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Optimization of a LSO-Based Detector Module for Time-of-Flight PET

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Abstract

We have explored methods for optimizing the timing resolution of an LSO-based detector module for a single-ring, “demonstration” time-of-flight PET camera. By maximizing the area that couples the scintillator to the PMT and minimizing the average path length that the scintillation photons travel, a single detector timing resolution of 218 ps fwhm is measured, which is considerably better than the ~385 ps fwhm obtained by commercial LSO or LYSO TOF detector modules. We explored different surface treatments (saw-cut, mechanically polished, and chemically etched) and reflector materials (Teflon tape, ESR, Lumirror, Melinex, white epoxy, and white paint), and found that for our geometry, a chemically etched surface had 5% better timing resolution than the saw-cut or mechanically polished surfaces, and while there was little dependence on the timing resolution between the various reflectors, white paint and white epoxy were a few percent better. Adding co-dopants to LSO shortened the decay time from 40 ns to ~30 ns but maintained the same or higher total light output. This increased the initial photoelectron rate and so improved the timing resolution by 15%. Using photomultiplier tubes with higher quantum efficiency (blue sensitivity index of 13.5 rather than 12) improved the timing resolution by an additional 5%. By choosing the optimum surface treatment (chemically etched), reflector (white paint), LSO composition (co-doped), and PMT (13.5 blue sensitivity index), the coincidence timing resolution of our detector module was reduced from 309 ps to 220 ps fwhm.

Index Terms

time-of-flight PET; LSO; timing resolution

I. INTRODUCTION

The past few years have seen a rebirth of time-of-flight positron emission tomography (TOF PET) [1–8]. Simple arguments predict that the statistical noise variance of PET images will improve by a factor of

$$\text{variance improvement} = 2D/c\Delta t \quad (1)$$

where D is the object diameter, c is the speed of light, and Δt is the coincidence timing resolution of the PET camera [9]. Timing resolutions of ~ 575 ps fwhm (full width at half maximum) have been achieved in commercial PET cameras [6, 8] based on lutetium oxyorthosilicate (LSO) [10–12], implying variance improvements (as compared to non-TOF PET) of approximately 4 for a 35 cm diameter “torso.” As better timing resolution promises further increases in the signal-to-noise ratio, there is a strong incentive to develop detector and camera systems with better timing resolution.

Previous work that investigated the individual factors that influence the timing resolution in a commercial PET detector module (the Siemens Accel [13, 14]) concluded that the coincidence timing limit when using a $6.15 \times 6.15 \times 25$ mm³ LSO crystal end-coupled to a photomultiplier tube (PMT) on the 6.15×6.15 mm² face is 550 ps fwhm [15], which agrees well with what was subsequently obtained [6, 8]. That work suggested that the timing resolution would be considerably better if the PMT were coupled to the 6.15×25 mm² face due to improved optics. We therefore designed a single-ring “demonstration” PET camera that utilizes the same LSO scintillator geometry (a closely-packed ring of $6.15 \times 6.15 \times 25$ mm³ crystals), but uses this coupling strategy. The goal is for the camera to obtain the best timing resolution possible without significantly altering the other PET performance measures (e.g., detection efficiency for gammas impinging on the ring and energy resolution). While we plan to use the camera to measure the noise reduction that is afforded by this improved timing resolution, the purpose of the work described herein is to optimize the timing resolution of the detector module that this camera will utilize.

II. BACKGROUND

A. Module & Camera Design

A photograph of the proposed detector module is shown in Figure 1. It consists of two LSO scintillator crystals, each $6.15 \times 6.15 \times 25$ mm³, that are coupled to a single Hamamatsu R-9800 PMT [16] on one of their 6.15×25 mm² faces. The five sides of each crystal that are not coupled to the PMT are covered with a white reflector, so there is no light sharing between the two crystals. However, the reflector on the face that is opposite the PMT has a hole in it (a 6 mm diameter semicircle) that is used to decode the crystal of interaction.

The R-9800 PMT was chosen because of its excellent timing properties. The manufacturer lists a 1 ns rise time and 270 ps fwhm transit time spread, and the timing resolution is very uniform over the face of the PMT. When a $4 \times 4 \times 22$ mm³ LSO crystal was coupled to 13 different positions on the face of the PMT and the timing resolution measured, the timing resolution varied by less than 6% rms [17].

