A High-performance DOI Encoding Algorithm for PET Detectors with High Coupling Ratio

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ABSTRACT – For single-ended readout positron emission tomography (PET) detectors, the simplest way to determine depth-of-interaction (DOI) is based on the ratio of the corresponding crystal photodetector signal to the overall detector signal with a light guide on top. However, as the crystal-photodetector coupling ratio increases to achieve higher resolution, the performance of this method gradually deteriorates. This paper proposes a new DOI encoding algorithm using the ratio of the combined top three signals to the total detector signal, in which the weighting coefficients are optimized through mathematical derivation. The proposed method was applied to our single-ended row-column summation readout PET detector with a 9:1 coupling ratio. Experimental results show that the new algorithm provides uniform DOI resolution across all crystals, achieving an average DOI resolution of 4.07 mm FWHM, which is a 12.1% improvement over the traditional method, without any hardware modifications.

Limitation of the Traditional Algorithm

Row-column summation is a widely used readout scheme for photodetector arrays, as illustrated in Fig. 1. The traditional DOI estimation method extracts depth information from the ratio of the maximum row and column charges to the total charge, then computes the interaction position via linear fitting. Nevertheless, under the 9:1 high coupling ratio where nine crystals are coupled to one SiPM channel, this approach leads to considerable DOI positioning errors due to the distinct scintillation light distribution and detection characteristics across different crystals.

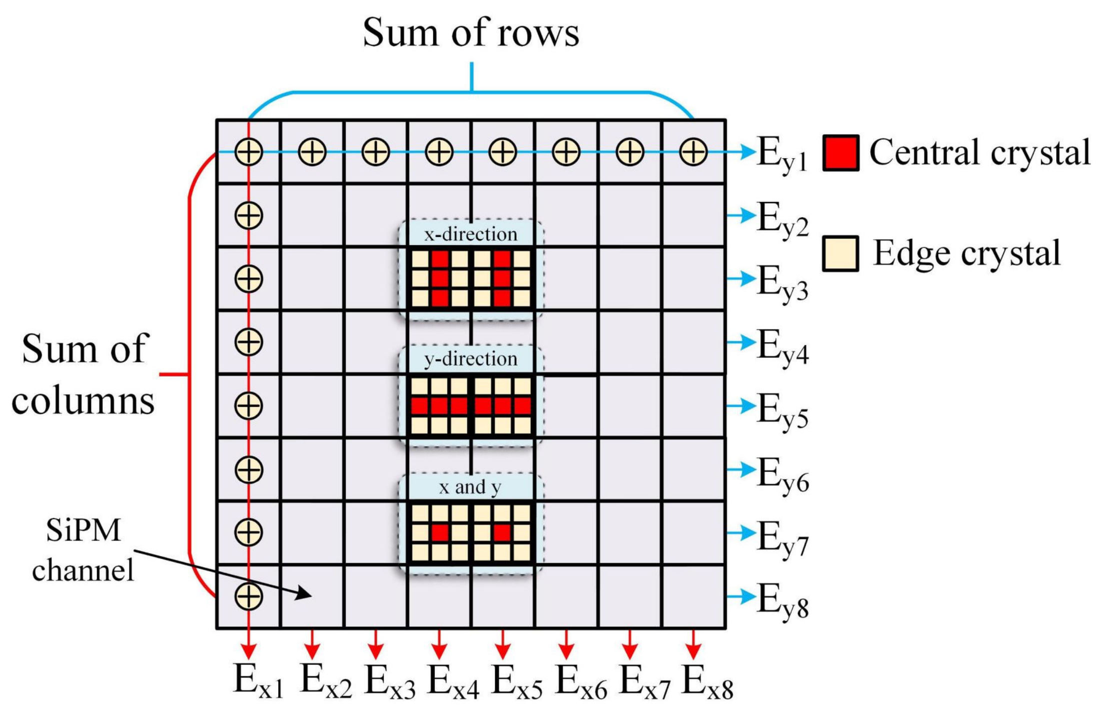

Fig. 1. Row–column summation readout schematic.

