Operation of SiPM Based Photosensor Modules Alongside PMTs in the

MAGIC Imaging Atmospheric Cherenkov Telescope Camera

by

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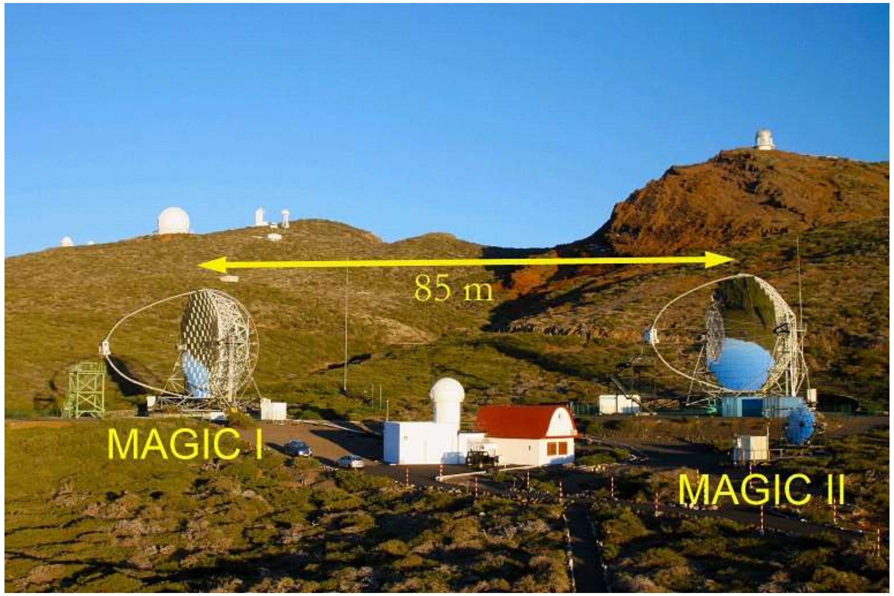
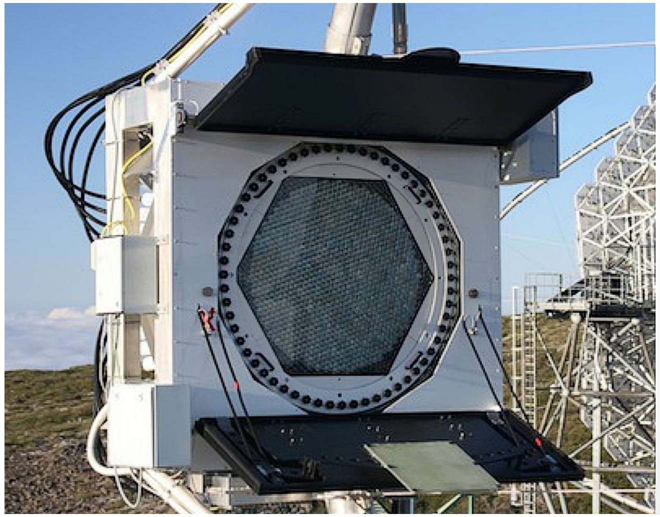
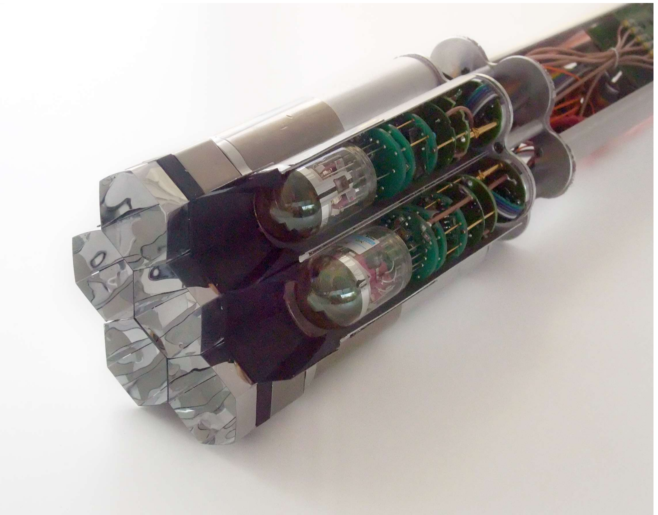
The MAGIC telescopes

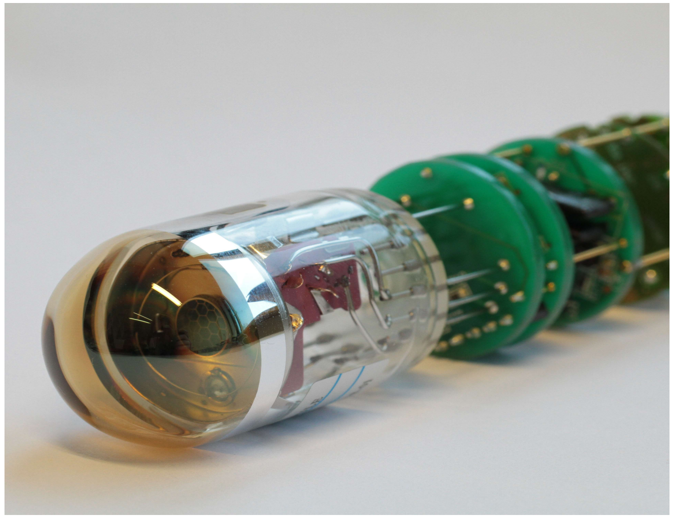
[1]



- Canary island of La Palma
- 2200 m above see level
- Two imaging atmospheric Cherenkov telescopes (IACTs)
- Each camera equipped with 1039 PMTs
- Up to 7 pixels partitioned in 169 clusters plus 6 open corner locations

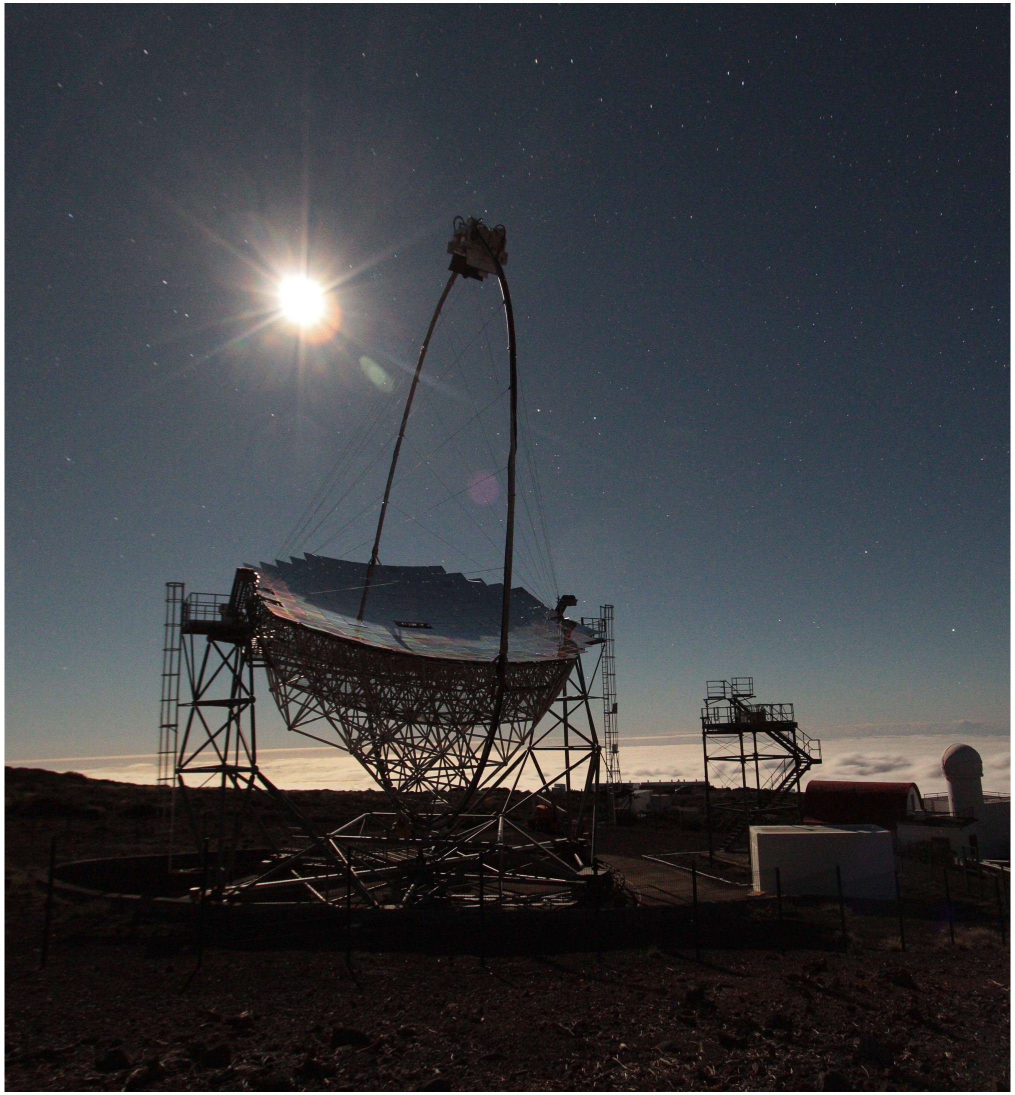






[2]

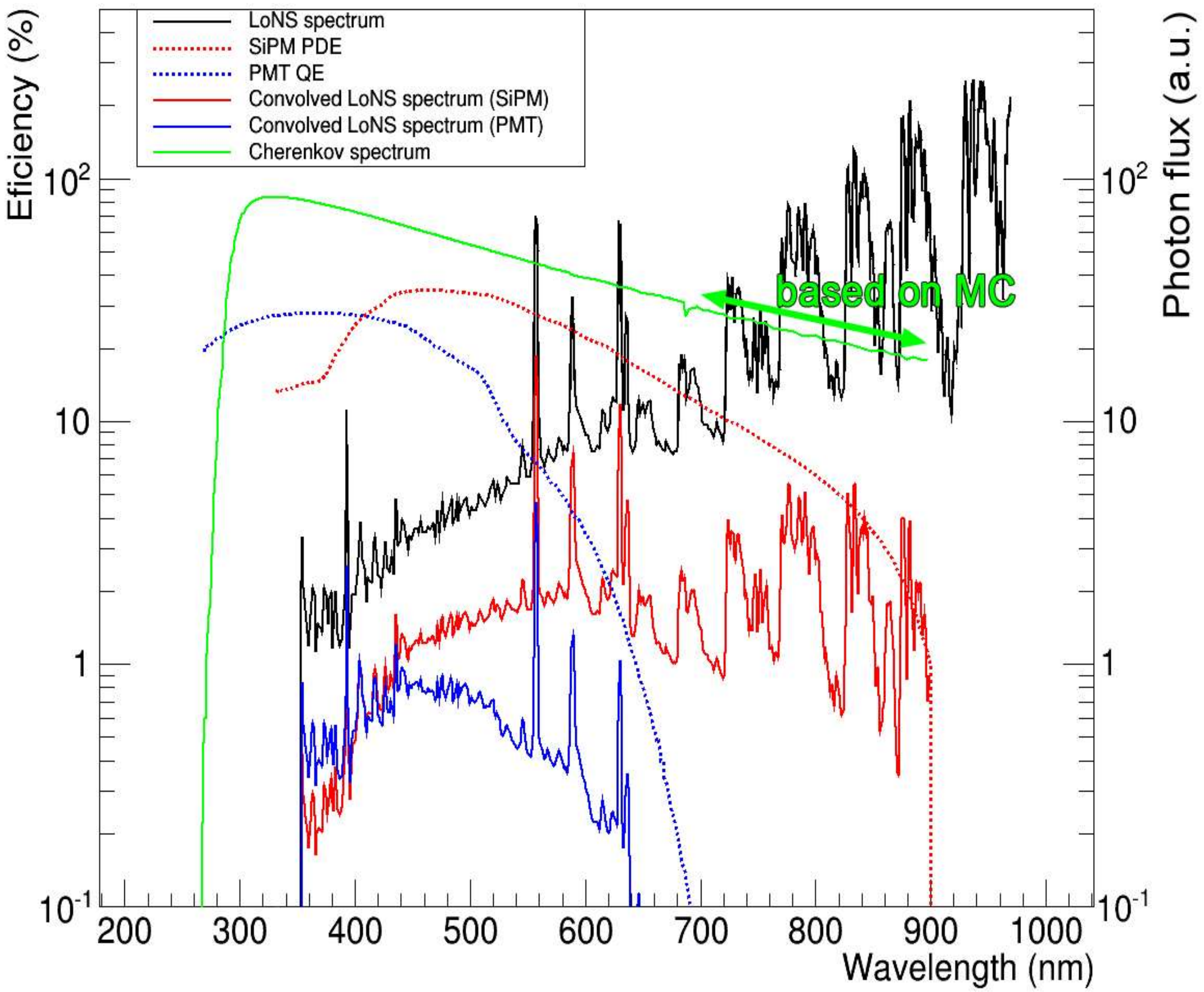
Motivation



Potential advantages of SiPMs vs. PMTs:

