Published in final edited form as:

IEEE Nucl Sci Symp Conf Rec (1997). 2007 October 26; 2007: 4314–4318. doi:10.1109/NSSMIC.2007.4437070.

Calibration procedure for a continuous miniature crystal element (cMiCE) detector

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Abstract

We report on methods to speed up the calibration process for a continuous miniature crystal element (cMiCE) detector. Our cMiCE detector is composed of a 50 mm by 50 mm by 8 mm thick LYSO crystal coupled to a 64-channel, flat panel photomultiplier tube (PMT). This detector is a lower cost alternative to designs that use finely pixilated individual crystal detectors. It achieves an average intrinsic spatial resolution of ~1.4 mm full width at half maximum (FWHM) over the useful face of the detector through the use of a statistics based positioning algorithm. A drawback to the design is the length of time it takes to calibrate the detector. We report on three methods to speed up this process. The first method is to use multiple point fluxes on the surface of the detector to calibrate different points of the detector from a single data acquisition. This will work as long as the point fluxes are appropriately spaced on the detector so that there is no overlap of signal. A special multi-source device that can create up to 16 point fluxes has been custom designed for this purpose. The second scheme is to characterize the detector with coarser sampling and use interpolation to create look up tables with the desired detector sampling (e.g., 0.25 mm). The intrinsic spatial resolution performance will be investigated for sampling intervals of 0.76 mm, 1.013 mm, 1.52 mm and 2.027 mm. The third method is to adjust the point flux diameter by varying the geometry of the setup. By bringing the coincidence detector array closer to the point source array both the spot size and the coincidence counting rate will increase. We will report on the calibration setup factor we are able to achieve while maintaining an average intrinsic spatial resolution of ~1.4 mm FWHM for the effective imaging area of our cMiCE detector.

Index Terms

Continuous crystal; high spatial resolution; PET detector; calibration

1. INTRODUCTION

We have previously reported on the continuous miniature crystal element (cMiCE) detector [1–3]. It is composed of a 50 mm by 50 mm by 8 mm thick slab of LYSO, coupled to a 64 channel flat-panel PMT (see Figure 1). Using a statistics-based positioning (SBP) algorithm,

it achieves an average intrinsic spatial resolution of better than 1.4 mm FWHM across its useful imaging area. 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. One drawback of the design is the length of time required to calibrate a detector. For our initial work, the detector was characterized with a sampling interval of 1 mm and interpolation was used to create LUTs with 0.25 mm binning. The procedure required 2401 (i.e., 49×49) sample points to characterize a detector. If data are collected for 20 minutes at each sample point, detector calibration takes ~800 hours.

We propose three techniques to reduce the amount of time for detector calibration. First, we have developed an electronically collimated multiple point source holder that allows us to illuminate up to 16 independent locations of the crystal simultaneously (see Figure 2). Using this device, we can decrease the calibration time by a factor of 16. Second, we will investigate what effect the sampling interval combined with interpolation has on the LUTs. Because we sample in two dimensions, increasing the sampling interval by a factor of 2 will decrease the number of sample points (and calibration time) by a factor of 4. Third, we will adjust the spot size of the photon flux. In our current apparatus the photon spot is ~0.5 mm FWHM at the surface of the crystal. The coincidence efficiency will go up if we change the geometry of our apparatus to increase the spot size. We will try spots sizes up to 0.70 mm FWHM. Using all of these techniques we can bring the total calibration time down to under 7 hours. We will determine how each of these methods affects the values in our LUTs and in turn how the intrinsic spatial resolution of the detector is affected.

II. MATERIALS AND METHODS

A. cMiCE Detector Module

A cMiCE detector module is pictured in Fig. 1. It is composed of a 50 mm by 50 mm by 8 mm thick slab of LYSO (Saint Gobain, Newbury, Ohio) coupled to a 64-channel multi-anode PMT (H8500, Hamamatsu Photonics K.K., Japan). One of the 50 mm by 50 mm surfaces was polished. All other surfaces were roughened. The polished side was coupled to the PMT using Bicron BC-630 optical grease. The face of the crystal opposite the PMT was painted white. The side surfaces of the crystal were painted black to reduce light reflections off the sides.

All 64 channels from the multi-anode, flat panel PMT were acquired for each coincidence event. Two 32-channel analog to digital converter (ADC) cards (N792 ADCs, CAEN, Italy) were used as part of a VME data acquisition system. The VME crate was connected to an Apple computer running OS X and the Orca software package [4] using a VME-PCI adapter card.

B. Statistics-based Positioning Method (SBP) [1]

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:

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

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. For our initial evaluation, the detector was sampled at 1.0 mm intervals in both X and Y and the LUTs were interpolated to 0.25 mm bins.

