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Study of PET Detector Performance with Varying SiPM Parameters and Readout Schemes

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Abstract

The spatial resolution performance characteristics of a monolithic crystal PET detector utilizing a sensor on the entrance surface (SES) design is reported. To facilitate this design, we propose to utilize a 2D silicon photomultiplier (SiPM) array device. Using a multi-step simulation process, we investigated the performance of a monolithic crystal PET detector with different data readout schemes and different SiPM parameters. The detector simulated was a 49.2mm by 49.2mm by 15mm LYSO crystal readout by a 12 by 12 array of 3.8mm by 3.8mm SiPM elements. A statistics based positioning (SBP) method was used for event positioning and depth of interaction (DOI) decoding. Although individual channel readout provided better spatial resolution, row-column summing is proposed to reduce the number of readout channels. The SiPM parameters investigated include photon detection efficiency (PDE) and gain variability between different channels; PDE and gain instability; and dark count noise. Of the variables investigated, the PDE shift of $-3.2 \pm 0.7\%$ and gain shift of $-4 \pm 0.9\%$ between detector testing and detector calibration had the most obvious impact on the detector performance, since it not only degraded the spatial resolution but also led to bias in positioning, especially at the edges of the crystal. The dark count noise also had an impact on the intrinsic spatial resolution. No data normalization is required for PDE variability of up to 12% FWHM and gain variability of up to 15% FWHM between SiPM channels. Based upon these results, a row-column summing readout scheme without data normalization will be used. Further, we plan to cool our detectors below room temperature to reduce dark count noise and to actively control the temperature of the SiPMs to reduce drifts in PDE and gain.

Keywords

Continuous crystal detector; Statistics-based positioning (SBP); SiPM

I. Introduction

Small animal PET offers researchers a non-invasive imaging technique to perform longitudinal animal studies. Since mice are generally three orders of magnitude smaller than

a human, it requires a small animal PET system to have very high spatial resolution and sensitivity. We have previously reported on a high resolution, monolithic crystal small animal PET detector design that provides depth of interaction (DOI) positioning within the crystal [1,2]. This design utilizes a novel sensor on the entrance surface (SES) design combined with a maximum likelihood (ML) positioning algorithm. Since the majority of interactions happen in the front section of the crystal, placing photosensors on the entrance surface could improve spatial resolution compared to placing photosensors on the exit surface of the crystal. Our preliminary results indicate that the SES design approach provides outstanding X, Y and DOI resolution and allows the detector to achieve nearly the same intrinsic spatial resolution for normally and 45° incident photon fluxes. In addition to our work there are a number of other laboratories investigating high resolution, monolithic crystal PET detector designs [3-8].

One of the keys to the SES design is the development of SiPM arrays [9,10]. SiPMs provide very high proportional signal gain, have potentially very fast timing, and can be fabricated in user specified geometries. Many research efforts have been devoted to utilizing this new photosensor technique for PET detectors [11,12]. In our application, we are taking advantage of the fact that SiPMs are very thin and can be placed on the entrance surface of the crystal without having a significant attenuation effect. In addition, SiPMs can be operated in high magnetic fields, which enables PET/MR multimodal imaging.

In order to achieve optimal PET detector performance with currently available SiPMs, simulations were conducted to investigate the impact on PET detector performance due to different data readout schemes and different SiPM performance parameters.

II. Detector Design and Methods

A. Detector setup

Figure 1 shows the detector setup using the SES design. For this initial work, the crystal was modeled as a 49.2mm by 49.2mm by 15mm slab of LYSO. An octagonal detector ring with 120mm inner diameter could be built with 8 of these detector modules. The thickness of the crystal was chosen to study the tradeoff between resolution and sensitivity [13]. One hope was that the SES approach could provide similar intrinsic spatial resolution as a monolithic crystal detector readout using a conventional approach but with a significantly thicker crystal detector. The sides of the crystal were painted black. Our previous work has shown that this improves positioning performance. The bottom of the crystal is painted white for high light collection efficiency. The top of the crystal is polished and coupled to the 12 by 12 array of 3.8mm by 3.8mm SiPM elements with 4.1mm center-to-center spacing. Considering the symmetry of the detector, one eighth of the crystal was simulated to speed up the calibration and testing process. For calibration, the events were simulated as having 0.6mm FWHM photon fluxes perpendicular to the detector to within 1.025mm of the crystal edge. The 0.6mm beam FWHM was selected since it corresponds with what we are able to experimentally achieve in our lab. Our previous simulation studies show that the 0.6mm calibration beam FWHM degrades the resolution by 7% compared to using point calibration fluxes (i.e., unpublished results). For testing, the events were simulated as having point fluxes of normal incidence to within 2.05mm of the crystal edge. The spacing between photon fluxes was 1.025mm along the X and Y axes and the effect of Compton scatter in the crystal was included for both calibration and testing data.

