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Performance of photomultiplier tubes for cryogenic applications

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ABSTRACT

The use of noble liquid detectors draws a great interest in particle physics research, especially for direct searches of Dark Matter. This kind of experiments requires to go to several tons of noble liquid in order to explore deeper regions of the parameter space. The signal produced in large tons of liquid is usually read out by photomultipliers.

In this paper we report on results of tests performed on 2 in. and 3 in. photomultiplier tubes developed by Electron Tubes Ltd. for operation at cryogenic temperatures in the WArP experiment. The measurements have been performed at the Photomultipliers Test Facility set-up in Naples laboratory. The Photomultipliers Test Facility cryogenic equipment uses fused silica fibers driven LED/LASER generated light in the 400 nm region.

The photomultipliers have been tested in liquid nitrogen (77 K). The behaviour of photomultipliers at cryogenic temperature has been studied on more than 350 samples. All the photomultipliers show typical gain behaviour when immersed in liquid nitrogen. Generally, this gain exponentially decreases to asymptotic values, some 20–30% lower. Charge resolution and signal-to-noise ratio show a long-term stability in cryogenic environment.

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0. Introduction

Particle interaction in noble gas liquids produces light due to the excitation of the lower singlet and triplet molecular states [1] and ionization of the atoms. The detection of both ionization and scintillation permits to reach a clear identification of the interacting particle. This makes this kind of detectors a proper tool for particle and astroparticle physics, in particular for Dark Matter searches. In this kind of experiments photomultiplier (PMT) tubes are usually used for light detection and are often directly immersed in the liquid. For this reason the photomultipliers operation at cryogenic temperatures is a crucial point.

Even though the main PMT characteristics (like gain, dark current, etc.) are provided by the manufacturer for each PMT, the companies do not provide calibrations at cryogenic temperatures immersing the PMT directly in the liquid as it will be in the experiment.

In order to examine the PMT's main features and operating performance at cryogenic temperatures the full sample of PMTs (more than 300) to be monitored in the WIMP Argon Programme (WArP) detector [2] has been tested in liquid nitrogen.

In this paper, we first discuss the experimental condition and the requests imposed on the characteristics of the PMT, then the experimental set-up and the measurements carried out.

1. The WArP experiment

The WIMP Argon Programme is an experiment for Dark Matter search in form of Weakly Interacting Massive Particles (WIMP) at LNGS (National Laboratory of Gran Sasso) in Italy. These particles are expected to weakly interact with nuclei of ordinary matter. The direct WIMP detection is based on the identification of nuclear recoils from elastic WIMP-nucleus scattering.

The detection principle is based on the peculiar features of the interaction of WIMPs with the atoms of liquefied noble gases. The ArgonWIMP-nucleus elastic scattering in liquid argon produces two scintillation signals (128 nm), the first one prompt in the liquid and the second one due to the electrons surviving recombination extracted into a gas phase and then accelerated.

The detector is made of two parts: an inner bi-phasic (liquid-gas) Time Projection Chamber and an outer veto detector filled with liquid argon. A scheme of the inner detector is shown in Fig. 1.

The light produced in liquid argon is a broad structureless band centered at 128 nm with a width of 10 nm. Common glass windows do not allow the passage of this short wavelength, so a wavelength shifter is usually used. In the WArP experiment the Tetraphenylbutadiene (TPB) is used to convert the light at

