HAPPEX-2 Photo-tubes Linearity

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mai 2003

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1 Introduction

Photomultiplier provide usually a good linearity in anode output current over a wide range of incident light levels so it has, by default, a good dynamic range. However, for large signals saturations occurs and the output begins to deviate from ideal linearity. This deviation, in an asymmetry measurement, causes a systematic effect in the determination of the mean value of the raw asymmetry and depend directly on the signal amplitude at the anode. Detector tubes and electronics should be linear within 2% over the range of measured current and for any gain setting used. In this report, I summarized the linearity tests conducted at Saclay and at Jefferson Lab.

2 Discussion

To get a feeling of the effect of the non linearity in the detector asymmetry, one can write the expression of the asymmetry from [1] where the integrated signal is a second order polynome :

$$S = P + \alpha L + \beta L^2 \tag{1}$$

P is the pedestal, α is the linear coefficient, β is the first nonlinear coefficient. Then, the measured asymmetry is given by :

$$A_{measured} = \frac{S_R - S_L}{S_R + S_L} = \frac{\alpha L_R + \beta {L_R}^2 - \alpha L_L - \beta {L_L}^2}{2P + 2\alpha L + 2\beta L^2} \tag{2}$$

Where $S = (L_R + L_L)/2$. It gives after some calculus :

$$A_{measured} = A_L \frac{1}{1 + \frac{P}{\alpha L} + \frac{\beta}{\alpha} L} \left[1 + \frac{2\beta}{\alpha} L\right] \tag{3}$$

Considering the first order approximation it follows :

$$A_{measured} \approx A_L \left(1 + \frac{\beta}{\alpha} L - \frac{P}{\alpha L}\right) \tag{4}$$

Note, the detector pedestal is easily determined by looking at the ADC signal without beam. So the last term is well estimated and we will forget about it in the following calculus. The deviation to linearity $\frac{\beta}{\alpha} L$ is directly proportional to the signal. We need to ensure that this term stay relatively small(1-2% level) over the dynamic range of use to keep nonlinearity negligible in our measurement, so:

$$\frac{\beta}{\alpha} L < 0.02 \tag{5}$$

Before starting characterizing the non linearity of the photomultiplier, one should take a look at the operating mode. HAPPEX-2 and HAPPEX-^{4}He will use the detector at low and high beam intensity which corresponds to two intervals of gain setting for the tubes :

- Low beam current, high gain, pulse mode :

  This first operation mode will be used for dedicated runs to study backgrounds and to perform the Q^2 reconstruction. The beam intensity will be reduced to few tenth μA to be able to reconstruct the trajectory of the scattered electrons using the Vertical Drifts Chambers. The rate will drop down to 10 kHz/cm^2 (a factor 200 smaller). Therefore the detector tubes will be set to high gain (1E6 - 1E7).

- High beam current, low gain, integrating mode :

  The second is production where 50 MHz of signal will be integrated per helicity window. This correspond to one pulse of light every 20 nanoseconds. At this rate, the Cerenkov signal arriving at the photo-cathode is faster than the intrinsec peak width of the tube (30 ns). The current output will average all the pulses in the helicity window. The tube will operate in continuous mode.

To get a complete linearity capability measurement of the BURLE 8854, we need to measure both the linearity in the pulse mode and in the continuous mode. We need also to ensure that change in the integrated signal at every helicity reversal or when the beam has tripped, doesn't lead to non negligible drift in the gain.

3 Linearity Tests

We have compared the linearity capability of the two bases which are candidates to be used for HAPPEX-2 and HAPPEX-4He experiments:

- The HAPPEX-1 base which was designed for high gain operation of the tubes. This is an active base where transistor regulates the voltage at particular stage of dynodes to avoid loose of gain.

- The "PROTO" base which is a purely resistive base. It ensures a good voltage stability on the firsts dynodes for low gain operation. This design was motivated for operation of the tubes in an relatively bright environment.

3.1 Pulse mode linearity

Non linearity in pulse mode occurs when the light amount reach a certain level. As the light get brighter, the current flowing through the dynode saturates and space charge effects appear. The result is a slow down in the increase of the current at the anode as the light flux increases.

The method we used to measure non linearity in pulse mode is to monitor a ratio G_S between a high amplitude LED pulse (L_f) and a lower one (L_a). S(L) is the photomultiplier response to the LED signal L:

$$G_s(L) = \frac{S(L_f)}{S(L_a)} \tag{6}$$

The ratio $R_{Att} = \frac{L_f}{L_a}$ of the light pulses is being fixed by an attenuator plugged at the output of the LED pulse generator. At some point, when the output signal is increasing the ratio will decrease due to saturation occuring first on the higher pulse amplitude.

