Continuous Scintillator Slab with Microchannel Plate PMT for PET

Heejong Kim, Chien-Min Kao, Henry Frisch, William W. Moses, Woon-Seng Choong, Jean-Francois Genat, Fukun Tang, Chin-Tu Chen

***Abstract*—A PET detector design using the continuous scintillator slab was investigated. The detector unit consists of two layers of LSO scintillator slab, each slab size of 102x102x5mm^3, and two large area microchannel plate(MCP) PMTs, 102x102mm^2, coupled to scintillator slabs. The optical photon inside scintillator was simulated using Geant4 package and the electrical signal of MCP was formed using the measured characteristics of MCP and Geant4 output. The signals from MCP were readout using the transmission line(TL) scheme with 4.25mm pitch. The multi-layers of structure enable us to extract the depth of interaction in addition to position, energy and timing in an event. The detector response was measured by impinging the pair of 511keV gamma upon the detector. As preliminary results, we obtained ∼12%(FWHM) of energy resolution at 511keV and ∼360ps(FWHM) coincidence timing resolution while keeping 14% detection efficiency at 511keV. The position resolution was measured ∼2.3mm(RMS) at the center. Due to its simplified structure, the detector can be easily extendable to several layers of slab to increase the sensitivity. The fast timing characteristics of MCP combined with the high sensitivity of LSO makes this design reliable for TOF PET application.**

I. Introduction

Using continuous crystal in PET design has some advantages over the pixelated one: higher packing fraction, convenience in crystal machining. The microchannel plate(MCP) photomultiplier tube(PMT) [1] is a promising photodetector for PET application because of its position sensitiveness, fast time response and relatively compact size to conventional PMT. We investigated a PET detector design: continuous LSO slab coupled with MCP PMT for photodetector. Due to the simplified structure, the detector can be easily extendable to several layers of slab to increase the sensitivity. The high sensitivity of LSO, and fast timing characteristics of MCP would also enable this design suitable for TOF PET application [2]. Transmission line(TL) readout scheme [3] was used to measure signal from the MCP PMT. One TL strip collects the signal from a row(column) of scintillator pixels. Energy, position and timing informations can be extracted in TL readout scheme while keeping the number of readout channels relatively smaller than fully pixelated readout. TL readout scheme would be the efficient way for the large area coverage. The extensive research efforts on the large area MCP PMT development [4] would eventually make it possible to reduce the costs for the production.

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We have conducted Geant4 [5] based simulation works to prove the design concept. Simulation of electrical signals at TL was also made using the Geant4 outputs on optical photons inside LSO scintillator. Simulation setup and results are presented.

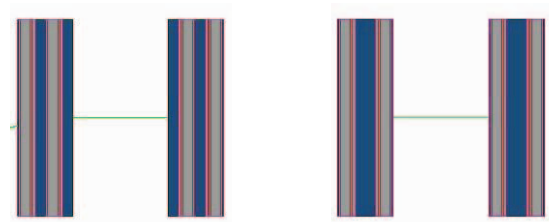

Figure 1. Simulation setup with two detector modules. Each module consists of two layers of scintillator slab, 5mm thick each, and MCP assembly.(left) Blue colored part is the scintillator slab and MCP is shown in grey. For comparison, 10mm thick single scintillator slab are coupled with two MCPs at both front and back side.(right)

II. Materials and Methods

A. Configuration

LSO was chosen for the scintillator because its high light yield(30,000/MeV) and fast decay time(∼40ns). Each LSO slab has dimension of 102mmx102mx5mm. One detector module consists of two layers of scintillator slab and two MCP assemblies which are coupled to each scintillator slab. The detector configuration is depicted in Figure 1(left). For comparison, an alternative configuration was simulated as in Figure 1(right): 10mm thick single scintillator slab are coupled with two MCPs at both front and back side. The side edge of the scintillator slab was treated black to avoid light reflection at the edge. The pair of 511keV gamma were generated with back to back at middle of two detector modules and sent to the center of each detector. The data set along the X axis were also generated to study the detector response uniformity. The optical photon's generation, transport and detection through the media were handled using Geant4 simulation package.

Figure 2 shows a 2 inch Photonis Planacon MCP(XP85022) [6] and transmission board, which were used as models for the simulation. In simulation, transmission line structure was embedded inside MCP assembly as well as photocathode and microchannel plate structure. The overall dimension of MCP in simulation was 102x102x9.15mm^3. The material effect due to front MCP on 511keV was turned

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out negligible by inserting a MCP unit in a separate real coincidence setup.

