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Test and Comparison of Photomultiplier Tubes at Liquid Argon Temperature

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Abstract

The most recent development in the field of photomultipliers operating at liquid Argon temperature is the Hamamatsu R11065 with peak QE up to about 35% A set of these photomultipliers has been extensively tested within the R&D program of the WArP Collaboration. During these tests the Hamamatsu PMTs showed extremely good performance and a light yield around 7 *phel*/keV$_{ee}$ has been achieved in a Liquid Argon detector with a photocathodic coverage of 12%. This shows that this new type of PMT is suited for experimental applications, in particular for new direct Dark Matter searches with LAr-based experiments.

Keywords: Noble-liquid detectors, liquid Argon Dark Matter, light yield

1. Introduction

   Hamamatsu Photonics recently developed and commercialized a new generation of photomultiplier tubes for cryogenic applications with an extremely high Quantum Efficiency at liquid Argon temperature

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(*Mod. R11065*). Dark matter experiments using liquid Argon as target can undoubtedly profit of this new device, increasing detector sensitivity especially at very low nuclear recoil energy. Within the on-going R&D activity of the WArP Collaboration a first set of R11065 PMTs has been subject to a series of tests including a comparison with a former generation of cryogenic PMT, produced by Electron Tubes Limited - Mod. ETL D750 (currently used in the WArP -100 detector).

The Hamamatsu R11065 [1] is a Box&Linear-focused 12-stages PMT, with Synthetic Silica 3" window (opaque to wavelenghts below 160 nm) and special Bialkali photo-cathode developed to efficiently operate down to LAr temperature in the spectral range from UV to VIS. Its prime features include fast time response, good time resolution and pulse linearity. However, the most noteworthy parameter of this model is its excellent Quantum Efficiency (QE). Hamamatsu declares it at around 35% peak value at 400 nm at room temperature, and guarantees it to be to be stable at LAr temperature.

2. Single PMT test

A single 3" PMT was mounted face-down on the top side of a PTFE cylinder (internal dimensions h=9.0 cm and ϕ=8.4 cm) containing 0.5 lt of liquid Argon. Since scintillation light of liquid Argon is in the VUV region of the electromagnetic spectrum (128 nm), the internal surfaces of the detectors (side and bottom end) were completely surrounded with a highly reflecting layer coated by a thin film[4] (about 300 μg/cm^2) of a very efficient wavelength shifter, *Tetraphenyl-Butadiene* (TPB) [2]. The reflector layer (3M-VIKUITI ESR) was a polymeric, totally dielectric, multi-layer plastic mirror with very high specular reflectivity (99%) in the visible.

The PTFE cell was housed in a stainless steel cylindrical vessel with internal volume of about 5 lt and contained, after filling, a total amount of at least 3.5 lt of LAr in order to have the PMT and its base fully immersed. After vacuum pumping (at about 10^{-5} mbar) the cylinder was filled with 6.0 Ar passed through an in-line set of filtering cartridges (Oxygen reactant and molecular sieve, Oxisorb and Zeolite). The DAQ system was structured with the PMT anode current output directly transmitted to a fast *Waveform Recorder* (Acqiris, DP235 Dual-Channel PCI Digitizer Card, up to 1 GS/s, 8 bit dynamic range). At each trigger the signal waveform is recorded with sampling time of 1 ns over a full record length of 15 μs.

The liquid Argon cell was exposed to a few γ sources and for each run (duration ~ one hour) single photo-electron (SER) pulses have been selected from out-of-trigger parts of the recorded waveforms in order to obtain photo-electron data needed for calibration. The area under the selected peak (in *ADC·ns* units, proportional to the SER charge) is evaluated by integration of the single photo-electron pulse after local baseline subtraction. A typical SER spectrum is reported in fig.1, [Left]. The position of the first Gaussian peak in the spectrum represents the gain of the PMT at actual bias voltage (and gives the calibration constant per single photo-electron). The gain dependence on the High Voltage applied to the PMT has been measured by changing the HV setting and measuring the corresponding position of the SER peak in the charge spectrum. The result is shown In fig.1, [Right]. The nominal gain $G = 5 \times 10^6$ (Hamamatsu data sheet) is achieved at a voltage supply of +1500 V. The Peak-to-Valley ratio in the SER spectrum and the resolution of the single electron peak as a function of the gain have been measured (fig. 2 [Left] and fig.2 [Right] respectively). At the nominal gain of 5×10^6 the maximum value of $P/V \simeq 3.7$ is reached and the resolution is found to be $R \simeq 28\%$. During the subsequent period of tests of the Hamamatsu tube a gain setting lower ($G = 3.1 \times 10^6$) than the nominal gain has been adopted (HV=+1400 V). Stability of the gain via the SER peak value has been monitored through the test period (about three days of data acquisition). The SER peak showed an almost stable behavior in time with a slightly decreasing exponential trend ($\tau \simeq 35$ h).