Then, to measure the pulse mode linearity the following ratio is defined :

$$\frac{\Delta G}{G} = \frac{G_S(L_0) - G_S(L)}{G_S(L_0)} \tag{7}$$

$G_S(L_0)$ is the ratio in an operating range where the tube is linear. In order to cover a wide range of peak current we have used a set of calibrated filters. The error on the value of the filter doesn't affect the $\frac{\Delta G}{G}$ ratio. We use the filter calibration to correct the horizontal axis values. The output current measured carry the information of the non linearity so one has to measure it in the linearity region and apply the filter ratio to get the other current values on the axis. A error of 20% on the value of the calibration doesn't change dramatically the scale of the effect and won't affect our conclusion.

Equation 7 is not exactly the quantity we are interested in : we need to relate this ratio to the ratio defined in equation 5. That will give the actual nonlinearity in our asymmetry measurement due to pulse mode nonlinearity. We can rewrite equation 7 in function of a quadratic pulse signal defined in 1 (S_F is for a full amplitude and S_A for an attenuated one) :

$$\frac{\Delta G}{G} = \frac{S^0{}_F/S^0{}_A - S_F/S_A}{S^0{}_F/S^0{}_A} \tag{8}$$

Assuming $\frac{\beta}{\alpha} << 1$ and knowing that $\frac{S_F^0}{S_A^0} = \frac{S_F}{S_A}$ this leads to :

$$\frac{\Delta G}{G} = \frac{\beta}{\alpha}\Delta L_F\left(1 - \frac{\Delta L_A}{\Delta L_F}\right) = \frac{\beta}{\alpha}\Delta L_F\,(1 - 1/R_{Att}) \tag{9}$$

where $\Delta S = S^0 - S$. It can be identify to the non linear term of equation 4 by normalizing by the factor $(1 - 1/R_{Att})$. The relevant ratio is then :

$$\frac{\frac{\Delta G}{G}}{(1 - 1/R_{Att})} \tag{10}$$

As shown on Fig. 1 the measurement are performed in a black box with two filter wheels remotely controlled, a blue LED and a pulse generator. $S_F(L)$ and $S_A(L)$ are recorded via an ADC and G_S is calculated. Then the filters allow to cover a large range of L.

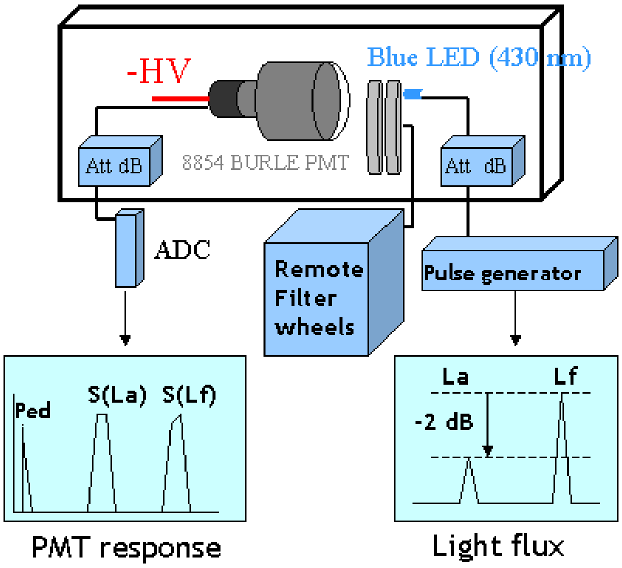


Figure 1: JLab setup for pulsed mode linearity measurements

On figure Fig. 4 are plotted the linearity curves for different gains versus the number of photoelectrons. For a same number of photelectrons, the high gain are more sensitive to non linearity than the low gains which is compatible with the hypothesis of a saturation due to space charge effects. It gives a good idea where the non linearity is really meaningfull in terms of quantity of light. if one consider only results from this curve it would be better to use a lower gain to keep a good dynamic range. However, one has to consider another constraint which is the output charge : it has to be high enough to be detected (>20 pC, see Fig. 5). So, choosing the operating gain is finding a good compromise between this two requirements. Note that the constraint at 2% deviation (red dash line) is more stringent that what we actually need because we won't compute asymmetries for high gain settings. If the linearity is well controlled at high gain, we will keep a good weight between events at the center of the detector and events at the edge.

Here are the interval of gain operation for both bases according to Fig. 4 and 5) :

- Resistive base :

  G=[10^6, 3 10^6], give an output signal range of I=[2, 8] mA. The corresponding charge interval is C = [30 10^{-12}, 120 10^{-12}]. It should be viable even with a filter cutting half of the light.

- Active base :

  G=[2 10^6,3 10^6] give an output signal range of I=[4, 8] mA. This values are still not at the end of the base dynamic range and if the signal is too low it could be set to a higher gain (limit around a couple of 10^7).

