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New Continuous Miniature Crystal Element (cMiCE) Detector Geometries

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Abstract

Continuous miniature crystal element (cMiCE) detectors are a potentially lower cost alternative to high resolution discrete crystal designs. We report on the intrinsic spatial resolution performance for two cMiCE PET detector designs with depth of interaction (DOI) positioning capability. The first detector utilizes a 50 mm by 50 mm by 8 mm LYSO crystal coupled to a 64 channel, multi-anode PMT. It provides 4 layers of DOI information. The crystal has beveled edges along two of its sides to improve the detector packing when placed in a ring geometry. The second detector utilizes a 50 mm by 50 mm by 15 mm, rectangular LYSO crystal coupled to a 64 channel, multi-anode PMT. It provides up to 15 layers of DOI information. The average intrinsic X, Y spatial resolution for the 8 mm thick, truncated crystal detector was 1.33 $\pm$ 0.31 mm FWHM (45.6 mm by 46.6 mm useful imaging area). The average DOI resolution was 3.5 $\pm$ 0.22 mm. The average intrinsic X, Y spatial resolution for the 15 mm thick crystal detector was 1.74 $\pm$ 0.35 mm FWHM (44.6 mm by 44.6 mm useful imaging area). In addition, the average DOI spatial resolution for 56 test points spanning a 26.4 mm by 12.2 mm region of the crystal was 4.80 $\pm$ 0.36 mm. We believe the 8 mm thick truncated crystal design is suitable for mouse imaging while the 15 mm thick crystal design is more suited for human organ specific imaging systems (e.g., breast and brain).

I. INTRODUCTION

We have previously reported on a high resolution, monolithic crystal PET detector design that provides depth of interaction (DOI) positioning within the crystal [1]. That design was for a 50 mm by 50 mm by 8 mm LYSO crystal coupled to an 8×8 Hamamatsu multi-anode PMT. Our initial results were reported for 1 bit of DOI; however, we have since extended the DOI positioning to 2 bits (or 4 bins). In this work, we report on two alternative cMiCE detector geometries to improve the detection efficiency of a cMiCE detector system. The first design uses a truncated crystal geometry illustrated in Figure 1. Using the truncated crystal design improves the effective packing fraction of the detector system versus using a rectangular crystal design as illustrated in Figure 2. The concept of using a truncated detector design is also being used by a number of other groups [2-4]. The second design uses a 15 mm thick LYSO crystal. Going to a 15 mm thick crystal versus an 8 mm thick crystal more than doubles the coincidence

detection efficiency. We report on the intrinsic spatial resolution characteristics of these alternative crystal geometries.

II. DETECTOR DESIGN AND METHODS

A. Truncated cMiCE detector

The geometry of the truncated cMiCE detector is illustrated in Figure 1. The entrance surface of the crystal was 45 mm by 50 mm. Only two sides are beveled, the other two sides are left square. The thickness of the crystal is 8 mm and the bevel is 22.5 degrees. The surface coupled to the multi-anode PMT is 50 mm by 50 mm. The detector was calibrated using 1.013 mm sampling intervals over the full surface (i.e., 50 mm by 50 mm) of the crystal. Events were positioned using our statistics based positioning method (described below) with 4 depth of interaction (DOI) look up tables (LUT). In addition, we took data with a photon flux at a 45 degree angle to the front surface of the detector to evaluate its depth of interaction positioning performance. The X position is used as an estimate of DOI as illustrated in Figure 3.

B. 15 mm thick cMiCE detector

The 15 mm thick cMiCE detector utilized a rectangular 50 mm by 50 mm by 15 mm LYSO crystal coupled to a Hamamatsu H8500 multi-anode PMT. The detector was calibrated using 1.013 mm sampling intervals over half of the surface (i.e., 25 mm by 50 mm) of the crystal. Events were positioned using our statistics based positioning (SBP) with 15 depth of interaction (DOI) look up tables (LUT). In addition, we took data with a photon flux at a 45 degree angle to the front surface of the detector to evaluate its depth of interaction positioning performance. The X position is used as an estimate of DOI as illustrated in Figure 3.

C. 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. [5] 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, $\mu_i(x)$, and standard deviation $\sigma_i(x)$.

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 calibration process.

