Feasibility Study of Using Two 3-D Position Sensitive CZT Detectors for Small Animal PET

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Abstract -- **An experimental small animal PET using two 3-D position sensitive CdZnTe detectors was developed and tested. Each 1.5×1.5×1 cm^3 CdZnTe detector employs 11 by 11 pixellated anodes wire-bonded to the VAS3.1/TAT3/MCR3 readout electronics. Each detector can obtain the deposited energy and 3-D coordinates for single-pixel and multiple-pixel events. Both systems achieved energy resolutions of better than 1.0% FWHM at 662 keV for single-pixel events and better than 1.5% FWHM at 662 keV for two-pixel events. The position resolution of each detector was estimated to be ~1.3×1.3×0.5 mm^3. Modifications to the firmware of the readout board and additions of custom-built circuitry enabled coincidence measurement between two 3-D CdZnTe detector systems using VAS3.1/TAT3/MCR3 readout systems. Spatial resolution improvements by using depth of interaction (DOI) and by identifying the first interaction using Compton scattering angle reconstruction are reported and discussed.**

I. INTRODUCTION

Conventional PET systems use scintillators (BGO, LSO, etc) and photo detectors (PMTs, photo diodes, etc) to detect 511 keV annihilation photons for their high efficiency, excellent temporal performance and low cost. These systems normally have a position resolution of a few millimeters. Nowadays, imaging of small animals, primarily mice, for molecular imaging and drug development using high resolution PET is gaining more and more interests. One major challenge for these systems is to achieve better spatial resolution while preserving the SNR per voxel. Room temperature semiconductor detectors, especially 3-D position sensitive CdZnTe detectors, are potential candidates for such applications for their excellent energy resolution, better position resolution and similar gamma-ray detection efficiency comparing to scintillation detectors. Furthermore, a 3-D position-sensitive CdZnTe gamma-ray spectrometer has the ability to provide energy and 3-D coordinates of each individual gamma-ray interactions so that it is possible to further increase the SNR by reconstructing and utilizing multiple scattering events.

We have been developing high-resolution high-efficiency 3-D position-sensitive CdZnTe gamma-ray spectrometers for more than six years[1-3]. These CdZnTe detectors utilize pixellated anodes. The pixel location provides the lateral coordinates of each interaction, while the cathode to anode signal ratio and the electron drift time are used to provide the interaction depths. The 3-D position sensitivity enables the correction of non-uniform detector response, including weighting potential, charge carrier trapping and material non-uniformity, and can therefore greatly improve the energy resolution. The 3rd-generation 3-D CdZnTe spectrometers have achieved excellent energy resolution of better than 1% FWHM at 662 keV for single-pixel events over the entire 2.25 cm^3 CdZnTe crystal [3]. The position resolution was estimated to be ~1.3×1.3×0.5 mm^3.

Having the excellent energy and position resolution and the ability to reconstruct multiple-scattering events, these 3-D position-sensitive CdZnTe detectors can be used to construct sub-millimeter high-efficiency PET systems. Therefore, we developed a prototype small animal PET using two 3-D position sensitive CdZnTe detectors to exploring the potential of these systems in PET application.

A critical property of a PET system is its timing resolution for annihilation 511 keV photons. Our group demonstrated in a separate work that it is possible to achieve about 10 ns FWHM timing resolution on 10 mm thick CdZnTe detectors [4], which should be appropriate for small animal PET systems. This paper focuses on the imaging reconstruction using unique capabilities of 3-dimension position sensing and excellent energy spectroscopy of CdZnTe detectors. Experimental results from this primitive system is presented and discussed

II. SYSTEM DESCRIPTION

The prototype small animal PET system consists of two 3-D position sensitive CdZnTe detector systems being operated in coincident mode. Each detector system consists of a CdZnTe detector with a ceramic substrate, an ASIC front-end board, and a controller card. Each CdZnTe detector is a 1.5 × 1.5 × 1.0 cm^3 CdZnTe crystal and each has an 11×11 pixellated anode and a planar cathode. The detector is wire-bonded to the ASIC inputs using an intermediate ceramic substrate with plated-through-via. The controller card is used to generate and send the readout clock signals to the ASIC and also convert the

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output of the ASIC from current to the voltage signals needed at the input of the data acquisition (DAQ) board.

The original readout electronics of the 3-D CdZnTe does not have coincidence readout capability and was not designed to have multiple systems working in synchronized mode. Hence the biggest challenge is how to integrate two separate 3-D CdZnTe systems into one system and adding coincident capability, while maintaining all normal functions of the system. The simplest solution of adding coincident function to the system is by connecting the trigger output of the two systems to an OR logic circuitry, whose output is used as the common trigger signal for both systems. The coincidence judgment is accomplished in the data processing program. However, the readout dead time for each triggered event is ~450 µs. Since most triggered events will be non-coincidence events, the system will be saturated by non-coincidence events with very low true coincident rate.

