Study of the correction factor for the R5900 PMTs

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presented by

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The single photoelectron analysis was applied on the spectra taken by Hamamatsu R5900 photomultipliers. The deconvoluted parameters have been used for finding the PMT correction factor needed for finding the calorimeter GeV-to-photoelectrons factor.

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1 Photomultiplier Response Function

1. The incident light can create photoelectrons from the PMT photocathode, as well as from the first dynode .
2. If three or less photoelectrons are collected by the first dynode, then the PMT response is expressed as a sum of responses of secondary electrons created on the first dynode, and in other cases it is a Gaussian.

$$S_{real}(x) = \sum_{n,k=0}^{\infty} \frac{\mu_{pc}^{n}\, e^{-\mu_{pc}}}{n!} \cdot \frac{\mu_1^k\, e^{-\mu_1}}{k!} \cdot intdx`\, S_n^{(1)}(x`) \cdot S_k^{(2)}(x - x`) \tag{1}$$

- $S_n^{(1)}(x)$is the PMT output charge initiated by n ph.e.'s from photocathode
- $S_k^{(2)}(x)$is the PMT output charge initiated by k ph.e.'s from first dynode

$$S_n^{(1)}(x) = \begin{cases} \sum_{m=0}^{\infty} \frac{K_1^m \cdot e^{-K_1}}{m!} \cdot S_m^{(2)}(x) & n = 1 \\ \sum_{m=0}^{\infty} K_1^m e^{-2K_1} \cdot S_m^{(2)}(x) \cdot \sum_{l=0}^{n} \frac{1}{(m-l)!l!} & n = 2 \\ \sum_{m=0}^{\infty} K_1^m e^{-3K_1} \cdot S_m^{(2)}(x) \cdot \sum_{l=0}^{m} \frac{1}{l!} \sum_{k=0}^{m-l} \frac{1}{k!(m-l-k)!l!} & n = 3 \\ G\left(x,\, Q_0 + nQ_1,\, \sigma_0^2 + n\sigma_1^2\right) & n = 0,\, n \geq 4 \end{cases} \tag{2}$$

- $Q_0,\, \sigma_0$ are the pedestal and its width;
- $Q_1,\, \sigma_1$ - the multiplication process parameters gain, one photoelectron response standard deviation;
- μ_{pc} - the light source intensity expressed in number of photoelectrons captured by the PMT dynode system;
- μ_1 - the number of photoelectrons created on the first dynode and captured by the PMT dynode system;
- K_1 - the secondary emission coefficient of the first dynode;
- $G\left(x, Q, \sigma^2\right)$ is a Gaussian distribution with the mean value of Q and dispersion σ^2:

For the response $S_m^{(2)}(x)$ the expression analogous to (2)but expansion is done only in the case 1 photoelectron

2 Limit Spectrum

For high intensity light sources ($\mu_{pc} \to \infty$ the PMT response function goes to the limit spectrum:

$$S_{real}(x) \quad \overrightarrow{\mu_{pc} \to \infty} \quad S_\infty(x) = \frac{1}{\sqrt{2\pi}\sigma_\infty} \exp\left(\frac{(x - Q_0 - Q_\infty)^2}{2\sigma_\infty^2}\right) \tag{3}$$

where

$$\begin{aligned} Q_\infty &= \mu_{pc} Q_1 + \mu_1 Q_2 = \mu_{pc} Q_1 \left(1 + \frac{\varepsilon}{K_1}\right) && (4) \\ \sigma_\infty &= \sqrt{\sigma_0^2 + \mu_{pc}\left(\sigma_1^2 + Q_1^2\right) + \mu_1\left(\sigma_2^2 + Q_2^2\right)} \quad \overrightarrow{\epsilon < 0.1} \quad \sqrt{\mu_{pc}\left(\sigma_1^2 + Q_1^2\right)} && (5) \\ & && (6) \end{aligned}$$

where $\epsilon = \frac{\mu_1}{\mu_{pc}}$ and $K_1 \equiv$ secondary emission coefficient on the first dynode.

It is useful to find a relation between the limit spectrum parameters (Q_∞, σ_∞) and the mean number of photoelectrons (μ_{pc}, μ_1). From (4) and (6) it follows:

$$\begin{aligned} \mu_{pc} &= f_{pmt} \cdot \frac{Q_\infty^2}{\sigma_\infty^2} && (7) \\ f_{pmt} &= \frac{\sigma_1^2 + \epsilon\sigma_2^2 + Q_1^2\left(1 + \frac{\epsilon}{K_1^2}\right)}{Q_1^2\left(1 + \frac{\epsilon}{K_1}\right)^2} \quad \longrightarrow \quad 1 + \frac{\sigma_1^2}{Q_1^2} && (8) \end{aligned}$$

The last relation is justified if the effect on the first dynode is small ($\epsilon < 0.1$). The factor f_{pmt} depends on the single photoelectron parameters (one photoelectron resolution) of the PMT in question, and its value is different from one. Typical values of f_{pmt} are expected to vary between 1.15 to 1.50 .

3 Relation Between Amplification Process Parameters

Assumptions:

- PMT has an N stage dynode system
- one electron hitting the i^{th} dynode will create on average k_i of secondary electrons.

The case when the charge multiplication starts from the j^{th}dynode:

$$Q_j = e \cdot k_j \cdot k_{j+1} \cdots k_N = e \cdot \prod_{i=j}^{N} k_i \tag{9}$$

$$\sigma_j^2 = Q_j^2 \left(\left(\frac{\delta_j}{k_j} \right)^2 + \frac{1}{k_j} \left(\frac{\delta_{j+1}}{k_{j+1}} \right)^2 + \ldots + \frac{1}{k_j k_{j+1} \cdots k_N} \left(\frac{\delta_N}{k_N} \right)^2 \right) \tag{10}$$

where Q_j and σ_j are mean charge and corresponding standard deviation for the case when the charge multiplication starts from j^{th} dynode and δ_i $(i = 1, \ldots, N)$ is the standard deviation of the number of secondary electrons created from the i^{th} dynode by one electron.

Assuming that the standard deviations δ_i are governed by a Poisson law:

$$\delta_i = \sqrt{k_i} \tag{11}$$

We have

$$\sigma_j^2 = Q_j^2 \left(\frac{1}{k_j} + \frac{1}{k_j k_{j+1}} \ldots + \frac{1}{k_j \cdots k_N} \right) \tag{12}$$

At a fixed voltage the factor in brackets is a PMT constant which can be determined as the PMT base repartition. If the repartition is $1:1:\ldots:1$, then for all dynodes $k_i = k$ and the formula (12) becomes

$$\sigma_j^2 = Q_j^2 \left(\frac{1}{k} + \frac{1}{k^2} \ldots + \frac{1}{k^N} \right) \tag{13}$$

where $j = 1, 2, ..., N - 1$.

4 Conclusions

The deconvolution method suggested for analysis of the single photoelectron spectra of metal channel photomultiplier works properly in the whole range of working voltages.

Using the single photoelectron parameters the PMT correction factor was calculated. It's value for the PMT 7M02C1 is 1.42 ± 0.05.

5 Tables

Table 1: Dependence of the R5600 PMT output spectrum parameters on the voltage applied to the PMT. The same intensity of LED light source was used ($\approx 2ph.e.$).

Voltage (V)	Q_1	σ_1	μ_{pc}	F_{PMT}	χ^2
600	6.57 ± 0.22	3.46 ± 0.15	1.716 ± 0.083	1.35 ± 0.083	0.73
650	10.05 ± 0.23	6.38 ± 0.16	1.967 ± 0.051	1.40 ± 0.027	0.64
700	16.07 ± 0.28	10.79 ± 0.20	2.106 ± 0.043	1.45 ± 0.023	0.71
750	26.39 ± 0.31	16.89 ± 0.22	2.096 ± 0.029	1.41 ± 0.014	0.59
800	41.76 ± 0.33	26.33 ± 0.27	2.092 ± 0.020	1.40 ± 0.010	0.64
850	63.69 ± 0.40	39.97 ± 0.31	2.130 ± 0.016	1.40 ± 0.008	0.69
900	92.89 ± 0.55	60.71 ± 0.39	2.198 ± 0.015	1.43 ± 0.007	0.81
950	130.13 ± 0.82	94.28 ± 0.53	2.341 ± 0.016	1.52 ± 0.009	0.75

Table 2: Dependence of the R5600 PMT output spectrum parameters on the voltage applied to the PMT. The same intensity of LED light source was used ($\approx 3ph.e.$).

Voltage (V)	Q_1	σ_1	μ_{pc}	F_{PMT}	χ^2
650	10.27 ± 0.31	6.35 ± 0.17	2.953 ± 0.104	1.38 ± 0.031	0.50
700	16.31 ± 0.29	10.59 ± 0.18	3.187 ± 0.068	1.42 ± 0.021	0.61
750	27.59 ± 0.54	16.93 ± 0.26	3.083 ± 0.078	1.38 ± 0.019	0.41
800	43.32 ± 0.36	26.26 ± 0.28	3.134 ± 0.031	1.38 ± 0.010	0.50
850	65.04 ± 0.43	41.00 ± 0.31	3.248 ± 0.025	1.40 ± 0.008	0.68
900	95.46 ± 0.50	61.48 ± 0.34	3.304 ± 0.020	1.41 ± 0.006	0.80
950	133.20 ± 0.79	93.66 ± 0.45	3.501 ± 0.023	1.49 ± 0.008	0.71

6 Comments to the figures

In Fig.1 the generator (GEN) is used to drive the light source (LED) as well as to trigger the ADC. The usual sampling frequency is 1 kHz and the gate for opening ADC is *80 nsec*. The amplification of the preamplifier(PA) is 62.3.

