Comparison between photon detection efficiency and TPB coating stability of PMTs immersed in liquid argon

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ABSTRACT

Detectors filled with liquid argon (LAr) are a very interesting detector option for neutrino experiments. The high density of LAr allows using it directly as target for neutrino interactions. The relatively large abundance of argon in the atmosphere, makes it also a cost-effective medium allowing the construction of detectors of several hundred tons, as ICARUS, and even several kton detectors are foreseen for the next generation of experiments, as the Deep Underground Neutrino Experiment (DUNE). Besides, being suitable to act as a target, LAr can serve at the same time as the detection medium for the charged particles outgoing from the interaction vertex. In the ionization of the LAr, electrons and photons are produced. The electrons are drifted afterwards in an external electric field towards the readout plane where they are collected; drift distances of several meters were achieved corresponding to drift times of few ms while the segmentation of the anode plane allows the reconstruction of the interaction in the plane perpendicular to the electric field, for the reconstruction of the interaction point along the drift the precise knowledge of t_0 is mandatory.
The interaction time, t_0 , can be determined by detecting the photons produced together with the electrons in the ionization process. These photons provide a prompt signal on the nanosecond scale. To detect them the integration of an efficient photon detection system (PDS) into the LAr detector is necessary. One difficulty here is related to the fact that the emitted photons have a wavelength in the VUV range (128 nm). The classical approach for the PDS is, therefore, the usage of photomultipliers (PMT) coated with tetraphenyl-butadiene (TPB) which shifts the VUV photons to about 430 nm, a wavelength to which the PMTs are directly sensitive. While the basic concept is well established and was used in several experiments as ICARUS, ArDM and Dark Side for example, some aspects of the coating are not well understood as the PMT preparation with using a sandblasted or a polished surface. To understand better the effect on the overall photon detection efficiency on one hand and the TPB stability during the cooling down, on the other hand, the quantum efficiencies of sandblasted and polished PMTs, coated following the same procedure, were measured with a setup at INFN, Pavia. Also, the immersion of the PMTs with different soak timing was tested showing a significantly different behavior for fast and slow immersion for the polished PMTs.

LIQUID ARGON TIME PROJECTION CHAMBER (LArTPC)

The Liquid argon technology has been chosen for the DUNE underground experiment for the 4×10 kt far detectors for the study of neutrino oscillations.

- WA105 is a large demonstrator of the dual-phase liquid argon TPC.
- Excellent tracking and calorimetric capabilities (superior to currently operating neutrino detectors).
- Cost effective solution.
- Provides excellent imaging capabilities.
- Built inside a cryostat tank.

The design of the WA105 detector (is shown in Fig. 1):

- The cryostat has walls 1 m thick which limit the heat transfer to maximal 5 W/m2.
- Inner volume has dimensions of 8.3x8.3x8.1 m3 (WxLxH) containing about 700 ton of LAr.
- The sensitive volume has dimensions of 6x6x6 m^3 and contains about 300 ton of active mass.
- The large depths of the detector lead to voltages of up to 600 kV at the cathode which consists of wires to achieve a high transparency for the photons of the primary scintillation light.
- A set of 36 PMTs (Hamamatsu R5912-02mod) are installed about 1 m below the cathode.

Since the PMTs are not directly sensitive to the 128 nm of the primary scintillation light, the surface of the PMTs was coated with (TPB). TPB shifts the light from 128 nm to about 430 nm, a wavelength at which the PMTs highly sensitive.