Figure 2 illustrates how the crystal decoding is achieved. In this design, the modules will be assembled so that the scintillator crystals form a continuous, closely packed ring. The face of the scintillator with the hole in the reflector comes in contact with the PMT photocathode from an opposing detector module, but is separated by a small (<1 mm) air gap. When a 511 keV gamma ray interacts with one of the scintillator crystals (say Crystal 2A in Figure 2), it

produces a large signal in the PMT that the crystal is glued to (PMT 2 in Figure 2). In addition, some of the light from this interaction is also detected by the air-coupled PMT (PMT 1 in Figure 2), so a smaller signal (because of the relatively poor optical coupling) is also produced by that PMT. This limited light sharing is used to decode which scintillator crystal the gamma ray interacts in. Thus, an interaction in Crystal 2A yields a large signal in PMT 2 and a small signal in PMT 1. Similarly, an interaction in Crystal 2B yields a large signal in PMT 2 and a small signal in PMT 3. Both the timing and the energy are derived solely from the PMT that the crystal is glued to—information from the air-coupled PMT is only used for decoding. While this design produces exceptional timing resolution, it is limited to an axial thickness of one crystal. It can, however, form a complete ring with minimal inter-crystal gaps (Figure 3), and the crystal size, ring diameter, and detector material are identical to that of the Siemens Accel [13, 14], so this design closely mimics a commercial whole-body PET camera.

B. Measurement Method

Unless noted otherwise, all of the measurements presented are the timing resolution for a single detector module—the expected coincidence timing resolution for a pair of identical modules would be $\sqrt{2}$ times the number reported. To measure this resolution, we excite a trigger detector and the detector under test with annihilation photons from a positron source and use NIM electronics to measure the coincidence timing resolution. A Canberra 454 NIM constant fraction discriminator (CFD) with a delay of 0.7 ns and a fraction of 0.2 generated the timing pulses for both detectors and the time difference between the two CFD pulses was measured with an Ortec 556 NIM time to amplitude converter and a National Instruments PXI-7831R 16-bit analog to digital converter (ADC) read out by a personal computer. The annihilation photons from a 200 μCi ^{68}Ge source impinged normal to the $6.15 \times 6.15 \text{ mm}^2$ surface, which was ~ 5 cm from the source. The trigger detector (a 1 cm cube of BaF_2 coupled to a Hamamatsu H-6531 PMT that was also ~ 5 cm from the source) had 150 ps fwhm timing resolution and was used for all measurements. The pulse height in the detector module under test was also measured for each event by integrating (Cremat 200 shaping amplifier with 1 μs shaping time [18]) and digitizing with the PXI-7831R ADC, and only events with a measured energy between 425 and 600 keV were accepted. The timing resolution of the detector under test was computed by taking the measured coincidence timing resolution and subtracting (in quadrature) the 150 ps fwhm contribution from the trigger detector.

All LSO scintillator material was produced by Siemens Medical Solutions. For simplicity, all measurements (unless noted) used a single LSO crystal coupled to the PMT and did not have the 6 mm diameter hole in the reflector (the presence of this hole had minimal effect—it decreased the light output in the well-coupled PMT by $4 \pm 1\%$ and degraded the timing resolution by $2 \pm 1\%$). The LSO crystal was, however, positioned off-center on the PMT face to emulate the coupling geometry expected in the final detector module.

When possible, measurements were made on multiple detectors (usually 5) and averaged to increase accuracy. Unless noted otherwise, when a measured value is given, the value is the average over the ensemble of measurements (i.e., individual detectors) and the error associated with it is the standard error of the mean. The standard error of the mean is obtained by computing the standard deviation of the ensemble of measurements that were used to compute the mean, then dividing by the square root of the number of measurements in the ensemble (i.e., the number of detectors).

III. OPTIMIZATION

A. Coupling Geometry Optimization

The starting point for the detector optimization was a $6.15 \times 6.15 \times 25 \text{ mm}^3$ crystal of LSO scintillator crystal with a “saw-cut” surface finish (the surface was not processed after cutting) wrapped on 5 sides with 4 layers of white Teflon plumber’s tape [19]. This crystal was coupled to the Hamamatsu R-9800 PMT on a $6.15 \times 6.15 \text{ mm}^2$ face with optical coupling grease. With this geometry, a single detector timing resolution of $384 \pm 12 \text{ ps}$ was measured, where the value given is the average over five different crystals. Given the simplicity of this detector, it probably represents the limit that can be obtained with a conventional LSO scintillator crystal end-coupled to a PMT. It is interesting to observe that when multiplied by $\sqrt{2}$, this corresponds to a coincidence timing resolution of 543 ps , which is very similar to (although marginally better than) that of commercial TOF PET cameras [6, 8].

