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Development of high-resolution detector module with depth of interaction identification for positron emission tomography

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ABSTRACT

We have developed a Time-of-flight high resolution and commercially viable detector module for the application in small PET scanners. A new approach to depth of interaction (DOI) encoding with low complexity for a pixelated crystal array using a single side readout and 4-to-1 coupling between scintillators and photodetectors was investigated. In this method the DOI information is estimated using the light sharing technique. The detector module is a $1.53 \times 1.53 \times 15\ \text{mm}^3$ matrix of 8×8 LYSO scintillator with lateral surfaces optically depolished separated by reflective foils. The crystal array is optically coupled to 4×4 silicon photomultipliers (SiPM) array and readout by a high performance front-end ASIC with TDC capability (50 ps time binning). The results show an excellent crystal identification for all the scintillators in the matrix, a timing resolution of 530 ps, an average DOI resolution of 5.17 mm FWHM and an average energy resolution of 18.29% FWHM.

1. Introduction

Dedicated positron emission tomography (PET) is an active area of research. Scanners with smaller ring radius have higher sensitivity, lower cost and smaller photon noncollinearity effect. Small animal PET Scanners require a spatial resolution of around 1 mm and a sensitivity of 5% or better. However, in small scanners there is a compromise between sensitivity and spatial resolution due to the depth of interaction (DOI) effect. Longer crystals means higher sensitivity. But, the spatial resolution of the scanner can be degraded by parallax error. Therefore, having the DOI information is key to improve the trade-off between sensitivity and spatial resolution. Various DOI encoding techniques have been studied including multi-layer crystals [1], double side readout of scintillator arrays [2] and light sharing encoding detectors [3–5]. The main drawbacks of these methods are the complexity and hence the cost. In this paper we propose a new method to obtain DOI information based on light sharing for highly pixelated scintillator array readout only from a single side with a silicon photomultiplier (SiPM) with excellent crystal identification, good energy and timing resolution without the need for one-to-one coupling between crystals and detectors.

2. Materials and methods

The DOI method in this work is based on light sharing together with the attenuation of light along the length of the crystals by means of a depolishing of lateral sides of the scintillators. The concept is illustrated schematically in Fig. 1. When a gamma ray interacts in a given scintillator pixel, the produced photons propagate through that crystal pixel and exit from both the coupled side to SiPM and the opposite side. Optically coupled to this opposite side is a light guide with the same external dimension of

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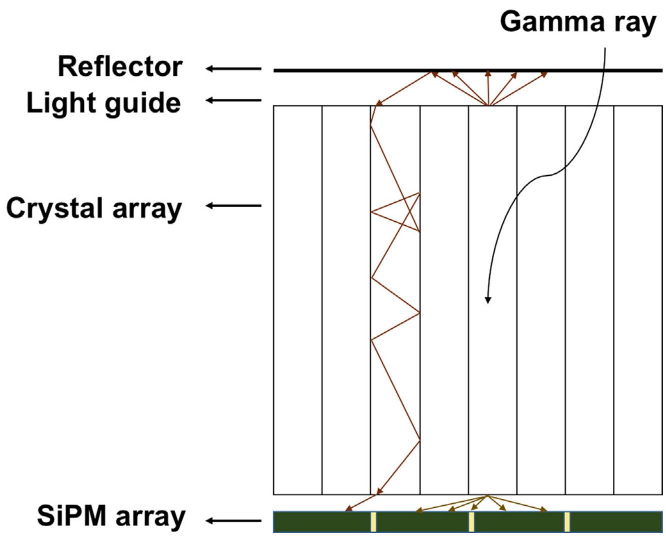


Fig. 1. Schematic representation of the DOI encoding method.

the crystal matrix, which is out covered by a reflective foil preventing light from escaping from the crystal redirecting it to MPPC instead. The ratio of the light at both ends depends on the interaction position of the gamma ray along the crystal. For each scintillation event in the crystal pixel with physical position in x–y plane x_i and y_i, the produced light is spread over multiple photodetectors. The crystal identification is based on the weighted average energy method to compute the coordinates U and V

$$U = \frac{1}{E}\sum_i^N E_i x_i \quad \text{and} \quad V = \frac{1}{E}\sum_i^N E_i y_i \tag{1}$$

where E_i is the energy deposited in the i-th detector, N is the total number of detectors and E is the sum of the energies collected by all the detectors

