Linearity test of HAPPEx PMTs

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Abstract

We present the experimental setup and method used to study the linearity of the HAPPEx PMTs. High voltage range is specified to operate each PMT in a linear regime (better than 1%).

1 Formalism

A non-linear response of a PMT to a given signal N is parametrized as

$$N^{\pm}_{PMT} = N^{\pm} \times (1 + \beta N^{\pm}) \tag{1}$$

where the $\pm$ superscript refers to the two beam helicity states.
Then under the approximations

$$A_{True} = \frac{N^+ - N^-}{N^+ + N^-} \ll 1, \qquad and \qquad \beta N \ll 1 \tag{2}$$

the experimental asymmetry writes

$$A_{exp} = \frac{N^+_{PMT} - N^-_{PMT}}{N^+_{PMT} + N^-_{PMT}} = A_{True} \times (1 + \beta N_0) \tag{3}$$

with

$$N_0 = \frac{N^+ + N^-}{2} \tag{4}$$

2 Experimental setup

The experimental setup is illustrated in figure 1. The goal of the continuous diode is to simulate the mean continuous current we expect out of the PMT in nominal running conditions. Another diode is turned On and Off at 30Hz in phase with the pairsync signal generating an asymmetry which size is controlled by the ratio of the two diodes amplitude. Each diode is fed by a 5V power supply connected in series with a $50k\Omega$ potentiometer which allows a fine tune of the light output.
Both diodes are located behind a same filter which attenuation can be changed remotely. Downstream the filter a light diffuser and some drift distance make sure the light is uniformly distributed across the PMT photo-cathode. First tests with no diffuser and the diode very close to the PMT window showed that the 5" HAPPEx PMT are pretty sensitive to space charge effects. The PMT output is integrated during each pairsync state of a pair by a 16 bits HAPPEx ADC and the corresponding asymmetry A_{exp} is computed for four different filter transmissions: 80%, 60%, 40% and 20%.
The light can also be blocked by a black screen in order to determine pedestals. A perfectly linear PMT would measure the same A_{exp} for all filter settings. Actual values of the filter attenuation don't have to be known accurately (see section 3) and can be measured via the mean value of the signal in the HAPPEx ADC. Main advantage of this method is to get rid of the variation of the PMT gain via measurement of asymmetries at high frequency (high w.r.t. the frequency of the gain drift).

3 Results

Four HAPPEx PMTs and 1 lumi PMT were tested in a HV range centered on the expected operating point in real conditions. The signal of the continuous diode is set close to 50000 ADC channels for each measurement except for few runs at low gain for which the light output couldn't be made large enough. The asymmetry is set at about 2%.
A typical result is shown on figure 2. The asymmetry is plotted versus the amplitude of the continuous diode in ADC channels for each filter setting. A linear fit gives a non-zero slope which should be equal to $A_{True}\beta$ according to Eq.(3). Nevertheless the very large residues clearly point to important systematic effects.

We believe the main source of false asymmetry is the non-homogeneity of the filters. Although both diodes stand behind the same filter, they illuminate different spots of its surface. A relative difference of transmission of few 0.1% between the two spots is enough to explain the observed effect. The simplest way to reduce the effect would be to illuminate the filter uniformly as we do for the PMT window but it couldn't be done for practical reason with the current setup. Instead we took pairs of runs with similar signal amplitudes and asymmetry but swapped the two power supplies of the diodes.
Let's call ϵ the relative difference of transmission between the two filter spots, P the amplitude of the pulsed diode and C the amplitude of the continuous diode. We have for each filter setting

$$A_{exp} = \frac{P(1+\epsilon_i)}{2C+P} \approx A_{True}(1+\epsilon_i) \tag{5}$$

where $P \ll C$. Finally the experimental asymmetry measured on figure 1 includes the combination of the two effects

$$A_1 = A_{True1} \times (1 + \beta N_1 + \epsilon_i) \tag{6}$$

where ϵ_i is the non-homogeneity of the ith filters, independent on the N_1 range. After swapping the diodes, the ϵ correction applies on C instead of P