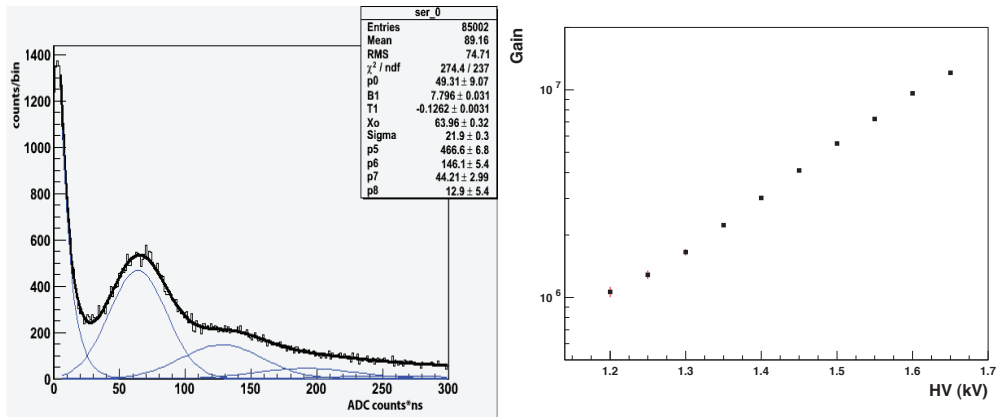[4]obtained by deposition with vacuum evaporation technique

Fig. 1. *[Left]Hamamatsu R11065 PMT SER spectrum. The fit superimposed is obtained by the sum of an exponentially falling function (dark count distribution) and three Gaussian functions for the single photo-electron (first peak; fit parameters $\mu = X_0$ and σ=Sigma) and multiple photo-electron distributions. [Right] Hamamatsu R11065 PMT test: Gain dependence on HV (measurement at LAr temperature).*

The LY measurement was performed by exposing the LAr cell viewed by the Hamamatsu PMT to a [241]Am monochromatic γ-source with emmision at 59.54 keV to obtain a reference energy deposit in LAr. Data acquisition runs with the source have been alternated with blank runs (background from ambient radiation).

By waveform integration, after local baseline evaluation and subtraction, the event signal amplitude $S1$ was obtained in ADC. It was normalized with the values obtained by fitting the SER spectra for each run giving its value in *phel* units. The pulse amplitude is proportional to the electron energy deposited in the LAr cell.

Standard cuts have been applied to remove low energy events ($E_{min} = 20$ *phel*), high energy ADC saturated events, pile-up and out of time events. Pulse amplitude spectra have been thus obtained for each source run. A [241]Am spectrum from one of the source runs collected is shown in Fig.3. As reported in the figure, the fit of the full absorption peak is found at 416 *phel*. Therefore, assuming full deposition of the 59.54 keV, the Light Yield of the detector can be evaluated as:

$$LY \;=\; 7.0\,\frac{phel}{\text{keV}} \;\pm\; 5\% \tag{1}$$

The stability in time of the LY has been monitored by applying the analysis to a large set of runs collected during the test period. All LY values lie within ±1.5% around a mean value of 6.9 *phel*/keV.

3. Direct Comparison of the R11065 with an ETL PMT

A second dedicated test has been envisaged (mid 2010) for a direct comparative test of two types of PMTs: one 3" HQE Hamamatsu R11065 (used in the single PMT test) and one 3" ETL - D750 (pre-production series of the PMT type [3] adopted in the WArP -100 experiment [4]).

