A study of the new hemispherical 6-dynodes PMT from Electron Tubes

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Abstract

The main electro-optical properties of the new fast and low gain hemispherical *PMT* from *Electron Tubes Ltd.* have been studied. This *PMT* is considered as photosensor for the camera of the $17m$ diameter air Cherenkov telescope MAGIC to be installed in two years at Canary island La Palma. The dependence of the single electron resolution and afterpulse rates as well as linearity on the interdynode voltages have been studied in detail.

Key words: Photomultiplier tubes; Air Cherenkov gamma ray telescopes; Single electron response; Afterpulsing; Linearity

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1 Introduction

Ground-based air Cherenkov telescopes (ACT) are currently the most promising instruments in the field of very high energy gamma ray astroparticle physics and many new projects are under consideration or already in the construction phase. One of the main goals is to measure the shape of the gamma ray energy spectra in the window between the upper energy limit of the satellites, e.g., $\sim 20 GeV$ and the energy threshold of the ground-based ACTs presently in use ($\sim 250 GeV$). This energy gap is the last unexplored window between $10^{-5} eV$ and $10^{20} eV$ energy in astronomy. Also, the current observations below and above this window indicate that fundamental changes in production, respectively gamma interaction with cosmological low energy photon fields must happen. Therefore the exploration of this window may lead to new understandings of many topics of fundamental astrophysical interest.

The $17m$ diameter MAGIC telescope [1], currently under construction, shall allow in its first phase (in which it will be equipped with a classical PMT image camera) to reduce the energy threshold down to $\sim 30 GeV$. This goal implies a challenging design for the camera. In particular the choice of photodetectors and state-of-the-art electronics design are very important subjects.

2 New Photomultipliers from ET

The specific requirements for MAGIC's photosensors are: i) camera diameter of $4°$ with a fine pixelized central section of $2.6°$ diameter; ii) central section pixel diameter of $30mm$, i.e., $0.1°$; iii) active area coverage of 100%; iv) very fast pulse detection with signal width close to $1nsec\ FWHM$; v) single photoelectron (PE) detection; vi) dynamic range up to $5{\cdot}10^3 PE$s; vii) little aging in the presence of night sky light background or moon light; viii) rejection of large angle stray light; ix) high quantum efficiency (QE) between 300 and $500nm$; x) low afterpulse rate; xi) high collection efficiency between photocathode and first dynode ($D1$); xii) acceptable price. Some requirements are contradictory or technologically not achievable and some compromises have to be made.

The new compact $25mm$ diameter photomultipliers from $Electron\ Tubes\ Ltd.$ (type $9116A$) was found to match most of our requirements. The PMTs fulfil the geometrical requirements of the central part of the MAGIC camera. They have a high blue sensitivity Rubidium-bialkali photocathode and 6 circular focused dynodes. The spectral response of these tubes has been measured in our lab (Fig.1) and has been found to be conventional for this type of photocathode and glass input window. [1]

The most attractive feature of these photomultipliers is their hemispherical

[1] The latest version of these tubes has a UV glass envelope what improves QE below $350nm$.

$\approx 2\pi$ str entrance window. This option is interesting for many applications which require a high aperture solid angle collection area. The usual design to avoid dead space between PMTs in ACT cameras is to use Winston cones [2] (or similar constructions) in front of the photodetectors. These cones help in two goals: firstly to concentrate without losses the light entering the (hexagonal) pixel entrance area onto the restricted (round) active area of the photocathode and secondly to reject the background light outside the aperture defined by the mirror dish.

A simple geometrical consideration shows that by placing a hemispherical photodetector at the output of the Winston concentrator one can improve the effective QE for a semitransparent photocathode because a fraction of Cherenkov photons will not be absorbed at the first surface and may have a second chance for absorption (Fig.2). Our estimates show that for a real cell design we can gain up to $\sim$20% in the effective QE although some geometrical optimization is needed. Indeed, the measurement of the QE using a $1mm$ beam spot from a monochromator pointed along and across the PMT axis exhibits a clear improvement for the latter case (Fig.3).

On top of that, as a consequence of the true hemispherical photocathode these PMTs are very fast and provide signals with rise time $\sim 700psec$ and $FWHM<$(1-1.2)$nsec$ enabling an efficient coincidence trigger design for the detection of Cherenkov flashes of gamma showers and suppresion of background light. Another contribution to the high speed comes from the use of only 6 stages and low gain avoiding space charge effects and half the interdynode time spread compared to conventional high gain PMTs with 12 stages.

3 Gain and Single Electron Response

Using photomultipliers in the low gain regime is an attractive and necessary concept for many experiments with high light background. It becomes an absolutely crucial requirement for photodetectors in the image camera of large diameter ACTs where the background light might induce PE rates in excess of a few hundred MHz. The Light of the Night Sky ($LONS$) has been measured to be $\sim 2 \cdot 10^{12} photons/m^2 \cdot str \cdot sec$ [3] causing large, DC anode currents and high afterpulse rates. In the case of operation in the presence of moonlight [4] this rate can increase easily by up to a factor 30. Using a low gain PMT and an AC-coupled fast, low noise preamplifier allows one to operate the PMT with manageable anode currents and detect the small Cherenkov light flashes down to a few PEs level. If we want to keep the PMT current flow due to $LONS$ on the level of, say, $\sim 1 \mu A$, then the PMT gain should not exceed (10-20)$\cdot 10^3$.