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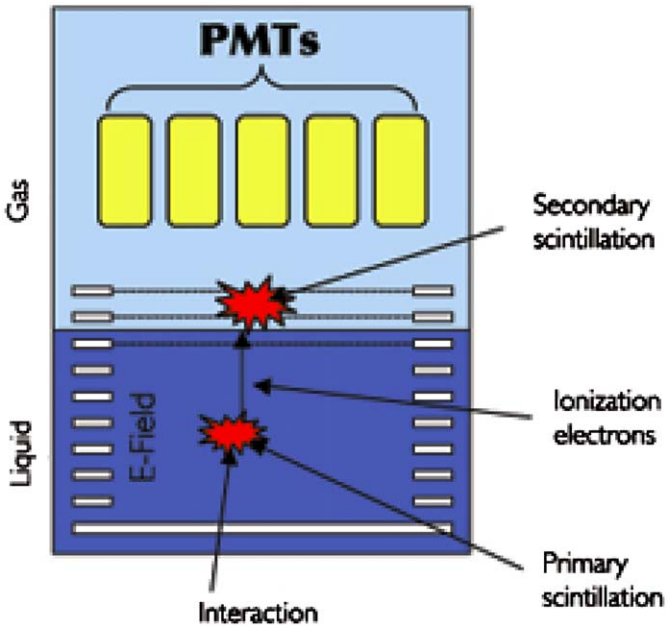

Fig. 1. Scheme of the inner detector.

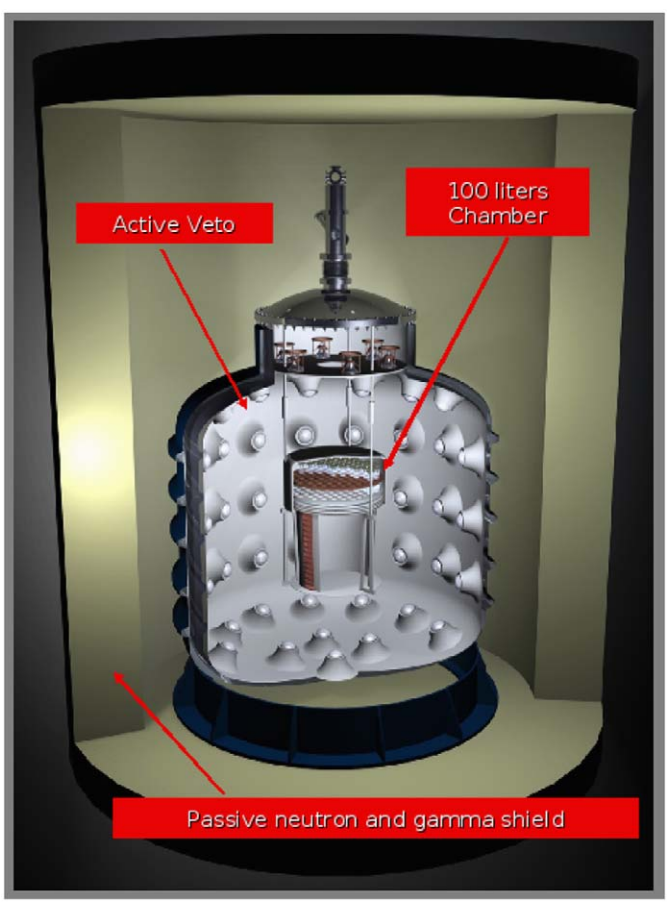

Fig. 2. Pictorial view of the WArP detector.

wavelengths around 420 nm. The TPB is deposited on the PMT's windows and detector's walls.

The detector will contain about 40 PMTs placed in the gas pocket and about 300 PMTs immersed directly in liquid argon (87 K).

At the moment the WArP detector is in construction at LNGS in Italy, a pictorial view of the detector is reported in Fig. 2.

