Operational Evaluation of Silicon Photomultiplier Based Prototype Detector Modules Installed in the MAGIC Telescopes

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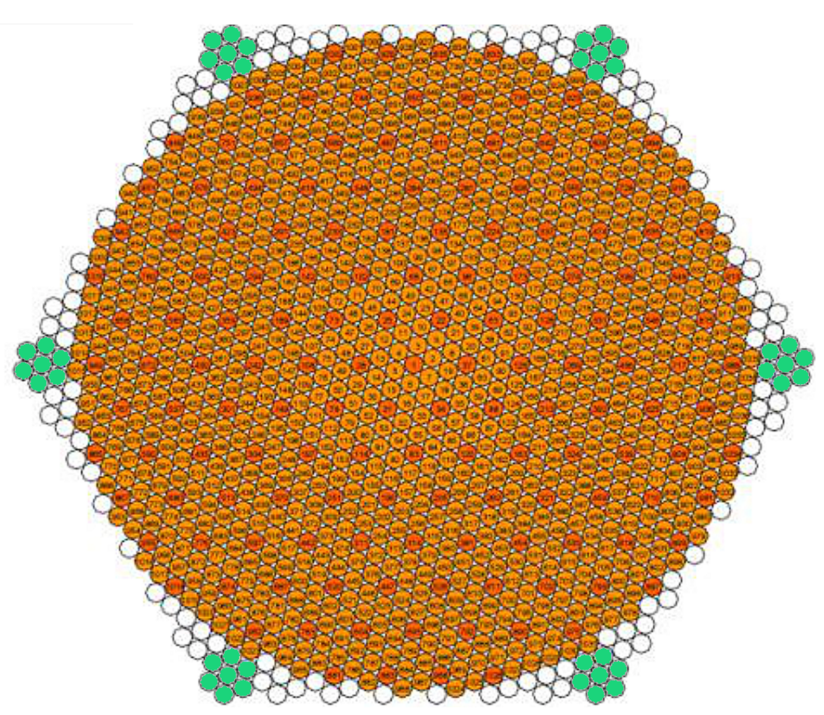
The MAGIC Telescopes

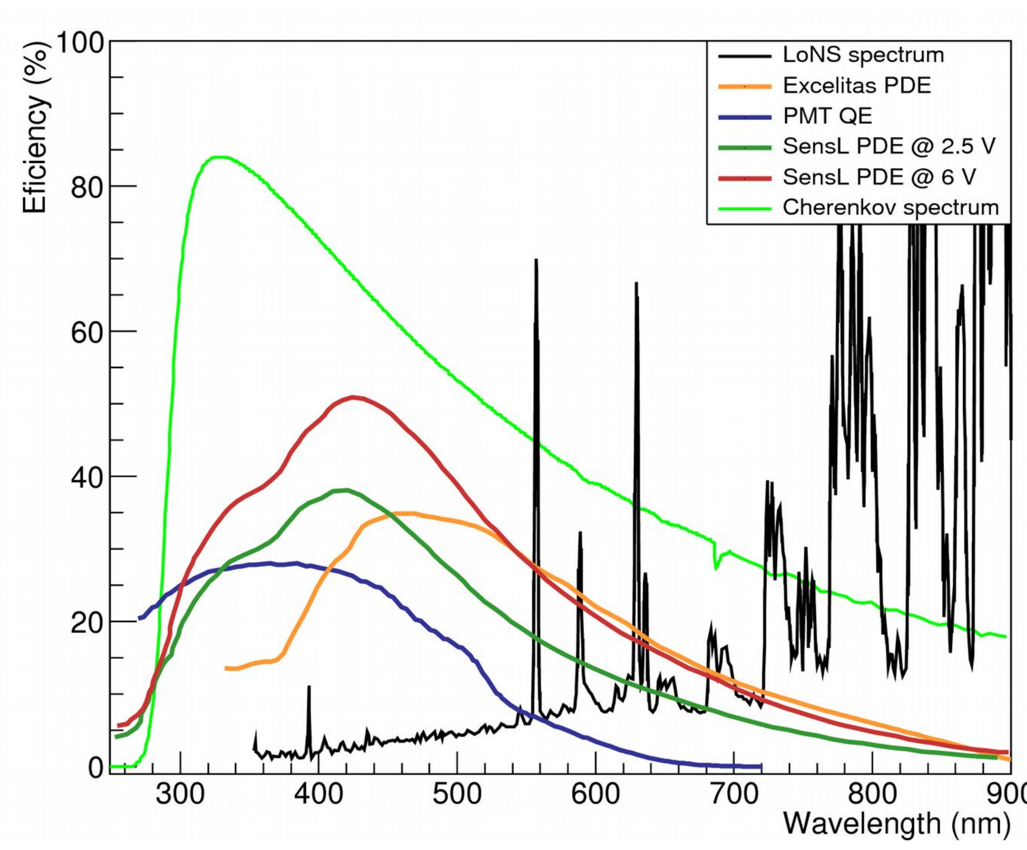
MAGIC is a stereoscopic system of two imaging atmospheric Cherenkov telescopes (IACTs) located at the Canary island of La Palma. Each imaging camera consists of 1039 1-inch diameter Hamamatsu photomultiplier tubes (PMTs). The PMTs are partitioned in 169 clusters with up to 7 light sensors each. The hexagonal camera structure of the MAGIC cameras offers the possibility to install up to six additional detector modules for prototyping in each camera. [1]



