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

Contents

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1. Introduction

A block detector module.
from HRRT, CTI(Siemens)

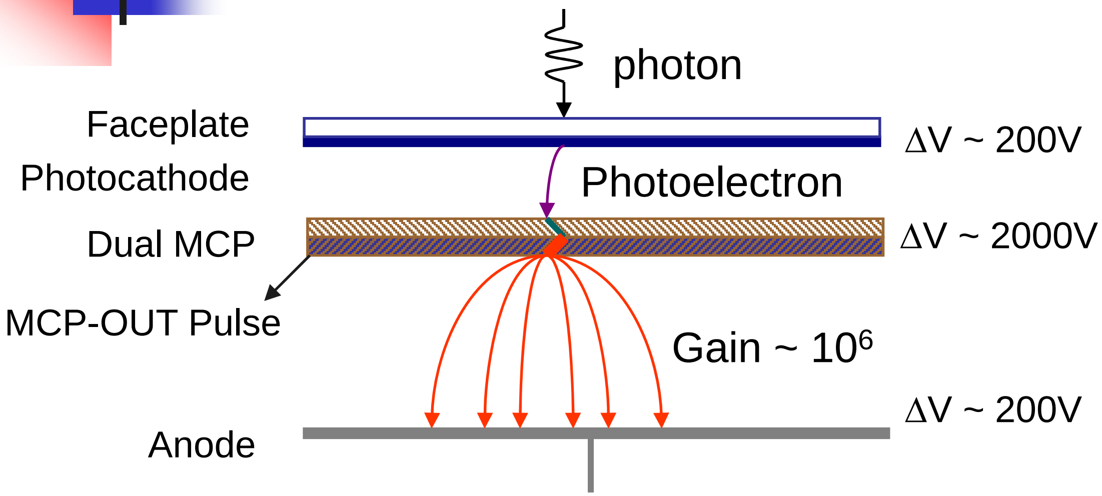
Positron Emission Tomography (PET)
detect two 511keV photons from e+ annihilation.

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



(from Paul Hink's slide at 2008 picosecond workshp)

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

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

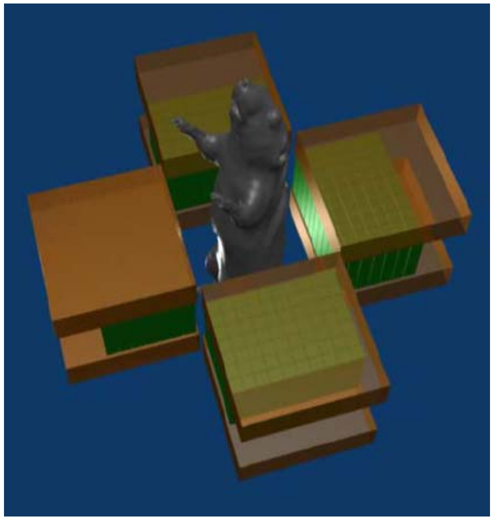
Large Area Picosecond Photo-Dectector (LAPPD) project

- 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.

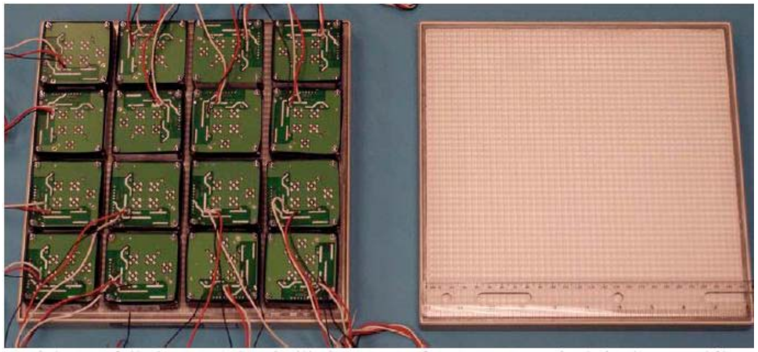
- Various PET design would be possible at reasonable cost.

Existing PETs using MCP-PMT



(from David Brasse's slide)
LYSO (1.5 x 1.5 x 25 mm^3)
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 12.5mm^3, 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.

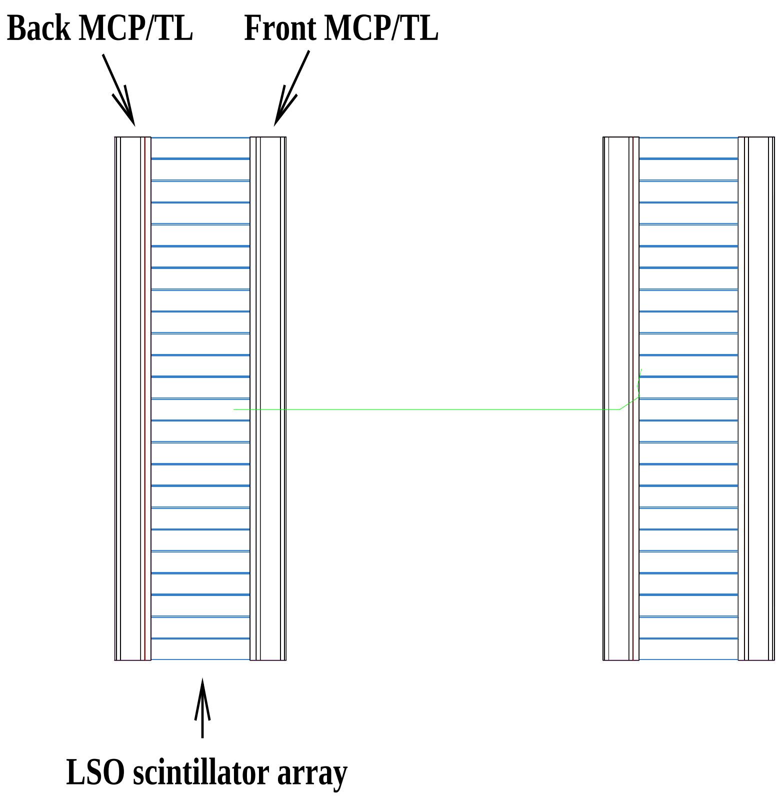
- Design Features
- Simulation Configuration and Setup

  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)