- Operation during moon time
  - dark nights only:
    IACT duty cycle 18 %
  - with moon and twilight:
    IACT duty cycle 40 %
- SiPMs are improving in performance – high photon detection efficiency (PDE), low cross-talk
- Goal: Compare performance of PMT and SiPM based detectors during telescope operation

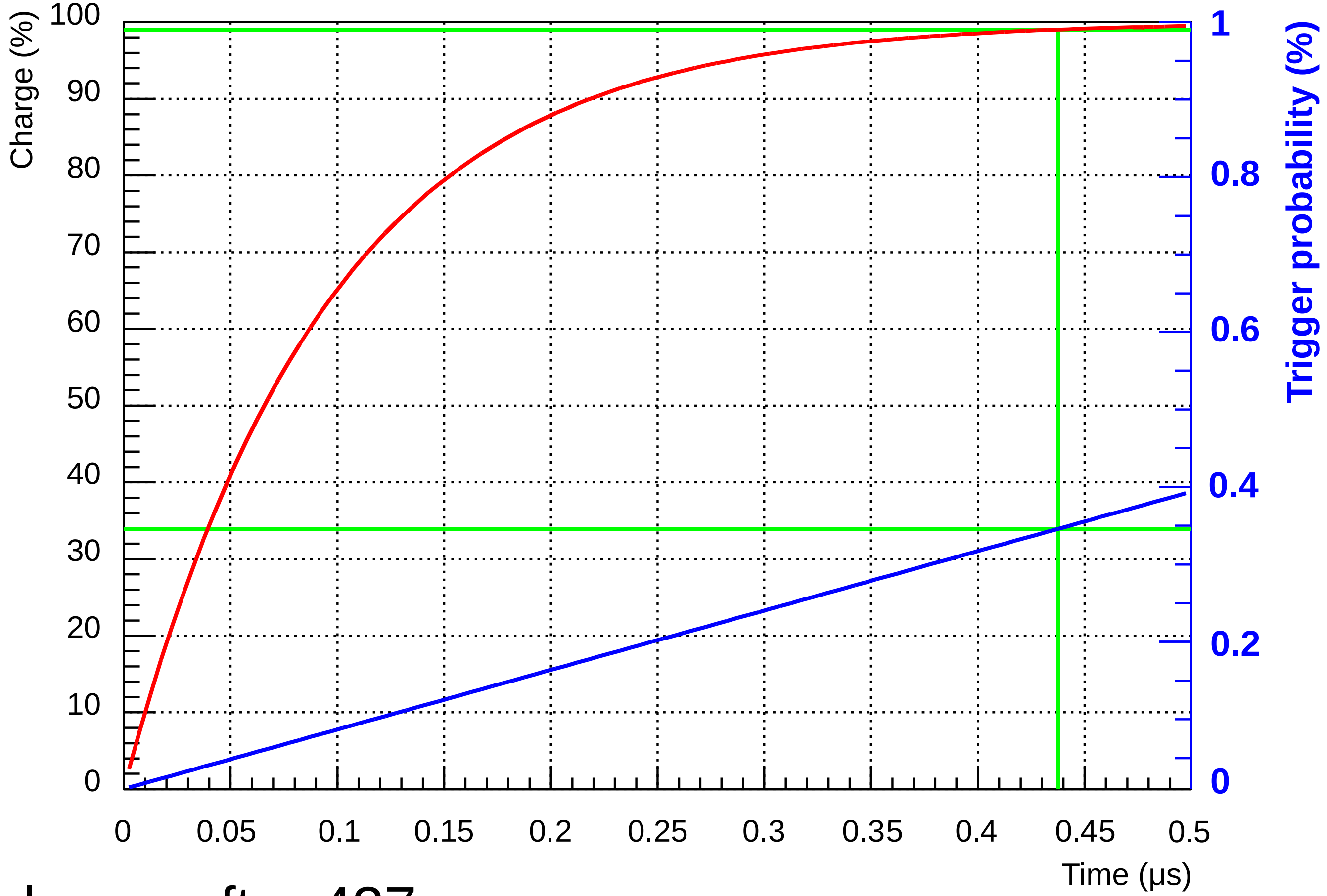
Operation Environment



- SiPM detect 4.3 times more LoNS than PMT
- 170 MHz in PMT
  => 780 MHz in SiPM
  (1 phe/1.3 ns)

  with signal FWHM ~ 5 ns
  => Pile-up spoils single phe extraction when camera is opened
- SiPM receives 57 % less Cherenkov photons than PMT (conservative approach)
- SiPM cells can re-charge with 99.66 % probability

Operation Environment

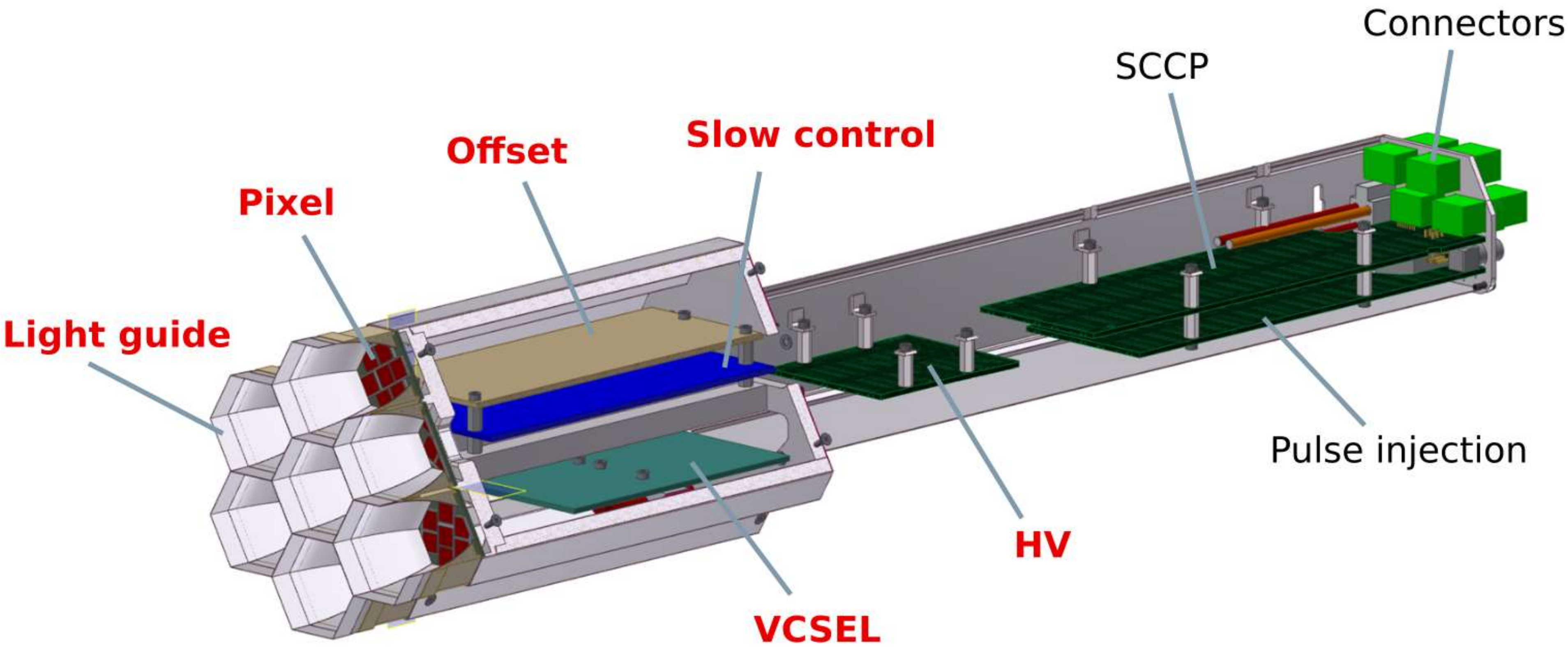


99 % recharge after 437 ns

⇒ 0.34 % prob. that next event happens before 99 % recharge

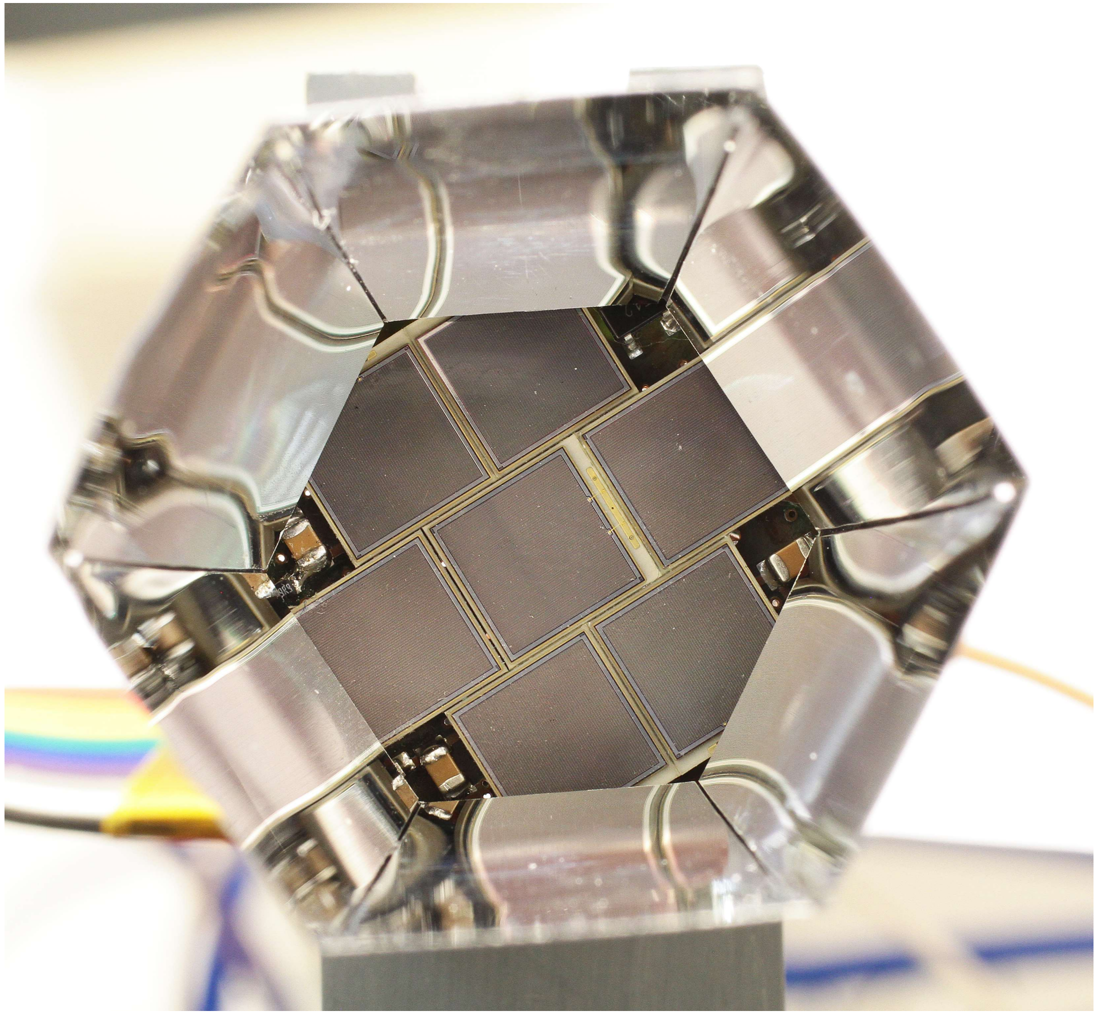
⇒ Cells can fully recharge between events

