Demonstration and comparison of photomultiplier tubes operation at liquid Argon Temperature

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Introduction

- Direct Dark Matter search in the form of WIMPs requires to detect very low nuclear recoil energies (few KeV).
- Liquid Argon based detectors reveal the recoil detecting the scintillation light following energy deposition.
- Light red-out is mainly performed by means of photomultiplier tubes (PMTs).
- A new type of PMT has been recently developed by Hamamatsu Photonics (Mod. R11065) which pushes the Quantum Efficiency up to 35% at liquid Argon temperature (87^o K).
- Within the on-going R&D activity of the WArP Collaboration (WIMP Argon Program at LNGS, 2009-11), a first set of R11065 PMTs has been subject to a series of tests aiming at their characterization in reference working conditions
- We operated the PMTs immersed in the liquid and optically coupled to LAr cells of various size.
- A comparison of the R11065 Hamamatsu PMT with a former generation of cryogenic PMT produced by Electron Tubes Limited - Mod. ETL D750 (currently in use with the WArP -100 detector) has been also carried out.

New high QE Hamamatsu PMT

HAMAMATSU

TENTATIVE DATA SHEET
Sept. 2009

PHOTOMULTIPLIER TUBE

R11065

For Low Temperature Operation down to -186 deg. C
Special Bialkali Photocathode (Bialkali LT), Low Radioactivity
76 mm (3 Inch) Diameter, 12-stage, Head-on Type, Synthetic Silica

General

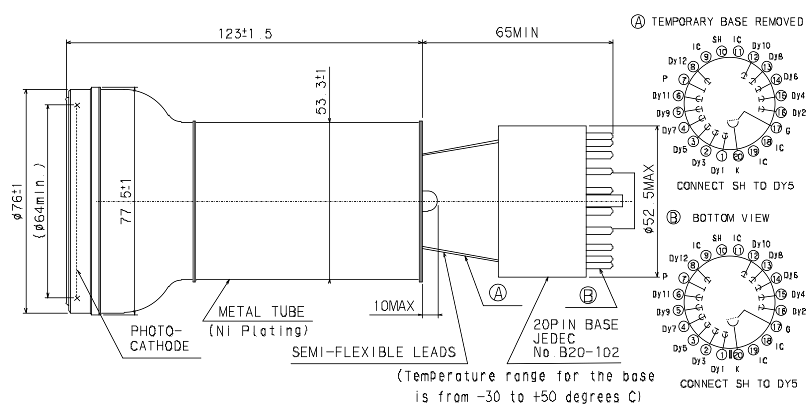
Parameter		Description / Value	Unit
Spectral response		160 to 650	nm
Wavelength of Maximum Response		420	nm
Window material		Synthetic silica	-
Photocathode	Material	Bialkali	-
	Minimum Effective Area	64	mm dia.
Dynode	Structure	Box & Linear-focused	-
	Number of Stages	12	-
Suitable Socket		E678-20A (supplied)	-
Operating Ambient Temperature		-186 to +50	deg. C
Storage Temperature		-186 to +50	deg. C

- Box&Linear-focused 12-stages PMT
- Synthetic Silica 3” window (cut-off around 160 nm)
- Working temperature down to -186˚ C
- QE ≥ 30% @ 420 nm
- Bialkali cathode without Pt underlayer
- High Collection Efficiency of photoelectrons at first dynode (above 95% with $\Delta V_{K\text{-}D1}$>300Volt)
- Voltage divider custom made on a G10 printed circuit (according to Hamamatsu specifications)

R11065 TEST DATA

January 12, 2010

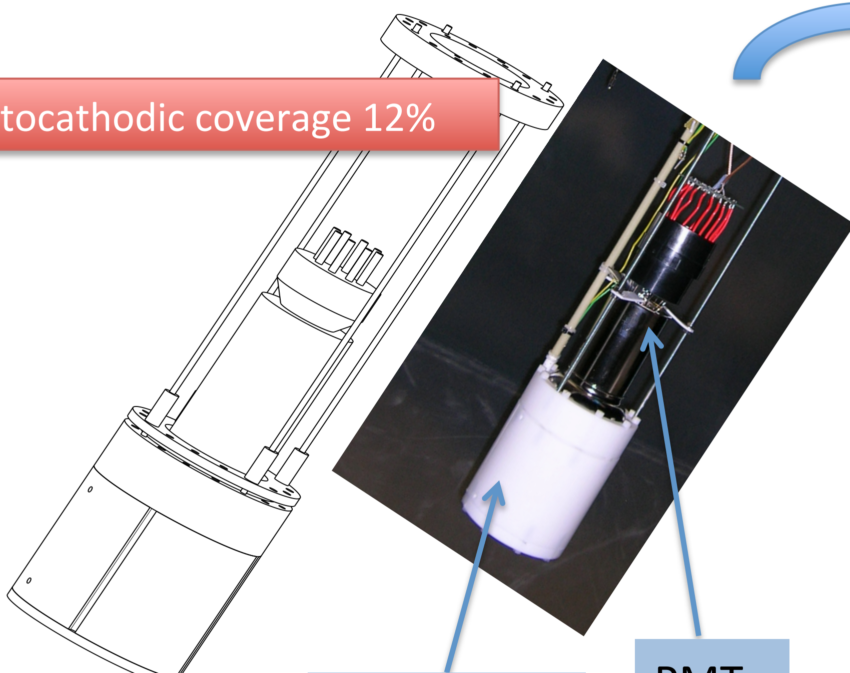
	SERIAL NUMBER	SK [uA/lm]	SKB	SP [A/lm] 1500 V	IDB [nA] 1500V	QE [%] 420 nm
1	ZK4998	124.0	14.70	783	44.0	33.8
2	ZK4999	157.0	15.00	1040	56.0	35.4
3	ZK5001	136.0	14.50	1100	27.0	34.6
4	ZK5002	138.0	14.00	1010	15.0	33.9
5	ZK5006	137.0	13.10	1050	12.0	31.0
6	ZK5172	163.0	14.60	1170	34.0	33.3
7	ZK5173	143.0	14.10	808	32.0	32.5
8	ZK5175	114.0	12.00	777	12.0	29.8
9	ZK5176	110.0	11.20	897	30.0	27.8



