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Study of electrode pattern design for a CZT-based PET detector

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Abstract

We are developing a 1 mm resolution small animal positron emission tomography (PET) system using 3-D positioning Cadmium Zinc Telluride (CZT) photon detectors comprising 40 mm × 40 mm × 5 mm crystals metalized with a cross-strip electrode pattern with a 1 mm anode strip pitch. We optimized the electrode pattern design for intrinsic sensitivity and spatial, energy and time resolution performance using a test detector comprising cathode and steering electrode strips of varying dimensions. The study found 3 mm and 5 mm width cathode strips locate charge-shared photon interactions near cathode strip boundaries with equal precision. 3 mm width cathode strips exhibited large time resolution variability as a function of photon interaction location between the anode and cathode planes (~26 ns to ~127.5 ns FWHM for 0.5 mm and 4.2 mm depths, respectively). 5 mm width cathode strips by contrast exhibited more stable time resolution for the same interaction locations (~34 ns to ~83 ns FWHM), provided more linear spatial positioning in the direction orthogonal to the electrode planes, and as much as 68.4% improvement in photon sensitivity over the 3 mm wide cathode strips. The results were understood by analyzing the cathode strips' weighting functions, which indicated a stronger “small pixel” effect in the 3 mm wide cathode strips. Photon sensitivity and anode energy resolution were seen to improve with decreasing steering electrode bias from 0 V to −80 V w.r.t the anode potential. A slight improvement in energy resolution was seen for wider steering electrode strips (400 μm vs. 100 μm) for charge-shared photon interactions. Although this study successfully focused on electrode pattern features for PET performance, the results are generally applicable to semiconductor photon detectors employing cross-strip electrode patterns.

Keywords

CZT; semiconductor detector; cross-strip electrode; charge collection; high resolution; PET; small animal

1. Introduction

Properties of cadmium zinc telluride (CZT) make it a suitable semiconductor for detecting ionizing radiation (Vaska *et al* 2005, Zhang *et al* 2005, Levin *et al* 2006, Levin 2008, Mitchell *et al* 2008, Morimoto *et al* 2010, Gu *et al* 2011, Levin 2012). We are developing an ultra-high resolution small animal positron emission tomography (PET) system based on a novel 3-D positioning CZT photon detector design. Pertinent figures of merit for PET photon detector performance are the detector spatial, energy, and time resolutions, and photon sensitivity uniformity. These parameters set fundamental limits on the resolution and contrast of reconstructed PET images.

This paper presents an experiment-based study investigating these performance parameters as a function of the electrode dimensions of CZT photon detectors, with the aim of optimizing detector performance. In particular we investigate the design of a fine-pitch cross-strip electrode pattern using a test detector with a variation of electrode features repeated with different dimensions.

The proposed CZT detector enables high-resolution 3-D positioning and precise energy measurement of each interaction in a multi-interaction event, which occurs often in CZT at 511 keV photon energy. Using the kinematics of Compton scatter, this multi-interaction information enables an estimate of the incidence angle of the photon hitting the detector. This opens a new class of signal processing algorithms for PET that exploit this photon incidence angle information to, for example, help to retain coincidence events such as multiple, singles, and tissue scatter that normally are rejected (Levin 2012, Chinn and Levin 2011). Pratz and Levin (2009) and Gu *et al* (2010) have shown that the ability to exploit Compton interactions in addition to photoelectric photon interactions in the detector would improve a PET system's effective photon sensitivity, as well as enable the ability to accurately identify the first interaction, in order to enhance the resulting image quality and image accuracy.

For the CZT detector under discussion, the energy resolution and the spatial resolution along two of the three Euclidean directions were previously studied by Gu *et al* (2011). In this work, the following relationships were studied:

1. Sub-pitch spatial positioning capability and spatial position linearity as a function of cathode strip width.
2. Time resolution as a function of cathode strip width.
3. Photon sensitivity as a function of cathode and steering strip width, and bias voltage.
4. Anode energy resolution as a function of steering strip width and bias voltage.
5. Photon sensitivity in the presence of crystal edge steering electrode.

We first present the design of the cross-strip electrode pattern and the small animal PET system for which it is intended. Next, we describe each of the experimental setups and analysis methods used in our investigation. The later sections present the experimental

results, followed by a discussion thereof, paying special attention to implications of the findings in the context of high-resolution PET imaging.

The results of this paper will be generally applicable to those radionuclide imaging researchers exploring 3-D position sensitive detectors and/or detector systems based on semiconductor crystals.

2. Materials and methods

Figure 1 shows a CZT photon detector and the basic cross-strip electrode pattern design. The detector comprises a monolithic CZT crystal measuring $40\text{ mm} \times 40\text{ mm} \times 5\text{ mm}$ with thin Kapton flex circuits for extracting the electrode signals (Gu *et al* 2011). Orthogonal gold anode and cathode strips that span the entire 40 mm width of the crystal are deposited on opposite faces of the crystal. The cross-strip design was chosen to simultaneously attain high spatial resolution while using fewer number of electronic readout channels, e.g. $2n$ vs. n^2 as compared to a square pixel electrode design.

In the coordinate system of figure 1 (a), x - y localization of photon interactions is achieved with the cross-strip electrode pattern by finding the intersection of the anode and cathode strips producing a signal. This way, the x - y pixel size is determined by the anode and cathode pitch sizes. Continuous positioning can be achieved in the z direction using the anode and cathode signals produced by a photon interaction. In particular, the charge drift time and/or the cathode-to-anode ratio (C/A ratio) – defined as the digitized cathode signal amplitude divided by the anode signal amplitude, allow one to accurately estimate the photon interaction's z coordinate. In this work, the z direction is also called the direction orthogonal to the x - y electrode planes (DOEP) when the reference coordinate system used is not obvious.

The anode strips are on a 1 mm pitch and just 100 μm wide to attain a strong “small pixel” effect (Gu *et al* 2011). This arrangement leaves a 900 μm non-metalized gap between adjacent anode strips in the anode plane (90% of the anode plane by area). As these gaps correspond to region of extremely low anode charge sensitivity, mobile electrons drifting into these gaps would induce minimal anode signal. Consequently, it is desirable to steer mobile electrons away from these gaps and have them converge on the anode strips instead. This would improve signal induction and hence detector sensitivity and signal-to-noise ratio (Gu *et al* 2011).

The desired charge steering pattern is achieved by interspersing the anode strips with steering electrode strips. The steering electrodes are located midway between adjacent anodes strips, and run parallel to and along the full length of the anode strips. On the test detector, the steering electrode strips take on different widths over one third of their length as shown in figures 1 (b) and (c), ranging from 100 μm to 400 μm .

