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A TOF-PET Detector based on Quadrant-Sharing PMTs and Optimized Leading-edge Timing Method

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Abstract. A time-of-flight positron emission tomography (TOF-PET) detector was developed based on a 6×9 LYSO array and four single channel photomultipliers (Hamamatsu R9800). Leading-edge timing circuit with optimized parameter was used instead of the constant fraction discriminator. The results showed that all 54 elements in the flood histogram could be identified clearly. The average coincidence resolving time was 402 ps FWHM.

1. Introduction

Positron emission tomography (PET）is a powerful functional imaging tool widely used in the early diagnosis of tumors. Time-of-flight (TOF) technique improves the signal-to-noise ratio of a PET image and consequently reduces dose and shortens scanning time.

PS-PMT and single channel PMT are both studied for TOF-PET by various researchers. Kim acquired 477 ps timing resolution by coupling LSO to Hamamatsu PS-PMT H8500 [1]. Szczesniak compared a series of fast PMTs and suggested that PMTs for TOF-PET should have low time jitter, high quantum efficiency (QE), and the best anode pulse shape quality [2]. The coincidence resolving time (CRT) of 422 ps was reported using PMT-quadrant-sharing LYSO detector and constant fraction discriminator (CFD) [3].

In this study, we developed a detector with LYSO array and quadrant-sharing PMTs and then incorporated the detector to a leading edge discriminator (LED). Good CRT was acquired.

2. Detector and electronics

The detector module consisted of crystals, a light guide, and PMTs. They were packaged in a detector box together with front-end electronics.

2.1. Crystals

Scintillators for TOF-PET application should exhibit high Z, high density, high light yield, and fast decay time. BaF_2, $LaBr_3$:Ce, and LYSO are all good candidates for TOF-PET. However, $LaBr_3$ deliquesce easily. The fast light output of BaF_2 peak at 220 nm, which requires PMTs with quartz window. Thus, LYSO was chosen as the scintillator of our detector based on the light output, stopping power, packaging technology, and cost.

According to a previous study on LSO scintillators for TOF-PET, the longer the LYSO crystal, the higher the detecting efficiency will be, although with worse timing resolution, and vice versa [4]. Therefore, an LYSO crystal with length of 20 mm was used to balance timing resolution and detecting efficiency.

2.2. PMTs

Hamamatsu R9800 was a single channel PMT with good timing ability. The anode pulse rising time was 1.0 ns, and the transmit time spread was 270 ps. The QE peak was at 420 nm, which matched well with the LYSO emission spectrum.

The QE of the photocathode border area of R9800 was relatively low because of the manufacturing techniques. Therefore, avoiding the use of the border area is important to obtain good timing resolution.

2.3. Detector Module Design

Four R9800 (2 × 2) were arranged in a light tight aluminum box. LYSO crystals each measuring 4.2 mm × 5 mm × 20 mm were wrapped together by 6 × 9 to form a scintillator block. The size of the block was 25.2 mm × 45 mm × 20 mm. The block was placed in the area outlined by the bold rectangular line in Figure 1. In fabricating large detectors based on this design, in the *x*-direction, the block covers half of the PMT sensitive area. In the *y*-direction, the block does not cover the entire two PMTs to avoid the border area of PMTs.

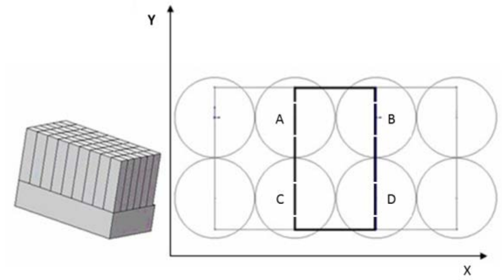

Figure 1. Schematic of the LYSO-R9800 detector module.

Figure 2. Photograph of the detector module.

As demonstrated in Figures 1 and 2, a light guide, made of K9 glass, with dimensions 45 mm × 45 mm × 9 mm, and all sides polished, was placed between the scintillator array and PMTs.

2.4. Electronics

The anode signals of four R9800s were processed individually. Each signal was amplified and shaped to quasi-Gaussian shape, 300 ns width. Leading-edge timing method was adopted in the timing electronics. The threshold of the comparer in the circuit largely influenced the timing performance. The optimum threshold of the circuit was acquired and described in section 3.2.

3. Measurement setup

3.1. Flood histogram and CRT measurement setup

We only fabricated one R9800-LYSO detector in this work. Therefore, another detector based on XP2020Q and BaF_2 with known timing resolution of 159 ps was used to build a coincidence time measurement system (Figure 3).

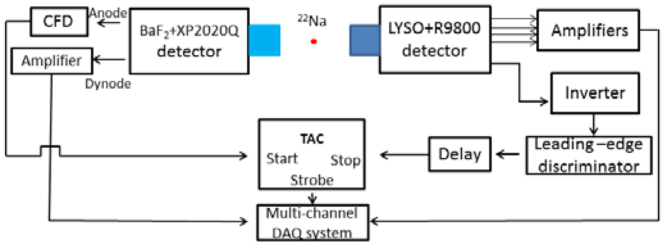

Figure 3. BaF_2-LYSO timing resolution measurement setup.

