Published in final edited form as:

IEEE Nucl Sci Symp Conf Rec (1997). 2007 October 26; 2007: 4308–4313. doi:10.1109/NSSMIC.2007.4437069.

Improving the intrinsic spatial resolution performance of the continuous miniature crystal element (cMiCE) detector

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Abstract

We have previously reported performance characteristics of a cMiCE detector composed of a 50 mm by 50 mm by 8 mm thick slab of LYSO, coupled to a 64 channel flat-panel PMT. In that work, all 64 PMT channels were digitized and a statistics-based positioning method was used for event positioning. In characterizing the detector, the intrinsic spatial resolution performance for the corner sections of the crystal was degraded compared to the central section of the crystal, even when using our SBP method. It is our belief that the poorer positioning performance at the corners is because much of the light is lost (i.e., not collected by our PMT). To offset this problem, we propose to place light sensors (i.e., micro-pixel avalanche photo diodes, MAPD) at the corners along the short edge of the crystal. The new design would require an additional 8 MAPD devices. Monte Carlo simulation was used to compare the performance of the original cMiCE design and this new enhanced design. Simulation results using DETECT2000 are presented. In addition to doing light ray tracing, GEANT was used to track gamma interactions (i.e., Compton scatter and photoelectric absorption) in the crystal. Thus the simulations include the effects of Compton scatter in the detector. Results indicate that adding the sensors improves the intrinsic spatial resolution performance from 0.99 mm FWHM to 0.79 mm FWHM for the corner section of the crystal, thereby nearly matching the intrinsic spatial resolution of the center section of the crystal (i.e., 0.73 mm FWHM). These results are based upon using dual-DOI look up tables. Additional results were that energy histograms were better using just the 64 channels from the flat panel PMT than using all 72 signal channels.

Keywords

Continuous crystal; high spatial resolution; PET detector; statistics-based positioning

I. Introduction

Discrete crystal detector modules have traditionally been used to achieve high spatial resolution for small animal positron emission tomography (PET) scanners [1-8]. However, cost goes up considerably as one uses smaller and smaller cross-section crystals. We have previously investigated a continuous miniature crystal element (cMiCE) detector composed

of a 50 mm by 50 mm by 8 mm thick slab of LYSO coupled to a 52 mm square, 64-channel flat panel photomultiplier tube (PMT, Hamamatsu H8500, Japan) as a lower cost alternative to high resolution discrete crystal designs [9,10]. A statistics based positioning (SBP) algorithm [11], similar to previously proposed Maximum-likelihood (ML) methods [12-14], is used which improves the positioning characteristics of the detector versus using standard or modified Anger positioning schemes. This improvement is most dramatic near the edges and corners of the crystal.

However even with this improved performance, the intrinsic spatial resolution for the corner sections of the crystal is still degraded compared to the central section of the crystal. It is our belief that the poorer positioning performance at the corners is because much of the light is lost (i.e., not collected by our PMT). The loss of light at the corner and edges of the crystal is exacerbated because we paint the edges of the crystal black to reduce reflection of light off the edges. In the extreme case, ~75% of the light produced in the crystal can be absorbed by the painted edges. To offset this problem, we propose to place light sensors (i.e., micro-pixel avalanche photo diodes, MAPD) at the corners of the crystal as illustrated in Figure 1. MAPDs are a new type of photodiode with Geiger mode operation [15,16]. Current devices have a 1 mm by 1 mm active area and are composed of ~1000 individual micro-channels, referred to as micro-cells. Even though individual micro-channels do not provide a proportional output because the micro-channels are very small (i.e., 20-100 μm on a side) when combined together the MAPD is able to provide a proportional signal if no micro-channel detects more than one optical photon during the avalanche and ‘recovery’ time of the device, typically 50-150 nsec. MAPDs provide very high signal gain ($\sim 10^5$), have potentially very fast timing ($< 100\text{ps}$), require a low bias voltage ($\sim 130\text{ V}$), can be fabricated in user specified geometries and can be operated in high magnetic fields. In our application, we are taking advantage of the fact that MAPDs are intrinsically very thin and therefore can be placed along the sides of the crystal without significantly reducing the packing fraction of a ring of detector modules. While placing MAPDs all along the edge of the crystal would probably lead to even better performance, we wanted to minimize the number of additional signal channels. Our proposed design only requires an additional 8 signal channels. Monte Carlo simulation was used to compare the performance of the original cMiCE design and this new enhanced design (cMiCE-72).

