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Response of piezoelectric lead zirconate titanate detector to oblique impact with hypervelocity iron particles

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A cosmic dust detector using piezoelectric lead zirconate titanate (PZT) is currently being developed for use onboard a spacecraft for the BepiColombo mission. The characteristics of the PZT detector were studied by carrying out hypervelocity impact measurements with iron particles supplied by a Van de Graaff accelerator. The measurements with particle velocities of less than 5 km/s showed a linear relationship between the output voltages obtained from the detector and the particle momenta. This linear relationship obtained was almost independent of the impact angle between the particle and the PZT surface.
Key words: Cosmic dust, dust detector, piezoelectricity, lead zirconate titanate (PZT), Mercury Dust Monitor (MDM).

1. Introduction

The aim of the BepiColombo mission is to explore Mercury (Hayakawa *et al.*, 2004). We have proposed the use of a Mercury Dust Monitor (MDM) onboard the Mercury Magnetosphere Orbiter (MMO) to clarify the dust environment around Mercury. The MDM will carry out in situ measurements of dust particles in the inner solar system (0.31–0.47 AU) for more than 1 year. It is expected that these measurements will enable the fluxes of low-eccentric Keplerian dust particles and β meteoroid particles to be determined. In addition, an effect of size shift by dust-dust collision in the neighborhood of Mercury may be estimated from the data observed. Since the MMO will be orbiting around Mercury, the information on the inflow of dust particles onto the surface of Mercury may also be useful in improving our understanding of the processes of space weathering and the formation of the tenuous atmosphere of Mercury.

We have been developing a cosmic dust detector using a lead zirconate titanate (PZT) target for use onboard the spacecraft (Miyachi *et al.*, 2003, 2004, 2005a, b, c). PZT is a piezoelectric ceramic. As such, it can be operated without a power supply, and it can be easily set up in arbitrary shapes. To implement measurements of cosmic dust parameters, such as mass and velocity in space, we carried out a series of test measurements with accelerated cosmic dust analogues using the Van de Graaff accelerators at the University of Tokyo and the Max-Planck-Institut für Kernphysik (MPI-K), Heidelberg.

The results obtained to date on the hypervelocity impact of particles are as follows (Miyachi *et al.*, 2005a, b, c). The output signals obtained from the PZT element immediately after the impact appear to have a waveform that is explicitly related to the particle velocity before impact. For velocities less than approximately 6 km/s, the signal was formed as an oscillation pattern, and the amplitude was proportional to the particle momentum of the impacting particle. For larger velocities, the signal gradually changed to a single waveform. The rise time of the single waveform was linearly related to the particle velocity for velocities above approximately 6 km/s. However, we have been unable to theoretically explain the production mechanism for the different waveform patterns emerging from the PZT element. In addition, from a practical point of view, an empirical formula to determine the particle's momentum and/or velocity from the detector signal is urgently required.

The PZT sensor, which is installed on the surface of a side panel of the MMO, will be bombarded with dust particles coming from various directions. Therefore, the effects of the impact angle between the PZT surface and the dust particles on the behavior of the sensor must be examined in order to develop the empirical formula. In this study, the characteristics of the PZT detector were investigated through collisions with iron (Fe) particles while changing

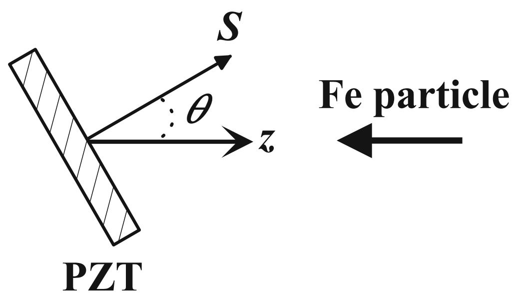

Fig. 1. Definition of θ as angle of collision.

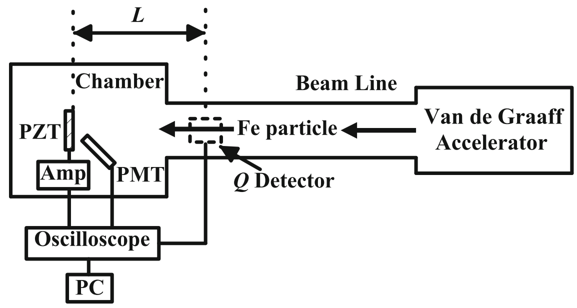

Fig. 2. Schematic view of experimental configuration. Here, the photomultiplier is indicated as PMT, the amplifier as Amp, and the personal computer as PC.

the angle of incidence (θ) between the PZT surface and the particles. The angle θ between the z axis and the normal S to the PZT surface is shown in Fig. 1. For estimating θ, we assumed that the incident direction of Fe particles was $-z$.