The foreseen electronic chain in the camera includes a fast low-noise amplifier and an optical analog link able to transmit without distortion the extremely fast PMT signals to the counting room. There, the signal is splitted into two branches:

— a fast one is used by the trigger coincidence logic unit and

— a slower one, conveniently shaped, is digitized by a $300 MHz$ $FADC$.

More detailed information about the described scheme and recent progress on the fast optical analog transmission can be found elsewhere [5].

Use of the PMT at such a low gain implies the need for a fast and low noise amplifier able to provide a desirable dynamic range while not disturbing noticeably the extremely fast PMT pulse shape and having at the same time a noise figure small enough to keep the single PE resolution capability of the PMT. These amplifier requirements will now be discussed in more detail.

— The dynamic range is given, on one hand, by the single PE signal being well above noise and on the other hand by the maximal expected signal which corresponds to a $\sim 10 TeV$ gamma shower (from low zenith angles) and is up to $5 \cdot 10^3 PE$s per camera pixel.

— The gain should be moderate, i.e., in our application a factor 7 for a PMT gain of about $10k$ and $1mV$ single PE signal with $FWHM \approx 1 nsec$.

— The amplifier noise level is dictated by the need to have a total Equivalent Noise Charge $ENC \leq 0.2$ electrons to be able to resolve the single PE signals. That implies to have an amplifier output noise of $\sigma_{noise} < 200 \mu V$.

Such parameters have been achieved by a modified single stage transimpedance preamplifier [6] on the basis of the $AT41533$ GHz silicon bipolar transistor.

The ability to resolve single PE signals is an important requirement for ACT photosensors since this feature allows for a relatively easy signal calibration. It should be noted that, in spite that these PMTs have not been especially designed for such a goal, most of them have a high enough $D1$ gain to provide good single PE response. Fig.4 shows the single PE spectrum obtained with a PMT gain of $\sim$20k. The spectrum shown can be fitted by two Gaussians and gives a total ENC $\sim$0.15 electrons.

Keeping in mind the noise introduced by the amplifier, one could improve the single PE response, for instance, by increasing the gain at $D1$. The dependence of the single PE resolution on the voltage between the photocathode and the $D1$ has been studied using a charge amplifier [7] with a shaping time (RC-CR) of 20$nsec$. Since this amplifier has a lower ENC value due to its limited bandwidth, it allows one to reduce $V(Photocathode - D1)$ to very small values but showing still a clear single PE peak. For these studies the $V(D1 - anode)$ has been fixed keeping uniform interdynode voltages. The fit results of the single PE and pedestal peaks have been used to define the single PE resolution (Fig.5). Several PMTs have been studied and it has been found that, in spite of having some resolution spread, all of them reach a "plateau" at $\approx$400Volts. This voltage was achieved by a (3R-R-R-R-R-R-R) distribution across the PMT for the overall HV providing the $\sim$20k PMT gain that we need. In our test we used an R of 200$KOhm$ and blocked the last two dynodes by 10nF. For example, the spectrum on Fig.4 has been obtained with such a base and HV=1100V which gives a PMT gain of 19k.

4 Afterpulsing

Having a high amplification at the first PMT stage contradicts the requirement of having a low afterpulse rate. The effect of afterpulsing is a very important restriction for many types of applications where the PMT system is working in self-trigger mode. In particular for ACT cameras it has been understood [8] that the lowering of trigger threshold setting is limited by the afterpulse rate caused by single PE pulses due to $LONS$.

The reduction of the afterpulsing in PMTs requires, at first, the reduced overall PMT gain to limit in general the ion flow and, secondly, a decrease of the cathode to $D1$ voltage. Fig.6 shows the time-probability distribution of afterpulses for ET PMT-$9116A$ at a gain of $20k$. In this figure, the signals produced by fast LED flashes are superimposed. The initial light pulses are followed occasionally by afterpulses which show up as a signal enhancement on our digital scope screen. There is a clear afterpulse concentration at about (350-400)$nsec$ after the main LED pulses. It corresponds roughly to the characteristic time needed by hydrogen ions [9] to travel from the $D1$ to the photocathode for the geometrical configuration of the ET PMT. The narrower signal enhancement at ∼80nsec is probably caused by the mesh placed in front of the $D1$. One may conclude that for these PMTs and our gain conditions the most important afterpulse source is the PMT front-end electron-optics part. Due to that, the cathode to $D1$ voltage is the most important parameter to keep the afterpulsing under control.

The effect of $V(Photocathode - D1)$ on the afterpulse rates has been studied in detail by measuring the probability to have an afterpulse with amplitude above a certain threshold originated from a single PE pulse. Such an approach allows to predict the accidental trigger rate due to the constant light background at a given threshold setting in each individual trigger photocell. The self-trigger mode has been used to obtain the spectra of the dark current pulses on a charge ADC with sensitivity $0.1pC/count$ for different values of $V(Photocathode - D1)$. In the remaining dynode system an uniform interdynode voltage has been used with $V(D1 - anode)$ fixed. These spectra (Fig.7) show clear tails of large amplitudes due to afterpulses above single PE dark pulses which mainly correspond to dark photocurrent. A gaussian fit has been used in the region of single PE peak and the values obtained are used to estimate the excess of the right-side spectrum over the predicted gaussian behavior. It should be noted that in such procedure we assume that there are no afterpulses with single PE amplitude, which is not completely correct and may lead to an underestimation of the afterpulsing [2]. Nevertheless since in practice we are mainly interested in the trigger threshold, which in any case will be above $1PE$, this method allows us to obtain directly the probability to observe afterpulses caused by single PEs as function of the trigger threshold (Fig.8). The normalization for both scales on this figure is done with the single PE peak parameters obtained by the fit mentioned above.