Single PMT test

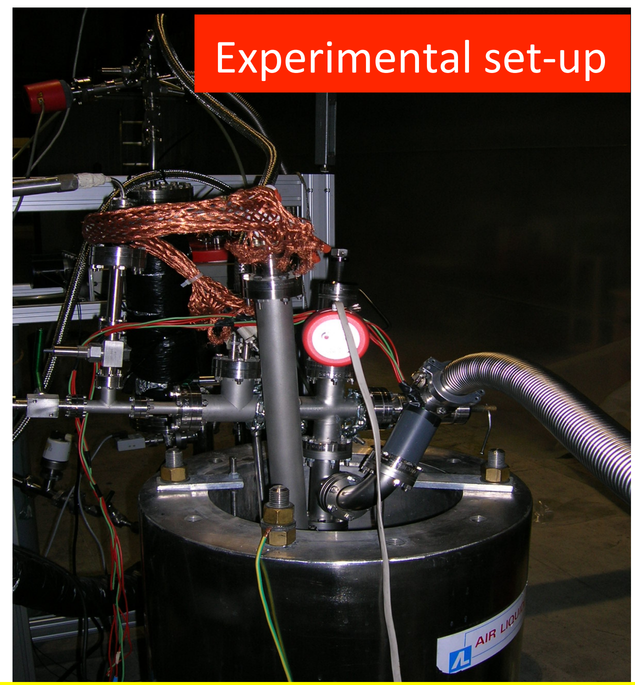
- PTFE cell containing 0.7kg of LAr (cylinder shaped h=9cm Φ=8.4cm) observed by one 3" R11065 PMT.
- Scintillation photons of LAr are in the VUV range (around 127 nm) and with two (main) different time constants ($\tau_S \simeq 5$ ns for the fast component and and $\tau_T \simeq 1.3$ μs for the slow component).
- Internal surfaces of the cell covered with reflective foils coated by a wavelength shifter -> TPB (peak emission 440 nm);
  - ✓ Multi-layer plastic mirror (3M-VIKUITI ESR) with high specular reflectivity in the visible (~ 99%) ✚ TPB film obtained by deposition with vacuum evaporation technique (about 300 μg/cm2);

Photocathodic coverage 12%



PTFE cell

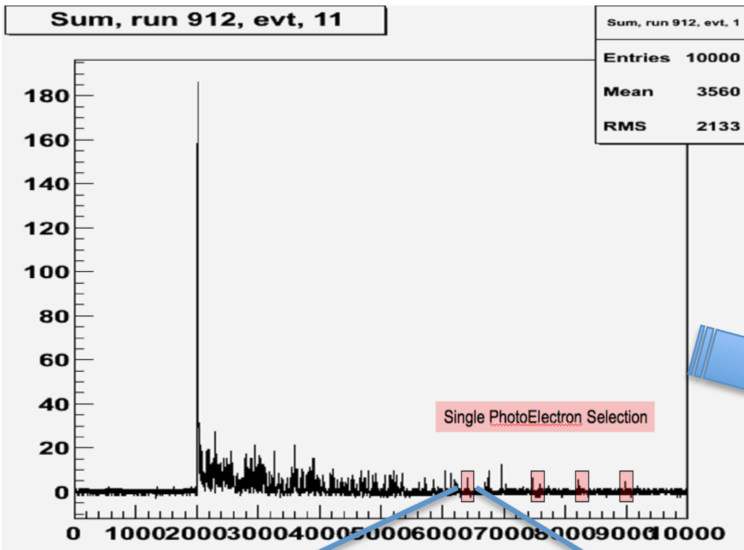
PMT

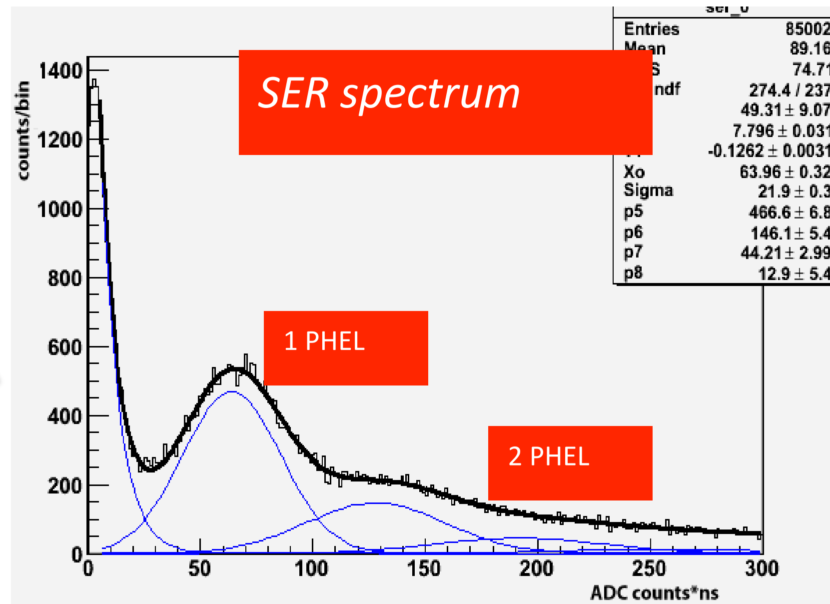


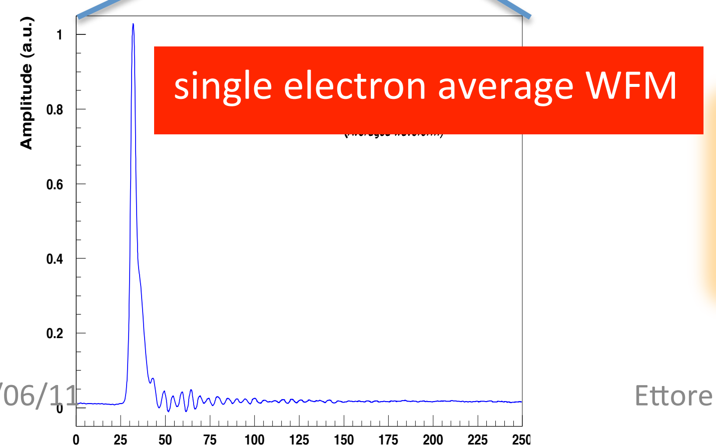
LAr filtered during filling (Oxisorb and Zeolite)

