Development of Three Silicon Photomultiplier Detector Modules for the MAGIC Telescopes for a Performance Comparison to PMTs

by

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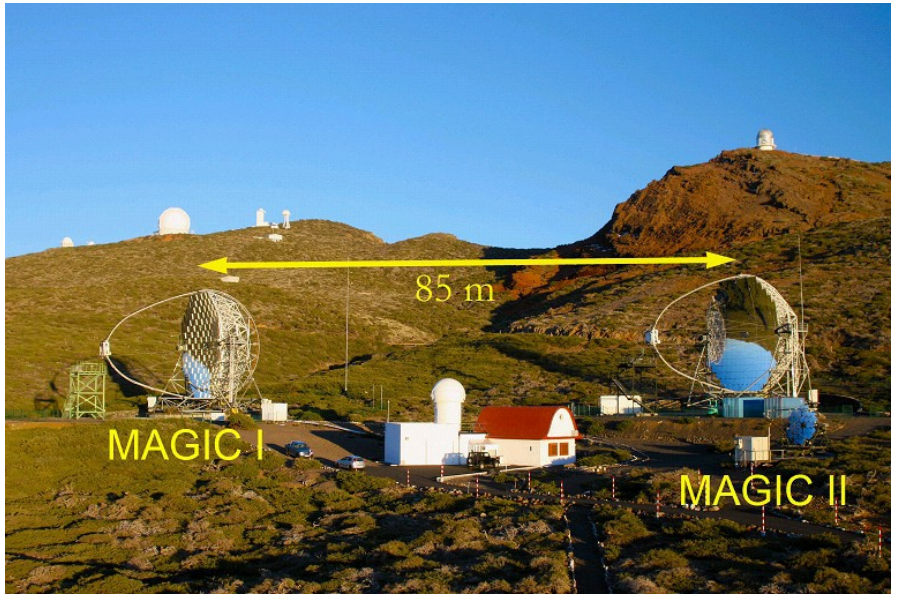
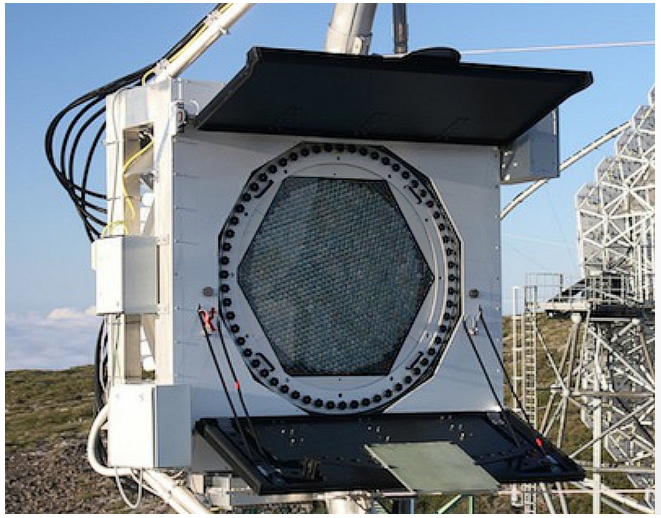
The MAGIC telescopes

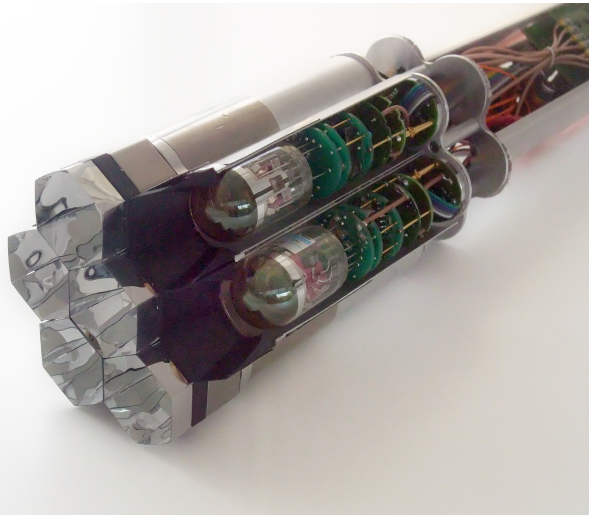
[1]



- Canary island of La Palma
- Two imaging atmospheric Cherenkov telescopes (IACTs)
- Each camera equipped with 1039 PMTs
- Up to 7 pixels partitioned in 169 clusters

[2]

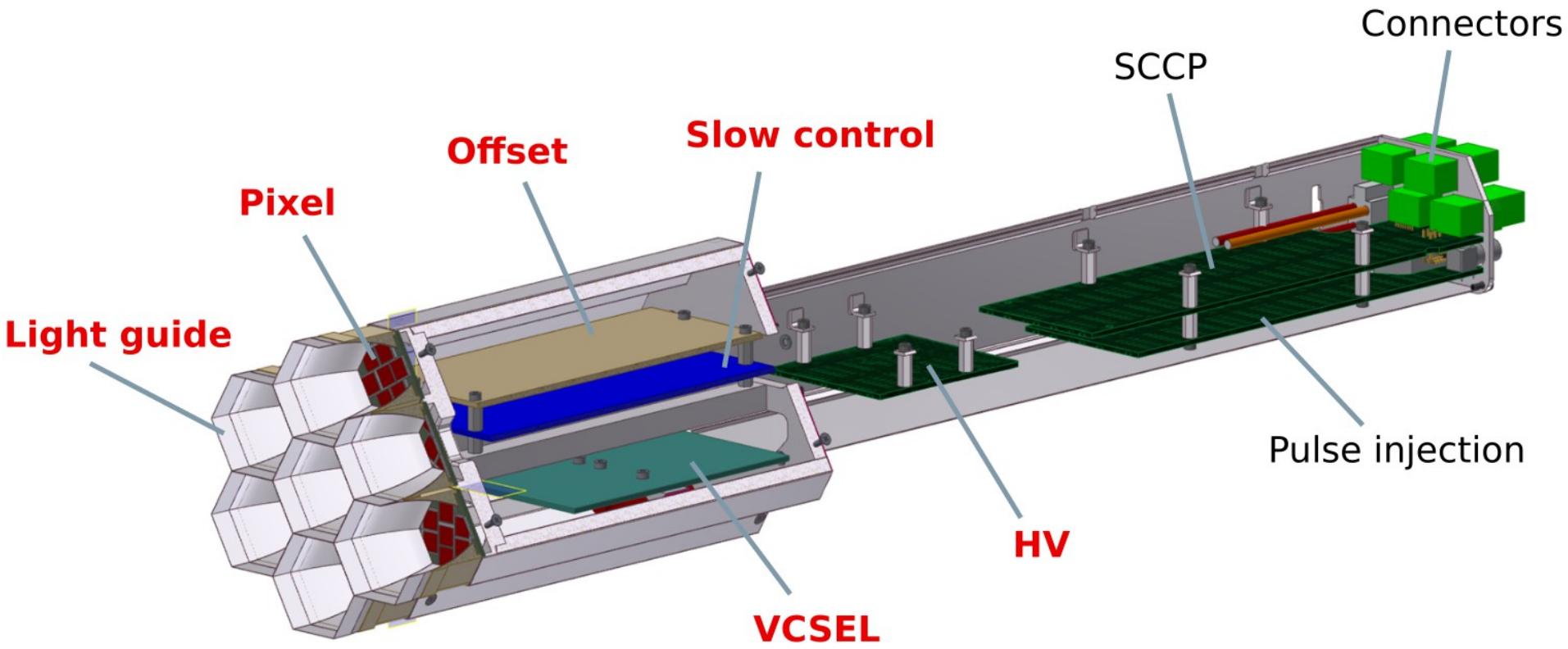




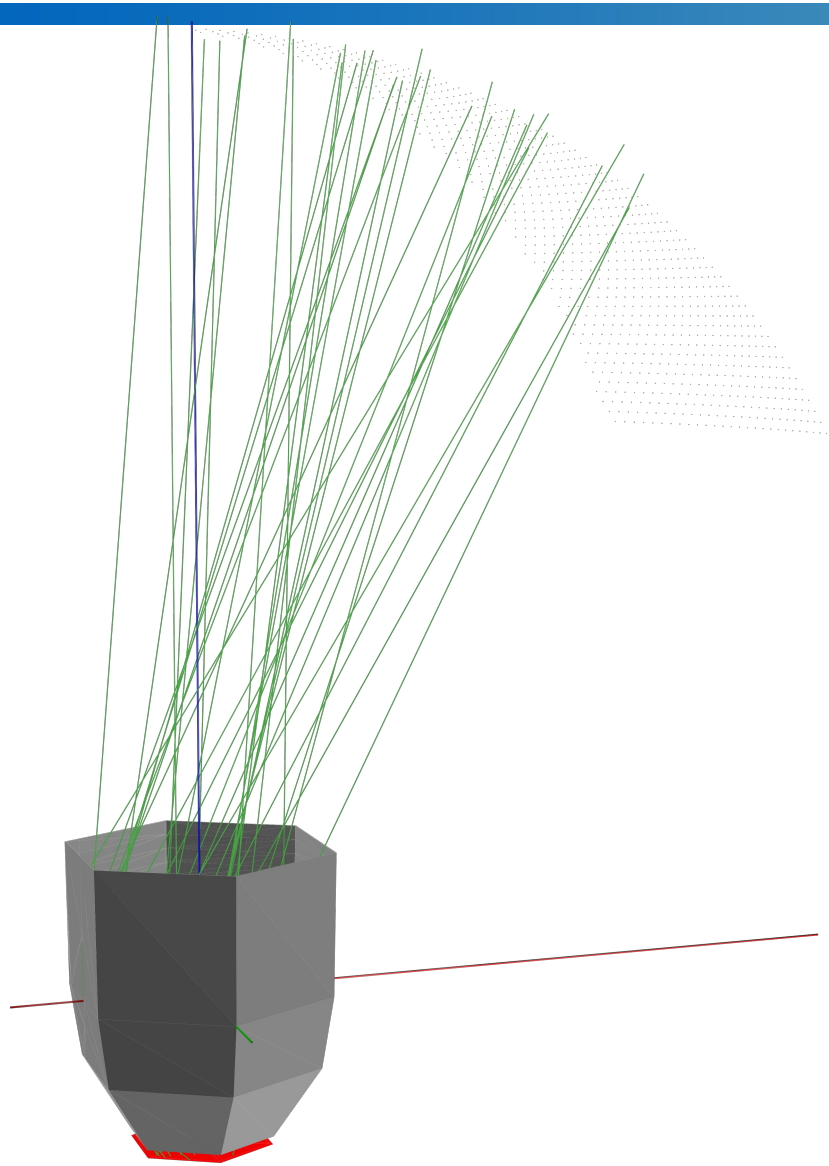
Motivation

- SiPMs can be operated during moon time
  - dark nights only:
    IACT duty cycle 18 %
  - with moon and twilight:
    IACT duty cycle 40 %
- SiPMs are continuously improving:
  high photon detection efficiency (PDE), low cross-talk

Cluster Design
Overview



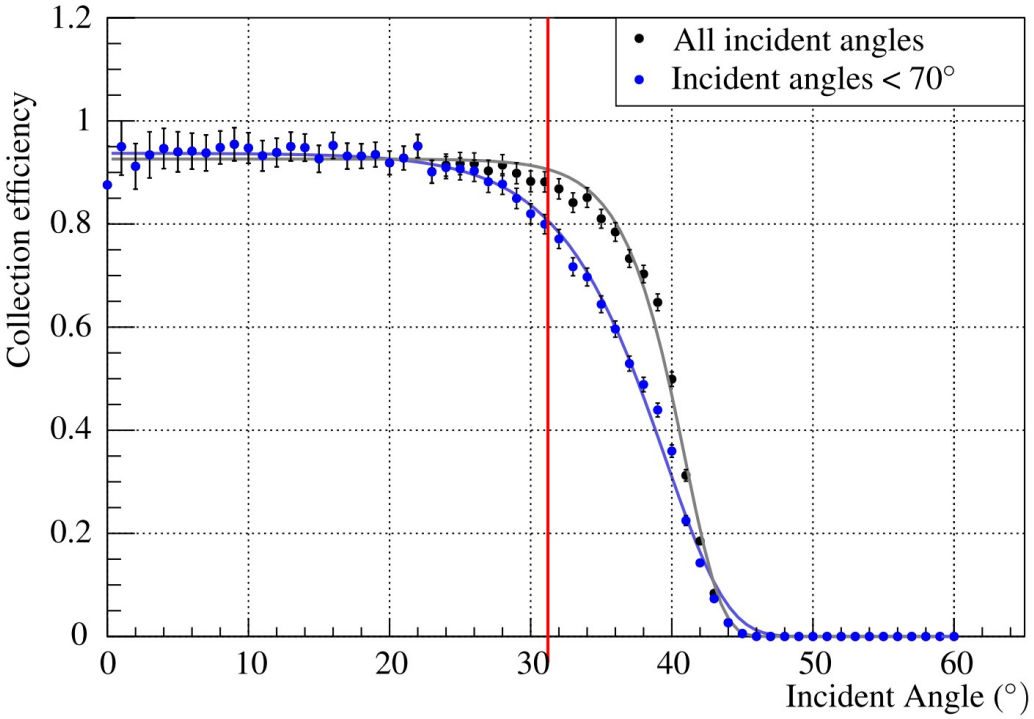
Cluster Design
Light guides

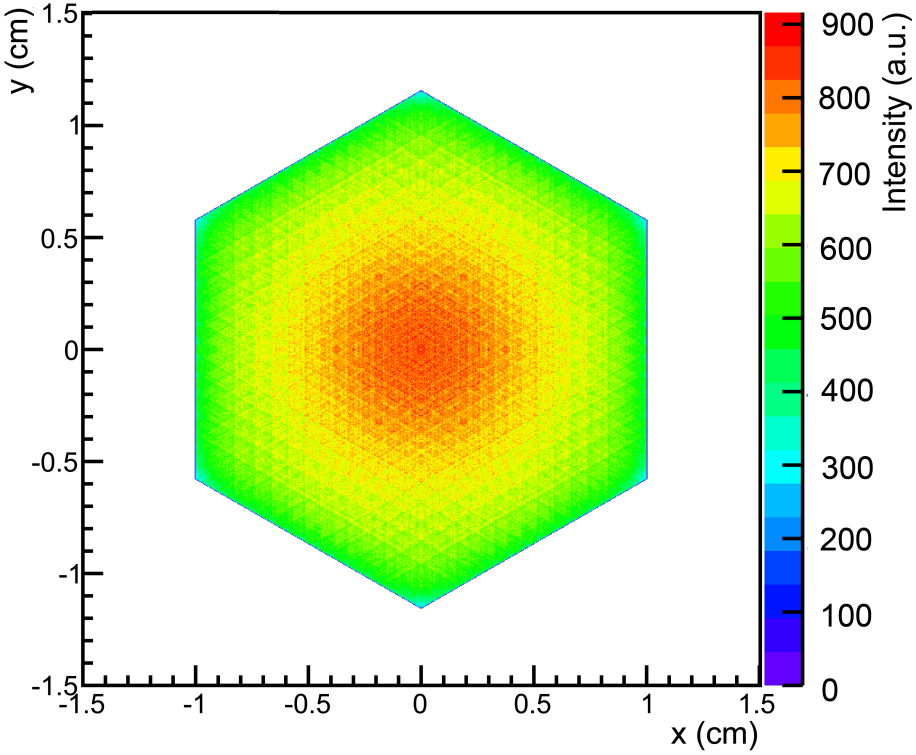


Simulating

- Parallel light from different angles
- Including Cherenkov spectrum and aluminized Mylar reflectivity
- Different exit apertures
- Different SiPM distances

