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RECEIVED: *September 5, 2012*
REVISED: *January 12, 2013*
ACCEPTED: *January 28, 2013*
PUBLISHED: *February 22, 2013*

Energy resolution of small scintillation detectors with SiPM light readout

M. Grodzicka,[1] **M. Moszyński, T. Szczęśniak, M. Kapusta, M. Szawłowski and D. Wolski**

National Centre for Nuclear Research,
A. Soltana 7, PL 05-400 Świerk-Otwock, Poland

E-mail: Martyna.Grodzicka@ncbj.gov.pl

ABSTRACT: The development of silicon photomultipliers (SiPMs) with a large number of APD cells and improved linearity of the pulse height response prompted interest in their application to gamma spectrometry with scintillators. Hamamatsu MPPC sensors equipped with 3600 and 14400 APD cells were chosen in our study because of their well pronounced single photoelectron spectra, which allowed us to precisely measure the photoelectron numbers (PHE) or fired APD cells and then to discuss, in a quantitative manner, the obtainable energy resolution. The studied detectors were first characterized in direct detection of laser light pulses and then in gamma spectroscopy with LFS and CsI:Tl crystals. In the study with the laser light pulses the linearity of the MPPC response versus a light pulse intensity monitored with PMT was measured. Two different methods were used for an evaluation of the MPPC response expressed in the number of photoelectrons (PHE) generated by light illumination. The direct method (PHEdir), based on the comparison of the light peak position to that of the single photoelectron peak, determined the upper limit of the PHE. The lower limit of the PHE was derived from an analysis of the measured pulse height resolution under the assumption of Poisson statistics and MPPC excess noise factor (ENF) of 1. Furthermore, the ENF of the MPPC is discussed with respect to the contributions of device dead time, optical cross-talk and after-pulses to the results obtained. In the scintillation tests, measurements of energy resolution and non-proportionality of the light yield were performed with LFS and CsI:Tl crystals, and both types of 3×3 mm MPPC detectors were used for light readout. The results are discussed in a quantitative manner based on the measured PHE.

KEYWORDS: Gamma detectors (scintillators, CZT, HPG, HgI etc); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc)

[1]Corresponding author.

doi:10.1088/1748-0221/8/02/P02017

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1 Introduction

Technical advances in silicon photomultipliers (SiPMs) with a large number of APD cells allows for and motivates an evaluation of their performance in their application to gamma spectroscopy with scintillators. The silicon photomultiplier (SiPM) is a solid state detector consisting of separate p-n or n-p junctions (APD cells) connected in parallel and operated in the Geiger mode. The Geiger discharge in the APD cell generates and amount of the charge defined by the operating bias voltage and APD cell capacitance regardless of the energy and number of photons triggering the discharge. The output signal from the SiPM is the sum of the signals from fired APD cells. Details of the operating principles, the theoretical model and the analysis of the linearity and pulse height resolution of SiPMs were extensively discussed and can be found elsewhere in the literature [1]–[7]. Every manufacturer uses their own name for this type of device, e.g. Hamamatsu introduced the name of Multi-Pixel Photon Counter (MPPC) for their product. In the course of the present work the MPPC detector response to either laser light pulses or scintillation light from LFS-3 [8] and CsI:Tl crystals was tested. Measurements were done on a Hamamatsu MPPC due to its well de?ned single photoelectron spectrum. This allowed for the precise measurement of photoelectron (phe) numbers (or fired APD cells). Two different methods were used to evaluate the MPPC response generated by light illumination, expressed in the number of photoelectrons (PHE) and, in consequence, as a calculation of the pulse height resolution. An analysis of the pulse height resolution (PHR) of the peaks, done under the assumption of the Poisson statistic, provides a complementary lower limit of the PHE [9]. A comparison of the results obtained by means of both methods allowed us to discuss the excess noise factor of the MPPC in relation to the optical cross-talk and after-pulsing. In studies using the laser light pulser the linearity of the MPPC response was checked versus a laser light pulse intensity monitored by a photomultiplier (PMT).

Table 1. Main parameters of the MPPCs used.

Manufacturer	Hamamatsu	
Type	S10362-33-025C	S10362-33-050C
Sample No.	3	23
Active area	3×3 mm	3×3 mm
Number of APD-cells	14 400	3 600
APD-cell size	25×25 μm^2	50×50 μm^2
Fill factor (%)	30.8	61.5
Spectral resp. Range (λ)	320–900nm (maximum sensitivity at 440nm)	
Photon Detection Efficeincy	21% at 550nm 26% at 440nm 52% at 440nm	42% at 550nm 25% at 420nm 50% at 420nm
Recommended voltage	68.97 V	68.84 V
Gain	2.75× 10^5	7.53 × 10^5
Dark count	4Mcps (10 ^{o}C)	6Mcps (25 ^{o}C)
Capacitance	320 pF	
Dead time of APD-cell[a)]	10 ns	15 ns

[a)] see ref. [7].

2 Experimental details

2.1 Multi-Pixel Photon Counter (MPPC), Laser diode pulse and Scintillators

Two types of Hamamatsu MPPCs, S10362-33-025C (MPPC 33-025C) and S10362-33-050C (MPPC 33-050C), with 14400 APD cells and with 3600 APD cells, respectively, were tested. Their main parameters as specified by the manufacturer are collected in table 1. All of the measurements were carried out in an air-conditioned laboratory at a temperature of 21 ^{o}C. The detectors studied were characterized by means of a laser light pulser, by LFS3 and CsI:Tl crystals. The LFS scintillator is a new crystal produced by Zecotek Co. with characteristics close to those of the LSO [8]. The chosen scintillators have significantly different decay times of the scintillation pulses and different wavelengths of maximum emission. All of the scintillators were 3x3x3 mm in size to match the MPPCs' 3x3 mm active area. An HL 6501MG laser pulse of 658nm wavelength and optical pulse power of 50mW was used. A rectangular pulse was used to drive the laser pulse. In the measurements laser pulses of different width (expressed by FWHM) were used. The pulse width was controlled by monitoring the signal from the last dynode on the PMT using an oscilloscope.

The crystals used in the tests were polished on all surfaces and wrapped in Teflon tape. Their bare optical surface was coupled to the MPPC or PMT by silicone grease. The main parameters of the crystals are collected in table 2.

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Table 2. Main parameters of the crystals used.

