Prospects of silicon photomultipliers for ground-based cosmic ray experiments

Christine Peters,
Thomas Bretz, Thomas Hebbeker, Julian Kemp, Markus Lauscher, Lukas Middendorf, Tim Niggemann, Johannes Schumacher

UHECR 2016
Kyoto, Japan
Outline

- Silicon photomultipliers - SiPMs
- The fluorescence telescope FAMOUS
- The muon detector upgrade SSD for AugerPrime
- The muon detector AMD

Aachen Muon Detector prototype

Surface Scintillator Detector

First Auger MPPC camera for the Observation of Ultra-high-energy air Showers
SiPMs are a mass product (0.50 $/mm^2)

High noise rate (30 kHz/mm^2)

Temperature dependence but can be corrected for.

Performance comparable to best available PMTs with future potential

Cheaper than PMTs

No significant ageing (moon!)

Very good timing (jitter)

Very easy to handle (U<100V)

Dark counts, crosstalk and afterpulses are no problem for Cherenkov / Fluorescence telescopes

Gain depends on
- temperature
- voltage drop at serial resistor (i.e., on night-sky brightness)

Why G-APDs (aka SiPM)?
SiPM response

Counts / arb. u.

Charge / p.e.

1 p.e. 2 p.e.

dark noise

crosstalk probability < 10 %

gain

Online gain monitoring

V(t) / mV

dark noise

1 p.e.

2 p.e.

5 mV

20 ns

5 mV

20 ns

1 p.e.

2 p.e.

Online gain monitoring
Why SiPMs? - photon detection efficiency

![Graph showing photon detection efficiency for SiPMs, PMTs, and data sheet values for different models.](image-url)
Extensive air showers - detection principles

SiPMs excellent choice as light sensors

Muon detector on ground

All-particles detector on ground

Fluorescence light

Cherenkov light
As an alternative to this traditional setup, a relatively new kind of semiconductor light sensor is used as the active detector component of the prototype fluorescence telescope FAMOUS (figure 1.1). The acronym, standing for First Auger MPPC camera for the Observation of Ultra high energy cosmic ray air Showers, emphasizes the usage of so-called Multi Pixel Photon Counters - also known as silicon photomultipliers (SiPMs) which are built from a Geiger-mode avalanche photodiode array. As the name suggests, these devices are sensitive enough to detect single photons and thus are suitable to detect fluorescence radiation. In comparison to photomultiplier tubes, SiPMs operate at much lower voltage and promise a higher photon detection efficiency in the future.

For the prototype FAMOUS, a refractive telescope design was chosen using a Fresnel lens of roughly half a meter diameter. On that scale, Fresnel lenses have certain advantages in comparison to bulky lenses if image quality is of secondary importance. As a Fresnel lens is significantly thinner than its bulky counterpart, the transmittance of light in the ultraviolet regime is much higher, which is important since the characteristic spectrum of fluorescence radiation reaches from 280 nm to 420 nm. On top of that, a more compact and lightweight construction is possible.

In this thesis, the optics of the fluorescence telescope FAMOUS is characterised with special regard to the properties of the Fresnel lens, including the form of the focal point, various aberrational effects like spherical and coma aberration, distortion, curvature of field and the transmittance. Therefore, the listed effects are measured for the Fresnel lens of FAMOUS and for a conventional lens of smaller diameter to understand the influence of the experimental setup. Furthermore, the results are compared to a simulation of the setup.

As a result of this analysis, the systematic effects and influence of the Fresnel lens on the detector response of FAMOUS as well as the cooperation of the lens and the SiPM camera pixels can be better understood and quantised. The results will help to compute the uncertainties for the detected fluorescence signal.
The fluorescence telescope FAMOUS

Fresnel Lens

502.1 mm

549.7 mm

120.4 mm

61 Pixel Camera
The fluorescence telescope FAMOUS

Fresnel Lens

549.7 mm

502.1 mm

21.4 mm

15.4 mm

Winston cone

UV-Pass Filter

SiPM

61 Pixel Camera

Light
The fluorescence telescope FAMOUS

FAMOUS news
First test measurements with 61 pixel telescope

Readout module based on TARGET7 (provided by FAU Erlangen)
- to be implemented
- trigger threshold to be calibrated
  external trigger so far
Cherenkov light

directed light cone

\[ \Delta t \sim O(10\text{ns}) \]

Fluorescence light

isotropic light emission

\[ \Delta t \sim O(1\mu\text{s}) \]
First measurement setup

4.2. Measurement with the TARGET 7

The output signal is connected to the external trigger input of the TARGET7-module. The TARGET7-module is connected to the power supply and to the second laptop through a switch. Furthermore, patch-board connects the TARGET7-module to 16 pixels of the FAMOUS telescope.