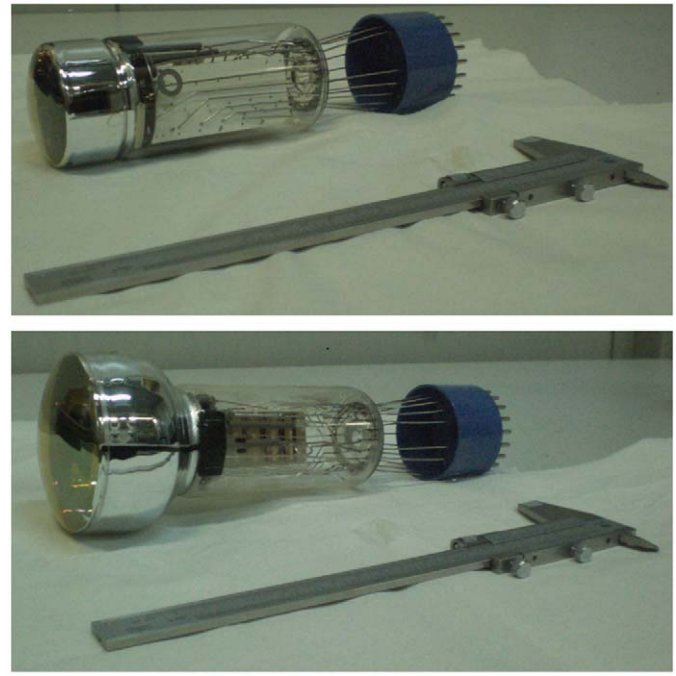

Fig. 3. Picture of the 2 in. D757UFLA (top figure) and 3 in. D750UFLA (bottom figure) photomultiplier tubes tested.

Photocathode	Bialkali with Pt and MnO underlayers
Typical quantum efficiency at 400 nm	19% (min 16%)
Diameter	2" and 3"
Active diameter	46 mm (2" PMTs) ; 68 mm (3" PMTs)
Number of dynodes	12 LF Cs Sb
Nominal gain (*)	5×10^6
First dynode gain	≈ 10
Single Electron Peak width (FWHM)	≈ 25%
Typical operating voltage	±1100 ÷ ±1600 V
Dark counts (at room temperature)	≈ 1000 cps
Max cathode current (at room temperature)	500 nA
Max anode current (at room temperature)	100 μA
Single electron rise time	2.5 ns

Fig. 4. PMT's specifications.

2. PMT characteristics

The PMTs to be used in the WArP detector have been developed according to the particular requirements imposed by the experimental conditions; we tested 2 in. (D757UFLA) and 3 in. (D750UFLA) photomultiplier tubes developed by Electron Tubes Ltd. (shown in Fig. 3). All the PMTs are based on a 12 stage linear focussed multiplier and bialkali photocathodes (K–Cs–Sb+Pt cathode).

PMTs with bialkali photocathodes are known to exhibit variations of the spectral sensitivity and loss of linearity of the response at low temperatures. For this reason, the tubes under test have been provided with an evaporated platinum layer under the photocathode [3].

In view of the strict radiopurity requirements imposed to WArP detector materials, PMT body and windows are made of glass with low radioactive contamination ~220 mBq/PMT. The typical quantum efficiency request at 400 nm at cryogenic temperature is around 20%. The main PMT's specifications are summarized in Fig. 4.

3. PMT Test Facility

The measurements have been performed at the PMT Test Facility (PTF) set-up in Naples laboratory. The PMTs have been

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tested in liquid nitrogen (77 K). A scheme of the equipment is shown in Fig. 5.

The PTF is equipped with a cryogenic system, a cylindrical dewar, 60 cm in diameter and 1.2 m in height which can host up to 18 tubes. A cage, made of stainless steel and polycarbonate, which hosts the PMTs, is hooked to the stainless steel flange. The flange is equipped with several feed-throughs for the HV cables, the PMT output signal cables and the controlled illumination device fiber. Liquid nitrogen arrives from external 3000 l dewar via vacuum-isolated cryogenic adduction line, that provides the necessary amount of nitrogen for long-term stability runs.

