Development of TOF-PET using Compton scattering by plastic scintillators

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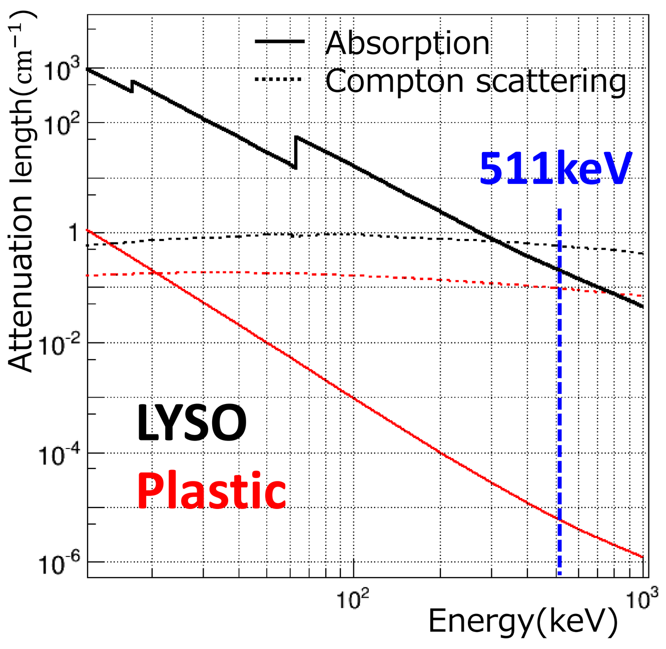
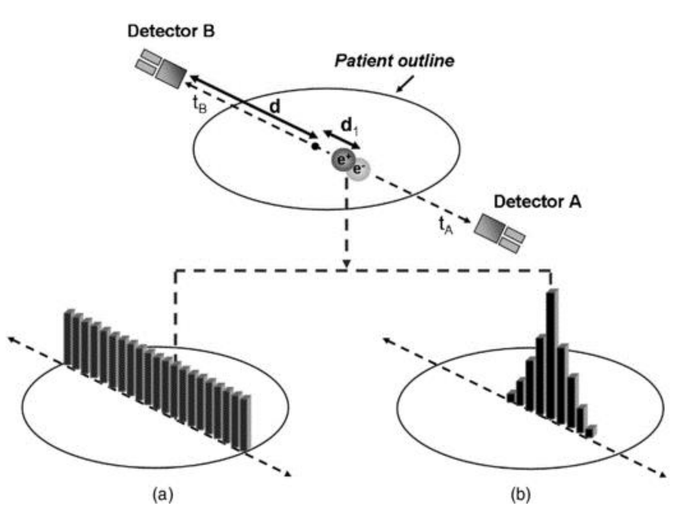
Abstract
Better time resolution could be achieved with faster scintillators due to less time jitter. We thus propose TOF-PET using Compton scattering with plastic scintillators (Compton-PET). We made a pair of timing measurement system for the coincidence events. First, we compared the time resolution of the plastic scintillator with that of LYSO(Ce) and GAGG(Ce) scintillators. The dimension of each scintillator was $3 \times 3 \times 3\ \mathrm{mm}^3$ coupled to $3 \times 3\ \mathrm{mm}^2$ MPPCs. Second we also evaluated the timing resolution of plastic scintillators with SiPM and its array. We also demonstrate the DOI capability with the plastic scintillators.

1. Introduction

Positron emission tomography (PET) is an effective method of cancer diagnostics. The Time-of-Flight (TOF) technique is used to improve the spatial resolution, where the initial position of back-to-back γ-rays is constrained by differences in arrival time. TOF-PET requires faster scintillators to avoid loss of time resolution due to the **time jitter**. We focused on a **plastic scintillator** faster than common scintillators for TOF-PET**.** The plastic scintillator has a much smaller cross section of photoelectric absorption because of its small density and effective atomic number. However the cross section of Compton scattering for plastic is comparable to from that of photoelectric absorption for LYSO(Ce). We propose new TOF-PET using Compton scattering by plastic scintillators, "**Compton-PET**".





Townsend (2008)

2. Compton-PET

Compton-PET consists of inner scattering layers(plastic scintillators) and outer absorbing layers(inorganic scintillators).