The same five crystals were each coupled to the PMT on a $6.15 \times 25 \text{ mm}^2$ face with optical coupling grease, the remaining 5 sides wrapped with 4 layers of Teflon plumber’s tape, and the timing resolution remeasured. With this side-coupled geometry, the average single module timing resolution was $218 \pm 8 \text{ ps}$, demonstrating the significantly improved timing resolution (a factor of 1.76) afforded by the side-coupled geometry.

B. Surface Treatment and Reflector Optimization

The reflection at the surface of the crystal was also optimized for timing, as both the surface treatment and the reflector affect the angular distribution of the reflected optical photons and therefore their path between the interaction point and the PMT. We therefore explored different combinations of surface treatment and reflector. The method used was to measure the timing resolution of a $6.15 \times 6.15 \times 25 \text{ mm}^3$ crystal of LSO scintillator twice. The first measurement was performed with saw cut surfaces that were coupled to the PMT on a $6.15 \times 25 \text{ mm}^2$ side and wrapped with Teflon tape on the other five sides. The same crystal then had a different surface treatment and reflector applied, the timing resolution with the new configuration was measured, and the ratio of the two timing resolutions computed. The surface treatments tested were saw-cut, chemically etched [20], and mechanically polished. The reflectors tested were Teflon, ESR (Enhanced Specular Reflector) film [21], Lumirror [22], Melinex [23], and white epoxy [24]. Some of these combinations had an air gap between the crystal and reflector, while for others the reflector was coupled to the surface (usually with glue) in such a way that there was no air gap.

The effects of the surface finish and reflector were evaluated by computing the ratio of the timing resolutions (test configuration divided by standard configuration). By measuring the same crystal with two different configurations, we eliminate other potential sources of crystal-to-crystal variation in timing resolution, such as light output or decay time. For each surface / reflector combination, the process was performed on five individual crystals, both the mean and the standard error of the mean were computed, and the results shown in Table 1. These data are shown in Table 1 and are from 110 individual LSO crystals, all of which were cut from the same boule of LSO and so presumably have very similar light output and decay time.

It is evident from Table 1 that there is not a large variation in timing resolution among the various combinations tested, and in most cases the ratio is consistent with 1.0. To help identify which surface treatment to use, we attempt to reduce the errors by assuming that all reflectors are identical, which increases the number of crystals in each ensemble from 5 to either 35 or 40, depending on the surface treatment. This larger number of samples both improves the accuracy in estimating the standard deviation of the measurement of the mean

and also increases the denominator in the standard error of the mean calculation. When we do this (the results are in the “Average” row in Table 1), we find that the timing resolution for the chemically etched surface is $5\pm1\%$ and $7\pm1\%$ better than the saw cut and mechanically polished surfaces respectively. A similar computation is performed to identify the best reflector (the “Average” column in Table 1), but there is no statistically significant difference between the reflectors.

The reflectors without an air gap tend to be more mechanically rugged than those with an air gap, which makes them appealing for use in a complete camera. This design also requires that there be a hole in the reflector in order to allow some light to be detected by the poorly-coupled PMT. Empirically, we found that a 6 mm diameter semi-circular hole allows an adequate amount of light to be detected by the poorly-coupled PMT (approximately 10%–20% of the light detected by the well-coupled PMT), and as stated in Section II.B, has minimal affect on the timing and energy resolution. Given these considerations, white spray paint [25] was chosen for the reflector, and a hole with reproducible dimensions was made by masking the crystal with an adhesive-backed paper label [26].

