

# High Quantum Efficiency Phototubes for Atmospheric Fluorescence Telescopes

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**Abstract.** The detection of atmospheric fluorescence light from extensive air showers has become a powerful tool for accurate measurements of the energy and mass of ultra-high energy cosmic ray particles. Employing large area imaging telescopes with mirror areas of  $10\text{ m}^2$  or more, showers out to distances of 30 km and more can be observed. Matrices of low-noise photomultipliers are used to detect the faint light of the air showers against the ambient night-sky background noise. The signal-to-noise ratio of such a system is found to be proportional to the square root of the mirror area times the quantum efficiency of the phototube. Thus, higher quantum efficiencies could potentially improve the quality of the measurement and/or lead to the construction of more compact telescopes. In this paper, we shall discuss such improvements to be expected from high quantum efficiency phototubes that became available on the market only very recently. A series of simulations has been performed with data of different types of commercially available high quantum efficiency phototubes. The results suggest a higher aperture and thus increased statistics for such telescopes. Additionally, the quality of the reconstruction can be improved.

**Keywords:** PMTs, Quantum Efficiency, Fluorescence Telescopes

## I. INTRODUCTION

The continuous development of photomultiplier tubes led, in the last few years, to a major progress for the photocathodes towards cathodes with higher quantum efficiencies. For instance today, such super or ultra bialkali photomultipliers can have efficiencies of over 40 % (compared to the “old standard” of 25 % – 30 %) and are now commercially available on the market.

This change is particularly interesting for fluorescence telescopes, whose detection of atmospheric fluorescence light from extensive air showers has become a powerful tool for accurate measurements of the energy and the mass of ultra high energy cosmic ray particles. Telescopes with mirror areas of  $10\text{ m}^2$  and more allow the observation of showers out to distances of 30 km. For this task it is essential to have low-noise photomultipliers which are able to detect the faint fluorescence light from the shower. The signal-to-noise ration for such a system is found to be

$$S/N \sim \sqrt{A \cdot \varepsilon_Q}, \quad (1)$$

where  $A$  is the mirror area and  $\varepsilon_Q$  the quantum efficiency of the photomultipliers in the camera. Hence, higher quantum efficiencies could potentially improve the quality of the measurements and/or led to a compact construction of telescopes.

In this work we discuss important properties of such super-bialkali and ultra-bialkali photomultipliers and describe simulations of atmospheric fluorescence telescopes employing such photomultipliers.

The major objectives for this simulations are the possible increase in the trigger efficiency, and thus the aperture, of the telescope and the possible better quality of the reconstruction.

## II. RELEVANT PROPERTIES OF HIGH QE-PMTs

The task of the optical detector in fluorescence telescopes is to pick out the faint and fast signal of air showers from the ambient night-sky background noise which is of the order of  $100\text{ photons per m}^2\text{ }\mu\text{s deg}^{-2}$  in the relevant wavelength range [1]. Thus, besides the cathode and anode luminous sensitivities, also the anode dark current and after pulses are of particular importance together with the linearity and a high dynamic range. Very detailed information based on large quantities of XP3062B photomultipliers [2] have been obtained from laboratory tests reported in [3]. Such information is not yet available for super and ultra bialkali photomultipliers becoming available only very recently. Thus, a smaller number of super-bialkali photomultipliers has been procured and is now under study in the laboratory, while the ultra-bialkali photomultipliers presently appear to be too expensive for being considered a realistic option for large quantities as needed in a fluorescence detector camera.

First tests aim for measuring the quantum efficiency as a function of wavelength in comparison to the XP3062B photomultipliers, the homogeneity of the photocathode response, the dark current, occurrence of after-pulses, and the dynamic range. When used in combination with MUG-6 filters in the aperture system, the absence of sensitivity to photons at wavelengths larger than 650 nm becomes another issue to be verified, as the filter becomes transparent again in this wavelength range. Preliminary studies show that the dark current of high quantum efficiency photomultipliers is increased compared to standard bialkali photomultipliers. This will be quantified and be reported together with other test-results at the conference.

