Statistical Analysis of Time Resolution of the J-PET Scanner

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***Abstract*—The commercial Positron Emission Tomography (PET) scanners use inorganic crystal scintillators for the detection of gamma photons. The Jagiellonian-PET (J-PET) detector exhibits high time resolution due to use of fast plastic scintillators and dedicated electronics circuits. Since the time resolution of PET scanner is influenced by numerous factors, e.g. a type of photomultipliers attached to the scintillators, the optimal selection of components of the J-PET system requires detailed understanding of the method for calculation the time resolution. In this paper we show the idea of this method, based on statistical analysis of the observed signals on the photomultiplier's output. The method is tested using signals registered by means of the single detection module of the J-PET scanner built out from 30 cm long plastic scintillator strips. We investigate two main factors affecting the photon registration probability, photomultipliers quantum efficiency and photomultipliers transit time spread. We demonstrate that the quantum efficiency of photomultipliers represents the most important factor influencing overall performance of the J-PET scanner.**

I. Introduction

THE state-of-the-art PET instruments use inorganic scintillator crystals as radiation detectors [1], [2], [3]. These are characterized by relatively long rise- and decay times of the order of tens of nanoseconds. In order to improve the Time of Flight (TOF) resolution and to increase geometrical acceptance of the PET device, the Jagiellonian-PET (J-PET) collaboration investigates the possibility of construction of the PET scanner from plastic scintillators. The J-PET detector is built out from scintillator strips forming a cylinder, in which signals from each strip are read-out by a pair of photomultipliers placed at opposite ends. The detector arrangement and implemented methods of signal processing, simulations, data analysis and reconstructions are described in detail in Refs. [4], [5], [6], [8], [7], [9], [10], [11], [12], [13].

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Superior time resolution for registration of low-energy gamma photons is of crucial importance in all nuclear medicine techniques, including PET. Currently, the time resolution of J-PET scanner of about 80 ps (σ) has been achieved for the registration of gamma photons in the 30 cm long plastic scintillator read-out at both ends by vacuum tube photomultipliers [6], [7], [14]. This value is by about a factor of two better than the time resolution achievable in commercial TOF-PET scanners. Further improvement of the time resolution of the J-PET detector requires a detailed analysis of many aspects of signal processing, e.g. the influence of the quantum efficiency of photomultipliers. The exact mechanism of error propagation through the detection system, from the moment of photon emission in scintillator material until the acquisition of signals at the photomultipliers, is difficult to describe. In fact, an experimental studies allow to investigate the effect of given parameter of a system on the overall time resolution of device. However, the experimental approach is very time and money consuming due to the need of installing of various types of system elements. Therefore, the development of a method capable to estimate the time resolution of J-PET detector, based on numerical and/or analytical studies of system parameters is of crucial relevance.

II. Materials and Methods

We estimate the time resolution of the PET system using statistical modeling of signals. The time of photon registration by the photomultiplier may be considered as a random variable, equal to the sum of three contributing values: the time of photon emission in scintillator material, its propagation time along the strip and the photomultiplier transit time. The description of probability density function of the time of the photon emission, followed by the interaction of the secondary

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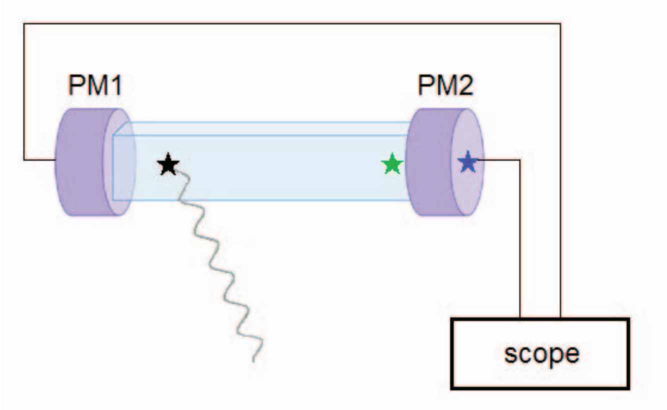

Fig. 1. Schematic view of the experimental setup with a single scintillator strip. Three modeled processes during the photon registration at PM2 are indicated with coloured stars: the moment of light photons emission (black star), the moment of light photons conversion at the photomultiplier frontier's (green star), and the moment of photoelectrons generations at the photomultiplier output (blue star).