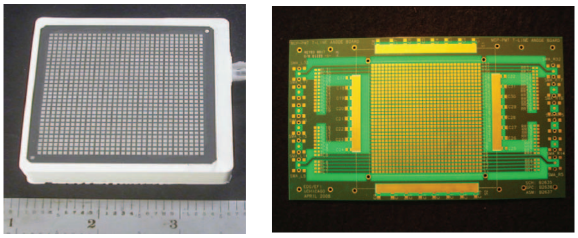

Figure 2. Photonis Planacon MCP(XP85022) with 1024(32x32) anodes(left) and Transmission line(TL) board with 32 microstrip(right). One microstrip is connected to one raw of MCP and signals are readout at both ends of a TL.

B. Simulation of electrical signal

The electrical signal was formed based on the measured XP85022 characteristics combining with the Geant4 simulation results: the optical photon's position and arrival time at photocathodes. Once the optical photon reaches at photocathode, photo electron comes out depending on the quantum efficiency photocathode, which is 22% at 350nm for XP85022. To each individual photo electron, an asymmetric Gaussian shaped pulse(with ~560ps rise time) was assigned, which was based on the measured MCP shape.

C. Readout scheme

Electrical signal for each TL was formed by summing pulses due to all the photoelectron within the area of TL strip. The signal formed in a TL then propagates to both ends of TL for energy and timing measurements. Inside MCP, all the TLs run vertically with 4.25mm pitch between adjacent TLs. By applying Anger logic to measured TL signals, a coordinate(along X axis) in horizontal direction can be reconstructed. The Y coordinate was determined by measuring time difference at both ends of the TL which has the maximum energy.

III. Experimental Tests

The test setup was built using a Photonis XP85022 MCP PMT and TL board. The main purpose of setup was to obtain the single photo-electron response of the MCP/TL. The simulation study can be more realistic by using the measured responses as inputs. The another aim is to measure the responses to 511 keV gamma. For this, the MCP/TL was coupled with LSO and an additional LSO/PMT was used for the coincidence setup. The real coincidence setup was also simulated separately and the measured results were compared with the simulation for validation.

Fig. 3 shows the assembled XP8500 MCP PMT on top of a TL board. XP85022 has a two layer of Chevron type MCP with the pore diameter 10 μm. The prototype TL board has 32 micro strips with 1.6 mm pitch. Currently only 4 channels of TL can be readout with SMA type connectors. The waveform from the TL board was recorded by Tektronix DP07354 digital oscilloscope that samples the waveform with 10-20 GSps.

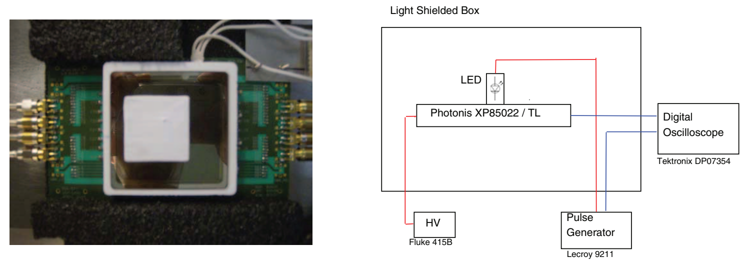

Figure 3. Assembled XP85022 MCP/TL.(left) Four TLs at the middle have SMA type connectors for readout. A block diagram to measure SER with LED as a light source.

A. Single Photo-electron Responses

The setup to measure the SER of XP85022 MCP/TL is shown in a block diagram of Fig. 3. The LED(CMD204UWC-ND, CML Tech. Inc.) cased in cylindrical holder was placed on the MCP PMT. The light from the LED was localized through a 0.8 mm diameter aperture and was controlled by a pulse generator(Lecroy 9211) at single photon level. The high voltage(HV) for the XP85022 was set typically at -2300V. The waveform of three TL were recorded by the oscilloscope. The pulse shape of single p.e. is shown at Fig. 4. The rise time of SER was estimated ~560 ps. The signal spread due to single p.e was larger than TL pitch and therefore the charge induced by single p.e, shown in Fig. 4, was obtained by integrating the pulses from three TLs.

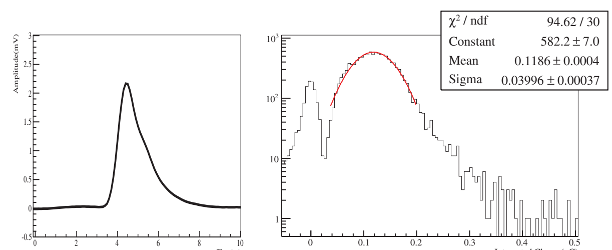

Figure 4. Averaged pulse shape of single p.e(left) Only the middle TL was considered for the shape. Integrated charge distribution due to single p.e.(right) Due to single spread, charges of 3 TL pulses were summed together.