In operation, steering electrodes are biased at a lower potential with respect to the anodes. This difference in bias voltage establishes a potential gradient transverse to the anode plane, creating electric field lines that repel mobile electrons away from the steering electrodes and non-metalized gaps, as desired. Figure 2 shows this effect. The electric pattern was

numerically calculated using Maxwell SV – a finite element analysis software solver for electromagnetic fields, by setting the boundary conditions of the electric potentials and the dielectric constant $\epsilon_r = 10.9$ of CZT.

The 40 mm $\times$ 40 mm cathode face on the opposite side comprises nine cathode strips of two different widths and pitch sizes. The center three cathode strips have 3 mm width and pitch, while the remaining cathode strips have 5 mm width and pitch.

To facilitate biasing and electrical contact between the data acquisition electronics and the crystal, thin Kapton flexible circuits carrying wire traces with matching pitch size to the anode and cathode strips are solder-bonded to both faces of the crystal. The flexible circuits connect to circuit boards via zero insertion force connectors.

Figure 3 shows the high-resolution small animal PET system using the described CZT photon detector. The system has a square, adjustable-size field of view (FOV) with maximum dimensions of 100 mm $\times$ 100 mm $\times$ 80 mm. The square FOV is formed by organizing the CZT crystals into 4 detector panels. The detector panels are able to slide along diagonal rails while remaining butted against each other. This way, the FOV maintains its square shape while its width is adjusted. The square adjustable-size FOV is a feature that serves to maximize photon detection efficiency over a range of imaging subject sizes (Habte *et al* 2007).

Each detector panel contains a 16-row by 3-column array of 48 CZT crystals. The crystals are oriented with their 40 mm $\times$ 5 mm edge face facing the FOV. In this “edge on” orientation, the axial direction of the FOV coincides with the z direction of CZT crystals (coordinate system of figure 1 (a)). The orientation of trans-axial planes coincides with that of the x - y plane in figure 1 (a). Consequently, the anode strip pitch (1 mm) sets the system’s tangential positioning resolution, while the cathode strip pitch (3 mm or 5mm) sets the radial positioning resolution, i.e. the “depth of interaction” (DOI) direction in conventional PET terminology.

This “edge on” orientation of crystals presents a minimum of 40 mm of CZT material to incoming annihilation photons. This, combined with the square shape of the CZT crystals and FOV, as well as the use of thin flexible circuits, realizes greater than 99% inter-module packing fraction and promotes greater than 86% intrinsic detection efficiency for single 511 keV annihilation photons (or >73% for coincident pairs) (Habte *et al* 2007).

The coordinate system used throughout the study is as shown in figure 1 (a). Unless otherwise noted, a detector bias of ~ 100 V/mm and a steering voltage of -40 V relative to the anodes were used. Data acquisition was performed using the RENA-3 (Readout Electronics for Nuclear Applications developed by NOVA R&D Inc., a Kromek company) application specific integrated circuit (ASIC). The ASIC was designed specifically to perform pre-amplification and shaping of semiconductor photon detector signals. Each photon interaction that triggers a readout results in the list-mode data pair (E, t) , where E and t denote, respectively, the signal pulse amplitude (energy) and time of photon interaction. The E values from the RENA-3 ASIC were converted to keV values via multi-energy gamma ray source calibration.

In all cases, precision positioning and translation of collimated photon beams were achieved using National Aperture Inc.'s MM-4M-EX-140 motorized linear stage.

2.1. Sub-pitch continuous positioning capability in y as a function of cathode strip width

A 500 μm width slit beam of 511 keV photons (^{22}Na) is used to scan across cathode strips along the y direction in 200 μm or 333.3 μm steps. When a photon interaction occurs near the boundary between two cathode strips, the charge cloud generated would straddle the boundaries of the two electrodes and induce a signal on both cathode strips, say $C1$ and $C2$. With only a 100 μm wide gap separating adjacent cathode strips, such charge-sharing can occur with little signal loss. Since the signal amplitude induced on each cathode strip, E_{C1} and E_{C2} , is proportional to the fraction of the charge cloud falling on each side of the electrode boundary, the ratio of E_{C1} and E_{C2} would be indicative of the photon interaction's position relative to the cathode strip boundary.

Exploiting this fact, we open the possibility of achieving sub-pitch positioning in the y or DOI direction for charge-shared photon interactions. Therefore, we investigated which of 3 mm or 5 mm wide cathodes strips was more capable in providing sub-pitch positioning of charge-shared photon interactions. Data analysis was performed using MATLAB.

In general, photons can be absorbed in CZT via either 511 keV photoelectric interactions or, more likely, a sequence of one or more Compton scatter interactions followed by a photoelectric interaction. However, the class of photon interactions that best reveals signal induction behavior near the cathode boundaries are those that trigger exactly one anode and either one or two cathode channels. That is, photon interactions with charge sharing only on the cathode face but not the anode face. This way we minimize the influence of any confounding factors.

For assigning the sub-pitch y coordinate position of one-anode-two-cathode (cathode charge-shared) photon interactions, the maximum a posteriori (MAP) method was used based on the joint probability density function (pdf) $f(E_{C1}, E_{C2}, p)$, where E_{C1} and E_{C2} are the signal amplitudes induced on two adjacent cathode strips by the same photon interaction, and p is the nominal position of the collimated slit beam relative to the cathode strip boundary i.e. the true mean position of the first photon interaction. Since p is simply the y coordinate of photon interactions, its distribution $g(p)$ was treated as uniform.

Equation (1) shows the MAP algorithm formulation. The equivalence between the first two lines is due to $g(p)$ being a uniform distribution. Lines two and three are equivalent by Bayes theorem, the last two lines are equivalent again because of the uniform distribution $g(p)$. The MAP rule is consequently equivalent to ML in this case, and reduces to finding the value p which maximizes $f(E_{C1}, E_{C2}, p)$ for a given (E_{C1}, E_{C2}) measurement pair.

$$\begin{aligned}
 p' &= \arg \max_p f(E_{C1}, E_{C2} | p) g(p) \\
 &= \arg \max_p f(E_{C1}, E_{C2} | p) \\
 &= \arg \max_p \frac{f(E_{C1}, E_{C2}, p)}{g(p)} \\
 &= \arg \max_p f(E_{C1}, E_{C2}, p)
 \end{aligned} \tag{1}$$

Data acquired at each slit beam position p were split into two sets for cross-validation. The first set was used to empirically estimate the joint probability density function $f(E_{C1}, E_{C2}, p)$ using the Parzen window estimation method. To ensure unbiased estimation of the underlying $f(E_{C1}, E_{C2}, p)$, an equal number of data points from each slit beam position were included in the learning set. The second data set was the test set on which MAP was applied to estimate the photon interaction positions p' , the estimated position is then plotted as a function of the nominal (true) position for assessment.

