

Status of the Silicon Photomultiplier Telescope FAMOUS for the Fluorescence Detection of UHECRs

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Abstract: An established technique for the measurement of ultra-high-energy-cosmic-rays is the detection of the fluorescence light induced in the atmosphere of the Earth, by means of telescopes equipped with photomultiplier tubes. Silicon photomultipliers (SiPMs) promise an increase in the photon detection efficiency which outperforms conventional photomultiplier tubes. In combination with their compact package, a moderate bias voltage of several ten volt and single photon resolution, the use of SiPMs can improve the energy and spatial resolution of air fluorescence measurements, and lead to a gain in information on the primary particle. Though, drawbacks like a high dark-noise-rate and a strong temperature dependency have to be managed. FAMOUS is a refracting telescope prototype instrumented with 64 SiPMs of which the main optical element is a Fresnel lens of 549.7 mm diameter and 502.1 mm focal length. The sensitive area of the SiPMs is increased by a special light collection system consisting of Winston cones. The total field of view of the telescope is approximately 12°. The frontend electronics automatically compensates for the temperature dependency of the SiPMs and will provide trigger information for the readout. Already for this prototype, the Geant4 detector simulation indicates full detection efficiency of extensive air showers of $E = 10^{18}$ eV up to a distance of 6 km. We present the first working version of FAMOUS with a focal plane prototype providing seven active pixels.

Keywords: Air fluorescence, extensive air shower, Fresnel lens, Geant4, silicon photomultiplier, Winston cone

1 Fluorescence Detection of High Energy Cosmic Rays

The fluorescence detection technique is employed in many experiments for the measurement of high energy cosmic rays with energies $E > 10^{17}$ eV as e.g. in the Pierre Auger Observatory located in Argentina [1].

As a (primary) particle penetrates the atmosphere of the Earth, a shower of secondary particles is produced continuously until the number of particles reaches a maximum at a slant depth X_{\max} and the shower dies out. The number of particles along the axis of the extensive air shower (EAS) can be described by the Gaisser-Hillas-parametrisation [2].

The secondary particles produced in the EAS excite the nitrogen molecules of the air. When the molecules transit to the ground state, fluorescence light in the regime of 290 nm to 440 nm¹ is emitted isotropically whereby the number of photons is proportional to the energy deposit $E_{\text{dep}}^{\text{tot}}$ [3]:

$$\frac{d^2 N_\gamma}{dX d\lambda} = Y(\lambda, P, T, u) \cdot \frac{dE_{\text{dep}}^{\text{tot}}}{dX} \quad (1)$$

The light yield Y depends on the wavelength λ , the atmospheric pressure P , the temperature T and the humidity u . In dry air with $P = 1000$ hPa and $T = 300$ K, the absolute value is $Y(\lambda = 337 \text{ nm}) \approx 5 \text{ MeV}^{-1}$ and $\int Y d\lambda \approx 19 \text{ MeV}^{-1}$ [3]. E.g. for a 6 km distant air shower with an energy of $E = 10^{18}$ eV, approx. 10^8 photons arrive at a telescope with an aperture of 500 mm diameter and a field of view of 12°.

Using the time of arrival information of the light, it is possible to obtain the Gaisser-Hillas-shape and X_{\max} of the EAS which gives access to the energy, direction and mass of the primary particle.

The telescope FAMOUS (“First Auger Multi pixel photon counter camera for the Observation of Ultra-high-energy-cosmic-ray air Showers”) is a compact refractor with a camera built-up of novel photodetectors: Silicon photomultipliers (SiPMs). The aim of this effort is to demonstrate the feasibility of SiPMs for the fluorescence detection of cosmic rays which would enable less expensive and possibly more accurate measurements of cosmic rays.

2 Silicon Photomultipliers

Silicon photomultipliers (SiPMs) are semiconductor photodetectors which are built-up of hundreds to thousands of small avalanche photodiodes, referred to as cells, operated in Geiger-mode. Thus, each cell is capable of single photon detection and the dynamic range of the whole device is defined by the number of cells situated on the SiPM (N_{cells}). Currently, cell pitches between typ. 25 μm to 100 μm are commercially available (see e.g. [4]). For very short photon pulses, the number of triggered cells N_{trig} can be expressed as a function of the number of incoming photons N_λ

