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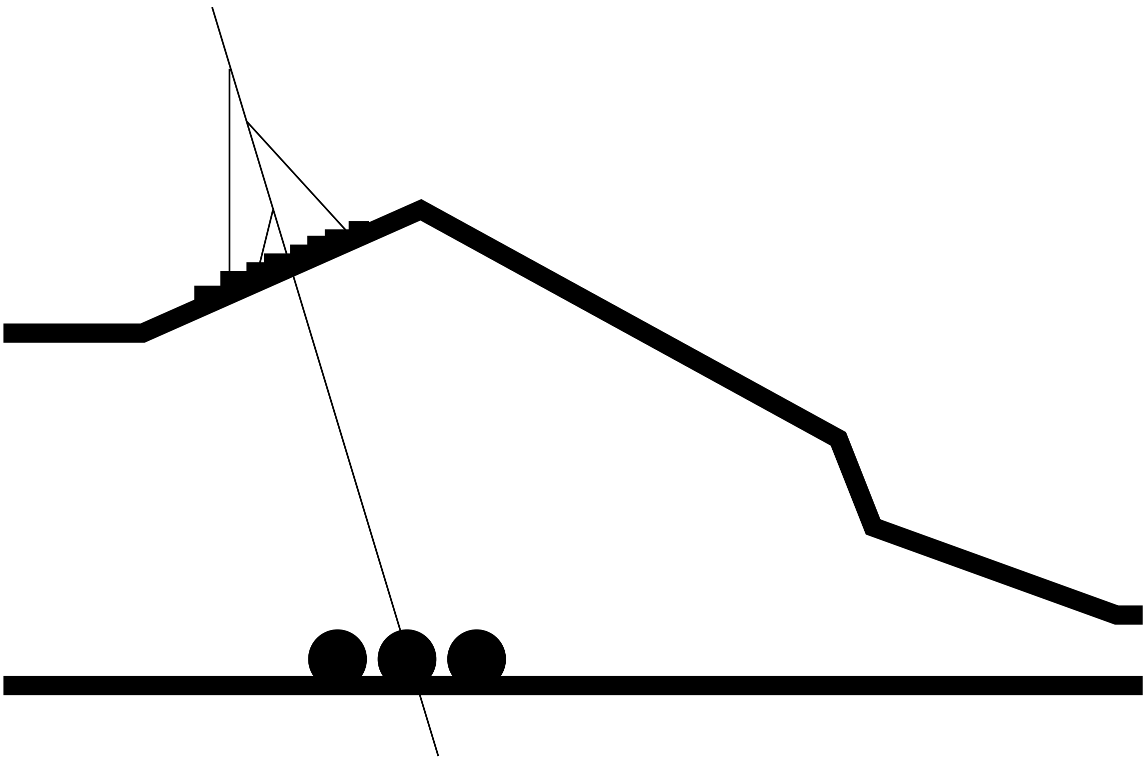

Setting of the predefined multiplier gain of a photomiltiplier

O.Ju.Smirnov[a]

INFN - Laboratori Nazionali del Gran Sasso

INFN - Istituto Nazionale di Fisica Nucleare

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O.Ju.Smirnov[a]

[a] *Joint Institute for Nuclear Research, Dubna, Russia*

Abstract

The method to set the predefined PMT gain with high precision is described. The method supposes the minimal participation of the operator. After the rough initial setting of the gain, the automated system adjusts the PMT gain within a predefined precision (up to 2%). The method has been successfully applied at the Borexino PMT test facility at LNGS for the gain adjustment of 108 photomultipliers for the CTF-II programme.

1 Introduction

Large scale liquid scintillator detectors like Borexino[1] (or its prototype CTF[2]) use big number of PMTs. The PMTs[1] delivered from the supplier (ETL) are factory tested and the operational high voltage (HV) is specified by the manufacturer. Mainly, because of the difference in the high voltage dividers used by ETL and the ones used in Borexino, the voltage should be remeasured. The total number of the PMTs to be tested was 108 for the CTF-II. In the near future the test of the 2200 PMTs for the Borexino detector will begin. It is clear that one needs an automated gain adjustment system in order to handle such a large number of the PMTs.

