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Depth of interaction measured with LYSO (Ce) scintillator in a new method

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Abstract

The importance of the information concerning the depth of interaction (DOI) in a PET device has been stressed by many authors. In this paper, the attenuation of the emitted light in a thin LYSO (Ce) scintillator crystal has been measured for the purpose of obtaining information about DOI from the ratio of the light output measured at both ends of the crystal. A pair of photomultipliers were attached to the two ends of the crystal for this purpose. An array of wave-length shifters (WLS) attached to the crystal from a side was used in order to find the hit point of the incident gamma rays along the crystal. The attenuation constant μ determined in this measurement is $\mu = 0.79 \pm 0.0007$ / cm. This value is experimentally demonstrated to be appropriate for the DOI estimation using the ratio of the amounts of light. The obtainable DOI resolution, when the crystal is read out using WLS and a new kind of position-sensitive photomultipliers in our next prototype, is estimated.

Index terms: Depth of interaction (DOI), positron emission tomography (PET), scintillation detector.

1. Introduction

The spatial resolution of the PET imaging device has reached nearly 1 mm [1], [2] at the center of the field of view (FOV). However, at distant points in the FOV from the center, the resolution becomes worse [1]. The main reason for that phenomenon is the finite thickness of the scintillator crystals. The lack of information on the depth of interaction (DOI), namely the lack of information as to where in a scintillator crystal the gamma ray has emitted the light, makes the definition of the β^+ annihilation vertex ambiguous. Thus to improve further the spatial resolution of the PET device, the acquisition of the DOI information is important [3].

Many trials have been reported with a view to obtaining reliable DOI information, for example, by combining scintillators with different decay times in a block. In that case, the measurement of the decay time in an event of the scintillators yields the DOI information.

Recently LYSO (Ce) scintillator crystal has come into use [4]. Its high effective-Z (66.4) and large density (7.1 g/cm^3) allow to use relatively thin crystals. In fact, according to a simulation using EGS [5], a 20 mm-thick crystal can stop almost 70% of 511-keV gamma rays. This means when this scintillator is used, a relatively coarse DOI information already allows good geometrical reconstruction.

Also it was found that this crystal has a relatively large light attenuation. This characteristic, unfavorable in general point of view, provides a possibility, on the other hand, to provide with a fairly good information about DOI, when the light output is measured at both ends of the crystal. The readout system needed for this new method, although classical in the field of nuclear physics, is simpler than that with the decay-time discrimination.

Naturally the precision of the above-mentioned light-amount method depends on the amount of light one can obtain. The statistical fluctuation of the number of photoelectrons detected dominates the precision.

In our method of scintillation light read-out using a wave-length shifter (WLS), the total amount of light one can obtain is rather limited. The motivation of the present study is to find out experimentally how much precision in DOI information one can obtain for a given amount of light output by the above-mentioned method.

The LYSO crystal of size 1 mm × 1 mm × 20 mm which we are using for the PET prototype was used in this study. Also for the definition of the light-emission point in the crystal, the WLS we use for the prototype was employed.

2. Experimental setup and method

A. Detector setup

Fig. 1 shows schematically the experimental setup used. A LYSO (Ce) crystal of size 1 mm × 1 mm × 20 mm was irradiated sideways by 511 keV gamma rays emitted from a ^{22}Na radioactive source. The source is a bead with a diameter of 1 mm which was placed at 5 cm from the

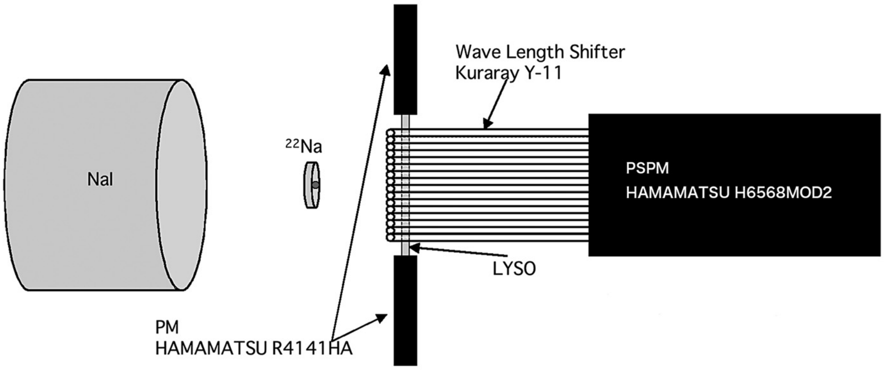

Fig. 1. Experimental setup.