II. Materials and Methods

A. Statistics-based Positioning Method (SBP) [11]

Suppose, the distributions of observing signal outputs $M = M_1, M_2, \dots, M_n$ for scintillation position x , are independent normal distributions with mean, $\mu(x)$, and standard deviation $\sigma(x)$.

The likelihood function for making any single observation m_i from distribution M_i given x is:

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

The maximum likelihood estimator of the event position x is given by:

$$\hat{x} = \underset{x}{\operatorname{argmin}} \left[\sum_i \frac{(m_i - \mu_i(x))^2}{2\sigma_i^2(x)} + \ln(\sigma_i(x)) \right] \quad (2)$$

The SBP method requires that the light response function versus interaction location be characterized for the detector. Two SBP look-up tables (LUTs) corresponding to the mean and variance of the light probability density function (PDF) versus (x,y) position are created during the characterization process.

B. Look-up Table Generation

Two sets of LUTs were generated. The first set assumed only photoelectric interactions in the crystal (PE LUT). The second set included the effects of both Compton scatter and photoelectric interactions (Compton LUT). In addition, single depth and dual depth of interaction LUTs were generated [10]. Generation of the LUTs is described below.

DETECT2000 simulations—The DETECT2000 simulation package [17,18] was used to model the detector module. For this initial work, the crystal was modeled as a 48.8 mm by 48.8 mm by 8 mm slab of LSO. An 8 by 8 array of anode pads (i.e., DETECT surfaces), 5.8 mm by 5.8 mm with 6.08 mm center-to-center spacing, was placed on the backside of a 2 mm thick glass PMT window. In addition, 6 mm by 6 mm MAPD DETECT surfaces were placed at the corners of the crystal as illustrated in Fig. 1. This results in a total of 72 DETECT2000 surfaces placed on the crystal. The short sides of the crystal not viewed by the DETECT2000 surfaces were modeled as being painted with low reflectivity paint (reflectivity coefficient = 0.10). For the DETECT2000 characterization all interactions were photoelectric (i.e., no Compton scatter). 2500 light photons were produced per detected event. This accounts for the light produced by LSO and the quantum efficiency of the PMT's photocathode. The crystal was divided into 0.1 mm thick DOI slices. The number of interactions in each DOI slice was adjusted to take into account the linear attenuation coefficient of LSO. However within each 0.1 mm zone, the probability of interaction was equally distributed.

Data from the above DETECT2000 simulations were used to generate the light propagation probability function $p_i(x, y, z)$, which is the probability of an isotropically outgoing light photon from location (x, y, z) inside the crystal reaching the i-th photosensor, where i goes from 1 to 72 (i.e., 64 PMT channels and 8 MAPD channels).

One eighth of the crystal (as illustrated in Fig. 2) was characterized. Since the crystal and photosensor array are symmetric, the results for one eighth of the detector are representative of the characteristics for the whole detector. The DETECT2000 characterization was then used in combination with GEANT [19] simulations to characterize the detector's light response function including the effects of Compton scatter (i.e., the Compton LUTs). Only the photoelectrically absorbed events are extracted to build the PE LUTs.

GEANT simulations—GEANT [19] was used to simulate the photoelectric absorption and Compton scattering of 10,000 perpendicularly incident annihilation photons at each characterization position as shown in Fig. 2. The output from the GEANT simulations provided the interaction locations and energy deposited for each interaction in the crystal. We assumed a LSO light yield N of 23,000 scintillation photons/MeV and a PMT efficiency Q of 22.5%. Non-proportional scintillation light production was implemented by discounting the expected number of light photons generated at each interaction vertex. The correction factor R was taken from the experimental electron response function from [20].

We assume that the actual number of scintillation photons released at each vertex follows a Poisson distribution. For each event the expected number of light photons received by the i-th PMT channel, λ_i can be calculated by

$$\lambda_i = Q \sum_j \text{Poisson} \left(N p_i \left(\frac{-}{x_j} \right) R(E_j) E_j \right) \quad (3)$$

where j is the index for each interaction vertex, E_j is the energy deposited at the j -th interaction vertex, and p_i is the light propagation probability function determined from the DETECT simulations. N , Q , and R are as described above. We further assume that the response of each channel follows an independent Poisson distribution with mean λ_i . Thus a new set of simulation data that included the effect of Compton scattering in the detector were generated.

