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Characterization of 8-stages Hamamatsu R5900 photomultipliers for the TILE calorimeter

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Abstract

This note is a summary of the laboratory tests and measurements on 8-stages R5900 Hamamatsu photomultipliers. We report on relative photocathode sensitivity, amplification, linearity and magnetic measurements.

1. Introduction

The conclusions of the 10-stages R5900 characterisation indicate that these PMTs fullfil almost all the specifications for the TILECAL readout system. Nevertheless, with a dynamic range going up to 50K photoelectrons, and a nominal amplification of 10^5 the 2% maximum deviation linearity limit is achieved with a 2.5:2.5:1–1:2.5:2.5 voltage repartition.

This 2.5:2.5:1–1:2.5:2.5 configuration is needed mainly by the fact that R5900 is a 10-stages PMT, and that its nominal operating conditions (800 Volts and an amplification of 10^6) are different of the TILECAL nominal amplification. That is why, we should use this special "gain killer" voltage repartition.

Preliminary discussions with Hamamatsu lead to the definition of a 8-stages R5900 that could be used in the TILECAL read-out system. This note is a summary of laboratory tests and measurements made on 4 protypes of this new 8-stages R5900 Hamamatsu photomultipliers. In Table (1) are given the standart characteristics of these 8-stages R5900, as measured by Hamamatsu using an overall supply voltage of 800 V with the following dynode voltage repartition (HV=10v):

K		Dy1		Dy2		Dy3		Dy4		Dy5		Dy6		Dy7		Dy8		A
	1.5		1.5		1.5		1		1		1		1		1		0.5	

The current amplification is obtained by taking the ratio of the anode to cathode luminous sensitivity.

Serial Number	Cathode Luminous Sensitivity ($\mu A/lm$)	Anode Luminous Sensitivity (A/lm)	Anode Dark Current (nA)	Current Amplification
6B23C7	62.8	35.0	0.06	5.57×10^5
6C11C9	70.3	40.0	0.06	5.69×10^5
6C05DA	85.2	104.0	0.85	1.22×10^6
6C06DA	83.7	94.0	1.69	1.12×10^6
$< 10 - \text{stages} >$	75.0	184.1	1.18	2.4×10^6

Table 1 : Characteristics of the four 8-stages R5900 as measured by Hamamatsu, and comparison with the averaged corresponding values for the set of 65 10-stages R5900 used for "Module 0".

2. Relative Photocathode Sensitivity

The relative photocathode sensitivity is obtained by measuring the variation of the photocathode current as a function of the voltage applied between the photocathode and the first dynode. The experimental set-up used for that measurement is shown on Figure (1): the light intensity is monitored by a photodiode. The PMT photocurrent is adjusted of the order of a few tens of nA.

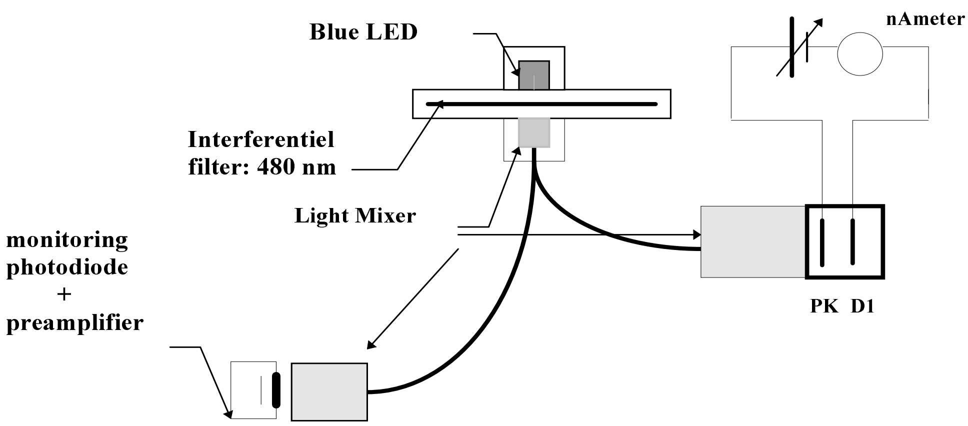

Figure 1: Experimental setup used for photocathode current measurement.

The photocathode current is measured operating the PMT with a specific configuration of the voltage divider as shown on Figure (2). In this measurement, one uses only the photocathode and all the others dynodes tied together as an anode. The photocurrent is measured between the photocathode and the ground.

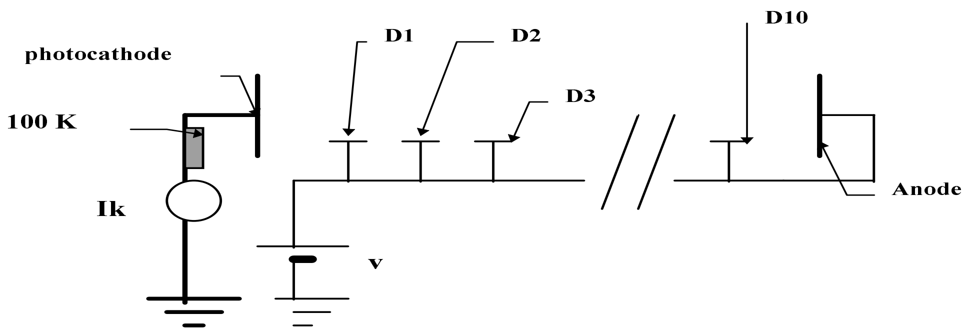

Figure 2: Specific voltage divider configuration used for photocathode current measurement.

A bialkali photocathode is generally very resistive, causing poor collection efficiency over a wide range of voltage even for photoemission currents as low as $10nA$. So the photocurrent is linear with the light flux, but if the photocathode current is too large ($\sim 100nA$), effects of the surface resistance of the photocathode could be very large, and linearity of the photocathode response gets deteriorated significantly.

The relative photocathode sensitivity as a function of the photocathode to first dynode voltage is also a test of the photocathode resistivity. The photocathode current should rise up to a plateau which corresponds to roughly the full collection efficiency: the faster the current goes to the plateau, the less is the photocathode resistivity.

The results for the 4 PMTs are shown on Figure (3). 90% **of the plateau value is reached for a photocathode to dynodes voltage equal to 20 Volts. So quality of the 8-stages are almost identical to the 10-stages.**

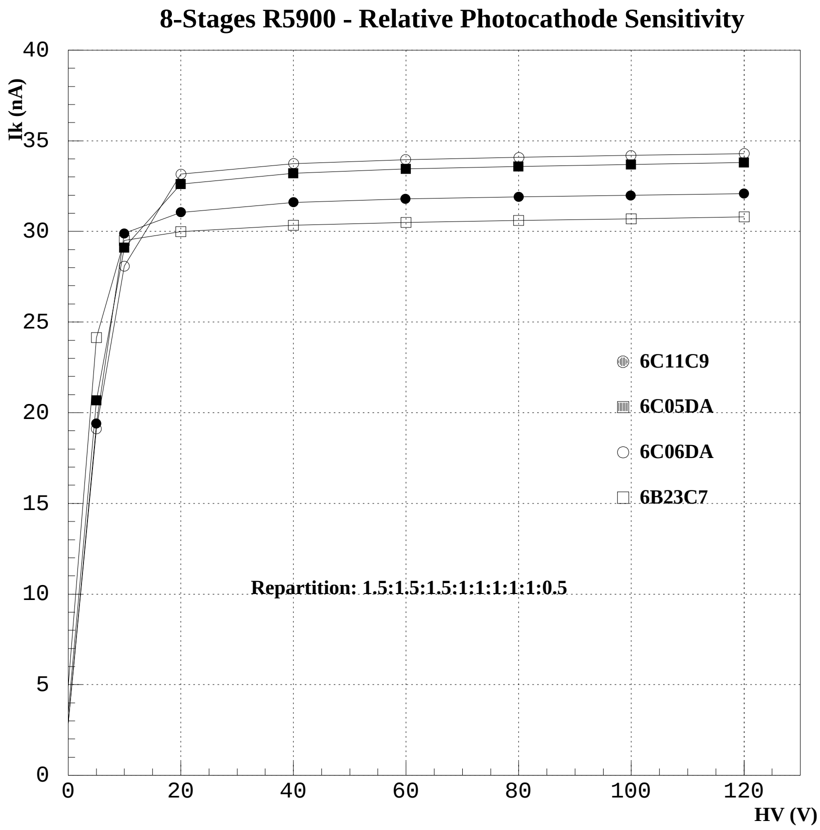

Figure 3 : Photocathode current (nA) of the four 8-stages R5900, as a function of voltage (Volts) between photocathode and all the other dynodes tied together as an anode. The saturation photocurrent is adjusted roughly to 30 nA, and monitored by the photodiode.

