

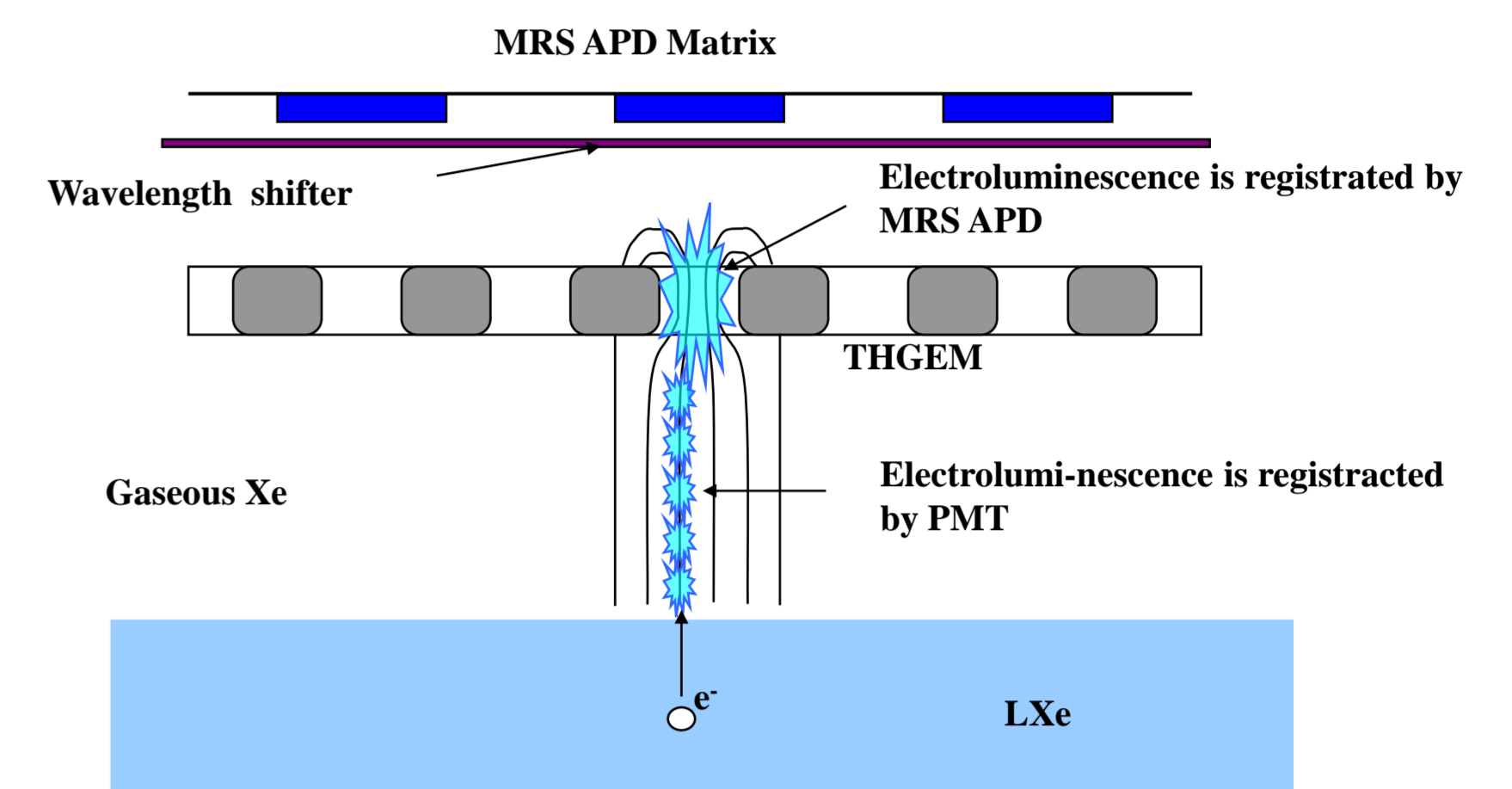
Development of very low threshold detection system for low-background experiments.

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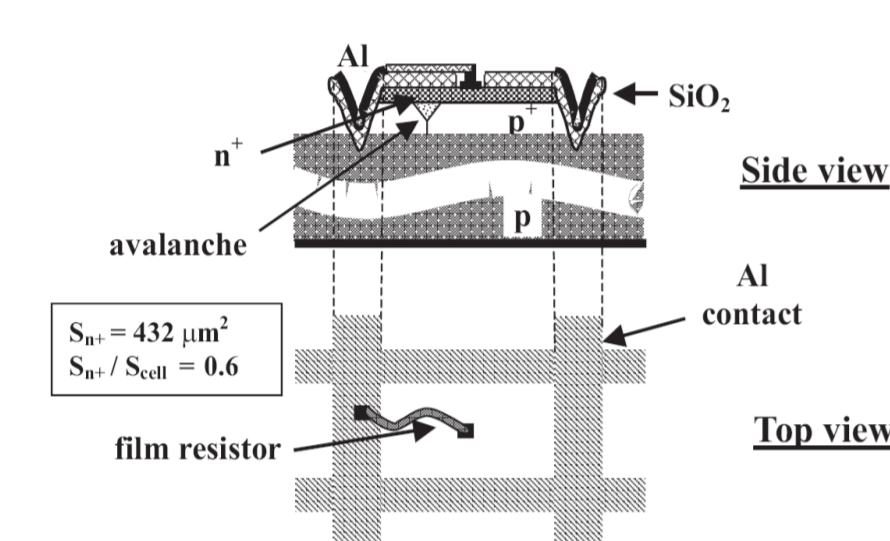
Introduction