[2] More detail study of afterpulses using complete analysis of waveforms recorded by $FADC$ is the subject of oncoming report.

One of the conclusions we can draw from this picture is that the ($3R$-R-R-R-R-R-R) voltage distribution for the ET PMT-$9116A$ is a good compromise from the point of view of both single PE resolution and afterpulsing for our application.

5 PMT linearity

At a PMT gain of $20k$ we are interested in collecting up to $5{\cdot}10^3$ PEs per pixel for the highest energy gamma showers. Therefore the PMTs have to be linear up to a $16pC$ pulse. Concerning the possible limitations in the PMT linearity we should distinguish between the gain variations due to changes of background ($LONS$) current flow and the eventual limitations in the amplification of fast pulses.

The first effect leads to a voltage redistribution across the PMT base mostly because of the increased PMT current drawn by the last dynodes and can be easily stabilized by the use of an active voltage network at these stages. In what concerns the second effect, the pulse linearity depends on the voltage configuration of the last dynodes and anode but is ultimately limited by the specific PMT technology. Usually, tapered base voltage distributions are used to remove the volume charge accumulated in the last stages during fast pulses.

In order to optimize that voltage distribution for the required linearity a two LEDs differential (L+ΔL) method has been used. Fast blue LEDs from $Nichia$ $Ltd.$ were used to produce (3-5)$nsec$ light pulses simulating Cherenkov flashes from high energy gamma ray showers. In such a measurement the signal from one LED (ΔL) is fixed while the signal from another (L) is varied. It allows to measure quite precisely the fractional deviation from linearity as the main signal L grows. For the following study the PMT gain has been adjusted to be $20k$ with a "standard" ($3R$-R-R-R-R-R-R) base which requires an overall $HV{\sim}1.1kV$ and provides interdynode voltages of $\sim 120V$.

The fractional deviation from linearity for the "standard" base is plotted in Fig.9 (open circles). The increase of the voltage across only the last dynode to anode (black triangles) has a marginal effect on the linearity behavior. We found that both last interdynode voltages are equally important and that a voltage increase by just $50V/dynode$ extends the pulse linearity up to the amplitudes we are interested in [3]. In part this reflects the fact that the PMT anode is placed in between two last dynodes. In all the above measurements the gain drop due to the increase of the voltage on the last stages has been compensated by adjusting the overall HV.

6 Conclusions

The electro-optical properties of the new fast hemispherical ET PMT-$9116A$ have been studied and the interdynode voltages have been optimized to satisfy

[3] It should be noted that in this study we have not tried to reach the highest possible linearity achievable for these tubes, which is very likely somewhat higher and is eventually limited by the dynode material and structure.

the requirements for the camera of MAGIC, a $17m$ diameter air Cherenkov telescope currently under development. It has been shown that the new PMTs with a gain of (1–2)$\cdot 10^4$ followed by a low noise transimpedance amplifier and a fast optical analog transmission link are able to fulfil the experimental requirements.

