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Investigation of the limitations of the highly pixilated CdZnTe detector for PET applications

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Abstract

We are investigating the feasibility of a high resolution positron emission tomography (PET) insert device based on the CdZnTe detector with 350 μm anode pixel pitch to be integrated into a conventional animal PET scanner to improve its image resolution. In this paper, we have used a simplified version of the multi pixel CdZnTe planar detector, 5 mm thick with 9 anode pixels only. This simplified 9 anode pixel structure makes it possible to carry out experiments without a complete application-specific integrated circuits readout system that is still under development. Special attention was paid to the double pixel (or charge sharing) detections. The following characteristics were obtained in experiment: energy resolution full-width-at-half-maximum (FWHM) is 7% for single pixel and 9% for double pixel photoelectric detections of 511 keV gammas; timing resolution (FWHM) from the anode signals is 30 ns for single pixel and 35 ns for double pixel detections (for photoelectric interactions only the corresponding values are 20 and 25 ns); position resolution is 350 μm in x,y -plane and ~ 0.4 mm in depth-of-interaction. The experimental measurements were accompanied by Monte Carlo (MC) simulations to find a limitation imposed by spatial charge distribution. Results from MC simulations suggest the limitation of the intrinsic spatial resolution of the CdZnTe detector for 511 keV photoelectric interactions is 170 μm . The interpixel interpolation cannot recover the resolution beyond the limit mentioned above for photoelectric interactions. However, it is possible to achieve higher spatial resolution using interpolation for Compton scattered events. Energy and timing resolution of the proposed 350 μm anode pixel pitch detector is no better than 0.6% FWHM at 511 keV, and 2 ns FWHM, respectively. These MC results should be used as a guide to understand the performance limits of the pixelated CdZnTe detector due to the underlying detection processes, with the understanding of the inherent limitations of MC methods.

1. Introduction

Our objective is developing high-resolution insert detectors and prototype positron emission tomography (PET) insert devices in order to improve the spatial resolution of conventional human and animal PET scanners (Komarov *et al* 2010, Janecek *et al* 2006, Song *et al* 2010, Tai *et al* 2006, 2008, Wu *et al* 2008a, 2008b). We have demonstrated that the combination of high-resolution insert detectors, high-sensitivity PET scanner and sophisticated image reconstruction algorithms can provide PET images with high-resolution and high-sensitivity despite the fact that the PET insert detectors may have relatively low sensitivity (Wu *et al* 2008b, Pal *et al* 2007, Keesing *et al* 2012). It is technically challenging to fabricate and use scintillator crystal arrays as PET detector when crystal size is significantly less than 0.5 mm (Qi *et al* 2011). In our development plan, we propose to use a planar CdZnTe detector ($11 \times 23 \times 5 \text{ mm}^3$) with a solid cathode and segmented 2048-pixel (32×64) anode structure with $250 \text{ }\mu\text{m}$ pixel size and $350 \text{ }\mu\text{m}$ pitch. Before creating the full scale system, we investigated the properties of the proposed CdZnTe detector as an insert detector.

The image resolution of PET systems is limited by the positron range, acolinearity of the annihilation γ -rays and spatial resolution of the detectors. The virtual-pinhole geometry used for our PET insert detector (Tai *et al* 2008) makes it possible to minimize the acolinearity effects by shortening the distance between two PET detectors. In this case the positron range and intrinsic detector resolution become the dominant factors in determining the image resolution. For our future detector the selection of the detector pixel size was based on the work (Stickel and Cherry 2005), which states that to obtain a spatial resolution of around 0.5 mm a detector pixel size of $250 \text{ }\mu\text{m}$ would be needed. We start our study from the slightly larger pixel pitch— $350 \text{ }\mu\text{m}$ —expecting some problems with the large range of the high energy photoelectrons in the detector. While the spatial resolution of the pixilated CdZnTe detector is closely related to the anode pixel pitch, it is unclear how the spatial resolution is affected by the range of the photoelectron when the size of the anode pixel starts to approach the projected range of photoelectrons.

At the same time, the improvement of the detector's energy resolution due to the 'small pixel effect' will be undone by charge sharing between neighboring pixels with very small pixels. At certain small pixel size, there will be no photoelectric detections where the charge can be collected by a single pixel. Thus, the minimal reasonable size of the anode pixels is limited by the charge sharing between the neighboring anode pixels collecting the electrons from the hole–electron distribution (charge cloud) created after gamma interaction. Charge sharing among anode pixels leads to a decrease in the number of events that are detected by single anode pixel. Exceedingly small anode pixels may decrease the detection efficiency of the detector if only the single pixel detections are employed. Alternatively, sophisticated processing of events that involve multiple anode pixels may allow one to utilize all events detected by small anode pixel CdZnTe detectors for imaging purposes. Although the characteristics of the CdZnTe detectors have been widely investigated over the last decade (Bolotnikov *et al* 1999, He *et al* 2000, Meng and He 2005), little has been reported about CdZnTe as a PET detector (Vaska *et al* 2007, Gu *et al* 2011) and we did not find any publication about a CdZnTe PET detector with anode pixel size less than 0.5 mm.

In addition to the spatial resolution, the detector timing is important for PET detectors that are used for coincidence detections. The long signal drift time (or charge carrier collection time) of CdZnTe imposes some restriction on the detection rate to avoid multiple detections within the drift time. The use of a large coincidence time window (due to the large uncertainty of charge collection time) implies increased random coincidences in such PET systems. To minimize the random coincidences, a more accurate estimate of the gamma-ray interaction time is needed. In principle, the timing estimated from the cathode signal (Meng and He 2005) can provide more accurate gamma interaction time. The fitting of the theoretical cathode waveform to the experimental one, which was used in Meng and He (2005), in order to obtain the correct detection time can be done only for the relatively large cathode signals and, as a result, some of the detections with small cathode signal (particularly the Compton detections and detections near the anode plane) will be lost because their timing cannot be accurately estimated. In contrast, the amplitude of the anode signal is almost independent of the depth-of-interaction (DOI) (except in the small region near the anode plane), and depends only on the energy deposited. The anode signal also has a relatively sharp rise time that provides high precision in estimating the timing of the signal. However, the anode signal has to be corrected for the electron drift time in order to estimate the correct timing of the gamma-ray interaction. In this work we investigated the feasibility of using the anode signal for the detector timing.

In contrast to the conventional scintillator detectors, the CdZnTe has relatively low probability for photoelectric interaction. For example, 1 mm of LSO is equivalent to 3 mm of CdZnTe. At the same time both materials have comparable detection efficiencies for the Compton interactions (1 mm of LSO ~1.4 mm of CdZnTe). The ratio of the numbers of photoelectric interactions to the number of Compton interactions for a 5 mm thick CdZnTe detector is 0.24. For this reason it will be interesting to consider using the CdZnTe detector in the mode 'all detection accepted'. This detector can be used for the PET system where the Compton scattering from the object is not significant or can be properly corrected.

