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Development of a highly efficient PMT Winston-cone system for fluorescence measurement of extensive air showers

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Fluorescence telescopes are important instruments to measure extensive air showers initiated by ultra-high energetic cosmic rays. They measure the longitudinal profile of the energy deposited in the atmosphere by detecting the de-excitation of nitrogen molecules in the UV-range. In recent years the development of photomultiplier tubes (PMTs) has led to an increase of more than 30% in photon detection sensitivity, by using newly developed super-bialkali (SBA) photocathodes. Thus, the telescopes can detect even fainter signals over a larger area resulting in a significant increase in aperture. To develop telescopes for a next generation cosmic ray observatory, the camera needs to have a maximal sensitive area in the focal plane. Winston cones can efficiently cover the dead area between the photocathodes of the PMTs. Such a highly efficient system composed of an SBA PMT and Winston cone has been developed, based on the design of the fluorescence telescopes of the Pierre Auger Observatory. This contribution shows the development of the optical detection system and first tests in one of the fluorescence telescopes.

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1. Motivation

The method of detecting cosmic rays by fluorescence light observations is a well established technique. High energy cosmic rays entering the atmosphere generate secondary particles, which cascade further into extensive air showers. During the shower development, charged particles excite the traversed air. De-excitation of, especially, nitrogen yields several spectral peaks in the UV-range, which can be measured with fluorescence telescopes during dark nights. In combination with water-Cherenkov detectors or scintillators, it provides a powerful observation technique for particles at the highest energies. With the limited duty cycle of these telescopes, one can increase the exposure by using more efficient detectors. In the past years, there were several improvements of photon sensors leading to a higher efficiency for detecting light in the UV-range. For photomultiplier tubes (PMTs) the quantum efficiency (QE), the probability of converting a photon into an electron, was improved. Also novel detectors in this field like silicon photomultiplier are being considered for operation in fluorescence telescopes.

2. Photomultiplier

Most of the emitted fluorescence light lies in the UV-range between 300 nm and 400 nm, with the most prominent peak at 337 nm (Fig. 1, left). The conventional way to detect fluorescence light is by a PMT. Common PMTs, with a suitable response in the UV-range, have bialkali photocathodes with a QE of $25-27\%$ at peak wavelength. In recent years, several manufactures have been able to increase the QE. By adjusting the photocathode, the QE of such PMTs can be increased to 35% for Super-bialkali (SBA) photocathodes and up to 43% for Ultra-bialkali (UBA) photocathodes. Simulations show that a higher QE used in the current fluorescence telescope of the Pierre Auger Observatory [1] increases the exposure by $\sim 10-35\%$, depending on the energy [2]. Particularly at lower energies and for the high elevation altitude telescopes (HEAT) [3], the benefit would be significant. For future high energy cosmic ray experiments using the fluorescence technique, it might be promising to use these newer detectors. To verify this, extensive tests of these detectors were performed before being tested in one of the Pierre Auger fluorescence telescopes.

Possible candidates, which were examined, are the R9420-100 and the newest R11920-100 PMTs by Hamamatsu (Fig. 2, right) [4]. Both PMTs are $1.5''$ tubes with linear focusing dynode structure and a Super-bialkali photocathode. The QE measured in the laboratory reaches 35% for the R9420-100 at peak wavelength, which is more than 30% higher than currently used models (Fig. 1, right). Over the entire fluorescence spectrum the benefit is significant while remaining similar or even less beyond 600 nm, where the filter suppressing stray light is less effective. A single test version of the R11920-100 with a frosted glass window in a hemispherical shape has a QE as high as 40%. Also a more uniform response is achieved. With the first series of R9420-100 suffering from afterpulsing, the production process was optimized and the amount of residual gases inside the tube was reduced. The amount of charge after an initial LED signal of a few hundred nanoseconds was lowered to $\sim 4\%$ (Fig. 2, left), which is still above the standard PMT with $\sim 1.1\%$ [5]. For the R11920-100, the design of the R9420-100 was optimized. By using the dynode structure of a smaller $1''$ PMT, the afterpulsing was reduced to less than 0.2%, which is well below the requirements of fluorescence telescopes. For both PMTs, a voltage divider was