In noble gas detectors of Dark Matter particles (WIMPs) of current generation, detection of scintillation and electroluminescence is performed by photomultipliers (PMTs). In future Dark Matter experiments, with increasing sizes and masses of detectors and reduction of radioactive background of experimental setups down to the ultralow values of 1 event/100 kg/year a question will arise on replacement of the PMTs which are currently the most radioactive elements to less radioactive photodetectors. Several experimental groups, which develop detectors for the Dark Matter experiments, are investigating new semiconductor devices — multipixel avalanche Geiger photodiodes, MRS APD (the widely used names are: SiPM, MPPC, MPPG). These photo detectors operate in a single photon counting mode and may replace PMTs in future because they are expected to contribute the negligibly low radioactivity (compared to the PMTs). Moreover, they are very thin. MRS APD can be assembled in a matrix with a ratio of active to total area of about 70-80% due to spacing between elements, package borders and places for contacts bonding. The cost of the matrix of the MRS APD is currently nearly approaching the cost of the PMTs with the equivalent area.

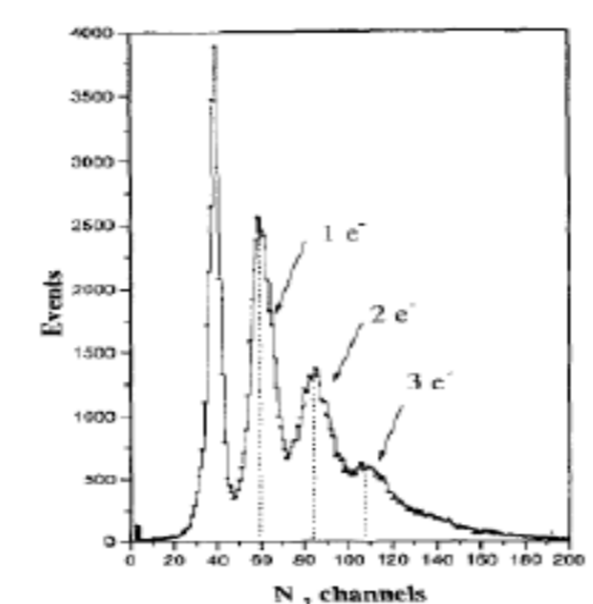
The main obstacles now for replacement of the PMTs by them are the lack of sensitivity in the VUV region of luminescence of noble gases and the high intrinsic thermionic noise level (in comparison with the noise level of the same area PMT). These obstacles do not allow one to build a large-area photosensitive plane for detection of the scintillation signal. However, these photodetectors, apparently, could be used for detection of the electroluminescent signal from the very low-energy events. Elegant system comprised of MRS APD together with a wavelength shifter (WLS) and a thick gas electron multiplier (THGEM) could be used for Dark Matter experiment. Additional amplification of the charge in the THGEM holes gives the large light signal of electroluminescence detected with an array of MRS APD. This readout system provides the mm accuracy for the very low-energy events, that is important for the reliable separation of the rare physical events from the background ones caused by spontaneous emission of the electrons from the liquid noble gas surface.



MRS APD

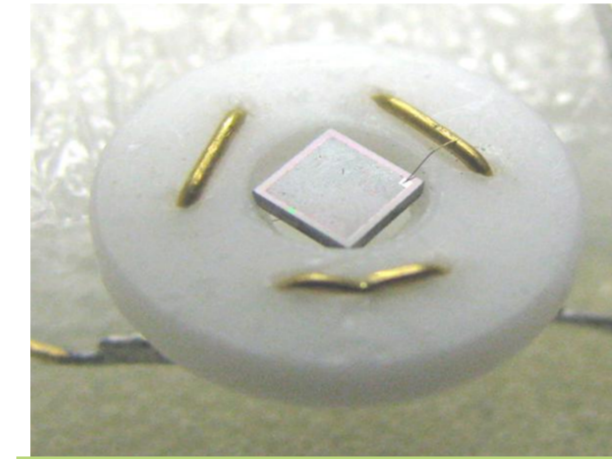


The very first Metall-Resistor-Semiconductor APD (MRS APD, SiPM) was invented in USSR in 1989. The idea was to create a photodiode as an array of microcells assembled on a common silicon substrate and to operate it at supply voltage above the value corresponding to the initiation of a breakdown to reach high gain. During discharge the subsequent voltage drop across the individual resistor (resistive layer) leads to the avalanche quenching and to localization of the discharge within the illuminated microcells, while the rest of the photodiode surface remains in the working state.