Left: Photo of a MAGIC camera; Right: PMT pixel positions in orange, open locations in green

SiPMs in IACTs

The lack of ageing and a potentially higher photon detection efficiency (PDE) with respect to PMTs are the main motivation for this project. A significantly lower operational voltage and smaller form factor are other benefits of SiPMs.
In IACTs the light sensors are operated under a high level of background light (LoNS) and under ambient temperatures. Drawbacks of SiPMs for this application are the temperature dependent PDE and the enhanced sensitivity towards longer wavelength which increases the rate of background events to several hundred MHz.
To replace a 1-inch PMT it is necessary to combine several SiPMs to a composite signal without combining the parasitic capacitances of the individual devices to preserve a fast pulse shape.



SiPM PDE of SensL and Exceiltas compared to the Cherenkov spectrum and the light of the night sky

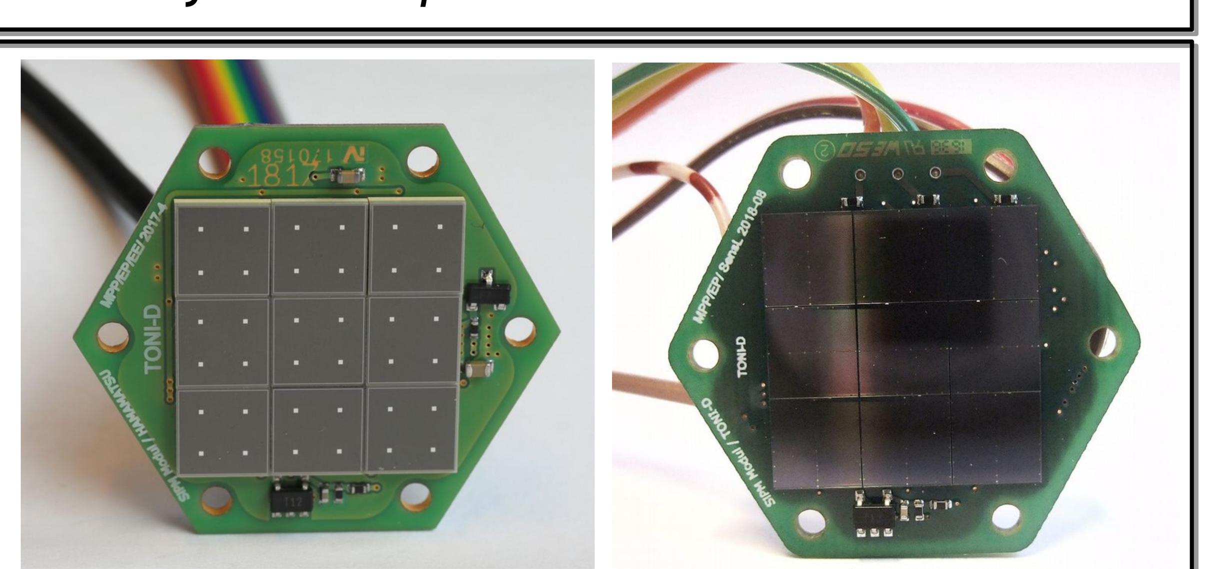
Gen. 1 Device

We used Excelitas SiPMs for our first prototype of a SiPM Module [2]. Each Gen. 1 pixel consists of 7 6x6 mm² Excelitas C30742-66-050X SiPMs. It was installed alongside the PMT Camera in 2015. It is included into the standard readout and data taking procedure [3].
The individual SiPMs of a pixel are summed to a composite output which equals the sum of the 7 SiPM currents.