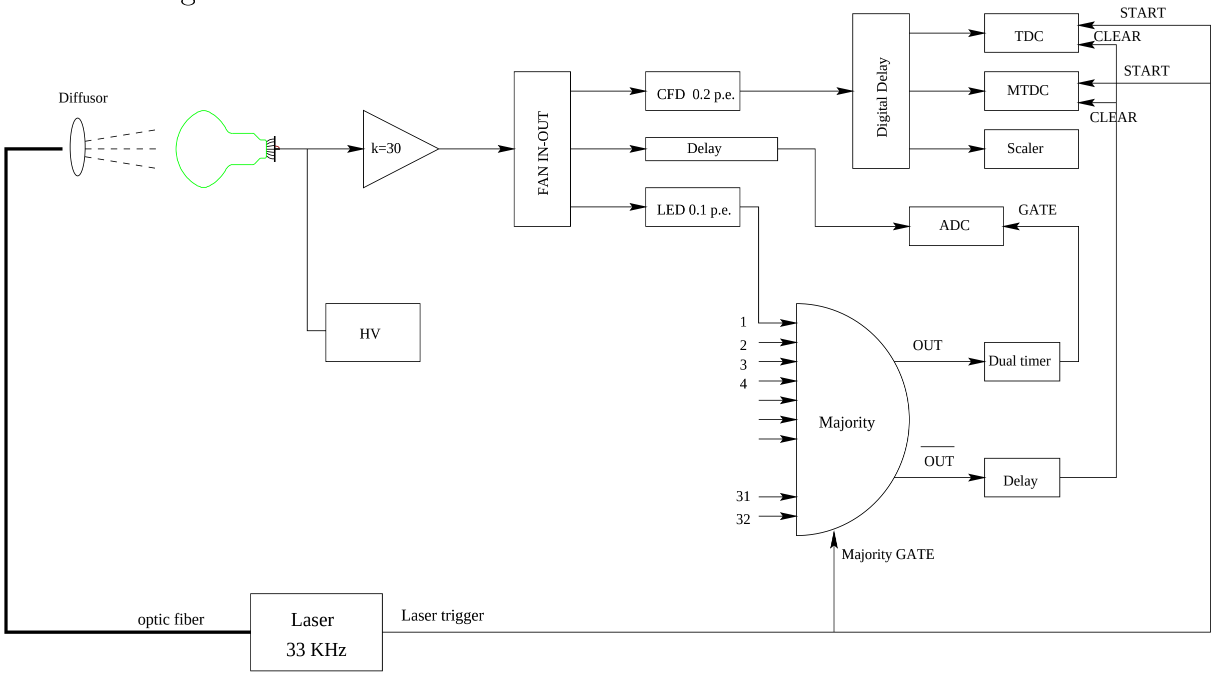
The methods for measuring a multiplier gain are described, for example, in [3]. The conclusion of the author is that it is unlikely one can obtain measurements of the gain with a precision better than 10%. The fundamental limit comes from the inability of a multichannel analyzer used in the measurements to access all the contributions from the low amplitude region. In our article [4] a method of photomultiplier calibration with a high precision has been discussed (up to a few percent). The method is based on the precision measurements of the PMT charge response to low intensity light pulses from a laser. It has been concluded that the precision of the method is limited only by the systematic errors in the discrimination of the small amplitude pulses from the electronics noise. On the basis of our experience with the precise PMT calibration, the fast procedure of PMT voltage tuning has been realized for the Borexino PMT test facility at the Gran Sasso laboratory.

2 PMT test facility at LNGS

One channel of electronics of the test facility is presented in fig.1. Up to 32 PMTs can be tested simultaneously. The system uses the modular CAMAC standard electronics and is connected to a personal computer by the CAEN C111 interface. The majority logic unit LeCroy 4532 is able to memorize the pattern of the hit channels. This information significantly increases the data processing rate. The electronics reading is activated when the majority LAM signal is on (the LAM is produced if one of the signals on the inputs is inside the external GATE on the majority logic unit). Otherwise, a hardware clear is forced (using $\overline{OUT}$ signal). The PMTs are illuminated by low intensity light pulses from a laser. Every pulse of the picosecond laser (Hamamatsu) is followed by an internal trigger. The trigger is used as the majority external gate. An example of the data acquired during a routine PMT test is presented in fig.2. It should be pointed out that the charge histogram in fig.2 is acquired together with the ADC pedestal, i.e. without a hardware threshold. This was realized by connecting the last (32-th) majority input to the external gate signal. In this case the system is triggered at the first trigger from laser that occurs when the electronics is not busy with the previous data transfer. During the HV tuning, the "cut" charge histograms are acquired with a hardware threshold of about $5\% - 10\%$

[1]Thorn EMI9351 PMTs are used in both experiments.

Figure 1: One channel of the electronics used in the measurements



of the "typical" Single Photoelectron Response (SER) mean value.[2]

The high precision calibration of each electronics channel had been performed before the measurements. Here calibration means the ADC response to a signal corresponding to 1 p.e.[3] on the system input with the ADC pedestal subtracted (the PMT in this measurement is substituted by a precision charge generator). The position of the ADC pedestals are defined and checked during the run.

