Few electron response and spurious background of linear focused photomultipliers

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Abstract

The compact, linear focused ten-stage photomultipliers Hamamatsu R 1450 and R 1355 have been studied with light pulses generating small numbers ($\overline{N}_e \leq 25$) of photoelectrons. Good amplitude resolution for single photoelectrons as well as for small signals in general was obtained by considerably increasing the supply voltage U_1 of the first dynode. The time resolution is dominated by the statistical variation of N_e. The importance of background from micro-discharges and Čerenkov radiation is discussed.

1 Introduction

Fast plastic scintillators are an indispensable component of almost any modern detection system for minimum ionizing particles in particle physics [1,2]. Their application helps to meet the increasing demand for 4π solid angle coverage in combination with high granularity and good multiplicity resolution; it will, however, also generate some experimental problems. The first one is the request for good energy and/or time resolution that has to be fulfilled with small numbers of photoelectrons released at the photocathodes of the light sensing photomultipliers. Secondly, the large number of scintillator elements requires an *intrinsic* gain and function control in addition to that provided e.g. by light pulser based monitor systems.

It is qualitatively obvious (and will be quantitatively discussed in this paper) that photomultipliers with good amplitude resolution for single electron response (SER) will at the same time show a good resolution $v_A = \sigma_A/\overline{A}$ of their current gain A. It is therefore worth optimizing the amplitude resolution of the SER, because both problems mentioned above will benefit from it.

In the present paper, the variation of the supply voltage U_1 for the first dynode is applied as a decisive parameter in this respect (Sect. 2.3). Our study continues a preceding work [3] on large samples of photomultipliers HAMAMATSU R 1355 and R 1450 chosen for the EDDA experiment [4,5] because of their compact construction and good linearity over a broad dynamic range. This paper will therefore be restricted to these two photomultiplier (PM) types.

A well resolved SER in each PM will allow to control the response of a scintillator to a given deposited energy and thus to monitor long term shifts. In addition the pulse height can be expressed in terms of a primary photoelectron number N_e. Therefore the time resolution Δt for a given deposited energy becomes predictable if Δt once has been measured as a function of N_e. This topic will be covered in Sect. 3.

Finally, Sect. 4 is devoted to a short study of low level background from micro-discharges and from ČERENKOV radiation generated in the glass body of the PM.

2 Single electron response

2.1 General remarks

In contrast to early types of photomultipliers most of the modern ones, especially those with a linear focused dynode system, show more or less well resolved single electron response (SER) peaks even in their background (dark) spectra, that is without illuminating the cathode at sufficiently low intensities. The SER resolution of photomultipliers not optimized in this respect may range from a bare separation from the dark noise to a clear separation of a two (and more) electron response if additional light is applied. They hereby approach the capability to resolve *multi* electron events found with specialized PMs with a highly efficient GaP first dynode. To recall this the upper part of fig. 1 presents a corresponding output pulse height spectrum obtained for the RCA PM 8850 when we illuminated it with low light level pulses from a green light emitting diode. But even for PMs with conventional dynode materials, a multi electron resolution may be recognizable in selected cases as shown by the spectrum in the lower part of fig. 1 recorded with a PM R 1355. This type as well as the R 1450 are considered in the following sections.

2.2 Gain resolution and SER

Neglecting electron transfer losses between the electrodes, the (current) gain A of an n-stage PM is the product of the secondary emission coefficients δi of the i-th out of n dynodes Di. The quantities A and δi are subjected to statistical fluctuations. Straightforward considerations yield for the respective relative variances v^2

$$v_A^2 = v_{\delta 1}^2 + \frac{v_{\delta 2}^2}{\overline{\delta 1}} + \frac{v_{\delta 3}^2}{\overline{\delta 1} \cdot \overline{\delta 2}} + \cdots + \frac{v_{\delta n}^2}{\overline{\delta 1} \cdot \overline{\delta 2} \cdot \overline{\delta 3} \cdot \cdots \cdot \overline{\delta (n-1)}}$$