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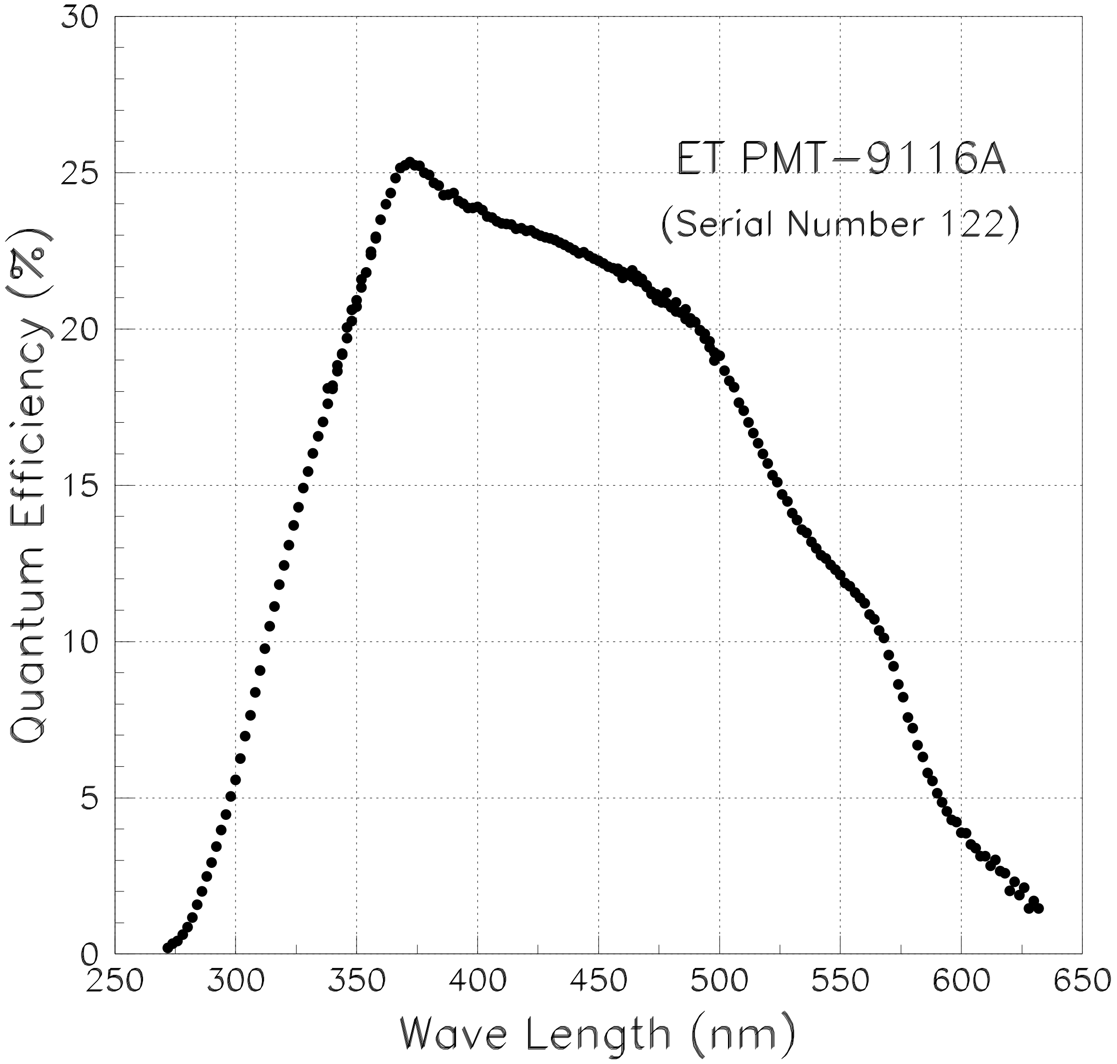

Fig. 1. Measured QE of ET PMT-9116A.

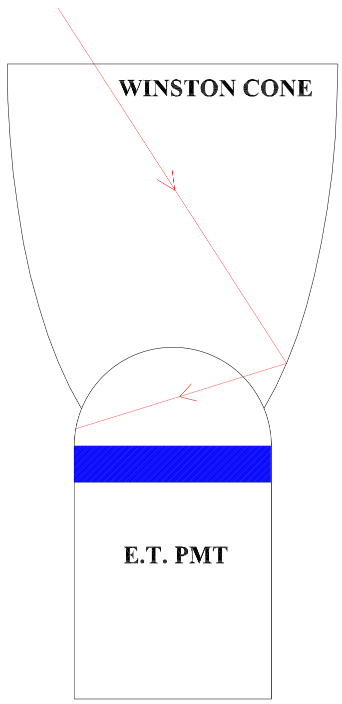

Fig. 2. A conceptual design of an ACT photocell using PMTs with hemispherical input window.