In this mode, the resistive base will have a gain near the limit of its dynamic range. This setting is still viable if we don't cut too much of the Cherenkov light with the filters (half of it maximum). The transistorized base has been designed for operating at high gain and have some confortable margin in case we signal is too small.

3.2 Linearity in continuous mode

The frequency of the light signal compared to the time response of the tube define the mode of use of the photomultiplicator. The amplitude of the anode current will correspond to the integration of the 50 MHz pulse over the 33 ms window. The amplitude at the anode is now a thousandth of the current in pulse mode. At this low value of current, the non linearities come generally from a limit of current flowing in the voltage divider and his structure when the signal increase. If the voltage divider is made to be stable enough at low gain, the non linearity will after come from saturation at the photo-cathode.

We have used two different methods to measure the non linearity in this mode.

- The first method was used at JLab, it uses calibrated filters to change the PMT signal. We used the same filter wheels as before but the ratio G is now define as follow :

$$\frac{\Delta G}{G} = \frac{\frac{S(L)}{S(L*f)} - 1/f}{1/f} \tag{11}$$

  f is the calibrated filter value. If deviation from linearity appears it will first occurs for S(L).

- The second method, used at Saclay, is well described in manufacturer's guide : two LEDs sitting behind a shutter operate as two continuous signal. We read the output current of the tube when opening the first shutter, the other, and both ones in order to compare the sum of the signal with the signal of the sum, Fig. 2. Shutters were remotely controlled so the conditions where identical for each measurements.

  The ratio is calculated as follow:

$$\frac{\Delta G}{G} = \frac{S_{(1+2)}}{S_1 + S_2} - 1 \tag{12}$$

Fig. 6 summarizes the results of the two methods for both bases as a function of the number of photoelectrons. The 2 LED method shows a relatively better stability in the results than the filter one. The deviation from linearity for the resistive base occurs approximately at the same number of photoelectrons for a couple of gain. This could be explained by a saturation at the photo-cathode. The active base shows deviation for different values. It is difficult in this case to interpret the origin of the non linearity. It could be the voltage divider, which tends to be less stable at low gain.

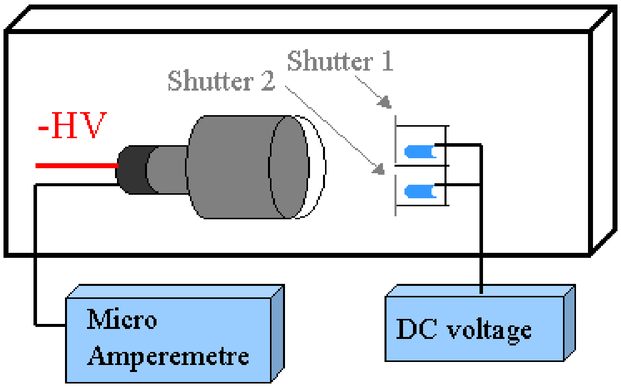


Figure 2: Saclay setup for continuous mode linearity measurements.

The next figure (Fig. 7) shows the same curves but now as a function of the output current of the tube. We have to consider that the real signal in the detector will have a pulse structure even if the period of pulse will be greater than the rise+fall time of the tube. In order to consider effects of non linearity of the pulse mode at low gain we will add a duty factor. This can be illustrated as in Fig. 3. In the real Cerenkov signal seen by the tube's photocathode, the light pulse will not be evenly distributed in time. The resulting overlap will increase the average value of the current.

In order to estimate an upper limit on this factor we have to consider an output current average times 2 or 3. On the plot depicted in fig. 7 we have to choose a gain curve where we are comfortably safe from deviation to linearity for a output current increased by this duty factor.

The tables below summarize the linearity deviation and the corresponding output current for a set of gain values. These numbers have been calculated for different numbers of photoelectrons :

