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PET detectors with 127 ps CTR for the Tachyon-II time-of-flight PET scanner

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Abstract

The signal-to-noise ratio (SNR) of the reconstructed image of Positron Emission Tomography (PET) can be improved by the timing measurement. In this article, we designed, fabricated and tested 32 time-of-flight (TOF) detectors for the second generation of Tachyon TOF-PET scanners. The detector module consists of two arrays of 2×12 lutetium-yttrium oxyorthosilicate (LYSO) crystal cubes of $6 \times 6 \times 6$ mm³. The discrete crystals were coupled to the 6 mm silicon photomultipliers (SiPMs) with optical glue. All the SiPM were tested for dark current. To correct the errors in the timing measurements caused by time-walk, two compensation methods (log-correction and linear-correction) based on the relationship between energy and timing information were purposed. As a comparison, the SiPM arrays coupled to 4 mm and 6 mm side crystal cube without optical glue were tested for coincidence timing resolution (CTR). The mean and standard deviations (SD) of dark current for the 1536 tested SiPMs were 12.72 ± 1.70 μ A at the bias voltage of 31.5 V and the temperature of 20 °C (± 1 °C). CTR performance has increased by ~5% within a narrow energy window, and ~10% in a wide energy window by log-correction. The mean and SD of the CTR of 6 mm side crystal cube glue coupled was 126.9 ± 3.6 ps for the 768 pairs of tested SiPMs. The detector is expected to provide a technical reference for the next generation of ultra-fast CTR commercial PET scanner using multilayer detectors.

Keywords

Positron emission tomography; TOF PET; Time resolution; Coincidence events; Energy resolution; Dark current

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1. Introduction

Positron Emission Tomography (PET) first became commercially available with a number of successful applications in oncology, cardiology, and neurology [1–4]. The idea of using timing information was originally proposed in the early developmental stages of PET scanners [5], which is being determined by the coincidence timing resolution (CTR). Time-of-flight (TOF) PET scanners can enhance the diagnostic accuracy of reconstructed images by locating positron emissions and improving the signal-to-noise ratio (SNR) of PET data [6,7]. It has been verified that an improved image quality of PET scanner can be achieved with a detector design that is capable of measuring TOF information [8–10].

The gamma detector is one of the key components, which has an impact on the imaging quality of PET scanner. Many factors can affect the CTR and light output of detector modules [11], which include: the intrinsic properties and shape of the scintillator crystals, the optical properties of the coupling materials, the surface treatment of the scintillator crystals, the optical reflectance properties of the reflectors [12] and the performance of the photoelectric sensor (i.e. the SiPM plus electronic front-end and acquisition system). An excellent TOF detector can be achieved by considering all factors.

Some of the TOF detectors have been proposed which employ different scintillation crystals or photon sensors. In the case of cubic crystals, the smaller the crystal volume, the better the timing performance [13]. However, a reduction in the crystal size inevitably leads to an increase in the cost and complexity of a PET scanner. Another noted issue is that, the longer the crystal length, the worse the timing performance when compared to other crystals with the same cross-section [13]. At the same time, shorter crystals greatly reduce the sensitivity of the PET scanner. In this regard, halogen crystals, especially Lanthanum (III) bromide (LaBr_3) and Cerium (III) bromide (CeBr_3), have been found to have excellent timing performance [14,15]. However, the hygroscopicity of these crystals makes it very hard to use them in clinical PET scanners. An alternative is lutetium-yttrium oxyorthosilicate (LYSO) crystals and it has been found that the timing performance of LYSO crystals co-doped with Ca and Ce can achieve an excellent time performance [16]. Besides, the detectors based on continuous crystals can also achieve good timing performance [17,18]. Nonetheless, by taking into account all the factors (cost, sensitivity, the performance of readout circuits and crystals, etc.), it remains difficult to design a PET scanner that is capable of excellent CTR.