The hardware, layout consists of an hybrid system that is injecting short 460 nm light pulses into light fibers and ultimately to the front of each PMT in the dewar. The optical system is equipped with an attenuator in order to produce signals from a few to several hundreds photoelectrons. The PMT signals are

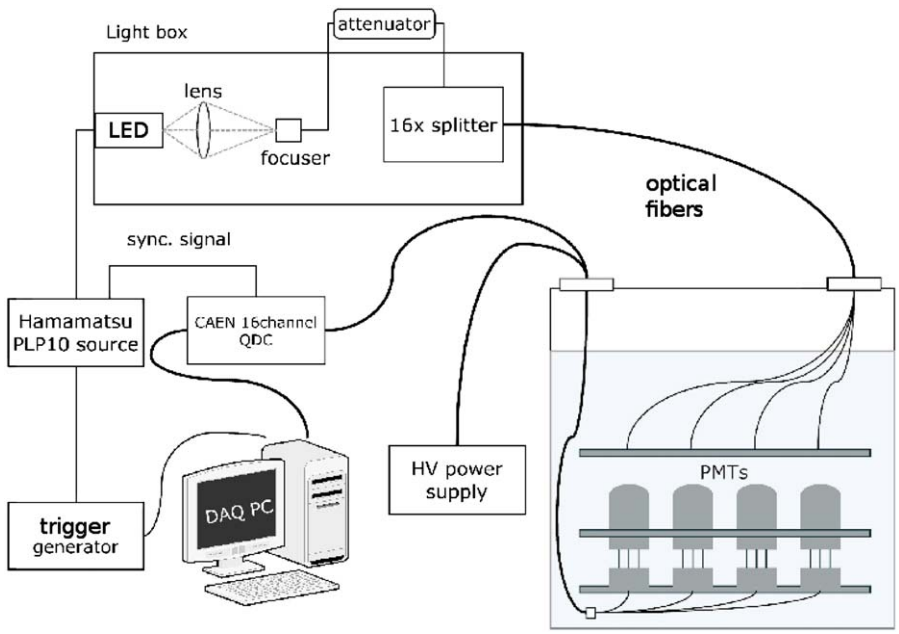

Fig. 5. Scheme of the experimental set-up.

