Future application of SiPMs for the fluorescence detection of extensive air showers

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Digital Counting Photosensors for Extreme Low Light Levels

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Cosmic ray induced extensive air showers (EAS)

- $\bullet\,$ Earth atmosphere is constantly hit by cosmic ray particles with energies up to several $10^{20}\,{\rm eV}$
- very low flux
 - \Rightarrow no direct detection possible
 - \Rightarrow use earth atmosphere as calorimeter with large ground based detector
- interaction of particles with air produces multiple secondary particles
 - \Rightarrow extensive air showers down to the ground level

Fluorescence detection of extensive air showers



- air emits fluorescence light isotropically when excited by shower particles (UV)
- light \propto number of particles \propto energy
- measure longitudinal air shower development
- determine energy and X_{\max}



The Pierre Auger Observatory

- $\bullet\,$ hybrid cosmic ray detector for energies above $10^{18}\,{\rm eV}$
- in Argentine Pampa
- measures properties of extensive air showers



Surface Detector

- 1600 water-Cherenkov detector stations
- 1.5 km tank spacing
- measures lateral distribution

Fluorescence Detector

- 4 fluorescence telescope sites
- 24 telescopes
- at array borders
- field of view (FOV) per site:
 - $6\cdot 30^\circ \times 30^\circ$

A Fluorescence Telescope



- Schmidt camera
- aperture diameter 2.2 m
- $\bullet~3.8\times3.8\,\mathrm{m^2}$ mirror
- $30^{\circ} \times 30^{\circ}$ field of view (FOV)
- UV-pass filter



- 440 hexagonally arranged PMTs
- 1.5° FOV per pixel
- PMT quantum efficiency pprox 30%

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- 1.5° FOV per pixel
- PMT quantum efficiency $\approx 30\%$





First Auger Multi-pixel-photon-counter camera for the Observation of Ultra-high-energy air Showers

Small prototype

fluorescence telescope for the measurement of extensive air showers with silicon photomultipliers

Developed in Aachen, Granada and Lisbon

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SiPMs for FAMOUS

- much higher possible photon detection efficiency (\sim 70 %) compared to currently used PMTs (\sim 30 %) demonstrated in prototypes (not currently available for purchase)
- better angular resolution possible

Build now to learn by manufacturing and demonstrate feasibility

Use Hamamatsu S10985-100C 2 \times 2 array with 100 μm pitch (6 \times 6 mm^2 total size), \approx 30 % PDE in UV range





Basic telescope design



Fresnel lens

- remove thick "dead material" of lens
 ⇒ concentric annular sections ("grooves")
- approximate curved surface with linear slopes
- keeps refraction power of original lens
- reduced weight
- reduced absorption
- cheap
- compromise in image quality (bigger spot size)
- small f/D possible
 ⇒ much light per solid angle
 ⇒ big field of view



Fresnel lens



- *D* = 510 *mm*
- f = 510 mm
- UV-transparent plastic (PMMA)

Point spread function





simulation with Geant4

point size sufficient for 1.5° field of view per pixel

Focal plane

- modular design
- hexagonal arrangement of pixels
- $\bullet\,$ one pixel: Winston cone (light concentrator) and $6\times 6\,\mathrm{mm}^2$ SiPM array
- UG-11 UV-pass filter
- 64 pixels planned
- manufacturing test with 7 pixels







- tilted paraboloid surface
- light concentrated by factor 5
- maximum transmitted incident angle $\theta_{\rm max} = \arcsin(r_2/r_1) = 26.6^{\circ}$
- high exit angles up to 90°



Emergent angle of light from Winston cone



Angle dependence of PDE



measured in Aachen

- Use LED to illuminate SiPM
- normalize signal to 0°
- correct for projection of active area

measurements can be described by Fresnel equation (transmission and reflection on surface of SiPM)

 $90\,\%$ relative PDE up to incident angles of 60°

Readout electronics

- based on MAROC3 chip
 - 64 channels (threshold)
 - 8 analogue sums (of 8 channels)
 - internal ADCs

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signals

- individual control of bias voltage for each pixel
- FPGA handles all digital functions including trigger



first prototype currently in production

Simulation of FAMOUS



FAMOUS event display

simulated vertical 10^{18.25} eV proton shower in 2 km distance



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SiPMs for fluorescence detection of EAS

Simulation of SiPM voltage traces



Expected performance

Expected event rates of air showers in Aachen for different energies E and shower distances R_p



Summary & Outlook

Summary

- extensive SiPM characterization studies done
- \bullet optical design for the new SiPM prototype fluorescence telescope FAMOUS chosen
- DAQ and trigger electronics currently under development
- mechanical production partly done
- simulations of FAMOUS make great progress

Outlook

- finalize and build electronics
- build FAMOUS
- first light this year

Backup

Absorption of Fresnel lens

Transmission of PMMA 8N (Reflexite, October 2004, d=3mm thickness)



Transmission is > 90 % for $\lambda >$ 350 m nm

- temperature dependent breakdown-Voltage
- photon detection efficiency
 - wavelength dependent
 - overvoltage dependent
 - angle dependent
- crosstalk probability
- afterpulse probability
- temperature dependent thermal noise rate