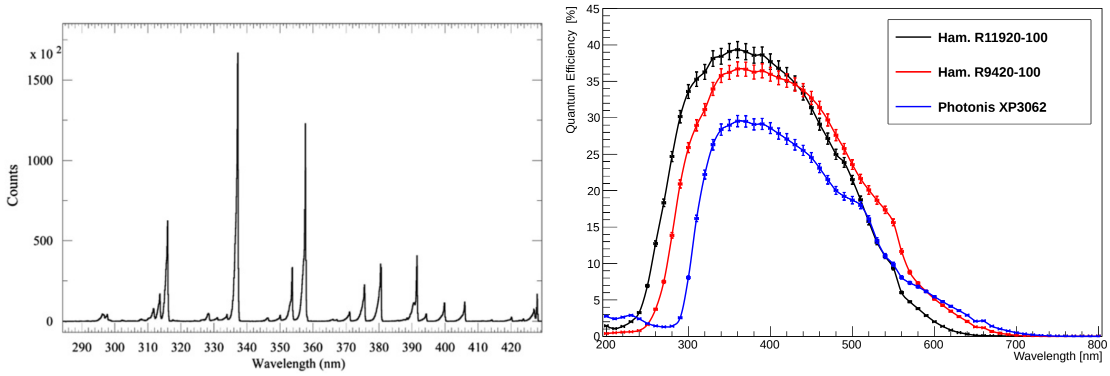

Figure 1: Left: Fluorescence yield of air, measured by AIRFLY [6]. Right: Quantum efficiencies measured in the laboratory for new PMT generation and actual used FD-PMT from Photonis.

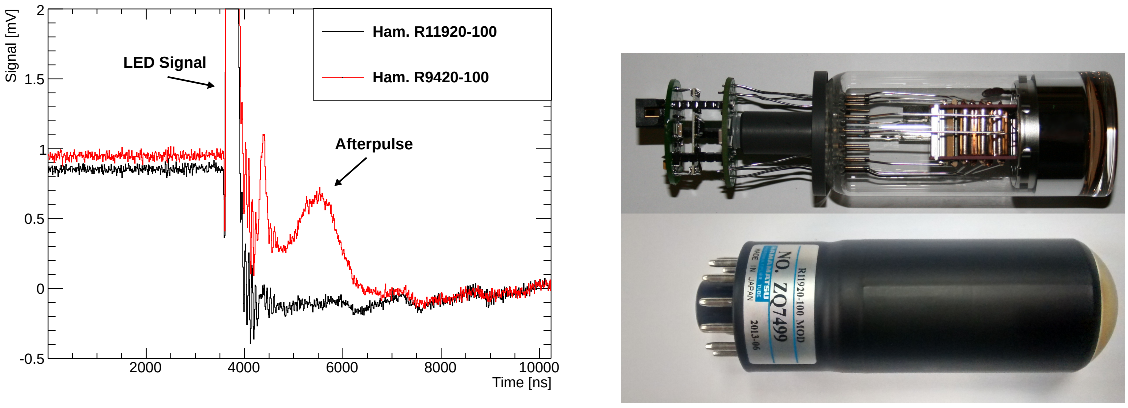

Figure 2: Left: Averaged PMT signal of 1000 short LED pulses showing the afterpulsing of the two Hamamatsu PMTs. Right: Hamamatsu R9420-100 with plane window (upper) and Hamamatsu R11920-100 with frosted, half-hemispherical window (lower).

developed to optimize the linear relation between input light intensity and measured signal over a wide dynamic range. By attenuating a light source with calibrated filters, the deviation to the expected signal was measured and resistor values for a tapered divider were adjusted. For run the PMTs at the same gain of 2×10^5, the operating voltages have been determined between 850 V and 1100 V.