$$A_{exp} = \frac{P}{2C(1+\epsilon_i)+P} \approx A_{True}(1-\epsilon_i) \tag{7}$$

and the experimental asymmetry writes

$$A_2 = A_{True2} \times (1 + \beta N_2 - \epsilon_i) \tag{8}$$

This hypothesis is in very good agreement with the data as shown in figure 3: the PMT is expected to be linear in this HV range and the slope of the fit (the combination of βN and ϵ) has flipped sign. Another argument in favor of this explanation is the reproducibility of the residues pattern for all measurements, pointing to a specific asymmetry offset associated with each filter.
The nonlinearity of the PMT itself at a given number of ADC channels N is then extracted from the average of Eqs.(6) and (8) according to

$$\beta N = \frac{\frac{A_1}{A_{True1}} + \frac{A_2}{A_{True2}} - 2}{N_1 + N_2} \times N \tag{9}$$

This quantity is computed for each filter setting (20, 40, 60 ,80%) and plotted versus $N = (N_1 + N_2)/2$, the amplitude of the continuous diode, for all the measured tubes and high voltages. This represent 10 pairs of runs illustrated in figures 4 to 13. The vertical axis is the extracted βN in %, the horizontal is N in ADC channels. The quantity β is the slope of a linear fit. Because the two diodes don't have the same light yield at the same voltage level one needs to retune both amplitudes after swaping the power supplies causing A_{True} and N to vary inbetween consecutive runs. N is just measured by the HAPPEx ADC but A_{True} is not known. In this analysis we assume the non-linearity effect is negligible for the lowest amplitude point of each run (20% transmission) and take the associated experimental asymmetry to be A_{True}. This is equivalent to say that the 20% filter is perfect and has no ϵ correction. Even if it has one, the first order effect in the analysis would be to shift all the other ϵ factors by the same amount but it wouldn't change the β slope.

The error on A_{True} is taken to be the RMS of the four experimental points in a run. The χ^2 values in figs. 4 to 13 clearly show this is an overestimate, especially when the non-linearity of the PMT is non negligible but it still allows non-linearity measurements at the 1% level. The residues of the linear fit are very small suggesting a good cancellation of the false asymmetries. The results are summarized in table 1.

As a cross-check, the ϵ_i factors can be extracted using the difference of Eqs.(6) and (8)

$$\epsilon_i = \frac{N_2 \frac{A_1}{A_{True1}} - N_1 \frac{A_2}{A_{True2}} + N_2 - N_1}{N_1 + N_2} \quad (10)$$

The results are illustrated on figure 14. They show a non-homogeneity of the filters at the 1% level. The fit of each ϵ_i is not compatible with a constant over the whole duration of these tests. The changes are correlated on all filters which could point to some change of transmission of the first filter, taken as a reference.

This analysis shows that Joe, William and Averell are linear at better than 1% for $|HV| > 1250V$. William and Averell are highly non-linear at 1150V, which explain the effect observed last year with one tube operating at 1190V. Jack's results can't rule out a 1% non-linearity. It was noticed this PMT has a gain a factor 5 smaller than the others.

PMT	HV (V)	A_{True1} (%)	A_{True2} (%)	N_1^{max} (ADC ch)	N_2^{max} (ADC ch)	βN_0 (%)
Joe	-1150	-2.7	-2.0	13000	44500	$+2.2 \pm 1.2$
	-1250	-2.1	-2.6	35000	36200	$+0.2 \pm 0.8$
	-1350	-2.4	-2.0	43000	45500	$+0.5 \pm 0.7$
Jack	-1250	-2.5	-2.1	29000	38500	$+0.6 \pm 0.8$
	-1350	-2.2	-1.5	14750	27200	$+2.7 \pm 1.7$
	-1450	-2.3	-2.5	34600	37700	$+0.5 \pm 0.9$
William	-1150	-2.2	-2.0	35800	35100	-6.7 ± 2.7
summarized	-1250	-2.1	-2.3	27300	30500	-0.4 ± 1.0
Averell	-1150	-2.2	-2.6	36850	34000	-7.7 ± 2.9
	-1250	-2.5	-2.2	26050	31400	$+1.0 \pm 1.0$

Table 1: Results of the 10 pairs of runs. The subscripts $_1$ and $_2$ refer to the first and second run in the pair. N^{max} is the maximum amplitude of the continuous diode (80% transmission). The quoted non-linearity corresponds to a signal at $N_0 = 50000$ ADC channels.

