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Research on output signal of piezoelectric lead zirconate titanate detector using Monte Carlo method

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ABSTRACT

The response of a radiation detector fabricated from piezoelectric lead zirconate titanate (PZT) was studied. The response signal due to a single 400 MeV/n xenon (Xe) ion was assumed to have a simple form that was composed of two variables, the amplitude and time constant. These variables were estimated by comparing two output waveforms obtained from a computer simulation and an experiment on Xe beam irradiation. Their values appeared to be dependent on the beam intensity.

1. Introduction

Lead zirconate titanate (PZT) is a ferroelectric material. It can be actively operated without a power supply because of its piezoelectricity. Moreover, it can be arbitrarily shaped because it is a ceramic material. These properties are advantageous under certain conditions such as when the available electric power and space are limited. In fact, PZT is to be used as a cosmic dust detector on board a satellite around Mercury [1]. In addition, PZT may be useful for a radiation detector because acoustic waves have been detected as an effect of radiation [2–4].

So far, we have studied the characteristics of PZT as a radiation detector using a 400 MeV/n xenon (Xe) beam, supplied by the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences [5]. The performance of the PZT detector has been examined by the following two methods. One is an indirect method; a liquid absorber is excited by the Xe beam and the subsequently generated pressure waves are measured using a set of PZT detectors in the absorber [6–8]. The other method is a direct method; the PZT detector is directly irradiated by the beam and the electric signal appearing on the PZT is measured [9–21]. Moreover, the resonant and antiresonant frequencies of the PZT detector, which acts as a resonator, have been measured [22,23].

We are interested in the contribution of a single Xe ion to the formation of the output voltage to clarify the quantitative relationship between the energy supplied to PZT and the output signal appearing on the PZT. In our previous studies, therefore, the output voltage appearing on the PZT detector was quantitatively discussed through the direct method. Possible effects due to time and spatial conditions were discussed by adjusting the pulsed beam parameters using a beam chopper [16] or collimators [20,21]. However, the mean time interval between ions was less than 1 μs in these experiments. In this study, the formation process of the output signal was examined for the case that the interval is more than 1 μs by comparing measured values and values calculated by Monte Carlo simulation. The results obtained are anticipated to help establish a signal formation mechanism for the PZT detector.

2. Experimental setup

Fig. 1 schematically shows the experimental configuration. The 400 MeV/n Xe beam was supplied by HIMAC. The beam was extracted for ~0.6 s (duration) every ~3 s (period) and the beam diameter was ~4 mm at the detector. The beam intensity was varied from 1.0×10^3 to 1.0×10^5 particles per spill (pps). Note that the Xe ions were not uniformly distributed over the ~0.6 s. The number of Xe ions contained

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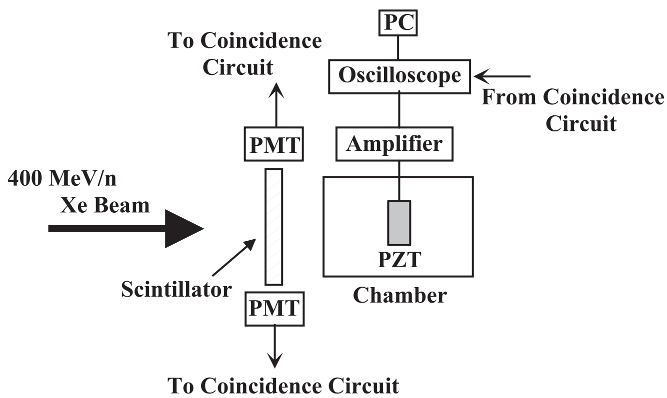

Fig. 1. Schematic of experimental configuration, where the photomultiplier is indicated as PMT and the personal computer is indicated as PC.

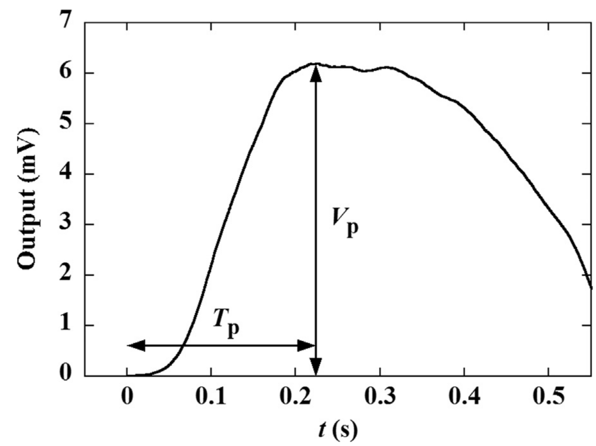

Fig. 2. Typical output signal obtained from PZT detector, which was processed to eliminate noise.