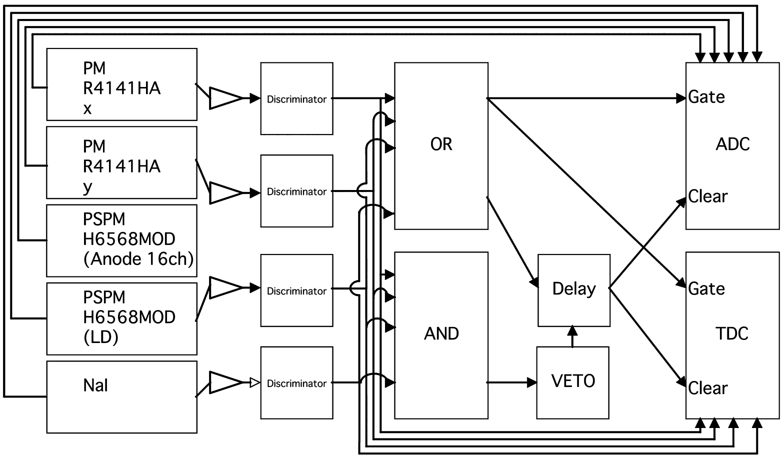

Fig. 2. Block diagram of data acquisition system.

crystal. The two ends of the crystal are connected to two Hamamatsu R4141HA photomultipliers (PM) using optical grease. To avoid the effect of natural radioactive isotope of ^{176}Lu contained in the crystal, a large NaI (Tl) crystal placed on the opposite side of the radioactive source detects the gamma ray emitted in coincidence. To determine the hit point of the gamma ray along the long crystal, an array of 16 Kuraray Y-11 double-clad wave-length shifter is attached to the crystal from a side as shown in the figure. The signals from the WLS were read out with 16 channel Hamamatsu H6568MOD2 position-sensitive photomultiplier (PSPM). The WLS has a cylindrical shape with a diameter of 1 mm. The array of the WLS was just pressed to the central part of the crystal.

B. Electronics and data acquisition system

The last dynode signal from the H6568MOD2 PSPM provided us with the sum of all the WLS

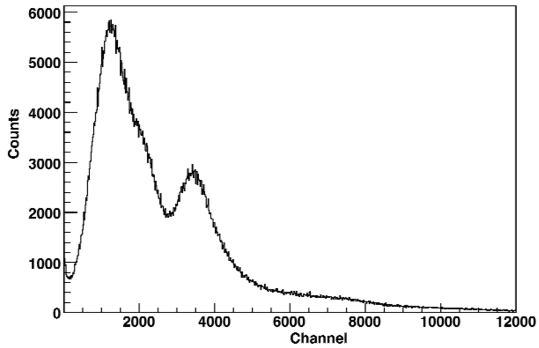

Fig. 3. Pulse height distribution of R4141HA PM.

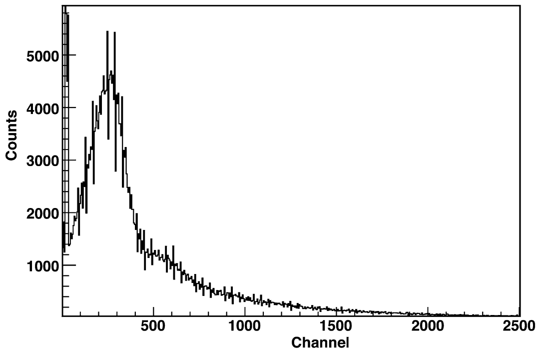

Fig. 4. Typical pulse height distribution of WLS.

signals. The trigger signal was formed with the signals from two R4141HA PM signals, the H6568MOD2 last-dynode signal and the signal from the NaI crystal. All the output pulses were also read with Hoshin C009-H 14 bit charge-sensitive ADC. Also the timing of all the signals were recorded with Phillips 7187 TDC after the discriminator.

The gate signals to the ADCs are formed with the coincidence signal of two R4141HA PM's only to avoid large delays needed for the H6568MOD2 anode signals. As the trigger signal comes later, the ADC input signals without the trigger signal were cleared.

3. Experimental results and analysis

Fig. 3 shows the pulse height distribution of PM (R4141HA) mounted on the ends of the crystal. One can notice a photo-absorption peak on the higher channel side, and a larger peak corresponding to the Compton scattering. All the events displayed in this figure were used for the further analysis.