Cluster Design
General Overview



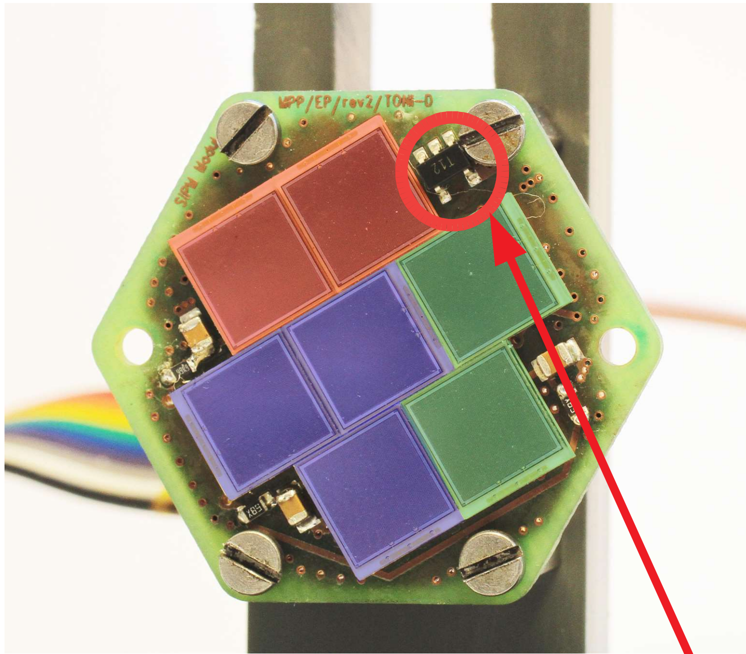
First Cluster Design

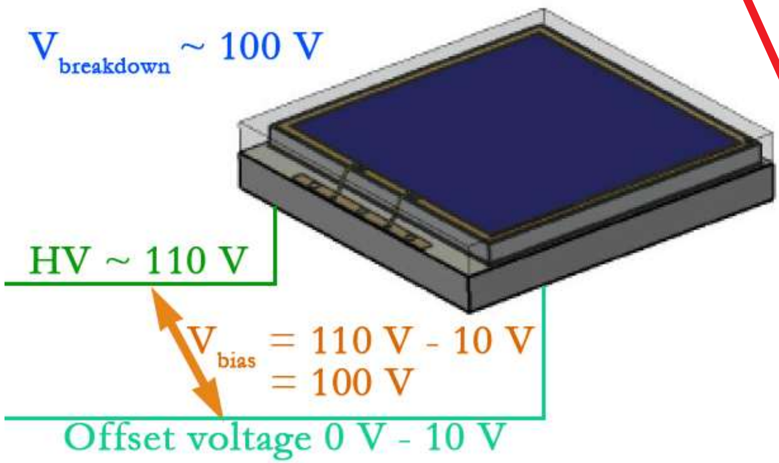
Pixel



- 95 % of active area can be accessed by light
- 69 % of light guide output is covered with active area

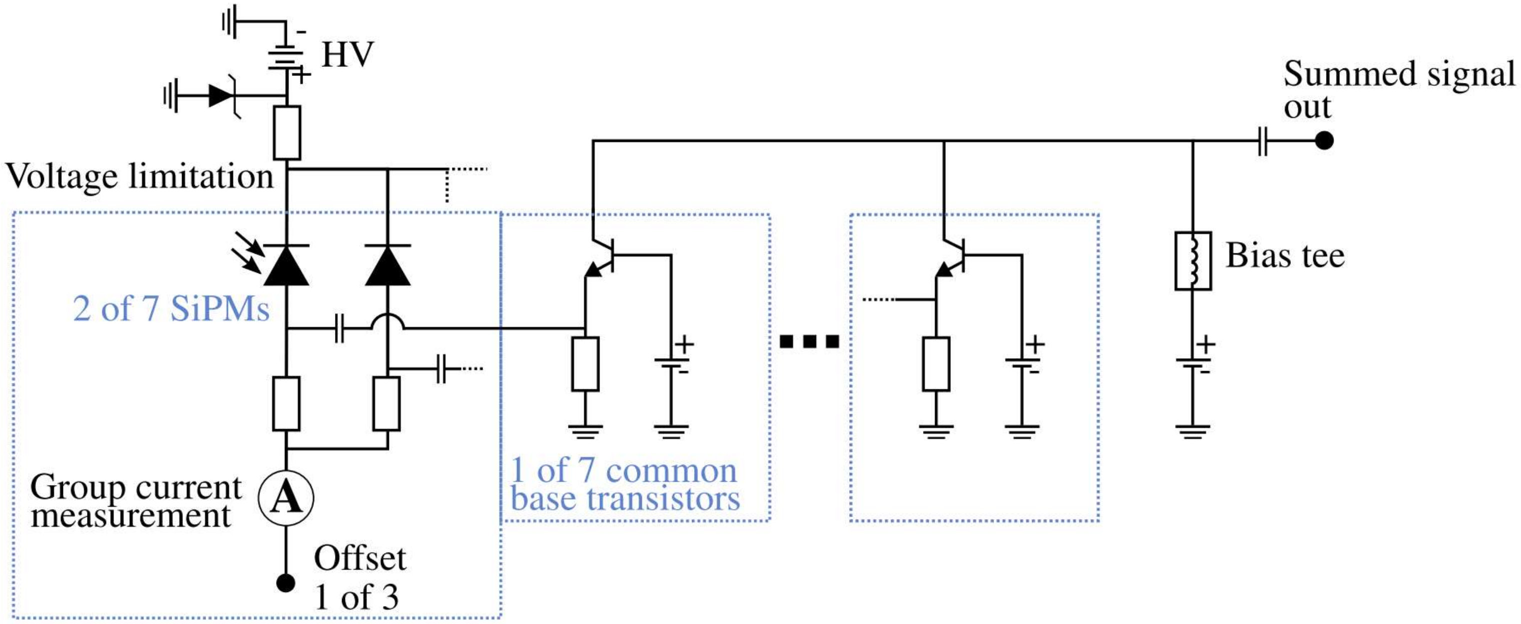
First Cluster Design
Pixel





- Excelitas C30742-66 SiPM breakdown ranges from 94.0 V to 107.1 V
- Three groups (2-3-2) of Excelitas 6x6 mm² SiPMs with same breakdown voltage
- Only one high voltage per cluster
- One offset voltage per group used to disable the pixel (star in FOV), adjust gain
- One temperature sensor next to sensors

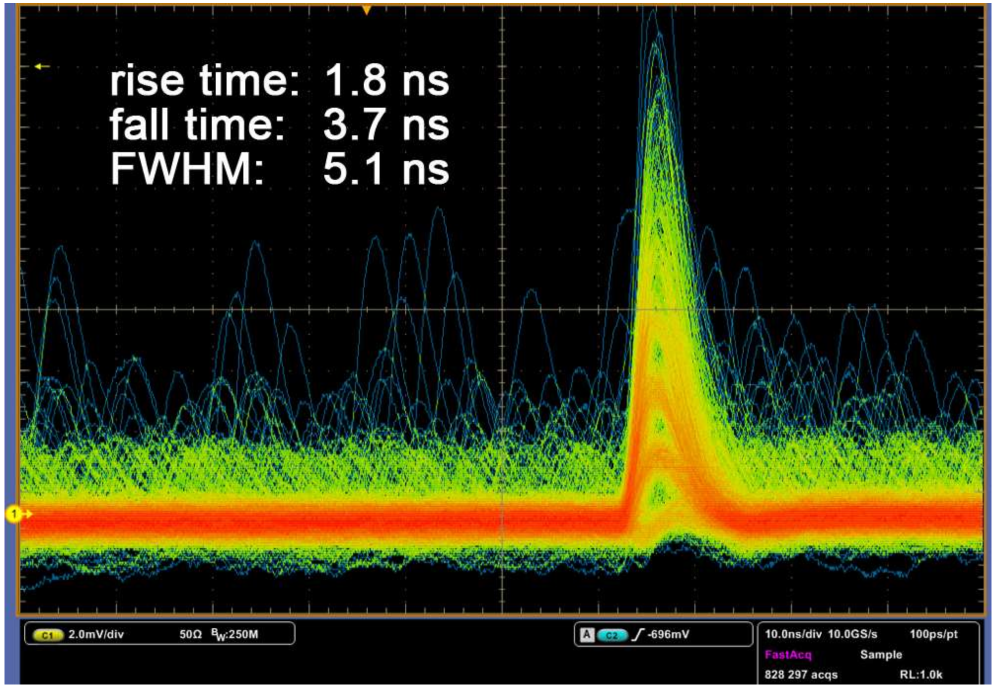
First Cluster Design
Pixel



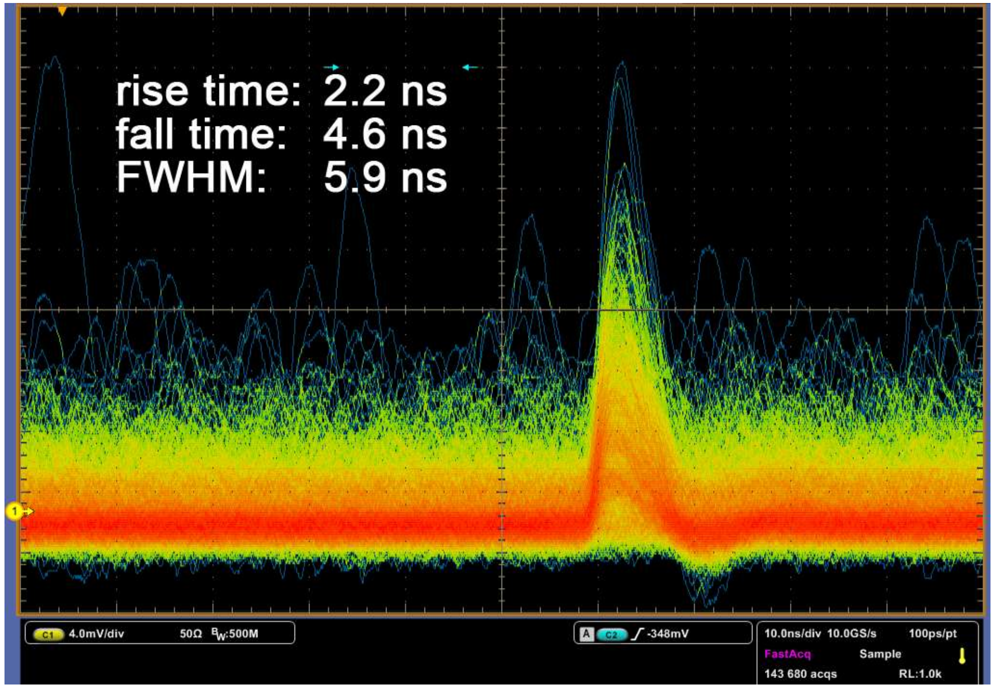
- One summed signal output
- Low input impedance common-base transistor circuit for amplification and decoupling
- High output impedance – current is sum of 7 (version 1) to 9 (version 2) common base amplifiers
- Prototype current consumption of ≈ 50 mA @ 5 V per pixel