1. The most dominant transition is at $\lambda = 337$ nm [3].

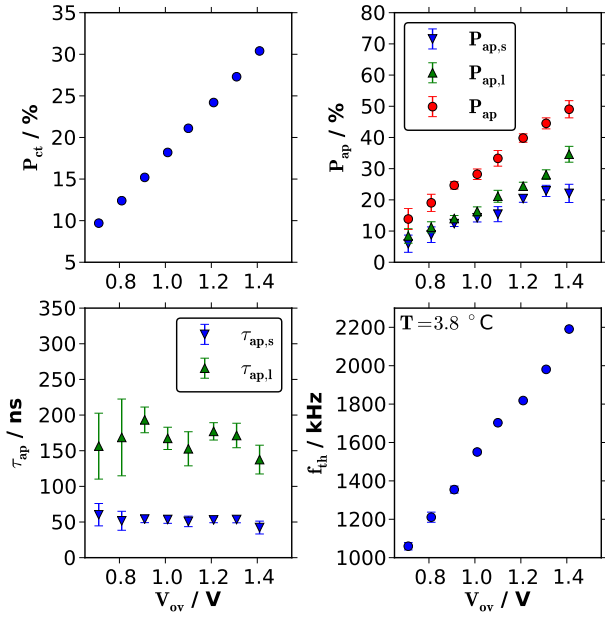


Fig. 1: Measurement of the SiPM operation parameters crosstalk- (P_{ct}) and afterpulse-probability ($P_{ap,s}$, $P_{ap,l}$, combined probability P_{ap}), the afterpulsing time constants ($\tau_{ap,s}$ and $\tau_{ap,l}$) and the thermal noise rate (f_{th}) as a function of the over-voltage V_{ov} for a Hamamatsu S10362-33-100C SiPM. The ambient temperature is $T = (3.76 \pm 0.03) ^\circ\text{C}$.

$$N_{trig}(N_\lambda) = N_{cells} \left(1 - e^{-N_\lambda PDE/N_{cells}}\right) \quad (2)$$

with the photon detection efficiency PDE which itself depends on the wavelength of the photons.

Due to the Geiger-mode, the gain of SiPMs is typ. in the order of 10^6 [5]. The gain depends linearly on the voltage excess V_{ov} of the applied bias voltage V_{bias} above the breakdown voltage V_{break} (typ. 70V)

$$V_{ov} = V_{bias} - V_{break} \quad (3)$$

By increasing the over-voltage, the PDE can also be increased but at the expense of increasing noise.

The SiPMs used in FAMOUS are of type Hamamatsu-S10985-100C which in turn is composed of an array of four Hamamatsu S10362-33-100C SiPMs. The photon detection efficiency at $\lambda = 420\text{nm}$ and $V_{ov} = 1.3\text{V}$ is $PDE = (33.1 \pm 0.8 \pm 5) \%$ [6].

2.1 Noise Phenomena

Even if operated in the dark, cell breakdowns can happen accidentally by thermal excitation. A typical thermal noise rate is

$$f_{th} = 1 \text{ kHz} \cdot N_{cells} \quad (4)$$

at room temperature. Additionally, SiPMs are subject to two kinds of correlated noise: optical crosstalk and afterpulsing.

Optical Crosstalk Charge carriers of the avalanche during the cell breakdown can recombine (probability approx. 10^{-5} per avalanche electron) to a photon which itself can cause an avalanche breakdown in a neighbouring cell. The probability for this process is $P_{ct} \approx 10 \dots 30\%$ depending on the over-voltage.

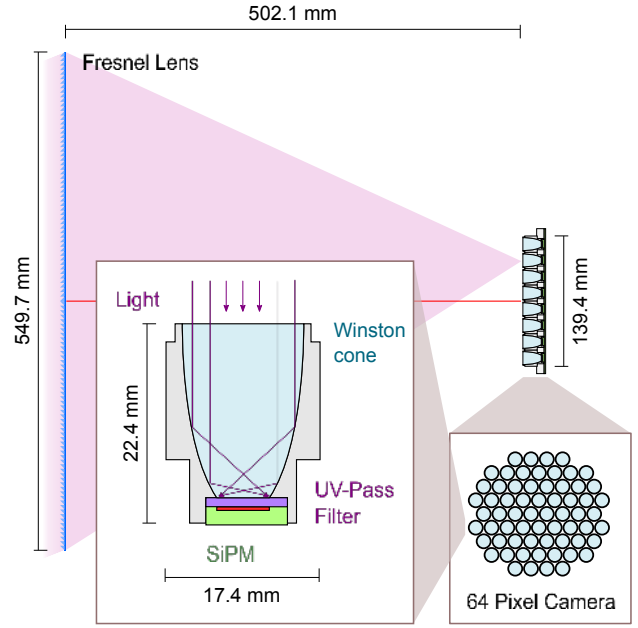


Fig. 2: Baseline design of FAMOUS. The incoming light is concentrated by the 549.7 mm diameter Fresnel lens with $f = 502.1$ mm focal length onto a camera with 64 SiPMs which are each located behind a UV-pass filter and a light concentrator, the Winston cone. The pixels are packed in a hexagonal layout. The illustration is true to scale.