2.2. DOEP spatial positioning uniformity as a function of cathode strip width

A 254 μm wide slit beam of 511 keV photons (^{68}Ge) in the x - y plane was directed at a 40 mm $\times$ 5 mm edge face, and scanned across the detector's thickness along the DOEP or z direction in 333 μm steps. Photon interaction positioning along z direction is achieved by using the ratio of the amplitude of shaped anode and cathode pulses i.e. the cathode-to-anode amplitude (C/A) ratio. This approach has been used in numerous prior works (Kalemci et al 1999, Li et al 2000, Hong et al 2003, Gu et al 2011). Correlation between the C/A ratio and z coordinate is a consequence of the combined effects of i) a factor of ~ 15 difference in the electron and hole lifetime in CZT (Erickson et al 2000), and ii) cathode's spatially varying sensitivity to space charge. In particular, due to high trapping and low mobility of holes, photon interactions near the cathode plane produce larger signals than interactions of the same energy far from the cathode plane; however anode signals are approximately independent of a photon interaction's z coordinate due to the higher electron mobility and anode's strong "small-pixel" effect (Gu et al 2011). The result is a monotonically increasing value of C/A ratio with decreasing photon interaction distance to the cathode plane.

Due to the intrinsic energy resolution of CZT and non-zero electronic measurement noise, the C/A ratio does not enable estimation of the z coordinate with infinite accuracy. However, the more linear the mapping between the C/A ratio and the z coordinate, the more uniformly accurate our z estimates would be, and the higher the spatial positioning uniformity along z .

Hence this part of the study investigated which of 3 mm or 5 mm wide cathode strips produced a more linear C/A-to- z relationship. In analysis, the C/A ratio was calculated for all photon interactions acquired at a given z coordinate of the collimated photon beam. The mean value and standard deviation of the C/A ratio for that z coordinate were then calculated. The mean C/A ratio is then plotted against the z coordinate across the full 5 mm crystal thickness.

2.3. Time resolution as a function of cathode strip width

A detector electrode's sensitivity to space charge within the detector volume is quantified by its weighting potential $\Phi(x, y, z)$. $\Phi(x, y, z)$ is a normalized and continuous scalar function of spatial coordinates (x, y, z) , and quantifies the electrode's sensitivity to a unit point charge at any position within the detector volume. $\Phi(x, y, z)$ is determined completely by the electrode and detector geometries (Ramo 1939), i.e. it is independent of bias voltage or detector material.

Contours of $\Phi(x, y, z)$ along the x - z plane can be analytically computed using equation 2 (Eskin *et al* 1995), where L and W denote, respectively, the thickness of the CZT crystal, and the width of the electrode strip. Figure 4 shows the $\Phi(x, y, z)$ contours along the x - z plane for electrode strips of width 1 mm, 3 mm, and 5 mm. A fixed quantity of charge placed anywhere along a contour would induce an equal magnitude of charge signal on the electrode, the amount of induced signal being higher for red contours (values near 1) and lower for blue contours (values near 0).

$$\Phi(x, z) = \frac{1}{\pi} \left\{ \tan^{-1} \left[\coth \left[\frac{\pi}{2L} \left(x - \frac{W}{2} \right) \right] \tan \left(\frac{\pi z}{2L} \right) \right] - \tan^{-1} \left[\coth \left[\frac{\pi}{2L} \left(x + \frac{W}{2} \right) \right] \tan \left(\frac{\pi z}{2L} \right) \right] \right\} \quad (2)$$

It is evident that $\Phi(x, y, z)$ has non-zero gradient across spatial locations, and this gradient in part determines the signal rise time. Specifically, for a photon interaction of given energy and relative position to electrodes A and B of different widths, if we have on average

$$\frac{\partial}{\partial s} \Phi(x, y, z)_A > \frac{\partial}{\partial s} \Phi(x, y, z)_B \text{ along } s, \text{ the mobile charge carriers' drift trajectory, then we}$$

also have $\frac{d}{dt} f(t)_A > \frac{d}{dt} f(t)_B$, where $f(t)$ is the induced charge signal.

Relating this to the detector's cathode time resolution, we note that the RENA-3 ASIC employs a leading-edge discriminator for time pick-off. For a leading edge discriminator, the time pick-off noise ε_t is related to the signal noise ε_f via equation 3.

$$\varepsilon_t = \frac{\varepsilon_f}{\frac{d}{dt} f(t)} \quad (3)$$

For a given level of electronic noise, we can deduce from equation (3) and figure 4 (b) and (c) that near the anode plane ($z = 5$ mm)

$$\begin{aligned} \nabla \Phi(x, y, z)_{5 \text{ mm}} &> \nabla \Phi(x, y, z)_{3 \text{ mm}} \\ \Rightarrow \frac{d}{dt} f(t)_{5 \text{ mm}} &> \frac{d}{dt} f(t)_{3 \text{ mm}} \\ \Rightarrow \varepsilon_{t \text{ 5 mm}} &< \varepsilon_{t \text{ 3 mm}} \end{aligned} \quad (4)$$

and near the cathode plane ($z = 0$ mm)

$$\begin{aligned} \nabla \Phi(x, y, z)_{5 \text{ mm}} &> \nabla \Phi(x, y, z)_{3 \text{ mm}} \\ \Rightarrow \frac{d}{dt} f(t)_{5 \text{ mm}} &< \frac{d}{dt} f(t)_{3 \text{ mm}} \\ \Rightarrow \varepsilon_{t \text{ 5 mm}} &> \varepsilon_{t \text{ 3 mm}} \end{aligned} \quad (5)$$

Experimentally, a 500 μm diameter pencil beam of 511 keV photons (^{68}Ge) oriented along the y direction was directed at a 40 mm $\times$ 5 mm edge face, and scanned across the detector's thickness along the z direction in 500 μm steps. The cathode time resolution measurements were referenced to a time stamp provided by a photomultiplier tube (PMT) that acquired data in coincidence with the CZT crystal. List-mode data were acquired and corrected for systematic errors following Reynolds *et al* (2011). The photon interactions analyzed were energy-gated around the photopeak with a 511 keV $\pm$ 4% energy window and further gated based on the C/A ratio in the range [0, 1.2]. Time resolution is quantified by the full width at half maximum (FWHM) of the timing histogram.