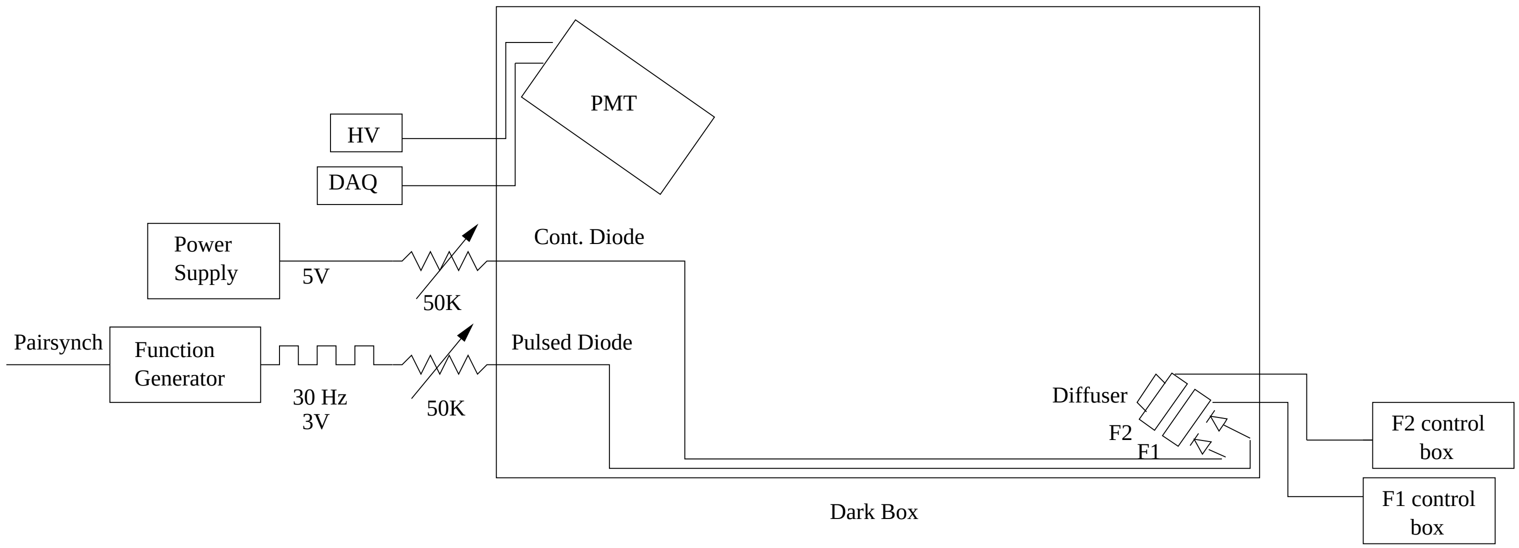

Figure 1: Setup of the PMT bench test.

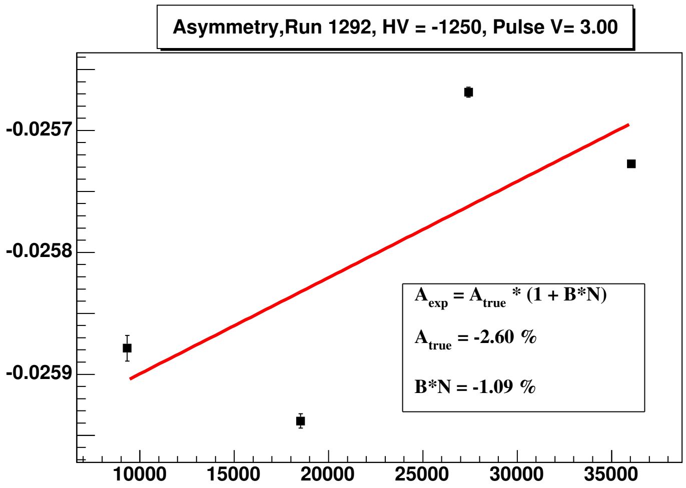

Figure 2: A_{exp} versus continuous diode signal in ADC channels. The quoted A_{True} and βN are extracted from the intercept and slope of the linear fit (see eq.3). N is chosen to be the maximum of the continuous signal (36000 channels in this case).