Dual depth of interaction LUT—We have previously published on a maximum likelihood clustering algorithm to build LUTs for two DOI regions (2-DOI LUT) [10]. The basic principle is that the magnitude of the light signals associated with the PMT channels nearest to the photon point of interaction in the crystal are correlated with DOI. The channel that carries the most DOI information is the one directly below where the interaction occurred. As the depth of interaction increases (i.e., interaction point gets closer to the PMT), the light signal collected by the PMT also increases. After an initial separation based upon the signal from the PMT channel directly under the point of interaction, the signals from a subset of channels are sorted into different DOI regions based upon the likelihood that the set of signals came from a given DOI region. In this work we divided the crystal into two DOI regions, but in principle the technique can be used to separate a crystal into more DOI regions depending upon the light response characteristics.

C. Performance Evaluation

The energy and intrinsic spatial resolution characteristics of the cMiCE-72 detector module were evaluated using only the 64 PMT channel signals and using all 72 (64 PMT channels plus 8 MAPD) signals. The intrinsic spatial resolution was determined using the PE and Compton LUTs and single depth and dual-depth LUTs.

The dual depth LUTs were also evaluated on how accurately events were assigned to the correct DOI layer. The misclassification rate (MR) was determined for LUTs and testing data with and without Compton scatter interactions. Since this study uses simulated data, the point of first interaction in the crystal is known and the data can be easily sorted between photoelectric only and events that include Compton scatter.

III. Results

Energy Spectra

Representative energy spectrum plots of the summed signal from 64 or 72 photosensors are illustrated in Figures 3 and 4. The energy spectra, Figure 3, are similar for interactions occurring near the center (i.e., center of X, Y axes) of the crystal. However, for interactions occurring near the corner of the crystal the energy spectrum using all 72 signal channels is double peaked, Figure 4.

Contour plots illustrating the FWHM for each of the point fluxes positioned using the 64 and 72 channel SBP LUTs including the effects of Compton scatter on the LUT generation are illustrated in Fig. 5.

Tables I and II summarize the intrinsic spatial resolution performance using either 64 or 72 signal channels and a single depth LUT. Table I lists the results for the center (i.e., central 8×8 points) and corner (i.e., 8×8 points in the corner, excluding last row and column at the

edge) regions of the crystal including the effects of Compton scatter. SBP-64 is using just the 64 PMT channels for positioning and SBP-72 is using the 64 PMT channels plus the 8 MAPD channels for positioning. Table II summarizes the overall intrinsic spatial resolution results with and without the effects of Compton scatter. The PE LUT tables were generated from photoelectric only interactions. The two sets of columns refer to the testing data. For the first two columns of results, the testing data set included all events (i.e., that underwent both Compton scatter and photoelectric absorption). For the second set of columns, the testing data set only included single interaction photoelectric events.

Tables III and IV summarize the intrinsic spatial resolution performance using either 64 or 72 signal channels and a dual depth LUT with and without the effects of Compton scatter.

Table V summarizes the DOI decoding performance of the dual depth LUTs. An event was considered misclassified if it was not assigned to the DOI layer in which the first interaction occurred.

IV. Discussion

The energy spectrum using all 72 sensor channels is better for events interacting near the center region (i.e., X, Y axes) of the crystal as slightly more light is collected. However, the energy spectrum using all 72 sensor channels is distorted for events occurring near the corner of the detector. Based upon the energy spectrum results we will only use the 64 PMT channels for energy information.

Event positioning was always better using the 72 channel LUTs. The improvement was pretty small for the central section of the detector; however, was significant for the corner section of the crystal. Having the corner MAPD sensors improved the intrinsic spatial resolution by ~20%. This improvement was achieved when using either the single depth or dual depth LUTs. The intrinsic spatial resolution achieved using simulation and the 64 PMT signals is better than our experimentally measured results. The main reasons for this is that for simulation the point source is infinitely small while experimentally it is at least 0.52 mm FWHM. In addition it is very difficult to create a focused point source without additional blurring due to small angle Compton scatter from the collimating assembly. While the absolute intrinsic spatial resolution values were different, the trends between the center and corner regions were similar. Thus we believe we will see similar improvement in going from 64 channels to 72 signal channels in our experiments.