B. SiPM parameters

SiPMs are widely recognized as a new generation of photosensors competitive with PMT and APD for PET detector applications because of their high gain, magnetic field insensitivity, compact size and fast timing. However, besides these advantages, SiPMs also

have non-ideal characteristics, that include nonlinear response, dark count noise and temperature sensitivity [14,15]

Different from many other photosensors, the performance of SiPMs is affected by the inherent nonlinearity of the SiPM response [14]. The measured electric signal exhibits a nonlinear relationship to the number of detected incident photons due to saturation, after pulsing, and crosstalk. When the number of detected incident photons is large compared to the number of microcells in a SiPM channel, saturation plays an important role. When the number of detected incident photons is small compared to the number of microcells in a SiPM channel, after pulsing and crosstalk effects are important. Corrections might be required if the nonlinear effects degrade the detector performance.

Two of the most important parameters for SiPMs are their photon detection efficiency (PDE) and gain uniformity between different channels. For a monolithic crystal PET detector, one crystal is readout by an array of SiPM elements. The PDE and gain for each channel are usually different because the breakdown voltage for each SiPM array element varies [16,17]. It is unclear how this PDE and gain variation within the SiPM array might affect the performance of a monolithic crystal PET detector and whether signal normalization is required.

Another complication is that the SiPM PDE and gain are temperature sensitive, since the breakdown voltage is dependent on temperature [17,18]. The fluctuation or shift in PDE and gain between detector characterization and data collection might lead to positioning bias and degrade spatial resolution. Therefore, temperature monitoring and control might be needed for optimal detector performance.

Like most semiconductor devices, SiPMs are susceptible to thermal noise. Preliminary results by us and other groups show that the dark count noise increases significantly with temperature [19,21]. The dark count noise due to thermally generated electrons may degrade the positioning resolution of a detector.

Finally the excess noise factor due to multiplication is usually 1.01~1.05, which is very low due to the negative feedback of SiPM [15].

C. Simulation program for evaluating detector performance

The simulation tools that we previously integrated were modified to investigate the PET detector performance with different SiPM parameters [22]. Figure 2 shows the multi-step modeling procedure.

GEANT [23] is used to track the gamma ray interactions (both Compton scatter and photoelectric) within the crystal. The non-proportionality of LYSO is modeled according to tables reported by Rooney [24,25]. DETECT2000 [26,27] is used to determine the probability that a light photon generated at a specific position in the crystal is detected by a specific photosensor channel.

For our SiPM array, we used an average PDE of 0.16. This is within the range of PDE's reported for different devices [19]. A Gaussian distributed normalization table with 12% FWHM is used to represent the PDE variability between different channels [16,17]. To test how PDE shifts affect the detector performance, the PDEs for the testing data were shifted by $-3.2 \pm 0.7\%$ compared to detector calibration. This represents the PDE shift caused by a -1°C temperature shift. [17,18]

To test how dark count noise affects detector performance, Poisson noise with mean value of 1 or 2 was added to each SiPM channel. Assuming 120ns signal integration time, this

represents dark count rates of 0.6MHz/mm² and 1.2MHz/mm², which corresponds to typical dark count rates at 20°C and 10°C for currently available SiPM devices [19].

The nonlinear response of the SiPM array due to saturation, crosstalk and after pulsing is simulated based on the model presented by Schaart's group [14]. We assume that there are 3080 microcells in each SiPM channel [19]. The crosstalk probability is 3% and the after pulsing probability is 5% [20]. The SiPM recovery time constant is 20ns [20]. The after pulsing time constant is 20ns [20]. The decay time of LYSO is 41ns [14]. Calculated using these parameters, the nonlinear response of SiPM is 1.07-1.01 for 1-1000 detected incident photons. It is greater than 1 because for a continuous crystal detector the number of detected incident photons is small compared with the number of microcells. Therefore, crosstalk and after pulsing play a more important role than saturation.