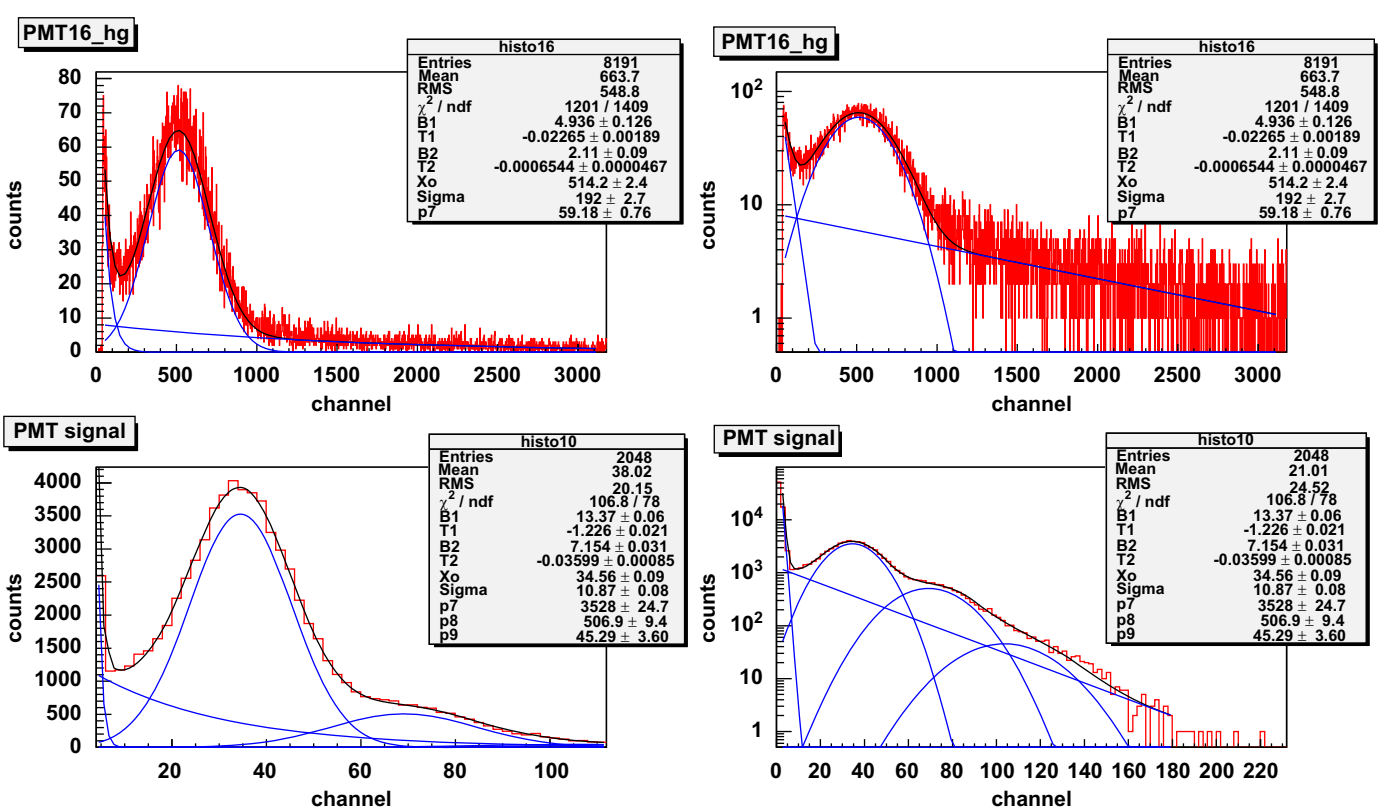

Fig. 6. Example of dark spectrum (top plots) and stimulated spectrum for PMT at cryogenic temperature in linear and logarithmic scales.

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directly fed into a 16 channels Charge-to-Digital converter (QDC) CAEN V965. The QDC operates by integrating the charge received in a time window defined by a GATE signal and common to all 16 channels. The QDC is read out by the DAQ computer via a VME-PCI Optical Link bridge. The same computer also drivers a waveform generator used to trigger the light pulser and to produce the GATE signal for the QDC.

4. Measurements

During the complete period of test more than 350 PMTs have been tested. For each PMT the acquired spectra were fitted in order to get basic PMT characteristics (gain, charge resolution, signal/noise, dark rate) and to control their behaviour with time. The PMT spectra were fitted automatically, with the possibility of manually controlling the fit quality. The typical stimulated response and dark spectra, acquired during the tests are shown in Fig. 6. The spectra were fitted with the superposition of one (for dark spectrum) or more Gaussians and two negative exponentials, describing electronic noise and interdynodic emission signals:

$$F(x) = e^{B_1+T_1x} + e^{B_2+T_2x} + \sum_n p_n \exp(-(x-nx_0)^2/2n\sigma^2).$$

In the function it is assumed, that if x_0 and σ are, respectively, the mean value and the standard deviation of the response to single photoelectron, then mean value and the standard deviation of the response to n photoelectrons satisfy the