3. Winston Cone

The fluorescence telescopes of the Pierre Auger Observatory [7] use a $\sim 13\,\mathrm{m}^2$ spherical mirror to project the image of a particle shower onto the camera located in the focal plane. A corrector ring bends the light at the outer rim of the entrance window and increases the aperture by a factor of two. The camera consists of 440 PMTs with hexagonally shaped photocathodes, arranged in a hexagonal structure to provide a maximum packing density. Since the focal plane of the camera is

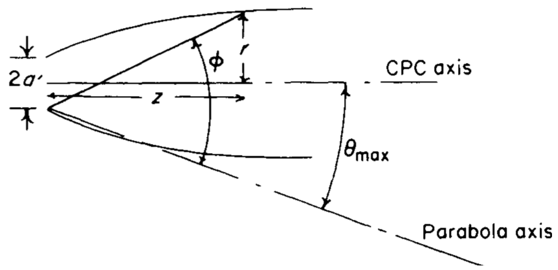

Figure 3: Schematic of the Winston cone design described by eq. 3.1 [8].

also spherical, unlike the typically plane field of a Cherenkov telescope, the hexagons are slightly irregular. To increase the effective photo sensitive area and to cover the dead area between adjacent photocathodes, simple light guides, made of Mylar foil, are used to fill the gaps between the single pixels. To use the new and more efficient PMTs with their circular face plates, the light guides had to be modified to maintain the size of sensitive area.

Design

An efficient version of a light guide is the compound parabolic concentrator (CPC), introduced by R. Winston *et al.* [8]. This so called Winston cone is a non-imaging concentrator. It is described by

$$r = \frac{2f\sin(\phi - \theta_{\mathrm{max}})}{1-\cos\phi} - a', \qquad z = \frac{2f\cos(\phi - \theta_{\mathrm{max}})}{1-\cos\phi}, \tag{3.1}$$

with $f = a'(1+\sin\theta_{\mathrm{max}})$ and the design of the cone is determined by the exit aperture a' (radius of PMTs sensitive area) and a maximum acceptance angle θ_{max}. The essential property of such a cone is a high concentration ratio with $C_{\mathrm{max}} = 1/\sin^2(\theta_{\mathrm{max}})$, up to a maximum acceptance angle θ_{max} (see Fig. 3). Incoming rays at an angle higher than θ_{max} are rejected and re-emitted from the entrance. This has the benefit of suppressing isotropic background radiation. An ideal Winston cone would be symmetric, mapping the entrance aperture to the smaller exit in a higher concentration by enlarging the exit angles due to Liouville's theorem. For usage in a fluorescence telescope, the hexagonal arrangement gives the highest packing density while the active area of the PMT is circular. Thus, a hexagonal entrance has to be transformed to a circular exit window. This was optimized by simulations of various designs within the limits of the manufacturing process. The resulting design is a Winston cone with conical cut-out in hexagonal form (see Fig. 8, left). Since the single pixels are arranged on a spherical surface, the conical cut needs to be slightly inclined to place the Winston cones as close as possible. The influence on the efficiency by cutting an inclined hexagonal cone into a Winston cone can be seen in Fig. 4, left. With one pixel of the Pierre Auger telescope covering 1.5°, the minimum tilt angle needs to be 0.75°. For the final design, a cut of 1° was chosen.

Spectral Reflectivity

The material for such a cone has to be highly reflective in the UV-range. Anodized aluminium, Alanod 4300UP [9] was also used for cones of the HISCORE experiment[10]. It is highly reflective

