Properties of large SiPM at room temperature

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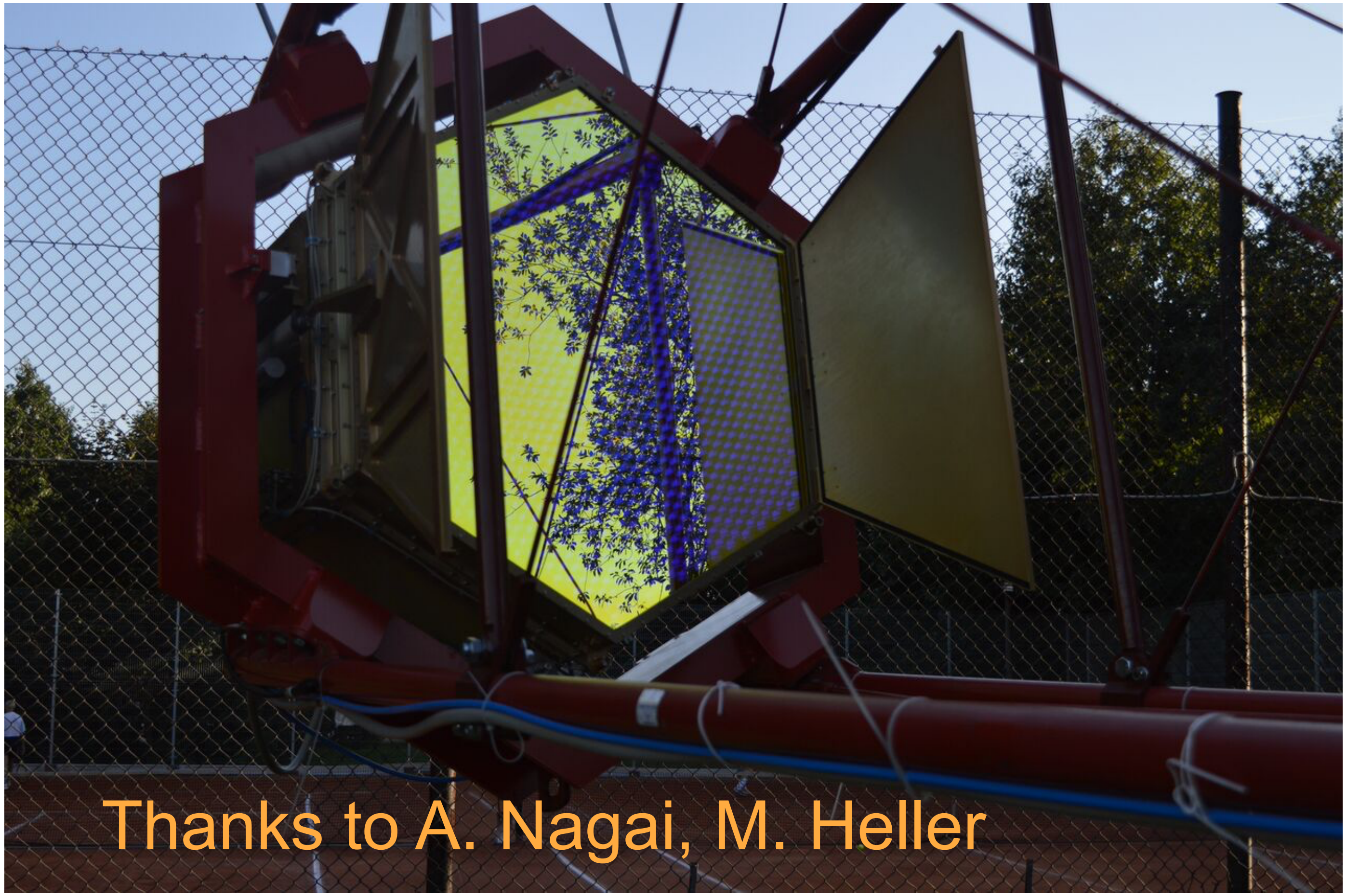
- Experienced acquired operating large area sensors of the SST-1M camera
- Evaluation of main working parameters
- Effect of continuous light illumination on working parameters



Thanks to A. Nagai, M. Heller

A SiPM camera for gamma-ray astronomy

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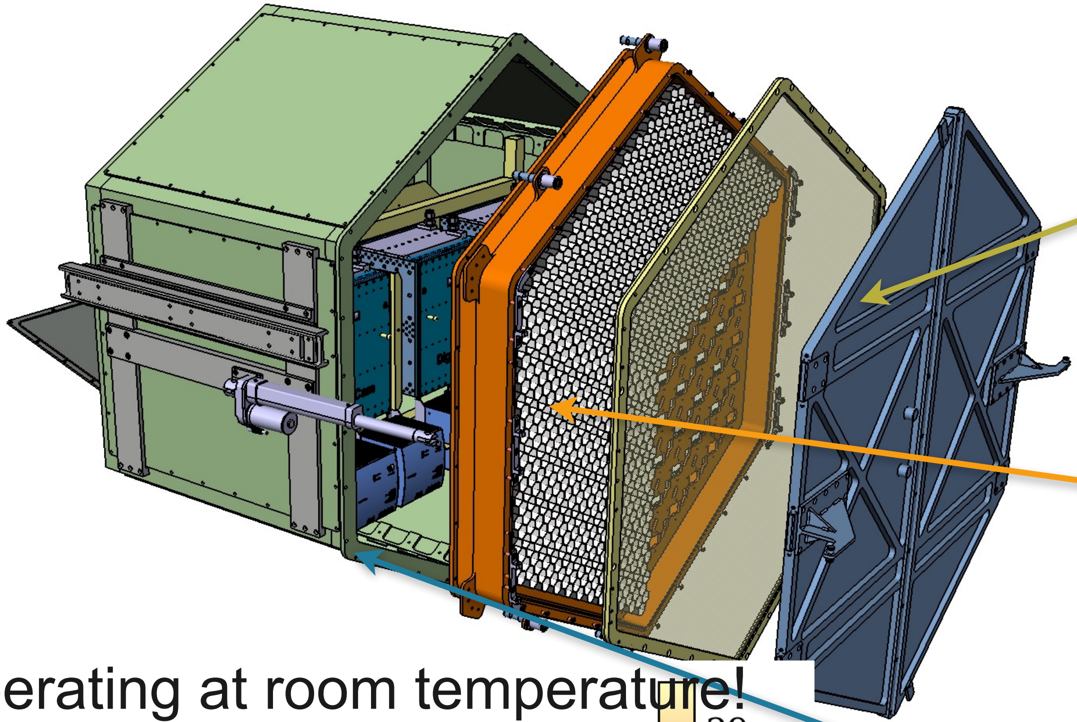
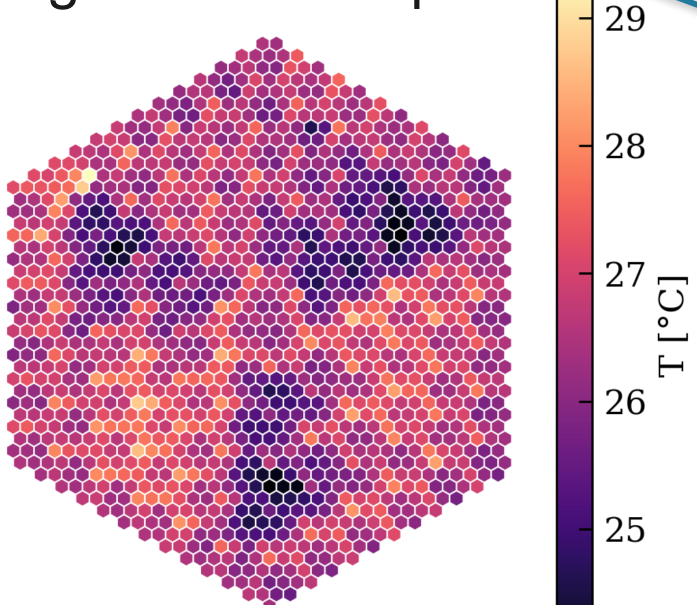


Entrance window:
- 3.3 mm Borofloat
- AR coating
- Cut-off filter at 540 nm for NSB rejection

Photo detection plane:
- 1296 pixels
- 0.24° angular size
- Power consumption 500 W
- Analogue signals over CAT5/ RJ45

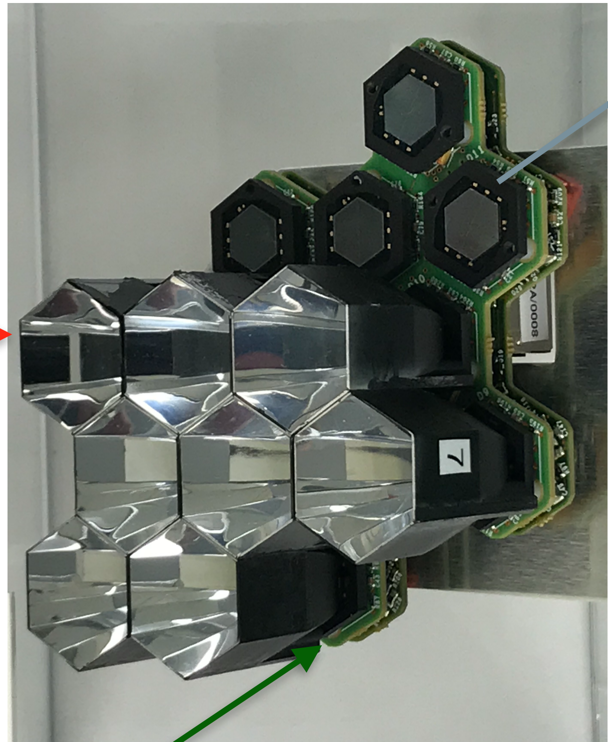
Digital electronics (DigiCam):
- 12 bits FADC @ 250 MS/s
- Fully digital trigger, decision every 4 ns
- Trigger path with reconfigurable algorithms and signal preprocessing
- Serial architecture based on multi-Gigabit links (both trigger and ADC data)
- Power consumption 1200 W

operating at room temperature!



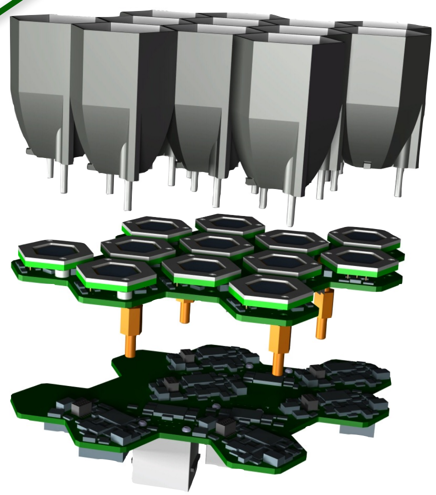
The photo-sensing plane

Hollow light guides:
- Plastic substrate (2592 halves glued) - injection molding
- dichroic coating
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of ~6



Sensor:
- 1296 hexagonal Hamamatsu MPPC - same technology of 50 um microcells
- 4 anodes per pixel with one common cathode
- Embedded NTC temperature sensor

Slow control board:
- 108/camera
- Temperature compensation loop (2 Hz)
- HV generation
- Differential output to DigiCam



Preamplifier board:
- 108 /camera
- discrete components
- Trans-impedance topology
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling

The sensor

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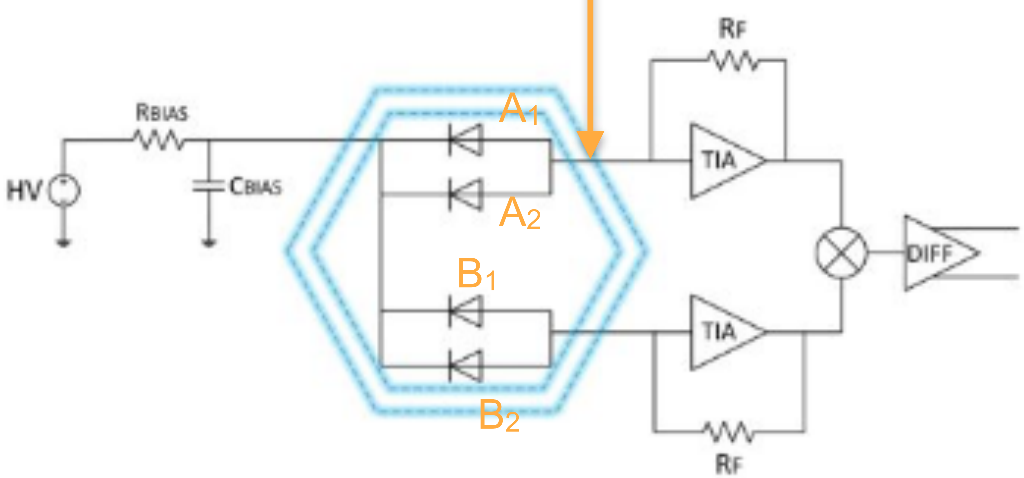
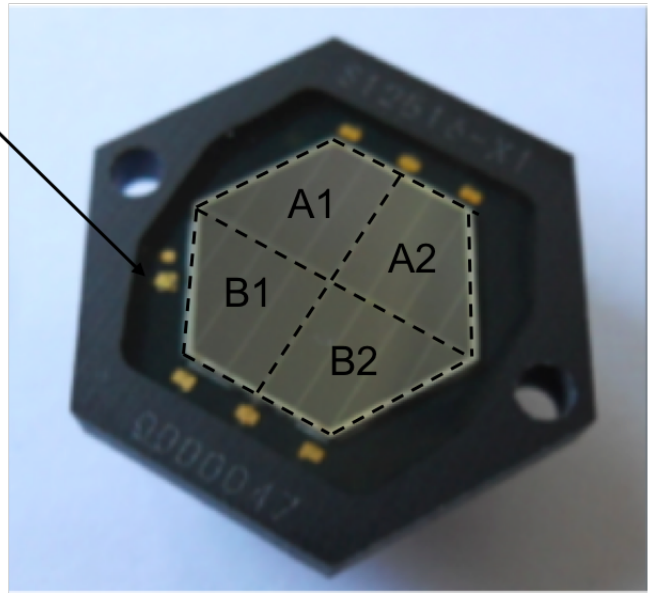
No capacitor => DC coupled readout of SIPM





From producer:
T = 25 °C and over-voltage $\Delta V = V_{op} + 2.8$ V

Nr. of channels	4
Cell size	$50 \times 50\ \mu m^2$
Nr of cells (per channel)	9210
Fill Factor	61.5%
DCR (@V_{op} per channel)	2.8-5.6 MHz
$C_{\mu cell}$ (@ V_{op} per channel)	85 fF
Cross-talk (@V_{op} per channel)	10%
V_{BD} Temp. Coeff.	54 mV/C°
Gain (@V_{op} per channel)	1.49×10^6

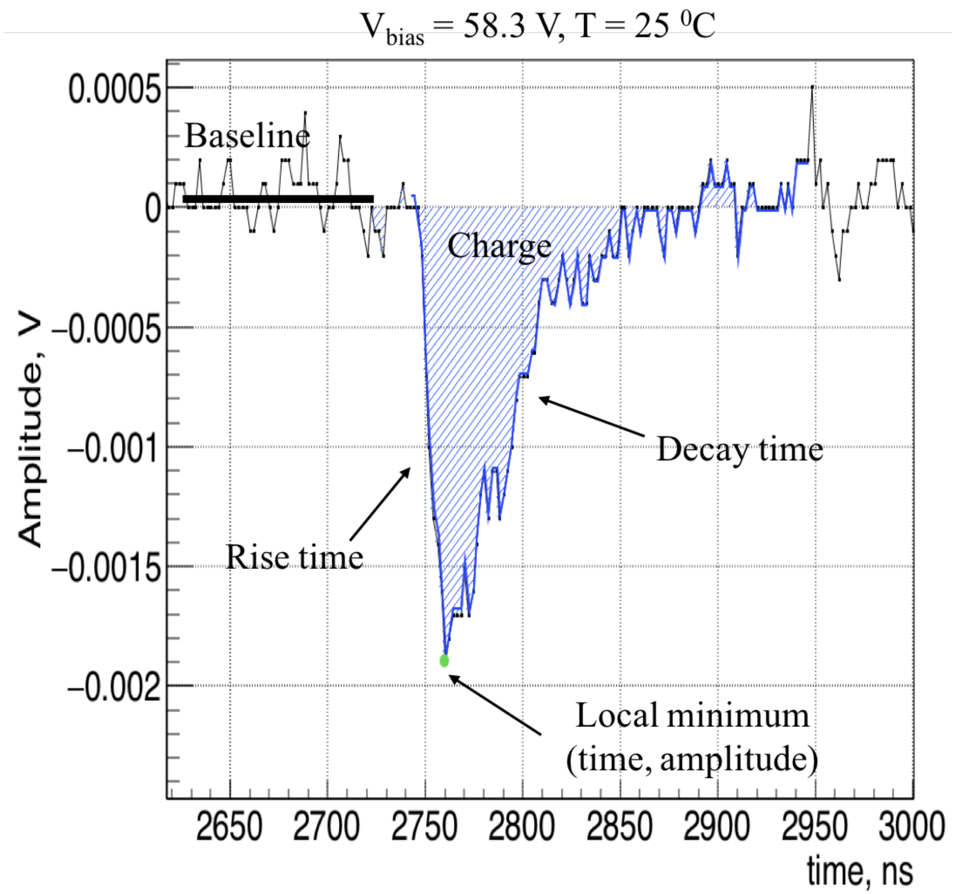
Hamamatsu MPPC S10943-2832(X) :
- Low Crosstalk Technology 2 (LCT2)
- 4 anodes per pixel with one common cathode
- Embedded NTC temperature sensor
- PDE (@ 2.8V, 472nm) = 35.5 %

DC coupling motivation

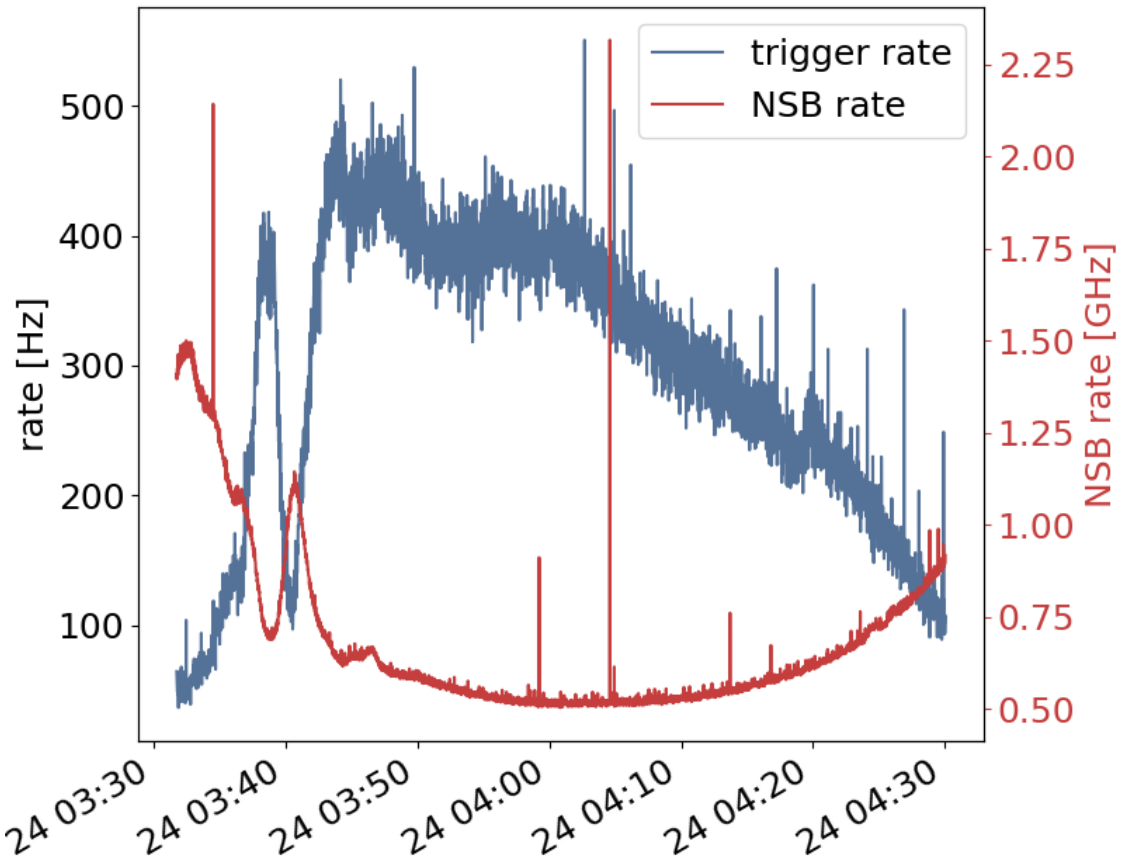
A DC couped camera is NSB monitor!

The Digicam can measure the BL before each pulse.

