# FAMOUS – A prototype silicon photomultiplier telescope for the fluorescence detection of ultra-high-energy cosmic rays

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**Abstract.** Due to their high photon detection efficiency, silicon photomultipliers (SiPMs) promise to increase the sensitivity of today's fluorescence telescopes which use photomultiplier tubes to detect light originating from extensive air showers. On the other hand, drawbacks like a small sensitive area, a strong temperature dependence, a high noise rate and a reduced dynamic range have to be managed.

We present plans for FAMOUS, a prototype fluorescence telescope using SiPMs and a special light collecting optical system of Winston cones to increase the sensitive area. The prototype will make use of a Fresnel lens. For several different types of SiPMs we measured their characteristics. Moreover, we will present the R&D in compact modular electronics using photon counting techniques. An evaluation of the performance of the optical telescope design is performed by means of a full detector simulation.
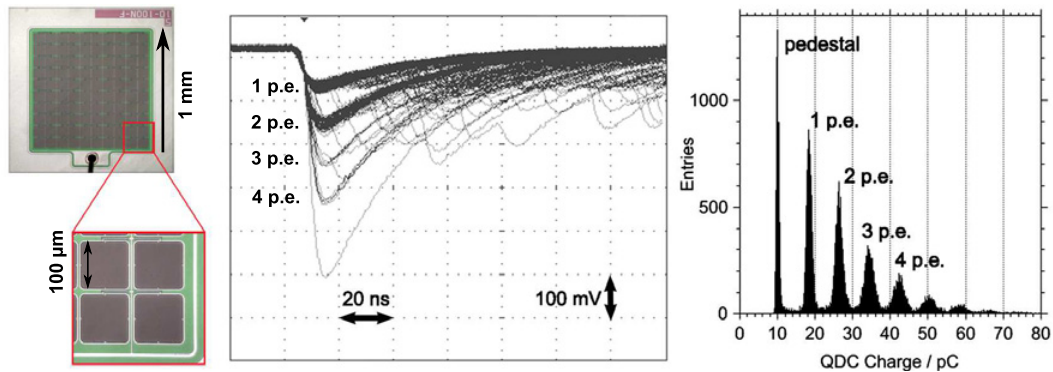
## 1. INTRODUCTION

The fluorescence detection of ultra-high-energy cosmic rays is a well established detection technique used for example by the Pierre Auger Observatory [1] and the Telescope Array [2]. Up to now fluorescence telescopes use photomultiplier tubes (PMTs) as the photosensitive part of their cameras. These PMTs typically have maximum photon detection efficiencies ranging from 27% to 37%. These values are already reached by currently available silicon photomultipliers (SiPMs). Prototypes reaching photon detection efficiencies of up to 60% with peak sensitivities in the UV-blue region, and thus for the fluorescence detection interesting wavelength range, have recently been presented [3]. In contrast to conventional PMTs, SiPMs are much smaller which can result in fluorescence telescopes with a better spacial resolution. In addition, SiPMs are rather new photon detectors and much progress can be expected for future types. Also, they offer the potential for low cost mass production. Altogether, they might be the right choice for the photosensitive component of a next generation, large scale fluorescence detector.

Nevertheless, SiPMs have a much more limited dynamic range than PMTs, a high temperature dependency of their characteristics and high dark noise rates as well as correlated noise effects. All of this has to be considered when evaluating the feasibility of a fluorescence detector applying SiPMs. This feasibility is studied in detail with FAMOUS, which is a small prototype fluorescence telescope instrumented with SiPMs. FAMOUS is currently under construction. A full detector simulation,
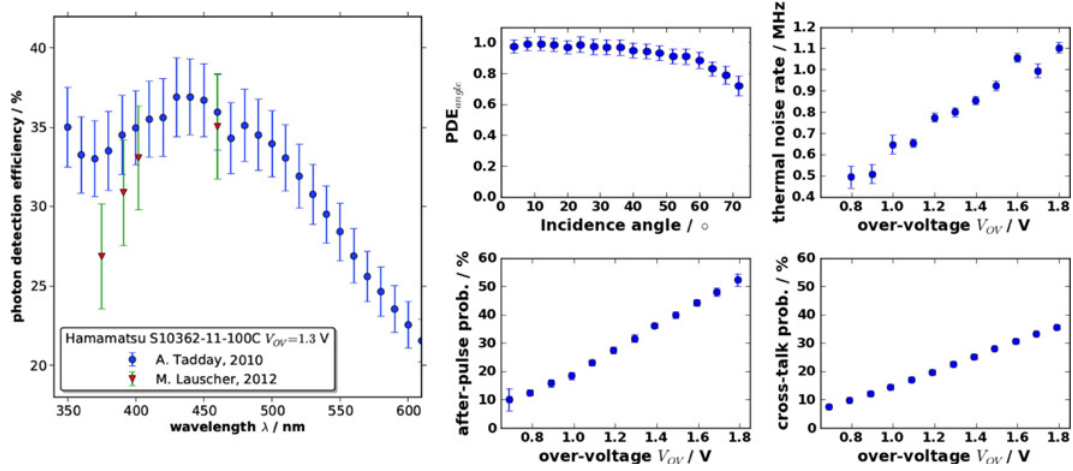
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**Figure 1.** *Left*: photography of an SiPM (Hamamatsu S10362-11-100C). The sensitive area is $1\,mm^2$, the cell pitch is $100\,\mu m$. The green area is dead space leading to a geometric fill factor of 74%. *Center*: oscilloscope screenshot of amplified SiPM signals. These are noise events since the SiPM is in a light-tight box. Signals from different numbers of cell breakdowns are clearly distinguishable. (p.e. = photon equivalent) *Right*: measured charge spectrum of signals of an SiPM which detects light from a pulsed LED. Peaks belonging to a certain number of cell breakdowns are clearly distinguishable. (The pedestal is different from zero since the used charge-to-digital-converter (QDC) has an internal pedestal current unequal to zero.) Image collection adapted from [4].