Constant fraction discriminator (CFD) and leading edge discriminator (LED) are the two most commonly applied triggering methods in the front-end readout electronics of TOF PET system [19]. When it comes to the modern TOF detectors constructed with SiPMs, the LED is preferred for the following reasons: (1) it requires fewer components, and (2) the LED can be set at a very low level to trigger on the initial group of the scintillating photons. Thus, an excellent timing resolution can be achieved with LED. One drawback of LED is that the timing measurements are affected by time walk, especially when Compton events should be used. This paper studies the effect of signal step on time measurement and the compensation method.

The purpose of this study is to design a demonstration TOF-PET scanner that could produce a CTR better than 150 ps. To achieve this, we designed, fabricated and tested detector modules based on a prototype detector. A key part of this was the testing and comparison of CTR and energy resolution of 4 mm and 6 mm side LYSO crystal cubes air or glue coupled to SiPMs.

2. Materials and methods

2.1. Detector design and assembly

The prototype detector was composed of two sub-modules which consisted of a 2×12 0.2% co-doped LYSO: Ce, Ca crystal array (provided by Suzhou Jtcrytal, JTC) with an overall size of $6.2 \times 12.2 \times 76.03 \text{ mm}^3$ and a 2×12 SiPM array, as shown in Fig. 1a. The two sub-modules were separated by opaque materials. The individual crystal size was $6 \times 6 \times 6 \text{ mm}^3$ and they were embedded by the opaque materials (barium sulfate, BaSO_4) with a gap thickness of 0.33 mm. The periphery of crystal array was also wrapped in 0.1 mm thick BaSO_4 . The coupling surface of each crystal was polished and the other five surfaces were left completely unpolished to reduce the likelihood of total internal reflection (TIR) and to increase the number of photons collected by the sensors. The SiPM array shown in Fig. 1b consists of 2×12 SiPMs and one-to-one coupled to the crystal array. The SiPM (MicroFJ-60035-TSV, SensL) possessed an active area of $6 \times 6 \text{ mm}^2$ with a pitch of 6.13 mm and 22,300 microcells of $35 \times 35 \mu\text{m}^2$. The breakdown voltage of the SiPM is range from 24.25 V to 24.75 V. Both standard and fast signals of the SiPM were used in the measurements. According to SiPM guidelines, a 0.35 mm thick protective layer of light-sensitive glass was placed on the top of SiPMs, although some of the photons will inevitably still leak out from the edges. Therefore, the coupling boundary between the crystal and SiPM arrays was also wrapped with Teflon tape to reduce leakage. Optical glue (301–2 form EPO-TEK) with a refractive index of 1.53 was used as the coupling material. For comparison, we also tested a crystal array that was directly coupled to SiPMs (the coupling material was air, which has a refractive index of 1.0). A cable connector with 24 channels was located in the center of the circuit board. This connected all SiPMs and was connected to the electronic module via two FPC cables of 8 mm. The two sub-modules were combined back-to-back in a dark box (Fig. 1c).

Multiple refractions occur when photons pass through the optical glue, because of the bubbles filled with air being hidden in the optical glue. As a result, some proportion of the photons get absorbed during the process, which has an impact on the light output and timing performance. We established a complete process for the assembly of the detectors to ensure a stable performance. As a first step, a vacuum pump was used to remove air bubbles from the optical glue. In the second step, a syringe was used to apply optical glue to the polished surface of the crystal. It is to be noted that the optical glue needs to be uniformly covered at least 2/3 of the area of the surface at the center and the syringe needle has to remain in the optical glue during injection to prevent the introduction of more air bubbles. Finally, after coupling SiPM array, a set of fixtures (including a jig, a pin, and two bars) were used to position and fix the module both horizontally and vertically. All the surfaces that were into contact with the module were taped to ensure that the optical glue could not damage the

fixtures. When the optical glue was cured, the fixtures and excess optical glue were removed and Teflon tape was used to wrap the module.

