Constraints in using APDs in Air Cherenkov Telescopes for γ-astronomy

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Abstract

The constraints in using *APDs* for future air Cherenkov telescope cameras due to the limited gain and the different electronic noise sources are discussed. Different operational strategies are presented. It is shown that in spite of the limitation to resolve single photons these devices could be used in future image cameras of Cherenkov telescopes.

Key words: Photosensors for Cherenkov Telescopes; APD; Excess Noise Factor

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1 Introduction

High energy γ-ray astronomy is currently in a rapid expansion. The most promising detectors are air Cherenkov telescopes (ACTs) with finely pixelized focal plane cameras. Current efforts concentrate on lowering the threshold down to ~20GeV where satellite detectors become insensitive due to area constraints. Fast, high quantum efficiency (QE) photosensors are the most promising element for future improvements as mirror sizes are already close to their technical limits [1].

Avalanche photodiodes (APD) are currently under consideration as a possible photodetector option for some of the new ACT image cameras [1]. The main advantage of such a photosensor is its intrinsically high quantum efficiency (QE>70%) and wide spectral range which should allow to reduce the trigger threshold of the telescope and to increase the image reconstruction efficiency just above threshold.

One of the best commercially available APD at the moment is the one produced by the RMD company [2]. Table 1 presents some important parameters for noise analysis of the RMD high gain APDs [2]. There devices have been

[1] This study has been carried out in connection to the proposal for the 17m diameter MAGIC telescope but the findings can easily be transferred to other ACTs or even air fluorescence detectors.

[2] Radiation Monitoring Devices, Inc., Watertown, USA.

advertised as approaching the ability to detect single optical photons [3] and that has been our main reason for chosing them for this study.

One of the characteristics of standard APDs working in linear mode is the important amplification noise due to the limited amplification per impact ionisation step. That noise is quantified by F, the excess noise factor (ENF), which in the specific case of the APDs, according to McIntyre's theory [4], can be expressed as:

$$F = k_{eff}M + (2 - 1/M)(1 - k_{eff}), \tag{1}$$

where k_{eff} is roughly speaking the effective ratio between the hole and the electron ionisation coefficients and reflects the correlation between the electron and hole amplifications. It is evident from (1) that even in the ideal case when only one type of carriers participate in the avalanche ($k_{eff} = 0$ in the case of electrons) the ENF can not be less than two at the high gains we are interested in. That implies that, by no means, the signal from individual photoelectrons can be resolved. In addition, as a result of the poor first amplification step ($1 \rightarrow 2$) the probability distribution of gains for single photoelectrons has an exponent-like falling shape [5]. Therefore, no single photoelectron peak can be expected.

However, the ability to see a single photoelectron peak, for example for system calibration, is not really a basic need of the ACT system to cope with its physics program. Furthermore, in most of the applications dealing with low level light detection in the presence of a large light background, the actual system performance will be anyway limited by the Poisson nature of the background.

Taking all the above considerations into account and using as a reference the APD parameters listed in table 1 we have performed several studies to check how such devices might be used to cope with the camera needs of future ACTs. This is the main subject of this work.

2 Noise consideration for APD+Preamplifier system

In the following we assume the use of a fast charge sensitive preamplifier with a $JFET$ input and a shaping amplifier leading to a bandwidth B. The rms detector shot noise current density for a bandwidth B is given by:

$$i_d/B^{1/2} = [2q(I_S M^2 F + I_{edge} + I_{bulk} M^2 F)]^{1/2}, \tag{2}$$

where q is the electron charge, M is the APD gain, I_S is the signal of interest, I_{edge} is the surface leakage current which yields conventional shot noise and I_{bulk} is the bulk leakage current which is amplified and together with I_S yields excess shot noise.