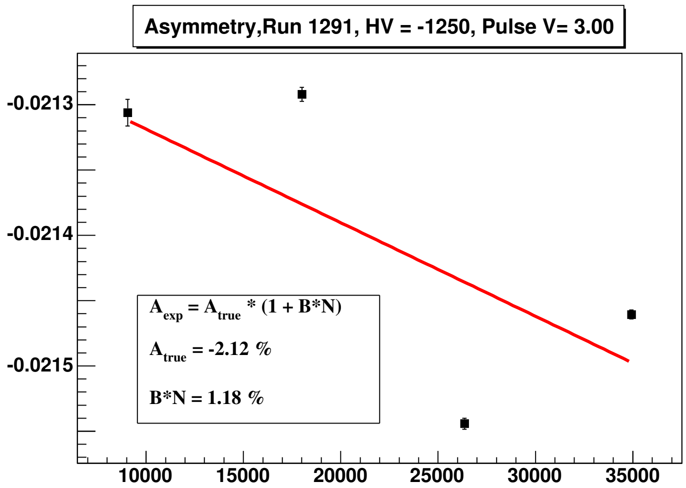

Figure 3: Same as figure 2 except the cables of the two diodes have been swapped.

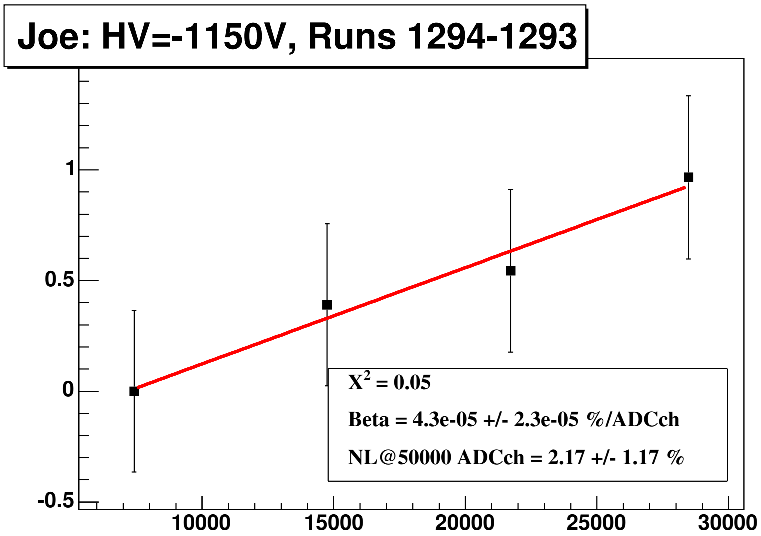

Figure 4: Linearity of tube "Joe" at -1150 Volts. Vertical axis is βN in %. Horizontal axis is the continuous diode amplitude in ADC channels.

