Simulation of Compton Reconstruction in Liquid Xenon PET

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Abstract–**We performed simulations of a liquid xenon positron emission tomograph, and analyzed the data with the use of a Compton reconstruction algorithm. We examined the sensitivity, scatter fraction, and noise-equivalent count rate of the detector, and performed an image contrast simulation and reconstruction of a micro-Derenzo contrast phantom.**

I. Introduction

We are exploring the use of liquid xenon as the detection medium to provide improved images for PET.

II. Liquid Xenon

Liquid xenon (LXe) is a promising technology for PET. The LXe time projection chamber (LXeTPC) provides truly 3D imaging capability with 1mm FWHM position resolution in all 3 dimensions, eliminating the parallax errors [1]. In addition, owing to its faster decay times (2ns fast component and 27ns slow component) compared to traditional scintillator crystals, timing resolution of 1ns or less can be achieved. Also, using scintillation and ionization charge signals, improved energy resolution of <9% FWHM is possible [2]. The LXe TPC allows the identification of individual Compton scattering points, enabling the use of Compton reconstruction algorithms to efficiently suppress random and scatter backgrounds to significantly improve the image quality.

III. Simulation

In order to evaluate the potential performance of the LXe technology for PET, we simulated the LXe PET detector shown in Fig 1. The simulation was done using the Geant4 software package [3]. The LXe detector, encased in 1 mm thick steel to account for the vacuum cryostat, had an inner diameter of 15 cm, an outer diameter of 39 cm, and an axial length of 12 cm. The primary phantom used was a scaled down version of the NEMA standard phantom to rat size which was 5 cm dia., and 15 cm in length made of polyethylene. A cylindrical cavity of 1.9 mm dia. was placed in the phantom at a radial offset of 15 mm, and filled with water in the simulation to act as the radiation source.

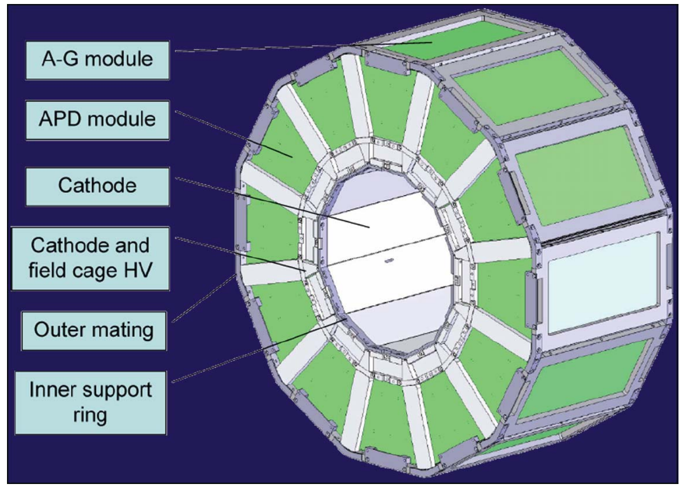

Fig. 1. Schematic drawing of the simulated LXe PET system.

A micro-Derenzo image contrast phantom made of acrylic was also simulated. It was 5 cm in a dia., and consisted of source rods of various diameters, from 0.4 mm to 1.4 mm, where the rod-to-rod separations were twice the associated rod diameters. The micro-Derenzo phantom was also immersed within a 6 cm diameter, 15 cm axial length water cylinder for the simulation.

IV. Compton Reconstruction

Since the LXe PET detector is capable of resolving individual Compton scattering points in 3-D, in order to obtain the best possible position resolution, the first scattering point must be efficiently identified to establish the correct line of response (LOR). Conceptually, this involves checking all possible interaction sequences, and at each scattering location computing a test statistic of this interaction by comparing the apparent scattering angle with the expected value based on the deposited energy and the Compton kinematics. In principle, the real sequence is the one most likely to have the smallest discrepancy and thus the smallest test statistic. This enables the identification of the correct interaction sequence and associated LOR with high probability. The algorithm employed was similar to that used in [4]-[5], but modified for PET application.

The simulated data were processed with a Compton reconstruction algorithm to identify the LOR associated with each event, which was projected into sinogram space. For the NEMA-like phantom, the resultant sinogram profile is shown in Fig. 2, which demonstrated a good signal-to-noise ratio. By setting an upper threshold on the test statistic, further background reduction can be achieved, as shown in Fig. 3.

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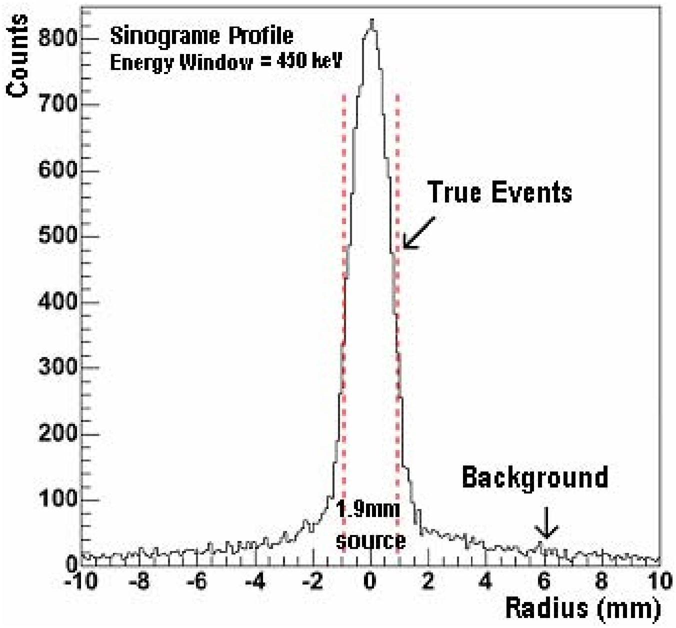

Fig. 2. Sinogram profile of a 1.9 mm diameter 1 mCi water line source inserted into the rat size phantom at a 15 mm offset from the center. Sinogram projections were centered on the source peak and combined. All true events were assumed to be within a 9 mm narrow band centered on the source peak. Background events within the narrow band were assumed to be constant and interpolated as the average of the counts at the edge of the narrow band.