Useful for correcting for changes of SIPM parameters



Rate of NSB in Krakow (including clouds and airplanes…)



Static Characterisation of sensors (DC)

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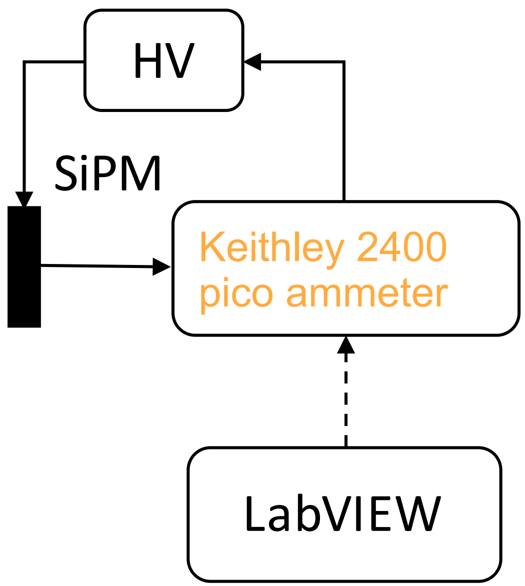


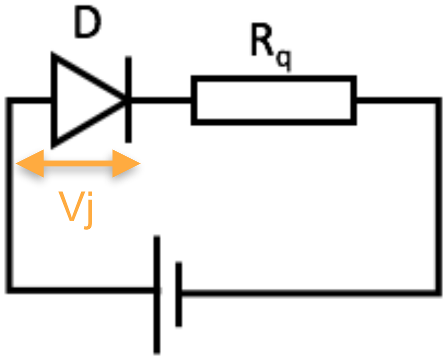
Reading constant current (static or DC)

Advantages:
- Simple;
- Fast;

Disadvantages:
- Limited information (only V_{BD}, R_q, working range)
- Limited precision

http://arxiv.org/pdf/1810.02275.pdf accepted by NIM

Forward IV: R_q calculation

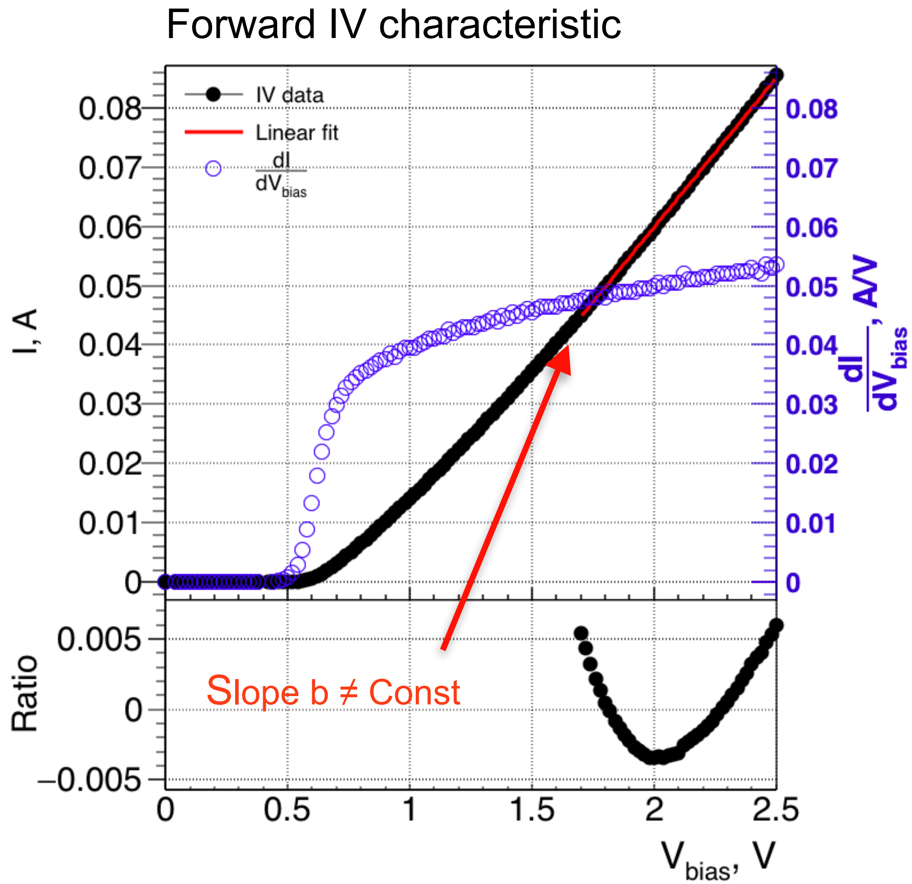


For a µcell (deal Shockley law):

$$I^d = I_s^d \left[exp\left(\frac{V_j}{\eta V_T}\right) - 1 \right] \qquad V_j = V_{bias} - I^d \cdot R_s$$

R_s ~100 Ω

diode reverse bias saturation current



SiPM = array of $N_{µcells}$ G-APDs connected in parallel, each is in series with a quenching resistor R_q

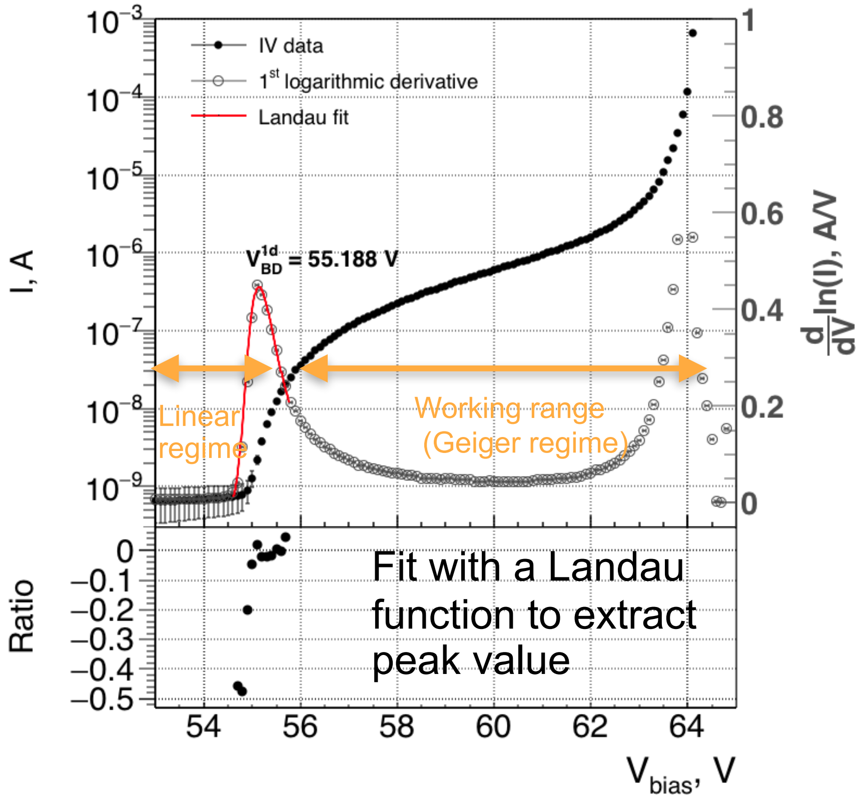
$$V_{bias} = \eta V_T \left[\ln\left(\frac{I}{I_s} + 1\right) \right] + I \frac{(R_s + R_q)}{N_{\mu cell}} \qquad R_q + R_s = \frac{N_{\mu cell}}{b} \underset{|R_q >> R_s|}{\simeq} R_q$$

R_q =182.9±0.3 (stat.) ± 31 (sys.) kΩ

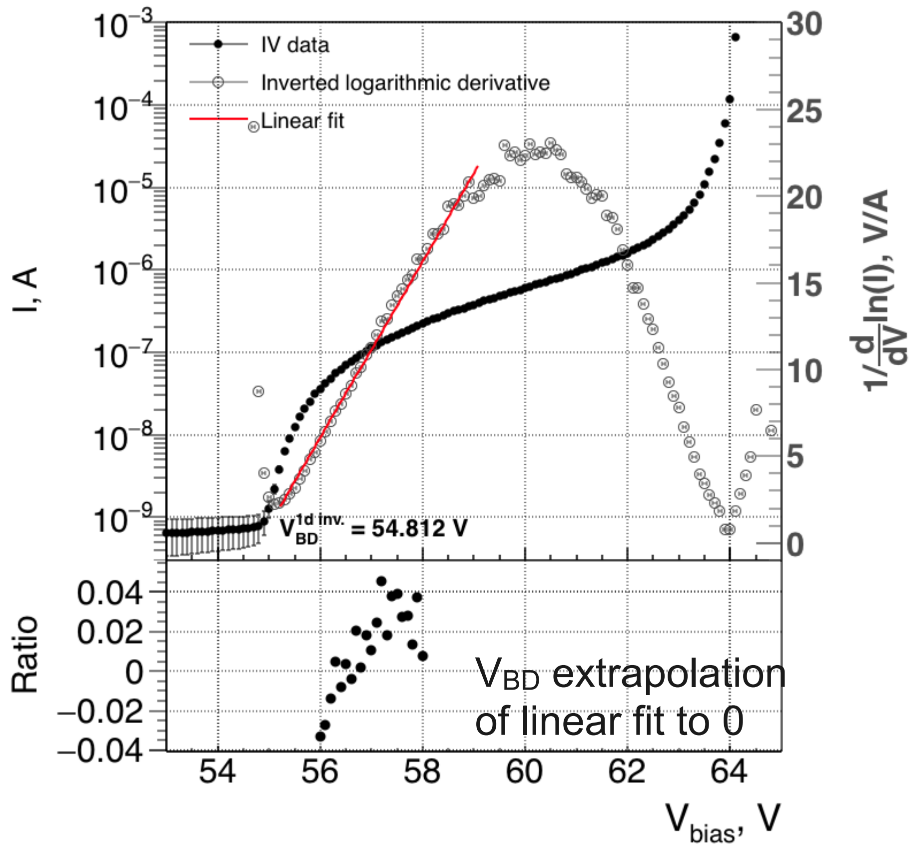
Since b is not constant R_q measurement has a systematic bias of about 17%

V_{BD} determination in DC: Reverse IV methods

Logarithmic derivative



Inverse log derivative:



DC (static) methods: Reverse IV

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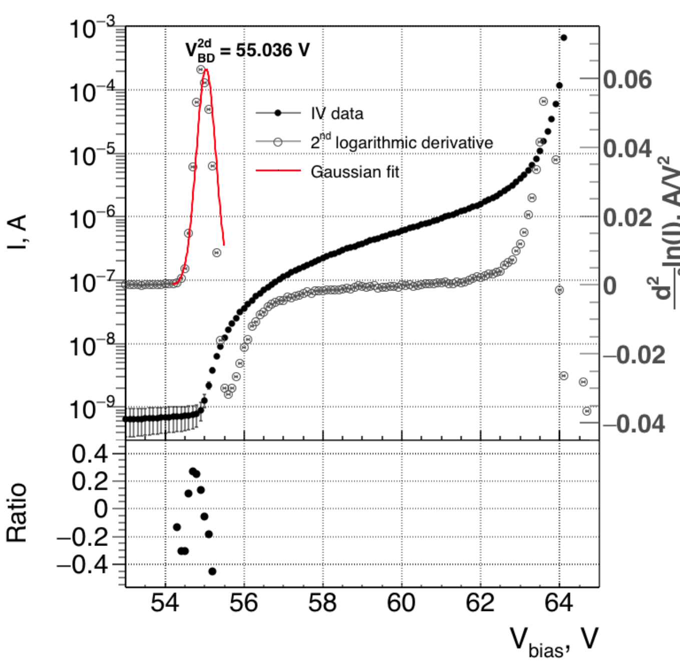

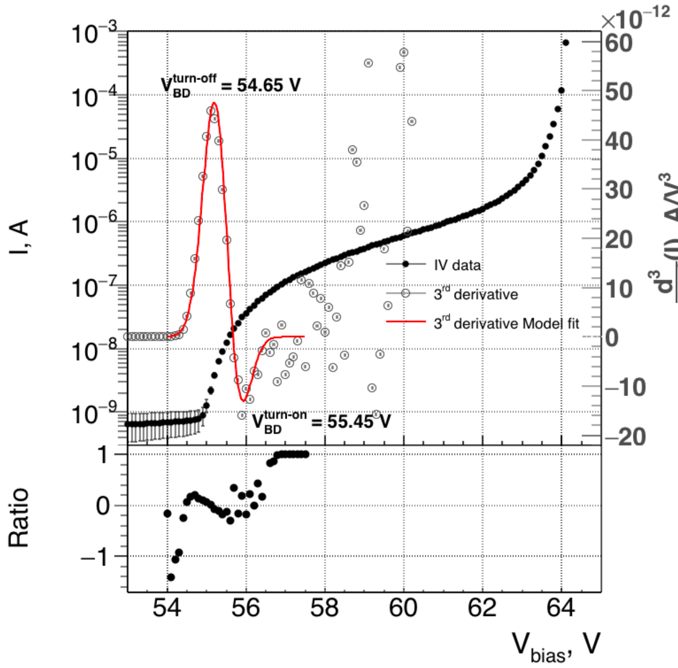

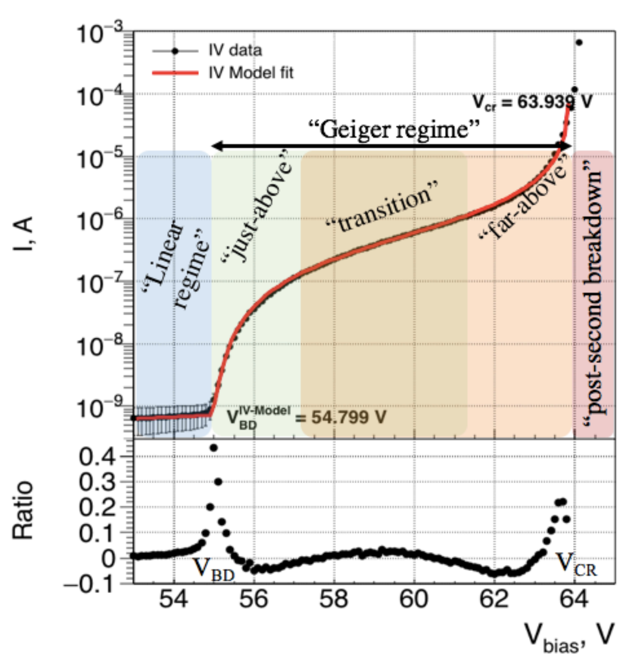

2nd log derivative:

Commonly used: seek for max of second derivative but the Gaussian fit is not perfect

Third derivative method:

2 separate breakdown voltages are assumed.
The turn-on is determined by the avalanche triggering probability P_G and the turn-off by the voltage at which quenching starts.

IV model

Fit with 4 regions identified and fit functions physically motivated (exponential for Geiger probability + increase of correlated noise)

AC (dynamic) measurement: V_{BD}

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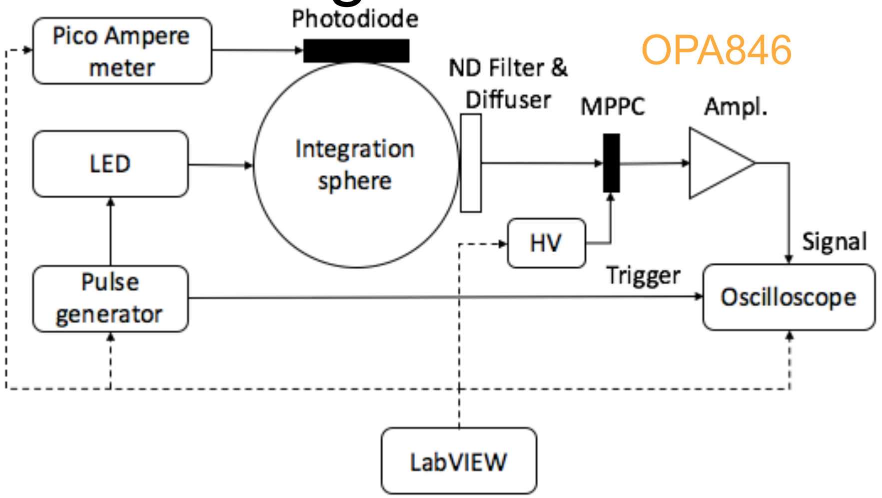
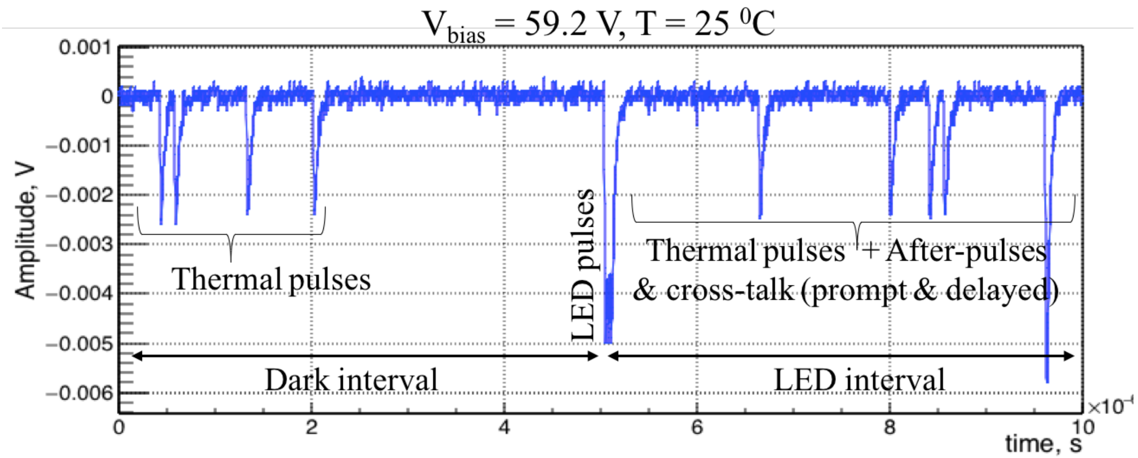
Pulsed light

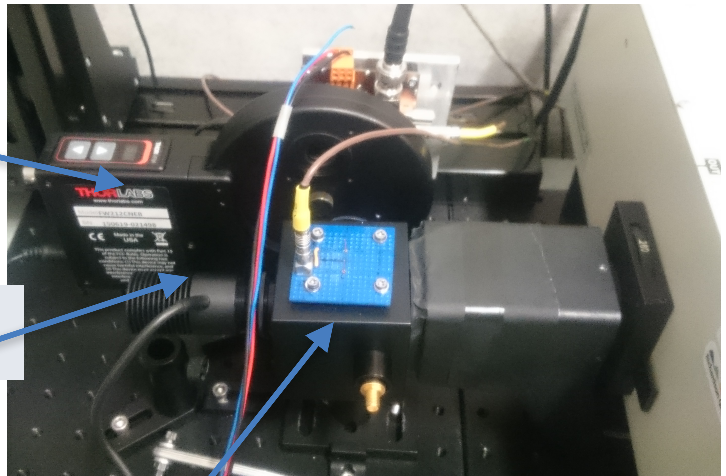




Read 10’000 x 10 μs WFs with an oscilloscope sampled at 500 MHz
Trigger at 5 μs adjusted to have ‘dark’ interval before and LED interval after

ND filters
(81.3% ÷ 0.01%)

LED`s :
280, 340, 375, 405, 420, 455, 470, 505, 525, 530, 565 & 572nm



Photodiode 10x10 mm^2
(S1337-1010BQ)

Advantages:
- in dark it is possible to measure V_{BD}, work range, G, DCR, $C_{\mu cell}$, P_{XT}, P_{ap}
- in light: PDE

Disadvantages:
- Relatively complicated set up
- Lots of data and DAQ time

AC measurements: Gain

Each ucell detects photons identically and independently => the sum of the photocurrents from each ucell combines to form an output providing the magnitude of photon flux

Ptactically, G can be measured from the time integration of the pulse in time subtracting the BL

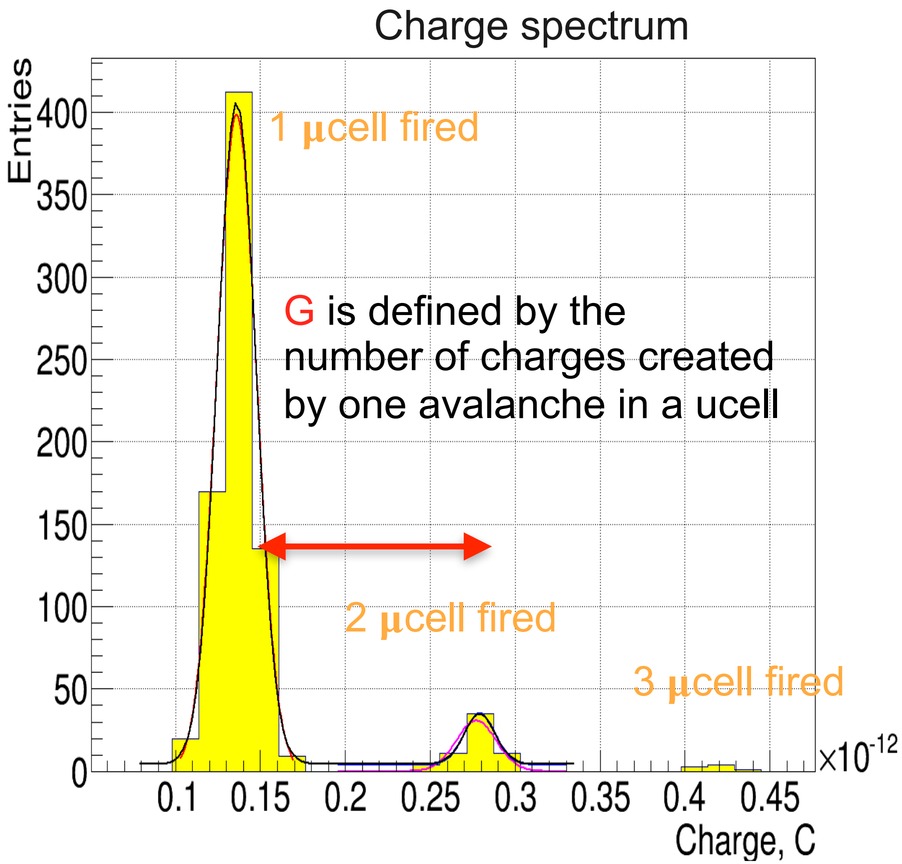
$$G = \frac{Q}{e} = \frac{1}{G_{Amp} \cdot e} \cdot \frac{1}{R} \int (V(t) - BL)\, dt,$$

