EXPERIMENTAL STUDY OF NON-LINEAR EFFECTS ON PHOTOMULTIPLIER GAIN

M. De Vincenzi^{*)}, G. Penso^{*)}, A. Sciubba^{*)} and A. Sposito^{*)}

Dipartimento di Fisica dell'Università "La Sapienza", Roma, Italy

Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy

Abstract

The experimental apparatus and the results of a study on the gain variation of photomultipliers at high average anode current are described. This gain variation was found to depend on the secondary emission process on dynodes; the last dynode gives the largest contribution to the overall photomultiplier effect. This contribution has been isolated and measured. The phenomenon may be due to more than one physical effect. The dominant one turns out to depend on the power released on the dynode by the incident electrons. A physical model is discussed which can take into account the observed phenomena.

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^{*)} At present visitors at CERN.

1. INTRODUCTION

For many years photomultipliers (PMs) have been used as linear light-to-charge converters. The gain (G) of a given PM, defined as the ratio between anode and cathode current, depends in first approximation only on the inter-dynode potential. For “high” average current this is no longer true: the PM gain depends on the average current itself. This effect, which is often referred to as “rate effect” or “short-term instability”, has already been observed but not fully understood [1,2]. As far as we have observed during many hours of measurements, it appears to be quite reproducible in the sense that a given PM at fixed working conditions always exhibits the same effect. As will be seen later, this effect has a characteristic time much longer than the rise-time of the PM pulses. In particular, if the average current of the PM undergoes a step variation, the PM gain changes and reaches its new value in a time which is of the order of few tenths of a second. Therefore for fast (10–100 ns) pulses the linear relationship between incident light and anode charge is still preserved, the proportionality factor being a function of the average PM current at that time.

In the present paper the results of a study on this effect for a sample of fifty PMs of type PM2034^{*)} are reported. Detailed measurements have been achieved on a particular PM of this sample, which exhibits a large gain variation. This study was performed in view of the construction of a hadronic calorimeter which will be part of the set-up of the WA78 experiment [3] to be performed at the CERN SPS accelerator. This calorimeter, which consists of a sandwich of absorber and scintillator sheets, will be used as a live dump for 350 GeV/c high-intensity pions beam. In these working conditions some of the PMs in the calorimeter may suffer from the aforementioned effect, which can result in a PM gain variation during the burst which can rise to 20%. This effect is very important, especially at the considered energies where the resolution of a hadronic calorimeter is $\simeq 3\text{--}4\%$.

In Section 2 the experimental method used for studying this effect is described. In Section 3 some characteristics of the whole sample of PM2034's examined are given. In Section 4 more detailed measurements on that particular PM which exhibits the highest effect is reported. In Section 5 the experimental method used to measure the contribution of the last dynode to the overall effect in that PM is described. The results obtained with this method are presented. In Section 6 a possible interpretation of the phenomenon is given. Conclusions are reported in Section 7.

2. EXPERIMENTAL METHOD

In order to study the behaviour of a PM which operates in conditions similar to the experimental ones, the set-up of fig. 1a was used. The PM to be tested was illuminated by two Light Emitting Diodes (LEDs). The LED R (Reference LED) is used to monitor the PM gain. The LED B (Background LED), which simulates the time structure of the SPS beam (10 s cycle with a burst duration of 2.5 s), was driven by a variable frequency pulse generator. The PM average anode current during the burst ($\langle I_a \rangle_b$) can be varied by changing either the frequency or the amplitude of the pulses driving the LED B. This allows the simulation of different working conditions of a PM. To avoid the piling up of light pulses from the two LEDs, LED B was anticoincided during 400 ns by LED R.

^{*)} The PM2034, manufactured by Philips, is a variant of XP2030. They both have venetian blind dynodes of CuBeO(Cs).

The HV divider used for the PM2034 is shown in fig. 1b. In order to avoid PM gain variation due to the voltage divider, the last three dynodes have been supplied, independently, with three stabilized power supplies. The anode is d.c. coupled to a 1024 channel analog-to-digital converter (ADC), with 256 pC full scale. The linearity of the PM for fast light pulses has been measured by using four reference LEDs which can be fired independently and concurrently. In this way all the PMs have been found to be linear within 2% up to a pulsed anode current of 100 mA, at a fixed average anode current.