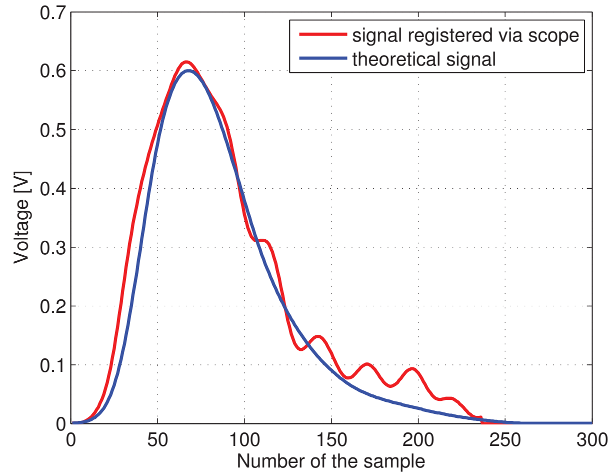

Fig. 3. Signals observed on the photomultiplier output; theoretically predicted signal is marked with the blue curve, and an example of signal registered via oscilloscope is marked with the red curve.

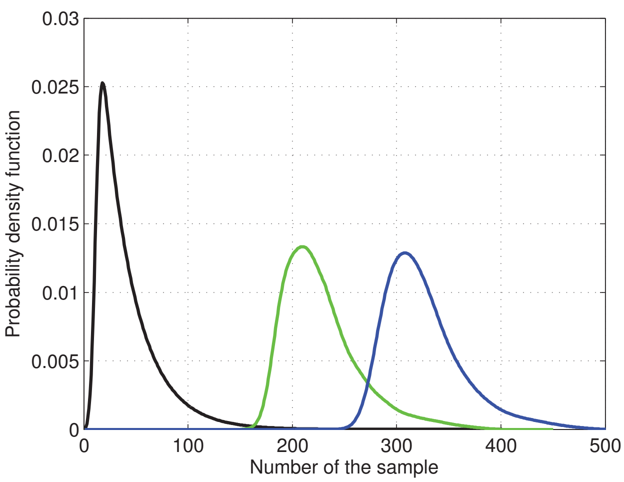

Fig. 2. Probability density functions of the registration time at three subsequent steps of the modeling. Three colours of the curves correspond to three positions indicated in Fig. 1 with stars. The resulting distribution of the registration time is marked with blue curve.

photon with the scintillator's material, is given in Ref. [15]. Statistical description of the photon propagation in scintillator strips, as well as the distribution of transit time spread of the photosensors, have been proposed in Ref. [16]. Assuming that those times are independent random variables, the probability density function (pdf) of registration time is given as the convolution of three corresponding pdfs. In subsequent figures the statistical process of signal generation is illustrated. Fig. 1 presents a schematic view of the test setup with a single scintillator strip. With three different coloured stars, three modeled phenomena have been indicated; the moment of light photons emission in the scintillator (black star), the moment of light photons conversion at the photomultiplier's frontier (green star), and finally the moment of photoelectrons generation at the photomultiplier's output (blue star). In Fig. 2, for each subsequent step of signal modeling, the corresponding pdf's are shown with the same colours as the indications with stars in Fig. 1. The resulting distribution of the registration time is marked in Fig. 2 with a blue curve.

In this work, we assume that the theortically expected signal registered at photomultiplier output has the same functional dependence on the time as the pdf of photon registration time. Therefore, the shape of the signal may be evaluated based on the distribution of photon registration time (the shapes of the blue curves describing the pdf and the voltage signal in Fig. 2 and 3, respectively, are the same). However, the signal acquired at photomultiplier output during the experiment, marked in Fig. 3 with a red curve, is influenced by an additive random noise. The correct estimation of parameters of the noise in the registered signal (red curve in Fig. 3) is essential to evaluate the time resolution of the PET scanner. In related work we have demonstrated that there is a closed-form formula to calculate the times resolution based on the noise observed in the signals [14], [16]. In this paper we extend previous research by including the influence of the most important parameters of the photomultipliers on the overall performance of the J-PET system.