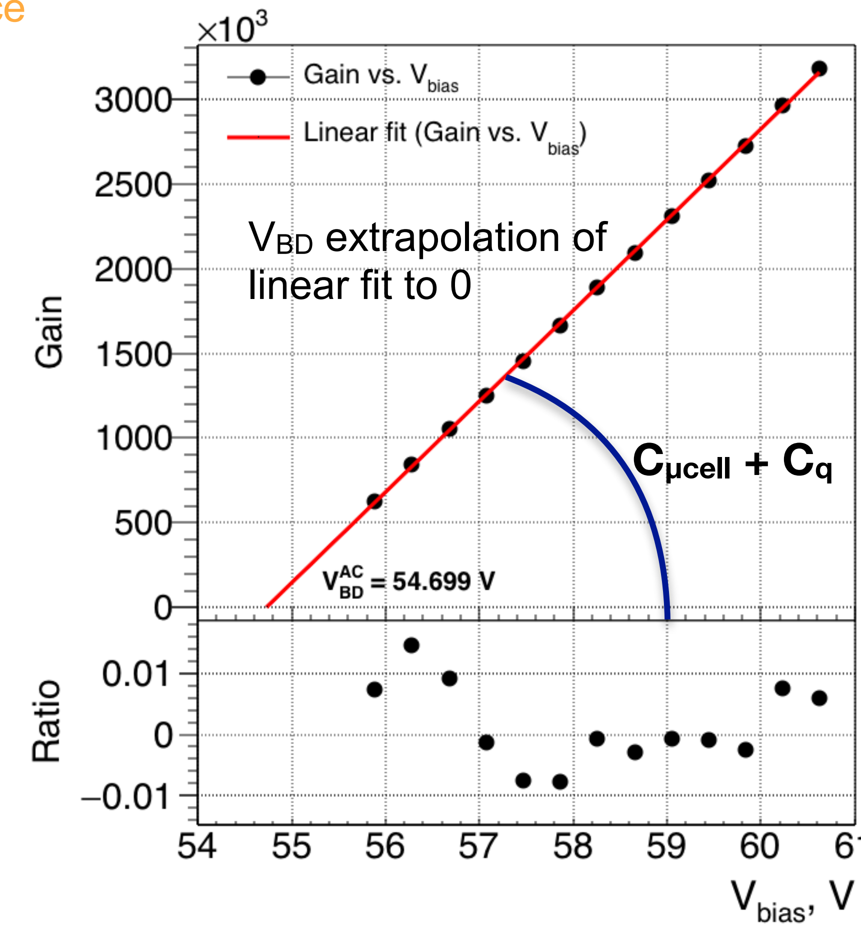
Amplifier input impedance

Parasitic capacitance

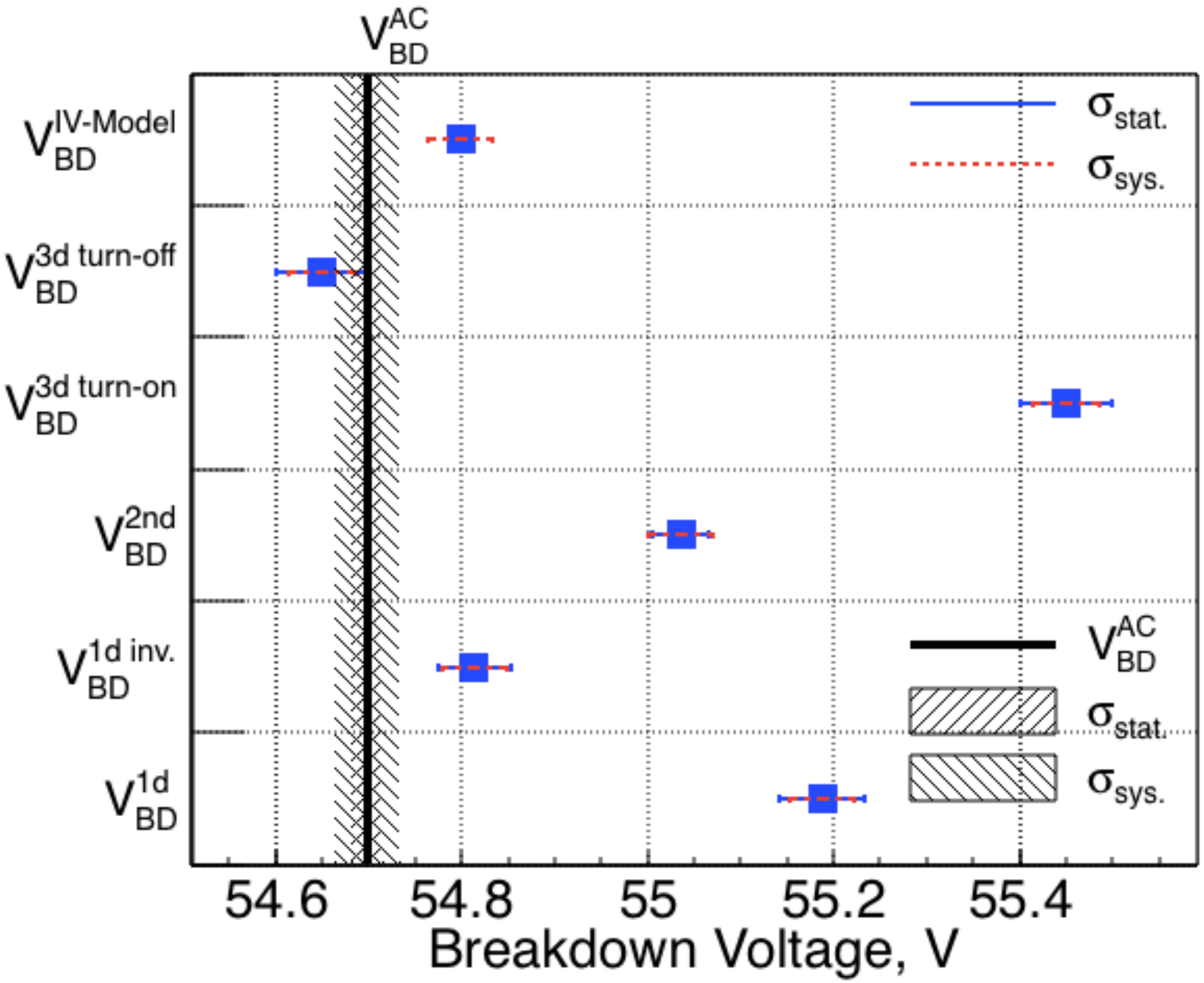
$$G = \frac{Q}{e} = \frac{(C_{\mu cell} + C_q) \cdot (V_{bias} - V_{BD}^{AC})}{e}$$

Q=N$_{fired}$·G·e





Comparison of V_{BD} methods



In the IV model and the Inverse log derivative we see the breakdown defined as the voltage at which the avalanche process starts.

In AC V_{BD} corresponds to the value when G = 0.

These values are close to the value close of the turn-off voltage of the 3rd derivative

when still the gain is 0, though the AC value is commonly used with the meaning of break down voltage.

Uncorrelated noise DCR: Counting method from WF

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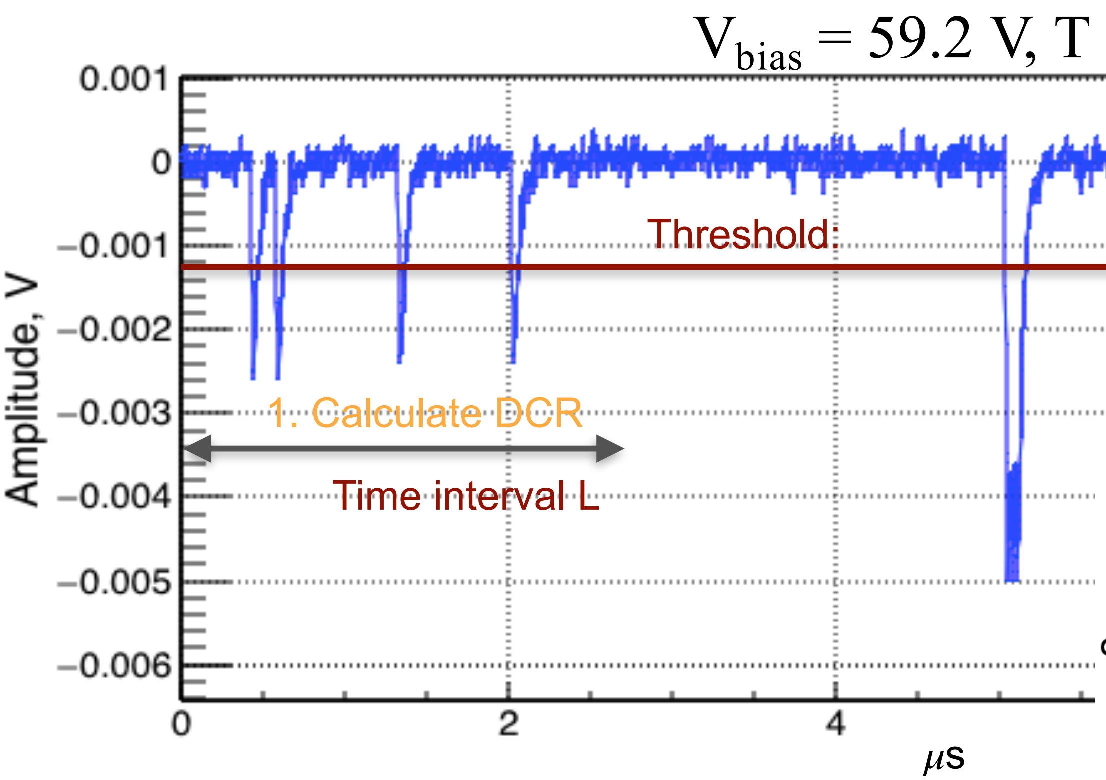

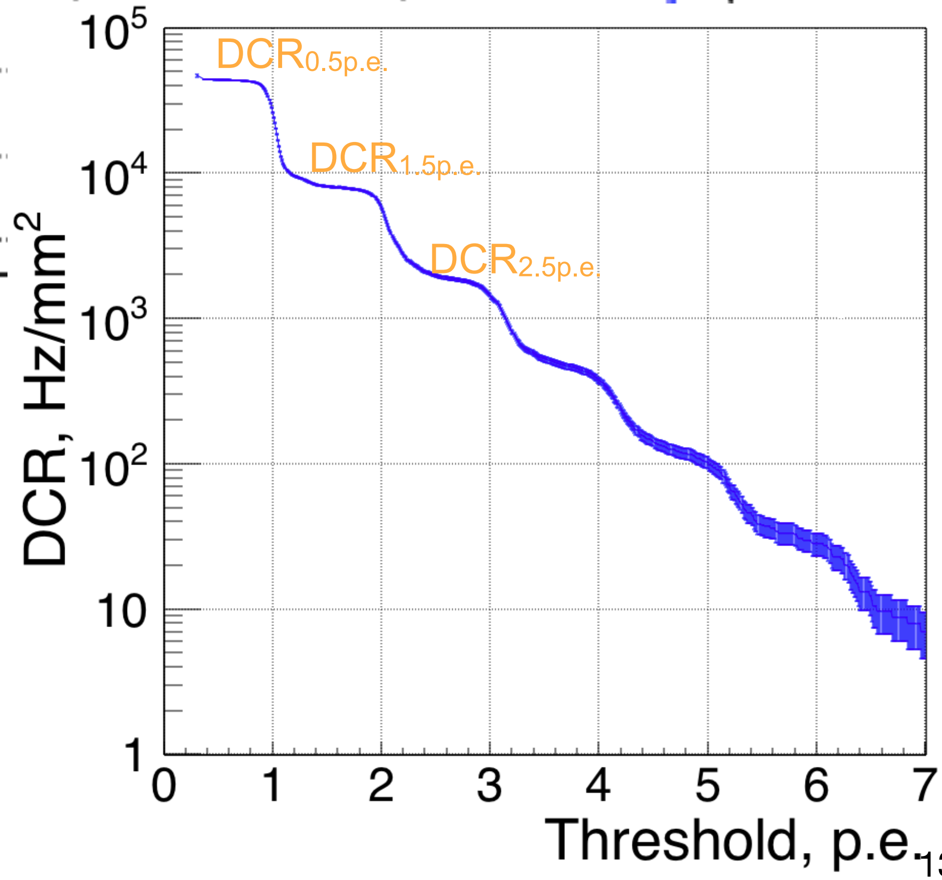

Count all pulses which cross given threshold within given time interval L:

$$DCR = \frac{N_{pulses}(Thr.)}{L}$$

This is affected by afterpulses.

DCR: Poisson method

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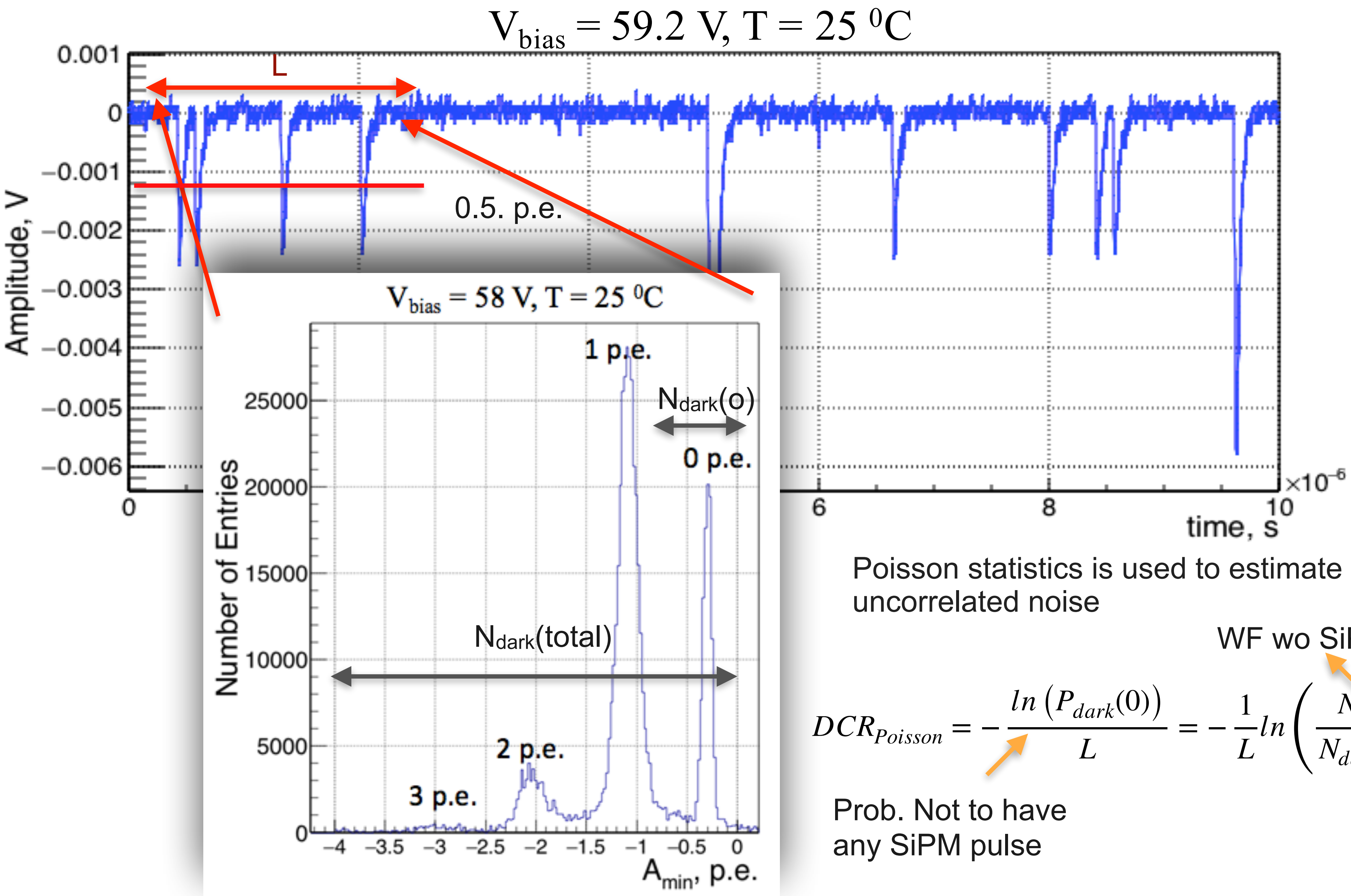
Count how many times in interval L the minimum is higher than 0.5 p.e.



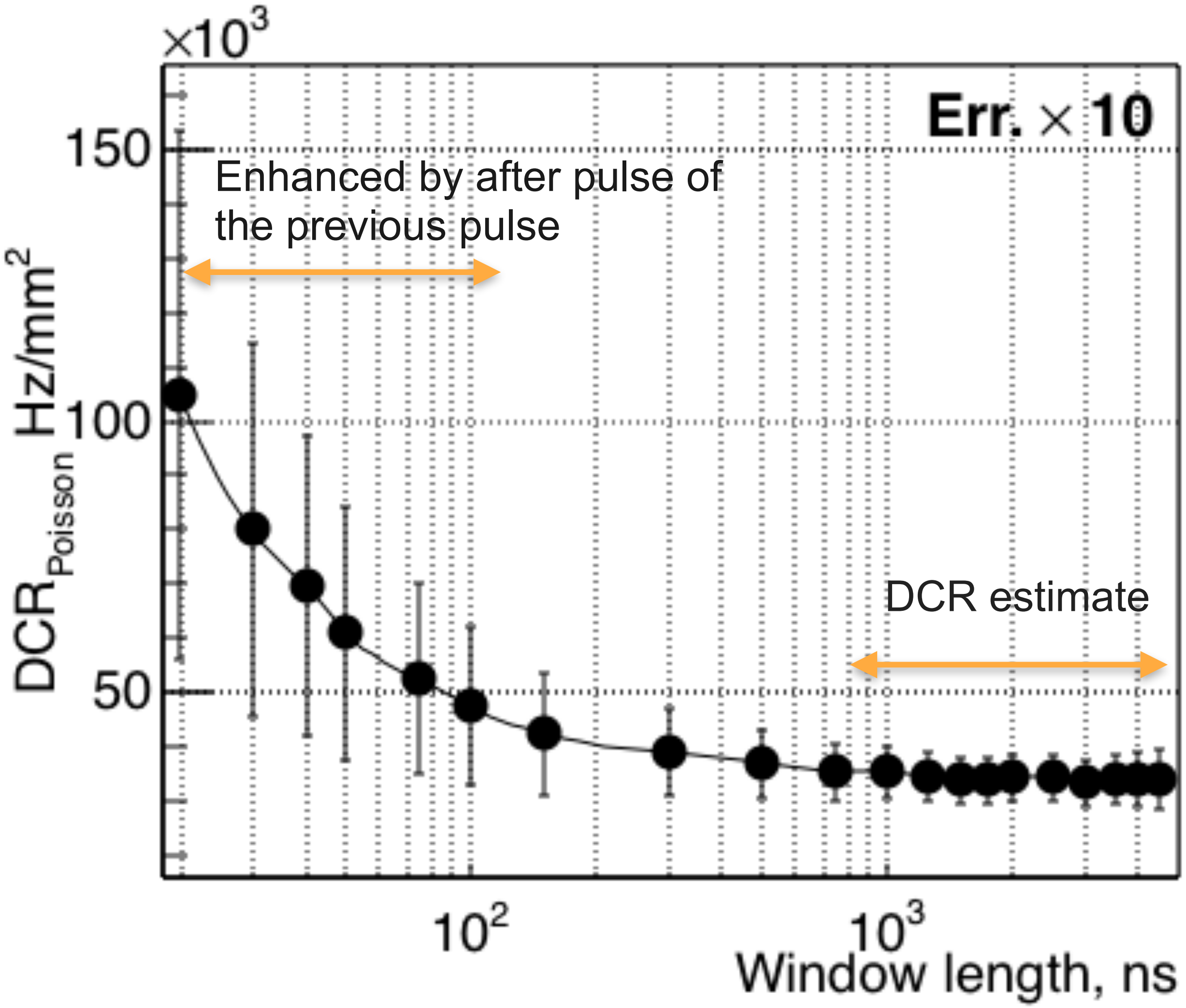
Poisson statistics is used to estimate purely uncorrelated noise

WF wo SiPM pulse in L

$$DCR_{Poisson} = -\frac{ln\left(P_{dark}(0)\right)}{L} = -\frac{1}{L}ln\left(\frac{N_{dark}(0)}{N_{dark}(total)}\right)$$

Prob. Not to have any SiPM pulse

Poisson method caveat:



Window length L should be long enough to include all after pulses corresponding to primary pulse, otherwise $DCR_{Poisson}$ will be overestimated.

Can correspond only to 0.5 p.e threshold

AC measurements: Uncorrelated Noise

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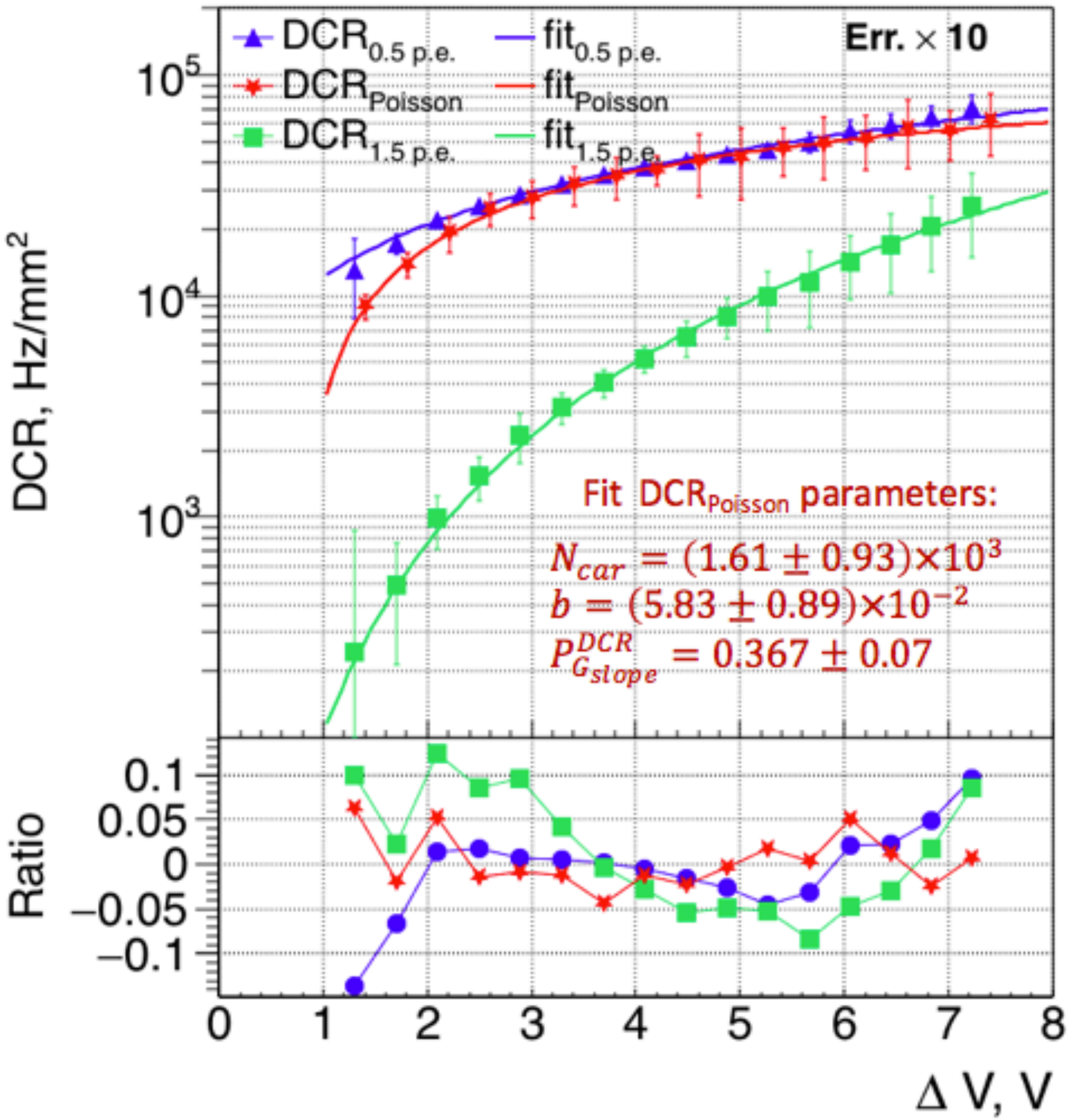


$$DCR = N_{car} \cdot P_G^{DCR} \cdot e^{b \cdot V_{bias}}$$

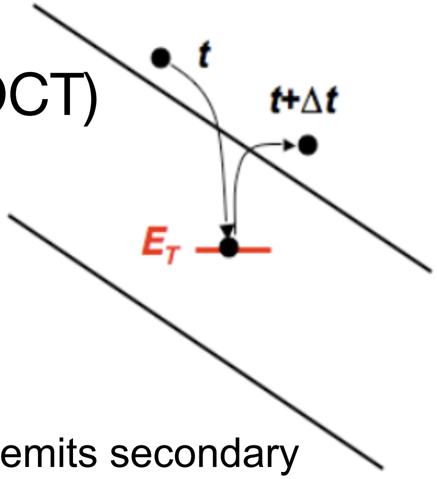
Geiger prob. Of DCR

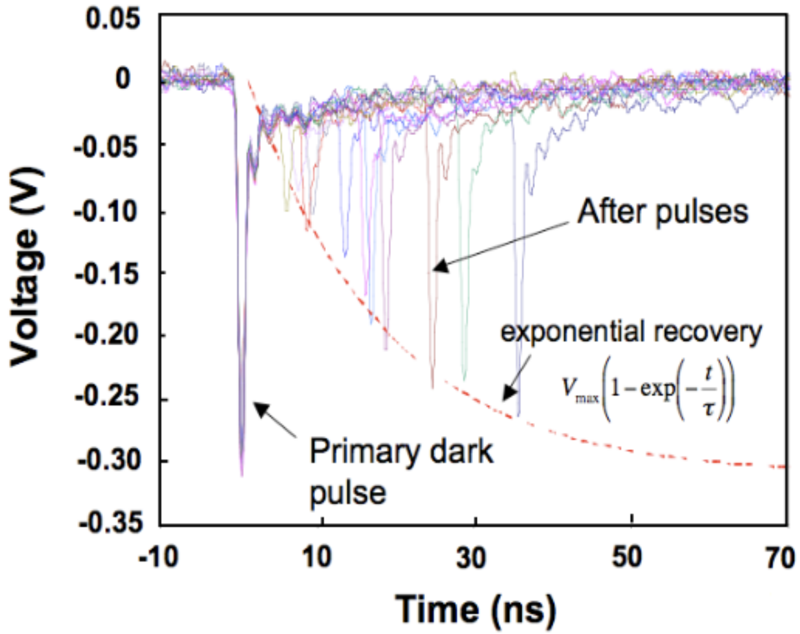
Increase of DCR with V_{Bias}

- Counting method from WF:
  - Commonly used;
  - Affected by correlated noise (eg after pulses)
- Poisson statistics:
  - Unaffected by correlated noise
  - Should be used with precaution (see previous slide)