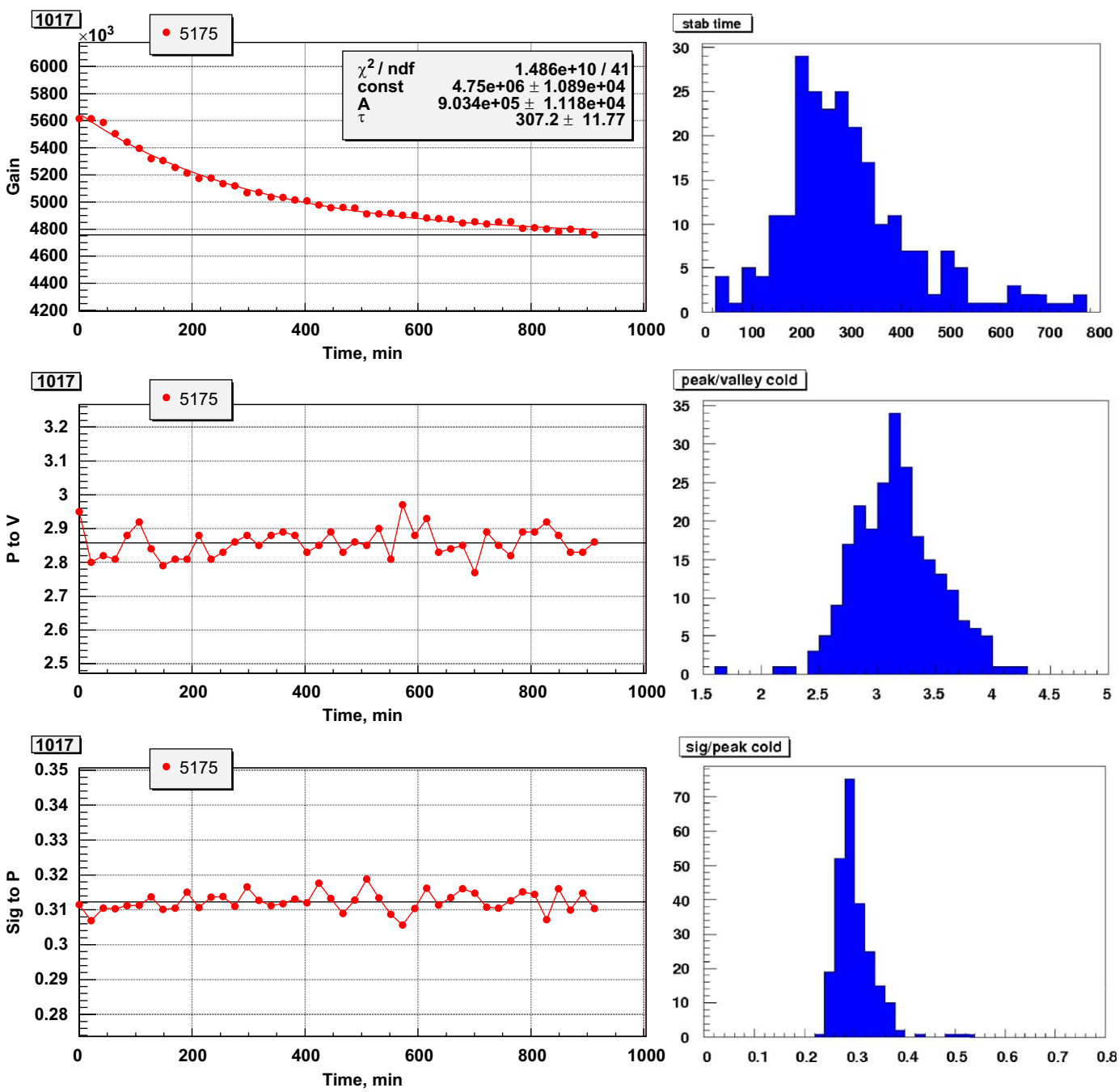

Fig. 7. Typical behaviour of gain, peak over valley and charge resolution with time at cryogenic temperature for one PMT (left plots) and respective resulting distribution of characteristic stabilization time τ, peak over valley and charge resolution for PMTs (right plots).

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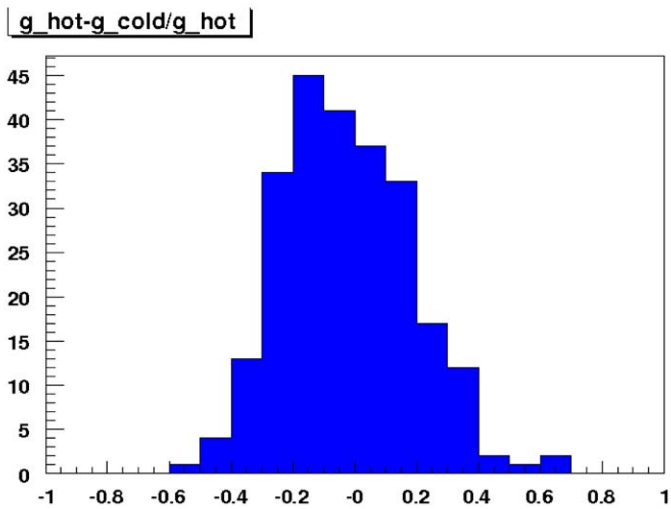

Fig. 8. Distribution of the proportional variation of gain at cryogenic and room temperature.

