PROCEEDINGS OF SCIENCE

# FAMOUS – A fluorescence telescope using SiPMs

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The FAMOUS telescope is a prove-of-concept study for the usage of silicon based photo sensors (SiPMs) in fluorescence telescopes. Such telescopes detect the fluorescence light emitted by ultra high energy cosmic-ray particles impinging on the atmosphere of the Earth. Available instruments, like the fluorescence telescopes of the Pierre Auger Observatory in Argentina, are using photomultiplier tubes for photon detection. The FAMOUS camera aims to make use of the advantages of recent developments in photo detection by SiPM sensors, like increasing the duty cycle due to the ability to operate SiPMs during bright moon light. Built in a 50 cm-diameter aluminum tube with a refractive optics driven by a Fresnel-lens, a seven pixel prototype camera has been developed and installed. First results look very promising. The next stage of the prototype will be equipped with a 61 pixel camera, a more light weight tube, more efficient light concentrators, and a custom made and more stable power supply. The results of the test measurements and the status of the next stage prototype will be presented.

*The 34th International Cosmic Ray Conference,*
*30 July - 6 August, 2015*
*The Hague, The Netherlands*

PoS(ICRC2015)649

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[*] Speaker.

## 1. Introduction

At the Pierre Auger Observatory, fluorescence telescopes are successfully operated to detect air showers of ultra high energy cosmic rays for many years [1]. Fluorescence telescopes image the light isotropically emitted by de-excitation of air molecules excited by a primary charged particle and secondary particles produced by the induced air shower cascade. Due to the composition of air, most of the de-excitation lines are Nitrogen lines and emission takes place mainly between 300 nm and 400 nm.

The surface detectors [2] of the Pierre Auger Observatory are installed with a large spacing to achieve a large detection area to account for the low rate of extensive showers induced by ultra high energy cosmic-ray particles which extend over several kilometers. Due to the large spacing, the information carried by the air-shower particles is only partially sampled and especially energy-reconstruction suffers comparably large systematic uncertainties. In contradiction to surface detectors, fluorescence telescopes detect the light emitted from all particles with energies above the ionization limit and therefore provide smaller systematic uncertainties.

While fluorescence telescopes are naturally able to survey large areas with a small number of instruments, their duty cycle is inherently limited by light conditions to about 10%. The main limitation comes from the faint brightness of air-showers, which requires observations during night. An additional limitation is imposed by the usage of photo multiplier tubes (PMT) for light detection because of aging if exposed to bright light as, for example, moon light.

Therefore, an obvious alternative are semi-conductor based photo sensors, in the following called SiPMs, which are robust against the exposure to bright light and have reached a similar performance as PMTs during the past years. Since 2011, the First G-APD Cherenkov Telescope (FACT) is operated on the Canary Island of La Palma [3], implementing the so-called imaging air-Cherenkov technique to image the Cherenkov light emitted by air-showers. Although the focus here is on TeV astronomy, the applied technology is essentially the same except the typically larger field-of-view of fluorescence telescopes and the application of waveband filters in fluorescence telescopes. The FACT Collaboration has proven the applicability of SiPMs in such cameras to a precision of the signal of less than 1%, only limited by the precision of their bias power-supply [4].

The telescope FAMOUS, has the goal to explicitly prove the applicability of SiPMs in fluorescence telescopes. In the ideal case, a duty cycle of about 30% should be achievable.

## 2. SiPMs

The advantage of semi-conductor based photo sensors is their low operation voltage compared with classical PMTs and their mechanical robustness combined with an increased photo detection efficiency.

The sensors discussed here are compiled from arrays of Geiger-mode Avalanche Photo Diodes (G-APDs). If an avalanche photo diode is operated above its breakdown voltage, a single photon can induce a complete release of their charge. Since G-APDs, with their typical size of several tens of micro-meters are large compared to the typical scale of today's semi-conductor structures of several tens of nano-meters, they can be produced with very high precision. Therefore, the released charge is very precise and ideally suited for single photon counting.