New DOI Encoding Algorithm

To improve performance, the new algorithm first divides the nine crystals corresponding to each SiPM channel into edge crystals, corner crystals and central crystals by position. Instead of using only the single maximum signal, it employs the three SiPM signals with the strongest energy deposition to expand the dynamic range and reduce relative deviation. For edge crystals, the new parameter is computed from the weighted sum of the strongest and the third-strongest signals:

$$w_{x_{new}} = \frac{E_{x1} + k \cdot E_{x3}}{\sum_{i=1}^{8} E_{xi}} = w_{x1} + k \cdot w_{x3}$$

Where k is a coefficient to be determined. For central crystals, it uses the strongest signal combined with the weighted average of the second-strongest and third-strongest signals:

$$w_{x_{new}} = \frac{E_{x1} + k \cdot (0.5 \cdot E_{x2} + 0.5 \cdot E_{x3})}{\sum_{i=1}^{8} E_{xi}}$$

Where the k is also a coefficient to be determined. The optimal weighting coefficient is determined through mathematical derivation. As shown in Fig. 2, experimental results show that the optimal coefficient is approximately −1 for both edge and central crystals, and this value is applied uniformly to all crystals in practice. Finally, the average of the parameters in the x and y directions is used to determine the DOI interaction position via linear fitting.

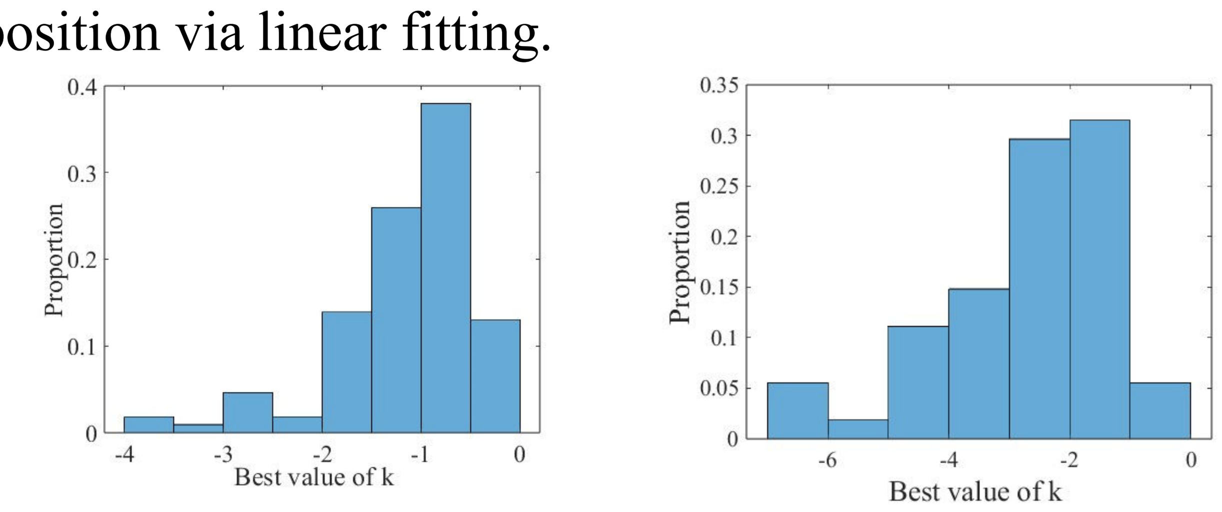

Fig. 2. The best value of k for edge crystals (left), The best value of k for central crystals (right).

Test Results

In the experiment, a 576-element LYSO scintillator array with a crystal size of 0.97 mm × 0.97 mm × 15 mm was used. The array had polished end faces, frosted lateral surfaces, and 0.075-mm ESR films between crystals. It was optically coupled to an 8×8 SiPM array at one end and a light guide at the other, with its sides wrapped in ESR film as shown in Fig. 3 . Signals were read out through row–column summation. DOI measurement was carried out using a collimation-based calibration method at five equidistant test points. After excluding the outermost readout channels, a 9×9 crystal subarray was selected for analysis, and crystals were classified into corner, edge, and central types.

The conventional method yielded an average DOI resolution of 4.63 mm, with 5.27 mm for corner crystals, 4.26 mm for edge crystals, and 3.58 mm for central crystals. In comparison, the improved method achieved a higher average resolution of 4.07 mm, representing a 12.1% improvement, with corresponding values of 4.36 mm (corner), 3.96 mm (edge), and 3.36 mm (central).

As shown in Fig. 4, the improved scheme effectively enhances all crystals, with the improvement being more significant for corner crystals.