In this paper, we concentrate on the measurement with the impact velocities within approximately 6 km/s, in which case the amplitude of the signal appearing on the PZT sensor will be correlated with the momentum of the impact particle. The results presented are considered to be useful for the calibration of our cosmic dust detector. Note that the report concerning the impact velocities above approximately 6 km/s will be published elsewhere.

2. Experimental Setup

The experimental configuration is schematically shown in Fig. 2. Fe particles, supplied by the Van de Graff accelerator at MPI-K, were used to simulate cosmic dust. In this experiment, the Fe particles were accelerated with an acceleration voltage (U) of 2 MV. The charge (q) of the particles was determined by the induced voltage (V_Q) at the Q detector, which was installed in the beam line, that is, $q = C_Q V_Q$ (here, C_Q is the electrostatic capacitance of the Q detector, 0.147 pF). The PZT element used has a square shape with sides of 20 mm and a thickness of 1 mm. Silver electrodes of a thickness of a few microns were coated onto both flat surfaces of the element. The PZT detector was polarized in the direction normal to the flat surface. The detector was supported by a frame consisting of epoxy resin. The frame was suspended on four springs in order to prevent noise arising from mechanical disturbances. The PZT detector was placed at a distance of 91 cm downstream from the Q detector (L). The chamber, in which the PZT detector, an amplifier, and a photomultiplier were set, was maintained at a pressure of approximately 10^{-6} Torr.

Using a photomultiplier (PMT), the light emitted upon impact was detected and used as a time reference (T_L). When T_Q was the time at which the signal of V_Q appeared at the Q detector, the velocity of the Fe particle (v) was determined by $v = L/(T_L - T_Q)$. Consequently, the mass of the particle (m) was estimated from $mv^2/2 = qU$. The signal obtained from the PZT detector was processed using an amplifier (Amp). Each signal obtained from the Q detector, the PMT, and the PZT detector was transferred to a digital oscilloscope. Digitally processed data were stored in a personal computer.

Figure 3 shows the signals of a typical event, where (a) is the signal obtained from the Q detector, (b) is the signal from the PMT and (c) is the signal from the PZT detector. In this case, the parameters of the Fe particle were as follows: $q \sim 0.08$ pC, $v \sim 3.3$ km/s, and $m \sim 29$ pg; thus, the momentum $p = mv$ was ~96 pg km/s. It was also observed that the signals at the PZT detector appeared simultaneously with the light flashes.

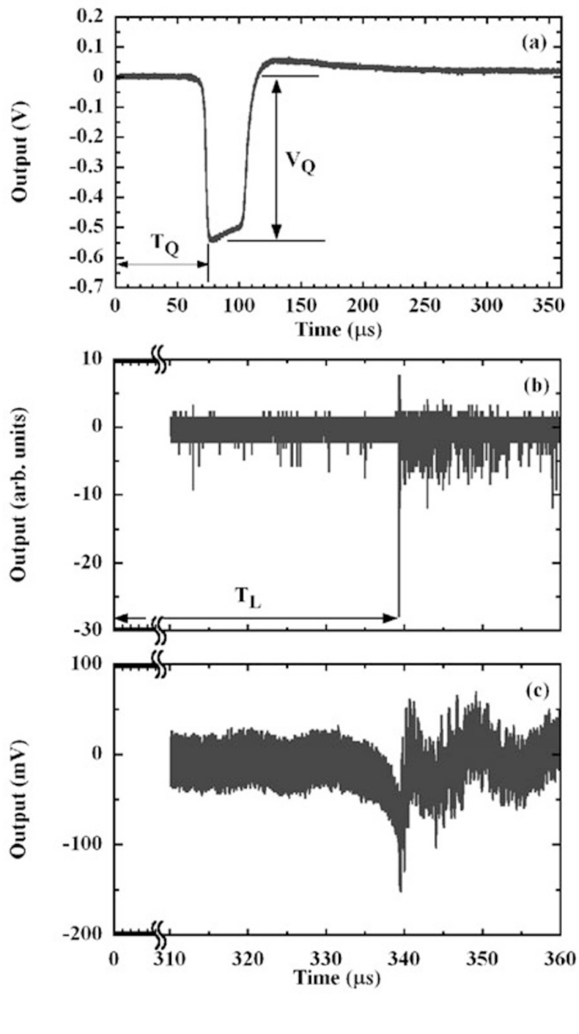

Fig. 3. Typical output signals observed from (a) Q detector, (b) PMT, and (c) PZT detector.