3 HV tuning procedure

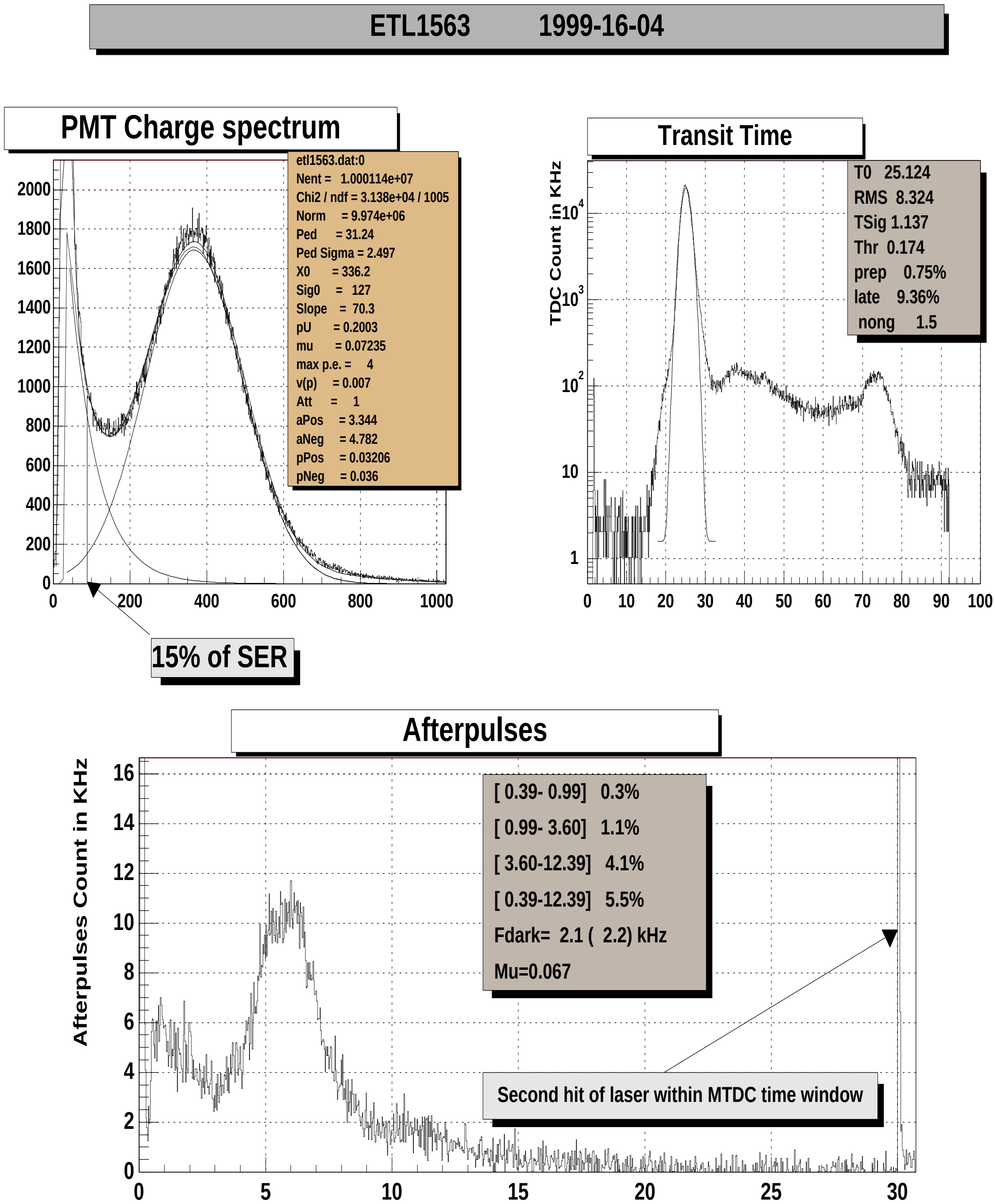
The HV tuning procedure starts with the HV set to the minimum value of 1300 V. Then the HV for the each PMT is increased in order to achieve a dark count rate of ≈ 1 KHz. During all the operations the PMT current is checked, and if it is too big or unstable the PMT is switched off.

After the initial adjustment of the HV, a short data acquisition cycle is performed. PMT charge histograms are inspected visually one by one, and further HV adjustment is applied as necessary (i.e. if the position of the charge SER mean value is too low or too high), aiming to achieve $k = 10^7 \pm 80\%$. Then the fine HV tuning is performed in a special mode of the data acquisition.

[2]signals at the majority inputs are formed by the Leading Edge Discriminator (LED) LeCroy 4413 with a threshold set to this value. A Constant Fraction Discriminator (CFD) Ortec 8200 with a higher threshold (about 20% of the "typical" SER mean value) is used for the timing measurements.

[3]or 1.6 pC charge

Figure 2: The characteristics of one of the PMTs under test. The PMT charge response is measured in ADC channels (1024 ADC channels corresponds to 256 pC), the transit time histogram scale is 100 ns, and the afterpulses are measured on the 30 μs scale.



The goal of the fine tuning is to find the HV value that will provide $k = 10^7$ electron gain factor for each PMT. The mean value of the charge SER q_1 is determined, and the HV is adjusted so that q_1 agrees with a calibration value c_1 to a predefined precision. Because of the hardware cut in the charge data, the following correction should be performed in order to obtain the $q_1$value from the cut distribution (see Appendix A):

$$q_1 = q_m \frac{1 - P(0) \cdot (1 + \mu \cdot p_t)}{\mu} (1 - P(0) p_t \frac{thr}{2})^{-1}, \tag{1}$$

here q_m is the mean value of the cut distribution (a software cut of 15% of c_1 is used in order to avoid the effects of the SER shape distortion near the hardware threshold);

μ is the mean p.e. number registered for one laser pulse, typically in the range 0.05-0.10;

p_t is the part of the charge SER under the threshold, in practice the average value obtained during the preliminary PMT test was used. For the 15% software threshold, the value $p_t \cong 0.07$ was used. The HV tuning algorithm was written before the bulk test of the PMTs; after a careful analysis of the data, this value was corrected to $p_t \cong 0.11$[4].

thr is the threshold level measured in the c_1 units (0.15 in the our case).

