Reduction of space charge effects and tests of larger samples of photomultipliers for the EDDA experiment

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Abstract

For the EDDA experiment at COSY, the response of the small, linear focused photomultipliers HAMAMATSU R 1450 and R 1355 has been studied with fast light pulses generating yields up to $2 \cdot 10^3$ photoelectrons/cm^2 or peak currents of 24 mA. Linearity was obtained with a tapered bleeder chain at a tolerable loss of gain. The serial test of altogether 140 photomultipliers revealed the close correlation between single electron and amplitude resolution. The influence of the photoelectron statistics on this correlation is discussed.

1 Introduction

In medium energy particle physics with hadronic projectiles in the GeV range there is an increasing demand for detector components that can be operated at high luminosities and allow to trigger on rare, low multiplicity events. These components must therefore offer a fast response and high granularity for on-line triggering, with additional off-line capabilities for improvement of (spatial and time) resolution. Examples for such experiments and detector systems may be found, e.g., in [1,2].

Plastic scintillators are the optimum choice for this task, and several detector designs make use of small scintillator elements in a variety of geometries, down to scintillating fibers. The ideal photomultiplier (PM) to read out the resulting, mostly small amounts of light, must meet several requirements, namely

(i) compact geometry

(ii) high ($\geq 10^6$) current gain

(iii) single electron response (SER)

(iv) linearity over a broad dynamic range

(v) narrow tolerances of general properties for large numbers of PMs.

The selection of PM types in the present work was motivated by requirement for the EDDA detector that is designed for a study of elastic *pp* scattering over a broad angular and energy range [3] at the (proton) Cooler Synchrotron COSY. Its outer detector layer (and trigger section) consists of 32 scintillator bars (material BC 408, length 95 cm, cross section 2.3 cm^2, read out on both sides) and 2×29 semirings (BC 408, radius 16 cm, cross sections 3–22 cm^2) and is facing integral count rates of up to 100 kHz. The off line reconstruction of proton trajectories rests in a comparison of energies deposited in adjacent overlapping scintillator segments that vary between 100 keV and 10 MeV. For this application, requirement (iv) is indispensable. The geometrical constraints of the detector geometry limited the outer PM diameters to 28 mm (for the scintillator bars) and 19 mm (semirings). As a result of prototype tests, the two types HAMAMATSU R 1355 and R 1450 were selected [4]. Both types are 10-stage, head-on linear focused PMs differing essentially in their photocathode diameter of 25 mm and 15 mm, respectively.

In Sect. 2 of this work, we focus on achieving linearity ranging from a few up to 2×10^3 photoelectrons released per cm^2 of the photocathode for the rather small type R 1450 by optimizing the bleeder chain in this respect. These studies were performed with one tube chosen at random.

Sect. 3 is devoted to a series test of both PMs that were commercially obtained at 70 pieces of each type. The features tested were a.) the gain for illumination by light pulses relative to the average gain value;

b.) the resolution for the amplitude distribution of the integrated output pulses for this type of illumination;

c.) the gain for single electrons from the cathode in units of the average value;

d.) the resolution of the peak in the single electron response (SER) which is identical to the gain resolution.

Our results are summarized in Sect. 4.

2 Space charge effects in photomultipliers

2.1 General remarks

Current limitation by space charge saturation is a well known effect since the early days of developing effective thermoemission cathodes and tubes for radio communication purposes. For the simple configuration of two plane-parallel electrodes (area a, distance d), one of them emitting electrons with an initial velocity $v_0 = 0$, the other one acting as an anode, straightforward calculations lead to the familiar law

$$I = \frac{4}{9} \cdot \epsilon_0 \cdot \left(2 \cdot \frac{e_0}{m}\right)^{1/2} \cdot \frac{a}{d^2} \cdot U^{3/2}$$

for the space charge limited current I as a function of the applied voltage U, where e_0/m is the electron charge-to-mass ratio and ϵ_0 the electric field constant. This expression holds for

$$0 < U < U_s = \left[\frac{9}{4 \cdot \epsilon_0} \cdot \left(\frac{m}{2 \cdot e_0}\right)^{1/2} \cdot \frac{d^2}{a} \cdot I_s\right]^{2/3} .$$

For $U > U_s$ the current remains constant at its saturation value I_s, where all emitted electrons reach the anode.