In addition to creating two-dimensional (i.e., x, y) LUTs, we have developed a Maximum-likelihood-based method for building LUTs with some depth of interaction (DOI) discrimination. The method to separate the data into different depth regions is described in [3]. After the data are sorted, SBP LUTs are generated for each depth region and the maximum likelihood estimator for event positioning is utilized as described above.

C. cMiCE Detector Characterization

Event positioning for the detector is accomplished using a statistics-based positioning method that requires the light response function for each PMT channel be characterized for all possible interaction locations within the crystal. The light response function at a given location is measured using an electronically collimated (i.e., using a coincidence detector) point source with a spot size of ~ 0.5 mm full width at half maximum (FWHM). To calibrate the full detector, the point flux is raster scanned across the face of the detector at a user specified sampling interval. For our initial evaluation, the detector was characterized using a single point flux with ~ 0.52 mm spot diameter at the front face of the crystal (~ 0.65 at the rear face of the crystal) and with 1 mm sampling. We propose three methods to reduce the time required to characterize the detector. For testing purposes, the average intrinsic spatial resolution was determined for one quarter of the useful imaging area of the detector spanning (i.e., to within 4 mm of the edge of the crystal). Due to symmetry the average intrinsic spatial resolution of a full detector should be similar to the numbers reported in this work.

Multi-Coincidence Source Detector—Our multi-point flux device is pictured in Fig. 2. It will hold up to 16 point sources. The point sources are 0.25 mm diameter ^{22}Na sources housed in a 1 cm³ cube produced by Isotope Products Laboratories (Valencia, CA). Each of these sources is $\sim 20\mu\text{Ci}$. The sources are positioned in a holder so they have 12.16 mm center-to-center spacing. To create an array of narrow point fluxes, a two-dimensional array of coincidence detectors with spacing matched to the point sources is used. Each of the coincidence detector crystals is $2 \times 2 \times 10$ mm³. By placing the point sources closer to the detector being calibrated, point fluxes with ~ 0.5 mm FWHM at the face of the detector are achieved. To limit the photon flux to the near detector (i.e., the one being calibrated), lead collimation is used. The multi-point flux assembly is mounted on to a computerized stage that allows translation along two axes for calibration of the detector module.

We evaluated the effect of using multiple point sources on the generation of the LUTs. The main concern is that even with the collimation there is a significant singles rate on the detector being calibrated (especially because of the 1.275 MeV gamma produced by ^{22}Na). Therefore, it is possible that as the number of point sources increases we could get a significant amount of pile-up in the detector that would distort the calibration files. The intrinsic resolution of the detector module was evaluated using LUTs created with 4, 8 and 12 point sources.

Sampling Interval—To investigate how the sampling distance affects the intrinsic spatial resolution of the detector, we acquired data with 0.76 mm and 1.013 mm sampling. This allowed us to also determine the intrinsic spatial resolution performance for LUTs built with 1.52 mm and 2.026 mm sampling. The sampling intervals were chosen to be a fraction of the center-to-center spacing of the PMT channels (i.e., 6.08 mm). The final LUT bin size was interpolated to 0.19 mm for the 0.76 mm sampled data. A cubic spline interpolation was used. For the other sampling intervals, the bin size was interpolated to 0.253 mm.

Photon Flux Spot Size—The third time reduction technique was to increase the coincidence count rate by altering the geometry of the test setup. By moving the coincidence detectors closer to the point sources, the coincidence count rate can be increased without increasing the photon flux rate to the detector being calibrated.

A spot size significantly smaller than the anticipated resolution of the detector is desirable. An ~0.5 mm FWHM spot size was used for our initial work. We altered the coincidence setup to allow for a 0.7 mm FWHM spot size and determined the intrinsic spatial resolution of the detector using LUTs generated with the larger spot.

III. RESULTS

Multi-Coincidence Source Detector

Contour plots representing the FWHM for point fluxes with 2.026 mm spacing are illustrated in Fig. 3. Fluxes go to within 4 mm of the edge of the crystal. Results are shown for LUTs generated using 4, 8 and 12 sources. The sampling interval for calibration was 1.013 mm in both directions. The photon flux spot size was 0.52 mm FWHM at the entrance surface of the crystal. The intrinsic spatial resolution results are listed in Table 1.

Sampling Interval

The results of using different sampling intervals for detector calibration are listed in Table 2 and illustrated in Figs. 4 and 5. Sampling intervals for 0.76 mm, 1.013 mm, 1.52 mm and 2.026 mm were investigated.

Photon Flux Spot Size

The photon flux diameter was broadened to 0.7 mm FWHM at the front surface of the detector by altering the geometry of the testing apparatus. With this setup the flux diameter was ~0.92 mm FWHM at the back surface of the crystal. The results are listed in Table 3 and Fig. 6.

