Setting of the predefined multiplier gain of a photomultiplier.

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Abstract

A method to set the predefined PMT gain with high precision is described. The method supposes 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 the 2000 photomultipliers for the Borexino detector.

1 Introduction

A large scale liquid scintillator detector Borexino [1] now under construction at the Gran Sasso underground laboratory (LNGS), is a low energy solar neutrino detector. The scintillation from the recoil electrons will be registered by 2200 photoelectron multiplier tubes (PMTs) placed around a transparent inner vessel containing a scintillating mixture. In addition 200 PMTs will be used as the external muon veto system.

Before installation in the detector, all PMTs are tested in the special facility. The procedure of the testing includes preliminary gain adjustment. In order to accelerate the high voltage adjustment an automatic system have been developed for the PMTs test facility. Though the algorithm of the HV adjustment was developed for the existing facility, it can be adapted for any similar system.

The tuning of the method has been performed during testing of 100 PMTs for the Counting Test Facility detector (the prototype of the Borexino detector, [2]). In August 2001 bulk testing of 2000 PMTs for the Borexino has been completed. The high efficiency of the method permitted us the HV adjustment and complete PMT testing in 4 months.

2 PMT ETL9351 and its characteristics

The Monte Carlo simulation of the Borexino detector showed that the mean number of the photoelectrons (p.e.) registered by one PMT in the scintillation event will be in the region $0.02 - 2.0$ for
an event with energy of 250-800 keV. Hence the PMTs should demonstrate a good single electron performance. After preliminary tests, the Thorn EMI9351 with a large area photocathode (8") has been chosen. The PMT of this model has 12 dynodes with a total gain of $k = 10^7$. The transit time spread of the single p.e. response is $1 - 1.5$ ns. The PMT has a good energy resolution characterized by the manufacturer by the peak-to-valley ratio. The manufacturer (Electron Tubes Limited, ETL) guarantees a peak-to-valley ratio of 1.5.

The PMTs delivered from the supplier are factory tested and the operational high voltage (HV) is specified by the manufacturer. Selective measurements of the PMTs at the factory specified voltage showed a high variance of the gain $k = (0.86 \pm 0.25) \times 10^7$. The high voltage divider used by ETL and the one used in Borexino are different. For these reasons the voltage should be remeasured. The Borexino PMT divider is shown in fig.[1] For proper signal termination the 50Ω resistor R1 is included in the scheme. The resistor decreases signal amplitude by a factor of 2. The signal attenuation is compensated by the higher operating voltage. Practically the photoelectron multiplier is operating at the $k = 2 \times 10^7$ gain.

### 3 PMT test facility at LNGS

In the frame of the Borexino programme the special PMT test facility was prepared at the LNGS. The test facility is placed in two adjacent rooms. In one room the electronics is mounted, and the other is a dark room with 4 tables designed to hold up to 64 PMTs. The dark room is equipped with an Earth’s magnetic field compensation system on the base of rectangular coils with an electric current ([6]). The non-uniformity of the compensated field in the plane of the tables is no more than 10%. The tables are separated from each other by black shrouds, which screen the light reflected from the PMTs photocathode.

One channel of electronics (out of the total 32) of the test facility is presented in fig.[2] The system uses the modular CAMAC standard electronics and is connected to a personal computer by the CAEN C111 interface. The PMT characteristics are defined during a 5 hour run. The stability of the parameters is defined every 12-24 hours during longer runs.

The PMTs are illuminated by low intensity light pulses from a laser. A picosecond Hamamatsu pulse laser was used in the tests. The model used has a peak power of 0.39 mW, the pulse width is 27.3 ps, and the laser wavelength is 415 nm, which is close to the maximum quantum efficiency of Thorn EMI 9351. The light pulse from the laser is delivered by a 6 meter long optical fibers into the dark-room. Each of the 4 fibers is supplied with a diffuser in order to provide a more uniform illumination of the tables.

The ADC gate and TDC “start” signals are generated using the laser internal trigger, which has negligible time jitter (< 100 ps) with respect to the light pulse. The “stop” signal for the TDC is formed by the constant fraction discriminator (CFD) with the threshold set at the 0.2 p.e. level.

The 32-inputs majority logic unit is able to memorize the pattern of the hit channels. This
Figure 1: High voltage divider used in the Borexino experiment.

BOREXINO

PMT voltage divider
Figure 2. One channel of the electronics used in the measurements.
information significantly increases the data processing rate. The reading of the electronics is activated when the majority LAM signal is on (a 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 the majority OUT signal. Every pulse of the laser 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.3. It should be pointed out that the charge histogram in fig.3 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 the 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% of the “typical” Single Photoelectron Response (SER) mean value.