2.4. Photon sensitivity as a function of cathode strip width

Figure 4 (a) illustrates that the 1 mm width electrode strip exhibits the so-called “small-pixel effect”, i.e. the electrode is sensitive to only space charge in its immediate vicinity. As the cathode width increases, the sensitive region extends progressively farther into the detector volume. The study investigated whether there would be a large difference in detector photon sensitivity due to the different sensitive region sizes in the 3 mm and 5 mm width cathode strips. Note that the gap width between 3 mm and between 5 mm wide cathode strips is the same, i.e. 100 μm , hence gap width would not be a source of sensitivity difference for the two cases.

This part of the study used the same data set as for the study on cathode sub-pitch positioning capability in y . The total number of photoelectric interactions detected was observed as a function of the collimated photon beam's y position, which spanned across both regions metalized with 3 mm and 5 mm width cathode strips. The photoelectric interactions counted include both charge-shared and non-charge-shared photon interactions falling within a 511keV $\pm$ 4% energy window.

2.5. Energy resolution as a function of steering strip width and bias voltage

Figure 5 shows the x - z plane $\mathcal{A}(x, y, z)$ profile similar to that computed in figure 4 as a relief plot for a 100 μm width anode strip. The small anode width gives rise to the sharp sensitivity lobe seen in figure 5 (a), creating the small-pixel effect, which is instrumental in attaining high energy resolution (Gu *et al* 2011). Beyond the lobe, the anode sensitivity to space charge falls rapidly to zero even at $z = 0$ cm (the anode plane).

In experiment, data was acquired with the CZT's cathode face illuminated by a ^{68}Ge point source positioned 195 mm away. The range of steering bias used ranged from 0 V, then -40 V to -100 V relative to the anodes in -20 V steps. The profile of the electric field within a CZT photon detector is determined by the steering electrode width and the bias potential. We studied the effect of these on two classes of photon interactions falling within the photopeak: i) those triggering exactly one anode and one cathode (to be referred to as “single-anode photon interactions”), and ii) those triggering two neighboring anodes and one cathode, i.e. anode charge-shared photon interactions. Anode charge-shared photon interactions result if photon interactions occur near the mid-point between adjacent anode strips. These interactions are of particular interest because their proximity to steering electrodes is expected to make them particularly sensitive to variations in the steering

electrode width and bias potential. Photon interactions involving e.g. multiple anode and cathode strips are excluded as they do not reveal steering electrode-related behavior, and would only add confounding factors to the experimental data.

FWHM energy resolution values were used to compare detector performance at different steering electrode conditions. The FWHM energy resolutions were calculated by fitting a Gaussian curve to the photopeak in the energy spectra.

2.6. Photon sensitivity as a function of steering strip width and bias voltage

Photon sensitivity is a further detector performance parameter that depends strongly on anode sensitivity to space charge. Since the steering electrodes can greatly modify the electric field near the anode plane of a CZT photon detector (figure 2), the effect of steering electrode width on detector photon sensitivity was investigated.

A 500 μm diameter pencil beam of 511 keV photons (^{68}Ge) oriented along the z direction was made to impinge on the cathode face, at the portion of steering electrodes where their widths vary. The beam scanned across anode and steering strips in the x direction in 167 μm steps. The steering voltage was varied as in section 2.5. As with the previous sub-study, we analyzed the class of photon interactions which do not introduce unnecessary confounding factors, e.g. Compton interactions involving multiple cathode strips or non-adjacent anode strips. Specifically, we focused on photon interactions that i) triggered exactly one cathode and either one or both anodes adjacent to the steering electrode, and ii) the sum energy of the photon interaction(s) falling within a $511\text{ keV} \pm 4\%$ photopeak window (a “full charge collection photon interaction”). The photon interactions rate was observed for each beam position and steering electrode bias combination for each steering electrode width. This rate corresponds directly to an anode strip’s ability to collect mobile electrons. Data collection took place over several weeks, so correction was applied for ^{68}Ge decay (270.95-day half-life).

Maxwell SV was used to calculate and visualize the electrostatic potential along the detector’s anode face. This was done to gain insight to the measured detector performance for different steering electrodes widths and steering bias values.

2.7. Photon sensitivity as a function of edge steering electrode

The last part of the study investigated how photon sensitivity changes along the periphery of the CZT detector crystal as compared to the detector’s central regions. In particular, we assessed if the presence of a steering electrode on the crystal edge helps to maintain photon sensitivity along the crystal edge, where fringe electric field may guide mobile charge carriers to the detector’s $40\text{ mm} \times 5\text{ mm}$ edge face instead of the anode or cathode planes.

A 1 mm diameter pencil beam of 511 keV photons (^{68}Ge) oriented in the z direction was directed at the cathode face, and scanned across the edge anodes and steering electrodes in 167 μm steps. Detector was biased at 120 V/mm at a steering bias of -100 V . For each beam position, the number of photon interactions in the $511\text{ keV} \pm 4\%$ photopeak window detected on each anode strip per second was noted. This count rate is then plotted as a function of the beam position for each anode channel, from which we obtain the anode strips’ point spread

function (PSF). The width and relative height of these PSFs give an indication of the detector's photon sensitivity profile near the edge.

3. Results

3.1. Sub-pitch continuous positioning capability in y as a function of cathode strip width

Figure 6 shows scatter plots of photon interactions. In this case, the cathode strips of interest were numbered 2 and 3. The clustering distribution of the photon interactions is seen to change from one slit beam position to another (relative to the two cathode strip boundaries).

Subplot figure 7 (a) is obtained by merging a series of scatter plots as those in figure 6 into a single 3-D scatter plot, where the z axis denotes the collimated slit beam position. Figure 7 (b) shows the iso-surfaces of the corresponding joint pdf $f(E_{C1}, E_{C2}, p)$ derived from applying Parzen window density estimation to the 3-D scatter plot.

Figure 8 plots, for both 3 mm and 5 mm width cathodes, the MAP-estimated photon interaction position (relative to the cathode strip boundary) versus the nominal slit beam position, which is taken to be the true photon interaction position. The spread in the MAP estimate of the photon interaction's y coordinate is quantified by the root-mean-square (rms, see error bars) deviation from the mean estimate. We note that the error bars include contribution from the 500 μm width of the collimated beam.