in the spill is denoted as *N*. The beam irradiated on the PZT detector was monitored using a 1-mm-thick plastic scintillator viewed with two photomultipliers (PMTs), which were placed ~700 mm downstream of the exit of the beam duct. The two signals obtained from the PMTs were transferred to a coincidence circuit. The time distribution of Xe ions within a spill of ~0.6 s was estimated by coincidence counting between the PMTs. The coincident time was registered on a digital oscilloscope event by event. The series of coincident times was regarded as the time distribution of incident ions. The detector was a PZT disk whose diameter and thickness were 10 mm and 8 mm, respectively. The PZT disk was polarized in the thickness direction, to which the Xe beam was incident. The front and back surfaces of the disk were entirely covered with a silver (Ag) electrode of ~5 µm thickness. The Ag electrode on the front surface where the Xe beam was incident was grounded. Since the range of 400 MeV/n Xe ion in PZT was estimated to be slightly less than 8 mm using the Bethe–Bloch formula, the thickness of 8 mm was reasonable for confining the Xe ions within the detector. A frame made of epoxy resin supported the PZT detector. The frame was suspended from four springs to prevent noise arising from mechanical disturbances. Moreover, to eliminate noise originating from the variation in atmospheric pressure, the PZT detector was set in a closed chamber. The chamber, which was made of transparent acrylic resin to enable visual confirmation of the alignment, was placed ~135 mm downstream of the scintillator. The output voltage between the two electrodes was processed using a charge-sensitive amplifier and then transferred to the digital oscilloscope.

3. Results and discussion

In this study, to increase the mean time interval between ions, *N* was set to 1.0×10^3, 3.0×10^3, 7.0×10^3, 1.0×10^4, 3.0×10^4, 7.0×10^4, and 1.0×10^5. Fig. 2 shows the typical output signal observed from the PZT detector when *N* was 3.0×10^4. Note that the output waveform was processed to eliminate the noise. Here, the magnitude of the output obtained during one spill was regarded as the zero-to-peak value (V_p) of the waveform and the time at which V_p appeared was denoted as T_p, as indicated in Fig. 2. In addition, the number of Xe ions contained during T_p was defined as N_p.

The values of V_p, T_p, and N_p were examined while varying *N* from 1.0×10^3 to 1.0×10^5. Fig. 3 shows the parameters estimated from the output waveforms obtained, where (a) shows the relationship between T_p and N_p and (b) shows that between V_p and N_p. Note that the values of N_p are averaged over all events and the horizontal error bars indicate 1σ deviations. It can be seen from Fig. 3(a) that T_p was between ~0.2 s and ~0.23 s regardless of the value of N_p. On the other hand, it can be seen from Fig. 3(b) that V_p increased with increasing N_p. The correlation coefficient between the measured values shown by closed circles and the approximate linear expression was ~0.99. This result

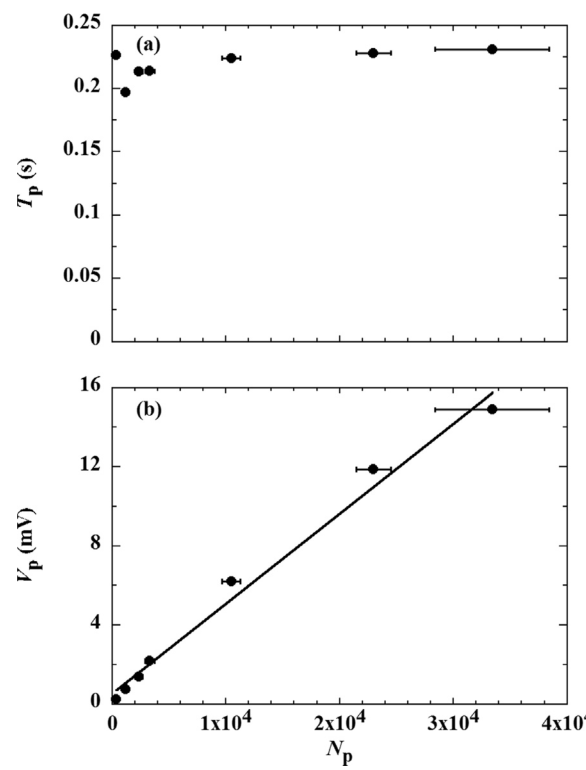

Fig. 3. Dependences of (a) T_p and (b) V_p on N_p.

suggests that the response to one Xe ion incidence reflected the formation of the output waveform within the limits of the experimental conditions.

We therefore assumed that the response function due to a single Xe ion observed at time *t* on the PZT detector had the form $A\exp(-\Delta t/\tau)$. This form means that an electric charge appearing on the detector is damped at a rate depending on the circuit constant, which is considered to be determined by the physical properties of the PZT and the performance of the amplifier used. Here, *A* and τ represent the amplitude and decay time of the output signal, respectively, which are to be determined by numerical computation, and Δt is a time factor described as follows. Let t_i be the time of the *i*th incident ion and *t* be the time at which the signal is observed, then $\Delta t_i = t - t_i$ is the time elapsed after the *i*th incident ion. Accordingly the summation of $A\exp(-\Delta t_i/\tau)$ with *i* ranging from 1 to *N* represents the output signal at time *t*. The time distribution of incident ions during one spill was integrated