3. EXPERIMENTAL RESULTS ON A SAMPLE OF FIFTY PMs

With the set-up previously described we have measured the gain behaviour of fifty PM2034's, during the simulated SPS cycle. The HV of the PMs was set at 1500 V. The light yield from the LED R and LED B was kept constant corresponding to about 5×10^4 photoelectrons per pulse. LED R was continuously driven at 100 Hz. LED B was triggered at 20 kHz during 2.5 s and then turned off during 7.5 s. In these working conditions, the fifty PMs examined exhibit quite different behaviour. As an example, in fig. 2a-d the percentage gain variation during the 10 s cycle is shown for four of them. As can be seen, the gain variation during the simulated burst can be very different for the PMs in the sample, both in absolute value and in time characteristics. All but one PM present an increase of the gain during the burst. In fig. 2d the response of that PM which presents a negative $\Delta G/G$ value is shown. Owing to the very long recovery time of this PM, the measurement was performed with a single simulated burst. In fig. 3 the values of $\Delta G/G$ just before the end of burst ($\Delta G/G|_{\text{eob}}$) are shown as a function of $\langle I_a \rangle_b$ for the fifty PMs considered and in the aforementioned working conditions. From this scatter plot it can be seen how the PMs of our sample differ in behaviour. In particular, no clear correlation between $\Delta G/G|_{\text{eob}}$ and G (which is proportional to $\langle I_a \rangle_b$) seems to be present. This differing behaviour of the PMs of the same type has already been observed [1]. It probably depends on the non-perfect reproducibility of the manufacturing conditions.

4. MEASUREMENTS ON THE PM WITH THE LARGEST $\Delta G/G$

Many causes may contribute [2] to the considered PM gain variation. Among them there is probably a physical effect related to the secondary emission mechanism at the surface of the dynodes. In order to obtain some information on this effect we have studied the behaviour of that particular PM which exhibits the largest $\Delta G/G$ value (see figs. 2a and 3). The dependence of the $\Delta G/G|_{\text{eob}}$ on $\langle I_a \rangle_b$ is shown in fig. 4. Roughly one finds a power law dependence on $\langle I_a \rangle_b$ with an exponent between 0.5 and 0.7. This behaviour is common not only to all the PM2034's of our sample but also to other PMs such as PM2242B and EMI 9839A. We have verified that $\Delta G/G|_{\text{eob}}$ depends on the frequency and amplitude of LED B pulses only through their product, which is proportional to the average anode current. In fig. 5 the rise-time (τ_R) and decay-time (τ_D) of the $\Delta G/G$ are plotted against $\langle I_a \rangle_b$. They are defined as the time to reach half of the $\Delta G/G|_{\text{eob}}$ value (see insert in fig. 5). As already observed [1], the rise-time decreases with increasing average PM current. Also the decay-time decreases with the average current but less rapidly than the rise-time. This different behaviour is only partially in agreement with ref. [1], in which the decay-time was found to be practically independent of the average current of the PM. In order to localize the source

of the observed gain variation we have changed the average current of the photocathode, by a factor of ≈ 50 , by acting on the frequency of LED B, keeping constant the average current on the last three dynodes and on the anode by a suitable variation of the potential of the first dynodes. This variation leaves the $\Delta G/G|_{\text{cob}}$ practically unchanged, and allows one to conclude that the contribution from the photocathode to the considered effect is, if any, negligible. Therefore the source of the effect must be localized on the dynodes and the PM gain variation is the convolution of many effects which take place on each dynode. We therefore decided to isolate and measure the effect on the last dynode alone, which should be the one most responsible for the overall PM effect (fig. 4) because it has the highest incident current.

5. SINGLE DYNODE GAIN VARIATION

The contribution of the last dynode to the overall $\Delta G/G$ has been measured by applying the following subtraction method. First the gain variation ($\Delta G/G$) of the PM was measured in the usual way. Then the last dynode was disconnected from the voltage divider and short circuited with the anode, the voltages of the other dynodes being unchanged (fig. 6 with switch S in position 2 and $\Delta V = 0$). In this new configuration, where the last dynode and the anode act as a unique electron collector, the PM gain variation $\Delta G'/G'$ was measured during the simulated burst. The gain variation of the last dynode ($\Delta g_{10}/g_{10}$) is obtained by subtracting the two measured quantities $\Delta G/G$ and $\Delta G'/G'$. In fact the overall PM gain in the two configurations is given by:

$$G = \prod_{i=1}^{10} g_i \quad (i = 1, \dots, 10)$$

$$G' = \prod_{i=1}^9 g_i \quad (i = 1, \dots, 9)$$

where g_i is the gain of the i -th dynode. From this formula we deduce, for small percentage gain variation, as in the present case,

$$\Delta G/G = \sum_{i=1}^{10} \Delta g_i/g_i \quad (i = 1, \dots, 10)$$

$$\Delta G'/G' = \sum_{i=1}^9 \Delta g_i/g_i \quad (i = 1, \dots, 9)$$

and therefore

$$\Delta g_{10}/g_{10} = \Delta G/G - \Delta G'/G'.$$

With this subtraction method we can study the characteristics of a single dynode (D_{10}) by varying independently the rate (current) and the energy (voltage) of electrons impinging on it. The current (I_{9-10}) is measured through the two amperemeters of fig. 6 (switch S in position 1), and can be changed by acting on LED B (fig. 1a). The voltage $V_{9-10} = |V_9 + \Delta V - V_{10}|$ can be changed by varying ΔV , without changing (see fig. 6) the working condition of the first part of the PM up to the 9th dynode. For each pair of values (I_{9-10} , V_{9-10}) $\Delta G/G$ and $\Delta G'/G'$ are measured and the subtraction method applied. As a check of the correct electron collection by dynode D_{10} for different V_{9-10} values, the collection characteristic of that dynode for four values of incident light

flux (Φ) from LED B are found as shown in fig. 7a. The dynode gain (g_{10}) as a function of V_{9-10} (at fixed incident light flux) is shown in fig. 7b. The gain variation $\Delta g_{10}/g_{10}$ of the dynode D_{10} during and after the simulated burst has been measured for four values of incident light flux (Φ) from LED B and for seven V_{9-10} values; for each couple of values of Φ and V_{9-10} , the corresponding I_{9-10} can be deduced from fig. 7a. In this series of measurements the burst duration was raised to 10 s and the total cycle to 30 s. In order to show how the subtraction method works we report, as an example, in fig. 8a,b the measured values of $\Delta G/G$ and $\Delta G'/G'$, and the calculated $\Delta g_{10}/g_{10}$ during the cycle, for two particular working conditions. In fig. 8b it can be seen that the slow rise of $\Delta G/G$ between 0.5 and 10 s is due to the contribution of the first nine dynodes ($\Delta G'/G'$). The effect on the dynode D_{10} ($\Delta g_{10}/g_{10}$) turns out to be slightly decreasing during that interval. The “overshoot” behaviour of $\Delta g_{10}/g_{10}$, which is placed in evidence here by the subtraction method, has already been observed [1] in particular working conditions for the overall $\Delta G/G$ of some PMs. We will return later to this point. In figs. 9 and 10 the value of $\Delta g_{10}/g_{10}|_{eob}$ and the rise- and decay-times are reported as a function of V_{9-10} for the four background light fluxes already considered. Within the large experimental errors, the decay-time seems to be less sensitive to V_{9-10} and background current than the rise-time, similarly to what was already observed for the whole PM. Figure 9 shows that the $\Delta g_{10}/g_{10}|_{eob}$ depends not only on the current impinging on the dynode, as expected (see fig. 4) from the behaviour of the whole PM, but also on V_{9-10} , i.e. on the incident electron energy.

6. POSSIBLE INTERPRETATION OF THE PHENOMENA

In order to try to explain the observed phenomena, we will consider three possible effects: i) a field effect due to the polarization of the emitting oxide layer at the dynode surface; ii) a thermal effect; iii) an “electron-enhanced conductivity” effect at the oxide surface. In any case, it is important to remember that the CuBe dynode is covered by an ~ 30 –100 nm thick [4] BeO layer, with a few Cs monolayers (~ 1 nm) deposited on it. Furthermore, at the considered incident electron energies (20–300 eV) the inelastic mean free path of the electrons penetrating into the dynodes is of the order of 1 nm [5,6]; therefore the secondary electrons escape from a depth of roughly 10 nm or less [2], i.e. from a few tens of BeO monolayers below Cs.