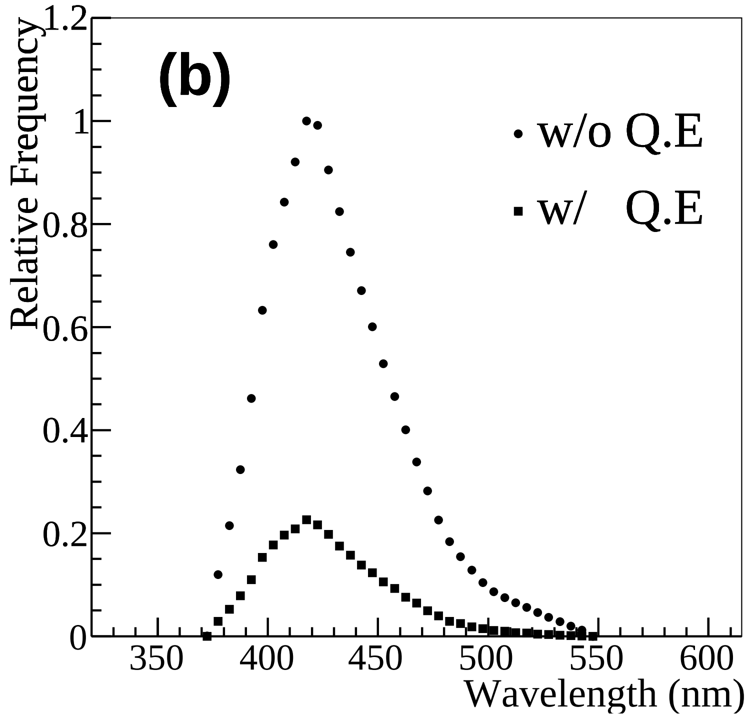


- Two detector modules facing each other.
  - 8 cm distance between them.
- One detector module consists of 24x24 array of LSO scintillator and 2 MCP/TL assemblies.
- LSO pixel dimension : $4x4x25mm^3$.
  - Crystal pitch : 4.25mm
- MCP assembly dimension : $102x102x9.15mm^3$. (4"x4" of area) It includes 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)



Optical photon spectrum from LSO

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

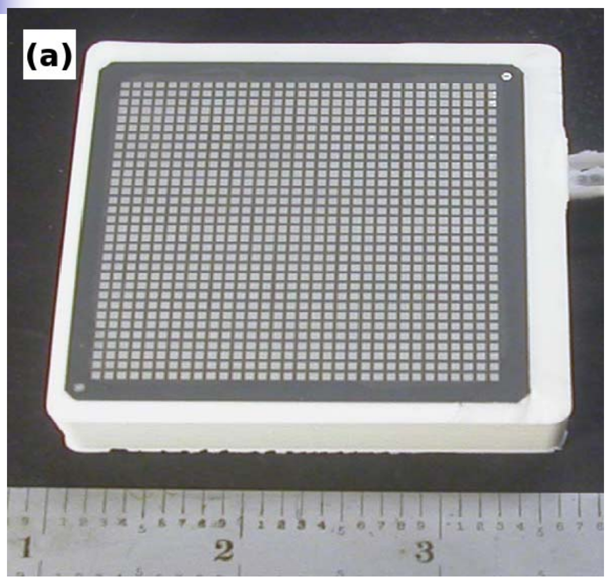
•Optical photons generated
reflection, refraction, absorption
•Detected at photo-cathode of MCP-PMT
•For each event, optical photon's
Energy (wavelength), Arrival time, Position
were recorded (ntuple)
•ROOT format

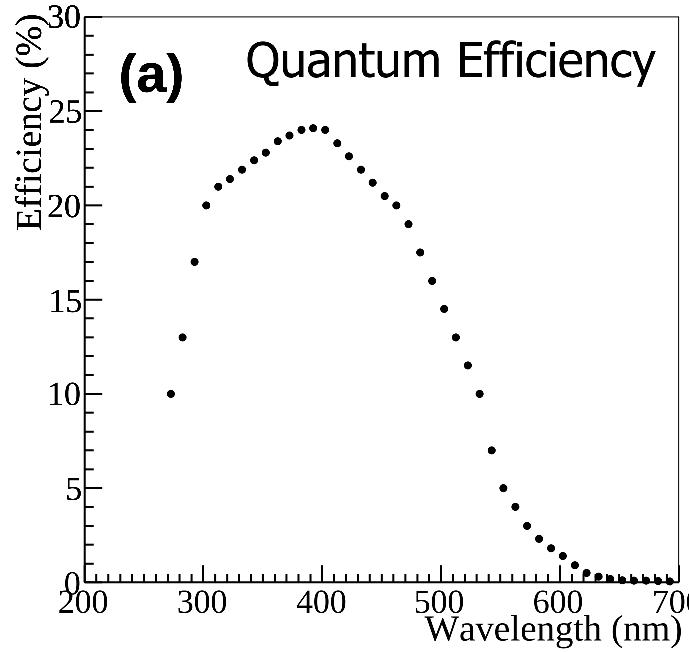
•Off-line analysis
•Applying Q.E of MCP
•……

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. Convolute 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.

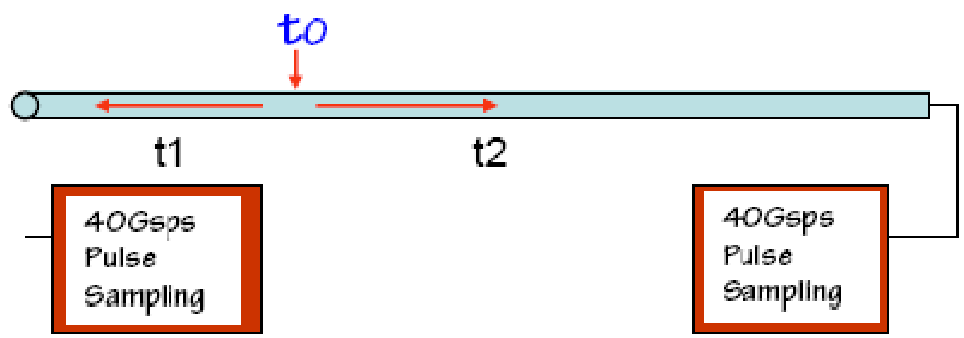
Photonis Planacon MCP-PMT (XP85022)