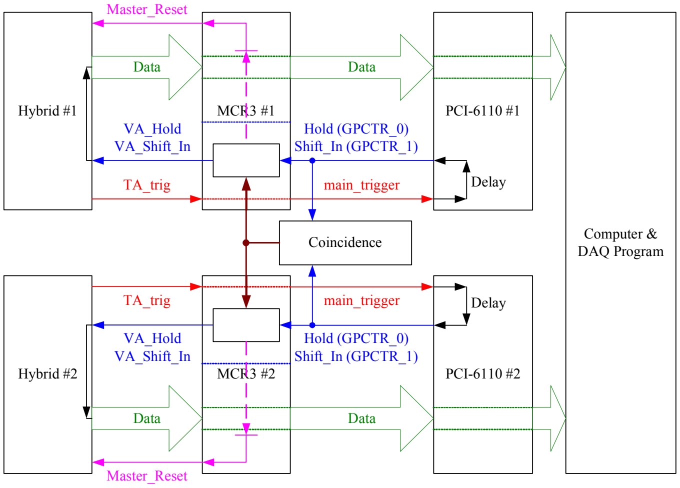

Fig. 1. Illustration of coincident readout of two 3-D CdZnTe systems.

The problem was solved by modifying the firmware on the controller board. The coincident output of the triggers from the two systems is used as a gate signal. If it is a coincident event, the controller boards will enable the two systems to continue the normal readout procedure. Otherwise the triggered system will be reset and ready for the next trigger. The structure of the two systems being operated under coincident mode is illustrated in Fig. 1. The dead time (reset) for a non-coincident event is reduced to ~10µs.

The two CdZnTe detectors are placed with their cathodes facing each other, as shown in Fig. 2. The distance between the cathodes is 60 mm (in z-axis). The offsets in x-axis is 0 mm, while the upper detector can move along the y-axis. An uncollimated ^{22}Na source (0.7 mm < Ø < 0.9 mm) is always located in the middle of the centerline of the two detectors. Hence the incident angle of the source changes with the position of the upper detector.

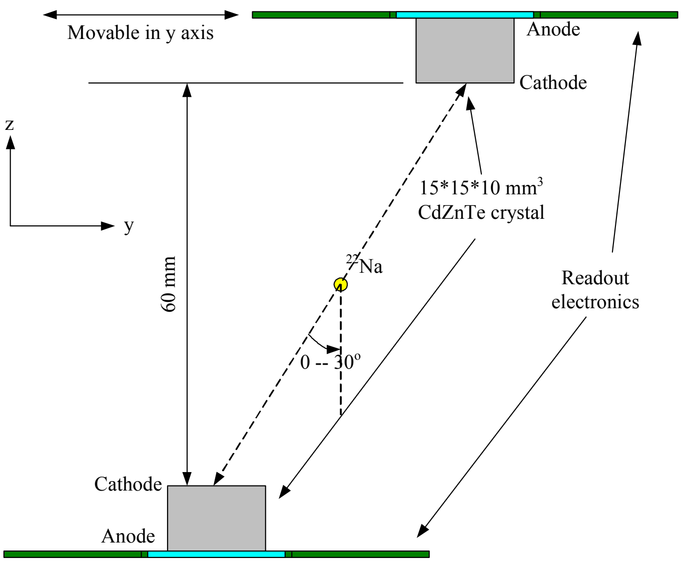

Fig. 2. Configuration of the prototype 3-D CdZnTe PET system.

III. DEPTH OF INTERACTION (DOI)

The images of the ^{22}Na source are reconstructed using simple filtered back-projection (linear ramp) for single-pixel events, as shown in Fig. 3.

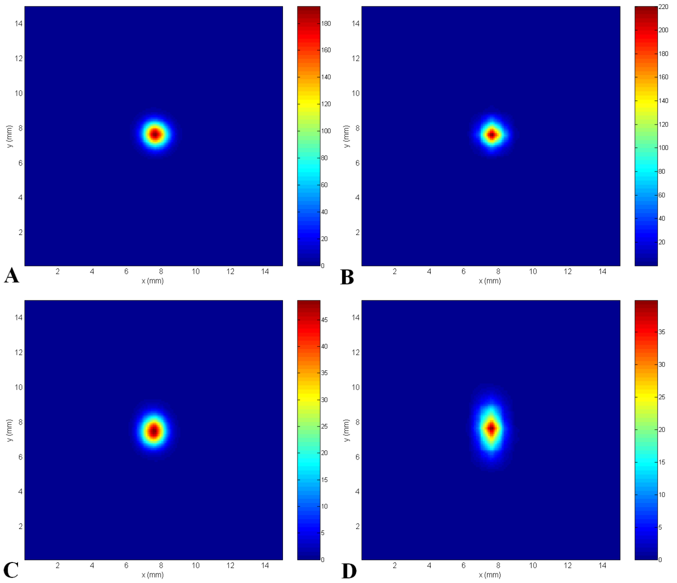

Fig. 3. Reconstructed images of a ^{22}Na source. (A). 0° incident, reconstructed with DOI. (B). 0° incident, without DOI. (C). 30° incident, with DOI. (D). 30° incident, without DOI.