with the relative standard deviation or "gain resolution" $v_A = \sigma_A / \overline{A}$, where $\overline{A}$, and accordingly $\overline{\delta i}$, indicate the corresponding mean values. Assuming $v_{\delta i}^2 = 1/\overline{\delta i}$ for each multiplication process, as it is valid e.g. for a poissonian distribution, leads to

$$v_A^2 = \frac{1}{\overline{\delta 1}} + \frac{1}{\overline{\delta 1} \cdot \overline{\delta 2}} + \frac{1}{\overline{\delta 1} \cdot \overline{\delta 2} \cdot \overline{\delta 3}} + \cdots + \frac{1}{\overline{\delta 1} \cdot \overline{\delta 2} \cdot \overline{\delta 3} \cdot \cdots \cdot \overline{\delta n}}.$$

This formula quantifies the familiar fact, that v_A is mainly determined by $\overline{\delta 1}$.

For a totally homogeneous PM, which means $\overline{\delta 1} = \overline{\delta 2} = \cdots = \overline{\delta n} = \overline{\delta}$, the result is the geometrical series

$$v_A^2 = \sum_{k=1}^{n} \left(\frac{1}{\overline{\delta}} \right)^k = \frac{\overline{\delta}^n - 1}{\overline{\delta}^n \cdot (\overline{\delta} - 1)}.$$

For a 10-stage PM ($n = 10$) and a typical value $\overline{\delta} \approx 4$ certainly $\overline{\delta}^n \gg 1$ holds. Thus the above expression reduces to

$$v_A^2(\overline{\delta}) = \frac{1}{\overline{\delta} - 1}. \tag{1}$$

If $\overline{\delta 1}$ or $\overline{\delta 2}$ are explicitely taken into account, eq. (1) is replaced by the relations

$$v_A^2(\overline{\delta 1}) = \frac{1}{\overline{\delta 1}} \cdot \frac{\overline{\delta}}{\overline{\delta} - 1} \tag{2}$$

and

$$v_A^2(\overline{\delta 2}) = \frac{1}{\overline{\delta}} + \frac{1}{\overline{\delta 2}} \cdot \frac{1}{\overline{\delta} - 1}. \tag{3}$$

The influence of $\overline{\delta}, \overline{\delta 1}$ and $\overline{\delta 2}$ on v_A, resulting from eqs. (1), (2) and (3), is presented in fig. 2. Curve a.) corresponds to eq. (1). A reduction of v_A by e.g. 50% requires an increase of $\overline{\delta}$ by roughly a factor of 3. To achieve this by raising the total supply voltage U_0 is impracticable if not impossible because it had to be enhanced by at least the same factor. The variation of v_A with $\overline{\delta 1}$ according to eq. (2) for a fixed value of $\overline{\delta} = 4$ is given by curve b.). Here a significant improvement by increasing $\overline{\delta 1}$ with the voltage U_1 between the photocathode and the first dynode $D1$ is feasible. This possibility will be discussed in this paper. Another well known technique to improve v_A is to use a negative electron affinity material for $D1$, such as Cs-doped GaP ($\overline{\delta 1} \approx 20$ at roughly 400 eV primary electron energy). Finally curve c.) follows v_A as a function of $\overline{\delta 2}$ as described by eq. (3) again for $\overline{\delta} = 4$. As expected no considerable improvement of v_A is attainable.

The influence of the gain resolution v_A on the detection of light pulses is described by the relation [6,7]

$$v_Q^2 = v_{N_{ph}}^2 - \frac{1}{\overline{N_{ph}}} + \frac{v_A^2 + 1}{\overline{N_{ph}} \cdot \overline{q}}. \tag{4}$$