Scattering and Absorption Event

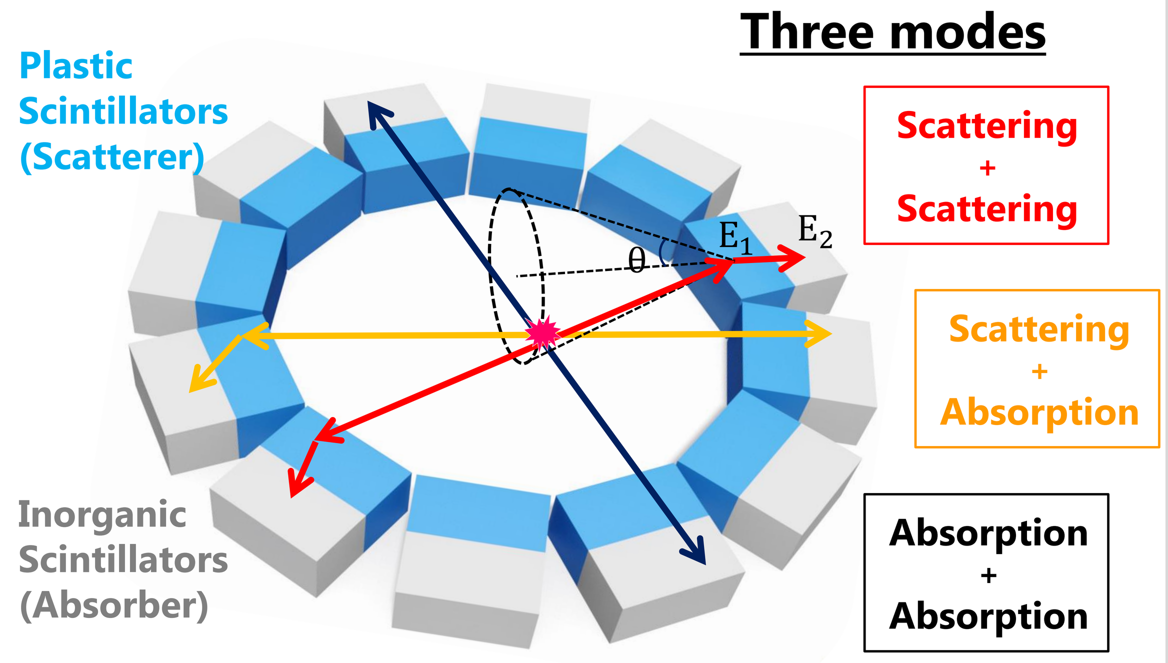
When we obtain the position and energy deposit for both scattering and absorption point, we can estimate the incident direction in a conical shape (**Compton-cone**).

Absorption Event without Scattering

Events without scattering in the plastic layer could be reconstructed in the same way as for a conventional PET scanner.

Compton-PET expects improvement of S/N ratio because of a high time resolution due to fast time constant of plastic scintillators and a restriction of the Compton-cone.

	Light Yield (ph/MeV)	Emission Peak (nm)	Decay time (ns)	Dencity (g/cm^3)
Plastic	10,000	430	2-3	1.03
LYSO(Ce)	30,000	420	40	7.10
LSO(Ce)	27,300	420	35-47	7.40
GAGG(Ce)	46,000	520	88,258	6.63



$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Detection efficiency of the Compton-PET

A brief Monte-Carlo simulation proves that the detection efficiency of the Compton-PET is relatively compatible to conventional PET in a ratio of 3:4.