2.2. Experiments

The energy spectrum and the CTR of the detector modules were tested. 64 SiPM arrays (1536 SiPMs) were tested for dark current to ensure that the SiPMs were working properly. The bias voltage of SiPM was set to 31.5 V. The photon detection efficiency (PDE) exceeds 50% at 420 nm scintillating photons. All the experiments were performed in a light-tightened box and the temperature inside the box was maintained at 20 °C (± 1 °C).

CTR was measured using the standard setup as shown in Fig. 2a. The readout system consists of two PET detectors, a Keithley 2400 source meter, two custom-designed amplifier boards, two leading edge discriminators (LEDs), a time-to-amplitude converter (TAC), an NI PCI-7833R board, and a PC. The readout electronics splined the input signal from SiPM into two branches. One branch was amplified and fed to an analog-to-digital converter (ADC) for energy measurements. The high-pass-filtered, amplified timing signals were fed to two LEDs (CANBERRA®, Model 454). The outputs of the LEDs were fed to the TAC (ORTEC®, Model 566), which measured the time interval between pulses to its start and stop inputs and generated an analog output pulse proportional to the measured time. The full scale of the TAC was set to 50 ns, and the FWHM of the timing resolution of the Model 566 TAC was 10 ps for all ranges according to the datasheet. The outputs of the TAC and the amplified energy signals were connected to the NI PCI-7833R board, a PCI-based reconfigurable I/O device with a FPGA and 8 analog-to-digital converters on-board. A Lab VIEW program was developed to control the FPGA to perform event triggering and read out the energy and timing signals.

The -3 dB bandwidth, slew rate and input impedance of the high-speed amplifier (AD8000, ADI Inc.) are 1.5 GHz, 4100 V/ μ s and 2 M Ω , respectively. The root mean square (RMS) electronic noise floor of the amplifier circuit was 5.1 mV. The average slew rate (dV/dt) of the input signal from a typical LYSO detector was approximately 330 V/ μ s.

For the CTR measurement of the detectors, the two sub-modules were placed horizontally at a distance of 10 cm. The coincidence time of two crystal cubes in the corresponding positions in two different arrays was measured according to the order shown in Fig. 2b. A ^{22}Na point source (J2-347, Eckert & Ziegler) with an activity of 0.74 MBq was centrally located between the two modules. For different test pixels, the source also moved. In this work, 64 sub-modules (1536 pixels) assembled using optical glue were measured. The timing resolutions in terms of their distribution, mean values and standard variations (SD) will be reported. SD is a statistic measure that is used to quantify the amount of variation or dispersion of a set of data values. For the purpose of comparison, a pair of 6 mm side crystal cubes coupled to SiPM array at the pixels of #03, #04, #07, #08, #11, #12, #15, #16, #19, #20, #23, and #24 without optical glue were also measured using the same method. During acquisition, the SiPMs transmitted all validated events to a computer where a preliminary selection of coincidence events was performed online using acquisition software with a coincidence time window (50 ns). The full-width-at-half-maximum (FWHM) of the 511 keV photon peaks and energy resolutions were calculated from the energy spectrum. A million

coincidences were collected at each pixel within the energy window of [440 keV 560 keV], which were then selected for the time spectrum and calculation of CTR.

As a comparison, a pair of 4 mm side LYSO crystal cubes coupled to the same SiPM array was tested. The surfaces of the 4 mm crystal were polished, which was different from the 6 mm crystal. The surfaces except the coupling surface were wrapped in three layers Teflon tape. As shown in Fig. 2c, the crystals were coupled to the center of the SiPMs at different pixels. The distance between the two crystals was ~8.53 mm. The point source was centrally located between the crystal cubes being tested. Thus, when the main crystal was coupled to the 1st, 2nd, 3rd, and 4th SiPMs, the reference crystal was coupled to the 5th, 6th, 7th, and 8th SiPMs and the source was placed on the 3rd, 4th, 7th and 8th SiPMs, respectively. 36 SiPM arrays coupled to 4 mm side cubic crystals without optical glue were tested, so a total of 432 sets of CTR data were collected based on 4 mm crystals.