To test how non-uniform gains affect the detector performance, the number of light photons detected by the SiPM array was adjusted by a Gaussian distributed table with 15% FWHM between different channels. To test how gain shifts affect the detector performance, the gains for the testing data were shifted $-4 \pm 0.9\%$ compared with the gains during detector calibration. At the end, Gaussian noise was added to account for the multiplication noise. The excess noise factor due to multiplication noise is 1.05.

D. Statistics-based positioning (SBP) algorithm with DOI decoding

A statistics based positioning (SBP) algorithm is used to improve the detector positioning characteristics of the detector compared to standard or modified Anger positioning schemes [27]. Figure 3 shows the procedure of the positioning algorithm.

Suppose, the distributions of observing signal outputs $M = M_{j=1, \dots, n}$ for scintillation position $\vec{x} = (x, y, z)$, are independent normal distributions with mean, $\mu_{i=1, \dots, n}(\vec{x})$, and standard deviation $\sigma_{i=1, \dots, n}(\vec{x})$. The likelihood function for making any single observation $m = m_{j=1, \dots, n}$ from distribution M given $\vec{x}$ is:

$$L[m | \vec{x}] = \prod_{i=1}^n \frac{1}{\sigma_i(\vec{x}) \sqrt{2\pi}} \exp \left(-\frac{(m_i - \mu_i(\vec{x}))^2}{2\sigma_i^2(\vec{x})} \right) \quad (1)$$

The ML estimator of the event position $\vec{x}$ is given by:

$$\hat{\vec{x}} = \arg \min_{\vec{x}} \left[\sum_{i=1}^n \frac{(m_i - \mu_i(\vec{x}))^2}{2\sigma_i^2(\vec{x})} + \ln(\sigma_i(\vec{x})) \right] \quad (2)$$

The SBP method requires that the light response function for each channel versus interaction location be characterized for the detector. Two SBP look-up tables (LUTs) corresponding to the mean and standard deviation of the light response function versus position are created during calibration.

To further improve the decoding performance of the detector, a ML clustering method is used to extract DOI information during the calibration of the detector module [28]. For the application in this paper, the DOI separation technique divides the calibration data into seven different DOI regions. LUTs are then created for each DOI region. Based on the 7-depth DOI LUTs, a third-order polynomial fit is applied to the mean and standard deviation for each (x,y) position. Then, 15-depth DOI LUTs are generated from the fitting result to allow 3D positioning within our detector module.

Three different readout schemes were investigated: individual channel readout with data normalization, row-column summing readout with data normalization and row-column summing readout without data normalization. The row-column summing readout scheme reduces the number of readout channels from 144 to 24, which could save the cost and computation time of the system. Data normalization before row-column summing might be needed to reduce the effects due to non-uniform PDEs and gains between the SiPM array elements and the nonlinear response of SiPMs.

III. Results

A. Results from different readout schemes

Figure 4 illustrates the 2 dimensional FWHM contour plots using different data readout schemes with 1.025mm spacing in X/Y to within 2.05mm of the crystal edge. To plot out the contour curves, 2 dimensional histograms of X/Y positioning results at different fixed testing positions were calculated first. Then the FWHM contour curves were plotted at 50% of the peak values of the histograms for each testing position. The calibration data and testing data use the same PDE table and gain table, which has 12% FWHM and 15% FWHM between different SiPM channels respectively. The average dark count rate is 0.6MHz/mm².

Table I summarizes the intrinsic resolution performance over all testing positions. To generate the average resolution, the local resolutions were computed at each testing position, then the average of these resolution values were calculated. The standard deviation of the resolution represents the resolution uniformity across the whole crystal. As expected, the individual channel readout scheme provides better spatial resolution performance than row-column summing readout schemes. When using the row-column summing readout scheme, whether applying data normalization or not before summing the data doesn't affect the X/Y/DOI spatial resolution.