Given the small number of photoelectrons expected in $ACTs$, the description of the signal in terms of a superposition of single photoelectron pulses is preferable to be considered instead of the current. According to Campbell's theorem the sum of mean square contributions of all preceding impulses equals the variance. It gives for incoming current I_{in} and amplifier with semi-gaussian shaping resulting variance $\sigma^2 = I_{in}\tau/q$, where τ is amplifier time constant [3]. In such a case the total signal fluctuation in Equivalent Noise Charge (ENC) if we exclude the intrinsic Poisson fluctuations of the incoming signal N_{signal} is

$$ENC^2 \approx (F-1)N_{signal} + F\frac{I_{bulk}\tau}{q} + \frac{I_{edge}\tau}{q}\frac{1}{M^2} + C^2_{APD}\frac{4k_BT}{1.5g_mq^2\tau}\frac{1}{M^2} \quad (3)$$

where the last term is the amplifier ENC and C_{APD}, T, k_B and g_m are the detector capacitance, temperature, Boltzmann constant and transconductance of the JFET preamplifier respectively.

For our calculation we have taken the measured data on ENC for an existing $JFET$ preamplifier based on the transistor $KP340A$[6] and we have scaled it according to the simple ($\sim C^2_{APD}/\tau$) behaviour for the real APD capacitance and shaping time suitable for an ACT camera [4].

[3] This formula is precise for ideal "cusp" pulse shape but could be used also for semi-gaussian shaping as realistic approximation of this ideal case.

[4] It should be mentioned that this $JFET$ transistor can not be considered as the best possible choice (in fact we shall use, whenever possible, a transistor with capacitance matched to the capacitance of the selected APD).

3 Optimal gain and cooling for a realistic APD system

In what concers the effects of cooling, in our calculations we have used the well known fact that the bulk leakage current decreases by a factor of two for every 10^{o}C reduction in the temperature. The actual quantitative prediction for the behavior of k_{eff} as function of temperature is not straightforward and depends on many considerations. Some detailed calculations along with precise measurements can be found elsewhere [7]. Inspired by these results, we have assumed here that k_{eff} does not change drastically with the temperature.

When talking about the implications of the use of APDs for low light level detection we shall consider two different classes of applications, in which it is necessary to use quite different detection techniques:

3.1 Single photoelectron detection

In this case the goal is to detect every photon incident in the detector. In such an application it is necessary to minimize as much as possible the pedestal width. Since there is no single-photoelectron peak, in such a case one is sensitive just to the right-hand side tail of the single photoelectron spectrum. Nevertheless, since the APD quantum efficiency is very high, the detection probability for single photons will still be high too. Here one should not worry about the excess noise coming from the useful signal and just put more gain to overcome the electronic noise. Fig.1(a) shows that the optimum gain needed is quite high, but it is still lower than the maximum gain attainable with the RMD APDs.

It is clear from Fig.1(a) that small shaping times would be preferable as less leakage will be accumulated during the measurement. Cooling is essential and helps substantially in this case especially for large surface APDs because it allows to reduce the dark current. Fig.1(b) shows that even for (10x10)mm^2 APDs, the requirements could be fulfilled at rather moderate cooling. Above certain gains, the increase of ENF starts to be dominant and limits the system performance.

3.2 Discrimination from night sky background

In this class of applications, which is more close to the ACT requirements, it is desirable to discriminate against single-photon-induced events (Light of Night Sky $-LONS-$ background in an ACT camera case) while at the same time detecting bunches of photons within a certain time duration with a high efficiency.

For example, the background from $LONS$ at La Palma where the MAGIC Telescope will be installed in the 300-600nm optical band has been measured to be [8] $(1.7 \pm 0.4) \cdot 10^{12} photons/m^2 \cdot sr \cdot sec$. For a $\sim 200m^2$ collection mirror, APD QE~70% and a preamplifier shaping time of 3$nsec$ we will have about

3 photoelectrons per 0.1^o pixel as a mean value of a Poisson distribution.

In this case the role of cooling is not so prominent and the improvements tend to saturate quickly as can be seen in Fig.2, where signal/ENC versus gain is presented. Having a variance of the background close to 3, we should put the threshold for useful signal above 2-3 σ to reduce the cell counting rate up to an acceptable level. The DC-level of the background signals could be eliminated by using AC coupling to the preamp electronic chain. There is no need in fact to discriminate between the bunches containing two and three or three and four etc. photons (photoelectrons) since, being deeply inside Poisson statistics at low level signals, we will anyway be, if not dominated at least largely influenced by its variance.

