Investigation of Liquid Xenon Detectors for PET: Simultaneous Reconstruction of Light and Charge Signals from 511 keV Photons

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***Abstract*—We investigated the detection of gamma rays in a small liquid xenon detector to assess elements of the performance for positron emission tomography. Scintillation light was detected by large area avalanche photodiodes while the ionization electrons were measured on the anode of a time projection chamber after drifting up to 3 cm. The optimum running conditions have been investigated as a function of electric field. An energy resolution <4% (rms) was achieved by combining scintillation light and ionization charge.**

I. Introduction

THIS work is aimed at studying the interactions of 511 keV photons in liquid xenon (LXe) detectors for applications to positron emission tomography (PET). The advantages of LXe for PET compared to currently used methods include improved energy resolution, sub-mm spatial resolution, inherent Compton event reconstruction, and high sensitivity.

We have developed a concept for a micro-PET detector shown in fig. 1 that takes advantage of the improved performances achieved by measuring light and charge in LXe. The scintillation light will be measured by large area avalanche photodiodes (LAAPD), which have been found to work well in LXe [1]. The charge measurement will be achieved by using a time projection chamber (TPC); the electrons drift at constant velocity onto a set of anode strips and wires located above the anode plane. Electrons produced within the liquid will drift to the anode plane under an electric field set between a cathode foil and the anode strips. The wires cross the anode strips perpendicularly and measure the current induced by the electrons as they drift in their vicinity. The third dimension is obtained measuring the electron drift time. In order to investigate this concept we have built a small test chamber allowing measurement of light and charge simultaneously.

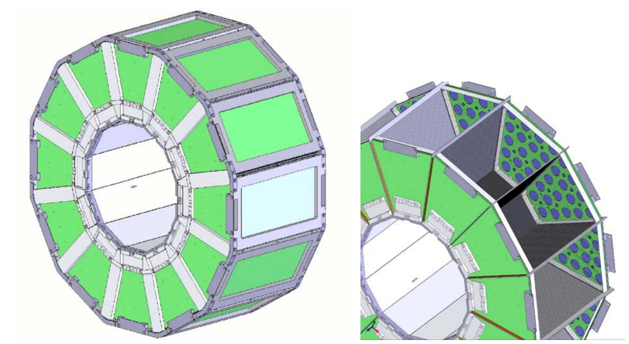

Fig. 1. The LXe PET ring concept. Scintillation light and charge are measured in each of the 12 modules consisting of a LXe time projection chamber viewed by avalanche photodiodes.

II. The Test Chamber

A small test chamber (27 cm^3) was constructed to measure light and charge signals. An electric drift field was applied between the cathode and the shielding grid located near the anode charge collection plane as shown in fig. 2. Two LAAPD (Advanced Photonics Inc.) were used to detect the scintillation light. Charge was collected on a central 1 cm diameter electrode (A1) or on an outer electrode (A2).

The 511 keV photons emitted by a ^{22}Na source entered the test chamber (along the z axis) through the cathode plane and coincidences with an external NaI detector were studied.

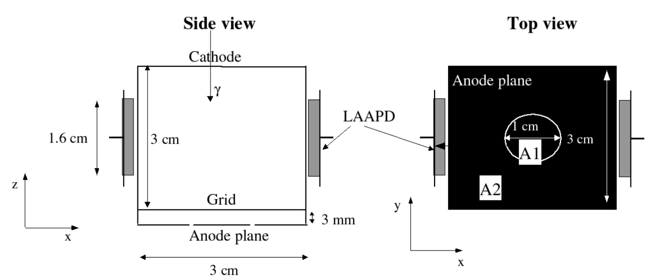

Fig. 2. Shematic view of the small test chamber. The side view illustrates the drift direction between the cathode and anode, viewed by two LAAPDs immersed in the LXe. The top view shows the segmentation of the anode.

III. Charge and Light Collection

The left panel of fig 3 shows the distribution of the charge measured on the central anode as a function of the drift time for a 1 kV/cm drift field. The shape of the distribution is the same for all drift fields. The 511 keV band rises sharply in less than 1 μs, and then falls slowly until the cutoff, which corresponds to the edge of the chamber. The

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TABLE I
ELECTRIC FIELD (E_d), DRIFT VELOCITY (v_d), AND NUMBER OF ELECTRONS (Q_{tot}) AND PHOTONS (N_{tot}) OBSERVED.

E_d [kV/cm]	v_d [cm/μs]	Q_{tot} (511 keV e^-)	N_{tot} (511 keV γ)
0.33	0.15 $\pm$ 0.01	16,000 $\pm$ 2,000	16,500 $\pm$ 2,000
1	0.17 $\pm$ 0.01	19,000 $\pm$ 2,000	14,500 $\pm$ 2,000
2	0.20 $\pm$ 0.01	21,000 $\pm$ 2,000	13,500 $\pm$ 2,000

sharp rise corresponds to photons interacting between the grid and anode. In that case only a fraction of the charge is measured proportional to the distance between the anode and the interaction point. When the interaction point is in between the grid and cathode, then the anode is not sensitive to the induced current, and the measured charge should be independent of the interaction position. Compton interactions are clearly visible below the 511 keV band due in part to photons entering the chamber with less than 511 keV.

