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OPTIMIZATION OF DETECTORS FOR TIME-OF-FLIGHT PET*

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The results of the study of time resolution of scintillation detectors based on LSO crystal coupled to photomultipliers and silicon photomultipliers are reviewed. The aim of the paper is to understand an influence of different parameters of crystals and photodetectors on time resolution.

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1. Introduction

Additional information about Time-of-Flight (TOF) of annihilation quanta, collected by Positron Emission Tomography (PET) scanners can improve their performance and image quality [1]. Presently, a majority of detectors for PET systems are based on LSO/LYSO scintillation crystals (decay = 40 ns, density = 7.4 g/cm^3). In all commercially available scanners scintillation light is read by photomultipliers (PMTs) [2] but extensive studies are also carried out on the application of silicon photomultipliers (SiPMs) in the future PET devices [3, 4].

The achieved level of TOF PET image quality improvement depends very strongly on precise optimisation of the detectors used, particularly their timing capabilities [5] which depends mostly on:

- "speed" of a scintillator expressed by its decay time constant,
- the number of photoelectrons (Nphe) produced in a photodetector by scintillation light being a function of the light output of the crystal and the photodetector properties. In the case of PMTs, Nphe is a function of quantum efficiency (QE) of a photocathode and photoelectron collection efficiency at the first dynode. In the case of SiPMs, Nphe is a function of photon detection efficiency (PDE) being a product of QE, geometrical fill factor of pixels and sensitivity threshold,

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- the transit time spread (time jitter) of a photodetector,
- variation of a photodetector gain expressed by the excess noise factor (ENF).

Moreover, the time resolution is limited by the rise time of the photodetector output pulse and particularly in its initial part [2].

The aim of this paper is to summarise experimental studies of time resolution of LSO based scintillation detectors with light readout by PMTs and SiPMs presented earlier in [2] and [4] reflecting an influence of the listed above parameters.

2. Photomultiplier studies

Left panel in Fig. 1 presents a comparison of time spectra measured with Photonis XP20D0 and Hamamatsu R5320 photomultipliers and LSO crystal. Note an excellent and comparable time resolution recorded with both PMTs, close to 200 ps. The excellent time resolution measured with the R5320 is a result of its very low time jitter of 140 ps, while in the case of the XP20D0 is due to a high number of photoelectrons and a screening grid at the anode [5].

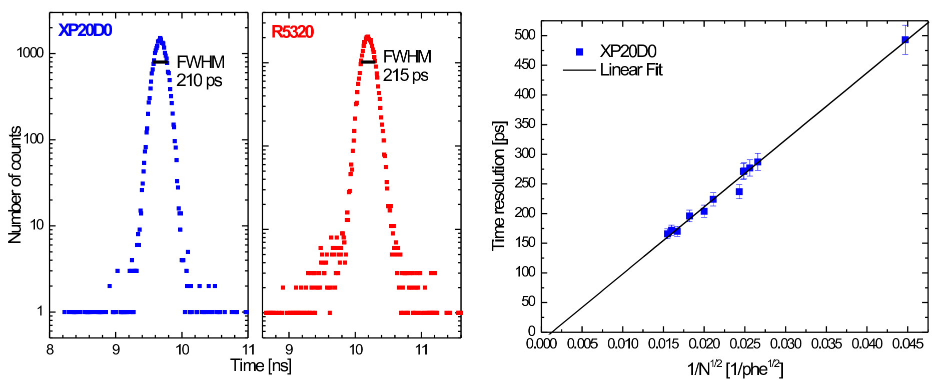

Fig. 1. Time spectra recorded with $10\times10\times5$ mm^3 LSO crystal coupled to Photonis XP20D0 and Hamamatsu R5320 PMTs, measured for the 511 keV full energy peak. The values corrected for the reference BaF_2 detector are equal to 166 ps and 173 ps, respectively [2]. In the right panel, the time resolution at FWHM measured with LSO *versus* number of photoelectrons collected in the PMT [2].

Right panel in Fig. 1 shows a dependence of time resolution measured with $10\times10\times5$ mm^3 and $4\times4\times20$ mm^3 LSO crystals coupled to the XP20D0 on the number of photoelectrons, (see [2] for details). The perfect linear dependence of timing on the reciprocal of the square root of the number of photoelectrons shows the importance of a high light output of scintillators and high quantum efficiency of a PMT photocathode in timing applications.

An influence of the time jitter on the measured time resolution can be shown using plot presented in the left panel of Fig. 2. Here, the time resolution, measured with a number of different PMTs, is normalised to the number of photoelectrons and the parameter, r, reflecting the gain dispersion of the electron multiplier (see [2] for details).