IV. DISCUSSION

Three schemes were investigated to reduce the time required to calibrate a cMiCE detector module. The first scheme was to use multiple point fluxes and collect characterization data at multiple locations of the detector simultaneously. Our results indicated that it is feasible to use at least 12 sources without degrading the quality of the LUTs. The intrinsic spatial

resolution along the edges was a little worse using 12 sources; however, the overall average intrinsic spatial resolution was within 5% of the 4 source and 8 source results. We are ordering 4 more sources and will investigate using 16 sources in the near future.

The second scheme was to broaden the sampling intervals. Increasing the sampling interval by a factor of two reduces the 4317 number of characterization locations by a factor of four. Independent of the sampling interval the LUT were interpolated to the same bin size. For this work the LUT bin size was 0.26 mm in each dimension. Our results show that going to 2.026 sampling intervals is feasible, as the average intrinsic spatial resolution increased by less than 5% in going from 0.76 mm sampling to 2.026 mm.

The third scheme was to alter the geometry of the setup to increase the sensitivity of the coincidence detectors. This leads to a broader photon flux that in turn can reduce the intrinsic spatial resolution characteristics of the LUTs. Going from a 0.52 mm diameter point flux to 0.7 mm diameter increases the coincidence sensitivity by approximately a factor of two, but only increased the intrinsic spatial resolution by 5%.

V. CONCLUSIONS

We investigated three schemes to reduce the amount of time required to characterize our cMiCE detector. Each of the methods led to an increase in intrinsic spatial resolution of 5% or less. In all testing, the average intrinsic spatial resolution of the cMiCE detector was <1.44 mm FWHM. Applying all three techniques, the time to fully characterize a cMiCE detector can be reduced by a factor of 128 (i.e., $16 \times 4 \times 2$) versus our original setup using a single coincidence detector. This translates into characterization times of <8 hours. It is anticipated that the full characterization of the detector module will only need to be done once during the initial characterization of the system. As future work we will investigate methods to rapidly retune detector modules to account for PMT fluctuations over time.

Acknowledgments

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

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Figure 1.
Picture of cMiCE detector with 8 mm thick LYSO crystal and white paint.

Figure 2.
Multi-point source setup to provide multiple electronically collimated point fluxes.

(a)

(b)

(c)

Figure 3.

Contour plots of the FWHM for point fluxes with 2.026 mm spacing. Fluxes got to within 4 mm of the edge of the crystal. LUTs were calibrated with different numbers of point sources: (a) 4 sources; (b) 8 sources; and (c) 12 sources.

(a)

(b)

(c)

(d)

Figure 4.

Contour plots of the FWHM for point fluxes with 2.026 mm spacing. LUTs were created from data sets using 8 point sources and with different sampling intervals: (a) 0.76 mm; (b) 1.013 mm; (c) 1.52 mm; and (d) 2.026 mm.

Figure 5. Contour plot of the FWHM for point sources with 2.026 mm spacing. LUT was generated using 12 sources, 2.026 mm sampling interval and 0.52 mm diameter spot size.

Figure 6. Contour plot of the FWHM for point sources with 2.026 mm spacing. LUT was generated using 8 sources with 1.013 mm sampling interval and 0.7 mm FWHM point flux diameter.

Table 1

Intrinsic spatial resolution versus number of point sources.*

	X FWHM (mm)	Y FWHM (mm)
4 sources	1.32 ± 0.49	1.36 ± 0.22
8 sources	1.44 ± 0.31	1.28 ± 0.25
12 sources	1.36 ± 0.34	1.42 ± 0.35

* Average intrinsic spatial resolution for one quarter of the detector to within 4 mm of the crystal's edge.

Table 2

Intrinsic spatial resolution versus sampling interval.*

	X FWHM (mm)	Y FWHM (mm)
0.76 mm	1.41 ± 0.34	1.32 ± 0.30
1.013 mm	1.44 ± 0.31	1.28 ± 0.25
1.52 mm	1.44 ± 0.31	1.40 ± 0.27
2.026 mm	1.46 ± 0.30	1.38 ± 0.31
2.026 mm (12 src)**	1.44 ± 0.34	1.38 ± 0.23

* Average intrinsic spatial resolution using 8 point sources.

** Results using 12 point sources for LUT generation.

Table 3

Intrinsic spatial resolution versus point flux spot diameter.*

	X FWHM (mm)	Y FWHM (mm)
0.52 mm to 0.65 mm	1.44 ± 0.31	1.28 ± 0.25
0.70 mm to 0.92 mm	1.42 ± 0.32	1.44 ± 0.23

* Spot size FWHM increases from the front to the rear of the detector.