3. Amplification measurements

- **Current amplification**

We measure first the current amplification. Assuming we operate the PMT with a constant light source (true on a short time scale), the current amplification is measured by taking the ratio of the anode (I_a) to the photocathode current (I_{pk}). To prevent a too high anode current ($10\ \mathrm{nA} \times 10^5 = 1000\mu\mathrm{A}$), we decrease the light flux by operating with a neutral filter of known attenuation (T_a between 500 and 1000). Then:

$$G = \frac{I_a(V) \times T_a}{I_{pk}(v)} \tag{1}$$

Here, V is the overall voltage supply and v the voltage applied between the photocathode and the first dynode in the complete configuration. For $V = 800\ V$ and 1.5:1.5:1.5:1:1:1:1:1:0.5 voltage repartition, we got $v = 120\ V$. As shown on Figure (4), all the measurements are done with a light mixer in front of the PMT and a baffle to avoid light reflection problems. The voltage divider was specific to that measurement ("three-stages" divider).

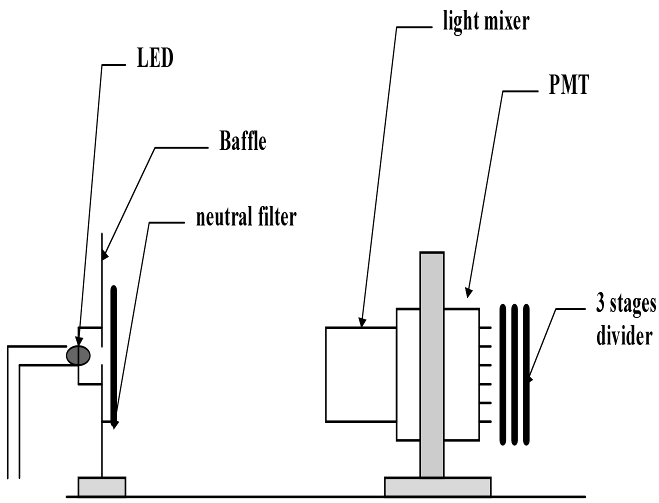

Figure 4: Experimental set-up used for current amplification measurement. This measure is achieved in a two steps procedure using the "three-stages" dividers.

The values of the gain for $HV = 800\ V$ are listed in Table (2) together with a comparison of the gain deduced from the Hamamatsu data. Using PMT # 6B23C7 as a reference, the Hamamatsu and our measured current amplification of the 4 PMTs are fully compatible. Nevertheless, comparing the the two set of current amplification absolute values, our data are systematicaly $\sim 40\%$ greather than Hamamatsu one.

Serial Number	Clermont measurement	Hamamatsu data	R
6B23C7	7.8×10^5 (1.00)	5.57×10^5 (1.00)	1.39
6C05DA	1.6×10^6 (2.05)	1.22×10^6 (2.20)	1.31
6C06DA	1.6×10^6 (2.05)	1.12×10^6 (2.01)	1.43
6C11C9	8.0×10^5 (1.02)	5.69×10^5 (1.02)	1.40

Table 2: Gain at $HV = 800$ V in DC mode and comparison with the gain deduced from the Hamamatsu data.

- **Amplification in pulsed mode**

We measure then 8-stages amplification using a pulsed light source, and the results will be compared to the current amplification.

The experimental setup is shown on Figure (5). The light, produced by the pulsed blue LED, is split in two different light beams. One of these light beam is used for the monitoring of the light source by a photodiode. The second light beam intensity is first modulated with a set 9 neutral filters of different attenuation. The attenuation ratio of the filters have been measured using the same LED and a photodiode. Then after the attenuation filter, the light is focused into a large acceptance "Liquid-fiber" which transports the light to the PMT test box. In this box the light is splitted into a few channels, each of them including a light mixer in front of the PMT under test. **The pulse width was in the order of 19 ns**. The PMT output may be either read by a charge ADC or by a digital scope.

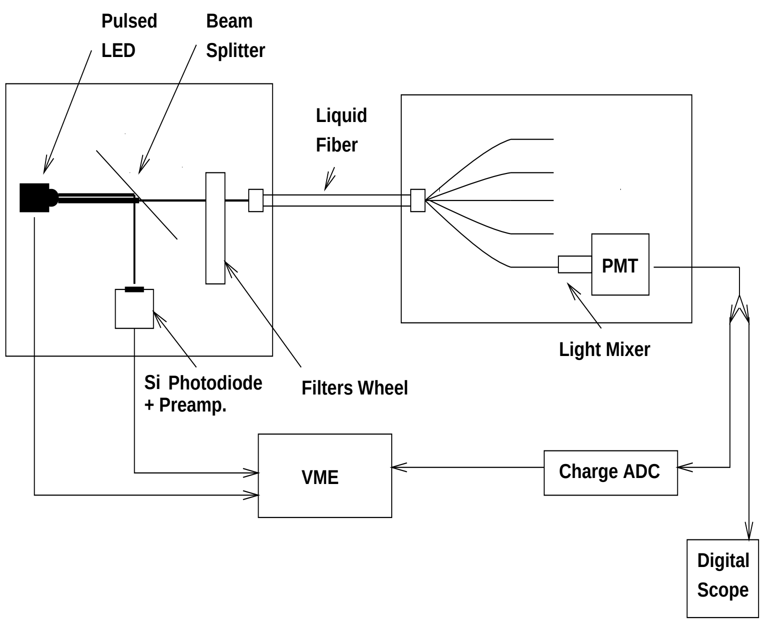

Figure 4 : Experimental set-up used for pulsed mode amplification measurement:

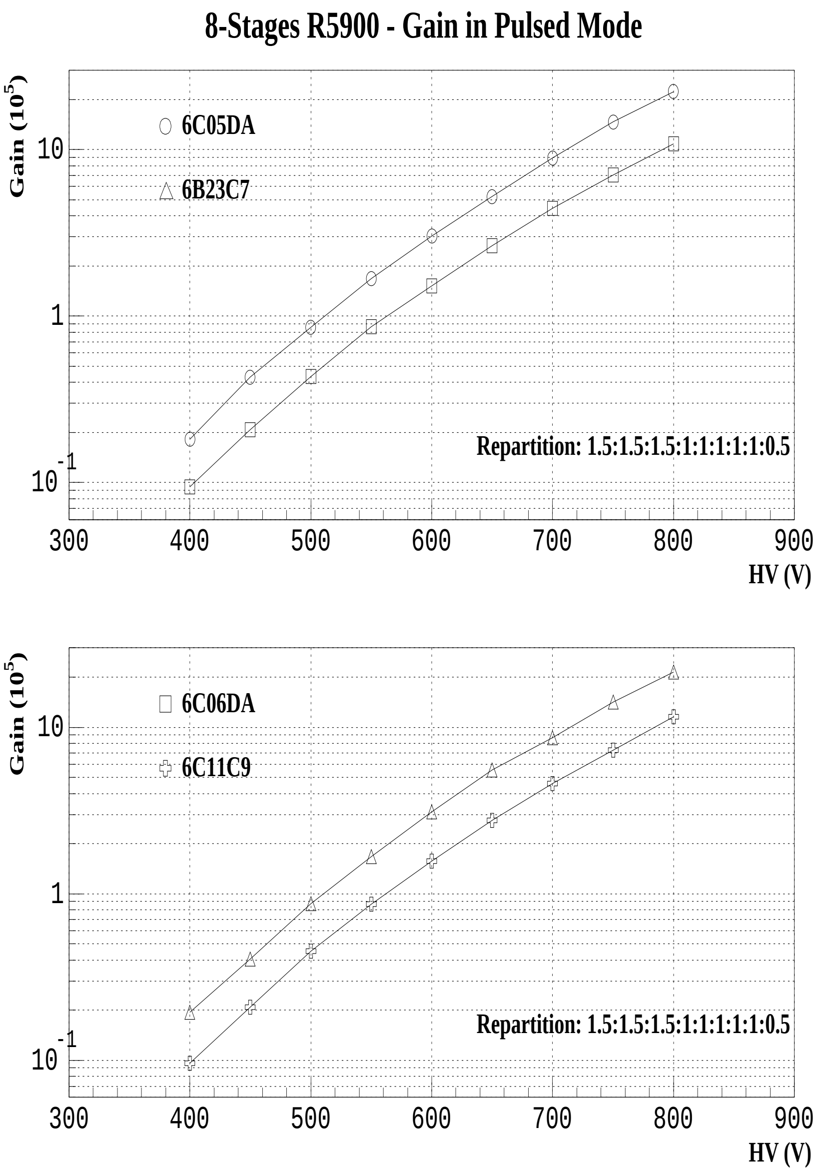

Figure 5 : Gain in pulsed mode for the 8-stages PMTs using the experimental set-up shown on Figure (4). Data had been fitted with $G = \alpha V^{\beta}$.