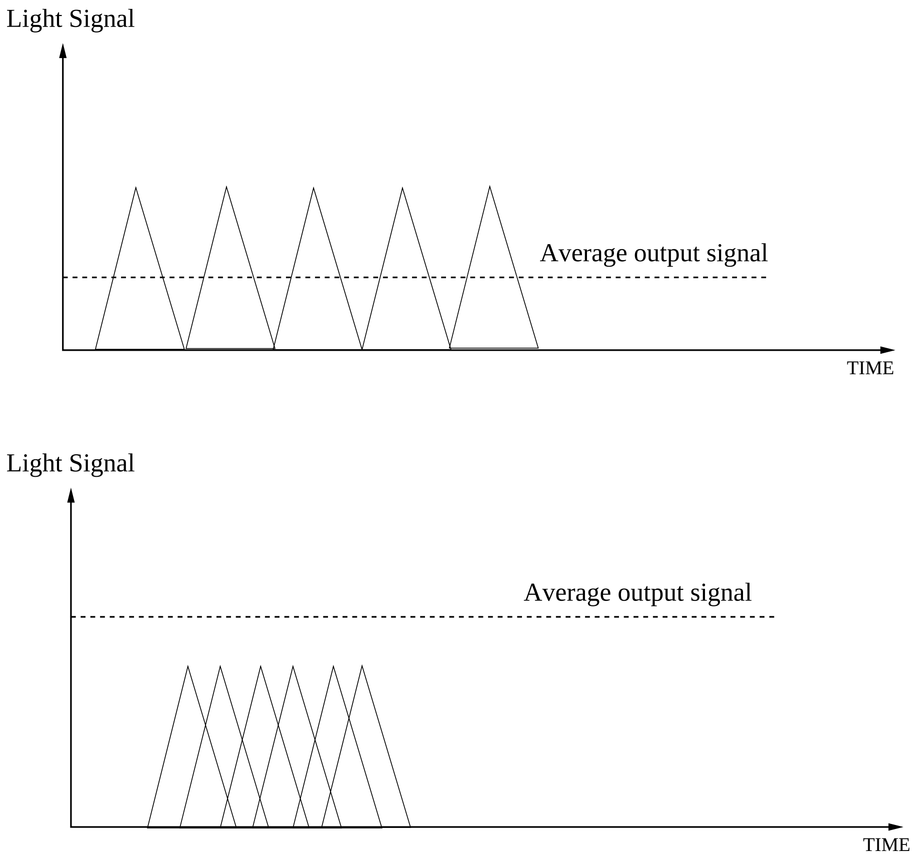


Figure 3: Photomultiplicator pulse distribution in time in continuous mode. First plot shows a pulse period where the average output current is less than the peak amplitude of a single pulse. The second plot shows very small period where pile up starts and the average output current is more than the actual peak current of one pulse.

Resistive base, filter method.					
	Gain	10^2	10^3	$5\ 10^3$	10^4
250 $\gamma e-$	output current (μA)	0.23	2	10	20
	$\frac{\beta}{\alpha}$L (%)	0	0	0	2
125 $\gamma e-$	output current (μA)	0.1	1	5	10
	$\frac{\beta}{\alpha}$L	0	0	0	0
50 $\gamma e-$	output current (μA)	0.05	0.5	2.5	5
	$\frac{\beta}{\alpha}$L	0	0	0	0
25 $\gamma e-$	output current (μA)	0.025	0.25	1.25	2.5
	$\frac{\beta}{\alpha}$L	0	0	0	0

Resistive base, 2 LED method				
	Gain	10^3	$5\ 10^3$	10^4
250 γe-	output current (μA)	2	10	20
	$\frac{\beta}{\alpha}$L (%)	1	0.5	0
125 γe-	output current (μA)	1	5	10
	$\frac{\beta}{\alpha}$L	0.5	0.5	0
50 γe-	output current (μA)	0.5	2.5	5
	$\frac{\beta}{\alpha}$L	0	0	0
25 γe-	output current (μA)	0.25	1.25	2.5
	$\frac{\beta}{\alpha}$L	0	0	0

Active base, filter method				
	Gain	$5\ 10^3$	10^4	$5\ 10^4$
250 $\gamma e-$	output current (μA)	10	20	100
	$\frac{\beta}{\alpha}$L (%)	0.5	5	-
125 $\gamma e-$	output current (μA)	5	10	50
	$\frac{\beta}{\alpha}$L	0	0	4
50 $\gamma e-$	output current (μA)	2.5	5	25
	$\frac{\beta}{\alpha}$L	0	1	1
25 $\gamma e-$	output current (μA)	1.25	2.5	12.5
	$\frac{\beta}{\alpha}$L	0	0	0

Active base, 2 LED method			
	Gain	10^3	$5\ 10^3$
250 γe-	output current (μA)	2	20
	$\frac{\beta}{\alpha}$L (%)	0	0
125 γe-	output current (μA)	1	10
	$\frac{\beta}{\alpha}$L	0	0
50 γe-	output current (μA)	0.5	5
	$\frac{\beta}{\alpha}$L	0	0
25 γe-	output current (μA)	0.25	2.5
	$\frac{\beta}{\alpha}$L	0	0

These numbers have been plot on Fig. 8 to find the appropriate gain and filter value. The delimited box materializes our requirement in term of linearity and current output. For each gain inside the box, we keep in mind the actual linearity range according to the output times the duty factor in Fig 7. We would like also not to cut to much of the light in integrating mode so we can run at not too high gain for the pulse mode.