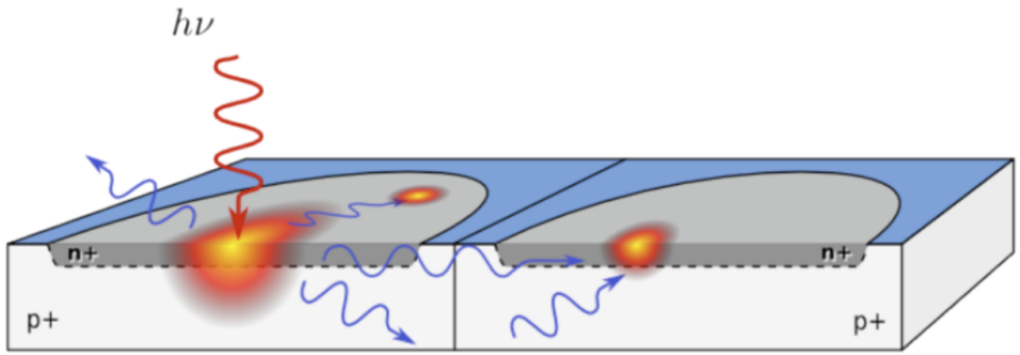
AC measurements: Correlated Noise

- Correlated noise:
  - Afterpulses;
  - Optical cross-talk (OCT)

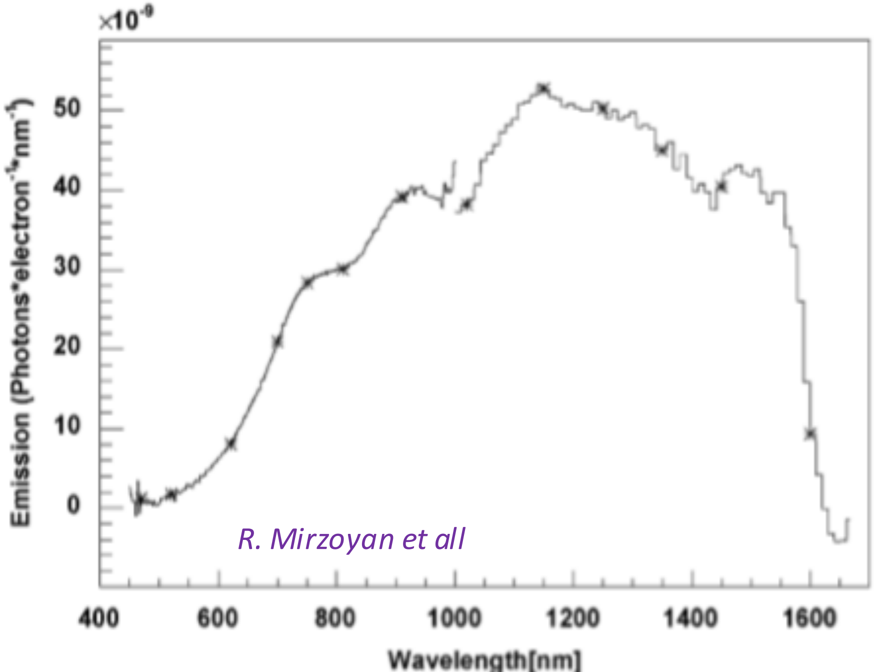




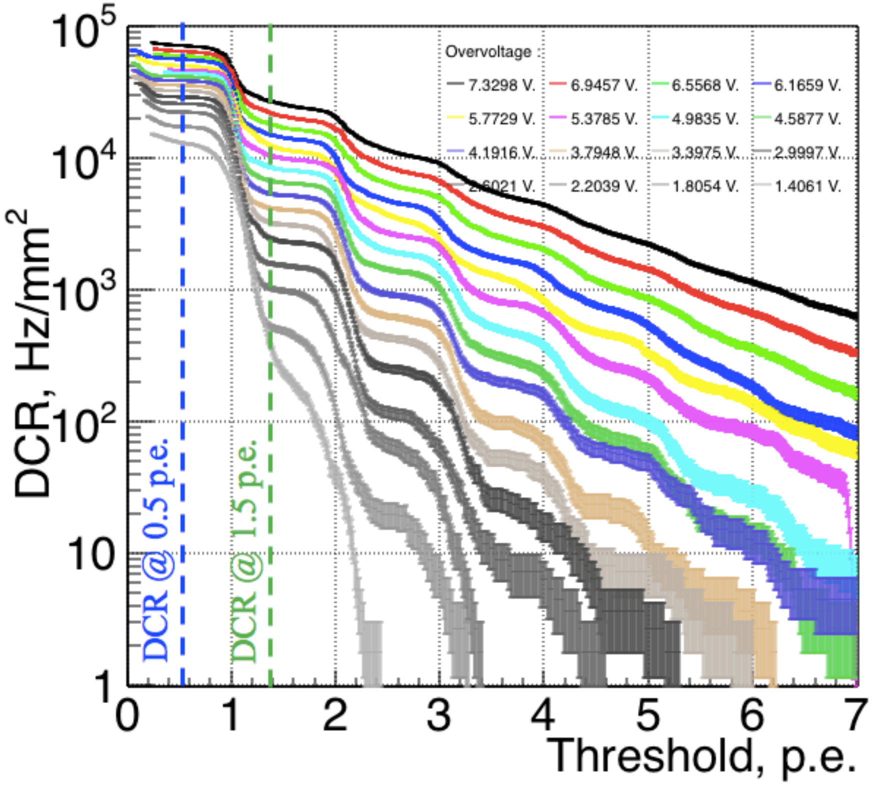
OCT : the avalanche process in a ucell emits secondary IR photons that are then detected by the surrounding ucells with a certain probability (P_{XT}).

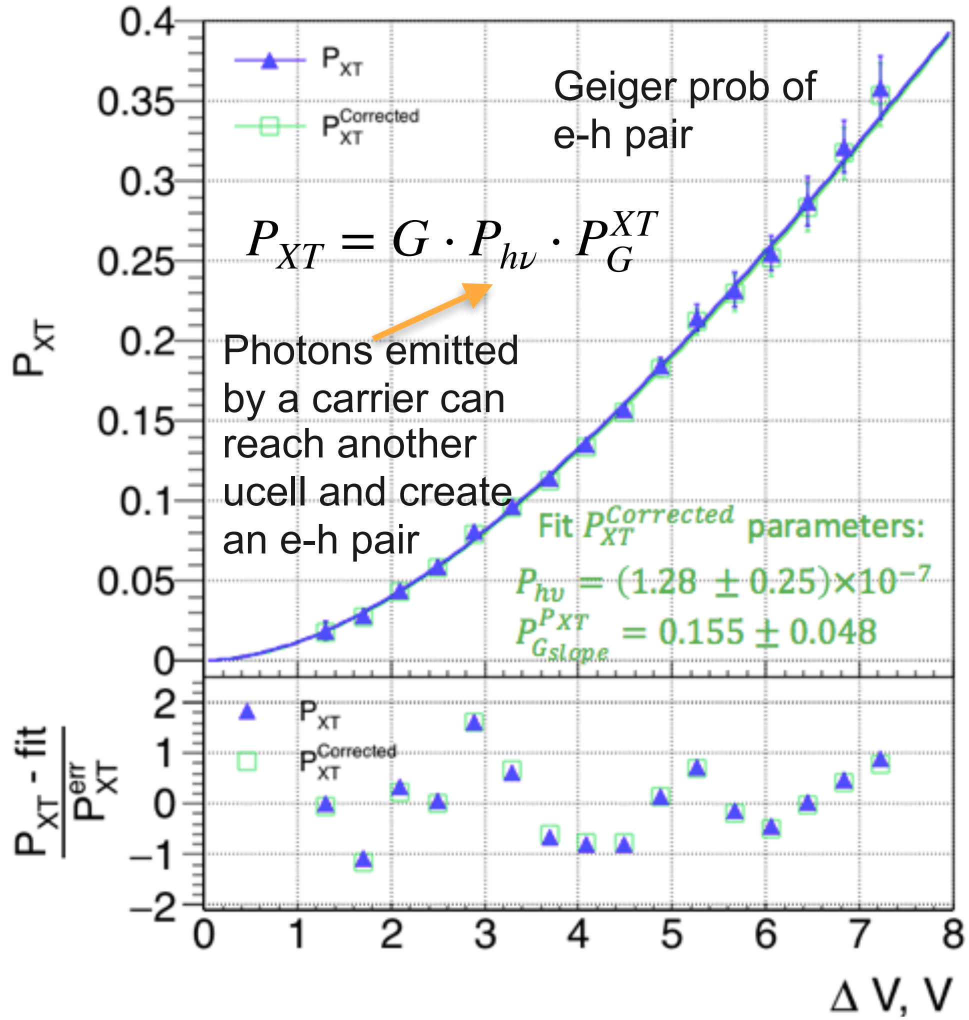


(Pagano, 2010)



AC measurements: Optical cross-talk





$$P_{XT}^{Corrected} = \frac{DCR_{1.5p.e.} - R_{total}}{DCR_{0.5p.e.} + R_{total}}$$

The correction is due to the probability that 2 or more dark pulses pile up in the time interval of 10 ns where afterpulses can be neglected

$$R_{total} = 2 \cdot \tau \cdot DCR_{0.5p.e.}^2 + 2 \cdot \tau^2 \cdot DCR_{0.5p.e.}^3 + \ldots = \frac{2 \cdot \tau \cdot DCR_{0.5p.e.}^2}{1 - \tau \cdot DCR_{0.5p.e.}}$$

DCR and afterpulses

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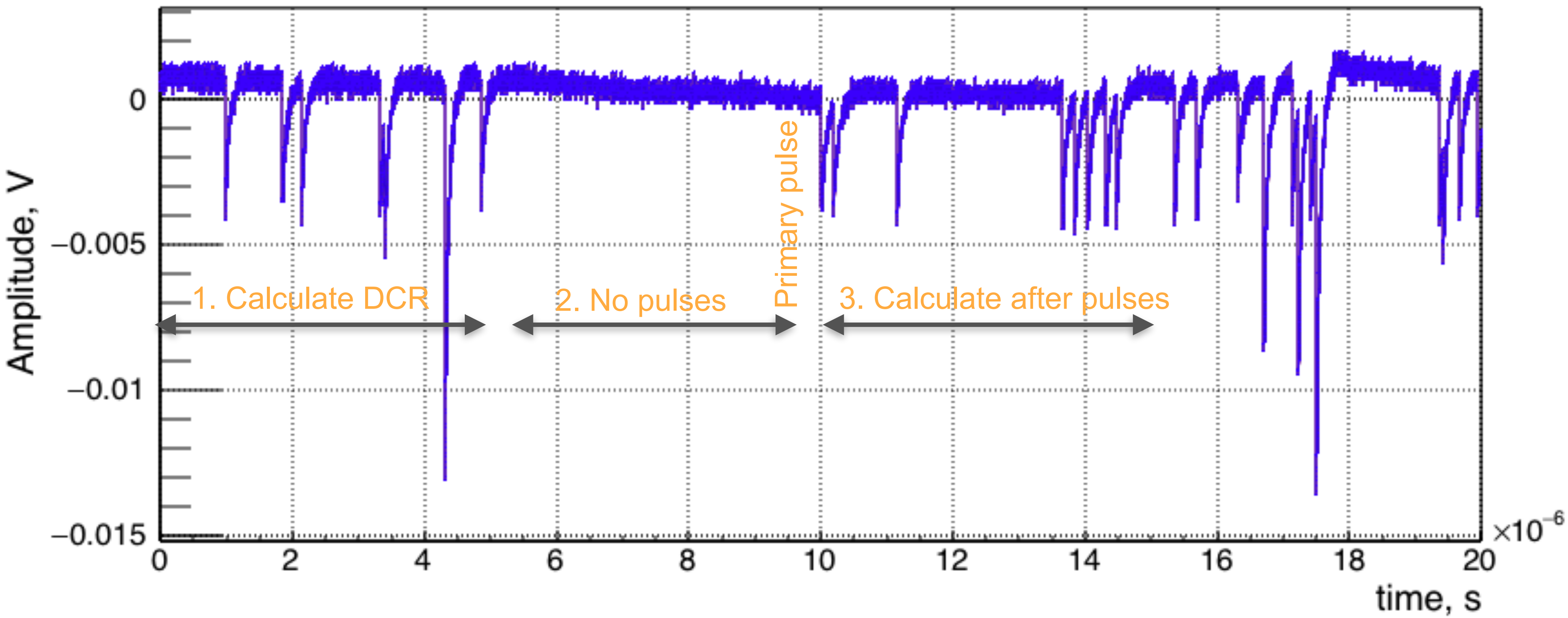
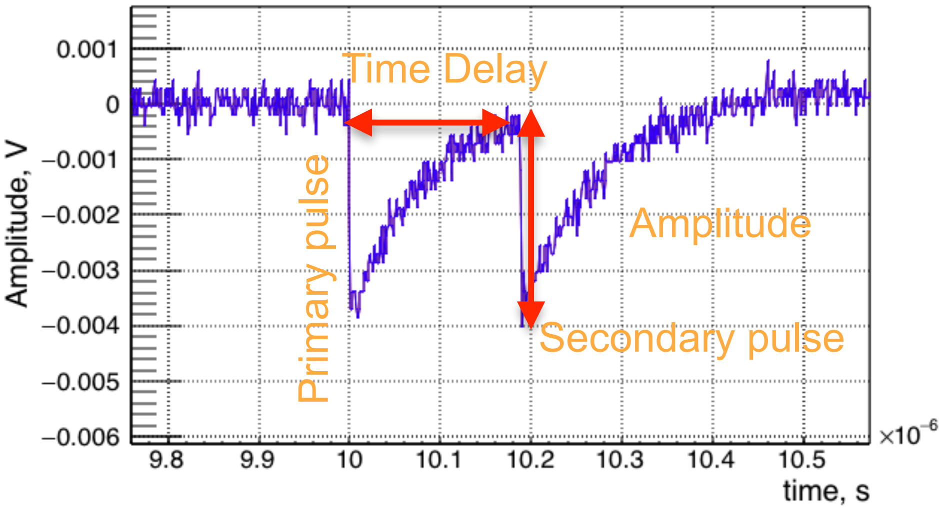
Data acquisition:

- Measurements in dark;
- 20 μs length;
- 0.5 p.e. amplitude trigger and no pulses 5 μs before trigger @ 10 μs



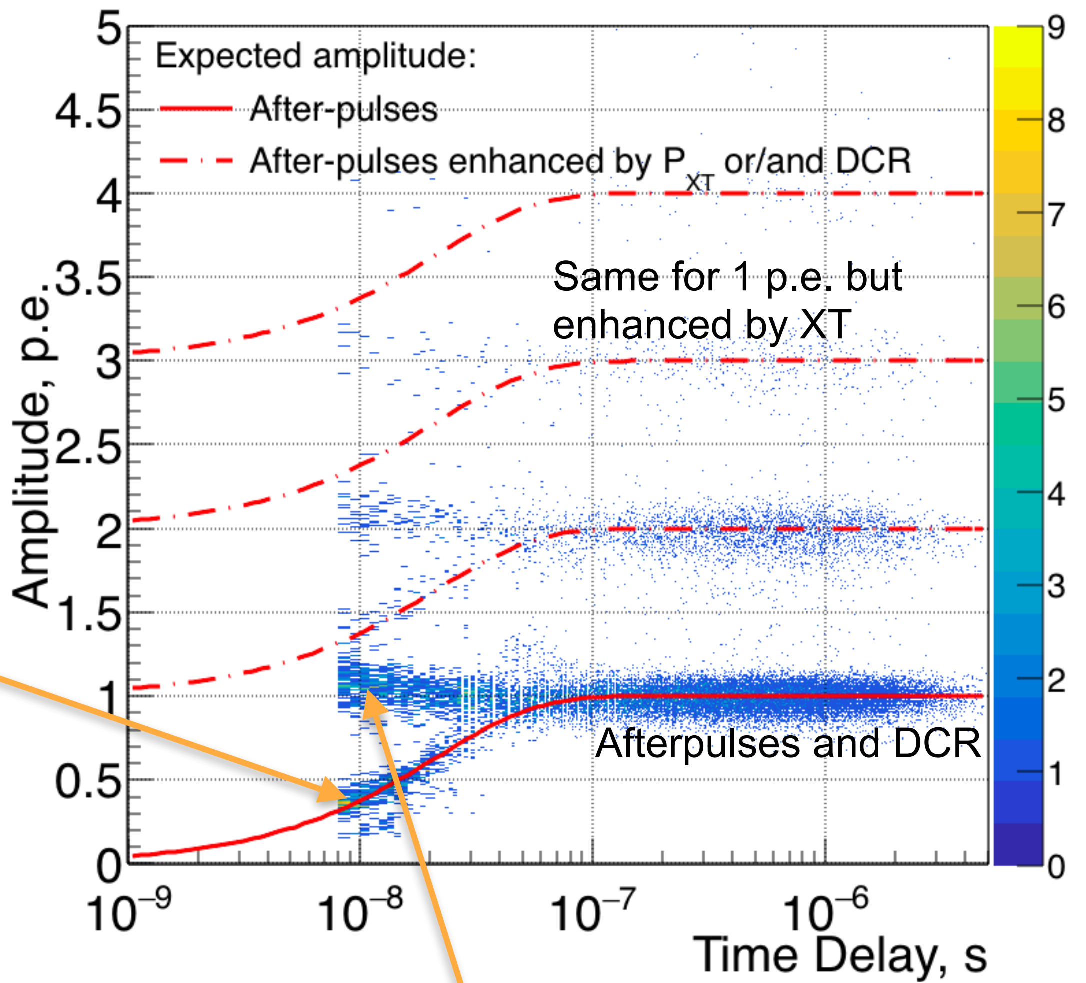
AC measurements: Afterpulses



Afterpulses before recovery

$$A_{AP} = A_{1p.e.} - A_{1p.e.} \cdot \exp\left[-\frac{t}{\tau_{rec.}}\right]$$

$R_q\ C_{ucell}$



Being 1 p.e. they should come from another cell than the oe recovering, so they are most probably cross-talk since the DCR probability at such short delay is small