When the source is at the perpendicular incident position (0° incident), the spatial resolution of the reconstructed image is ~1.1 mm FWHM (c.f. Fig. 4A), including the ~0.8 mm diameter of the source. Therefore, the intrinsic spatial resolution of the image should be ~0.75 mm FWHM. For 30° incident angle, degraded spatial resolution in the y-axis is clearly observed, while the spatial resolution in the x-axis remains unchanged. This is due to the simple linear ramp filtered back-projection method used to reconstruct the image. The reconstructed image with the depth of interaction (DOI) has clearly much better resolution (in y axis) and better shape than the image without DOI. The image without DOI seems to be sharper in x-axis, but has visible artificial distortion.

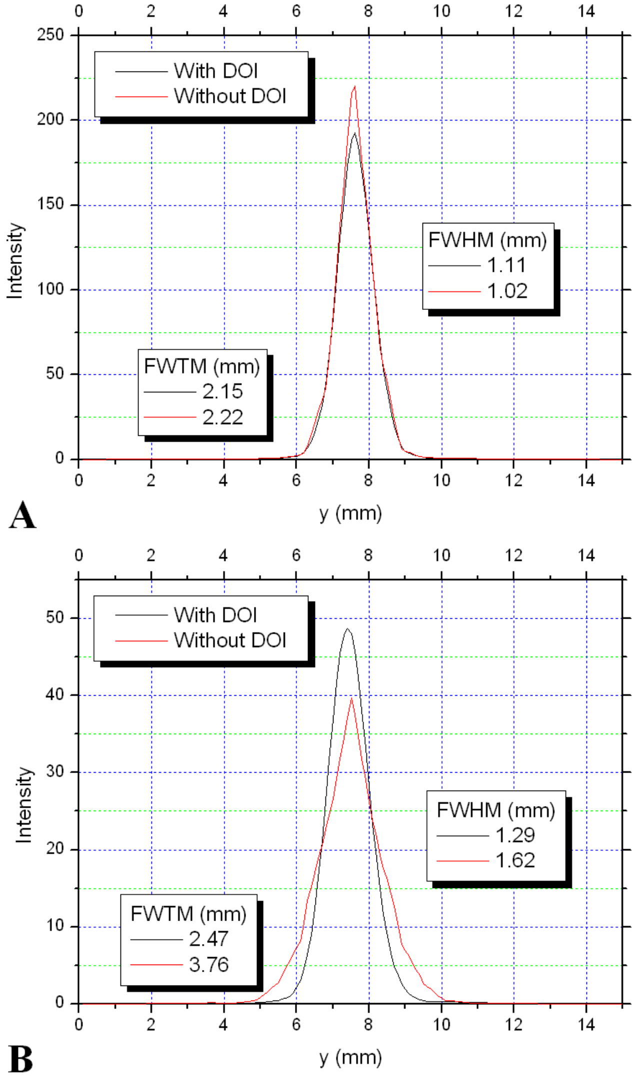

Fig. 4. Comparison of the cross-section of the images from the center of the source along the y-axis. (A). 0° incident. (B). 30° incident.

The effect of interaction depth is much more clear for 30° incident angle, as shown in Fig. 4B. The spatial resolution is much better in the case with DOI than without DOI. Furthermore, the distortion in the image shape without DOI is also more prominent in non-perpendicular incident configuration.

IV. COMPTON SCATTER ANGLE RECONSTRUCTION

When a 511 keV gamma ray undergoes multiple scattering inside one detector, a multiple-pixel event is formed. Two different methods are used to reconstruct the image of the ^{22}Na source (0° incident) for non-charge-sharing two-pixel/one-pixel events (one detector records a two-pixel event while the other detector records a single-pixel events).

One method is the conventional method assuming the detector system cannot determine the location of each individual interaction – energy-weighted centroids, in which the energy-weighted centroid position of the two interactions is used for reconstruction. The deviation from the true first interaction position results in resolution degradation.

However, this PET system can provide the energy and 3-D location for each interaction. This information can be used to calculate the direction of the incident 511 keV photon using Compton imaging technique [5]. Then, the more probable first interaction of the two can be chosen for image reconstruction. This method achieved much better position resolution than the previous method, as can be seen from Fig. 5&6.