Crystal	Size (mm)	Decay time (ns)	Wavelength of emission peak (nm)	Light Output (ph/MeV)
LFS-3 [a)]	3x3x3	39.7	420	30300±1500
CsI:Tl	3x3x3	1000	550	51000±2500 [b)]

[a)] see ref. [8].
[b)] measured with the calibrated XP2020Q at 6.4 μs peaking time (integral QE = 8.3% for CsI:Tl).

In all the measurements a standard spectrometry electronic setup was used. It consisted of a Canberra 2005 charge sensitive preamplifier and a Tennelec TC244 spectroscopy amplifier. The TC 244 was operated with a 0.25 μs bipolar shaping time constant in all of the measurements with the LFS 3 crystal. CsI:Tl required a longer shaping time for proper light integration. In this case 6 μs bipolar shaping was used. Experiments with the laser light pulses were done with both shaping times and with 40ns and 1000ns pulse widths.

2.2 Experimental Methods

In the present work we address MPPC performance for scintillation light readout in gamma spectroscopy and quantitatively analyse the results obtained .

For a SiPM-based scintillation detector, just as for those based on the other photodetectors, the energy resolution of the full energy peak is limited by the following factors [10]:

$$(\Delta E/E)^2 = (\delta_{sc})^2 + (\delta_p)^2 + (\delta_{st})^2 + (\delta_n)^2 \tag{2.1}$$

where: δ_{sc} is the intrinsic resolution of the crystal, δ_p is the transfer resolution [10], δ_n is the dark noise contribution (measured separately), δ_{st} is the statistical contribution of photodetector.

In measurements with laser light pulses there is no contribution of δ_{sc} and δ_p. In this case, the statistical contribution of SiPM ($(\delta_{st})^2$=$(\Delta E/E)^2$-$(\delta_n)^2$) to the energy resolution can be described in a similar way to a PMT:

$$\delta_{st} = 2.355 \times (ENF/PHE)^{1/2} \tag{2.2}$$

where: PHE is the number of photoelectrons and ENF is the excess noise factor.

ENF for modern PMTs has a low value of 1.1 – 1.2 (see in table IV in ref. [9]), in case of PIN photodiodes is equal to 1, and for APDs is at least 2 or larger (see in figure 5 in ref. [11]).

By using eq. (2.2) an excess noise factor of the SiPMs can be estimated. In the analysis of laser light pulses we assumed the value of the SiPM excess noise factor to be equal to 1 and, consequently, that δ_{st} would be determined by the lower limit of the PHE number.

The other factor included in equation (2.2) is the number of photoelectrons. The PHE in the case of a SiPM is proportional to the Photon Detection Efficiency (PDE). PDE for a single photoelectron is defined in the following way:

$$PDE = QE \times FF \times PG \tag{2.3}$$

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where FF is geometrical fill-factor i.e. the ratio of the active to the total area of the device, QE is quantum efficiency i.e. the probability that an electron-hole pair is generated and PG is the combined probability of electrons and holes to initiate Geiger breakdown [4].

Both the fill-factor and the quantum efficiency are practically insensitive to device operating conditions, while PG strongly depends on operating bias voltage and temperature. A correct evaluation of the PDE and ENF factors is necessary for an objective and quantitative analysis of the measured energy resolution.

The number of photoelectrons was measured using two methods: the direct method and the PHR method. The direct method (PHE_{dir}), introduced by Bertolaccini et al. for photomultipliers [12], is based on a comparison of the single photoelectron's peak position with the position of the measured light pulse peak. The PHR method (PHE_{phr}) is based on the calculation of the photoelectron's number from the pulse height resolution of a laser light peak assuming a Gaussian curve and an ENF value of 1. The PHE_{phr} was calculated using eq. 2, thus $PHE_{phr} = (2.355/\delta_{st})^2$.

The number of photoelectrons per unit energy (phe/MeV) was measured using the direct method (PHEdir) for tested crystals illuminated with the ^{137}Cs γ-source.

The energy resolution and peak position were determined by Gaussian fit to the full energy peaks using procedures included in the Multi-Channel Analyzer Tukan 8k [13]. The Gaussian fit was also used in the case of an analysis of complex double peaks for K X rays and those exhibiting an escape peak.

The non-proportionality of the light yield is defined here as the photoelectron yield measured at a specific gamma ray energy relative to the photoelectron yield at a 662keV gamma peak, and it was measured in the energy range from 14.4keV up to 1.332 MeV.

3 Results and discussion

3.1 Single photoelectron

For the purpose of a precise evaluation of the primary photoelectron number (fired APD cells) and in order to determine the range of SiPM operating voltage, single photoelectron spectra were recorded using a setup as depicted in figure 1. In the insert the details of the MPPC connection to the charge sensitive preamplifier are shown. A pulse generator, HP 8082A, was used to drive the laser light pulser. The number of photons detected by the MPPC was adjusted by varying the amplitude of the pulse driving the laser. The Multi-Channel Analyzer (Tukan 8k) was gated by the coincidence between the trigger output signal of the HP pulse generator and the output pulse signal of the MPPC under study, selected at the output of the spectroscopy amplifier by the single channel analyzer with the threshold set well below the single photoelectron peak.

Figure 2 presents the response of the MPPC 33-050C to a low light level illumination. The distance in ADC channels between two successive photoelectron peaks represents the charge of 1 phe.

We were able to record the single and multi photoelectron spectra from the MPPC 33-050C and MPPC 33-025C for a bias voltage range of 67.75V to 69.00V and 68.5V to 71.0V, respectively. The dependence of the relative gain of single photoelectron signals on the bias voltage for both MPPC devices is shown in figure 3. The straight lines, extrapolated to a negligible charge, for both types of MPPCs cross the abscissa at the value of 67.1V$\pm$0.1, called the device breakdown

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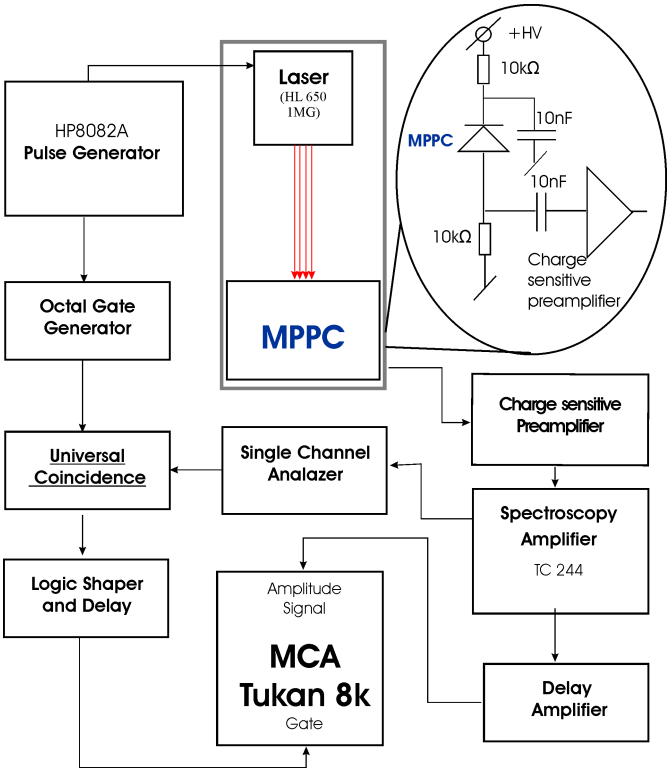