In Figs.2 - 5 the results of simulation are presented. The PMT response has been simulated provided that the multiplication process has Poisson nature and no additional inhomogeneities are present. The purpose of the simulation was to look at the form of PMT response in cases when multiplication process was initiated by a small numbers of photoelectrons, particularly the cases with 1,2 and 3 were of our special interest. These studies are need for understanding of the PMT response function used in the single photoelectron analysis.

The spectra shown in Figs.6 - 10 have been taken employing the same amplitude driving LED light source. It's intensity was ($\approx 2ph.e.$).

In Figs.11 and 12 are shown dependences of the gain (expressed in amplitudes of ADC channels) and the PMT correction factor, respectively, on the PMT voltage using the same light source ($\approx 2ph.e.$).

The dependencies in Figs.16 and 17 have been obtained by averaging the gain (Q_1) and PMT correction factor (F_{pmt}), respectively, at each voltage using the values of Q_1 and F_{pmt} retrieved from the spectra initiated by different input light signal.

List of Figures

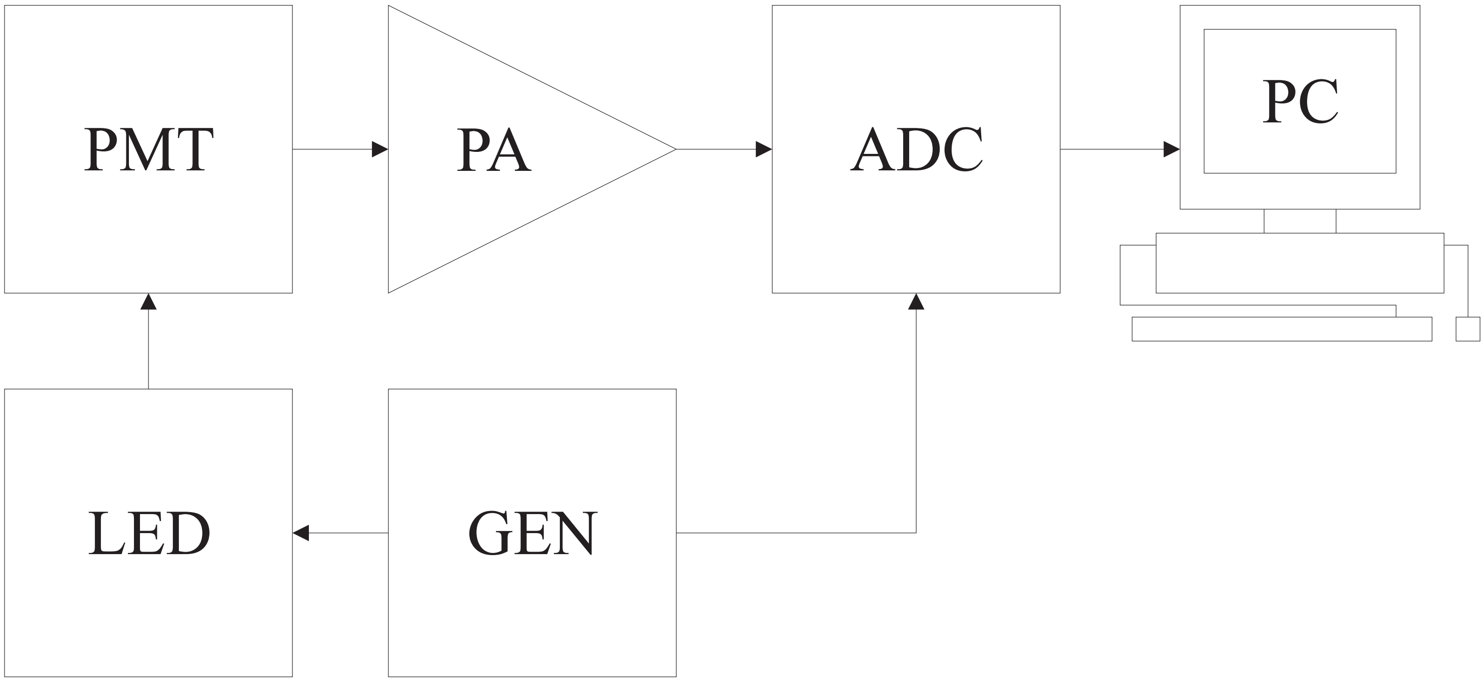

Figure 1: Block scheme of the experimental setup for the measurement of single photoelectron spectra. tested PMT: R5900 (7M02C1), Voltage repartition: 2 : 2 : 1 : ... : 2 : 3 : 2, PMT voltage: 600 - 950 V, Amplification: 62.3x

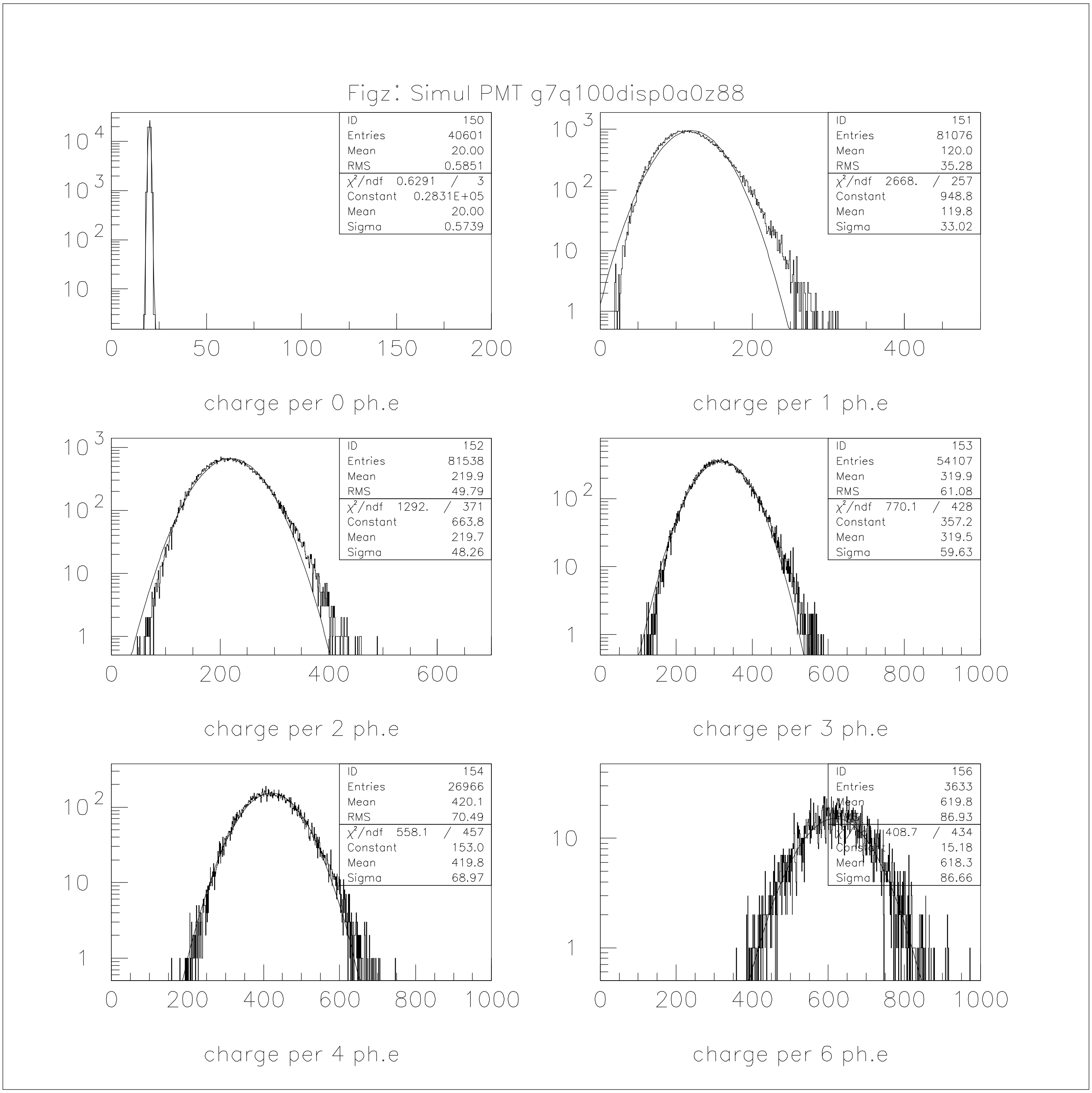

Figure 2: Simulated spectrum (no inhomogeneities) spectral components initiated by different number of photoelectrons: 0,1,2,3,4 and 6 at gain 10^7.