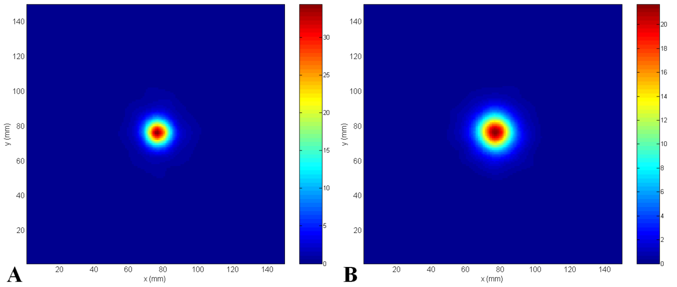

Fig. 5. Images of a 22Na source from non-charge-sharing two-pixel events reconstructed using two different methods. (A). First interaction identification using Compton scattering angle. (B). Approximation of the interaction location using the energy-weighted centroids.

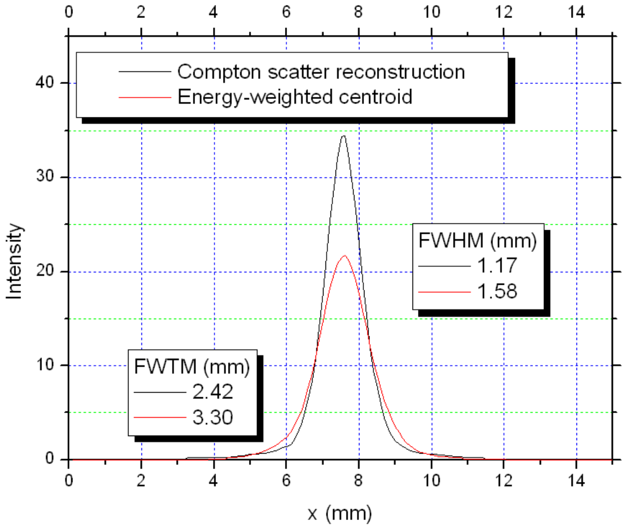

Fig. 6. Comparison of the cross-section of the images from the center of the source along the x-axis.

V. SUMMARY

A prototype small animal PET system using two 3-D position sensitive CdZnTe detectors has been developed and tested. Firmware and hardware modifications were made to greatly reduce the non-coincidence dead time and enable the coincident operation of two 3-D CdZnTe detectors.The system has achieved a spatial resolution of ~0.7 mm FWHM.

The improvement in spatial resolution using the depth of interaction has been demonstrated for non-perpendicular incident events. The 3-D position sensitivity also enables the reconstruction of the direction of the incident gamma rays, which can be used to determine the first interaction of the multiple-pixel events. Significant improvement in spatial resolution has been observed in reconstructed images for two-pixel events.

However, the pretty slow readout time (~500 μs) and non-coincidence reset time (~10 μs) limit the coincidence rate capability of the system. Furthermore, the poor timing resolution (> 100 ns) due to the slow rising cathode signal and the time-amplitude walk caused by the leading edge triggering increases the chance coincidence rate. One of our recently published paper experimentally showed a timing resolution of ~10 ns for large volume CdZnTe detectors [4]. Therefore the timing resolution of current 3-D CdZnTe PET system can be greatly improved to ~10 ns in the future by specially handling the cathode signals (trigger).

VI. REFERENCES

[1] Z. He, W. Li, G. F. Knoll, D. K. Wehe, J. E. Berry, and C. M. Stahle, "3-D position sensitive CdZnTe gamma-ray spectrometers," *Nuclear Instruments & Methods A*, vol. 422, pp. 173-178, 1999.

[2] F. Zhang, Z. He, D. Xu, G. F. Knoll, D. K. Wehe, and J. E. Berry, "Improved Resolution for 3D Position Sensitive CdZnTe Spectrometers," *IEEE Transactions on Nuclear Science*, vol. 51, pp. 2427-2431, 2004.

[3] F. Zhang, Z. He, G. F. Knoll, D. K. Wehe, and J. E. Berry, "3D Position Sensitive CdZnTe Spectrometer Performance Using Third Generation VAS/TAT Readout Electronics," *IEEE Transactions on Nuclear Science*, vol. 52, 2005.

[4] L. Meng and Z. He, "Exploring the limiting timing resolution for large volume CZT detectors with waveform analysis," *Nuclear Instruments & Methods A*, vol. 550, pp. 435-445, 2005.

[5] C. E. Lehner, Z. He, and F. Zhang, "4π Compton Imaging Using a 3-D Position-Sensitive CdZnTe Detector via Weighted List-Mode Maximum Likelihood," *IEEE Transactions on Nuclear Science*, vol. 51, pp. 1618-1624, 2004.