The experimental set-up was very similar to the one used for the single PMT test. A PTFE cell with 0.4 lt internal volume (h=8.0 cm and ϕ=7.6 cm), lined with a TPB coated reflector layer on the lateral wall, hosted the two PMTs: the HQE Hamamatsu face down on top and the ETL face up at the bottom, both with
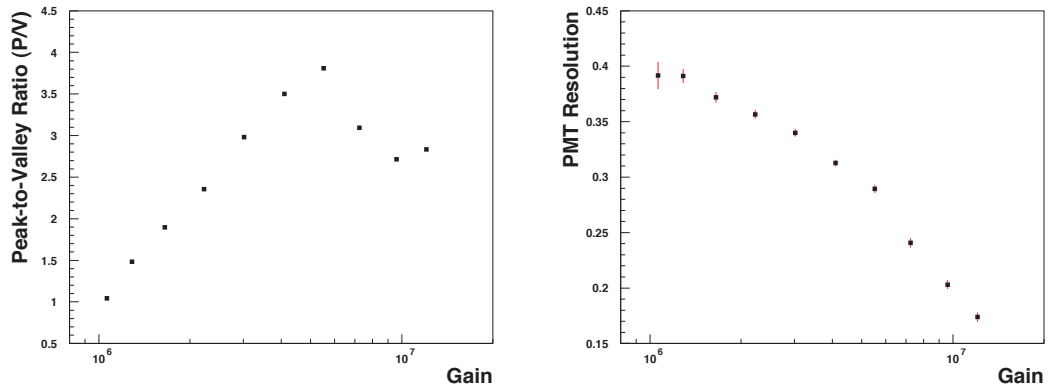
Fig. 2. *Hamamatsu R11065 PMT test: SER Peak-toValley ratio determined at different gain values [Left]. SER peak resolution at different gain values [Right]. (Measurements at LAr temperature).*
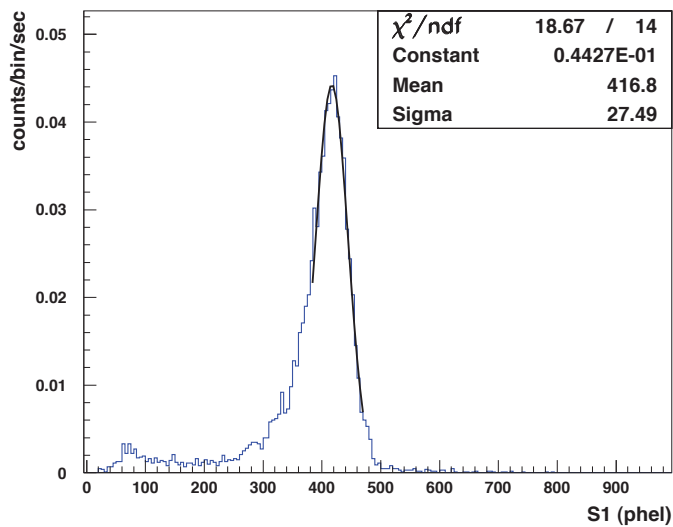

Fig. 3. *Hamamatsu R11065 PMT test:* ^{241}*Am source spectrum (blank spectrum subtracted). The relative energy resolution at the peak energy is* $\frac{\sigma_E}{E} \simeq 7\%$.

naked windows not covered in wavelength shifter. The read-out, data treatment and the off-line analysis codes were the same as in the single PMT test (Sec.2).
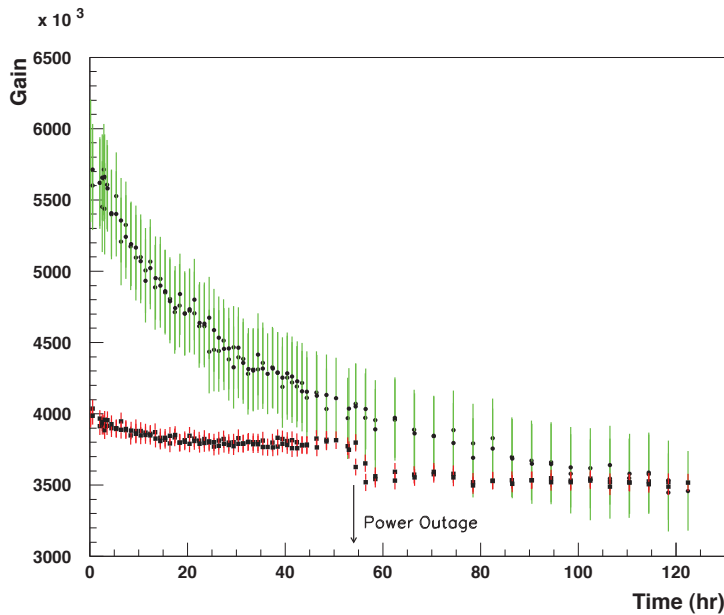

Fig. 4. *Hamamatsu vs ETL Test with the 0.5 lt LAr cell: gain variation in time (ETL PMT [dots with green error bar], Hamamatsu PMT [squares with red error bar]).*

After the LAr filling of the chamber one day was left for PMT thermalization. Subsequently, the Gain Stability in time has been monitored over about one week of run, fig.4. The gain of the ETL PMT showed a (quite steep) decreasing trend over the period of the measurements while the gain of the Hamamatsu PMT exhibited a slight decrease over the first day after activation and then stabilized to a constant value.[5] The cause of the much steeper gain loss and much longer stabilization time of the ETL tube is not yet clear and is under investigation.