Let us consider 8 photoelectrons as a realistic value for the threshold setting in a single cell[5]. The optimal gain for such signals will be even lower and the signal-to-noise ratio even a bit better as the two upper broken lines in Fig.3 demonstrate. As we see, the accessible signal-to-noise ratio could be considered as acceptable but still, the natural Poisson fluctuations will be raised by a factor two.

Above, the worst case (large surface APDs) has been considered. If we are able to concentrate the light into the surface of a (5x5)mm^2 APD using, for

[5] The real threshold will depend in particular on the DAQ rate capability and the acceptable dead time.

instance, high refractive index lightguides, we can gain a lot because of both: reduction in the APD capacitance and in the bulk dark current. This is shown by the two upper solid lines on Fig.3. Finally, what can we expect if the k_{eff} will be reduced by, say, a factor 10? This case is illustrated by the set of lower curves in the same Fig.3 for two sizes of APD and for two different levels of signal.

4 Comparison between APD, PMT and Intevac HPD on trigger level

From the trigger point of view the most important criteria to choose the type of image camera photodetector are defined by the 1-st level trigger where we have to keep the threshold for useful signals as low as possible and, at the same time, trying to suppress the background rate up to an acceptable level for the DAQ. It is clear that, if all the other characteristics would be equal, the device with the highest QE will be preferable because of the features of Poisson statistics. In reality there is an interplay between different factors among which the most important ones are the QE, the ENF (which defines the broadening of the spectra) and the ENC of the electronic chain. We neglect the influence of the signal time spread assuming that all the devices under consideration (and their amplifiers) may provide the 3 nsec time response needed. The parameters used for this study (along with some comments) are presented in the table 2.

The simulated spectra for different photodetectors (Fig.4) agree with the ones observed in reality. In particular the PMT spectrum shows a single photoelectron peak with just a tiny indication of the second photoelectron. The HPDs allow more than that because of their extremely small ENF. All together proves that the parameters chosen for the analysis are reasonable. Note that these spectra are ENC-normalised and take into account the QE of the photodetectors. Therefore, the 3 photon light bunch spectra correspond to the expected background from $LONS$ in MAGIC for all the photodetectors considered.

The dependence of the "registration efficiency" on the threshold set, is shown in Fig.5(a). The curves marked as "3 photon bunch" should be considered as the background suppression efficiency. The dependence of the registration efficiency on the background suppression for different levels of signal is shown in Fig.5(b). One can see that up to factor 1000 in background suppression (what corresponds to about $300 kHz$ background rate in a single channel for a chosen time duration) the APDs give better signal registration efficiency than the PMTs. Further background suppression is limited by the nongaussian tails in the APD spectra discussed above. The same effect but with different physical origine takes place in the PMT system as well: due to afterpulses, the PMT 3 photon suppression curve presented on Fig.5(a) as single exponent has in reality a second shoulder which defines the background rate [9]. In Fig.5 we did not take this effect into account, although it clearly would make things much worse for PMTs (and for HPDs) for large background suppression requirements. Nevertheless, such afterpulses may affect the system performance even in the case of the Intevac HPD where special care has been taken at the design level to avoid afterpulses. If we believe that this effect is negligible for these devices, the Intevac HPD is the best choice from the trigger point of view since the curves in Fig.5(b) almost follow ideal Poisson features. It should be stressed, however, that having HPDs with the best ENF but with QE similar to usual PMTs we would bring the system performances down to the ones achievable in the APD case.

5 Conclusion

We have shown that, in spite of the inherent limitations of the "standard" APDs to resolve single photons in the high gain regime, they could still be used for ACT camera application in an effective way using the proper strategy providing better performances than ones achivable by a classical PMT system. This study shows also that, from the manufacturing point of view, the reduction of the Excess Noise Factor is the most promising direction.