i) The excess of emitted electrons with respect to the incident ones charges positively the surface of the oxide layer. The potential at the oxide surface and the electric field inside it is therefore modified by the presence of the electron current. This phenomenon can change the effective energy of the primary electrons, as well as affect the possibility for the secondary electrons to reach the oxide surface and to escape from the dynode. At equilibrium (i.e. at about eob) the electric field inside the oxide layer (which we assume to have a finite and constant resistivity) changes proportionally to the current through it^{*)}: $I^* = I(g - 1)$ where g is a function of V (fig. 7b). In this case $\Delta g/g|_{eob}$ should depend on V and I only through I^* . In fig. 11 the measured $\Delta g/g|_{eob}$ values are plotted against I^* . As we can see, for a given value of I^* , $\Delta g/g|_{eob}$ is still dependent on Φ (i.e. on I , see fig. 7a). We conclude that this field effect, if not negligible, cannot account for the observed phenomena.

ii) We now consider a possible thermal effect due to a local heating of the emitting oxide layer. In this case, after the incident current is turned on, the surface temperature of the oxide increases up to an equilibrium value which is reached when the power (W) released by the electrons on the

*) From now on, for simplicity, we will denote g_{10} by g , I_{9-10} by I , and V_{9-10} by V .

oxide layer is equal to the heat leakage due to thermal conductivity toward the bulk of the dynode. Actually W is the difference between the incoming power (W_{in}) brought in by the primary electrons and the outgoing power (W_{out}) taken away by the secondary electrons. We have:

$$W = W_{in} - W_{out},$$

where

$$W_{in} = I(V + \langle E \rangle / e)$$

$$W_{out} = gI\langle E \rangle / e.$$

Here e is the electron charge, $g(V)$ is given in fig. 7b, and $\langle E \rangle$ is the average energy of the secondary electrons when escaping from the dynode surface. It should be noted that in evaluating $\langle E \rangle$ we must take into account both the true secondary electrons and the primary ones which are elastically or inelastically scattered by the dynode. The true secondary electrons have an energy of a few electronvolts, which is practically independent of the energy of the primary electrons, while the others have higher energies which depend on the energy of primary electrons, i.e. on V . Nevertheless, we will assume for simplicity that $\langle E \rangle$ does not depend on V . In fig. 12 we have plotted $\Delta g/g|_{eob}$ against W for $\langle E \rangle = 20$ eV. Contrary to what happens in fig. 11, $\Delta g/g|_{eob}$ appears now to depend on V and I only through the variable W . Within the experimental errors this feature remains valid for $\langle E \rangle$ ranging from 15 to 25 eV. These values of $\langle E \rangle$ seem to be in agreement with what is reported by different authors [7–9], especially if we consider that 10 to 30% of the incident electrons can be back-scattered by the dynode [2,10].

The effect of gain variation of a dynode during the burst seems therefore connected with the power released on it. A local heating can be considered as a possible candidate. In fact, with reasonable assumptions, we can estimate an initial rate variation of the temperature in the emitting layer of the order of 100–1000 °C/s, for $W = 1$ mW. Therefore if a thermal equilibrium is reached in few tenths of a second after the incident current is turned on, the local temperature at the surface of the dynode should increase by few tens or hundreds of degrees centigrade. Although few authors [9] have found, for particular emitters, an increase of the secondary emission coefficient with temperature, it has been observed [8–10] that in general this coefficient is either independent or slightly decreasing with temperature. Moreover, the rise- and decay-times of the phenomenon should be independent of W . This is in contrast with what is shown in fig. 13, where the measured rise- and decay-times of $\Delta g/g$ are reported as a function of W . We conclude that a thermal effect, if any, cannot account for the observed phenomena; nevertheless the variable W seems to be the right one to describe them.

iii) Let us now suppose that the secondary emission coefficient g depends on V , as well as on an unknown physical quantity (x) which characterizes the state of the emitting dynode. When the power (W) released on the dynode is switched on, x varies from its initial value $x(0)$ to its final value $x(\infty)$, with a time dependence $x(t)$. The relatively small percentage variation of g , allows one to make a linear approximation for $g(x)$:

$$\Delta g(t)/g = [g[x(t)] - g[x(0)]]/g[x(0)] \simeq A[x(t) - x(0)].$$

The behaviour of $\Delta g/g|_{\text{eob}} \simeq \Delta g(\infty)/g$ and $\tau_{R,D}$ as a function of W , which are roughly proportional to $(W)^{1/2}$ and $(W)^{-1/2}$ respectively (figs. 12, 13), suggests that the function $x(t)$ should be a solution of the differential equation:

$$dx/dt = W - a[x(t) - x(0)]^n$$

with $n = 2$. In fact in steady conditions, $dx/dt = 0$ and therefore $\Delta g/g|_{\text{eob}} \sim x(\infty) - x(0) \sim (W)^{1/n}$. Moreover, the W dependence of $\tau_{R,D}$ is very sensitive to the value of n . For $n = 1$ $\tau_{R,D}$ are independent of W , while for $n = 2$ they are proportional to $(W)^{-1/2}$, as we roughly found experimentally.