which was a crucial part of the design process, took all of the effects mentioned above into account.
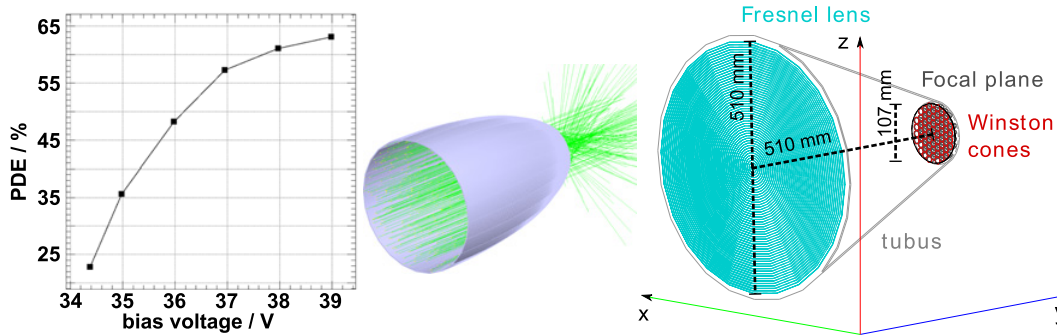
The structure of this paper is the following: in section 2 we briefly describe the working principle of SiPMs and present some of our characterization measurements and their impact on an SiPM fluorescence telescope. The optical design of the prototype is discussed in section 3.

## 2. SILICON PHOTOMULTIPLIERS

Silicon photomultipliers (SiPMs) are arrays of Geiger-mode avalanche photodiodes (G-APDs). A G-APD is operated with an external bias voltage which is high enough to create an electric field within the pn-junction of the diode to allow both, electrons (e) and holes (h) to create further eh-pairs by means of impact ionization. This avalanche is self-sustaining and needs to be quenched to set the diode back to its initial state. This is typically achieved by a quenching resistor connected in series to the diode. G-APDs reach typical gains of $10^5$–$10^6$. The initializing eh-pair can either be created by the absorption of an incoming photon or by thermal excitation. Since the G-APD creates a standard signal for each cell breakdown, its output signal is not proportional to the number of detected photons within the recovery time of the diode. This proportionality can be achieved by an SiPM which is an array of several hundreds to thousands of *cells* connected in parallel to a common load. Each cell is a G-APD and its quenching resistor. As long as the incoming photons are distributed uniformly on the surface of the SiPM, the output signal of the device will be proportional to the number of incoming photons. Of course the dynamic range of an SiPM is limited due to the limited number of cells. In general, one can realize a high number of cells on a certain area, but smaller cell pitches lead to more dead space between the individual cells. This decreases the geometric fill factor and with it the photon detection efficiency (PDE) of the SiPM. Thus, the demand for a high dynamic range and the demand for a high PDE are opposed. Typical cell pitches reach from $25\,\mu m$ to $100\,\mu m$ and SiPMs have typical active areas of $1 \times 1\,mm^2$ to $3 \times 3\,mm^2$. A photography of an SiPM is shown in figure 1. The figure also shows a screenshot of an oscilloscope displaying amplified SiPM signals. Integrating over SiPM signals gives the characteristic charge spectrum (see also figure 1). Both the screenshot and the spectrum demonstrate the photon counting ability of SiPMs since the different peaks are clearly distinguishable from each other. For a detailed description of SiPMs please refer to e.g. [5].