Figure 1. Experimental setup used for single photoelectron measurements.

voltage. The value of the device breakdown voltage serves as a base for the evaluation of an overvoltage — a parameter used for specification of device operating conditions. An overvoltage is the value of the device bias voltage exceeding the breakdown voltage. The breakdown voltage depends on the temperature showing a positive temperature coefficient.

3.2 Linearity

The MPPCs' linearity response was measured with the laser light pulser simultaneously illuminating the MPPC and the PMT in the experimental setup shown in figure 4. The excellent linearity of a R5320 PMT allows to monitor the light intensity and evaluation of the MPPC linearity. The purpose of this experiment is to compare the linear range of the MPPCs with a different number of APD cells. Also, a cross-check was done to see how the decay time constant of the tested crystals and widths of the laser light pulses influence the MPPCs' linearity. Results obtained with the laser light pulses are presented in figures 5, 6 and 7, together with the corresponding points measured for the scintillation light of the CsI:Tl and LFS-3 crystals. The number of photoelectrons in the MPPC was evaluated using the direct method.

Figure 5 shows the linearity plots of the MPPC 33-025C and the MPPC 33-050C devices obtained with the 1000ns wide laser light pulses. The linearity of the MPPC's response, expressed in the number of photoelectrons, is checked by comparing it to the response of an R5230 PMT expressed as the peak position of the laser light pulses recorded in simultaneous illuminations.

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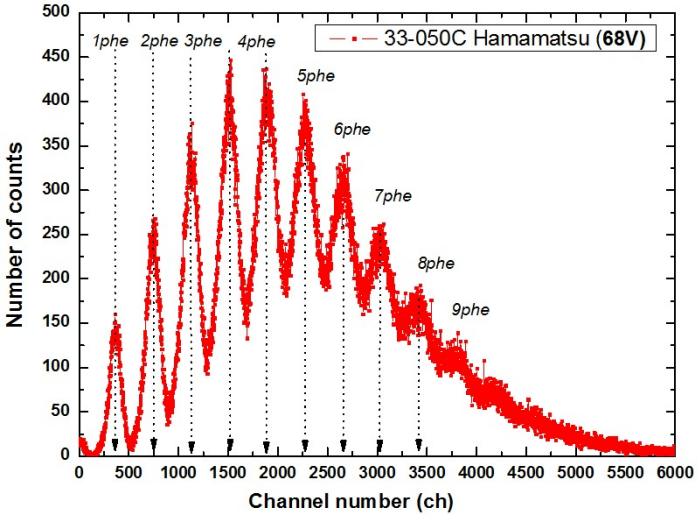

Figure 2. Response of the MPPC 33-050C to the low level of light illumination (pulse width=40ns, shaping time=0.25μs).

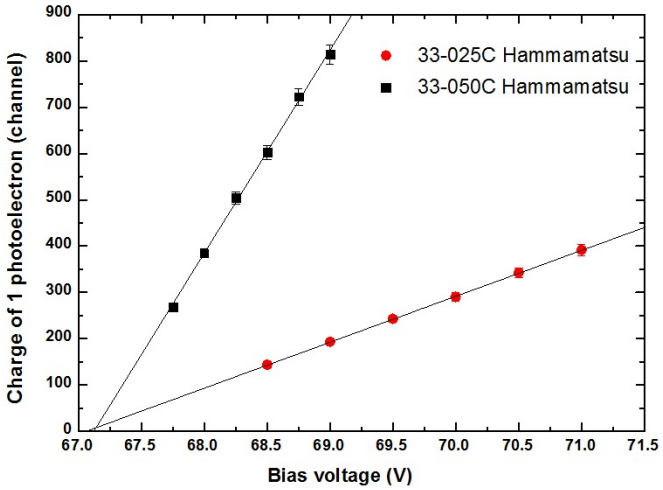

Figure 3. Relative gain characteristics of the tested MPPCs.

Figures 6 and 7 present the linearity range of both MPPCs for two different laser light pulses of 1000ns and 40ns in width.

In illumination with 1000ns wide laser light pulses, 14400 APD cells, the MPPC 33-025C showed linear behavior in the whole measured range up to 7000 phe, which corresponded approximately to 1332.5keV energy of gamma rays detected in the CsI:Tl crystal with a ^{60}Co radiation source illumination. The MPPC 33-050C with 3600 APD cells was linear only up to 2500 phe. This corresponds to the linear behavior for energies of gammas up to 320keV in measurements with CsI:Tl. In tests with the 40ns wide laser light pulses, a linear response only up to 1500 phe and 600 phe was measured for MPPCs 33-025C and 33-050C, respectively. This

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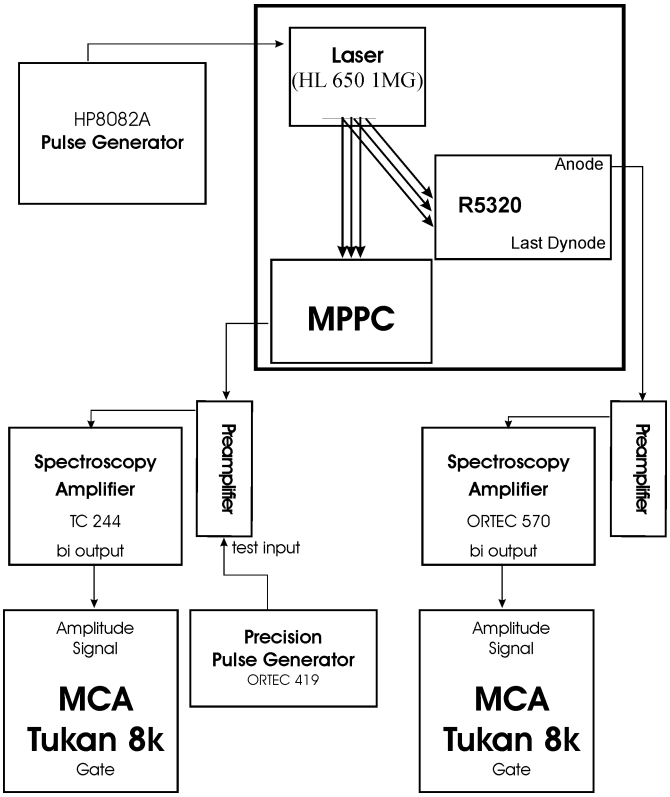

Figure 4. Experimental arrangement used to check the MPPC response in relation to that of the PMT.