The afterpulses are registered by the multihit TDC (MTDC) which is able to memorize in the internal register up to 16 hits inside a 32 µs window.

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.\(^2\) on the system input with the ADC pedestal subtracted (the PMT in this measurement is substituted by a precision charge generator LeCroy 1976). The position of the ADC pedestals are defined and checked during the run.

4 Electron multiplier gain measurements

For the HV tuning it is necessary to provide a robust method of the gain measurement. The method of a multiplier gain measurement with multichannel analyzer in the self-triggering mode has a precision worse than 10% \([3]\). 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. The systematic uncertainty of the methods using the SER modeling (see i.e.\([5]\)) are difficult to estimate, especially during bulk testing. Another disadvantage of these methods is the high statistics necessary to estimate the SER parameters.

A method of photomultiplier calibration with a high precision of up to a few percent has been discussed in the article \([4]\). The method is based on 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 \([4]\), a

\(^{1}\)signals at the majority inputs are formed by the Leading Edge Discriminator (LED) with a threshold set to this value. A Constant Fraction Discriminator (CFD) with a higher threshold (about 20% of the “typical” SER mean value) is used for the timing measurements.

\(^{2}\)multiplied by a factor of \(10^7\) by the electron multiplier and giving 1.6 pC charge
Figure 3: The characteristics of one of the PMTs under test: charge spectrum (upper plot) and afterpulses (lower plot). The PMT charge response is measured in ADC channels (1024 ADC channels corresponds to 256 pC). The peak at $\sim 30 \, \mu s$ in the lower plot corresponds to the laser frequency.
Figure 4: Dependence of the PMT gain on the HV applied. The 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 (5) with $n=3.5$.

The fast procedure of PMT voltage tuning has been realized for the Borexino PMT test facility at the Gran Sasso laboratory.

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 $c_1 = 1.6\,pC$ 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):

$$q_1 = q_m \left( 1 - P(0) \cdot (1 + \mu \cdot p_t) \right) \mu^{-1} (1 - P(0)\cdot p_t \cdot thr)^{-1}, \quad (1)$$

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);

$\mu$ is the mean p.e. number registered for one laser pulse (see fig.5);

$p_t$ is the part of the charge SER under the threshold. For the 15% software threshold, the value $p_t \approx 0.11$ was used, defined during the tests of 100 PMTs of CTF programme (see fig.6);

$thr$ is the threshold level measured in the $c_1$ units (0.15 in the our case).
Figure 5: The mean number of the photoelectrons registered for one laser shot.

Figure 6: $p_t$ parameter defined during the tests.
For small $\mu$, equation (1) can be significantly simplified:

$$q_1 = q_m \frac{1 - \frac{\mu}{2} - p_t}{1 - p_t \text{thr}}. \quad (2)$$

The mean p.e. number is defined during the test by estimating the probability of two sequential non-zero signals on PMT. Assuming a Poisson distribution of the light detection process, one can write:

$$\mu = -\ln(1 - \frac{N_{ev}}{N_{Triggers}}) \simeq \frac{N_{ev}}{N_{Triggers}}, \quad (3)$$

where $N_{Trigger}$ is the full number of the system triggers and $N_{ev}$ is the number of events that are followed by the non-zero pulse (the first signal in a two pulses sequence is triggering the system and thus is always present). 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, estimated from the Multihit TDC histogram (see fig.3). For these events the hardware cut on the CFD is about 20% of the SER. The precision of the $\mu$ estimation using these $N_{Triggers}$ and $N_{ev}$ values is approximately 10%, which is good enough for our purpose.

5 The dependence of the multiplier gain on the HV

The PMT divider (fig.1) provides a fixed voltage difference between the photocathode and the first dynode ($U_{D_1} = 600$ V). The remaining potential is distributed between 11 dynodes: $U = U_{D_2} + U_{D_3} + U_{D_4} + ... + U_{D_{12}} = 13.5U_0$, with the last 9 voltage steps being equal, $U_0 = \frac{U - 600V}{13.5}$, while $U_{D_2} = 2U_0$ and $U_{D_3} = 1.5U_0$ respectively. For the typical PMT the HV value is in the 1200-1700 V range (see fig.7), 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 (see fig.9 of [7]). If the electron multiplication on the first dynode is $g_1$ and amplification of the dynode at the $U_0$ voltage is $g = k_d \cdot U$, then the total gain of the 12-dynodes system is:

$$k = 3 \cdot g_1 \cdot (k_d \cdot \frac{U - 600}{13.5})^{11-n} g_n, \quad (4)$$

where $n$ is introduced in order to take into account the influence of the spatial charge on the last dynodes, where the dynode gain is practically independent of the applied high voltage. The total gain on the last dynodes is assumed to be $g_n$. The relative variation of the gain versus the variation of the applied voltage is:

$$\frac{dk}{k} = (11 - n) \cdot \frac{dU}{U - 600}. \quad (5)$$

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30 $\mu$s corresponds to the laser repetition rate of 33 kHz. The laser repetition rate is fixed in the measurements at this value.
This equation gives an exponential law for the gain factor as a function of applied voltage.

