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New Photonis XP20D0 photomultiplier for fast timing in nuclear medicine

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Abstract

Growing interest in the time-of-flight positron emission tomography (TOF PET) prompts the study of a new Photonis XP20D0 photomultiplier, equipped with a screening grid at the anode, in application to a fast timing with LSO and $LaBr_3$ crystals. The high time resolution of 200 ± 4 and 210 ± 4 ps was obtained for 511 keV annihilation quanta using $LaBr_3$ and LSO crystals in the coincidence experiment with a small BaF_2 crystal, respectively. It reflects an importance of the grid and high quantum efficiency of the XP20D0. A high-time resolution observed in the present experiments makes good prospects for a development of TOF PET.

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Keywords: Fast photomultipliers; Fast timing; LSO and $LaBr_3$ scintillators; Time-of-flight PET

1. Introduction

Fast photomultipliers (PMTs) for timing experiments in nuclear and high-energy physics are of great importance for more than 50 years. Their quality is characterized in general by a low transit time jitter and a fast response of the anode signal.

Recently, we have observed a growing interest in studying a future application of a time-of-flight positron emission tomography (TOF PET) [1–3]. New heavy and fast scintillators such as LSO and recently $LaBr_3$ were introduced to the market. It prompts also a development of better PMTs, which will assure the ultimate time resolution with new heavy crystals to be below 500 ps for the future TOF PET scanners, recognized as a limit for TOF PET [1]. The first TOF PETs [4,5] proposed in the early 1980s were not successful because of a low stopping power of BaF_2 crystals for annihilation quanta. LSO in this respect is very promising [1].

The aim of this work was to evaluate the performances of a new Photonis 51 mm diameter XP20D0 PMT with enhanced timing capability due to a screening grid at the anode and enhanced quantum efficiency of modern photocathodes (PCs). It was done by means of timing studies of the PMTs with LSO and $LaBr_3$ crystals.

2. Outline of the problem

The time resolution capabilities of fast PMTs are associated with [6]:

- the transit time jitter of electrons traveling from the PC to the first dynode,
- the number of photoelectrons released from the PC and collected on the first dynode. This number is a function of the PC sensitivity and efficiency of photoelectron collection on the first dynode,
- the spread in the gain of the electron multiplier, which affects pulse height and time distributions of the output pulses.

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Increase of the gain of the first dynode has reduced considerably the contribution of the time jitter originating in the dynode structure of PMTs [7].

The improvement of timing due to a lower time jitter of PMTs is, however, limited because of a contribution of the light collection time spread in typical scintillators used in different measurements [6,8], reflected by the standard deviation of about 0.25–0.5 ns for 2.5 cm high crystals.

New PCs introduced recently by PMT manufacturers exhibit higher blue and white sensitivities. This increases the number of photoelectrons and improves the time resolution. However, a cut-off of the PC sensitivity at longer wavelengths affects the time jitter because of a larger initial velocity of released photoelectrons [9].

The study carried in Ref. [10] suggested strongly that there is another source of time resolution degradation in the fast PMTs associated with the commonly used construction of the anode.

The anode built as a grid is placed inside the last dynode, see Fig. 1. This configuration ensures a low time-of-flight of electrons from the last dynode to the anode and a good charge collection at the anode. However, one can note easily that the anode signal consists of two components: the main one due to the collection of electrons from the last dynode and a parasitic one induced at the anode by electrons traveling towards the anode from the pre-ultimate dynode. This parasitic component is shifted in time relative to the main component and, in fact, its charge triggers mainly fast discriminator. Thus, the triggering point is far too high compared to that resulting from the statistical properties of the scintillation detectors requiring a low fraction of the anode pulse height for the best time resolution [6,11].

The above problem was solved in Ref. [10] by an application of so called dynode timing to XP2020 and RCA 8850 PMTs. The output signal in the XP2020 was picked from the dynode 9 and the number of active dynodes was reduced to 10. It allowed improving time resolution measured with various scintillators, including fast plastics, as NE111 and NaI(Tl) crystal, by a factor of 1.2.

