Characterization and magnetic shielding of the large cathode area PMTs used for the light detection system of the prototype of the solar neutrino experiment Borexino

Gioacchino Ranucci, Danilo Giugni, Istvan Manno, Anna Preda and Patrizia Ullucci

Istituto Nazionale di Fisica Nucleare, via Celoria 16, 20133 Milano, Italy

Alexei Golubchikov and Oleg Smirnov

Joint Institute for Nuclear Research, Dubna, Moscow region, Russian Federation

Received 11 June 1993

In this article we discuss the results of the testing of ∼ 50 Thorn Emi 9351 phototubes used for the light detection system of the Counting Test Facility, prototype of the solar neutrino experiment Borexino, presently under installation at the Gran Sasso Laboratory. The tests were aimed to a systematic evaluation of the spread of the main characteristics of the device and to a thorough evaluation of the shielding effectiveness of μ-metal shields of different lengths.

1. Introduction

To approach the final step of the full size Borexino detector [1], proposed for installation at the Gran Sasso Laboratory, a prototype for preliminary tests is presently under construction in the same experimental site. This prototype (called CTF, Counting Test Facility) comprises ∼ 100 photomultipliers for collection of the light produced by events in the 4 tons of liquid scintillator acting as detection medium.

The photomultiplier type used is the large photocathode area (8 in. diameter) Thorn Emi 9351 tube. In this article we describe the results of the measurements performed to characterize the performances of a first production batch of 56 of such devices. These data complement those already obtained on some preliminary samples of this tube during the selection phase of the photomultiplier to be used in the Borexino detector [2]; furthermore, they give a reliable indication of the reproducibility of the performances of the device when produced in sizable production batch (this is particularly important for Borexino where ∼ 1700 tubes will be used).

A further topic covered in this article, of specific relevance for the experiment, is the experimental evaluation of the shielding effectiveness against static magnetic fields of μ-metal shields of different lengths.

2. Experimental setup

The light source adopted to excite the phototubes was a Hamamatsu PLP-01 picosecond light pulser, emitting blue light at a wavelength of 410 nm. The main features of this device are a very narrow output light pulse (around 50 ps as FWHM), practically representing a δ-like excitation, a high repetition rate (up to some MHz), allowing high statistics measurements in limited time, and a trigger output featuring an inherent low jitter with respect to the output light pulse (less than 10 ps). Since the tubes had to be tested in the single photoelectron regime, the light from the laser was properly attenuated to achieve this condition; the attenuated light was used to feed four optical fibres which carried the light to four dark boxes used to obscure the devices. In this way four tubes were tested concurrently.

The tubes in the box were subjected to full photocathode illumination. This condition was achieved, taking into account the broad irradiance pattern of the
light from the fibre, by locating the end of the fibre at a proper distance from the cathode surface.

With such an arrangement the quantities measured, after adjusting the voltage for a multiplier gain of $10^7$, were the single photoelectron transit time spread, the single electron response, and, switching off the laser, the dark noise count rate and spectrum.

Furthermore, through spot illumination, the overall uniformity of the anode response of the devices was monitored. Two maximum diameters across the cathode surface were scanned for each PMT, respectively along and across the dynodes, by putting at the end of the fibre at a distance of $\sim 1$ mm from the faceplate of the tube.

All these measurements were done after compensation of the Earth's magnetic field. To achieve such a compensation each box was equipped with a $\mu$-metal shield completely surrounding the device.

At a first stage the shield was done following the usual prescription that it should extend in front of the device, from the photocathode surface, for a length equal at least to one radius, i.e. $10$ cm in this case. On the other side the shield was prolonged up to the base of the device, to be sure to enclose with a certain margin the entire dynode chain. The diameter of the cylindrical shield was $24$ cm, the length $35$ cm and the thickness $0.5$ mm.

This shield, while tested for its effectiveness (see section 2), proved to be suited to compensate the effect of magnetic fields of intensity at the level of that of the Earth. Hence all the four boxes were equipped with shields of these dimensions for the routine measurements of the 56 tubes.

To test the susceptibility of the device to static magnetic field, and to control the shielding effectiveness of the shield described above and of other two of different lengths, one of the box was located in the central region of a double set of horizontal and vertical Helmholtz coils. The dimension of the coils were large enough to allow a region of almost uniform field encompassing the whole device. By properly tuning the currents flowing in the coils it was possible to zero the Earth's magnetic field in this region and also to create vertical and horizontal fields of known intensity.

3. Electronics readout system

The readout electronics is shown in fig. 1. The system, realized with a modular architecture, is expandable up to a maximum of 32 channels, thus allowing the concurrent testing of up to 32 devices.