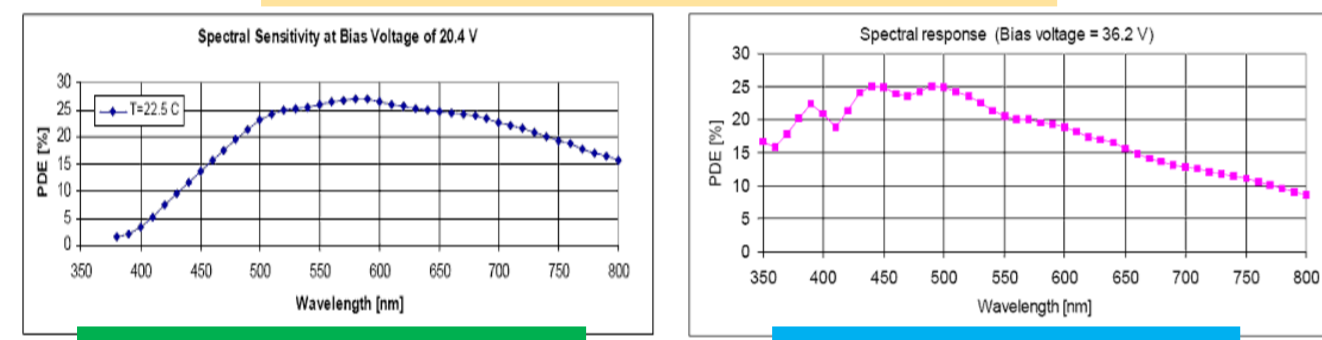
LED pulse spectrum (A. Akindinov et al., NIM 387 (1997) 231)

the total signal is a sum of the pulses with equal amplitude from all fired cell



2 x 2 mm, 1584 pixels

Typical PDE for CPTA 2x2 mm²



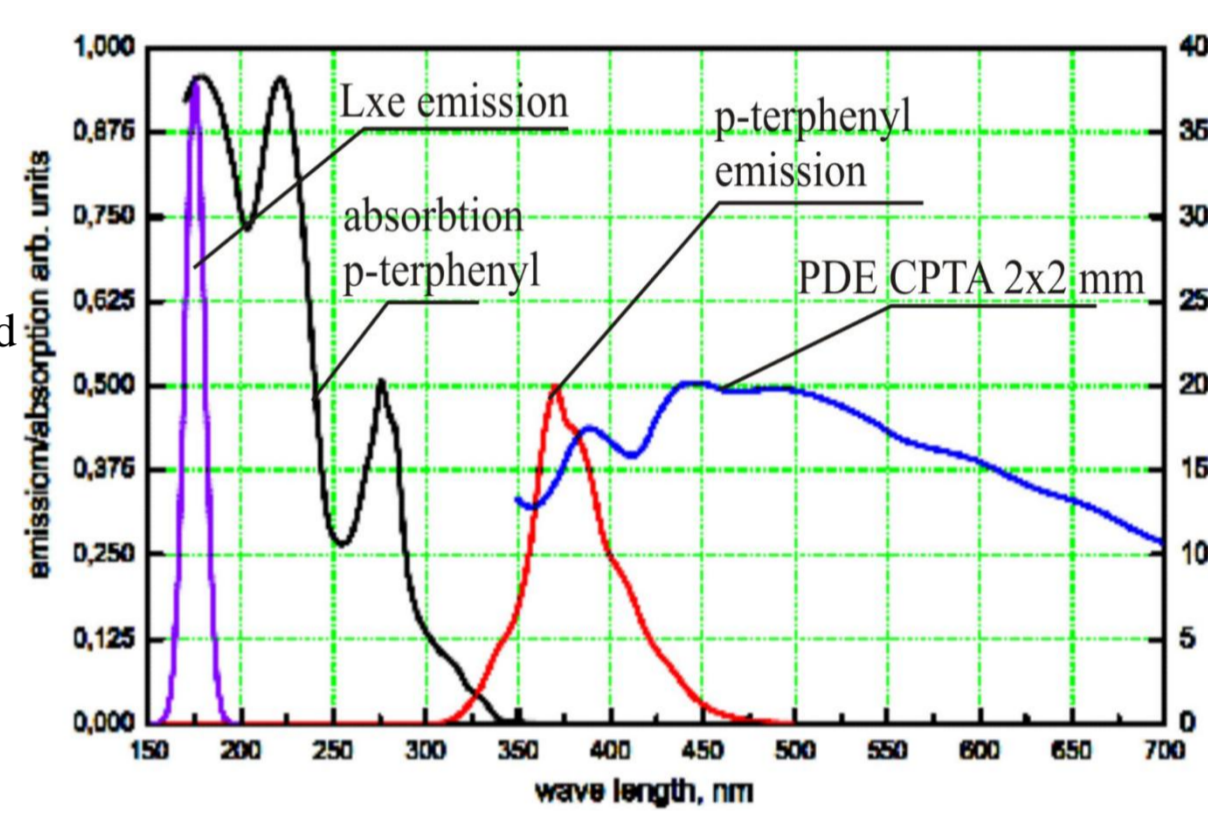
CPTA "green"

CPTA "blue"

Since the Geiger discharge probability R_G is higher for electron than for holes, and an absorption length in silicon is different for different wavelength, there are two currently existing basic structures: $n^+p\text{-}p\text{-}n^+$ for long wavelengths "green", and $p^+n\text{-}n\text{-}p^+$ for short wavelengths "blue".