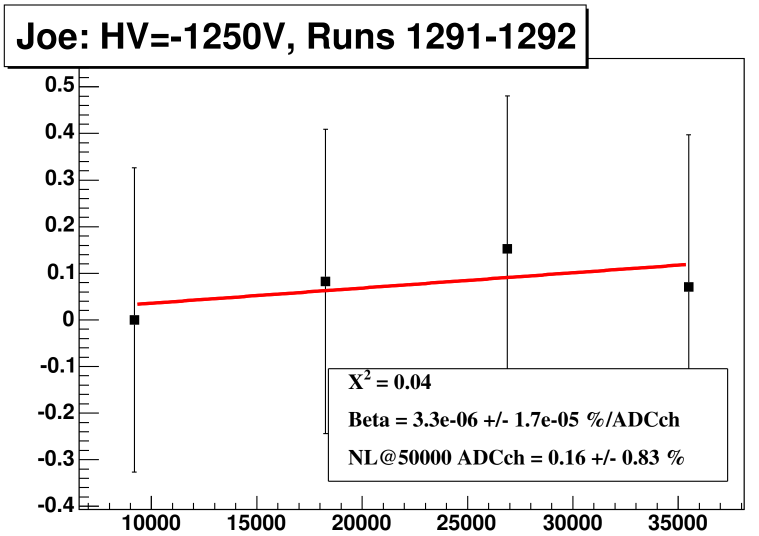

Figure 5: Linearity of tube "Joe" at -1250 Volts.

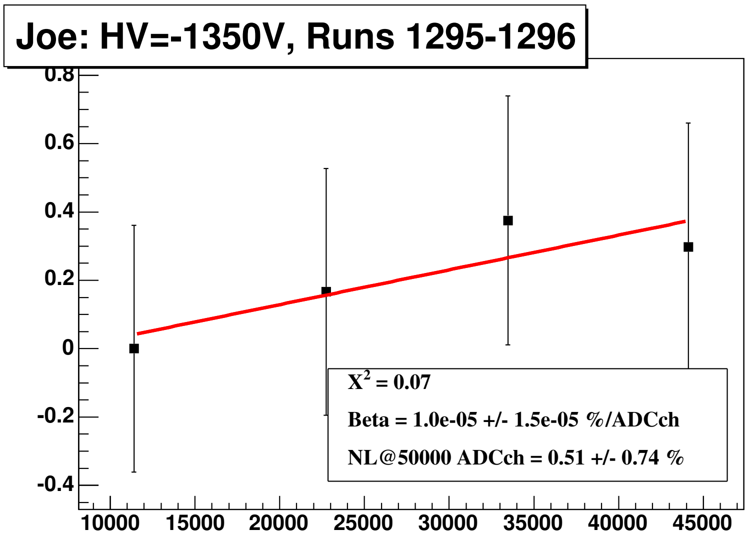

Figure 6: Linearity of tube "Joe" at -1350 Volts.

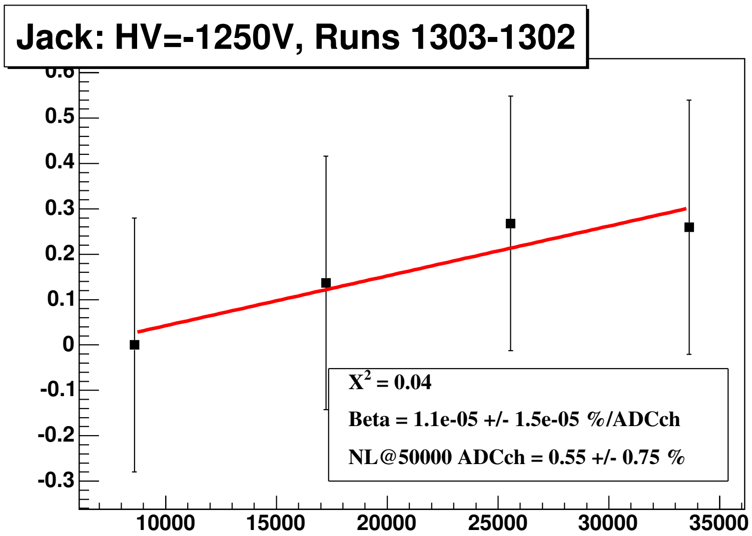

Figure 7: Linearity of tube "Jack" at -1250 Volts.

