sensitivity. The ideal real–time space dosimeter should have the following properties: (1) position sensitivity, (2) construction with tissue-equivalent materials, (3) neutron sensitivity, (4) capability to measure LET in a wide range from 0.2 to 1000keV/μm, and (5) a wide detection view (~4π). Evaluations of dose equivalents for charged particles and neutrons have been performed separately, due to differences in detection methods. If LET distribution can be measured from the secondary charged particles produced by the incident neutrons, neutron dose can be evaluated directly without information on the neuron energy spectrum.

We have developed a new conceptual space dosimeter, the Position Sensitive Tissue Equivalent Chamber (PS-TEPC), which is based on a time projection chamber (TPC) using a Micro Pixel Chamber (μ-PIC) as a two-dimensional (2D) position-sensitive detector (Fig. 1). In PS-TEPC, the LET and the absorbed energy of a particle can be measured simultaneously, event by event, in real time. We have already demonstrated the feasibility of PS-TEPC as a space dosimeter, using the large TPC equipped with μ-PIC (10 x 10cm) [4]. In the present study, we designed and constructed a prototype of PS-TEPC. Our final goal is to establish a dosimetric system in space, using PS-TEPC. To investigate the response of a prototype of PS-TEPC to heavy ions, we performed irradiation tests in experiments using beams from an accelerator. In this paper, we describe the details of PS-TEPC and heavy-ion irradiation test experiments and discuss the results.

2. Experimental procedure

The μ-PIC [5] is a recently developed micro-pattern gas detector using fine printed circuit board (PCB) technology. Figure 1 schematically depicts the TPC based on μ-PIC. In μ-PIC, the anode and the cathode strip electrodes are orthogonally arranged with a pitch of 400μm on both sides of the 100μm-thick polyimide insulation layer. Each cathode strip has 260μm-diameter openings with a pitch of 400μm. Pixel-like anode electrodes of 50μm are also formed at the center of each cathode hole. Due to an electrical field between the anode and the cathode, a gas gain of $\sim 10^4$ is obtained without any additional gas multiplication devices. Using μ-PIC, we can obtain a 2D fine position resolution (typically 120μm rms). Adding a drift-plane electrode forms an effective detection volume in TPC.

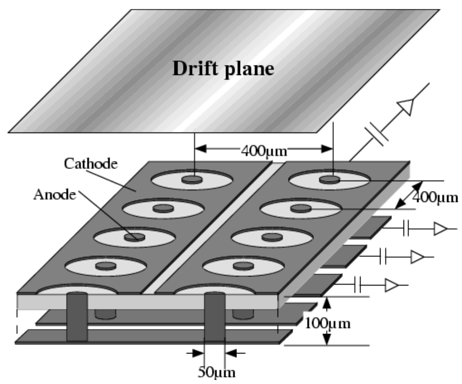

Fig. 1. A schematic drawing of a time projection chamber based on μ-PIC

As described previously, we constructed a TPC equipped with μ-PIC of 100 x 100mm^2 with 100mm drift length (a large TPC) and performed irradiation tests using heavy-ion beams (e.g., C^{6+} (400MeV/n), Si^{14+} (800MeV/n) and Fe^{26+} (500MeV/n)) from the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS), to examine the response of the TPC to heavy charged particles [4]. The TPC was filled with a mixture of Ar + 10%C_2H_6 of atmospheric pressure. The results confirmed the feasibility of applying this type of TPC to PS-TEPC, though the TPC was not made of tissue-equivalent materials.

In order to develop a practical detector, we designed a new 26 x 26mm^2 μ-PIC (Fig. 2), and manufactured a small TPC using this μ-PIC (effective detection volume 26 x 26 x 50mm^3). By connecting two electrodes neighboring each other in this μ-PIC, the readouts of 32 x 32 channels were maintained, and it was possible to simplify the readout circuits, although the position pitch was degraded (800μm). Tissue-equivalent plastics (A150) were employed to construct electrodes in the drift plane and the field tube system in the TPC. Teflon having a composition close to tissue-equivalent was used as the insulator.