C. LSO Composition Optimization

The time dependence of the light output of a scintillator is often modeled as a single exponential decay, or

$$I(t)=I_0\exp(-t/\tau) \quad (2)$$

where I is the intensity (photons / ns), t is time, I_0 is the initial intensity (photons / ns), and τ is the decay time of the scintillator. Integrating Equation 2 over time from zero to infinity to get the total light output L , we see that

$$L=I_0\tau \text{ or } I_0=L/\tau. \quad (3)$$

Finally, we note that when the initial intensity is relatively high, the theoretical timing resolution of a scintillator scales inversely with the square root of the initial photoelectron rate [27, 28], which is equal to the initial intensity I_0 multiplied by two constants (the photon collection efficiency and the PMT quantum efficiency), that is:

$$\text{Timing Resolution} \propto 1/\sqrt{\varepsilon \cdot \text{QE} \cdot I_0}, \quad (4)$$

where ε is the collection efficiency and QE is the quantum efficiency.

Thus, theory predicts that timing resolution can be improved by increasing the scintillator light output and/or decreasing its decay time. Recent work has suggested that co-doping LSO with Ca can both increase its light output and reduce its decay time [29]. To test whether the timing resolution depends on these properties in the anticipated way, we obtained eight 5 mm cubes of “normal” LSO and fourteen additional 5 mm cubes of LSO that had atypical decay times and light output, including LSO with four different Ca concentrations (0.1%, 0.2%, 0.3%, and 0.4%). Figure 4 shows the light output and decay time for each sample, where a relative light output of 1.0 is defined as the average light output of the normal LSO. This figure shows that there is a substantial spread in both the decay time and the light output, and that the co-doped LSO (especially 0.1% and 0.2% Ca) had both higher light output and shorter decay time than normal LSO. As we have only a single sample of each type of LSO, we could not estimate an error based on measurements of multiple identical samples, and instead estimated them by re-wrapping, re-coupling, and

re-measuring a single sample ten times and computing the standard deviation of these measurements.

The values for decay time and relative light output shown in Figure 4 were used to compute I_0 , as given by Equation 3. The measured timing resolution was then plotted as a function of I_0 in Figure 5, as well as a theoretical curve with the same functional form as Equation 4 (i.e., the curve is inversely proportional to the square root of I_0). The data show that the measured timing resolution was consistent with the theoretical prediction, and that the co-doped LSO (especially 0.2% Ca, which had 178 ps time resolution) consistently outperformed the normal LSO (which averaged 205 ps time resolution). While the values for timing resolution shown in Figure 5 do not represent what we expect in our modules due to the different crystal geometry (5 mm cubes rather than $6.15 \times 6.15 \times 25$ mm³ parallelepipeds), we use the ratio of the timing resolutions for normal and Ca co-doped LSO to estimate that co-doped LSO will have ~15% better timing resolution than normal LSO. We therefore plan to use co-doped LSO to construct the camera.

D. Photomultiplier Tube Optimization

Equation 4 states that timing resolution is inversely proportional to the square root of the initial photoelectron rate, which is in turn proportional to the PMT quantum efficiency. Recent years have seen PMT manufacturers offer bialkali PMTs with higher quantum efficiencies than the 28% that is often considered typical [30, 31]. In particular, Hamamatsu Photonics has produced versions of the R-9800 PMT with enhanced quantum efficiency.

We therefore explored the dependence of the timing resolution as a function of the PMT “Blue Sensitivity” that is provided by the manufacturer. We used the blue sensitivity as a measure of the PMT response rather than the quantum efficiency, as the emission wavelength of LSO is centered at 415 nm and the blue sensitivity is a measure of the quantum efficiency between approximately 400 and 420 nm. This is contrasted to the quantum efficiency, as the manufacturer provides the “Peak QE,” which is the maximum value in the quantum efficiency versus wavelength curve, and usually occurs at wavelengths near 335 nm, which are not as representative of the LSO emissions.

To make this comparison, we prepared a “standard” crystal that is a $6.15 \times 6.15 \times 25$ mm³ parallelepiped of normal (not co-doped) LSO that is chemically etched and has Lumirror reflector (without a semi-circular hole) glued to it. This reflector was chosen because it had similar performance to the painted crystal, but is extremely rugged, particularly with respect to having optical coupling grease applied and cleaned off many times. This “standard” crystal was coupled to the different PMTs to be tested (4 PMTs having higher blue sensitivity and 13 “normal” PMTs) and the timing resolution is measured and plotted in Figure 6. As we have only a single PMT of each type, we could not estimate an error based on measurements of multiple identical PMTs, but estimated them instead by measuring a single PMT ten times and computing the standard deviation.