The summary of gain (G) and filter (f) configuration is the following :

- Resistive base :

  G=[5 10^3, 10^4], f=(0.5) give an output signal interval of I=[2.5, 10] μA

- Active base : G=[10^4, 2 10^4], f=(0.5,0.2) give an output current range of I=[2-20] μA

4 Conclusion

The linearity capability of the 8854 BURLE PMT with the two bases has been measured. The deviation from linearity has to be less than 2% to keep nonlinearity in the asymmetry measurement negligible. A combination of gain and filter for the photomultiplier has been found for each kind of base according to the linearity and output current requirements. These requirements are :

- $\frac{\beta}{\alpha}L < 0.02$
- average current 5 to 20 μA, high enough to reduce effect of pedestal noise.
- Nγe^- high enough so that we can detect individual pulse at low beam current.
- Keep a safety margin according to the duty factor.

The operation setting for both bases is summarized below :

- Resistive base :

  in pulse mode

  G=[10^6, 3 10^6], give an output signal range of I=[2, 8] mA. The corresponding charge interval is C = [30 10^{-12}, 120 10^{-12}].

  in continuous mode

  G=[5 10^3, 10^4], f=(0.5) give an output signal interval of I=[2.5, 10] μA

- Active base :

  in pulse mode

  G=[2 10^6,3 10^6] give an output signal range of I=[4, 8] mA.

  in continuous mode

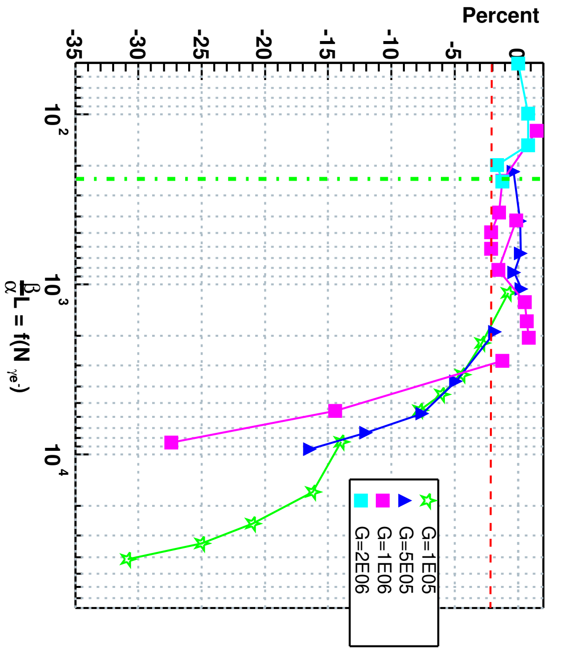
  G=[10^4, 2 10^4], f=(0.5,0.2) give an output current range of I=[2-20] μA.

These tests was a first characterization of the linearity capability of the two bases for HAPPEX-2 and HAPPEX-^{4}He. In the next step we plan to implement some electronics with LEDs to monitor in real time the photomultiplicator response around their operating gain setting. This will help quantifying precisely the linearity capability in the real condition of use.

References

[1] R. S. Holmes, *Pedestal and Linearity for HAPPEX 1999*, (1999).

[2] A. Vacheret, D. Lhuillier, *Detectors for parity experiments in JLab HAll A* (2002).



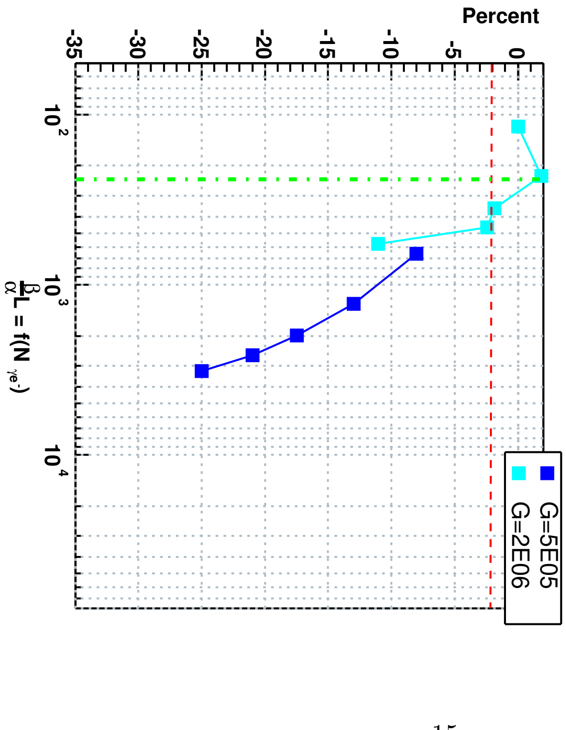
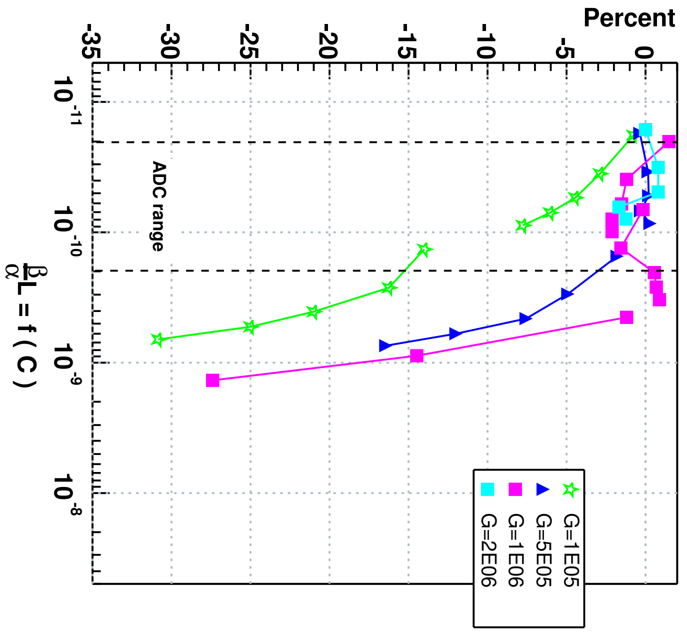