For small μ, equation (1) can be significantly simplified:

$$q_1 = q_m \frac{1 - \frac{\mu}{2} - p_t}{1 - p_t \frac{thr}{2}}. \tag{2}$$

The mean p.e. number is defined during the test by estimating the probability of the PMT hit. Assuming a Poisson distribution of the light detection process, one can write:

$$\mu = -\ln(1 - \frac{N_{ev}}{N_{Triggers}}).$$

In practice we take as $N_{Trigger}$ the number of the events in the charge histogram (i.e. with a $5\% - 10\%$ hardware cut), and as N_{ev} we take the number of events after a $30\,\mu s$ delay[5] estimated from the Multihit TDC (LeCroy 2277) histogram (see fig.2). The Multihit TDC (MTDC) is able to register up to 16 signals in the $32\,\mu s$ window. For these events the hardware cut on the CFD is about 20% of the SER. The precision of the μ estimation using these $N_{Triggers}$ and N_{ev} values is approximately 10%, which is good enough for our purpose.

For the following discussion the relation between the mean value of the SER and its r.m.s. is important. The relative variance $v_1 = (\frac{\sigma_{q1}}{q_1})^2$ of the SER was estimated during the tests (see [5] for details). The maximum value of this parameter for the PMTs under test is about 0.4; hence we used this value for the σ_{q_1} estimation ($\sigma_{q_1} = \sqrt{v_1} q_1$). For the spectrum of $N_{Triggers}$ events the statistical precision of the mean charge estimation

[4] an underestimation of the p_t value leads to an underestimation of the q_1 value, as it can be deduced from formula (2). As a result of the underestimation (0.04 difference), the PMTsgains were set to 96% of the expected value (see Results section).

[5] $30\,\mu s$ is the laser repetition rate

is $\sigma_q = \frac{\sigma_{q_1}}{\sqrt{N_{Triggers}}}$ (not taking into account that the precision gets worse because of the uncertainties introduced by the spectrum cut).

The fine tuning starts with the acquisition of $N_{Triggers} = 100$ events, then the q_1 is estimated (μ is not estimated in the first stages and is assumed to be 0.05 p.e.). If the q_1 value is inside the $c_1 \pm 5\sigma_q$ interval, the maximum number of the events is doubled and another $N_{Triggers}$ events are acquired in order to increase the statistics. If $\mid q_1 - c_1 \mid > 5\sigma_q$ the HV is adjusted, the data are cleared, and the data acquisition starts again for the $N_{Triggers}$ events (after the short delay necessary to set new HV). We start with only 100 events, so that the HV is adjusted very rapidly if q_1 is far from c_1[6]. The logic of the fine HV tuning is presented in fig.3. The interval $5 \cdot \sigma_q$ is chosen in order to take into account the possible systematic errors.

The maximum (preset) number of the events is 12800, which provides a 1% statistical precision ($\frac{\sqrt{v_1}}{\sqrt{12800}} < 0.01$). When the event number achieves the maximum value (i.e. 12800), the condition $\mid q_1 - c_1 \mid < p_{HV} \cdot c_1$ is checked, where p_{HV} is the predefined precision of the HV adjustment (typically 2%). If the condition is true, the acquisition in the channel is stopped and discriminator output is disabled, increasing in such a way the data acquisition rate for the remaining channels.

The HV correction is calculated from the following considerations. If the deviation is big ($> 10\%$) the correction is set to a fraction of the maximum deviation of 100 V in proportion to the deviation from the calibration value $\frac{q_1 - c_1}{c_1}$. The value of 100 V has been estimated from formula (4) with the HV set to the minimum value of 1300 V ($\frac{3}{2}\frac{U_{min}-600}{11} \approx 100\,V$), so that any possible overvoltage is avoided.

If the deviation is small enough, the correction can be calculated more precisely. The PMT divider (fig.4) provides a fixed voltage difference between the photocathode and the first dynode ($U_{D1} = 600$ V). The remaining HV is distributed between 11 dynodes ($U = U_{D2} + U_{D3} + U_{D4} + ... + U_{D12} = 12.5U_0$), with the last 9 voltage steps being equal ($U_0 = \frac{U-600V}{12.5}$), while $U_{D2} = 2U_0$ and $U_{D3} = 1.5U_0$ respectively. For the typical PMT the HV value is in the 1300-1700 V range, i.e. $U_0 < 80$ V. The Be-Cu dynodes of the EMI 9351 have a gain that changes linearly with the applied voltage up to 200-250 V[7]. If the proportionality coefficient is k_d ($g = k_d \cdot U$) then the overall gain of the 12 dynode system is $k = 3 \cdot g_1 \cdot (k_d \cdot \frac{U-600}{12.5})^{11}$. The relative variation of the gain versus the variation of the applied voltage is