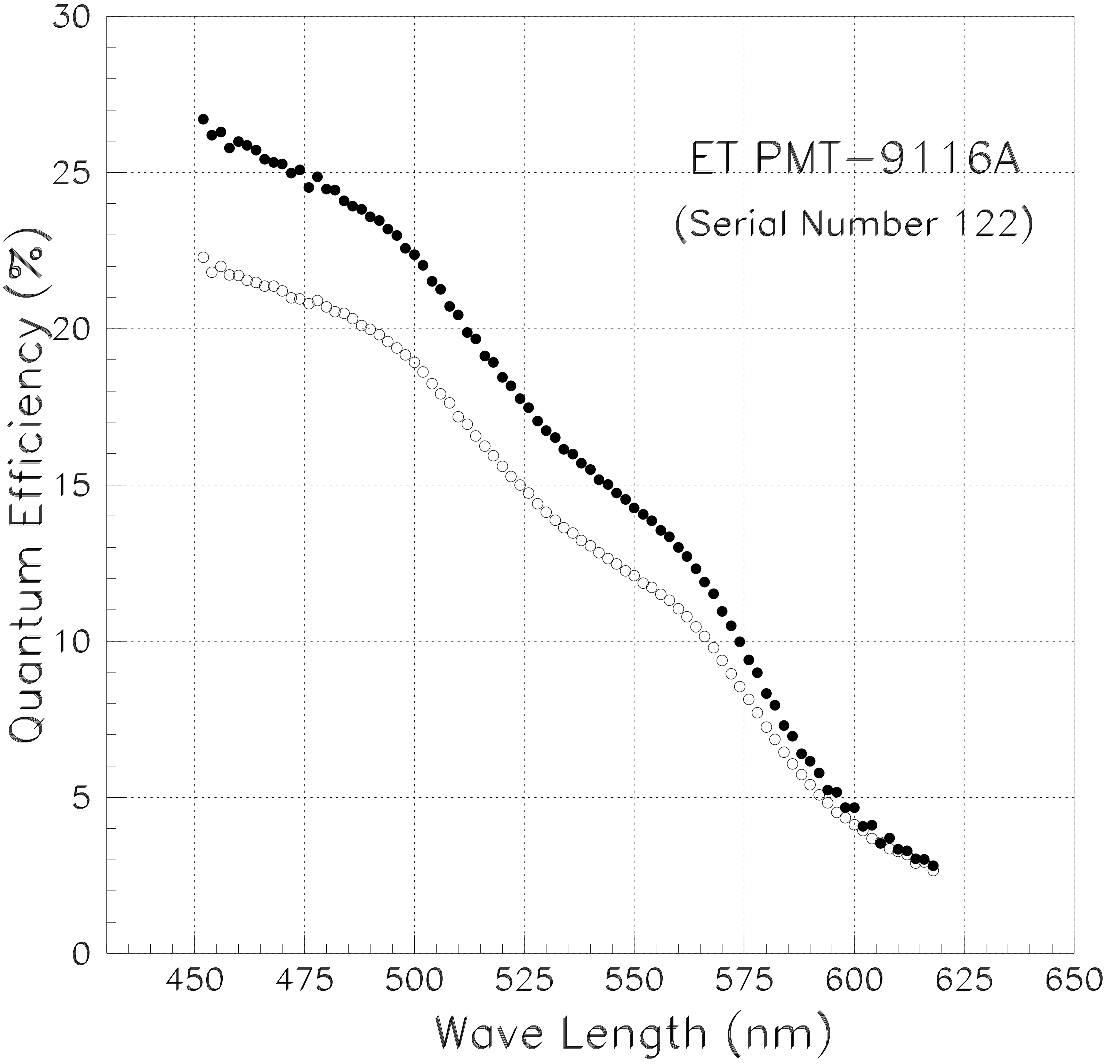

Fig. 3. Measured QE of the hemispherical ET PMT using a $1mm$ light beam pointed along (open dots) and across (black dots) the PMT axis.

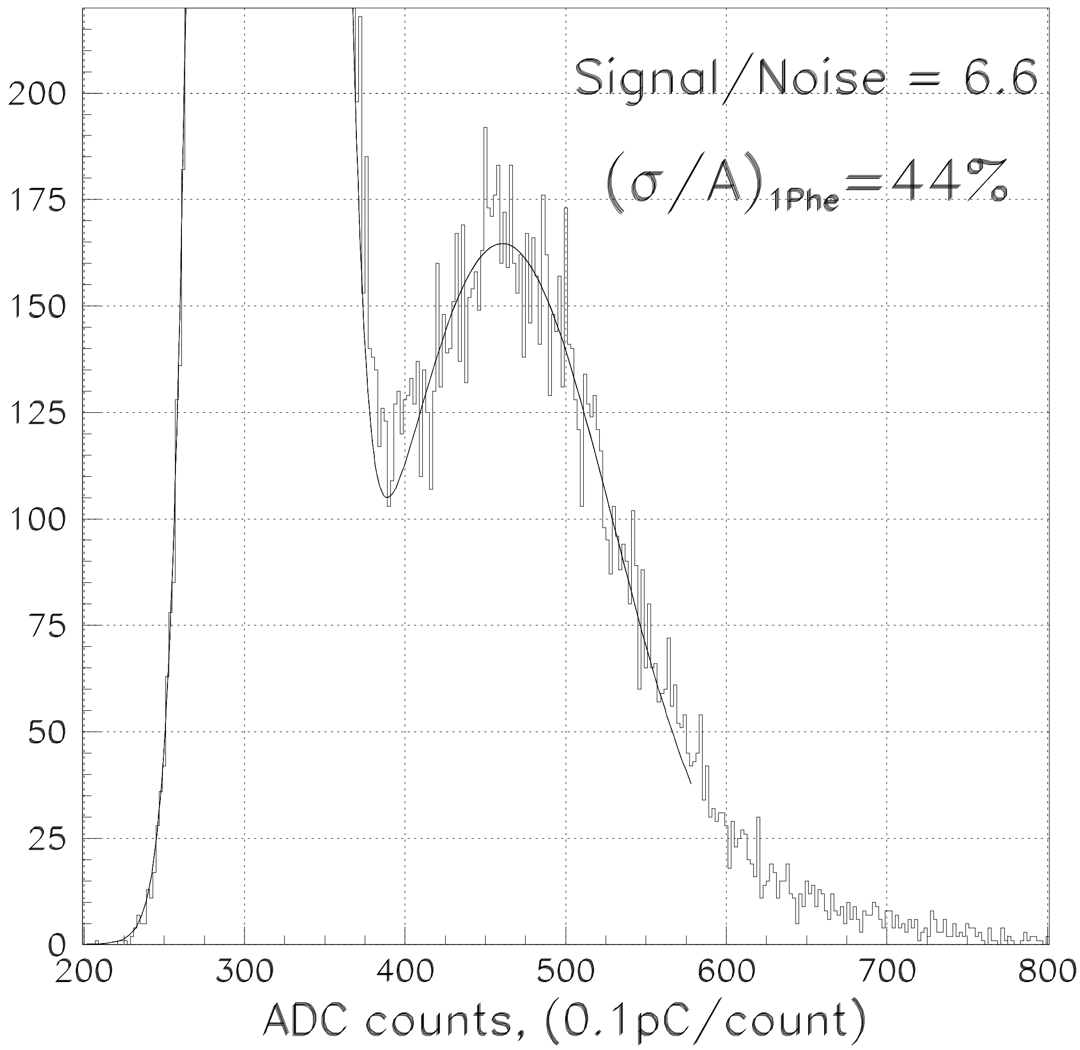

Fig. 4. Single PE response of a ET PMT with $\sim 19k$ gain followed by a fast transimpedance amplifier. See the text for more detail.