The dynodes of four R9800 were combined to do the timing. The inverted pulse was amplified, and then, fed to the self-developed LED. The output of the LED was delayed and fed to a time-analog converter (TAC) to act as the stopping channel. The anode signal of XP2020Q-BaF_2 detector was conducted to a CFD (ORTEC 935) to do the timing. The timing signal was fed to the TAC to act as the starting channel. The coincidence signals of the two detectors were used to strobe the multi-channel data acquisition (DAQ) system. The anode signals of R9800 and XP2020Q were used to select 511 keV gamma photon events.

The amplified anode signals (S1, S2, S3, and S4) of four R9800s (A, B, C, and D) were fed to the DAQ system. The two-dimensional position information of the crystal array can be obtained by X (S1+S3), Y (S1+S2), and E (S1+S2+S3+S4) [5]. A flood histogram of the scintillator array was displayed on a LabWindows user interface. The flood histogram was utilized to create the position and energy tables of every single LYSO crystal in the scintillator array. Then, the CRT between every crystal and the BaF_2 detector (TR_s) was measured. After deducting the timing resolution value of the XP2020Q-BaF_2 detector, we obtained the timing resolution of R9800+LYSO detector (TR_L) and the CRT of two R9800-LYSO detectors (TR_C).

3.2. Best threshold of leading-edge timing circuit

In our previous studies, we found that the timing resolution is largely influenced by the threshold of the comparer in the timing circuit. The special value of the threshold for various detectors should be investigated.

A similar system with CRT measurement in section 3.1 was used to study the optimum threshold of the timing circuit. The scintillator array was replaced by an LYSO crystal fixed in the middle of the light guide. The crystal measured 4 mm × 4 mm × 22 mm, with five sides wrapped with Teflon. The timing resolution of the single LYSO detector at FWHM to 511 keV gamma photon was recorded along with the changes in the LED threshold.

4. Results

4.1. Special threshold of LED

The relationship between timing resolution and threshold of LED is plotted in Figure 4. The best timing resolution of 218 ps was obtained when the threshold was 15.6 mV. Accordingly, we can conclude that the CRT of two such detectors was $218 \times \sqrt{2} = 309$ ps. This result was better than using ORTEC 935 CFD with 351 ps CRT. These results indicate that LED may be more appropriate for an LYSO detector than CFD to obtain better timing resolution.

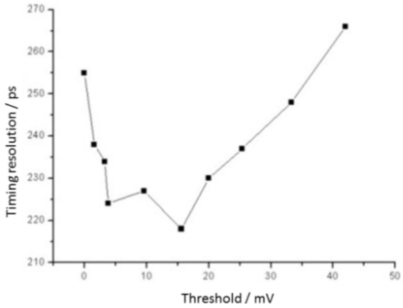

Figure 4. Relationship between timing resolution and the LED threshold.

4.2. Spatial resolution and timing resolution results

All 6 × 9 elements of the LYSO array can be resolved clearly in the flood histogram (Figure 5). The peak-to-valley ratio was better than 4:1. The results show that the detector had good spatial resolution ability for human-scale TOF-PET.

Using the system mentioned in section 3.1 and the optimized parameter of timing circuit, the average CRT with BaF_2 detector of the 54 LYSO crystals was measured as 326 ps. The coincidence time spectrum is shown in Figure 6. Therefore, the CRT of two identical R9800-LYSO detectors developed in this work could be calculated according to equation 1:

$$CRT_{LYSO\text{-}LYSO}=\sqrt{2}\times\sqrt{CRT^2_{LYSO-BaF_2}-TR^2_{BaF_2}}=\sqrt{2\times(326^2-159^2)}=402\ \text{ps} \quad (1)$$

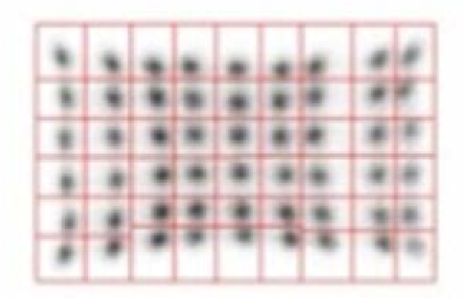

Figure 5. Flood histogram and one-dimensional projection.

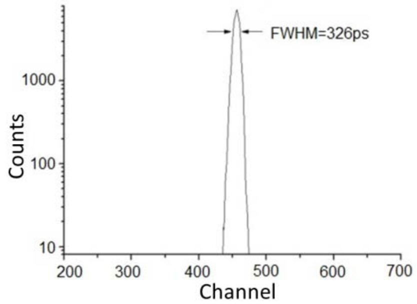

Figure 6. CRT spectrum between LYSO-R9800 and BaF_2-XP2020Q.

5. Summary

We developed a TOF-PET detector based on an LYSO array and four R9800 PMTs. All the LYSO crystals measuring 4.2 mm × 5 mm × 20 mm in a matrix was identified. CRT of 402 ns was obtained using an LED. The detector developed in this work can be easily extended in one direction, with high cost effectiveness and large detecting area. We are currently developing whole body TOF-PET detector modules based on this study.

The LYSO crystals are obtained from a local factory. The average light output is less than 80% of the output of Saint Gobain LSO crystals. An improved timing resolution will be acquired if all the LYSO crystals are replaced with better ones.

Acknowledgement

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