First Cluster Design
Pixel

- Comparison of 1 vs. 7 SiPM output (1^{st} gen Excelitas)
- Sum has slightly lower amplitude/longer pulse width, but still preserves resolution of single photon peaks

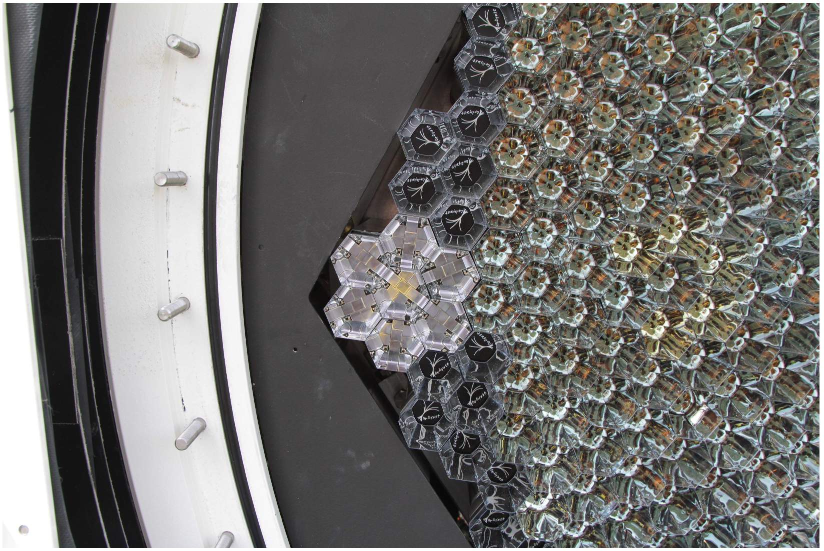


Single SiPM channel output

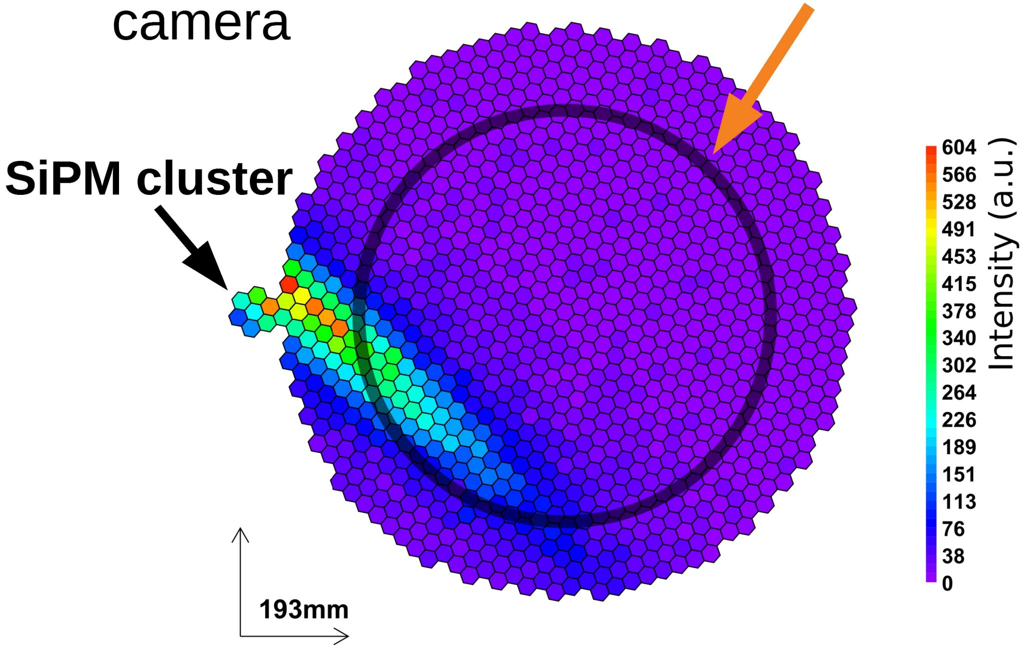


Sum of 7 SiPM channel output

Installation first SiPM cluster

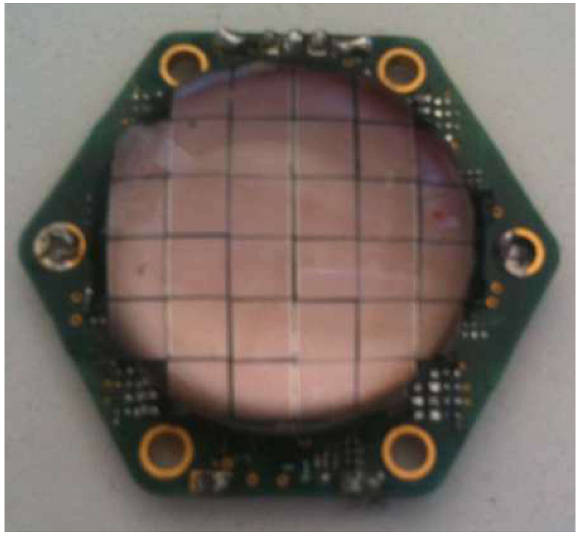


- First SiPM cluster installed in May 2015
- Mounted next to PMT pixels
- Integrated to standard readout
- Operated in parasitic trigger mode on events triggering the inner region of the camera



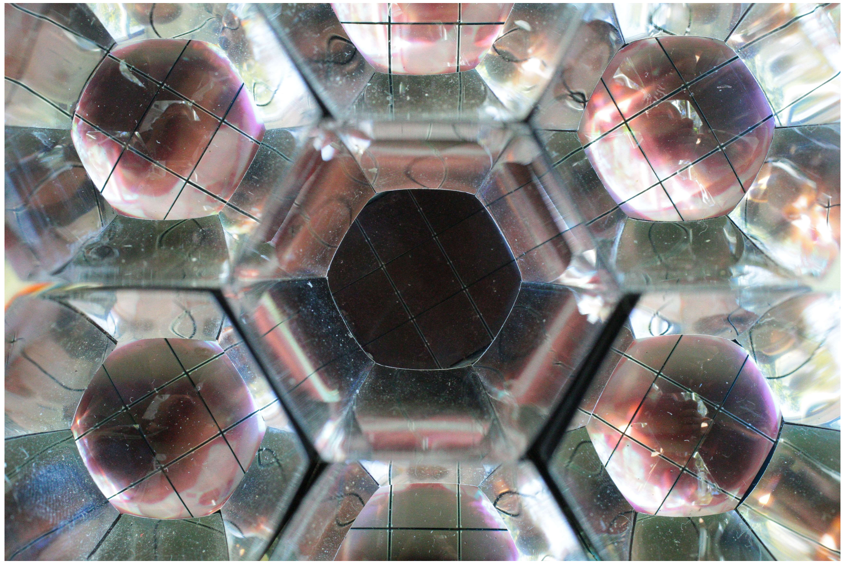
INFN Cluster

Istituto Nazionale di Fisica Nucleare (INFN) Padova and MPP SiPM cluster



[4]

- M. Mariotti, R. Rando, D. Corti, I. Reichardt
- Based on up to 32 FBK 3x3 mm^2 SiPMs
- UV transparent lens
- Prototyping for LST

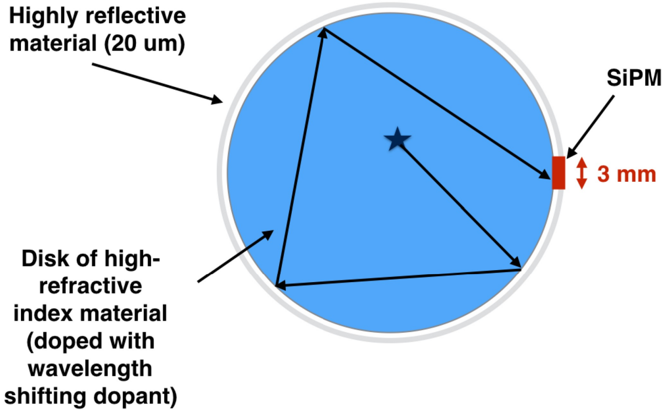


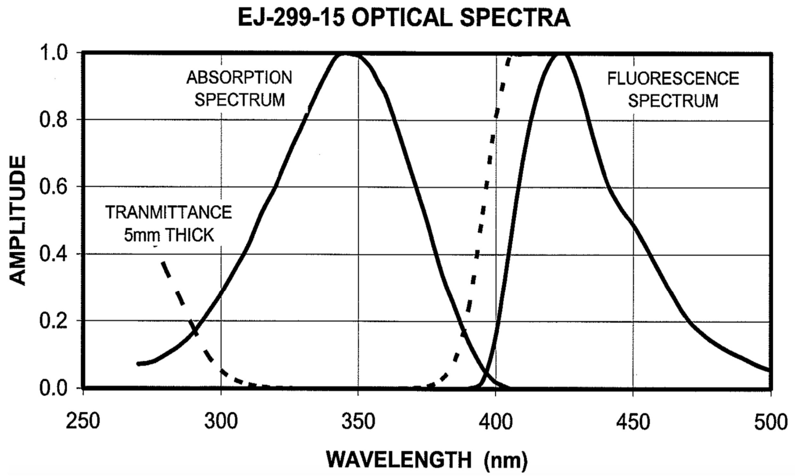
MAGIC class prototype

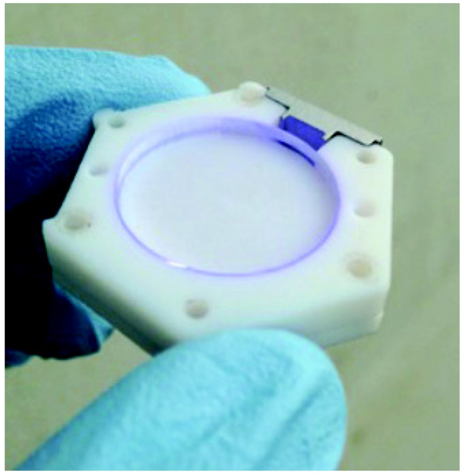
- 9 FBK 6x6 mm^2
- One pixel without lens for comparison
- High power consumption and heat dissipation
- Installed 10/2015 - 11/2016