Cluster Design
Light guides



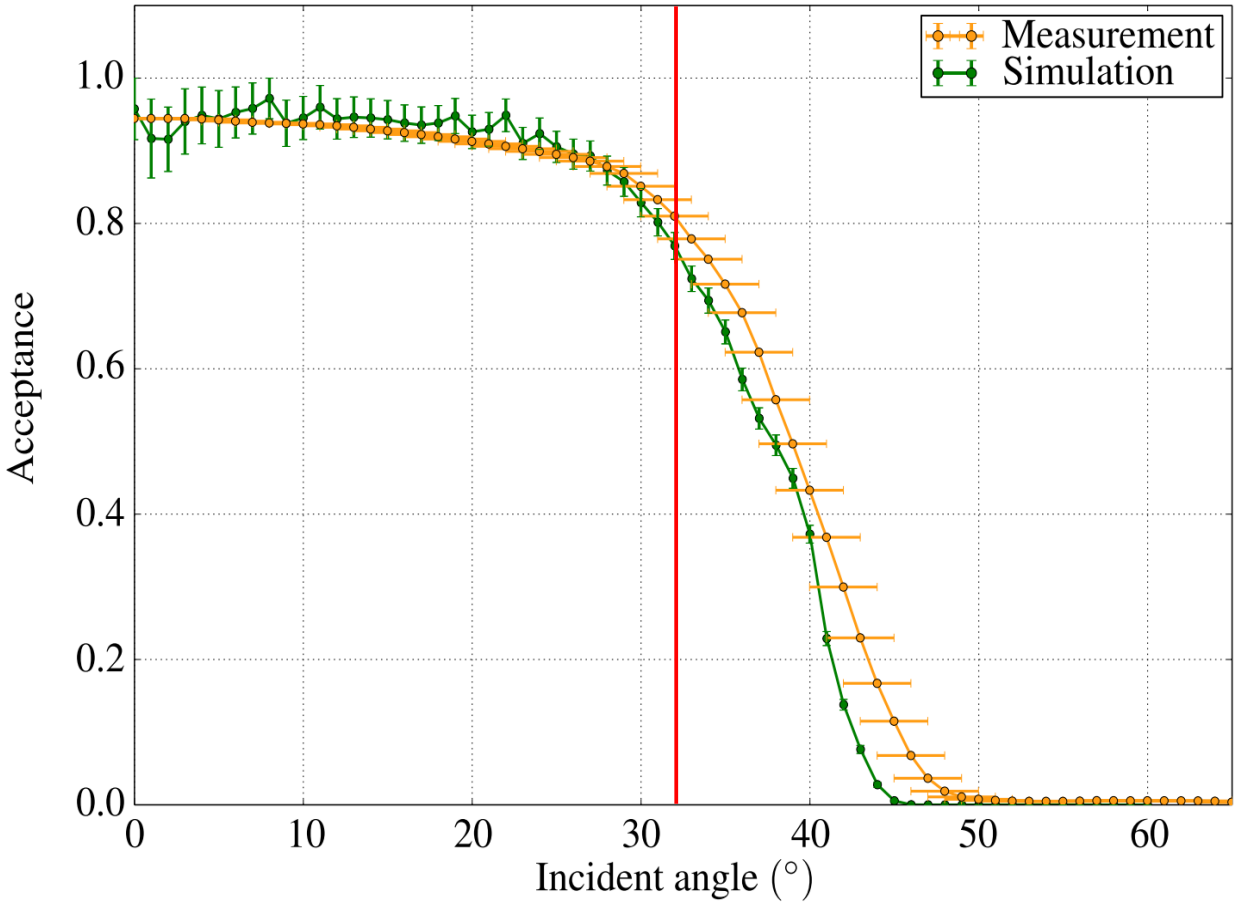


Simulation results

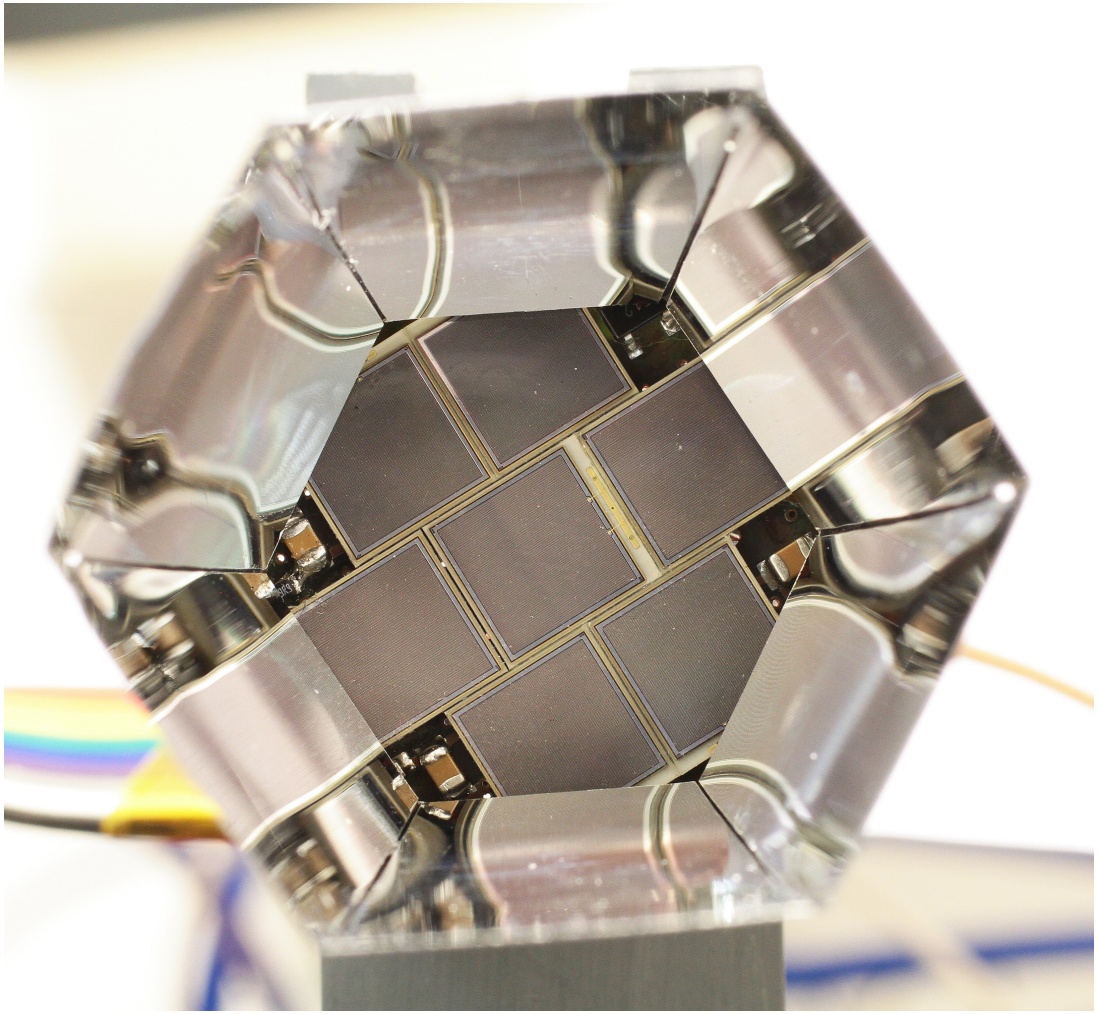
- Concentration ratio 2.25
- Collection efficiency 91.8 % ± 0.3 %
- SiPMs directly at exit
- Well distributed light

Cluster Design
Light guides

- Measurements in dark room
- Measured collection efficiency: $92.1\ \%^{+0.7\ \%}_{-1.0\ \%}$
- Absolute difference 0.3 % between simulation and measurement

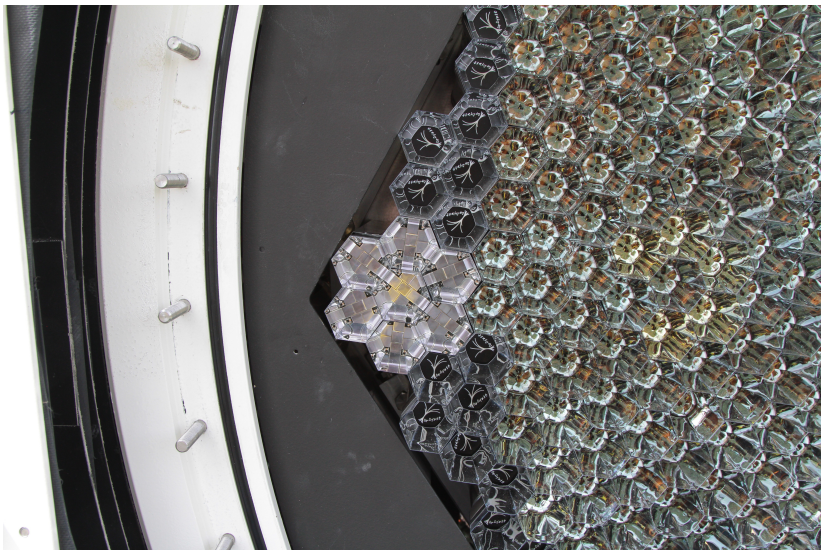


Cluster Design
Pixel

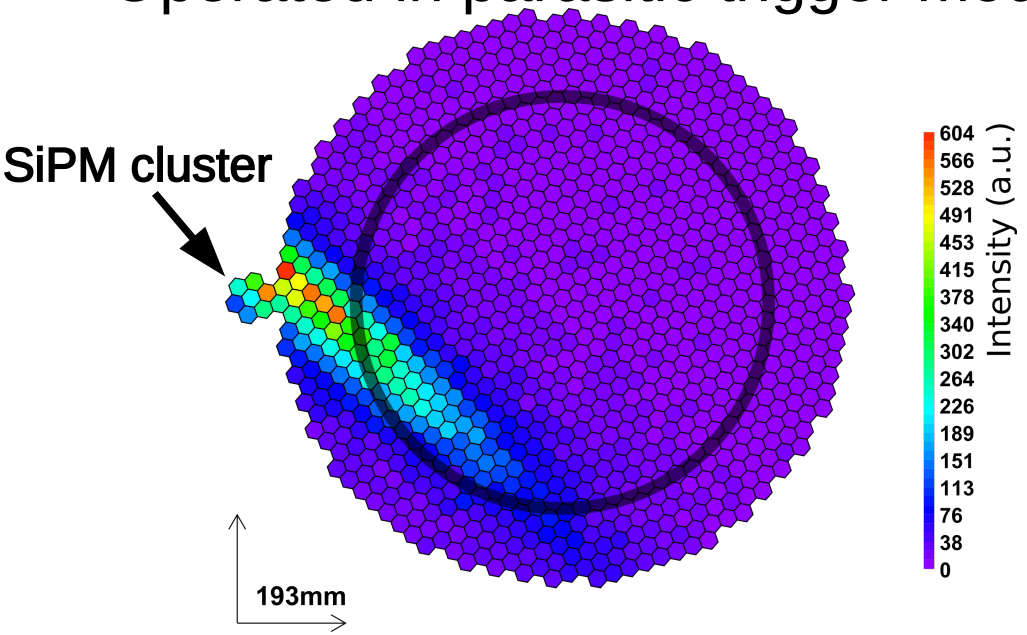


- 95 % of active area can be accessed by light
- 69 % of light guide output is covered with active area

Installation

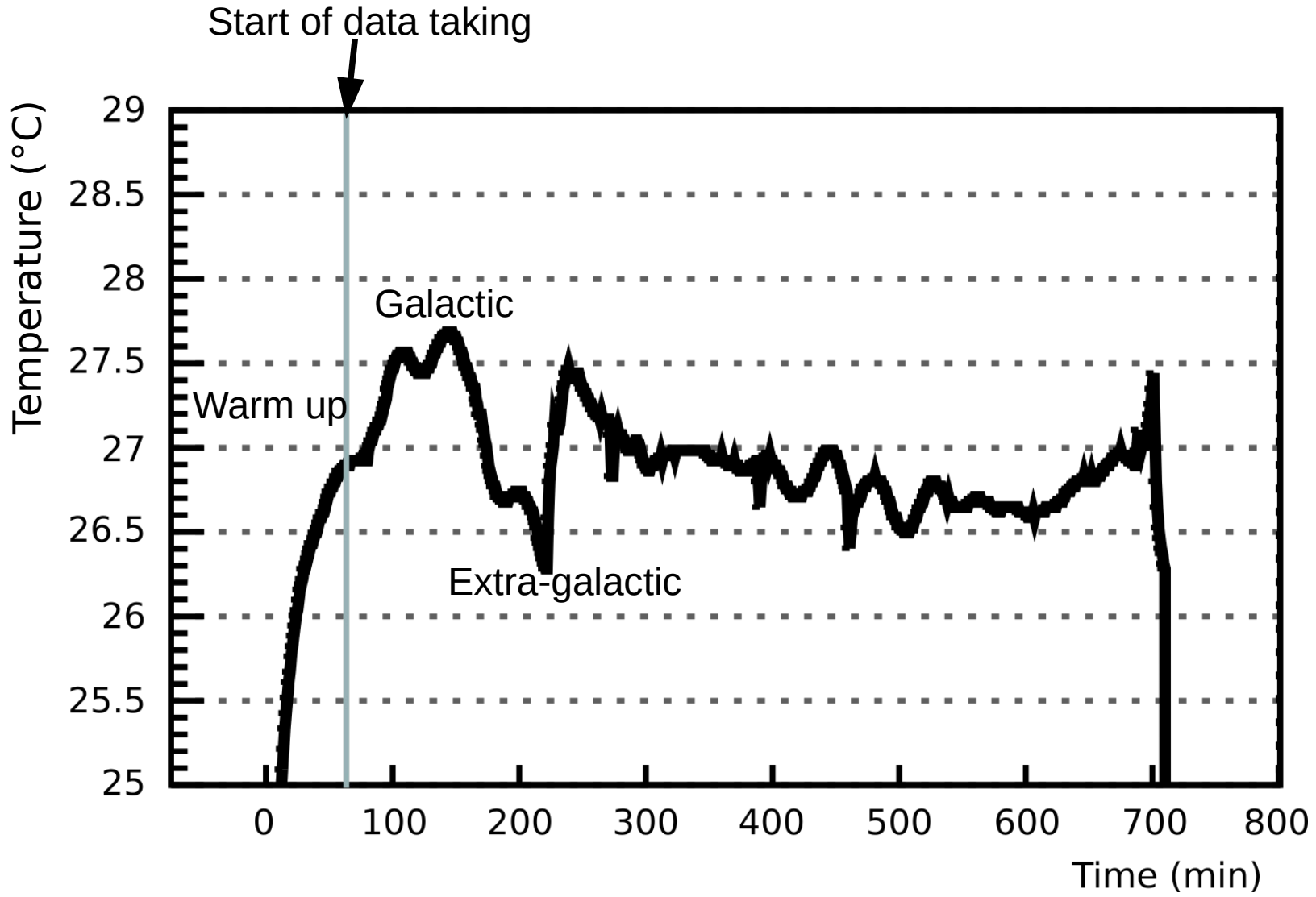


- First SiPM cluster installed in May 2015
- Mounted next to PMT pixels
- Integrated to standard readout
- Operated in parasitic trigger mode