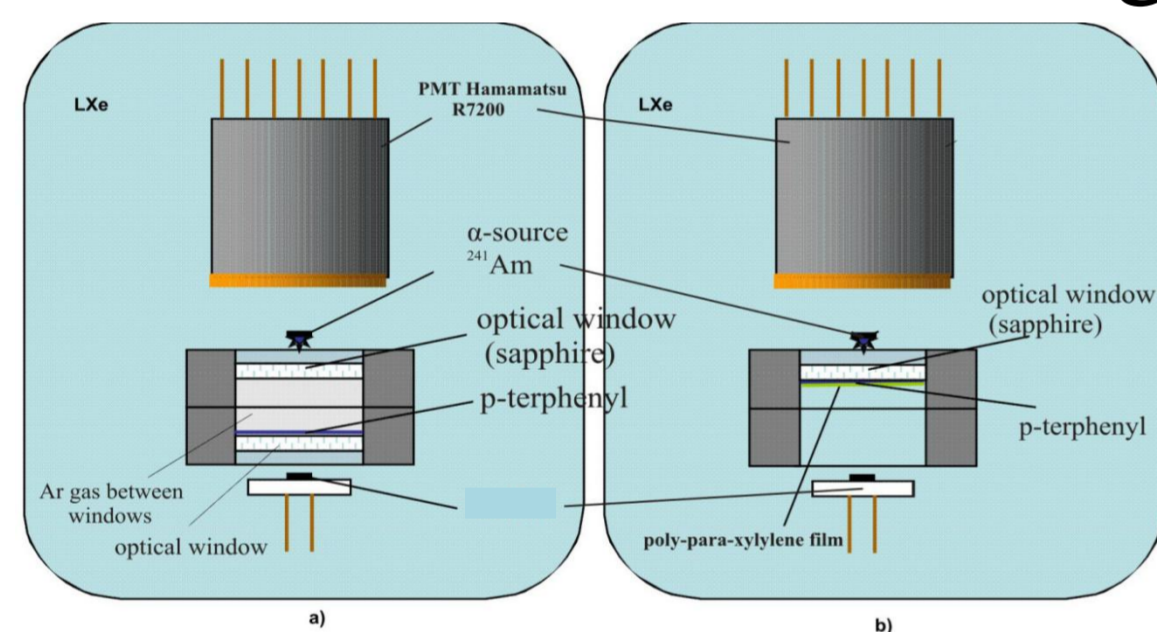
Wavelength shifter

A p-terphenyl (1,4-diphenylbenzene) has been chosen as a wavelength shifter. Absorption spectrum of a molecular solution of p-terphenyl in an n-heptane has two maxima: at $\lambda = 276$ nm with molar extinction coefficient $\epsilon = 33800 \text{ mol}^{-1} \text{ cm}^{-1}$ and $\lambda = 206.5$ nm and $\epsilon = 56300 \text{ mol}^{-1} \text{ cm}^{-1}$. These maxima correspond to singlet transitions $S_0 \rightarrow S_1$ and $S_0 \rightarrow S_2$ with $E_{S_0 \rightarrow S_1} = 4.5$ eV and $E_{S_0 \rightarrow S_2} = 6$ eV. A fluorescence quantum yield of p-terphenyl is as high as 0.9, and emission spectrum has a maximum at 338 nm. There are no data on p-terphenyl absorption below 200 nm ($S_0 \rightarrow S_3$). The energy of the $S_0 \rightarrow S_3$ transition can be obtained from an empirical rule for p-electron singlet states of aromatic molecules: $E_{S_0 \rightarrow S_2} = 1.35 E_{S_0 \rightarrow S_1}$ and $E_{S_0 \rightarrow S_3} = 1.6 E_{S_0 \rightarrow S_1} = 7.2$ eV. For p-terphenyl one obtains $E_{S_0 \rightarrow S_2} = 6.075$ eV which corresponds to 204 nm. The energy of the $S_0 \rightarrow S_3$ transition is estimated then as $E_{S_0 \rightarrow S_3} = 7.2$ eV which corresponds to 172 nm. Therefore, the p-terphenyl must intensively absorb the Xe emission light (a molecular continuum in a vacuum ultraviolet region with a maximum at 175 nm).



Since absorption and fluorescence spectra of molecular crystals are usually slightly different from those of molecular solutions, we have studied absorption of a thin (50 nm) polycrystalline p-terphenyl layer vacuum deposited on a fused silica optical window. The absorption spectrum has been measured in the wave length range from 180 to 350 nm. The peak corresponding to the $S_0 \rightarrow S_2$ transition has shifted from 206.5 to 220 nm while the peak corresponding to $S_0 \rightarrow S_1$ transition remained at the same wave length. The molar extinction coefficient ϵ reached the value of $10^4 \text{ mol}^{-1} \text{ cm}^{-1}$ at 180 nm ($S_0 \rightarrow S_3$ transition) which corresponds to optical density equal 1.08. Therefore, the thickness 150 nm of a polycrystalline p-terphenyl layer is enough for absorption of 99.9% of the xenon light. The measured fluorescence spectrum of the polycrystalline p-terphenyl is shown by curve red in figure. The spectrum has a maximum at 370 nm.

First tests with wavelength shifter and MRS APD



The p-terphenyl is known to be quite volatile. It is even possible that the p-terphenyl layer may be sublimated and completely pumped out (according to our experience) if the pumping process is sufficiently long. On the other hand, the long pumping is required to obtain the good vacuum and the high purity of the LXe detection medium. The p-terphenyl may also seriously contaminate the test chamber and the gas system.

To avoid this, we protected the LXe from p-terphenyl pollution by two ways. In the first one, the vacuum deposited on an optical window p-terphenyl layer with a thickness of 450 nm was encapsulated between two windowed 1.33" CF flanges (see figure a).