DAQ and calibration

- PMT anode current transmitted to a fast Waveform Recorder (Acqiris, DP235 Dual-Channel PCI Digitizer Card2, 1 GS/s, 8 bit dynamic range) => signal waveform recorded with 1 nsec sampling time over a full record length of 15 μs;
- Detector exposed to a ^{241}Am source with monochromatic γ-emission at 59.54 keV;
- For each source run a Single Photo-electron Response (SER) spectrum is computed.

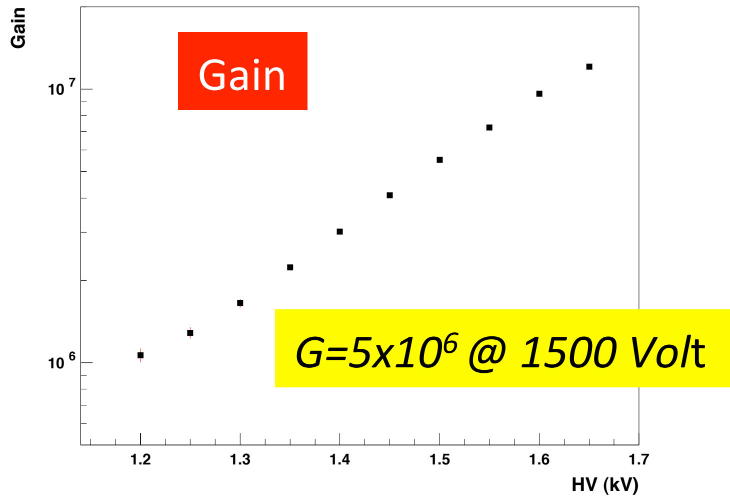


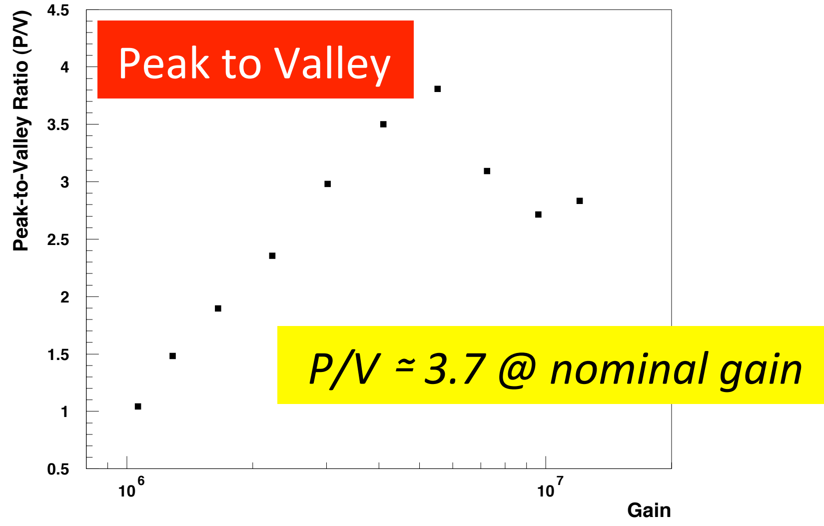


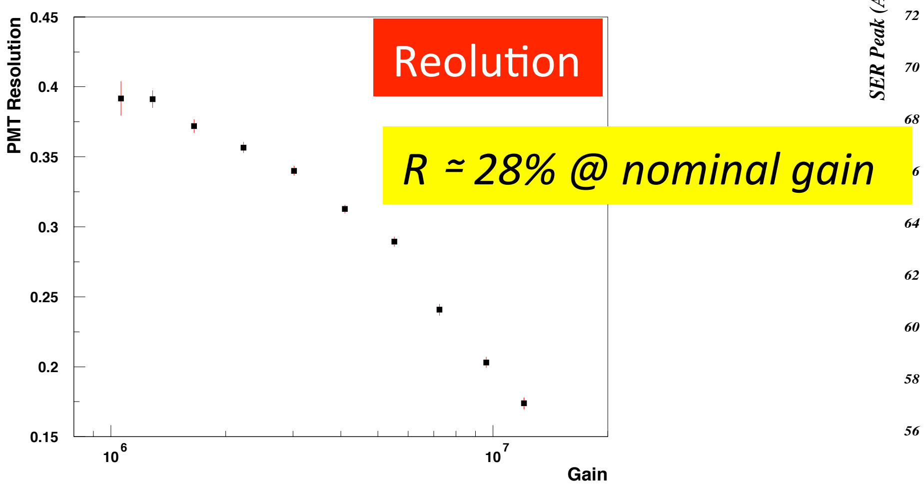


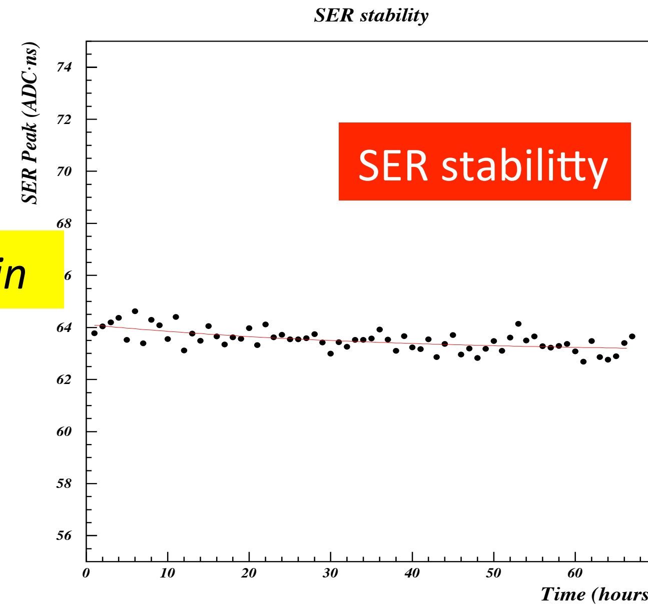
The mean value of the 1PHEL peak is proportional to the actual gain of the PMT and gives the calibration constant per single photo-electron