The single photoelectrons signal from the PMT (working at a gain of $10^7$) has a mean amplitude of $\sim 15$ mV and a time width of $\sim 5$ ns at FWHM. The fast linear amplifier amplifies 50 times the signal; its output is used to feed an analog fan-out. Four discriminators with eight channels each, with the threshold set at a level of 0.1 photoelectrons, discriminate the 32 channels. The outputs of these discriminators are connected to the input of a majority logic unit; this unit performs the OR of input signals when a proper GATE signal is applied. The GATE is generated via the trigger output of the laser, delayed of 60 ns and shaped at a width of 30 ns using a dual timer. When at least one of the 32 channels produces a signal in coincidence with the GATE input, the majority unit sets the LAM line, stores in its inner memory the pattern of the hits and gives the start to the timer which provides a 55 ns long integration gate for the ADCs, whose inputs are fed by the outputs of the fan-out modules.

In order to avoid the generation of the gate while the data acquisition cycle is not yet completed, the MDO (majority discriminated output) reversed signal is used to veto the Dual Timer. When the majority unit has stored the pattern of the hits into the ram the computer reads the inner memory; hence the data transfer is accomplished only for the ADC channels in coincidence with the laser. Each fan-out feeds also a CAMAC constant fraction set at a threshold of 0.2 pe. The outputs of these discriminators are connected to the inputs of the TDCs used to perform the time measurements. The common start to these devices is provided by the laser trigger output, properly delayed ($\sim 200$ ns) and shaped at 30 ns.

A clear signal of a TDC is necessary, too. This is due to the difference between the rate (100 kHz) of the start signals, driven directly by the laser TRIGGER OUTPUT, and that of the stop signals. It must be reminded that to achieve single photon illumination condition the direct light from the laser had to be attenuated, thus producing only few photons randomly impinging upon the photocathodes at a rate much lower than the original laser rate. Hence the situation more frequently occurring is that of a start not followed by a stop command, causing an overflow of the TDC and a disabilitation of the block. To solve this problem the start signal is splitted, delayed of 600 ns, shaped by a dual timer and then used to clear the module, if a stop signal is not detected. In fact a VETO signal inhibits the dual timer providing the CLEAR when the majority unit detects a coincidence condition.

The data acquisition cycle is very simple. After detection of the LAM from the majority, the host computer reads the inner memory of this unit, waits the LAM from TDCs, reads their digitized data, then waits the LAM from ADCs, reads their data and finally clears all the blocks.
...large cathode area PMTs...
4. Summary of the characteristics of the 56 phototubes

The histogram in fig. 2 represents the distribution of the dark count rate for the whole sample of the 56 devices. These data were obtained with a threshold of 0.2 pe (photoelectrons), after a suitable period of darkening (at least one day) at ambient temperature (~20°C). It can be noted that the most probable rate ranges from 1.2 to 2.2 kHz; however some devices were characterized by higher rate, up to a maximum of 18 kHz.

In fig. 3 the distribution of the peak-to-valley ratio of the dark noise spectra of the PMTs is plotted. An example of such a spectrum of one of the PMTs is illustrated in fig. 4. On the X axis the digitized values from the ADC are reported; the electronics chain was calibrated such that channel 320 corresponds to the charge associated to \(10^7\) electrons. It is worth to observe that almost all the tubes feature a clearly evident single electron peak in the dark spectrum. There were only four tubes characterized by a peak-to-valley ratio equal to 1 (i.e., without a peak).

On the other hand the distribution of the peak-to-valley ratio relative to the spectra recorded while exciting the devices with the laser is reported in fig. 5. From these data it can be asumed that in general the light excited single photoelectron distribution has a more pronounced peak, as indicated by the higher peak-to-valley ratio, whose most probable value is 3; furthermore also the tubes without a peak in the dark spectrum showed a peak in the latter case. As an example in fig. 6 the light induced spectrum \((P/V = 2.2)\) of the same tube whose dark spectrum is shown in fig. 4 \((P/V = 1.6)\) is reported.

![Diagram](image_url)
It can be noted that the experimental curve features, on the right side, a non-Gaussian tail and a satellite peak: the ratio of the excess area in this portion of the curve to the area of the fitted Gaussian (2.6% for the curve in fig. 8) is an indication of the deviation with respect to the ideal Gaussian profile. The result of this evaluation for the 56 devices is reported in fig. 9, from which it emerges a most probable value of 3%, indicating the inherent regularity of the transit time of the tube.
Finally in fig. 10 the maximum variation of the data obtained from the photocathode scanning are reported. The results for one device are shown in figs. 11 and 12, respectively for two diameters across (x axis) and along (y axis) the dynodes (see also the axis definition in fig. 15). The angle in abscissa in the two figures is measured with respect to the centre of curvature of the cathode. It can be noted that there is a large variability of the results from tube to tube: some samples were very uniform while others were largely nonuniform.

5. Effect of static magnetic fields on the performances of the device

It is well known that the magnetic field can affect dramatically the PMT performances. First, it causes a deviation of the trajectories of the photoelectrons during the flight from the photocathode to the first dynode, resulting in a fraction of photoelectrons failing to hit successfully the first dynode, and hence in a decrease of the absolute detection efficiency of the device. Second, it affects also the trajectories of the secondary electrons in the dynode chain, originating a loss in the multiplication gain and a degradation of both the amplitude resolution and the timing properties of the output pulse.