$$E = \sum_i^N E_i \tag{2}$$

The DOI variable is defined as

$$W = \frac{E_{max}}{E} \tag{3}$$

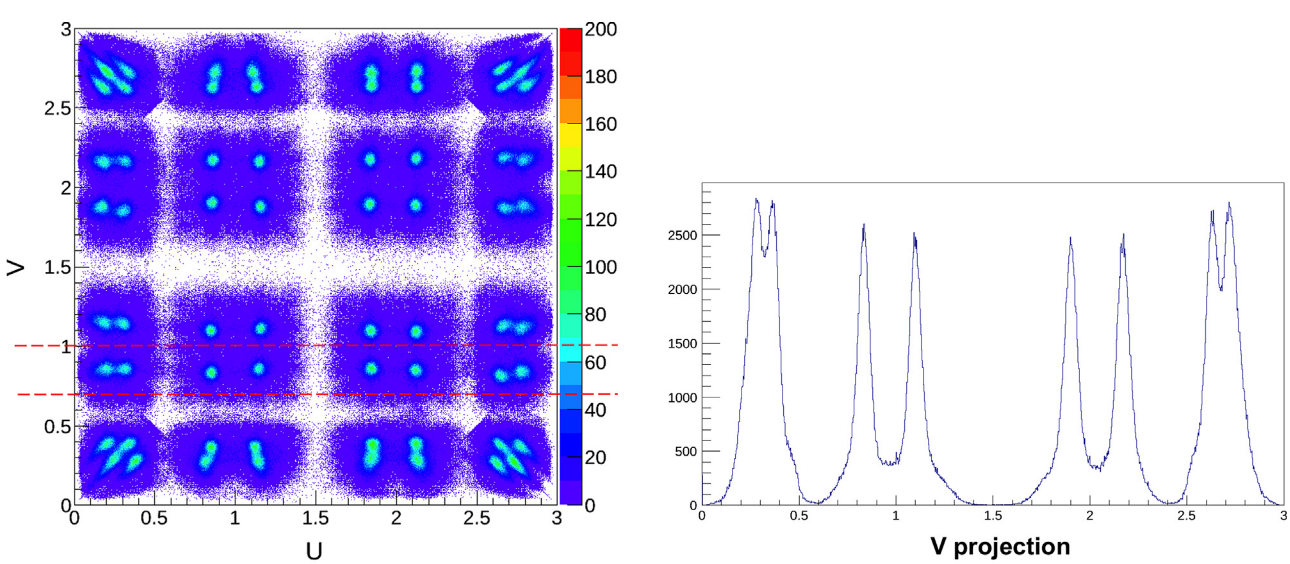
where E_{max} is the amount of energy deposited in the photodetector coupled to the interacted crystal pixel.

The detector module is composed of 8×8 scintillator matrix produced by Crystal Photonics Inc., being each pixel $1.53 \times 1.53 \times 15$ mm^3 coupled onto a Hamamatsu SiPM array (S12642-0404PB) with 4×4 pixels each with 3×3 mm^2 active area and 3.2 mm pitch. All crystal pixels are optically depolished. Reflectors are placed between the crystal pixels and also wrapped around the crystal matrix itself. The overall dimensions of the crystal array is $12.8 \times 12.8 \times 15$ mm^3, and the pitch between crystals is 1.6 mm. Therefore, 4 crystals of the scintillator array are coupled to each SiPM pixel. The crystal matrix and the associated SiPM array plug directly in the FrontEnd Boards forming a compact detecting unit. The FrontEnd boards integrates two ASICs allowing the readout and digitization of 128 MPPC pixels. On-chip TDCs produce two time measurements allowing the determination of the event time and the time-over-threshold (ToT). A Concentrator board reads the data from the FrontEnd boards and transmits assembled data frames through a serial link to the PCIe based DAQ board in the data acquisition PC [6]. The entire setup is contained within a completely dark box, where temperature is kept constant at 19 °C by the cooling system. Energy measurement is based on the Time-over-Threshold (ToT). The expected ToT curve is nonlinear so an internal calibration circuitry is used for energy calibration which generates test pulses to obtain the ToT curve as function of the deposited charge.

3. Results

3.1. Crystal identification

To evaluate the characterization of the detector module, Na-22 source (1 mm active area) is placed approximately 3 cm away from the side of the crystal opposite to the SiPM array. Using Eq. (1), the 2 dimensional flood histogram of (U,V) variables and the projection for the selected crystals are shown in Fig. 2. For the depolished crystal array, the locations of the crystals in the flood histograms change with depth, that is why the crystals located at the edges are not well separated. To overcome this limitation in identifying all the 64 crystals, the three dimensional flood histogram of the variables (U,V,W) is plotted (Fig. 3). Then, by means of



(a) (b)

Fig. 2. (a) Flood histogram and (b) the corresponding projection for the selected crystals.

