A Design of a PET detector using Micro-channel Plate PMT with Transmission Line Readout

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Heejong Kim
Department of Radiology, University of Chicago, IL
1. Introduction

Positron Emission Tomography (PET) detect two 511keV photons from e+ annihilation.

Most of PET instrument
• Scintillator + Photo-detector + DAQ electronics

Photomultiplier tube (PMT) has been widely used Photo-detector in PET instrumentation.
• Fast response time
• High sensitivity
• Stability
• Bulky
• Sensitive to magnetic field

PET detector improvements in photo-detector (keep light output as much as large/fast)
• SiPM, High Q.E PMT, ....
• Micro-channel Plate PMT
Micro-channel Plate PMT

- Faster time response
- Compact size
- Position sensitive
- Expensive cost

Large Area Picosecond Photo-Detector (LAPPD) project
- Aiming to develop large area (8”x8”) MCP-PMT
- Collaboration of Univ. of Chicago, Argonne, Fermilab,…
- Estimates a factor of ~10 cheaper than PMT per area.

When available, it can be applicable to PET instrument.
- Various PET design would be possible at reasonable cost.

Photonis XP85022 MCP-PMT
(2”x2”, 14mm thickness)

(from Paul Hink’s slide at 2008 picosecond workshop)
Existing PETs using MCP-PMT

(from David Brasse’s slide)
LYSO (1.5 x 1.5 x 25 mm³)
Use Photonis XP85023 MCP.
(1024 anodes)
S. Salvador et al.,
IEEE TNS, V56, 2009, p.17

Developed for mobile cardiac PET
25cm x 25 cm field of view.
NaI (5 x 5 x 12.5mm³, 5.5mm pitch)
Use 16 MCP-PMT (Photonis XP85002)
4 pads in each MCP-PMT.

A. Weisenberger et al,
IEEE NSS/MIC Record 2007, p.3705
2. Materials and Methods

Investigated the feasibility of a PET design using large area MCP-PMT by simulation study.

Simulation parameters were not optimized yet.

- Design Features
- Simulation Configuration and Setup
  - Geant4 with optical photon process
- MCP-PMT model
- Transmission Line Readout
PET Design Features (simulation)

- **LSO(LYSO) scintillator**
  - High Light yield (25000~30000/MeV)
  - Fast decay time (~40ns)

- **Micro-channel Plate (MCP) PMT. (4”x4” area)**
  - Position sensitiveness.
  - Fast time response.
  - Compact size than conventional PMT

- **Transmission Line readout scheme.**
  - Readout both ends of the strip.
  - Position measurement by time difference
  - Efficient reduction of # of readout channel (NxN -> 2N)

- **Readout at both ends (Scintillator sandwiched by MCPs)**
  - Possible to extract Depth of Interaction (DOI)
Detector Configuration (simulation)

- Two detector modules facing each other.
  - 8 cm distance between them.

- One detector module consists of 24x24 array of LSO scintillator and 2 MCP/TL assemblies.

- LSO pixel dimension: 4x4x25mm³.
  - Crystal pitch: 4.25mm

- MCP assembly dimension: 102x102x9.15mm³. (4”x4” of area)
  It includes photocathode and TL structure.

- MCP is coupled to LSO at both front and back ends.
Optical Photon Simulation

- Optical Photon generation and transport was simulated by Geant4.
- Two 511keV gammas are generated back to back at the middle of two detector modules and sent to the detector centres.
- The reflective media was inserted between crystals.
- The surface between LSO and MCP glass was optically coupled with the optical grease.
- LSO characteristics (simulation input parameters)
  - Light yield : 30,000/MeV
  - Decay time : 40ns
  - Resolution : 10.4%( FWHM)
Simulation Flow (in each Event)

- 511 KeV gamma interaction at LSO
- Photo-electric effect, Compton Scattering

- Optical photons generated reflection, refraction, absorption
- Detected at photo-cathode of MCP-PMT
- For each event, optical photon’s Energy (wavelength), Arrival time, Position were recorded (ntuple)
- ROOT format

- Off-line analysis
- Applying Q.E of MCP
- .......

Optical photon spectrum from LSO
Signal Read-out Scheme

- Electrical signal was formed based on the measured XP85022 characteristics combining with the Geant4 simulation outputs: optical photon’s position and arrival time at photocathode.

- For each individual photo electron, the measured single photo electron response was assigned. Convoluted pulses due to all the photo-electron within the area of TL strip.

- TL signal then propagates to both ends of TL.

- In the forward MCP, 24 TL strips run vertically. By applying Anger logic to measured TL signals, X coordinate can be obtained.

- TLs runs horizontally in the backward MCP to get Y coordinate in the same way.

- The position also can be measured from the measured time difference at both ends of TL.
Photonis Planacon MCP-PMT (XP85022)

- **Window material**: Borosilicate, Corning 7056 or equivalent
- **Photocathode**: Bialkali
- **Multiplier structure**: MCP chevron (2), 25 μm pore, 40:1 L:D ratio
- **Anode structure**: 32×32 array, 1.1 / 1.6 mm (size /pitch)
- **Active area**: 53×53 mm
- **Open-area-ratio**: 80%
Principles of Transmission Line read-out

\[ t_0 = \frac{t_1 + t_2}{2} \]
\[ x_i = \frac{t_1 - t_2}{t_1 + t_2} \]
\[ E_i = q_1 + q_2 \]

[Borrowed from Fukun Tang’s slide]
Prototype Transmission Line board

- 32 micro-strip Z=50Ω lines
  - Width = 1.1mm
  - Pitch = 1.6mm
- 6 strips have SMA connectors for test read-out
- Developed at U. of Chicago EDG.
3. Experimental Tests

A. Single photoelectron responses (SER)
   - Gain measurement
   - Absolute calibration
   - Pulse shape of single p.e. -> used in simulation to make waveform due to optical options.