3. Results and Discussion

We investigated the response of the PZT detector to impacts of Fe particles with velocities between 3 and 5 km/s

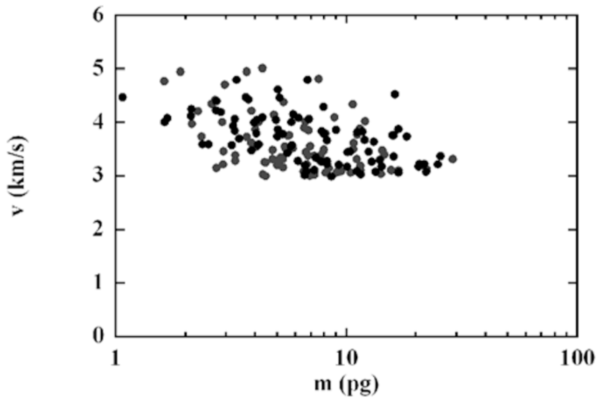

Fig. 4. Distribution of mass versus velocity of Fe particles.

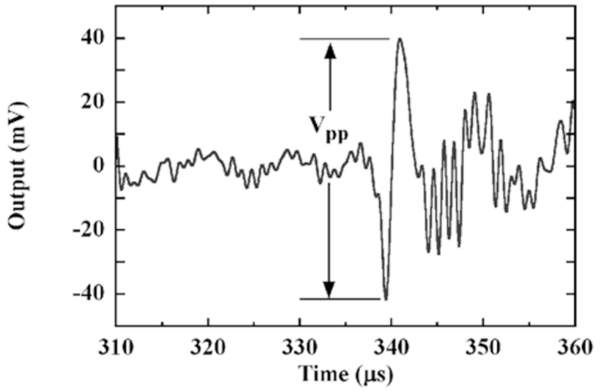

Fig. 5. Output waveform obtained from PZT detector, reconstructed by inverse Fourier transformation, when the velocity of the Fe particles was ∼3.3 km/s, the mass was ∼29 pg, and the angle of collision was 0°. Only frequency components from 100 kHz to 1 MHz were used.

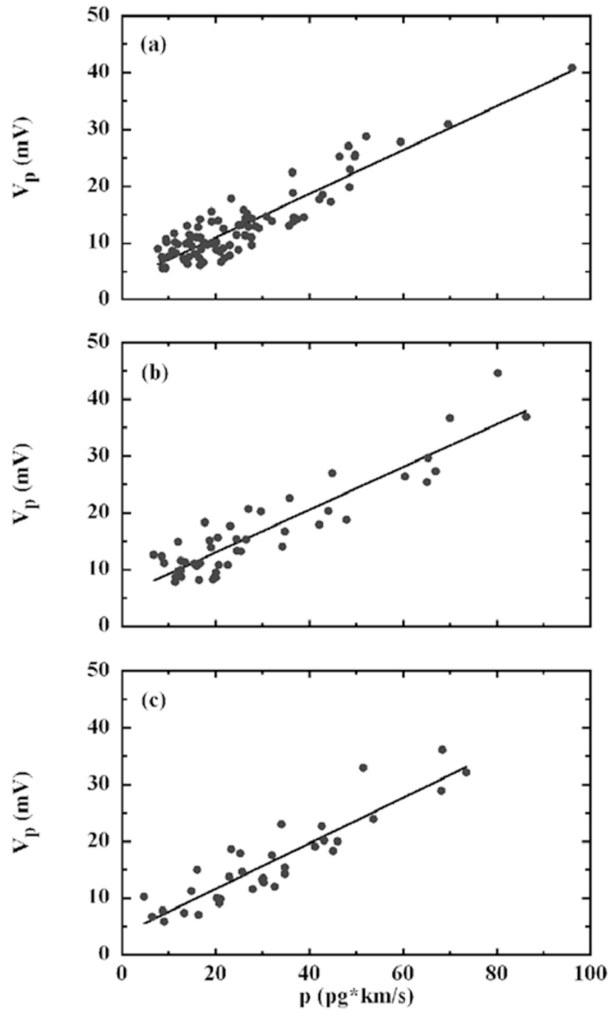

Fig. 6. Dependence of V_p obtained from PZT detector on p of Fe particles when θ was (a) 0°, (b) 30° and (c) 60°.

and incident angles of 0°, 30°, and 60°. Figure 4 shows the distribution of the mass versus the velocity of the Fe particles used in this experiment. The range of m was from 1 to 30 pg, and the range of v was from 3 to 5 km/s. We considered that this range of v corresponds to the following case: the output signal obtained from the detector immediately after the collision was in the form of an oscillation pattern, and the amplitude was proportional to the particle momentum.