3.2. DOEP spatial positioning uniformity as a function of cathode strip width

Figure 9 shows the mean C/A ratio plotted against the z coordinate of the collimated slit beam. 0 mm denotes the cathode plane. Data points in red correspond to the 5 mm width cathode strip, and those in black to the 3 mm wide cathode strip. The solid lines represent third order polynomials fitted to the data points, and the error bars indicate the extent of the standard deviation of C/A ratio distribution at each z coordinate.

The data extends from 0 mm to 4 mm, and the detector crystal is ~4.8 mm thick (nominally 5 mm). In the remaining ~800 μm thick region closest to the anode plane the sensitivity is very low and thus event statistics is poor. This is because the cathode strips' weighting potential is near zero in this region; combined with poor hole mobility, photon interactions in the region close the anode often do not lead to cathode signals above the trigger threshold, which is set above a non-zero noise floor. The effect of the resultant "gaps" in photon sensitivity along the axial direction of the final PET system is not uncommon in high-resolution PET, and can be partially accounted for via photon sensitivity normalization during iterative image reconstruction.

3.3. Time resolution as a function of cathode strip width

Figure 10 shows the cathode-PMT time difference spectrum for both the 3 mm wide and 5 mm width cathode strips. The outline-only and red histograms represent, respectively, timing spectra before and after correction for systematic error as per Reynolds *et al* (2011).

By gating the data in figure 10 according to the collimated beam's z coordinate, we can calculate the FWHM cathode-PMT coincidence time resolution as a function of z . The

FWHM measures are based on Gaussian curves fitted to the histogram peak derived for each z position. The result is shown in figure 11. $z = 0$ mm corresponds to the cathode plane.

3.4. Photon sensitivity as a function of cathode strip width

Figure 12 shows the detector photon sensitivity as a function of slit beam position. The vertical axis is in logarithmic scale, and the sensitivity is expressed in terms of the number of detected photon hits per second. The square markers denote the photon interactions in a $511 \text{ keV} \pm 4\%$ energy window.

3.5. Energy resolution as a function of steering strip width and bias voltage

The FWHM energy resolutions of both single-anode as well as charge-shared photon interactions were calculated. Figure 13 shows the FWHM anode energy resolution of single-anode and anode charge-shared photon interactions (dotted lines) as a function of the steering bias potential for $100 \mu\text{m}$ and $400 \mu\text{m}$ width steering electrodes. For the latter, the energy resolution was based on spectra formed from the histogram of the sum energy of two adjacent anodes.

3.6. Photon sensitivity as a function of steering strip width and bias voltage

Figure 14 shows the measured full-charge-collection photon interaction rate for different combinations of collimated beam position and steering bias values. Data from steering electrodes of different widths are merged in figure 14 as the mean interaction rates across all steering electrodes did not differ widely despite their different widths. This is evidenced by the relative size of the standard deviation.

Likewise in figure 15, data from different beam positions were merged. The figure shows a relatively constant photon interaction count rate across the full anode pitch across a range of steering bias values, e.g. the count rate at -40 V steering bias (square-marked line) changed by less than 8.1% for a factor of 4 difference in steering electrode width ($100 \mu\text{m}$ vs. $400 \mu\text{m}$). This verifies the overall effectiveness of the steering electrodes.

Figure 16 shows the Maxwell SV calculated electrostatic potential profile at the anode plane across a single anode pitch with steering electrodes centered at the 0 mm position in each subplot. The visualization provided by figure 16 is extended along the z direction in figure 17, where the electric potential profile through the entire 5 mm thickness of the detector is shown as a surface. The surfaces are overlaid with their corresponding electric field lines, so that the drift direction of mobile charge and their effect on anode charge collection can be easily visualized. We observe that when steering electrodes of $100 \mu\text{m}$ and $400 \mu\text{m}$ width are both biased at -100 V with respect to the anodes, the electrostatic potential and electric field lines in the two cases exhibit only minor differences.

3.7. Photon sensitivity as a function of edge steering electrode

Figure 18 shows the detector photon sensitivity measured over three consecutive anode strips at the CZT crystal edge, i.e. anodes 37, 38 and 39. The vertical axis shows the number of photon interactions detected per second on each anode strip in a $511 \text{ keV} \pm 4\%$ energy window.

For verification, the detector's photon count response was modeled for a 1 mm diameter pencil beam. The simulated sensitivity profile was tuned to visually match the experimental observation. The modeled response is shown by the dotted line in figure 18, and the underlying photon sensitivity profile is shown in figure 19. Over the observed range, the sensitivity was modeled to have a linear profile changing from 1 (a.u.) at anode position 37 mm to 0.95 (a.u.) at the detector edge.

4. Discussion

4.1. Sub-pitch continuous positioning capability in y as a function of cathode strip width

The symmetry of cluster distribution about the $y = x$ line in figure 6 (a) verifies that the charge cloud is shared evenly across the boundary gap. Clustering along the $x + y = 511$ keV is absent due to the relatively short mean free path of holes in CZT. In particular, the relatively high levels of hole trapping causes the cathodes to have poor energy resolution so that it does not exhibit a photopeak (and hence clustering) at 511 keV.

When the slit beam is incident on just one of the cathode strips at 1.67 mm from the cathode boundary however (figure 6 (b)), the distribution of signal amplitudes become more clustered along the horizontal axis (denoting cathode strip 2), because the photon interactions are now closer to cathode 2's weighting potential lobe. This demonstrates the clustering center of signal amplitudes shifts rapidly with photon interaction position relative to the cathode boundary. This is made explicit in figure 7 (a), which shows the clustering shift across a range of photon interactions centered on the cathode boundary. Note that for both 3 mm and 5 mm wide cathode strips, the clustering pattern changes little beyond ~1 mm from the cathode boundary. This can be accounted for by the cathode weighting potential's low lateral sensitivity to photon interactions far from the cathode edge (figure 4 (b) and (c)), so that beyond ~1 mm from a cathode strip boundary, non-charge-shared photon interactions dominate.

Exploiting this charge sharing behavior, figure 8 suggests that continuous sub-pitch photon interaction positioning capability in y is achievable using, e.g., MAP estimation based on the 3-D joint pdf $f(E_{C1}, E_{C2}, p)$ of figure 7 (b). This is true at least within 1 mm of the cathode boundary. In this region, figure 8 further indicates that the 3 mm and 5 mm wide cathode strips in fact provide similar sub-pitch positioning rms MAP estimation error.

Taken together, the results show that if the cathode pixel or strip width is much more than ~2 mm, then non-charge-shared photon interactions would dominate (see figure 12) and the detector's spatial resolution capability would be determined primarily by the pitch of the electrode pixel or strips. For pixel or strip widths less than ~2 mm, charge-shared photon interactions would dominate (see figure 12), and continuous positioning of charge-shared photon interactions based on relative signal amplitudes is achievable.