From the ADC distribution, one generally estimate the number of photoelectron using the following formula:

$$N_{p.e.} = [\frac{M - Ped}{\sigma}]^2 \tag{2}$$

where M represents the mean value of the distribution, Ped the pedestal value, and σ the sigma of the distribution.

Knowing the number of photoelectron, the gain G of the PMT is directly obtained from the PMT output charge in Coulomb, Q, using:

$$N_{p.e.} \times G \times 1.6 \times 10^{-19} = Q \tag{3}$$

Figure (5) represents the variation of the gain versus the overall voltage supply. Amplification data had been fitted by the following expression.

$$G \ = \ \alpha V^{\beta} \tag{4}$$

Table (3) gives the gain corresponding to $HV = 800\ V$. Is also given R, the ratio of the gain measured in pulsed mode to the gain measured in DC mode for $HV = 800\ V$. To obtain the same gain, the HV should be 20 V greather in DC mode than in pulsed mode. This discrepancy has also been observed for 10-stages PMTs. The last column indicate the value of the β amplification parameter of equation (4).

PMT	Gain in pulsed mode	R	β
6B23C7	1.08×10^6	1.38	6.906 ± 0.083
6C05DA	2.22×10^6	1.39	6.850 ± 0.081
6C06DA	2.16×10^6	1.35	6.850 ± 0.081
6C11C9	1.16×10^6	1.45	6.902 ± 0.081

Table 3 : Gain at $HV = 800\ V$ in pulsed mode. R is the ratio of the gain measured in pulsed mode to the gain measured in DC mode. The last column indicate the value of the β amplification parameter of equation (4)

- **Correction from the noise factor**

Let us assume that one electron impinging on the dynode #i releases, in average, k_i secondaries with variance $\sigma^2_{k_i}$. The secondary emission ratio, k_i, is a function of the interdynode voltage. **Using cascade events statistics**, the gain and the fluctuations from all the stages are given by:

$$\overline{m_8} = \prod_{i=1}^{i=8} k_i \tag{5}$$

and

$$\sigma^2_{\overline{m_8}} = (\overline{m_8})^2 \times [\frac{\sigma^2_{k_1}}{k_1^2} \ + \ \frac{\sigma^2_{k_2}}{k_1{k_2}^2} \ + \ ....\frac{\sigma^2_{k_8}}{(k_1k_2....k_7)k_8^2}] \tag{6}$$

Defining F, the noise factor as:

$$F = \frac{\sigma^2_{k_1}}{k_1^2} \ + \ \frac{\sigma^2_{k_2}}{k_1{k_2}^2} \ + \ ....\frac{\sigma^2_{k_8}}{(k_1k_2....k_7)k_8^2} \tag{7}$$

The signal to noise ratio for the multiplier chain is given by:

$$\frac{\overline{m_8}}{\sigma_{\overline{m8}}} \ = \ [\frac{\sigma_1^2}{k_1^2} \ + \ \frac{\sigma_2^2}{k_1k_2^2} \ + \ ....\frac{\sigma_8^2}{(k_1k_2....k_7)k_8^2}]^{-1/2} \ = \ \frac{1}{\sqrt{F}} \tag{8}$$

The anode current I_a is given by the following equation:

$$I_a \ = \ I_{pk} \times k_1 \times k_2 \times ....k_8 \ = \ I_{pk} \times \overline{m_8} \tag{9}$$

From now one define $\overline{m_8}$ as the gain of the PMT. But up to now only the noise contributions from the multiplier chain were considered. These results can be combined with the photocathode noise contribution in order to obtain the signal-to-noise ratio for the photomultiplier as a whole. The average number of photoelectrons, after conversion, from the photocathode in a time Δt is given by:

$$N_{p.e.} = \eta . N_\gamma \tag{10}$$

where η is the quantum efficiency, and N_γ is the mean number of photons impinging the photocathode. The variance of $N_{p.e.}$ is given by:

$$\sigma^2_{N_{p.e.}} \ = \ N_{p.e.} \tag{11}$$

Using these expressions to describe the input to the photomultiplier chain, and assuming full collection efficiency, the average number of electrons collected at the anode can be stated as follows:

$$N_a \ = \ N_{p.e.} \times \overline{m_8} \tag{12}$$

where $\overline{m_8}$ is given by equation (5). The variance for the output electron stream is calculated, considering that photoconversion and multiplication are cascade events and so given by:

$$\sigma^2_{N_a} \ = \ \overline{m_8}^2 \times \sigma^2_{N_{p.e.}} + N_{p.e.} \times \sigma^2_{\overline{m_8}} \ = \ \overline{m_8}^2 \times N_{p.e.} + N_{p.e.} \times \sigma^2_{\overline{m_8}} \tag{13}$$

where $\sigma^2_{\overline{m8}}$ is given by equation (7). Equation (13) can be rearranged as follows:

$$\sigma^2_{N_a} \ = \ N_{p.e}(\overline{m_8}^2 + \sigma^2_{\overline{m_8}}) \ = \ N_{p.e}\overline{m_8}^2(1+F) \tag{14}$$

The signal-to-noise ratio at the anode is:

$$\left(\frac{\sigma_{N_a}}{N_a}\right)^2 \ = \ \frac{N_{p.e}\ \overline{m_8}^2\ (1+F)}{N^2_{p.e}\ \overline{m_8}^2} \ = \ \frac{(1+F)}{N_{p.e}} \tag{15}$$

Finally:

$$\left(\frac{N_a}{\sigma_{N_a}}\right)^2 \ = \ N_{p.e} \times \frac{1}{1+F} \tag{16}$$

When taking account the noise factor, expression (2) becomes:

$$\left(\frac{< M > -Ped}{\sigma}\right)^2 \ = \ N_{p.e.} \times (\frac{1}{1\ +\ F}) \tag{17}$$

so the noise factor corrected amplification is simply scaled by the factor $1/(1+F)$. When applying this correction to the 8-stages R5900, one should estimate the noise factor for the 1.5:1.5:1.5—1:1:0.5 repartition. With that configuration, one should calculate in equation (7), the following expression.

$$[\frac{\sigma^2_{k_1}}{k^2_1} \ + \ \frac{\sigma^2_{k_2}}{k_1{k_2}^2} \ + \ ....\frac{\sigma^2_{k_8}}{(k_1k_2....k_7)k^2_8}] \tag{18}$$

or with notation $k_{(1,2,3)} = k'$ and $k_{(4,5,6,7,8)} = k$, and assuming that $\sigma_{(k,k')} \ = \sqrt{(k,k')}$,

$$F \ = \ \frac{1}{k'} \ + \ \frac{1}{(k')^2} \ + \ \frac{1}{(k')^3} \ + \ \frac{1}{(k')^3k} \ + \ ....\frac{1}{(k')^3k^5} \tag{19}$$

After some straightforward calculations, equation (19) could be written,

$$F \ = \ \frac{1}{k'}[1 \ + \ \frac{1}{k'} \ + \ \frac{1}{k'^2k^5}\left(\frac{1-k^6}{1-k}\right)] \simeq \frac{1}{k'}[1 \ + \ \frac{1}{k'} \ + \ \frac{1}{k'^2}\left(\frac{k}{k-1}\right)] \tag{20}$$

The interdynode amplification (k,k') are functions of the interdynode voltage (v) and could be parametrised as:

$$k = \alpha'\ v^{\beta'} \longrightarrow log(k) = \beta' log(v) + log(\alpha') \tag{21}$$

together with,

$$k' = \alpha'\ (1.5 \times v)^{\beta'} \longrightarrow log(k') = \beta'(log(v) + log(1.5)) + log(\alpha') \tag{22}$$

as

$$G \ = \ {k'}^3 \times k^5 \ = \ \alpha \times V^{\beta} \tag{23}$$

$$log(G) = 8\beta' log(v) + 8 log(\alpha') + 3\beta' log(1.5) \ = \ log(\alpha) \ + \ \beta log(V) \quad (24)$$

with the 1.5:1.5:1.5:1:1–1:0.5 repartition, $V \ = \ 10v$ and,

$$log(G) = 8\beta' log(V) \ + \ \beta'(3log(1.5) - 8log(10)) \ + \ 8log(\alpha') \quad (25)$$

so,

$$\beta \ = \ 8\beta' \ \text{ and } \ log(\alpha) \ = 8log(\alpha') + \beta'(3log(1.5) - 8log(10)) \quad (26)$$

Considering the set of 8-stages PMTs, the fitted value of the β parameter, are listed in Table (3). So we first fix β and use this value to estimate then α, using the amplification measured at nominal value of the HV in DC mode. By the way of expressions (26), one calculate α' and β', the k and k' values for each of the 4 PMTs, and finally the noise factor from expression (20).