**Figure 2.** *Left*: photon detection efficiency (PDE) of an SiPM with $1 \times 1\,\mathrm{mm}^2$ detection area and $100\,\mu\mathrm{m}$ cell pitch (Hamamatsu S10362-11-100C) as a function of the wavelength. Triangles show data from our laboratory [6] in comparison to earlier measurements [7] (circles). The over-voltage is $V_{\mathrm{OV}} = 1.3\,\mathrm{V}$. A parametrization of [7] is used in our telescope simulations. *Right*: *Top-left* - PDE as a function of the incident angle of light relative to an angle of $0°$. *Remaining plots* - Thermal noise rate, optical crosstalk and afterpulse probabilities as functions of the over-voltage $V_{\mathrm{ov}}$. The over-voltage is the difference between the bias voltage of the SiPM $V_{\mathrm{bias}}$ and the breakdown voltage $V_{\mathrm{bd}}$ above which cell breakdowns can occur: $V_{\mathrm{bias}} = V_{\mathrm{bd}} + V_{\mathrm{ov}}$. Ambient temperature $T = (25.5 \pm 0.1)\,°\mathrm{C}$. The results are for the S10362-11-100C type. - Systematic uncertainties are not shown.



**Figure 3.** *Left*: photon detection efficiency (PDE) of a Dolgoshein-type SiPM (cf. [3]) vs. bias voltage measured at our laboratory. *Center*: simulation of a hollow Winston cone made from polished aluminium. Light entering the cone from the left is concentrated to a smaller area at its exit where an SiPM will be mounted. The light is partly reflected inside the cone so that larger exit angles occur. *Right*: Geant4 visualization of FAMOUS. Light enters the telescope from the left. A Fresnel lens focuses it onto the focal plane where 64 pixels are hexagonally arranged. Each pixel consists of a Winston cone, UV pass filter and four $3 \times 3\,\mathrm{mm}^2$ SiPMs whose signals will be summed up.

One of the most important characteristics of a photon detector is its detection efficiency. The photon detection efficiency of an SiPM is $\mathrm{PDE} = \mathrm{QE} \cdot \epsilon_{\mathrm{geo}} \cdot P_{trigger}$. Here the quantum efficiency QE is the probability that an incoming photon creates an eh-pair, $\epsilon_{\mathrm{geo}}$ is the geometric fill factor already mentioned above and $P_{\mathrm{trigger}}$ is the probability of eh-pairs to trigger an avalanche within the cell. Figures 2 and 3 show our measurements of the PDE for different types of SiPMs. The Dolgoshein-type (Fig. 3) reaches a higher PDE but is not yet commercially available. Thus for now, our prototype telescope will make use of SiPMs manufactured by Hamamatsu (Fig. 2). Other very crucial characteristics of SiPMs are given in Figure 2: The relative PDE depending on the incident angle of light is of interest, since the

light in the telescope will hit the SiPM under different, partially large angles (cf. center of Fig. 3). Noise, like thermal noise[1], optical crosstalk[2] and afterpulsing[3] have to be studied in detail to evaluate the feasibility of an SiPM fluorescence telescope. For a more detailed description and measurements of these effects please refer to [4], [6]. The next section will present the optical design of the prototype telescope FAMOUS. Taking into account this design together with the just mentioned characterization measurements, a full detector simulation will allow the performance evaluation of the telescope.

## 3. OPTICAL DESIGN OF FAMOUS

FAMOUS is a small prototype SiPM fluorescence telescope, currently under construction, designed to study the feasibility of fluorescence detection with SiPMs. Its camera consists of 64 hexagonally arranged pixels each with a field of view of $1.5°$. This leads to a full field-of-view of approximately $12°$. Since fluorescence light is in general of low intensity, a large aperture is needed. The aperture diameter $D$ as well as the focal length $f$ is set to $510$ mm. To keep the camera out of the light path and achieve $f/D = 1$, we refrain from standard mirror systems. Thus, FAMOUS will be a refracting telescope with a Fresnel lens as the refractive element. This lens is made from UV-transparent acrylic with 10 grooves per mm and a transmission efficiency of approximately 70%. Simulations show that the imaging properties of the lens are sufficient for our needs: For all allowed angles under which parallel light will enter the telescope, more than 90% of the photons will be refracted onto an area smaller than a camera pixel. One pixel will consist of four $3 \times 3$ mm$^2$ SiPMs with a cell pitch of $100\,\mu$m which are housed in the same package (Hamamatsu S10985-100C), coupled to Winston cones to increase the effective sensitive area. The Winston cones concentrate the light coming from the lens onto the SiPMs. They are rotationally symmetrical and made from polished aluminium with a diameter at their entrances of 13.4 mm (defining the area of a camera pixel) and a diameter at their exits of 6.0 mm. Between the Winston cone and the SiPM a UG11 [8] UV pass filter is mounted to reduce any but the UV-fluorescence light. Visualizations of the telescope and a Winston cone are given in figure 3. For more information on the optical design please refer to [9].