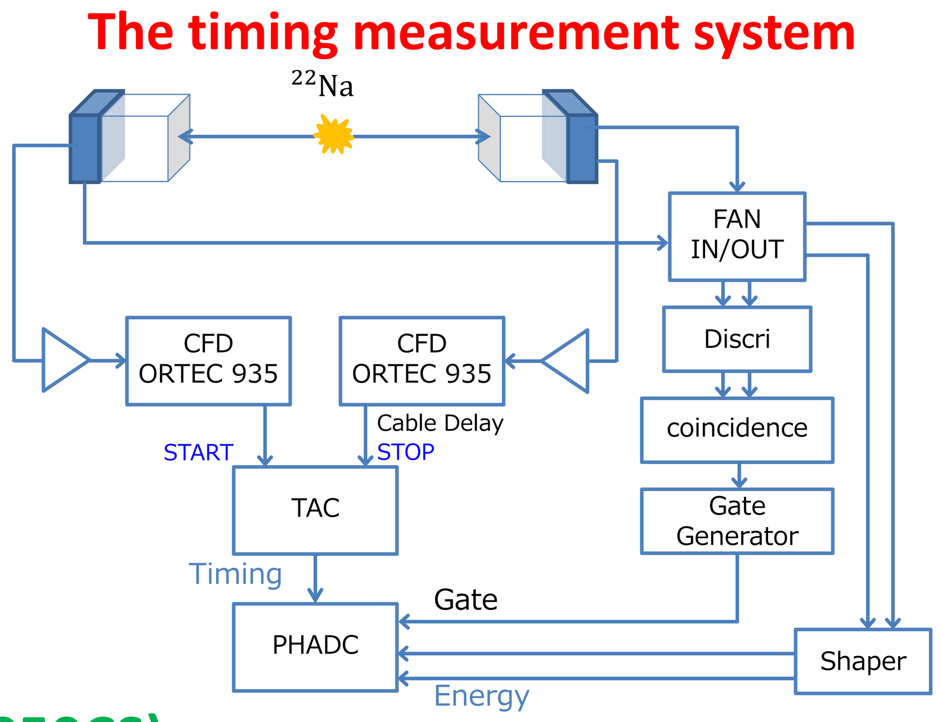
To estimate the capability of Compton-PET

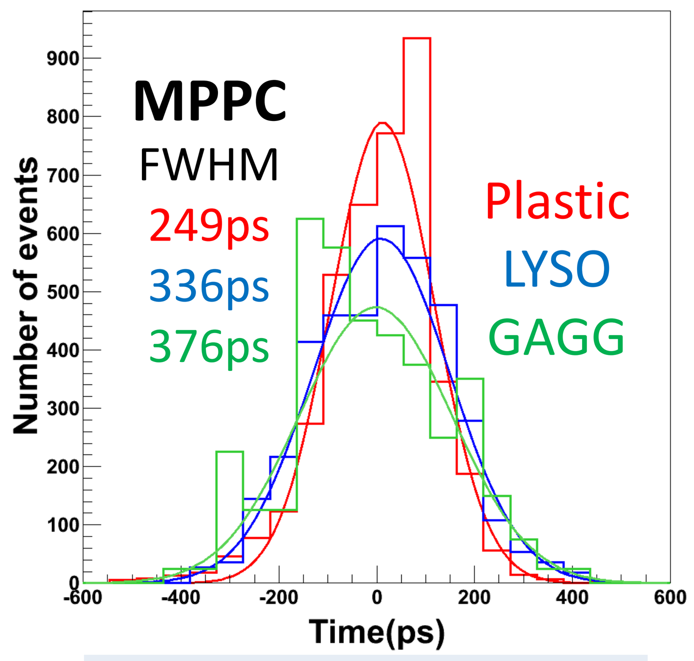
We have to demonstrate (1) the high time resolution of the plastic and (2) accuracy of the interact position and deposit energies for the plastic and the absorber. While 3D-measurement in inorganic scintillators has been actively studied, capability with the plastic scintillators are unknown. In this paper we present the TOF time resolution and the depth-of-interaction (DOI) resolution.

3-1. Time Resolution

We made one pair of timing measuring system as shown in the right figure. Since the energy deposit of the Compton scattering varies in a wide range, we used the constant fraction discriminator (CFD: Ortec 935) in order to reduce the time-walk effect. We applied a time-to-analog converter which consists of TDC-GPX (27 ps/bit). The timing resolution of this system of 41 ps (1s) was evaluated using a test pulse.