One could state that β parameter is determined from pulsed mode and α from DC mode. But in fact, the difference between the two sets of measured amplification is only relative, and so the β parameter should be the same.

On the other hand, α is sensible to the absolute scale and by definition (expression (9)) is best extracted from DC mode amplification. Moreover, the noise factor is not so sensible to variation of k and k'. A variation of 10% on k and k' induce a variation of only 3.5% on the scaling factor $1/(1 + F)$.

The data reported in the last column of the Table (4) correspond to the noise factor corrected amplification, and could be compared to the DC amplification measurements. There remains a systematic difference of 15% between the two set of data.

PMT	F	F-Corr. pulsed mode Gain	DC Gain
6B23C7	0.1731	0.921×10^6	7.8×10^5
6C05DA	0.1562	1.926×10^6	1.6×10^6
6C06DA	0.1562	1.874×10^6	1.6×10^6
6C11C9	0.1726	0.997×10^6	8.0×10^5

Table 4 : Gain at $HV = 800\ V$ in pulsed mode after correction from the noise factor F. The last column indicate the gain measured in DC mode.

- **Collection efficiency Correction**

For such PMT the collection efficiency is estimed in the range 90% – 95%. Implication in the amplification measurement are the following. In DC mode measurement, equation (9) becomes:

$$I_a \ = \ I_{pk} \times C.E. \times \overline{m_8} \quad (27)$$

where $C.E.$ is the collection efficiency. When measuring I_{pk} all the created photoelectrons are collected by any part of the PMT, and so participate to the measured current.

So the current amplification is really:

$$\overline{m_8} = \left(\frac{1}{C.E.}\right) \times \left(\frac{I_a}{I_{pk}}\right) \tag{28}$$

For a collection efficiency of 90%, the measured current amplification should be multiplied by a factor of ~ 1.1.

In pulsed mode, equation (12) is:

$$N_a = N'_{p.e.} \times \overline{m_8} \tag{29}$$

where $N'_{p.e.}$ is the number of photoelectrons that come really in the amplification ($N'_{p.e.} = C.E. \times N_{p.e.}$). So, in that method collection efficiency does not affect the determination of the amplification. The signal-to-noise ratio at the anode is still:

$$\left(\frac{\sigma_{N_a}}{N_a}\right)^2 = \frac{N'_{p.e}\ \overline{m_8}^2\ (1+F)}{{N'_{p.e}}^2\ \overline{m_8}^2} = \frac{(1+F)}{N'_{p.e}} \tag{30}$$

Finally:

$$\left(\frac{N_a}{\sigma_{N_a}}\right)^2 = N'_{p.e} \times \frac{1}{1+F} \tag{31}$$

together with

$$N'_{p.e} \times G \times 1.6 \times 10^{-19} = Q \tag{32}$$

- **First Dynode photoconversion Correction**

Recent analysis of the one photoelecton spectra indicate that photoconversion does not only occur in photocathode, but also in the first dynode metal where a deposition of Sb-K^2-Cs is needed to achieve secondary emission.

In fact, this effect is a direct consequence of the specific structure of R5900 PMT, with a large surface of dynode in front of the photocathode window.

For more conventional PMTs, the light transmitted by the photocathode is partialy masked before impinging dynode surface by focusing electrodes that in the same time provide a large photoelectron collection efficiency.

When measuring photocathode sensitivity, this effect is still there, that is measured current I_{pk} is in fact the addition of two currents as show in Figure (6).

• In case #1 photoconversion occurs on first dynode surface, and give current I_{dk}.

• In case #2 photoconversion occurs on photocathode. The photoelectron goes in the normal way to the amplification process, and taking into account the collection efficiency, give current $C.E. \times I_{pk}$.

• In case #3 photoconversion also occurs on photocathode. But does not create an amplification, because the secondaries are lost, or there are no secondaries since secondary emission follows Poisson statistic.

• In case #4 photoconversion also occurs on photocathode. But the photoelectron is lost before impinging on first dynode.

The two last cases correspond of some configuration that make collection efficiency less than 100 %. The more the voltage between photocathode and first dynodes (focusing electrodes), the best is the collection efficiency. Nevertheless, it still remains some residual unefficiency ($\sim$ 10%).

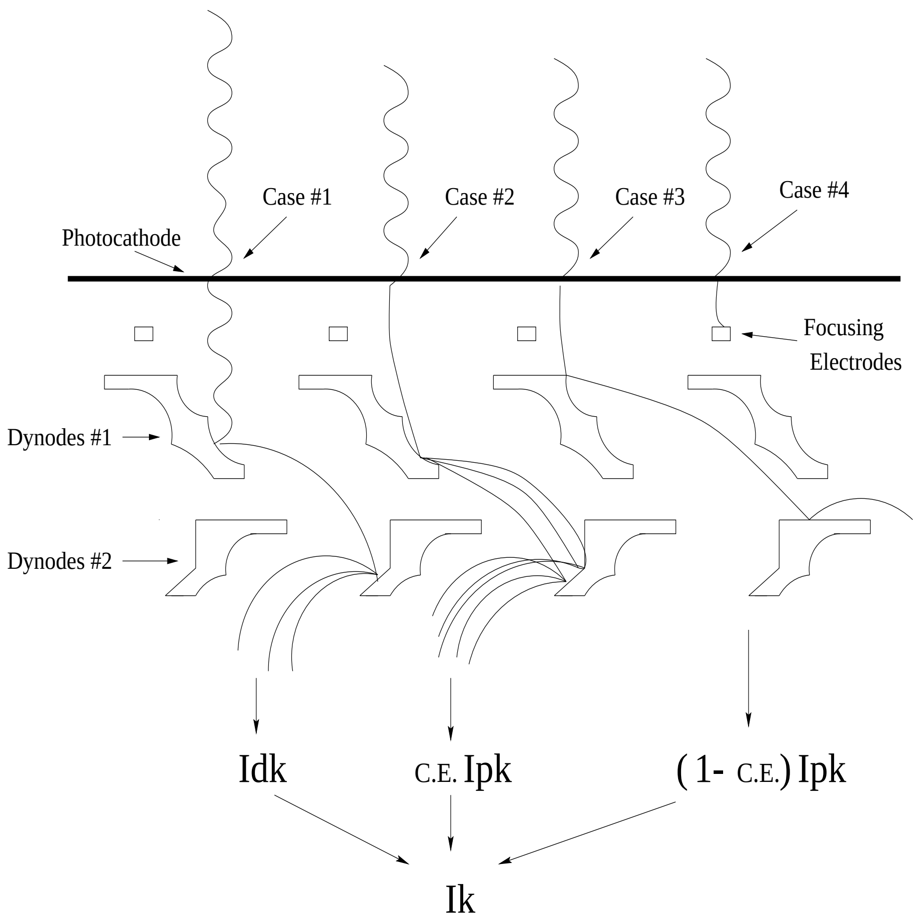

Figure 6 : Some of the configuration for photoelectron production: case #2 corresponds to a normal amplification, case #1 corresponds to photoconversion on first dynode, other cases represent unefficient photoproduction.

When measuring the photocathode sensitivity, the resulting current corresponds to all these photoelectrons.

$$I_k \;=\; I_{pk} \;+\; I_{dk} \;=\; (C.E. \times I_{pk}) \;+\; (1 - C.E.) \times I_{pk} \;+\; I_{dk} \qquad (33)$$

When measuring the anode sensitivity, on should take into account of the subset of photoelectron coming from photoconversion on the first dynode, and the anode current,I_a, is equal to:

$$I_a \;=\; I_{pk} \times C.E. \times \overline{m_8} \;+\; I_{dk} \times \frac{\overline{m_8}}{k_1} \qquad (34)$$

where k_1 is the averaged first stage amplification. When operating R5900 in one photoelectron mode, analysis of the spectra indicate that the ratio between event with one photoelectron coming from photoconversion on the photocathode to event with 1 photoelectron coming from photoconversion on the first dynode is $\sim$ 10%. Expressing the ratio probability of the two types of events, one get :

$$\frac{N_\gamma \times \eta \times C.E.}{N_\gamma \times \alpha \times \eta} \;\sim\; 10 \;\sim\; \frac{C.E.}{\alpha} \qquad (35)$$

where α is the probability for a photon to be the source of 1 photoelectron on the first dynode. One could write equation (33) as follow:

$$I_k \;=\; I_{pk} \;+\; I_{dk} \;=\; \frac{N_\gamma \eta}{\Delta t} \;+\; \frac{N_\gamma \eta \alpha}{\Delta t} \;=\; \frac{N_\gamma \eta}{\Delta t}(1+\alpha) \;=\; I_{pk}(1+\alpha) \qquad (36)$$