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

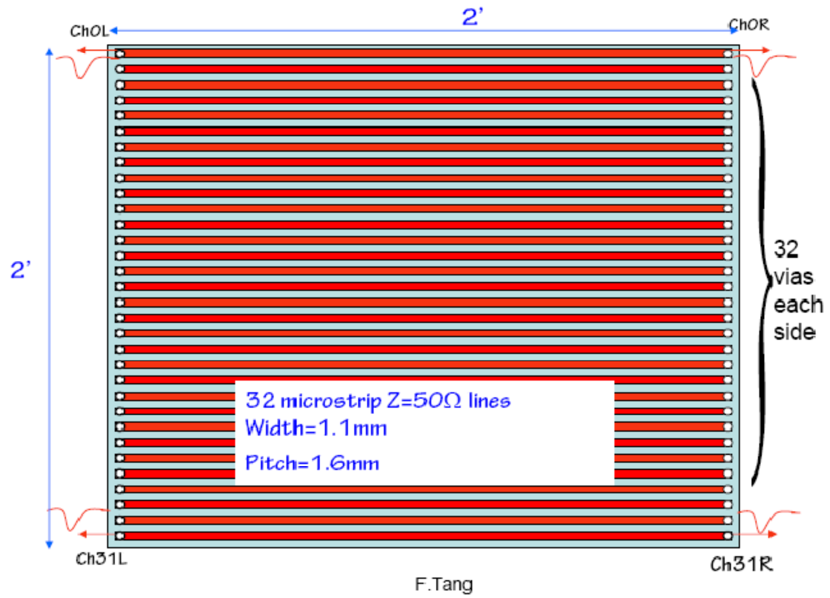


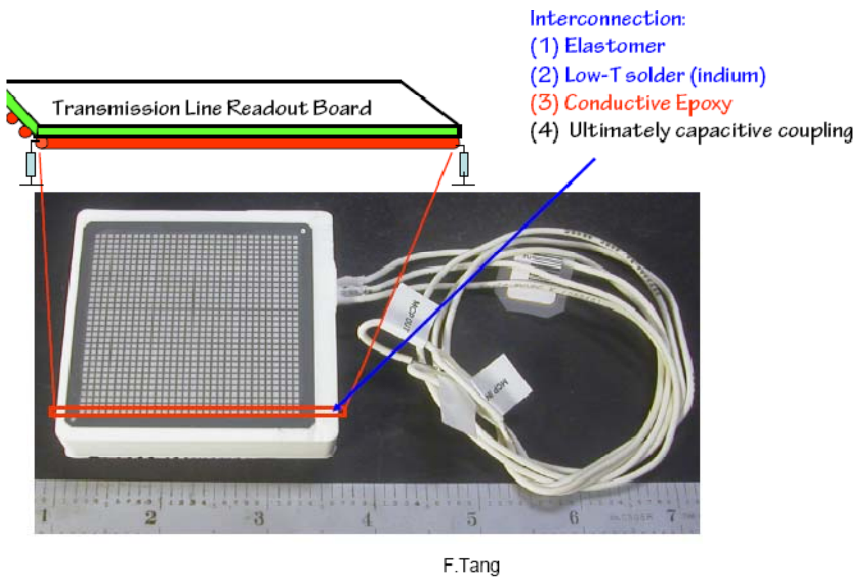
Timing: (Sampling over the peak)	$t_0 = \dfrac{t_1 + t_2}{2}$
Position:	$x_i = \dfrac{t_1 - t_2}{t_1 + t_2}$
Energy: (Full waveform sampling)	$E_i = q_1 + q_2$

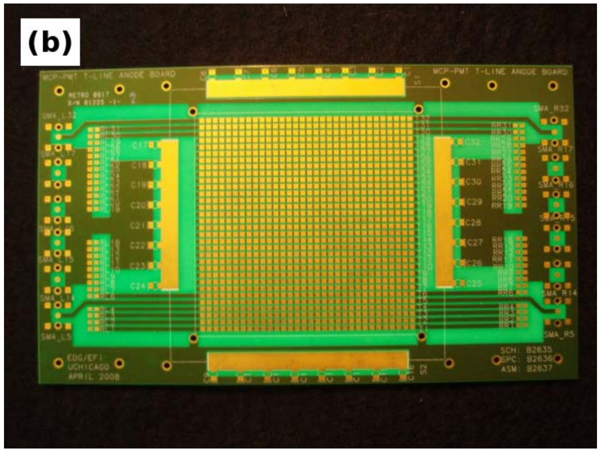
F.Tang 8

[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

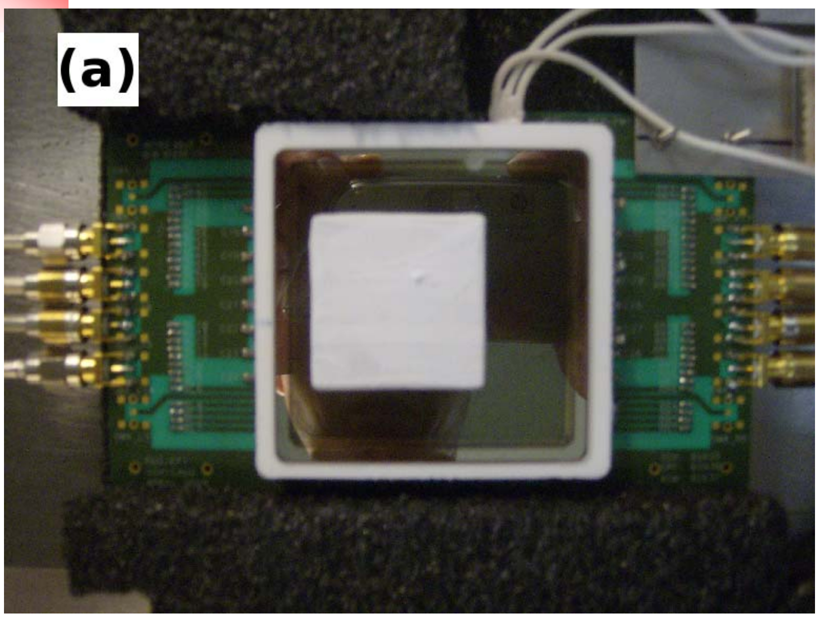
A. Single photoelectron responses (SER)

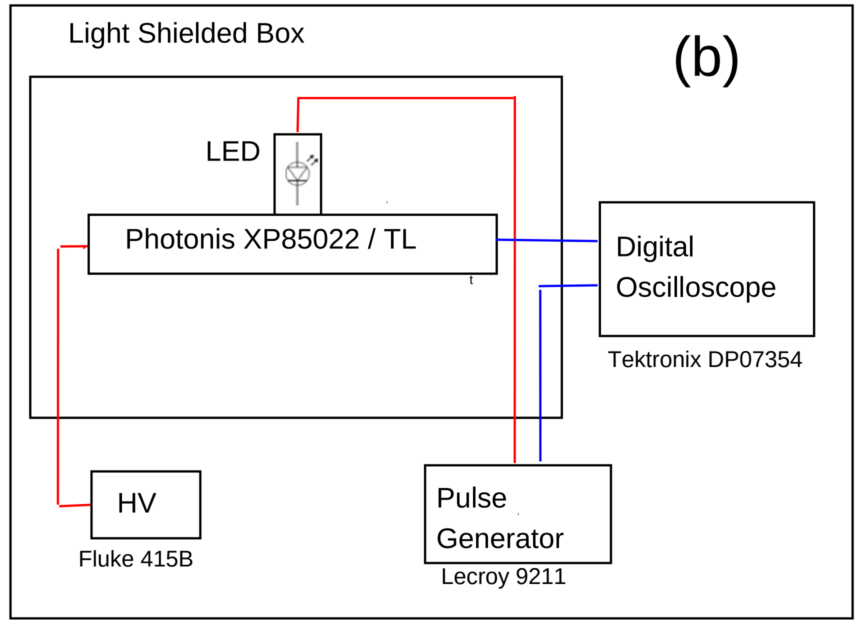
- Gain measurement
- Absolute calibration
- Pulse shape of single p.e. -> used in simulation to make waveform due to optical optons.

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.