Gain, Peak to Valley and Resolution





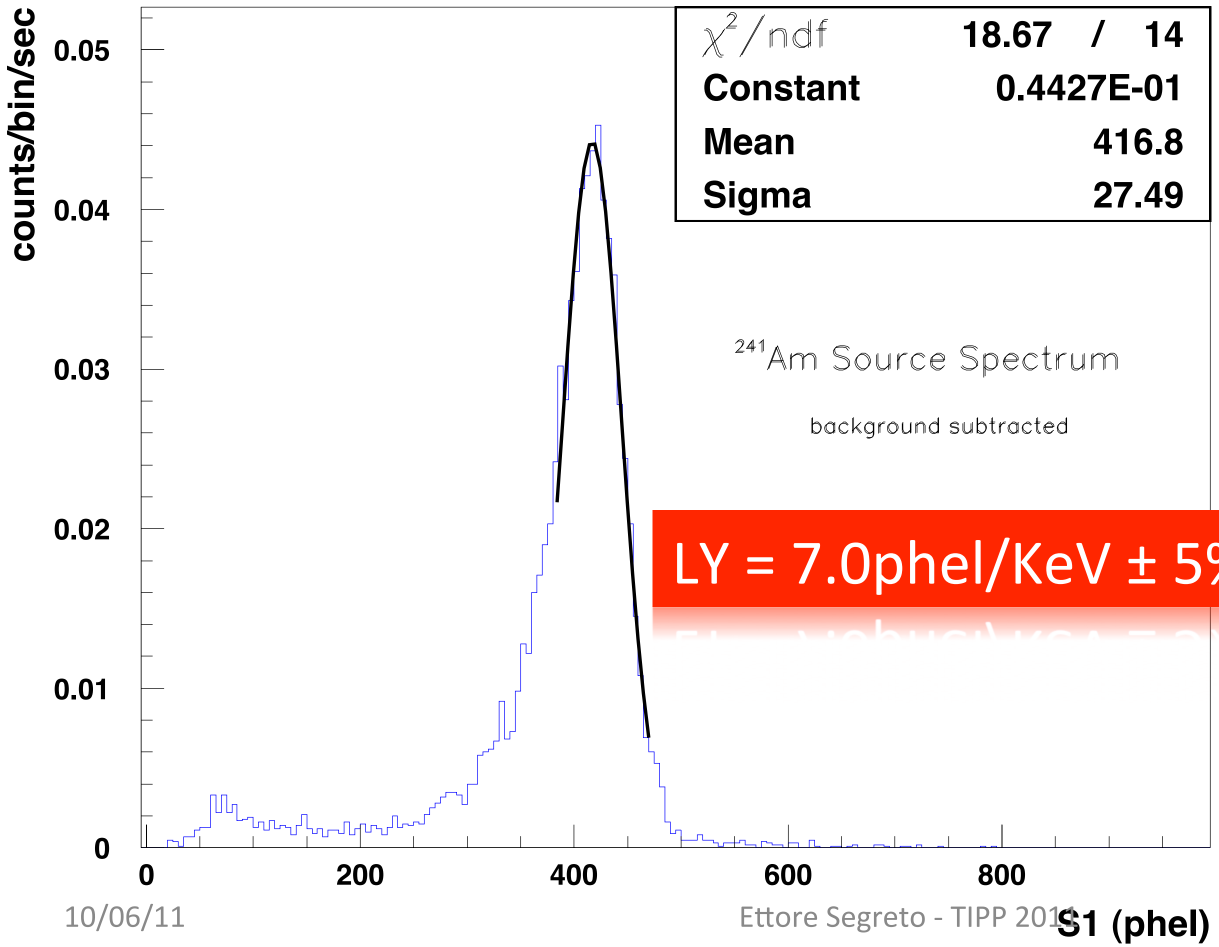




slightly decreasing exponential trend (τ ≃ 35 h) attributed to residual effects of thermalization of the PMT at LAr temperature.

Light Yield measurement

- LY measurement performed by exposing the detector to the ^{241}Am monochromatic γ-source (59.54 keV);
- Pulse amplitude spectrum in photo-electrons obtained by waveform integration and application of the calibration factor determined by SER fit;