The timing measurement system

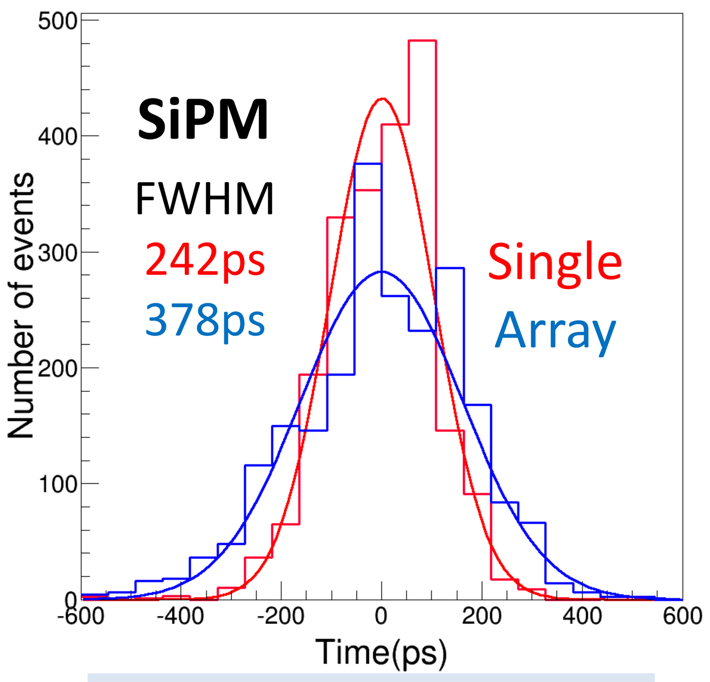




MPPC(S13360-3050CS)
Over voltage : 3.0V
Gain : 1.7×10^6

■ MPPC(S13360-3050CS)

We compared the time resolution of the plastic scintillator with that of LYSO(Ce) and GAGG(Ce). Each scintillator has a dimensions of $3 \times 3 \times 3\ \mathrm{mm}^3$ and was coupled to a $3 \times 3\ \mathrm{mm}^2$ MPPC. Events with an energy deposit of 511 keV ($\pm 1\sigma$) are selected for the LYSO and GAGG, while those with 100-340 keV for the plastic. Despite using Compton scattering events, the plastic scintillators achieved the best time resolution. This result indicates that the fast rise time of plastic scintillators are effective to improve the timing resolution.

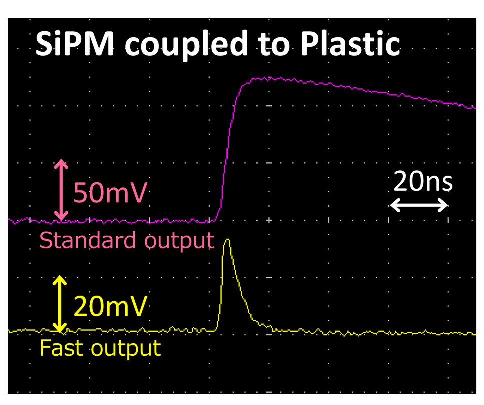


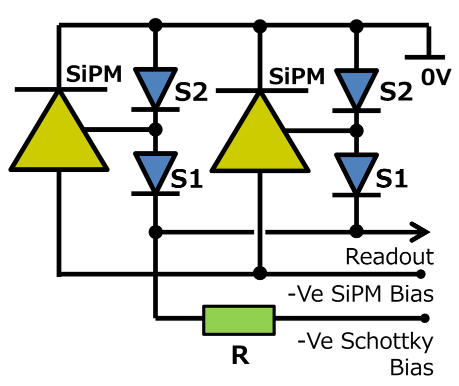
SiPM(MicroFC-SMTPA-30050)
Over voltage : 4.5V
Gain(Standard) : 4.7×10^6
Gain(fast) : 2.7×10^4

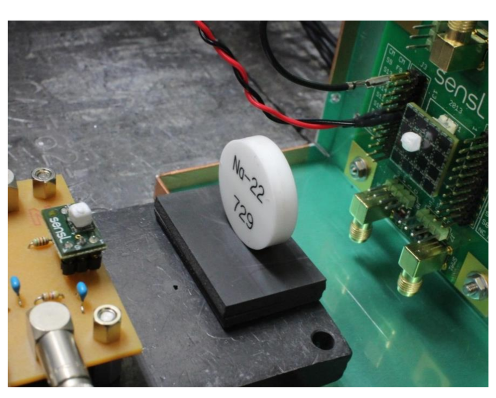
SiPM array(ArrayC-30035-16P)
Over voltage : 4.5V
Gain(Standard):2.9×10^6
Gain(fast) : 3.3×10^4

■ SiPM(MicroFC-SMTPA-30050)
■ SiPM Array(ArrayC-30035-16P)

We also measured the time resolution of the plastic using SiPM supplied by SensL, Technologies, Ltd. Their SiPM equips fast (but with a smaller gain) and standard outputs. We compared time resolution in the cases with a pair of single-single SiPMs and single-array. For the array's fast readout we applied the schottky diodes circuits[2] to multiplex all the channels to minimize the number of the channels for future extent. The result shown in the left turned out that the singe-single case was better, indicating the schottky circuit may limit the time resolution. Due to the lower gain of the fast output, significant improvements were not seen compared to the MPPC.