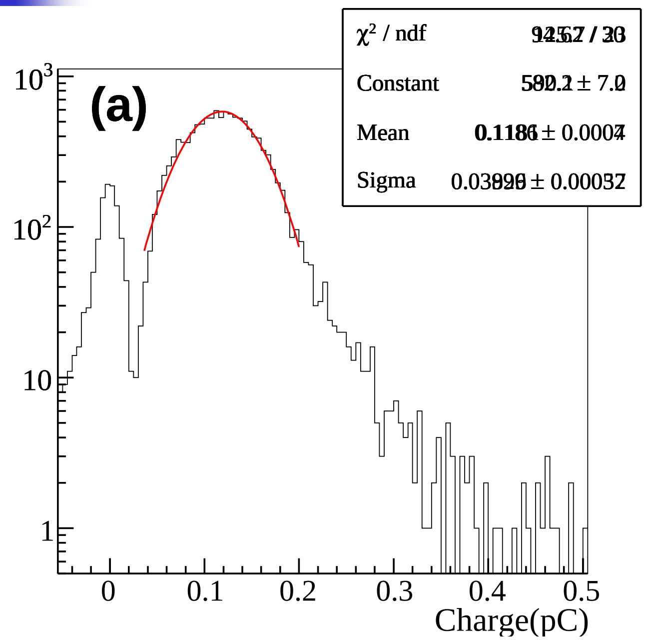
A. Single Photoelectron Response (SER)



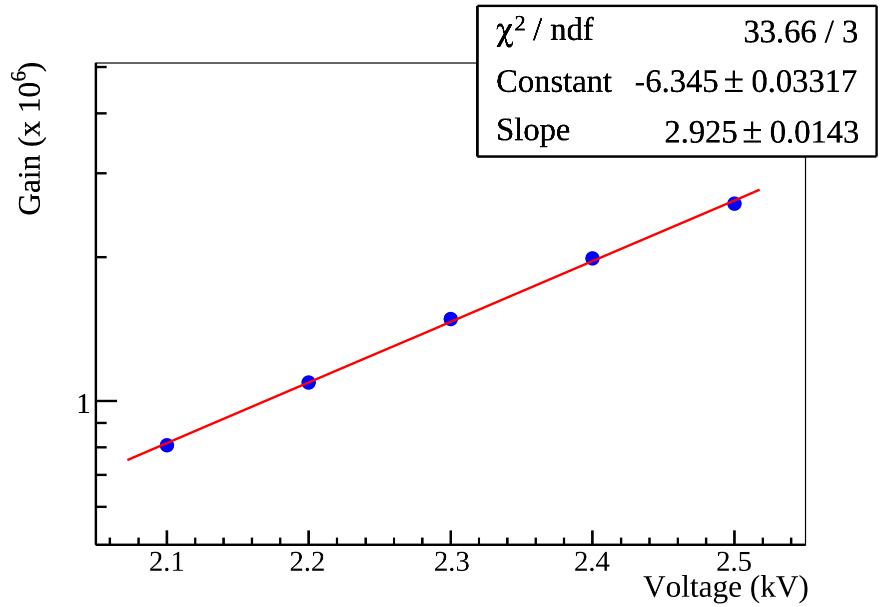


- The test set-up was built using a XP85022 MCP and TL board to measure the characteristics of the MCP.
- Block diagram for test set-up using LED.
- 4 TL channels were connected through SMA to the DPO7354 oscilloscope (Tektronix).
- 3GHz bandwidth, 20GS/S sampling.

Integrated charge of single p.e.



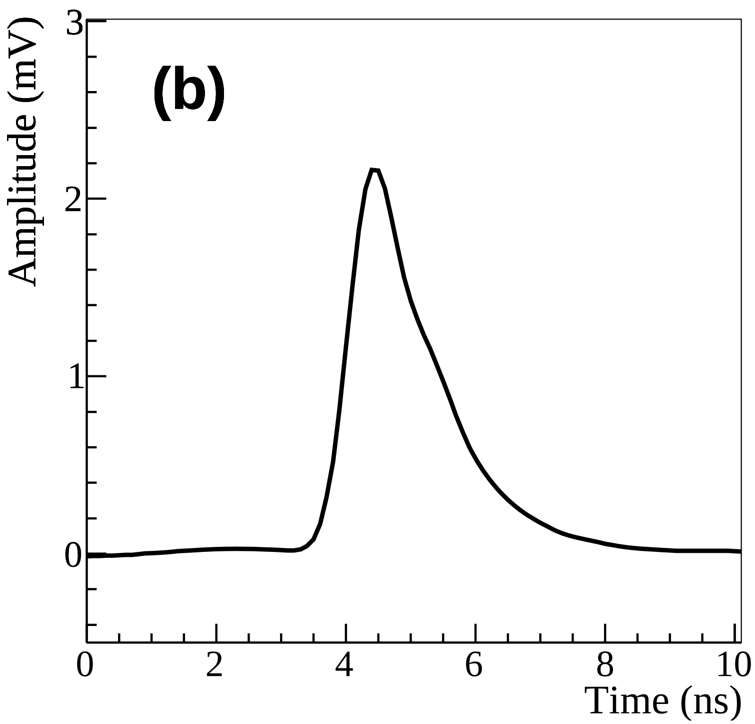
Integrated charge of single p.e



XP85022 MCP gain as a function of HV

- 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 : 1.5×10^6

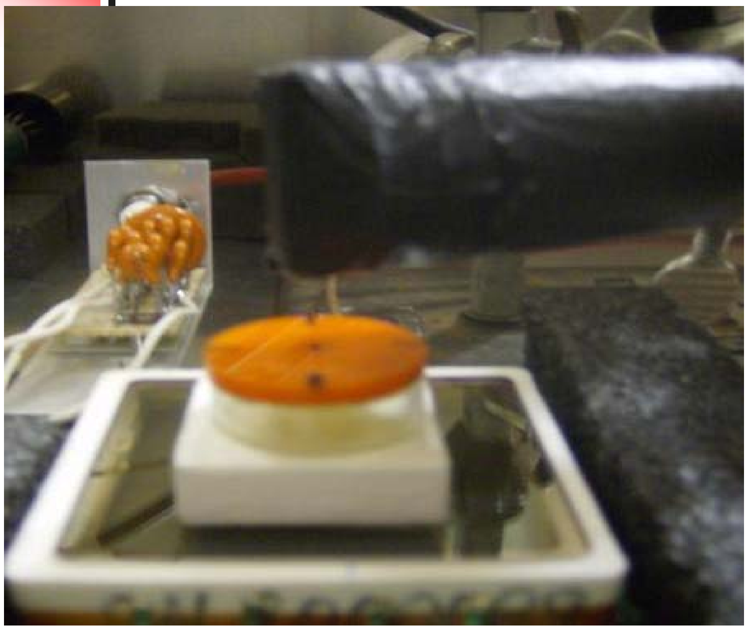
Pulse shape of single photoelectron

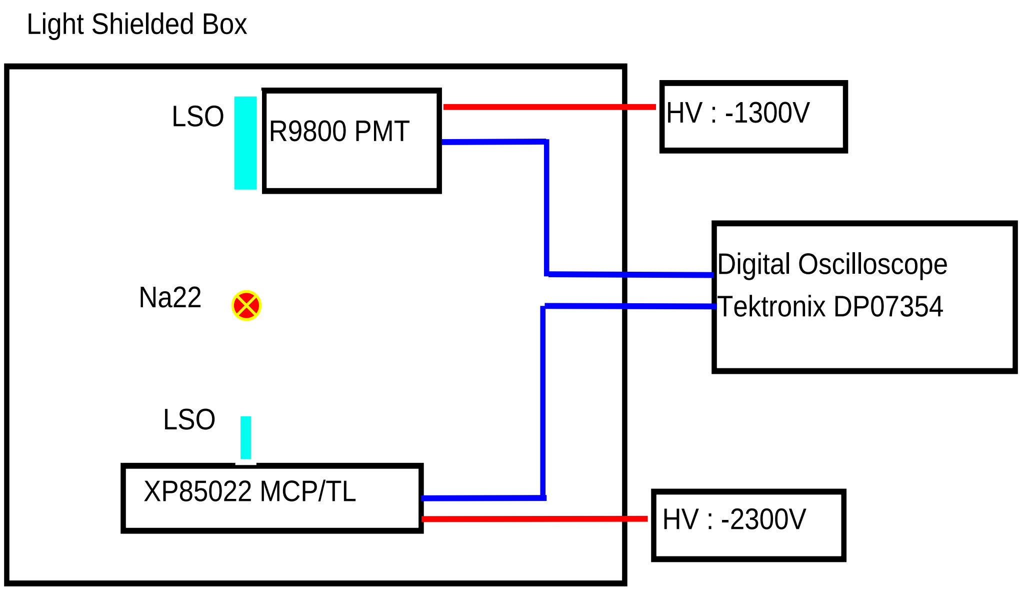


Averaged waveform of SER.
The maximum TL signal only.
The rise time of SER was measured ~560ps.