The absolute gain of XP85022 was measured from the integrated charge. By varying HV in -2100V and -2500V range, the gain as a function of HV was obtained as shown in Fig. 5 and was found well fitted by the exponential function as expected. The gain at -2300V, which was the nominal HV for the other tests, was ~1.5x10^6. During the readout, only one side of TLs was used and the other was terminated with 50Ω. This was corrected by multiplying the factor 2 for the absolute gain.

B. Responses to 511 keV gamma

A LSO scintillator of 25x25x8.5 mm^3 was coupled to the XP85022 MCP/TL to measure the responses to 511 keV gamma. All the surfaces of the scintillator was polished. For a coincidence detector, another LSO of 6.25x6.25x25 mm^3 coupled to a Hamamatsu R9800 PMT was placed 3 cm apart.

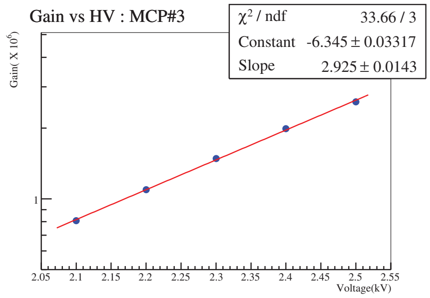

Figure 5. XP85022 MCP gain as a function of HV. Each data point was calculated from the measured charge distribution.

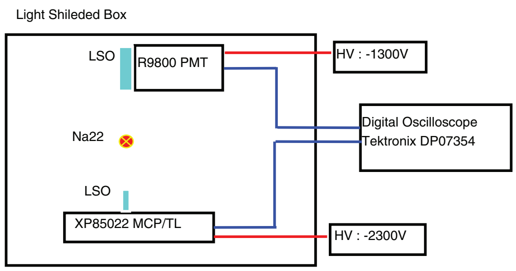

Figure 6. Setup for 511 keV gamma coincidence event.

Na^{22} of $\sim$1 μCi activity was used as positron source at the middle of two units. The waveforms from three TLs and R9800 PMT were recorded by the digital oscilloscope. The coincidence event was triggered by requiring thresholds of 40 mV for the R9800 PMT and 8 mV for the MCP/TL, respectively. Fig. 6 shows the block diagram of the coincidence setup.

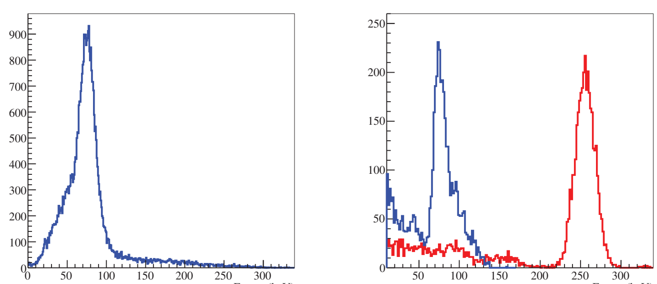

Figure 7. Energy distribution of the MCP/TL from the experiment(left) and the simulation(right). Energy from the three TLs were summed.

The energy of the MCP/TL is shown in Fig. 7. Energy from the three TLs were summed in the figure; Only one side were readout among two ends of each TL. In Fig. 7(right), energy sum of all 32 TS are shown in red histogram. The energy conversion was done to make the peak at half of 511 keV. Due to the light spread within the scintillator, three TLs contains only partial energy of 511 keV gamma: the peak is at $\sim$75 keV. The collection efficiency of MCP in the simulation was adjusted to have the peak of 3 TL energy sum at 75 keV.

Fig. 8 shows the coincidence time distributions between the

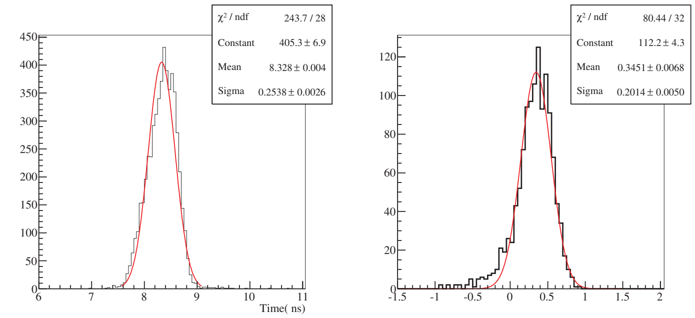

Figure 8. Coincidence timing distributions: the experimental test(left) and the simulation(right).

MCP/TL and R9800 PMT. Both for the real and simulation data, the timing was determined by the leading edge time pickup method by applying 3 mV and 50 mV thresholds for MCP/TL and R9800 PMT, respectively. To select coincidence events, [400, 600]keV was required for the energy from the R9800 PMT. For the MCP/TL, the event with [60, 90]keV of three TLs was regarded as having the energy around 511 keV. The measured coincidence timing resolution, $\sim$590 ps, was worse than $\sim$470 ps from the simulation. The contribution from R9800 PMT on the coincidence timing was measured $\sim$200 ps from the coincidence setup using two identical LSO/R9800 PMT.