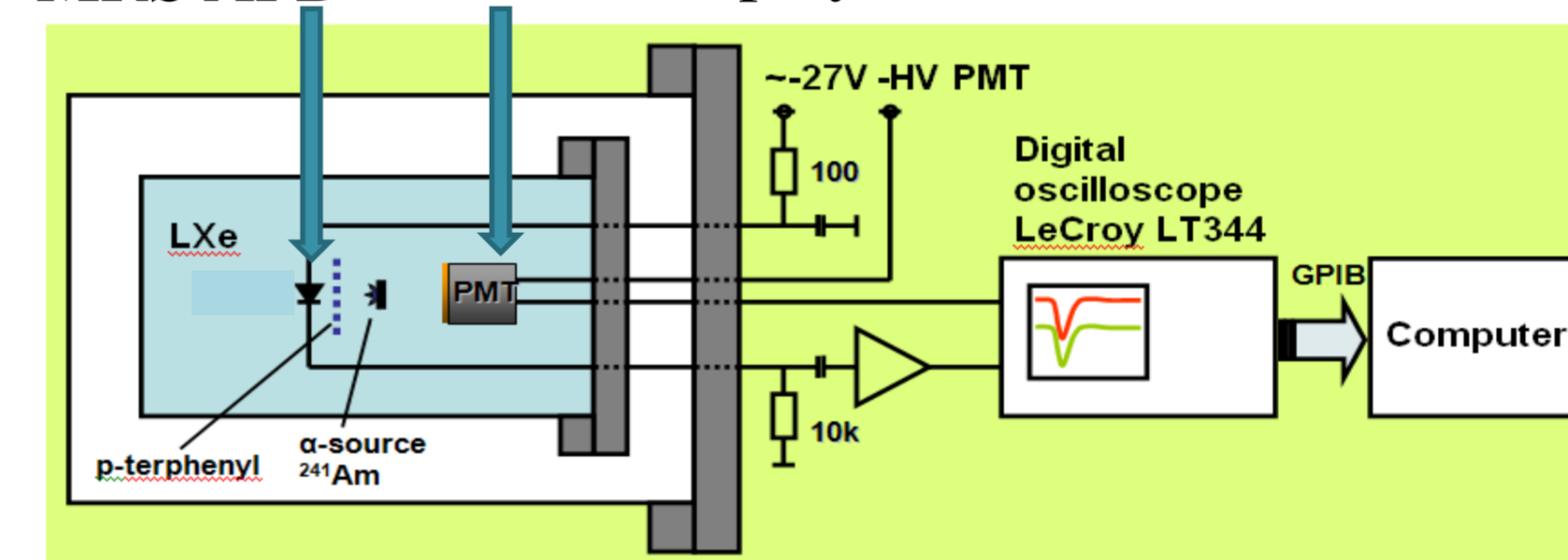
This window was located in front of the photodetector. The window was made of sapphire which is transparent for VUV. Sealing of the construction was performed in an argon atmosphere to exclude the presence of oxygen between the windows (oxygen strongly absorbs the VUV light). In the second case, the p-terphenyl layer was made thinner (140±15 nm) and, visually, with much better quality. It was coated then by a 1-μm poly-paraxylene film (see figure b). Polypara-xylylene (Parylene N) was chosen due to its well known properties such as the very low permeability to gases, and the possibility to form a conformal optically transparent film practically free of pin-holes even for several tens °A thicknesses. A newly developed by CPTA LTD, Russian Federation "blue sensitive" MRS APD was used for our experimental study. The size of the photodetector is 2x2 mm, and it contains 1584 cells (40 x 40 cells, with some dead area left for ultrasonic welding of a wire).

The p-terphenyl evaporated layer is clearly visible when irradiated by a UV lamp



Scheme of measurements

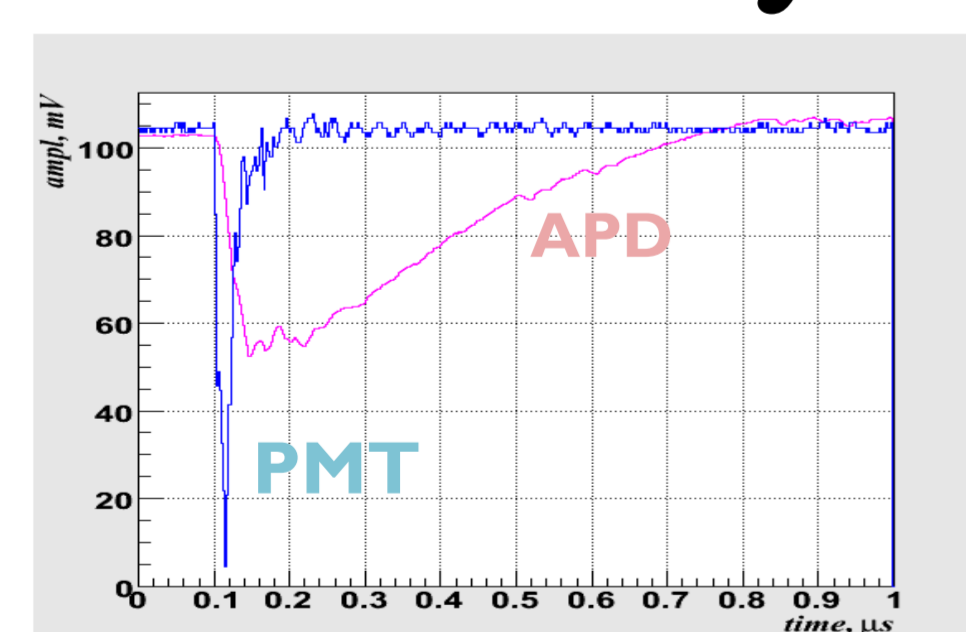
MRS APD Photo multiplier



An alpha-source (²⁴¹Am) was used to produce a scintillation light (175 nm). A Hamamatsu R7400-06 PMT was used to detect the light reemitted by the p-terphenyl in backward direction (with respect to the direction of incident light), thus providing a triggering signal. In both cases (figure a and b), the mechanical construction was kept the same: in the case (b) the windowed flange was replaced by the stainless steel one with the same sizes but without optical window. This assembly was installed in a test chamber (cryostat), filled with liquid xenon. The test chamber has been pumped out by a zeolite and then by a titanium discharge pump down to $\sim 10^{-5}$ torr without heating which was not allowed because of the photodetectors installed inside.