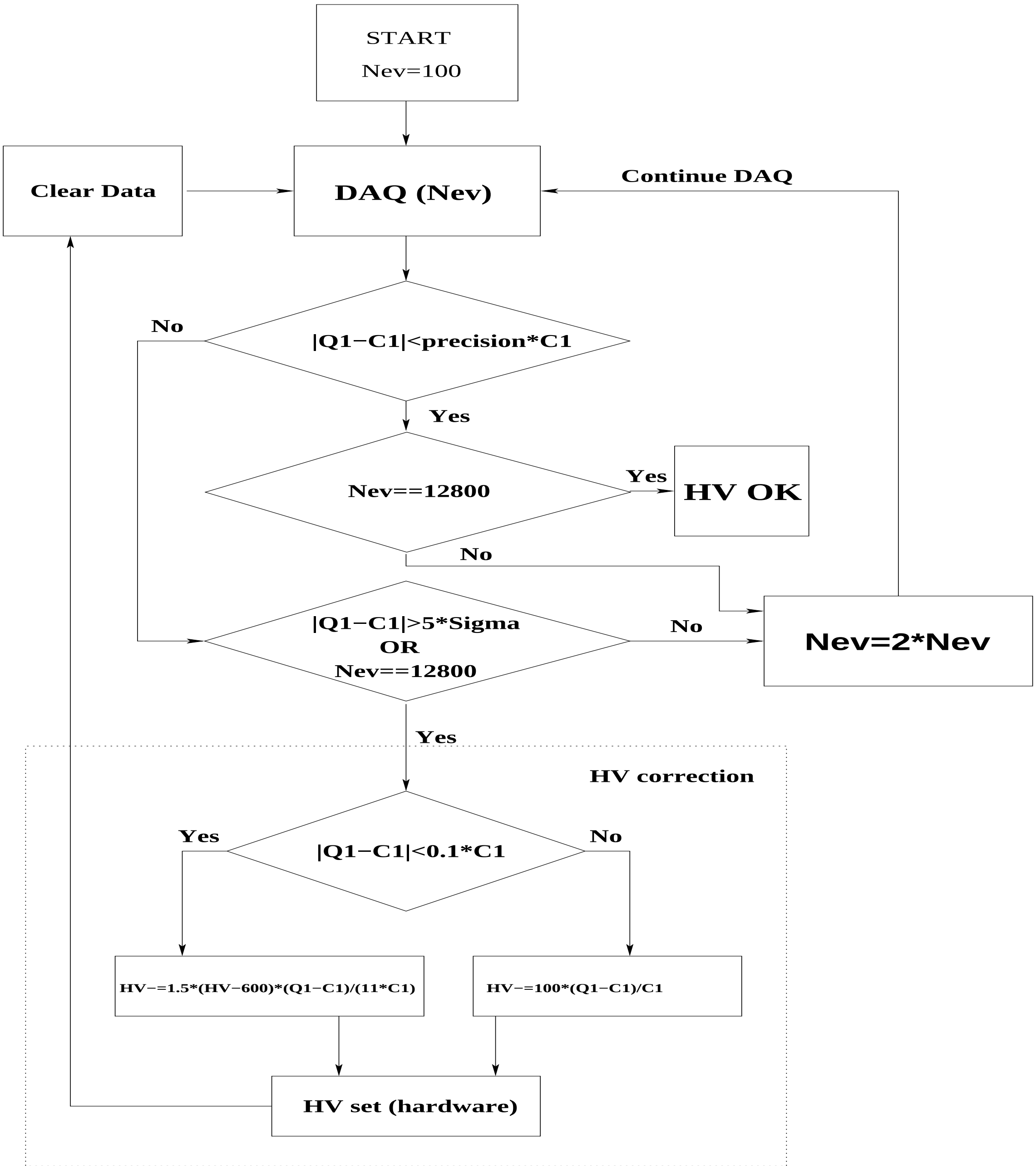
$$\frac{dk}{k} = 11\frac{dU}{U-600}. \tag{3}$$

This equation gives an exponential law for the gain factor as a function of applied voltage. Measurements with 4 different PMTs have been performed in order to check equation (3). The results of the measurements are reported in Appendix B. The variation of the gain

[6] nevertheless, 100 events statistics provides about 20% precision of the calibration at this stage ($5 \cdot \frac{0.4}{\sqrt{100}}$)

[7] see Thorn EMI Electron Tubes catalogue, 1993 fig.9

Figure 3: The flow chart of the high voltage tuning



is better described by the formula

$$\frac{dk}{k} = \frac{2}{3} 11 \frac{dU}{U - 600}. \tag{4}$$

So, for small deviations from the calibration (< 10%) the correction can be calculated as:

$$\Delta U = -\frac{3}{2} \frac{U - 600}{11} \frac{q_1 - c_1}{c_1}. \tag{5}$$

4 Results

We find the algorithm is sufficiently fast; for 32 PMTs at 4 KHz acquisition rate the HV is adjusted in 15-20 minutes with 2% precision.

The results of the HV tuning with the precision set to 2% are presented in fig.5. These results are obtained during the high precision tests after the HV adjustment. The mean value of k=0.96 doesn't agree with the expected k=1.0, because of the underestimation of the part of the signals under the threshold ($p_t = 0.07$ was used instead of $p_t = 0.11$). Taking into account that the PMT gain is sensitive to the Earth's magnetic field and that the μ-metal screening is different from the magnetic field compensation used in the Borexino test facility, there is no need for a more precise HV tuning during the test.