Figure 4: Linearity plot for the two bases versus the number of photoelectrons. Red line is the constraint at 2%. The green line is the maximum number of photoelectrons per scattering electron showering in the detector [2].



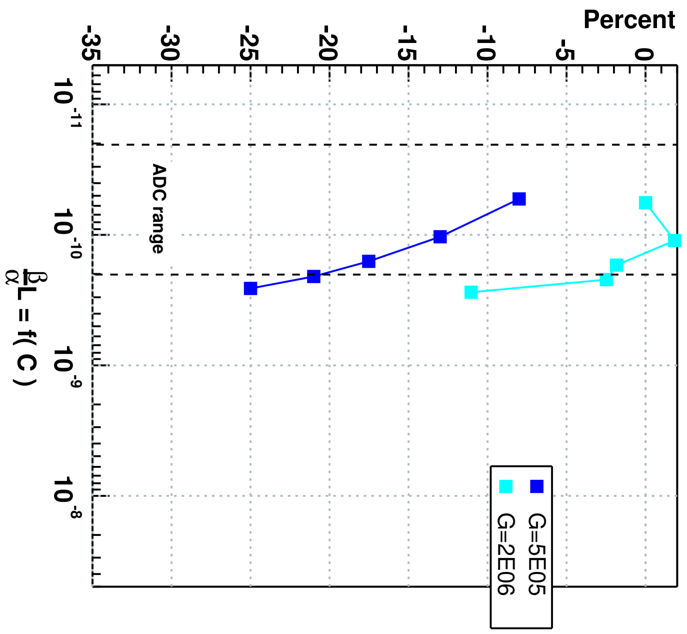


Figure 5: Linearity plot for the two bases versus the number of photoelectrons. Red line is the constraint at 2%. The green line is the maximum number of photoelectrons per scattering electron showering in the detector [2].