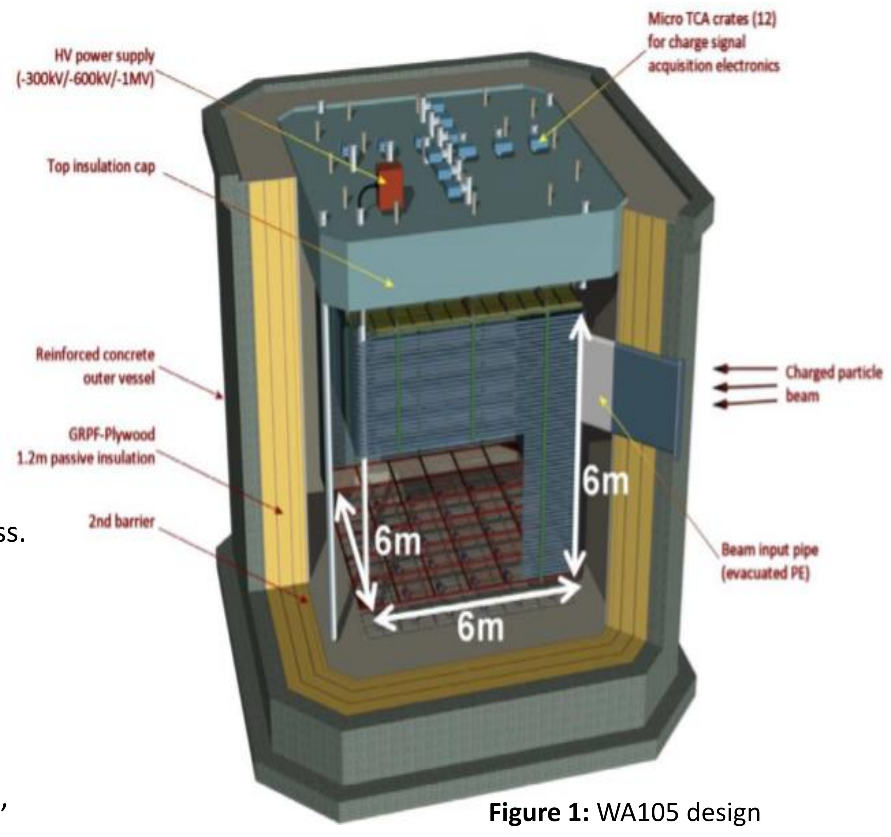


Figure 1: WA105 design

The basic principle of a LAr TPC is the following (Fig. 2):

- A charged particle traversing the LAr ionizes the argon atoms creating a large amount of electron-ion pairs on its way through the gas.
- Applying an external electric field, the drift field, the electrons and ions are separated and drift to the anode and cathode respectively.
- Electrons produced in the liquid argon are extracted in the gas phase.
- A readout plane based on Large Electron Multipliers (LEM's) provides amplification before the charge collection itno an anode plane with strip readout.
- S1 production for $t_0 + triger$ to be detected by an array of PMTs.

The PMTs (Hamamatsu R5912-02mod) used have :

- Polished convex surface.
- relatively large detection area (diameter of 8 inch).
- 14 linearly focused dynode stage.
- narrow spread in transit time.
- excellent charge resolution.
- Gain ~ 1×10^9.

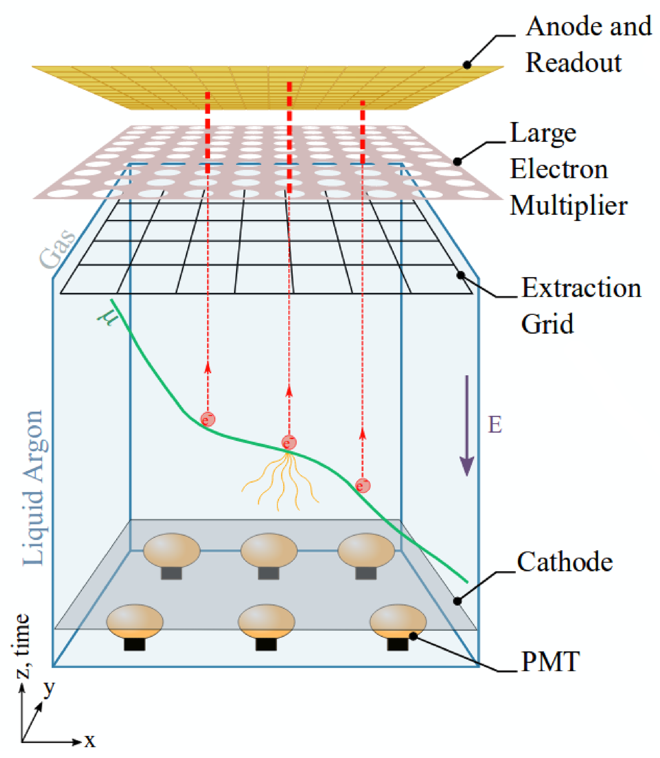


Figure 2: Basic principle of the LArTPC

COATING SETUP

An evaporation system (Fig. 3) suitable to large and convex surfaces (instead of a flat one) was designed for the coating of the convex surface of the PMTs used for the 360 PMTs inside the ICARUS T600 detector.