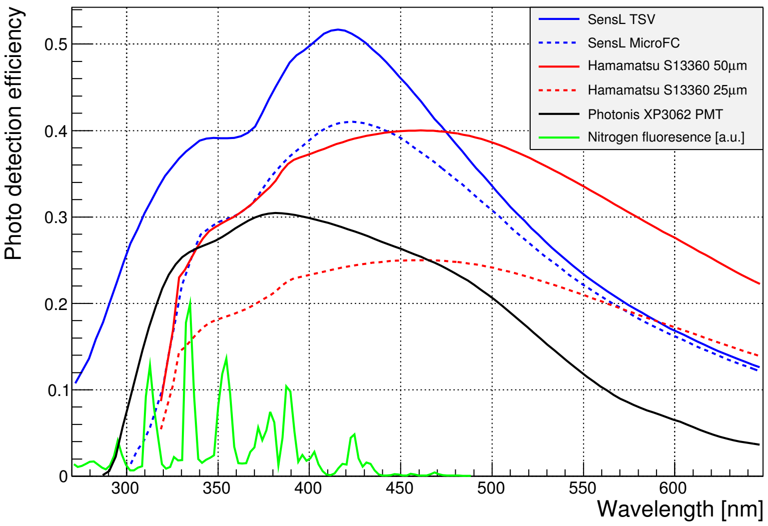

**Figure 1:** Shown is the PDE of the most recent SiPMs currently available on the market compared with the Photonis XP 3062 PMT as used in the fluorescence telescopes of the Pierre Auger Observatory. The green line shows the fluorescence spectrum of Nitrogen in arbitrary units.

Due to the limited number of diodes in one sensors and the fact that even a double-hit of a single diode would release the stored charge only once, the dynamic range of SiPMs is inherently limited. However, because of the statistical process with which random photons hit individual diodes on a sensor, non-recoverable saturation only takes place at a photon hit count of around five times the number of available cells times the effective photon detection efficiency.

Another effect with a small impact on the dynamic range and the resulting signal is the so-called optical crosstalk. Originating from emitted photons during recombination which can trigger neighboring diodes, it mainly increases the induced signals on average and therefore slightly reduces the dynamic range. Its effect can be neglected compared to the pure Poissonian counting error [5].

While previous generations of G-APDs suffered from afterpulses, the afterpulse probability of current devices is typically well below 1% so that afterpulses can be neglected. This was achieved by a significantly improved quality of the silicon waver which also reduces the dark counts to typical rates of 50 kHz/mm$^2$, cf. [6, 7, 8]. Such sensors are nowadays available in 6×6 mm$^2$ for prices as low as 0.5 €/mm$^2$ if ordered in large quantities [9].

Figure 1 compares the photo detection efficiency of sensors available on the market with a standard PMT and the fluorescence emission spectrum of Nitrogen.

## 3. A seven channel prototype

As a first concept study, a 7-pixel version of the FAMOUS telescope was built [10] (see Figure 2). Its mechanical structure consists of an aluminum tube with slightly more than 50 cm diameter. As imaging optics, a Fresnel lens ($D = 500$ mm, $F/D \sim 1$) is used to focus the light on the focal plane. The focal plane is comprised by seven Winston cones [11] ($d_{in} = 13.42$ mm, $d_{out} = 6.00$ mm) increasing the effective photon detection area of the individual sensors. This yields a field-of-view

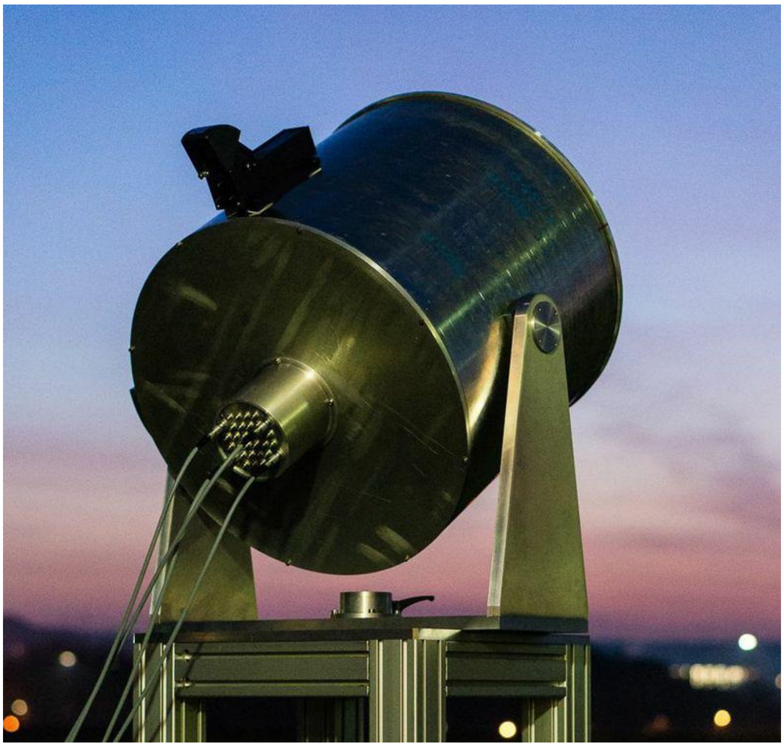

**Figure 2:** The FAMOUS prototype with the aluminum tube and the 7-pixel camera seen from the back while observing the sky over Aachen

per pixel of 1.5°. To increase the signal-to-noise ratio, a filter made of Schott UG11 is installed behind the cone, mainly transparent around the main Nitrogen emission lines, therefore, absorbing a significant fraction of the photons from the diffuse night-sky background. For light detection, Hamamatsu S10985-100C ($6\times6\,\text{mm}^2$) sensors are in use. Although those sensors belong to an older generation of SiPMs, they are already well suited for the presented application. The sensors are read out by two DRS 4 evaluation boards[1] and their bias voltage is supplied by a custom made power supply.

