TIME-OF-FLIGHT POSITRON EMISSION TOMOGRAPHY WITH RADIOFREQUENCY PHOTOTUBE*

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In this paper γ-detector, based on the radiofrequency (RF) phototube and recently developed fast and ultrafast scintillators, is considered for Time-of-Flight positron emission tomography applications. Timing characteristics of such a device has been investigated by means of a dedicated Monte Carlo code based on the single photon counting concept. Bi-exponential timing model for scintillators have been used. The calculations have shown that such a timing model is in a good agreement with recently measured data. The timing resolution of γ-detectors can be significantly improved by using the RF phototube.

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1. Introduction

It is well known that the statistical noise variance in positron emission tomography (PET) can be reduced significantly by using Time-of-Flight (TOF) information. This reduction can be obtained by improving the coincidence timing resolution. The potential impact of this development is large, especially for oncology studies in large patients, where it is sorely needed. TOF PET was extensively studied in the 1980s and a number of PET cameras incorporating TOF measurement were built (see [1] and references therein). These cameras achieved timing resolution of ~ 500 ps and observed the anticipated improvement in statistical noise. Achieving this timing resolution required BaF_2 or CsF scintillators, which imposed trade-offs that degraded other PET performance aspects such as spatial resolution and efficiency. The disadvantages seemed to outweigh the advantages, as

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few TOF PET cameras were constructed after the 1980. Recent advances in technology (scintillators, photodetectors, and high speed electronics) have renewed interest in TOF PET, which is experiencing a rebirth [1].

Recently we have developed principles of a new photon detector, namely radiofrequency (RF) phototube [2], which is high rate ($>$ 1 MHz), high resolution (better than 20 ps rms for single photoelectron, PE) and highly stable (10 fs in 1 s) [3] timing technique. In this paper we are considering γ-detector based on the RF phototube and recently discovered and developed fast and superfast [1, 4, 5] scintillators. Timing resolution of such device is studied by using Monte Carlo (MC) code based on the single photon counting concept. The bi-exponential timing model [6] has been used for emission time profile of scintillators. The calculations are compared with the measurements [4,5] of several newly developed fast scintillators to check the validity of the MC code.

2. γ-detector with RF phototube for TOF PET applications

When 511 keV γ-ray, from positron annihilation, is absorbed in scintillator, tiny flash of visible photons are produced. This photon flash has time duration ranging from few ns to several tens of ns depending on the scintillator material. The scintillator emission time profile is determined by rise time, τ_{r} and decay time, τ_{d}. The RF phototube transposes the time structure of this photon flash into spatial PE image on a scanning circle and detected (see details in [2]). It was already demonstrated (see [6] and references therein) that best timing resolution for scintillator detector can be achieved by timing with a first PEs. To be able to detect all produced PEs and measure the time of first PE, we are proposing to use a dedicated position sensitive anode and signal readout scheme for RF phototube, which is depicted in Fig. 1. The position sensitive anode consists with n pixels. Each pixel operates like an independent PMT and detected PEs in a fixed time interval, $\Delta T = T/n$, where T is the period of the applied RF field. The total number of pixels, n, will be determined taking into account the requirement of the experiment *e.g.* to detect all PEs with negligible pile-up.

The pulses from pixels are amplified and by using linear fan-in fan-out schemes are divided into two identical copies. One of these copies is detected by fast constant fraction discriminators (CFD). The output pulses of the CFDs and Trigger pulse, generated by the same RF signal, which is used for driving the RF phototube, are used as start/stop pulses and time between them are determined by time-to-digital converter (TDC). The expected time resolution of the system consisting with CFD and TDC is about 100 ps, rms. The TDC output therefore is used as an address word for the measured data (pixel's and TDC's channels numbers) memory. By this way at least the early ($\leq$ 2 ns) arriving part of the scintillator light pulse is digitized

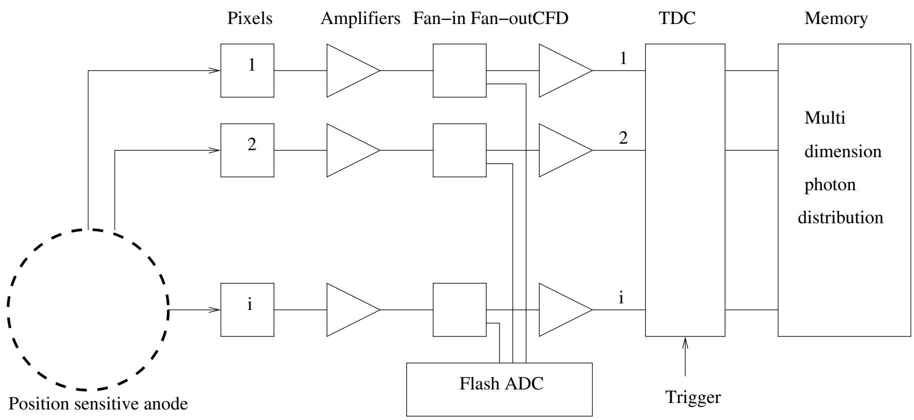

Fig. 1. Schematic of the position sensitive anode and the readout electronics.