- A motorized rotating feedthrough on the top of a vacuum chamber, on which the PMT is mounted at an angle of 40 with respect to the cover.
- A Knudsen cell is mounted below the PMT.

Evaporation is carried out following a protocol that guarantees a high optical yield and uniformity. The procedure takes only 3 h for each PMT.

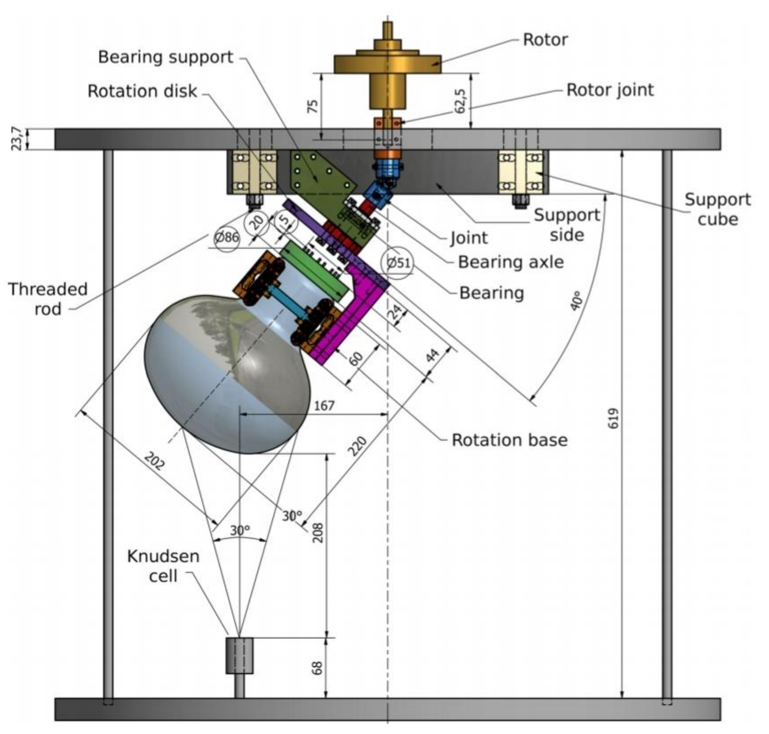
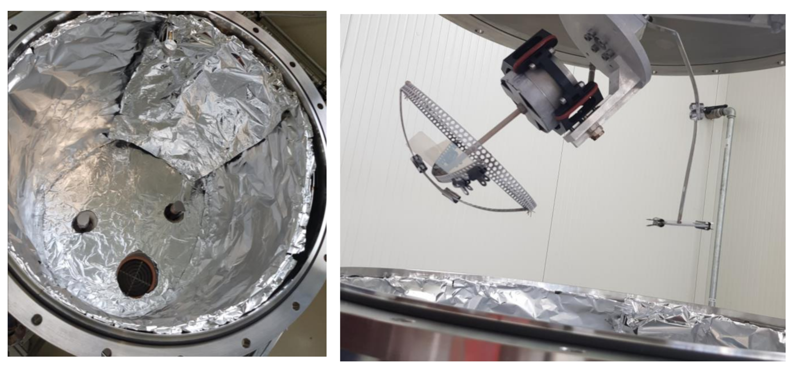


Figure 3: Evaporation system setup.

- When the pressure inside the vacuum chamber is of the order of 3×10^5 mbar.
- The motor starts to rotate at 10 turns/min.
- The temperature regulator is set to 220 ºC.
- When the temperature reaches 190 ºC.
- The shutter over the cell is opened, letting the material to reach the PMT by evaporation.
- The monitor displays the deposition thickness value both per unit of time.