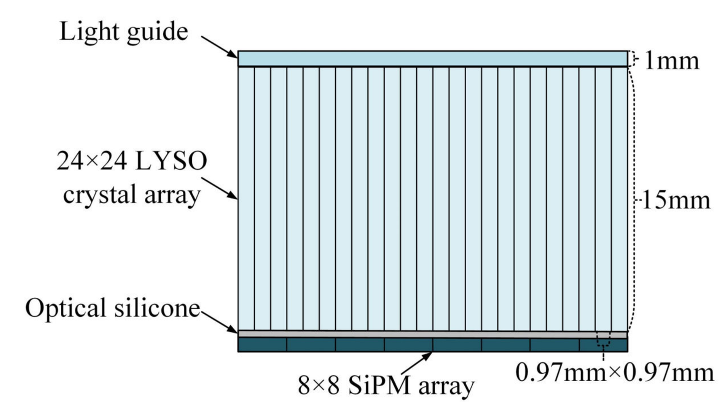

Fig. 3. Schematic diagram of the crystal array structure.

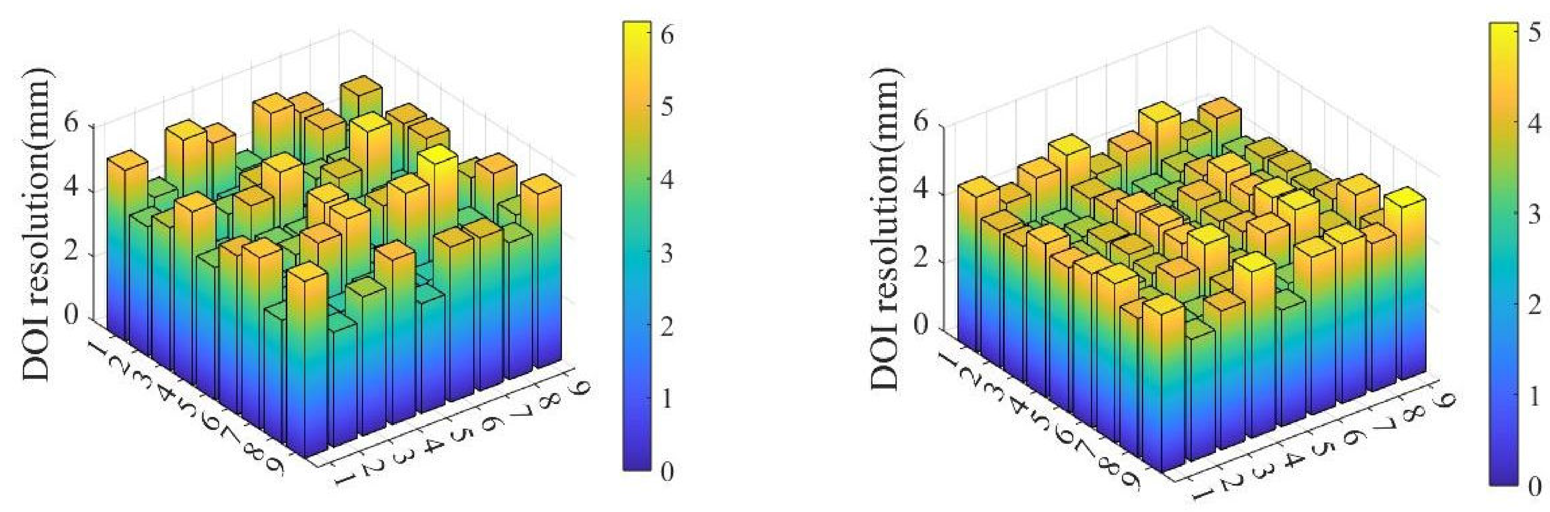

Fig. 4. DOI resolution distribution under the traditional algorithm(left), DOI resolution distribution under the improved algorithm(right).

Conclusion

In this study, a novel encoding algorithm is proposed, which characterizes the DOI of γ photons via weighted combination of the three readout channels with the highest energy deposition. The optimal weighting coefficients for signal combination are mathematically derived, yielding marked improvements in DOI resolution over conventional encoding schemes. Experimental results demonstrate that the improved encoding strategy achieves an average depth resolution of 4.07 mm, representing a 12.1% enhancement over the traditional method (4.63 mm), with particularly notable improvements observed for edge and corner crystals. Importantly, the proposed method does not require any additional hardware complexity or electronic readout channels, thereby retaining the cost-effectiveness and practicality of the single-ended readout configuration.