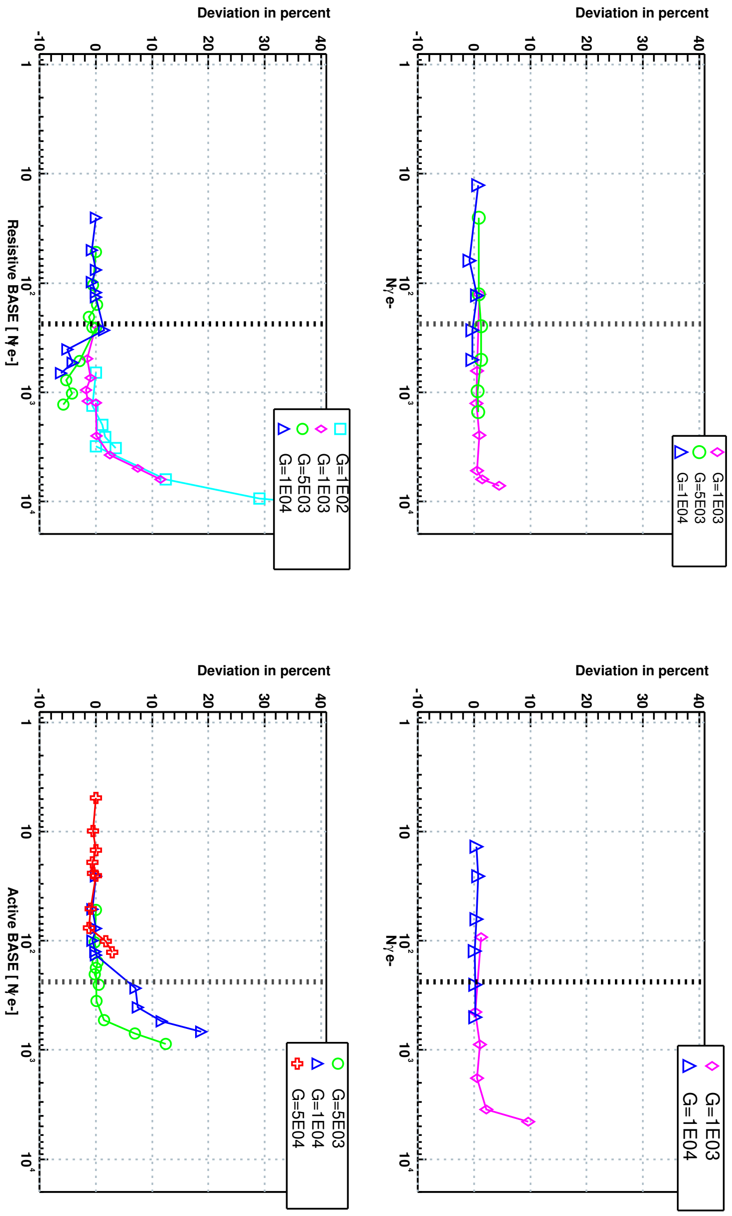


Figure 6: Linearity in continuous mode versus the number of photoelectrons. Upper plots use the 2 LED method. Bottom plots show curves measured with the filter method. Left plots show measurements with the resistive base, right ones with the active one.