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

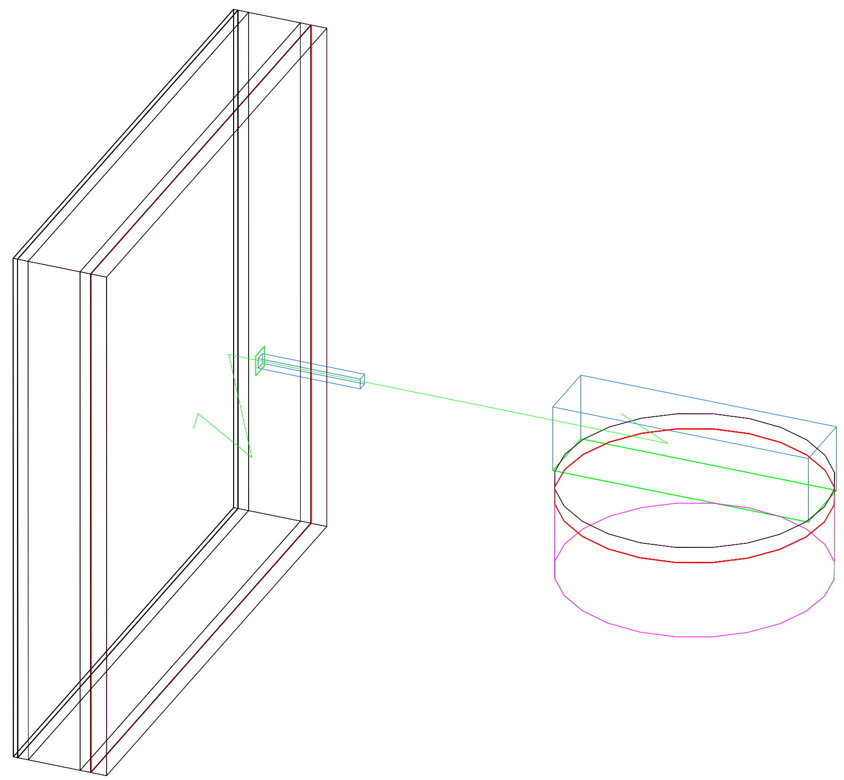
B. Responses to 511 KeV gamma





- 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

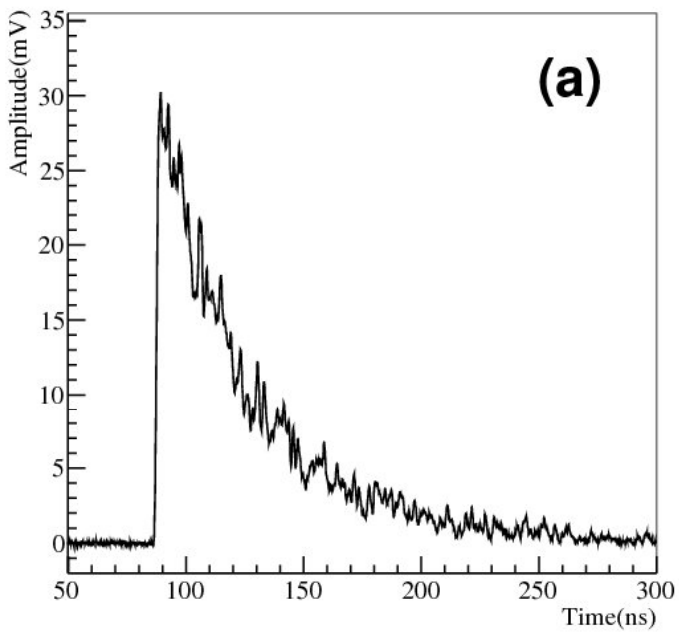
Intermediate simulation setup



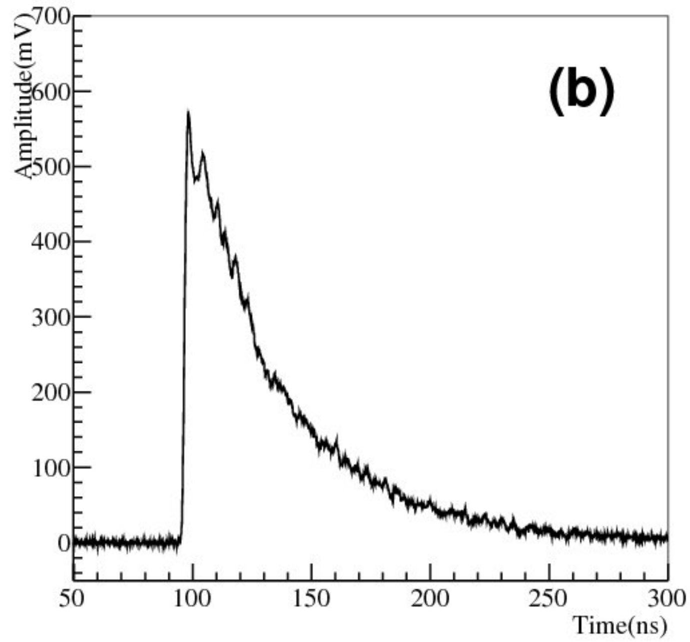
MCP-PMT(2"x2")
$1x1x10mm^3$ LSO crystal

R9800 PMT
$6.25x625x25mm^3$ LSO

Waveform from MCP/TL & R9800 PMT



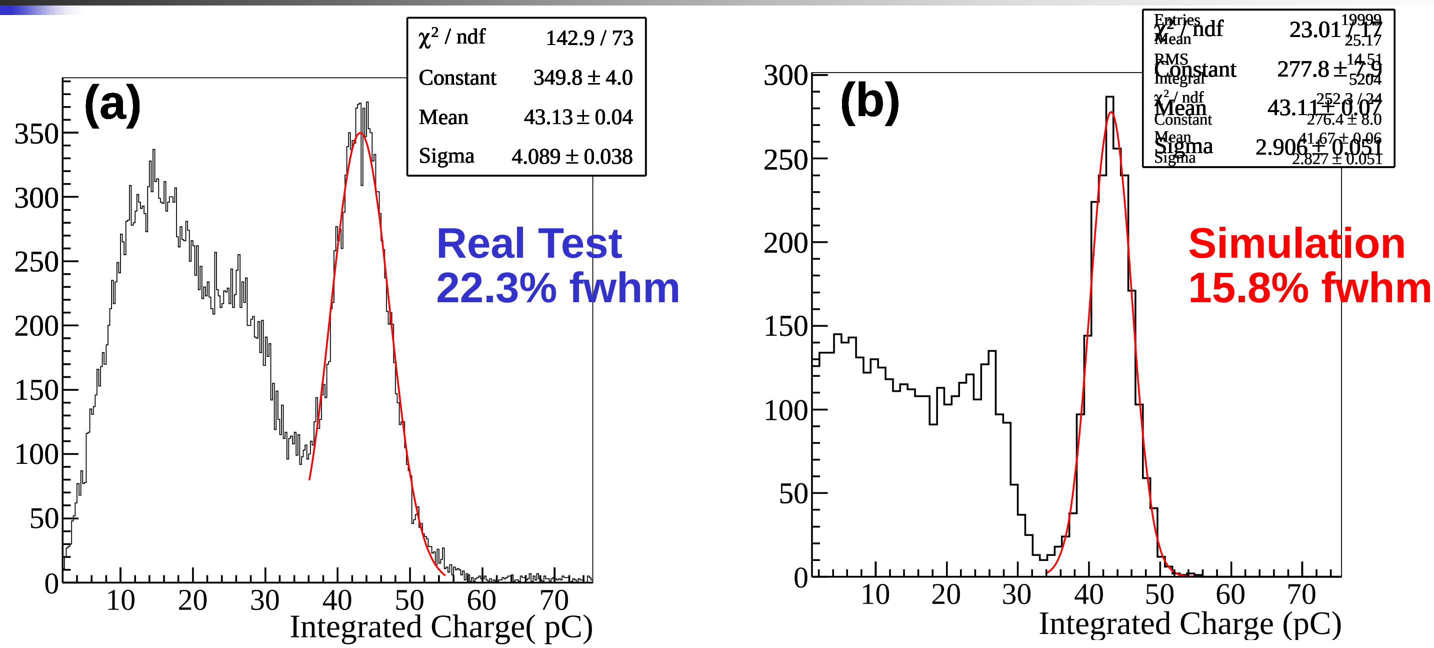
Waveform of MCP/TL+LSO.



Waveform of R9800 PMT+LSO