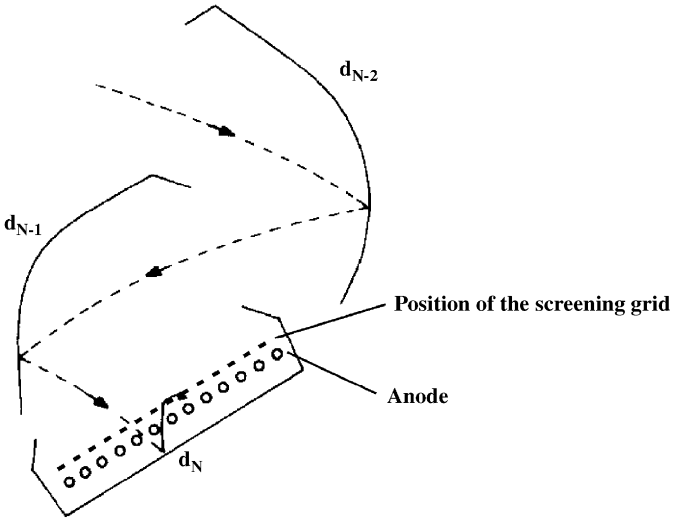

Fig. 1. Geometry of the last dynodes and the anode in the typical linear-focused photomultiplier. Note that the anode is built as a grid inside the last dynode [20]. The position of the screening grid is also shown.

The superiority of the dynode timing was further confirmed for a number of different PMTs and scintillators [12–14], as well as, in a number of experimental arrangements [15,16].

It is worthy to mention, following Ref. [10] that in the past, in the XP1021 PMT, a special grid was placed in front of the anode to improve the initial slow rise of the anode pulse [17], or, in the other words to avoid the parasitic component. Indeed, the time resolution measured with the scintillation detectors consisting of the small NE111 plastics coupled to the XP1021 was equal to 130 ps for ^{60}Co γ-rays [11]. Note that this old PMT was equipped with S11 PC and only 900 phe/MeV was measured with NE111 plastic, thus 30% less than in contemporary PMTs equipped with bialkali PC.

The usefulness of the screening grid at the anode was verified in the studies of two types of experimental PMTs, XP2020UR-M [18,19] and XP20Y0Q/DA [20]. In both the experiments done with fast NE111 plastic, and BaF_2, LSO, $LaCl_3$ and NaI(Tl) crystals the improvement of timing by about a factor of 1.15–1.2 over standard PMTs, without grid, was observed.

In consequence, Photonis has recently introduced a new XP20D0 PMT to the market. In comparison to the classical XP2020, the screening grid was applied at the anode and the number of dynodes was reduced to 8, to avoid the influence of space charge effect on time resolution [10].

3. Experimental details

The properties of the studied PMTs equipped with the screening grid at the anode are collected in Table 1. The XP20Y0/DA is the prototype of XP20D0, tested earlier in Ref. [20], while XP20D0 tubes represent the current Photonis production. Note the high blue sensitivity of all tested PMTs. Time jitter, expressed by the standard deviation σ, listed in Table 1, was measured using a light pulser based on an XP22 light emitting diode.

All the measurements were done with LSO and $LaBr_3$:Ce ($LaBr_3$) crystals. The LSO crystal was wrapped with several

Table 1
The main parameters of the tested photomultipliers

Parameters	XP20Y0/DA No. 021	XP20D0 No. 2025	XP20D0 No. 2026
Photocathode	Bialkali		
Blue sensitivity (μA/lmF)	12.2	13.1	13.7
White sensitivity. (μA/lm)	110.2	150	150
Time jitter, σ (ps)	280 ± 13	260 ± 13	220 ± 13
No of dynodes	8	8	8

Table 2
Tested scintillators

Crystal	Size (mm)	Manufac-turer	λ_{pk} (nm)	Decay time (ns)	Light output (ph/MeV)
$LaBr_3$, 5%Ce	$\varnothing 25 \times 25$	Saint Gobain	360	15	74000[a]
LSO:Ce	$10 \times 10 \times 5$	CTI	420	42[b]	30500 ± 500[b]

[a]See Ref. [21].
[b]See Ref. [22] for the tested crystal.

layers of Teflon tape, while the $LaBr_3$ crystal had been encapsulated by the manufacturer. An overview of the crystal properties is given in Table 2.