IFAE Cluster

[5]

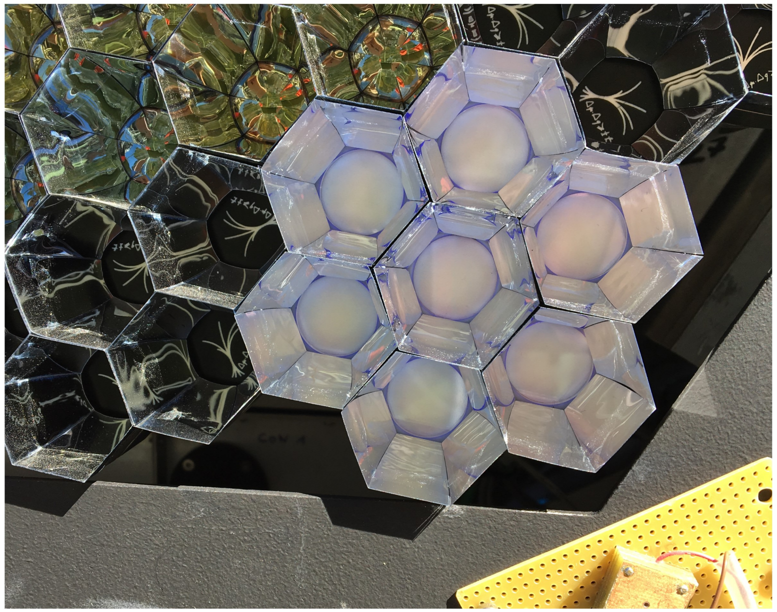






Institut de Fisica d'Altes Energies (IFAE) and MPI SiPM cluster

- J. Cortina, J. Ward, D. Guberman
- So-called light trap ≡ Wavelength shifter doped PMMA disk
- Absorb UV Cherenkov light re-emit at SiPM peak PDE
- Reject LoNS photons
- Provide cheap large detector area
- Installed in May 2017

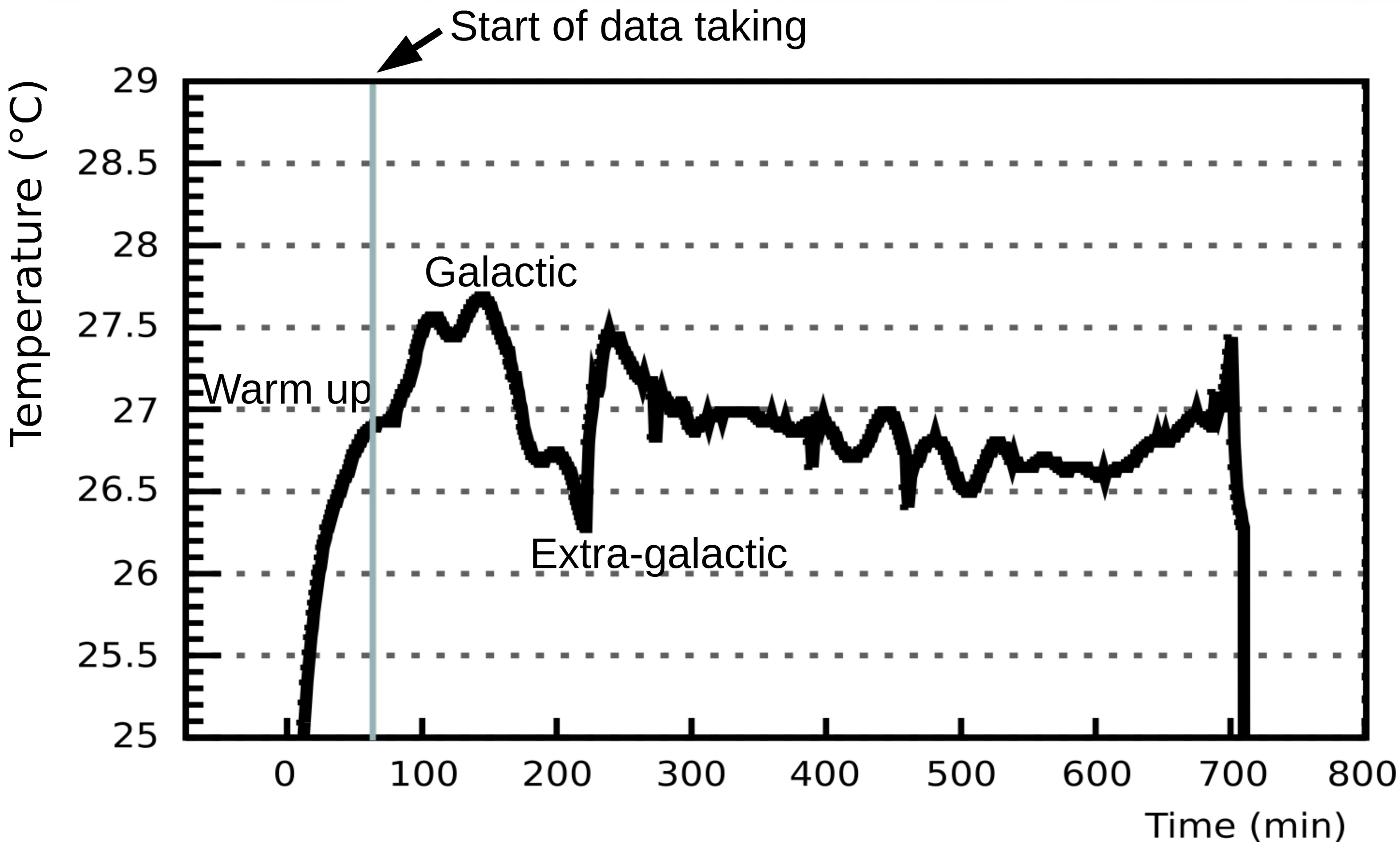


Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Operation and first results of the Max Planck Institute for Physics SiPM clusters

Results

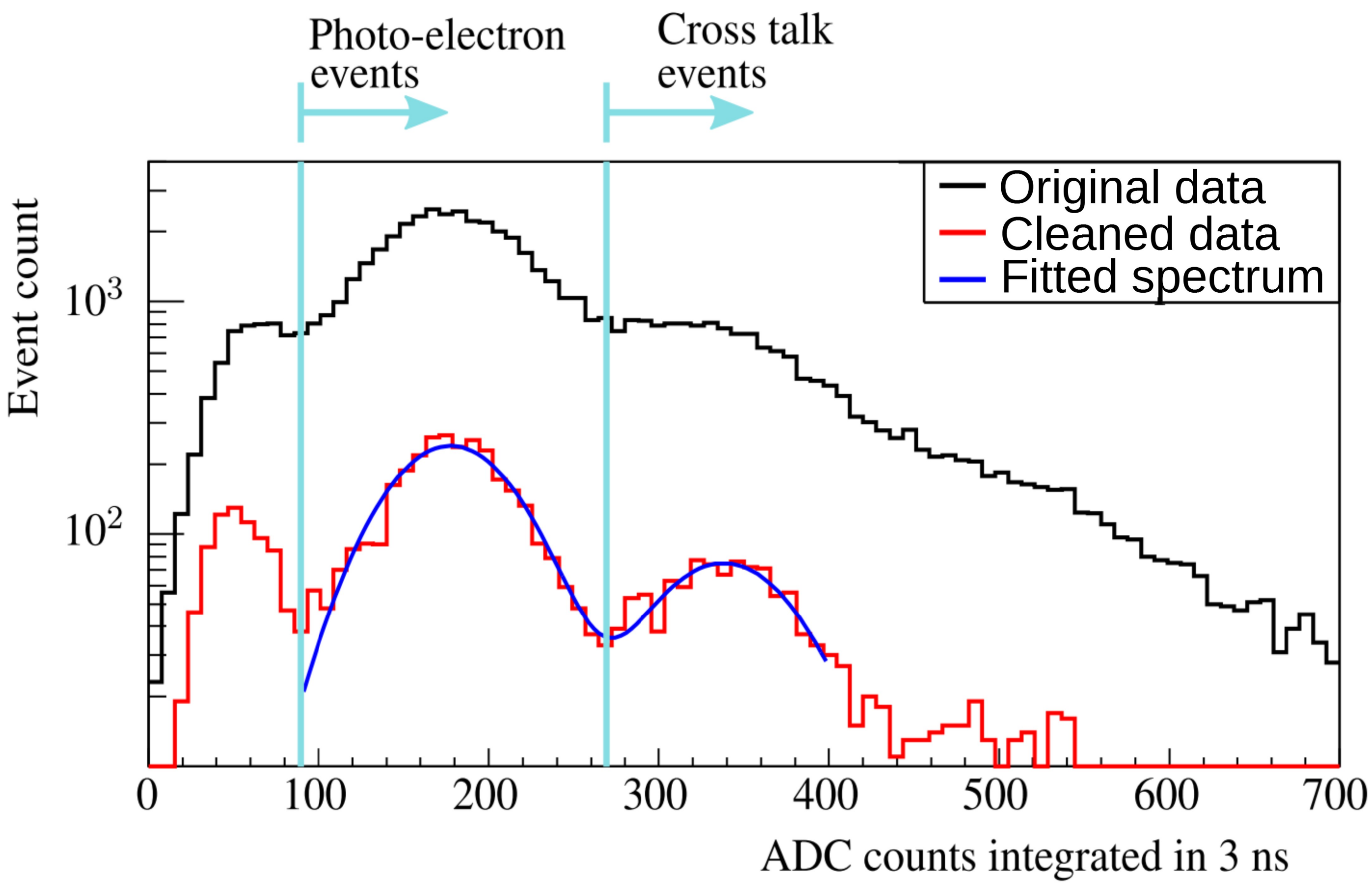
Temperature



- Sensor temperature remains stable during typical observations
- Al core PCBs in second generation should improve stability and lower operating temperature

Results

Calibration - gain and cross talk



- 100 kEvents random trigger with closed lids
  - Taken before data taking ⇒ No observation time is lost
- Selection of good events

  -Efficiency of 5 %
- Fitting spectrum for gain calculation
- Integrate original data for cross-talk estimation