This differential equation (with $n = 2$) describes [11] the time behaviour of the photoconductivity effect, at least in a first approximation. In that case W is the incident light flux and x is proportional to the conductivity of the illuminated sample. This suggests the following model in order to explain the observed phenomena: the power released on the dynode by the primary electrons acts as the light flux in photoconductivity effect, and increases the conductivity of the surface layers of the emitting oxide by raising some electrons from the valence band to the conduction band. As a consequence, the valence and conduction bands near the oxide-Cs interface are bent in such a way as to reduce the effective work function. The secondary electrons can therefore escape more easily from the dynode and the secondary emission coefficient is increased [12]. Moreover the rise- and decay-times of the photoconductivity effect can be [11] of the same order as that which we have observed in dynode gain variation.

In order to test our “electron enhanced conductivity” model, we will consider a more refined picture of the photoconductivity effect, which is similar and where traps are also taken into account. In that case [11] the time behaviour of the effect is determined by an equation of the type:

$$dx/dt = W - a[x(t) - x(0)]^2 - b[x(t) - x(0)].$$

The solution of this equation is:

$$\Delta g(t)/g \simeq A[x(t) - x(0)] = [2AW/(b + c)] [(e^{ct} - 1)/(e^{ct} - d)]$$

where

$$c = \sqrt{(b^2 + 4aW)}$$

$$d = (b - c)/(b + c).$$

The rise- and decay-times, as already defined, are given by

$$\tau_R = (1/c) \ln [(6aW + b^2 - bc)/(2aW)]$$

$$\tau_D = (1/b) \ln [(3b + c)/(b + c)].$$

Leaving A , a , and b as free parameters, we fit our experimental data. The best fit, obtained for $A = 1.06 \times 10^3 \text{ J}^{-1}$, $a = 10^5 \text{ J}^{-1} \text{ s}^{-1}$, $b = 0.7 \text{ s}^{-1}$, is reported in figs. 12, 13, and 14. Within the

experimental errors the predictions of our model agree quite well with the experimental data for $W < 1$ mW. At higher W values the experimental $\Delta g/g$ values are lower than the predicted ones, while the rise- and decay-times are higher. We must observe (fig. 14) that at these high W values the time behaviour of $\Delta g/g$ presents an overshoot, which is not predicted by our model. A possible interpretation of this fact is the appearance, at high W values, of a new effect^{*)} which tends to decrease g and has a slower time behaviour. The interplay of this negative effect with that described by our “electron enhanced conductivity” model could explain these overshoots. Moreover this possible effect could account for the negative $\Delta G/G$ values sometimes observed. From our measurements it is not possible to obtain any reliable indications of the characteristics of this eventual second negative effect. In fact the subtraction method used to extract the single dynode contribution to the overall $\Delta G/G$ of the PM may introduce some systematic errors which are hard to evaluate.

7. CONCLUSIONS

The so-called “rate effect” on PMs gain is most probably due to the interplay of many phenomena. We have isolated one of them which, at least for the considered PM, was the dominant one, and which can be well described by invoking an “electron enhanced conductivity” effect, similar to photoconductivity, at the oxide surface. In this hypothesis the observed rate effect turns out to be an increasing function of the power released on the dynodes:

$$W = I(\langle E \rangle / e) [1 - g(V)] + IV,$$

Therefore the dynode material which minimizes W (i.e. maximizes the power efficiency $\eta = W_{\text{out}}/W_{\text{in}}$ of the dynode), at fixed I and g , is expected to be less sensitive to this effect. For a given $\langle E \rangle$, this corresponds to those emitting materials which present the required g value at the lowest voltage V . These considerations seem to be confirmed by the experimental fact that PMs with SbCs dynodes present a rate effect lower than those with CuBe ones: in fact, for example, a gain of $g = 5$ is obtained at $V \simeq 100$ V with a SbCs dynode, and at $V \simeq 150$ V or higher for a CuBe one [2,13]. Similar considerations are expected to be valid also for GaP dynodes. It should be noted that, for a more precise evaluation of this effect, the exact dependence of $\langle E \rangle$ on both V and dynode material must be known. Another consequence of the W dependence of $\Delta G/G$ is that, for a fixed PM gain G , and for a given dynode material, the number of dynodes and the PM voltage divider can be optimized in order to have the lowest overall PM rate effect. This optimization can easily be done on the basis of the formulae previously reported.