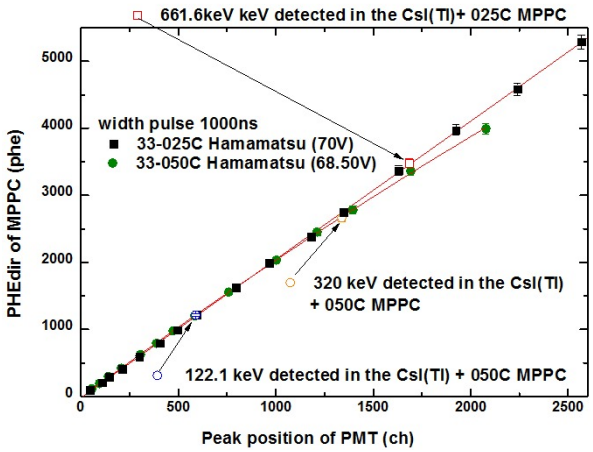

Figure 5. Linearity of MPPC 33-025C (14400 APD cells) and MPPC 33-050C (3600 APD cells) for a 1000ns laser light pulse. The marked points correspond to the photoelectron numbers produced by selected gamma rays in the CsI:Tl crystal.

corresponds to the linearity range in the detection of gamma rays with an LFS 3 scintillator of 320keV and 122keV for MPPCs 33-025C and 33-050C, respectively.

The obtained results show a strong dependence of the MPPC linearity range on the number of the device's APD cells and the intensity distribution of the illuminating photons. Because of the

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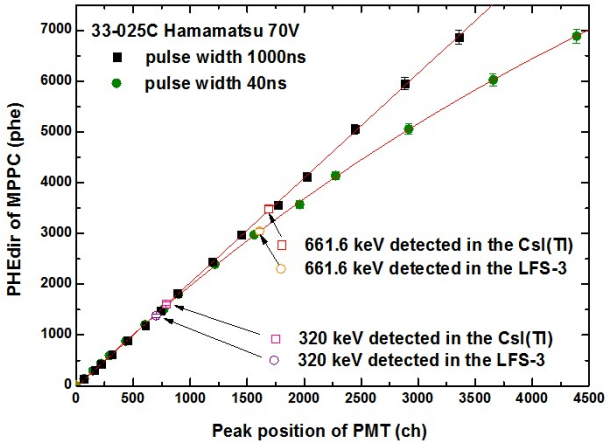

Figure 6. Linearity of the MPPC 33-025C measured for 1000ns and 40ns wide laser light pulses.

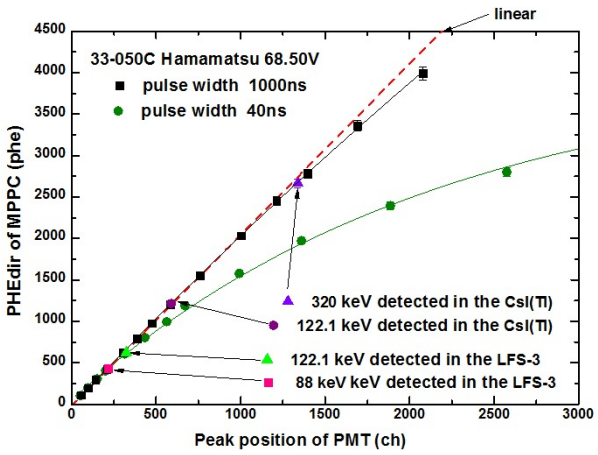

Figure 7. Linearity of the MPPC 33-050C measured for 1000ns and 40ns wide laser light pulses.

limited linear range of the MPPC 33-050C (the response is non-linear for the 662keV gamma ray from a ^{137}Cs source measured with CsI:Tl and LFS-3 crystals), further measurements with laser light pulses and CsI:Tl and LFS-3 crystals were done using only the MPPC 33-025C device.

A good linear response of the MPPCs for scintillation light from the CsI:Tl is the effect of a low peak intensity of the photons in the light pulse and a negligible contribution of the 10ns dead time of the APD cell in relation to the decay time of the scintillation pulse of 1000ns. On the contrary, for the fast scintillators, such as LFS, the APD-cell dead time is comparable with the scintillation decay time and together with the large peak intensity of photons it strongly limits the linear range of MPPC operation.

The linear range of the MPPC response vs. intensity of the illuminating photon flux is defined by the probability of registration of two photons by the pixel in a time shorter than its dead time.

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3.3 Excess noise factor and pulse height resolution

The number of photoelectrons in scintillation detection with a photomultiplier readout can be measured using the direct method based on a comparison of the scintillation light peak position to that of the single photoelectron peak, or it can be calculated from the pulse height resolution (PHR) of the laser light peak of the charge equal to the scintillation light peak [10]. The PHR method is based on eq. (2.2), and the Excess Noise Factor (ENF) is determined from the pulse height resolution of the single photoelectron peak.

These simple methods are more complex in the case of the MPPC. The number of photoelectrons measured directly is, in fact, overestimated because of the optical cross-talk and the after-pulses which produce an excess of photoelectrons in relation to the primary production [4]. By using the PHR method we assume an excess noise factor value of 1, which leads to an estimation of the lower limit of the photoelectron number.

The MPPC response was described by the laser light pulse position in the spectrum and pulse height resolution. The laser light pulse height resolution of the MPPC signal is determined by the statistical (δ_{st}) and dark noise (δ_n) contributions. Dark noise is caused by thermally generated carriers that trigger Geiger discharges further integrated in processing electronics and noise of preamplifier input circuitry.

The dark noise contribution (δ_n) was measured using signals from an ORTEC 419 precision pulse generator sent to the test input of the Canberra 2005 charge sensitive preamplifier processing the MPPC's signals (see figure 4). A quadratic relation between the laser light pulse height resolution PHR_{laser} and its contributing components allows for an evaluation of the statistical contribution of δ_{st} knowing the dark noise component expressed by the measured resolution (PHR_{test}) of the signals sent to the test input.