In a realistic case, one has to start from a velocity distribution $f(v_0)$ of the emitted electrons, and an analytical and quantitative derivation of a space charge law becomes much more tedious. Even for simple analytic expressions $f(v_0)$ only approximative results can be obtained, at best.

As an example for a *measured* result, fig. 1 shows space charge influenced I_A vs. U characteristics at various saturation currents I_s for the PM R 1450. Here I_A denotes the anode current and U the voltage between the last (10^{th}) dynode and the anode. The voltage distribution along the dynode chain was kept constant. The photocathode was illuminated continuously and uniformly with a green light emitting diode and I_s changed by varying the intensity. Obviously and as expected, the curves resemble the well known characteristics of a vacuum diode. The observed current for $U < 0$ results from the distribution $f(v_0)$.

Scintillation signals, however, give rise to anode current pulses randomly distributed in time. In this case, quantitative predictions on a space charge influence are impossible, because too many parameters (pulse shape, count rate, dynode structure, energy and angular distribution of the secondary electrons, last dynode-anode configuration etc.) are involved. The anticipated qualitative feature is an increasing flat-topping and broadening of the anode pulse with amplitude. Fig. 2 demonstrates this phenomenon [5]. The pulses were recorded by a fast oscilloscope and generated by scintillations in an NE 110 plastic scintillator that was exposed to a collimated 3 GeV electron beam from the DESY Synchrotron. Different light yields were achieved by varying the scintillator thickness traversed by the beam. The bleeder chain for the PM (R 1450) was essentially that recommended by the manufacturer.

2.2 Experimental set up and procedure

The main components of the experimental set up are shown in fig. 3. It is a schematic presentation and not to scale. The pulsed light from a linear array L of four green light emitting diodes was converted with a cylindrical (plastic) lens C into a nearly parallel beam. It passed a grey wedge G, which could be moved across it, and reached the photocathode of the photomultiplier PM (R 1450). B is the bleeder chain under test. L was driven by a fast pulse generator PG [6] at a rate of about 10 kHz yielding anode pulses with a 3 ns rise time and a fall time constant of roughly 20 ns. The pulses were fed into a pulse height analyzer PHA via a fast linear gate FG controlled by PG and an integrating amplifier A.

If ℓ and d_0 denote the length and maximal thickness of the grey wedge and x_1, x_2 the fixed positions of its edges on an x-scale attached to it, then the thickness $d(x)$ at the position x of the beam axis, is

$$d(x) = \frac{x - x_1}{\ell} \cdot d_0. \tag{1}$$

Thus the amount $L(x)$ of light transmitted per pulse of given total length T_0 is determined by the attenuation length λ of the wedge material, viz.

$$L(x) = \int_0^{T_0} i(t) \cdot dt = L_0 \cdot e^{-d(x)/\lambda} = L_0 \cdot e^{-\gamma \cdot (x - x_1)}. \quad (2)$$

Here, $L_0 = L(x = x_1)$ is the amount entering the wedge, $i(t)$ its distribution in time and $\gamma = d_0/(\lambda \cdot \ell)$. Under ideal conditions, the corresponding anode charge per pulse within a gating interval T

$$Q(x,T) = \int_0^{T} I_A(t) \cdot dt = Q_0(T) \cdot e^{-\gamma \cdot (x - x_1)} \quad (3)$$

with $Q_0(T) = Q(x = x_1, T)$ should be proportional to $L(x)$. From $x - x_1 = \ell - (x_2 - x)$, it then follows that a plot of $\ln(Q/Q_0)$ versus $x_2 - x$ is a straight line with a slope γ.