## 4. Measurements

As a proof-of-principle, first measurements have been carried out in the field. Therefore, the telescope has been brought to a field near the RWTH Aachen University Campus during a moonless night with reasonably good weather. Data was taken with a threshold set as low as possible but high enough to keep the dead time of the data acquisition reasonably low. With a software threshold, the rate was analyzed as a function of the threshold. A clear excess at high thresholds, i.e. high amplitudes, was found as compared to data taken under cloudy weather conditions which absorb the light emitted by air showers. Looking into individual high amplitude events further, they are found to be significantly brighter than the expectation for triggers on the diffuse nigh-sky background and several channels show signals in close coincidence of only a few nanoseconds as expected from the

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[1] `http://www.psi.ch/drs/`

**Figure 3:** A comparison between the old Winston cone with an additional edge for assembly (right) and the new one with a smaller rim (left). The inner geometry is identical

Cherenkov light flash of very high energy air-showers. The measurements and their results are further discussed in [12].

## 5. Construction

Although, the first measurements have given a clear hint of the detection of air-showers from cosmic-rays, the next steps are the detection of isolated images of air-showers and a clear time development in the image. An image which is not leaking at the border of the camera will allow the comparison of the image shape with expectations from Monte Carlo simulations. Although the majority of recorded images will be images of the emitted Cherenkov light of air-showers, elongated images with a significant development in time could be identified as distant fluorescence showers. While the detection of a fluorescence shower with such a small instrument and limited observation time is not likely, the energy threshold of the instrument will be low enough to detect a reasonable amount of very high energy showers in Cherenkov light. As compared to the FACT telescope, the light collection efficiency is in the order of a few percent. Consequently, about 20 to 30 times more light is required to detect an air-shower event. Since the Cherenkov light output scales with the number of particles which is proportional to the energy, the energy threshold of such an instrument will be about 20 to 30 times higher. Given that a FACT like telescope has an energy threshold for hadron induced showers of a few TeV, the energy threshold of FAMOUS is supposed to be below 100 TeV.

To achieve this goal, several improvements are currently under construction. The main upgrade will be the increase of the number of pixels from previously seven to 61. This number has been chosen to maximize the symmetry of the final camera. To increase the light collection efficiency, the cones have been re-designed with a significantly smaller wall but same optical properties to avoid unnecessary dead area between the pixels, see also Figure 3.

As sensors, Hamamatsu S12573-100C will be used. These sensors have already been purchased a while ago. Their main difference to the S13360 series (included in figure 1) is that they combine four $3\times3\,\mathrm{mm}^2$ sensors made of a single silicon-waver in a $6\times6\,\mathrm{mm}^2$ package. Usually, all four tiles have slightly different breakdown voltages. The supply with a single voltage per sensor increases gain fluctuations. Newer $6\times6\,\mathrm{mm}^2$ sensors have improved quality of the silicon-waver and are therefore available as single-piece sensors.

Since SiPMs require a supply voltage which needs to be adjusted according to their temperature to keep their properties stable, a new 64-channel power supply with built-in temperature adaptation has been designed and constructed [13].

For data acquisition, readout electronics based on the Target-7 chip [16] as developed for the CHEC camera [14] of the Cherenkov Telescope Array (CTA, [15]) will be used. Each module consists of four Target-7 chips each able to sample 16 channels at sampling rates between 200 MHz and 1.4 GHz and an effective resolution of at least 10 bits. Each channel has a large buffer of 16,384 samples corresponding to a sampling depth of more than 16 $\mu$s at a sampling rate of 1 GHz. Originally developed to allow for coincidence triggers between several telescopes in the Cherenkov Telescope Array even for highly inclined showers, the buffers are also well suited for the comparably long time duration of the fluorescence showers which can last several micro-seconds. With these properties and an expected power consumption of less than 10 W these modules are ideally suited for the described application.

The Target-7 chip implements 16 analog sums of four channels, each sum with a discriminator downstream. The output of each discriminator can then be processed externally and a single trigger signal is returned to the readout chip. Due to the comparably long lasting fluorescence showers, this logic might not work well with fast signals. Monte Carlo studies are performed to optimize the trigger logic. Either the signal can be stretched or an external trigger path can be implemented.