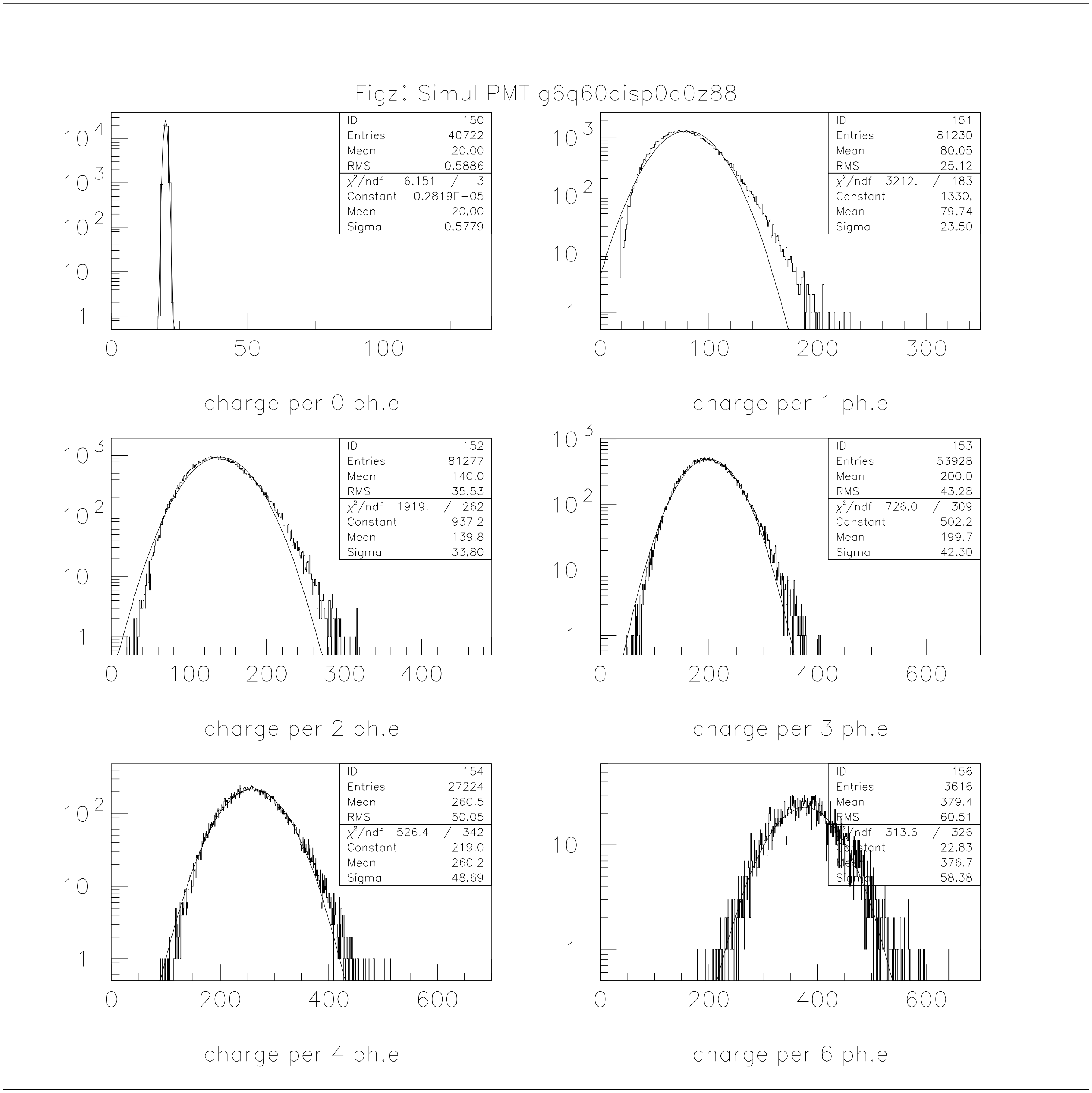

Figure 3: Simulated spectrum (no inhomogeneities) spectral components initiated by different number of photoelectrons: 0,1,2,3,4 and 6 at gain 10^6.

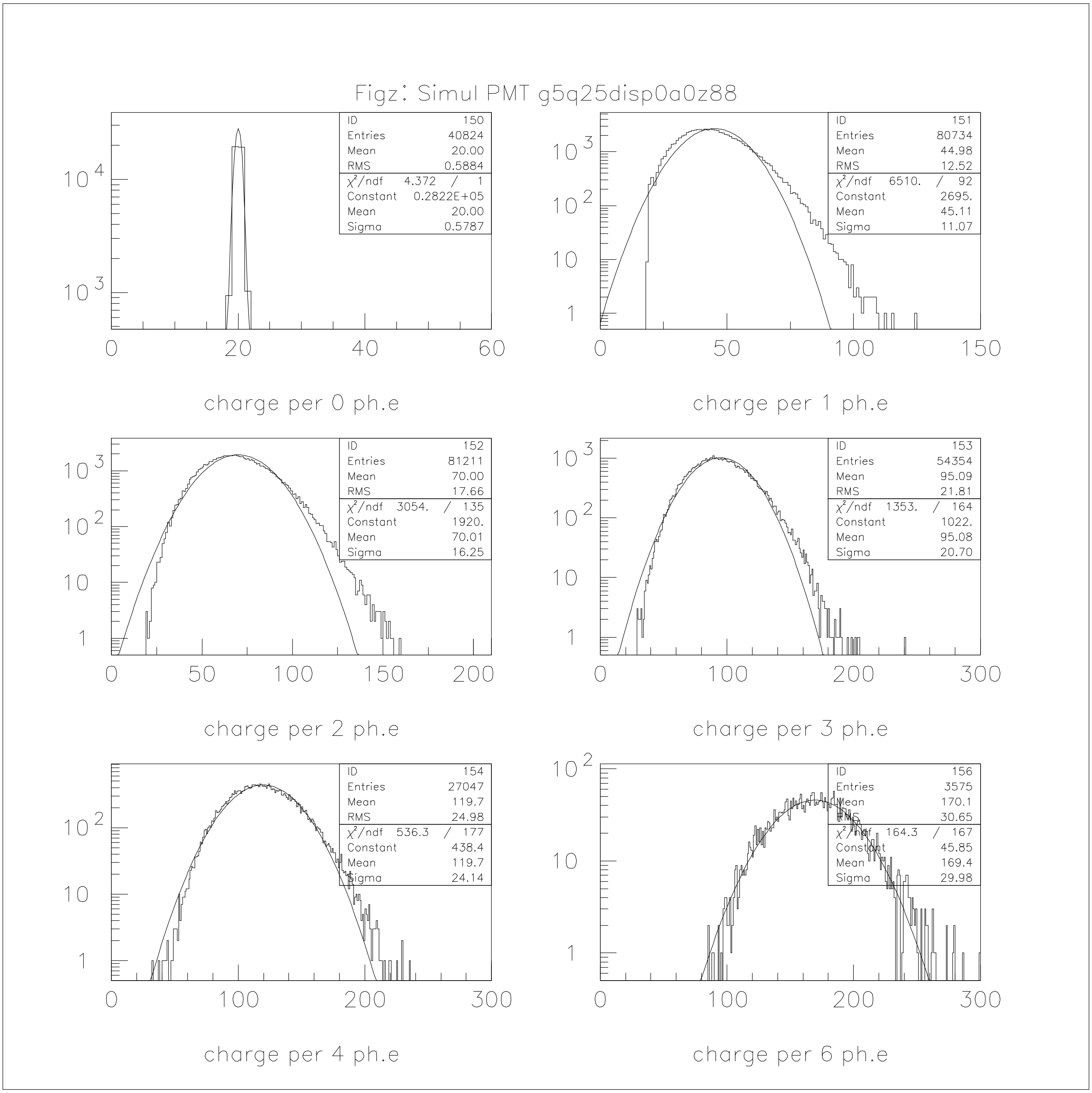

Figure 4: Simulated spectrum (no inhomogeneities) spectral components initiated by different number of photoelectrons: 0,1,2,3,4 and 6 at gain 10^5.

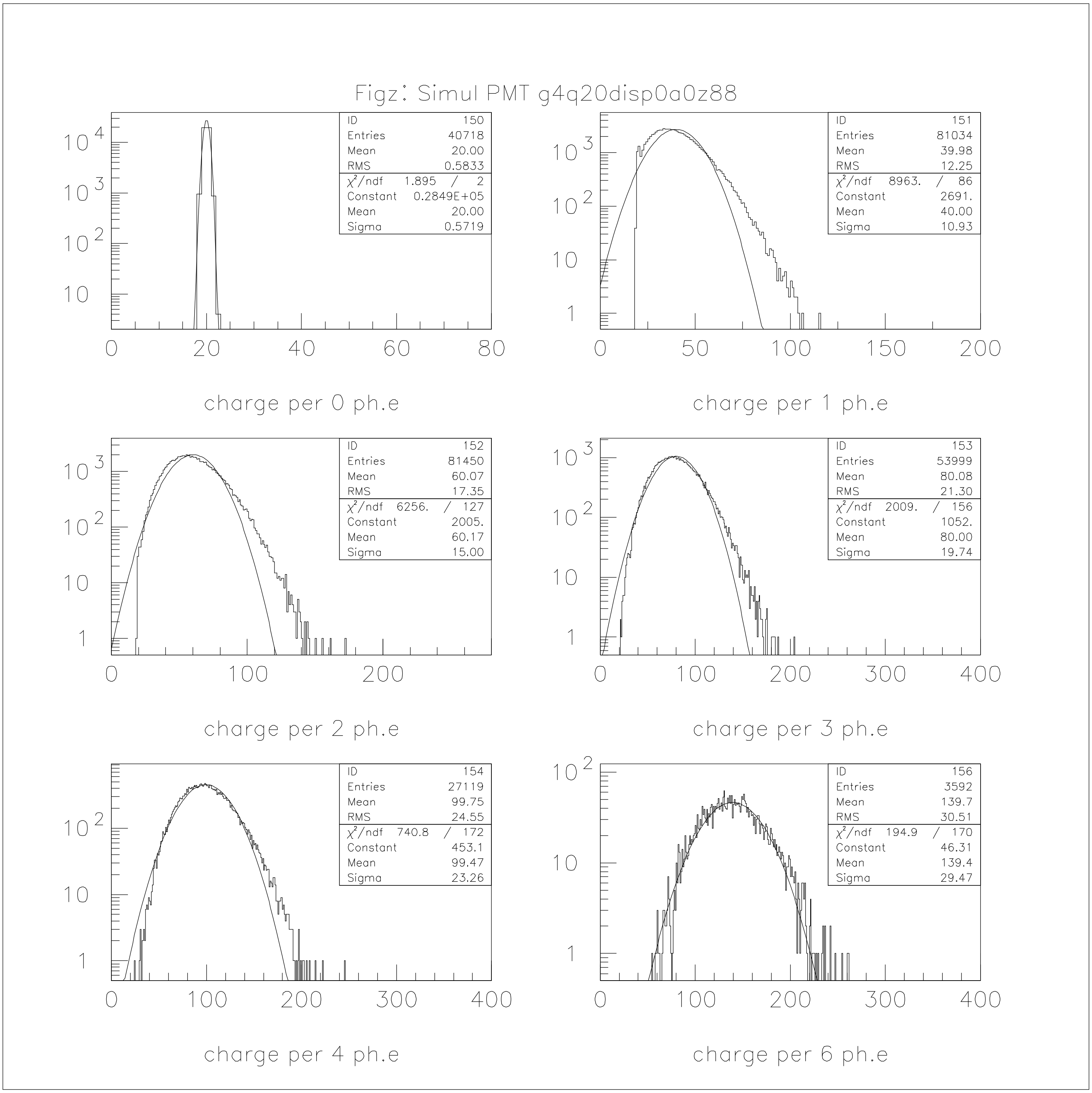

Figure 5: Simulated spectrum (no inhomogeneities) spectral components initiated by different number of photoelectrons: 0,1,2,3,4 and 6 at gain 10^4.