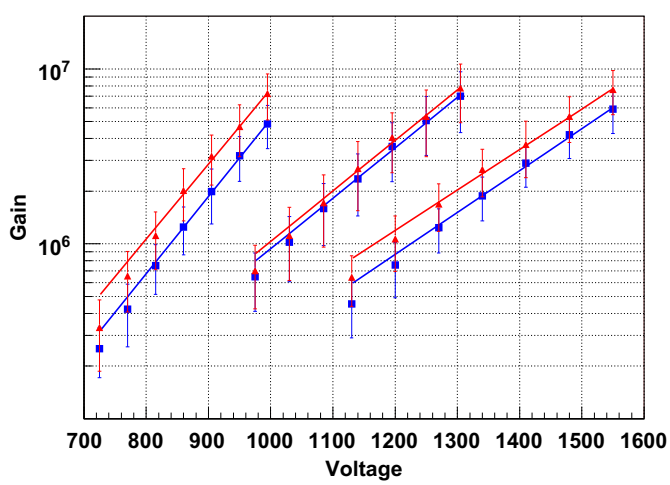

Fig. 9. Gain vs anode voltage for a sample of three PMTs at room (triangles) and cryogenic (squares) temperatures.

following relations: $x_n = nx_0$, $\sigma_n = \sigma\sqrt{n}$, that are valid in case of linear response. Assuming Poisson distribution for emitted photoelectrons, it is easy to estimate the average number of photoelectrons per trigger, μ, using the relation $P_n = P_{n-1}\mu/n$. For the spectrum displayed in Fig. 6, a value $\mu = 0.29$ is inferred from the ratio $P(2)/P(1)$.

When the PMTs are immersed in liquid nitrogen the rate and the gain values suffer an increase due to the lower temperature, therefore the PMTs are kept for a few hours at cold and dark. After this settling period the SER (Single Electron Response) is monitored for several hours. The recorded spectra are then fitted with the previous function and the main fit values extracted.

The observed behaviour shows an exponential decrease of gain (usually by 20–30%) at cryogenic temperature with characteristic time around $\tau \approx 4-5$ h. For this reason the cold runs were performed over night to provide $3-4\tau$ run duration time and to allow for the PMTs to stabilize. Except gain, all other PMT characteristics show a stable behaviour (see Fig. 7 left panel). The gain is obtained from the position of the single photoelectron peak. The peak over valley ratio in the same distribution is related to the signal-to-noise ratio and is stable during the run as well as the charge resolution, given by the SER distribution sigma to x_0 ratio.

The dependence of gain on time at cryogenic temperature was fitted with an exponential function. The resulting distributions of stabilization time τ, peak over valley and charge resolution for PMTs are given in the right panel of Fig. 7, the mean value of stabilization time constant is around ≈ 290 min.

Since the PMTs show an exponential decrease of gain at cold the distribution of the proportional variation of gain at cryogenic and room temperature is shown in Fig. 8, the asymptotic value at low temperature is around the nominal one.

The gain dependence on the anode voltage for a sample of three PMTs with different operating voltages was measured at liquid nitrogen and a room temperature (Fig. 9). The same characteristic behaviour is observed at cryogenic and room temperature.

5. Conclusion

High statistics tests of specially manufactured PMTs have been carried out in cryogenic environment for the first time. The photomultipliers have been immersed in liquid nitrogen at the temperature of 77 K and kept in these conditions for several days. In the long runs more than 350 samples manufactured by Electron Tubes Ltd. with a special photocathode equipped with a Pt under-layer have shown stable characteristics in terms of gain, charge resolution and signal-to-noise ratio. These PMTs have been selected for use in the LAr 8 ton VETO detector of the WArP experiment for Dark Matter search.

Acknowledgement

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