In previous studies (Miyachi *et al.*, 2005a, b, c), the dependence of the waveform obtained from the PZT detector on v was estimated in terms of Young's modulus (E) of PZT. According to this estimation, it was considered that PZT underwent a stress $\sigma < E$ due to an impact with a Fe particle at a velocity below ∼5 km/s. Under the condition $\sigma < E$, the state of PZT was expected to be predominantly elastic.

It can be seen from Fig. 3(c) that the output signal contained a noise component. To eliminate the noise signal, the signals observed from the PZT detector were processed by inverse Fourier transformation using frequency components from 100 kHz to 1 MHz. Figure 5 shows the resulting waveform obtained from the PZT detector for an impacting particle with mass $m \sim 29$ pg, impact velocity $v \sim 3.3$ km/s, and impact angle $\theta = 0°$. The peak-to-peak value of the output signal V_{pp} is indicated in the figure.

Figure 6(a) shows the relationship between the signal amplitude V_p obtained from the PZT detector and the momentum of the Fe particles p for $\theta = 0°$. Here, V_p is defined as $V_{pp}/2$. Note that there was difference between the peak value in a positive direction and that in the negative one for many of the impact events evaluated. It can be seen that there is a linear relationship between V_p and p. When least-squares fitting is applied to the data in Fig. 6(a), the slope of the solid line is ∼0.39. Figures 6(b) and 6(c) shows the relationships between V_p and p for $\theta = 30°$ and 60°, respectively, which confirm the linear relationship between V_p and p regardless of the angle of collision. Similarly, when least-squares fitting is applied to the data in Figs. 6(b) and 6(c), the slopes of the solid lines are found to be ∼0.38 and ∼0.40, respectively. That is, the two slopes are almost the same as that observed for $\theta = 0°$. This implies that the linear relationship between V_p and p is almost independent of the angle of collision of the particle, suggesting that the particle momentum can be inferred from the signal amplitude observed from the PZT detector without further accounting of the impact angle of the particle—provided that the particle velocity is less than 5 km/s and the impact angle is smaller than 60°.

In addition, the two correlations between the V_p and the kinetic energy $K = mv^2/2$ of the impact particle and between the V_p and the dynamic pressure $D = \rho v^2/2$ (ρ is the mass density of Fe, ~7.86 g/cm^3) of the impact particle were also studied. Although a linear relationship between V_p and K did exist, the correlation coefficient was smaller than that obtained between V_p and p. On the other hand, there was no linear relationship between V_p and D. These results suggest that the mass (or size) played an important role in the production mechanism of the acoustic signal in piezoelectric PZT within the limits of the experimental conditions. However, we are still unable to explain theoretically the proportionality of the signal amplitude of V_p obtained from the PZT detector to the momentum of the particle on impact when the impact velocity is less than 5 km/s, or the reason why not only the momentum parallel to the polarized direction in PZT but also the momentum perpendicular to that contribute to the output signal. Therefore, it is necessary to study which parameters determine the output signal that appeared on PZT with the hypervelocity impact from both experimental and theoretical viewpoints. In addition, from a practical point of view, it is necessary to establish an empirical formula for determining the particle parameters using the output signal obtained from the PZT detector by analyzing more experimental data acquired over a wider range of impact velocities.

4. Conclusions

We investigated the characteristics of our PZT detector upon hypervelocity impacts of Fe particles with impact angles of 0°, 30°, and 60°. The relationship between the output voltage obtained from the PZT detector and the momentum of the Fe particles was studied for impact velocities 3–5 km/s. We found that the relationship between the above two physical quantities was linear and almost independent of the angle of collision. To complete the practical cosmic dust detector using PZT, the piezoelectric effect must be further examined over an extensive range of particle impact velocities. Further investigation is also required to determine the production mechanism of the signal generated from piezoelectric PZT.

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