Here N_{ph} is the number of photons per pulse reaching the cathode, $\overline{q}$ the mean quantum efficiency of the cathode and Q the charge delivered to the anode. Thus v_Q is the "amplitude resolution" of the integrated anode pulses. The corresponding value v_{Q1} for a *single electron* leaving the cathode can be deduced from eq. (4) by simulating this particular case with a light source emitting *exactly* one photon per pulse onto a cathode with $\overline{q} = 1$. This means $\overline{N_{ph}} = 1$ and $v_{N_{ph}}^2 = 0$, which results in $v_{Q1} = v_A$. *Thus the amplitude resolution v_{Q1} of the SER peak observed at the anode directly represents the gain resolution v_A.* If N_{ph} follows a poissonian distribution $\left[v_{N_{ph}}^2 = 1/\overline{N_{ph}}\right]$, then eq. (4) reduces to

$$v_Q^2 = \frac{v_A^2 + 1}{\overline{N_{ph}} \cdot \overline{q}}. \tag{5}$$

In case transfer losses are taken into account characterized by an efficiency αi for the transport of the secondary electrons between Di and $D(i+1)$, the coefficients δi in the above relations have to be replaced by $\alpha i \cdot \delta i$.

2.3 Experimental procedure and results

Our experimental procedure for the SER measurements was very simple. The photocathode of the PM under test was continuously illuminated by a green light emitting diode at an intensity low enough to ensure, that the probability of releasing more than one photoelectron within the integration time of the amplifier connected to the anode was negligible (single photon counting condition [8]). The $Q1$-spectra were stored in a pulse height analyzer and dark noise spectra, normalized to the same time, subtracted. In order to study exclusively the influence of $\overline{\delta 1}$ on v_A by varying U_1, the bleeder chain current had to be kept constant to maintain the original voltage distribution from $D1$ to the anode irrespective of the actual U_1 value. Details may be found in [9].

The recorded data are two series of background corrected SER spectra for the two PM types obtained at ten different voltages. Some selected ones are compiled in fig. 3.

Although the dark spectra are subtracted, a background-like contribution rising continuously towards small pulse heights still remains. This is well known and essentially attributed to so-called "edge effects". It means that the photoelectrons emitted near the rim of the cathode are not optimally focused onto the central region of $D1$ but onto its edges. This results in a poor starting position for an effective focusing of the secondary electrons onto the next dynode, and so on. Thus appreciable transfer losses within the dynode system have to be taken into account. In addition, photoemission from the first dynodes due to light passing the semitransparent cathode can contribute to this part of the spectrum. It extends into the peaked region of the SER and can introduce a noticable shift between the real and the observed peak position. A rough estimation shows that for the spectra discussed here this shift can be neglected in all cases but those for the PM R 1450 at $U_1 = 100$ V and 150 V.

The position of the SER peak is proportional to $\overline{\delta 1}$. The variation with U_1 of its relative value $\overline{\delta}_r = \overline{\delta 1}(U_1)/\overline{\delta 1}(U_{1,norm})$ with $U_{1,norm} = 150$ V is presented in the upper part of fig. 4. The data points follow the expected trend. According to eq. (2), an increase of $\overline{\delta}_r$ improves the gain resolution v_A leaving the product $\overline{\delta}_r \cdot v_A^2$ unchanged. The corresponding results are plotted in the lower part of fig. 4. The standard deviation and thus v_A were determined from the undisturbed shape of the SER peak beyond the maximum. According to eq. (5), a change of the gain resolution from $v_{A,1}$ to $v_{A,2}$ yields

$$\frac{v_{Q,2}}{v_{Q,1}} = \sqrt{\frac{v_{A,2}^2 + 1}{v_{A,1}^2 + 1}}$$

for the resulting charge resolutions. For instance the values $v_{A,1} = 0.71$ and $v_{A,2} = 0.32$ obtained for the PM R 1450 yield $v_{Q,2} = 0.8 \cdot v_{Q,1}$. This improvement is small compared to the factor 2.2 of the ratio $v_{A,1}/v_{A,2}$. The dashed lines in fig. 4 indicate the mean values of $\overline{\delta}_r \cdot v_A^2$. The rather large deviations of the first two points given in parentheses from a constant value for the PM R 1450 probably originate from the peak shift mentioned in the preceding paragraph.