2.3. Time walk compensation

The timing measurements are affected by the time walk of the LED method. Trigger time differs for incidences with the same rising time but different peak energy. Therefore, timing measurements are not accurate when LED is implemented, especially for the large range of energy windows. We proposed two methods to calibrate the time signal in terms of the energy value. (1) Linear-correction (Formula 1). As shown in Fig. 3a, a correction line generated by the relationship between the energy differences ($E_2 - E_1$) and time difference of coincidence events served to calibrate the CTR, which are non-linear. (2) Log-correction (Formula 2). As shown in Fig. 3b, the log-correction line was generated by the relationship between the logarithm of the energy ratio and the time difference of coincidence events which has a much better linearity.

$$(E_2 - E_1) V_s \cdot (T_2 - T_1) \quad (1)$$

$$\left(\log \frac{E_2}{E_1} \right) V_s \cdot (T_2 - T_1) \quad (2)$$

E_1 (E_2) and T_1 (T_2) were energy and trigger time of the coincidence events. For the sake of investigating the effect of the energy window on compensation accuracy, the energy window is set as (x, 560 KeV). The X is the low energy cut, ranging from 50 KeV to 450 KeV. The FWHM and full-width-at-tenth-maximum (FWTM) were utilized to calculate the CTR and evaluate the compensation methods.

3. Results

3.1. Dark current and breakdown voltage

Fig. 4 shows the histogram of the dark current of the SiPMs. The mean and SD of dark currents of the 1536 individual SiPM pixels were 12.72 μ A and 1.70 μ A at the bias voltage of 31.5 V and a temperature of 20 °C (± 1 °C). It could be noted that there are some dark currents that far exceeded the average, and thus there might be some damage due to the patching process. A further measurement and analysis of the timing performance of these

abnormal SiPMs have been performed as discussed below. The mean measured breakdown voltage of 6 mm SiPM without coupling crystal was 24.7 V. The example of the IV curve is shown in Fig. 4(b).

3.2. Energy resolution and light output

Fig. 5 shows the typical energy spectra for different coupling materials and crystal sizes without correction for saturation effects of SiPMs. The FWHM of energy spectra was used to calculate the energy resolution. When the 4 mm polished crystal were directly coupled to the SiPMs, the mean energy resolution was 10.4% at the peak (Fig. 5a). When the 6 mm side crystal cubes were directly coupled to the SiPMs without optical glue, the mean energy resolution was 9.2%. When they were coupled to the SiPMs with optical glue, the mean energy resolution was 8.9% (Fig. 5b). Excellent energy resolutions were achieved for different crystals and coupling materials. Fig. 6a shows the energy resolution of different pixels. The energy resolution of 6 mm side crystal cubes is uniform at different pixels. Conversely, the energy resolution of a 4 mm polished crystal is fluctuating.

Fig. 6b shows the peak position of the detectors. The TIR angle without optical glue coupling (33.5°) was less than for coupling with optical glue (57.1°). The mean light outputs were 100%, 87.6% and 74.2% for 6 mm side cubes coupled to SiPM with optical glue and 6 mm and 4 mm side cube crystals air coupled, respectively. The 6 mm side cube had a higher light output as compared to the 4 mm side cube. One of the reasons may be the difference in surface treatment. The light output of a polished crystal is lower than that of an completely unpolished crystal due to TIR. The saturation effect of SiPM may also be one of the reasons. The 6 mm side cubes was coupled to more microcells as the 4 mm side cubes.

3.3. Time walk compensation

A pair of 6 mm side cube crystals coupled with optical glue were randomly selected to verify and compare the compensation algorithm. Figs. 7a and 8b demonstrate the CTR comparison between linear-correction and log-correction for different energy windows. Low energy cut was between 50 and 500 KeV, and high energy cut was set as 560 KeV. The effect of the time walk compensation on the CTR is important. The log-correction and linear-correction achieved similar improvements for FWHM CTR. When the low energy cut was less than 350 KeV, the log-correction was better than the linear-correction for FWTM CTR.