AC measurements: Afterpulses

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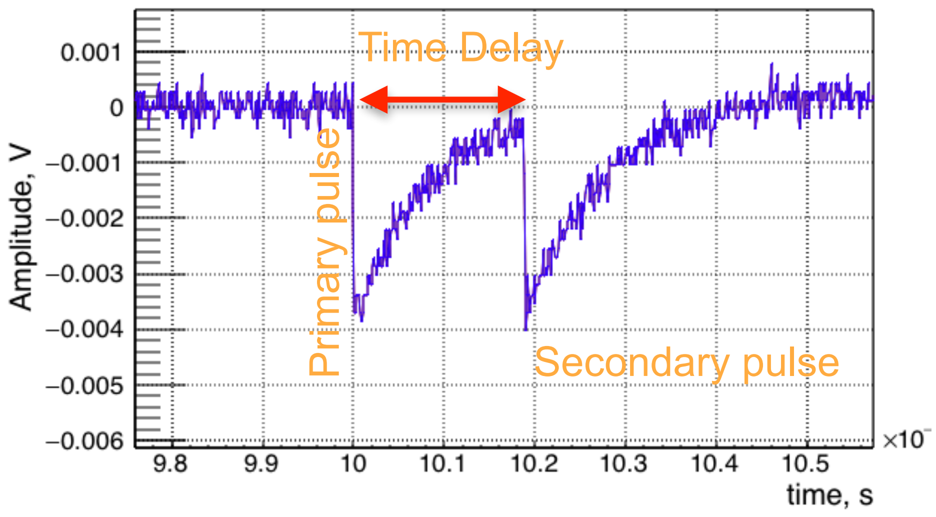
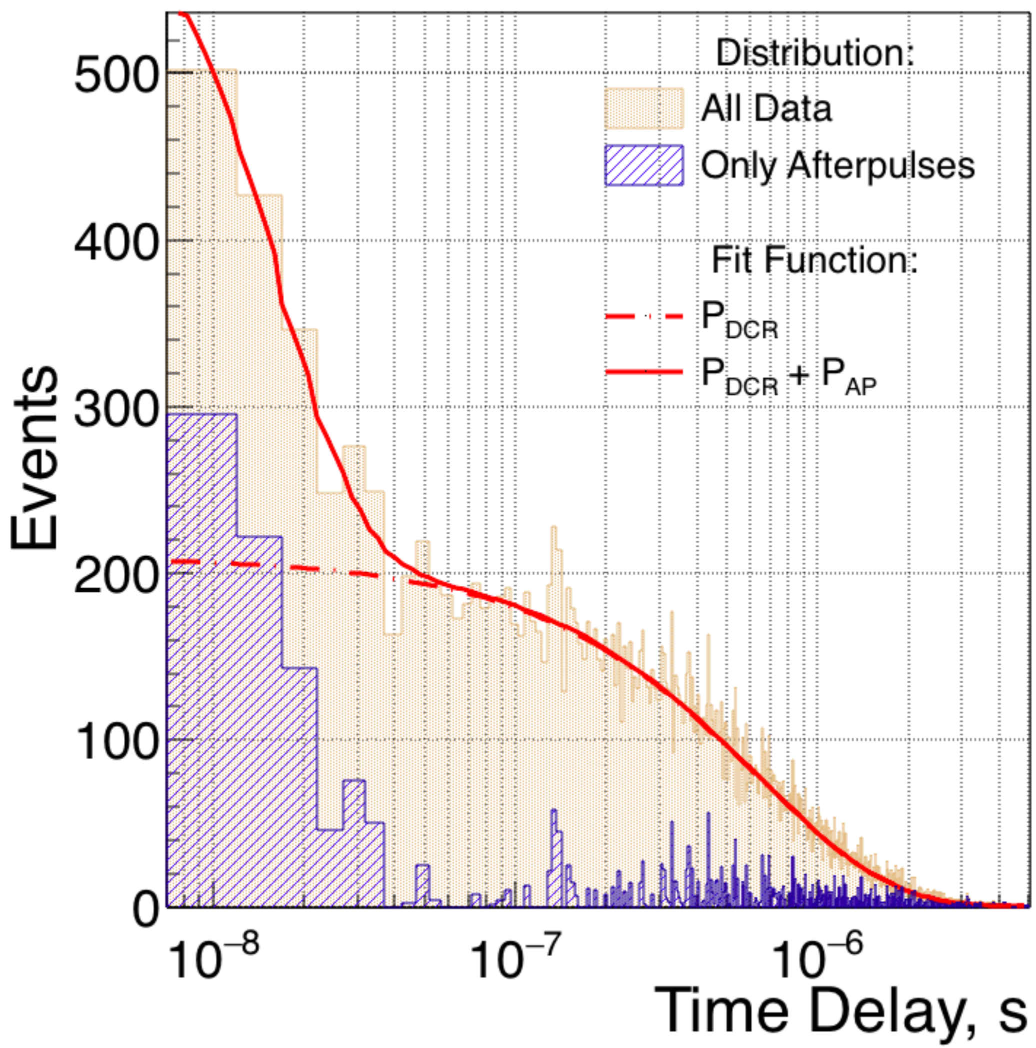


$$N_{total}(\Delta t) = N_{DCR}(\Delta t) + N_{AP}(\Delta t)$$



DCR = $1/\tau_{DCR}$

$$N_{DCR}(\Delta t) = \frac{n_{DCR}}{\tau_{DCR}} \cdot exp\left(\frac{-\Delta t}{\tau_{DCR}}\right)$$

$$N_{AP} = \frac{n_{AP}}{\tau_{AP}} \cdot exp\left(\frac{-\Delta t}{\tau_{AP}}\right) \cdot \left|1 - exp\left(-\frac{\Delta t}{\tau_{rec.}}\right)\right|$$

τ_{AP} : Afterpulses livetime

Term due to decrease of PDE due to cell recovery

AC measurements: Afterpulses

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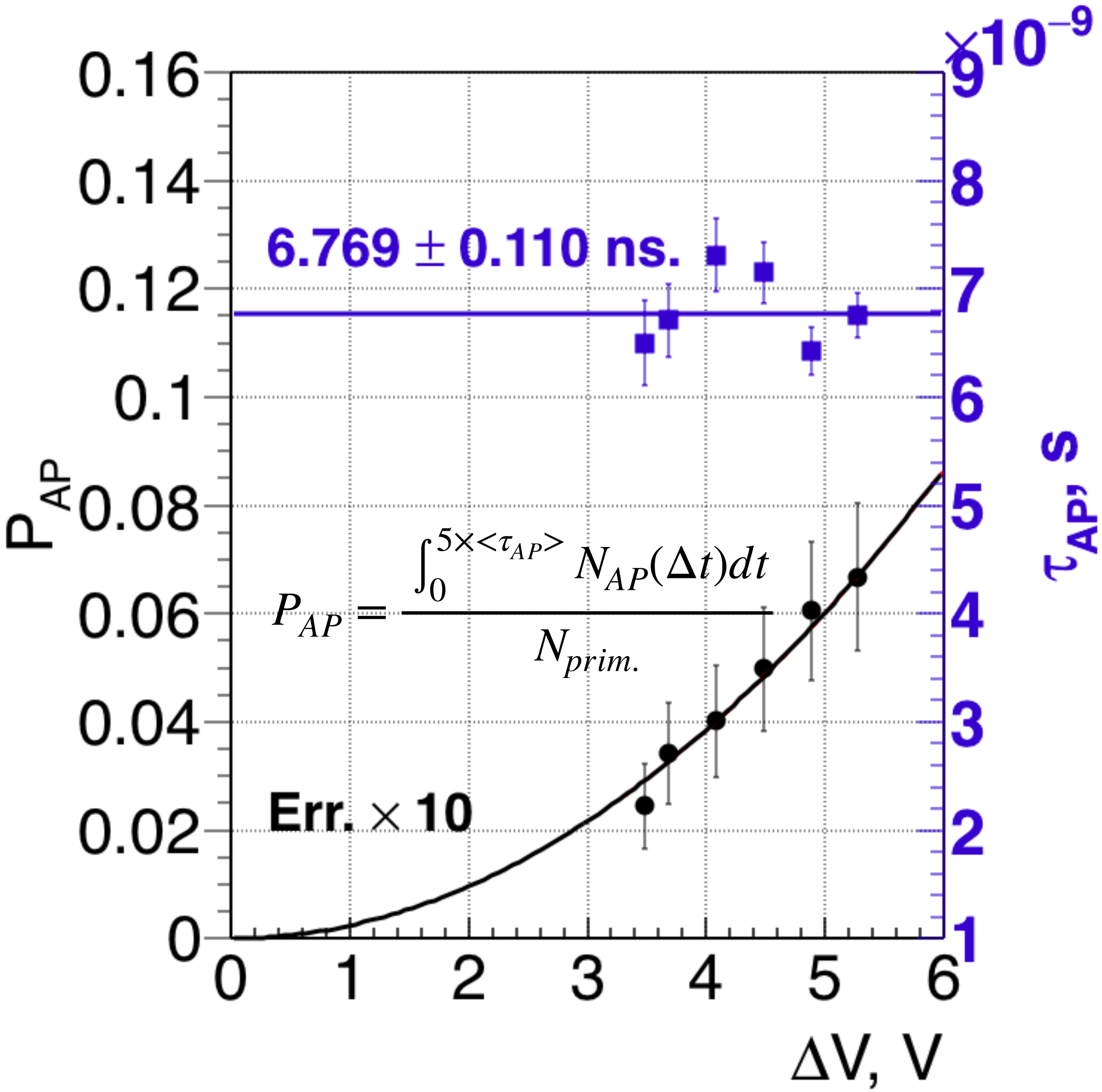

- Afterpulse lifetime: average time of charge trapping in impurities
- Afterpulse probability increase with over voltage but lifetime is constant

Optical measurements: set-ups

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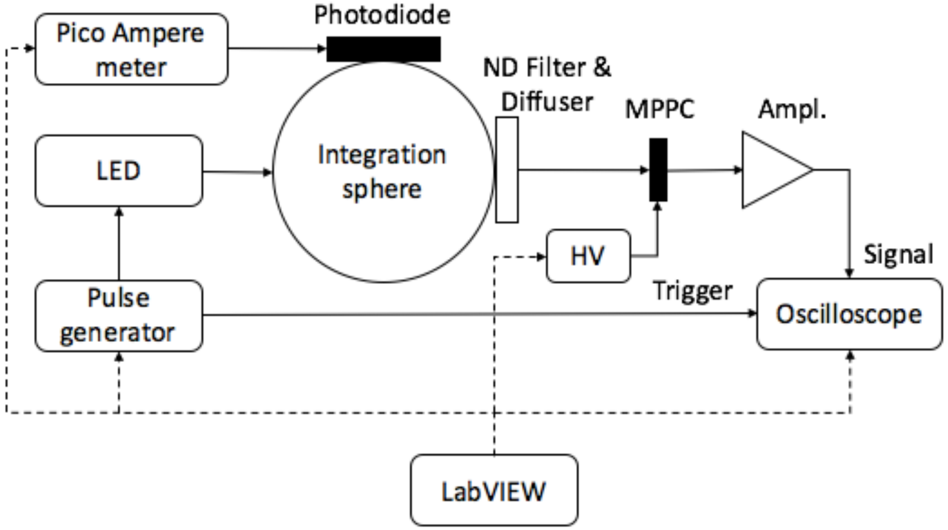
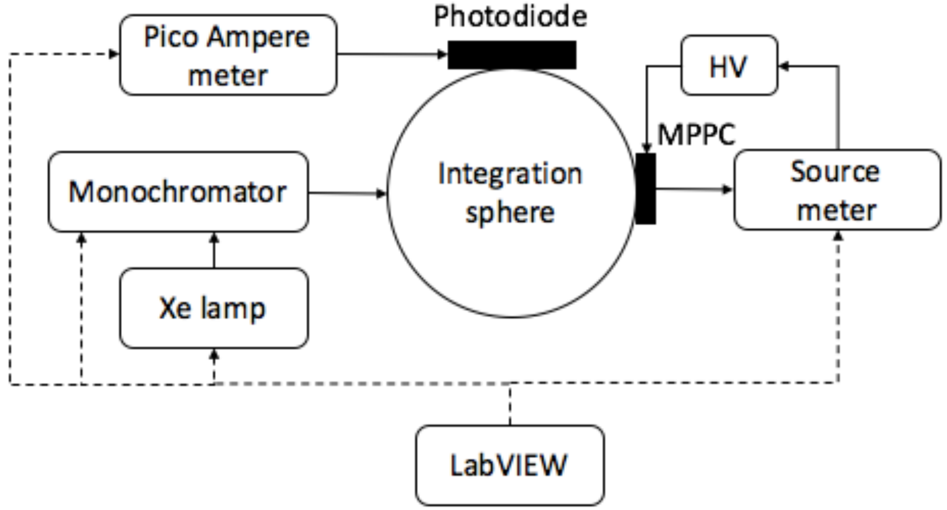
Pulsed light

Light disuniformity < 2%



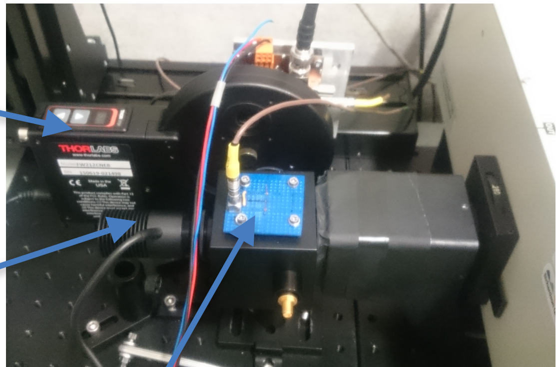
Continuous light



ND filters (81.3% ÷ 0.01%)

LED`s :

280, 340, 375, 405, 420, 455, 470, 505, 525, 530, 565 & 572nm



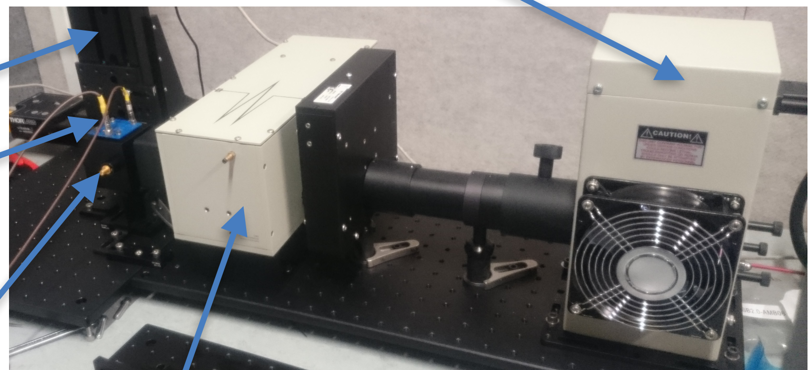
Calibrated Photodiode 10x10 mm² (S1337-1010BQ) 5% precision

Xe 75 W lamp: 250 ÷ 1800 nm

Translation stage

Photodiode (S1337-1010BQ)

Integration sphere



Monochromator

$$PDE = QE(\lambda) \times \epsilon \times P_G(\Delta V, \lambda)$$

Pulsed light: absolute PDE from photon counting

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- Poisson distribution:

$$P(n_{p.e.}) = \frac{(k)^{n_{p.e.}}}{n_{p.e.}!} \times e^{-k}$$

- Probability to have 0 p.e. on the SiPM:

$$P(0) = e^{-k} = \frac{N(0)}{N(total)}$$

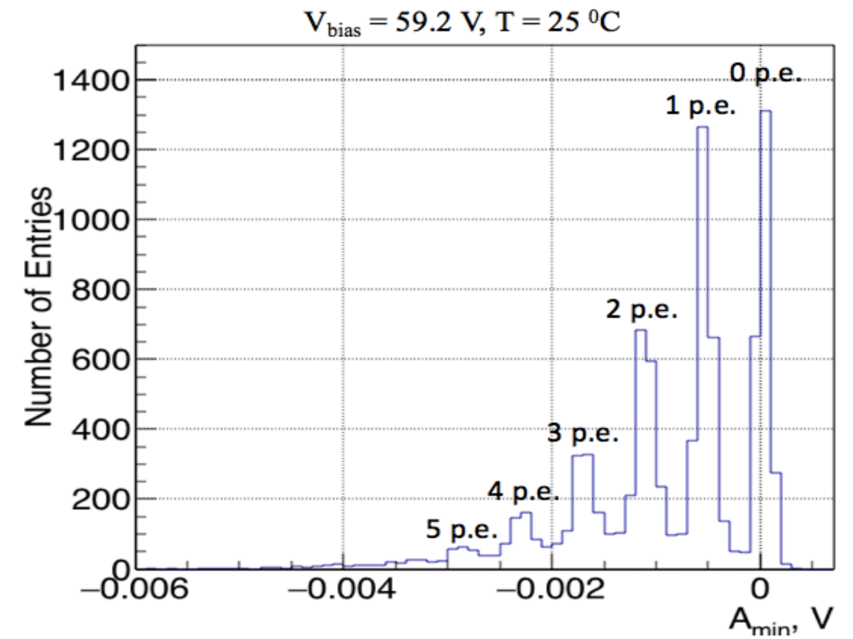
- Average number of detected photons:

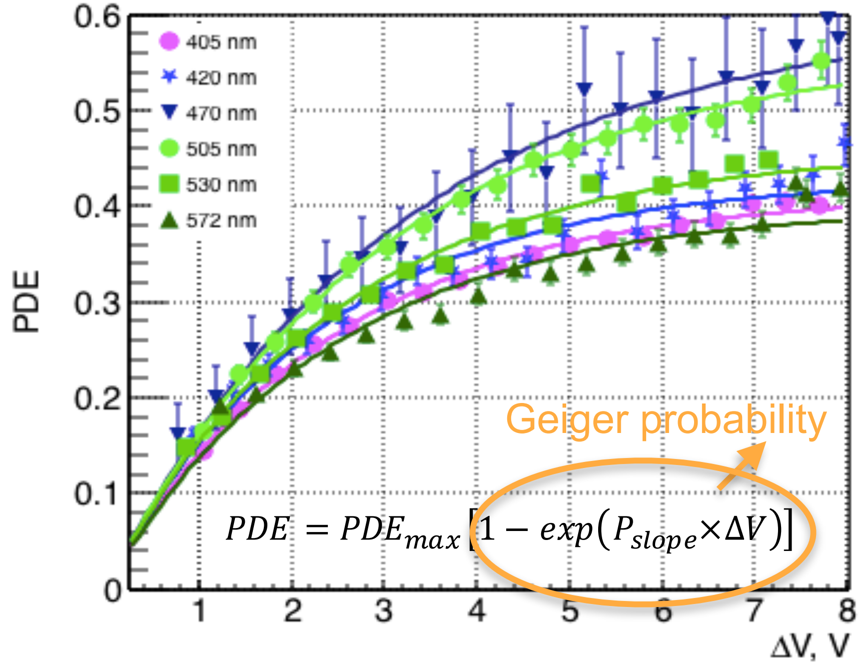
$$k = -\,ln(P(0)_{LED}) + ln(P(0)_{dark})$$

Pulse Rate

Ratio of light intensity on PD and SiPM x transparency of ND filter

$$PDE = \frac{k}{N_{photons}} = k \times \frac{f \cdot QE_{PD} \cdot e}{I_{PD} \cdot R}$$





Continuous light: Relative PDE

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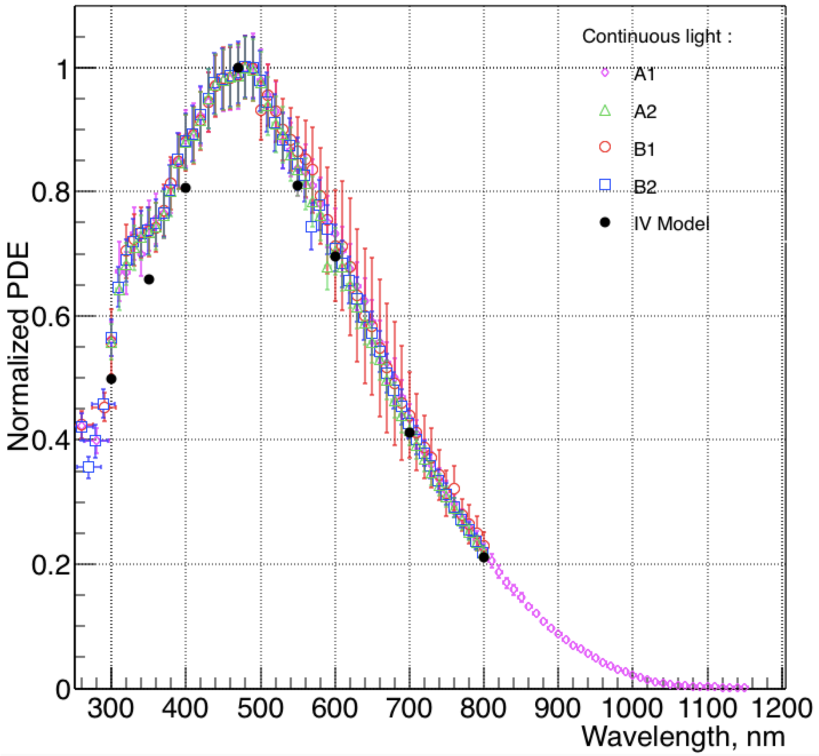
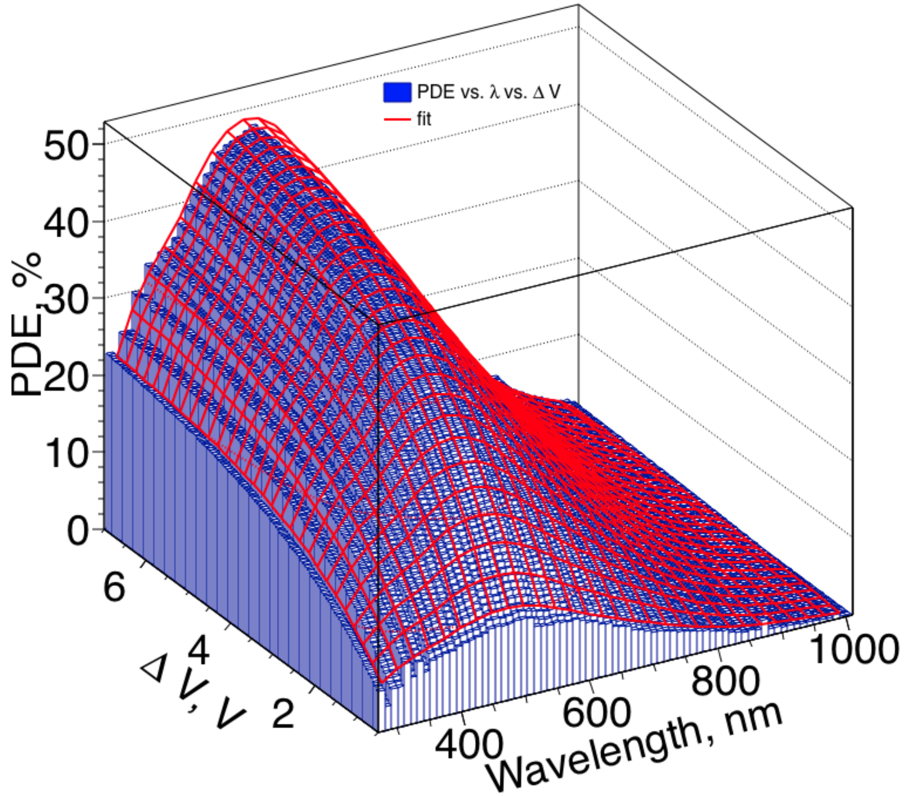
Wavelength (nm)



Relative PDE normalised to absolute values:



$$PDE(\Delta V, \lambda) = \frac{I_{SiPM}^{light} - I_{SiPM}^{dark}}{e \times N_{Ph} \times G_{SiPM}^{eff.}(\Delta V)} \propto \frac{I_{SiPM}^{light} - I_{SiPM}^{dark}}{I_{PD}^{Light}(\lambda)}$$

Rate continuous light .