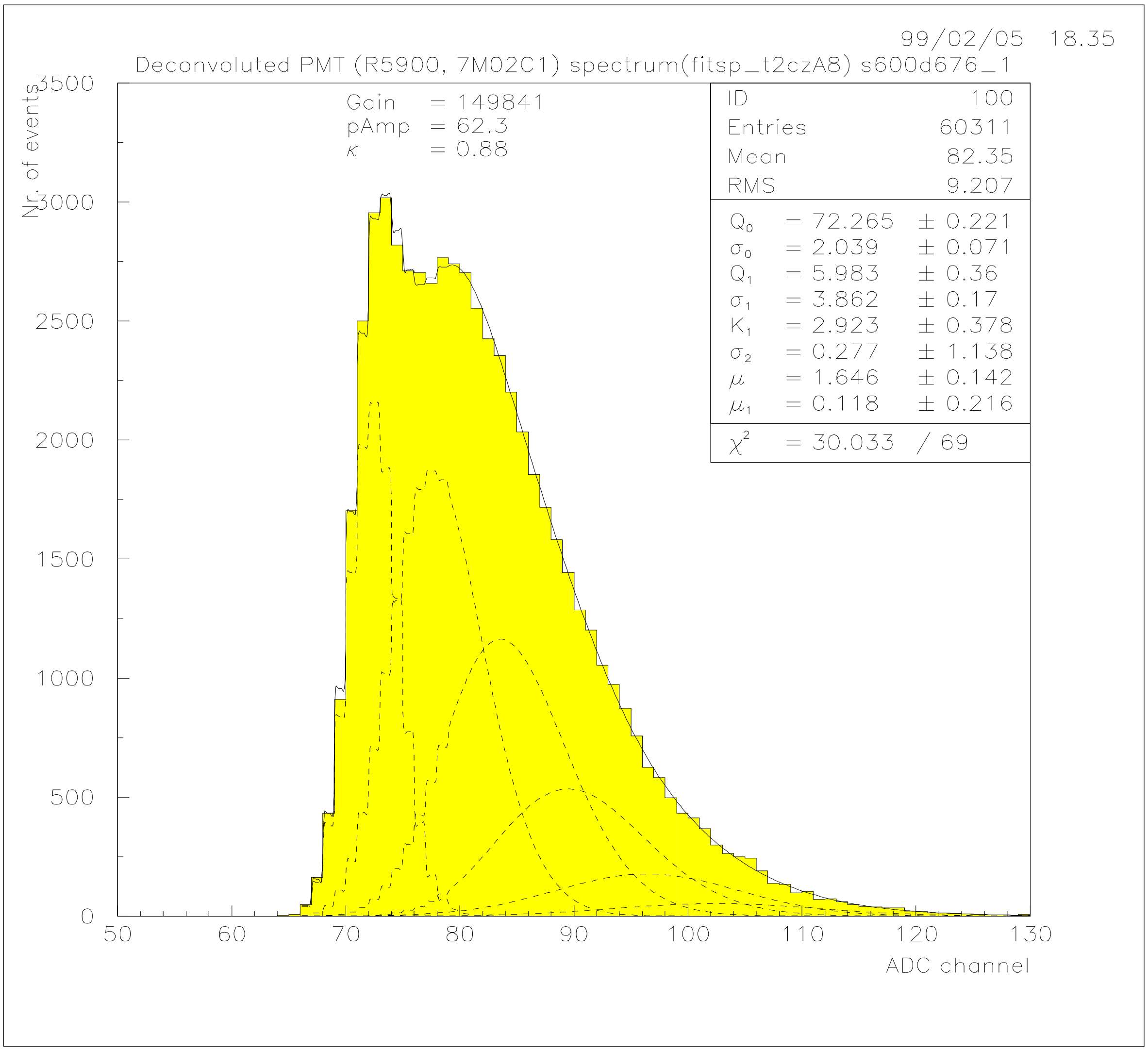

Figure 6: The deconvoluted LED spectrum taken at 600 V by a Hamamatsu R5600/7M02C1 photomultilier.

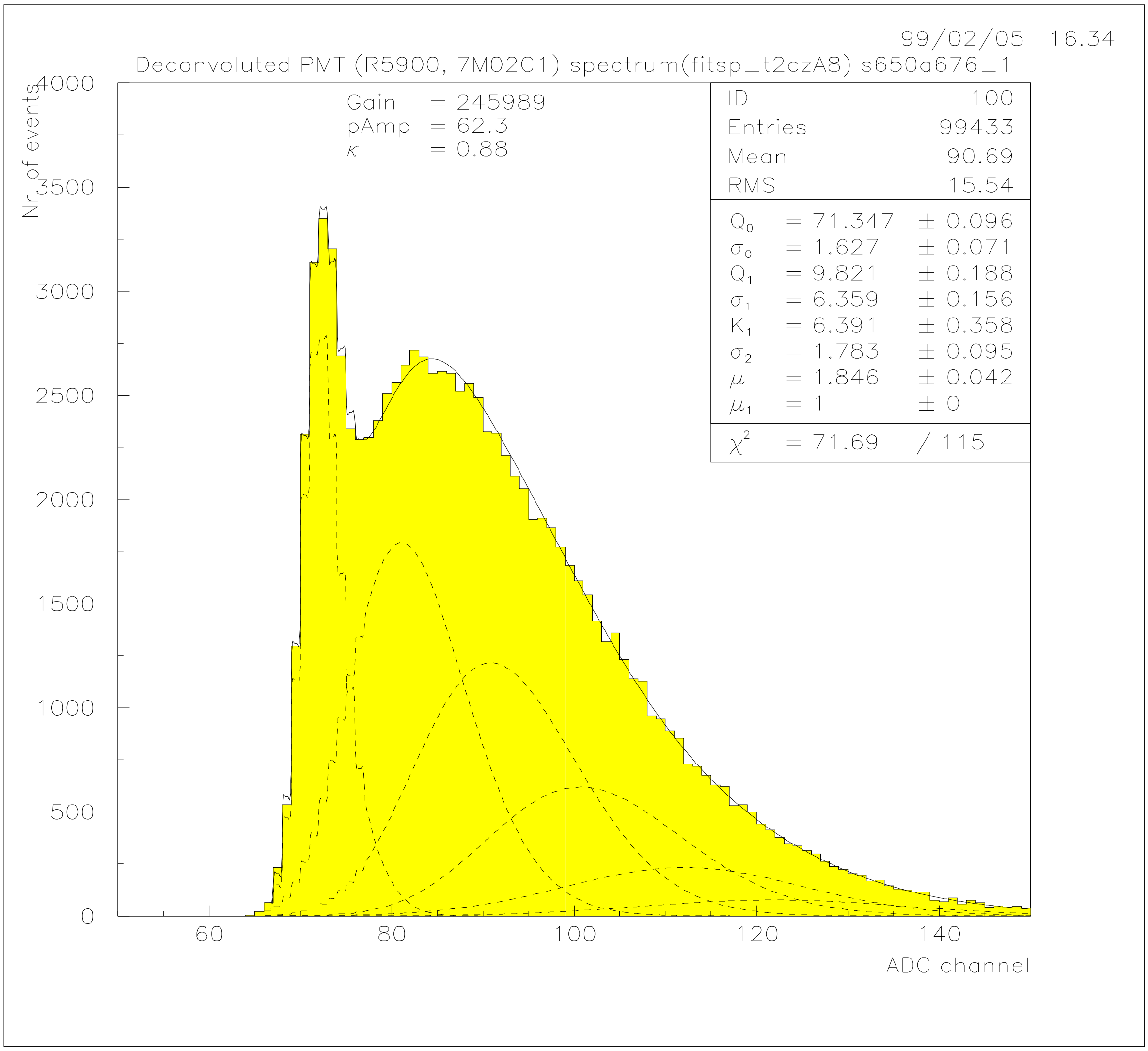

Figure 7: The deconvoluted LED spectrum taken at 650 V by a Hamamatsu R5600 / 7M02C1 photomultilier.