In order to check the dependence of the PMT gain on the applied high voltage, a special set of measurements has been performed for 4 PMTs with different operational voltages. The results are presented in fig. 4. It was found that $\frac{dk}{k}$ is better described by a straight line calculated with formula (5) with a constant factor $n \simeq 3.5$.

6 HV tuning procedure

The HV tuning procedure starts with the HV set to the minimum value of 1200 V. Then the HV for the each PMT is increased in order to achieve a dark count rate of $\approx 1000 \text{ s}^{-1}$. 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.

For the following discussion the relation between the mean value of the SER and its r.m.s. is important. The relative variance $\nu_1 = \left(\frac{\sigma_{q_1}}{q_1}\right)^2$ of the SER charge spectrum was estimated during the tests (see [8] for details). The maximum value of this parameter for the PMTs under test is about 0.4; hence we used this value for the $\sigma_{q_1}$ estimation ($\sigma_{q_1} = \sqrt{\nu_1}q_1$). For the spectrum of $N_{\text{Triggers}}$ events the statistical precision of the mean charge estimation is $\sigma_q = \frac{\sigma_{q_1}}{\sqrt{N_{\text{Triggers}}}}$ (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 ($\mu$ 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 $|q_1 - c_1| > 5\sigma_q$ the HV is adjusted, the data are cleared, and the data acquisition starts again for the $N_{Triggers}$ events. We start with only 100 events, so that the HV is adjusted very rapidly if $q_1$ is far from $c_1$. The logic of the fine HV tuning is presented in fig. The interval $5 \cdot \sigma_q$ is chosen in order to take into account the possible systematic errors.

4nevertheless, 100 events statistics provides about 20% precision of the calibration at this stage ($5 \cdot 0.4 \sqrt{100}$)
The maximum (preset) number of the events is 12800, which provides a 1% statistical precision \( \left( \frac{\sqrt{1}}{\sqrt{12800}} < 0.01 \right) \). When the event number achieves the maximum value (i.e. 12800), the condition \( |q_1 - c_1| < p_{HV} \cdot c_1 \) 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, in such a way increasing 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 low enough value of 100 V has been used, so that any possible overvoltage is avoided. For small deviations from the calibration (< 10%) the correction can be calculated more precisely from (5), namely:

\[
\Delta U = -\frac{3}{2} U - 600 \frac{q_1 - c_1}{c_1}.
\] (6)

7 Results

We find the algorithm is sufficiently fast; for 30 PMTs at 1 kHz acquisition rate the HV is adjusted in 15-20 minutes with 2% statistical precision.

The results of the HV tuning with the precision set to 2% are presented in fig.9. These results were obtained during the high precision tests after the HV adjustment. The mean value of \( k \) agrees with the expected \( k = 1.0 \times 10^7 \).

The systematic error of the method is connected mainly with the substitution of the parameter \( p_t \) by its mean value \( p_t = 0.11 \), the error caused by the precision of \( \mu \) estimation is negligible. The variance of the \( p_t \) parameter is \( \sigma_{p_t} = 0.018 \) (see fig.6). As follows from the formula (2) the contribution of the systematic error is equal to \( \sigma_{p_t} \). Summing quadratically the systematic (0.018) and the statistical (0.02) errors one will obtain the full error of \( \sigma \approx 0.027 \). The variance of the gain distribution (0.028) agrees with the calculated value.

8 Conclusions

The described method is not based on any specific single photoelectron spectrum model and hence can be used for the gain adjustment of the PMT with an arbitrary single electron response. Other advantages of the method are the simplicity of calculations, the predictable precision and very high speed of the algorithm. The method can be adapted for use with any type of PMT designed to operate in single electron regime.

The results of the high voltage tuning for the 2000 PMTs of the Borexino experiment confirmed that the method is robust and very effective.
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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:

\[ q_m = \int_{q_{th}}^{\infty} \sum_{N=0}^{\infty} P(N) f_N(q) q \, dq = \sum_{N=0}^{\infty} \int_{q_{th}}^{\infty} f_N(q) q \, dq = \sum_{N=0}^{\infty} P(N) \overline{q_N(q_{th})}, \]  

(7)

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 (7) as
\[ q_m = \frac{1}{1 - P(0) - p_t P(1)} \left[ P(1)(1 - p_t)q_1(q_{th}) + \sum_{N=2}^{\infty} P(N)Nq_1 \right]. \]

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

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