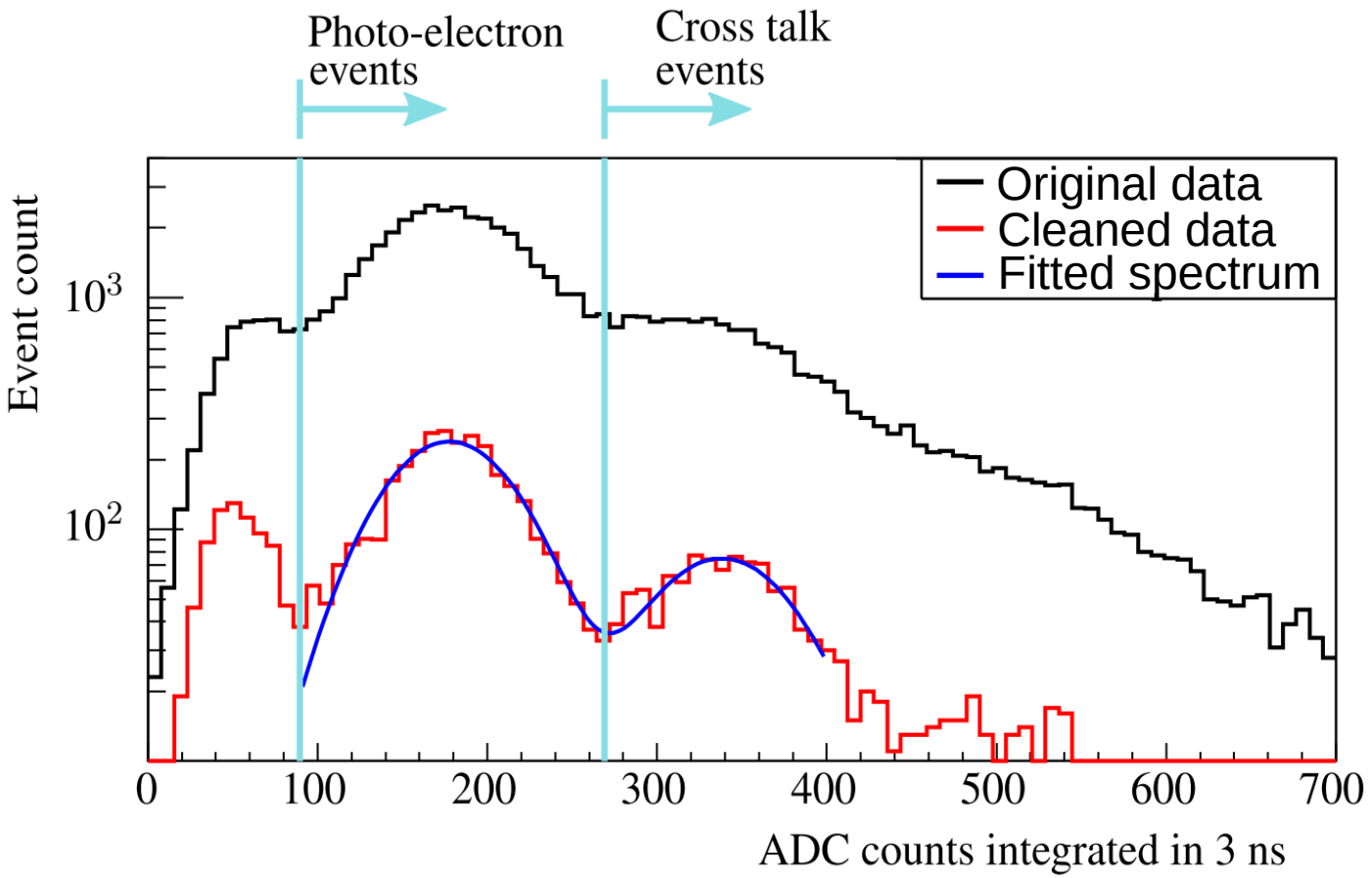
Results

Temperature



Results

Calibration - gain and cross talk



- 100 kEvents random trigger with closed lids
- 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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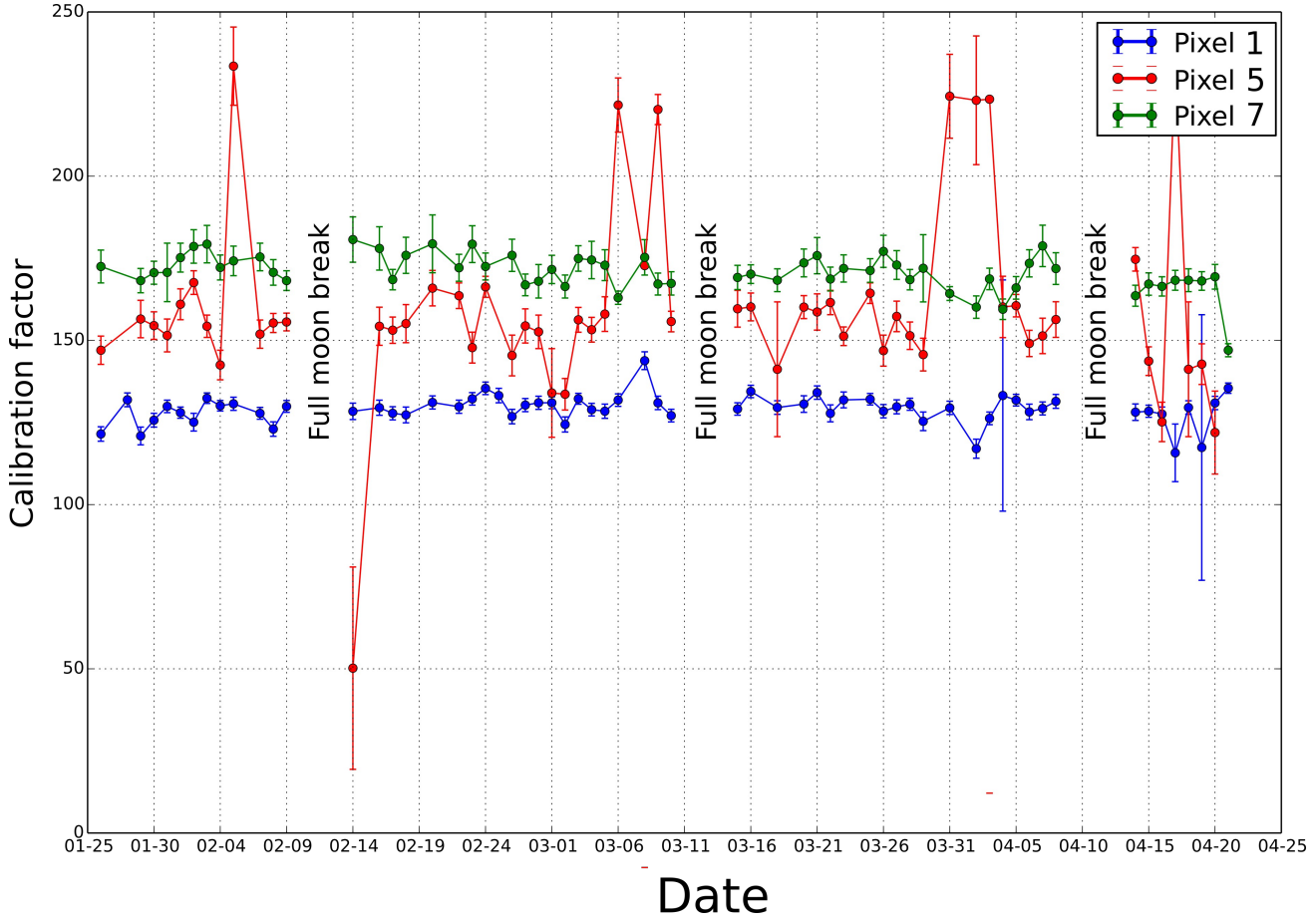
(Werner-Heisenberg-Institut)

Nightly calibration



- SiPM calibration can be performed beginning of every night when shifters turn on SiPMs during start-up
- Works for high and low bias voltages (pixel 1, 7)
- Some outliers where spectrum fit does not converge
  => Needs to be investigated more deeply

Results

Calibration - updating

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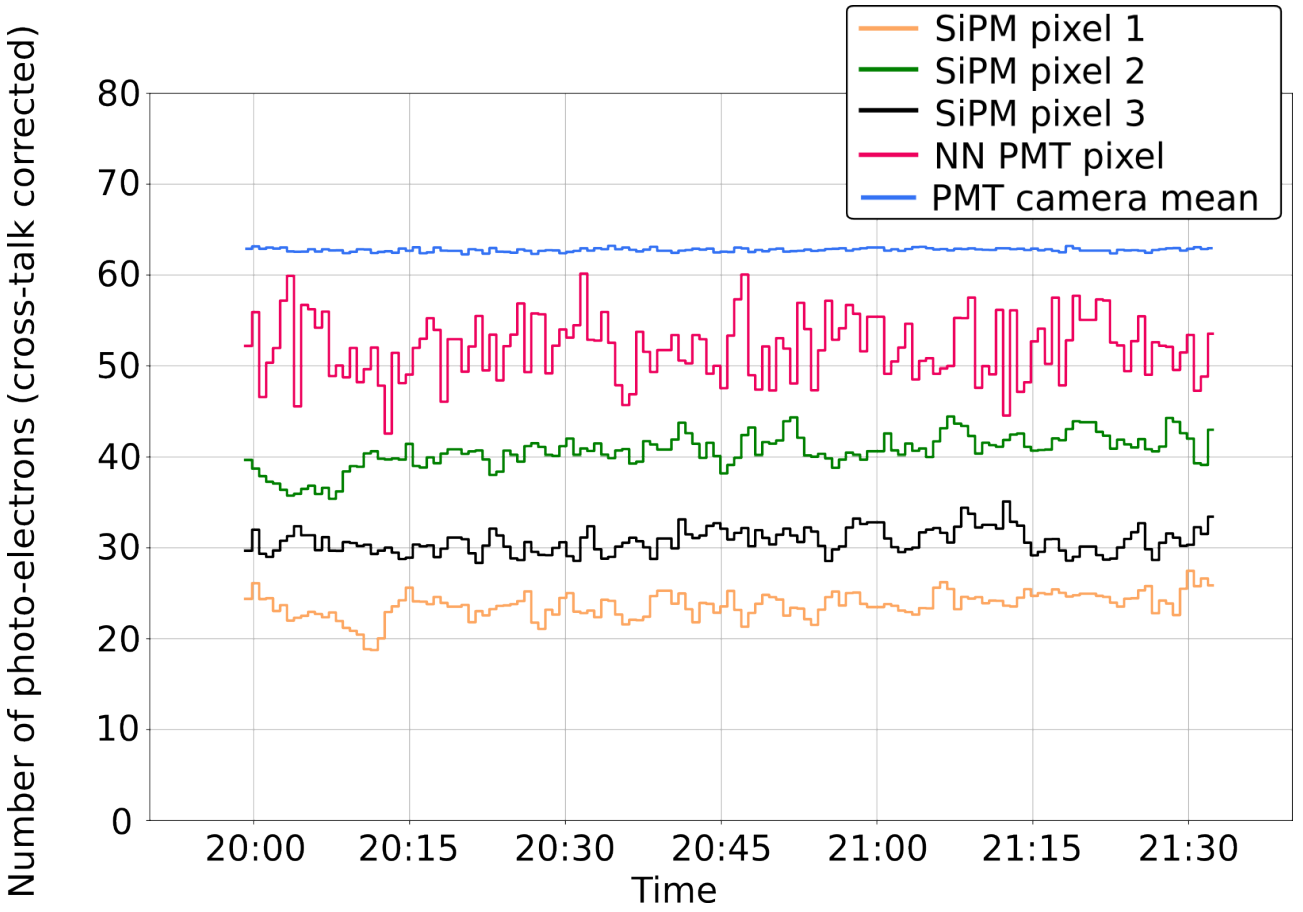
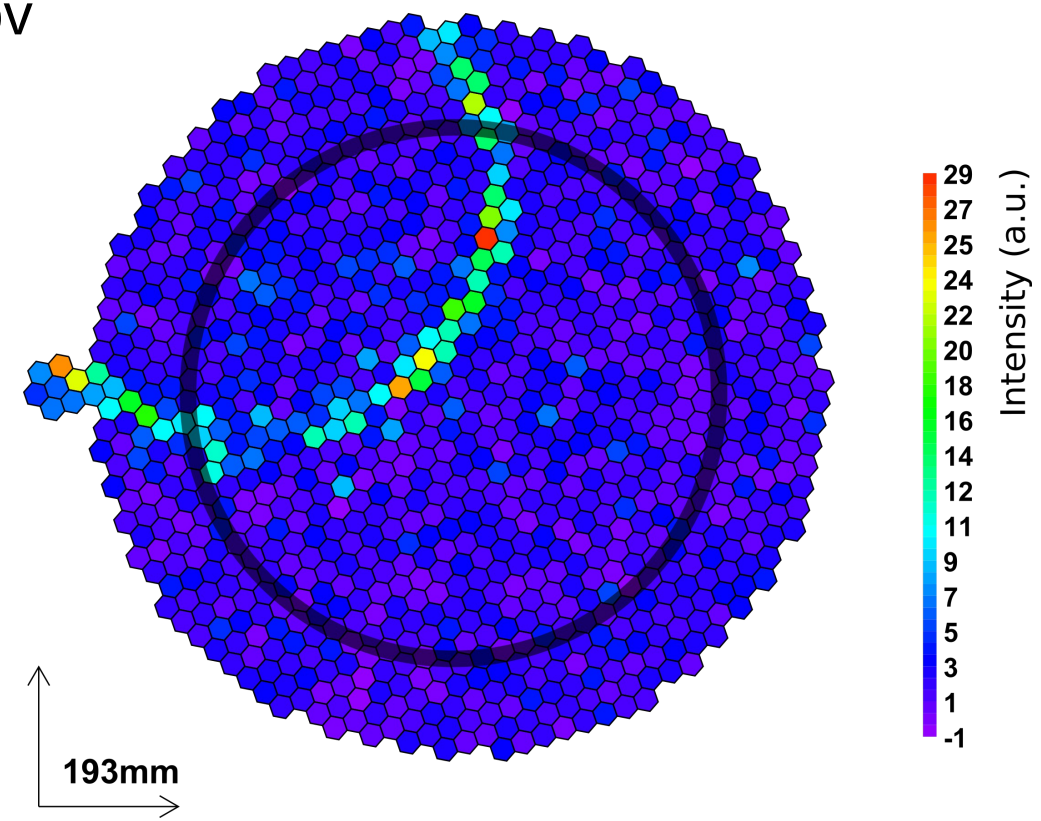
Intra-night stability (one source)



- 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))

Outlook

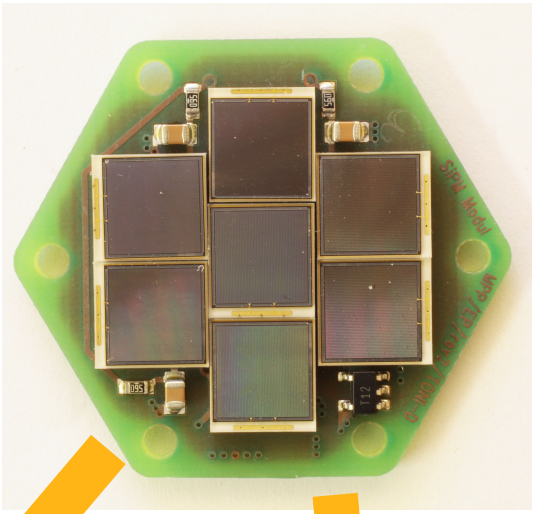
- First prototype
  - Comparison of real Cherenkov event distribution (ongoing)
  - Investigation of the outliers in the nightly SiPM calibration (ongoing)
  - Rate scan / Mount SiPM cluster in trigger region => estimation of energy threshold
  - Calibration with muon events



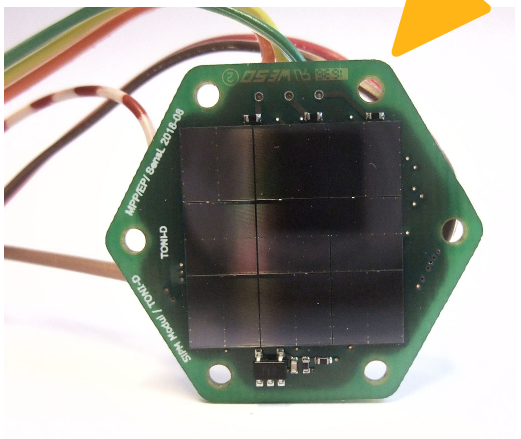
Outlook

Second + Third Prototype

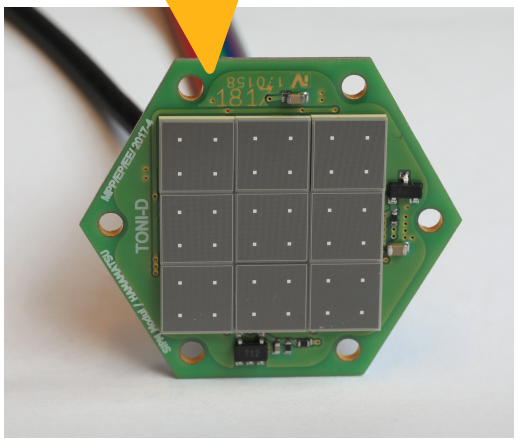
- Using Hamamatsu and SensL SiPMs
  ⇒ comparison of three major suppliers
- Increase active area to 9 SiPMs/pixel
- Optimizing electronics and heat flow
- 3D printed light guides will be evaluated
- Lower breakdown voltage:
  Excelitas ~ 95 V
  Hamamatsu ~ 50 V
  SensL ~ 30 V



Excelitas



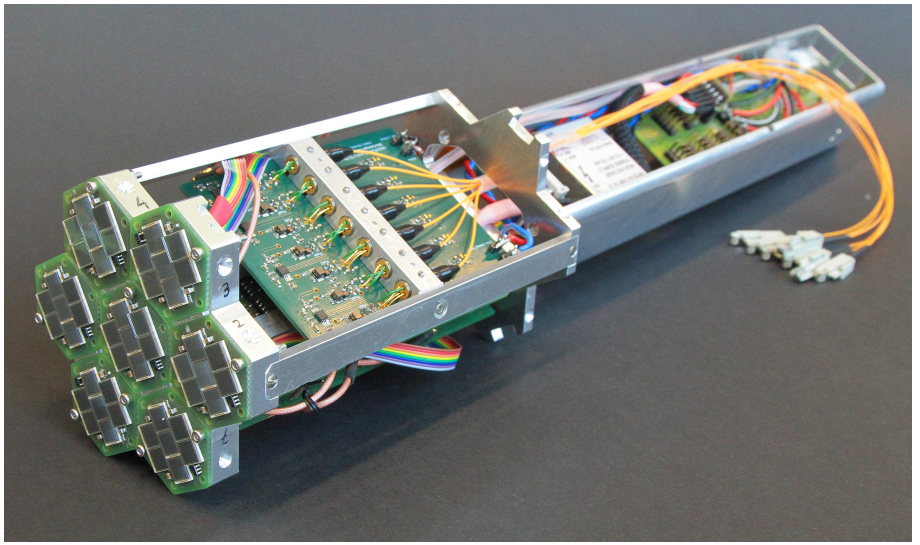
SensL

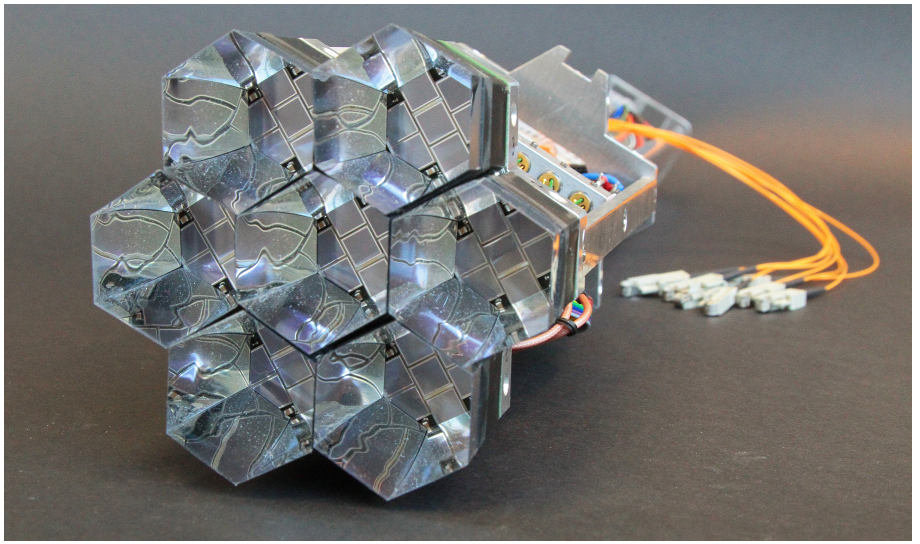


Hamamatsu

Summary

- Successfully developed the first SiPM-based module for a large IACT
- Optimized light guides
- Integrated in standard readout and control
- Developed a basic concept of the calibration
- Measurements in agreement with predictions
- Finishing a new prototypes