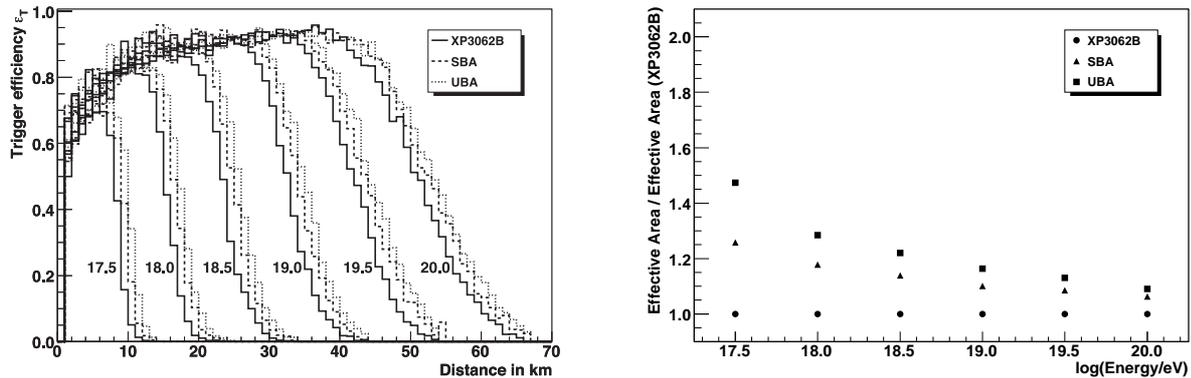


Fig. 1. The results of the trigger efficiency analysis. *Left*: The dependence of the trigger efficiency on the distance from the telescope for different energies, indicated by  $\log(\text{Energy/eV})$ , and photomultipliers. The distance bin-size is 1 km. *Right*: The dependence of the effective area on the energy and the different photomultipliers.

### III. SIMULATIONS

The simulations involve three different steps, their details will be explained in this section: the shower simulation, the telescope simulation and the shower reconstruction.

As sample for photomultipliers with different quantum efficiencies the data of:

- a Photonis XP3062B, which is the photomultiplier used for the Pierre Auger Observatory and the former HiRes experiment, with  $\epsilon_Q \sim 28\%$  [2],
- a Hamamatsu R9420-100 SBA (super-bialkali) with  $\epsilon_Q \sim 35\%$  [4] and
- a Hamamatsu UBA (ultra-bialkali) photocathode with  $\epsilon_Q \sim 43\%$  [4]

are used. For the second and third case only the data of the photocathodes, and not the, potentially, different gain of the multipliers, is important. This ensures an observation of effects only due to the quantum efficiency.

#### A. Shower simulation

For a fluorescence telescope the interesting part of an airshower is its longitudinal profile and the emitted fluorescence light, but not the whole particle content of the shower. For this purpose the simulation program CONEX [5], [6] was chosen. It uses a combination of Monte Carlo simulations and solutions of the cascade equations for airshowers and is, thus, a very fast alternative to pure Monte Carlo simulation programs.

The primary particles were chosen to be protons with an energy distribution uniformly in  $\log(E)$  in steps of 0.5 from  $10^{17.5}$  eV to  $10^{20}$  eV. For each energy step 25 000 showers have been simulated with a uniform azimuth angle distribution and a zenith angle distribution according to  $dN/d\cos\theta \sim \cos\theta$  between  $0^\circ$  and  $60^\circ$  to take into account the flat surface on which the showers will be distributed.

#### B. Telescope simulation

The actual simulations of the different photomultipliers is done in this step. For convenience, we use the example of the Pierre Auger Observatory, which has four fluorescence detector sites. To exclude effects coming from showers seen in more than one site, only one of these is simulated. For the simulations we used the so called Offline Framework [7], which is a simulation and reconstruction tool developed and used for the Auger Observatory.