G enhanced by correlated noise

Comparison from different labs

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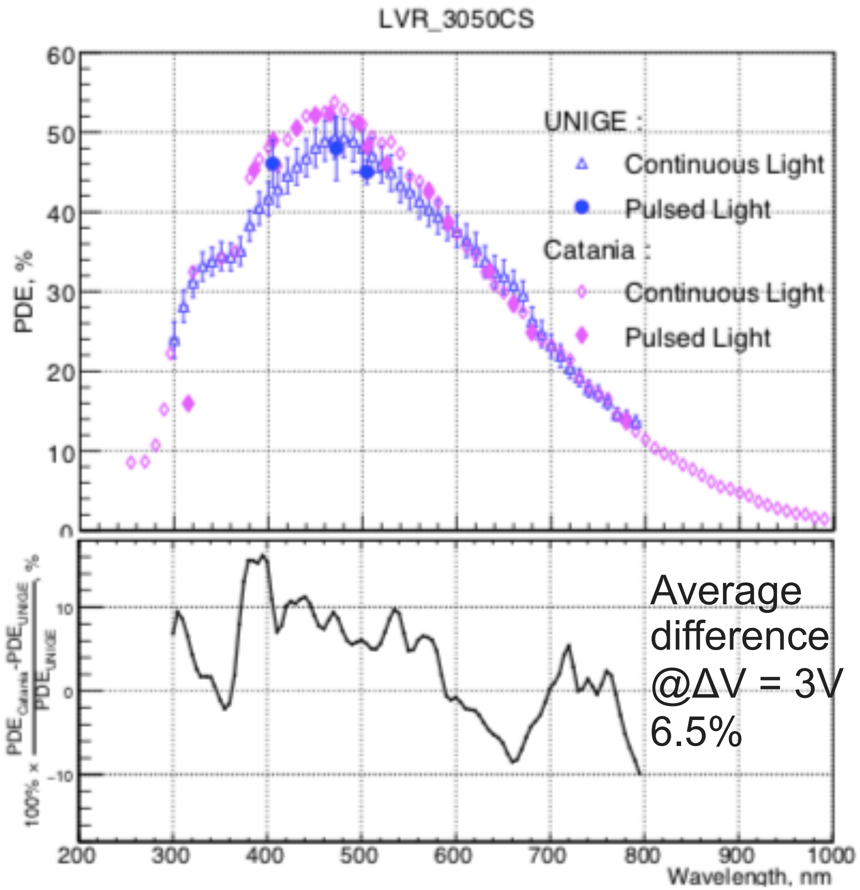
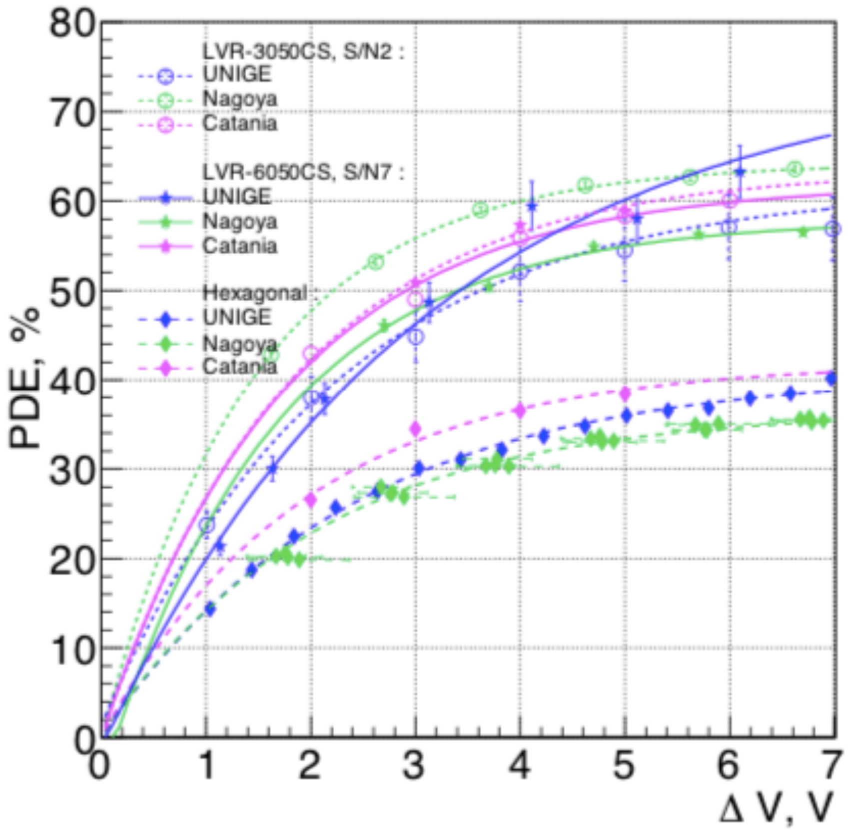
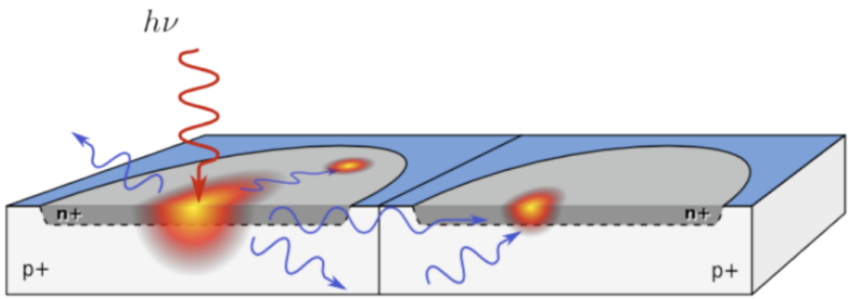


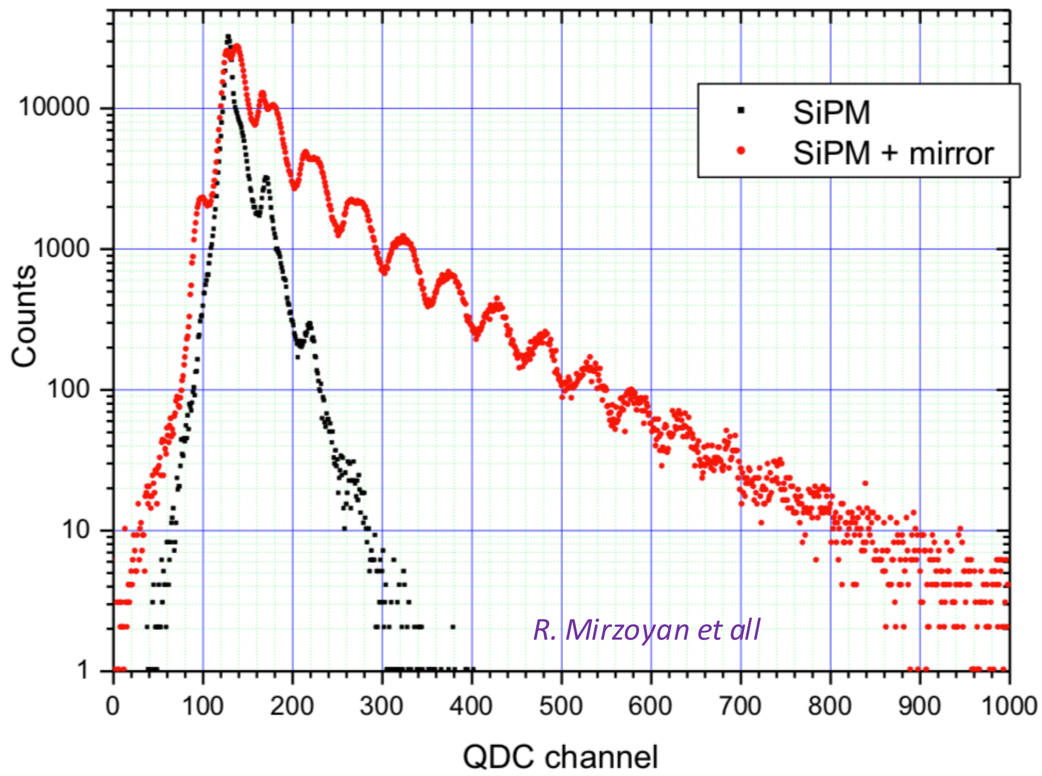


Nagai et al. Nucl.Instrum.Meth. A912 (2018) 182-185

SENSE

Optical crosstalk induced optical elements

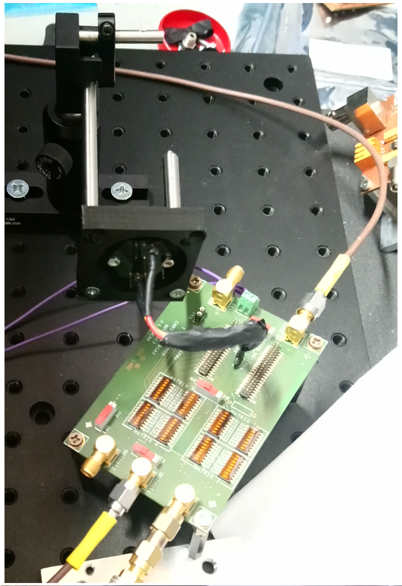


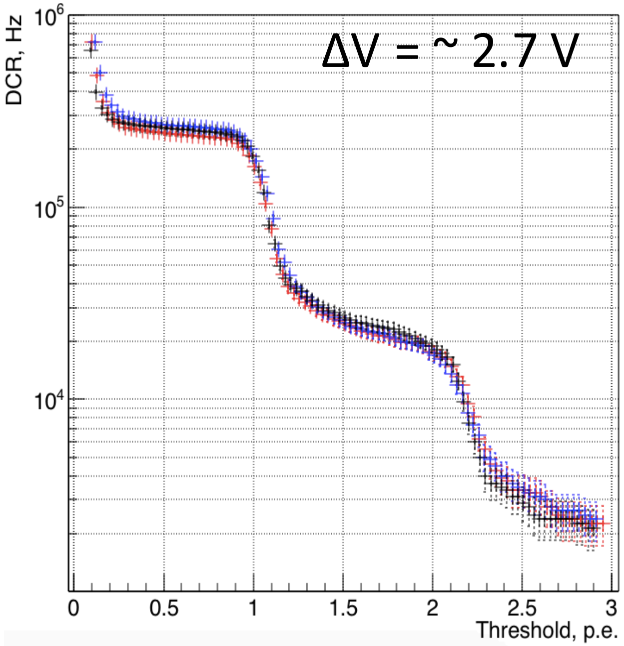


OXT photons which are going out from SiPM might be reflected by optics and lead to increase of total optical crosstalk. Also coating itself would do the same (Bonanno et al, NIM A908 (2018) 117-12)

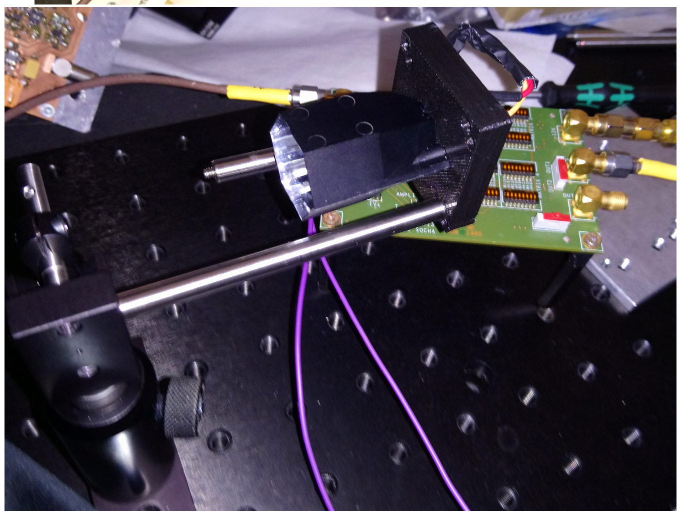
Optical crosstalk test

SiPM:

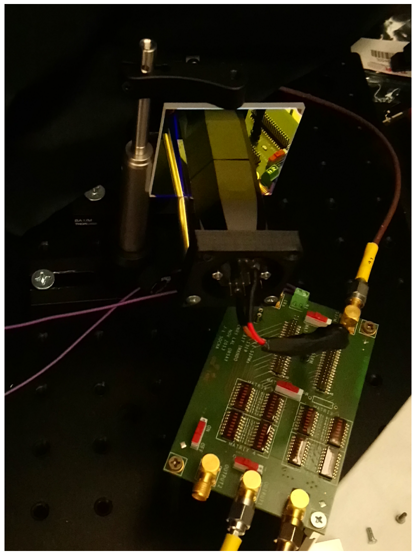




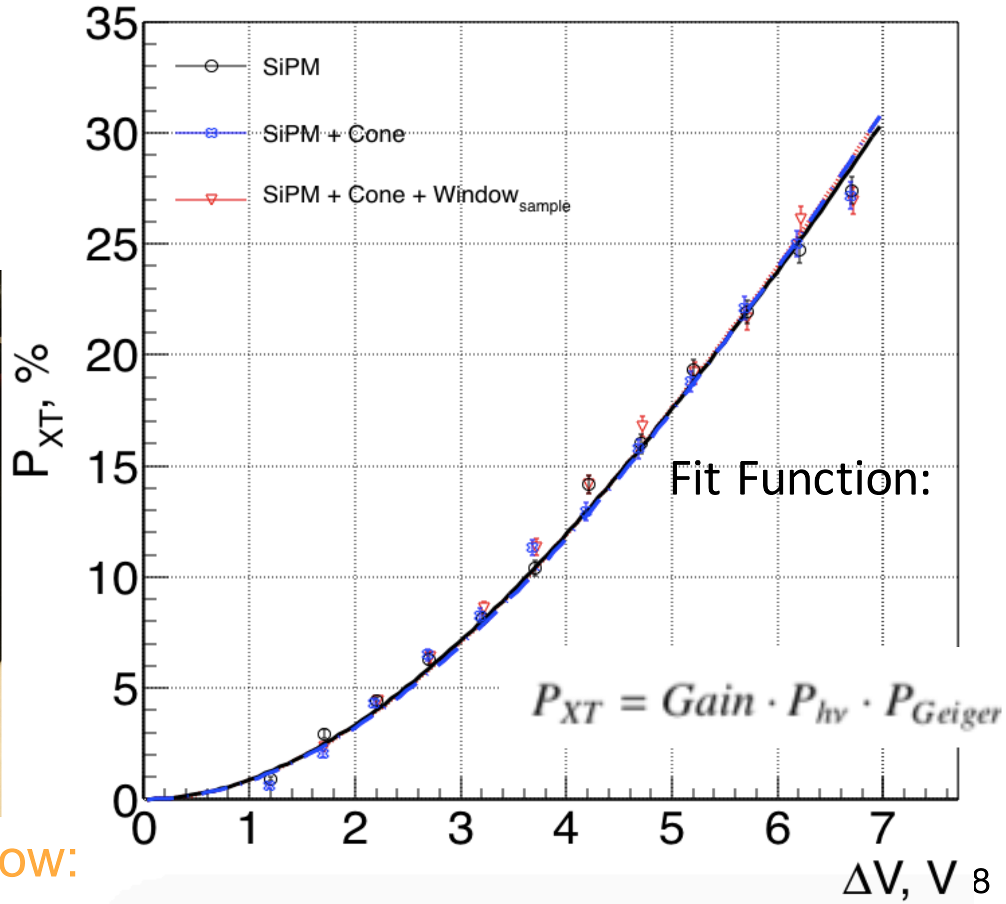
No P_{XT} increase observed



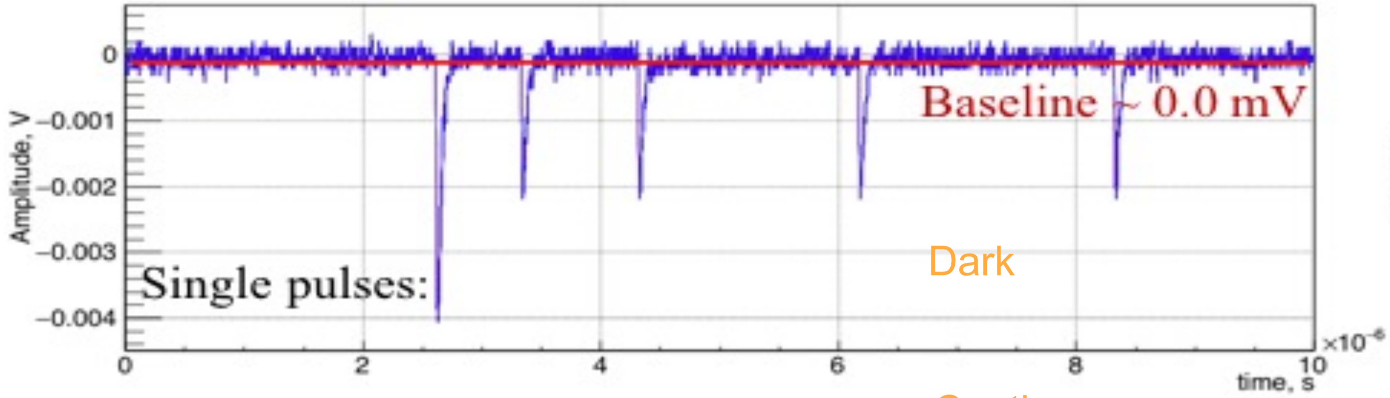
SiPM + lightguide (LG):

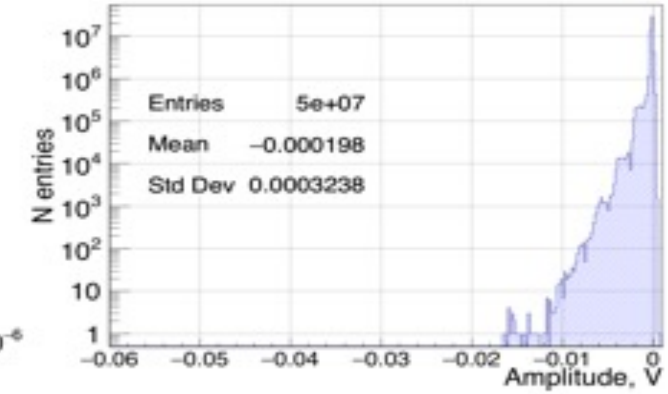


SiPM + LG + Window:



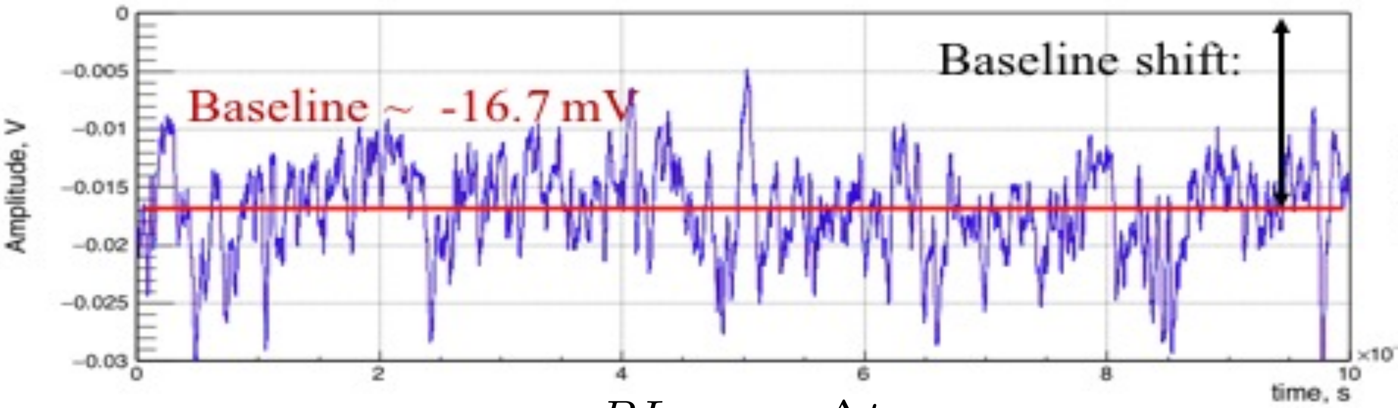
SiPM under continuous light

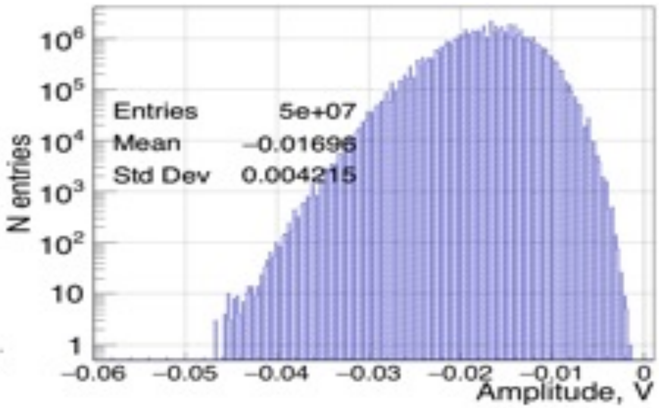




Dark

Continuous





$$N_{av} = \frac{BL_{shift} \times \Delta t}{Q_{1p.e.}}$$

integral of 1 p.e. pulse over time

$$N_{p.e.} = \frac{N_{av} - DCR \times \Delta t}{(1 + P_{XT})(1 + P_{ap})}$$

$$N_{ph} = \frac{N_{p.e.}}{PDE}$$

Voltage drop

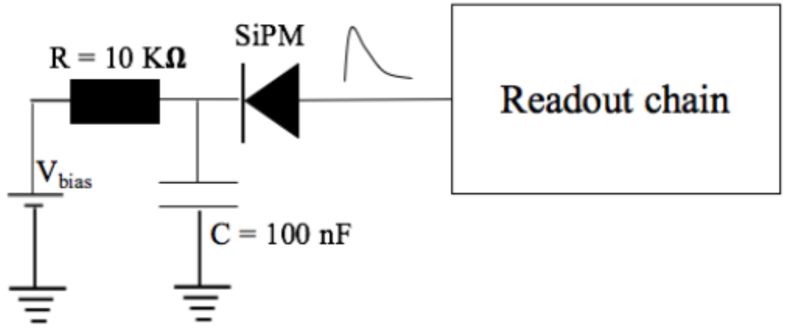


Figure 2: Typical schematics to bias SiPM device.