In this study, we used a simplified version of the CdZnTe detector with only 9 anode pixels (see figure 1(a)). This special 9-pixel structure allows us to read out the 350 μm pitch anodes using discrete components on printed circuit board (PCB) with pogo-pin connectors (2.5 mm pitch). The central anode pixel A5 is connected directly to the PCB through a pogo-pin, while the other 8 anode pixels are connected through large readout pads deposited on the anode surface of the detector. This approach offers a temporary solution before the dedicated application-specific integrated circuits (ASIC) developed for PET application at the University of Illinois at Urbana Champaign is ready. It was assumed that the detector response for interactions over the central region of the 9 anode pixel structure will be similar to that of the 2048-pixels detector. For this reason we consider only detection events with non-zero signal from A5.

For all experiments, we used the Modified High-Pressure Bridgman (MHB) CdZnTe slab from Orbotech (Yavne, Israel). The 125 nm thick gold cathode and 100 nm thick titanium anode structures were deposited on opposite sides of the CdZnTe crystal in a 'clean room' of the Department of Physics at Washington University in St. Louis.

In this work we first provided the electrostatic calculations (section 2) to demonstrate that the central pixel (A5) in our special anode pattern is similar to the anode pixels from the proposed 2048-pixels anode structure. Therefore, data from this simplified anode structure can be used to evaluate the performance of the pixelated CdZnTe detector.

We further investigated the position resolution (section 4), energy resolution (section 5) and timing properties (section 6) of the CdZnTe detector. All of these properties are important for using CdZnTe as a PET detector. The Monte Carlo (MC) simulations (described in section 3) were used to find the limitation for the detector performance implied by the spatial charge distribution.

It should be noted that we gave special attention to the charge sharing events in this study because they represent a large fraction of all detected events for detectors with a relatively small anode pixel pitch (<1 mm). Assuming the size of the hole–electron pair cloud ~100 μm we can estimate that the charge sharing events for the 1 mm pitch detector will be one-third of all detections. For the 0.5 mm pixel pitch, more than half of all detections are the charge sharing detections.

The following are some conventions used in this manuscript: (1) the charges induced in anode pixels (A1–A9) and cathode at the end of detector integration time are referred as anode signals (A1–A9) and cathode signal C; (2) we only include in our analysis the detections where anode signal $A5 > 0$ because A5 is the only pixel that closely resembles the response of multi-pixel detectors; (3) ‘single pixel detection’ is a detection where all anode signals except A5 are below a pre-selected energy threshold; (4) ‘double pixel detection’ or ‘charge sharing detections’ are a detection where the signals of anode A5 and one of its neighboring anodes are above a pre-selected energy threshold, while the signals of all other anodes are below this threshold; (5) photopeak-like detection is a gamma interaction in the detector with full energy deposition (photoelectric interaction and Compton absorption—Compton interaction (or interactions) followed by subsequent photoelectric interaction). The anode and cathode signals obtained in experiments are presented in ADC channels—there is no calibration for the raw data. Although the result of MC simulation is the total charge induced on the electrode (anode or cathode), the results of MC simulations in this paper are presented in keV. To transform charge to energy (or electrons to keV), we multiply the induced charge to the energy needed for the one hole–electron production in CdZnTe (4.64 eV). If all charges are collected, the signal of electrode in keV will be exactly equal to the energy deposited. Nevertheless, due to the hole and electron trapping, the obtained signal will always be smaller than the deposited energy. Thus the presented MC signals in keV do not necessarily correspond exactly to energy deposit in keV.

2. Electric field and weighting potential calculation

The calculation of the static electric field and weighting potentials were done by the numerical solution of the Laplace equation:

$$\nabla(\varepsilon \nabla \varphi) = 0 \quad (1)$$

where ε is a permittivity of material and φ is an electric potential.

The finite differences method was used for the numerical solution of (1). The electrodes' surfaces with known potentials were considered as a boundary condition. To include the edge effects, the detector was placed in a large box with grounded walls (this is an approximation of the boundary condition at infinity). The potentials $\varphi_{i,j,k}$ were calculated for the nodes of the regular equidistant 3D grid (i,j,k) (see figure 2). The grid step was small enough to reproduce the electrode structure of the detector (25 μm steps in the final calculation).

The known potentials were assigned to the corresponding nodes and considered as a boundary condition. For the rest of the N nodes with unknown potential, the finite difference approximation of (1) is

$$\begin{aligned} &\varepsilon_{i+1,j,k}(\varphi_{i+1,j,k} - \varphi_{i,j,k}) - \varepsilon_{i-1,j,k}(\varphi_{i,j,k} - \varphi_{i-1,j,k}) + \varepsilon_{i,j+1,k}(\varphi_{i,j+1,k} - \varphi_{i,j,k}) \\ &- \varepsilon_{i,j-1,k}(\varphi_{i,j,k} - \varphi_{i,j-1,k}) + \varepsilon_{i,j,k+1}(\varphi_{i,j,k+1} - \varphi_{i,j,k}) - \varepsilon_{i,j,k-1}(\varphi_{i,j,k} - \varphi_{i,j,k-1}) = 0. \end{aligned} \quad (2)$$

This gives a system of N linear equations (SLE) with N unknown variables. If we move the elements with known potentials from the left-hand side (LHS) of (2) to the right-hand side (RHS) and renumber the unknown potentials by a new index k running from 1 to N , we can write SLE as

$$\sum_{k=1}^N a_{ik} \varphi_k = b_i \quad (3)$$

or in more general form

$$\mathbf{A}\varphi = \mathbf{b} \quad (4)$$

where $\mathbf{A} = \{a_{ik}\}$ is a 'seven-diagonal' matrix (where seven elements a_{ik} in (3) are non-zero), and φ and $\mathbf{b}$ are the N -dimensional vectors. These non-zero elements can be arranged around the diagonal of the matrix $\mathbf{A}$. SLE (3) was subsequently solved using the steepest descend method (SDM).

The same algorithm was applied to the electric field and the weighting potential calculations. The only difference was in the boundary condition applied to the detector: (1) for the field calculation, the cathode was at -1000 V and all other electrodes were at 0; (2) for the weighting potential calculation, the selected electrode was at unity potential whereas all other electrodes were at zero potential.

The field and weighting potentials were calculated for two anode designs (see figures 1(a) and (b)). The 18 anode pixel structure (figure 1(b)) was used as a reference to compare the results of two calculations because the field and anode weighting potentials in this structure

are a better representation of the field and anode weighting potentials of the 2048-pixel CdZnTe detector.

The calculations were carried out in two steps. The first step is the calculation for the detector placed in a large grounded box (universe) with a coarse calculation grid (with 1 mm period). The second step is the field calculation for the reduced volume of the detector (only for the region over the anode structure) with a fine grid (with 0.025 mm period) where the result of the previous calculation is used as a boundary condition. This procedure significantly reduces the simulation time without loss in precision.