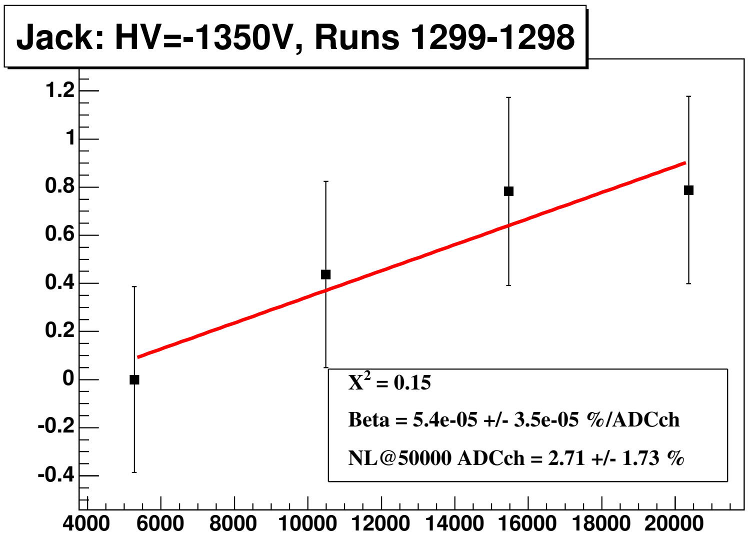

Figure 8: Linearity of tube "Jack" at -1350 Volts.

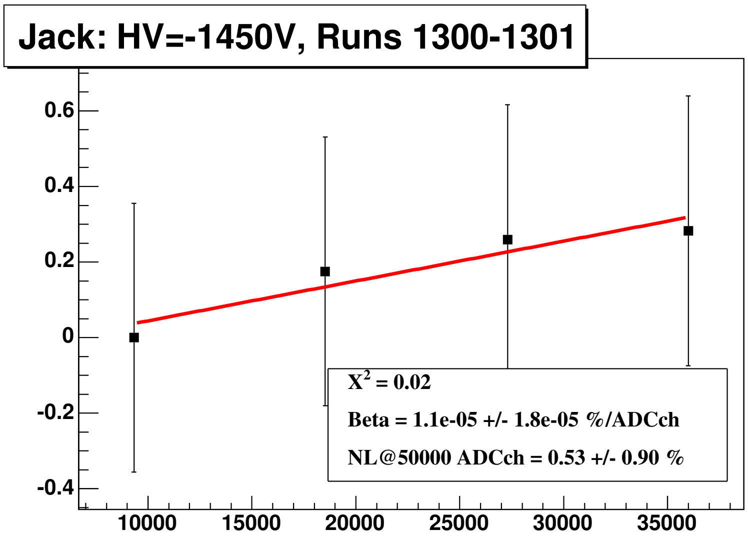

Figure 9: Linearity of tube "Jack" at -1450 Volts.

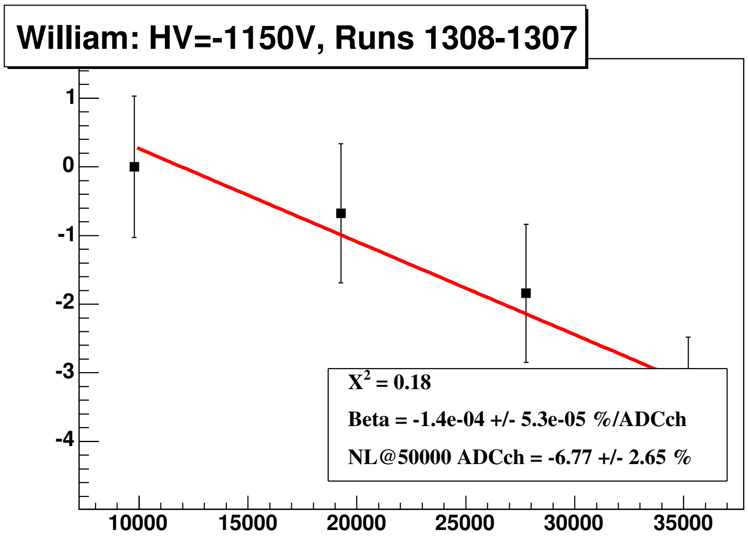

Figure 10: Linearity of tube "William" at -1150 Volts.