We also designed a new front-end data acquisition system so as to separate the detection part from the readout circuit systems in the small TPC. To examine performance, irradiation tests with heavy charged particles were conducted

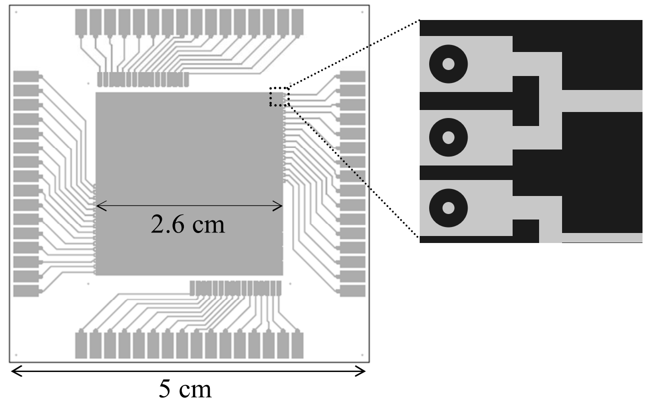

Fig. 2. New Micro-Pixel Chamber designed for the small TPC. Two electrodes neighboring each other are connected to reduce readout channels.

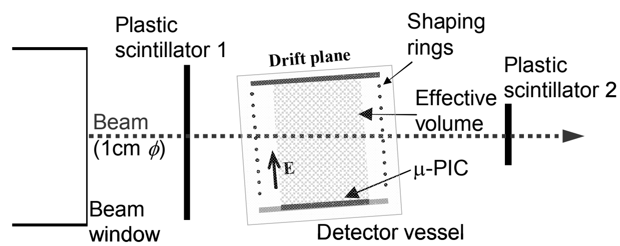

Fig. 3. The experimental setup for beam irradiation tests at HIMAC.

at HIMAC, using procedures similar to those with the large TPC. Figure 3 depicts the experiment setup at the beam line in HIMAC. The detector was horizontally inclined at several degrees in order to evaluate the Z-direction of the beam tracks. The electrons produced by the particle drift to μ-PIC along the electric field, and are multiplied in the neighborhood of the anode pixels. The strip electrodes are connected to Amplifier Shaper Discriminator (ASD) chips with a time constant of 80nsec. The digital signals from the ASD chips are fed to the front-end position-encoding module (PEM) based on five Field Programmable Gate Arrays (FPGAs). The hit positions of the electrodes are encoded as a three-dimensional (3D) image. Thus, the 3D track is reconstructed using the clock information together with the X- and Y-information. To analyze the pulse shape from the anode, all the analog signals from ASDs are summed up into one channel, which is fed to a 100MHz flash ADC (FADC). The energy deposit of each incident particle is obtained from the integrated wave form, using the calibration data. In the experiments in HIMAC, two plastic scintillators are set before/after the TPC to obtain trigger signals to the data acquisition system when a particle passes through them. This type of TPC can, of course, operate using a self-triggering system.

The TPC was filled with a gas mixture of C_3H_8 + 39.6%CO_2 + 5.4%N_2, or of Ar + 10%C_2H_6. The former is a propane-base tissue-equivalent gas, and the latter is a mixture used widely in TPC experiments. A high voltage (1500 to 2500 V) was applied to the drift plane; the distance from the drift plane to μ-PIC was 50mm. The TPC was irradiated with heavy-ion beams of He^{2+} (230MeV/n), C^{6+} (400MeV/n), Si^{14+} (800MeV/n), and Fe^{26+} (500MeV/n) in HIMAC.

3. Results and discussion

Figure 3 depicts a typical result for 3D tracking of He^{2+} beams (230MeV/n) obtained in the tissue-equivalent gas. The image was reconstructed using 50 events of He–ion incidence. The beam used in the experiment was 1cm in diameter, and the obtained image seems to be somewhat wider and scattered. Except for a noise problem, this is mainly due to the straggling of He ions. The result demonstrates approximately the actual incidence position, the direction, and the shape of the beams. Figure 4 plots the energy distribution measured for the He^{2+} beams in the tissue-equivalent gas. Figure 5 plots the distributions of track lengths, and Fig. 6 plots those of the energy deposited in the TPC measured for Fe^{26+} beams (500MeV/n) in Ar+10%C_2H_6. The deposit energy of the particle along the track was also successfully measured (Figs. 4 and 6), while the distributions were considerably wide (30 to