Four bleeder chains specified in table 1 and denoted by B_1 to B_4 were studied. B_1 is the bleeder chain recommended by the manufacturer. Data were taken by recording the PHA channel number associated with the mean value $\overline{Q(x,T)}$ as a function of the wedge position $x_2 - x$ for various gating intervals T. Additional information is given in [7].

2.3 Results and discussion

The results presented were selected as typical to illustrate the problems. Fig. 4 shows a set of data plotted semilogarithmically for all bleeder chains and a gating time of $T = 60$ ns. Those for B_2, B_3 and B_4 could be fitted satisfactorily by parallel straight lines over the full range as expected from eq. (3). From the common slope the parameter $\gamma \sim \lambda^{-1}$ can be determined. Those for the bleeder chain B_1 intended for standard applications exhibited substantial deviations from linearity due to saturation effects beyond $x_2 - x = 9$cm which corresponds to photoelectron numbers of 10^3 and more. The supply voltage U_0 was chosen to maintain a bleeder chain current of $I_0 \approx 2$ mA without going beyond the tolerable maximum value of $U_0 = -1800$ V. The vertical displacement of the lines reflects the different gains explainable by the individual structure of the bleeder chains. It should be mentioned, that B_4 was suggested by SUZUKI [8] for best linearity.

According to eq. (2) the wedge position and the amount of transmitted light are related via

$$x_2 - x = \frac{1}{\gamma} \cdot \ln(L/L_0) + \ell. \quad (4)$$

From this point of view the plots of fig. 4 are double-logarithmic and therefore compressed presentations of Q versus L. Thus nonlinearities appear less pronounced. To make them stand out more clearly, *linear* plots of Q vs. L may be obtained with eqs. (3) and (4) by making use of the experimental result for γ. Two examples for bleeder chain B_1 and B_3 and two gate widths $T_1 = 35$ ns and $T_2 = 100$ ns are displayed in fig. 5. The straight line is the response for B_3. It reproduces the measured data that follow this line better than can be indicated. The other two curves refer to B_1. Gate width T_2, in contrast to T_1, nearly extends over the total anode pulse length (cf. fig. 2). The horizontal axis is calibrated in numbers N_e of photoelectrons released by $L(x)$. The two vertical scales (note the differences) give the charge $Q(x, T)$ relative to the gain $A(B_3)$ of bleeder chain B_3 and are measured in electron charges e_0. The calibration was performed with the aid of the peak in the dark noise single electron response of the PM with an accuracy of roughly $\pm$ 10%.

A comparison of the two results of fig. 5 shows, that the deviation from linearity is considerably stronger for T_1 than for T_2. This can be simply understood for instance from fig. 2. The space charge current limitation is most pronounced in the vicinity of the pulse peak and on the average weaker, if the total pulse is considered. It is obvious, that the bleeder chain B_1 must be discarded for all applications requiring linearity beyond $N_e \approx 200$.

A rough estimate of the peak currents involved can be obtained in the following way: Within a fairly good approximation the observed anode pulses decay exponentially with a time constant of $\tau \approx 20$ ns. Thus the total pulse charge Q and the peak current I_{A0} are related by

$$Q = \int_0^\infty I_A(t) \cdot dt = I_{A0} \cdot \int_0^\infty e^{-t/\tau} \cdot dt = I_{A0} \cdot \tau.$$

Assuming a gain of $A(B_3) = 10^6$ and $Q/A(B_3) = 3000 \cdot e_0$ then yields $I_{A0} = 24$ mA. So B_3 guarantees linearity of the PM response up to peak currents of this order of magnitude and was finally chosen for the application outlined in Sect. 1.