To compare different potential distributions we have to define the characteristic length in what we can say that: 'two potential distributions are similar'. The characteristic length can be derived based on the assumption that the timing resolution of typical PET system is ~1 ns, and that within this time the electrons drift in a field $2 \cdot 10^3 \text{ V cm}^{-1}$ is approximately ~0.02 mm. If the equipotential surfaces of two potential distributions will be spatially separated less than this length, the waveforms of these two signals will be indistinguishable.

The electric fields simulated for both anode structures in region $z > 0.2 \text{ mm}$ were very close to the uniform field (see figures 3(a) and 4(a). The simulated weighting potentials of the central pixel A5 in 9-pixel anode structure (see line contours in figures 3(b) and (c)) was very similar to the weighting potentials of the anodes from the 18-pixel anode structure (see figure 4(c)) where all 18 weighting potentials were almost identical (see figure 4(b)).

The electric field over the anode A5 is also similar to the electric field over the anodes from 18-pixel anode structure. Since it is assumed that the 18-pixel anode structure is very close to the pixel structure of the 2048-pixel detector, we can conclude that the central anode pixel A5 can be used to emulate the charge collection properties and signal response of the anode pixels in the 2048-pixel detector.

Although the weighting potentials of the neighboring anodes in a region that is close to the central anode A5 are extended more in z -direction, both potentials are almost identical starting from the weighting potential level > 0.5 (0.5 levels are shown by white dotted lines in figure 3(b)). The weighting potential of the anode pixel A6 is shown in figures 3(b) and (c) by the gray colored contours.

The future fully pixilated CdZnTe detectors will have a large number of the anode pixels and the calculation of the individual weighting potentials for every anode will be impractical and a simpler model of the detector has to be used. In figure 3(d), the comparison of the weighting potentials of the central pixel A5 (gray colored contours) with weighting potential of the pixel (0.35 mm) from the infinite continues anode pixel structure (line contours) is presented. The weighting potential of the anode from the infinite continuous anode structure was calculated using an exact solution of the Laplace equation (from Eskin *et al*'s work (Eskin *et al* 1999)):

$$\varphi_{\text{pixel}}(r, z) = \frac{1}{L^2} \int_{\text{pixel}} d^2r' \sum_{n=1}^{\infty} n \sin \frac{\pi z n}{L} K_0 \left(\frac{\pi n |r - r'|}{L} \right) \quad (5)$$

As it can be seen in figure 3(d), the difference between both weighting potentials are very small (except for a small region $z < 0.1$ mm over the gap between the anodes). At the same time the electric field of the simulated anode structures, as mentioned before, is close to the uniform electric field for $z > 0.1$ mm. If the charge loss between anode pixels can be neglected, the infinite continuous anode structure will be a good approximation for the 2048-pixel detector.

3. Monte Carlo simulations

In Monte Carlo simulations we did not intend to reproduce the signals obtained in the experiment. We concentrate our attention on the influence of the charge distribution after interaction of the gamma with CdZnTe material—the most dominant effect on the position resolution and the main cause of the charge sharing between pixels. The need of this simulation was to find the limits implied on the detectors rather than the actual characteristic of the detector that can be measured directly. The second reason for the MC simulation was to develop and confirm the procedures for utilizing charge sharing detection. For these reasons the MC simulations were performed for the ‘ideal’ detector and only the gamma interaction, charge cloud creation and charge carriers drift (including diffusion and charge trapping) were properly modeled. The CdZnTe parameters (as mobility, trapping time and so on) were used from the documentation ‘as is’.

The interaction of the 511 keV gammas with CdZnTe material was simulated using EGSnrc Monte Carlo code (Kawrakow 2000). This code simulates the electron–gamma shower produced in interaction. In our setup, the code tracks every gamma and electron with energy more than 50 keV until they leave the CdZnTe detector or until their energy falls below the 50 keV energy threshold. It was assumed that the gamma and electrons with energy lower than 50 keV are absorbed immediately with a full energy deposit. In every simulation step, the continuous energy loss of the high energy electron is approximated by a discrete energy deposit in the current position of the electron (i.e. the end position of the electron in the previous simulation step). The energy deposit is the difference between electron energies before and after the current simulation step. A total of 10^6 unique 511 keV gamma interactions (if any) were simulated and the results were stored in a file. In further simulations the original gamma coordinates ($x = 0$, $y = 0$) were randomized to form gamma beams with desired flux density distribution in different positions over the detector.

An example of the energy deposit distribution simulated by the EGSnrc code is shown in figure 5. This is one of the EGSnrc simulated tracks of the 511 keV electrons produced after a photoelectric interaction. The size of the bubbles is proportional to the electron energy. The location of the bubbles corresponds to the discrete energy deposition of the electron being tracked. The energy deposited at each location is the difference of electron energy between the previous and the current locations.

It was assumed in simulation that all the deposited energy goes to the hole–electron pairs creation. The number of the hole–electron pairs created by energy deposit E was approximated by the Gaussian distribution with a mean value $N_{e,h} = E(\text{eV})/4.64 \text{ eV}$ and variance $\sigma^2 = F N_{e,h}$ where F is the Fano factor (in our simulation $F = 0.15$).

The holes and electrons created at energy deposit points drift along the electric field toward the cathode/anode with drift velocities proportional to the electric field. The hole and electron mobilities used in simulation are $\mu_e = 1000$ and $\mu_h = 80 \text{ cm}^2 \text{ Vs}^{-1}$, respectively.

The charge trapping was modeled using mean trapping times τ_e and τ_h . The life time for the charge carrier in MC simulation is $t = -\tau \ln(\vartheta)$ (where ϑ is a uniformly distributed random number in open unit interval (0,1)). The corresponding mobility to trapping time products used in simulations are $\mu_e \tau_e = 3 \times 10^{-3}$ and $\mu_h \tau_h = 5 \times 10^{-5} \text{ cm}^2 \text{ V}^{-1}$.

Diffusion was emulated by generation of the random diffusion steps. The diffusion steps in x -, y - and z -direction are generated from the normal distribution with $\sigma = \sqrt{2D\Delta t}$, where $\Delta t = 1 \text{ ns}$ is a simulation time step and D a diffusion coefficient given by the Einstein relation

$$D_{e,h} = k_B T \mu_{e,h} / |q_e|. \quad (6)$$

Since hole and electron tracking takes a long time, we used this diffusion model only for the signal timing simulation where the charge collection time was limited by 300 ns. This time is large enough to collect all electrons but not holes. Nevertheless, the shape of the cathode and anode signals is mostly determined by the electrons and a 300 ns collection time is appropriate for these simulations.

To emulate the diffusion in the charge sharing MC experiments, we have used a random walk with a fixed step σ in x - and y -direction only: first we calculated the drift steps for charge carriers (holes and electrons) according to the local electric fields, then we randomize its positions using fixed diffusion steps in x - and y -directions (random walk). Since these simulations require less computation, the collection time was increased up to 2 μs as in a real detector that we used in the actual experiments.