Although there is scatter in the data, Figure 6 shows that the timing resolution for the PMTs with higher blue sensitivity was about 5% better than those with the conventional photocathode. This improvement is consistent with the theoretical prediction in Equation 4—since blue sensitivity is proportional to QE, the resolution should be inversely proportional to the square root of the blue sensitivity. The manufacturers believe that the blue sensitivity can be increased to ~14.5, suggesting that an improvement of ~10% in timing resolution compared to PMTs with a conventional photocathode (blue sensitivity of ~12) can be realized.

IV. VERIFICATION

Section III describes the attempts to optimize several factors that affect timing resolution. At the time that we performed the optimization, we usually could not measure the timing resolution in the exact configuration that we desired, as appropriate components were not available. For example, we could not measure the effect of co-doping with $6.15 \times 6.15 \times 25 \text{ mm}^3$ etched LSO crystals, as the only co-doped crystals were 5 mm cubes with a saw-cut surface finish.

However, we can estimate the performance of a camera based on these optimizations by computing a multiplicative improvement factor (the timing resolution before optimization divided by the timing resolution after optimization) for each optimization step. By sequentially applying these multiplicative factors to the measured timing resolution from a starting configuration, we can estimate the timing resolution as the various improvements are applied. These improvement factors and the anticipated timing resolution (now given as the *coincidence* timing resolution, as this is more appropriate for a camera) are listed as the “Predicted Improvement Factor” and “Predicted Timing Resolution” columns in Table 2.

To verify that we could obtain this predicted performance, we constructed five modules of each type of configuration listed in Table 2. Many of the individual components were re-used when going from line to line in Table 2 in an attempt to minimize the number of changes. For example, the same PMTs and crystals were used in lines 1 (initial configuration) through line 3 (reflector change), the “normal” LSO crystals were replaced in line 4 with co-doped LSO crystals (which were used in both lines 4 and 5), and in line 5 only the PMTs were changed. The single module timing resolution of each of these modules was measured, and the mean timing resolution and the standard error of the mean computed. These values were multiplied by $\sqrt{2}$ to estimate coincidence timing resolutions and are listed in the “Measured Timing Resolution” column of Table 2. The measured values agree fairly well with the predictions. We also present the energy resolution for two configurations in Table 2, and note that the final detector module: 1) had significantly better energy resolution than that of the Initial Configuration and 2) is acceptable for a PET camera.

V. DISCUSSION & CONCLUSIONS

We performed a series of experiments to optimize the timing performance of a detector module based on a $6.15 \times 6.15 \times 25 \text{ mm}^3$ crystal of LSO. Changing the surface that was coupled to the PMT from a $6.15 \times 6.15 \text{ mm}^2$ surface to a $6.15 \times 25 \text{ mm}^2$ surface caused the timing resolution to improve by a factor of 1.76, which was by far the largest effect that we observe. The next most significant effect was to co-dope the LSO scintillator material to increase the light output and shorten the decay time, which improved the timing resolution by 15%. Using PMTs with higher quantum efficiency (a blue sensitivity index of 13.5 as opposed to 12) improved the timing resolution by an additional 5%. The surface finish and reflector used had minimal affect on the timing performance, with an etched surface being the only modification that gave a statistically significant performance difference. However, it is important to note that these results are for a side-coupled geometry—it is likely that the surface finish and reflector will have a greater affect with an end-coupled geometry.

These results confirm the importance of I_0 , the initial photoelectron rate, on the timing resolution. All the efforts to increase I_0 , whether by increasing the scintillator light output, decreasing the scintillator decay time, or increasing the PMT quantum efficiency, had essentially the same quantitative affect—the timing resolution improved by the square root of I_0 . These results also suggest that the crystal geometry plays a major and possibly underappreciated role in the timing performance. Changing the face of the scintillator crystal

that the PMT is coupled to from the “end” to the “side” improved the timing resolution by nearly a factor of two. Virtually all PET cameras with a non-trivial axial extent utilize end-coupling, which appears to limit their coincidence timing resolution (with LSO) to slightly more than 500 ps fwhm. This work suggests that major improvements are most likely to be gained by moving to a side-coupled geometry.