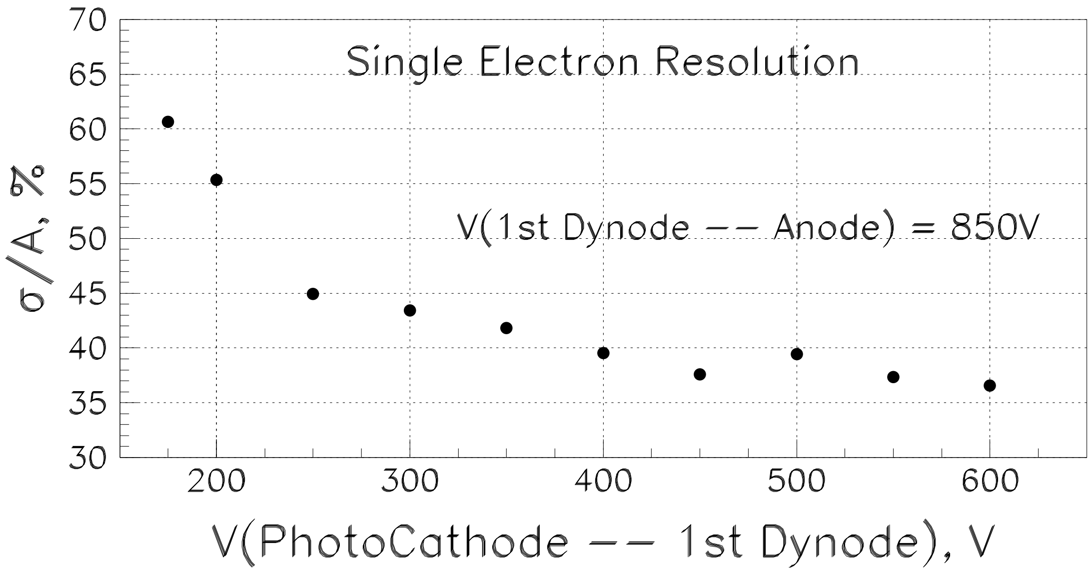

Fig. 5. Typical dependence of single PE resolution on $V(Photocathode - D1)$ for the ET PMTs.

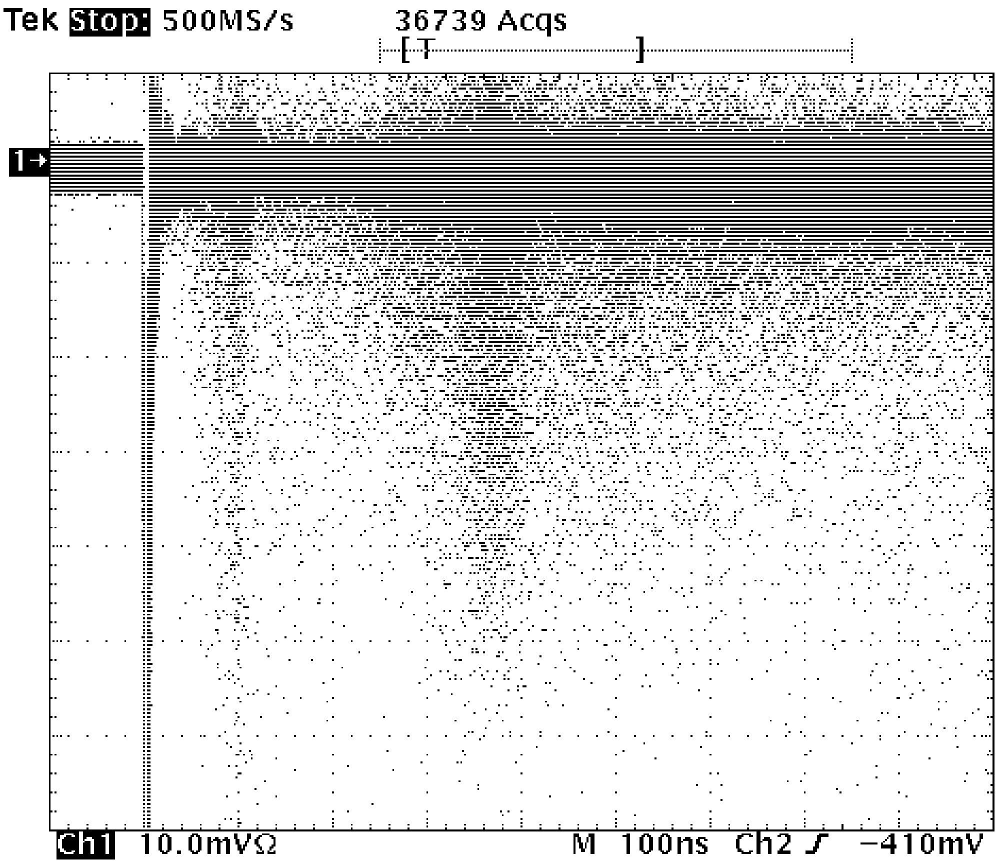

Fig. 6. Time-probability distribution of afterpulses for $ET\ PMT$ at $\sim 20k$ gain. In this measurement the amplitude of single PE signal is about $3.5mV$.