The difference of a factor of about 1.5 in the number of photoelectrons evaluated by the direct and PHR methods was measured for 1000ns wide laser pulses in a large dynamic range as shown in figure 8. This factor of 1.5 represents the upper limit of the effective ENF of the MPPC operating in the conditions of this test, i.e. 70V bias voltage.

Figure 9 shows the plots of the PHE determined by the PHR method versus the PHE determined by the direct method for 1000ns and 40ns wide laser light pulses. The dashed line in figure 9 represents the ideal case when both numbers are equal, which means the excess noise factor of MPPC is equal to 1. In the measurement done with the 40ns wide laser light, the MPPC response was limited to a signal magnitude of about 1000 photoelectrons. Above this value the large excess of photoelectrons calculated by means of the PHR method was evaluated because the strong nonlinearity of the MPPC response resulted in a departure from the Gaussian curve and an incorrect evaluation of the MPPC contribution to the pulse height resolution based on equation (2.2).

This is clearly seen in figure 10, which shows the square root of the calculated excess noise factor versus the number of photoelectrons measured using the direct method.

The square root of the excess noise factor presented in figure 10 and calculated for the 1000ns wide pulses is constant in the whole range of the light pulse intensities. The same test done with the 40ns wide laser light pulses shows a continuous diminishment of the light intensity of the incorrectly calculated excess noise factor, thus reflecting the nonlinear response of the MPPC for signals larger than 1000 primary photoelectrons.

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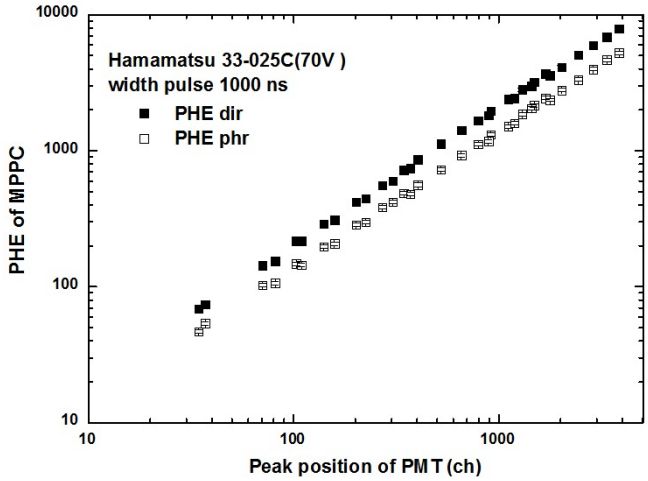

Figure 8. Comparison of the number of photoelectrons by the direct method and by the PHR method assuming an excess noise factor of 1, measured for 1000ns wide laser pulses.

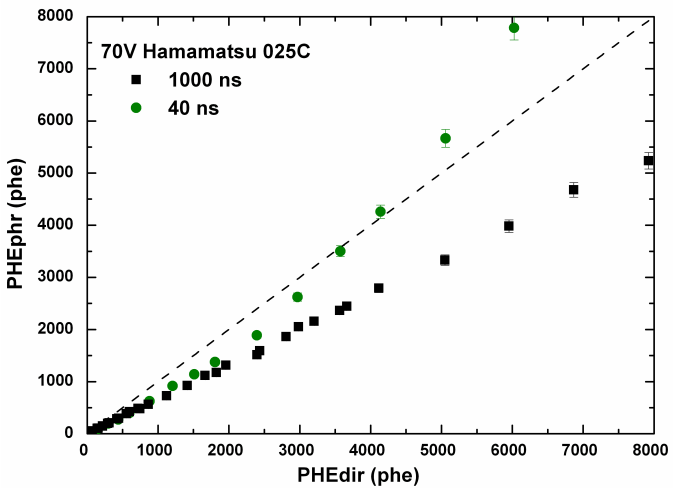

Figure 9. PHE determined from the pulse height resolution versus PHE determined by the direct method measured for two different laser light pulses. The dashed line represents the ideal case when both numbers are equal, which means that the excess noise factor of MPPC is equal to 1.

Figure 11 shows the dependence of the average value of the excess noise factor on the MPPC bias voltage measured for optical pulses of 200ns, 300ns, 500ns and 1000ns in width. At each bias voltage the excess noise factor was calculated four times. Spreads of the values obtained for different pulse widths are inside the error bars. The excess noise factor increases with the bias voltage (see figure 11) mainly due to cross-talk and after-pulses.

An increase of the bias voltage increases the PDE and, in turn, the number of detected photoelectrons, but also secondary photoelectrons from the optical cross-talk cause a rise in the excess noise factor and, in consequence, degradation of the energy resolution. The shape of

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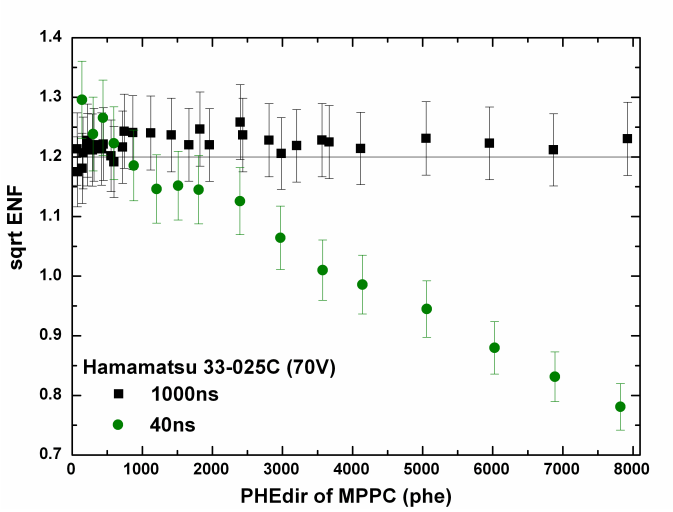

Figure 10. Sqrt of the excess noise factor of the MPPC 33-025C for 40ns and 1000ns wide laser light pulses.