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Breakdown Voltage, Volts	1855
Maximum Gain	10000
APD Area, mm^2	1 to 169
K-factor (k_{eff})	7.2×10^{-4}
Bulk Dark Current, pA/mm^2	4
Edge Dark Current (at Gain≈3000), nA/mm	24
Capacitance (at Gain≈3000), pF/mm^2	0.64
Parallel Resistance, GΩ·mm	120

Table 1
The parameters of RMD high gain APD at room temperature.

	APD	PMT	Intevac HPD
QE, %. Mean value (300-600)nm	70	10	40 GaAsP-photocahtode [10]
ENF	Depends on gain (formula 1).	1.2	1.025
Noise, ENC	See Capture 2	0.1 Defined by photocathode dark current and/or preamp noise.	0.3 Achieved with a 300 Mhz transimpedance amplifier[11].
Cooling	-60C^o saturates performances (Capture 3.2). Operation at room T is possible.	No.	No.

Table 2
The parameters for the analysis of the photodetectors at trigger level.

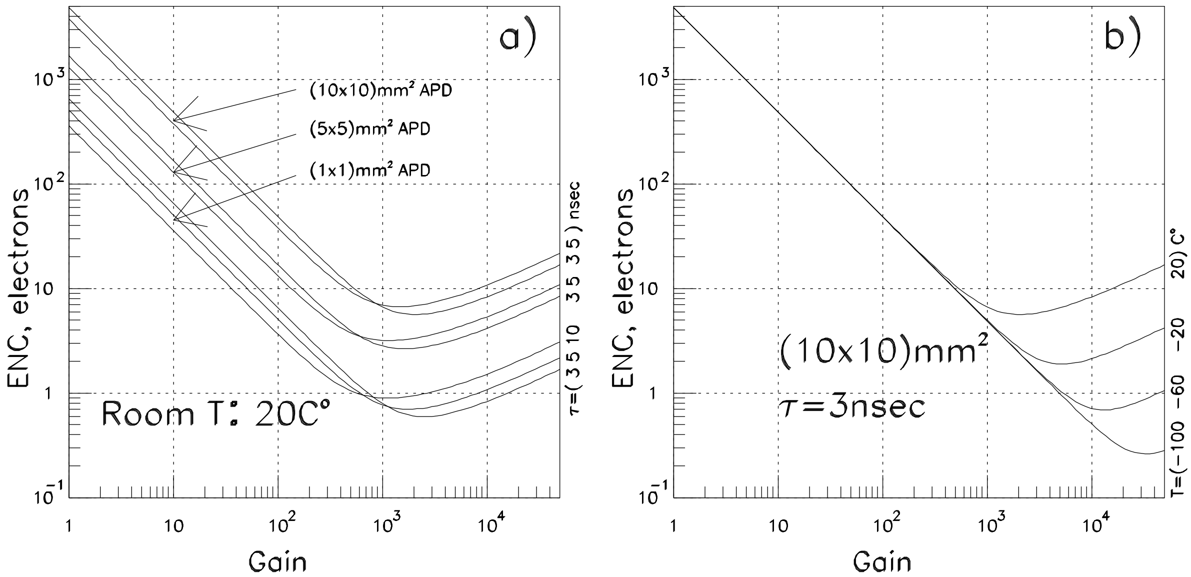

Fig. 1. Equivalent Noise Charge of the APD+Preamplifier chain as function of APD gain in presence no signal.