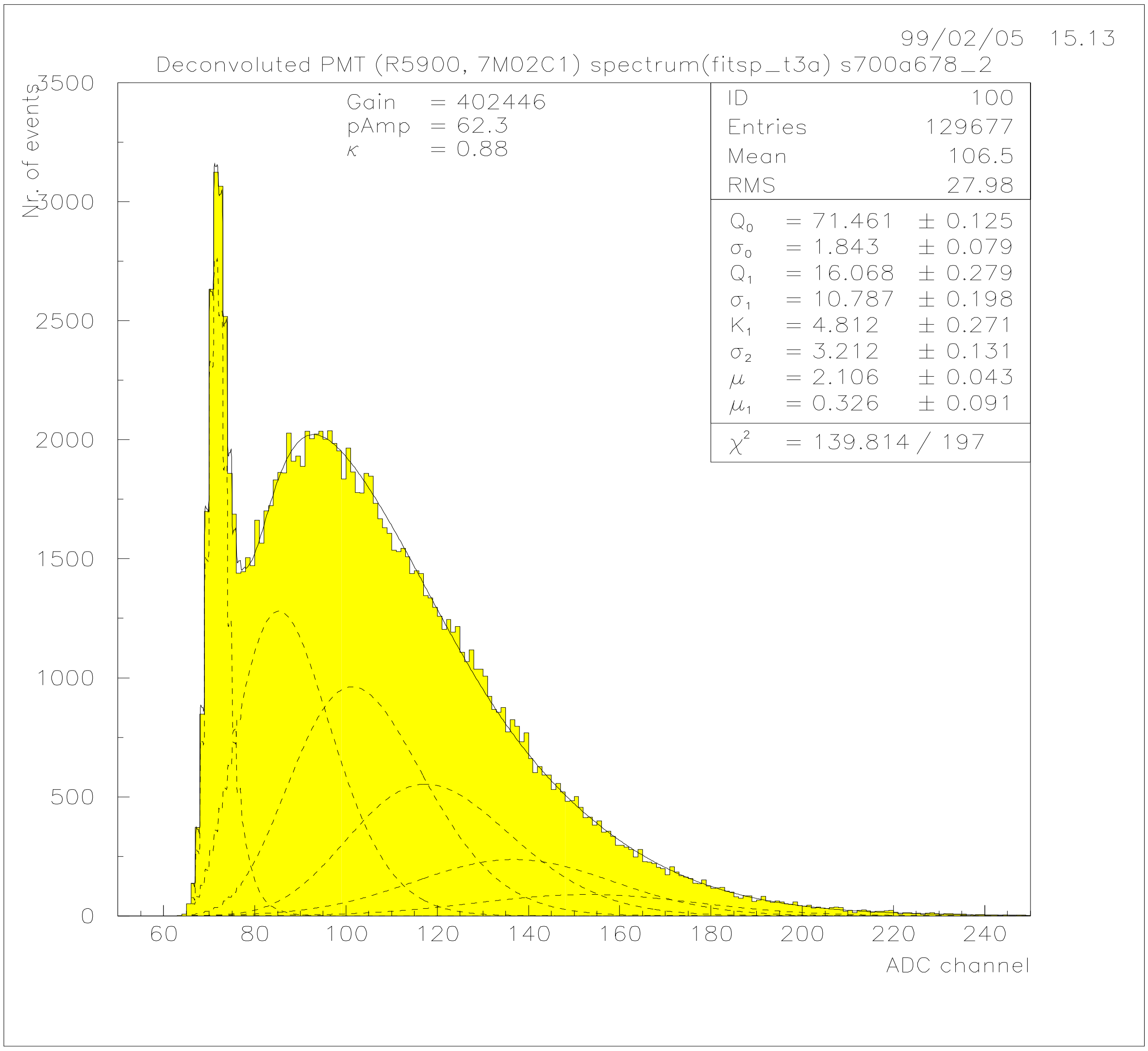

Figure 8: The LED spectrum taken at 700 V by a Hamamatsu R5600/ 7M02C1 photomultilier.

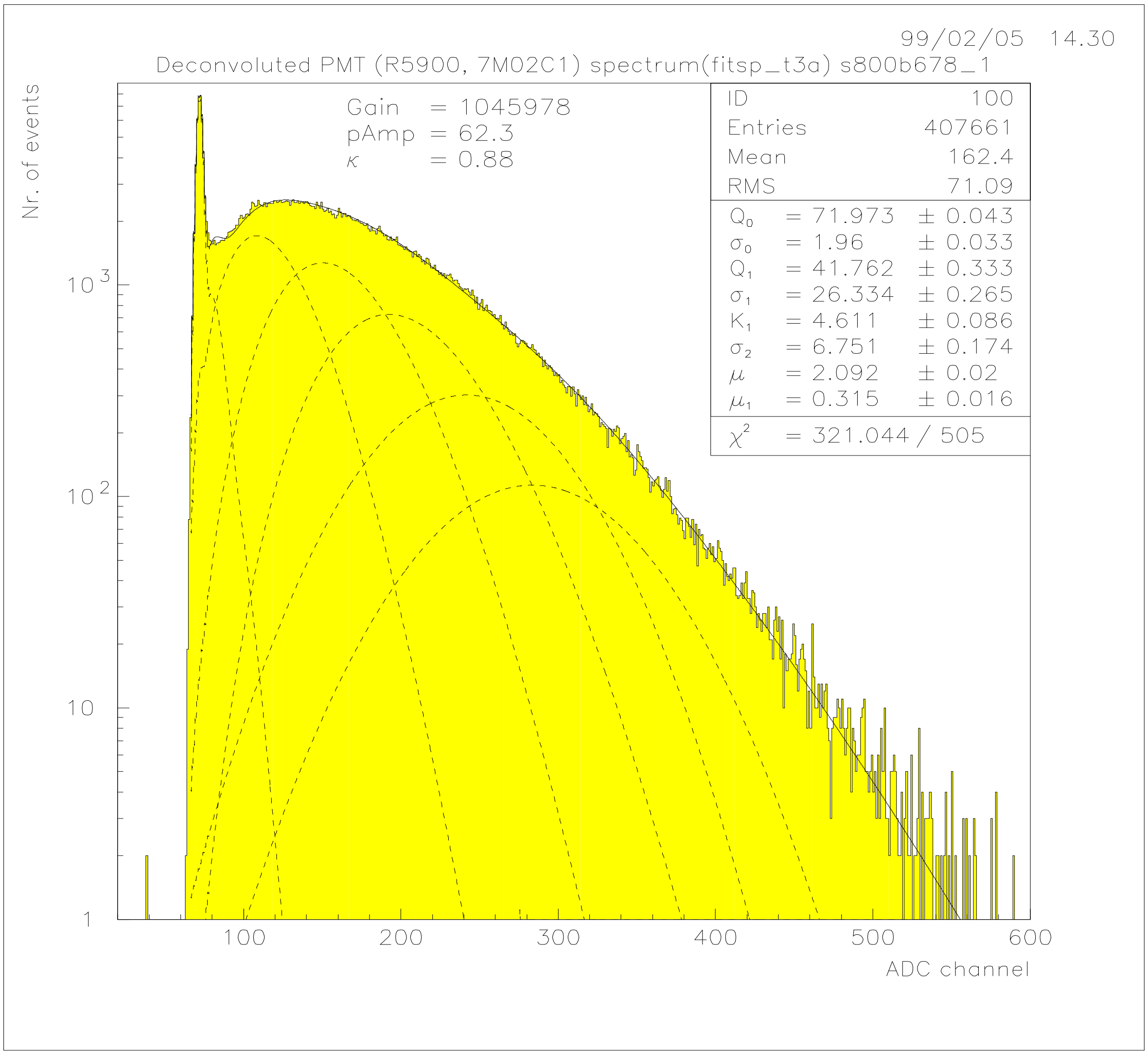

Figure 9: The LED spectra taken at 800 V by Hamamatsu R5600 / 7M02C1 photomultiplier.