3 Series tests of photomultipliers

3.1 Experimental set up

The experimental set up is shown in fig. 6 schematically and not to scale. Eight PMs were mounted on a common board inside a light tight box and pointed towards a green light emitting diode L driven by a fast pulse generator PG [6] at a rate of about 10 kHz. They were wired in parallel and supplied by a common bleeder chain R_1 to R_{11}. During a light pulse all PMs are active and thus heavily loading the bleeder chain. To avoid resulting changes in the potential distribution along the bleeder chain, the voltages of the last three dynodes were stabilized externally by a multichannel high voltage supply HV which also delivered the (negative) voltage for the photocathodes. In addition, the last four dynodes were grounded via nF-capacitors. The light emission of L into the cone extending over the PM array was fairly isotropic yielding up to 200 photoelectrons per PM. Remaining anisotropies in the order of a few percent depending on the PM position were corrected for. The anode pulses were fed successively into an integrating amplifier and were then pulse height analyzed. Again, additional details may be found in [7].

3.2 Results and discussion

The gain A_L under illumination (respectively A_1 for the SER case) was measured via the channel numbers K_L resp. K_1 of the peak positions in the corresponding pulse height spectrum as qualitatively indicated in fig. 7. K_L and K_1 are proportional to the mean charges $\overline{Q}_L$ and $\overline{Q}_1$ per anode pulse. Measurements were performed for all 70 PMs of each type. The resulting average gain is denoted $<A>$, the distributions of $A_L/<A_L>$ and $A_1/<A_1>$ are presented in fig. 8 in the form of bar diagrams. The characteristics, width and high gain tailing, have been observed for samples of similar photomultipliers, too [9]. The widths of the bars in fig. 8 were adapted to the accuracy in determining the peak positions. This is relatively poor for the SER peak because the steeply rising background towards small amplitudes interfered for different tubes with varying extent. To emphasize this, fig. 9 shows two examples of a dark noise spectrum obtained for the PM R 1355, one with a rather diffuse, the other with a distinct and clear SER peak.

Assuming the simplest case of an ideal and homogeneous n-stage PM, the gain A depends on the secondary emission coefficient δ as $A = \delta^n$ such that the gain ratio $A^{(2)}/A^{(1)}$ for two samples is

$$A^{(2)}/A^{(1)} = (\delta^{(2)}/\delta^{(1)})^n.$$

Thus for a ten-stage PM deviations in δ by only $\pm 10\%$, for instance due to uncontrollable influences during the fabrication process, already lead to $A^{(2)} = 2.6 \cdot A^{(1)}$ resp. $0.35 \cdot A^{(1)}$, which covers the range of amplifications seen in fig. 8.

It should be noted, however, that the two upper diagrams of fig. 8 do not represent the mere gain distributions. Although the light source L and its operating conditions were the same throughout the whole test program, individual fluctuations in the quantum efficiency of the photocathodes may occur which were not considered here. $\overline{Q}_L$ is proportional to $\overline{Q}_1$:

$$\overline{Q}_L = \overline{N}_e \cdot \overline{Q}_1,$$

where $\overline{N}_e$ is the mean number of photoelectrons released per light pulse. The distribution of the values $\overline{Q}_L$ is therefore not identical with that of the values $\overline{Q}_1$, but is subject to additional variations caused by the spread of $\overline{N}_e$ among the PM tubes. If $\overline{Q}_L$ and $\overline{Q}_1$ could be determined exactly and if $\overline{N}_e$ would be constant for all samples of the same type, then the data points in a $\overline{Q}_L$- versus $\overline{Q}_1$-plot would follow a straight line with (positive) slope $\overline{N}_e$. The result obtained for the PMs R 1355 presented by fig. 10 shows this trend. However, since $\overline{Q}_L$ and $\overline{Q}_1$ are given in relative units (channels), the observed slope cannot be interpreted as sample average $<\overline{N}_e>$. The straight line is merely to guide the eye.