Using expression (35):

$$I_{pk} \;=\; \frac{I_k}{1 + (C.E./10)} \quad \text{and} \quad I_{pk} \;=\; \left(\frac{C.E.}{10}\right) \times \frac{I_k}{(1 + C.E./10)} \qquad (37)$$

expression (34) for I_a is

$$I_a \;=\; \left(\frac{I_k}{1 + C.E./10}\right) \times C.E. \times \overline{m_8} \;+\; \left(\frac{C.E.}{10}\right) \times \frac{I_k}{(1 + C.E./10)} \times \frac{\overline{m_8}}{k_1} \qquad (38)$$

$$I_a \;=\; \overline{m_8} \times C.E. \times \frac{I_k}{(1 + C.E./10)} \times \left(1 + \frac{1}{10k_1}\right) \qquad (39)$$

As a numerical application, using $C.E. \sim 90\%$, $k_1 \sim 4$, one gets:

$$\frac{I_a}{I_k} \;=\; \overline{m_8} \times 0.85 \qquad (40)$$

When the amplification is measured in pulsed mode, the effect of the statistic for photoelectrons that are collected on first dynode and then give up to a cascade is given by equations (12) and (14). So finally N_γ photons impinging on the photocathode will results in $\eta N_\gamma \times CE$ photoelectron giving up a cascade from dynode # 1, that is N_{a1} electrons at the anode.

$$\begin{aligned} N_{a1} &= N_\gamma \times \eta \times C.E \times \overline{m_8} &(41)\\ &= N_{p.e.} \times C.E. \times \overline{m_8} &(42)\end{aligned}$$

Using cascade events statistic:

$$\sigma^2_{Na1} = (C.E.)^2 \times N_{p.e.} \times \overline{m_8}^2[1 + F_1] \qquad (43)$$

F_1 given by equation (20)

Second contribution will occurs from photoelectrons converted on dynode #1, and gives up a cascade starting from dynode #2 and so N_{a2} electrons at the anode.

$$\begin{aligned} N_{a2} &= N_\gamma \times \eta \times \alpha \times \frac{\overline{m_8}}{k_1} &(44)\\ &= N_{p.e.} \times \alpha \times \overline{m_7} &(45)\end{aligned}$$

Using cascade events statistic:

$$\begin{aligned} \sigma^2_{Na2} &= \alpha^2 \left[\overline{m_7}^2 \sigma^2_{N_{p.e}} \ + \ N_{p.e.}\sigma^2_{\overline{m_7}}\right] &(46)\\ &= \alpha^2 N_{p.e}\overline{m_7}^2[1 + F_2] &(47)\\ &= \left(\frac{C.E.}{10}\right)^2 N_{p.e}(\frac{\overline{m_8}}{k_1})^2[1 + F_2] &(48)\end{aligned}$$

Ratio of σ^2_{Na2} over σ^2_{Na1} is equal to

$$\frac{\sigma^2_{Na2}}{\sigma^2_{Na1}} = \left(\frac{C.E.}{10}\right)^2 \left(\frac{1}{C.E.}\right)^2 \left(\frac{1}{k_1}\right)^2 \frac{[1 + F_2]}{[1 + F_1]} = \left(\frac{1}{10k_1}\right)^2 \frac{[1 + F_2]}{[1 + F_1]} \sim \left(\frac{1}{10k_1}\right)^2 \qquad (49)$$

In most or the measurement σ^2_{Na2} could be neglected, and finally signal-to-noise ratio at the anode is

$$\left(\frac{N_a}{\sigma_{Na}}\right)^2 = \frac{(N_{a1} + N_{a2})^2}{\sigma^2_{Na1}} \qquad (50)$$

$$\begin{aligned} \left(\frac{N_a}{\sigma_{Na}}\right)^2 &= \frac{[N_{p.e.} \times \overline{m_8}(C.E \ + \ \alpha/k_1)]^2}{C.E.^2 \times N_{p.e.} \times \overline{m_8}^2 \times [1 + F_1]} &(51)\\ &= N_{p.e} \times \frac{1}{1 + F1} \times \left(\frac{1 + 10}{k_1}\right)^2 &(52)\\ &\sim N_{p.e} \times \frac{1}{1 + F1} &(53)\end{aligned}$$

This means that pulsed mode amplification measured is practically not perturbed by the first dynode photoproduction. Finaly Table (5) report comparizon between the two corrected amplification measurement:

• The corrected DC mode amplification, using an average $C.E. \sim 90\%$.

• The noise factor corrected pulsed mode amplification. For that data we recalculate the noise factor F using the corrected DC mode amplification data.

This table shows that now the corrected measured amplification are roughly identical.

PMT	F	pulsed mode Corr Gain	DC-Corr. Gain
6B23C7	0.1689	0.92×10^6	0.918×10^6
6C05DA	0.1525	1.92×10^6	1.88×10^6
6C06DA	0.1525	1.87×10^6	1.88×10^6
6C11C9	0.1634	0.99×10^6	0.941×10^6

Table 4 : Gain at $HV = 800\ V$ in pulsed mode after correction from the noise factor F. The last column indicate the gain measured in DC mode.

4. Pile-up effect on PMT amplification

These measurements were done in order to try to reproduce what the conditions in the ATLAS detector will be and to have an idea of the behaviour of a PMT in such conditions. Using the worst-case scenario of an average of 20 minimum bias events at each bunch crossing, one finds an average value for the anode current of the order of 2 μA.

The setup for this test is the same as the one described for the pulsed light test (Figure (4)). The DC background is produced by a DC LED which is added at the PM test box level. The tests have been performed with 4 DC background current values: 100 nA, 1 μA, 2 μA and 5 μA.

Figure (7) represents the variation of the gain of the PMT versus the anode current and for the different values of the DC background current. For a 100 nA DC current the variation of the gain is negligible but **under the extreme ATLAS conditions ($I_{DC} = 2\ \mu A$) this variation goes up to around 1 %, variation which is no longer negligible and somehow has to be taken into account**. The explanation of the gain increase is the following: when an intense DC current circulates through the PMT, the voltage distribution of each dynodes varies. Since the overall voltage is kept constant by the HV source, the loss of the interdynode voltage at the latter stages (stages which the most affected) is redistributed to the first stages. Then the voltage distribution of the first dynodes increases and then the gain of the PMT increases. We remenber that for 10-stages PMTs and under the same conditions the gain variation is a little bit higher.