Afterpulsing Also during the avalanche, charge carriers may be trapped at impurities of the silicon substrate of the SiPM and be released after a characteristic time τ which usually exceeds the time needed to replenish the avalanche zone of the SiPM cell. The released charge carriers can cause the cell to break down again. Measurements of Hamamatsu devices revealed a short (with $\tau_{ap,s} \approx 50\text{ns}$) and a long time constant (with $\tau_{ap,l} \approx 170\text{ns}$) with a combined afterpulsing probability (combined probabilities $P_{ap,s}$ and $P_{ap,l}$ for the short and long time constant) of $P_{ap} \approx 10 \dots 40\%$.

The SiPM properties discussed above are presented in figure 1 for a Hamamatsu S10362-33-100C SiPM as a function of V_{ov} .

A dramatic suppression of thermal and correlated noise is expected with the release of future devices [7].

3 Baseline Design of FAMOUS

FAMOUS is a refracting telescope. A commercial Fresnel lens [8] with an aperture of $d = 549.7$ mm diameter (design goal $d = 510\text{mm}$) and a focal length of $f = 502.1$ mm (design goal $f = 510\text{mm}$) is used to concentrate the light onto the camera composed of 64 circular pixels arranged in a hexagonal layout. Each pixel has a circular field of view of 1.5° . A schematic of the baseline design is presented in figure 2.

3.1 Fresnel Lens

To minimise weight and light loss due to absorption, a Fresnel lens is divided into concentric, annular sections while the bulk material of the sections is reduced to the minimum possible. The Fresnel lens of FAMOUS has 10 sections per millimeter and is made of UV transparent



Fig. 3: Photo of the assembly of the FAMOUS^{SEVEN} prototype focal plane with seven active pixels. The SiPMs (Hamamatsu-S10985-100C) are located behind the circular Winston cones.

acrylic [9, 10]. The overall transmission has been simulated to $T \approx 70\%$ over the whole fluorescence light regime.

The image quality has also been determined by ray-tracing simulations to $R_{90} = 1.88\text{ mm}$ [10]. R_{90} signifies 90% of encircled energy in the image plane for incidence of parallel light, here perpendicularly to the lens. Recent measurements resulted in $R_{90} = 2.89\text{ mm}$ which is good enough for the application in FAMOUS and reasonably matches the simulations considering that the simulations did not account for surface imperfections and shape deviations, and the incoming light used for the measurement was not perfectly parallel.

3.2 Camera Pixel

Each pixel of FAMOUS consists of a light concentrator made of polished aluminium (Winston cone [11]), a 1 mm thin UV-pass filter (Schott UG-11 [12]) and a Hamamatsu-S10985-100C SiPM, i.e. an array of four $3 \times 3\text{ mm}^2$ Hamamatsu S10362-33-100C SiPMs yielding a total area of $6 \times 6\text{ mm}^2$, and a cell pitch of $100\text{ }\mu\text{m}$.

The Winston cone is a non-imaging parabolic concentrator with a circular entrance of $r_1 = 6.71\text{ mm}$ radius and an exit radius of $r_2 = 3\text{ mm}$. Thus, up to $\theta_{\text{max}} = 26.6^\circ$ incidence angle, over 90% of the incoming light is transmitted to the exit [10]. Due to manufacturing processes, the Winston cones of FAMOUS are circular, but in principle rectangular or even hexagonal shapes are also possible.

3.3 FAMOUS^{SEVEN}

The first version of the focal plane features seven pixels to test the feasibility of the mechanical design (c.f. figures 3 and 4) and the scalability of the amplifier electronics developed in-house.

A dedicated readout with 64 individual channels and a programmable FPGA chip for triggering developed in Lisbon is currently being tested and will be ready soon for the implementation in the 64 pixel version of FAMOUS.

4 Expected Performance

To evaluate the baseline design of FAMOUS, a dedicated Geant4 [13] ray-tracing-simulation has been developed



Fig. 4: Photo of the fully assembled FAMOUS^{SEVEN} prototype with the Fresnel lens attached to the telescope tube which is fixed onto an altitude-azimuth mount.

[10, 14, 15]. The air shower simulations have been carried out with CONEX [16].

The trigger probability determined by the detector simulation is presented in figure 5. It can be used as a benchmark quantity for the evaluation of the performance of the real telescope. An EAS has been considered as successfully triggered if the fluorescence signal exceeded the noise in a pixel of FAMOUS by a certain threshold. The noise is dominated by the night-sky-brightness. The night-sky-background-radiance was measured in Aachen, Germany, to $L \lesssim 1.9 \cdot 10^{12}\text{ m}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$ in the fluorescence light regime [14]. Thus, a 10^{18} eV shower is detectable at a shower-to-telescope distance of 6 km (at full efficiency) and at a rate of a few ten EAS in total per measurement night. Since SiPMs are invulnerable to too much light and the image quality of the Fresnel lens is sufficient, measurements at full moon or twilight may become possible.