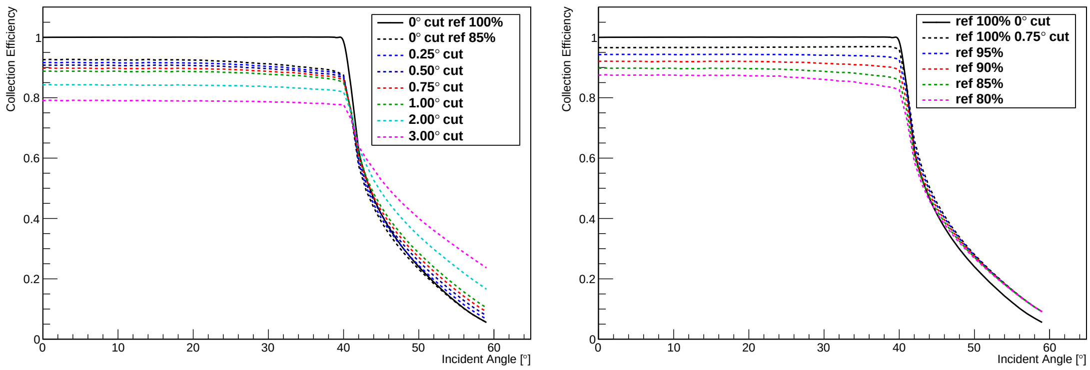

Figure 4: Ray tracing simulations of a Winston cone with hexagonal cutouts performed with ROBAST [11]. Left, the influence of inclined cutting (as illustrated in Fig. 5, left) for a material reflectivity of 85% is shown. Right, shows the collection efficiency of an inclined cut of 0.75° for various material reflectivities. Due to the conical cut, the typical drop in efficiency for incident angles higher than θ_{max} is smeared out.

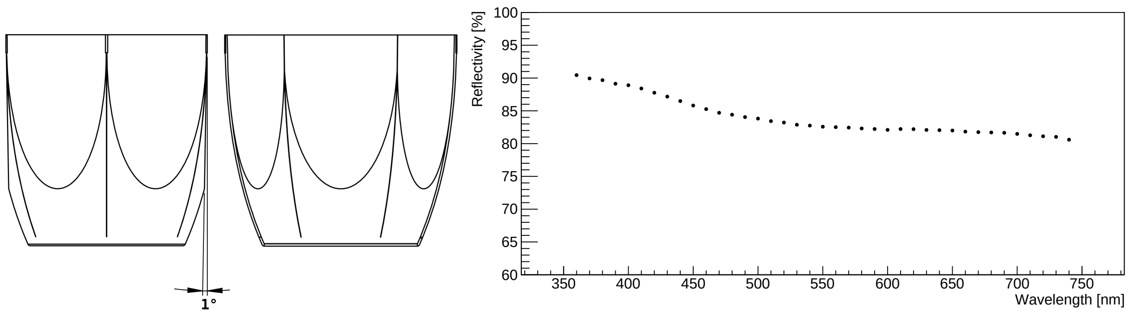

Figure 5: Left: Schematic of the Winston cone design in two side views of different orientation, showing the cutout at an inclination angle of 1° with respect to the vertical direction. Right: Specular reflectivity of Alanod 4300UP measured with a spectrometer.

in the UV-range. The reflectivity measurement was performed using a spectrometer by Konica Minolta (see Fig. 5, right). With the specular reflection achieving about 90%, the fraction of diffusely scattered light is quite low. The effect of reduced reflectivity on the cone's efficiency is shown in Fig. 4, right.

Collection Efficiency

The gain in sensitive area can be seen in Fig. 6. Using a 405 nm laser with a spot size of 1.1 mm the R9420-100 without (left) and with the Winston cone was scanned with a step size of 1 mm. The QE is determined by comparison to a calibrated photodiode. One can see slight loss in efficiency at the inner edges of the hexagon, where the material was stressed too much in the manufacturing process. The overall gain for parallel light is 20%. For the R11920-100 (right) the gain is even higher. With the hemispherical windows reaching into the cone, rays with a large exit angle hit the photocathode at a shallower angle.