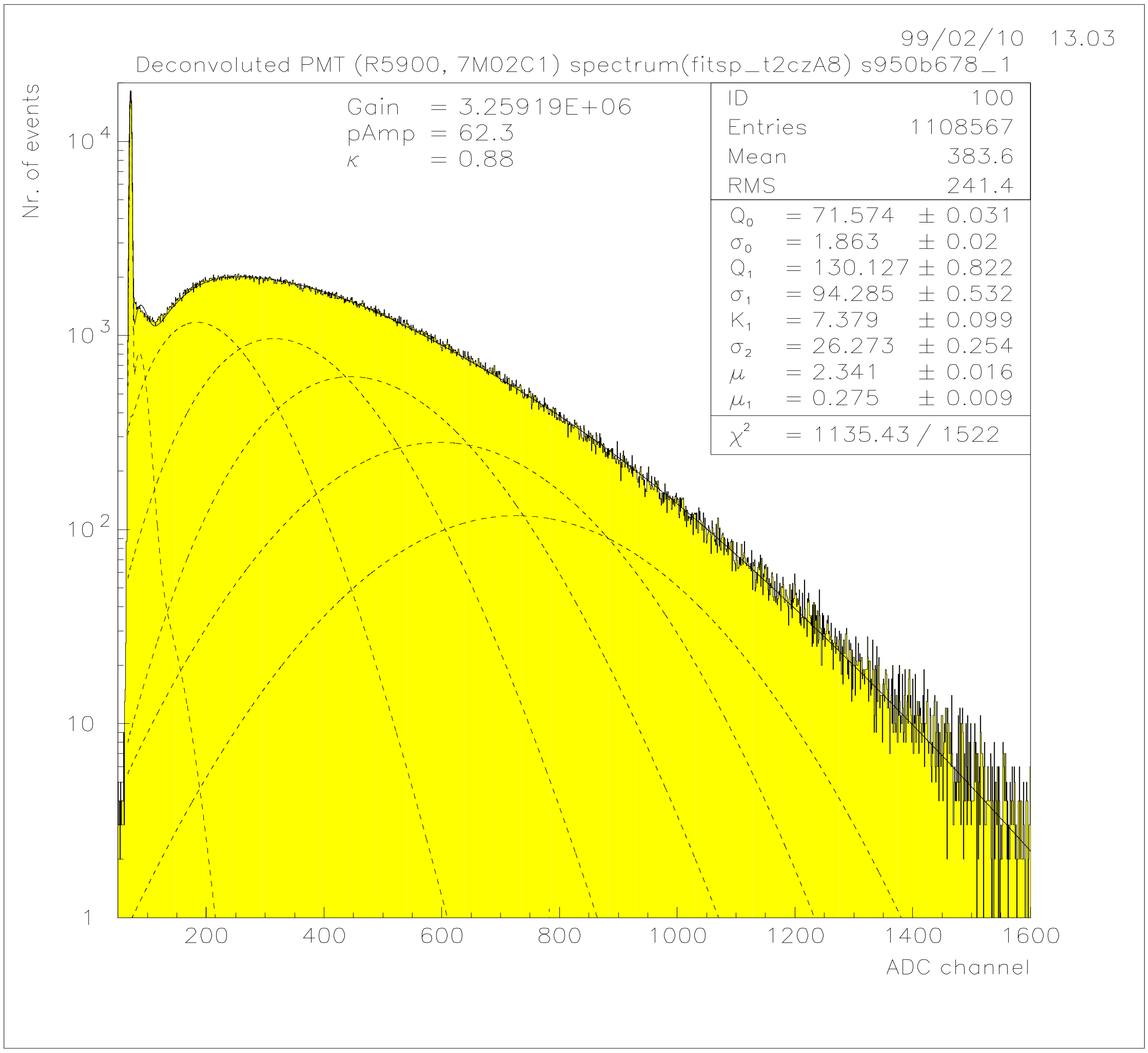

Figure 10: The LED spectra taken at 950 V by Hamamatsu R5600 / 7M02C1 photomultiplier.

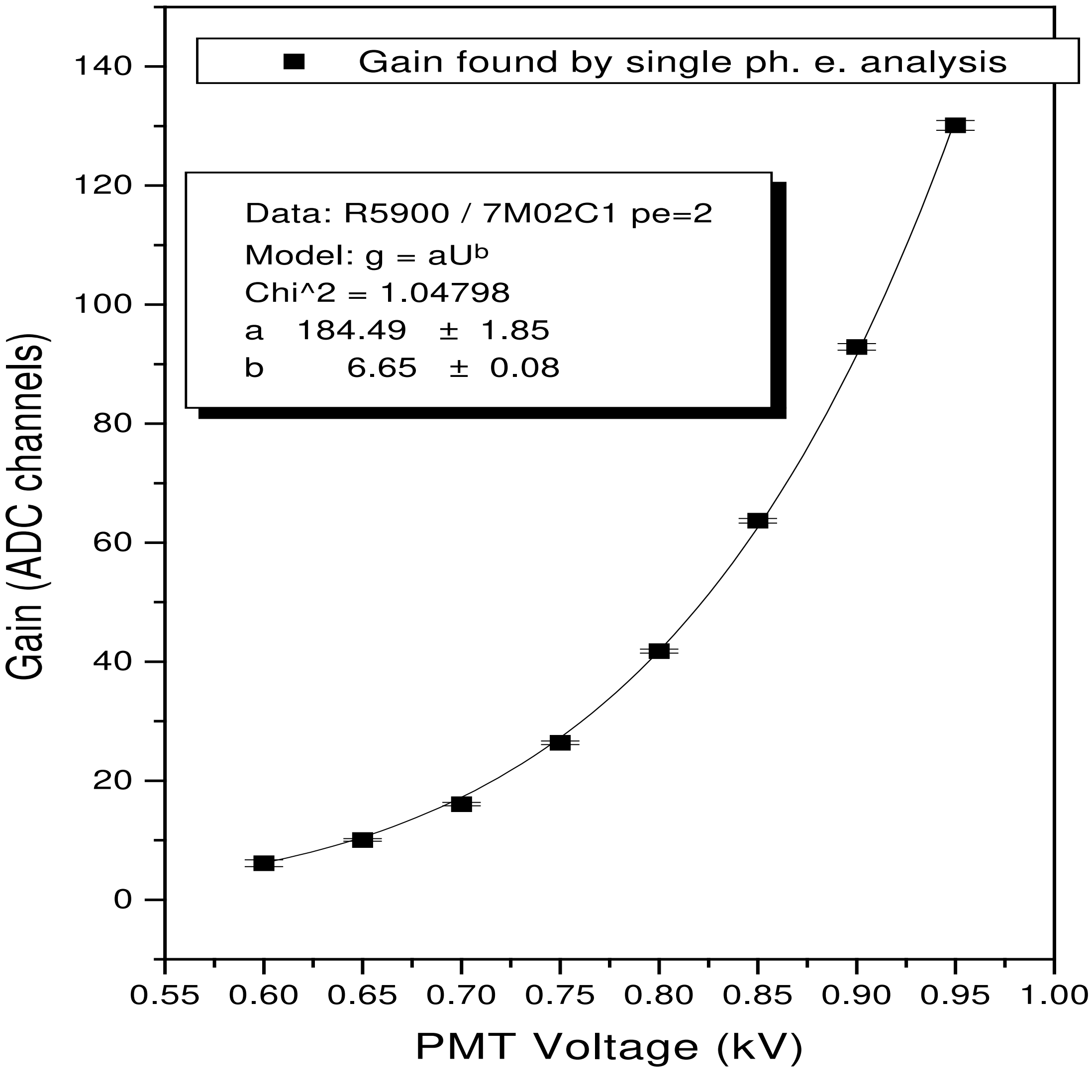

Figure 11: Dependencies of the gain (parameter Q_1) on voltage (R5900/7M02C1 photomultiplier).

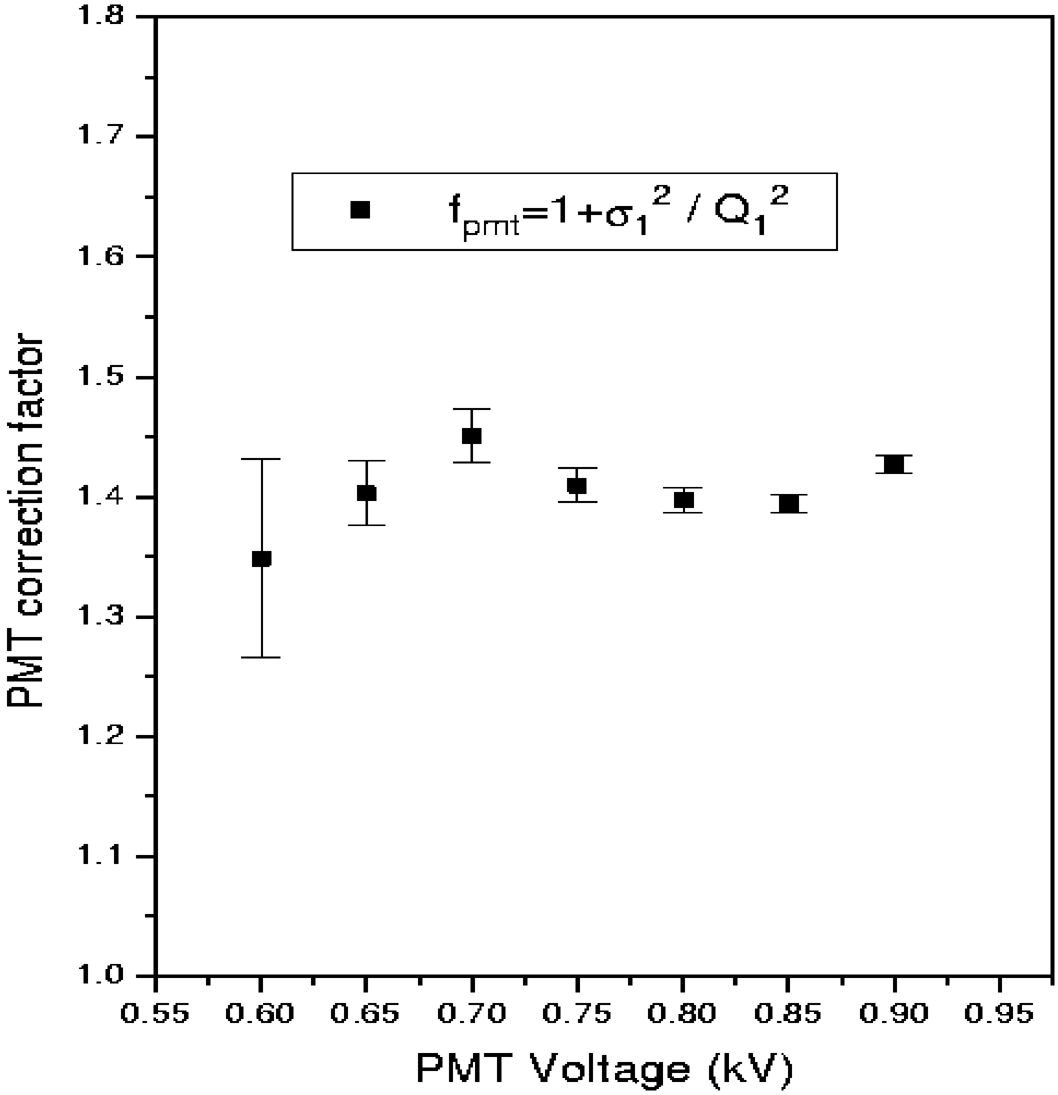

Figure 12: Dependencies of the PMT correction factor on voltage (R5900/7M02C1 photomultiplier)