III. Experimental results

As shown in Ref. [16], the two main factors influencing the size of the noise term are the photomultipliers quantum efficiency and the photomultipliers transit time spread. In the first case, the perturbation of pdf function of the registration time is introduced by limited number of input photon signals. In the latter situation, the pdf function of registration time is blurred by photomultipliers transit time spread. In the situation when the photomultipliers transit time spread tends to the zero, the observed signal at photomultiplier output would not be blurred. In that case the green and blue curves describing the pdfs before and after photons propagation through the photomultiplier would differ only with the time shift. The exact values of the noise contribution to the registered signals depend on the type of photomultiplier applied in the PET scanner. The J-PET scanner is designed to be equipped with

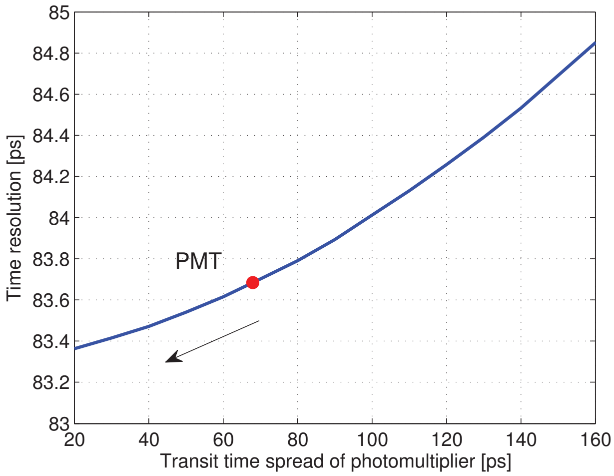

Fig. 4. Time resolution as a function of photomultiplier transit time spread. The parameter describing the quantum efficiency is fixed and equal to 0.25 as for PMT photomultiplier.

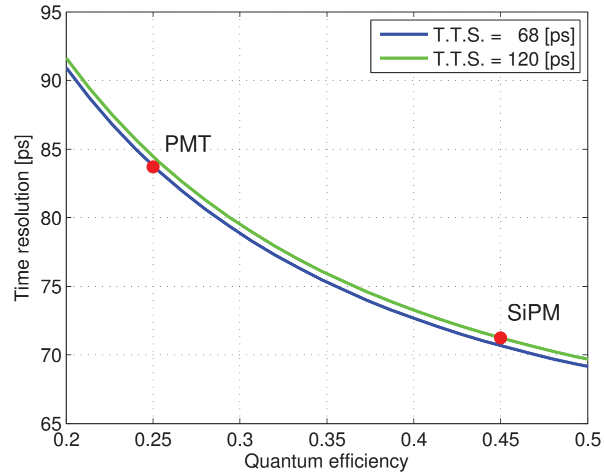

Fig. 6. Comparison of time resolutions of the J-PET systems with PMT and SiPM photomultipliers.

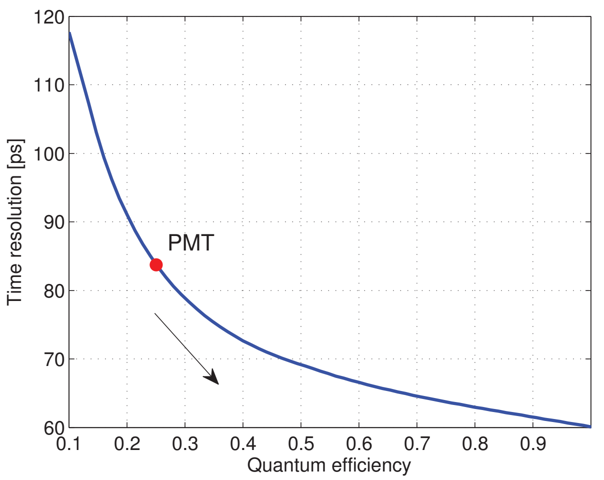

Fig. 5. Time resolution as a function of of photomultiplier quantum efficiency. The parameter describing the transit time spread is fixed and equal to 68 ps as for PMT photomultiplier.

different types of photomultipliers. In this work we consider two types of photomultipliers:

- PMT - vacuum tube photomultiplier;
- SiPM - silicon photomultiplier.