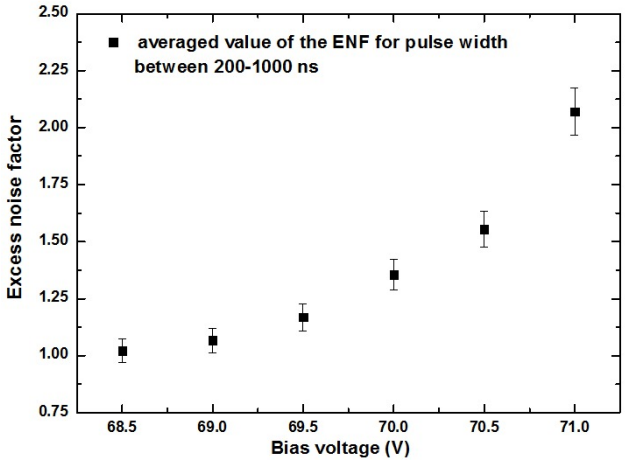

Figure 11. Mean value of the excess noise factor versus the bias voltage measured for the MPPC 33-025.

the curve follows those presenting the cross-talk and after-pulse contributions versus the MPPC gain/overvoltage given in ref. [4] as measured for a 1×1 mm MPPC 025.

We also measured the bias voltage dependence of the photoelectron numbers using both the direct and PHR methods for 1000ns wide laser light pulses with an intensity corresponding to the 662keV peak of the ^{137}Cs detected in the CsI:Tl crystal. The obtained results are shown in figure 12. Note that the presented curves define the upper and lower limits of the photoelectron numbers and that their ratios at a given bias voltage represent values of the ENF.

Figure 13, in turn, presents the pulse height resolution of the laser light peaks versus the MPPC bias voltage measured in the same conditions as the data shown in figure 12. A good energy resolution was obtained at 70V and we consider this voltage to be the optimal operating bias for the tested MPPC. The advantage of such a high voltage is a higher PDE and improved energy resolution. The upper limit of the excess noise factor for this voltage is equal to 1.35.

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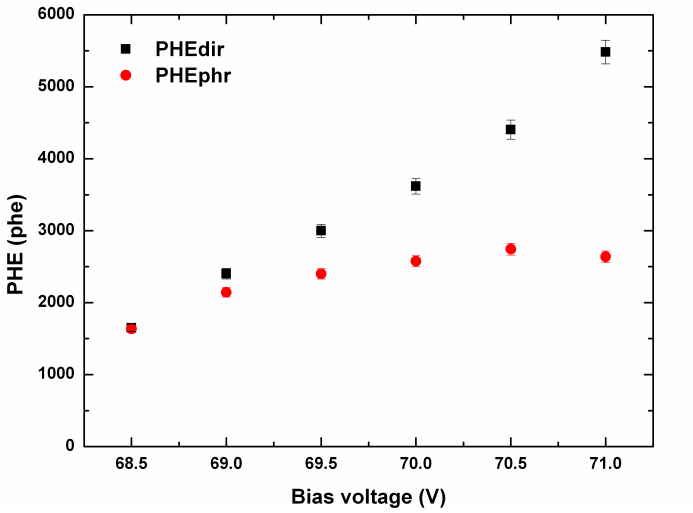

Figure 12. Photoelectron number measured by the direct and PHR methods for the 1000ns wide laser light pulse with an intensity corresponding to the 662keV gamma peak in the CsI:Tl crystal.

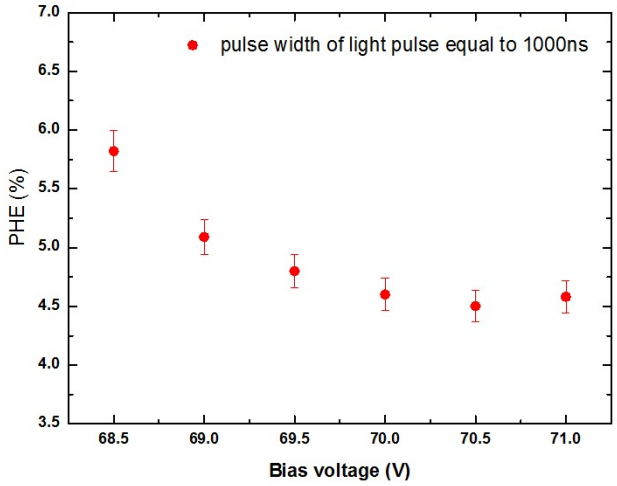

Figure 13. Pulse height resolution of the laser light pulser peaks, as used in figure 12, versus the bias voltage at the MPPC.

Studies of the photoelectron number detected in the MPPC in response to laser light pulse illumination were performed using the direct and PHR methods. The obtained results depend on the method applied, as the upper and lower limits of the photoelectron number were evaluated by the direct and PHR methods, respectively. The upper limit of the PHE determined using the direct method contains contributions by cross-talk and after-pulses of 10–20% for each process [4]. The lower limit of the photoelectron number was evaluated using the PHR method and the assumption that the MPPC excess noise factor is equal to 1.

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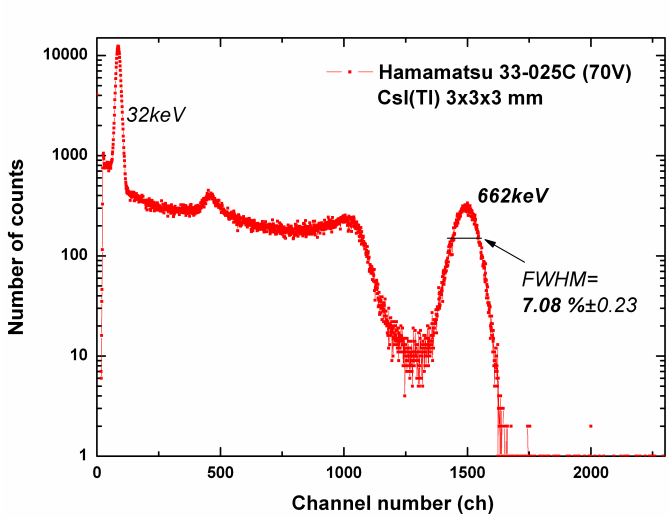

Figure 14. Energy spectrum of 662keV gamma rays from a ^{137}Cs source, as measured with CsI:Tl crystals $3\times3\times3$ mm^3 in size and coupled to the MPPC 33-025C (at 70V).

3.4 Gamma spectrometry with CsI:Tl and LFS scintillators

In the performance study of the MPPC in scintillation detection, LFS and CsI:Tl crystals $3\times3\times3$ mm^3 in size were used. Both crystals were polished on all surfaces, wrapped in Teflon tape and coupled to the MPPC with silicone grease.

The measurements covered tests of the energy resolution and non-proportionality of the crystals with the MPPC readout. The MPPC 025 device readout was used in this study because of its large linear dynamic range. The obtained results were compared to those reported with the XP2020Q PMT readout.