Fig. 2 presents the energy spectrum of γ-rays from a ^{22}Na source measured with the $LaBr_3$ crystal. Note the excellent energy resolution of 3.65% for 511 keV peak, superior over all scintillators.

All the timing studies were carried out with an Ortec 935 Constant Fraction Discriminator adjusted separately for the best timing for each combination of scintillators and PMTs. Time spectra were measured with an Ortec 456 Time-to-Pulse Height Converter and recorded by a PC-based multichannel analyzer (Tukan). In all the studies the slow-fast arrangement was used for a precise selection of the required energy windows.

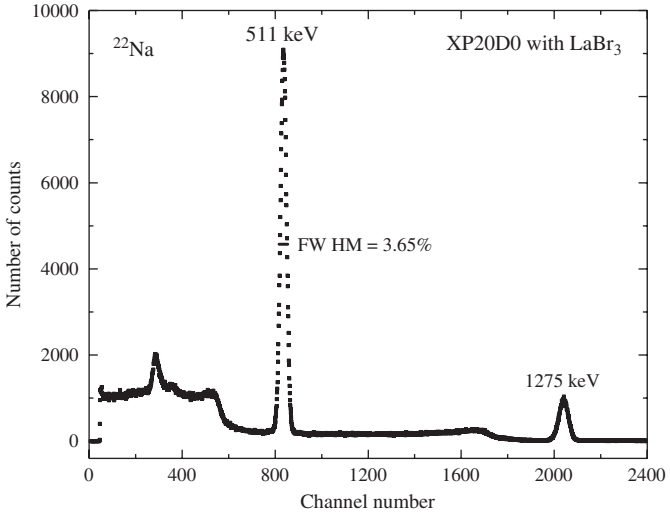

Fig. 2. Energy spectrum of γ rays from a ^{22}Na source measured with the $LaBr_3$ crystal

4. Results

The timing measurements with LSO and $LaBr_3$ were performed using ^{60}Co and ^{22}Na γ-sources. The energy windows in the side channel of tested crystals were set at 1.33 MeV full energy peak in the ^{60}Co energy spectrum or at the 511 keV full energy peak in the ^{22}Na γ-spectrum, respectively. In the reference detector the truncated cone BaF_2 crystal coupled to the XP20Y0Q/DA was used, following [20]. Its time resolution was equal to 90 ± 4 and 128 ± 4 ps for ^{60}Co and ^{22}Na, respectively. Moreover, for all studied detectors, the numbers of photoelectrons were measured.

Fig. 3 presents the time spectra recorded with the $LaBr_3$ crystal coupled to the XP20D0, no. 2026, for ^{60}Co and ^{22}Na γ-rays. The measured time resolution of 140 ± 4 and 200 ± 4 ps correspond to 107 ± 4 and 154 ± 5 ps, respectively for the $LaBr_3$ detector alone. The number of photoelectrons produced by the light of the $LaBr_3$ crystal in the tube no. 2026 was equal to 17600 ± 500 phe/MeV.

Fig. 4 shows the time spectra measured with the LSO crystal coupled to the XP20D0, no. 2026. Again a high-time resolution of 146 ± 4 and 210 ± 4 ps was measured for ^{60}Co and ^{22}Na γ-rays, respectively. The high number of photoelectrons of 8100 ± 240 phe/MeV is due to a very high blue sensitivity of the XP20D0, no. 2026.

Particularly important is the time resolution obtained for 511 keV annihilation quanta with the LSO crystal. This makes good prospects for a development of TOF PET. Note the superior time resolution of the LSO detector, corrected for the contribution of the reference BaF_2 detector, equal to 166 ± 5 ps. It leads to the time resolution of 234 ± 7 ps for the pair of LSO detectors.