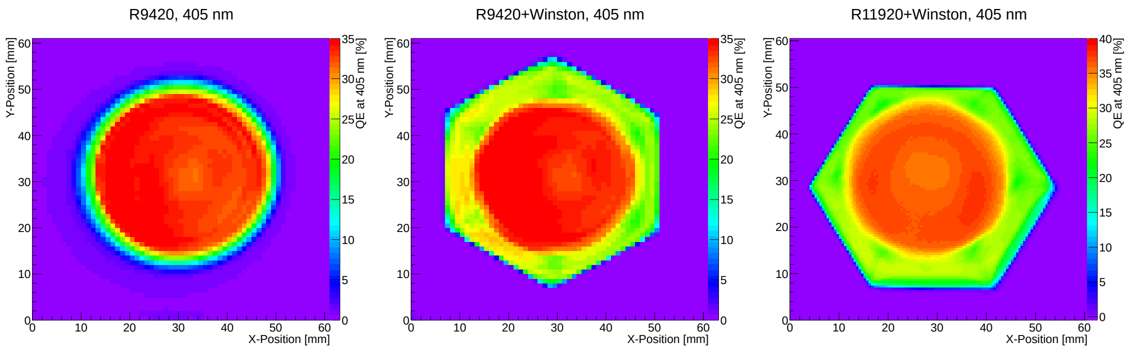

Figure 6: Scan of one R9420-100 with a 405 nm laser without (left) and with (middle) Winston cone, using a step size of 1 mm. Right: R11920-100 with Winston cone measured with 0.5 mm step size.

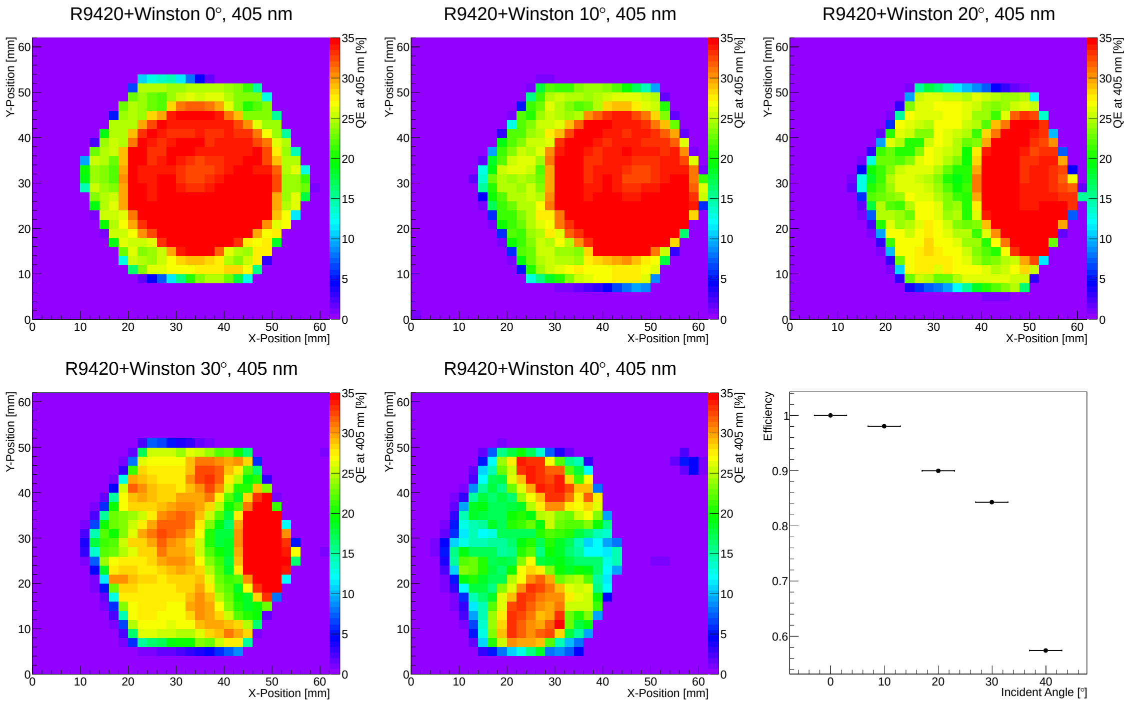

Figure 7: Angular response of R9420-100 with Winston cone at 405 nm. The step size of the scan was 2 mm. Relative efficiency to 0° response shown in bottom right.