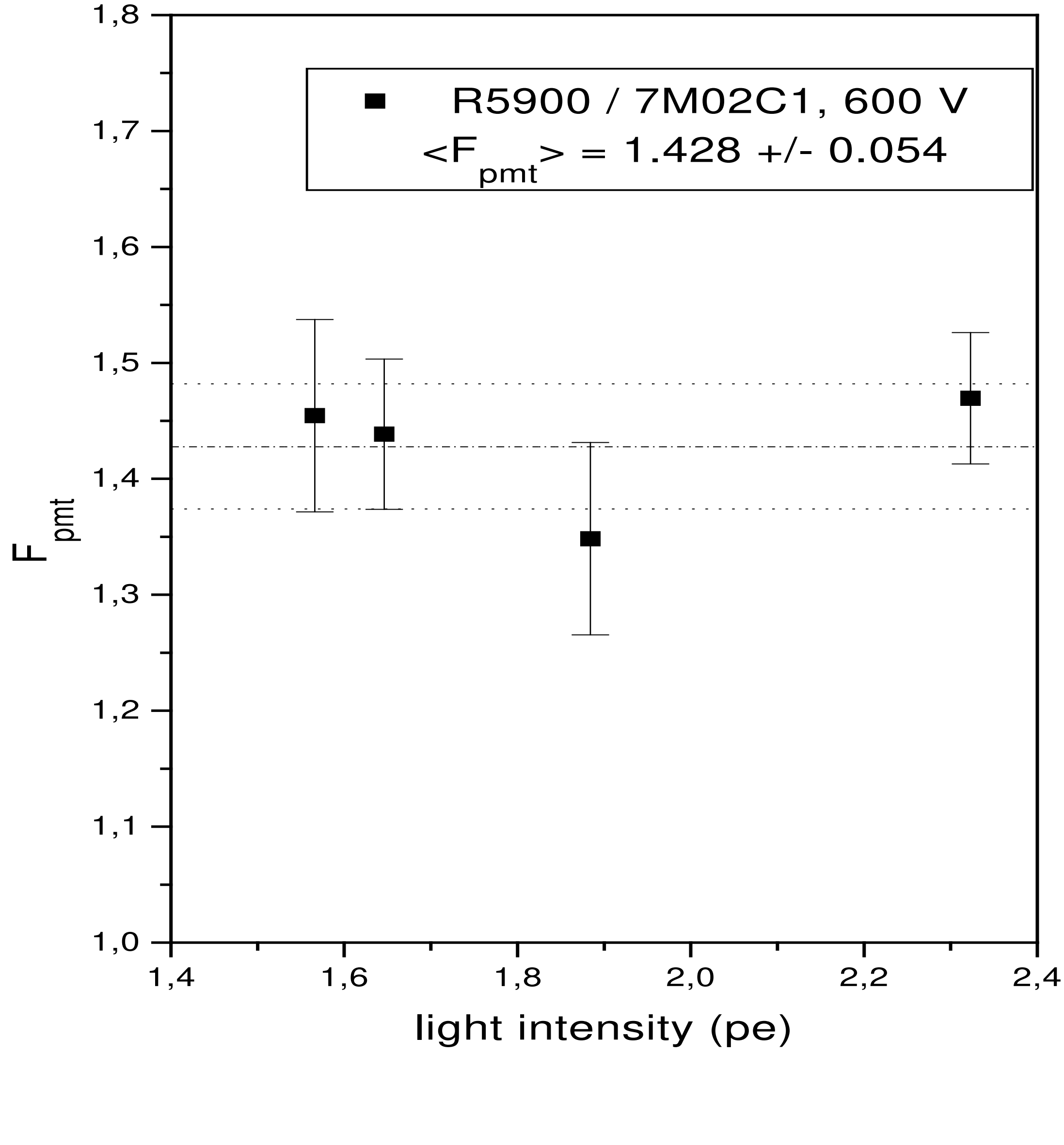

Figure 13: Dependencies of the PMT correction factor on light source intensity at the voltage 600 V (R5900/7M02C1 PMT).

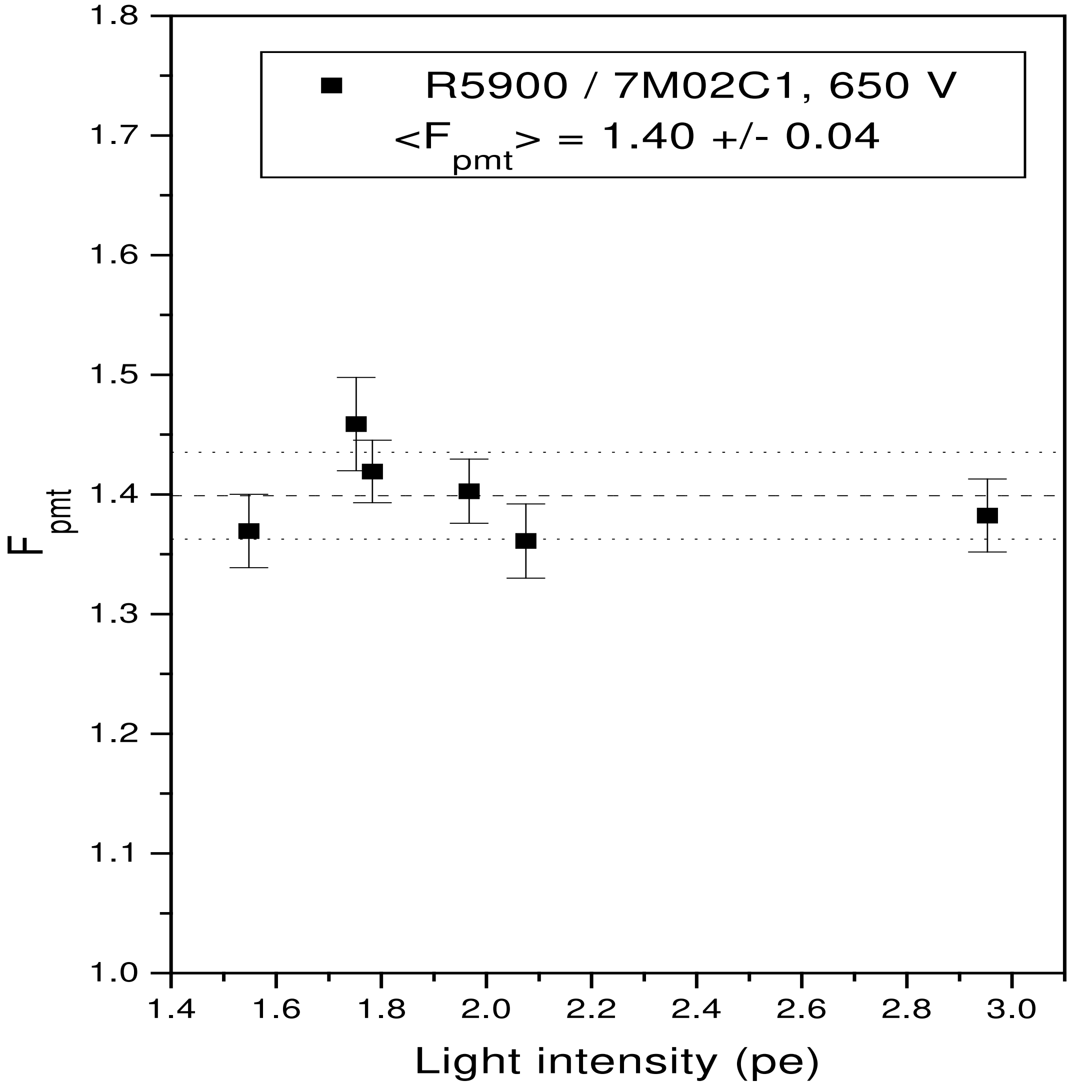

Figure 14: Dependencies of the PMT correction factor on on light source intensity at the voltage 650 V (R5900/7M02C1 PMT)