First generation SiPM module with opened cluster body. It holds 7 pixels each with 7 Excelitas SiPMs

Gen. 2 Devices

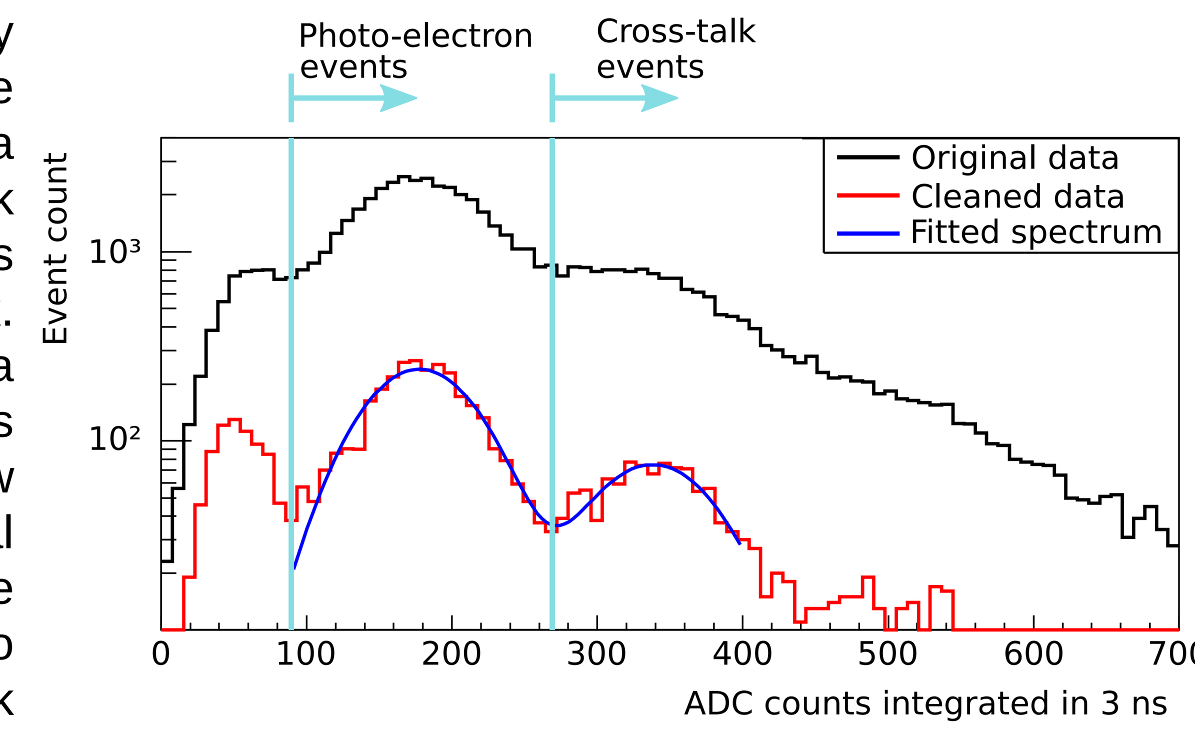
Based on the experiences from the Gen. 1 cluster we built two enhanced SiPM prototype modules using SensL TSV-60035 and Hamamatsu S13360-6075VS SiPMs. The active area of each pixel was increased by using 9 SiPMs. The Gen. 2 pixels use very similar summation electronics and slow control design concept as Gen. 1.



Left: Hamamatsu pixel Right: SensL pixel
Gen. 2 SiPM pixels using 9 6x6 mm² SiPMs. The individual signals are summed on the backside of the PCBs to a composite output.