Results

Calibration - gain and cross talk

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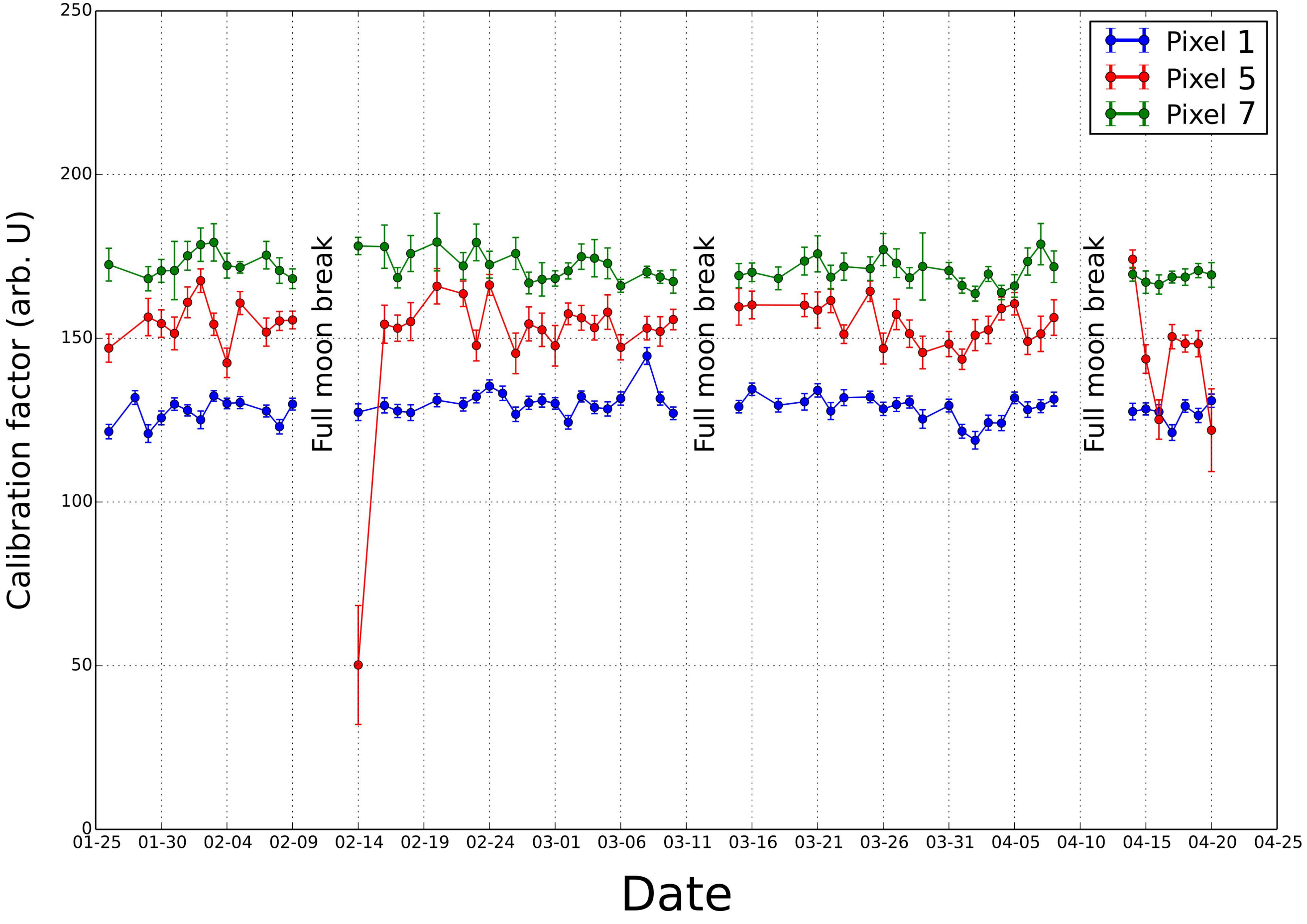
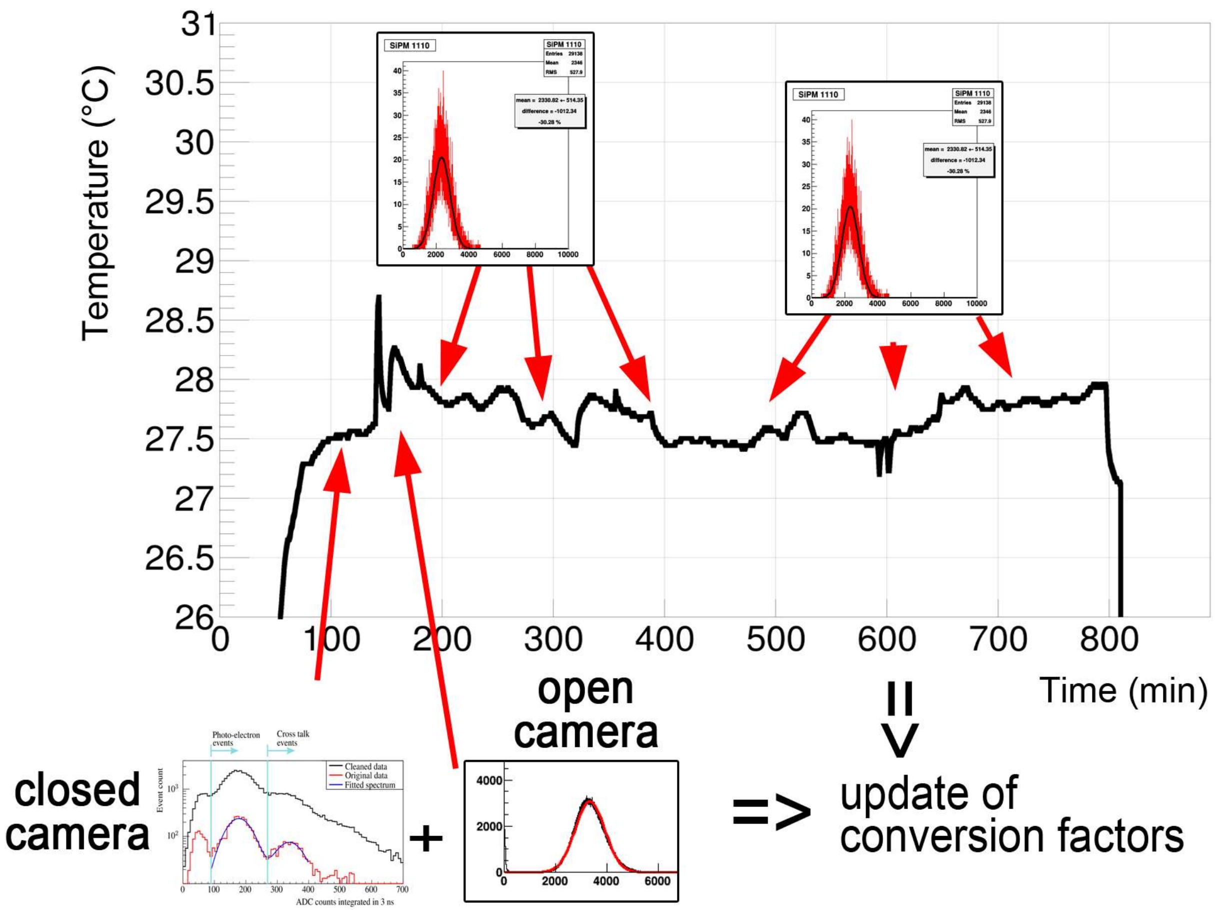
Nightly calibration



- SiPM calibration can be performed beginning of every night
- Works for high and low bias voltages (pixel 1, 7)
- Few outliers where spectrum fit does not converge
  ⇒ Needs more investigation

Calibration of SiPM data during data taking



1) Determination of gain

2) Determination of cross talk

3) Associate with a calibration pulse peak position

4) Update of conversion factors

Results

Calibration - updating

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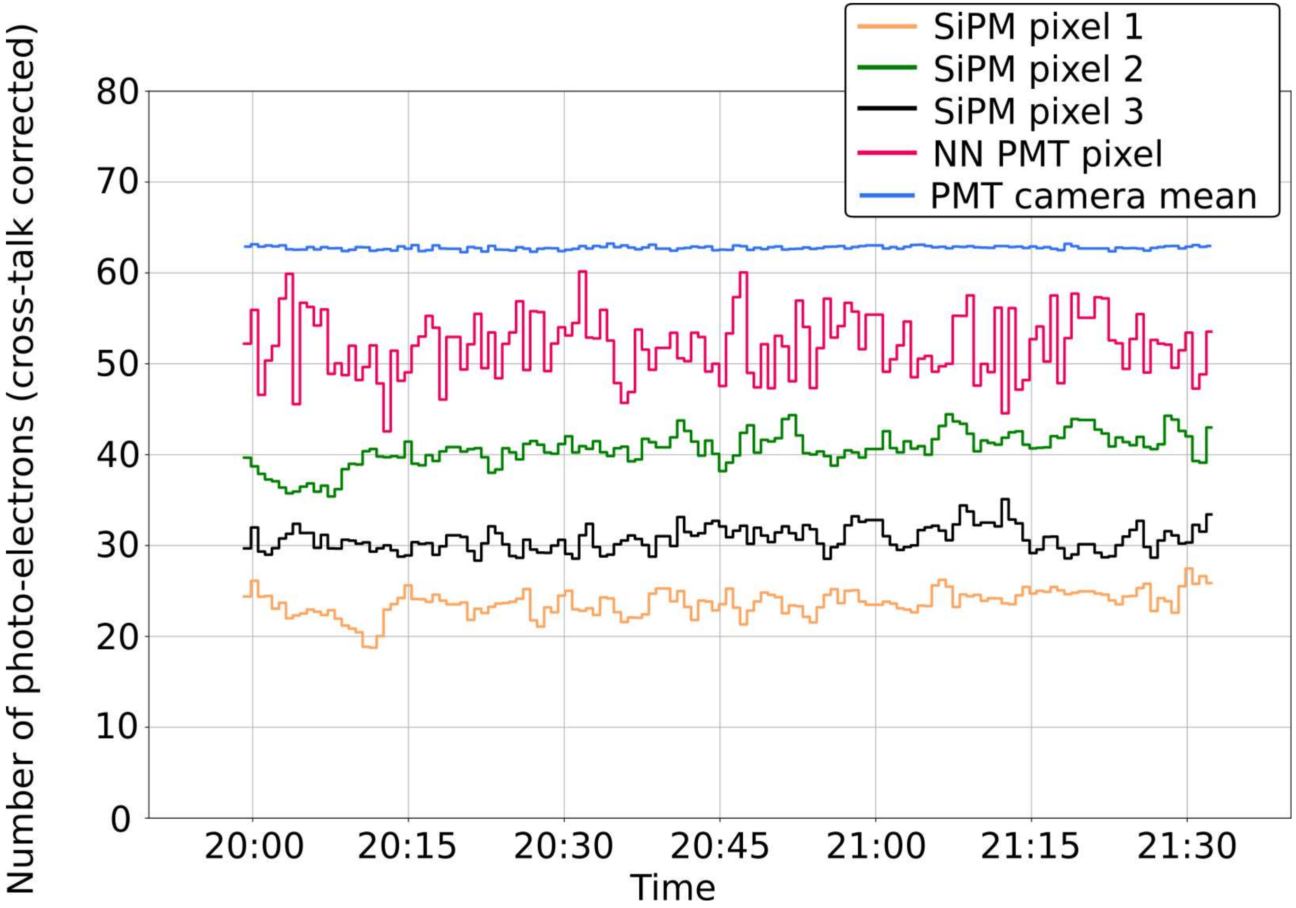
Intra-night stability (one source)