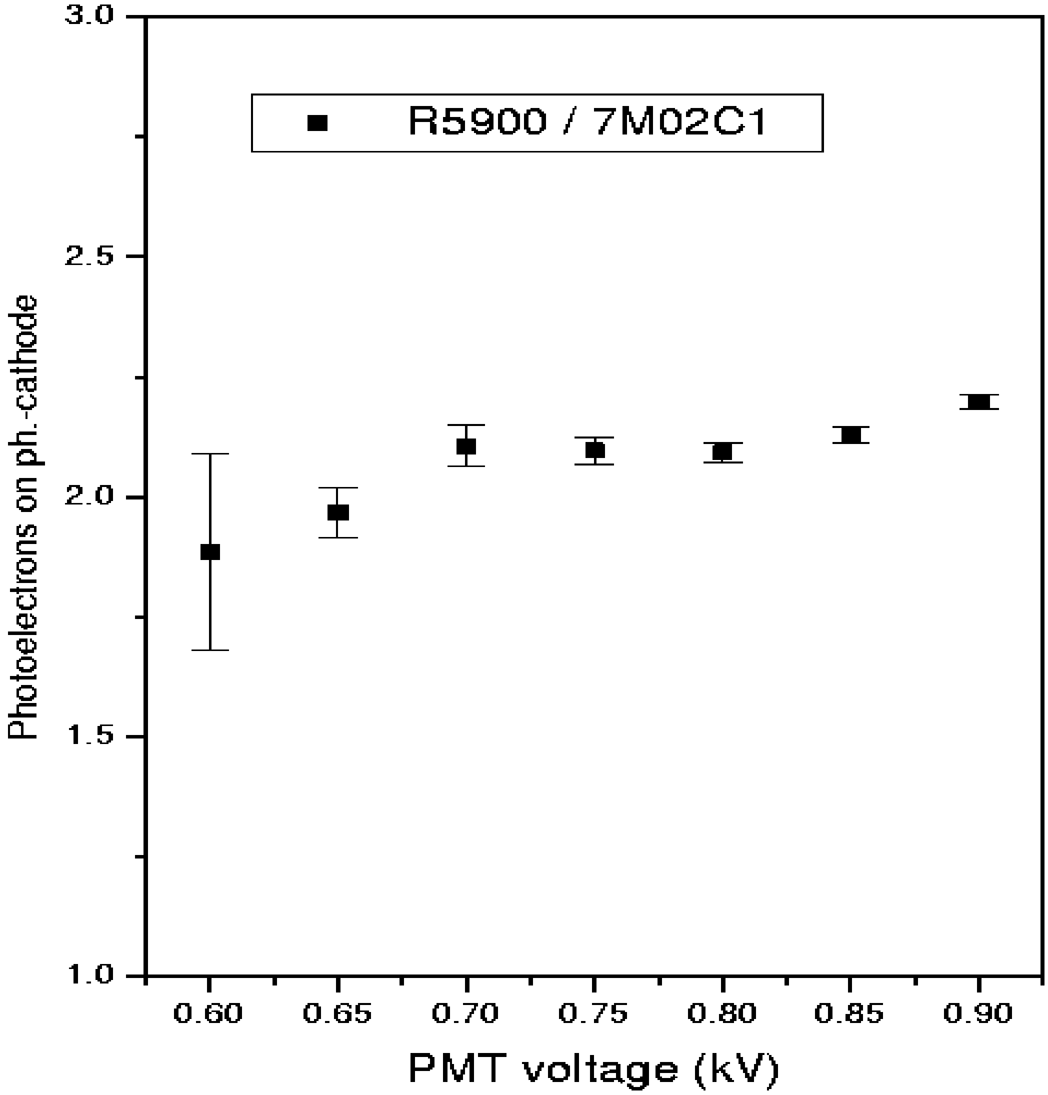

Figure 15: Number of photoelectrons (μ) on voltage for the same input light signal.

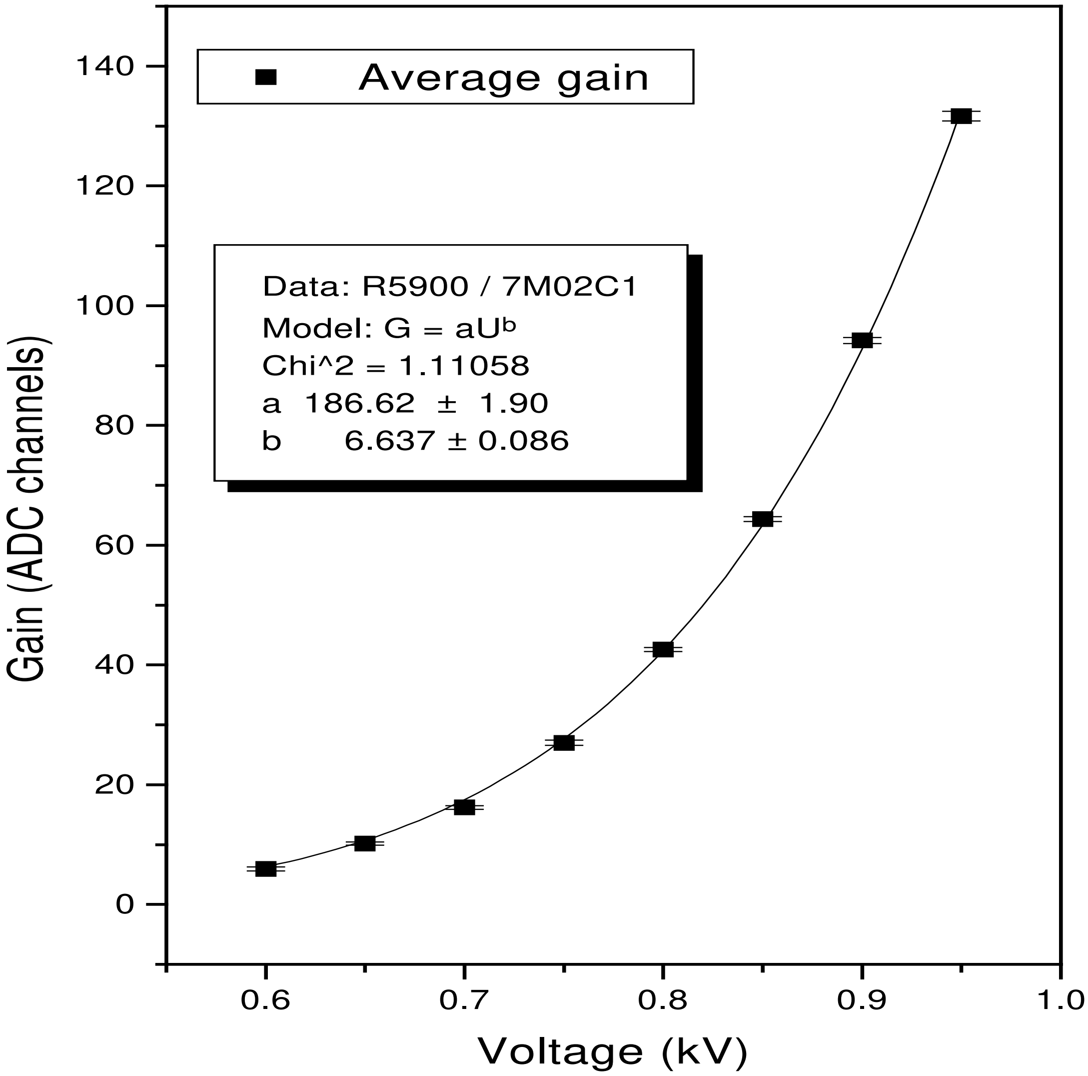

Figure 16: Dependencies of the gain (parameter Q_1) on voltage (R5900/7M02C1 photomultiplier)- mean value of the gain at each voltage has been used.

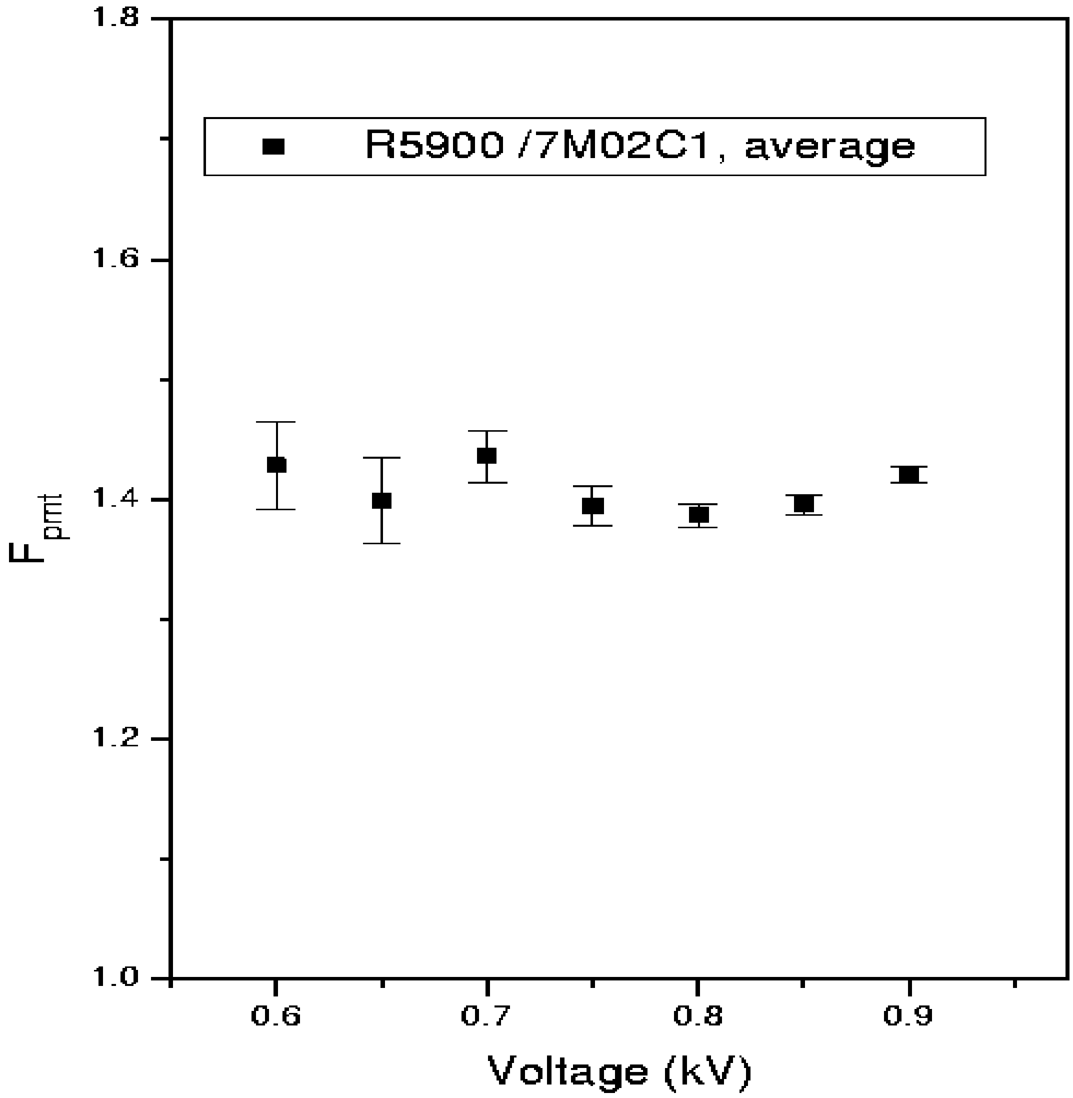

Figure 17: Dependencies of the PMT correction factor (F_{pmt}) on voltage (R5900/7M02C1 photomultiplier)- mean value of F_{pmt} at each voltage has been used.