5 First Test Measurements

Upon completion of the assembly of FAMOUS^{SEVEN}, first test measurements were performed. In figure 6, a charge spectrum of a single pixel signal read out by the amplifier electronics of FAMOUS^{SEVEN} is presented. The data have been taken with a pulsed LED whose peak wavelength is at 400nm. The pulse width was 20ns and the integration time of the charge-to-digital-converter (QDC) 150ns. The photon equivalent peaks are clearly distinguishable which enables characterisation studies and is necessary for the over-voltage respectively gain calibration of the pixels.

6 Summary & Outlook

The refractive optics of the air fluorescence telescope prototype FAMOUS consists of a commercial Fresnel lens with $d = 549.7\text{ mm}$ nearly equal to the focal length

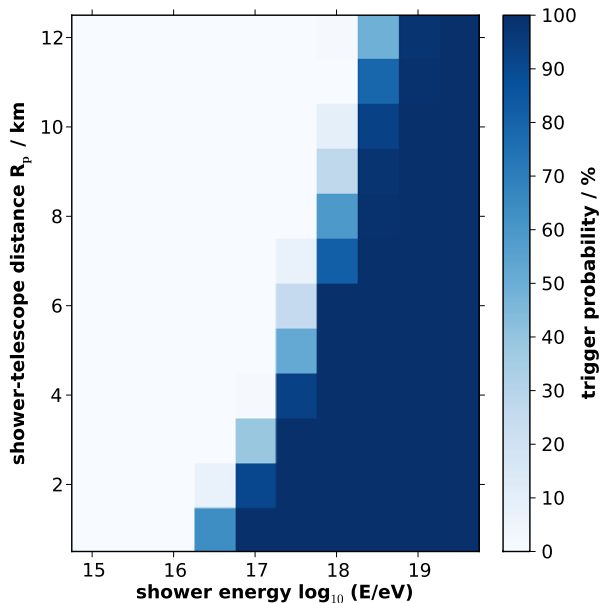


Fig. 5: Simulated trigger probability for vertical EAS as a function of the shower-to-telescope distance and the shower energy.

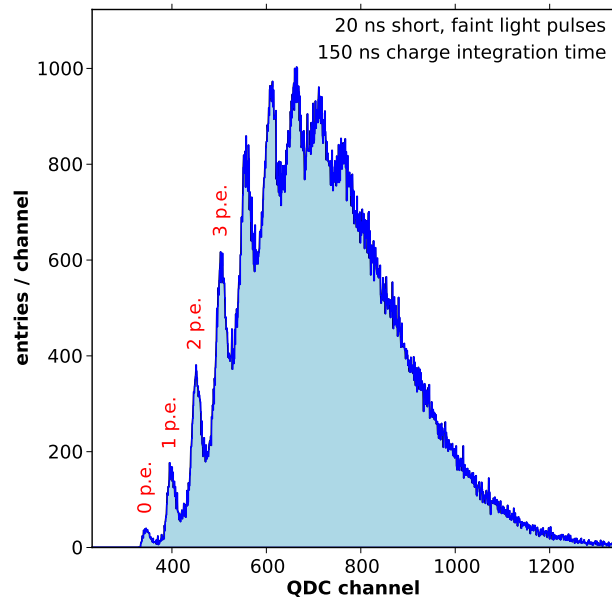


Fig. 6: Charge spectrum of a single pixel of FAMOUS when illuminated by pulsed LED light (peak wavelength 400 nm) measured with a QDC. The single peaks of the photon equivalents can be easily distinguished.

$f = 502.1$ mm. To match an effective field of view of 1.5° per pixel, the sensitive area of the Hamamatsu S10985-100C SiPM (i.e. an array of four 3×3 mm² SiPMs) is increased by a special light concentrator, a Winston cone. The Winston cone has an entrance radius of $r_1 = 6.7$ mm. The focal plane of FAMOUS features 64 hexagonally collocated pixels in total.

CONEX air shower and detailed Geant4 detector simulations have been performed, and successfully demonstrated the ability of FAMOUS to detect air showers even with its small aperture considering contemporary air fluorescence telescopes.

The first version with seven pixels, FAMOUS^{SEVEN}, is fully assembled and operational. Later this year, the focal plane of FAMOUS will be extended to 64 pixels as soon as the dedicated electronics are finished and programmed.

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