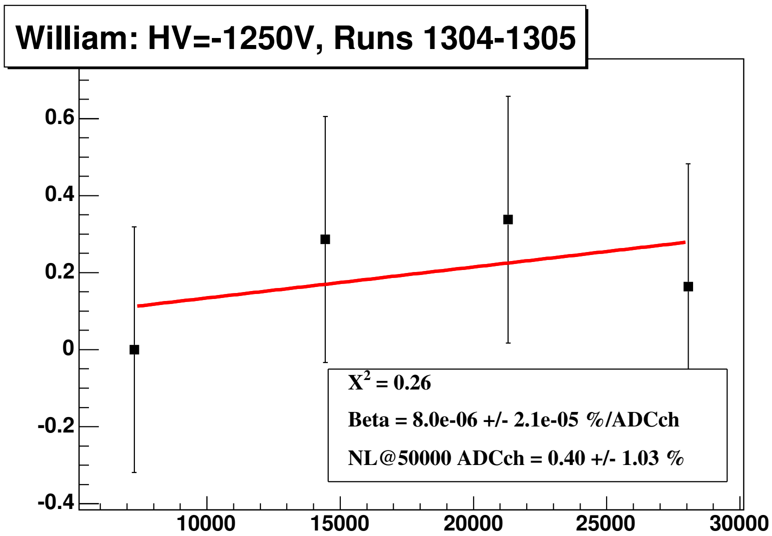

Figure 11: Linearity of tube "William" at -1250 Volts.

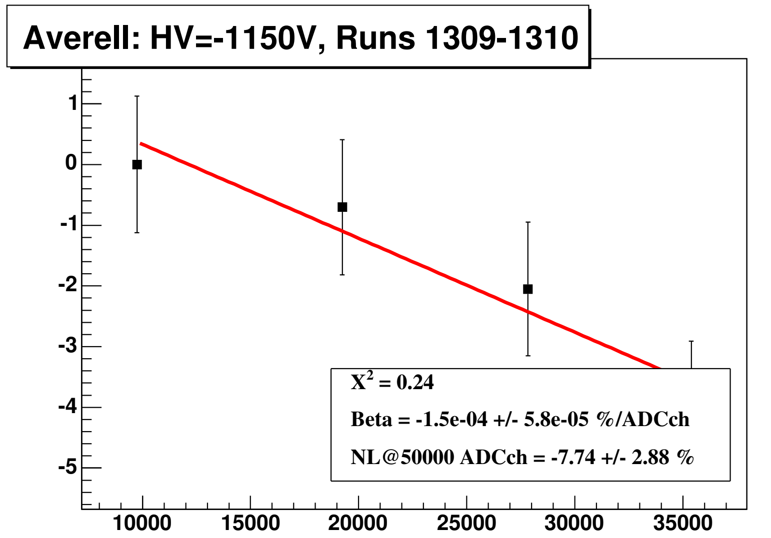

Figure 12: Linearity of tube "Averell" at -1150 Volts.

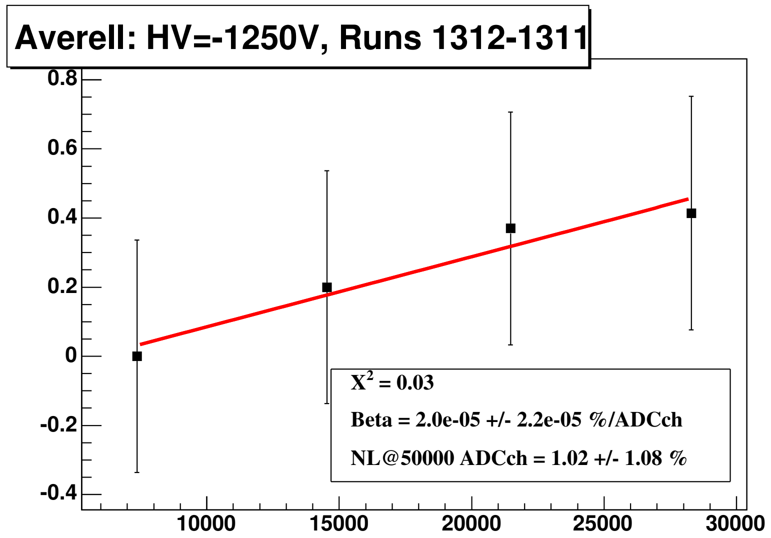

Figure 13: Linearity of tube "Averell" at -1250 Volts.