SiPM devices are usually biased through an RC filter to:

- filter high frequency electronic noise coming from the DC bias source
- limit the current, therefore protect the sensor in case of intense illumination.
- Increase MTBF (mean time before failure) of sensor (usually not provided by producer)

- But this resistor also induces a **voltage drop** at the sensor cathode in presence of continuous light, which reduces the bias voltage and therefore changes its operation point

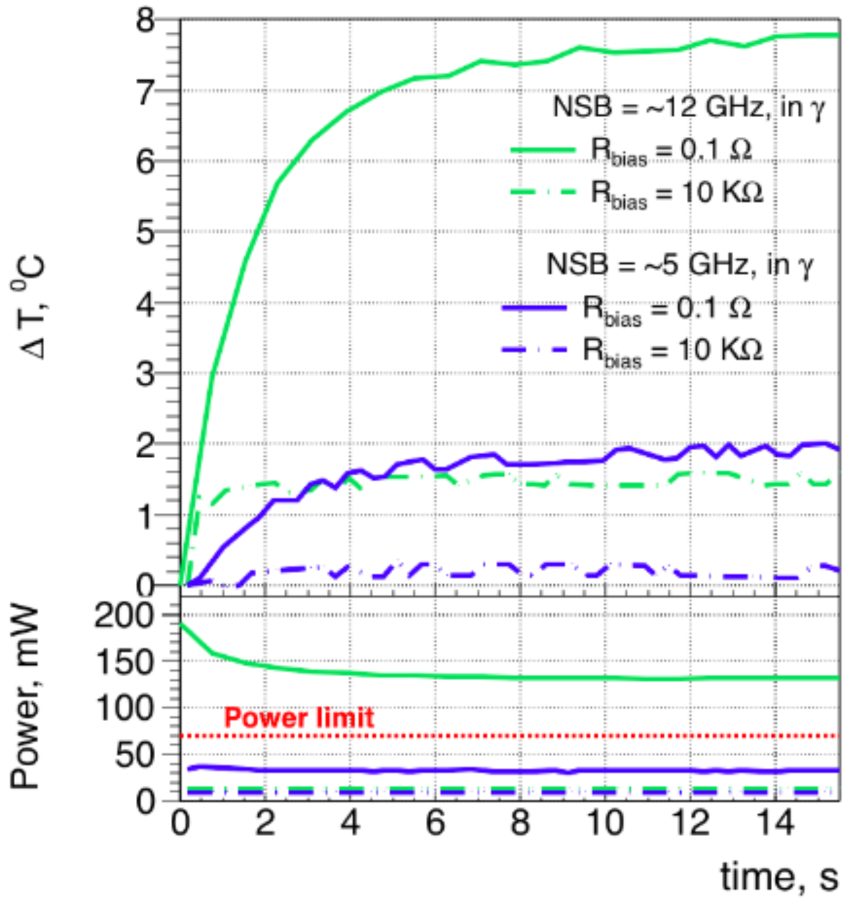
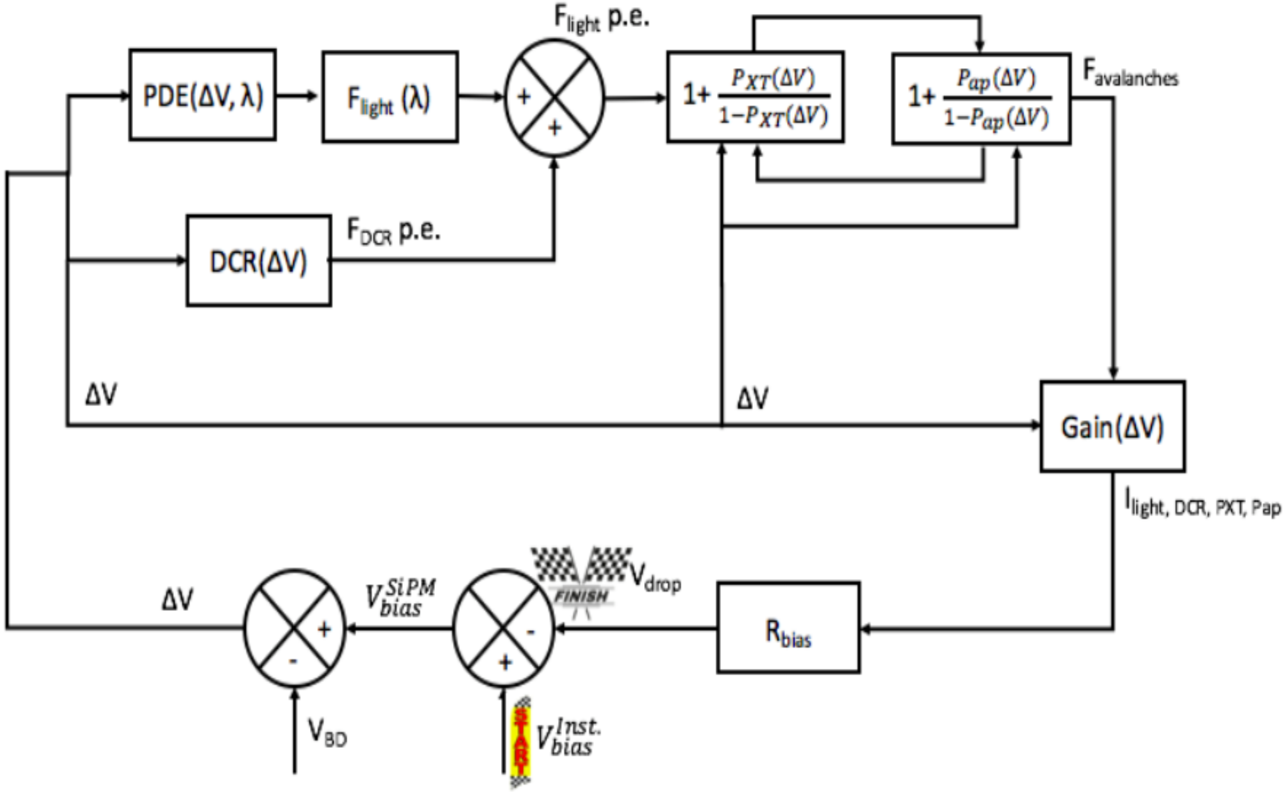
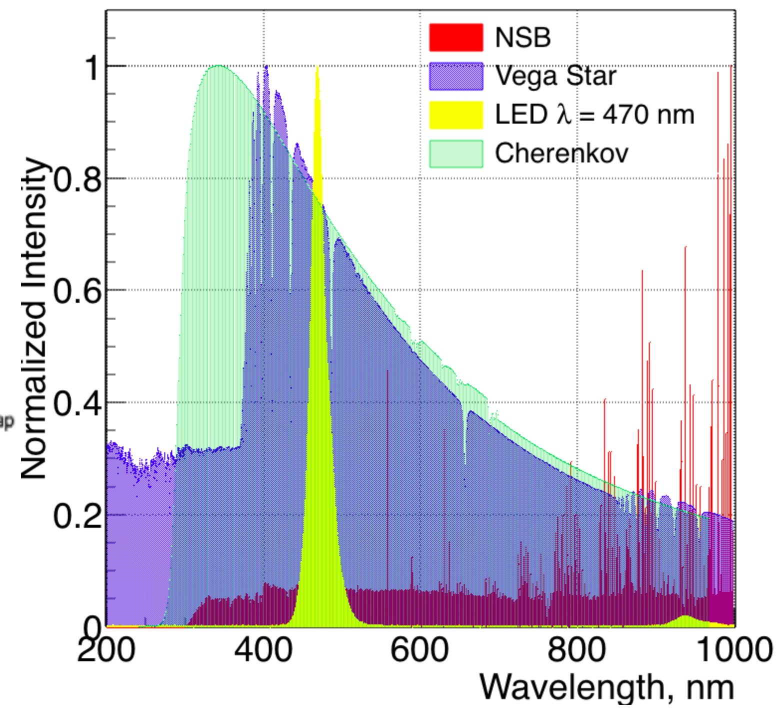


Figure 3: SiPM temperature (upper) and Power consumption (bottom) at initial $\Delta V = 2.8$ V and under $12 \times 10^9\ \gamma/s$ vs. time for $R_{bias} = 0.1\ \Omega$ (solid line) and $R_{bias} = 10\ K\Omega$ (dashed line). The highest acceptable power consumption for a sensor (provided by producer) is represented by red dashed line.

Voltage drop: Toy MC model scheme



Different light sources can be used:

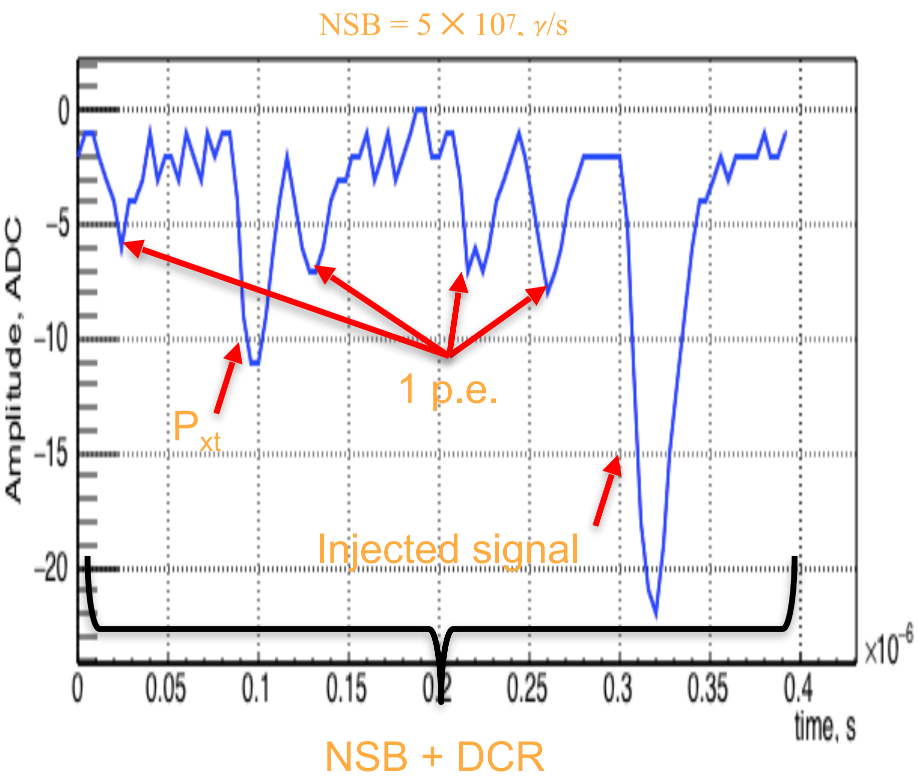


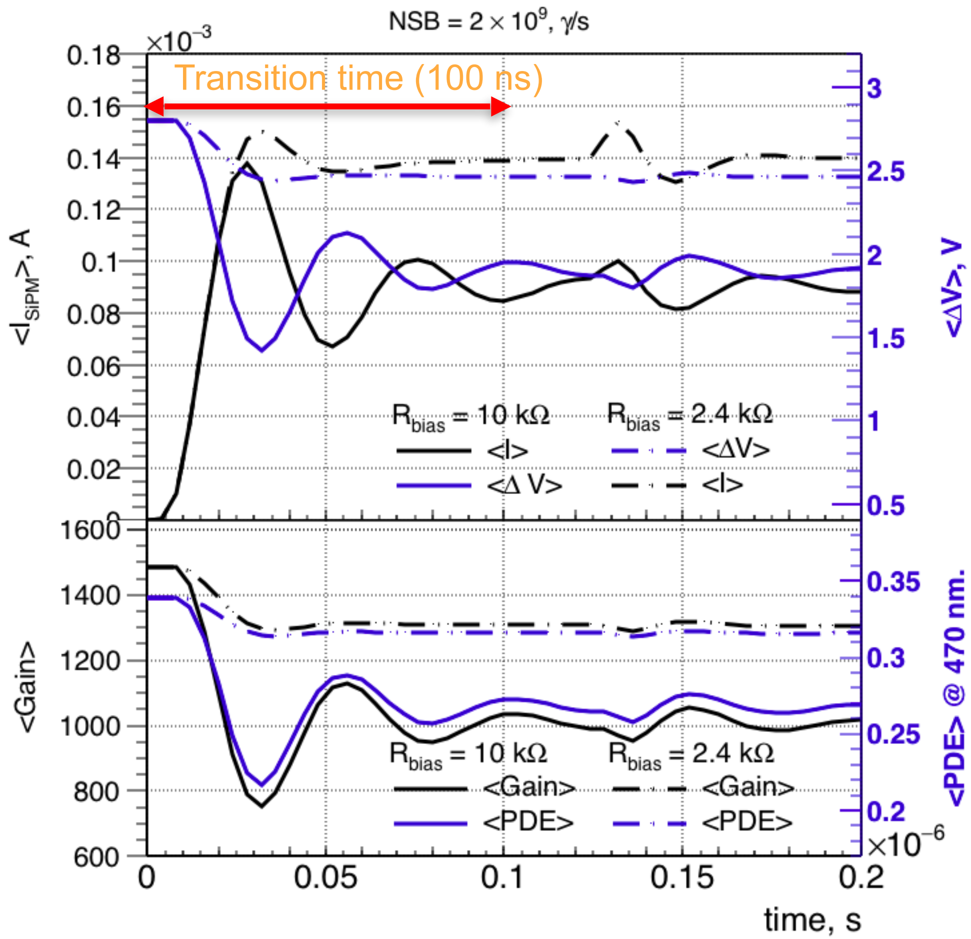
Time dependent toy MC simulation was developed to account for these effects:

- Gain (Amplitude) & σ_{Gain}
- PDE(λ)
- Noise: P_{XT}, P_{AP}, DCR
- Baseline Shift & $\sigma_{Baseline\ Shift}$

Voltage drop: Toy MC model

Simulation Example:





Voltage drop: Model Validation @ Cern/Unige

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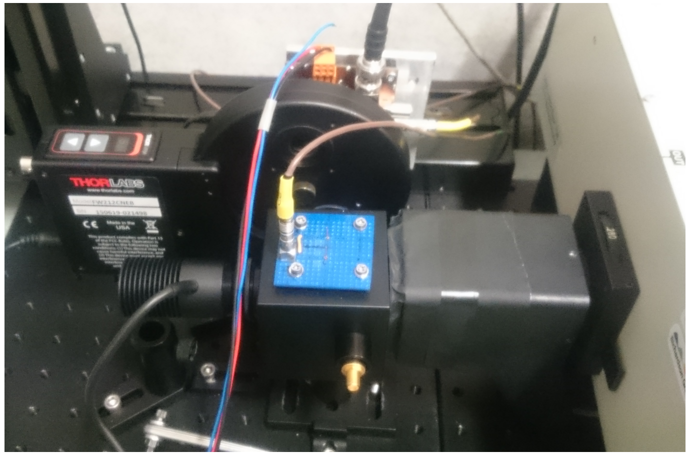
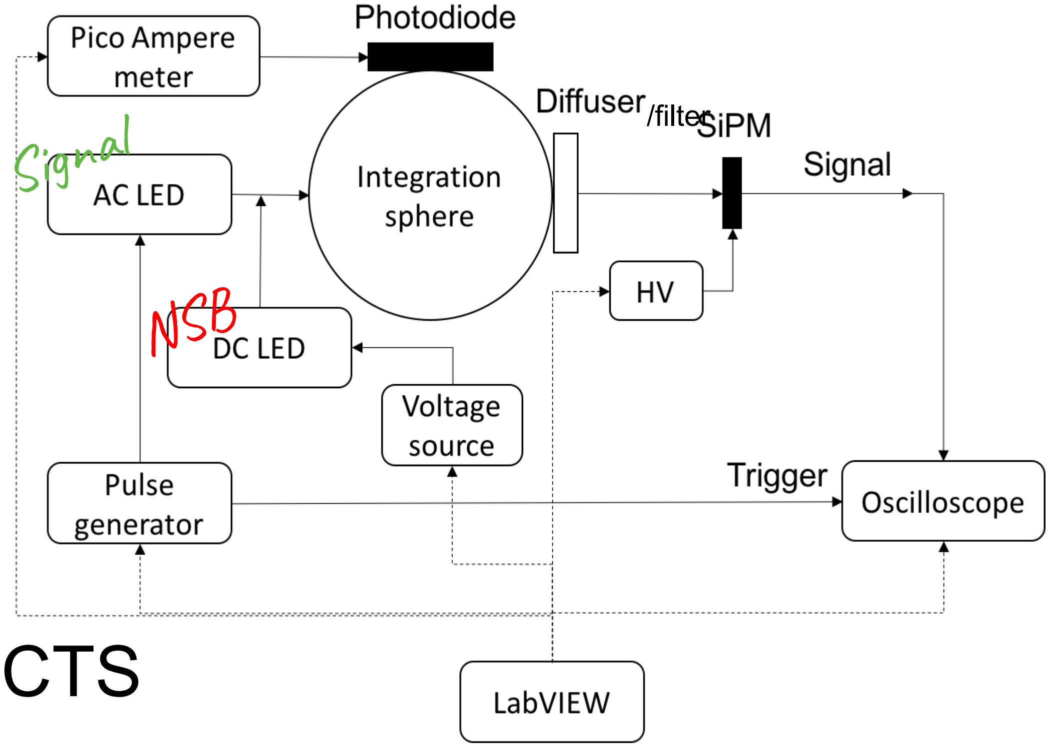
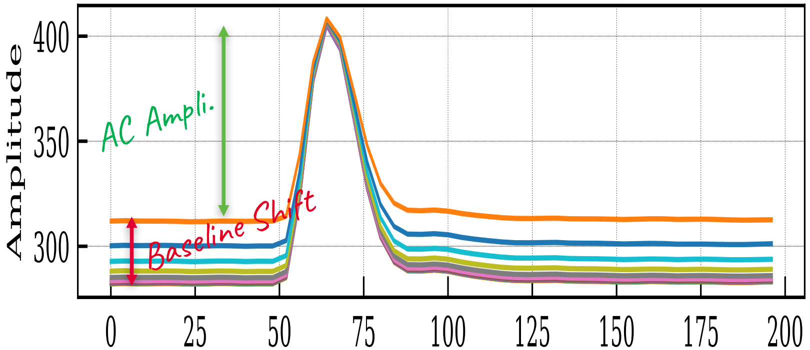
1.@ Unige/Ideasquare

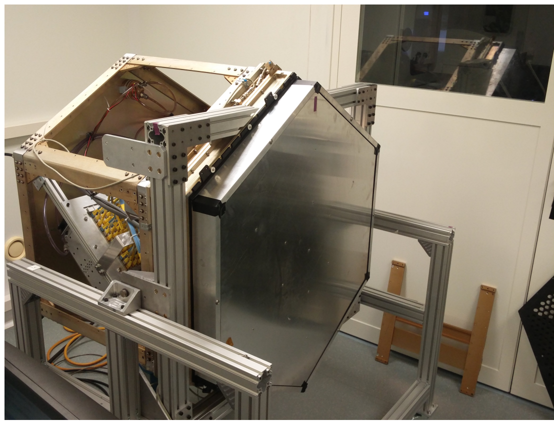


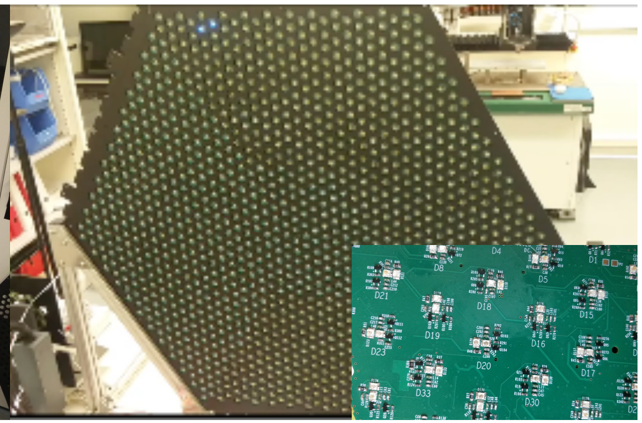


5. With SST-1M camera and CTS

- DC LED (470 nm)/ch mimic NSB
- AC LED (470 nm)/ch mimic Shower







AC/DC scan: Model Validation @ Cern/Unige

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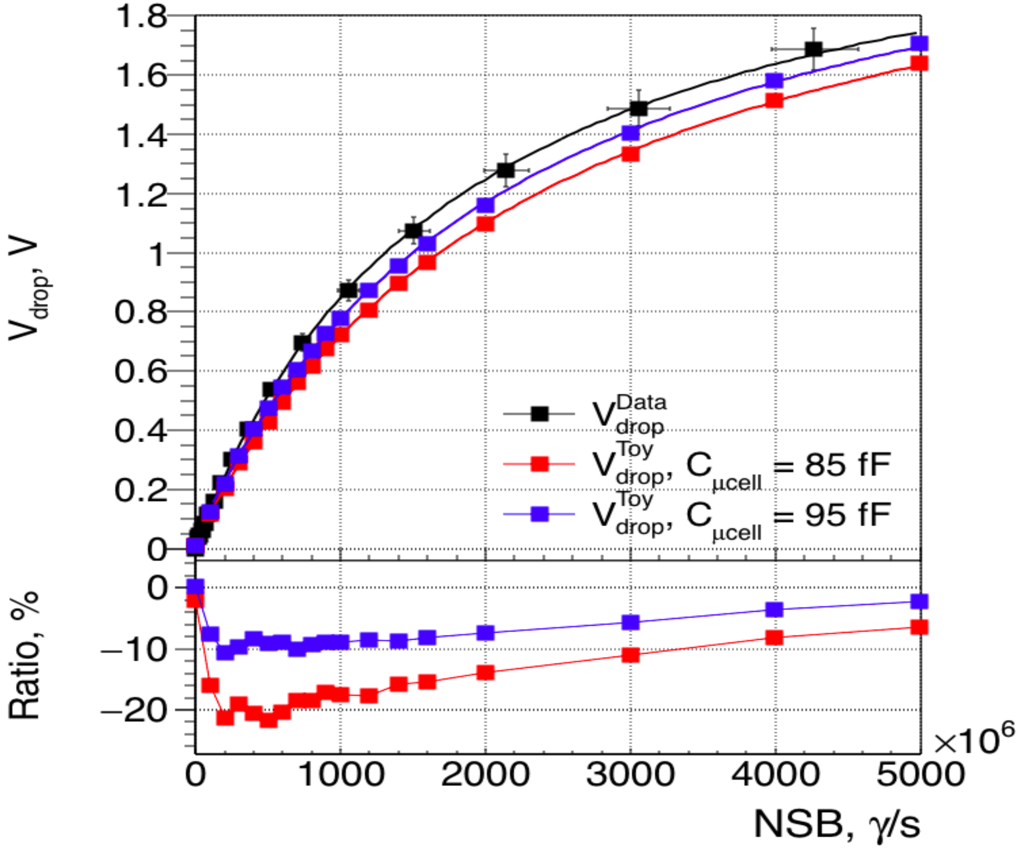
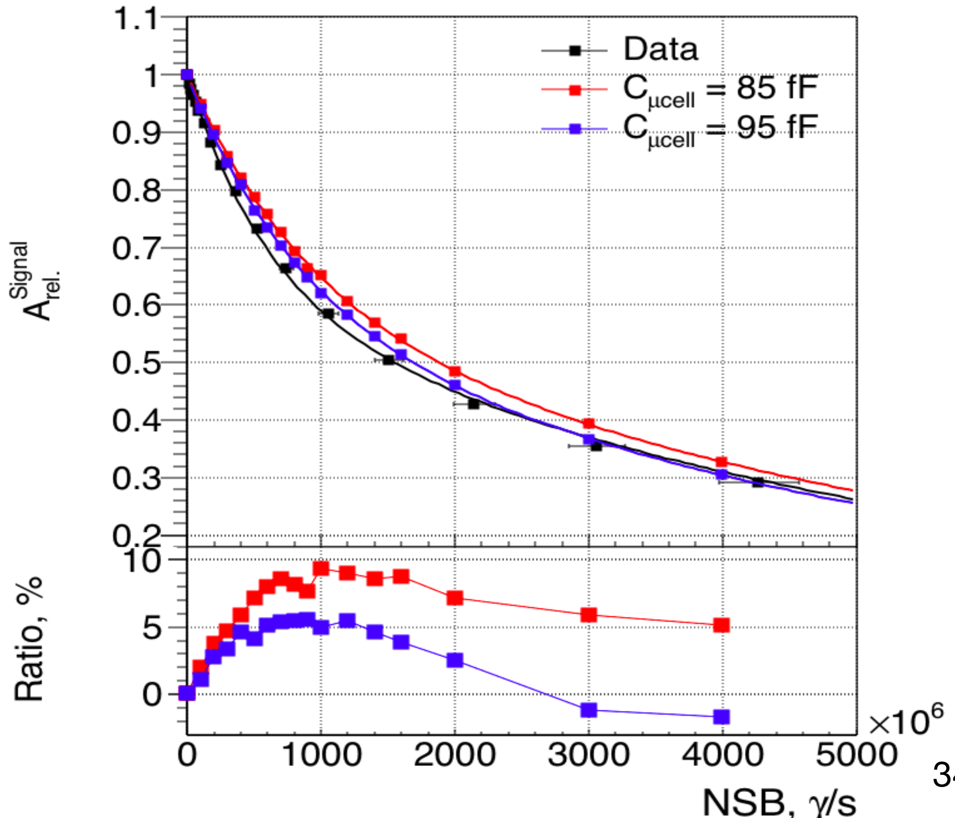
- DC intensity scan:
  - V_{drop} vs. NSB;
  - Baseline Shift vs. NSB