with 20 ps interval bins ($n = 100$, $T = 2$ ns) and the time of the first PE is determined within error better than 20 ps. The second copy of signal is detected by the flash ADC, and can be used for determining the total number of PEs and reconstructing the full shape of scintillator light pulse.

The characteristics of such a system were investigated by using dedicated MC code. The bi-exponential timing model [6] has been used for scintillators. This model includes three parameters of a scintillator detector: scintillation rise time, $\tau_{\rm r}$, scintillation decay time, $\tau_{\rm d}$ and total PE yield, $N_{\rm PE}$, from the photon–electron conversion. The final timing resolution included the timing resolution of the photon detector, $\tau_{\rm pd}$ as well.

The distribution of the bi-exponential timing shape with $\tau_{\rm d} = 46200$ ps decay, $\tau_{\rm r} = 480$ ps rise times and distribution of first photoelectron times from total number of $N_{\rm PE} = 1932$ PEs, obtained by means of MC simulations are shown in Fig. 2 (a), (b) respectively. The photon detector resolution is $\tau_{\rm pd} = 125$ ps, FWHM. The obtained timing resolution is 207 ps, FWHM. These parameters represent the experimental conditions of Ref. [4], where 212 ps, FWHM timing resolution has been obtained for LSO (Lu_2SiO_5:Ce) scintillator and Philips Photonics XP2020Q PMT. Recent studies [5] have measured the timing resolution of $LaBr_3$:Ce at different Ce concentrations, as well as detailed rise and decay time constants, total photoelectron yield and intensities of multi-time components. The measured data are listed in table along with the results obtained by MC simulations with the same parameters. The total photoelectron yield is chosen at the level that corresponds to the 250 keV energy thresholds which was applied in the measurement. The calculation uses the same $\tau_{\rm pd} = 160$ ps, FWHM timing resolution for photon detector as the PMT (Hamamatsu H5321) used in the experiment.

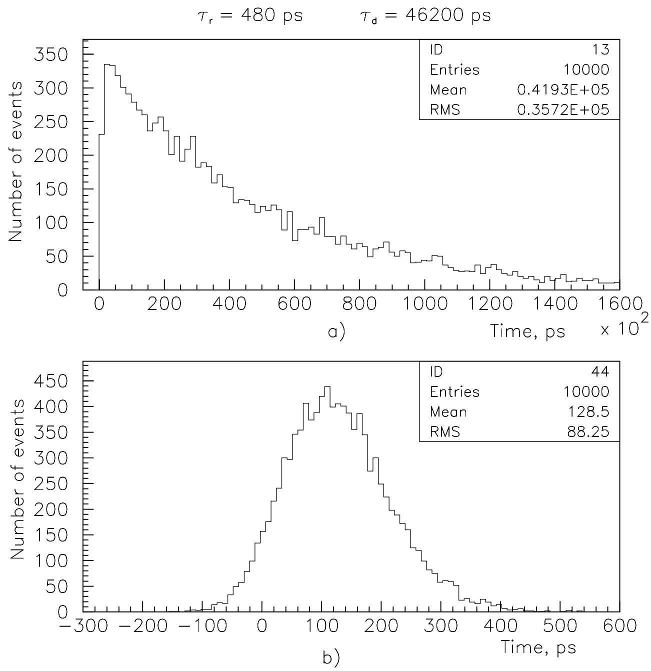

Fig. 2. (a) The timing distribution simulated with bi-exponential timing model, photon detector timing resolution is included, $\tau_{\mathrm{r}} = 460$, $\tau_{\mathrm{d}} = 46200$, $\tau_{\mathrm{pd}} = 125$ ps, FWHM. (b) The distribution of the first PE times from total number of $N_{\mathrm{PE}} = 1932$ PEs in each event. These parameters are equivalent to the experiment [4].

TABLE I

Scintillation parameters and timing resolutions of $LaBr_3$:Ce.