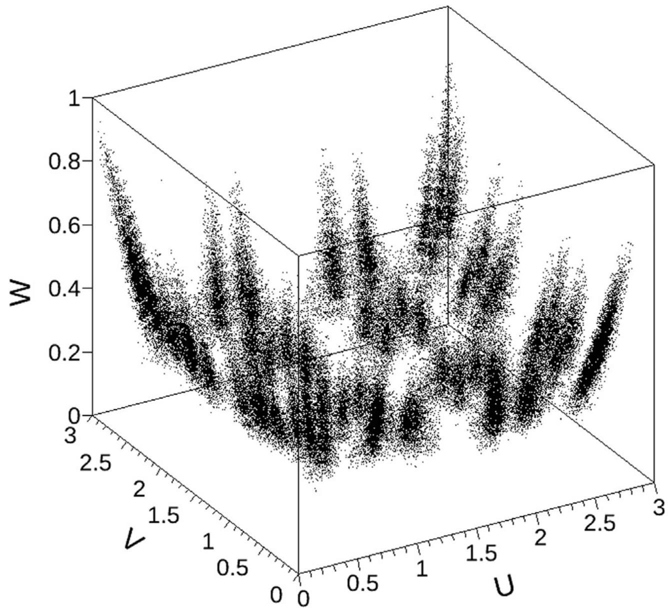


Fig. 3. 3D flood histogram of the variables (*U*,*V*,*W*).

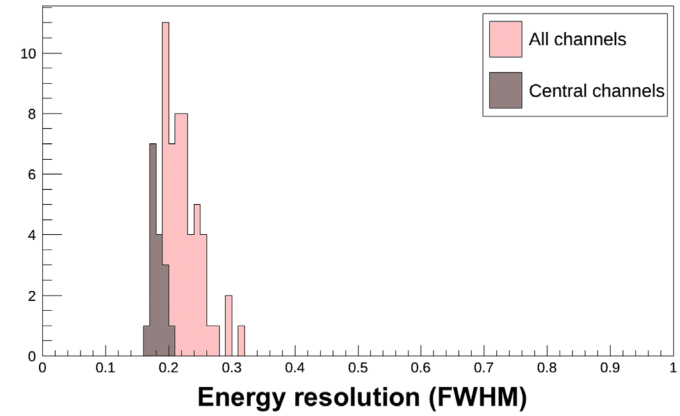


Fig. 5. Distribution of 511 KeV FWHM energy resolution.

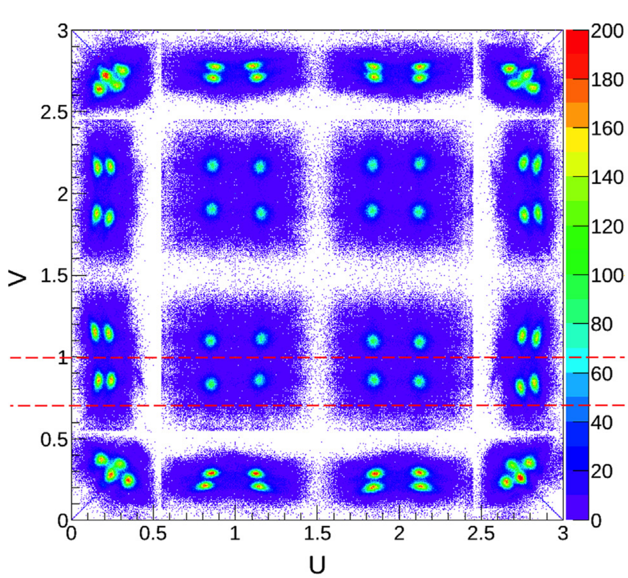
an appropriate rotation of data in a way that the vertical axis of each 3D volume corresponding to each crystal pixel is as normal as possible to the plane (*U*,*V*), the corrected 2D flood is extracted in which the crystals at the edges of the module are now well separated (Fig. 4).