The variance of the gain distribution (0.02) agrees with the preset precision of the adjustment. This means that the goal has been achieved; the PMT gains have really been adjusted within 2% precision.

5 Acknowledgements

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I would also like to thank my colleagues from the Borexino collaboration.

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Figure 4:

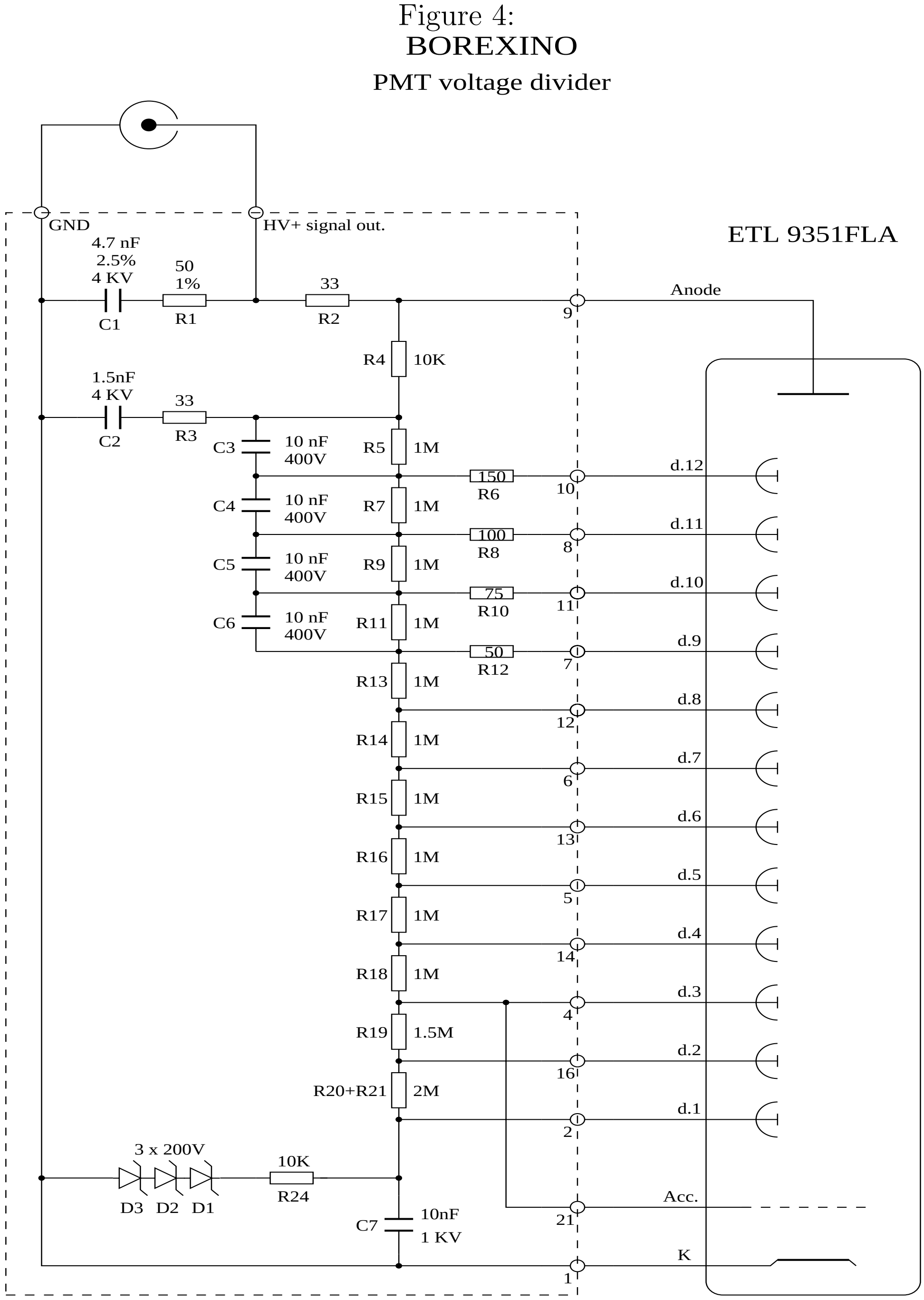
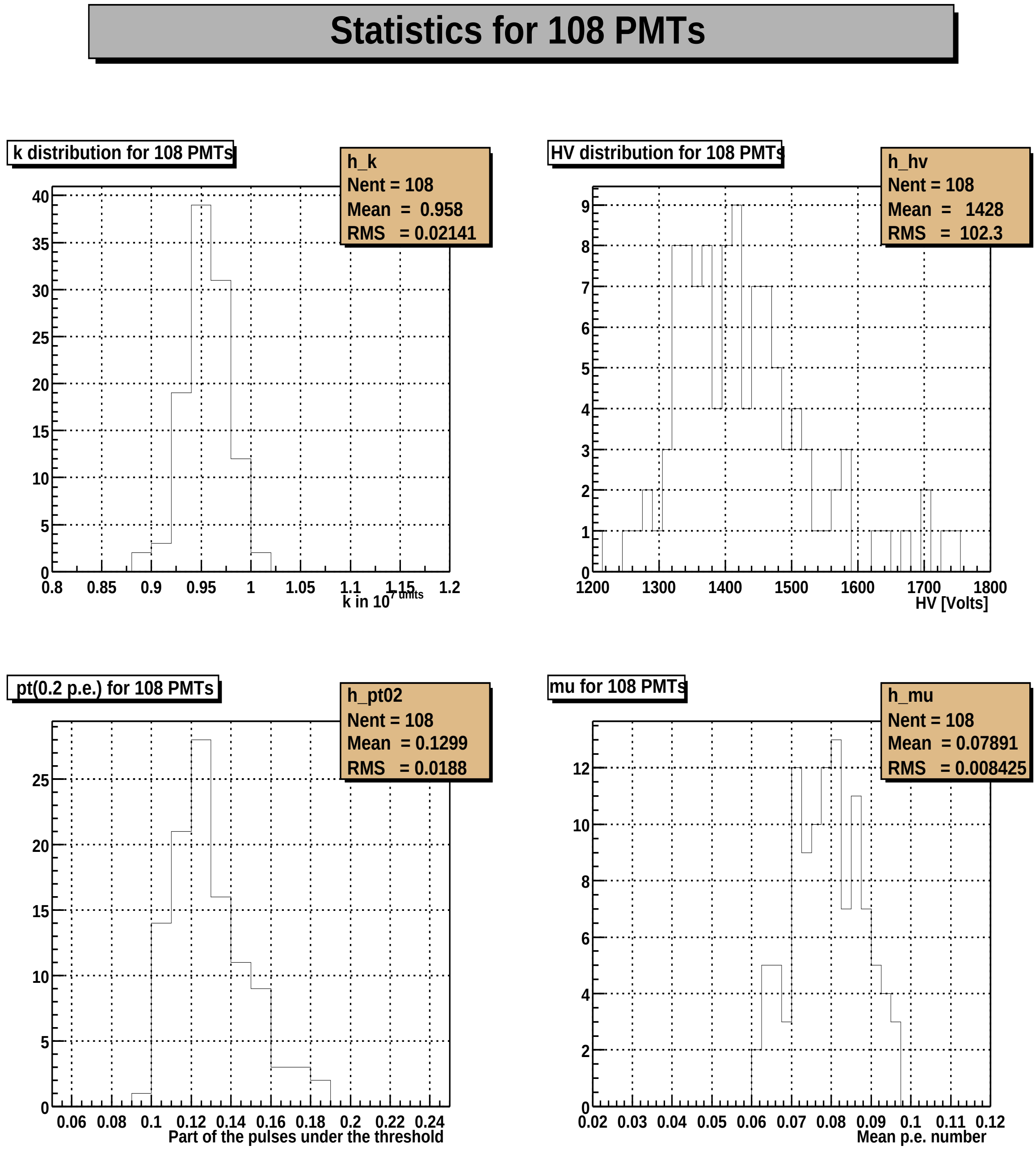