EVAPORATION UNIFORMITY OVER THE PHOTOCATHODE SURFACE

The most important parameters of the evaporation process have been evaluated by evaporating TPB over a PMT mockup, covered in part with small squeart maylar foil used as sample points. Figure 4 shows the mock-up.
The uniformity of the evaporation over the entire convex photocathode is measured by weighting each sample before and after the process, with a high precision scale. The TPB density as a function of different distances from the PMT window center and the TPB density at different rotation angles at fixed radial distances from the center (5–20 cm) (Fig. 5).

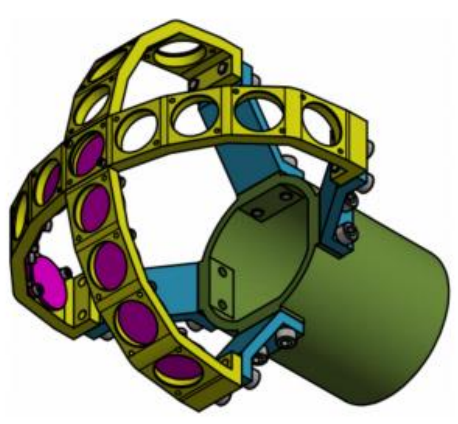


Figure 4: Mock-up.

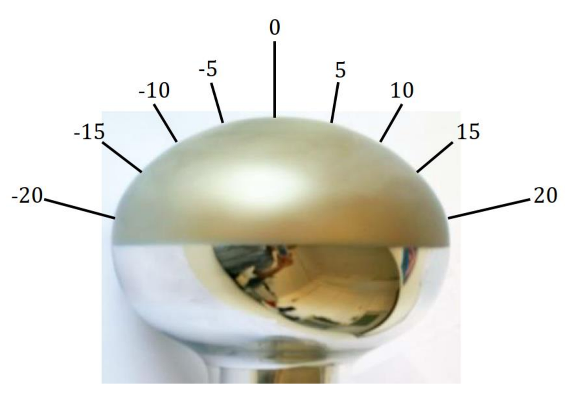


Figure 5: Fixed radial distances from the center.

Figure 6: Coated PMT.

TEST OF THE COATING RESISTANT

The coating done to the PMTs was summited to a test of resistant inside a small dewar (Fig. 6):

- Fast filling (PMT covered with LAr in less that 1h).
- LAr boiled and LAr drops reached the surface.
- Small holes observed only for polished PMTs due to thermal shock when drops landed (Fig. 8).

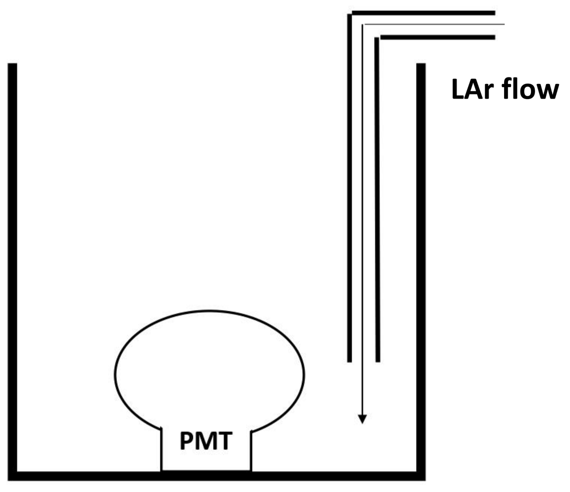


Figure 6: Small dewar setup.

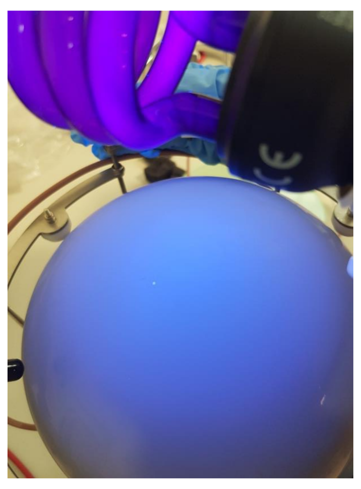


Figure 7: Coating PMT before the test.