To evaluate the performance of the presented design, a full detector simulation is performed: A shower library[4] of vertical extensive air showers has been created using CONEX [10]. Afterwards the Offline framework of the Pierre Auger Collaboration [11] is used to simulate the generation and propagation of the fluorescence light from the air shower to the telescope. Finally, the telescope is simulated with Geant4 [12], including a phenomenological SiPM model that outputs the voltage traces of the individual camera pixels. This model contains all of the SiPMs characteristics mentioned in section 2 as well as further characteristics like temperature dependencies, recovery time and dynamic range. Since the main background to the fluorescence signal is the night-sky brightness we measured its photon flux with a one-pixel-SiPM telescope[5] near Aachen, Germany (which is an urbanized environment) and calculated an upper limit for the photons in the range of $300$ nm to $400$ nm to $1.2\,10^{12}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$. Thus, the night-sky brightness leads to approximately 0.3 detected photons per ns in a camera pixel of our prototype telescope. This contribution is about 90% of the overall noise, 10% is due to thermal cell breakdowns and its correlated noise. The knowledge of the background allows to calculate the signal-to-noise ratio (S/N) for the above mentioned simulated showers. Figure 4 shows the S/N as a function of the energy of the air shower and its distance to the telescope. Demanding a certain
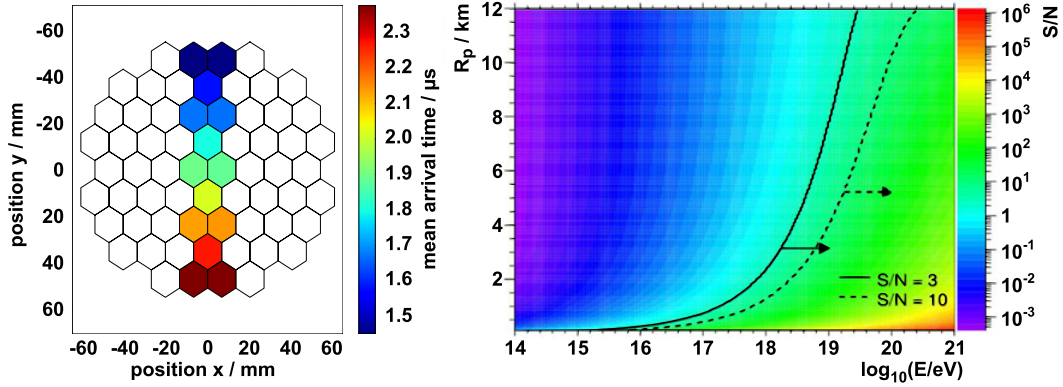
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[1] i.e. cell breakdowns due to eh-pairs created by thermal excitation.

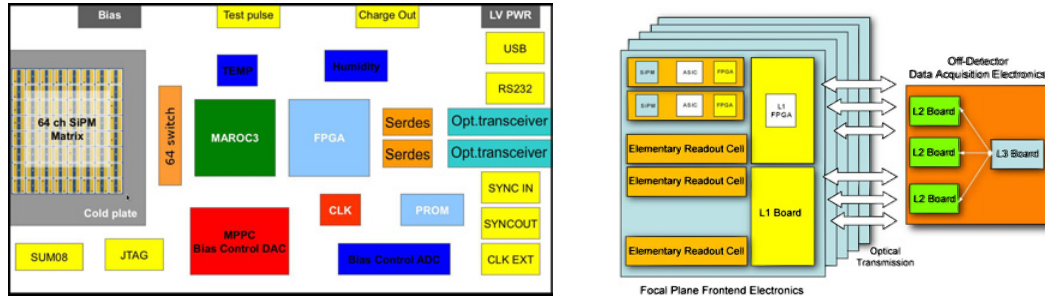[2] Electrons and holes recombine to photons which trigger cell breakdowns in neighboring cells.

[3] Charge carriers, which are trapped at impurities in the silicon, trigger cell breakdowns when they are released with a delay.