B. Responses to 511 KeV gamma
   - Coincidence setup: MCP/TL + R9800 PMT
   - Make an intermediate simulation.
   - Calibrate simulation with experiment results by comparing energy and timing.
The test set-up was built using a XP85022 MCP and TL board to measure the characteristics of the MCP.

- Block diagram for test set-up using LED.
- 4 TL channels were connected through SMA to the DPO7354 oscilloscope (Tektronix).
- 3GHz bandwidth, 20GS/S sampling.
Integrated charge of single p.e.

- SER was measured using the pulsed LED as a light source.
- Charges was measured by integrating waveforms.
- The SER signal was spread in ~5 TL.
  -> need to increase number of readout channels.
- The XP85022 gain at HV = -2300V : $1.5 \times 10^6$
Pulse shape of single photoelectron

Averaged waveform of SER. The maximum TL signal only. The rise time of SER was measured ~560ps.

The measured pulse shape of SER was used for simulating electrical signals of MCP-PMT by applying it to individual optical photons.
B. Responses to 511 KeV gamma

- MCP/TL coupled to 1x1x10mm$^3$ LSO crystal.
- Hamamatsu R9800PMT with 6.2x6.2x25mm$^3$ LSO for coincidence
- Use Na22 for positron source.
- Waveform recorded by Tektronix DPO7354 scope
Intermediate simulation setup

MCP-PMT (2”x2”)  
1x1x10mm³ LSO crystal

R9800 PMT  
6.25x625x25mm³ LSO
Waveform from MCP/TL & R9800 PMT

Waveform of MCP/TL+LSO.
Waveform of R9800 PMT+LSO

Waveforms were recorded at 20GS/S sampling.
Waveform of MCP/TL is for the middle TL among 3 TLs.
Energy spectrum of MCP/TL

- Charge sum of 3 TL signal: only left side of TL.
- Compton + 511keV peak structure is clearly found.
- Discrepancy between the real test and simulation.
  - E resolution: 22.3% vs 15.8% (at 511keV peak)
  - Shape of compton continuum.
  - Due to simplified simulation setup (gamma direction).
Event selection requirement for the coincidence timing.
- R9800PMT: $400 < E < 600$ keV
- MCP 3TL Sum: $35 < \text{Int. Charge} < 60$ pC
- Leading Edge threshold: 3 mV (MCP/TL) 50 mV (R9800 PMT)
- Coincidence timing resolution = \(~416\) ps (FWHM)
- Contribution from R9800PMT side = \(~200\) ps (FWHM)
4. Results : Design Simulation
Sum of 5 TL signals around the maximum amplitude.

Energy resolution : ~11%

Use the measured XP85022 SER for the TL signal.

The event time was extracted by Leading Edge (LE) to the maximum TL signal. (Threshold : 3mV)


The detection efficiency : ~40% (~63% for one module).

Coincidence timing resolution : ~323 ps.
Position determination

Reconstructed X using the centroid  Reconstructed Y using timing difference

511 KeV gamma injected on the center of a crystal (x=2.125, y=2.125)
Two ways of position determination.
• Energy weighted using 5 TLs (Centroid) (left)
• Time difference of the maximum TL at both left/right ends. (right)
  -> gives the coordinate orthogonal direction to the centroid method.
• Position resolution : ~2.5mm of FWHM in both method.
Energy asymmetry and timing difference between back and forward: for DOI

- 511keV gamma injected from side of detector with 1mm step along Z axis.
- Energy asymmetry and time difference of front and back due to different interaction depth.
  - \( \frac{(E_{\text{Front}} - E_{\text{Back}})}{(E_{\text{Front}} + E_{\text{Back}})} \)
- Clear correlations were found.

Energy asymmetry as a function of depth

Time difference as a function of depth
5. Summary & Plans

- A PET detector design using pixelated array of LSO scintillator and MCP PMT with Transmission Line readout was studied.
- Geant4 was used for optical photon simulation.
- Real test setup using XP85022 MCP and TL board was built to measure SER of MCP. The measurement from the test setup was fed to the simulation for TL signal forming.
- The preliminary results from the study show promising results.
  - Energy resolution ~11% at 511keV was obtained.
  - The coincidence time resolution ~323ps with ~40% detection efficiency were estimated.
  - Readout at both ends of scintillator makes it possible to extract the DOI information.
Summary & Plans - continued

A prototype detector module is planned. MCP-PMT + Transmission Line + Waveform sampling

1. Increase the read-out channels (4 -> 32) would allow more precise measurement. continuous X-tal (>1cm) can be investigated. uniformity can be studied as well.
2. Readout electronics.
   4 channel digital oscilloscope -> 62 channel VME board using DRS4 sampling chips.
   A prototype (using DRS4 chips at 5GS/s sampling) was developed at EDG of U. of Chicago. (under test)
   (CAEN will produce 32 channel VME board using DRS4).

ARS16 board
(Analog Ring Sampler)
VME interface
16 ch. 1 GS sampling
LPC Clemont, France

DRS4 evaluation board
USB interface
4 ch. 5 GS sampling
PSI, Switzerland
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