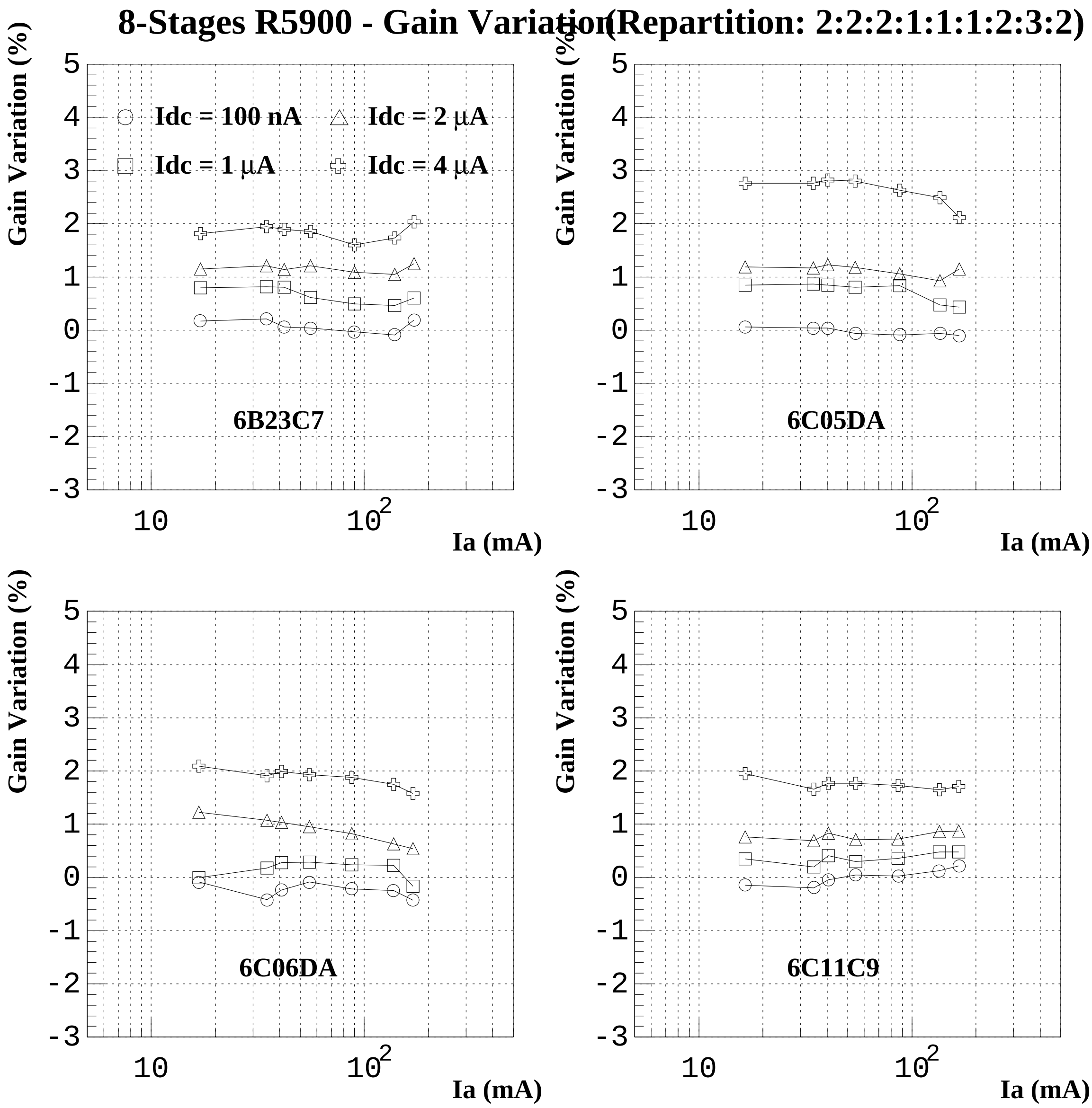

Figure 7 : Variation of the gain versus the anode current for different values of the DC background current.

5. linearity

5.1 Hamamatsu results

When investigating a 8-stages R5900. It was first requested to Hamamatsu preliminary studies on the linearity of such a device. Results of Hamamatsu linearity test of a set of 8-stages R5900 PMTs are shown in Figures (8) to (11). For all these tests **the pulse width was 50 ns**.

Left part of Figure (8) presents the results for a set of 8-stages PMTs operated at 10^5 with the 2:2:2:1-1:2:3:2 configuration. The 8-stages PMTs results could be directly compared to those of right part, corresponding to 10-stages PMTs operated with the same conditions. It appears clearly that for a given value of the anode current (and so a given value of $N_{p.e.}$), the linearity deviation of 8-stages PMTs are lower: for 30 mA the averaged value of the linearity deviation is equal to 1.07% for the 10-stages PMTs instead of 0.5% for the 8-stages PMTs. This could be explained by the voltage repartition: for 10-stages PMTs with an amplification of 10^5 the averaged value of the HT is equal to 618 Volts instead of 727 Volts for 8-stages PMTs. So the interdynode voltage are much higher for the 8-stage configuration, and so could in a easier way overcome the charge space effect.

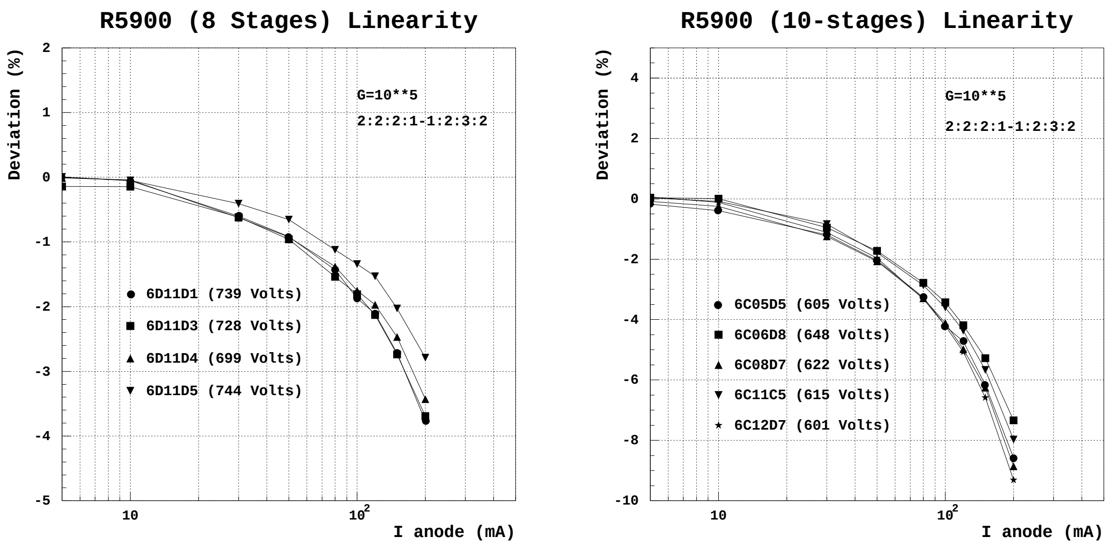

Figure 8 : Linearity test results for R5900 operated with an amplification of 10^5 *and a 2:2:2:1-1:2:3:2 configuration.* **Pulse width was** $50ns$. *On left 8-stages R5900, on right 10-stages R5900*

Figures (9) represents the linearity deviation for a specific 8-stages PMT (6C11C9) on left, and a specific 10-stages PMT (6C11C5) on right, operated both with a 2:2:2:1-1:2:3:2 voltage repartition but with different values of the HV (and so with different amplifications). It seems that 8-stages PMT allows to operate the PMT at a much lower amplification without a high linearity deviation. For 600 Volts, corresponding to an amplification of 3×10^4, the 3% linearity deviation occurs at 100 mA anode for the 8-stages PMT instead of $\sim$ 50 mA anode current for the 10-stages.

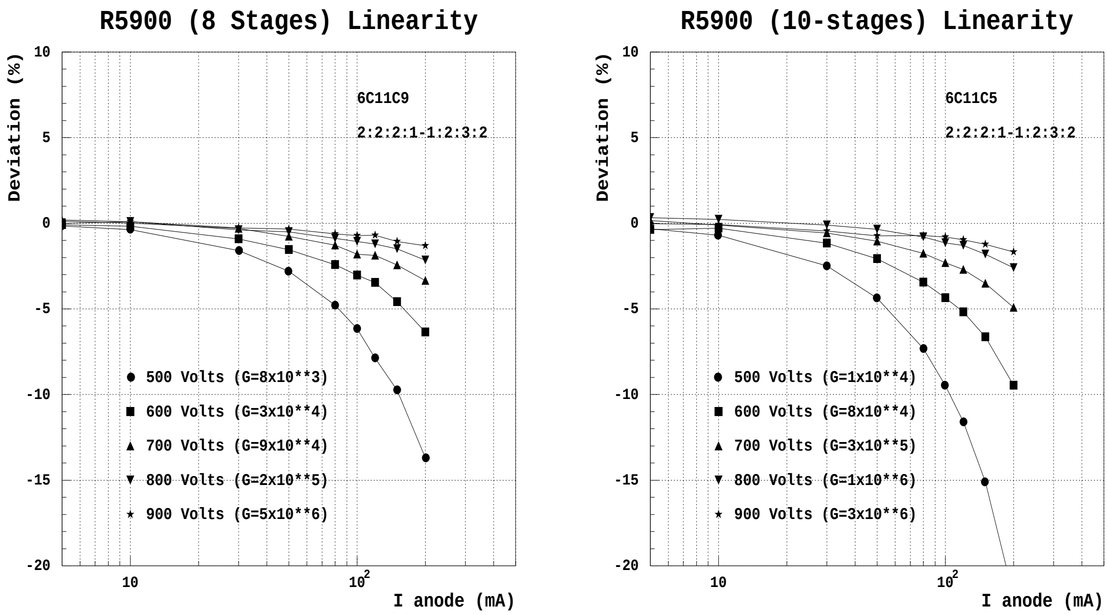

Figure 9 : Linearity test results for 8-stages (left), and 10-stages (right) operated both with a 2:2:2:1-1:2:3:2 voltage repartition but with different values of the HV. For each value of the HV the PMT amplification is indicated.

Figure (10) represents the linearity deviation for a set of 8-stages PMT operated with the same amplification (10^5) but with two different voltage repartitions: a 3:3:3:1-1:2:3:2 and a 2:2:2:1-1:2:3:2 configuration. This figure confirms that increasing the interdynode voltage on the first stages has the consequence to decrease the electric field in the final stages. The overall result is that for 30mA anode current the averaged value of the linearity deviation is equal to 0.83% for the 3:3:3:1-1:2:3:2 repartition instead of 0.5% for the 2:2:2:1-1:2:3:2 repartition.