Table 1. *Characteristic features of the Hamamatsu and ETL PMTs (Peak-to-Valley ratio and SER resolution) at fixed gain $G \simeq 3.7 \times 10^6$.*

	Peak-to-Valley ratio	SER resolution
Hamamatsu R11065	3.5	32 %
ETL D750 (pre-series)	1.9	50 %

A gain of 3.7×10^6 has been set for both PMTs for the subsequent set of source runs. At this gain value the characteristic features of the two PMTs (Peak-to-Valley ratio and SER resolution) are reported in tab.1 for comparison.

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[5]During the second day of operation an unexpected power outage occurred at the experimental site (WArP cryogenic facility - LNGS). The PMT HV power supplies were powered using an UPS but the effect of the power outage is visible on the R11065 PMT as a sudden drop of gain, which was slowly recovered over the following days of running.
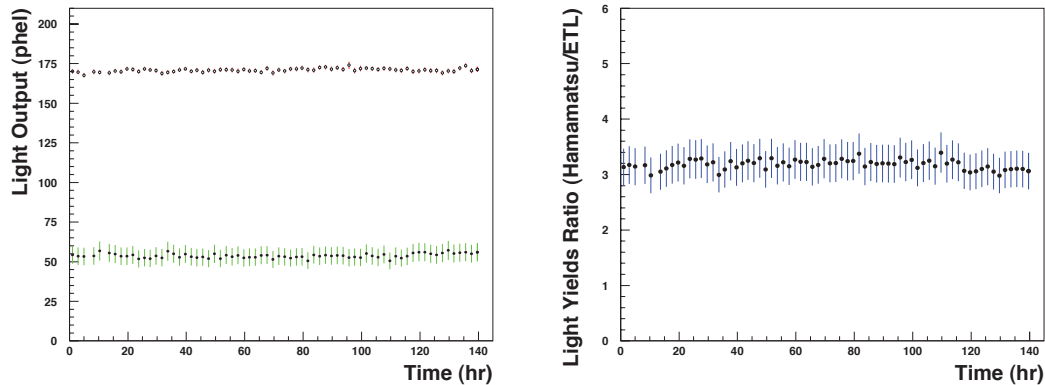
Fig. 5. *Hamamatsu vs ETL Test with the 0.5 lt LAr cell: [Left] Mean Light Output (in [phel] units) - Hamamatsu 3" PMT [dots], ETL 3" PMT [dots with green error bars, bottom]. [Right] Hamamatsu-to-ETL Light Yield ratio.*

The light yield of the two PMTs has been determined by exposure to the ^{241}Am gamma-source. In fig.5 [Left] the mean light output values for the recorded runs, over a two-week period of operation, is shown. These values were then normalized to the source energy to obtain the Light Yield for each PMT. The Hamamatsu-to-ETL LY response ratio was found to be in the **3 : 1 range** and was stable during the operation period.This was found to compatible with the measured ratio of the PMTs Quantum Efficiencies.[6]

4. Four-PMT test

A third experimental test has been thus performed to check if it is possible to repeat the obtained Light Yields in a detector about ten times bigger in volume compared to the one used with the first test reported above (sec.2). The PTFE mechanical structure of the detector was taken from the WArP -2.3 lt prototype developed for a former set of experimental measurements [5] (we refer to it for more details on the detector set-up). The chamber (4.3 lt of internal volume) was equipped with *four* R11065 HQE Hamamatsu PMTs.

The boundary surfaces (lateral and bottom) were prepared as in the previous tests, similarly, the PMT glass windows were left naked. The photo-cathodic surface was about 12% of the total boundary surface (~equivalent to the coverage of the *single PMT* test set-up). The 4 PMT anode signals were directly digitized by two Acqiris Boards (Mod. U 1080 A, 2-chs. each with 8-bit dynamic range and 1GS/s) at 1 ns sampling time over 15 μs time interval. This corresponds to the read-out chain currently implemented in the WArP -100 experiment. DAQ and off-line codes were the same as for the previous tests reported above.