LY = 7.0phel/KeV ± 5%

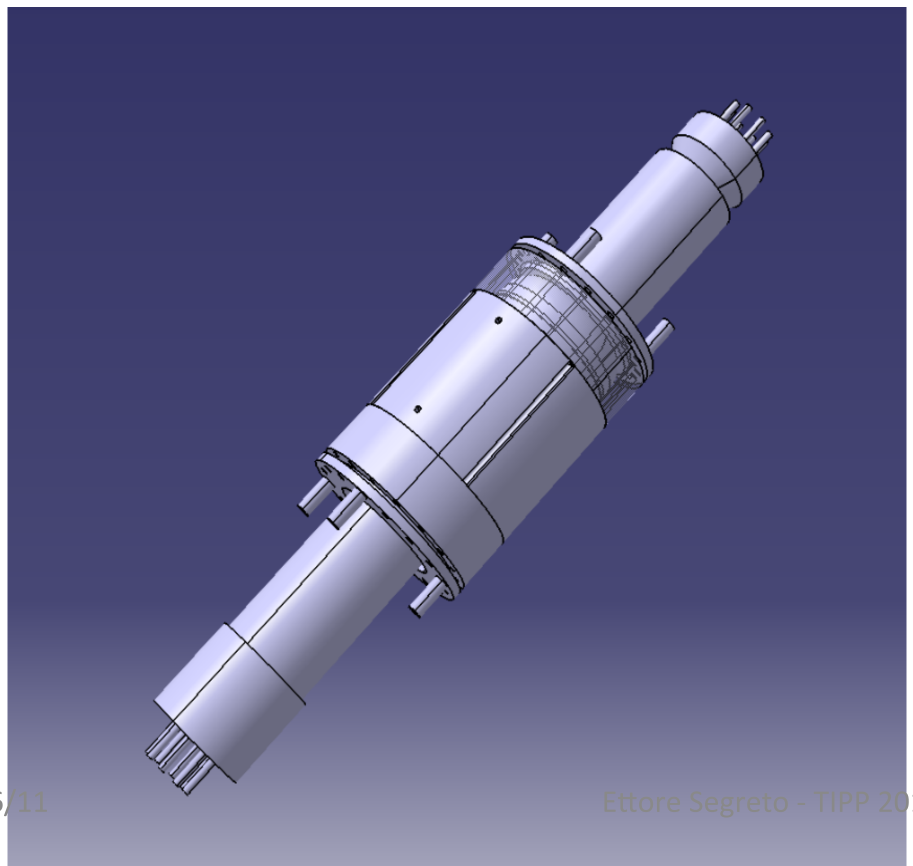
Result fully compatible with MonteCarlo expectation based on standard assumptions

Light Yield very stable during the test: fluctuations within ±1.5%

Test repeated after few weeks (same PMTs, same TPB coated reflector surfaces) -> LY measurements fully confirmed this result.

Two-PMTs test: ETL vs HAMAMATSU comparison

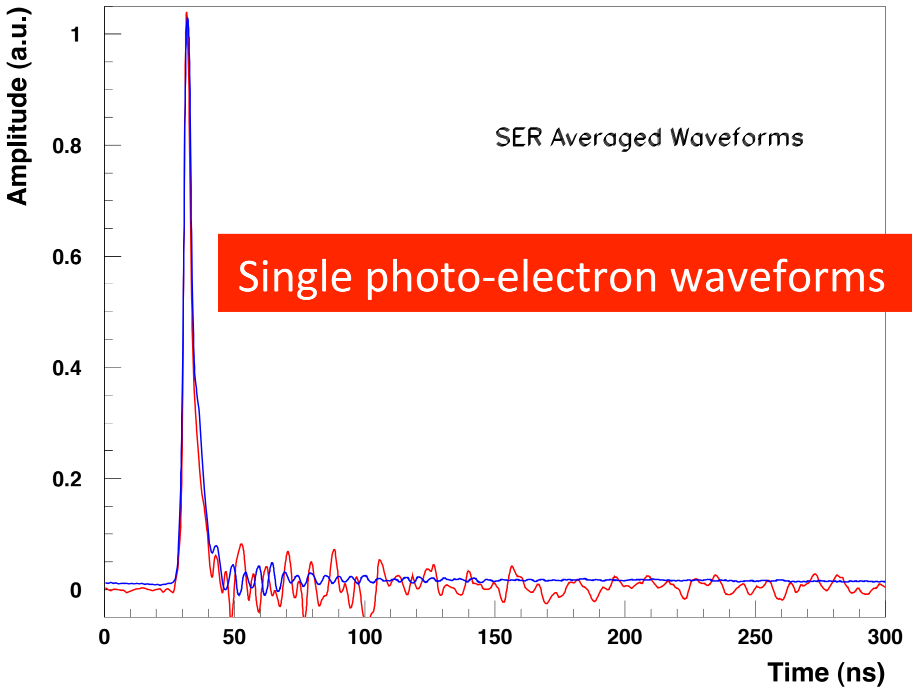
- A second test (mid 2010) for a direct comparative test of two types of PMTs: 3" HQE Hamamatsu R11065 (the same used in the previous test) and 3" ETL - D750 (pre-production series of the PMT in the WArP -100 experiment);
- LAr volume viewed simultaneously by the two PMT => comparison of the light outputs independent from the actual detector conditions;
- A PTFE cell, about 0.4 lt of internal volume (h=8.0 cm and ϕ=7.6 cm), lined with a TPB coated reflector layer on the lateral;