Since the Target-7 solution offers 64 channels and the symmetric camera layout implements only 61 channels, the additional three readout channels will be connected to blind pixels, with and without SiPMs attached. These blind channels will allow for an online monitoring of the noise.

In addition to the changes in the electronics, the aluminum tube is replaced by a tube made from carbon fiber reinforced plastic which significantly lowers the weight of the tube from tens of kilograms to less than five.

## 6. Monte Carlo

Since the light output of the Cherenkov and fluorescence signal scales linearly with the number of particles in the shower and therefore with the energy of the primary particle, the performance of the system can easily be estimated knowing the total light collection efficiency. However, the additional influence of the camera geometry, the optics, the electronics and especially the trigger electronics, is hard to estimate. Consequently, a dedicated Monte Carlo study is in progress.

The geometry of the system and its optics has been implemented in Geant 4, for a full featured simulation of the SiPMs, the Geant 4 based package G4SiPM[2] [17] is used. The shower development is simulated with CORSIKA [18].

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[2] `https://forge.physik.rwth-aachen.de/projects/g4sipm`

**Figure 4:** The new focal plane of the FAMOUS telescope. Visible is the PCB which will host the 64 SiPMs and an aluminum grid into which the 61 Winston cones will be glued. As an example one SiPM is shown. The three blind pixels are hidden by the aluminum border.

## 7. Status

Up to date, all mechanical parts are available and currently the telescope is under assembly. The new 64-channel power supply board is available and has passed the first tests already, proving its excellent performance. Until the Target-7 module will be available, two pre-amplifier and readout boards borrowed from the FACT collaboration will be used to digitize the fast Cherenkov light flashes, as well as a professional multi-channel 62.5 MHz FADC to acquire data from the slower fluorescence events. A running system is expected to be available autumn this year.

## 8. Summary and Outlook

With the field measurements of a 7-channel prototype fluorescence telescope, the applicability of SiPMs in fluorescence telescope analogous to the application in Cherenkov telescopes has already been proven. A 61-channel version is currently under assembly and will be used to study the technology in more details. For this, a new precise and flexible power supply which corrects the bias voltage of the SiPMs automatically according to the ambient temperature has been developed. After full system tests have been carried out shortly after assembly, the next step is the application of SiPMs in a working fluorescence telescope. The Pierre Auger Observatory contains a partially equipped fluorescence telescope to avoid the bright light of a nearby town being focused on their PMTs. The application of SiPMs to fill this gap will be an ideal test for the application under real environmental conditions and to prove the robustness against bright light once more. In addition, newer sensors with improved PDE can be applied giving a significant improvement on light collection efficiency.

## Acknowledgments

This work is funded by the European astroparticle physics network ASPERA and the German Federal Ministry of Education and Research BMBF under Contract No. 05A11PAA. Additionally, the authors would like to thank the mechanical and electronics workshops in Aachen and the local IceCube group.

## References

[1] J. Abraham et al., Nuclear Instruments and Methods A 620 (2010) 227-251 [arXiv:0907.4282].

[2] I. Allekotte et al., Nuclear Instruments and Methods A 586 (2008) 409-420 [arXiv:0712.2832].

[3] H. Anderhub et al., JINST 8 (2013) P06008 [arXiv:1304.1710].

[4] A. Biland et al., JINST 9 (2014) P10012 [arXiv:1403.5747].

[5] T. Bretz et al., In Proc. NSS-MIC 2013 [arXiv:1403.3573].

[6] SensL C-Series, Datasheet (2014).

[7] Hamamatsu, MPPC Datasheets.

[8] Hamamatsu, MPPC Technical Note.

[9] SensL offer, March 2015.

[10] T. Niggemann et al., In Proc. of the 33rd ICRC 2013 [arXiv:1502.00792].

[11] R. Winston et al., *Nonimaging optics*, Academic Press, Jan 2005.

[12] J. Auffenberg et al., In Proc. of the 34th ICRC, PoS(ICRC2015)1047.

[13] J. Schumacher et al, In Proc. of the 34th ICRC, PoS(ICRC2015)605.

[14] M. K. Daniel et al., In Proc. of the 33rd ICRC 2013 [arXiv:1307.2807].

[15] M. Actis et al., Experimental Astronomy 32 (2011) 32 [arXiv:1008.3703].

[16] K. Bechtol et al., Astroparticle Physics 36 (2013) 156-165 [arXiv:1105.1832].

[17] T. Niggemann et al., NIM A 787 (2015) 344 – 347.

[18] Heck, D. et al., FZKA 6019 (1998).