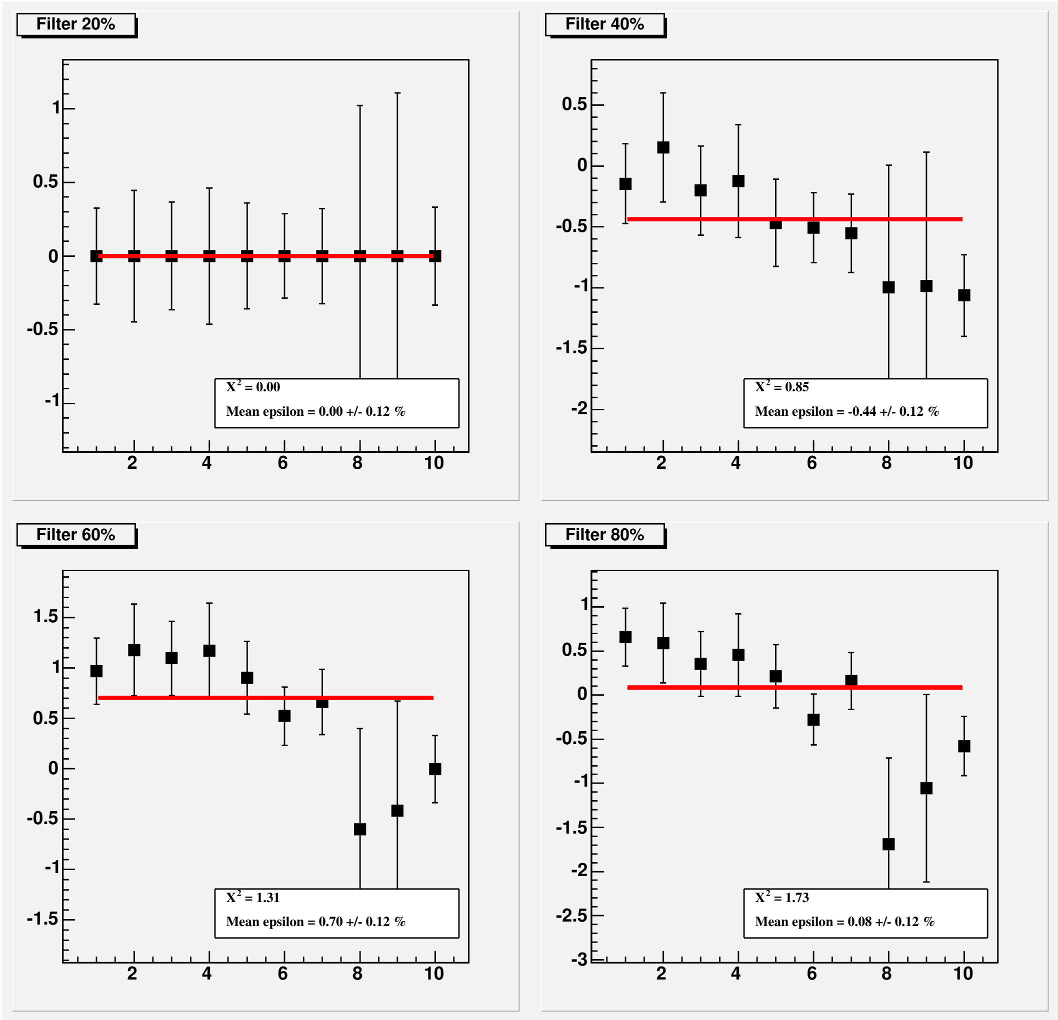

Figure 14: Relative attenuation ϵ of the diodes for each filter (%). Because the first filter is taken as the reference to determine A_{true}, $\epsilon = 0$ for this one (see text).