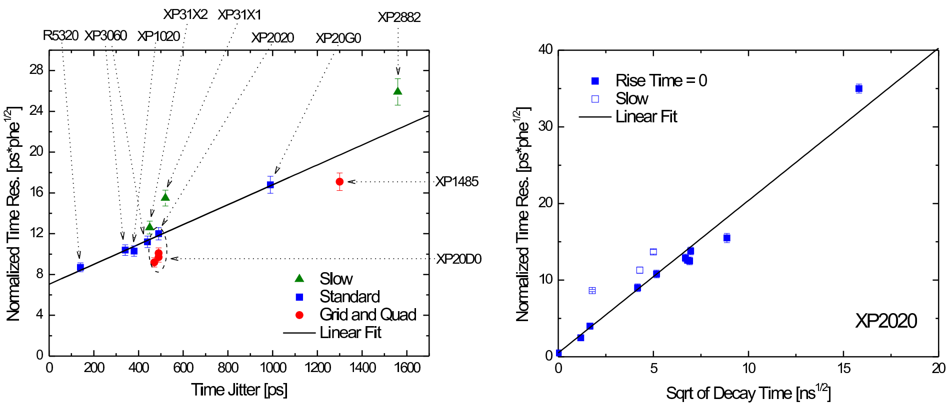

Fig. 2. Normalised time resolution at FWHM measured with LSO crystal *versus* time jitter of a different kind of PMTs (left panel). Normalised time resolution *versus* square root of the decay time of the light pulse measured with various scintillators (right panel). See [2] for details.

The square points represent measurements done with classic, fast PMTs. The plot displays the linear growth of the time resolution *versus* time jitter. The value, in ideal case of time jitter equal to 0, corresponds to a slow decay time of the LSO light pulse. The time resolution measured with LSO and other slow decaying scintillators depends stronger on the statistics of photoelectrons produced in decay process of the light pulse, while the time jitter of the PMT weaker influences the measured time resolution [5]. This effect was predicted by the Hyman theory of timing [6] and it was known in the past for NaI(Tl) crystal [7] which time resolution was often discussed in terms of Post and Schiff theory [8].

The triangular points show results obtained with the semi-fast PMTs characterised by a slower rise time of the anode pulse. In this case also a linear dependence could be assumed but shifted alongside of the classic PMTs line. Similar situation applies to the circle points at the bottom which represents PMTs with different way of anode construction, it means equipped with the screening grid at the anode. It was shown in [9] and [10] that the application of the screening grid in a PMT anode improves time resolution by a factor of 1.2 due to improved rise time of the initial part of the anode pulse.

The plot of the normalised time resolution *versus* square root of the decay time constants of different kind of scintillators is presented in the right panel of Fig. 2. All the measurements discussed in this part were made with the same type of XP2020 photomultipliers and a large set of various crystals. The time jitter represents an ideal scintillator with the decay time constant equal to 0.

In general, a linear dependence can be easily observed giving the best time resolution for the fastest crystals. However, a group of points (open squares) above a general trend can be observed. This group reflects timing tests done with NE213, $LaBr_3$ and $LaCl_3$ scintillators characterised by a finite rise time of the light pulses. Such time resolution deterioration is very well known for ternary plastic [11] or liquid scintillators and was reported recently for the $LaBr_3$ and $LaCl_3$ crystals [12].

Success of TOF PET demands a further development of PMTs that combine the performance of the XP20D0 and R5320 phototubes such as: high quantum efficiency, improved anode pulse shape quality (due to the screening grid at the anode) and the lowest possible time jitter.

3. Silicon photomultiplier studies

Application of SiPMs in fast timing with scintillation detectors or TOF PET is one of the alternative to PMTs.

The studies were carried out with SiPM from Hamamatsu called Multi Pixel Photon Counter (MPPC), type S10362-33-050C of an area of 3×3 mm^2 and micro-pixel size of 50 μm [4]. The time resolution measurements were performed with ^{22}Na gamma source and $3 \times 3 \times 3$ mm^3 LSO or LFS-3 (Lutetium Fine Silicate) [13] crystals.

An example of the output pulse recorded with the MPPC and LSO in comparison to the PMT anode pulse is presented in the left panel of Fig. 3. An influence of the large terminal capacitance of 320 pF in 3×3 mm^2 MPPC is reflected in the 15 ns rise time of the MPPC output signal. The right panel of Fig. 3 presents an example of the timing spectrum recorded with the optimised experimental setup. The time resolution of the single MPPC+LFS-3 detector, calculated on the basis of the results corresponding to the plot in Fig. 3, is equal to 199 ± 13 ps. This value is slightly worse than the best results, below 170 ps, obtained with fast photomultipliers like Photonis XP20D0 and LFS-3 or LSO crystals [2, 5, 13].

In order to better understand the observed time resolution a number of photoelectrons produced by LFS-3 crystal in the MPPC and its time jitter were measured.