3.2. Energy resolution

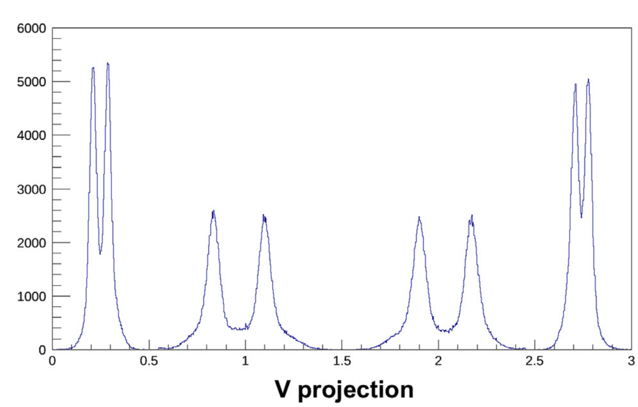
The energy spectra for all the 64 crystals are obtained after the crystal separation. Energy spectra for each crystal pixel where interaction happens is the sum of the energies deposited in all the SiPM channels for that interaction. In Fig. 5 the distribution of 511 keV FWHM energy resolutions for all the 64 crystals and for the crystals located in the middle of the module is plotted. The energy resolution is degraded for the crystals located on the sides of the module because of the light leakage through the lateral surfaces of the crystals. On average, the energy resolution for the 16 crystals coupled to the 4 central SiPMs is $18.29 \pm 0.3\%$ FWHM.

3.3. Depth of interaction

In order to study the possibility to obtain DOI information, an electronic collimating setup has been developed to be able to scan the crystal along the depth as shown in Fig. 6. In this setup a single 3×3 mm^2 LYSO crystal glued to an MPPC is in coincidence with the crystal module. The Na-22 point source is placed between the module and the individual crystal pixel. The distance between the source and the individual pixel is such that the coincidence events in the module are restricted in a circular spot of 1 mm. Then, by precisely moving the module up or downwards, the whole length of the crystal is scanned. In each depth, the 64 coordinates of all 64 pixels are found by 2D Gaussian fitting. The distribution of the W variables for events in 511 keV photopeak for different depths are plotted for each crystal pixel. The peak positions of the *W* variable distributions are linearly correlated to the depths (Fig. 7). The linear fitting functions between the DOI and the *W* histogram peak are extracted for all 64 crystals. Having the fitting functions for all the 64 crystals, the extracted DOI minus the real DOI for each depth is calculated to obtain the DOI resolution. The Gaussian fitting of the distribution of the DOI resolutions gives an average of 5.17 ± 0.05 mm FWHM (Fig. 8).



(a)



(b)

Fig. 4. (a) Corrected flood histogram and (b) the corresponding projection for the selected crystals.

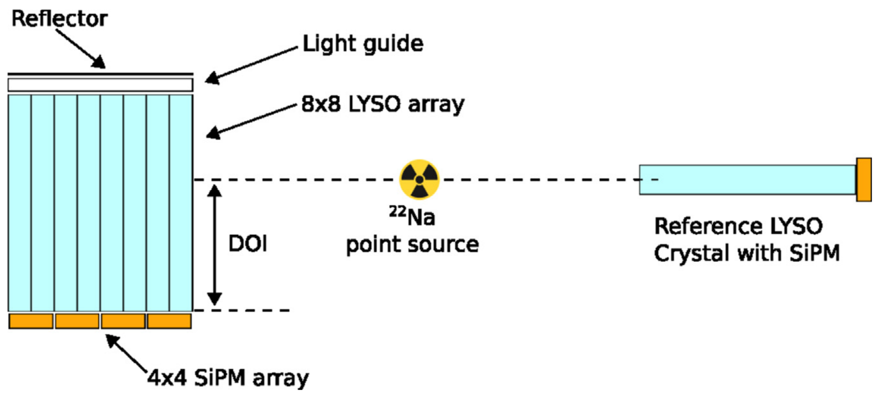
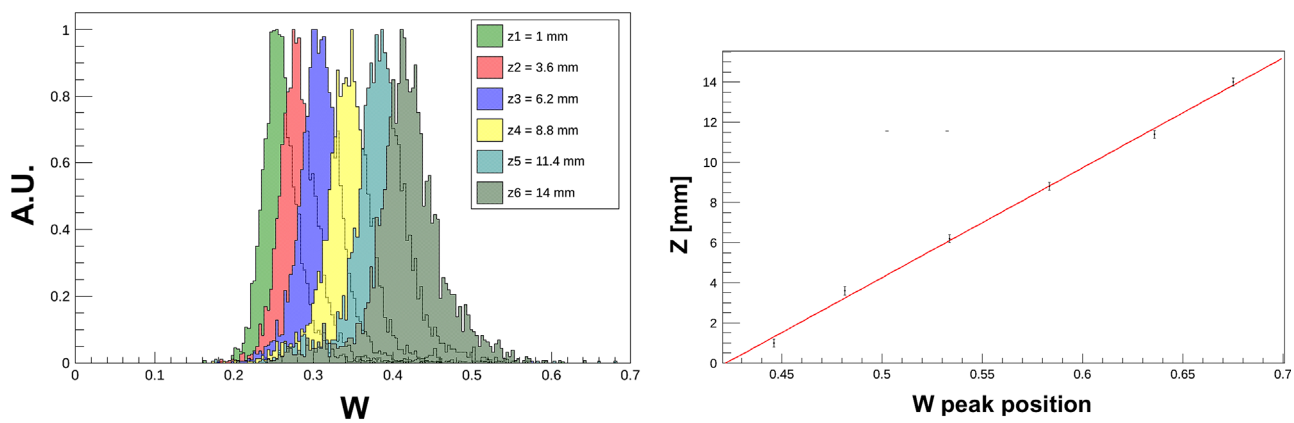