The shower cores are distributed on a  $5^\circ$  slice in front of the telescope. The maximum distance between shower core and telescope was chosen in a way that the trigger probability (for the standard photomultiplier) for a shower outside this radius is lower than 1%.

#### C. Shower reconstruction

The last step of the simulation chain is the reconstruction of the shower. This is again done by using the Offline framework, which then yields all the important quantities, such as the reconstructed profile, energy and the position of the shower maximum ( $X_{\max}$ ).

## IV. RESULTS

#### A. Trigger efficiency

The first expectation on photomultipliers with higher quantum efficiency is the possibility to observe fainter signals, which for airshowers correlates to the possibility of observing more distant showers. One observable to measure this effect is the trigger efficiency against the distance. As trigger efficiency we define the ratio  $\epsilon_T = N_T/N_S$ , the number of showers which trigger during the telescope simulation over the total number of simulated showers. This ratio is calculated for each energy-distance bin. The result is shown in figure 1a. As expected, for all energies the trigger efficiency rises if the quantum efficiency of the photomultipliers becomes higher, or in other words, the telescope can see showers of  $\sim 2$  km farther away.

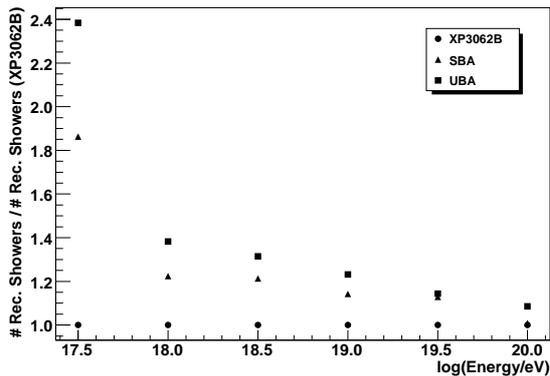


Fig. 2. The relative number of reconstructed showers which pass the quality cuts, compared to the number for the standard photomultipliers.

For a clean atmosphere the expectation would be a factor of  $r(\text{new})/r(\text{old}) = \sqrt{\varepsilon_Q(\text{old})/\varepsilon_Q(\text{new})}$  due to the  $1/r^2$  intensity loss, valid for all energies. But Mie and Rayleigh scattering attenuate this effect for larger distances.

To see the result in a more quantitative way it is useful to look at the effective areas defined as

$$A_{\text{eff}} = \int \varepsilon(r)r \, dr \, d\varphi \sim \sum_r \varepsilon(r)r, \quad (2)$$

where the sum runs over the different distance bins with a bin-size of 1 km. Figure 1b shows the relative effective areas compared to the one obtained for the standard photomultipliers. The increase for all energies is obvious and becomes larger for smaller energies because of a geometrical reason, i.e. the relative area growth of a slice is of the order  $\mathcal{O}(\Delta r/r)$ .

### B. Number of reconstructed showers

Before having a look at the reconstructed showers, the shower sample has to be cleaned up by applying several quality cuts. The main cuts are:

- the reconstructed shower maximum shall lie inside the observed energy deposit profile,
- the absolute uncertainty ( $\Delta X_{\text{max}}$ ) of the reconstructed shower maximum is smaller than  $40 \text{ g/cm}^2$ ,
- the relative uncertainty of the reconstructed energy ( $\Delta E/E$ ) is smaller than 20 %,
- the reduced  $\chi^2$  of the Gaisser-Hillas fit is smaller than 5 and
- the estimated amount of Cherenkov light at the aperture should be smaller than 50 %.

Since the effective area increases for higher quantum efficiencies, we expect to have more “good” reconstructed showers in these cases. The result in figure 2 shows a significant increase of the relative number of successfully reconstructed showers. For lower energies this effect becomes larger, which is correlated to the behaviour of the effective area described in the last section.