5. Discussion

The results of the measurements and the analysis of the time resolution for 511 keV annihilation quanta in respect to the number of photoelectrons measured at 511 keV peak are collected in Table 3.

The measured time resolution, presented in the second column, is corrected for the contribution of the reference BaF_2 detector and collected in the third column. In the forth column the number of photoelectrons corresponding to the 511 keV peak are listed. The last column shows the time resolution of the tested detector normalized to the number of photoelectrons. The presented numbers show that the time resolution follows well the number of photoelectrons.

The time resolutions measured in the present experiments can be compared to the recently reported resolution for both LSO [1] and $LaBr_3$ [21] crystals measured with a very fast R5320 PMT [23]. This PMT is characterized by a time jitter of 151 ps at FWHM [1]. A good time resolution of 300 ps was reported in Ref. [1] for 511 keV annihilation quanta from ^{22}Na, as measured with $3 \times 3 \times 3\,mm^3$ LSO crystals. However, the time resolution of 212 ps for one detector is significantly worse than that given in Table 3.

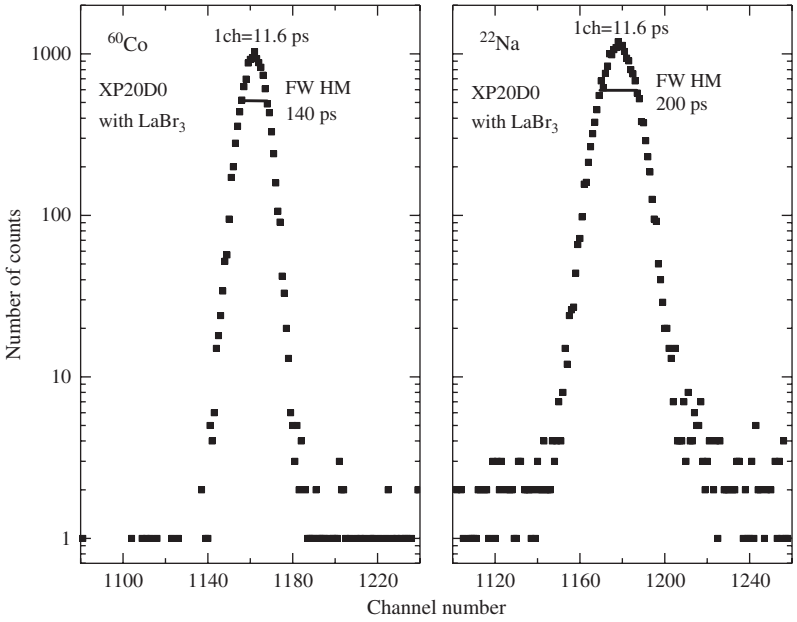

Fig. 3. Time spectra of ^{60}Co and ^{22}Na γ-rays detected in the $LaBr_3$ crystal coupled to the XP20D0, no 2026, measured in relation to the BaF_2 detector.