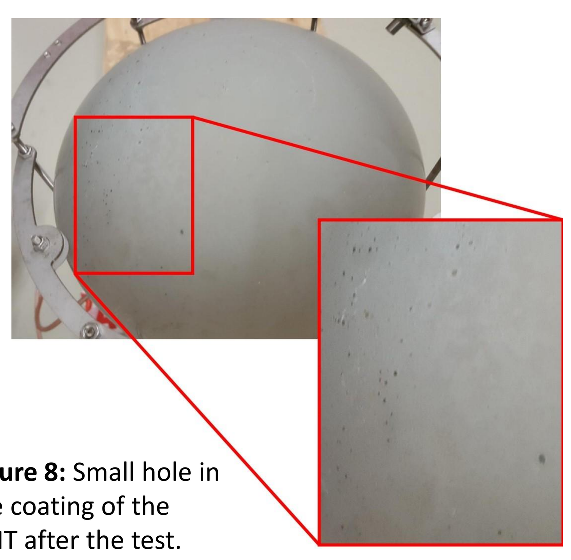


Figure 8: Small hole in the coating of the PMT after the test.

QUANTUM EFFICIENCY VUV MEASUREMENT SYSTEM

The optical characterization of the detector after the coating process was carried out by means of a VUV measurement system developed at the INFN Pavia (Italy). It allows the characterization of detectors in terms of absolute quantum efficiency (Q_{eff}) in the VUV range (Fig. 9).

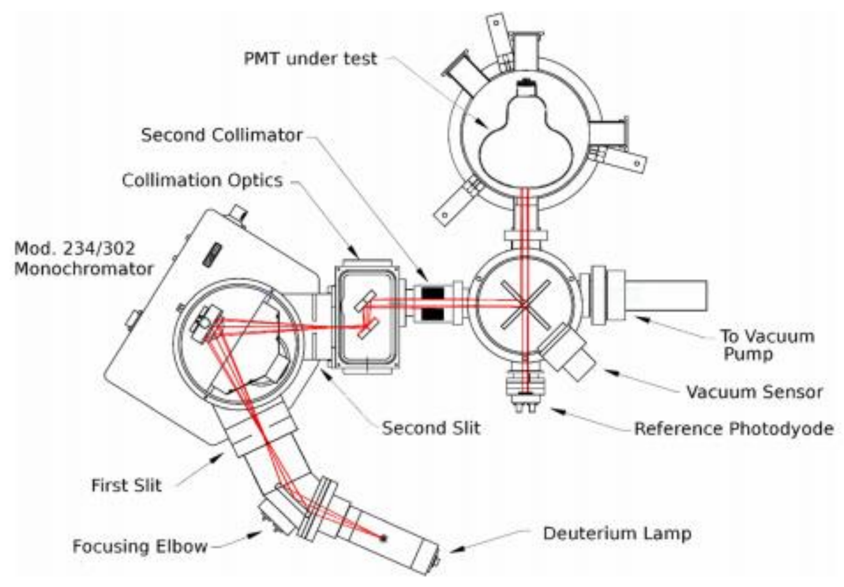


Figure 9: VUV measurement system.

Figure 10: Different PMT's: polish (left) and sandblasted (rigth).

The study was done for two tipes of PMT's surface: polishd and sandblasted (Fig. 10).
A comparison between the current delivered from the two devices, measured alternatively with a Keithley PicoAmmeter and corrected by the photodiode Q_{eff} given by NIST, provides the relative Q_{eff} of the device under test. Available wavelength ranges from 120 to 250nm with a maximum resolution of 1 nm. The mounting of the device on a rotating feedthrough allows the measurements of the Q_{eff} in various positions of the photocathode.