An example of the simulated charge diffusion and trapping is demonstrated in figure 6. To better illustrate the diffusion expansion and separate it from the effect of the original charge cloud distribution, the simulation presented in this figure was done for the photoelectric interaction of a 122 keV gamma (and, thus, for 122 keV electron) where the size of the original charge cloud is very small ($\sim 10 \mu\text{m}$) and can be neglected. The shape of the detected electron distribution (figure 6(b)) is determined mostly by the electron diffusion but not the original charge cloud distribution.

The charge induced in electrodes is calculated using the Ramo–Shockley theorem (Ramo 1939). The total charge induced in electrode A is given by the sum over all holes and electrons:

$$Q_A = \sum_{x=e,h} q_x W_A(\mathbf{r}_x) (V^{-1}), \quad (7)$$

where q_x is a carrier charge, $\mathbf{r}_x$ is a position of this carrier and $W_A(\mathbf{r}_x)$ is a weighting potential of the electrode A at this point.

Several effects were not included in our simulation. These include surface and junction effects, detrapping, surface and leakage currents. The carriers that reach the surface of the CdZnTe (including the surface of electrodes) stay at the surface, the trapped charges stay trapped till the end of the collection time. There are no random coincidences—all gammas were simulated separately.

Examples of anodes (A5 and A6) and cathode signal waveforms simulated for the 9-pixel anode structure (see figure 1(a)) are shown in figure 7. The corresponding experimental signal waveforms are presented in figure 8. ('Corresponding' means 'corresponding approximately'—the exact position of interaction in experiment is not known.) Note that the experimental data was acquired using a 16-channel 105 MHz continuous sampling analog-to-digital converter (ADC) by Lyrtech (Quebec City, Canada).

4. Position resolution

The position resolution of a pixelated detector is typically limited by the anode pixel size. An ideal planar detector with very small anode pixels can provide information only about (x,y) -distribution of the charges produced in interaction (or distribution of the energy deposited). An output of this detector will be energy weighted position of interaction

$$r_{EW} = \sum_i E_i r_i / \sum_i E_i \quad (8)$$

where r_i and E_i are position and energy, respectively, deposited in point i . The information about the first interaction r_0 will be lost even if the centroid of the charge cloud can be measured accurately. Thus, the position resolution of our detector is also limited by the charge cloud size.

From EGSnrc simulations (described in section 3), we have obtained a distribution of the energy weighted positions r_{EW} for 10^6 simulated 511 keV gammas entering normally into CdZnTe 5 mm thick infinite slab. This 2D distribution of the energy weighted detection positions (8) around the gamma entry point (0,0) averaged over all detections can be considered as the PSF of the 'ideal' CdZnTe detector. 'Ideal' means that we can always find the centroid of the charge distribution collected by anodes and thus, the centroid of the energy deposited. The distribution (or PSF) presented in figure 9 is based on the detected events with full energy deposition—511 keV photoelectric interactions and Compton absorptions. For multiple interactions the summing in equation (8) also assumes the summing over all tracks of the high energy electrons produced in these interactions. Full energy deposit is 511 keV within 1 keV which was a precision of the simulation data output. This distribution, when fitted with a Gaussian function, has a full-width-at-half-maximum (FWHM) of $170 \mu\text{m}$ ($\sigma = 71 \mu\text{m}$) and is related to the inherent uncertainty between the 'initial interaction location' and 'detected location' of 511 keV gammas in CdZnTe. Accurate measurement of the charge cloud distribution does not eliminate the uncertainty revealed in figure 9. Therefore, figure 9 represents the intrinsic resolution limit for 511 keV gamma detection by CdZnTe.

In this study we consider only single and double pixel detections. The resolution of a pixelated detector usually corresponds to its pixel pitch. However, if the charge produced in an interaction was collected by a few anode pixels, this interaction occurred somewhere over these pixels and, thus, the resolution of this charge sharing detection will be a few pixels pitch. Nevertheless, the knowledge about whether it was single or double pixel detection can possibly provide us information about subpixel position resolution: (1) an interaction that was detected by only one anode pixel most probably occurred in some region over the pixel center (possibly smaller than pixel pitch); (2) an interaction that was detected by two pixels occurred in some region between those pixels. Additional subpixel resolution can be possibly obtained for the double pixel detections, i.e. we can find the centroid of interaction from the balance of the charges collected by those neighboring pixels.

An experimental measurement of the position resolution of ultrafine detectors is complicated due to the difficulty in forming a narrow 511 keV gamma-ray beam. Yin *et al* presented the experimentally measured resolution of a similar detector (Yin *et al* 2011). In this experiment, four tungsten blocks (3.5 cm thick) were used to form a square collimator ($0.17 \times 0.17 \text{ mm}^2$ opening) for ^{68}Ge source. The collimated beam of 511 keV gammas was used to scan the detector surface in *x*-direction (25 μm step) to obtain the charge sharing (double pixel detections A4 and A5) and single pixel detection (A5) profiles—i.e. number of detections as a function of the beam position. The setup of the experiment is illustrated in figure 10(a). The obtained experimental profiles are presented by dots in figure 11.

The experimental event profile contains contributions from both the beam width and PSF. Neither the beam profile nor the real PSF in experiment are known exactly. While the beam profile can be estimated from the geometry of the experiment, the real detector response cannot be approximated by the PSF of the ‘ideal’ detector because the ideal PSF provides only the mean position of the energy deposit and contains no information about the charge cloud size and shape. For this reason we performed MC simulation using the same approach described in section 3. We estimated from the geometry of the experiment (see figure 10(a)) that the tungsten collimator forms a rectangular ($<0.4 \times 0.4 \text{ mm}^2$) beam with trapezoid photon density distribution and beam divergence less than 0.5° . In the MC simulation study, we used a parallel beam of 511 keV gammas with the density distribution shown in figure 10(b) to mimic the experimental setup. We simulated seven different positions of the collimated gamma-ray beam, moving from the center of anode A5 toward the anode A4 with 60 μm step, and compared the MC simulation results against the experimental results.

The single pixel detection selection was done using ‘cathode C *versus* anode A5’ (for single A5 detections) and ‘anode A4 *versus* anode A5’ (for double A5 and A4 detections) scatter plots. Examples of the corresponding scatter plots obtained in MC simulations for two different beam positions 0 and 0.18 mm are presented in figure 12. The photoelectric interaction line can be clearly seen in the ‘cathode *versus* anode A5’ for all simulated beam offset positions $>-0.3 \text{ mm}$ (see examples presented in figure 12(a)). The photoelectric detections shared between two pixels A5 and A4 can also be clearly seen in the ‘anode A4 *versus* anode A5’ scatter plots for all simulated beam offset positions (see examples presented in figure 12(b)). The surface scan profiles obtained in MC simulations are shown in figure 11 and represented by solid lines. (The symmetry was used for single pixel (A5)

detections—the plot was mirrored around the origin. It could not be done for double pixel detections since there is no symmetry.)