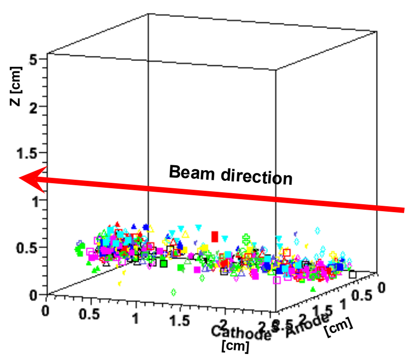

Fig. 3. Reconstructed 3D tracking image for He^{2+} particles (230MeV/n) incident to the TPC filled with propane-based tissue-equivalent gas.

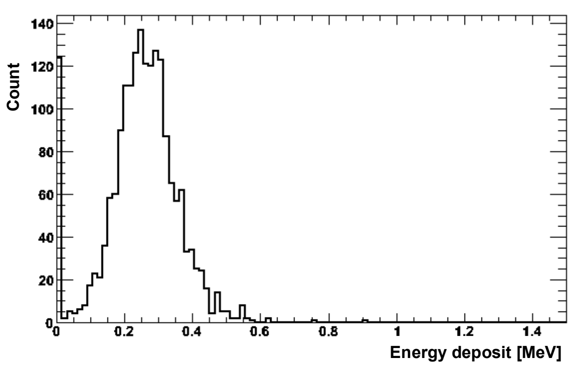

Fig. 4. Distributions of the energy deposited in the TPC obtained for He^{2+} beams (230 MeV/n) in propane-base tissue-equivalent gas.

50%).

Figure 8 summarizes the distributions of LET obtained from the deposit energy and the track length measured for He^{2+} (230MeV/n), C^{6+} (400MeV/n), Si^{14+} (800MeV/n), and Fe^{26+} (500MeV/n) in the propane-based tissue-equivalent gas. The mean value of LET (the moment of distribution) for each particle was compared with the value calculated using the Stopping and Range of Ions in Matter (SRIM) code [6]. The results are plotted in Fig. 9. The dashed line in Fig. 9 indicates where the measured value agrees with the calculated one. The differences are 12% for Fe^{26+}, 6% for Si^{14+}, 30% for C^{6+}, and more than 50% for He^{2+}.

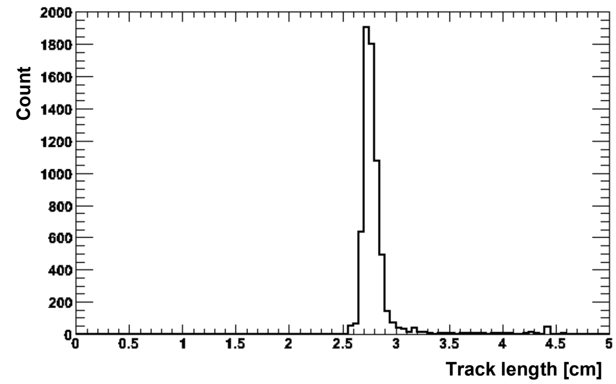

Fig. 5. Distributions of the track length measured for Fe^{26+} beams (500 MeV/n) in Ar+10%C_2H_6.

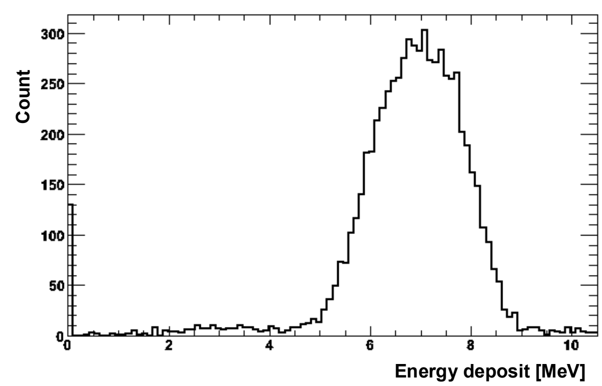

Fig. 6. Distribution of the deposited energy measured for Fe^{26+} beams (500MeV/n) in Ar+10%C_2H_6.