To further improve the decoding performance of the detector, a maximum-likelihood (ML) clustering method is used to extract depth of interaction (DOI) information during the calibration of the detector module [1]. The DOI separation technique divides the calibration

data into different DOI regions. The algorithm utilizes the fact that the light distribution pattern varies continuously and smoothly with DOI so scintillation events happening in similar DOI regions of the crystal will produce similar light distribution patterns. LUTs are then created for each DOI region. The full set of DOI LUTs allows 3D positioning within our detector module. Our ML clustering technique has been used to extract up to 7 DOI regions from our 15 mm thick cMiCE detector. Based on the 7-depth DOI LUT, a third-order polynomial fit is applied to the mean and variance respectively for each (X,Y) position. Then, a 15-depth DOI LUT is generated from the fitting result. For a detailed description refer to [1] or [5].

III. RESULTS

Table I shows the average X,Y intrinsic spatial resolution for the two detector geometries. The useful imaging area for the truncated crystal design was 45.6 mm in X and 46.6 mm in Y. The useful imaging area for the 15 mm thick crystal design was 44.6 mm in X and 22.3 mm in Y (we only used $\frac{1}{2}$ of the crystal for the work reported here).

Figure 4 shows a contour plot for the 8 mm truncated crystal design. The contours represent the FWHM of the point fluxes. The dots show the locations of the point fluxes for testing. The test points were separated by 2.026 mm. Note that the X and Y axes are switched in the figure and that the central points along the vertical axis are only separated by 1.013 mm.

Figure 5 shows the FWHM contour plot for the 15 mm thick crystal. Again the dots show the location of the point fluxes for testing and are separated by 2.026 mm.

In addition to the intrinsic spatial resolution performance, Figures 6 and 7 show examples of the estimated X (DOI) position for events assigned to different depths for a photon flux at a 45 degree angle to the front surface of the detector. Figure 6 is for the 8 mm truncated crystal with 4 depth LUTs and figure 7 is for the 15 mm thick crystal with 7 depth LUTs for this example. Using the X position as a surrogate for depth of interaction an average FWHM DOI resolution of 3.50 ± 0.22 mm was measured across the face of the 8 mm thick detector. A FWHM DOI resolution of 4.80 ± 0.36 mm was measured for a sample of 56 test points for the 15 mm thick crystal detector. The test points spanned a 26.338 mm by 12.156 mm region of the crystal. A sample DOI error plot for the 15 mm thick crystal detector is shown in Figure 8. Since we are using the X position as a surrogate for DOI and we know that the X positioning resolution is between 1.33 and 1.74 mm FWHM, we believe the average DOI resolutions are closer to 3.2 mm and 4.5 mm FWHM for the 8 mm and 15 mm thick detectors, respectively.

IV. DISCUSSION AND CONCLUSION

Both the 8mm thick truncated crystal and 15 mm thick rectangular crystal detector have the potential to improve the coincidence detection efficiency of a ring system built with cMiCE detectors. While the 8 mm thick truncated crystal design is suitable for mouse imaging, the 15 mm thick crystal may be more appropriate for an organ specific systems (e.g., breast or brain) as the intrinsic spatial resolution characteristics are more limited. Of course the detector packing fraction for the 15 mm thick detector could also be improved by going to a truncated design.

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Figure 1.
Illustration of truncated crystal, only two of the edges are beveled. The other two edges are square. The beveled edges allow better detector ring packing fraction.

Figure 2. Illustration of detector ring using truncated crystal detector design. The beveled detectors allow for better packing fraction and improved detector coincidence detection efficiency than for detector ring with rectangular crystals.

Figure 3.

A point flux incident at 45 degrees relative to the surface. The depth of interaction in the crystal is equal to the spatial positioning along the X-axis.

Figure 4.
FWHM contour plot of 4 depth SBP positioning for 8 mm truncated crystal. Average resolution is 1.33 mm FWHM.

Figure 5. FWHM contour plot of 15 depth SBP positioning for 15 mm thick crystal. Average resolution is 1.74 mm FWHM.

Figure 6.

Projection of counts along the X axis for the total summed counts and the events assigned to different DOI regions for 8mm truncated crystal. X position is used as a surrogate for DOI.

Figure 7.

Projection of counts along the X axis for the total summed counts and the events assigned to different DOI regions for 15mm crystal. X position is used as a surrogate for DOI.

Figure 8.

Estimate of DOI positioning error for 15mm crystal. Using a Gaussian fit the FWHM for data shown is 4.41 mm. Average DOI resolution for 56 test points was 4.80 ± 0.36 mm.

Table I

X, Y intrinsic spatial resolution

	X FWHM (mm)	Y FWHM (mm)	Y FWHM (mm)
Truncated crystal (8mm thick)	1.31 +/- 0.29	1.34 +/- 0.32	1.34 +/- 0.32 (two Y FWHM)
Rectangular crystal (15 mm thick)	1.78 +/- 0.31	1.70 +/- 0.39	1.70 +/- 0.39