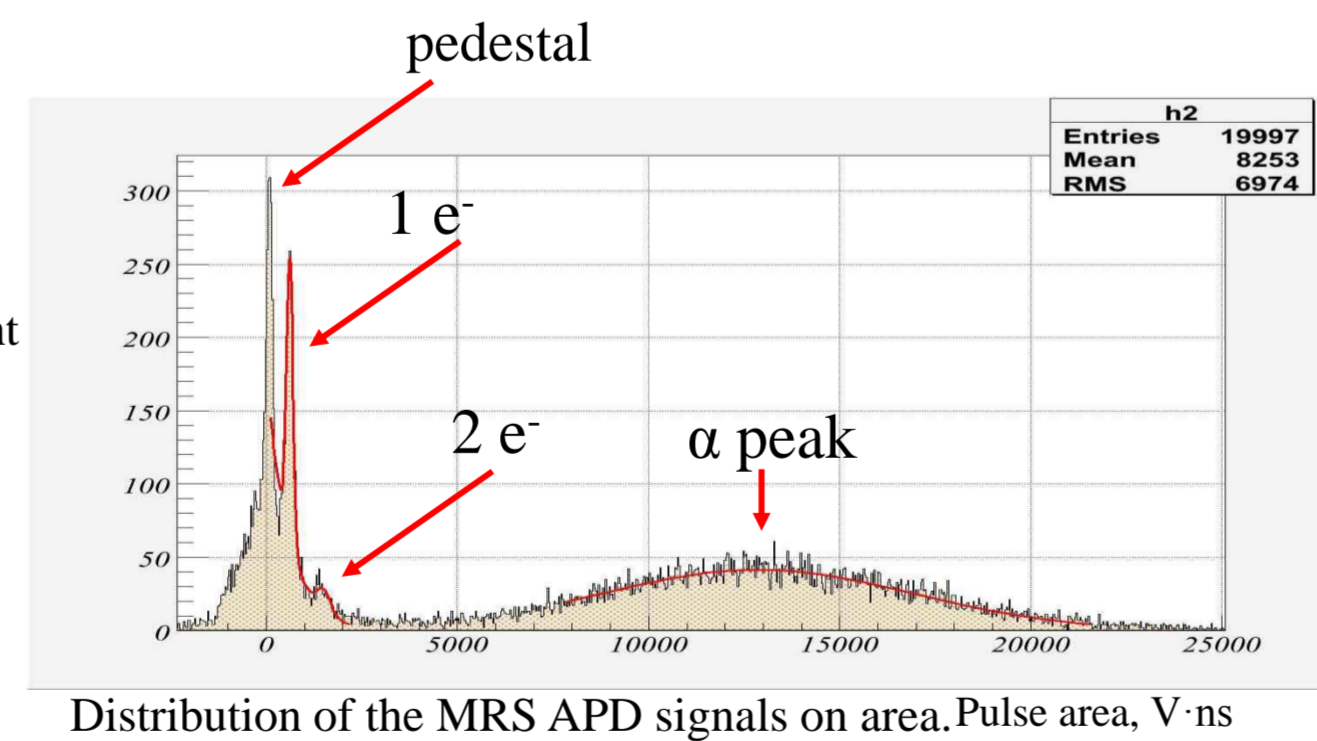
Before filling the chamber, xenon had undergone purification procedure with a Mykrolis Megaline purifier. Signals from the MRS APD were amplified and, together with the PMT signals, arrived to the inputs of the LeCroy LT344 digital oscilloscope having a digitization frequency of 500 MHz. The signal waveforms were stored in a computer for subsequent processing.

Data analysis



Data analysis included event-by-event calculation of the areas of the recorded signals (both the MRS APD single-cell noise ones and those produced by scintillation in the LXe) and plotting the area distributions. A ROOT code was used for data processing. Typical waveforms of signals from the PMT and from the MRS APD are shown on the left figure. The shape of the PMT signal is in accordance with a decay time of LXe scintillation (27 ns). The decay time of the MRS APD signal is defined by a cell capacitance and a resistance of a cell polysilicene resistor

The distribution of area of MRS APD signals has a peak corresponding to the energy of alpha particles the right panel part of figure. The left panel part of right figure shows a typical noise distribution (with random triggering) where the peaks corresponding to one or two fired cells are visible. The single cell signal area was used then to obtain the number of the fired cells corresponding to the alpha peak position.