The number of photoelectrons was measured using two methods [14]. In the first method the peak position of gamma rays detected in scintillator was compared to that of the single photoelectron. In the second method

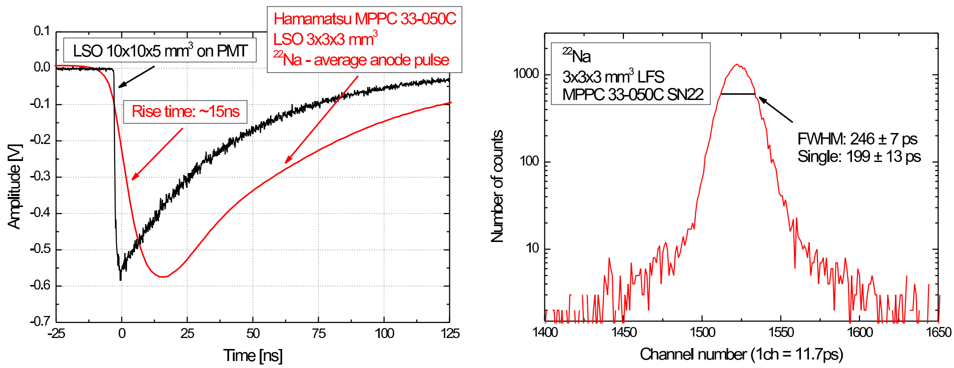

Fig. 3. Average light pulse shapes of the MPPC and PMT recorded with $3 \times 3 \times 3$ mm^3 LSO crystal (left panel). Example of timing spectrum recorded with $3 \times 3 \times 3$ mm^3 LFS-3 crystal coupled to MPPC (right panel).

the photoelectron number was determined from the pulse height resolution of the light pulser peak. The ratio of values obtained using both methods allowed estimation of the excess noise factor (see [4] for details).

The time jitter of the tested MPPC was measured using PicoQuant Diode Laser LDH-P-C-405 with 49 ps pulse width (FWHM) and wavelength of 403 nm. The laser intensity was set in the way that assured detection of only single photons. The left panel of Fig. 4 presents a dependency of a time jitter at FWHM on a bias voltage applied to MPPC. The measured FWHM of the time jitter spectra was corrected for the dark noise contribution.

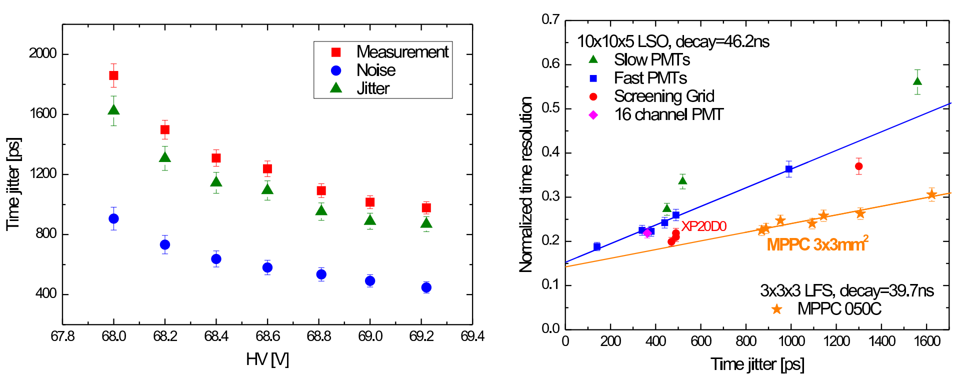

Fig. 4. The MPPC time jitter and noise dependence on applied bias voltage (left panel). Normalized time resolution *versus* time jitter for various photomultipliers and MPPC (right panel). Measurements were performed for the $10 \times 10 \times 5$ mm^3 LSO crystal (PMTs) and $3 \times 3 \times 3$ mm^3 LFS-3 crystal (MPPC).

The measured time resolution, number of photoelectrons, excess noise factor and time jitter allowed comparison of the timing properties of the detectors based on MPPC and PMTs. The plot of normalized time resolution *versus* time jitter for both MPPC and PMTs is shown in right panel of Fig. 4. Since measurements with PMTs were done with the LSO crystal with the decay time of 46.6 ns, while the MPPC was tested with faster LFS crystal (39.6 ns) the time resolution was further normalised also to the decay time of scintillators.

The calculated normalised time resolution, presented in Fig. 4, shows similar timing capabilities of the studied MPPC in comparison with fast photomultipliers. In the case of the fast PMTs the time jitter is always lower than 500 ps, however high potential of silicon photomultipliers in timing applications is clearly visible even despite its poor time jitter. Large difference in rise time of the slow MPPC pulse comparing to the fast photomultipliers together with a high dark counts rate has significant influence on MPPC timing performance and leads to its further deterioration. High quantum efficiency of SiPMs, which leads to very high photoelectron numbers, is its biggest advantage. The photoelectron statistics compensates drawbacks of the MPPC like high time jitter, high excess noise factor and poor rise time of the output pulse.

No doubt that silicon photomultipliers can find a wide application to TOF PET detectors, particularly in PET/MRI dual modality scanners.

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