Thank you for your attention

References

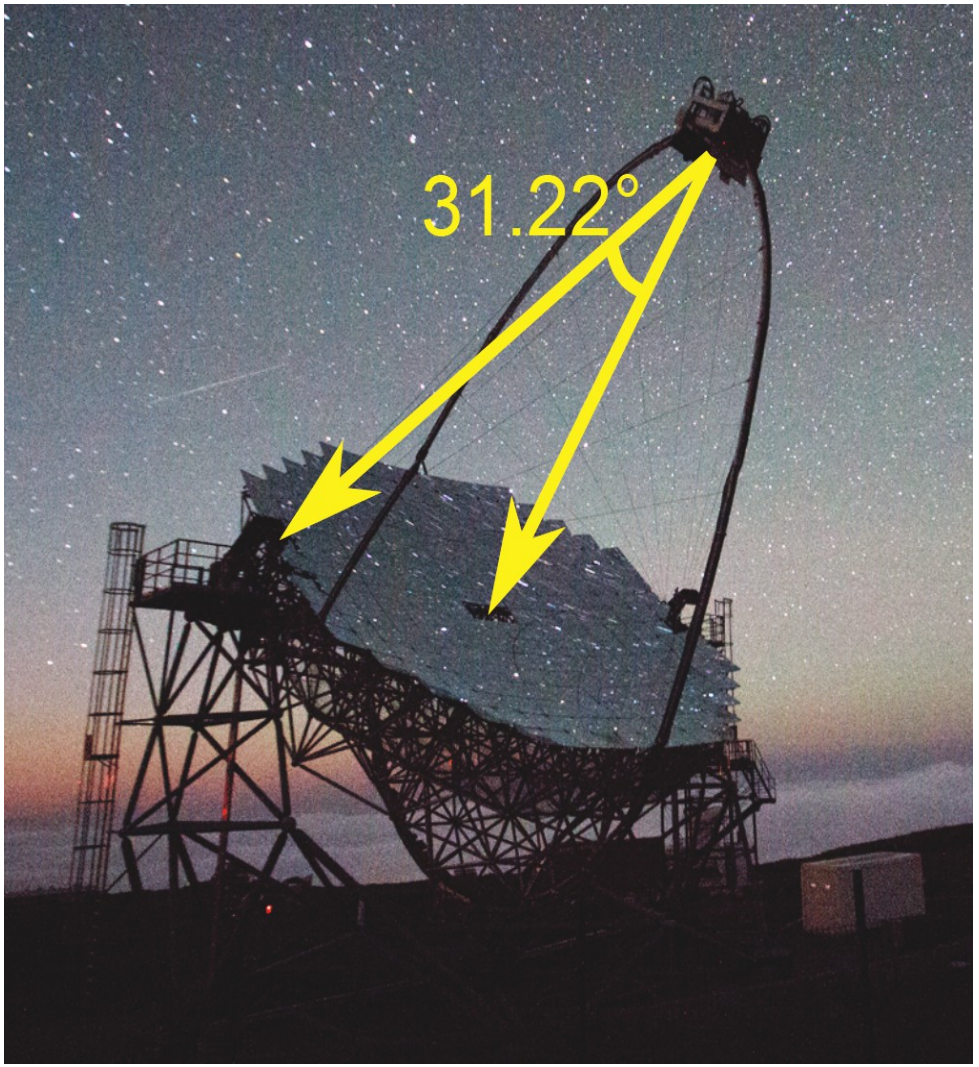
[1] R. Wagner. Picture gallery of the MAGIC telescopes. https://magicold.mpp.mpg.de/gallery/pictures/ . Retrieved 10 2014

[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.

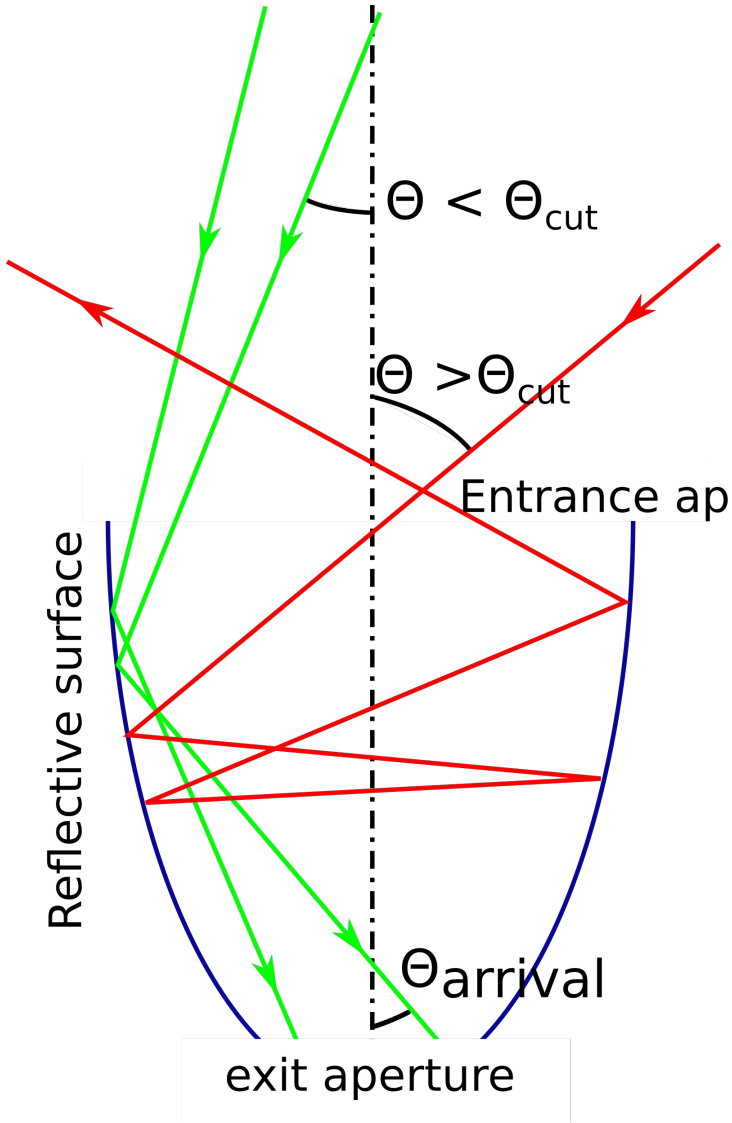
BACKUP

Cluster Design
Light guides



- Same entrance size as PMT pixel
- Acceptance cut-off at 31.22°
  (MAGIC mirror area)
- Incident angle on SiPM must be smaller than 70°
  (detectable for SiPM)
- Light guide design constrains the other mechanics

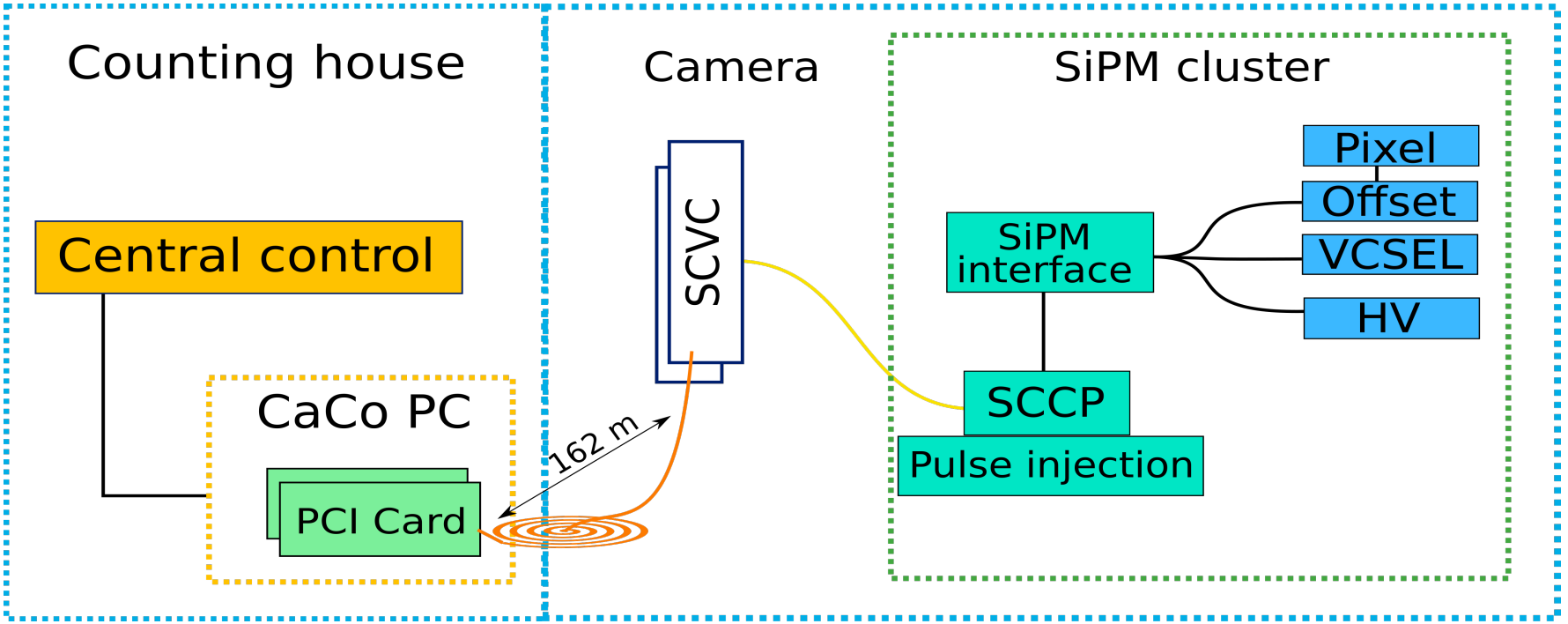
Cluster Design
Light guides



Compound Parabolic Concentrator (CPC) or Winston cone

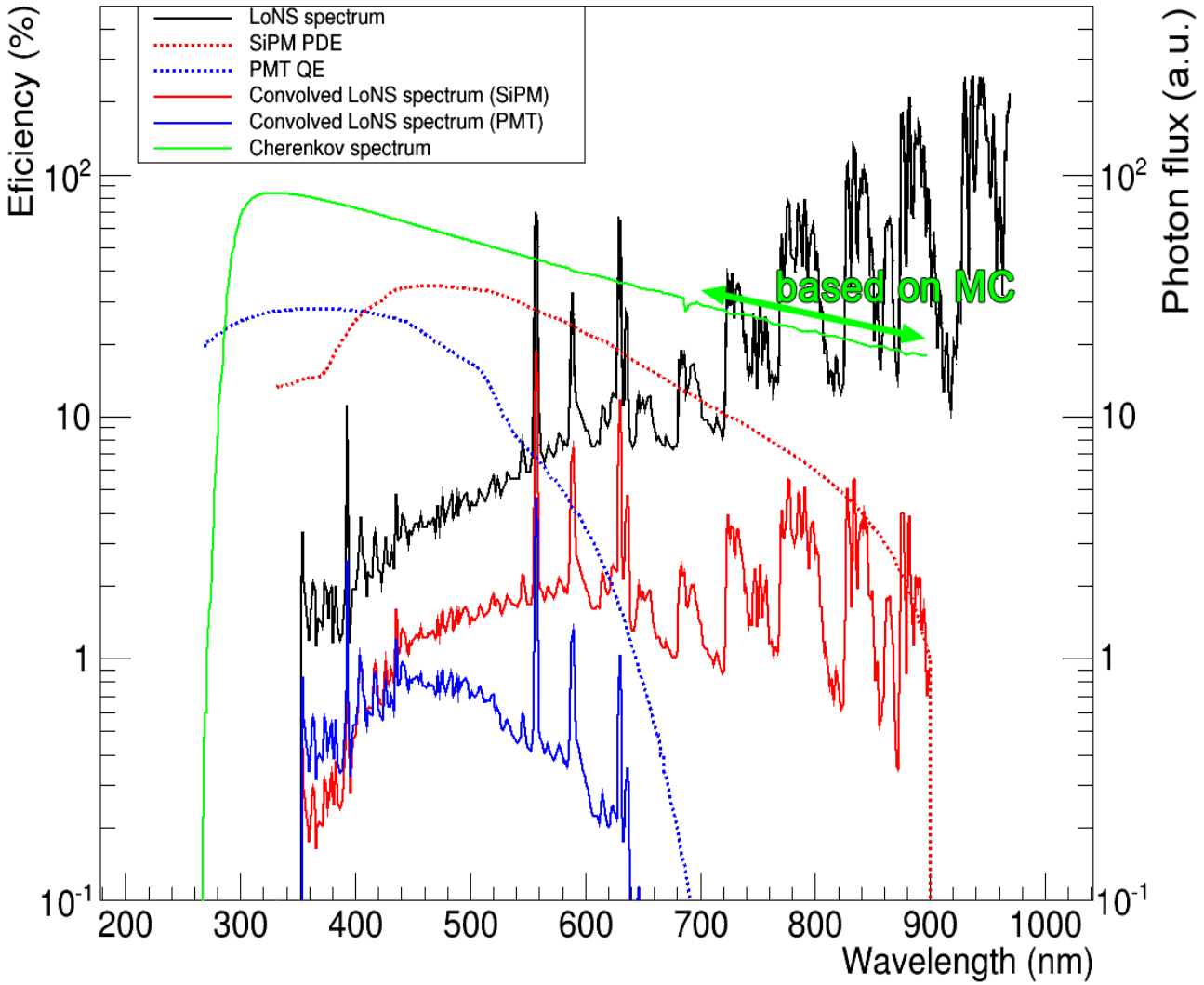
- Acceptance is step-function with cut-off at Θ_{cut}
- Light weight
- We can use spare parts from MAGIC

Cluster Design
Slow control



- 28 current sensors, 21 offset voltages, 14 temperature sensors, and 1 HV
- Set/Read by 48 ADC and 40 DAC channels, 12 bit each
- Implemented to standard Camera Control (CaCo)

Results
Expectations



- SiPM detect 4.3 times more LoNS than PMT
- 170 MHz in PMT
  => 780 MHz in SiPM

  with signal FWHM ~ 5 ns
  => 1 phe/1.3 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

Backup

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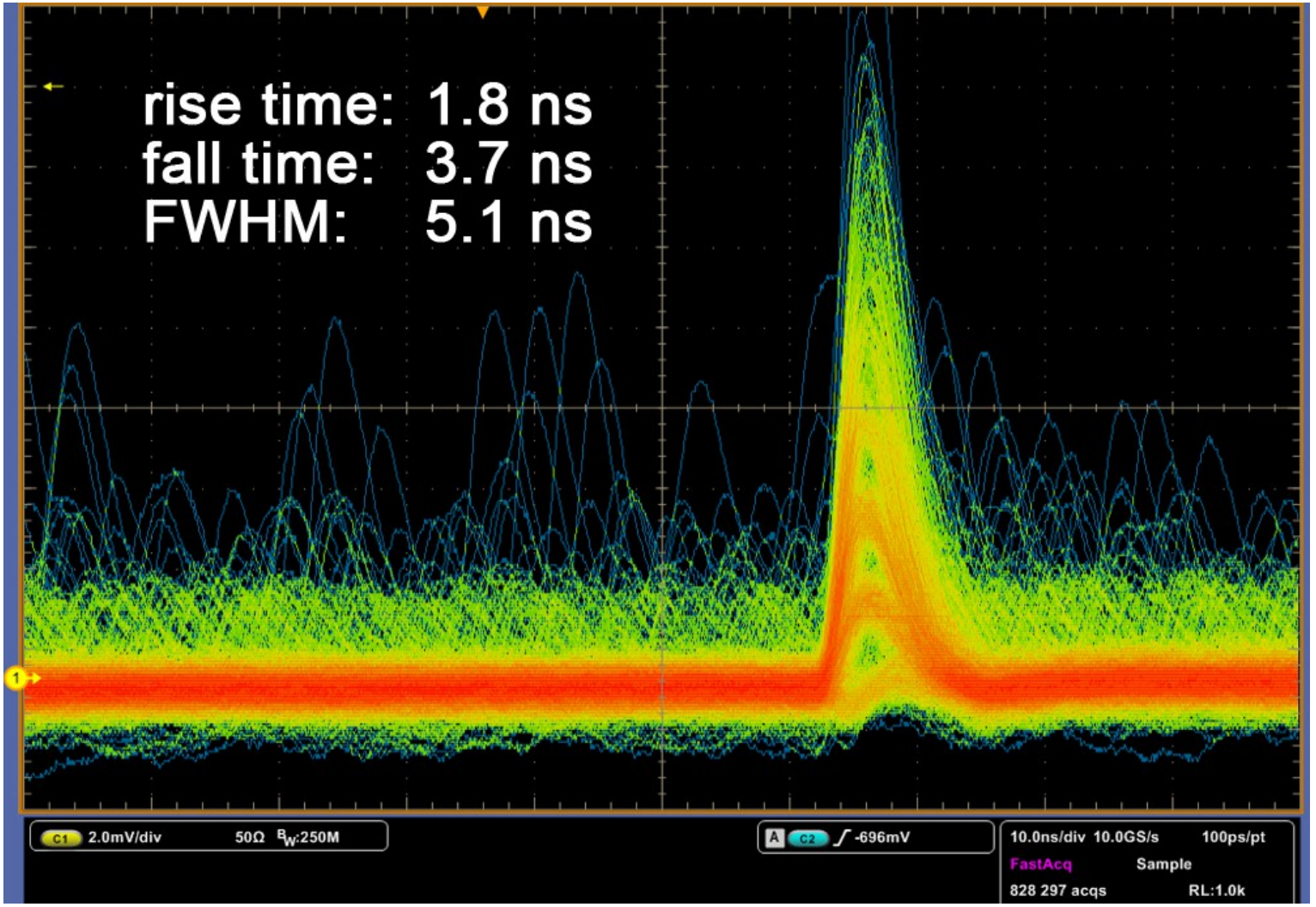
Single SiPM