[4] Air shower energies $E$ in the interval [$10^{15}$ eV, $10^{20}$ eV] with discrete energies of distances $\log_{10}(\Delta E/\text{eV}) = 0.25$. 100 showers per bin. Each shower is then placed at a distance of 1, 2, 3,...12 km.

[5] Telescope: commercial Newton reflector Bresser PN 203, D = 203 mm, f = 800 mm. Pixel: Winston cone and SiPM, $3 \times 3$ mm$^2$, $100\,\mu$m cell pitch (Hamamatsu S10362-33-100C).

**Figure 4.** *Left*: simulated event viewer: Each hexagon represents one camera pixel. The signals within white pixels do not exceed a certain threshold. Color-coded is the arrival time of the fluorescence light within a pixel. Air shower energy $E = 10^{18}$ eV, distance to telescope $R_{\mathrm{p}} = 2$ km. *Right*: simulated signal-to-noise ratio (S/N) as function of the energy of an air shower and its distance to the telescope. The noise is dominated by the rather bright night-sky in Aachen, Germany used in this simulation. If e.g. a S/N > 3 is desired a $10^{18}$ eV air shower is visible up to a distance of approximately 2 km. Lines of constant S/N will shift to the left for larger telescope apertures or more efficient SiPMs in combination with a smaller field-of-view of the pixels as well as for darker observation sites.



**Figure 5.** *Left*: layout of the frontend electronics to be used in FAMOUS. (LV PWR: power input - MAROC3, FPGA: see text - SERDES: serializer/deserializer - SUM08: analog sum outputs - JTAG: joint test action group (test port) - CLK: internal clock - PROM: programmable ROM - CLK EXT: external clock) *Right*: architecture of the data acquisition system. Each focal plane frontend electronics board offers 64 channels. The total system is modular with a pyramidal scheme connecting several frontend electronics boards to the off-detector DAQ electronics by optical transmission if desired. (L1, L2, L3: trigger levels) For more information see also [14].

minimum S/N we can see which air showers can be detected. E.g. a $10^{18}$ eV shower is visible up to a distance of about 2 km for the choice of S/N > 3. Altogether, the performance of the prototype telescope is already very promising, even though its aperture is very small (and will be increased for successive telescopes) and the simulations consider an urbanized and thus bright observation site. Moreover, the Hamamatsu SiPMs have a lower photon detection efficiency than recently presented prototypes.

## 4. FOCAL SURFACE DATA ACQUISITION DESIGN AND ARCHITECTURE

Due to the fact that the size of a camera pixel is rather small and that FAMOUS with its 64 pixels is just a first prototype and successive telescopes should possess much more pixels, we require a compact and modular design for the frontend electronics. Additionally, minimum cabling between the SiPMs and the electronics will lead to reduced noise pickup and electrical crosstalk. This is achieved by early

digitization within the prototype board called Elementary Readout Cell (ERC). The early digitization is performed by a MAROC3 chip [13]. It is a 64 channel readout ASIC with a power consumption of 3.5 mW per channel. Each channel has a low-impedance amplifier with adjustable gain. The chip offers three different pulse shapers for each channel (unipolar, bipolar, half-gain-bipolar) and in-core DACs define thresholds. Moreover, the MAROC3 also outputs eight freely configurable analog sums of up to eight input channels. The trigger information as well as the serial data-stream from the MAROC3 are passed to an FPGA where algorithms decide whether the received signals are produced by an air shower or should be discarded. Optical links with maximum transmission rates of 3.125 Gbps allow to forward the signals to the off-detector data-acquisition electronics, which also provides further trigger instances, but also allows to connect several ERCs if more than 64 channels are needed. The FPGA is also provided with data from temperature and humidity sensors, thus allowing to control the bias voltage of the SiPMs and compensate temperature dependent changes of their characteristics. For more information please refer to [14]. First ERCs have been manufactured recently and are currently being evaluated.

## 5. SUMMARY AND OUTLOOK

Silicon photomultipliers (SiPMs) have the potential to be the right choice as the photosensitive component within a future large scale air shower fluorescence telescope. To study the feasibility of SiPM fluorescence telescopes we are currently constructing a small prototype named FAMOUS with 64 pixels and a full field of view of approximately $12°$. It will be a refracting telescope with a Fresnel lens as the refractive component ($D = f = 510$ mm). Full detector simulations look very promising: Already this small prototype with currently available SiPMs is able to detect nearby ultra-high-energy cosmic rays in an urbanized and thus rather bright environment. Dedicated frontend electronics, which are based on a modular design, have recently been manufactured and are currently being evaluated. FAMOUS is expected to measure first light within this year.

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