Figure 5 shows the X/Y/DOI resolution and bias using row-column summing readout without data normalization. Consistent with the contour plots in figure 4 (c), the X/Y/DOI resolution is better at the crystal center and worse at the crystal edges. The X/Y bias is very small except at the very edge of the crystal, which is biased towards the edge of the crystal. The DOI bias is towards the bottom of the crystal. The grid pattern seen in the figures is due to gaps between different SiPM channels.

Figure 6 shows how DOI resolution depends on depth. As expected, the DOI resolution is better for events occurring closer to the SiPM arrays, which shows the advantage of placing photosensors on the entrance surface of the crystal, since most interactions occur in the front section of the crystal. The DOI resolution for the last (15th) depth is slightly better than the 14th depth because of the truncation at the bottom of the crystal.

In order to test the statistical accuracy of the quoted X/Y/DOI resolution, 50 sets of testing data with the same parameters were generated and positioned using the same SBP algorithm based on row-column summed data without data normalization. Figure 7 displays the resolution results for the 50 runs. The X/Y resolution in FWHM is 0.863 ± 0.002 mm. The DOI resolution in FWHM is 1.953 ± 0.002 mm.

B. Results with different dark count rates

Figure 8 shows the 2 dimensional FWHM contour plots with average dark count rate of 1.2MHz/mm² with 1.025mm spacing in X/Y to within 2.05mm of the crystal edge. The same PDE and gain tables as described above were used. Row-column summing without data normalization was used for SBP positioning.

As seen in Table II, the X/Y/DOI resolution averaged over all testing positions degrades when dark count noise increases. When reducing the average dark count rate from 1.2MHz/mm² to 0.6MHz/mm², 6% improvement for X/Y resolution and 5% improvement for DOI resolution are achieved.

C. Results with PDE shift and gain shift

Figure 9 (a) shows the contour plots when there is a -1°C temperature shift that corresponds to a PDE shift of $-3.2 \pm 0.7\%$ and gain shift of $-4 \pm 0.9\%$ for testing data with 1.025mm spacing in X/Y to within 2.05mm of the crystal's edge. The 12% PDE variation and 15% gain variation remain the same. The average dark count rate is 0.6MHz/mm². Row-column summing without data normalization and SBP were used for positioning. As shown, for testing positions 3.075mm from the crystal edge, the X/Y resolution is degraded and there is positioning bias. The testing positions 2.05mm from the crystal edge seem to have good resolution because events positioned to within 1.54mm were thrown away.

Figure 9 (b) shows the contour plots for the same positioning results as figure 9 (a), except that only testing events to within 3.075mm of the crystal were shown and events positioned within 2.56mm of the crystal edge were thrown away.

Table III shows the X/Y/DOI resolution averaged over all testing positions to within 3.075mm of the crystal edge. Events positioned within 2.56mm of the crystal edge were thrown away. When there is a PDE shift of -3.2% and gain shift of -4% for the testing data, the DOI resolution is degraded by 14%; the variability in X/Y/DOI resolution increases. The events are positioned towards the edge and bottom of the crystal.

IV. Discussion and conclusion

A multi-step simulation study was conducted to evaluate the performance characteristics of a monolithic crystal PET detector with SES design. The performance characteristics of the SiPM were modeled in the simulation. Different data readout schemes were studied. The impact on the detector performance due to varying SiPM parameters was investigated.

Of the varying data readout schemes investigated, individual channel readout with data normalization provides the best positioning performance. However, we will choose row-column summing readout scheme for our proposed PET scanner since it reduces the number of readout channels from 144 to 24 and still provides acceptable spatial resolution performance. No data normalization is required for PDE variation of up to 12% FWHM and gain variation of up to 15% FWHM before row-column summing the data. Data normalization might be needed if there is greater PDE variation and gain variation between different SiPM channels or the nonlinear effects of SiPM are greater.

A -1°C temperature change corresponding to a $-3.2 \pm 0.7\%$ PDE shift and $-4 \pm 0.9\%$ gain shift between testing data and calibration data leads to not only degraded X/Y/DOI resolution but also positioning bias. For a negative gain shift, the testing events are biased towards the edge and bottom of the crystal, which can introduce artifacts in the reconstructed images. The biggest impact is seen near the edges of the crystal. Since the PDEs and gains of the SiPMs are sensitive to temperature, the temperature of the system needs to remain constant for optimal system performance. We will also investigate monitoring the temperature of the detectors and using PDE/gain calibration tables to compensate for any temperature changes to the system or using temperature calibrated look up tables to remove bias in the event positioning similar to linearity correction tables for gamma cameras. Since the biggest distortion to the positioning results occurs near the edges of the detector, we can reduce the useful imaging area of the detector if the techniques proposed above are not effective. This

will reduce the sensitivity of the detector; however, potential artifacts for the reconstructed image would be removed.