For a single electron leaving the cathode, the corresponding number N_1 of electrons at the anode is obviously equal to A. Thus the relative standard deviation or "amplitude resolution" σ_1/K_1 of the SER peak (see fig. 7) directly represents that of A or the "gain resolution". This means

$$v(Q_1). = \frac{\sigma(Q_1)}{\overline{Q}_1} = \frac{\sigma_1}{K_1} = \frac{\sigma(e_0 \cdot N_1)}{e_0 \cdot \overline{N}_1} = \frac{\sigma(A)}{\overline{A}} = .v(A). \tag{5}$$

Concerning the influence of $v(A)$ on the detection of light pulses, rather straightforward statistical considerations lead to the relation [10,11]

$$v^2(Q_L) = v^2(N_{ph}) - \frac{1}{\overline{N}_{ph}} + \frac{v^2(A)+1}{\overline{N}_e}. \tag{6}$$

Here N_{ph} is the number of photons per light pulse reaching the cathode and (see fig. 7) $v(Q_L). = \sigma(Q_L)/\overline{Q}_L = \sigma_L/K_L$ is the amplitude resolution of the integrated anode pulses. The corresponding value $v(Q_1)$ can be deduced from this formula by generating a single electron emission with a light source emitting exactly one photon per pulse onto a cathode with a quantum efficiency of 100%. This means $\overline{N}_{ph} = \overline{N}_e = 1$ and $v(N_{ph}) = 0$ and consequently $v(Q_1) = v(A)$ in agreement with eq. (5). If N_{ph} obeys Poisson statistics, may be assumed for the light from a pulsed diode, eq. (6) reduces to

$$v^2(Q_L) = \frac{v^2(A)+1}{\overline{N}_e} \tag{7}$$

and is frequently applied in this form [12,13].

For each of the 140 PMs under study, pulse height spectra of the type shown in fig. 7, were deduced and the values of $\sigma_1/K_1 = v(A)$ and $\sigma_L/K_L = v(Q_L)$ were determined. The results are shown in fig. 11 as a $v(Q_L)$- versus $v(A)$-plot. The two groups of 70 data points per PM type are clearly separated. This is due to the noticable difference in the cathode areas ($a_1 = 177$ mm^2 and $a_2 = 491$ mm^2) and thus to the corresponding difference in $\overline{N}_e$. Here the indices 1 and 2 refer to the types R 1450 and R 1355, respectively. The predictions of eq. (7) are shown, too, for the indicated values of $\overline{N}_e$. Without performing best fits, one can estimate average values $<\overline{N}_{e1}> = 70$ and $<\overline{N}_{e2}> = 190$ yielding a ratio of 0.37 in excellent agreement with the expected value $a_1/a_2 = 0.36$. For these numbers of $<\overline{N}_{e1}>$ and $<\overline{N}_{e_2}>$ and for the averaged results $<v_1(A)> = 0.465$ and $<v_2(A)> = 0.418$, which were obtained from the recorded σ_1 and K_1 values, eq. (3) predicts $<v_1(Q_L)> = 0.132$ and $<v_2(Q_L)> = 0.079$ for the average amplitude resolution. The experimental results taken from σ_L and K_L yield $<v_1(Q_L)> = 0.135$ and $<v_2(Q_L)> = 0.079$ in agreement with the predicted ones.

Fig. 12 is a plot of all data points showing the dependence of the amplitude resolution $v(Q_L)$ on the normalized amplitude $\overline{Q}_L/<\overline{Q}_L>$. The horizontal lines indicate the average experimental values. The points for the PM R 1450 scatter symmetrically around this line. In contrast, those for the PM R 1355 show a systematic increase with decreasing amplitudes. According to eq. (6) this reflects either a decrease of $\overline{N}_e$ and/or an increase of $v(A)$. The first explanation implies a decrease of the quantum efficiency since $\overline{N}_{ph}$ is constant. The second one, a deterioration in gain resolution, is mainly affected by the mean secondary emission coefficient $\overline{\delta}_1$ of the first dynode. Thus the observed sample variations in gain for the PM R 1355, particularly in the low A region (see fig. 3), are obviously partly connected to fluctuations in the quantum efficiency of the photocathodes and in $\overline{\delta}_1$ probably caused by imponderable effects during manufacturing.