The difference between experiment and simulation results can be explained by the difference in the energy thresholds between them and, also, by the difference in event selecting logic used for the single and double pixel detection selection. In simulation, the double pixel detections are $(A5 > 0)$ and $(A5 + A4 > E_{\text{PhotoMin}})$ where $E_{\text{PhotoMin}} = 500$ keV (without DOI correction it corresponds ~ 460 keV) is the minimal energy for the photopeak selection, while in experiment they are $(A5 > A5_{\text{min}})$ and $(A4 > A4_{\text{min}})$ and $(A5 + A4 > E_{\text{PhotoMinExp}})$ where $A5_{\text{min}}$ and $A4_{\text{min}}$ are pre-selected thresholds.

It should be noted that the real single pixel detection will be classified as ‘single pixel detection’ regardless of the selection thresholds used. Thus, for the beam position where the charge sharing is minimal (the center of the pixel A5) the number of single pixel detection should be approximately the same for both MC simulation and experiments, despite the fact that different selection thresholds were used in these two cases. Similarly, for the beam position where the charge sharing is maximal (exactly between the pixels A4 and A5), the number of the double pixel detection will be similar for both cases (as long as the selection energy threshold is small enough). This agrees well with figure 11. When a finite energy threshold is applied in the selection logic, some of the real double pixel detections will be classified as ‘single pixel detection’ instead. The choice of energy threshold for event selection affects mainly the tails of the distributions. Considering these effects, the experiment and simulation results are in fact in good agreement. In principle, the experimental data should converge to the MC data with decreasing anode energy threshold used in experiment setup but it could not be done in practice due to unavoidable electronic noise.

The surface scan does not provide direct measurements of the detector resolution but rather the information about the pixel size or beam width. Figure 10(d) shows the dependence of the FWHM of the surface scan profile as a function of the pixel size W of an ‘ideal detector’ for two different beam distributions: curve (1) is for original trapezoid beam distribution; and curve (2) is for trapezoid beam distribution convolved with PSF from figure 9. Using plot (2) we can obtain the effective pixel width for our detector setup—the pixel width of an ‘ideal detector’ that provides the same FWHM of the measured profiles. The same can be done for double pixel detections—assuming some region between pixels as a ‘virtual pixel’. This is not a resolution of the detector but rather the estimation of the regions where the interaction of selected type is the most probable.

For PET applications, all detectors should be paired into the line-of-responses (LORs). The pixel pitch determines the width of these LORs for the single pixel detection events. However, for charge sharing events among double-pixels, they are either assigned to near-by LORs that correspond to the pixel with the highest signal amplitude, or to an imaginary detector pixel that has to be created between these two real pixels. This is why we introduced the term ‘effective pixel size’ whose size varies as one changes the selection energy thresholds of the single- and double-pixel events. This will be a convenient term to use when computing the distribution of the detection events through LORs (or, more

correctly, through tube-of-response) for image reconstruction proposes. (LOR is a line connecting two different detectors. To find image voxel types inside an LOR, there is practical need to know the ‘effective’ size of the detectors that form this line.) As an example, the effective pixel sizes are $350\ \mu\text{m}$ for the single pixel detections and $440\ \mu\text{m}$ for the double pixel detections for the event selection threshold used in the experiments. For the MC simulations, these sizes are $220\ \mu\text{m}$ and $\sim 500\ \mu\text{m}$, respectively. (It was assumed that the tail of the double pixel detection profile should follow the tail of the single pixel detection profiles since the event selection criterion of double pixel detections used in our MC study includes the single pixel detections).

The DOI resolution and possibility of the subpixel resolution through the balance of the charges collected by two neighboring pixels will be discussed in section 7.

5. Energy resolution

The CdZnTe is a single charge carrier detector, meaning that the cathode signal strongly depends on the DOI (figure 8(a)), while the anode signal has small dependence on the DOI (figure 8(b)). The electron loss can be DOI corrected to improve the energy resolution of the detector.

In typical ‘cathode *versus* anode’ scatter plots (e.g. figure 12(a)) we can clearly see the sector of ‘single pixel events’—sector between the diagonal line cathode–anode (this line corresponds to the interactions near the cathode where both cathode and anode signals are determined mostly by the electrons) and the line limiting the cathode signals from below (this line corresponds to the interactions near the anode surface where both cathode and anode signals are determined mostly by the holes). To analyze separately single and double pixel detections, we conducted two independent MC simulations using uniform 511 keV gamma beams with cross-section of $0.2 \times 0.2\ \text{mm}^2$ located at: (1) the center of the anode pixel A5 ($z = 0\ \text{mm}$); and (2) exactly between pixels A5 and A6 ($z = 0.175\ \text{mm}$). To minimize the computation time, only the detections with energy deposited inside the beam region were considered. (We have to point out that the diffusion expansion does not cause event rejection and these events are included in consideration.) To save simulation time, events with energy deposition less than 100 keV were ignored. The anode signal for double pixel detections is considered as the sum of two anode signals $A = A5 + A6$. Together these two simulations cover the rectangular region of $375 \times 200\ \mu\text{m}^2$ over CdZnTe detector (using the system symmetry, it is equivalent to a region of $550 \times 200\ \mu\text{m}^2$ over the center of anode pixel A5). The event rejection for the single pixel detection is done assuming that if the energy will be deposited outside the beam region, the detection would be a double pixel detection due to charge sharing (especially after the diffusion expansion) and would be rejected. The same approach was used for the double pixel detections—most of the events where the energy is deposited outside the beam region would be charge sharing events with other pixels or they would be single pixel detections. (Although some small fraction of ‘wide’ rejected events is possible double pixel detection, we prefer to use the same beam for both simulations.) Results of these two simulations are presented in figures 13(a)–(c).

In scatter plots ' C/A versus A ' (see figure 13(a)), one can clearly see 511 keV photopeak lines. Assuming that anode and cathode signals are proportional to the energy deposited for any given depth in the detector, we can use 511 keV photopeak line as a reference to calibrate the loss of signal at each DOI location. Using the parameterization of this line $A_{\text{photo}}(C/A)$ (photopeak anode signal as function of C/A), we can correct detected anode signal A for the DOI as follows:

$$A_{\text{Corr}} = E_{\text{photo}} A / A_{\text{photo}}(C/A) \quad (9)$$

where C is a cathode signal and E_{photo} the gamma energy, i.e. 511 keV. (The parameterizations were done by the polynomial splines by sorting code for every individual histogram.)

This DOI correction procedure is similar for both types of detections—single and double pixel. The results of DOI correction of the anode signals are shown in figures 13(b) and (c). As can be seen from figure 13(c), the DOI correction in MC simulations improves the energy resolution of single pixel ($\sim 0.6\%$ FWHM for 511 keV) and double pixel detections ($\sim 1\%$ FWHM for 511 keV). Keeping in mind the purpose of these simulations, these results can be considered as the upper limit for the energy resolution that can be obtained from our CdZnTe detector.

The results from experiments demonstrate significantly lower energy resolution than that of MC simulations for both types of detections, i.e. single and double pixel.