Ce^{3+} concen- tration(%)	Total PE yield PE/MeV	Decay/rise times (intensity) (ns/ns(%))	Timing resolution (ps) FWHM	
			Measured [5]	MC this work
0.5	15132	19/15(56%), 15.2/2(28%), 55(16%)	361	273
5.0	15600	15/0.38(70%), 15/2.2(27%), 55(3%)	214	127
10.0	14664	16.5/0.5(89%), 4.5/0.5(5%), 55(6%)	106	131
20.0	14352	17.5/0.16(89%), 4.5/0.15(5%), 55(6%)	97	109

Compared with measured data, the calculations have shown that the MC timing model accurately reproduced observed experimental timing resolutions of LSO and $LaBr_3$:Ce scintillators with different rise times, decay times, photon yields and photodetector timing resolutions. The calculations are sensitive to the used parameters, *e.g.* if for $LaBr_3$(0.5%)Ce scintillator, MC simulations carry out by using single timing shape with $\tau_d = 19000$ ps decay and $\tau_r = 9400$ ps rise times, as suggested in Ref. [6], then 362 ps timing resolution instead of 273 ps can be obtained, which is in good agreement with experiment.

The rms of the distributions of first PE times of a scintillator detector with $\tau_r = 500$ ps and $\tau_d = 40000$ ps, being similar to those measured from LSO and LYSO ($Lu_{1.8}Y_{0.2}$ SiO_5:Ce) crystals, as a function of a photon detector timing resolution, for $N_{PE} = 2000$ and $N_{PE} = 6000$, obtained by means of MC code, are shown in Fig. 3 (a). The same quantities but obtained with $\tau_r = 500$ ps and $\tau_d = 16000$ ps, being similar to those measured from $LaBr_3$:Ce, are shown in Fig. 3 (b).

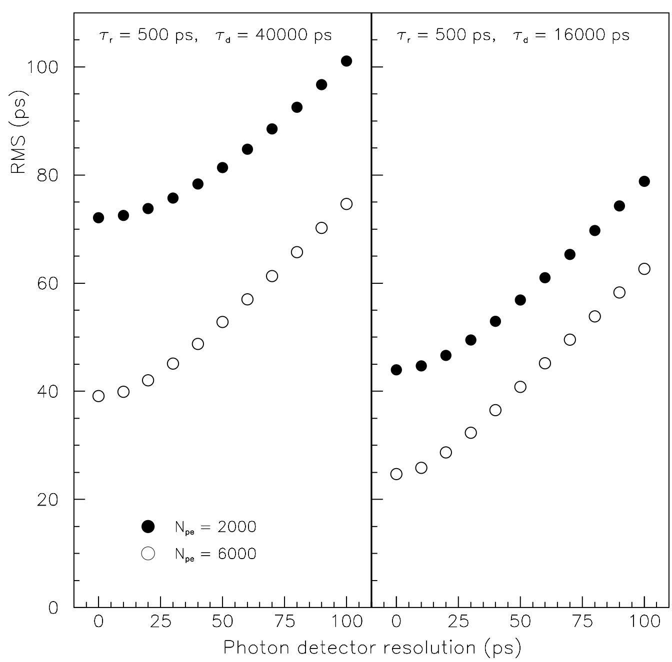

Fig. 3. The scintillator detector timing resolution, calculated with a first photoelectron as a function of photon detector timing resolution (see text for details).

From these calculations it follows that the photon detector timing resolution become crucial for superfast scintillators with short decay times and high PE yields. The expected timing resolution of the scintillator detector with $\tau_r = 500$ ps, $\tau_d = 2000$ ps, $\tau_{pd} = 20$ ps, rms and $N_{PE} = 6000$ is about 15 ps, rms, *i.e.* the coincidence timing resolution of two scintillator detectors with such a parameters is about 50 ps, FWHM. These parameters are similar to the parameters of the recently developed Cs_2LiYCl_6:Ce scintillator [7].

3. Summary

The readout scheme for γ-detectors, based on the RF phototube, is proposed. Timing characteristics of such a device were investigated by means of dedicated Monte Carlo code. Bi-exponential timing model for scintillators have been used. The calculations have shown good agreement with recently measured data. The timing resolutions of fast scintillators can be significantly improved by using RF phototube. The coincidence timing resolution of two identical scintillator detectors, with $\tau_r = 500$ ps, $\tau_d = 2000$ ps, $\tau_{pd} = 20$ ps, rms and $N_{PE} = 6000$ PEs, can reach 50 ps, FWHM which will be great achievement for TOF-PET.

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