4 Summary

The test performed with the compact linear focused PM Hamamatsu R 1450 exposed to a light source of variable intensity showed that space charge effects causing nonlinearities of the PM response could be overcome or at least minimized by careful modifications of the bleeder chain. These essentially consisted in increasing the voltages across the last dynodes and/or the last dynode and the anode in order to surpass the values where space charge can limit the currents. The tested photomultiplier had a photocathode of active area 1.7 cm^2; it was possible to establish a linear dynamic range from the single electron response up to pulses corresponding to $3 \cdot 10^3$ photoelectrons that result e.g. from 15 MeV electron energy deposited in a typical plastic scintillator assembly.

The serial test of 70 PMs each of the linear focused, 10-stage types R 1450 and R 1355 (active photocathode area 4.9 cm^2) revealed the dominant impact of the photoelectron statistics on the correlations between gain (or single electron) resolution $v(A)$ and amplitude resolution $v(Q_L)$. The expected linear relation between light pulse and single electron response was observed with an additional scatter due to the individual photoelectron yield $\overline{N}_e$ among the PMs. The correlation between $v(A)$ and $v(Q_L)$ is in quantitative agreement with values for $\overline{N}_e$ being in proportion to the active photocathode areas. In addition, indications were found among the larger PMs for fluctuations in the quantum efficiency or the secondary emission coefficients.

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Table Caption

Table 1: Specifications of the tested bleeder chains. The numbers give R_1 to R_{11} in kΩ (as ratios). The bridging capacitors are $C_8 = C_9 = 2$ nF, $C_{10} = 5$ nF, $C_{11} = 10$ nF for B_1, B_2, B_3 and $C_8 = C_9 = 5$ nF, $C_{10} = 10$ nF, $C_{11} = 20$ nF for B_4.

Figure Captions

Fig. 1: $I_A - U$ characteristics for the PM R 1450. Total supply voltage: $U_0 = -1000$ V (dashed lines: $U_0 = -1500$ V).

Fig. 2: Space charge influenced anode pulses for the PM R 1450.

Fig. 3: Experimental set up (L: light emitting diode array; C: cylindrical lens; G: movable grey wedge; PM: photomultiplier type R 1450; B: bleeder chain under test; PG: pulse generator; LG: fast linear gate; A: integrating amplifier; PHA: pulse height analyzer).

Fig. 4: Uncalibrated anode charge Q per light pulse versus grey wedge position $x_2 - x$ for all tested bleeder chains B_1 to B_4 and a gating interval of $T = 60$ ns.

Fig. 5: Anode charge Q per light pulse devided by the gain $A(B_3)$ versus light amount L per pulse for the bleeder chains B_1 (curves; $U_0 = -1500$V, $I_0 = 2.17$ mA) and B_3 (straight line; $U_0 = -1600$ V, $I_0 = 1.92$ mA) and two gating intervals $T_1 = 35$ ns and $T_2 = 100$ ns.

Fig. 6: Experimental set up for serial test of PMs R 1355 and R 1450 with a light emitting diode array L driven by the pulse generator PG.

Fig. 7: Explanation of nomenclature for serial study of PMs.

Fig. 8: Distributions of the gain A_L under light pulse illumination and A_1 for single electrons from the cathode.

Fig. 9: Selected single photoelectron spectra of PMs R 1355.

Fig. 10: Mean anode charge $\overline{Q}_L$ per light pulse versus mean anode charge $\overline{Q}_1$ per single electron from the cathode.

Fig. 11: Amplitude resolution $v(Q_L)$ under light pulse illumination versus gain resolution $v(A)$ obtained from the SER peak. (v denotes the relative standard deviation.)

Fig. 12: Amplitude resolution $v(Q_L)$ under light pulse illumination versus the normalized mean anode charge $\overline{Q}_L/<\overline{Q}_L>$ per light pulse. The dashed lines give the experimental average.

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