3 Timing properties

The timing properties of the two photomultipliers were studied with a conventional set up: The cathode of the photomultiplier PM under test was illuminated by short light pulses from a green light emitting diode driven by a fast pulse generator [10]. The light yield per pulse reaching the cathode was controlled by an adjustable attenuator consisting of a pair of polarizing filters turnable with respect to each other. The anode pulses with a rise time of about 2 ns and a fall time constant of roughly 5 ns were fed into the stop input of a time-to-pulse height converter via a fast amplifier, a constant fraction discriminator and a variable delay. The start signals were taken from the pulse generator. A pulse height analyzer stored the time spectra. In addition, the anode pulses could be integrated by an amplifier. From the recorded anode charge spectra, the mean number $\overline{N_e}$ of photoelectrons released per light pulse from the PM cathode could be determined by comparing the position of the light induced charge peak to that of the SER peak. $\overline{N_e}$ could be varied with the light attenuator. Before each run for a given number $\overline{N_e}$ or a preset value U_0 of the PM supply voltage, the gain of the fast amplifier was readjusted to yield approximately the same mean pulse height at its output in order to minimize possible time walk influences introduced by the constant fraction discriminator.

The time resolution Δt obtained as a function of $\overline{N_e}$ and expressed by the FWHM of the recorded time peaks is plotted in the upper part of fig. 5. The lines are fits to the data according to

$$\Delta t = \sqrt{\alpha^2 + \frac{\beta^2}{\overline{N_e}}}$$

where α describes noise contributions from the PM and the electronics that are independent on the light output, and the β term includes the photoelectron statistics. The fit results are $\alpha = 0.30$ ns (0.56 ns) and $\beta = 1.41$ ns (1.73 ns) for the larger (smaller) PM R 1355 (R 1450); these numbers demonstrate the dominance of the photoelectron statistics for $\overline{N_e} \leq 10$.

The variation $\Delta T = T - T_0$ of the transit time T as a function of U_0 and relative to the reference value T_0 for $U_0 = 1000$ V was determined from the shift of the time peak with U_0. The results are shown in the upper part of fig. 5 and may be compared to the transit times $T = 23$ ns (R 1450: 19 ns) and their spread $\delta T = 650$ ps quoted by the manufacturer [11]. It can be seen that the variations ΔT extend over 30% of these transit times.

4 Some selected background aspects

A noticable contribution to the background of a photomultiplier may arise from microdischarges or sparks originating at sharp edges of those electrodes which are on a high potential relative to their environment. In the case the PMs are operated with their anodes at ground potential, the electrodes in question are the photocathode, the first dynode and those of the input focusing system. For PMs with moderate cathode diameters and not specially designed e.g. for fast timing purposes, a simple and effective focusing system may be realized in a way sketched in fig. 6 taken from [8]. The focusing electrode FE is a metallic lining evaporated onto the inner surface of the glass envelope and connected to the photocathode PH. The accelerating electrode AE is a ring in contact with the first dynode $D1$. The dashed lines indicate some equipotential planes. The shaded area includes all paths of photoelectrons emitted from one point of PH at an energy of about 1 eV into a rather large solid angle for a PH-$D1$ voltage of about 200 V. The most critical regions for discharges or sparking towards the glass envelope are the rims R of FE and AE where correspondingly high field strengths arise.

A discharge contribution to the background may lead to serious consequences. The produced light can release up to several hundreds of photoelectrons from PH resulting in large output pulses severely deteriorating interesting pulse height spectra. Furthermore the unstable physical mechanism of such discharges causes pulse bursts with unpredictable pulse shapes and rates preventing reliable informations on the background spectrum.

An effective and well known remedy is a conductive coating on the outer surface of the glass envelope at a potential in the vicinity of that of the cathode reducing the field strengths in the problematic regions. The efficiency of such a coating is demonstrated by fig. 7 for the background spectrum of the PM R 1450. Spectrum A was recorded without, spectrum B with an external coating. Obviously all events above roughly 500 channels are due to the discussed discharges. Increased ohmic leakage does not contribute to this region. As a consequence all PMs for the EDDA detector were provided with a coating.