Distribution of the MRS APD signals on area. Pulse area, V ns

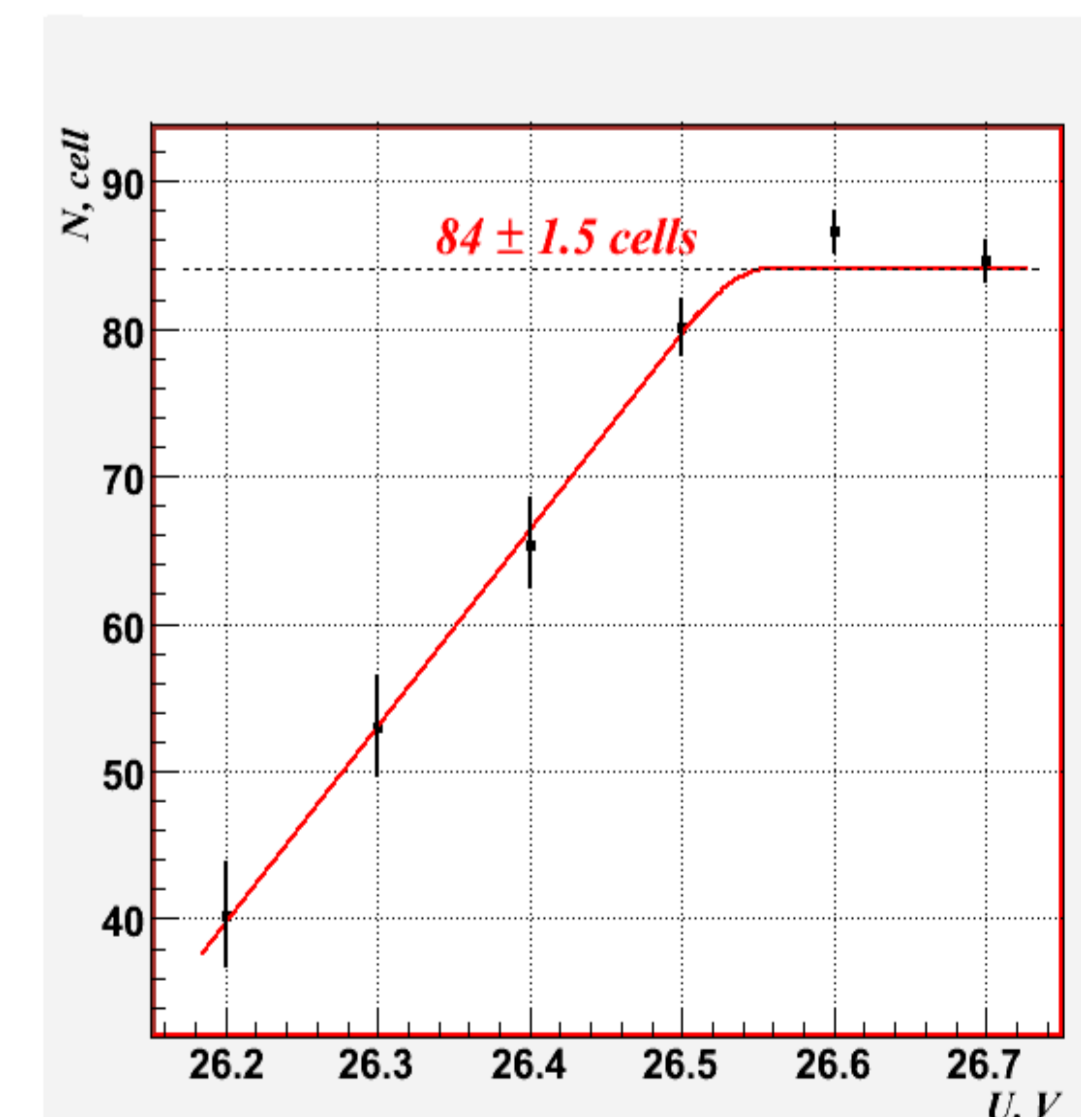
PDE calculations

To ensure that the photo detector did operate at a plateau of photo detection efficiency (PDE), the signals were recorded at different bias voltages. The voltage at which the number of fired cells in the alpha peak position reached a plateau was chosen as an operation point. In the first and second series of measurements (figure a and figure b, correspondently), this was at 26.4 V and 26.6 V with a plateau value of $N_{\text{cells}} = 27.0 \pm 0.5$ and $N_{\text{cells}} = 84.0 \pm 1.5$. To obtain the real number of photoelectrons N_{phe} one must correct these numbers for the cross-talk between MRS APD cells. The correction is made with a formula:

$$N_{\text{phe}} = N_{\text{cells}} (1 - \alpha)$$

where a cross-talk probability α is obtained from the ratio of the peaks corresponding to one and two cells in the noise distribution