BOREXINO
PMT voltage divider
GND
HV+ signal out.
ETL 9351FLA
4.7 nF
2.5%
4 KV
C1
50
1%
R1
33
R2
Anode
9
R4
10K
1.5nF
4 KV
C2
33
R3
C3
10 nF
400V
R5
1M
150
R6
10
d.12
C4
10 nF
400V
R7
1M
100
R8
8
d.11
C5
10 nF
400V
R9
1M
75
R10
11
d.10
C6
10 nF
400V
R11
1M
50
R12
7
d.9
R13
1M
12
d.8
R14
1M
6
d.7
R15
1M
13
d.6
R16
1M
5
d.5
R17
1M
14
d.4
R18
1M
4
d.3
R19
1.5M
16
d.2
R20+R21
2M
2
d.1
3 x 200V
D3 D2 D1
10K
R24
C7
10nF
1 KV
21
Acc.
1
K

Figure 5: The results of the PMTs gain tuning (first histogram) and the resulting HV (the second one). Two parameters used in the algorithm (p_t and μ) are presented as well. The $p_t(0.2)$ here is defined for the 20% SER software cut, it is slightly higher than the value used in the algorithm.



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A Appendix: Correction of the calibration for the cut spectrum

Let us calculate the mean of the PMT charge spectrum cut at a certain level (i.e. the pedestal and the small amplitude pulses cut). The mean registered charge in this case can be defined as:

$$q_m = \int_{q_{th}}^{\infty} \sum_{N=0}^{\infty} P(N) f_N(q) q\, dq = \sum_{N=0}^{\infty} \int_{q_{th}}^{\infty} f_N(q) q\, dq \equiv \sum_{N=0}^{\infty} P(N) \overline{q_N(q_{th})}, \tag{6}$$

here $f_N(q)$ is the PMT response to the N photoelectrons (p.e.). We will assume that the probability distribution for N p.e. registered by the PMT is Poissonian. In order to take into account the fact that a charge less than the threshold will not be registered, the Poisson probabilities should be renormalized (more precisely, the conditional probabilities should be calculated):