As a second background aspect the response of a photomultiplier to high energy electrons was studied. For this purpose a collimated 3 GeV electron beam of about 2 mm in diameter from the test facility at the DESY synchrotron was used. These electrons produce Čerenkov light in the glass envelope of the PM, which can reach the photocathode and lead to a background contribution. Fig. 8 presents three selected results of output pulse height spectra for the PM R 1450 obtained under different conditions. In the first case the beam was directed parallel to the PM axis onto the centre of the entrance window, where it generates Čerenkov radiation. Because it is emitted into a narrow forward cone it completely arrives at the cathode. The observed output spectrum shows a peak at channel 65. When the beam traverses the PM axially in the opposite direction after passing the bleeder chain assembly and the socket, the peak shifts to lower channels. In addition a broad distribution towards higher amplitudes appears. This second component may be attributed to Čerenkov light from the glass base of the PM reaching the cathode via light guiding by the glass envelope or via reflections at its inner surface. The peak may be due to light from the entrance window partially conducted to the cathode by multiple reflections within the window. For the support of the assumption, that the recorded pulse height spectra are indeed due to or at least mainly caused by ČERENKOV radiation, a 6 mm thick glass plate was mounted onto the window in a third run. The position of the PM relative to the beam direction was the same as in the first case. Now a rather broad but fairly symmetric peak at channel 120 is observed. Based on the known yield of ČERENKOV radiation of 3 GeV electrons in glass, this pulse height is expected to correspond to about 20 photoelectrons. Thus the mean output amplitude has roughly doubled compared to the first situation. It should be noted finally that of course contributions from scintillations excited by the beam in the PM envelope cannot be totally excluded.

5 Summary

The present paper supplements our test [3] of large samples of the linear focused, ten-stage photomultipliers R 1355 and R 1450. These compact PM's are of particular interest for the readout of small scintillators sampling small amounts of energy deposited; the timing and pulse height performance of such detector components is then crucially dependent on their response to low light intensities. Our studies of the single and few electron response yielded the following main results.

(i) The relative gain resolution v_A, being closely related to the relative amplitude resolution of the SER, can be most effectively improved by increasing the voltage U_1 of the first dynode and thereby its secondary emission coefficient $\overline{\delta 1}$, because $v_A \sim (\overline{\delta 1})^{-1/2}$, see eq. (2) and lower part of fig. 4.

(ii) For low photoelectron numbers $N_e \leq 10$, the time resolution is determined by their statistical variation and approaches $\Delta t = 300$ ps (560 ps) FWHM for the R 1355 (R 1450) with growing N_e; an increase of the overall supply voltage U_0 may change the intrinsic transit time T by up to 30% and thus influence coincidence requirements.

(iii) Low level counting and spectroscopy requires minimization of background from micro-discharges by means of a conductive coating on the surface of the glass body, and from ČERENKOV radiation from the glass body by optimizing the alignment of the PM with respect to the fast charged particles penetrating.

Acknowledgements

The authors would like to thank the staff of the DESY II test beam facility for their help and Mrs. M. Berghaus for preparing the drawings and the manuscript. This work was financially supported by the Bundesministerium für Forschung und Technologie (contract 06 HH 613).

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Figure Captions

Fig. 1 Few electron spectra obtained with the PMs RCA 8850 (GaP first dynode material) and HAMAMATSU R 1355 (conventional first dynode material).

Fig. 2 Dependence of the gain resolution v_A of photomultipliers on the secondary emission coefficients $\overline{\delta}, \overline{\delta 1}$ and $\overline{\delta 2}$.

Fig. 3 Single electron spectra for various voltages U_1 between the photocathode and the first dynode.

Fig. 4 Variation of the (relative) first dynode secondary emission coefficient $\overline{\delta}_r$ (upper part), and of the gain resolution v_A (lower part) with U_1.

Fig. 5 Timing properties: Time resolution Δt as a function of the number $\overline{N}_e$ of photoelectrons and transit time variations ΔT as a function of the supply voltage U_0.

Fig. 6 Principal layout of an input focusing system in (linear focused) photomultipliers.

Fig. 7 Contribution of micro-discharges to the background spectrum for glass envelopes without (A) and with (B) coating.

Fig. 8 Contributions of ČERENKOV radiation to background spectra.