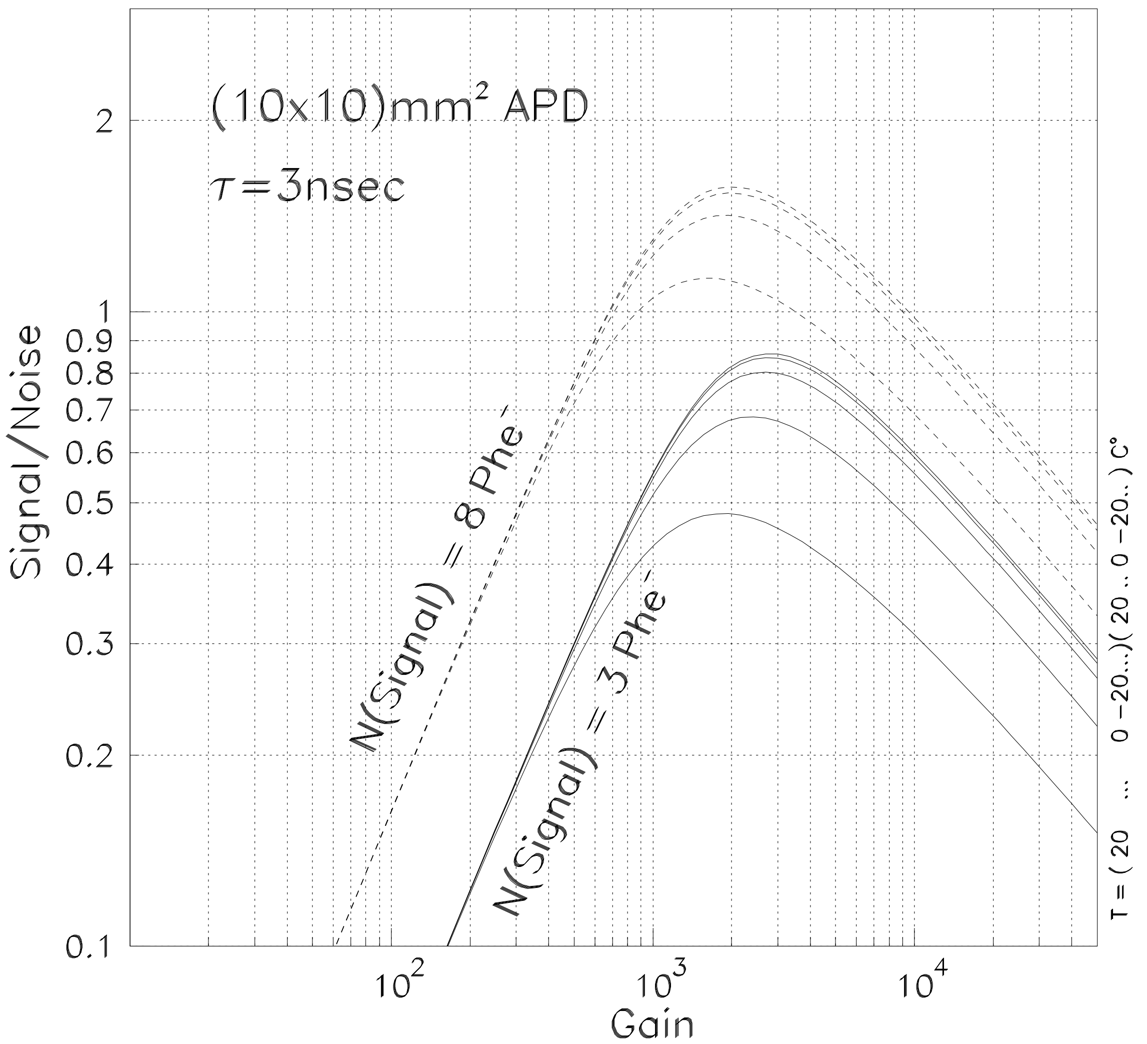

Fig. 2. (Signal/Noise) ratio versus APD gain.