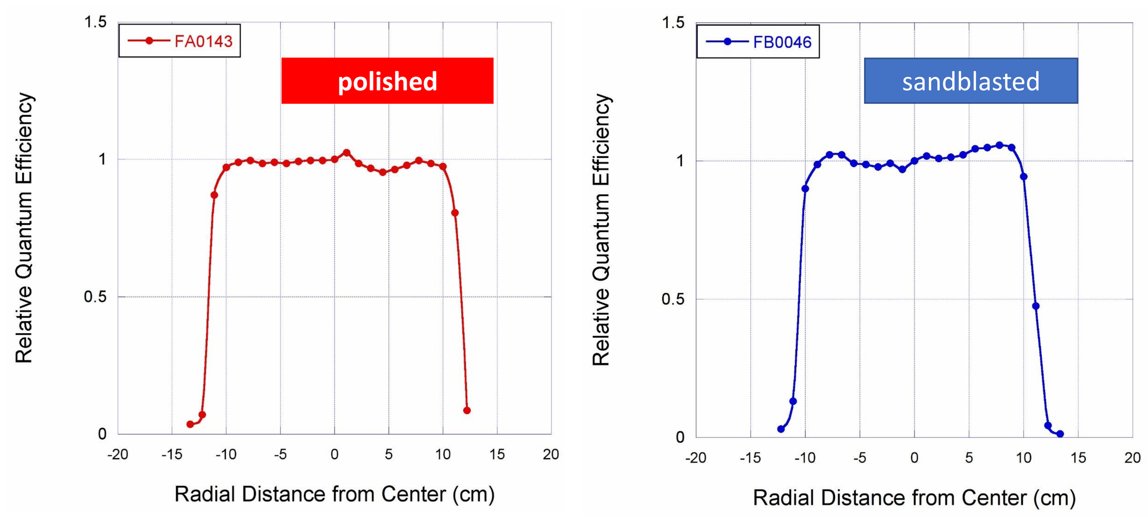


Figure 11: Relative Q_{eff} for different PMT's: polish (left) and sandblasted (rigth).

A sample of PMTs, were characterized in terms of quantum efficiency at $\lambda = 128$ nm and the distribution of the relative Q_{eff} is shown (Fig.11). The obtained values are distributed in the 10%–15% range, with an average value of 0.14 ± 0.02 and 0.12 ± 0.01 for polished and sandblasted PMTs respectively. Fluctuations are mainly due to different sensitivity of the bialkali photocathode on different devices.

CONCLUSION

For the next generation of neutrino oscillation experiment detectors with about 10 kton active mass will be needed. The WA105 detector is a necessary intermediate step for these detectors to prove their technical feasibility and will provide also a deeper understanding of the detector performance due to its exposing to a well defined beam of particles at CERN.

- 36 PMTs were coated successfully.
- Q_{eff} for $\lambda = 128$ nm , was measured the for polished to 0.14 ± 0.02 and sandblast PMTs to 0.12 ± 0.01
- Coating of sandblasted PMTs show to be less sensitive to thermal shocks.
- For safty reasons TPB was replaced by a PEN-foil for a part of the 36 PMTs.
- Photon Detection System of ProtoDUNE-DP successfully commissioned.
- Relevant findings for the design of the final DUNE far detector.

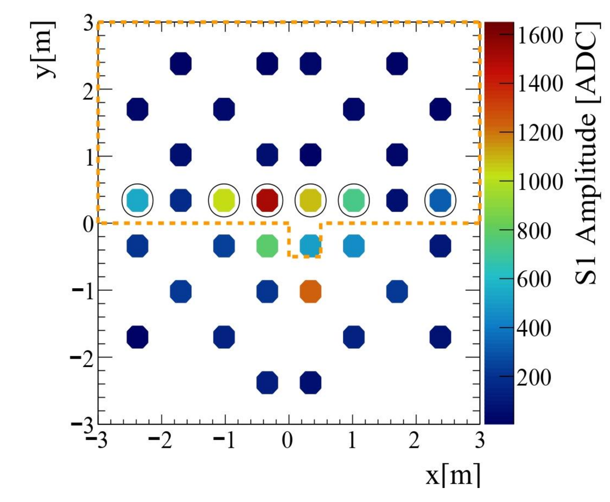


Figure 12: Example of one event measured (Event display ProtoDUNE-DP).

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