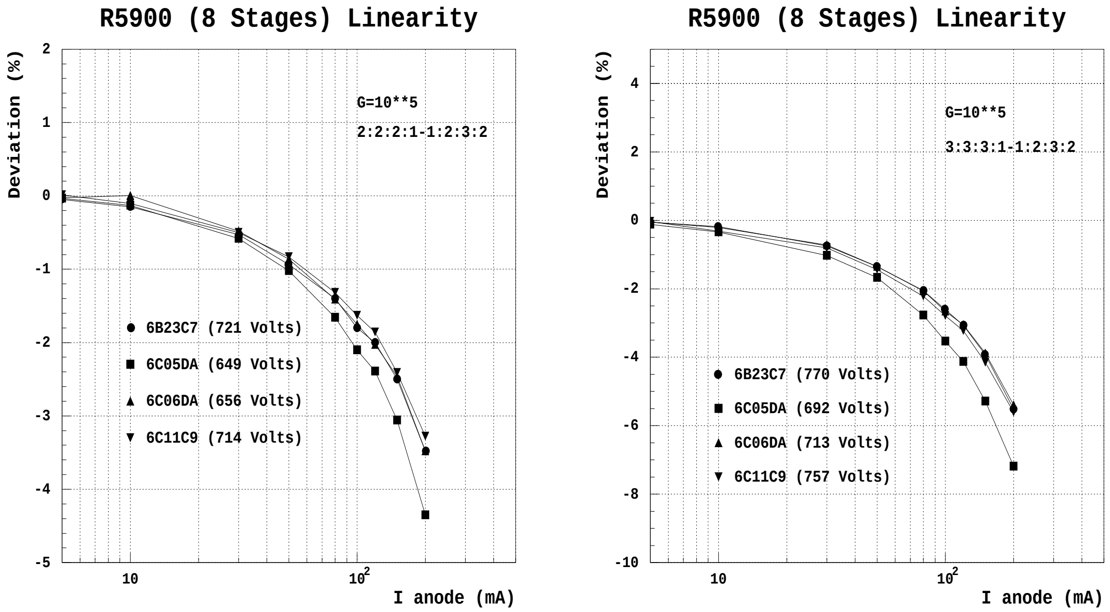

Figure 10 : Comparison of linearity test results for 8-stages R5900 operated with an amplification of 10^5*, the 3:3:3:1-1:2:3:2 (top) and 2:2:2:1-1:2:3:2 (bottom) configuration. Pulse width was* $50ns$*.*

In order to optimise the voltage divider, variations in the voltage repartition are shown on Figure (11) for a specific 8-stages PMT (6C05DA) operated with an amplification of 10^5. Associated data are reported in Table (9). The tested repartition and corresponding voltage were:

A: 1.5:1.5:1.5:1:1:1:1:1:0.5 $\longrightarrow$ 560 Volts

B: 1:1:1:1:1:1:1:1:1 $\longrightarrow$ 574 Volts

C: 2:2:1:1:1:1:1:1:2 $\longrightarrow$ 684 Volts

D: 2:2:1:1:1:1:1:2:3 $\longrightarrow$ 730 Volts

E: 2:2:1:1:1:1:2:3:3 $\longrightarrow$ 717 Volts

F: 2:2:1:1:1:1:2:3:2 $\longrightarrow$ 675 Volts

G: 2:2:1:1:1:1:2:2:2 $\longrightarrow$ 659 Volts

For an anode current of 30mA, the lowest linearity deviation is achieved for the repartition F (2:2:1:1:1:1:2:3:2), with a voltage of 675 Volts for which the linearity deviation is less than 1%. It could be compared to the isorepartition **B** (1:1:1:1:1:1:1:1:1) for which the deviation is of the order of 1%. The worse configuration is **A** (1.5:1.5:1.5:1:1:1:1:1:0.5) that correspond to 2% deviation but only 560 Volts (and so the possibility to have a large amplification range when increasing the voltage up to 900 Volts).

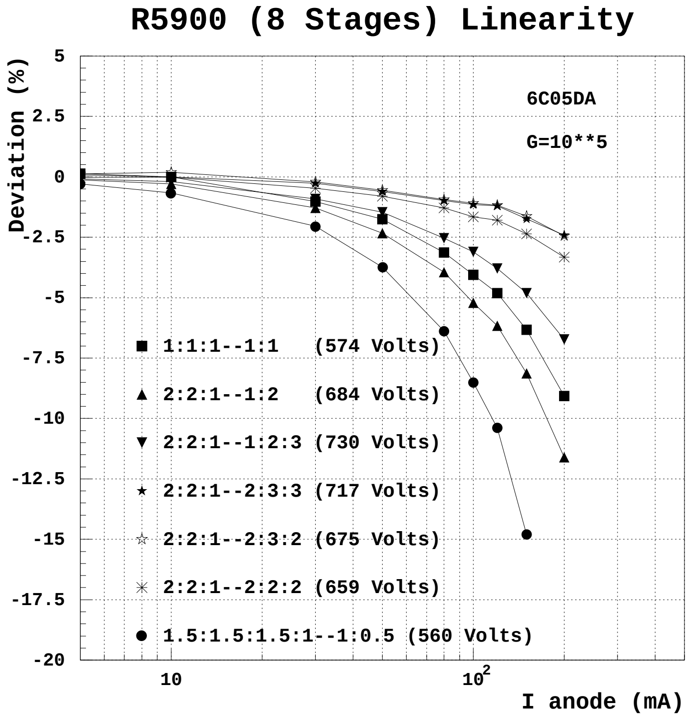

Figure 11 : Linearity test results for a 8-stages R5900 (6C05DA) operated with an amplification of 10^5 *and with different voltage repartitions.*

5.2 Clermont results

To confirm the Hamamatsu results, we performed linearity test using the same setup as for the gain measurement in pulsed mode shown on Figure (4). Hamamatsu calculates deviation from linearity using anode current amplitude instead of charge. However, we have to keep in mind that non linearity could appear first looking on pulse amplitude rather than on charge of the signal. Nevertheless, comparison between Clermont linearity measurements and Hamamatsu results for the same PMT (10-stages) had shown that both methods give the same results. The main difference is that now **the light pulse width provided by the LED is** ~ 19 **ns; that is more close to the TILECAL pulse**.

Let us call Q_{PM} the output charge of a photomultiplier measured by an ADC in response to a light pulse and Q_{Ph} the output charge of the photodiode in response to the same ligth pulse, ie using the same filter. The deviation from linearity is estimated using the following formula:

$$D(\%) = 100 \times \frac{(Q_{PM}/Q_{Ph}) - (Q_{PM0}/Q_{Ph0})}{(Q_{PM0}/Q_{Ph0})} \tag{54}$$

Here Q_{PM0} and Q_{Ph0} are the charges corresponding to the high attenuation filter.

It has been used as a reference assuming that for this filter, there is no deviation from linearity. The photomultipliers have been operated using the following voltage repartition 2:2:2:1:1:1:2:3:2 and at a high voltage corresponding to a gain of 10^5. The results are presented in Figure (12), they confirm the Hamamatsu measurements. We will note that an error of at least $\pm 0.5\%$ should be assigned to each data point. For this configuration, it clearly appears that pratically no deviation from linearity shows up, even for pretty high anode currents ($Ia > 150\ mA$). We remenber that typical deviation values for 10-stages PMTs and for anode currents of 100 mA are in the range: $-5\% < D < -10\%$.

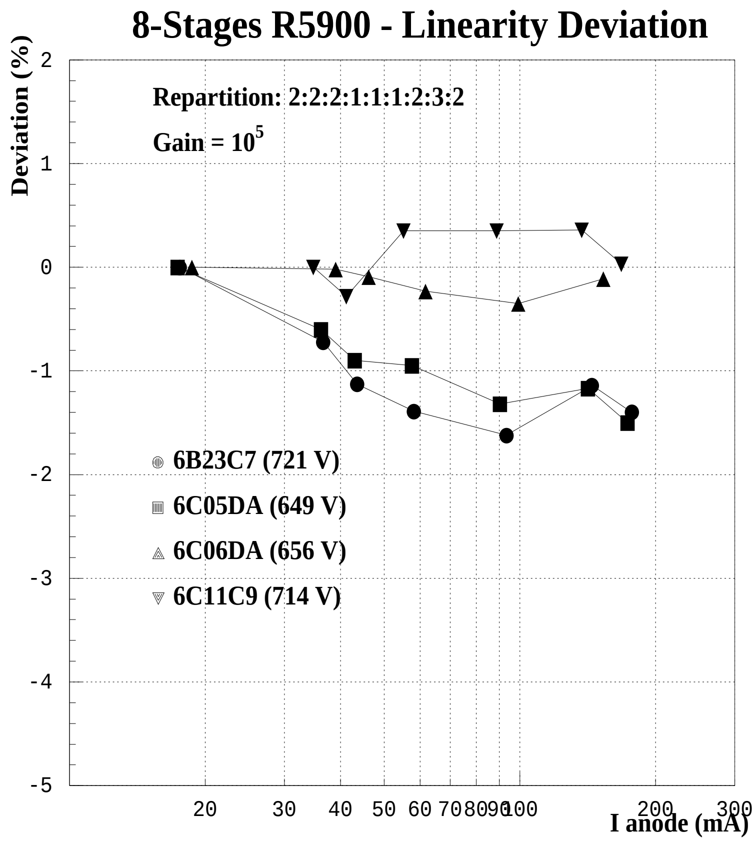

Figure 12 : Linearity test results for 8-stages R5900 measured using the set-up shown on Figure (4). One of the high attenuation filter is used as a reference assuming that for this filter, there is no deviation from linearity.