$$P(N) \rightarrow \frac{P(N)}{1 - P(0) - p_t \cdot P(1)}.$$

Part of the signals under the threshold is interpreted as a no response signal i.e. $P(0) \rightarrow P(0) + p_t P(1)$ and $P(1) \rightarrow P(1)(1 - p_t)$. We assume here that the part of the PMT response under the threshold is negligible for 2 and more p.e. registered, and all the response to 0 p.e. remains under the threshold. The part of N=1 response under the threshold is p_t by definition. In this case $\overline{q_N(q_{th})} = N \cdot q_1$ for $N \geq 2$. The response to N=0 p.e. has a mean value $\overline{q_0(q_{th})} = 0$. In order to obtain the mean value of the N=1 response we will use the following approximation for the N=1 response (with a rectangular part under the threshold):

$$f_1(x) = \begin{cases} 0 & q < 0 \\ \frac{p_t}{q_{th}} & 0 < q < q_{th} \\ Ser(q) & q > q_{th} \end{cases}$$

then $q_1 = (1-p_t)\overline{q_1(q_{th})} + p_t \cdot \frac{q_{th}}{2}$ and we can rewrite (6) as

$$q_m = \frac{1}{1 - P(0) - p_t\, P(1)} \left[P(1)(1-p_t)\overline{q_1(q_{th})} + \sum_{N=2}^{\infty} P(N) N q_1 \right].$$

Noting that

$$\sum_{N=2}^{\infty} P(N)N = \sum_{N=0}^{\infty} P(N)N - P(1)$$

and

$$\sum_{N=0}^{\infty} P(N)N \equiv \mu$$

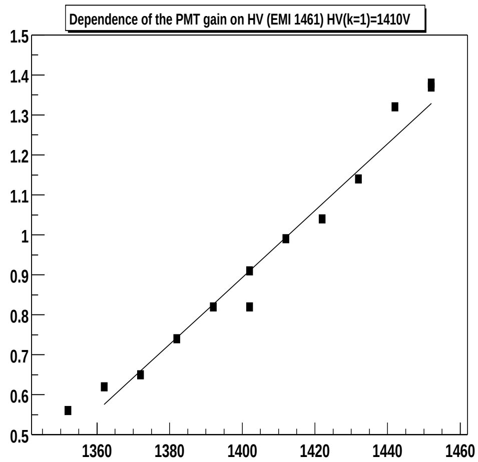
we can finally obtain

$$q_m = \frac{\mu \cdot q_1}{1 - P(0) - p_t\, \mu\, P(0)} \left[1 - P(0) p_t \frac{q_{th}}{2q_1} \right].$$

B Appendix: PMT gain dependence on the HV applied

The results of the measurements performed in order to check the dependence of the PMT gain on the applied high voltage are presented in fig.6. It was found that $\frac{dk}{k}$ is better described by a straight line calculated with formula (3) multiplied by a constant factor 2/3. This means that the overall gain of the PMT is formed by 2/3 of the dynodes.

Figure 6: Dependence of the PMT gain on the HV applied. HV is measured in Volts, the PMT gain is measured in units of 10^7. The straight lines on the plot are calculated using formula (4).



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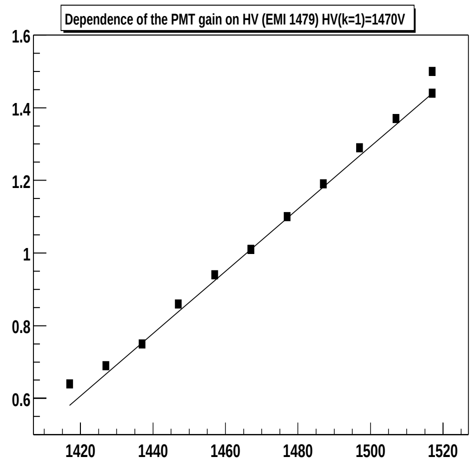
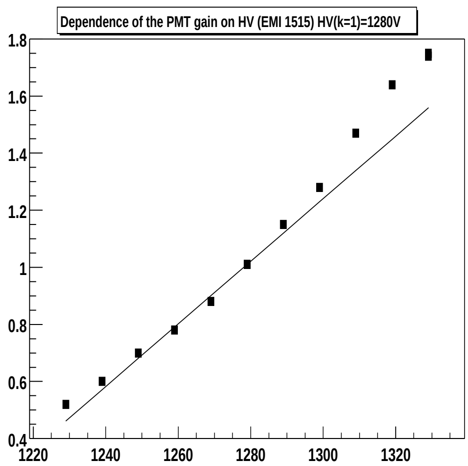


b)



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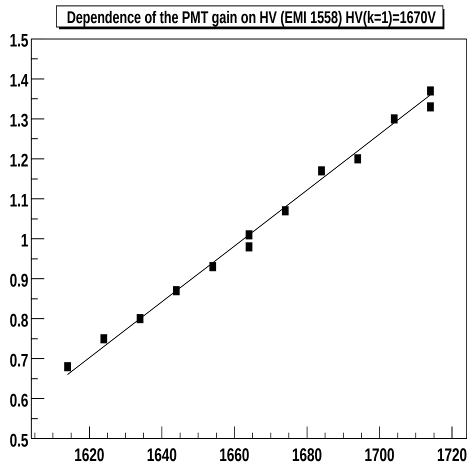

d)