Among the SiPM parameters investigated here, dark count noise also has a relatively large impact on performance. Therefore, we have plans to cool the system below room temperature (e.g., 10°C) to reduce the dark count rates at which the SiPMs will be operating. We plan to stay above the temperature where condensation will become a problem.

In summary, based on this simulation study, row-column summing readout with signal normalization will be used for our proposed PET scanner. We plan to cool and actively control the temperature of the SiPM array below room temperature to reduce the dark count rate and gain shifts due to temperature variations.

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Fig. 1.
SES design PET detector with sensor on the entrance surface of the crystal.

Fig. 2.
Flow chart illustrating the multi-step simulation procedure to evaluate the PET scanner performance.

Fig. 3. Flow chart for 3D SBP positioning algorithm. DOI decoding is based upon light distribution function.

Fig. 4. 50% contour plots of SBP positioning for dark count rate of 0.6MHz/mm^2 and no gain shift. (a) Individual channel readout with data normalization; (b) Row-column summing readout with data normalization; (c) Row-column summing readout without data normalization.

Fig. 5.

The spatial resolution and bias using row-column summing readout without data normalization for dark count rate of 0.6MHz/mm^2 and no gain shift. (a) X/Y resolution; (b) X/Y bias; (c) DOI resolution; (d) DOI bias.

Fig. 6.

DOI resolution for different depths of SBP positioning using row-column summing readout without data normalization for dark count rate of 0.6MHz/mm^2 and no gain shift.

Fig. 7. Spatial resolution of SBP positioning for different runs using row-column summing readout without data normalization for dark count rate of 0.6MHz/mm^2 and no gain shift, using row-column summing readout without data normalization. (a) X/Y direction; (b) DOI direction.

Fig. 8.
50% contour plots of SBP positioning using row-column summing readout without data normalization for dark count rate of 1.2MHz/mm^2 and no gain shift.

Fig. 9.

50% contour plots of SBP positioning using row-column summing readout without data normalization for dark count rate of 0.6MHz/mm^2 and PDE shift of $3.2\pm 0.7\%$ and gain shift of $4\pm 0.9\%$. (a) Testing events to within 2.05mm of the crystal's edge; (b) Testing events to within 3.075mm of the edge of the crystal.

Table I

Varying readout scheme, dark count rate = 0.6MHz/mm^2 , no PDE or gain shift

Readout	Dimension	Bias (mm)	FWHM (mm)
Individual channel With normalization	X/Y	0.01 ± 0.03	0.75 ± 0.12
	DOI	0.02 ± 0.16	1.76 ± 0.20
Row-column sum, With normalization	X/Y	0.01 ± 0.04	0.86 ± 0.13
	DOI	0.00 ± 0.16	1.94 ± 0.24
Row-column sum, No normalization	X/Y	0.01 ± 0.04	0.86 ± 0.14
	DOI	0.01 ± 0.17	1.95 ± 0.26

Table II

Varying dark count rate, no PDE or gain shift, row-column summing without normalization.

Dark count rate	Dimension	Bias (mm)	FWHM (mm)
0.6MHz/mm ²	X/Y	0.01±0.04	0.86±0.14
	DOI	0.01±0.17	1.95±0.26
1.2MHz/mm ²	X/Y	0.01±0.04	0.91±0.14
	DOI	0.02±0.18	2.05±0.26

Table III

Varying PDE and gain shift, dark count rate = 0.6MHz/mm², row-column summing without normalization.

PDE/Gain shift	Dimension	Bias (mm)	FWHM (mm)
No shift	X/Y	0.00±0.02	0.84±0.09
	DOI	-0.02±0.14	1.91±0.21
PDE: -3.2% Gain: -4%	X/Y	0.06±0.07	0.85±0.13
	DOI	0.07±0.35	2.18±0.45