It is clear that when optimizing for detector spatial resolution, a narrower cathode strip would be preferable due to its finer spatial discretization and mitigated dominance of non-charge-shared photon interactions. Recall however that given the CZT detectors' orientation in the small animal PET system, the cathode width and pitch corresponds to the DOI

resolution, which does not affect the reconstructed PET image resolution as much as the tangential resolution (determined by the anode pitch size). Consequently, in a globally optimized sense, a larger cathode pitch may be an acceptable tradeoff if it would enhance other aspects of detector performance e.g. positioning linearity, photon sensitivity, and time resolution uniformity.

4.2. DOEP spatial positioning uniformity as a function of cathode strip width

Figure 9 shows that the C/A ratio changes more linearly with the z coordinate of photon interactions for 5 mm wide cathode strips (red line). This can be understood through the contour plot of the cathode (x, y, z) in figure 4, which shows the contours for both 3 mm and 5 mm wide cathode strips being relatively uniformly spaced near the cathode plane (0 cm on the vertical axis in figure 4). Farther from the cathode plane however, the 5 mm wide cathode strip maintains more uniformly spaced contours than the 3 mm wide cathode strip. This means for the latter, space charge in a larger portion of the detector volume would map to a similar range of signal amplitude. This reduced sensitivity to variations in space charge position accounts for the smaller changes in C/A ratio for photon interactions with $z > \sim 3$ mm in figure 9.

The benefit of the wider 5 mm width cathode strips in this case is apparent, particularly for photon interactions far from the cathode plane. This suggests that a 5 mm wide cathode strip would be the better candidate for attaining linear z positioning.

4.3. Time resolution as a function of cathode strip width

Good coincidence time resolution leads to enhanced ability to filter out random coincidences in PET imaging, resulting in higher contrast and accuracy in reconstructed images.

The cathode-PMT coincidence peak in the time difference spectra of figure 10 exhibits large dispersion (~ 100 ns) before correction for systematic errors due to cross-talk, channel delay and DOEP dependent effects (Reynolds *et al* 2011). The correction procedure reduced the coincidence peak dispersion to yield FWHM values of 29 ± 5 ns and 39 ± 3 ns, respectively, for the 3 mm (figure 10 (a)) and 5 mm (figure 10 (b)) wide cathode strips. These are the aggregate time resolution values derived from photon interactions throughout the CZT detector's full thickness.

The first observation is that CZT photon detector's time resolution is about an order of magnitude worse than scintillation crystal-based photon detectors. This is because in semiconductor photon detectors the electrode sensitivity to charge carriers is spatially varying, furthermore, given that CZT detector signals depend on charge transport, they are produced with higher temporal variance compared to the propagation and collection of scintillation light (Levin 2008). The result is that CZT detectors have more timing jitter and time walk, which degrades the coincidence time resolution. Meng and He (2005) have shown that time resolution of ~ 10 ns may be achieved if the full waveform from each event were digitized for analysis. However, our RENA-3 based data acquisition system does not enable this as it samples only the pulse peak value, and uses a leading edge discriminator for time pick-off.

The time resolution was also seen to vary as a function of the z coordinate. Most events in the experimental data of figure 10 (b) were collected from the $z \in [0.5 \text{ mm}, 2.5 \text{ mm}]$, for which the FWHM coincidence time resolution is generally in the 40 ns range. This accounts for the similarity between the aggregate and the best achieved FWHM time resolution.

The full relation is quantified in figure 11. Here we see the 3 mm wide cathode strip providing better time resolution than the 5 mm wide cathode strip for photon interactions near the cathode plane (near field), e.g. $\sim 26 \text{ ns}$ vs. $\sim 34 \text{ ns}$ between 0.5 mm and 1.5 mm from the cathode plane. This can be attributed to the weighting potential profile of figure 4 (b) and (c). Compared to the 5 mm wide cathode strip, the larger $\nabla(x, y, z)$ of the 3 mm wide cathode strip for small z means i) faster signal rising edge for interactions near the lobe, and ii) enhanced insensitivity to reverse polarity charge induction by trapped electrons beyond the immediate vicinity of the cathode strip. This leads to larger amplitude signals and hence short rise time. While shorter rise times could also be achieved by inducing higher mobile charge drift velocities by, e.g. applying a higher detector bias, this mode of rise time reduction is limited by the onset of drift velocity saturation. In contrast, the effect of the weighting potential profile is intrinsic to the electrode geometry, and unconstrained by detector operating conditions. For small z , the net effect of the weighting potential profile of the 3 mm width cathode strip is reduced sensitivity to time walk and reduced jitter from electronic noise, consistent with the conclusion of equation (5).

For large z however ($z > \sim 3.7 \text{ mm}$), the time resolution of the 3 mm width cathode becomes significantly worse than that of the 5 mm width cathode e.g. $\sim 127.5 \text{ ns}$ vs. $\sim 83 \text{ ns}$ at $z = 4.2 \text{ mm}$ – a 53.6% difference. This is consistent with equation (4) and can again be accounted for by the weighting potential profile shown in figure 4 (b) and (c). We also note that although the larger metalized area of the 5 mm width cathode strips increases the stray capacitance at the preamplifier input (which amplifies electronic noise), for large z (far field), the combined effect of its capacitance and weighting potential nevertheless yielded a time resolution better than that of the 3 mm width cathode strips over at least half the detector thickness, i.e. $z \in [2 \text{ mm}, 4.5 \text{ mm}]$.

Overall, although 5 mm wide cathode strips offer somewhat worse near-field time resolution, their deeper field of view helps to maintain more uniform time resolution performance throughout the detector volume, hence they are preferable in this context.

4.4. Photon sensitivity as a function of cathode strip width

Figure 12 show that one-anode-one-cathode photon interactions dominate at cathode centers, while charge-shared photon interactions dominate near cathode boundaries. The detector nevertheless preserves uniform photon sensitivity across cathode strips of a given width as evidenced by the horizontal trend of black data points in figure 12. This is true for both energy-gated and non-energy-gated photon interactions. The results confirm highly uniform photon sensitivity and negligible signal loss to the inter-strip gaps regardless of the cathode strip width.