Fig. 4 shows the typical pulse-height spectrum observed on one of the WLS. The hit point of

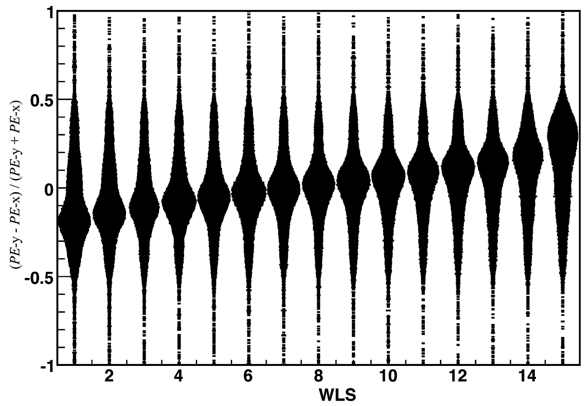

Fig. 5. 2D histogram of factor *f* (vertical axis) versus hit point (horizontal axis).

the gamma ray along the crystal was determined with the WLS signal.

When multiple WLS fired, the WLS providing with the largest signal is considered as the one pointing to the hit point. According to a simulation assuming perfectly flat and parallel surfaces for the scintillator crystal, the average multiplicity of the WLS's which fire is about 2. In reality, the multiplicity measured was 5. However, when the multiplicity was higher than 1, the largest pulse height seen in one WLS is usually more than 3 times larger than in other WLSs. Thus the determination of the hit point along the crystal is rather straightforward.

The pulse heights from the two PMs (R4141HA) have been roughly normalized. They are denoted by *PE*-x and *PE*-y. Fig. 5 shows the population of events as a function of hit point along the crystal (horizontal axis) and the quantity defined as

$$f = (PE\text{-y} - PE\text{-x}) \;/\; (PE\text{-y} + PE\text{-x}), \qquad (1)$$

(vertical axis). When the hit point is between the outermost WLS and the ends of the crystal, almost all the events yield maximum pulse height in the outermost WLS, and thus these WLSs count many more times than others. For that reason, those two WLSs are dropped from the histogram.

Fig. 6 shows a histogram of *f* at one hit point (WLS = 8). This is just a vertical slice of the histogram shown in Fig. 5. One can see that this shows a clear single peak despite the fact that the raw pulse height shown in Fig. 3 has a structure.

This histogram was fitted with a gaussian, and the peak position as a function of hit point

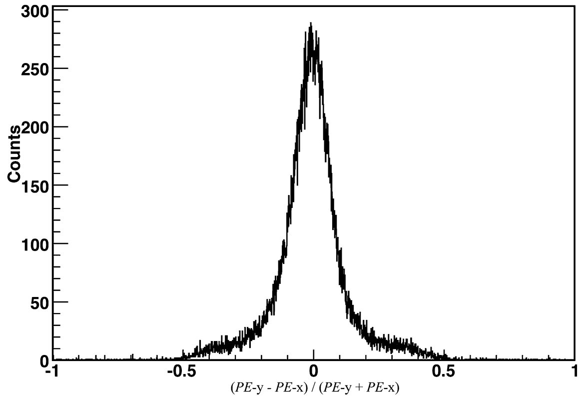

Fig. 6. Vertical slice of the 2D histogram shown in Fig. 5 at the center of scintillator crystal

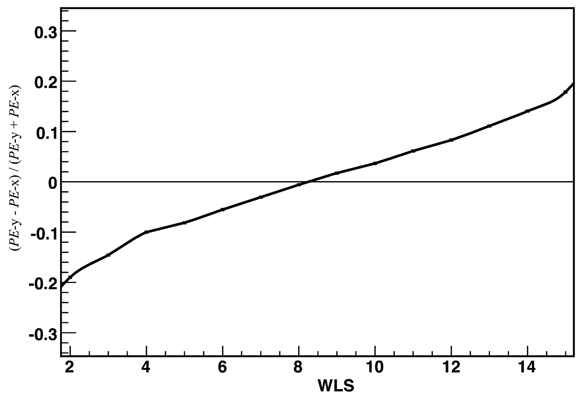

Fig. 7. Peak positions of vertical slices of the 2D histogram of Fig. 5 at each WLS point. The vertical slices are fitted with a gaussian.

(WLS) is displayed in Fig. 7. The inclination of this curve at the center can be considered to give the average attenuation factor *m* of the light in the crystal, and the extracted value from the data is $\mu = 0.79 \pm 0.007$ / cm.