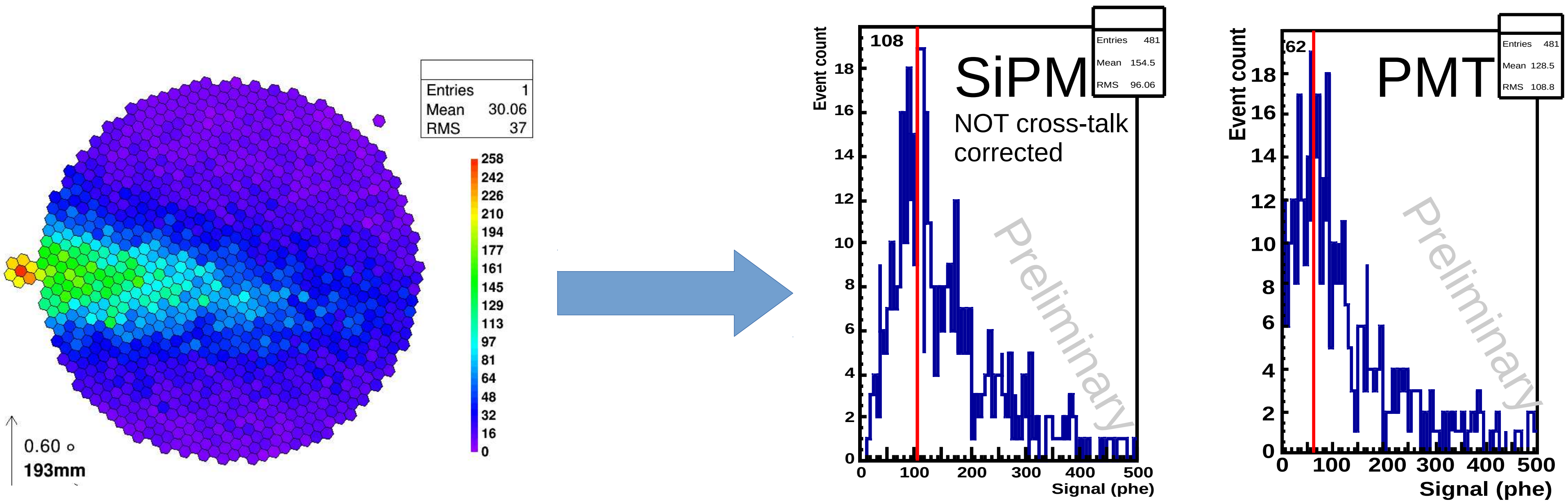


- Updating of calibration
- Simultaneous updating of cross talk:
  - Assuming linear dependency
    ⇒ valid for small changes
- Number of phe in expected range
  (dead area of pixel, PDE(λ))

Results (preliminary)

Cherenkov event comparison

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



- Compare number of detected photons of Cherenkov events
  - Low statistics ⇒ Peak has large uncertainty

⇒ More data needed for comparison

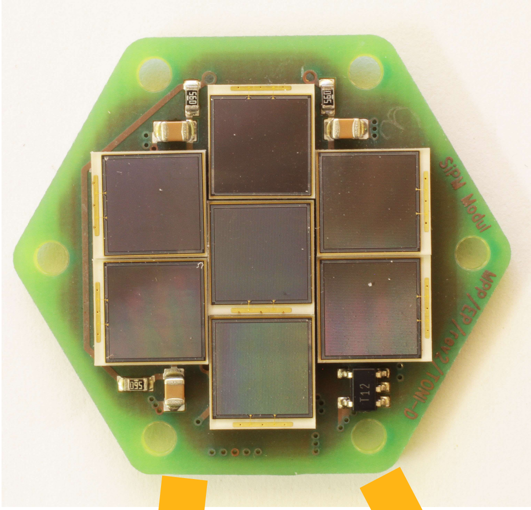
Second gen. SiPM
Pixel Design

Second + Third Prototype

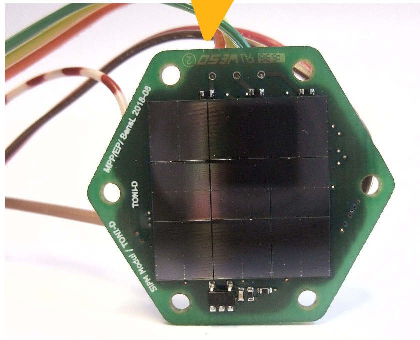
- Using Hamamatsu and SensL SiPMs
  ⇒ comparison of three major suppliers
- Increase active area to 9 SiPMs/pixel
- Optimizing electronics and heat flow
- 3D printed light guides will be evaluated
- Lower breakdown voltage

Sensor type	Breakdown voltage
Excelitas C30742-66	~ 95 V
Hamamatsu S13360-6075VS	~ 50 V
SensL MicroFJ-60035-TSV	~ 30 V

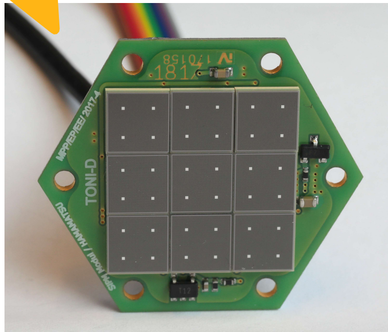
- Higher device C requires use of “fast” output (SensL) or high pass C (Hamamatsu)



Excelitas 2-3-2



SensL 3x3



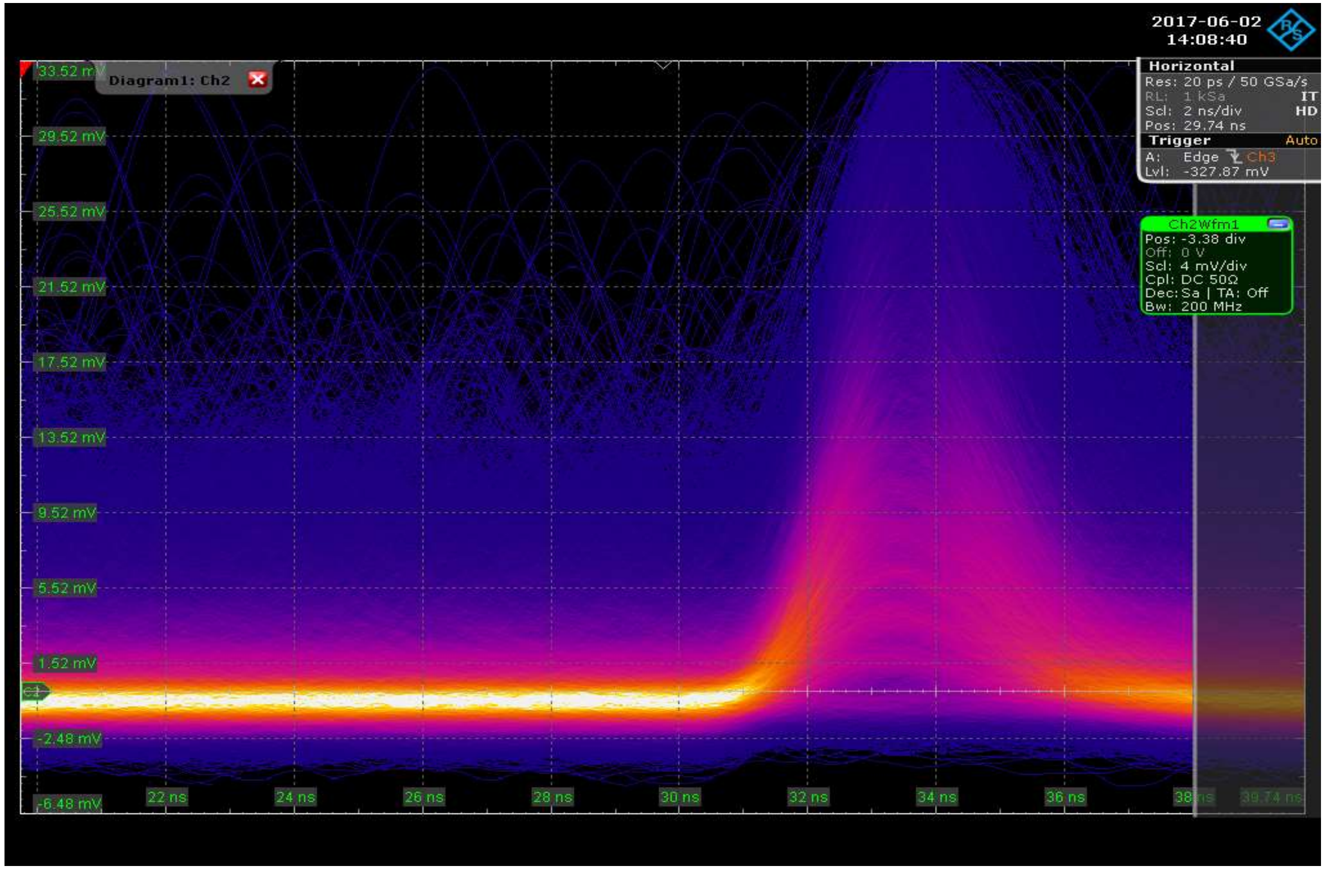
Hamamatsu 3x3

Second gen. SiPM

Pixel Design

Second+Third Prototype

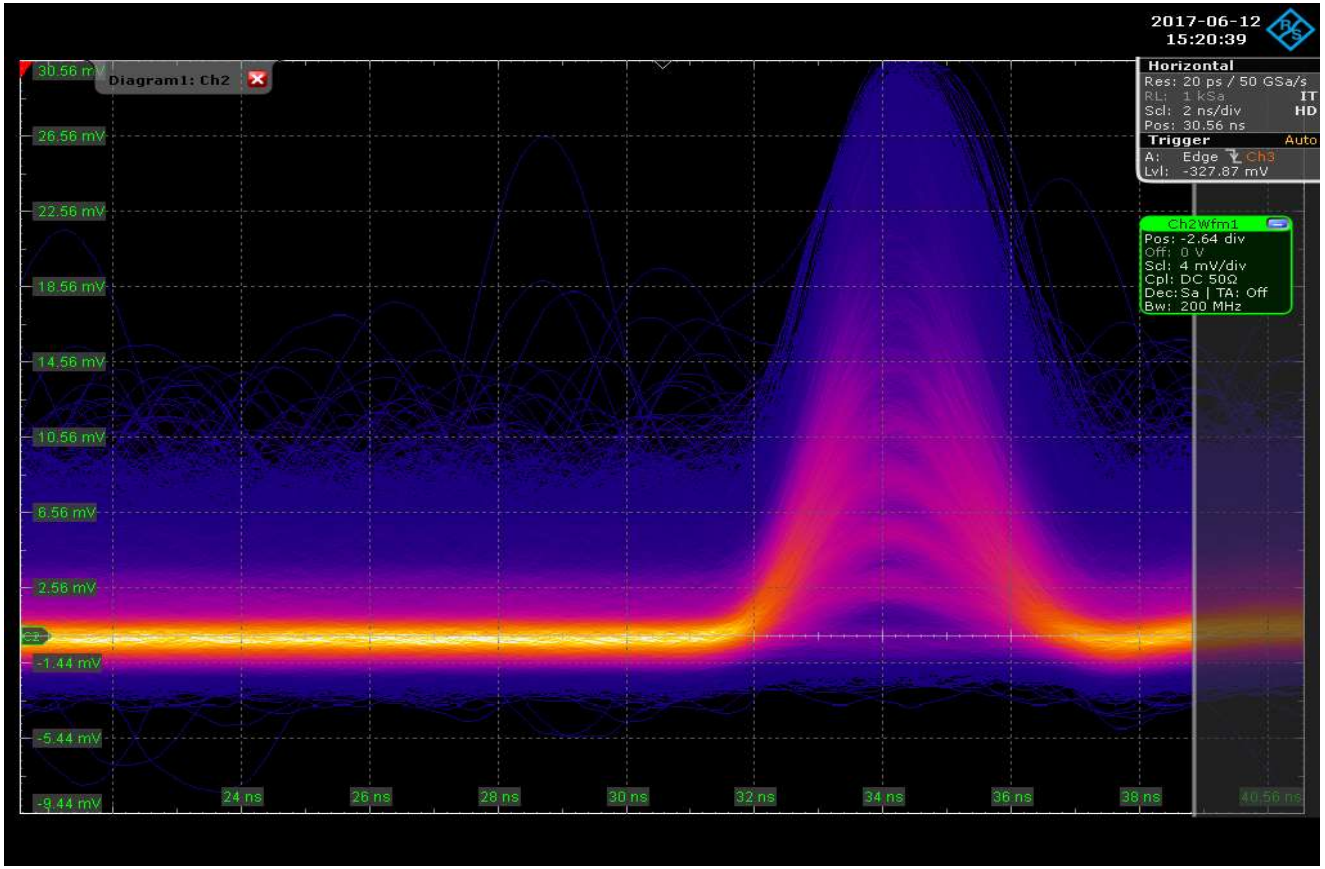
- Full chain of slow control, **SensL** SiPM pixel (9 sensors), VCSEL and optical receiver