In terms of the absolute photon sensitivity, recall that the 5 mm width cathode strips exhibit weaker small-pixel effect, so they would be more sensitive to photon interactions in a larger

portion of the detector than their narrower counterparts. This is quantified in figure 12, which shows 5 mm wide cathode strips offering a 68.4% improvement in photon sensitivity over 3 mm wide strips for non-energy-gated photon interactions ($\sim 89.5/\text{s}$ vs. $\sim 53.1/\text{s}$), and 19.9% improvement for energy-gated photon interactions ($\sim 7.2/\text{s}$ vs. $\sim 6.0/\text{s}$). Hence 5 mm width cathode strips are preferred in this context.

4.5. Energy resolution as a function of steering strip width and bias voltage

Figure 13 suggests that for single-anode photon interactions (solid lines), i.e. no charge-sharing, in spite of a factor of four difference in electrode width (100 μm vs. 400 μm), and a 60 V difference in steering bias (-40 V vs. -100 V), the energy resolution is relatively insensitive to these changes, remaining largely constant at $3 \pm 0.5\%$ FWHM at 511 keV.

For charge-shared photon interactions on the other hand (dotted lines), the energy resolution varies noticeably with increasing steering bias potential. Figure 13 shows energy resolution of $\sim 13.2\%$ and $\sim 6.6\%$, respectively, at steering biases of -40 V and -100 V on a 100 μm wide steering electrode. Similar improvement is seen for a 400 μm wide steering electrode. The sensitivity of energy resolution to changes in steering electrode width is much less dramatic, showing only a $\sim 35\%$ change ($\sim 6.6\%$ vs. $\sim 4.9\%$) for a 400% difference in electrode width (100 μm vs. 400 μm).

From these observations, two major conclusions can be drawn. Firstly the energy resolution improves with larger steering bias for charge-shared photon interactions. This reveals that a high lateral (x direction) electric field component is crucial in achieving good charge collection of charge clouds that straddle the detection volumes of two adjacent anode strips. Secondly, the 400 μm wide steering electrodes provide slightly better energy resolution performance than 100 μm wide steering strips.

We also note by comparing the single-anode and charge-shared data in figure 13, that the energy resolution of single-anode photon interactions is superior to those of charge-shared photon interactions for any steering electrode width-bias combination. This is because in the single-anode case, we have electronic noise contribution from a single channel of the RENA-3 ASIC, while with charge-shared photon interactions, we have uncorrelated noise contributions from two RENA-3 channels.

In conclusion, to achieve superior energy resolution, it is desirable to i) maximize the steering electrode width, and ii) operate the steering electrodes at below ~ 80 V relative to the anode potential.

4.6. Photon sensitivity as a function of steering strip width and bias voltage

The photon sensitivity is largely insensitive to the steering electrode width (figures 14 and 15). The similarity between figures 17 (a) and (b) explains the relative invariance of photon sensitivity to steering electrode width, consistent with the similarity between figures 13 (a) and (b).

On the other hand, figures 14 and 15 show the photon sensitivity is highly sensitive to the steering bias. The 0 V case shows by far the lowest count rates. To appreciate this, consider

figure 2 (b). When both the anode and steering electrodes are held at 0 V, most of the electric field lines terminate on the steering electrodes by virtue of their relative width to the anode strips. As a result, most of the mobile electrons are lost to the steering electrodes. With increasing magnitude of the steering bias however, the detector photon sensitivity also increases.

To understand this result, we first note that charge loss occurs over any region near the steering electrode that is at a lower potential than the steering electrode, e.g. between -0.15 mm and 0.15 mm for $100\text{ }\mu\text{m}$ wide steering electrode in figure 16 (a). As the potential difference between the steering electrodes and anodes increase, the size of the region responsible for charge loss is narrowed as illustrated in figure 16 (b), and subsequently eliminated at -80 V (figure 16 (c)) and -100 V (figure 16 (d)). At this point, further lowering the steering potential does not provide additional advantage. This accounts for fact that the photon count rate at steering bias values of -80 V (square-marked lines) and -100 V (circle-marked lines) in figure 14 are similar.

The findings here are that i) photon sensitivity is largely insensitive to the steering electrode width, ii) photon sensitivity is highly sensitive to the steering bias, iii) photon sensitivity improves as the steering bias becomes more negative with respect to the anode strips, up to about -80 V, beyond which the improvement becomes negligible.

4.7. Photon sensitivity as a function of edge steering electrode

Detector photon sensitivity is preserved at the detector edge as shown in figures 18 and 19. Specifically, sensitivity of the edge anode strip is seen to differ less than $\sim 5\%$ from the sensitivity of the anode strips further away from the edge.

The experimental results indicate that with a steering electrode on the detector edge, we can expect little loss in photon sensitivity along the periphery of the CZT crystal. This means that photon sensitivity uniformity would be preserved when the CZT crystals are stacked into arrays in the final system. In terms of imaging, this means there will be little or no artifacts in reconstructed images due to sensitivity discontinuities across detector boundaries.

4.8. Summary of findings

The major findings drawn from across each sub-study are summarized in tables 1 and 2.

5. Conclusion

This paper presented an in-depth and experiment-based study of the dependence of CZT photon detector performance on the dimension of its electrode pattern features. The study was successful in optimizing the performance of CZT photon detector intended for a high-resolution small animal PET imaging system in a quantitative and methodic manner.

Experimental results verified the sub-millimeter positioning capability and superior energy resolution characteristic of the CZT photon detector. In particular, by employing 5 mm wide cathode strips and $400\text{ }\mu\text{m}$ wide steering electrode strips, the CZT photon detector's

performance will be optimized to yield PET images of high spatial resolution, superior resolution uniformity, noise uniformity, contrast, and contrast-to-noise ratio. When compared to conventional scintillation crystal-based PET imaging, the CZT photon detector's time resolution of ~34 ns to ~83 ns is relatively poor. However, this could be compensated for in part by exploiting its excellent spatial and energy resolutions and using Compton kinematics-based direction window collimation in identifying random coincidences (Chinn and Levin 2011).

Lastly, we note that in spite of this study's focus on CZT photon detector for PET imaging, the insights and findings can be readily generalized to the class of semiconductor photon detectors employing cross-strip or pixilated electrode patterns, e.g. CdTe, Ge, or Si photon detectors with applications in astronomical imaging, radiation detection, CT, SPECT etc.

In future work, the CZT photon detector performance will be assessed in the final assembled PET system *in situ*, so that efficacy of CZT photon detector can be established both in terms of its raw detector performance metrics, as well as the PET images it yields.

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Figure 1.

Subplot (a) shows the prototype detector and the reference co-ordinate system. Subplot (b) shows the anode electrode pattern, comprising anode strips interspersed with steering electrodes. Subplot (c) shows a magnified view of steering electrodes where their width is varied. Subplot (d) shows the cathode electrode pattern.