Although in general, a smaller attenuation is preferable for a scintillator crystal, this relatively large attenuation allows us to measure the DOI relatively easily from the ratio of the pulse height measured at the ends of a crystal, as was mentioned previously.

Figs. 8 and 9 show now the horizontal slice of the histogram shown in Fig. 5 and these show how much DOI resolution we can obtain from the measure factor *f*. The resolution is worst when $f = 0$ (near the center). The RMS of the peak is about 2.34 mm. The histogram shown in Fig. 8 is a slice of Fig. 5 at $f = 0.017$. The maximum of the population corresponds to WLS = 2, namely 55

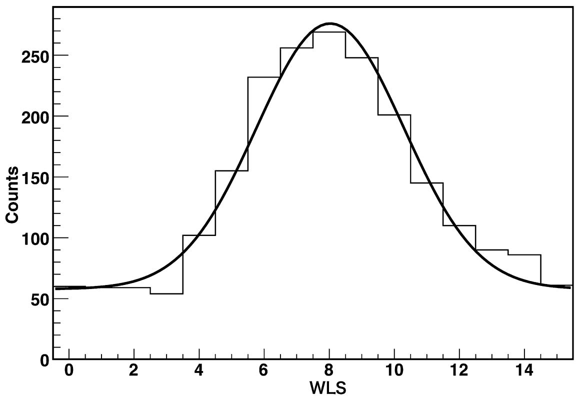

Fig. 8. Horizontal slice at $f = 0$ of the 2D histogram shown in Fig. 5.

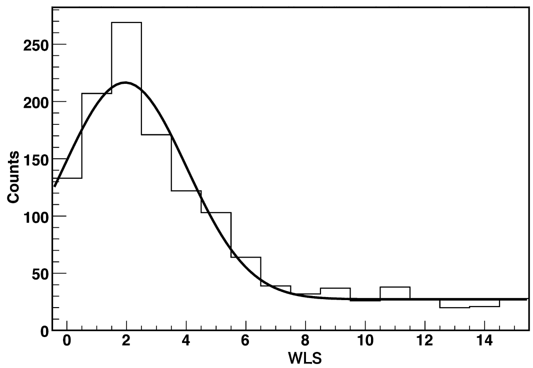

Fig. 9. Horizontal slice at $f = 0$ of the 2D histogram shown in Fig. 5.

mm from the center. The RMS of the peak is about 2.30 mm. Fig. 10 summarizes the result. The vertical scale indicates the estimated hit position (DOI) where the center is 0 (unit: mm). The vertical error bars indicate the RMS of the peak at each value of f.

It is important to know how much light has been recorded on each R4141HA PM in this measurement. To measure this, the PM was replaced temporarily by a H6568MOD2 PSPM. This PSPM has a special characteristics to show very clearly the single photoelectron peak. By measuring the amount of light in an unsaturated condition, and comparing the averaged position of the peak of the histogram constructed for the amount of light with the position of the single photoelectron peak observed, one can easily estimate the number of photoelectrons. The estimated number of photoelectrons recorded on the PSPM's (H6568MOD2) was about 80.

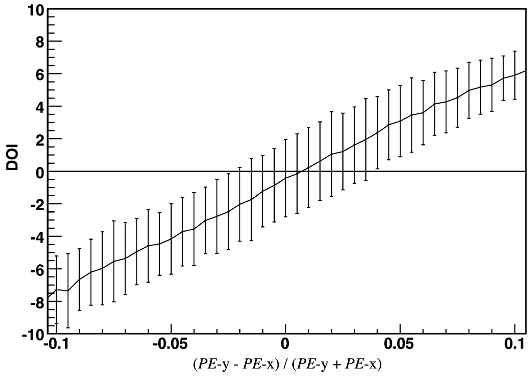

Fig. 10. Peak positions of horizontal slices of the 2D histogram of Fig. 5 at every 0.05 point of *f*. The horizontal slices are fitted with a gaussian. The vertical scale is the estimated hit position (DOI), where the unit is mm and 0 indicates the center of the crystal.

4. Conclusion

It was experimentally shown that LYSO (Ce) crystal of size 1 mm × 1 mm × 20 mm shows a fairly large attenuation of the light inside, as large as $\mu = 0.79 \pm 0.007$ / cm. This large attenuation, however, gives a good DOI information when the light output of the crystal is measured at both ends. In our study where a matrix of small crystals bundled are read out with parallel WLS arrays at both ends of the pads.

Acknowledgment

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