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Study of spatial resolution of proton computed tomography using a silicon strip detector

Y. Saraya [a], T. Izumikawa [b], J. Goto [b], T. Kawasaki [a,*], T. Kimura [a]

[a] Graduate School of Science and Technology, Niigata University, Niigata 920-2181, Japan
[b] Radioisotope Center, Niigata University, Niigata 951-8510, Japan

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ABSTRACT

Proton computed tomography (CT) is an imaging technique using a high-energy proton beam penetrating the human body and shows promise for improving the quality of cancer therapy with high-energy particle beams because more accurate electron density distribution measurements can be achieved with proton CT. The deterioration of the spatial resolution owing to multiple Coulomb scattering is, however, a crucial issue. The control of the radiation dose and the long exposure time are also problems to be solved. We have developed a prototype system for proton CT with a silicon strip detector and performed a beam test for imaging. The distribution of the electron density has been measured precisely. We also demonstrated an improvement in spatial resolution by reconstructing the proton trajectory. A spatial resolution of 0.45 mm is achieved for a 25-mm-thick polyethylene object. This will be a useful result for upgrading proton CT application for practical use.

1. Introduction

In proton radiation therapy, the electron density distribution is measured to precisely control radiation dose and position. Nowadays, X-ray computed tomography (CT) is commonly used to measure the image of electron density. However, an error of several percent can occur in calculating the electron density with X-rays owing to the fundamental difference between the way X-rays interact and the way protons interact with electrons. Proton computed tomography (pCT) is a medical imaging technique that uses high-energy proton beams (~ 250 MeV) to penetrate the human body. It is possible to measure the electron density with a precision of less than 1% since translation of the interaction difference is not necessary. Pioneering efforts have been made in the 1980s to demonstrate the ability of pCT [1]. However, the demands on exposure time and spatial resolution could not be met owing to the quality of the proton beam and slow data-taking system. Recently, further refinement of cancer therapy is in high demand. Thanks to the progress of technology for particle measurement and the widespread use of proton therapy, pCT activity started again in the late 2000s [2–7].

We aim to achieve a spatial resolution of less than 1 mm as a target from the viewpoint of medical application. To avoid deterioration of spatial resolution by multiple Coulomb scattering, reconstructing the single proton trajectory is a promising method to collect as much information as possible. Precise position measurement with a low material budget is possible by using silicon strip detectors (SSDs), which were originally developed for particle physics experiments. To employ the method, drastic improvement in the data-taking rate (with the goal of a few megahertz) is, however, necessary to complete the imaging within a reasonable time period (a few minutes). Although radiation detectors and computing electronics have evolved considerably recently, their performances are still not enough to achieve the target speed. Additional data reduction schemes need to be considered. For example, the reduction of the readout channel or the binary readout is one solution, but this seems contradictory to the requirement on spatial resolution. In this study, we have constructed a prototype pCT system and performed a study on how we can reduce the data size while keeping good spatial resolution for CT imaging.

2. Principle of proton CT

For pCT imaging, the position and the energy of a proton penetrating an object are measured. To calculate the energy loss of a high-energy proton in the material, one uses the following Bethe–Bloch formula:

$$\frac{dE}{ds}=\frac{N_A\rho Z 4\pi z^2 e^4}{A\quad m_e c^2\beta^2}\left(\log\frac{2m_e c^2\beta^2}{I(1-\beta^2)}-\beta^2\right) \tag{1}$$

$$\frac{dE}{ds}=n_e(x,y,z)f[I,\beta(E)] \tag{2}$$

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[*] Corresponding author. Tel.: +81 25 262 6124; fax: +81 25 262 6138.
E-mail address: kawasaki@hep.sc.niigata-u.ac.jp (T. Kawasaki).

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where c is the speed of light, m_e the rest mass of the electron, e the elementally electric charge, N_A is Avogardo's number and z the electric charge of an incident proton. Z, A and ρ are the atomic number, the atomic mass and the density of the target material, respectively. Here s is the length of the proton path, $n_e(x,y,z)$ is the electron density of the material traversed by the protons, $f[I,\beta(E)]$ is a function depending on the ionization potential of the material, I, and velocity of the incident proton, β. If the ionization potential is approximately constant in the body, one can use separation of variables as follows:

$$\int_{E_{IN}}^{E_{OUT}} \frac{dE}{f[I,\beta(E)]} = \int n_e(x,y,z)\, ds. \tag{3}$$

E_{IN} is the average energy of the incident protons and E_{OUT} is the average energy of the transmitted protons. This expression means that the integrated electron density along the proton path is provided by measuring E_{IN} and E_{OUT}. The image projected onto the beam direction is reconstructed with the electron density measured and the position information.