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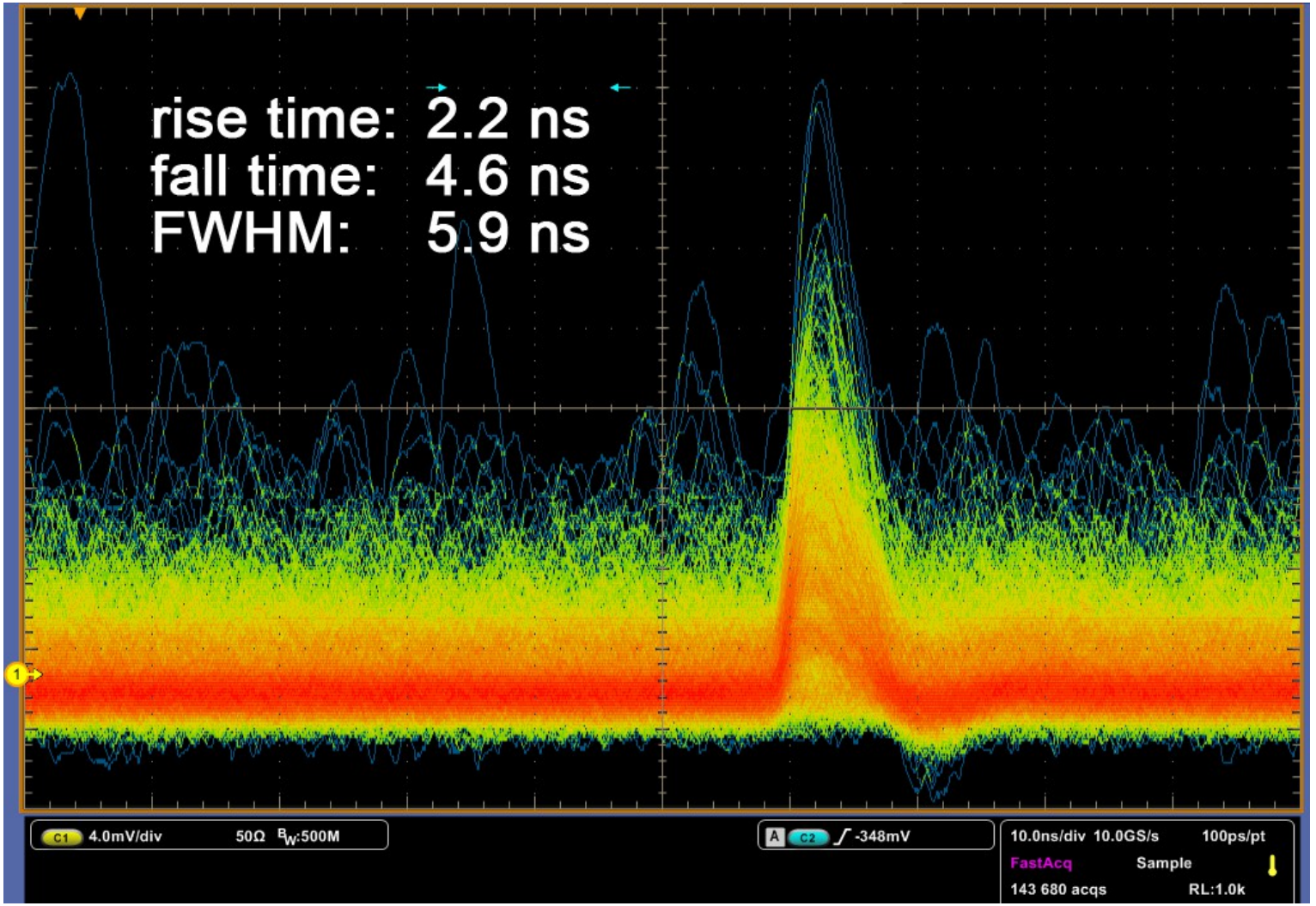
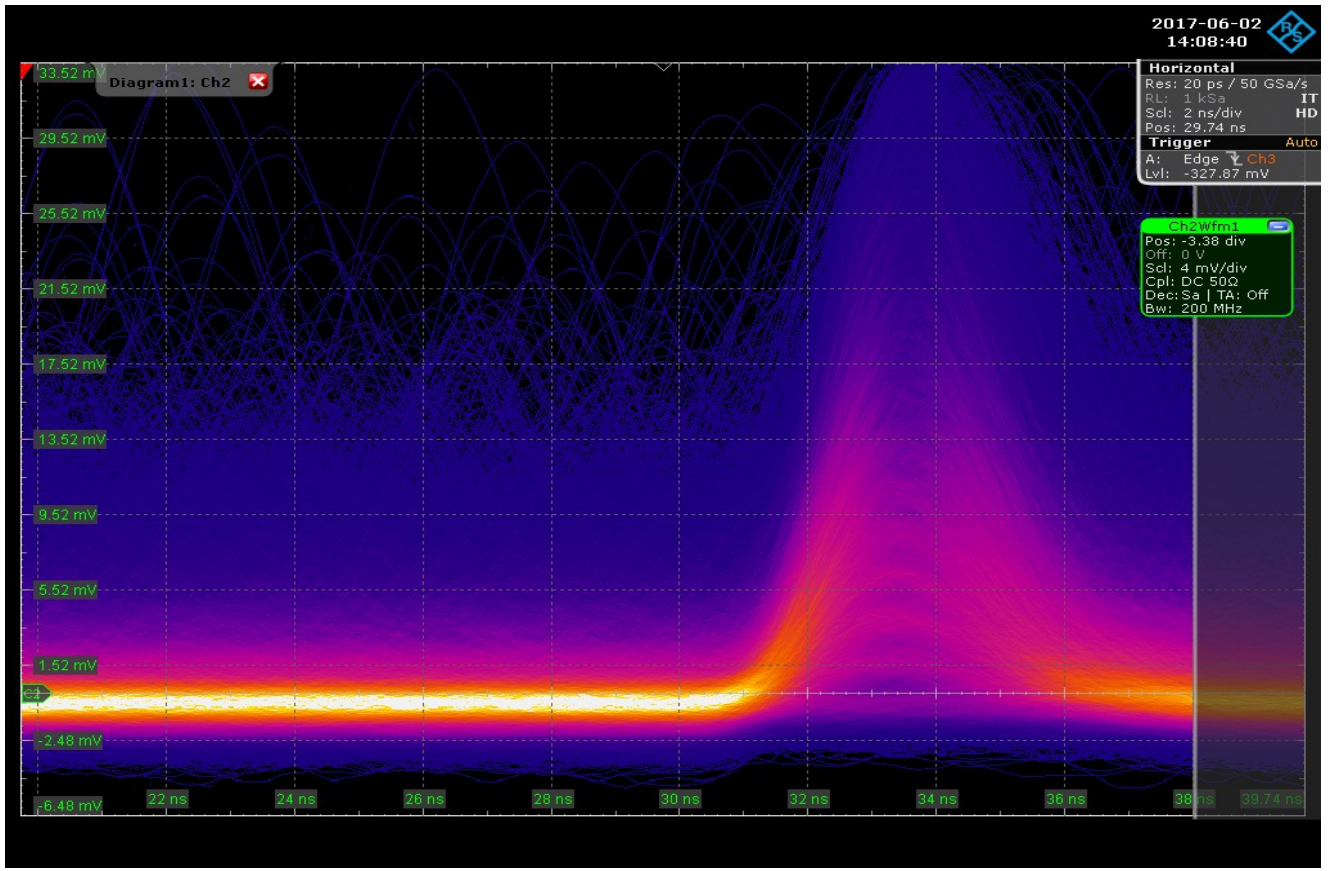
Seven summed SiPMs



Backup

Second+Third Prototype

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

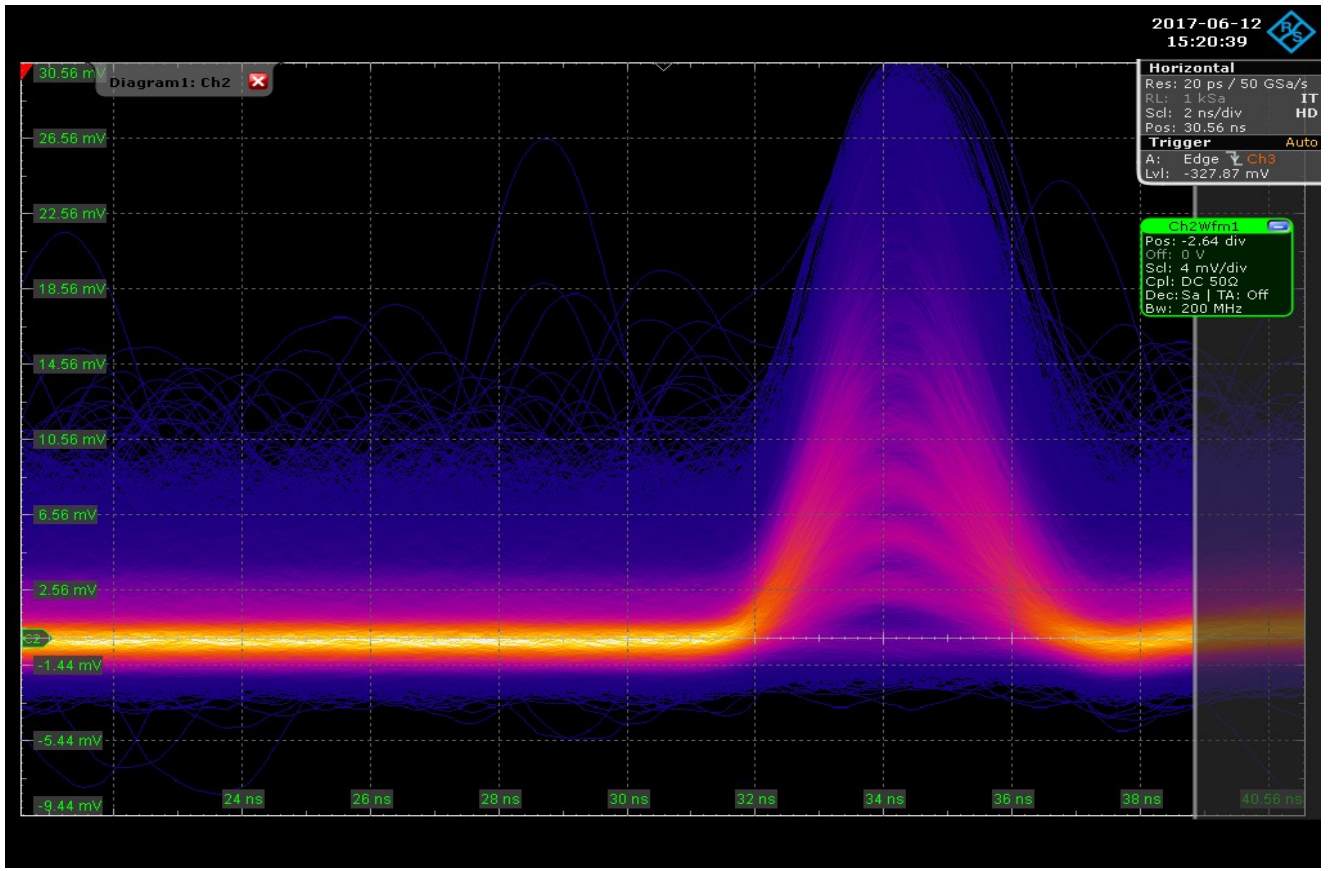


- Single phe can be resolved
- Readout doubles noise
  => still single phe resolution expected
- ~ 100 phe dynamic range

Backup

Second+Third Prototype

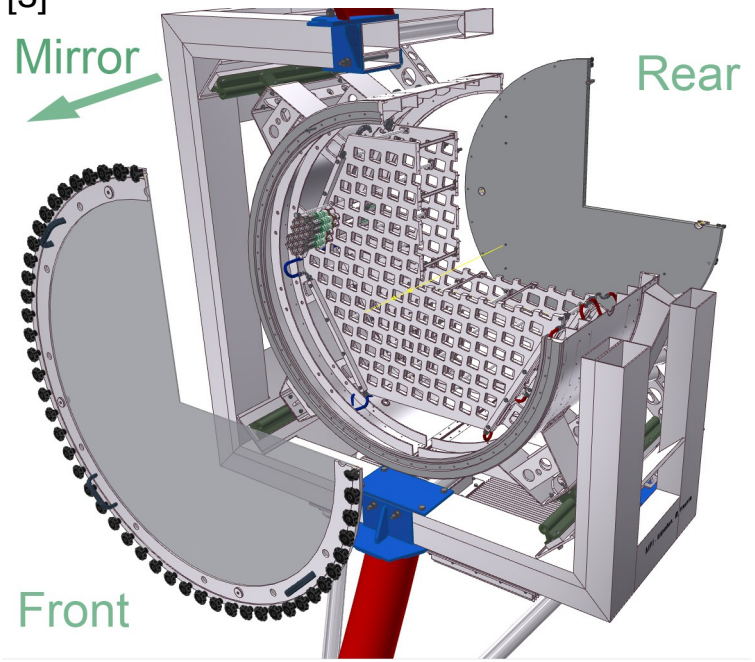
- Full chain of slow control, **Hamamatsu** SiPM pixel (9 sensors), VCESL and optical receiver



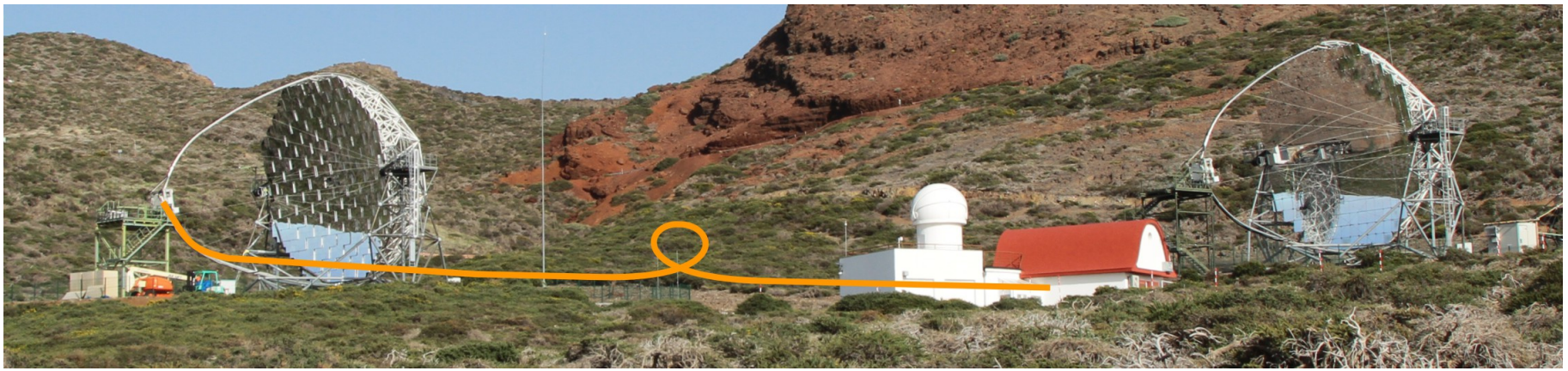
- Single phe can be resolved
- Readout doubles noise
  => still single phe resolution expected

Bakcup

[3]

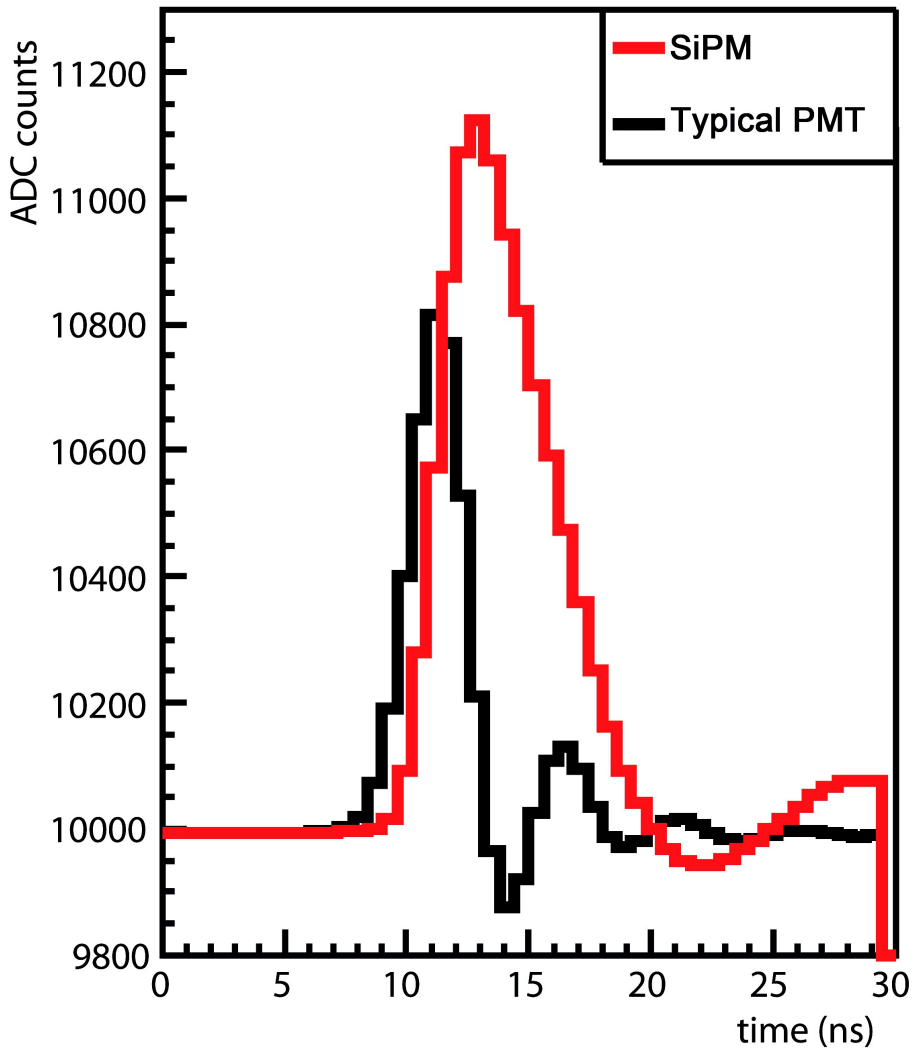


- Mechanical
- Available power
- EM and heat radiation
- Signal transmission
- Slow control