While a practical side-coupled geometry with good timing resolution has not yet been realized, appropriate technology is perhaps not too far away. Figure 7 shows a configuration where small scintillator pixels (4 mm cubes) are individually coupled to pixels of a silicon photomultiplier (SiPM) array. SiPMs have been shown to have appropriate performance for PET and in particular have been shown to have excellent timing resolution [32]. In addition, it has been shown that silicon photodetectors such as these can be thinned and inserted between layers of scintillator such that a closely packed array of scintillator crystals with negligible dead space between them could be created [33]. Because this proposed design utilizes small scintillator crystals individually coupled to photodetectors with good timing resolution, excellent timing resolution is expected. Other PET performance aspects are not sacrificed with this geometry. It is buttable with minimal dead space on four sides, and so can be used to create a multi-slice PET camera with a high scintillator packing fraction. As an added feature, it can be used to measure the depth of interaction on an event-by-event basis, and so would eliminate the radial elongation artifact and thus improve the camera's spatial resolution.

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Figure 1. Photograph of the detector module. Two optically isolated LSO crystals are attached to a single PMT. A semicircular hole in the reflector on each crystal decodes the interaction crystal—see text for details.

Figure 2.

Exploded view of the detector ring. When the detector modules are brought together (one of the groups of four modules is moved vertically), the crystals form a continuous ring with minimal gaps between crystals. Each crystal is well coupled optically to one PMT (via glue) and the opposing surface is poorly coupled (via an air gap) to another PMT.

Figure 3. Section of the camera ring. The camera is composed of 196 detector modules that form a single, complete ring. Lead shielding is used to reduce radiation from outside of the axial field of view.

Figure 4. Decay time and relative light output of LSO samples. Errors for the decay time are typically <2 ns, while errors for the relative light output are typically <5%.

Figure 5.

Timing resolution versus initial intensity I_0 for various LSO samples. The solid curve shows the theoretically predicted scaling with I_0 . Errors are fixed at ± 9 ps.

Figure 6. Timing resolution vs. blue sensitivity for several PMTs. The solid curve shows the theoretically predicted scaling with the initial photoelectron intensity. The data points indicated by large squares are the ones with higher blue sensitivity. Errors are fixed at ± 9 ps.

Figure 7. Conceptual design of a multi-layer TOF PET detector module. a) A portion of the module, consisting of eight individual 4 mm cubes of scintillator coupled to an 8×8 array of 4 mm square SiPM pixels. The SiPM array is thinned to be several hundred microns thick. b) A complete module is made by stacking alternate layers of SiPM arrays and scintillator pixels.

Table 1

Summary of surface treatment and reflector optimization. For each combination of surface treatment and reflector, we report the ratio between the measured timing resolution and the timing resolution of the same crystal with a saw cut surface finish and Teflon reflector (measured before the final surface treatment and reflector were applied). Error bars are the standard error of the mean.

Reflector	Saw Cut	Chemically Etched	Mechanically Polished	Average
Air Gap				
Teflon	1.00±0.08	0.94±0.04	1.06±0.02	1.00±0.02
ESR	1.01±0.04	0.96±0.07	1.08±0.04	1.02±0.02
Lumirror	1.03±0.06	0.96±0.03	1.04±0.05	1.01±0.02
No Air Gap				
ESR	0.99 ±0.04	0.98±0.01	1.01±0.08	0.99±0.02
Lumirror	1.04±0.04	0.97±0.04	0.98±0.10	1.00±0.02
Melinex	1.01±0.07	0.99±0.03	1.01±0.09	1.00±0.02
Epoxy	1.00±0.07	0.95±0.04	1.00±0.07	0.98±0.02
Paint		0.96±0.01		
Average	1.01±0.01	0.96±0.01	1.03±0.01	

Table 2

Summary of optimization factors. Measurements in Section III are used to compute multiplicative improvement factors, which are sequentially applied to obtained Predicted Timing Resolutions. These are compared to Measured Timing Resolutions obtained with test detector modules fabricated in the appropriate configuration. All timing resolutions are given as coincidence timing resolutions.

Configuration	Predicted Improvement Factor	Predicted Timing Resolution (ps fwhm)	Measured Timing Resolution (ps fwhm)	Measured Energy Resolution (fwhm)
Initial Configuration (End coupled, saw cut, Teflon tape, normal LSO, conventional PMT)		544	544±17	29±5%
End Coupling → Side Coupling	1.76	309	309±12	
Saw Cut, Teflon Tape → Etched, Paint, Semicircular Hole	1.04	297	321±14	
Normal LSO → Co-Doped LSO	1.15	258	258±13	
Conventional PMT → High QE PMT	1.05	245	220±11	18±3%