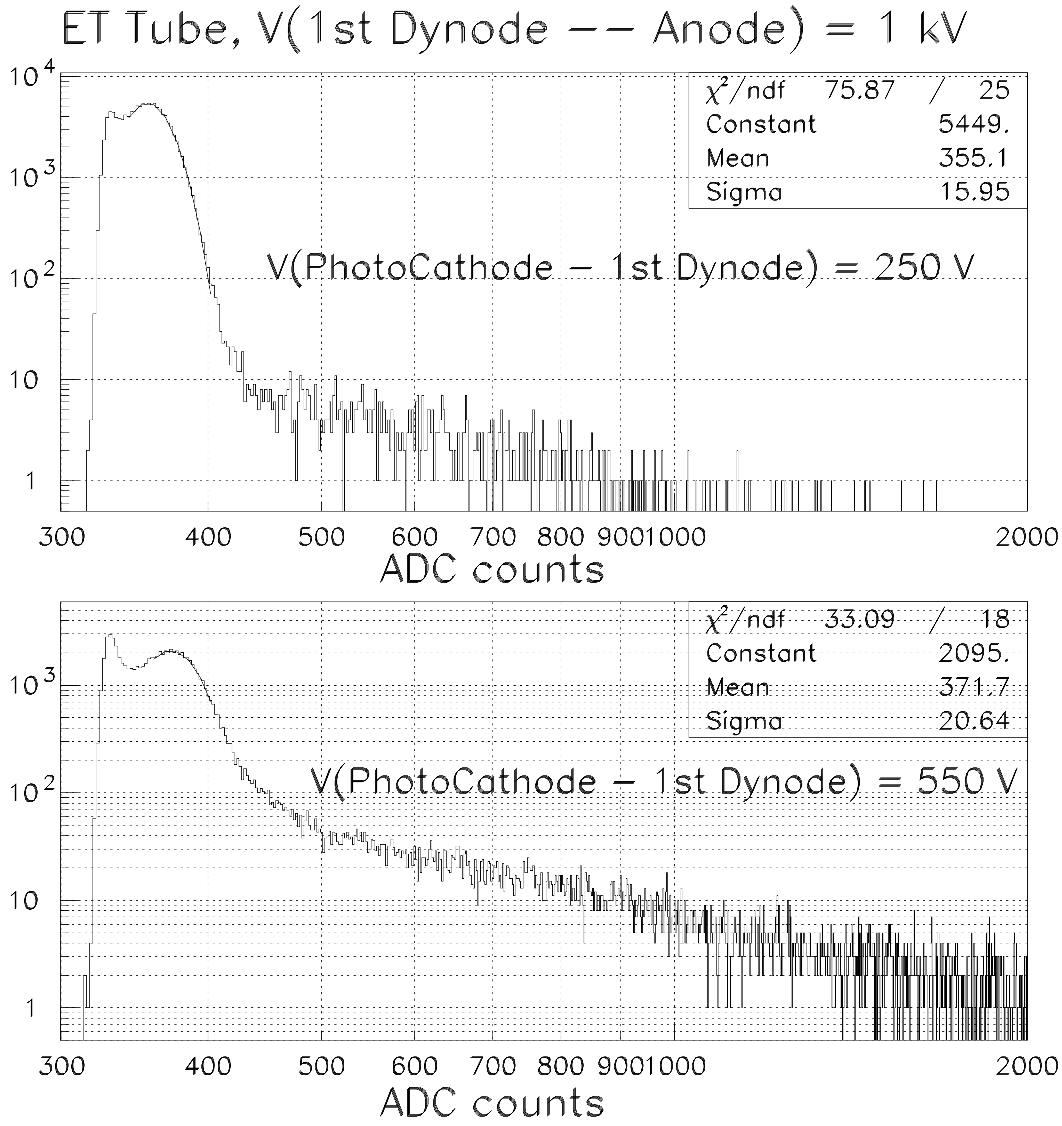

Fig. 7. An example of the *ET PMT* dark current pulse spectra for different $V(Photocathode - D1)$.