IV. Results

A. Energy

Figure 9 shows the energy distribution of 511keV gamma. For energy reconstruction, the maximum signal TL was searched first in an event and then charges of 5 TLs were summed with the maximum energy TL at the center. 12%(FWHM) of energy resolution was measured at 511keV with Gaussian fit.

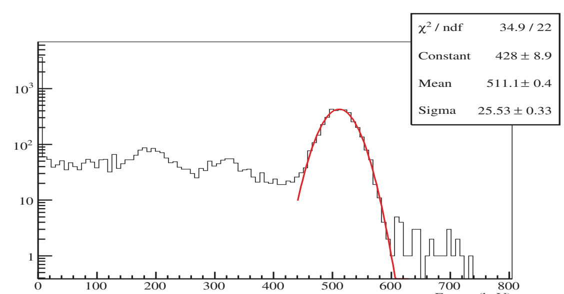

Figure 9. Energy distribution. The event without interaction within the scintillator volume are shown with zero energy entries in the figure.

B. Timing

The event time was extracted by applying the leading edge pick-up(3mV threshold) to the maximum TL signals. The event time difference from up and down stream module is shown in Figure 10 and $\sim$360ps(FWHM) was measured for the coincidence time resolution. The energy window of [400, 600]keV was used to select coincident events. The detection efficiency of coincident event was ∼14%(∼37% for one module). The alternate configuration shown in Figure 1(right) showed ∼600ps of coincidence time resolution. The larger light spread due to relatively long path to MCP may cause this worse result.

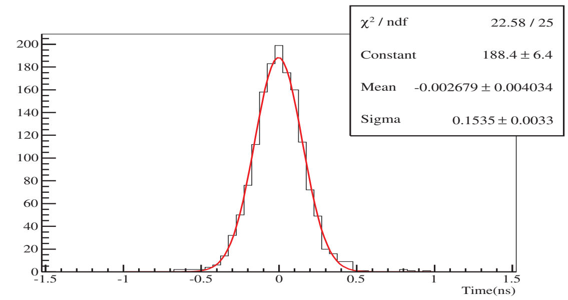

Figure 10. Event time difference of coincident event. Event time in each module was determined by the leading edge pick-up with 5mV threshold.

C. Position

The position of gamma interaction was determined by applying the Anger logic to most energetic 5 TLs in an event. Figure 11(left) shows reconstructed X coordinate distribution with 511keV gamma injected 20mm off the detector center on the X axis. Figure 11(right) shows the deviation of reconstructed coordinate from the injection position($X_{recon} - X_{gamma}$) as a function of distance from the detector center. The full width of error bar on the figure is the RMS value, which is ∼2.3mm. The edge effects due to absorbing light at the side of scintillator slab was found within 10mm from the edge. The Y coordinate determined from time difference at both ends has somewhat worse result: the average RMS is ∼3.2mm.

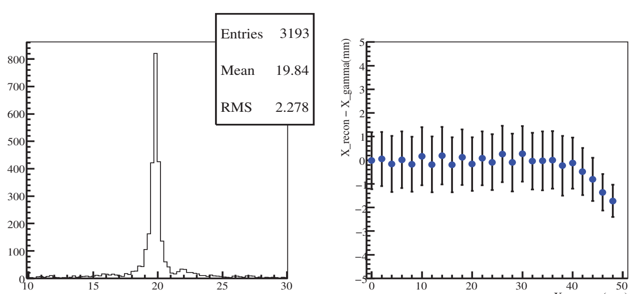

Figure 11. Reconstructed X coordinate(left). The 511keV gamma was injected 20mm off the center along the X axis. The deviation of reconstructed position from gamma injection point($X_{recon} - X_{gamma}$) (right).

V. Discussion and Summary

A PET detector design based on continuous scintillator was investigated using Geant4 simulation: A detector module consists of two layer of LSO scintillator slab coupled with MCP PMTs. As preliminary results, we obtained ∼12%(FWHM) of energy resolution at 511keV and ∼360ps(FWHM) coincidence timing resolution while keeping 14% detection efficiency at 511keV. The position resolution was measured ∼2.3mm with TL pitch 4.25mm. By design, the depth of interaction can be inferred from the position of the first hit layer. The fast timing characteristics of MCP combined with the high sensitivity of LSO makes this design suitable for TOF PET application. The detector configuration with a single thick continuous slab showed similar performances as the layered design except timing resolution: ∼12% of energy resolution and ∼2.5mm(RMS) in position measurement. The results shown here were obtained assuming the charge sensitive ADC and TDC with the leading edge in TL signal digitization. The full waveform sampling would be a possible option for the signal digitization ,which is expected to give improved energy and timing performances [7].

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