![Figure 4.14: Layout of the camera in FAMOUS. The yellow marked pixels are connected to the TARGET7-module, the blue pixels are used as the trigger-pixels.](image)

4.2.2. Data acquisition

The following settings are used during the measurement outside:

- The overvoltage of the SiPMs are set to 1 V for measuring higher p.e.-signals and because of the bright environment.
- The external trigger of the TARGET7-module is used, because the self-trigger does not work yet.
- A trigger delay of 424 ns is used, to see the signals in the trace, which caused the read out.
- The threshold for the trigger board is set at 0.93 V, which causes an average frequency of 0.44 Hz of triggering. 8 successfully measurements have been done, each with a length of 5 min.

The trigger pixels are not chosen randomly. Each trigger pixel is surrounded by pixels, connected to the TARGET7-module (figure 4.14). If Cherenkov light hits the trigger pixel, the probability of hitting more pixels next to the trigger pixel is very high. If the trigger pixel causes a read out, coincidental events next to the trigger pixel should be noticed.

4.2.2.3 Evaluation

To start the evaluation, the traces are inspected, whether high signals can be seen at the first look. Indeed, it is possible to find some high SiPM-signals in some traces, like it is shown in figure 4.15. These traces are all already corrected by N. H"onlich.

The SiPM-signal is about 70 times higher, than the signal in figure 4.11. This could be an evidence, that the signal could be caused by Cherenkov-light. To support this suspicion, other channels must be analysed in a similar time frame.
First Cherenkov-like candidates!
SiPM progress in astroparticle physics

First SiPM Cherenkov telescope running since 5 years!

Dedicated monitoring IACT with the possibility to observe during strong moon light
SiPM progress in astroparticle physics

First SiPMs at South pole
Deployment of FAMOUS based design
IceAct Cherenkov telescope at South pole
SiPM progress in astroparticle physics
SSD - scintillator detector for AugerPrime

Preliminary design report - arXiv:1509.03732

Different detector response of scintillator detector and water Cherenkov tank

- One goal: Mass composition by number of muons

- Both detectors have ≈ 100% duty cycle!

First prototypes in the field
Start of data taking: 2018

SiPMs excellent option for light sensor
4.2 THE SCINTILLATOR DETECTOR

Figure 4.2 shows a sketch of two bars with the fiber readout. The two-ended readout of the scintillator strips also provides a better longitudinal uniformity in light response.

Two companies, Kuraray and Saint Gobain, produce suitable WLS multi-clad optical fibers for our application. The Kuraray fibers have a higher light yield and are more readily available. They have also been used for optical read-out in most large area scintillator counter experiments. For these reasons they were chosen as the baseline design option. However, the Saint Gobain WLS fiber may have a lower cost and the possibility to make use of them is currently under investigation.

For the baseline design, the Kuraray Y11 WLS multi-clad optical fiber with 1 mm diameter is chosen, with a concentration of fluorescent dye at either 200 or 300 parts per million. As shown in Figure 4.3, the absorption spectrum of the K27 dye (Y11 fiber) matches perfectly the scintillator emission. On the other hand, the WLS fiber emission is shifted toward longer wavelengths than the absorption peak of a standard bialkali photocathode, thus suggesting some caution during the selection of the read-out photodetector.

The WLS fibers will be of S-Type to allow shorter bending diameter (Figure 4.4) and minimize the risk of damage during the detector assembly. In fact, the S-type fiber core has a molecular orientation along the drawing direction. This fiber is mechanically stronger against cracking at the cost of transparency; the attenuation length of this type is nearly 10% shorter than the standard type. Kuraray conservatively recommends a bend diameter 100 times the fiber diameter. Accordingly, the fiber routers have been designed with curvature...
**Aachen Muon Detector**

- **tank** used as shielding

- **scintillator tile**
  - 30x30x0.5 cm³
  - 64 tiles / detector

- **light is collected in fibre**

- **steel housing**
  - 2 / SD station

- **tray**
  - 8 tiles / tray

- **tray cover**
  - sealing

- **clear waveguide**

- **Voltage Supply**

- **1 EASIROC SiPM ASIC**

- **SiPM Carrier Board**
  - 1 board / tray
  - located at the end of tray

- **SiPM**
  - 1x1 mm²
  - 1 SiPM / tile

**Alternative detector concept - many channels**
Proof of concept - MiniAMD

Potential calibration device for SSD
- 8 tiles and one SiPM each
- Size SiPM: 1.3 mm x 1.3 mm
- SiPMs directly connected to tile
- Weight: ~ 25 kg

MiniAMD

Water Cherenkov tank

SSD

Muon
electron

MiniAMD
Summary

Determination of number of muons

- **SiPMs excellent option** for detection of muons

- **SSD**: First modules in field, few equipped with SiPMs

- **AMD**: MiniAMD at Auger site next year

**FAMOUS**

- Successful commissioning of the new 61 pixel focal plane

- Measurement of first shower candidates
The very near future

Exciting time ahead!