In the experiment an uncollimated ^{22}Na source was used. All detections were sorted to A5 single pixel detection (multiplicity $M=1$) and A5 + Amax double pixel detections (multiplicity $M=2$ —see figure 14). The detections of higher multiplicity were ignored. Here, Amax is one of the eight neighboring pixels that collects charge in addition to A5 anode pixel. The effect of the DOI correction on energy resolution is shown in figure 15. In this case, DOI correction does not significantly improve the energy resolution—there is small improvement from 8% to 7% FWHM for the single pixel detection and there is no visual improvement for the double pixel detections (both corrected and uncorrected energy resolutions are $\sim 9\%$ FWHM). The relatively high energy resolution obtained in experiment for the detections near the cathode (3% FWHM for the single pixel detection and 4% FWHM for the double pixel detections for $C/A \sim 0.9$) drops significantly with increased DOI (up to 9% FWHM and 10% FWHM for the single and the double pixel detections, respectively, for events with $C/A \sim 0.5$).

6. Detector timing

As we can see in figures 7 and 8, the cathode signal rises slowly with a relatively long rise time that is DOI dependent (from 0 to 300 ns). Its signal amplitude depends not only on the energy deposited but also on the DOI. In contrast, the anode signal rises steeply with a short rise time. Its signal amplitude is almost independent of the DOI. For these reasons, the anode signal is more preferable for detecting the event timing if the electron drift time (or DOI) can be corrected. Our goal in this work is to develop the procedure for timing detection

that is independent of the amount of energy deposited and of the DOI. We propose using the time value when the anode signal's rising slope is the steepest (i.e. the time of the largest anode current) as the detection time, which can be detected by a constant fraction discriminator (CFD), followed by the correction for the electron drift time using the cathode-to-anode ratio. The procedure was tested for events without charge sharing (single A5 pixel detections) as well as for events with charge sharing (double pixel detections involving A5 and one of the neighboring anode pixels).

We first tested this approach using the MC simulation data that was used in section 5. For single pixel detections, the timing is based on the time when anode A5 signal reaches its maximum slope, as previously described. For double pixel detections, the timing is based on the time of the anode that has the largest signal amplitude. From the 'cathode-to-anode ratio *versus* anode time' scatter plots (figure 16(a)), we can see a linear correspondence between those two variables (except for a small region near the cathode surface). The electron drift time can be estimated from these scatter plots and should be subtracted from the timing estimated from anode signal to give the corrected time of the detection. This procedure works equally well for the double pixel detections, despite the fact that the shapes of the weighting potential A5 and A6 are slightly different (see figure 3(c)) which should not affect the timing of the maximum anode current. The timing resolution (after the DOI correction) for the single and double pixel detections from MC simulations are within ~3 ns FWHM (see figure 16(b)).

To evaluate this timing method experimentally, we set up a coincidence timing measurement using the CdZnTe detector (figure 1(a)) and a LSO crystal array read out by a position-sensitive PMT. A ^{22}Na source was placed between the two detectors at distances that are 0.5 cm from CdZnTe detector and 5 cm from the LSO crystal array. In this experiment we sampled the waveforms of the PMT, cathode and all 9 anode signals using 105 MHz ADC (Lyrtech, Quebec City, Canada). The anode and cathode signals were each amplified by an Amptek A250 preamp and an ac coupled gain amplifier board with $\times 10$ gain. The only shaping time is in the A250 preamp that has ~4 ns rise time and ~300 μs fall time (decay constant). No additional shaping was used. The anode A5 in coincidence with the PMT signal was used as the trigger for the data acquisition system. The logical CFD (based on waveform analysis instead of analog CFD module) was applied to the recorded anode and PMT waveforms to extract the timing of the events. To minimize the noise, the tails of the cathode and anode signals were averaged over the last ten waveform samples. The same procedure was performed for the first ten samples to find the baseline for every detection event. This was implemented because the baseline is fluctuating around its zero position, as can be seen in figure 19(a). Since the timing performance of the LSO-PMT detector is significantly better than that of the CdZnTe detector, the timing of the event estimated from the PMT signal was used as the reference to evaluate the performance of the proposed method.

The results of the experimental timing measurement are shown in figure 17. The time resolution for the single anode (A5) detection is 30 ns FWHM for all events and 20 ns FWHM for the photoelectric events only. However, the time resolution for the double pixel detection is 35 ns FWHM for all events and 25 ns FWHM for the photoelectric events only.

We further compared the above results to the detector timing obtained from the cathode signal. A linear fit was applied to the cathode waveform samples in the region between 20% and 80% of the cathode signal maximum. The zero-crossing point of the line fitted to the cathode signal was considered as the detection time of the event. To make a fair comparison between these two timing approaches, the cathode timing was evaluated using the same detection events that were used for the anode timing involving single pixel (A5) detections only. For the events where the cathode signal was large enough (photoelectric detections near the cathode), the time resolution was close to that obtained from the anode signal. However, for all 511 keV photoelectric events throughout the detector volume, the time resolution from the cathode signal degrades to 25 ns FWHM (compared to 20 ns from the anode timing). For the events with small cathode signals, particularly for the detections with detected energy below the Compton edge, the linear fit becomes very sensitive to noise and the time resolution from cathode signal becomes worse than 40 ns FWHM (see figure 18).

It should be noted that the proposed method has its inherent limitation. It may not provide accurate timing of events that involve Compton scatter and multiple photon interactions at different pixel locations and DOI.

7. Discussion and conclusion

In this study we demonstrate the importance of the double pixel detections—detection with multiplicity $M = 2$. Extending this to the detection of events with higher multiplicity may be reasonable (e.g. 2×2 pixels) for increasing the detection efficiency, but these detections have lower position resolution—the original interaction position will be somewhere within a few pixels. The multiplicity distribution for our detector obtained in experiment with non-collimated source shows that the single and double pixel detections constitute 82% of all detections: $M = 1$ —37.5%; $M = 2$ —44.7%; $M = 3$ —13.3%; $M = 4$ —4.3%; $M > 5$ —0.2%. Thus, the choice to use the events with $M < 3$ may be reasonable since it simplifies the event analysis at the cost of the loss of a small fraction of detections with poor position information.

Comparison of figures 13 and 15 shows that the experimentally measured energy resolution is significantly lower than that obtained from MC simulations. One of the contributing factors is the signal's baseline drift during the experiments. This may be the result of slow discharging of charges in the CdZnTe detector caused by the previous interactions. If this hypothesis is true, the cathode signal should be strongly affected by this effect since the cathode is common for all detector elements. During the experiment we recorded the baseline position for all signals. The distributions of the baseline position for cathode and anode A5 signals are shown in figure 19(a). (The distributions of the baseline position for the rest of anodes are not shown since they are very similar to A5). The results show that the FWHM of baseline position distribution for cathode is indeed twice as large as that of the anode. However, correction of the baseline drift for all events does not appear to improve the poor energy resolution much (around 1% for photoelectric interactions), which suggests that the baseline drift was not the primary cause of the poor energy resolution from the experimental data.