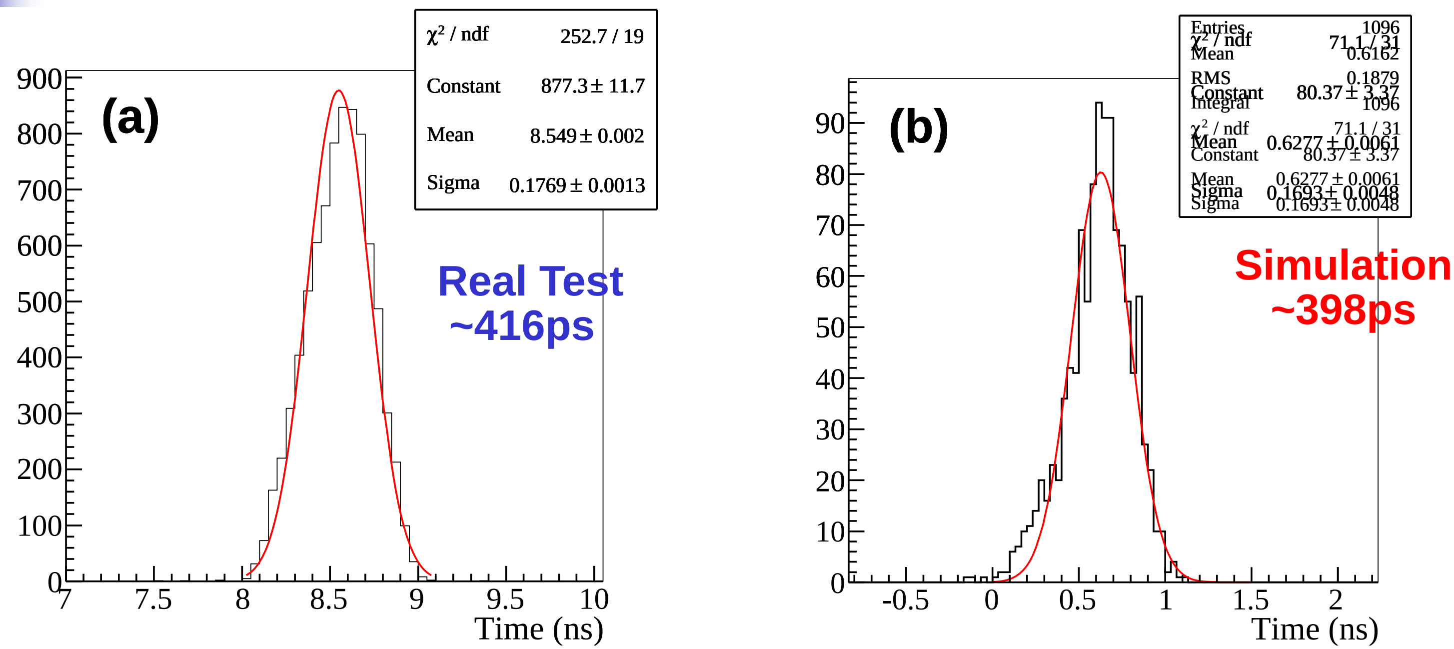
Waveforms were recorded at 20GS/S sampling.
Waverform of MCP/TL is for the middle TL among 3 TLs.

Energy spectrum of MCP/TL



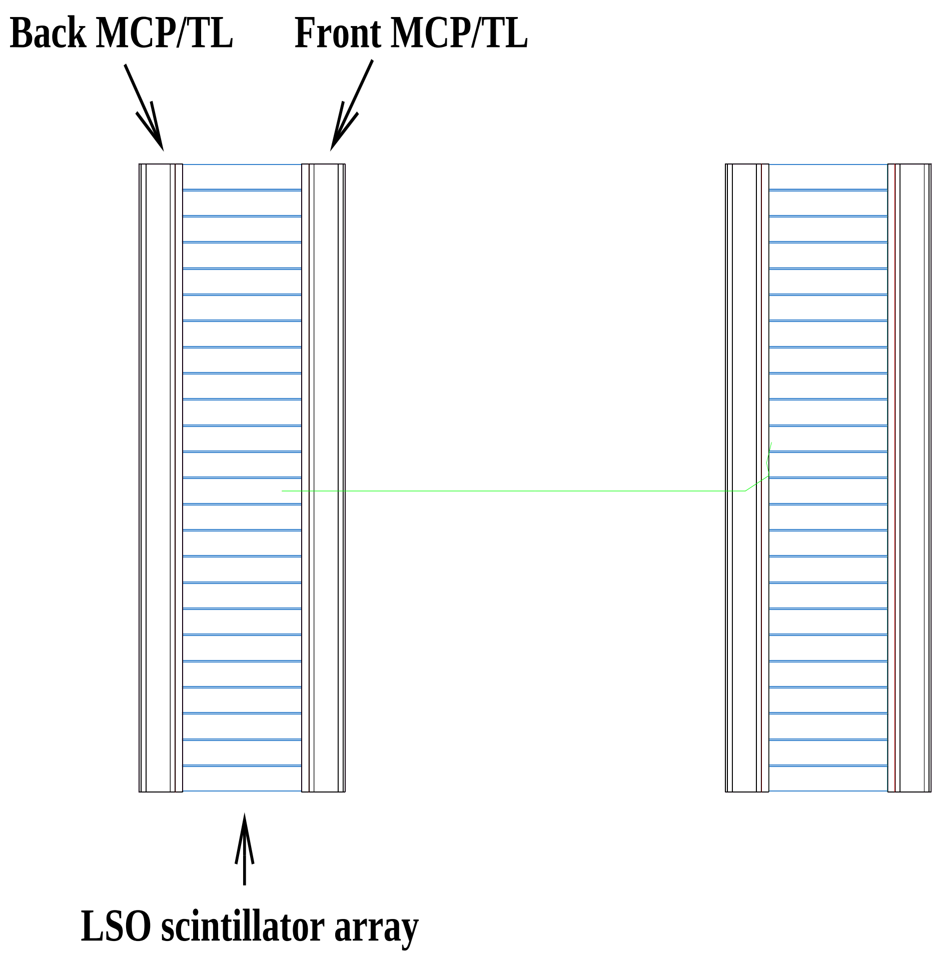
- Charge sum of 3 TL signal : only left side of TL.
- Compton + 511keV peak structure is clearly found.
- Discrepancy between the real test and simulation.
  - E resolution : 22.3% vs 15.8% (at 511keV peak)
  - Shape of compton continuum.
  - Due to simplified simulation setup(gamma direction).