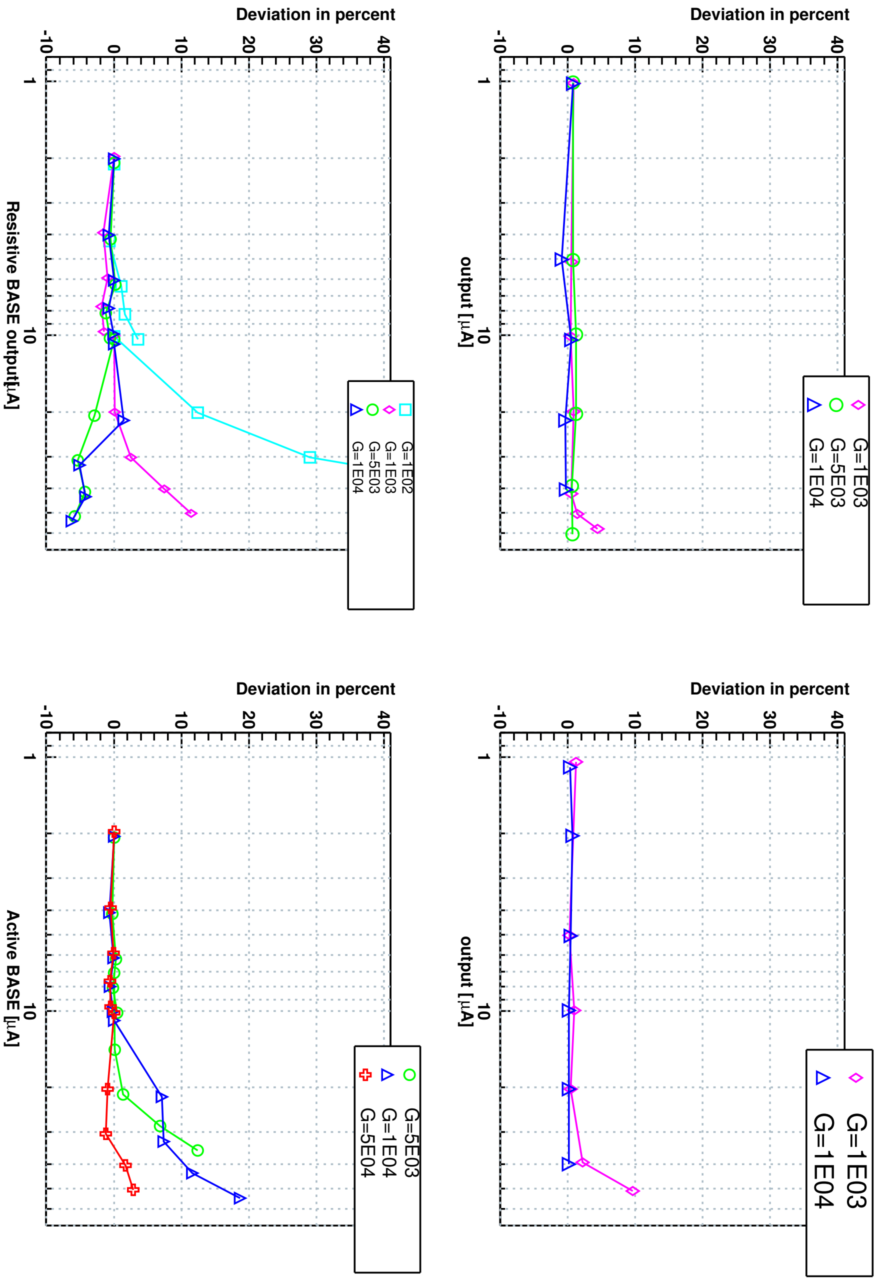


Figure 7: Linearity in continuous mode versus the tube output current. Upper plots use the 2 LED method. Bottom plots show curves measured with the filter method.Left plots show measurements with the resistive base, right ones with the active one.

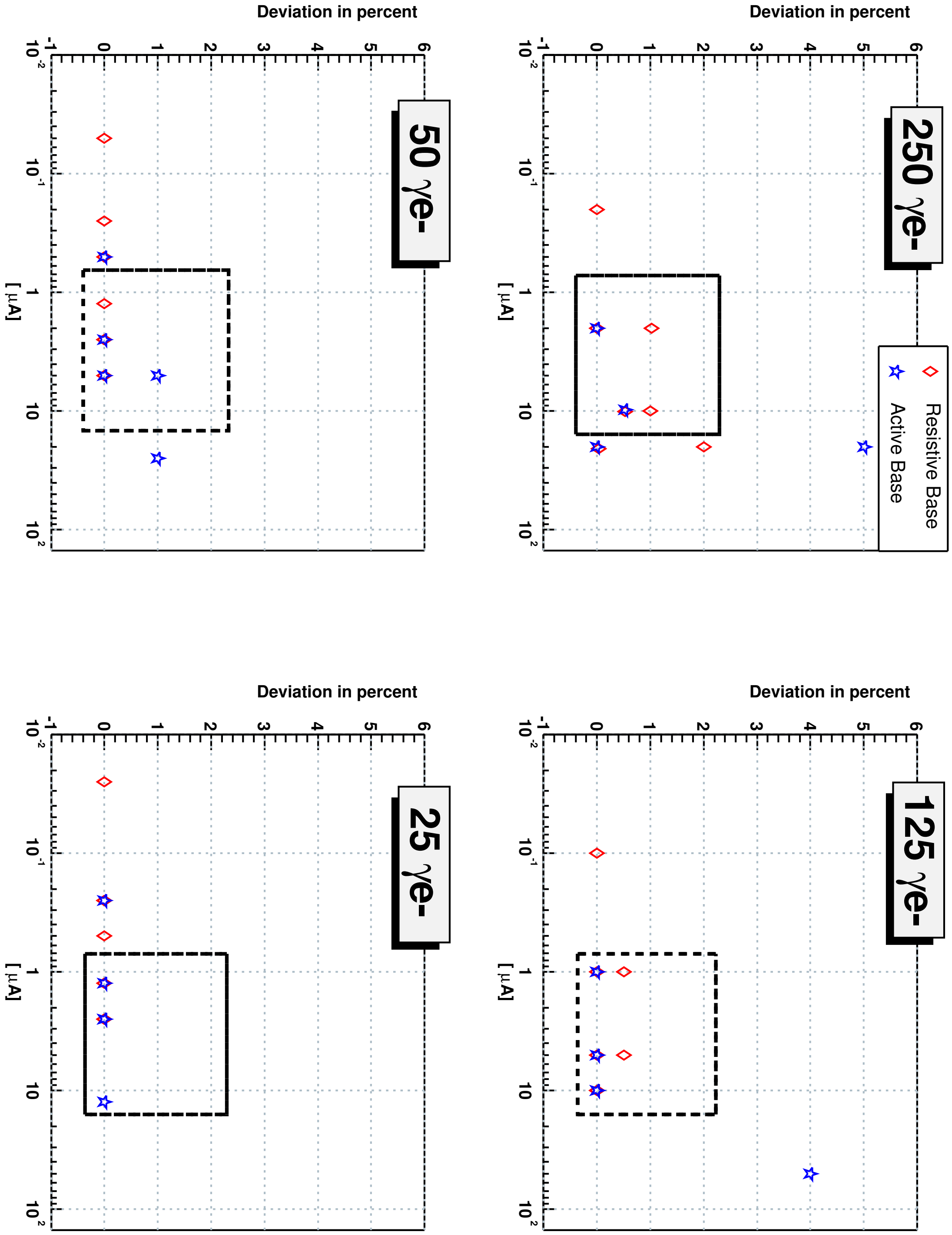


Figure 8: linearity versus the output current for the range of gain (one gain by point) from measurement in fig 6. the box delimits the current range with the linearity requirements.