The three-dimensional CT image is provided by using the following expressions:

$$n_e(x,y,z) = \int_0^{\pi} \hat{p}(t,z,\theta)\, d\theta \tag{4}$$

$$\hat{p}(t,z,\theta) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left(\int_{-\infty}^{\infty} n_e(x,y,z)\, ds\right)\omega e^{i\omega t}\, d\omega. \tag{5}$$

Here $\hat{p}(t,z,\theta)$ is the image of the integrated electron distribution projected onto the t–z plane when the proton beam is injected into the object with a rotation angle of θ along the z-axis. Therefore, the integrated electron densities from various directions are needed. Essentially, the method is the same as that used in X-ray CT.

3. Experiment

3.1. Experimental setup

We performed the beam test at the HIMAC SB2 beamline, the National Institute of Radiological Sciences (NIRS), Japan. All measurements were done with a proton beam of 160 MeV. The object for imaging is small (~ 25 mm in thickness) in this test. To cover the size of the imaging region, the size of the proton beam was widened to 30 mm in horizontal and vertical directions. Because the data-taking speed of the total system is low, the intensity of the proton beam was reduced. The beam intensity was measured as 20 protons/cm^2/s with trigger counters.

Fig. 1 shows the setup of the test beam. The position of the proton is measured by tracking detectors. Two sets of two-dimensional tracking detectors were placed upstream and downstream of the object, respectively (XZ1 to XZ4). Each tracking detector consists of two strip sensors, whose strips are rotated by 90° to get X and Z position of the proton (for example, XZ1 consists of X1 and Z1 detectors). The sensitive area of each tracker is 4.5 cm in the horizontal direction and 1.5 cm in the vertical direction. The distances between XZ1 and XZ2 and between XZ3 and XZ4 are 10 cm. The object for imaging is situated between XZ2 and XZ3, at a distance of 20 cm. The proton energy was measured with a calorimeter at the most downstream position. Two trigger counters are placed at the most upstream and downstream XZ4.

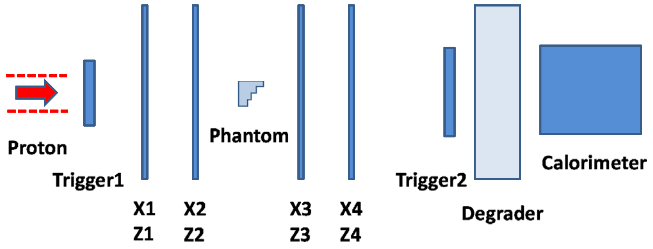

Fig. 1. Test beam setup. Two sets of tracking detectors were placed upstream and downstream of the object. A layer measures two-dimensional information.

As an object for imaging, the phantom was made of polyethylene (density=0.89 g/cm^3). It has a four-step shape as shown in Fig. 2. In this measurement, the phantom was not rotated during the data taking. We do not reconstruct the three-dimensional CT images but reconstruct only the image projected onto the beam direction since the CT imaging requires huge amounts of data. Study of the spatial resolution is done with the projected images

3.2. Tracking detector

The spatial resolution of the pCT image is determined by magnitudes of multiple Coulomb scattering in detector material and the resolution of the position measurement of the tracking detector. Therefore, a thin and precise position detector is adequate. We chose a single-sided silicon strip detector that was developed for high-energy physics experiments [8] as a tracking detector. It has a large area (~ 9 × 9 cm^2) and strip pitches of 228 μm. We read out every second strip to reduce the number of readout strips. The SSD specifications are summarized in Table 1.

The SSD and the front-end LSIs, VA1' [9], in which preamplifier, shaper, and multiplexer for 128 input channels are integrated, are mounted on a printed circuit board. The signal from the SSD is digitized by a data acuisition (DAQ) board (National Instruments) strip by strip so that the analog information from all strips is stored. The data-taking rate is limited up to 5 kHz at the front end and 200 Hz at the data-taking PC owing to the multiplexed readout scheme. Details of the hit reconstruction are described in Section 4.1. Fig. 3 shows a module of the tracking detector we developed.

3.3. Calorimeter

The energy deposited in the object is reconstructed as the difference between the incident proton energy and the measured energy downstream. Proton energy is measured with a downstream calorimeter. The calorimeter must have a resolution as good as the beam energy spread. A 3-in. NaI(Tl) crystal and photomultiplier tube (PMT) were used for the measurement of proton energy downstream. The NaI counter chosen is commercially available and has good resolution to measure proton energy. If the energy is higher than 160 MeV, the proton does not stop within the NaI scintillator and then the energy is not measured correctly. In such case, an acrylic block is placed upstream of the calorimeter to degrade the proton energy.

4. Results and discussion

The events were taken by coincidence of two trigger counters. In total, 2 × 10^5 protons were stored during 4.5 h of data taking. The DAQ rate is around 30 Hz at maximum. The duty cycle of the beam delivery is 1/3. We selected events where the proton penetrates all the SSDs and is stopped in the NaI crystal. The energy measured at the calorimeter is required to be from 87 to 150 MeV.