To identify the possible reason for poor energy resolution, we fit the outlines of the MC simulated photoelectric interaction line and Compton edge (i.e. the dotted lines in figure 15(a)) to the experimental data by superimposing the Compton edges obtained from both MC simulation and experiments. As we can see in figure 15(a), the experimental anode signals from the photoelectric events near the cathode are smaller than the corresponding anode signals obtained in MC simulation. At the same time, the variation in the anode signal amplitude is increased significantly with the DOI, and the mean anode signal approximately follows the simulated photoelectric line. This could be explained by the existence of nonuniform distribution of the trapping centers inside the detector (illustrated in figure 19(b)). The charge clouds of interactions that happen near the cathode (events 1 and 2 in the figure 19(b)) are more subjected to the thermal expansion than those that happen in the middle of the detector (event 3 and 4) due to the longer drift time. Thus, the charge clouds formed near the cathode become more uniformly distributed before they reach the anode when compared to the charge clouds formed in the middle or the lower half of the detector. For this reason all charge clouds formed near the cathode lose approximately the same amount of charge in trapping centers. On the other hand, the irregular shape of the charge clouds formed in the middle of the detector leads to a larger variation in anode signals depending on whether the charge cloud passes thorough trapping centers or not. Thus, we hypothesize that the difference between experiment and simulation results is due to the uniform trapping used in our MC simulations, which does not model the distribution of the trapping centers in actual CdZnTe crystals. Proof of this hypothesis is beyond the scope of this work and will be left for future investigation.

The experimental timing measurements show promise if one considers the sampling rate of our data acquisition system (105 MHz, 9.52 ns sampling interval). This leads to large uncertainties of the order of 5 ns for both anode and PMT timings. Nevertheless, the results demonstrated that 20 ns FWHM time resolution is achievable.

From the electron drift time measurements we can estimate the DOI position. The DOI position resolution can be estimated as a product of the time resolution and the electron drift velocity. As a result, the DOI resolution for our system is estimated to be 0.4–0.6 mm FWHM based on the experimentally measured timing resolution, and may be further improved with the theoretical limit of 0.04–0.06 mm based on the MC simulated timing resolution (see figure 20). (This resolution does not contradict figure 9 where the obtained PSF is for full 511 keV energy deposit, while figure 20 is for all detection where the Compton detections are dominant.)

Finally, we also considered the possibility of extracting subpixel resolution for the charge sharing detections through the balance of the charges collected by the neighboring pixels. We tested the possibility of using the charge balance in MC simulations. Although interpolation works well for the energy weighted position (the interpolation curve can be clearly seen in figure 21(a) and can be parameterized), it gives a very rough estimation of the actual position of the first interaction for the photoelectric interaction (see figure 21(b)). The width of interpolation curve is more than the pixel pitch of 350 μm , which suggests limited possibility for an accurate estimation of the actual interaction point using interpolation for full energy deposit detections. Nevertheless, the subpixel resolution is achievable for the

Compton detections, but only in very narrow region ($\sim 50 \mu\text{m}$) between pixels. From the distribution of the interaction position for all detection events presented in figure 21(c), the accuracy of position resolution may be as high as $\sim 30 \mu\text{m}$ FWHM.

In these MC simulations, we ignored the effect of detector electronics and assumed an ideal readout system. Therefore, the simulation results represent the performance limit of the position, energy and timing resolution of our future pixelated CdZnTe detector.

One critical conclusion of this study is the intrinsic spatial resolution of the CdZnTe detector. Our results suggest that the intrinsic position resolution of the CdZnTe detector is limited by the uncertainty between the initial interaction point and the measured centroid of the charge cloud distribution, which is defined as the PSF of an ideal detector with an estimated FWHM of $\sim 170 \mu\text{m}$. The improvement in spatial resolution may be limited even if one makes the anode structure pitch smaller than this value or significantly improves the timing resolution of the detector in order to improve the DOI resolution. Although the experimental data do not contradict this estimation, we have to point out that all MC simulations employ simplified physics models and are inherently limited in accuracy. For example, energetic electrons lose energy along continuous trajectories in real materials, but are modeled using trajectories of discrete steps in the EGSnrc code. In this work, we used the EGSnrc code to track the photoelectrons and Compton electrons following gamma-ray interactions in CdZnTe. The production of electron-hole pairs, trapping and diffusion of charge carriers, tracking of charges and signal induction at electrodes were all based on CdZnTe characteristics and theorems published in literatures. It is beyond the scope of this work to verify the accuracy of all MC codes and published parameters employed in our simulation study. The results of this study should be used as a guide to understand the performance limits of the pixelated CdZnTe detector due to the underlying detection processes, with the understanding of inherent limitations of the accuracy of MC methods.

In conclusion, we have studied the characteristics of pixelated CdZnTe detectors and their potential use for PET imaging applications through MC simulations and experiments using a special 9-pixel anode pattern with $350 \mu\text{m}$ pitch. For single pixel 511 keV photoelectric detections obtained in experiments, our CdZnTe detector demonstrates: (1) position resolution in the x - and y -direction of $\sim 350 \mu\text{m}$, position resolution in DOI direction of ~ 0.4 mm; (2) energy resolution of 7% FWHM at 511 keV and (3) timing resolution estimated from anode signal of 20 ns FWHM. This study also shows the importance of the charge sharing detections. For pixel pitch comparable to charge cloud size, the charge sharing detections will form the majority of the detected events. For double pixel 511 keV photoelectric detections, the measured characteristics are: (1) effective virtual pixel size $\sim 450 \mu\text{m}$; (2) energy resolution of 9% FWHM; (3) timing resolution of 25 ns FWHM. The interpixel interpolation for 511 keV photoelectric detections can slightly improve position resolution up to $350 \mu\text{m}$. For applications where Compton scattering is not significant (such as small animal PET imaging applications) or can be properly corrected, the CdZnTe detector can be used in 'all detection accepted' mode. It will significantly improve the photon sensitivity of the detector.

Additional investigation using a CdZnTe detector with uniform anode pixel pattern and high-density readout electronics (likely with an ASIC) is needed in order to fully validate the feasibility of such detector technology for ultra-high resolution PET imaging applications.

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Figure 1.

Two anode structures of CdZnTe detector ($20 \times 20 \times 5 \text{ mm}^3$) with $250 \mu\text{m}$ pixel size and $350 \mu\text{m}$ pitch: (a) 9 pixels structure is designed for the pogo-pin connection to the PCB; (b) 18 pixels structure is a better approximation of the future 2048-pixel CdZnTe detector. In this work anode structure (b) was used as a reference for the comparison of the calculated fields and weighting potentials. Cathode voltages for both detectors are -1000 V . All anodes and surrounding area are at the ground potential. The origin of the coordinate system is at the center of anode pixel A5 throughout the paper.

Figure 2.

The 8-nodes calculation cubic cell with the local system of coordinates (ξ, η, ρ) . The potential of any arbitrary point inside the cell can be interpolated from the known potential φ_n of the 8 corner nodes.

Figure 3.