Backup

Calibration – laser events



355 nm laser pulses with constant intensity from the calibration box in the centre of the mirror dish

- Laser was intensively checked for other harmonics
- Superimposed averaged calibration events of a SiPM and a PMT pixel
- Undershoots due to data acquisition system
- FWHM(PMT) ≈ 2 ns
  FWHM(SiPM) ≈ 5 ns

Backup

Calibration - updating

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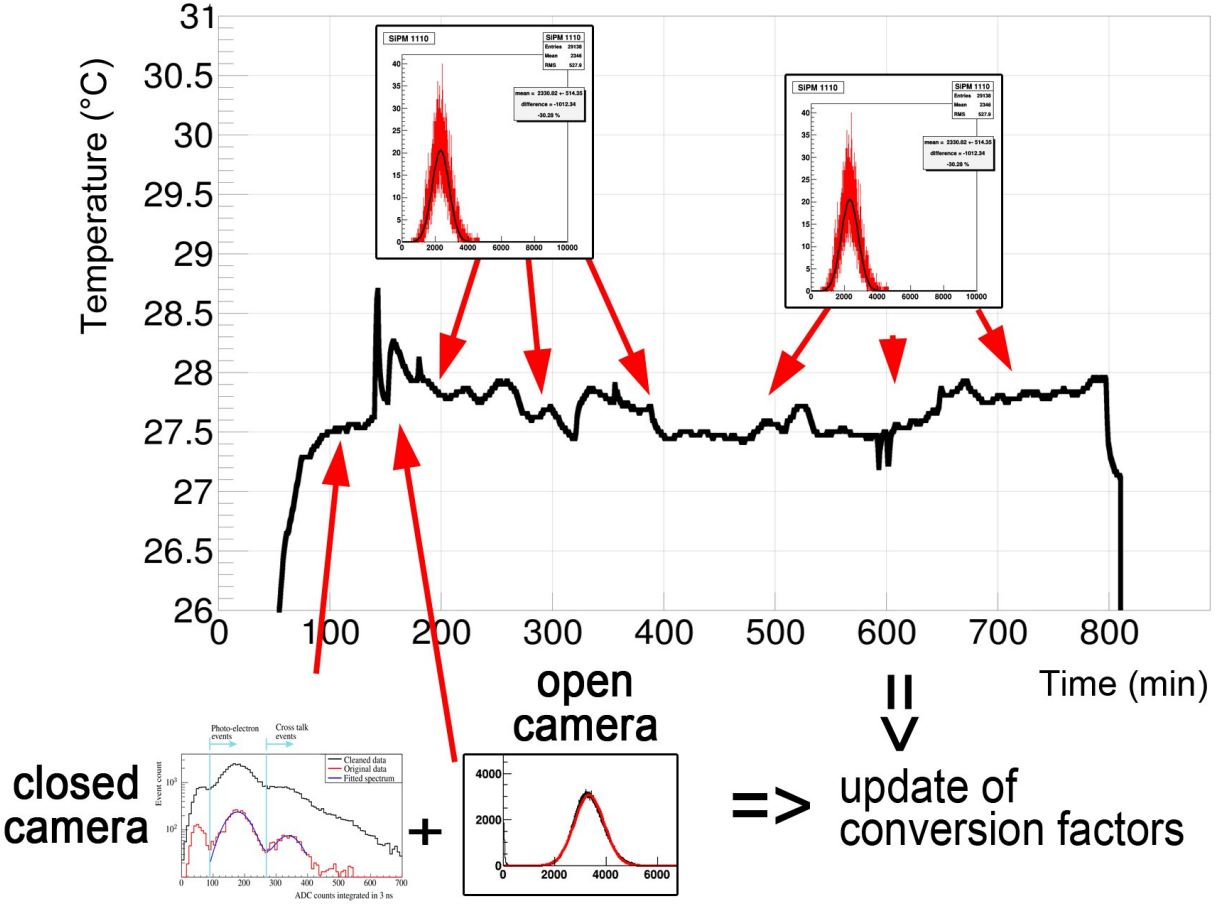
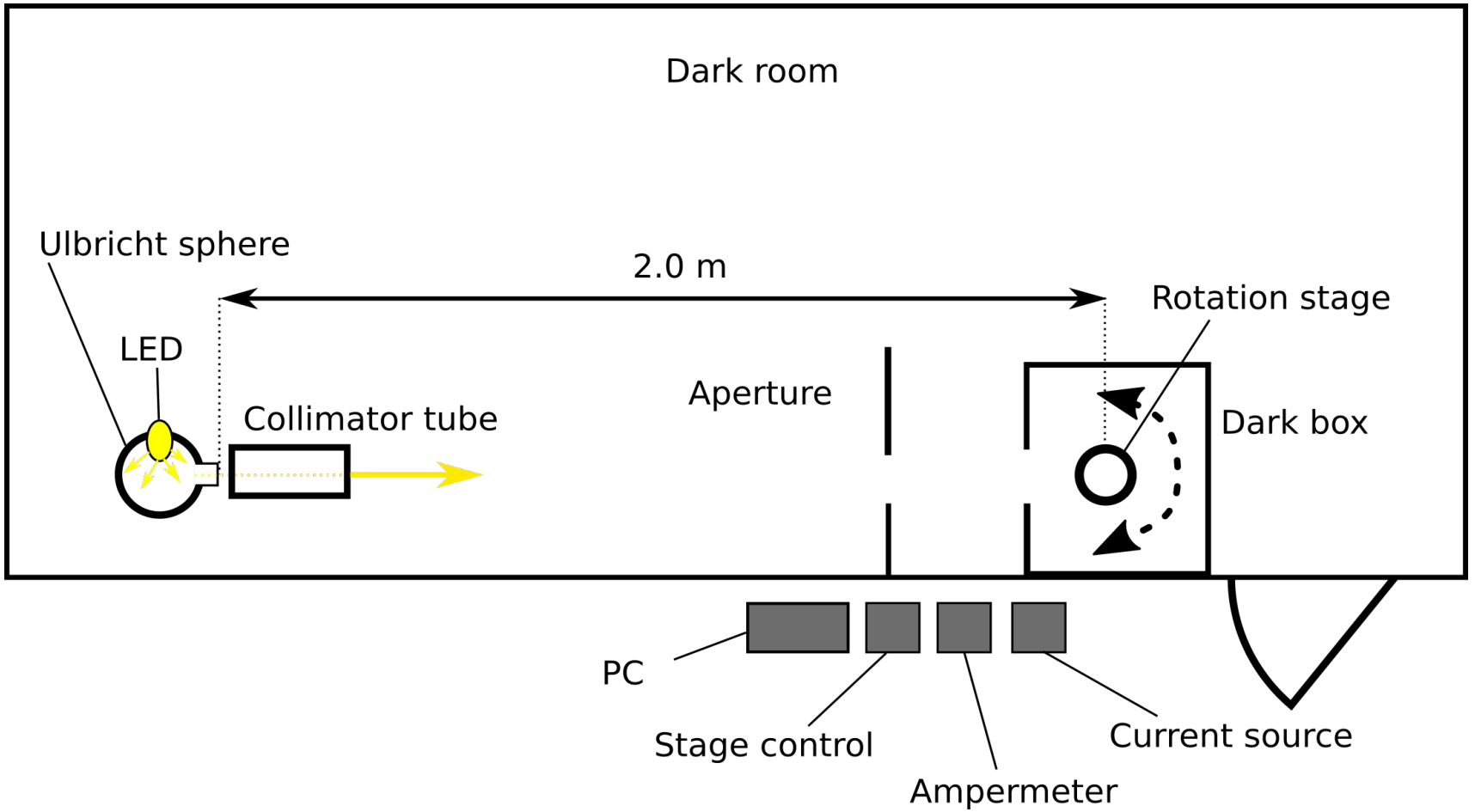
Calibration of SiPM data during data taking



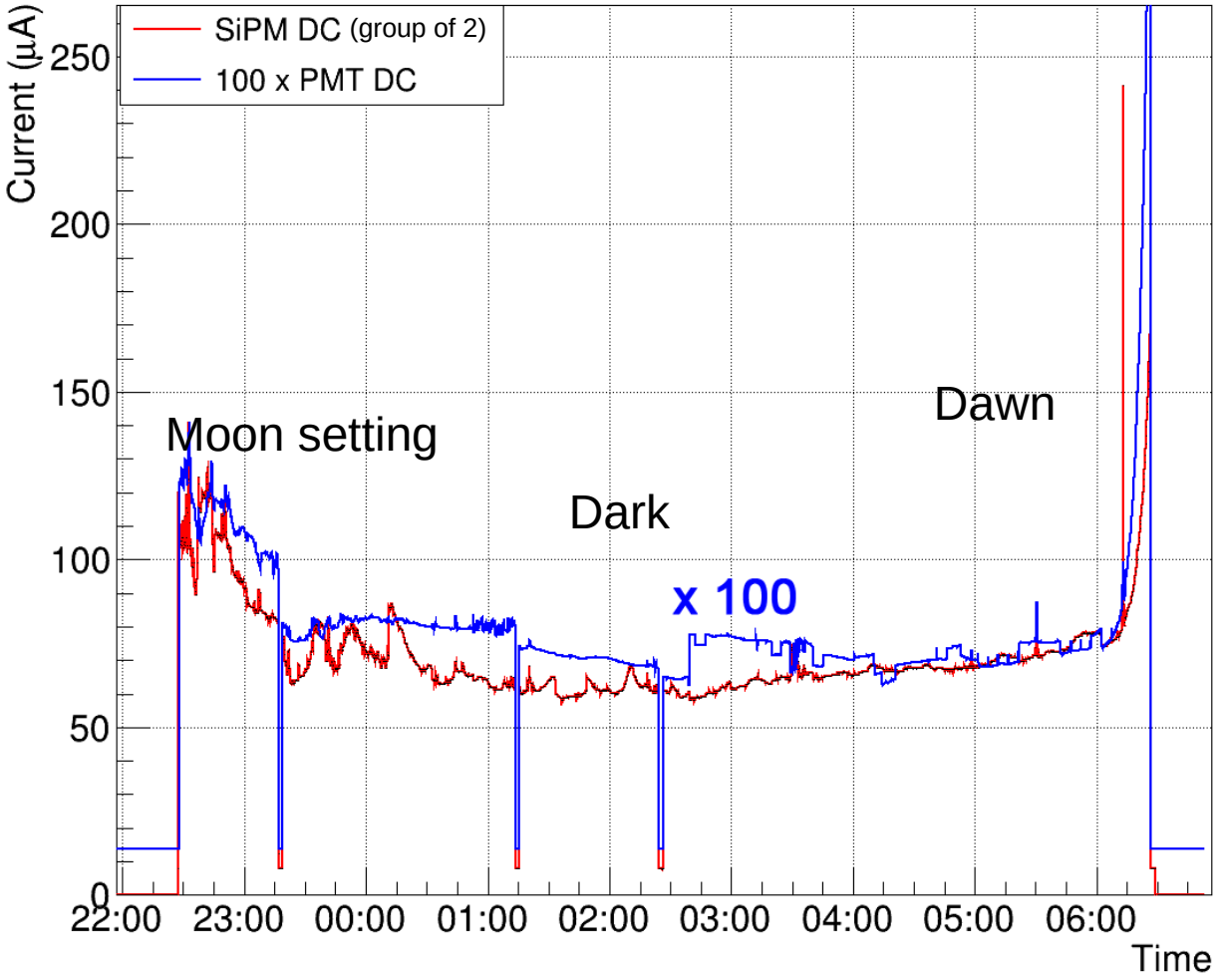
- Determination of gain
- Determination of cross talk
- Associate with a calibration pulse peak position
- Update of conversion factors

Backup
Light guides



Backup

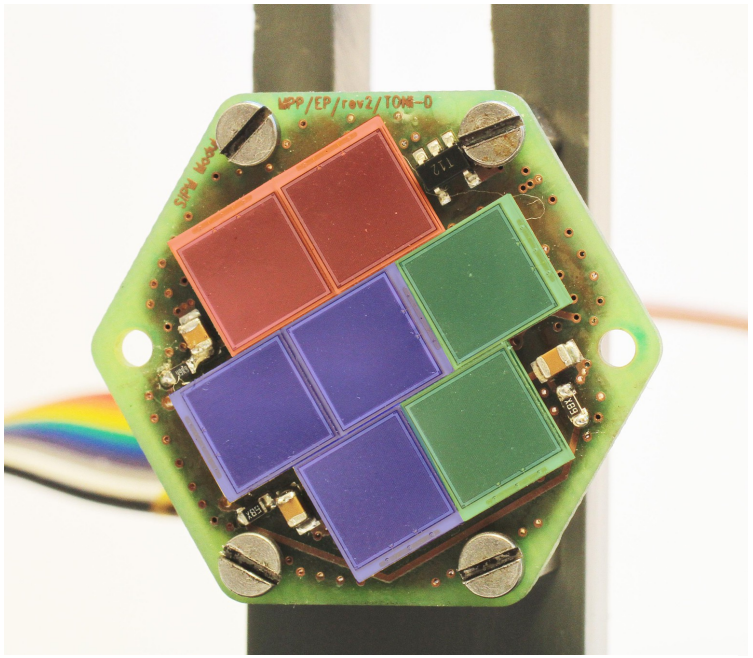
Signal currents

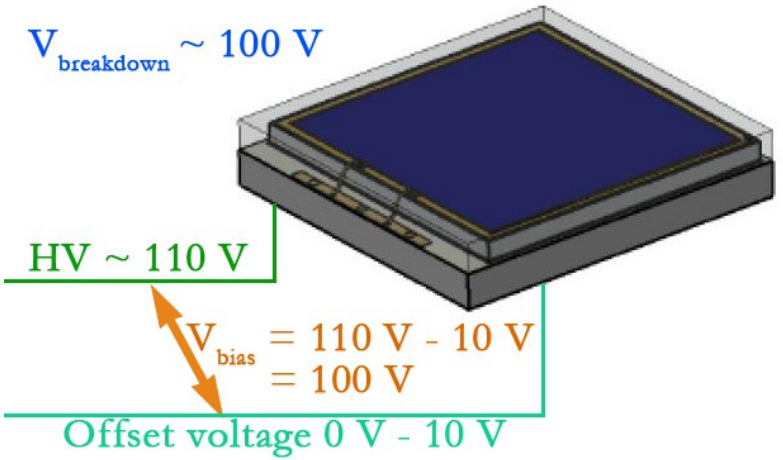


- SiPM and PMT DCs show same behaviour
- Due to 56 Ω series resistor no significant bias voltage drop