Coincidence timing: real test vs. simulation



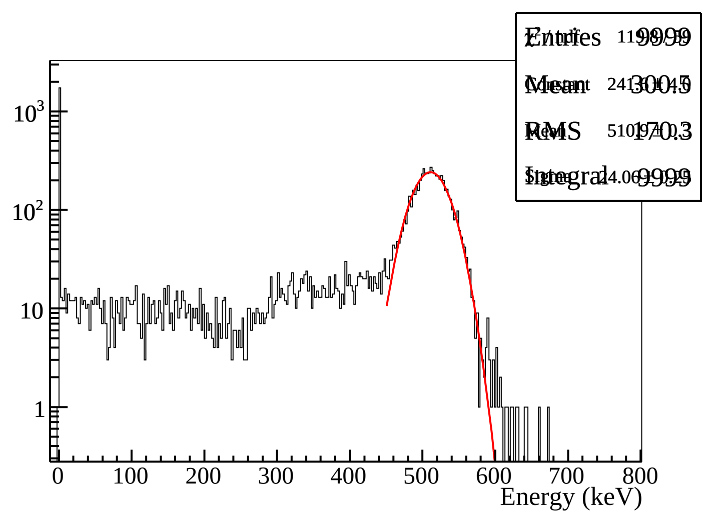
- Event selection requirement for the coincidence timing.
  R9800PMT :   400 < E < 600 keV
  MCP 3TL Sum :   35 < Int. Charge < 60pC
  Leading Edge threshold : 3mV (MCP/TL) 50mV (R9800 PMT)
- Coincidence timing resolution = ~416ps(FWHM)
  contribution from R9800PMT side = ~200ps (FWHM)

4. Results : Design Simulation

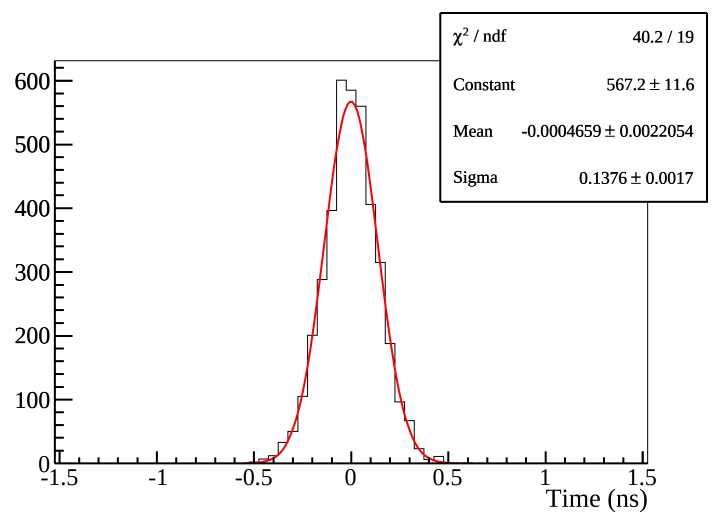


Coincidence Energy & Timing : Simulation

- **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)**
- **Energy window [450, 600] KeV required for coincidence event.**
- **The detection efficiency : ~40%(~63% for one module).**
- **Coincidence timing resolution : ~323 ps.**