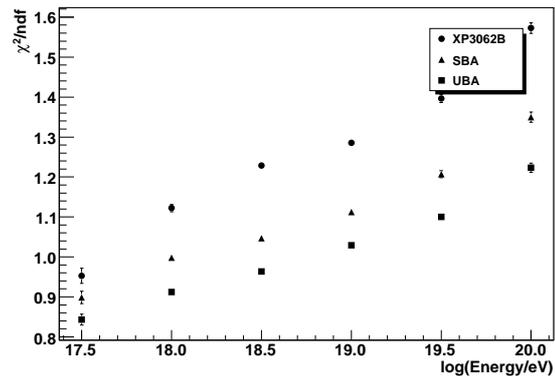


Fig. 3. The  $\chi^2/ndf$  distributions of the Gaisser-Hillas fits. Shown are the means of the distributions and their corresponding errors.

### C. Gaisser-Hillas profile

A good indicator for the quality of the reconstruction is the goodness of the Gaisser-Hillas fit, which gives the shower profile. The goodness is described by the  $\chi^2/ndf$  of the fit. Figure 3 shows the means of the different  $\chi^2/ndf$  distributions as function of the energy. As can be seen, higher quantum efficiencies yield a significant improvement of the goodness of the fits and thus of the quality of the reconstruction. This effect is as expected because higher quantum efficiencies should yield more signals in the camera and thus facilitate the reconstruction.

### D. Energy and $X_{\text{max}}$ resolution

Since the Gaisser-Hillas fit becomes significantly better for photomultipliers with higher quantum efficiencies, we can assume that also the resolution of the quantities derived from the profile will become better. Namely, these are the energy and the position of the shower maximum ( $X_{\text{max}}$ ). Their mean residuals are shown in figure 4a and figure 4b, respectively. As expected they tend to lower values and thus to more precise energy and  $X_{\text{max}}$  reconstructions.

## V. DISCUSSION AND OUTLOOK

The results of the simulations done in this work clearly show that photomultipliers with higher quantum efficiencies can significantly improve the quality of airshower measurements. Furthermore, they allow the observation of more distant showers or of showers with lower energies at given distance. Both of this increases the aperture of the telescopes.

The simulation of these new photomultipliers with high quantum efficiencies is, of course, only the first step towards a real usage in an experiment. As a next step samples of these photomultipliers are currently tested to determine their properties under conditions typically for a fluorescence telescope. A final step might then be the equipment of a whole telescope with these new photomultipliers.

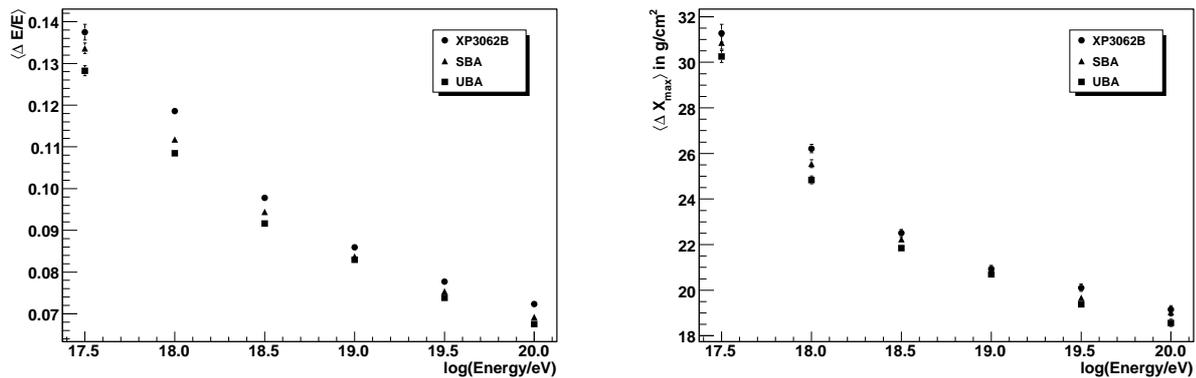


Fig. 4. *Left*: The energy resolutions for the different quantum efficiencies. *Right*: The  $X_{\text{max}}$  resolutions for the different quantum efficiencies. In both cases the means and their corresponding errors of the different distributions are shown.

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