FWHM CTR reinforced by a factor of 1.15 from 178 ps to 155 ps with energy window [220 keV 560 keV], 1.05 from 130 ps to 124 ps with energy window [440 keV 560 keV] after the log-correction was applied. FWTM CTR reinforced by a factor of 2.3 from 756 ps to 328 ps with energy window [220 keV 560 keV] after the log-correction was applied. The non-linearity in the relation between the energy and timing may be caused by the electronic system. Our electronic system is intrinsically a high-pass system that may lead to the logarithmic relation between energy and measured time.

3.4. Coincidence timing resolution

Fig. 8a shows the typical timing spectra (Gaussian fitting) for the 4 mm side crystal cubes air coupled and the 6 mm side cubes air or glue coupled to SiPMs. For the 4 mm side crystal

cubes, the mean and SD of the timing resolution was 157.7 ± 10.3 ps. Fig. 8b shows the histogram of the CTR where 432 pairs of SiPMs coupled to the 4 mm side crystal cubes without optical glue were tested. For the 6 mm side crystal cubes, when they were coupled to the SiPMs without optical glue, the mean and SD of the timing resolution was 166.9 ± 11.4 ps, but when they were coupled to the SiPMs with optical glue, the mean and SD of the timing resolution was 126.9 ± 3.6 ps. Fig. 8c shows the histogram of the CTR measured when 768 pairs of SiPMs and crystals were tested.

Table 1 shows the mean CTR for the 4 mm side crystal cubes air coupled to different SiPMs. We divided the detector into three areas: the left area (SiPM #01-SiPM #08), the middle area (SiPM #09-SiPM #16) and the right area (SiPM #17-SiPM #24). The mean CTRs for these areas were 160.1 ps (left), 154.2 ps (middle) and 159.0 ps (right) respectively, as shown in Fig. 9a. There is a noticeable trend that the CTR in the middle area was better than it was at the edge. It is to be noted that the same pair of 4 mm side crystal cubes was used for all the experiments. The connector was in the center of the board, and the distance from the edge crystal to the connector was about 3 cm, while the distance from the middle crystal to the connector was under 1 cm. Therefore, we can infer that the difference in the length of the wire was one of the reasons for the difference in the CTR.

The CTRs for the 6 mm side crystal cubes air coupled to the SiPM array are shown in Table 2. The CTR curves of odd and even SiPMs are shown in Fig. 9b. There is no definite regularity based on the results. This may be due to the small number of samples tested. For the 6 mm side crystal cubes coupled to SiPMs by optical glue, the mean CTRs at different pixels are shown in Table 3. The mean and SD of the CTR curves are shown in Fig. 9c. There are two curves: one for the CTR of the odd-numbered SiPMs and the other for the CTR of the even-numbered SiPMs. We can observe once again that the CTR in the middle position was better than it was at the edge for both curves. This confirms that the length of the signal cables, include the signal cables in SiPM, the signal cables to the front-end, and the transmission lines used in printed circuit board are the crucial aspect of TOF-PET design.

4. Discussion

The thickness of the crystal is only 6 mm, which is not long enough for commercial PET scanners to achieve a higher sensitivity. But it is possible to use a multi-layer detector method to build a PET scanner that can achieve ultra-high CTR, depth-of-interaction (DOI) decoding and system sensitivity.

The log-correction method achieved a 5% boost within a narrow energy window, and a 10% boost in a wide energy window for the FWHM CTR. The result is based on LYSO crystals with a photoelectric absorption probability (PE) of ~33% of 511 keV photons. That compensation method will be more effective for the halogen crystal (such as LaBr₃, ~14% PE) [20]. In this situation, a wider energy window is usually prefer to increase the sensitivity of the detector.