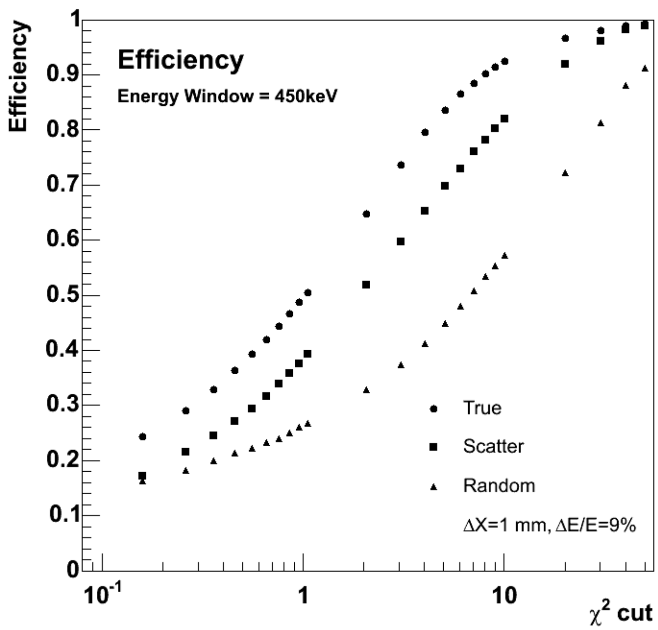

Fig. 3. Normalized efficiency vs. $\chi2$ of the Compton reconstruction algorithm for true, scatter, and random events at 70 MBq. The difference in efficiency allows background suppression via an upper $\chi2$ threshold cut.

Other important simulation results such as the sensitivity, scatter fraction, and NECR are given in Table I for the same NEMA-like phantom with an energy window of 450-500 keV and a conservative coincidence window of 6 ns.

TABLE I
PERFORMANCE OF LXE MICRO-PET WITH A NEMA-LIKE RAT SIZE PHANTOM, USING A 450-550 KEV ENERGY WINDOW AND A 6 NS COINCIDENCE WINDOW

Property	Performance	Description
Sensitivity	12%	Attenuation-less true coincidence rate divided by the activity with a simulated point source at the center of the field of view.
Scatter Fraction	18%	Scatter events divided by the total number of events at low activity obtained by assuming constant background in sinogram projection using NEMA-2001 standards [6].
Maximal NECR	510kcps @ 70 MBq	Noise-Equivalent Count Rate = $(\text{True Rate})^2$ / (Total Rate)

In addition to the above simulations, we also performed image reconstruction with the micro-Derenzo image contrast phantom immersed in water, taking into account the effects of positron range. The reconstructed image is shown in Fig. 4 with rods of 1.0mm and greater diameters clearly resolvable.

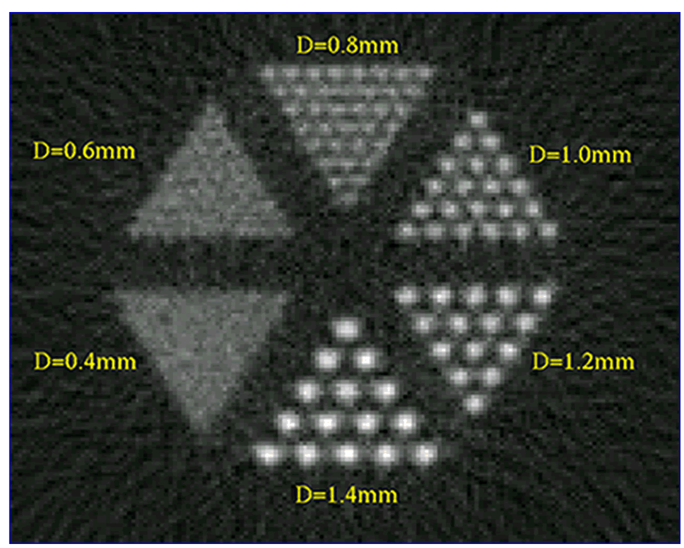

Figure 4: Image reconstructed for a simulated micro-Derenzo image contrast phantom with source rods of various diameters immersed in a 6 cm diameter water phantom. Rod-to-rod separation was equal to twice the associated rod diameter. The image was reconstructed using a Filter-Back Projection algorithm [7] with a modified Ramp filter having a cut-off at the Nyquist frequency. The data count rate was equivalent to a 20 min scan at 1 MBq total activity.

V. CONCLUSION

Based on the simulations described here, liquid xenon with its excellent properties in position (1 mm FWHM in 3D), timing (<1 ns FWHM), and energy (<9% FWHM) resolutions can be expected to provide enhanced imaging power and noise reduction capability for PET applications.

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