Figure 2.

Subplot (a) shows detector electric field lines at 0 V anode bias, -500 V cathode bias and -60 V steering bias for $200\text{ }\mu\text{m}$ width steering electrode. (b) shows the electric field lines at the same anode and cathode bias, but 0 V steering bias for $200\text{ }\mu\text{m}$ wide steering electrodes. The anode strips are centered at -0.5 mm and 0.5 mm (red), and the steering electrodes are located at -1 mm, 0 mm and 1 mm (blue). The thickness of electrodes is exaggerated for illustration purposes.

Figure 3.

(a) SolidWorks rendered image of the final assembled 3-D high-resolution small animal PET system under development. (b) Illustration of detector array arrangement, and orientation of figure 1 (a)'s reference coordinate system in the PET system. Coordinates systems in the red and blue quadrants are identical but for a 90° rotation about the PET system axis (the z direction). Similarly coloured quadrants use the same corresponding coordinate system.

Figure 4. Calculated weighting potential profiles of cathode strips of varying widths. 0 mm along the vertical axis corresponds to the cathode plane, and 5 mm corresponds to the anode plane.

Figure 5.

Subplot (a) shows the calculated weighting potential profile of a 100 μm wide anode as a function of the x and z positions as defined in figure 1 (a). The lobe centered on the anode axis corresponds to the region of high charge sensitivity. Subplot (b) shows subplot (a)'s corresponding contour plot.

Figure 6.

Scatter plot of signal amplitudes on cathode 2 vs. cathode 3 for two slit beam positions. Each photon interaction is represented as a point whose position corresponds to the magnitude of signal it induced on two adjacent 5 mm wide cathode strips. (a) Slit beam incident at midpoint between two 5 mm width cathode strips. (b) Slit beam incident 1.67 mm from the cathode boundary on one 5 mm wide cathode strip. Only charge-shared photon interactions are shown.

Figure 7.

(a) Scatter plot of charge-shared photon interactions on cathodes 2 and 3, i.e. (E_{C1}, E_{C2}) vs. slit beam position relative to the cathode strip boundary. 0 mm corresponds to the gap location between the cathode strips; the y center of cathode 2 is at beam position 2.5 mm, and of cathode 3 is at -2.5 mm. Figure 7 (b) shows the iso-contours of $f(E_{C1}, E_{C2}, p)$ derived from applying pdf estimation based on the data points in (a).

Figure 8.

MAP-estimated photon interaction position vs. true photon interaction position. 0 mm corresponds to the gap between two adjacent cathode strips. 1.5 mm and -1.5 mm correspond, respectively, to the middle of adjacent 3 mm width cathode strips. The error bars indicate the extent of the rms deviation from the mean estimate.

Figure 9.
C/A ratio as a function of photon interactions' z position.

Figure 10.

Cathode-PMT time difference histogram before and after calibration for cross-talk, channel delay and DOEP dependent effects. The data set contains photon interactions with $z \in [0 \text{ mm}, 5 \text{ mm}]$, and which are non-charge shared, i.e. one anode-one cathode only. (a) 3 mm wide cathode strips, 29 ± 5 ns FWHM after calibration. (b) 5 mm wide cathode strips, 39 ± 3 ns FWHM after calibration.

Figure 11. Calibrated cathode-PMT time difference as a function of photon interaction distance from the cathode plane. Error bars correspond to 95% confidence interval of the fitted parameter.

Figure 12.
Photon sensitivity as a function of photon interaction position across a cathode pitch for (a) 3 mm and (b) 5 mm wide cathode strips.

Figure 13.

FWHM energy resolution at 511 keV as a function of steering electrode bias voltage for single-anode (solid lines) and anode charge-shared (dotted lines) photon interactions. In subplot (a) the steering electrode width is 100 μm , and in (b) it is 400 μm . The error bars denote the 95% confidence interval of the fitted energy resolution.

Figure 14.

Full-charge-collection count rate as a function of beam position. Each line corresponds to measurements at one steering bias, encompassing data across steering electrodes of all widths. Error bars show the extent of the standard deviation about the mean count rate. The centers of anode strips are at -0.5 mm and 0.5 mm on the x axis, the steering electrode is at the 0 mm position.

Figure 15. Measured full-charge-collection count rate as a function of steering electrode width and negative of steering bias voltage. The error bars depict the standard deviation.

Figure 16.

Electric potential profile at the anode plane as a function of the cross-pitch position (x coordinate) for different steering electrode widths at (a) -40 V, (b) -60 V, (c) -80 V and (d) -100 V steering bias. The steering electrode strips are centered at 0 mm, the adjacent anode strips are centered at -0.5 mm and 0.5 mm.

Figure 17.

Visualization of the detector's internal electrostatic potential overlaid with electric field lines. The cathode bias is -500 V, the steering bias is -100 V and the steering electrode widths are (a) $100\text{ }\mu\text{m}$ and (b) $400\text{ }\mu\text{m}$. The anode and cathode planes are at, respectively, $z = 5\text{ mm}$ and $z = 0\text{ mm}$.

Figure 18.

Observed (solid lines) vs. modeled (dotted lines) photon sensitivity response at detector edge.

Figure 19.
Modeled underlying photon sensitivity profile.

Table 1

Summary of cathode strip width preferences by CZT photon detector performance parameter.

	<u>Cathode width</u>		Comments
	3 mm	5 mm	
Spatial positioning in y direction			Narrower cathode strips provide finer spatial discretization, and promotes a higher fraction of charge-shared photon interactions for continuous positioning for higher PET image resolution.
Spatial positioning linearity in z direction			Weaker small pixel effect of 5 mm wide cathode strip provides more uniform discrimination of C/A ratio as a function of z coordinate for higher PET image resolution uniformity.
Time resolution			Weaker small pixel effect of 5 mm wide cathode strip provides lower near-field time resolution, but more uniform aggregate time resolution across the range of z values. This will achieve better overall random coincidence rejection and higher PET image contrast.
Photon sensitivity			Weaker small pixel effect of 5 mm wide cathode strip provides enhanced photon sensitivity near the anode plane for higher contrast-to-noise ratio of PET images.

Table 2

Summary of steering electrode width and bias preferences by CZT photon detector performance parameter.

	Steering electrode width	Steering bias
Anode energy resolution	Prefer wide (400 μm)	Prefer high (< -80 V)
Photon sensitivity	No preference.	Prefer high (< -80 V)