Calibration using the single photo-electron spectrum

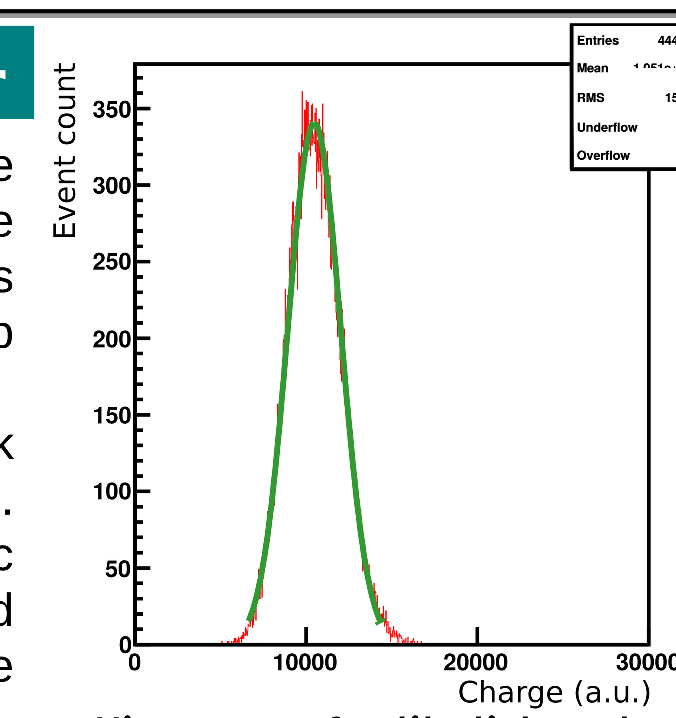
Recording events at a fixed frequency in the dark will result in a charge histogram showing a pedestal peak, a single photo-electron peak from dark counts and multi photo-electron peaks from dark counts affected by cross-talk. The resulting spectrum suffers from a poor signal to noise ratio and the peaks are barely separated. Therefore the raw data events are filtered taking the signal shape and baseline into account. The cleaned data histogram can be used to calculate the gain and the cross-talk probability more accurately.



Unfiltered and filtered charge spectrum of a Gen. 1 pixel

Calibration using the excess noise factor

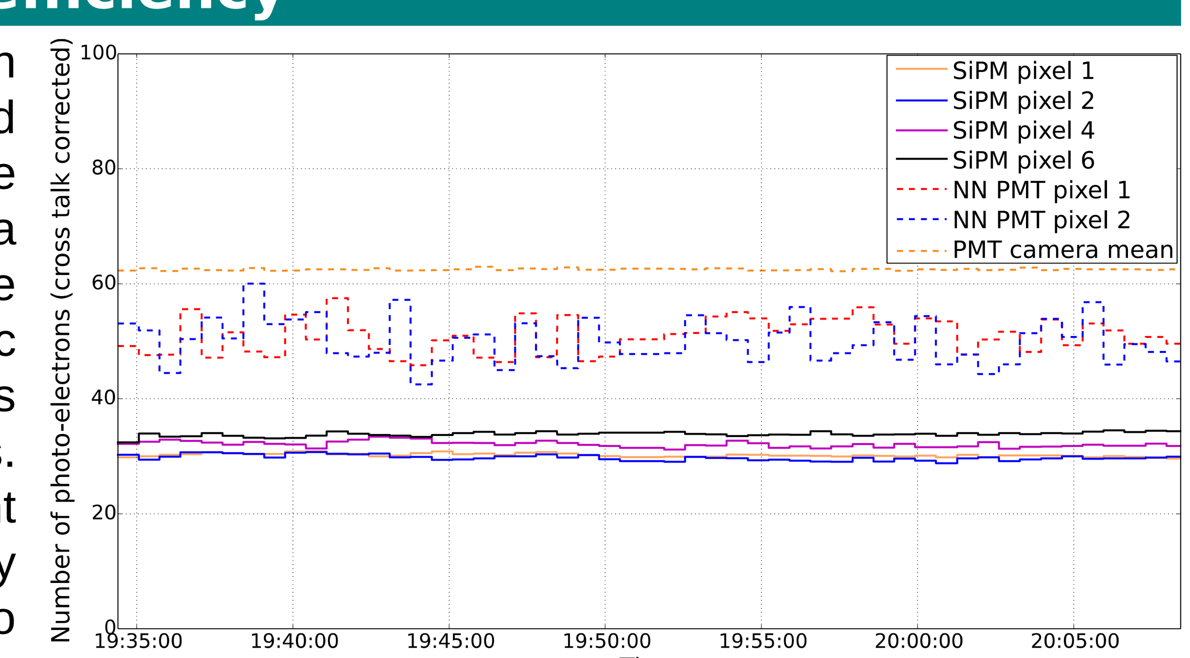
When the charge separation is not good enough to separate the individual photo-electrons a calibration using the excess noise factor (ENF) can be applied similar to PMTs. The ENF is determined by the cross-talk probability [4]. In a laboratory setup the cross-talk is measured in dependence of the dark current.
For data taking, the ENF is determined by reading the dark current of the SiPMs and comparing it to the lab measurements. The camera is illuminated with short flashes of a monochromatic calibration light source during operation. From the FWHM and mean of the resulting charge distribution, one can calculate the detected number of photo electrons using the determined ENF.