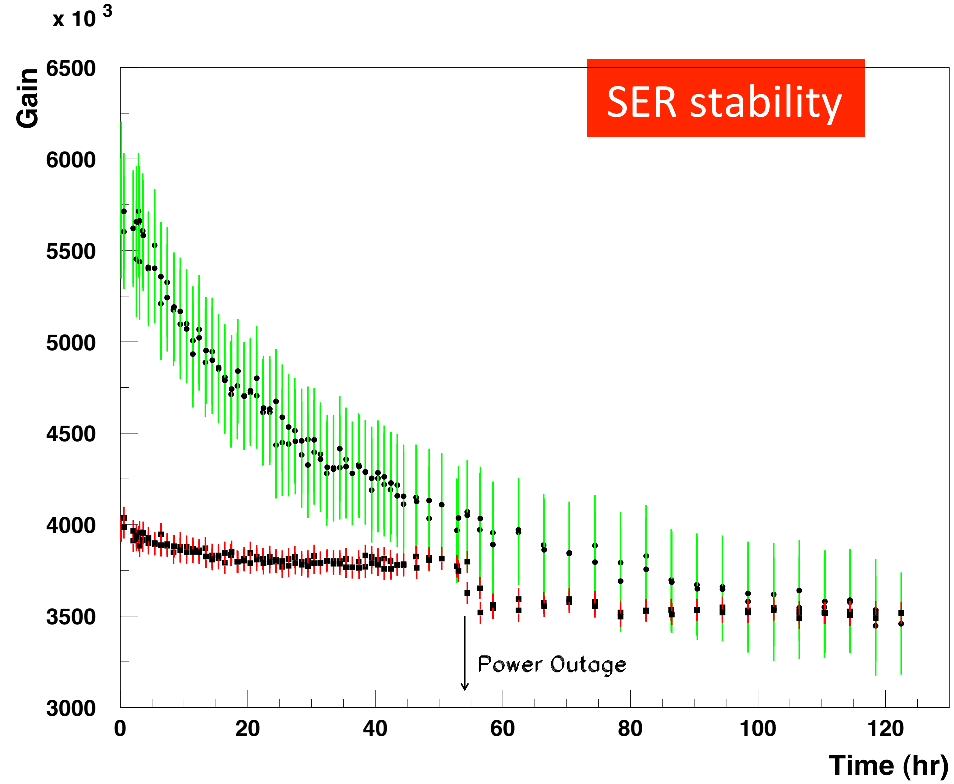


- Signals from each PMT were directly recorded by the 8-bit Fast Waveform 13Digitizer Acqiris board (DP235) at 1 GHz over a 15μs time interval (as for the single PMT test);
- Data treatment and the off-line analysis code -> same as in the single PMT test.

Single Electron Response of the two PMTs

- ✓ Very similar pulse shapes for single electron;
- ✓ The gain of the ETL PMT showed a steeper decreasing trend.
- ✓ The gain of the Hamamatsu PMT has a slight decrease over the first day after activation and then stabilized to a constant value.





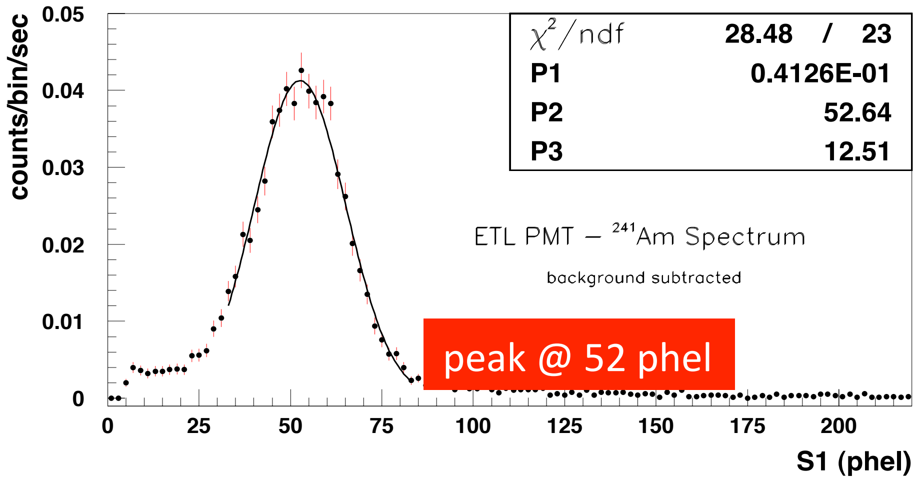
	Peak-to-Valley ratio	SER resolution
Hamamatsu R11065	3.5	32 %
ETL D750 (pre-series)	1.9	50 %