In the measurements, the distributions in the energy and the track length spread because noise was not sufficiently reduced; thus, the LET distribution became wider. Though certain differences in LETs of less than 0.3MeV/n exist between the measurement and the calculation, it may be concluded that the mean values of LET are consistent with the calculated values. In the present study, we could construct a small TPC using tissue-equivalent materials (e.g., plastic, acrylic acid resin, and gas). The results of the performance tests conducted thus far for this tissue-equivalent TPC are also consistent with those obtained with the previous detectors.

The small TPC, as the prototype of PS-TEPC, is basically close to the final form of PS-TEPC used in space. However, the present TPC has several problems to be the final form. The main challenges are to reduce noise and to establish circuit linearity for small energy depositions. In parallel with the improvement of these, the amplifier systems on which hybrid multi-stage low-noise charge-sensitive preamplifiers are mounted are currently being examined. They are directly attached to the μ-PIC readouts in the detector unit to achieve good signal-to-noise ratios. Other circuits (e.g., signal processing, data analysis, and data transmission to the ground) are installed together in the control unit.

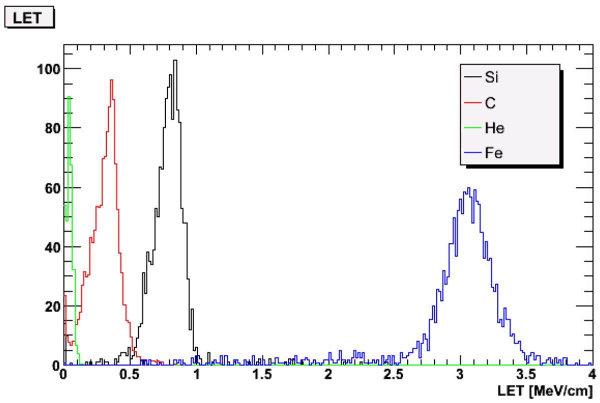

Fig. 8. LET distributions measured for heavy-ion beams in the TPC filled with propane-base tissue-equivalent gas. The distribution corresponds to that measured for He^{2+}、C^{6+}, Si^{14+} and Fe^{26+} in order of increasing LET.

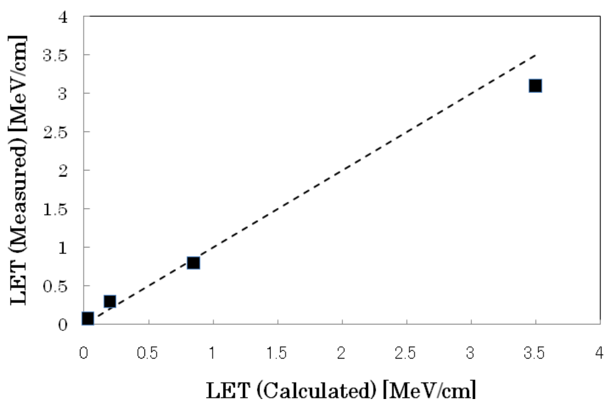

Fig. 9. Mean values of LET measured for heavy-ion beams in the TPC filled with propane-based tissue-equivalent gas plotted as a function of LET calculated using the SRIM code. The data corresponds to that measured for He^{2+}、C^{6+}, Si^{14+}, and Fe^{26+} in order of increasing LET. The dashed line indicates where the measured value agrees with the calculated.

4. Summary

We designed the PS-TEPC, which is based on a TPC using μ-PIC as a 2D position-sensitive detector candidate for the ideal real-time space dosimeter. A prototype PS-TEPC was constructed, and its operational performance was examined by irradiating it with different species of heavy charged particles He^{2+} (230MeV/n), C^{6+} (400MeV/n), Si^{14+} (800MeV/n), and Fe^{26+} (500MeV/n). The 3D tracking of beams was successfully performed for each particle. The beam profiles and track lengths of the particles measured from the tracking data are consistent with those expected from the experiment setup geometry. The LET distributions were obtained from these data, and the results were obtained from measurements of deposit energy. The mean value of LET distribution for each particle was consistent with the value calculated using the SRIM code. This study confirmed that the PS-TEPC is a promising space dosimeter for measuring LET and the deposited energy of the charged particles.

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