Results of the field calculations for the detector with 9 anode pixels (see figure 1(a)): (a) electric field over anodes A5 and A6 in $(X, Y=0, Z)$ plane; (b) weighting potentials of the anode pixels A5 (black contour lines) and A6 (gray-scale contours) in $(X, Y=0, Z)$ plane (contours for 0.5 V are shown by white dotted line); (c) weighting potential of the anode pixels A5 (black contour lines) in $(X=0, Y, Z)$ plane and weighting potential of the anode pixels A6 (gray-scale contours) in $(X=0.35 \text{ mm}, Y, Z)$ plane (these planes are shown on (b) by arrows A5 and A6); (d) comparison of the weighting potentials of the anode A5 (gray-scale contours) with weighting potential of the anode from the continuous anode pixel structure with period 0.35 mm calculated using equation (5). All contours use the same step 0.05 V in potential.

Figure 4.

(a) Isopotential contours of the detector with 18-pixel anode structure; (b) weighting potentials for 1–9 anodes from the 18-pixel anode structure in plane XZ ($Y=-0.175$ mm) (weighting potentials for the anodes from 1 to 9 are shown together in the same plot); and (c) comparison between weighting potentials of anode 5 from 9-pixel anode structure (dotted line) and anode 5 from 18-pixel anode structure (solid line).

Figure 5. EGSnrc simulated track of 511 keV photoelectron. The energy of the electron is approximately proportional to the size of the bubble.

Figure 6.

Hole–electron charge distribution produced by 122 keV electron: (a) the simulated trapped charge distributions in CdZnTe and (b) the distribution of the electrons that reach anode plane (122 keV). Interaction point is (0, 0, 4.5 mm).

Figure 7.

Simulated cathode and anode (A5 and A6) signals for the photoelectric detections: (a) detection near the anode without charge sharing; (b) detection near the cathode without charge sharing; (c) detection near the anode with charge sharing between A5 and A6; (d) detection near the cathode with charge sharing between A5 and A6.

Figure 8.

Cathode (a) and anode (b) signals (A5 and A6) obtained in experiment for the photoelectric detection without charge sharing: (1) ‘near the anode’; (2) ‘in the middle of the detector’ and (3) ‘near the cathode’. (c) An example of the charge sharing (between A5 and A6) event.

Figure 9. Distributions of the energy weighted detection positions $(x, y)_{EW}$ in CdZnTe detector normalized to the total number of the photoelectric-like interactions (interactions with full 511 keV energy deposit). The standard deviation of the 2D Gaussian distribution fit is shown in the plot.

Figure 10.

Surface scan experiment: (a) the experiment setup; (b) an estimation of the beam density 2D distribution close to the anode plane after the tungsten collimator (this distribution was used in MC simulation); (c) dotted line (2) is the result of 1D convolution of the original 1D beam distribution (dashed line (1)) with PSF (approximated by normal distribution with $\sigma = 71$ μm); (d) the FWHM of the scan profiles that would be obtained by 'ideal detector' as a function of the pixel size/pitch W —solid line (1) is for the trapezoid beam distribution (distribution (1) in (c)); and dotted line (2) is for the beam distribution (2) presented in (c).

Figure 11.

Number of the single photoelectric interactions detected by pixel A5 and photoelectric interaction detected by both pixels (A5 and A4) for different beam offset positions. Top solid line (MC) and open circles (experiment) are for the double pixel events (A5 and A4). Bottom line (MC) and solid circles (experiment) are for single A5 pixel events.

Figure 12. MC simulation results: (a) ‘cathode *versus* anode A5’ and (b) ‘anode A4 *versus* anode A5’ coincidence scatter plots for beam offset positions: (left) $\Delta = 0$ mm; (right) $\Delta = 0.18$ mm.

Figure 13.

Single A5 pixel detections and double A5 + A6 pixel detections for MC simulated $0.2 \times 0.2 \text{ mm}^2$ ^{511}keV gamma beam at two offset positions, : (a) 'cathode-to-anode ratio *versus* anode A' scatter plots; (b) 'DOI corrected cathode-to-anode ratio *versus* anode A' scatter plots; and (c) fragments of energy spectra with and without DOI correction.

Figure 14.

Double pixel detections ($M=2$) in ‘anode Amax *versus* anode A5’ coincidence scatter plot. (Amax is a signal of the anode pixels that is in coincidence with anode A5).

Figure 15.

Depth-of-interaction correction (DOI) obtained in experiment with uncollimated ^{22}Na source for single A5 pixel detections ($M = 1$) and A5 + A_{max} double pixel detections ($M = 2$; these events are also shown in the scatter plot presented in figure 14): (a) ‘cathode-to-anode ratio *versus* anode A’ scatter plots; (b) DOI corrected ‘cathode-to-anode ratio *versus* anode A’ scatter plots and (c) DOI corrected energy spectra. The dotted lines in (a) are the Compton edges and photoelectric interaction lines (photopeak) extracted from MC simulations in figure 13 superimposed to the experimentally detected Compton edges.

Figure 16.

Single A5 pixel detections and double A5 + A6 pixel detections for MC simulated 0.2×0.2 mm² 511 keV gamma beam at two offset positions, : (a) ‘cathode-to-anode ratio *versus* anode A time’ scatter plots and (b) DOI corrected (for the drift time) anode timing spectrum measured against the reference PMT time. For the double pixel detections the anode time is the anode time of the largest anode signal.

Figure 17.

Detection time from the experimentally measured anode signal for the single ($M = 1$: (a) and (b)) and double pixel ($M = 2$: (c) and (d)) detections. The distribution of corrected detection times are presented on the right. Plots (b) and (d) are the timing for 511 keV photoelectric detections only. T_A and T_{PMT} are the anode and PMT times, respectively, detected by the corresponding CFD. T_{Drift} is the correction time estimated from the linear fit to the scatter plot.

Figure 18.

Distribution of experimentally measured cathode time relative to the PMT time: solid line is for the 511 keV photoelectric detections and dotted line is for the Compton detections.

Figure 19.

(a) Baseline drift around zero signal: solid line is for A5 anode signal and dotted line is for cathode signal (conversion factor: ~ 0.5 keV/channel); (b) illustration of nonuniformity in charge trapping for detections of events originated at different DOI.

Figure 20.

Obtained in MC simulations ‘cathode-to-anode ratio *versus* DOI position’ for double A5 + A6 pixel detections. Simulation was done for $0.2 \times 0.2 \text{ mm}^2$ wide 511 keV gamma beam. Beam offset position is $= 0.175 \text{ mm}$.

Figure 21.

Subpixel resolution from the balance of the charges collected by the neighboring pixels. The 2D histograms show the distribution of the event locations obtained from MC simulation when $0.2 \times 0.2 \text{ mm}^2$ 511 keV gamma beam was located exactly between pixels A5 and A4 (beam offset position is -0.175 mm). The A5–A6 region of the data is a mirror reflection of the simulation results obtained from the A4 to A5 region. (a) Count distribution of the x -coordinate of energy weighted positions (calculated using equation (8)) of all detected interactions; (b) distribution of x -coordinate of the first interaction with full energy deposit (511 keV); (c) distribution of x -position of the first interaction for all detections—including photoelectric and Compton interactions.