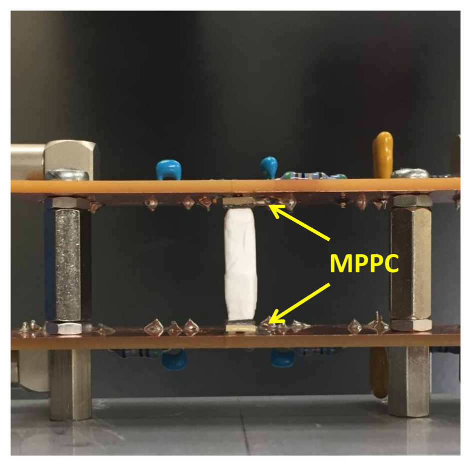




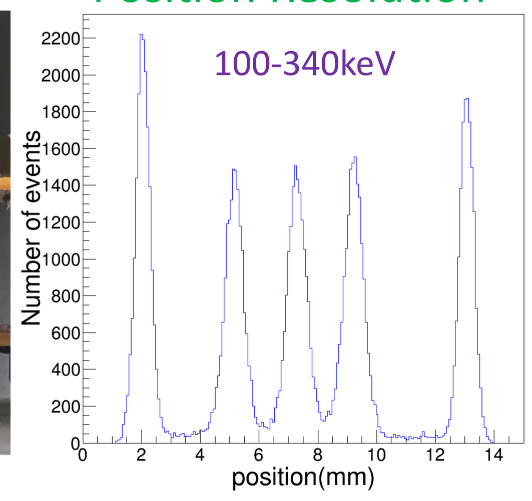


3-2. DOI Position Resolution

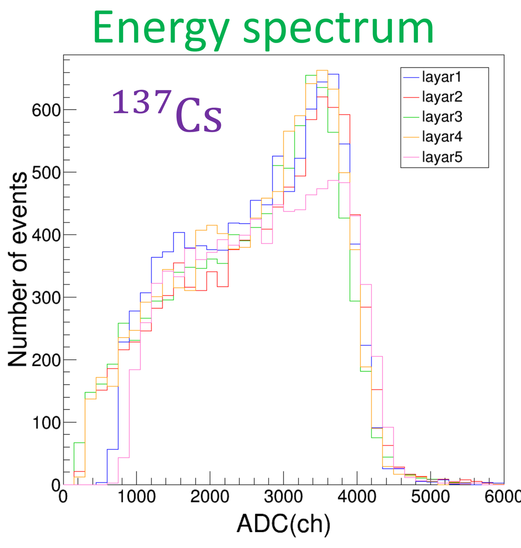
DOI technique can improve the image resolution at the edge of the FOV. In the case of Compton-PET, in addition, the finer position resolution will lead to precise Compton-cone determination and then better S/N ratio can be expected. We arranged five $3 \times 3 \times 3\ \mathrm{mm}^3$ plastic scintillators in a line separated by air layers and attached MPPCs (S13360-3050PE) at the both end of this array. We then irradiated a γ-rays from a ^{137}Cs source. The distribution of the interaction position is reconstructed by the pulse height ratio obtained from the MPPCs[3], where the averaged position uncertainty was **0.73 mm** (FWHM). Although the light yield of plastic scintillators is less but this result proves the plastic scintillators to resolve < 1mm.



Position Resolution



Energy spectrum



4. Summary

We propose "Compton-PET", which utilizes the plastic scintillators to improve the timing resolution of TOF-PET. Compton-PET is operated relatively compatible detection efficiency as much as conventional PET scanners. We performed some basic experiments in order to estimate the possibility of Compton-PET. We demonstrated the high timing resolution with plastic scintillators. This result suggest that the fast time constant of plastic scintillator is valid to improve the timing resolution. The result of DOI measurement proves the plastic scintillators to resolve < 1mm. We will proceed to demonstration of the Compton cone reconstruction.

Reference

[1]David W. Townsend, J Nucl Med., vol. 49, 938-955(2008)
[2]SensL, TECH NOTE, http://www.sensl.com/
[3]Kishimoto et al., IEEE-TNS,60,38 (2013)