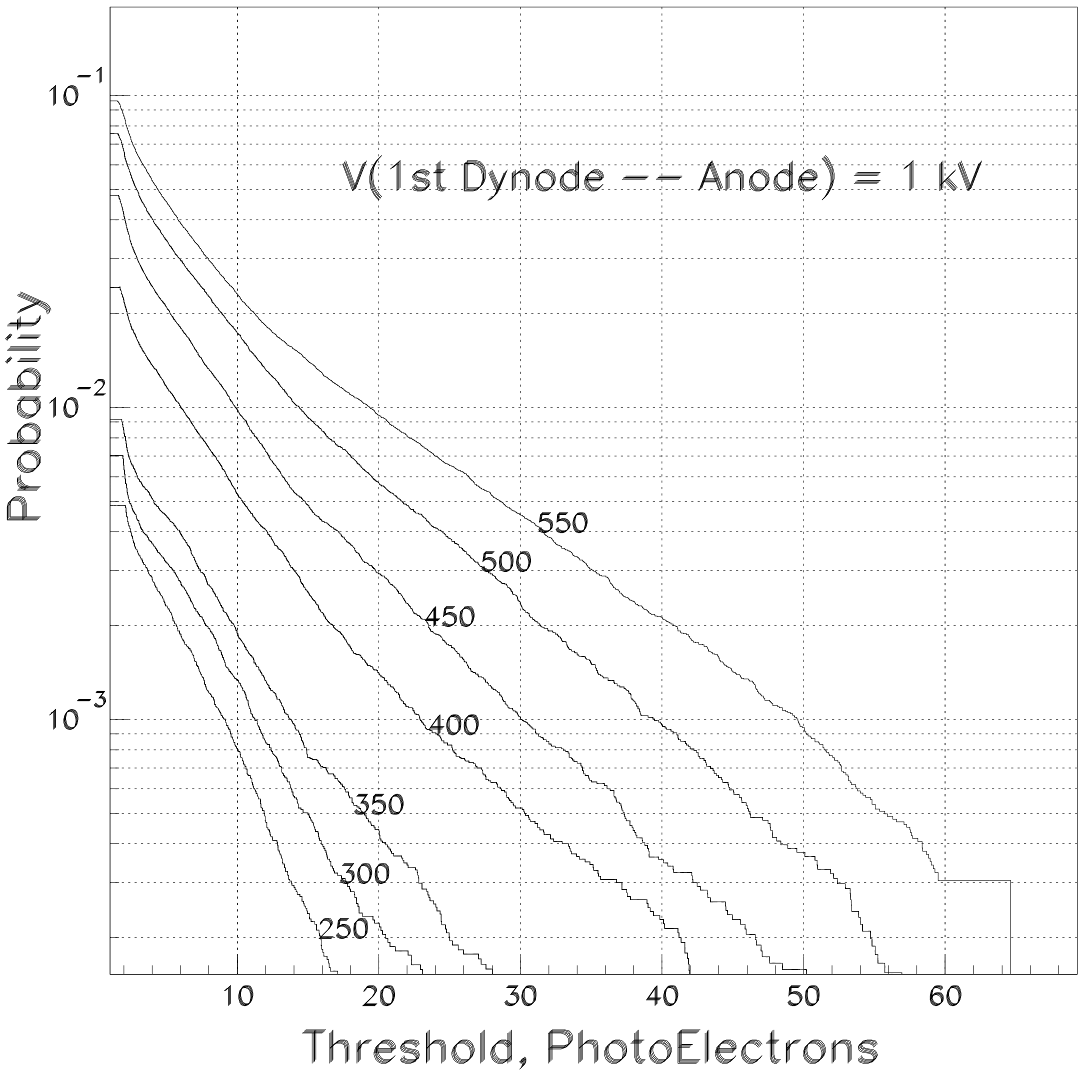

Fig. 8. Probability to observe afterpulse caused by a single PE as function of preset threshold. The numbers at the plotted lines indicate $V(Photocathode - D1)$ in Volts.

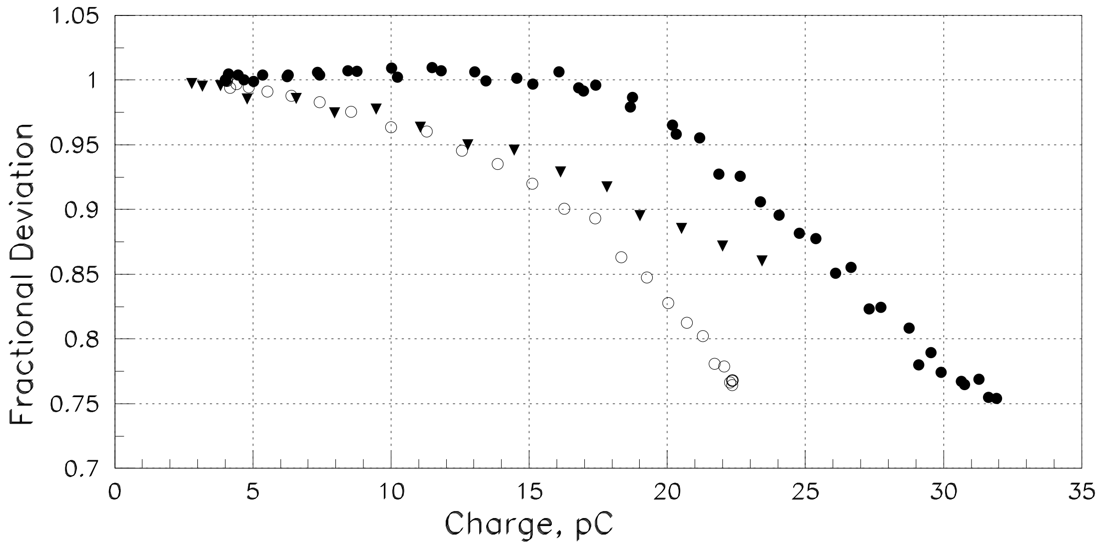

Fig. 9. Measured fractional deviation from linearity for *ET PMT* with $20k$ gain in pulse mode. *Open circles:* linear base chain, $V_{interdynode} = 120V$. *Black triangles:* $V_{6-dynode} = 175V$. *Black circles:* $V_{5-dynode} = 350V$, $V_{6-dynode} = 175V$.