- Single phe can be resolved
- FWHM: 2.8 ns
- Readout expected to double noise
  ⇒ still single phe resolution expected
- ~ 1000 phe dynamic range

Second+Third Prototype

- Full chain of slow control, **Hamamatsu** SiPM pixel (9 sensors), VCSEL and optical receiver



- Hamamatsu version uses coupling capacitor to isolate the fast portion of the signal
- Can impact signal form, not a problem for “low” energy gamma events
- FWHM: 2.5 ns
- 2-3x more signal charge available compared to SensL

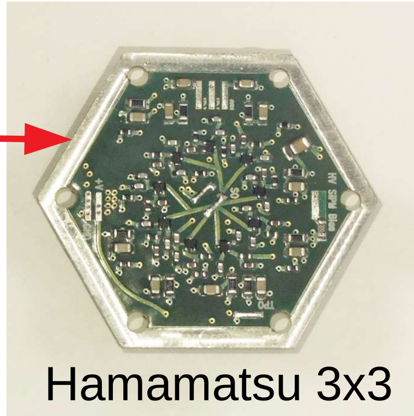
Second gen. SiPM

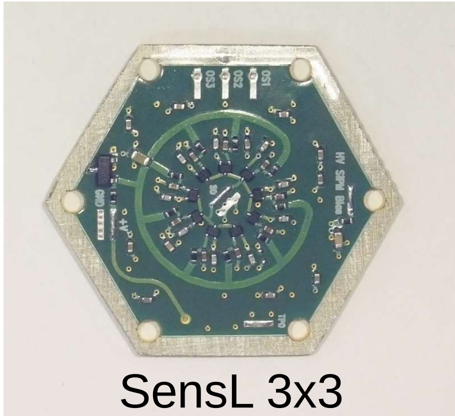
Temperature

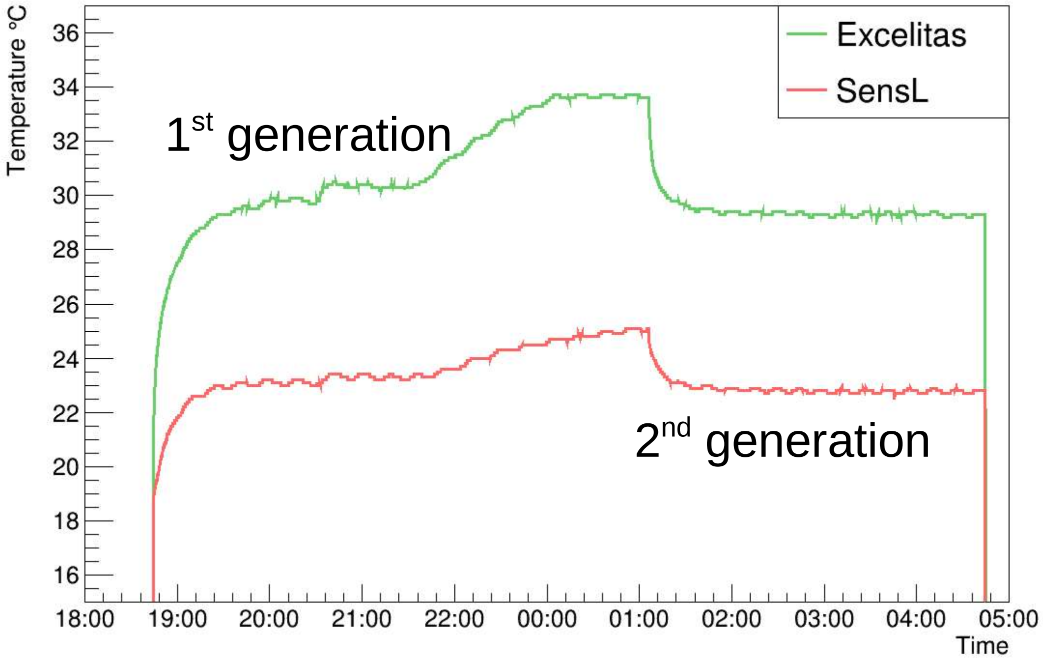
- Aluminium core PCBs
- Improved heat conductivity from pixel to cooling plate

➔ Reduced operational temperature

➔ Reduced temperature variation due to changing LoNS condition

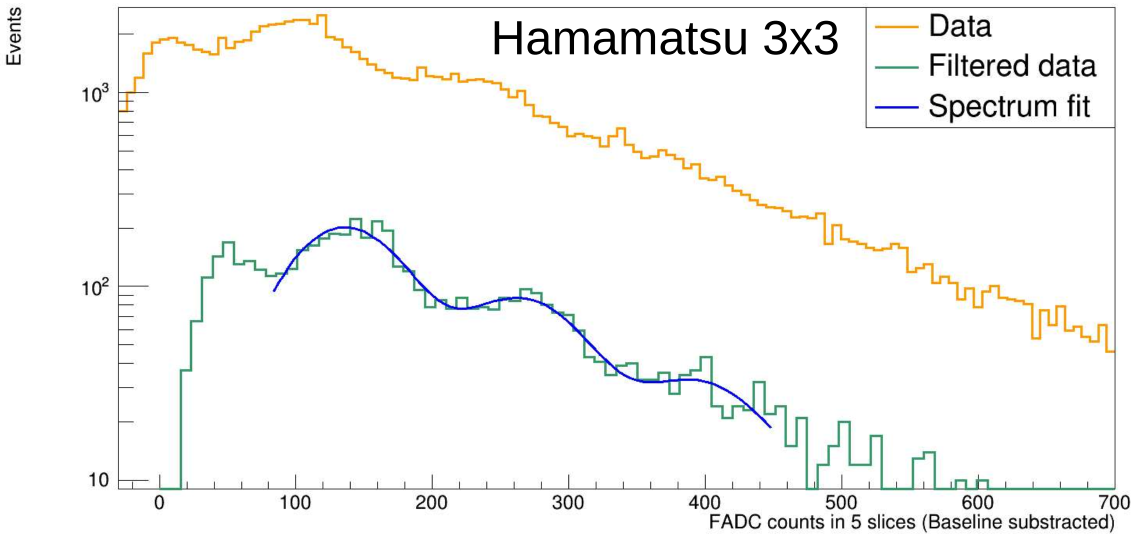


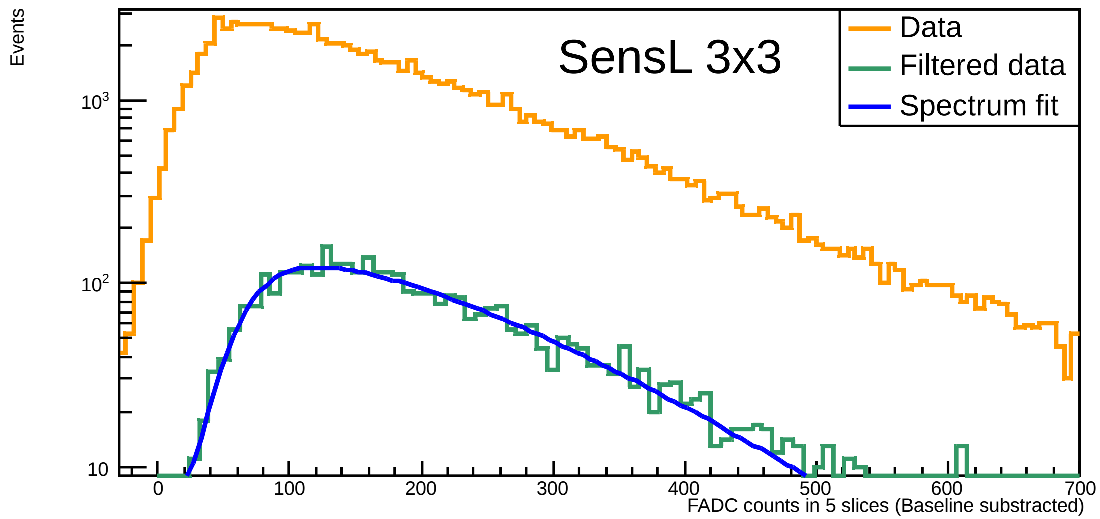




Second gen. SiPM
Calibration

- Calibration procedure developed for the 1st generation SiPM cluster can be applied to 2nd gen
- Hamamatsu pixels can be calibrated
- So far no success with the SensL pixels
  ⇒ more investigation needed





Summary and Outlook

First prototype to date:

- SiPM pixel to replace 1'' PMT using 7 Excelitas SiPMs w/modified light guide and cluster installed in MAGIC camera
- Stable temperatures without active controlling during normal observation
- Demonstrated a calibration procedure
- First measurements are in range of expected values

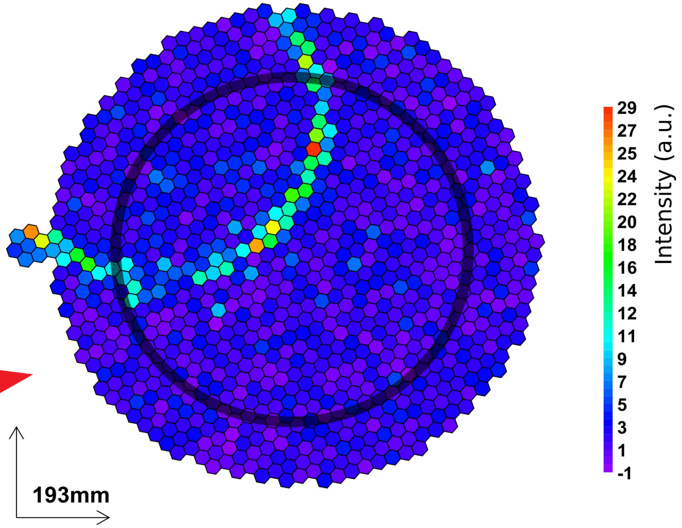
Second generation prototypes:

- SiPM pixel to replace 1'' PMT using 9 SensL or Hamamatsu SiPMs with improved performance
- Demonstrated improved thermal management
- Hamamatsu SiPM pixels can be calibrated

Further Work:

- Comparison of real Cherenkov event distribution (ongoing)
- Investigate problems with single phe spectrum of SensL pixel
- Rate scan / mount SiPM cluster in trigger region

  ⇒ energy threshold estimation
- Calibration with muon events

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References

[1] R. Wagner. Picture gallery of the MAGIC telescopes. https://magicold.mpp.mpg.de/gallery/pictures/ . Retrieved 10-2014

[2] D. Nakajima, et al. New Imaging Camera for the MAGIC-I Telescope, 2013. Proc. of 33rd International cosmic ray conference.

[3] H. Wetteskind. Private communications. Image courtesy of MPP engineering department.

[4] R. Rando, et al. Silicon Photomultiplier Research and Development Studies for the Large Size Telescope of the Cherenkov Telescope Array, 2015. Proc. of 34th International cosmic ray conference.

[5] D. Guberman, et al. Light-Trap: A SiPM Upgrade for Very High Energy Astronomy and Beyond, 2017. Proc. of 35th International cosmic ray conference.