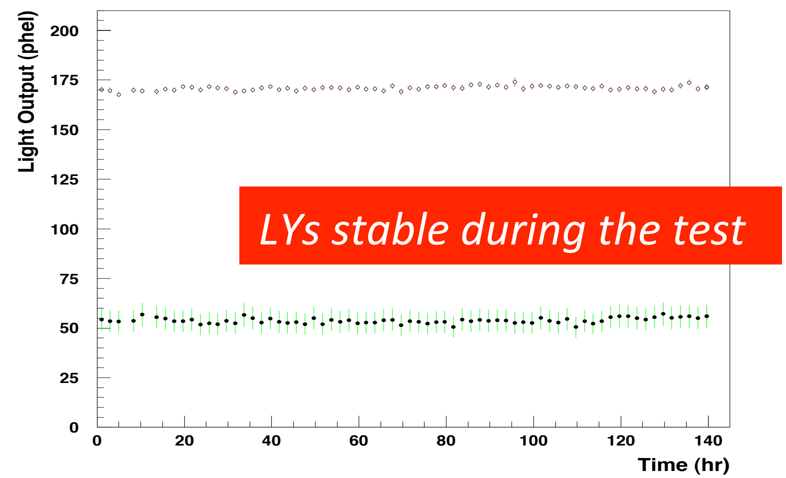
Peak to Valley @ 3.7×10^{6} gain

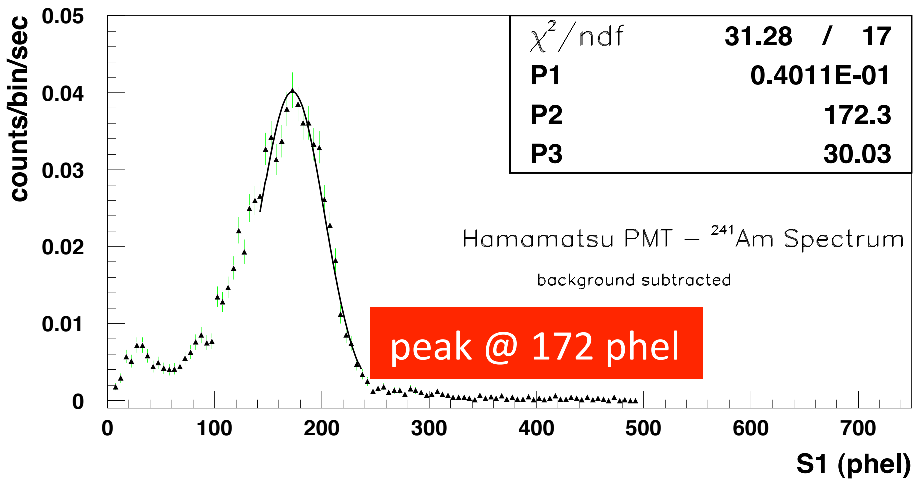
Light Yield measurement

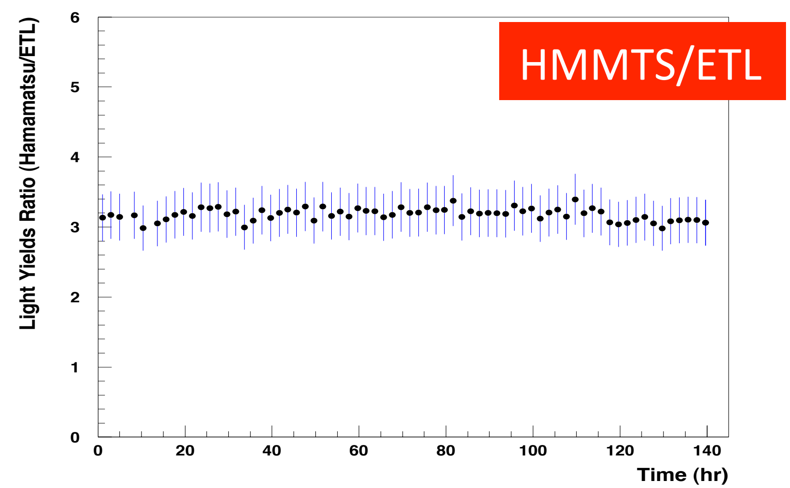
- ✓ *LYs determined by exposure to the ^{241}Am gamma- source (59.54 keV)*

The Hamamatsu-to-ETL ratio of LY found in the 3 : 1 range → *consistent with the ratio of the QE*









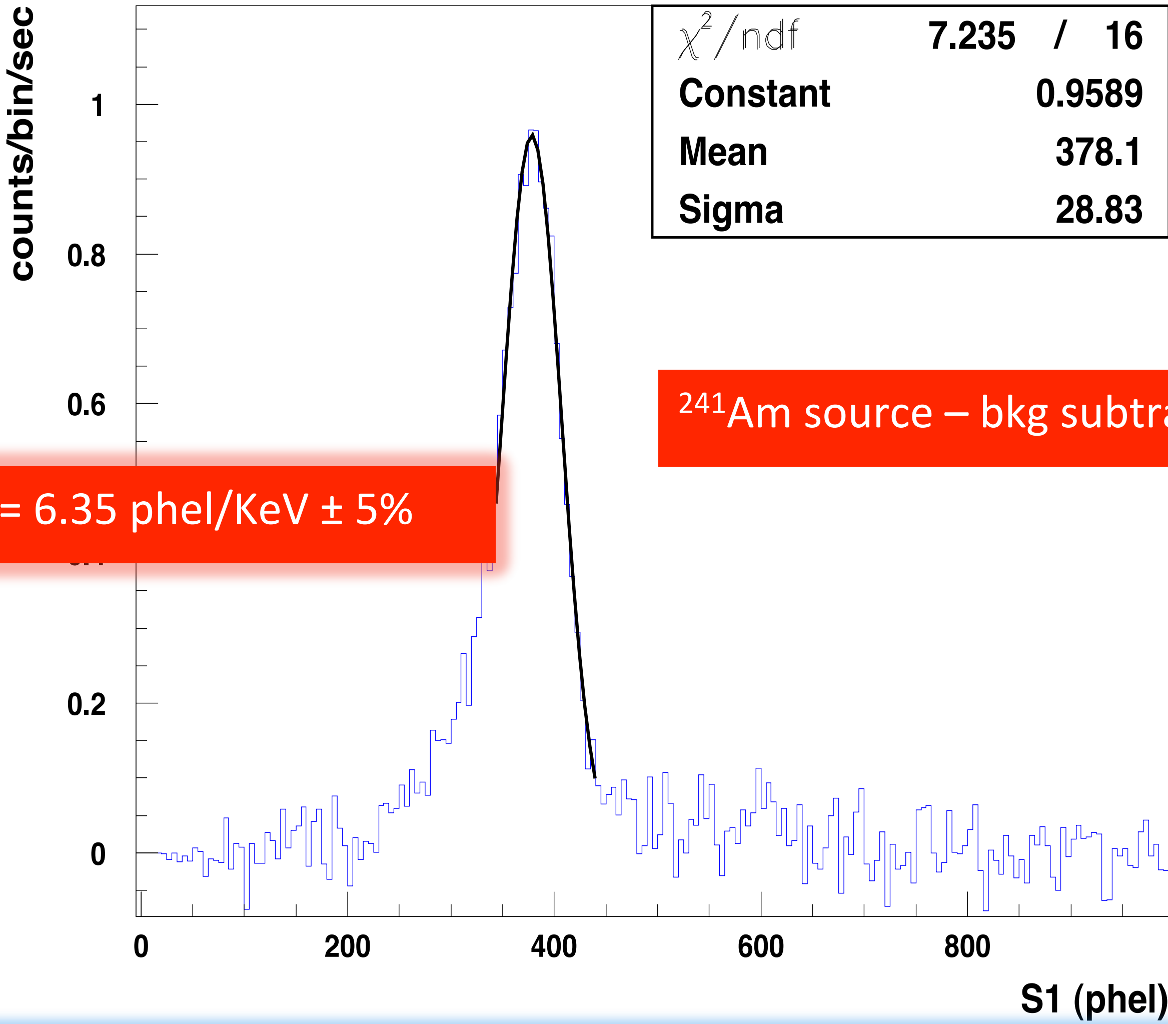
Four-PMTs test

- The scaling-up capability of the implemented technology tested with a detector about ten times bigger than the one with one PMT;
- The WArP 2.3l prototype used for this test (4.3 liters internal volume)-> equipped with 4 HQE Hamamatsu PMTs R11065 (photo-cathodic coverage ~ 12 %) ;
- Internal surfaces covered with VIKUITI ESR reflector layer + TPB (density about 300 μg/cm^2)
- PMT windows naked (no wavelength-shifter);
- 4 PMT anode signals 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;

- All internal component baked @ 80^{o}C;
- Detector housed in a low-radioactivity stainless steel vessel deployed in a LAr open bath;
- Detector completely filled with LAr -> PMTs' bases immersed;
- LAr filling through an in-line filter (Oxygen reactant and molecular sieve);
- No electric field;
- PMTs equalized @ 3x10^6 gain (around 1400 Volt).