The values of photomultipliers transit time spread are delivered by the the photomultiplier producers, and for Hamamatsu R4998 photomultiplier (PMT) is equal to 68 ps, and for silicon photomultiplier S12572-100P (SiPM) is equal to 120 ps [17]. On the other hand, comparative analysis of the quantum efficiencies of both types of photomultipliers indicates that, in the range of wavelengths emitted in plastic scintillator, the quantum efficiency of silicon photomultipliers is by factor 1.5 higher with respect to the quantum efficiency of vacuum tube photomultipliers [16]; the quantum efficiency of SiPM photomuliplier is equal to 0.45 and the quantum efficiency of PMT photomultiplier is equal to 0.25. The time resolution obtained with the experimental scheme with PMT photomultipliers was reported to be equal to about 80 ps [6], [7], [14]. Our calculation shows that the application of the proposed estimation method can give very similar result of 83.7 ps (see Fig. 4 and 5). According to the results shown in Fig. 4, there is a negligible influence of the transit time spread value of photomultipliers on the performance of the reconstruction method of the interaction moment of photon gamma. For fixed value of the parameter describing the quantum efficiency of PMT photomultiplier, equal to 0.25, in the selected range from 20 ps to 160 ps of photomultiplier's transit time spread, time resolution of the J-PET scanner differs by 1.5 ps (see Fig. 4 for details). On the other hand, the obtained results demonstrate that the quantum efficiency of photomultipliers is the one of the most important factors that influences the overall performance of the PET scanner. For fixed value of parameter describing the transit time spread of PMT photomultiplier, equal to 68 ps, in the selected range from 0.1 to 1.0 of photomultiplier's quantum efficiency, time resolution of the J-PET scanner differs by 60 ps (see Fig. 5 for details).

Consistency of experimental and theoretical results, obtained for J-PET scanner equipped with PMT photomultipliers, confirms that the proposed method may be applied in order to investigate further possibilities of improvement of the time resolution of the J-PET scanner. We provide the comparative analysis of the performance of the J-PET tomograph equipped with the PMT and the SiPM photomultipliers. In Fig. 6 the two characteristics describing the dependence of the time resolution on the quantum efficiency of photomultipliers for the fixed value of parameters describing the transit time spread of PMT (68 ps) and SiPM (120 ps) photomultipliers are marked with blue and green curves, respectively. The results show that there is small shift between two characteristics equal to about 0.7 ps, introduced by the different values of transit time spread of PMT and SiPM photomultipliers. However, the replacement of the PMT photomultipliers with the SiPM photomultipliers allows to improve the time resolution to about 72 ps, due to higher quantum efficiency of the latter ones.

IV. Summary

The J-PET scanner is designed to be equipped with different types of photomultipliers. In addition to the vacuum tube photomultipliers, considered as basic ones in the J-PET prototype, there is possibility to mount, for example, the silicon photomultipliers [16]. The proposed approach allows to investigate various aspects of signal processing of the J-PET system. One of the most important factors that influences the time resolution of PET detector, is the type of photomultipliers.

We found that two main factors are relevant for the efficiency in detecting the gamma photons, the photomultipliers quantum efficiency and photomultipliers transit time spread. Comparative analysis of the quantum efficiencies of both types of photomultipliers indicates that, in the range of wavelengths emitted in plastic scintillator, the quantum efficiency of silicon photomultipliers is by more than 1.5 higher with respect to the quantum efficiency of vacuum tube photomultipliers. On the other hand, the transit time spread of the considered silicon photomultipliers is almost two times larger than the transit time spread of vacuum tube photomultipliers used in the current version of the J-PET scanner. We show that the influence of the transit time spread on the perfermance of the reconstruction method is negligible. Therefore, we can conclude that the quantum efficiency of photomultiplier is the relevant parameter for the performance of the scanner. In detail, the replacement of the vacuum tube photomultipliers with the silicon photomultipliers allows one to improve the time resolution of the J-PET detector by about 10 ps.

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