The dual depth LUTs provided slightly better intrinsic spatial resolution performance compared to the single depth LUT. This is significant because the intrinsic spatial resolution was evaluated for photon fluxes perpendicular to the surface of the detector. Having an additional bit of DOI information will lead to even more improvement in the positioning accuracy for events entering the detector at oblique angles.

The DOI misclassification rate was ~13% and did not vary much between using the 64 or 72 channel LUTs. Thus adding the MAPDs will not improve the DOI decoding capabilities of the detector module. However, use of different size MAPDs and/or a different arrangement could improve the DOI decoding. Using LUTs created only from photoelectric interactions did not improve the DOI decoding accuracy. In results not shown, the DOI misclassification rate for photoelectric absorption only events in the crystal is ~5%. And all the photoelectric only events that are misclassified are within ± 1 mm of the DOI cutoff within the crystal. Thus Compton scatter in the crystal is the main source of DOI positioning error.

V. Conclusions

In summary, the addition of MAPD sensors placed at the corners of a monolithic crystal detector module can significantly improve the intrinsic spatial resolution for the corner region of the detector, from 0.99 mm FWHM to 0.79 mm FWHM. This is significant because even when using statistics-based positioning methods, decoding performance degrades near the corners of the detector. At 0.79 mm FWHM, the intrinsic spatial resolution is very close to the 0.73 mm FWHM spatial resolution achieved for the center region of the crystal.

The introduction of MAPD and other Geiger mode avalanche photodiode devices will allow these extra sensors to be added to current monolithic detector designs without sacrificing geometric packing fraction.

While the additional sensors will improve the intrinsic spatial resolution characteristics, it is better to just use the PMT signals for energy information. And for the configuration that we tested, the addition of MAPDs did not improve the DOI decoding performance of the detector module.

Acknowledgments

This work was supported in part by NIH-NIBIB grants: R21/R33 EB001563 and R01 EB002117.

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Figure 1.
cMICE crystal with MAPD sensors placed at the corners.

Figure 2.
Grid locations (1.52 mm spacing) used to characterize the detector.

Figure 3.

(a) Energy spectrum using 64 PMT signals for interactions occurring near the center of the crystal. (b) Energy spectrum using 72 signals (64 PMT + 8 MAPD) for interactions occurring near the center of the crystal.

(a)

(b)

Figure 4.

(a) Energy spectrum using 64 PMT signals for interactions occurring near the corner of the crystal. (b) Energy spectrum using 72 signals (64 PMT + 8 MAPD) for interactions occurring near the corner of the crystal.

Figure 5. SBP positioning performance (a) using all 72 detector channel signals and (b) using the 64 PMT signals only. Events were positioned using the dual DOI LUT.

Table I

Intrinsic spatial resolution (single depth LUT)

center	FWHM (mm)	Bias (mm)
SBP-64	0.81	0.01
SBP-72	0.78	0.005
corner		
SBP-64	1.07	0.03
SBP-72	0.83	−0.005

Table II

Intrinsic spatial resolution (single depth LUT)

	Compton and PE interactions		PE interactions only	
	FWHM (mm)	Bias (mm)	FWHM (mm)	Bias (mm)
SBP-64	0.91	0.01	0.83	−0.01
SBP-72	0.84	0.00	0.77	−0.01
SBP-64 (PE LUT)	0.89	0.02	0.82	0.01
SBP-72 (PE LUT)	0.82	0.01	0.76	0.00

Table III

Intrinsic spatial resolution (dual depth LUT)

center	FWHM (mm)	Bias (mm)
SBP-64	0.76	0.01
SBP-72	0.73	0.006
corner		
SBP-64	0.99	−0.01
SBP-72	0.79	−0.002

Table IV

Intrinsic spatial resolution (dual depth LUT)

	Compton and PE interactions		PE interactions only	
	FWHM (mm)	Bias (mm)	FWHM (mm)	Bias (mm)
SBP-64	0.84	0.00	0.78	−0.02
SBP-72	0.78	0.00	0.73	−0.01
SBP-64 (PE LUT)	0.82	0.01	0.75	0.00
SBP-72 (PE LUT)	0.76	0.01	0.70	0.00

Table V

DOI misclassification rate

	Misclassification rate (%)	
	Center	Corner
SBP-64	12.7	13.9
SBP-72	12.7	13.7
SBP-64 (PE LUT)	12.5	12.7
SBP-72 (PE LUT)	12.5	12.6