Figure 14 presents the energy spectrum of gamma rays from a ^{137}Cs source. The 662keV photoelectron peak energy resolution of $7.1\pm0.2\%$ reflects good performance of the MPPC 33-025C at 70V bias voltage. The measured energy resolution is comparable to that recorded with the XP2020Q PMT of $6.7\pm0.2\%$ (see table 3).

The points in figure 15 illustrate an improvement of the photon detection efficiency with an increase in the bias voltage applied to the MPPC. However, mainly at higher bias voltages the photoelectron number is also enhanced by cross-talk and after-pulses [4]. The performance in gamma spectrometry of the CsI:Tl and LFS-3 scintillators with MPPC 33-025C and XP2020Q PMT readouts is compared in table 3. The number of photoelectrons per unit energy (phe/MeV) was measured using the direct method and normalized for the 662keV full energy peak in a ^{137}Cs γ-source spectrum. The listed parameters show comparable energy resolution measured with the CsI:Tl crystal coupled to the MPPC and XP2020Q, while the energy resolution of the LFS degrades with the MPPC 33-025C readout because of a lower photoelectron number.

The measured light output of the tested crystals with the calibrated XP2020Q PMT allows to estimate the PDE of the MPPC 33-025C for the emission light wavelengths of the LFS and the CsI:Tl (see table 3). The number of photoelectrons measured in the direct way was divided by the number of photons measured with the XP2020Q. The PDEs for both scintillators are significantly

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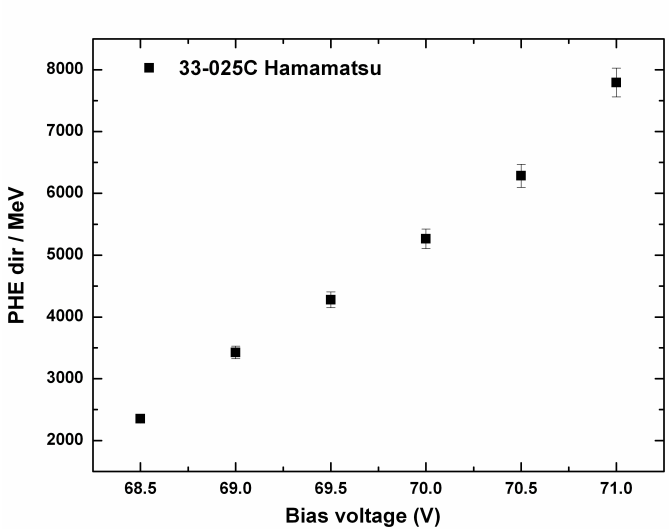

Figure 15. Photoelectron number versus bias voltage for the CsI:Tl crystal coupled to the MPPC 33-025C. The curves reflect the PDE.

Table 3. Comparison of PMT XP 2020Q and MPPC 33-025C in gamma spectrometry with CsI:Tl and LFS-3.

Detectors				PMT XP2020Q Photonis (bias voltage = 1500 V, excess noise factor = 1.2)			MPPC 33-025C Hamamatsu (bias voltage = 70 V, excess noise factor = 1.42)			
Crystal	Size (mm)	Shaping time constant - bipolar	Light output (ph/MeV)	PHE (phe/MeV)	ΔE/E at 662 keV	ΔE/E at 320 keV	PHE (phe/MeV)	PDE (%)	ΔE/E at 662 keV	ΔE/E at 320 keV
LFS-3	3x3x3	0.25μs	30300 ±1500	5940 ±180	8.5 ±0.3 %	11.8 ±0.4 %	4600 ± 40	15 ±1.5 %	9.6 ±0.3 (non-linear)	13.2 ±0.4 %
CsI:Tl	3x3x3	6 μs	51000 ±2500	**4800** ±**120**	**6.7** ±**0.2 %**	9.3 ±0.3 %	**5260** ±**160**	10 ±1	**7.1** ±**0.2 %**	9.7 ±0.3%

lower than those quoted by the manufacturer data, in spite of the fact that they are overestimated by the cross-talk and after-pulses. A similarly low PDE of about 9% was reported in [5], as measured with an LSO pixel crystal of 3x3x20 mm^3 coupled to the MPPC 025; however, at a lower bias voltage of 69V. The lower PDE can be related to the smaller contribution of the contamination of photoelectron numbers by the cross-talk and after-pulses (see a lower ENF at this voltage in figure 11).

The non-proportionality of the light yield is an important characteristic of the crystal strongly influencing the linearity and energy resolution of the scintillation detector [14]. Its shape should be independent of the crystal readout device. Figure 16 presents the non-proportionality curves measured with the CsI:Tl crystals coupled to the MPPC 33-025C and the XP2020Q PMT. The non-proportionality curves are nearly identical, which confirms good linearity of the MPPC 33-025C operating at a bias voltage of 70V.

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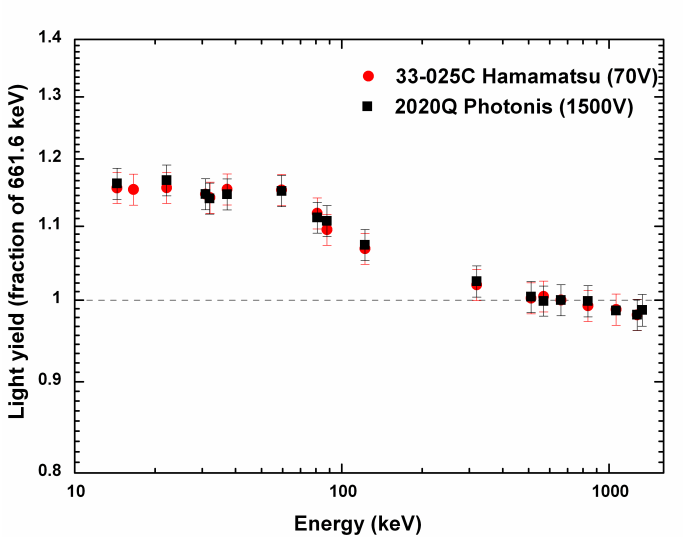

Figure 16. Non-proportionality functions measured with the CsI:Tl crystal coupled to the MPPC 33-025C and XP2020Q PMT.