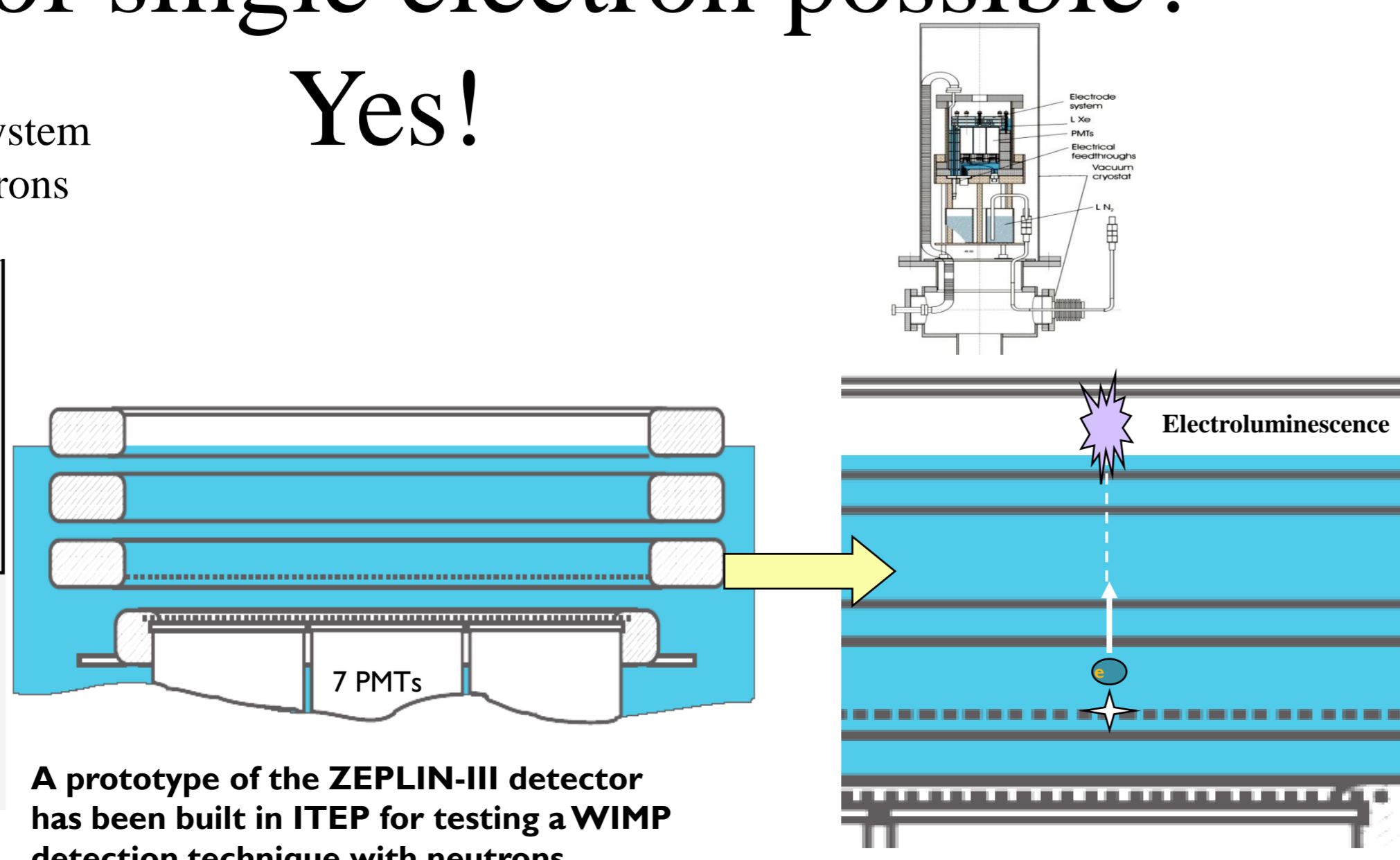
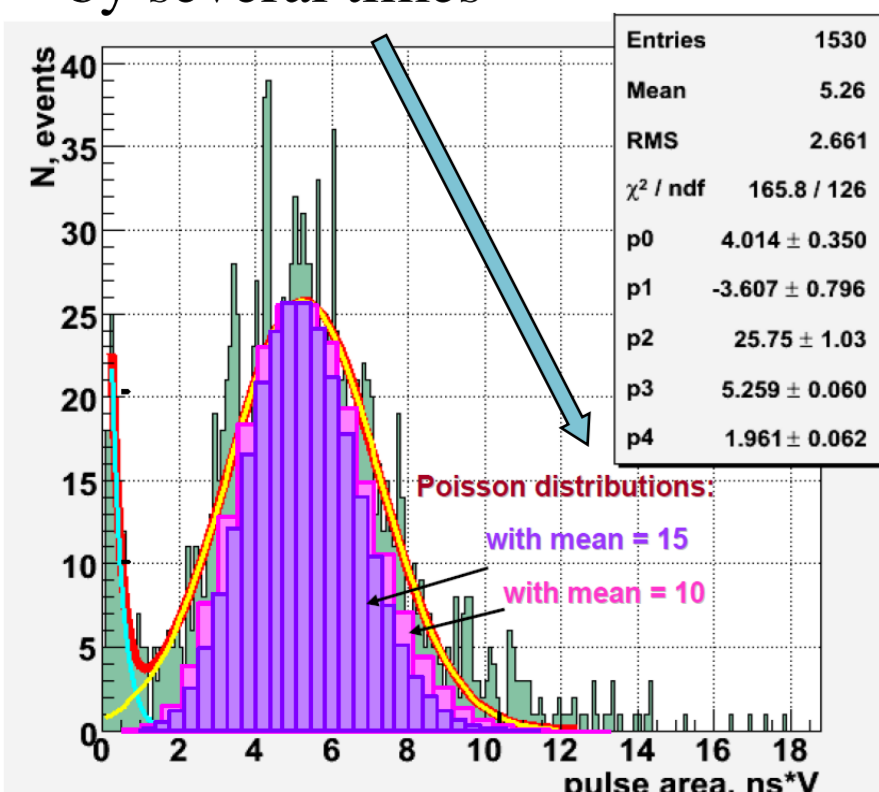
Series of measurements	N_{cells}	PDE ⁰ , %
p-terphenyl is sealed between two optical windows	24±0.5	9.7±1.2
p-terphenyl is coated by a poly-paraxylene film.	72±1.5	8.4±1.1



Is detection of single electron possible?

Yes!

We expect with use proposed system to increase number photo electrons by several times



Status of experiment