6. Magnetic sensibility

A magnetic shielding is necessary to avoid effects of the residual magnetic fields on the PMTs. In order to provide a large safety factor, the initial goal was to have a maximum gain variation of 1% for a field of 500 Gauss in every direction. Over the last 2 years various tests have lead to the current PMT block configuration which gives very satisfactory results. We have performed new tests on 8-stages PMTs using the same PMT block configuration than for the 10-stages R5900.

We measured the gain variation for several field direction. The definition of the angles (α and ϕ) are shown on Figure (13). We define the limit for the maximum gain variation to be below 1.4 in absolute scale, 0.4 coming from the relative accuracy of the measurement.

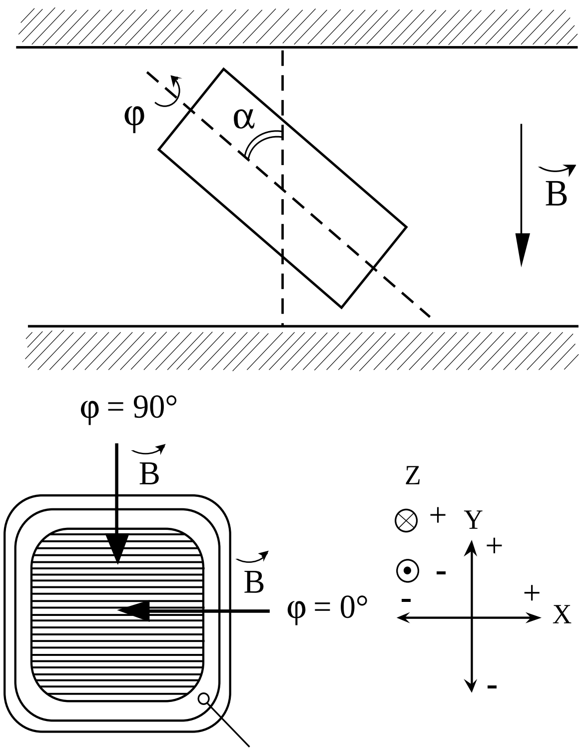

Figure 13 : Definitions of the angles ϕ and α and referential used when testing the R5900.

The results are presented on Figure (14). They are comparable to the ones obtained with 10-stages R5900s. For a longitudinal field ($\alpha = 0$), the gain variation remains within the limit up to $B_{||} \approx 250$ Gauss. For a transverse field ($\alpha = 90$ and any ϕ), the gain variation remains within the limit up to $B_{\perp} \approx 800$ Gauss. We define a safety factor as being the ratio of the fields corresponding to the limits of shielding to the largest simulated values. For both field directions, the safety factor is at least 40.

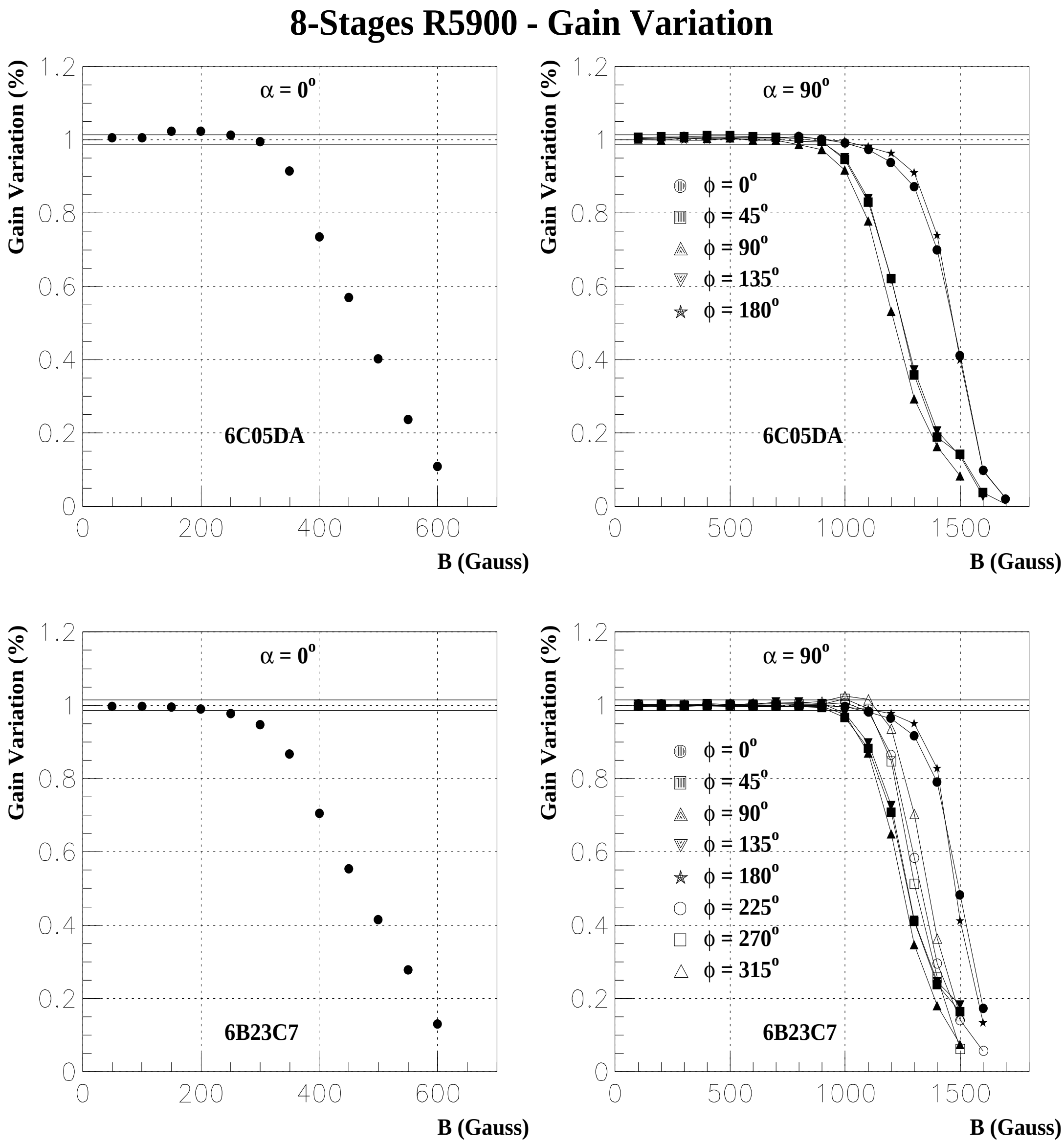

Figure 14 : Effects of magnetic fields on shieldied R5900 PMT's, for two PMTs (#): a) field parallel to the z-axis ($\alpha = 0°$)in the range (0, 600 gauss). b) field perpendicular to the z-axis ($\alpha = 90°$), with various ϕ angles, in the range (0, 1600 gauss).

7. Conclusions

Even if these tests had been performed on a set of 4 samples, it appears mainly that **the 8-stages R5900 are much more linear than the 10-stages**. To summarize, when using the 2:2:2:1-1:2:3:2 voltage repartition, the laboratory measured linearity is of the order of 1% for an anode current of 50 mA; that is two time less than for 10-stages PMT.

The other performances are rougly identical for 8-stages and 10-stages PMT.

• Photocathode sensitivity are fully equivalent: for 30 nA photocathode current, 90% of the saturation value is reached for $\sim$ 20 Volts between photocathode and dynodes.

• Amplification of such 8-stages PMT in standart configuration is still large; this could be a consequence of the improvment in the manufactoring process. The β parameter of such PMTs is 6.9 on the average, to be compared to 8.328 for 10-stages PMTs.

• Using some corrective effects, one could achieve compatibility between DC mode and pulse mode amplification measurements.

Effects of magnetic fields on the shielded 8-stages PMTs are completely identical to the effects on the 10-stages.

• When adding a pile-up effect, by the way of DC light component, the worst case corresponding to 2 μA ($\sim$ 20 minimum bias events), produce a PMT amplification variation of the order of 1%.

• Moreover, using a 8-stages PMT would allow to reduce of $\sim$ 5 mm the longitudinal space needed for the PMT in the PMT block. That should certainly help the electronic integration , as well as improve longitudinal magnetic field shielding.