A determination of these effects was already performed on the first prototypes of the device measured during the selection phase [2]; a systematic analysis was repeated on one of the 56 devices of this first production batch. This test was carried out locating the device in the center of the Helmholtz coils (without any shielding), and varying the current in the coils to create a field of known intensity and direction. The applied fields were measured through a Hall probe; in particular when tuning the currents to zero the Earth's field (∼400 mG), the residual field resulted below 5 mG.

In order to perform a thorough check of the behaviour of the tube for different directions of the applied field, the mechanic assembly of the test equipment was such to allow the generation of fields parallel to the three main axes of the device. The Thorn Emi 9351 is equipped with a linear focused dynode chain; the three main axes in this case are defined as shown in fig. 15: the x axis is across the dynodes, the y axis is along the dynodes and the z axis is the symmetry axis of the PMT.

While increasing the transit time of the peak-to-valley ratio obtained are reported.

These data show that the field parallel to the z axis is significantly affecting the performance when the field is parallel to the tube axis, while the effect is negligible for the x and y axes.

6. Effect of μ-metric fields on the static magnetic field

A common problem with the static magnetic field is
probe; in particular, we want to check the Earth's field values, which are below 5 mG.

The results obtained are reported respectively in figs. 13 and 14.

These data show that for fields greater than 100 mG and parallel to the y axis, the measured quantities are significantly affected. On the other hand, the dependence is less pronounced for the x axis and practically negligible for the z axis.

6. Effect of \( \mu \)-metal shields of different lengths

A common procedure to compensate the effect of the static magnetic field is to enclose the photomultiplier with a \( \mu \)-metal shield. The shielding efficiency depends upon the ratio between the internal and external radius of the \( \mu \)-metal cylinder and upon the length of the shield protruding above the cathode surface.

In order to deduce experimentally the actual length of the shield needed to achieve a sufficient degree of compensation, we enclosed the PMT with shields of different lengths.

In particular, we adopted three shields of the same diameter (24 cm) and thickness (0.5 mm), differing only in the length, equal respectively to 35, 20.5, and 18 cm.
The dimensions of the first, already described in section 1, were chosen in such a way to be sure of its shielding effectiveness. Indeed when a tube, with this shield around, was located inside the Helmholtz coils, no impacts on its characteristics were detected for fields up to 600 mG.

However mechanical consideration for the assembly of the devices in the CTF forced us to consider shields of reduced length. The two additional shields evaluated, as shown in fig. 15, have one end corresponding to the middle of the neck of the device, while the other end of the longer shield is prolonged 2.5 cm from the top of the cathode and that of the shorter one is coincident with the top of the cathode itself. The very interesting result obtained testing these two shields is that they are both effective to compensate the field effect on the PMTs. In addition; as shown in fig. 18, the two additional shields slightly improve the performance of the PMTs as compared to the single one reported in figs 13 and 14.
Fig. 17. Compensation of the transit time broadening obtained with the shortest \( \mu \)-metal shield for field applied along the \( x \) axis.

Fig. 18. Compensation of the transit time broadening obtained with the shortest \( \mu \)-metal shield for field applied along the \( y \) axis.

Fig. 19. Along the \( z \) axis, due to the limited magnetic field influence, there is no difference between the situations with and without the shield.

7. Conclusion

The results of the measurement of the first batch of phototubes EMI 9351 confirmed the data already obtained in the testing of the prototypes of this device. Hence the excellent timing properties and pulse height resolution in the single photoelectron regime were largely confirmed. Furthermore, the interesting result obtained testing the effectiveness of magnetic shields of different lengths must be outlined. It was demonstrated that for this tube a shield extending up to the photocathode surface is enough to suppress the impact of the Earth’s magnetic field on the performances of the device.

Acknowledgement

The authors would like to thank G. Bacchiocchi, A. Brigatti, R. Cavaletti and S. Grabar for preparing the mechanical assemblies used to install the experimental setup and for their continuous assistance during the measurements.
A setup for an experiment

D. Nath, B. Lenzen
Department of Physics
Received 20 July 1993

A new experiment for studying the complex character of the electromagnetic shower in a large area pulse detector, named the Gran Sasso experiment, is described in this paper.

1. Introduction

The distribution of the number of charged particles in the EAS core, the energy (E_p) at the nuclear interaction, the composition of the EAS, and the properties of the proton and muon fluxes can be studied with the experiment described in this paper. The mean and distribution of the arrival time of particles on the detector, as well as the number of particles in the shower, can be used to study the EAS. The structure of the EAS is determined by the number of particles in the shower and the number of particles in the arrival time distribution. The structure of the EAS is presented in detail in this paper.

2. Experimental

The setup consists of an 8-inch plastic scintillation counter with a loam filter (XP2050) and a PMT (XP2050B) as a single-channel detector (CD). The CD is connected to one PMT (XP2050B) in a photon-pulse detector (PPD) with a band pass filter. The setup is installed in a University air shower array at an altitude of 1450 m (91°45' E, altitude 1200 m). The counter array is an 8-channel array.

The experiment was performed with an individual channel gain setting.