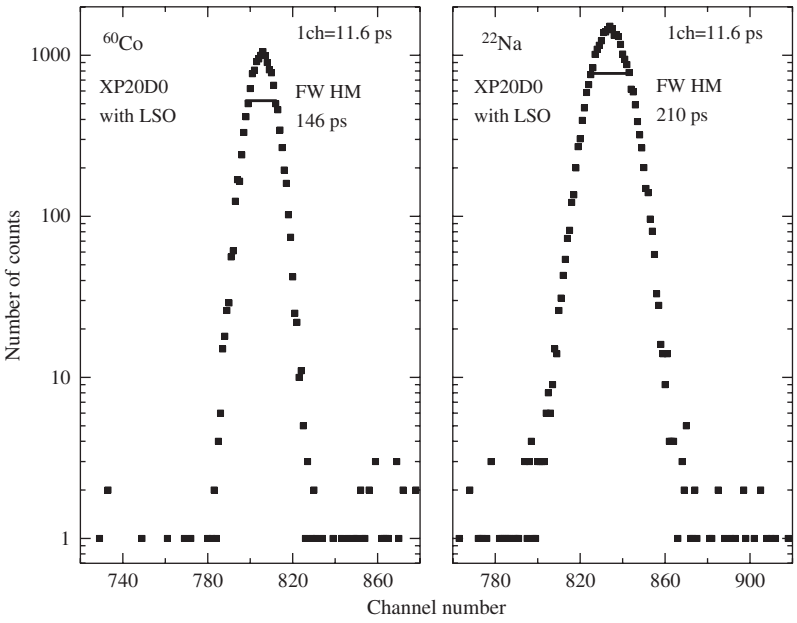

Fig. 4. Time spectra of ^{60}Co and ^{22}Na γ-rays detected in the LSO crystal coupled to the XP20D0, no 2026, measured in relation to the BaF_2 detector.

In Ref. [21] the time resolution of a small $LaBr_3$ crystal with 5% Ce doping was reported to be 214 ps for a single detector, again worse than that given in Table 3. This discrepancy is even more significant, if the larger size of the $LaBr_3$ crystal tested in the present work is taken into account.

The above comparison has a qualitative character, as different crystals were used. Additionally, the results could be affected by the particular adjustment of timing. However, it unambiguously confirms that the XP20D0, in spite of a poorer time jitter, is comparable or better than the very fast R5320. No doubt that it suggests that for rather slow crystals as LSO and $LaBr_3$, a very low time jitter of PMT is less important than a large number of photoelectrons.

In the case of timing with fast plastic scintillators the time jitter of PMTs is of great importance [11,24]. However, the time resolution measured with LSO and other slow decaying scintillators depends stronger on the statistic of photoelectrons produced in the decay process of the light pulse, while time jitter of the PMT has a weaker influence on measured time resolution. This effect was predicted by the Hyman theory of timing [24,25] and it was known in the past for NaI(Tl) crystals [26], when time resolution was often discussed in terms of Post and Schiff theory [27].

Table 3
Time resolution measured with $LaBr_3$ and LSO crystals for 511 keV annihilation quanta

Crystal/PMT number	Time resolution, δt (ps)		N^b(phe)	$\delta t\sqrt{N}$ (ps$\sqrt{}$phe) $\times 10^3$
	Measured	Tested detector[a]		
$LaBr_3$/PMT No				
021	210±4	166±5	8200±300	15.0±0.5
2025	204±4	159±5	8700±300	14.8±0.5
2026	200±4	154±5	9000±300	14.6±0.5
LSO/PMT No				
021	225±4	185±5	3500±100	10.9±0.4
2025	214±4	172±5	3930±100	10.8±0.4
2026	210±4	166±5	4140±100	10.6±0.4

[a]Corrected for the contribution of the BaF_2 reference detector of 128 ps.
[b]Phe number for 511 keV peak.

The advantages of the XP20D0 are associated with the screening grid at the anode, which improves time resolution by the factor of about 1.15 [20] and a high sensitivity of the PC. The tested PMTs showed a very high blue sensitivity. However, the typical blue sensitivity of 12 μA/lmF of XP20D0 [28] is also about 30% higher than the typical one of R5320, equal to 9 μA/lmF [23]. It leads to the further improvement of time resolution by a 1.15 factor due to a higher photoelectron number. Thus, one can expect the total improvement by a 1.32 factor due to both the grid and the higher blue sensitivity in XP20D0, which compensate a poorer time jitter.

It is also interesting to compare time resolutions measured with $LaBr_3$ and LSO. A very high light output of $LaBr_3$ and a faster decay time are weakly reflected in the measured time resolution. No doubt that it is the effect of a poor rise time of the light pulse of $LaBr_3$ crystal with 5% Ce doping, close to 1 ns, according to Ref. [21]. In this case a larger doping by Ce is of the great importance [21].

6. Conclusions

The present study confirms the very good capabilities of XP20D0 PMTs for timing experiments. The importance of the screening grid at the anode and the high quantum efficiency of the XP20D0 were pointed out.

A high time resolution measured with LSO for 511 keV annihilation quanta suggests strongly that the XP20D0 can be used in the realistic project of TOF PET.

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