=> SiPM Bias is constant at all relevant DCs

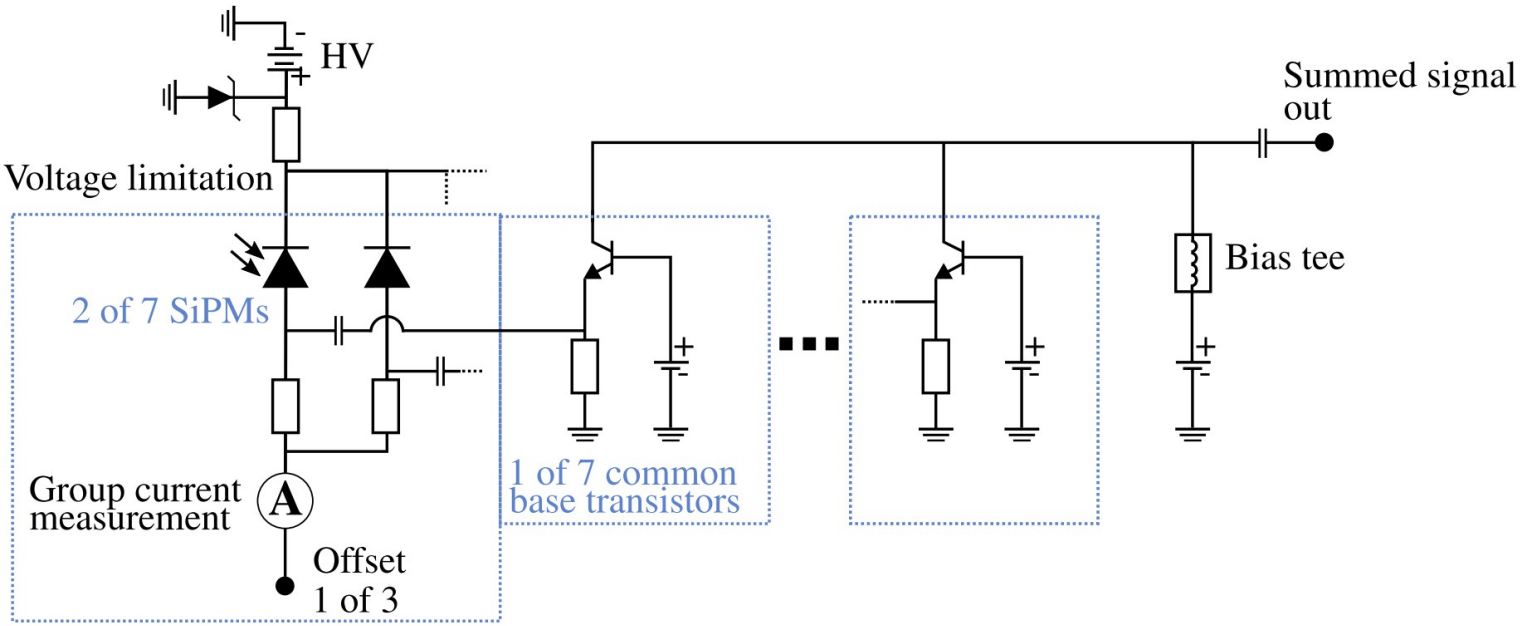
Backup
Pixel





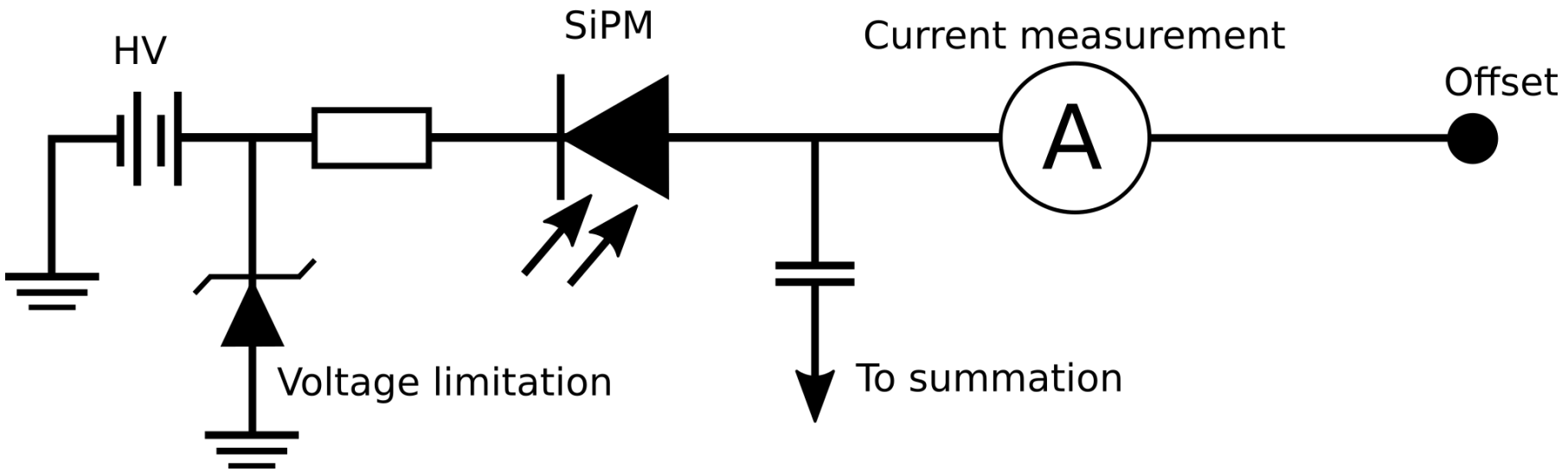
- Excelitas SiPM breakdown ranges 94.0 V to 107.1 V
- Three groups (2-3-2) of Excelitas 6x6 mm² SiPMs with same breakdown voltage
- Only one high voltage per cluster
- One offset voltage per group used to disable the pixel (star in FOV), adjust gain
- One temperature sensor next to sensors

Backup
Pixel



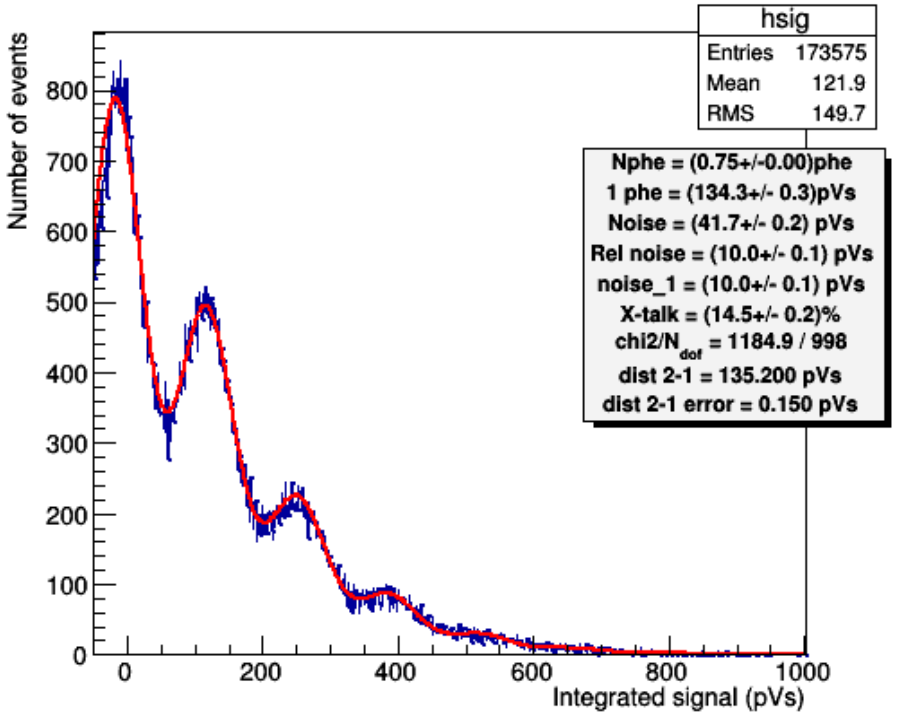
- One summed signal output
- Low input impedance common-base transistor circuit for amplification and decoupling
- High output impedance (current is sum of 7 CB amplifiers)
- Prototype current consumption of ≈ 50 mA @ 5 V per pixel

Backup

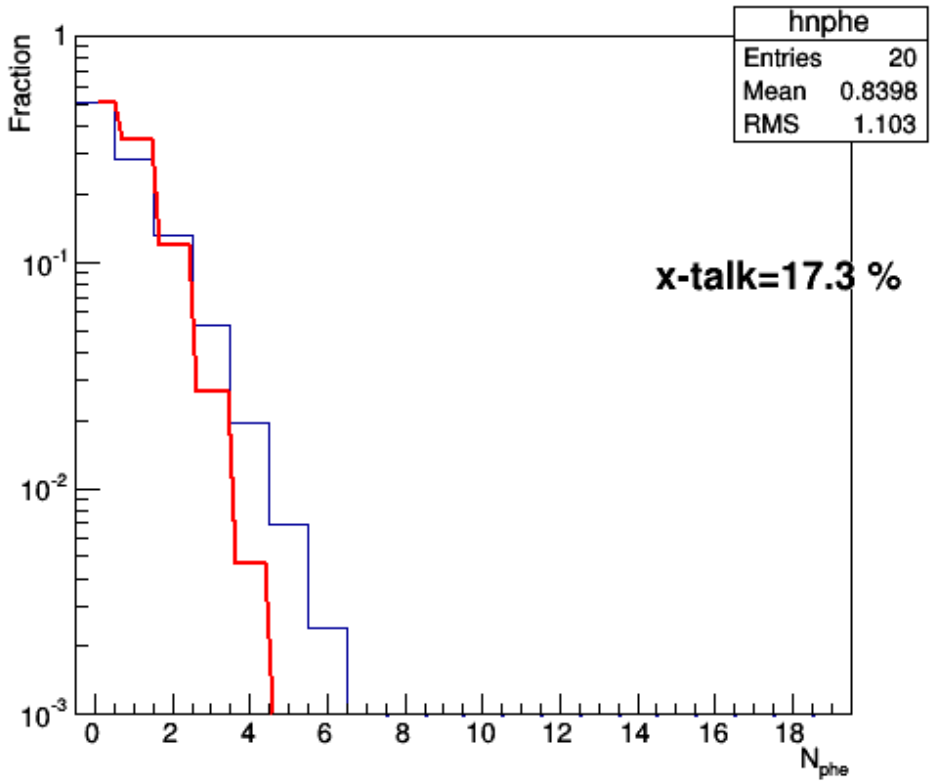

HV
SiPM
Current measurement
Offset
A
Voltage limitation
To summation

Backup

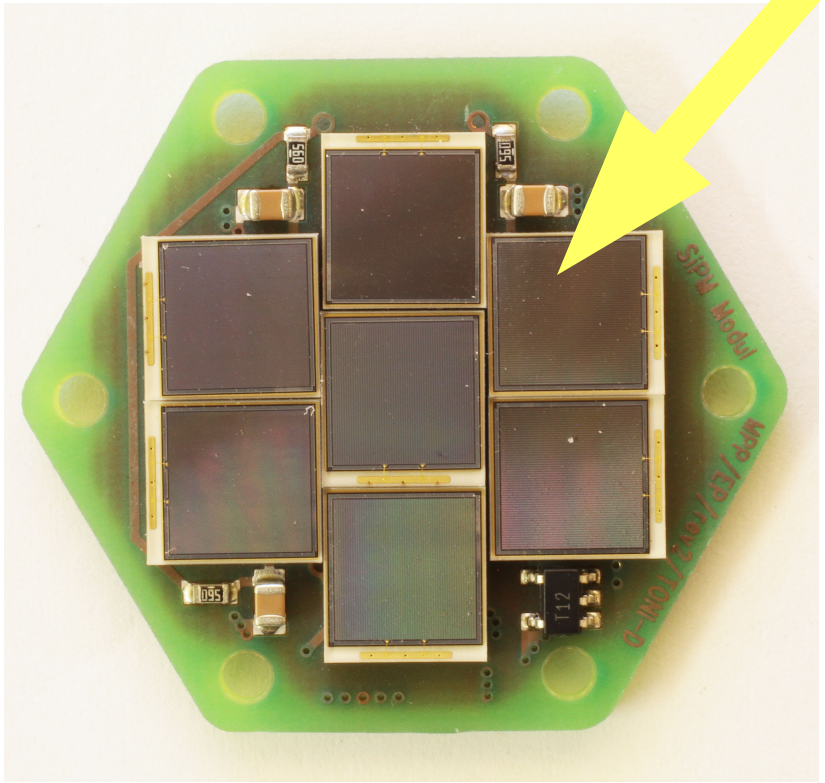
Spectrum fit



Comparison to ideal Poisson distribution



Backup



14 400 cells/SiPM Excelitas C30742-66

=> ~ 7.76 kHz/cell due to LoNS

$$R_q = 1\,M\Omega,\ C_{cell} = 95\,fF$$

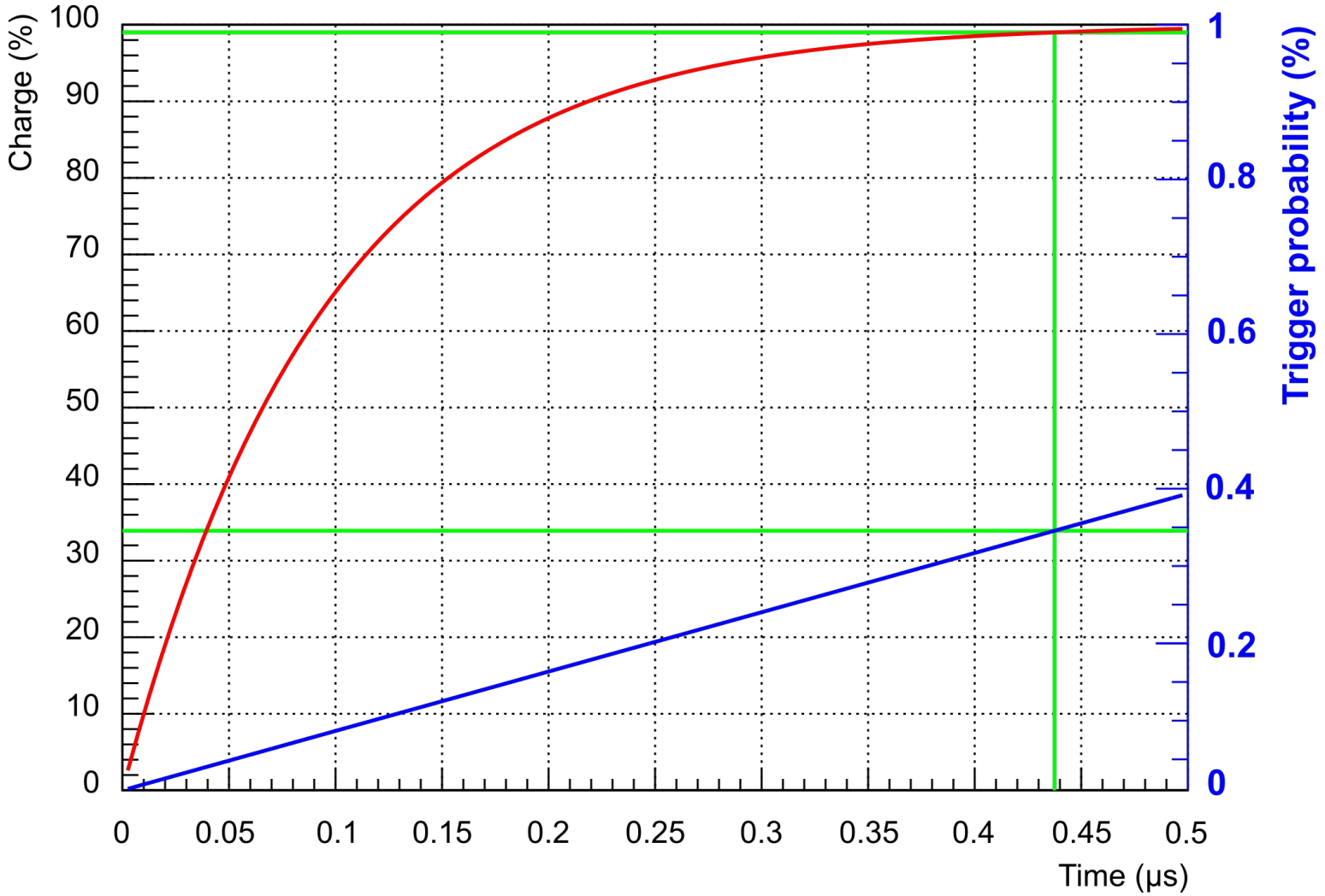
$$\Rightarrow \tau \sim RC \approx 100\,ns$$

=> 99 % recharge after 437 ns

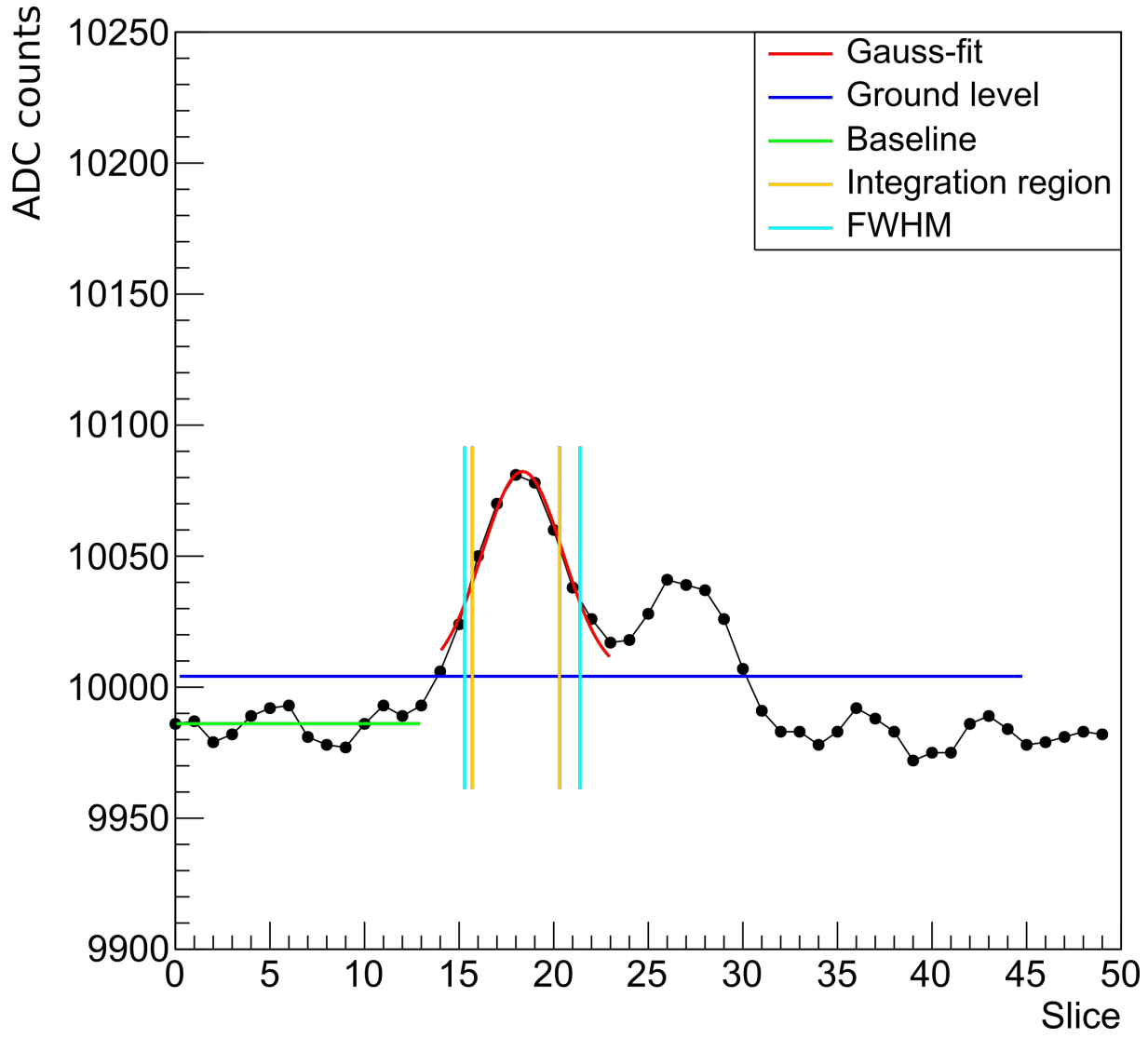
=> 0.34 % prob. that next event happens before 99 % recharge