Acceptance Angle

With imaging in fluorescence telescopes via a spherical mirror, angles up to 35° can occur at the single pixels. Simulations show the typical sharp cut for light collection at angles higher than $\theta_{\max}$. To verify this, measurements were performed, scanning a PMT plus Winston cone for different incident angles (Fig. 7). Normalized to the collected signal for incoming light at 0°, and taking the geometric reduction into account, the efficiency stays higher than 80% up to an incident angle of 30° and shows an expected drop around 40°.

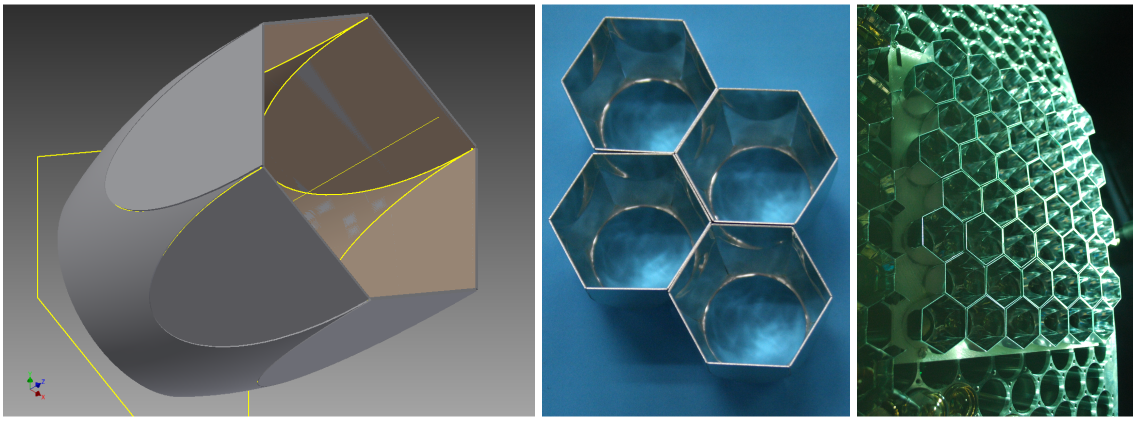

Figure 8: Left: Winston cone design in CAD. Middle: Four Winston cones, bent and welded at the top. Right: First prototype of 48 Winston cones on a mounting plate implemented in an existing telescope.

4. Production

The cones were manufactured by Alux Luxar [12] from anodized aluminium sheets. The lower part was carefully pressed into the parabolic shape. Afterward, the sides were bent up and welded at the six top edges. The final cone has a height of 47 mm with a hexagon side length of 25.23 mm and an exit aperture diameter of 34 cm.

A first prototype, consisting of 48 R9420-100 PMTs plus Winston cones, was installed in a test camera in Fall 2014. To keep the current focal plane of the telescope, the Winston cones have to be mounted precisely. Thus, a mounting plate was produced with a 3D printer to fit the spherical cut-out. The material is PLA with a size of 30 cm $\times$ 25 cm. The cones were fixed with epoxy at the bottom part. Finally the plate was screwed to the camera frame (Fig. 8, right).

5. Summary

New PMTs for the use in a future fluorescence telescope have been characterized. With their increased quantum efficiency it is possible to detect fainter signals and enlarge the exposure. To use these sensors in an existing telescope, the optical system needed to be adjusted. A new light concentrator was introduced to retain the size of sensitive area and to manage the transition from a hexagonal entrance aperture to a circular exit. The photon detection efficiency of the system composed of a PMT and Winston cone has been measured for direct and inclined incident angles. A first prototype of 48 PMTs was installed in 2014 and is currently running without any problems. By the end of 2015, one Auger telescope will be fully equipped with the novel type of PMTs plus Winston cones.

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