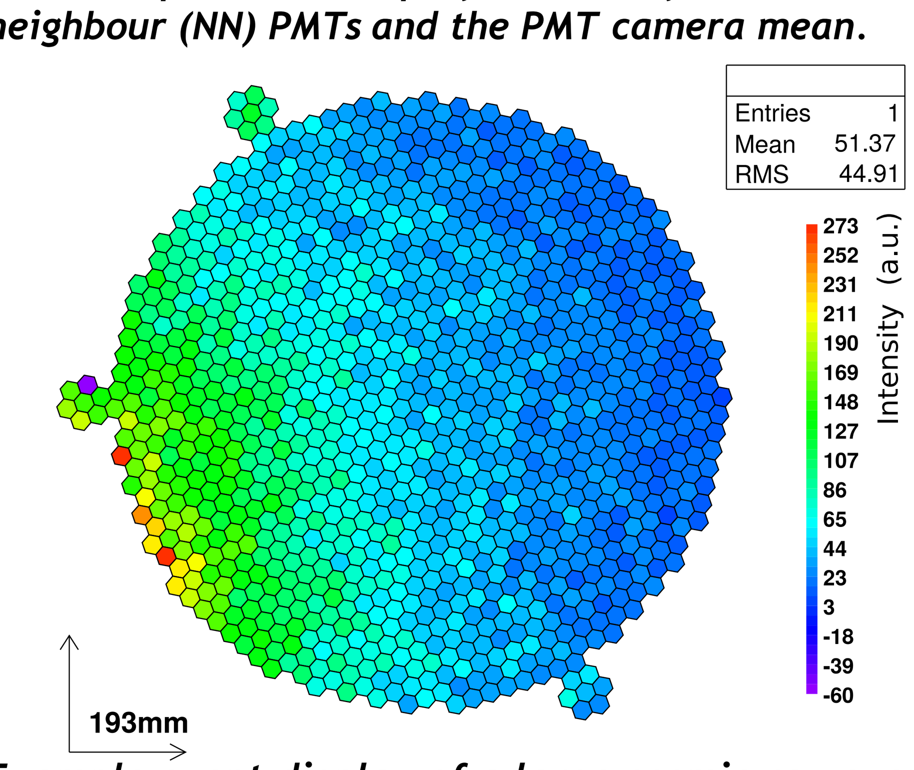
Histogram of calib. light pulses

Comparison of detection efficiency

The comparison of the detection efficiency between SiPM based pixel and PMT pixel is done by comparing the amount of detected photo electrons of a given signal source. As signal source we use the artificial monochromatic calibration light pulses as well as Cherenkov light from large air showers. A direct comparison of the two different sensor technologies is simplified by using the calibration light pulses due to the homogeneous camera illumination and a known external trigger. The result of the Gen. 1 SiPM pixels is in agreement with our predictions of about 50 % the detection efficiency of a PMT pixel due to dead area and PDE at the wavelength of the calibration pulses.
However, just using monochromatic light pulses neglects the characteristics of the Cherenkov spectrum. Therefore the final comparison must be based on Cherenkov events. Since the SiPM clusters are located at the camera rim but the camera is triggered by events penetrating the inner region, only large cosmic ray events can be used for the direct comparison. This reduces the number of suitable events to only several tens to hundred events per night. The study is ongoing and comparison results based on Cherenkov light from air showers are expected in the near future.



Detected number of photo-electrons of a Gen.1 SiPM pixel compared to the performance of the next-neighbour (NN) PMTs and the PMT camera mean.



Example event display of a large cosmic ray event

Outlook

We will compare the ENF based calibration method to the calibration based on the single photo-electron histogram. The detection efficiency comparison between SiPM based pixels and PMT pixels using Cherenkov light from air showers is expected to be finished end of 2018. We consider a possible way to circumvent the restriction to large air showers by installing the SiPM clusters close to the camera centre, into the trigger region of the telescope.

References and Further ReadingReferences and Further Reading

[1] J. Aleksić, et al. *The major upgrade of the MAGIC telescopes, Part I: The hardware improvements and the commissioning of the system.* Astroparticle Physics, 72:61-75.
[2] D. Fink, et al. *SiPM Based Focal Plane Instrumentation Prototype for the MAGIC Atmospheric Cherenkov Telescope*, International Conference on New Photo-detectors PoS(PhotoDet2015)006
[3] A. Hahn, et al. *Development of a composite large-size SiPM (assembled matrix) based modular detector cluster for MAGIC*, Nuclear Inst. and Methods in Physics Research A, 845:89-92, Jun. 2016.
[4] S. Vinogradov, Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk, Nuclear Inst. and Methods in Physics Research A, 695:247-251, Dec. 2012