5. Conclusions

We have currently measured 32 detectors (1536 individual pixels in total). The average and standard deviation of the FWHM CTR for the detectors was 126.9 ± 3.6 ps for the 6 mm side crystal cubes glue coupled to SiPMs. From this study, the following conclusions could be drawn: (1) The 4 mm side crystal cubes produced a better timing performance than the 6 mm side crystal cubes when air coupled. A possible reason could be that the larger the crystal volume, the longer the distance and time involved in the photons transiting the crystal before they are absorbed by the SiPMs. The second possible reason could be that the increased cross-talk for the coupling crystals with larger area leads to higher baseline-fluctuations. (2) Optical glue significantly increased the CTR. This is because of the increase in light output resulting from an increased acceptance angle due to better optical impedance matching. (3) The length of the signal cables is crucial for TOF-PET design. A shorter signal cable can improve the CTR significantly. Overall, the performance of the detectors meeting the expectations and currently a demonstration body TOF-PET (Tachyon-II) scanner with them is under construction.

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Fig. 1.

(a) A partially assembled detector module composed of two sub-modules. (b) The LYSO array and SiPM array. (c) An assembled detector module in a dark box.

Fig. 2.
 (a) The schematic of the experimental system, (b) CTR experimental method of sub-modules with 6 mm side crystal cubes, (c) Pair of crystal cubes air coupled to different SiPMs in the array.

Fig. 3. Relationship between the time differences and (a) the energy differences and (b) the logarithm of the energy ratio.

Fig. 4.

(a) Histogram of the dark current, (b) the example of the IV curve.

Fig. 5.

(a) For 4 mm polished crystal cubes air coupled to different SiPMs. (b) For 6 mm side crystal cubes air and glue coupled to different SiPMs. From top to bottom and left to right, the graphs are the typical energy spectra for pixels #3, #7, #11, #15, #19, and #23 respectively.

Fig. 6.

(a) The energy resolution without corrected for saturation effects of SiPMs and (b) Peak position of the measured crystals.

Fig. 7.

(a) FWHM CTRs and (b) FWTM CTRs at different low energy cuts using linear-correction and log-correction.

Fig. 8.

(a) Typical timing spectra (Gaussian fitting) for the 4 mm and 6 mm side crystal cubes air coupled and 6 mm side crystal cubes glue coupled to SiPMs. (b) The histogram of the CTR for the 4 mm side crystal cubes air. (c) The histogram of the CTR for the 6 mm side crystal cubes glue coupled.

Fig. 9.

(a) The distribution of the mean CTR across the three areas for the 4 mm polished crystal cubes air coupled, (b) The CTRs for the 6 mm side crystal cubes air coupled, (c) The mean and SD of the CTR curves for 6 mm side cubes glue coupled to odd-numbered SiPMs and even-numbered SiPMs.

Table 1

The mean CTRs for the 4 mm side crystal cubes air coupled. (36 SiPM arrays were tested).

Pixels	1(5)	3(7)	9(13)	11(15)	17(21)	19(23)
CTR (ps)	162.3	159.4	157.6	155.7	158.3	160.9
Pixels	2(6)	4(8)	10(14)	12(16)	18(22)	20(24)
CTR (ps)	161.8	157.1	150.9	152.4	159.8	157.1

Table 2

The CTRs for the 6 mm side crystal cubes air coupled to SiPMs. (A pair of SiPM array was tested).

Pixels	3	7	11	15	19	23
CTR (ps)	166.0	166.2	165.0	165.1	167.5	173.8
Pixels	4	8	12	16	20	24
CTR (ps)	165.7	159.7	167.0	169.1	167.8	169.9

Table 3
The mean CTRs for the 6 mm side crystal cubes coupled with optical glue. (32 pairs of SiPM arrays were tested).

Pixels	1	3	5	7	9	11	13	15	17	19	21	23
CTR (ps)	130.2	129.9	126.1	127.1	126.0	125.5	125.3	125.8	127.2	126.4	129.8	130.1
Pixels	2	4	6	8	10	12	14	16	18	20	22	24
CTR (ps)	130.1	127.6	128.4	126.6	127.0	124.8	124.2	126.6	126.1	127.8	127.8	123.0