The detector was mainly exposed to the ^{241}Am source. The four signal waveforms were individually recorded for scintillation events in which the pulse from three of the four PMTs was above a threshold corresponding to 1.5 *phel*.
During each source (or blank) run, single photo-electron pulses were selected in order to provide the SER data needed for calibration.
A lot of attention has been given to the quality of the TPB coating on the VIKUITI ESR reflector. Before inserting it into the detector, the wavelength-shifting efficiency of the TPB coated reflector sheets was measured using a dedicated setup. We installed sheets of the best quality and with the highest conversion efficiency.

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[6]This ratio has been directly measured in a facility at CERN.

An example of a Pulse Amplitude spectrum ($S1$ distribution) from the ^{241}Am source is shown in fig.6 (background subtracted), with the full absorption peak at 378 *phel* as determined by a gaussian fit of the spectrum. Therefore, the Light Yield of the detector can be evaluated as:

$$LY = 6.35 \frac{phel}{keV} \pm 5\%$$ (2)

The LY value determined with Compton spectra obtained from exposures to other sources at higher γ-energies (^{133}Ba, ^{57}Co and ^{137}Cs) was less precise, but in good agreement with the above LY value.

The LY was monitored over several time intervals during the test period and it resulted to be stable within
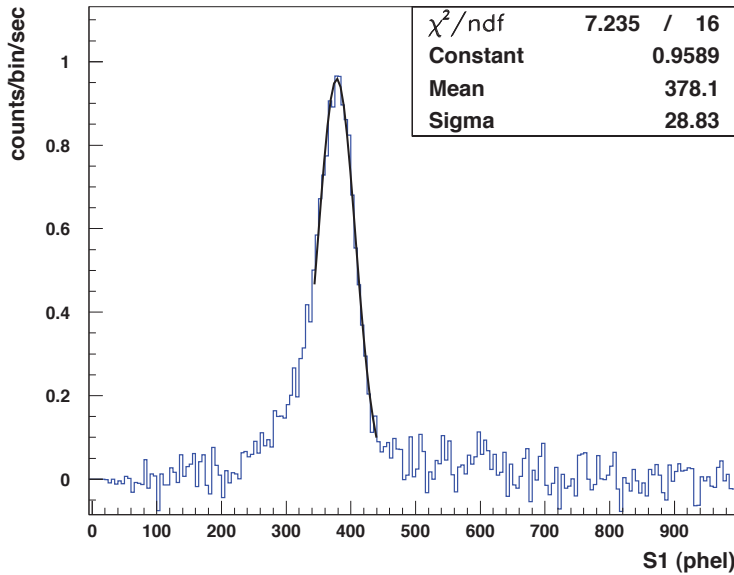

Fig. 6. *Four Hamamatsu PMTs test with the "WArP-2.3 prototype":* ^{241}*Am spectrum (background subtracted). Peak value and width determined by a gaussian fit (superimposed). The relative energy resolution at the peak energy is $\frac{\sigma_E}{E} \simeq 8\%$.*

2%.

The purity of the liquid Argon was inferred from the slope of the slow scintillation component of an average waveform calculated with a huge sample of individual waveforms (~ 10000). The measured value of 1130 ns, if compared to 1300 ns for asymptotically pure liquid Argon [6, 7], indicates that a residual concentration of impurities was still present in the liquid and a direct measurement with a mass spectrometer showed the presence of Nitrogen in the liquid at the level of 1ppm.[7] The reduction of the long-decay time constant (via quenching effect of the Ar_2^* excimers in triplet state) results in a ~10% loss of light [7] (and correspondingly in the LY value).

Therefore, the result with this 4.3 lt chamber (4 HQE Hamamatsu PMTs) agrees in good approximation with the result obtained with the 0.5 lt detector equipped with one HQE PMT (LY $\simeq$ 7 *phel*/keV) and characterized by an equivalent photo-cathodic coverage (~12% in both chambers). The difference in measured values can be attributed in full to a higher N_2 concentration in the second measurement.

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[7]Nitrogen impurities are not filtered out with the implemented set of filters (dedicated to O_2 and H_2O removal).

5. Conclusions

The new PMT developed by Hamamatsu Photonics, Mod. R11065, with a very high Quantum Efficiency (up to 35 %) at liquid Argon temperature has been extensively tested in the course of the R&D program of the WArP Collaboration.

The main working parameters of this PMT were measured at LAr temperature and its optimal performance has been demonstrated.

It has also been shown experimentally that Liquid Argon detectors with HQE photo-cathodic coverage of the order of 12% (and on a wide range of volumes - from ∼ 0.5 lt to ∼ 5 lt) can achieve a light yield around 7 *phel*/keV (at null electric field), sufficient for detection of events down to few keV of energy deposition in the liquid.

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