Fig. 6. DOI setup.



(a) (b)

Fig. 7. (a) Histograms of the W variables for 6 different z positions along the crystal length for 511 keV events in photopeak and (b) the linear correlation between the centers of the irradiation spots and the positions of the W histogram peaks.

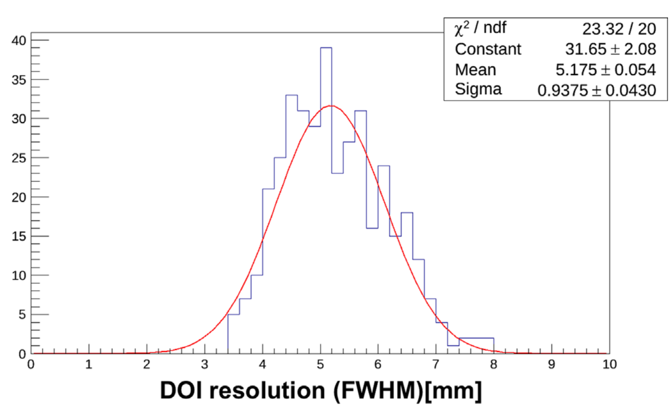


Fig. 8. Distribution of the DOI resolution for all the 64 crystals.

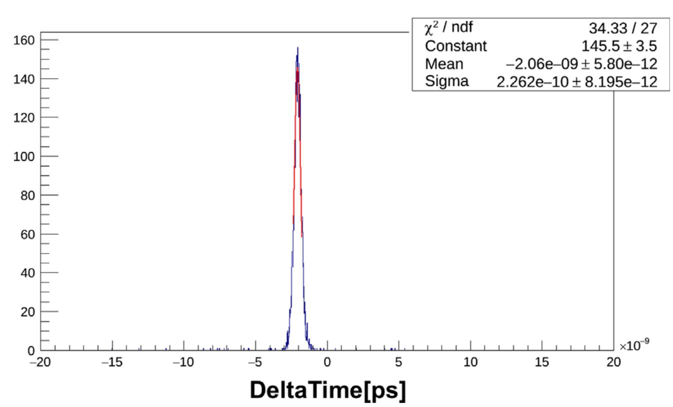


Fig. 9. Distribution of time difference between two modules in coincidence.

3.4. Timing resolution

The timing performance of the detector module is assessed by putting two identical detector modules face to face and a Na-22 point source is placed halfway between them. For each two channels in coincidence ToT spectra is obtained. Photoelectric events are selected from ToT spectra and the histogram of the time difference between the two channels is obtained (Fig. 9). The average coincidence timing resolution of 530 ps FWHM is acquired.

4. Conclusions

A new method for DOI determination in PET scanners with single side readout and four to one coupling between the crystals and SiPMs has been developed and tested. An average DOI resolution of 5.17 mm FWHM over 15 mm long crystal was obtained. The crystal separation in this method is excellent. Some degradation in crystal separation was seen for the crystals at the edges of the module due to the dependency of the locations of the crystals in the flood histogram on depth. But, by doing an appropriate rotation in 3D, very good crystal separation was achieved. The energy resolution of 18.29% FWHM at 511 keV was obtained. The timing resolution was evaluated as 530 ps FWHM. The performance of the detector module has been shown that the suggested DOI method can be effectively used to develop high resolution PET scanners while having low complexity.

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