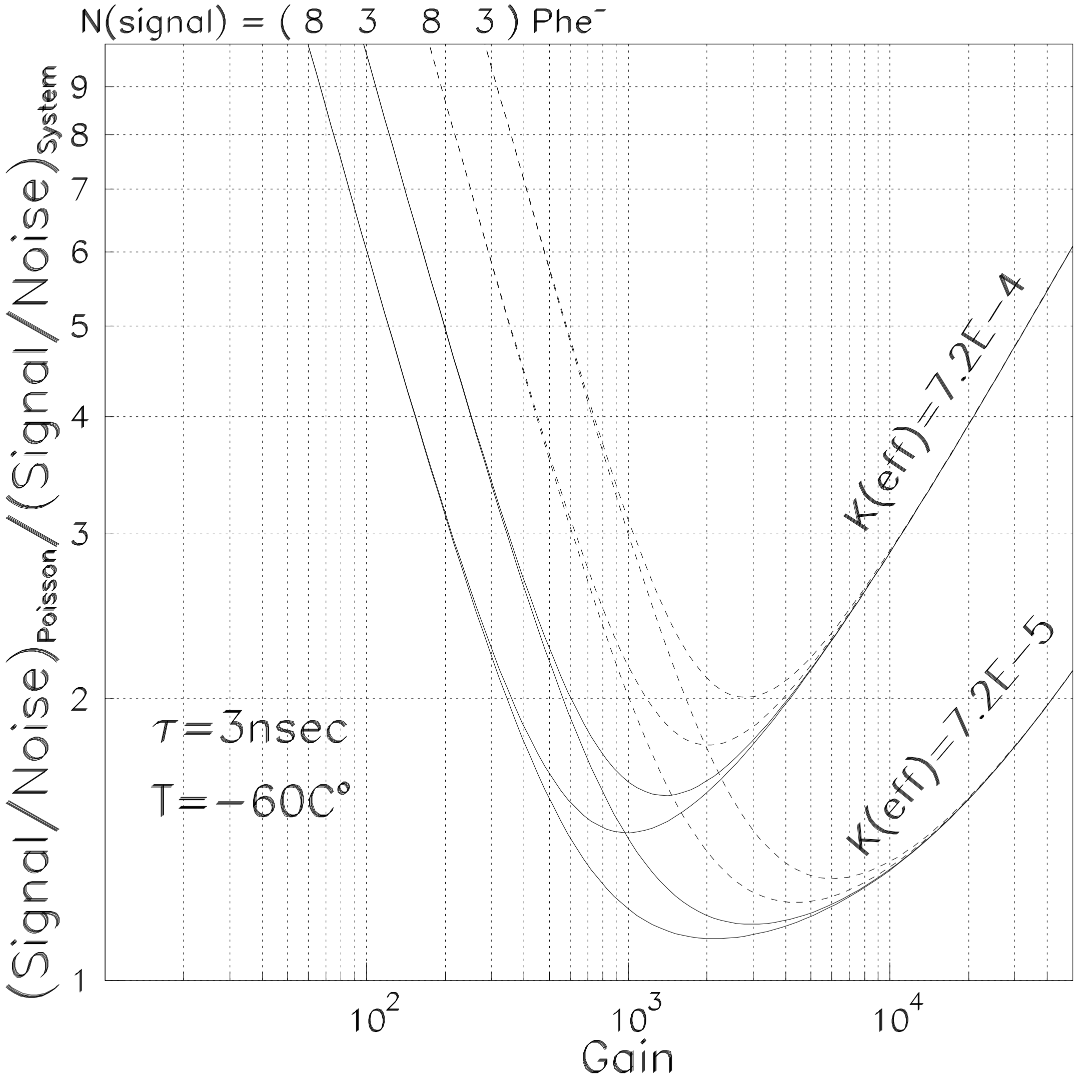

Fig. 3. Ratio between (Signal/Noise) due to Poisson fluctuations and (Signal/Noise) due to detecting system versus APD gain for (5x5)mm^2 (solid line) and (10x10)mm^2 (broken line) surface $APDs$.