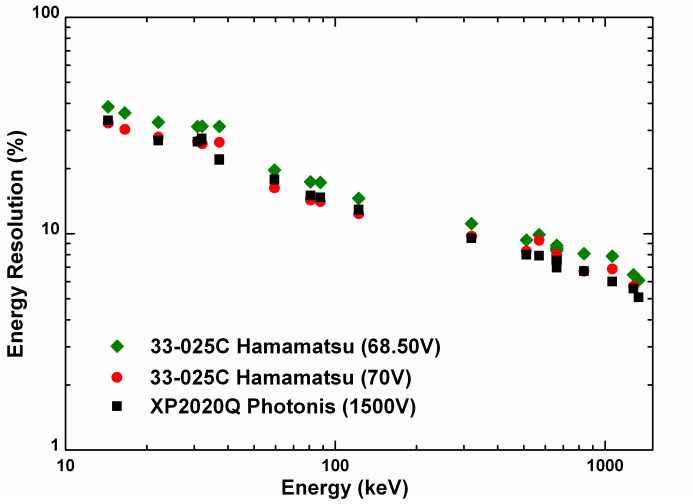

Figure 17. Energy resolution measured with CsI:Tl $3\times3\times3$ mm^3 coupled to the MPPC 33-025C, biased with two different voltages — 68.50 and 70V. The same energy resolution but measured by means of PMT XP2020Q — 1500V. Error bars are within the size of the points.

Figure 17 shows the dependence of the energy resolution on the energy of the gamma rays measured with the CsI:Tl crystal coupled to the MPPC 33-025C and the XP2020Q PMT. The curve measured with the MPPC at its optimal 70V bias voltage is fully comparable to that obtained with the XP2020Q readout. The same characteristic measured with the MPPC at a bias voltage reduced to 68.5V showed a systematically worse energy resolution. This is related to the decrease of the MPPC PDE and, consequently, a smaller number of the detected photons (see figure 13).

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4 Conclusions

The study of an MPPC in gamma spectrometry performed with LFS and CsI:Tl scintillators and the complementary study of the pulse height resolution of the laser light pulses from a laser pulser led to the following conclusions:

- the linearity of the MPPC response, because of the finite number of APD cells, is strongly limited for intense, fast light pulses, like those of the LFS/LSO/LYSO scintillator family. The response to the LFS scintillation light is linear only up to a gamma ray energy of about 320keV, as for the slow pulses of the CsI:Tl the MPPC 33-025C is fully linear up to a gamma energy of about 1.3 MeV. The broad linear range of the MPPC response to the CsI:Tl scintillation light can be explained by the low peak intensity of the light and a negligible contribution of the APD cell dead time of 10ns in relation to the 1 μs decay time of the scintillation pulse. The linearity of the response to the fast light pulses of the LFS/LSO is strongly affected by the APD cell dead time comparable to the scintillation decay time constant of 40ns.

- The photoelectron number measured by the direct method, where the light peak position is compared to that of the single photoelectron peak, is overestimated due to cross-talk and after-pulse events. It represents the upper limit of the photoelectrons generated in the MPPC.

- The evaluation of the photoelectron number from the pulse height resolution of the laser light pulser peak, performed assuming a value of MPPC excess noise factor of 1, leads in turn to the lower limit of the photoelectron number. This is because the effective excess noise factor of the MPPC is larger than 1 — a value used in our evaluations. The increase of the ENF is mainly caused by cross-talk and after-pulse contribution.

- The optimal bias voltage of 70V, for gamma spectrometry with the tested MPPC, was evaluated. The upper limit of the excess noise factor of 1.35 was measured at this voltage. The advantage of such a high voltage is a higher PDE and an improved energy resolution.

- The good performance of the MPPC 33-025C in gamma spectrometry with CsI:Tl has to be pointed out. The energy resolution and non-proportionality characteristics are very close to those measured with the XP2020Q PMT.

Summarizing, the MPPCs performance in gamma spectrometry is very application specific in comparison to PMTs. When considering the energy measurements using fast scintillators, the linearity of the device depends not only on the number of APD cells, but also on their recharge time in relation to the scintillation light intensity and decay time. For the MPPC to obtain the best detector performance a certain trade-off between the PDE and excess noise factor has to be achieved. The flexibilities of PMTs in spectroscopy applications are much broader than those of currently commercially available MPPCs.

Acknowledgments

This work was supported in part by the EU Structural Funds Project no POIG.01.01.02-14-012/08-00.

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References

[1] P. Buzhan et al., *Silicon photomultiplier and its possible applications*, *Nucl. Instrum. Meth.* **A 504** (2003) 48.

[2] D. Renker, *Geiger-mode avalanche photodiodes, history, properties and problems*, *Nucl. Instrum. Meth.* **A 567** (2006) 48.

[3] D. Renker and E. Lorenz, *Advances in solid state photon detectors*, 2009 *JINST* **4** P04004.

[4] P. Eckert, H.-C. Schultz-Coulon, W. Shen, R. Stamen and A. Tadday, *Characterisation studies of silicon photomultipliers*, *Nucl. Instrum. Meth.* **A 620** (2010) 217 [arXiv:1003.6071].

[5] A. Nassalski et al., *Silicon photomultiplier as an alternative for APD in PET applications*, *IEEE Trans. Nucl. Sci.* **57** (2010) 1008.

[6] H.T. van Dam et al., *A comprehensive model of the response of silicon photomultipliers*, *IEEE Trans. Nucl. Sci.* **57** (2010) 2254.

[7] S. Vinogradov et al., *Efficiency of solid state photomultipliers in photon number resolution*, *IEEE Nucl. Sci. Symp. Conf. Rec.* (2009) 1952.

[8] M. Grodzicka et al., *Characterization of LFS-3 scintillator in comparison with LSO*, *Nucl. Instrum. Meth.* **A 652** (2011) 226.

[9] M. Moszyński et al., *Characterization of scintillators by modern photomultipliers — a new source of errors*, *IEEE Trans. Nucl. Sci.* **57** (2010) 2886.

[10] M. Moszyński, *Energy resolution of scintillation detectors*, *Proc. SPIE* **5922** (2005) 16.

[11] M. Moszyński et al., *Comparative study of avalanche photodiodes with different structures in scintillation detection*, *IEEE Trans. Nucl. Sci.* **48** (2001) 1205.

[12] M. Bertolaccini, S. Cova and C. Bussolati, *A technique for absolute measurements of the effective photoelectron yield in scintillation counters*, in *Proc. Nucl. Electronics Symp.*, Versailles France (1968).

[13] Z. Guzik et al., *TUKAN — an 8K pulse height analyzer and multi-channel scaler with a PCI or a USB interface*, *IEEE Trans. Nucl. Sci.* **53** (2006) 231.

[14] A. Syntfeld et al., *Non-proportionality and energy resolution of CsI:Tl*, *IEEE Trans. Nucl. Sci.* **54** (2007) 1836.

2013 JINST 8 P02017