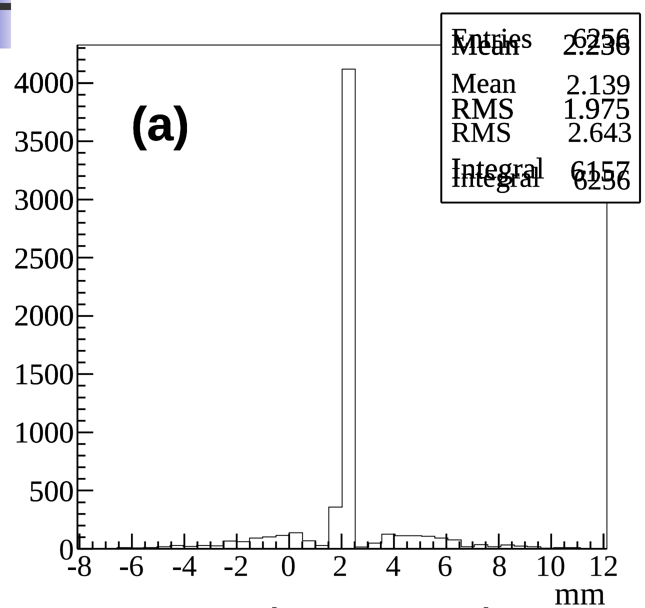


Energy spectrum of coincidence event

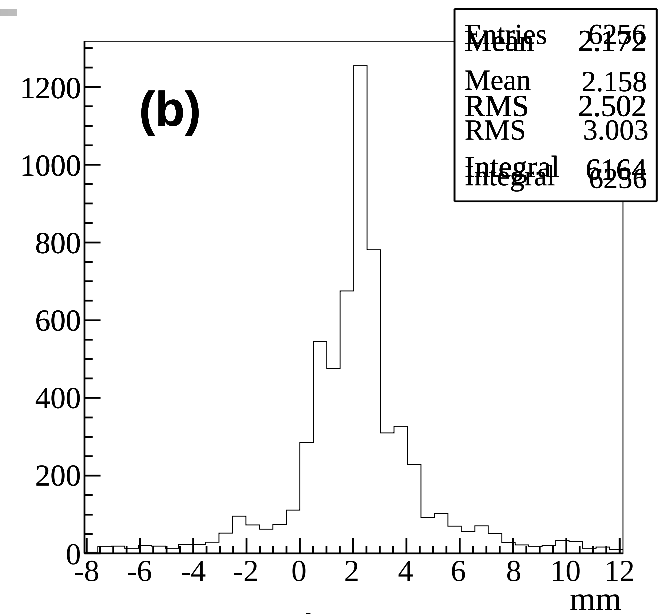


Coincidence timing distribution

Position determination



Reconstructed X using the centroid



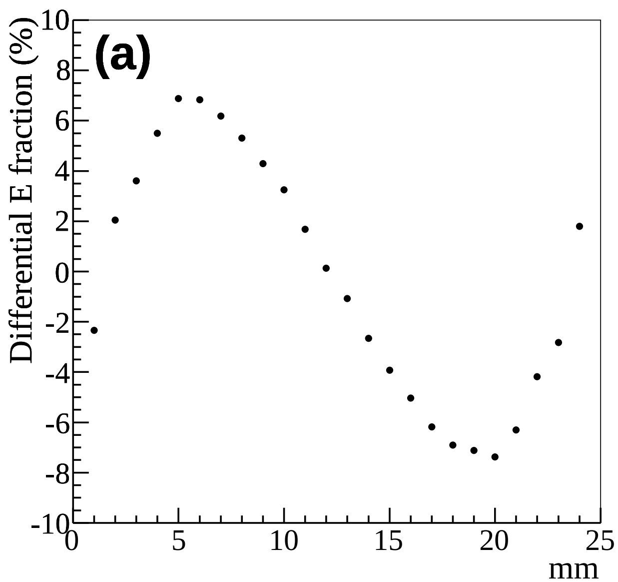
Recontructed Y using timing difference

511 KeV gamma injected on the center of a crystal (x=2.125, y=2.125)
Two ways of position determination.

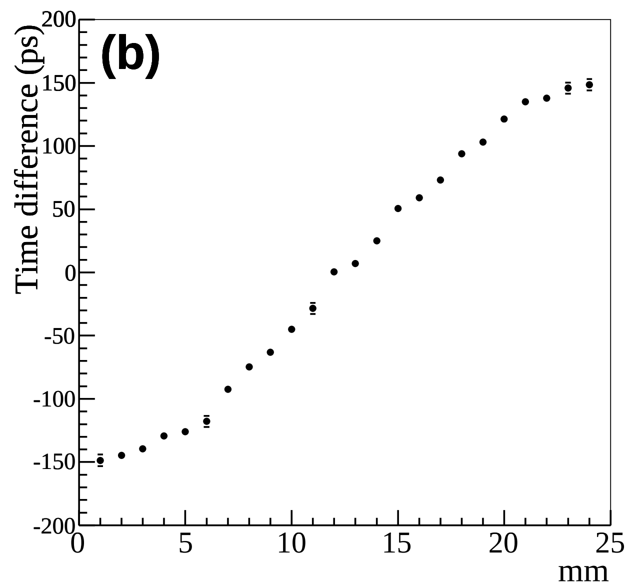
- Energy weighted using 5 TLs (Centroid) (left)
- Time difference of the maximum TL at both left/right ends. (right)
  -> gives the coordinate othogonal direction to the centroid method.
- Position resolution : ~2.5mm of FWHM in both method.

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.
  - $(E_{Front} - E_{Back})/(E_{Front} + E_{Back})$
- Clear correlations were found.



Energy asymmetry
as a function of depth



Time difference
as a function of depth

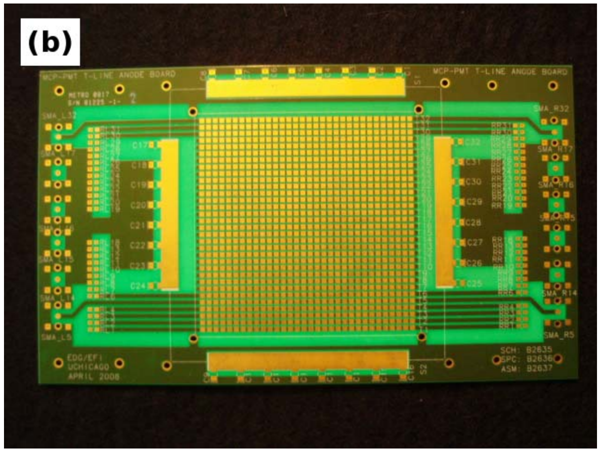
5. Summary & Plans

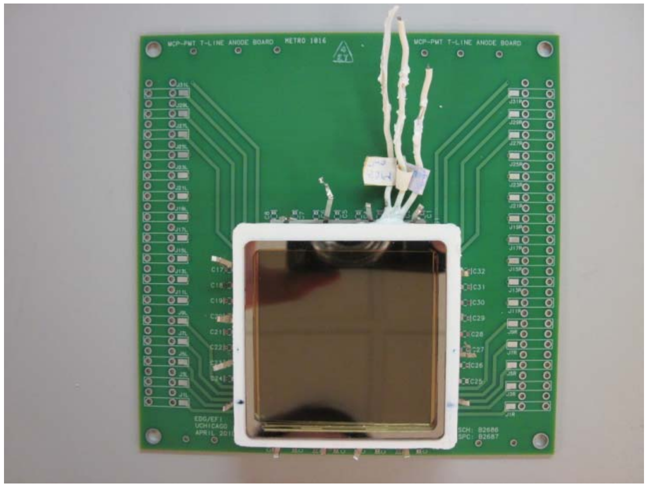
- A PET detector design using pixelated array of LSO scintillator and MCP PMT with Transmission Line readout was studied.
- Geant4 was used for optical photon simulation.
- Real test setup using XP85022 MCP and TL board was built to measure SER of MCP. The measurement from the test set-up was fed to 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.





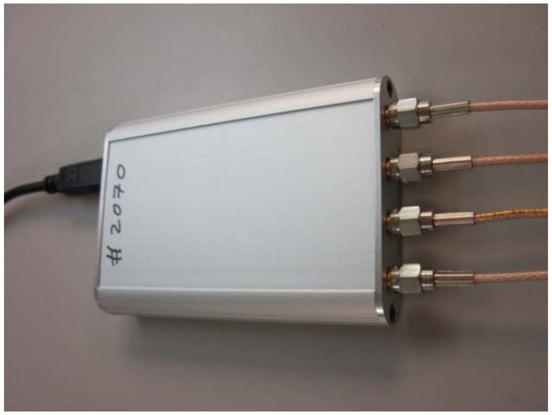
Summary & Plans - continued

2. Readout electronics.

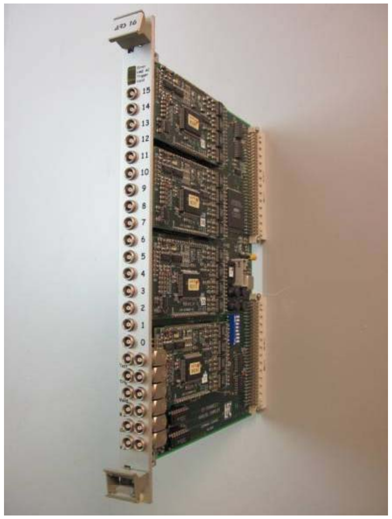
 4 channel digital oscilloscope -> 62 channel VME board using DRS4 sampling chips.

 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).



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



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

Acknowledgement

Collaborators

C-T.Chen, C-M.Kao, H.Kim (Radiology, U. of Chicago)

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