The right panel of fig 3 shows the sum of the number of photons measured by both LAAPDs as a function of the electron drift time for the events where all the charge is collected on the central anode. The bell shape is due to the solid angle subtended calculated by performing a ray tracing Monte Carlo. The solid angle varies significantly with the position of the photon interaction. The arrival time of the electrons provides a handle on solid angle variation in the drift direction. The total number of photons drops with increasing drift voltage, which is in agreement with previous measurements [2], [3].

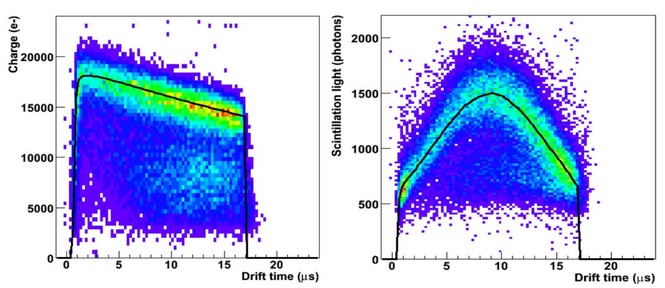

Fig. 3. Charge (left) and light (right) collection as a function of drift time for a 1 kV/cm drift field. The curves are fits based on parameterizations obtained from current calculations and solid angle.

From the observed charge distributions, the drift velocity, total charge, and the charge attenuation length (or electron drift lifetime) were measured. From the light distribution the total number of photons observed and also the charge drift velocity were obtained. Table I gives results for charge and light collection at different drift fields for 511 keV photons.

The spatial resolution (rms) in the drift direction using only the observed light amplitude of the two LAAPDs for photo-peak events was 3 mm; the spatial resolution from charge measurements is expected to be approximately 0.3 mm in all three dimensions.

IV. Energy Resolution

To study the energy resolution we focused on the central region of the test chamber (A1 at z=1.5 cm from the cathode).

TABLE II
ENERGY RESOLUTIONS (RMS) OBSERVED AT DIFFERENT DRIFT FIELDS.

Drift Field [kV/cm]	Energy Resolution [%]		
	charge	light	combined
0.33	9.21 $\pm$ 0.38	13.90 $\pm$ 0.19	4.70 $\pm$ 0.11
1	5.38 $\pm$ 1.04	12.39 $\pm$ 0.32	4.30 $\pm$ 0.22
2	5.69 $\pm$ 0.29	12.41 $\pm$ 0.28	4.54 $\pm$ 0.12
2.66	4.78 $\pm$ 0.16	12.73 $\pm$ 0.16	3.78 $\pm$ 0.09

Fig. 4 shows the energy distributions observed for charge, light and the combination of both.

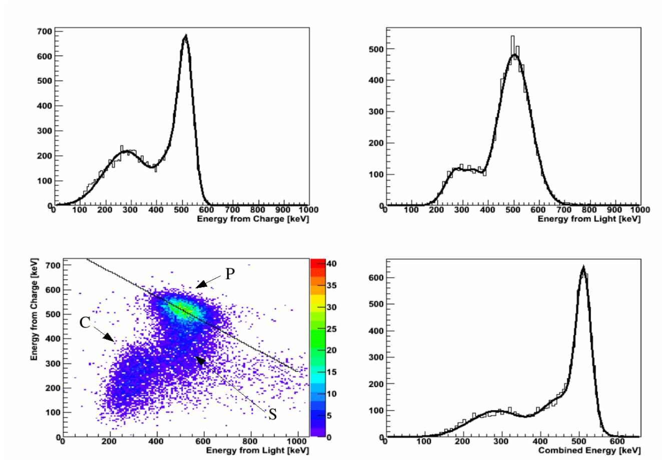

Fig. 4. The observed charge spectrum (upper left plot), light spectrum (upper right plot), correlation between light and charge signals (lower left plot), and combined spectrum using the correlation (lower right plot) for 511 keV photons with a drift field of 2.66 kV/cm. The data points in the correlation plot that are not part of the Compton (C) or the photoelectric peak (P) are due to photons that scattered outside the detector (S).

The lower left plot shows the linear anti-correlation between the light and charge measurement and the axis of the ellipse. The upper left plot shows the charge spectrum collected on the anode which is equal to a projection of the correlation along the light axis. In the upper right plot the projection of the correlation along the charge axis can be seen, giving the spectrum of the collected light. The lower right plot demonstrates the improved energy resolution of the combined spectrum: The 511 keV region ellipse of the charge-light anti-correlation was fit and projected along the ellipse axis. An energy resolution (rms) as low as 3.78% was achieved as given in Table II. The charge resolution is corrected for the noise that is picked up by the anode which is about a 4% effect. The same method of combining the charge and light signals using the anti-correlations has been used in [2] and [3].

V. Conclusion

With the small test chamber we were able to obtain electron lifetimes as high as 200 μs. A time resolution of 1 ns was achieved with the LAAPDs. It was demonstrated that energy resolutions below 4% are possible with a combination of charge and light signals in liquid Xenon. The spatial resolution obtainable from light alone is 3 mm. The spatial resolution from charge measurements is expected to be approximately 0.3 mm in all three dimensions.

As a next step a complete single sector for a PET ring is under construction. This will be followed by coincidence measurements using two or more sectors.

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