=> Cells can fully recharge between events for dark time observations

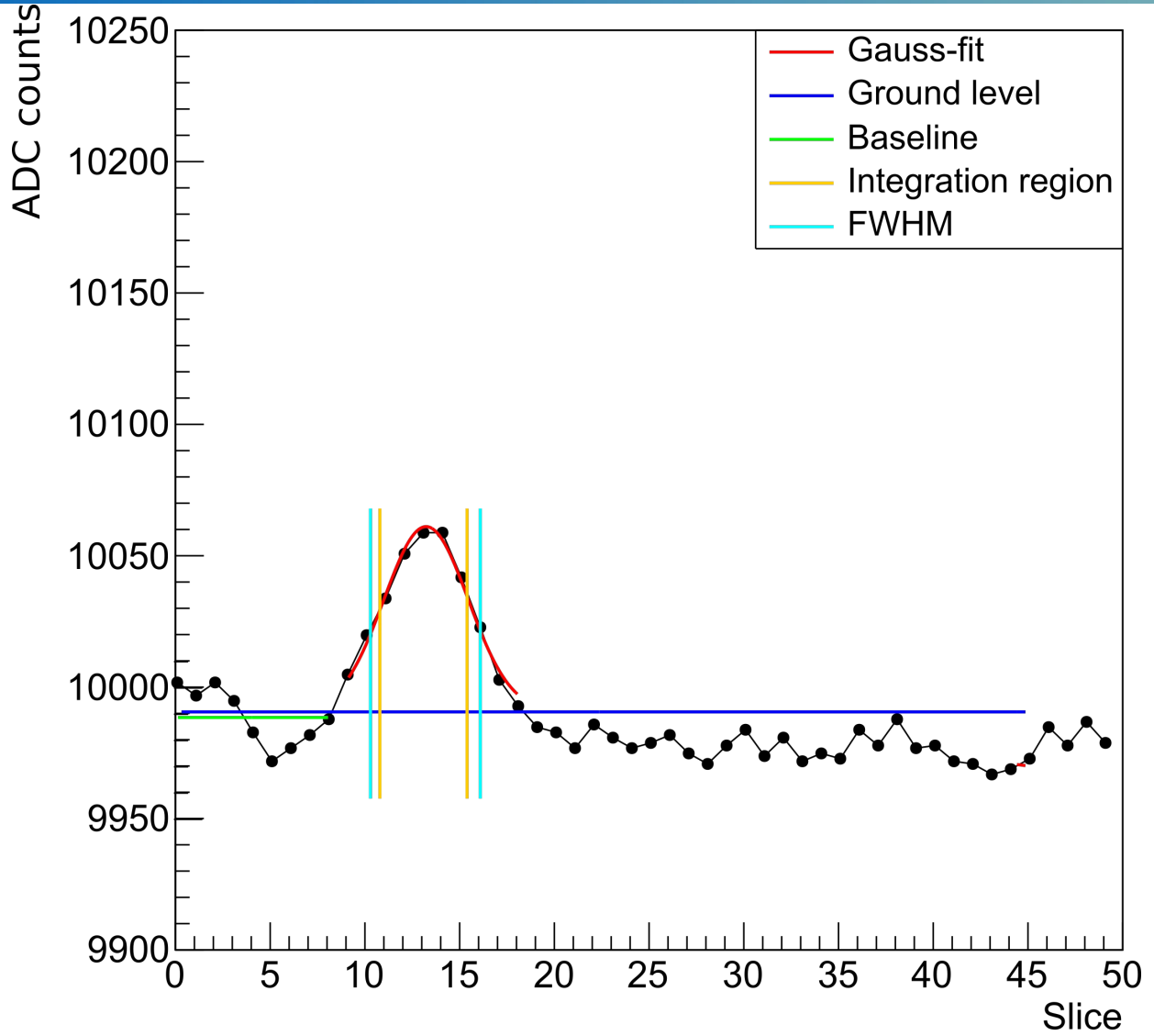
Backup


Charge (%)
100
90
80
70
60
50
40
30
20
10
0
1
0.8
0.6
0.4
0.2
0
Trigger probability (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Time (μs)

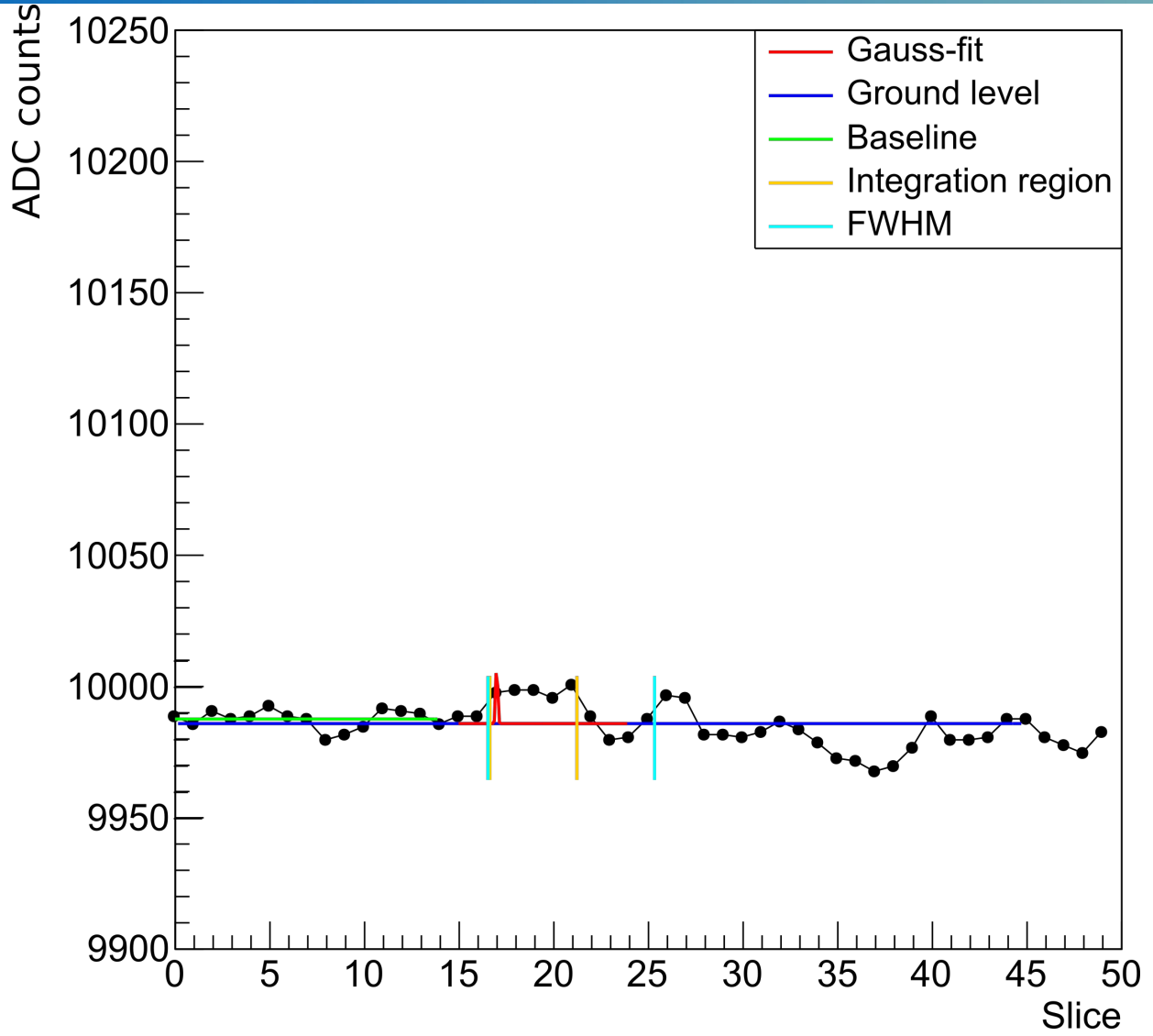
Backup


ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

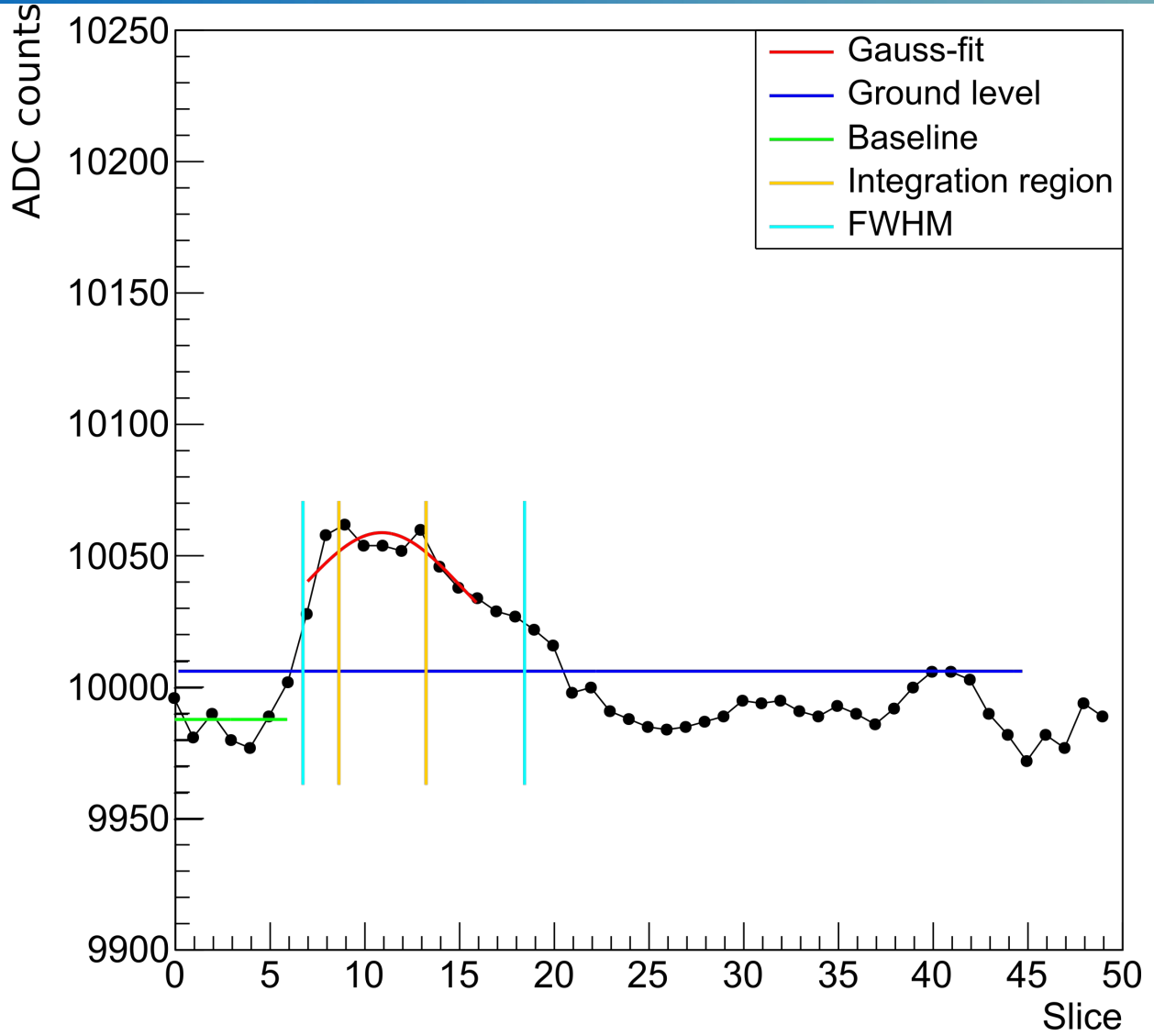
Backup


ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

Backup


ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

Backup

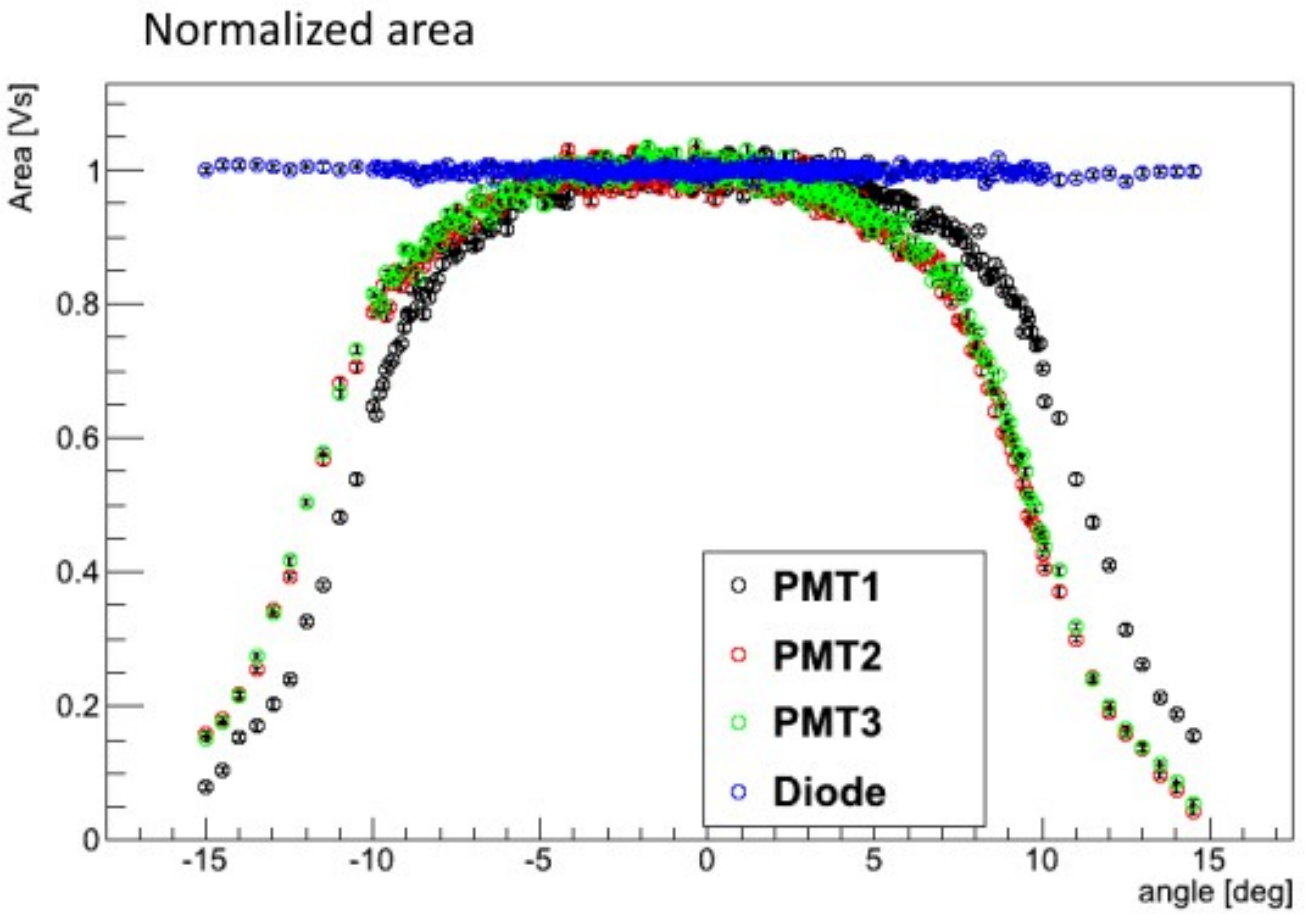

ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

Backup

Filter variable	Filter level
Event must occur in samples	between samples 5 and 45
Baseline Chi-squared less than	1000
Baseline amplitude within	FWHM of Gaussian fit to global baseline distribution
Pulse fit Chi-squared less than	11000

Backup

Uniformity in illumination



Backup

- SiPM pixel signal needs do be scaled with active area