Finally, we want to point out that it would be quite desirable to check the validity of the proposed model and in particular the W dependence of the observed effect, with an especially designed experiment, where the electrons incident on the dynode are obtained with an electron gun. This facility would avoid the subtraction method we are compelled to use.

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^{*)} For example a thermal effect or a field effect like those previously considered.

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Figure captions

- Fig. 1 :** a) Experimental set-up and electronic block diagram used for measurement of PM gain variations during the simulated accelerator burst. PG = pulse generator; BS = burst simulator; PS = pulse shaper.
b) PM voltage divider. The values of the resistors are given in $k\Omega$ and those of the capacitors in nF.
- Fig. 2 :** a), b), c) Three examples, among the fifty observed of PM gain behaviour during the simulated burst.
d) The behaviour of the only PM found to have a negative gain variation.
- Fig. 3 :** Gain variation at the end of a 2.5 s burst as a function of $\langle I_a \rangle_b$, for the fifty observed PMs, under fixed working conditions (see text). The abscissa is proportional to the PM gain G.
- Fig. 4 :** Gain variation at the end of the 2.5 s burst as a function of $\langle I_a \rangle_b$, for the selected PM. The curve is an eye fit to the points.
- Fig. 5 :** Rise- and decay-times (defined in the insert) of gain variation as a function of $\langle I_a \rangle_b$ for the selected PM. The curves are an eye fit to the points.
- Fig. 6 :** High-voltage divider of the selected PM modified for the subtraction method described in the text. Resistor and capacitor values are the same as in fig. 1b. Switch S is placed in position 1 or 2 for measuring $\Delta G/G$ or $\Delta G'/G'$, respectively. When S is in position 1 the two amperemeters (short-circuited for pulse operation) allow measurement of the electron current incident on dynode D_{10} . By varying ΔV the kinetic energy of these electrons can be changed without modifying the behaviour of the first nine dynodes of the PM.
- Fig. 7 :** a) Electron collection characteristic of the dynode D_{10} for different incident light fluxes (Φ) from LED B.
b) Gain of the dynode D_{10} at a fixed light flux Φ_2 , as a function of the voltage difference between D_9 and D_{10} .
Lines are eye fits to the points.
- Fig. 8 :** Two examples of application of the subtraction method (see text); a) light flux Φ_3 , $V_{9-10} = 123$ V; b) light flux Φ_4 , $V_{9-10} = 323$ V. Burst and cycle duration have been set at 10 and 30 s, respectively.
- Fig. 9 :** $\Delta g_{10}/g_{10}|_{eob}$ as a function of V_{9-10} for different light fluxes. To each couple of values of Φ_i and V_{9-10} corresponds one value of the current incident on D_{10} (see fig. 7a).
- Fig. 10 :** a), b) Rise- and decay-times of the $\Delta g_{10}/g_{10}$ as a function of V_{9-10} for different light fluxes Φ .
- Fig. 11 :** $\Delta g/g|_{eob}$ as a function of the current passing through the emitting oxide layer at the dynode surface. Lines are eye fits to the points corresponding to the same light flux Φ .
- Fig. 12 :** $\Delta g/g|_{eob}$ as a function of the power released on the considered dynode. The curve is the best fit of the data with the proposed model. The parameter A is fixed by normalizing the curve at $W = 100 \mu W$.
- Fig. 13 :** a), b) Rise- and decay-times of $\Delta g/g$ as a function of the power released on the dynode. The curves are the best fit of the data with the proposed model.

Fig. 14 : Time dependence of $\Delta g/g$ during and after the 10 s simulated burst, for eight W values. The curves are absolute predictions of the proposed model, once the parameters A , a , b have been fixed by fitting the data of Figs. 12 and 13. The disagreement at high W values may be due to the setting in of a new effect, with a longer rise-time, which contributes negatively to $\Delta g/g$ and is therefore responsible for its overshoot time behaviour.

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