Data Analysis and Results (I)

✓ *Detector exposed to ^{241}Am, ^{133}Ba, ^{57}Co and ^{137}Cs sources*



^{241}Am source – bkg subtracted

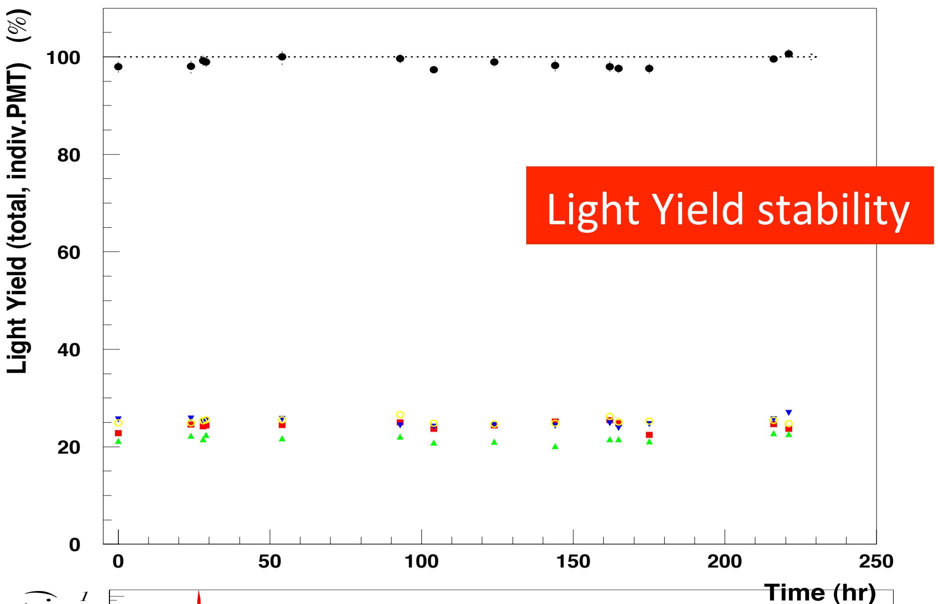
LY = 6.35 phel/KeV ± 5%

LY determined with other sources less accurate but fully compatible with ^{241}Am value

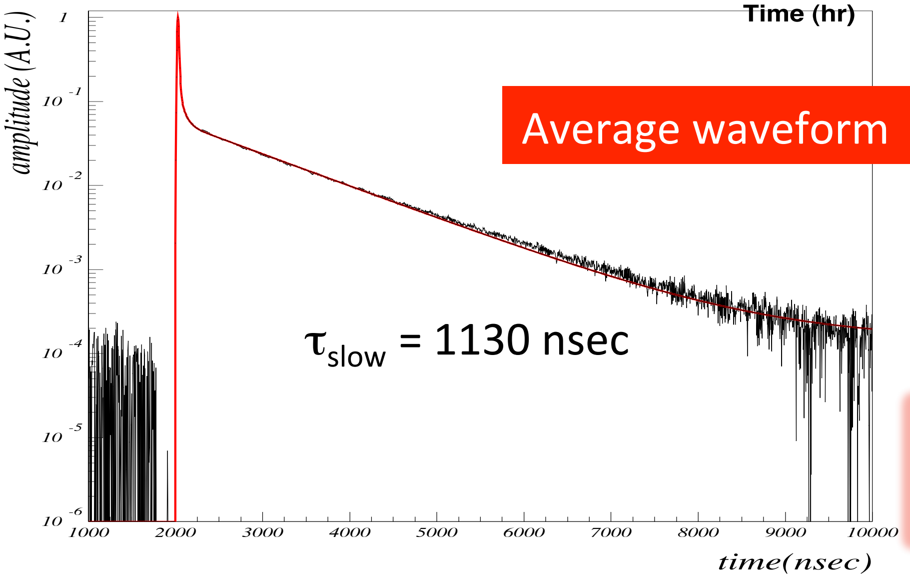
Detector geometry is a scaled-down version of the WArP -100 detector (100 lt of active volume, 37 PMTs, ~ 12% of photo-cathodic coverage);

The LY from this detector test can be assumed as predictive of the LY from the WArP 100 Inner Detector, when operated under equivalent conditions

Data Analysis and Results (II)



- LY stable within 2%;
- One PMT has a systematic lower light yield -> not yet understood (PMTs have almost the same Quantum Efficiency);
- With four PMTs working in the same way -> LY ≃ 6.6 phel/keV



- Slope of the slow scintillation component: 1130 ns (1300 nsec for clean Argon). This reduces the light yield of about 10%.
- Direct measurement with mass spectrometer showed the presence of ~ 1 ppm of N_2 (not captured by our filters);

In case of clean Argon the LY would have been in the range of 7 phel/KeV.

Conclusions

- A new PMT type with enhanced Quantum Efficiency photo- cathode and operating at LAr temperature has been developed by Hamamatsu Photonics Mod. R11065 with peak QE up to about 35%. PMT's of this type have been extensively tested along with the R&D program of the WArP Collaboration;

- The main working parameters of this PMT were measured at LAr temperature and its great performances have been clearly demonstrated;

- Liquid Argon detectors with HQE photo-cathodic coverage in the 12% range 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 -> suited for direct Dark Matter searches with LAr-based experiments.