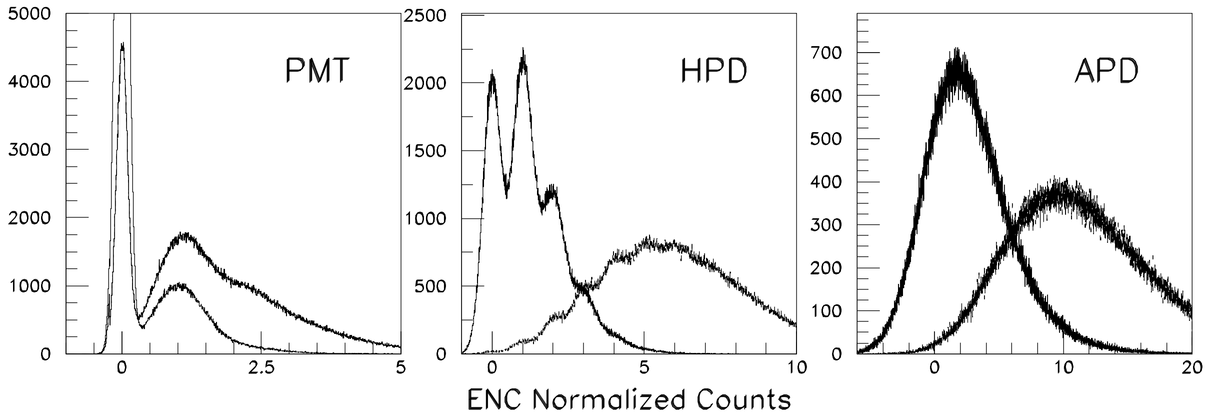

Fig. 4. Simulated spectra for light bunches containing 3 and 15 photons.

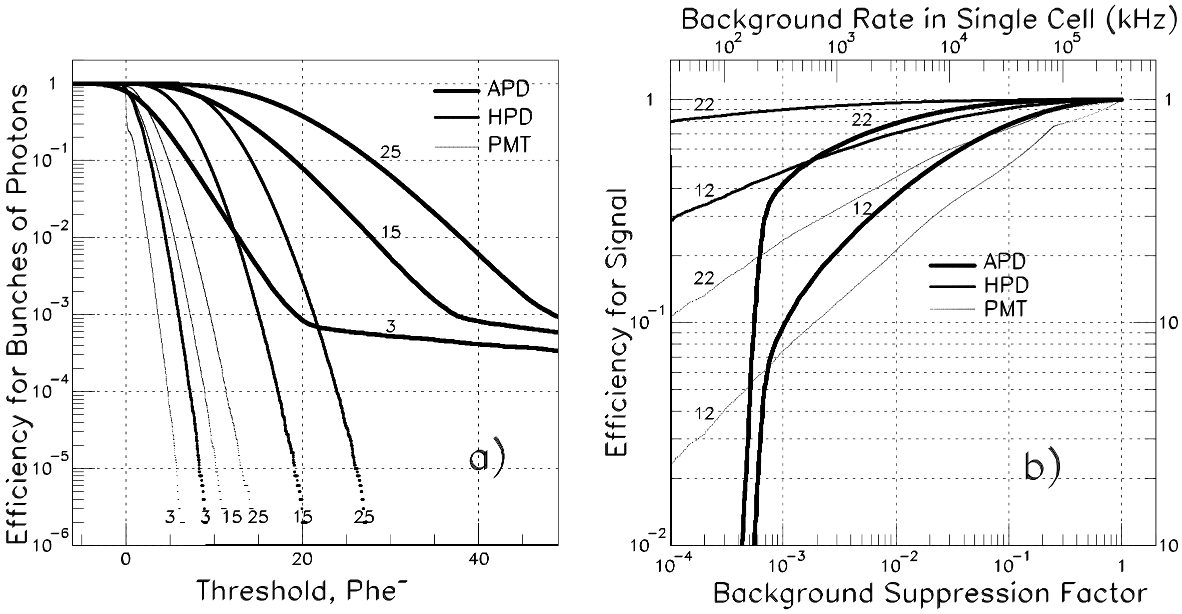

Fig. 5. a). Registration efficiency versus threshold for different photodetectors and signal level (amount of photons in 3 nsec time duration are shown around the curves). b). Registration efficiency as function of background suppression/background rate in single channel. The digits around the curves show amount of photons in light bunches above the mean background level (see text for details).