- AC/DC scan: AC intensity constant and DC intensity changes
  - Amplitude vs. NSB
  - Amplitude vs. Baseline Shift

$$A_{rel.} = \frac{AC\ Ampli.(NSB)}{AC\ Ampli.(NSB = 0)}$$





The CTS as calibration tool and AC/DC scan

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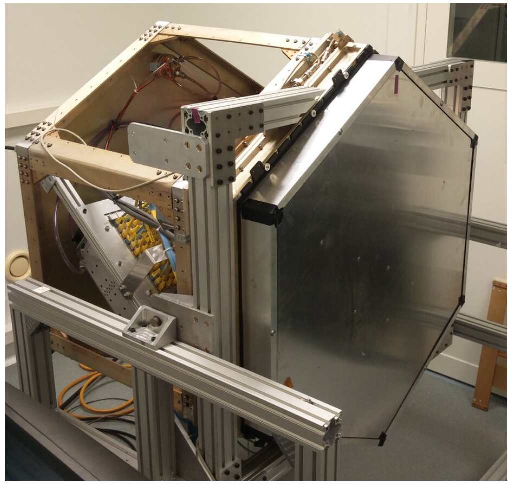
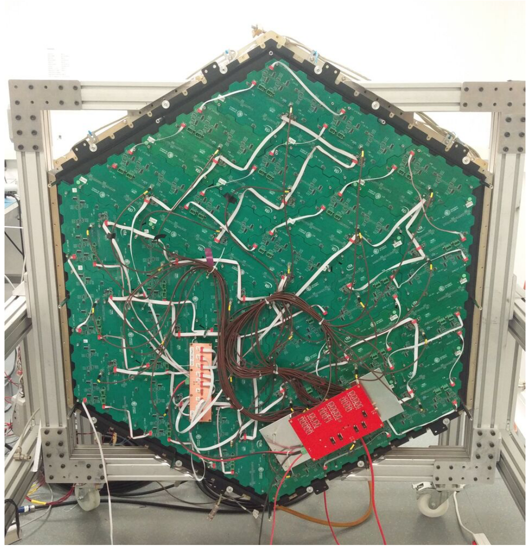
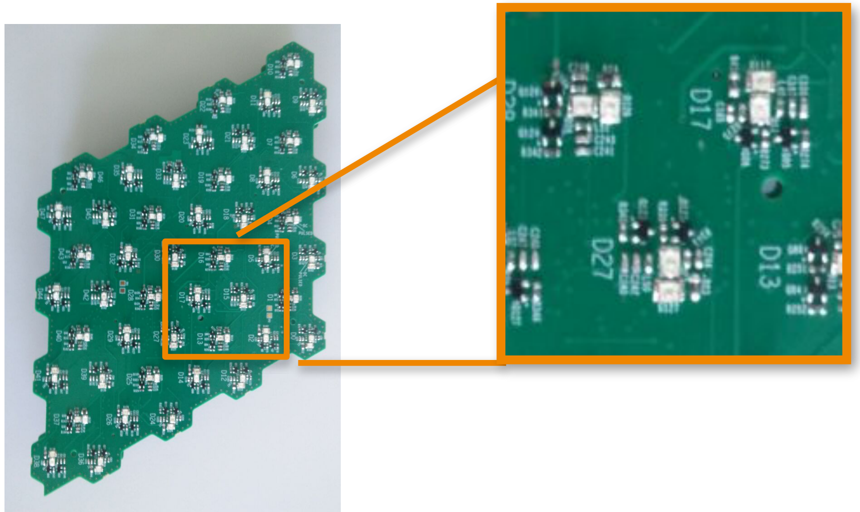
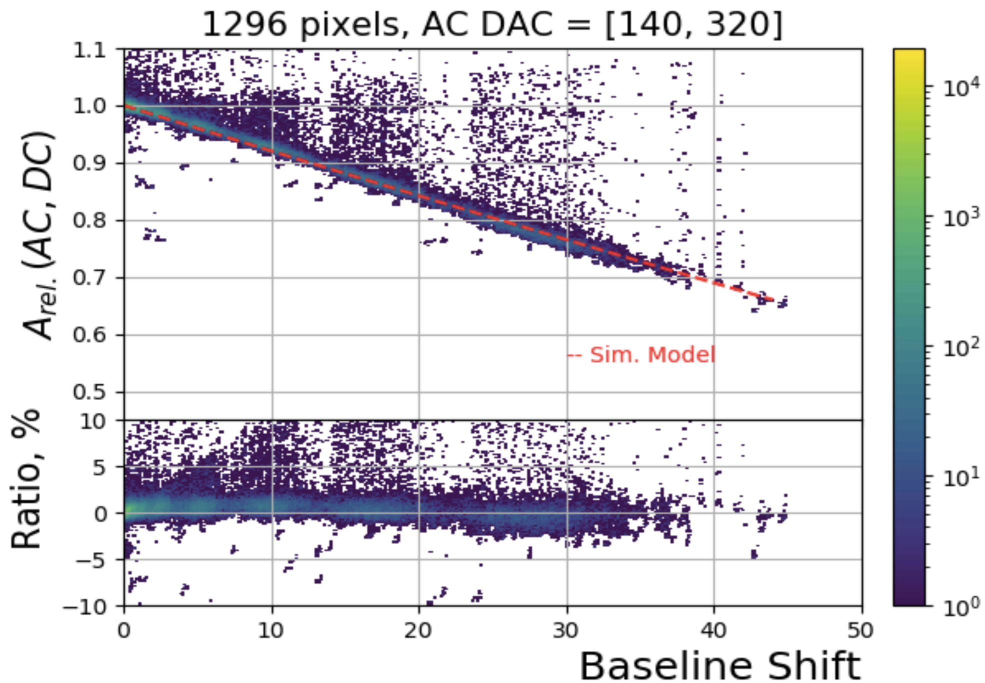


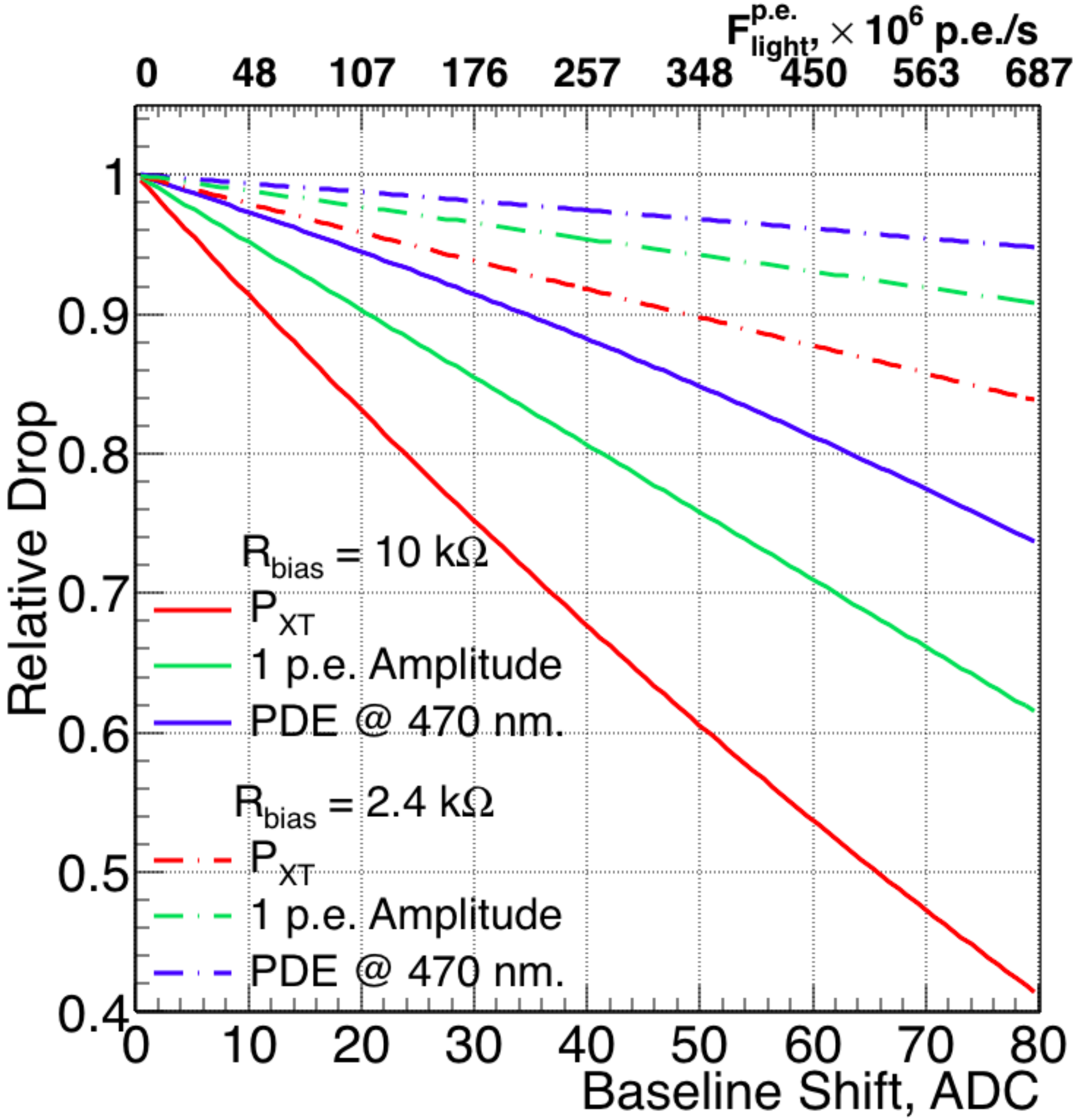


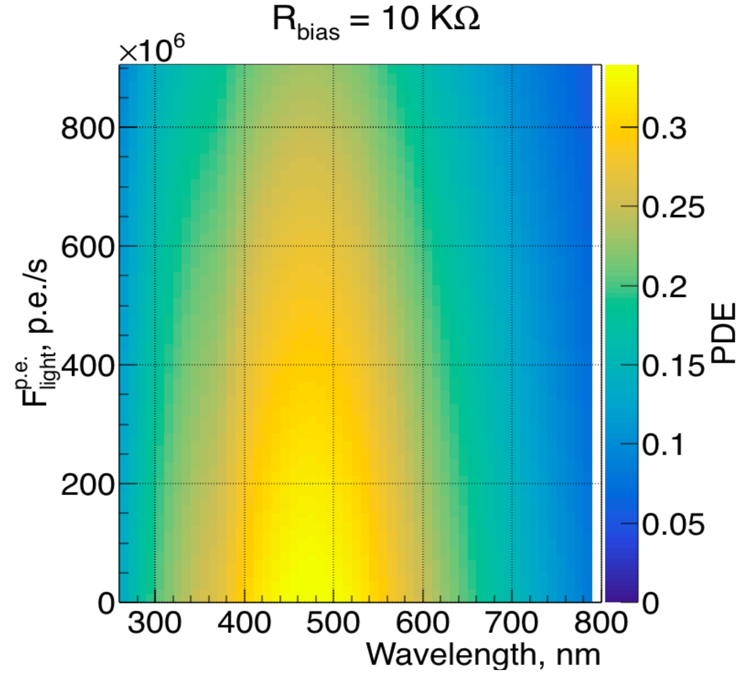


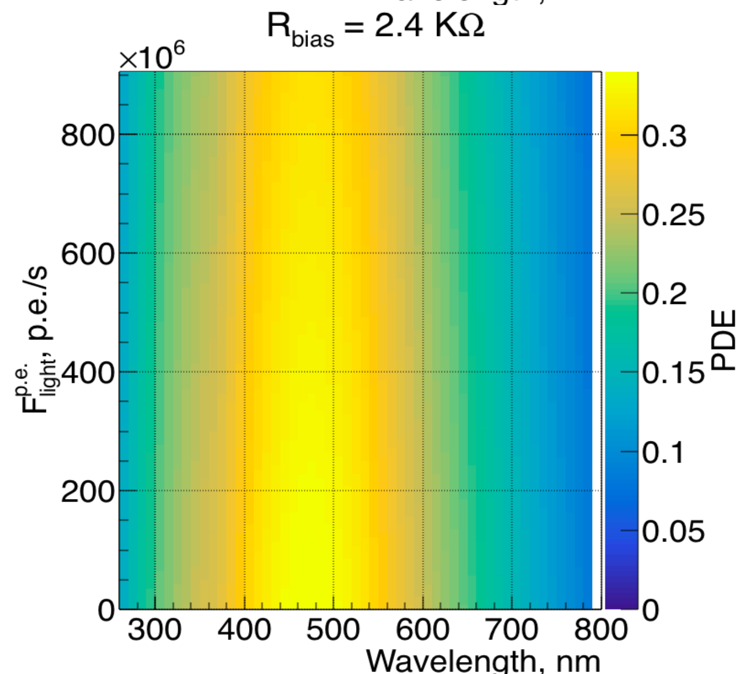
- Pulsed and continuous light for each pixel (2 LEDs)
- Status (On/Off) controllable for each LED
- Calibration of SST-1M camera in 1 day after calibrating the LEDs
- Fully autonomous (just requires 230 V), can be operated on site for camera recalibration (e.g. after module replacement)



Results: SiPM under NSB

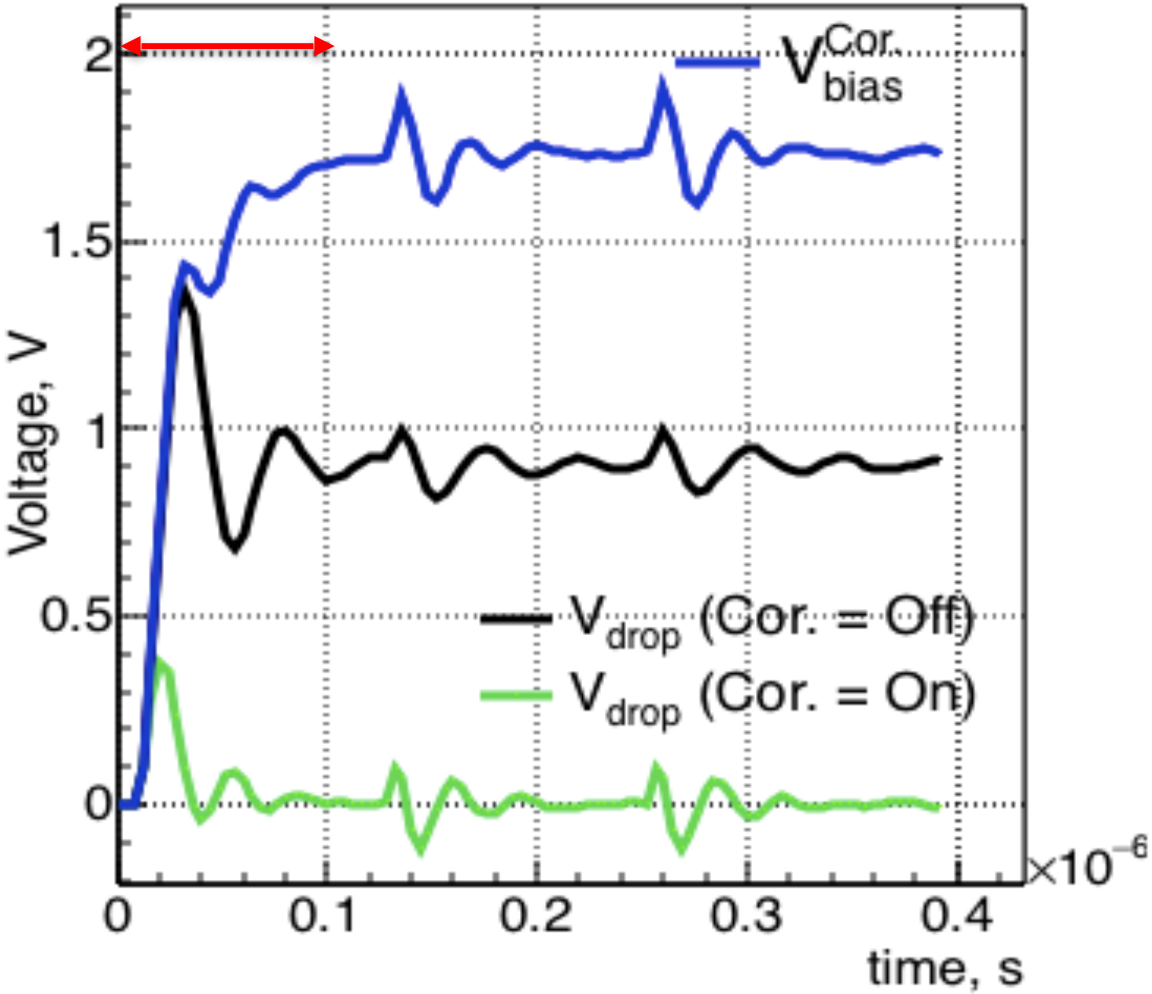






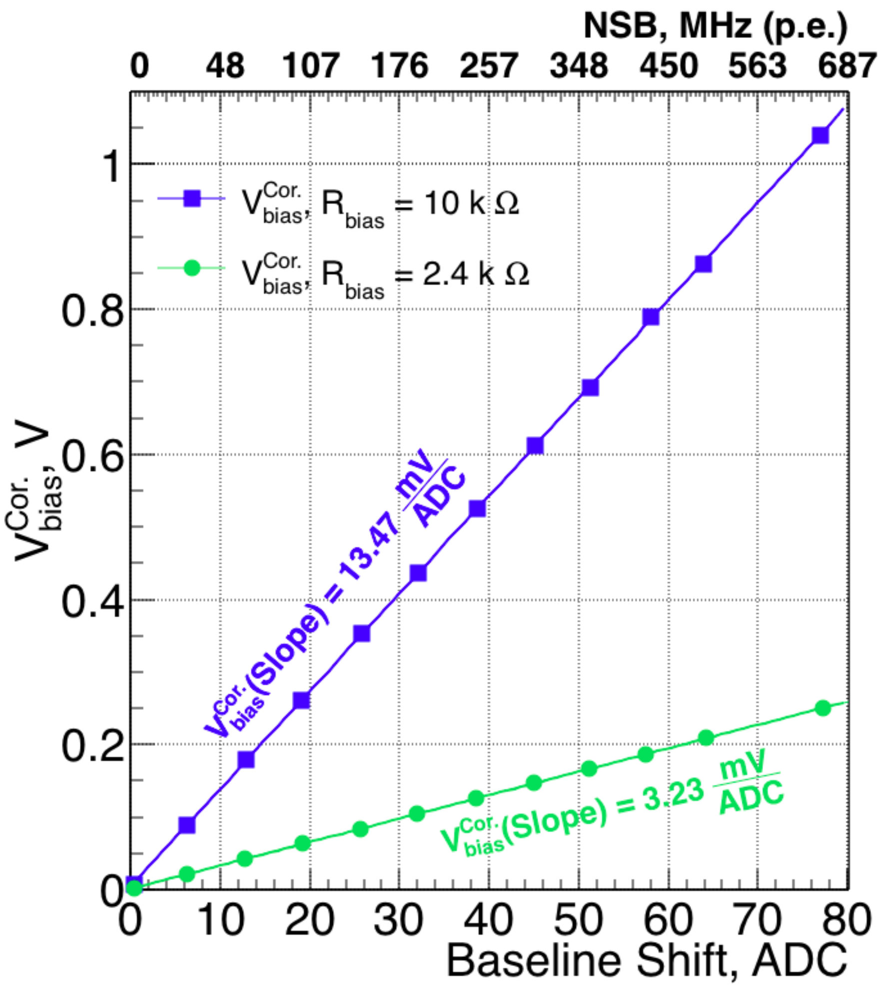
Voltage drop: compensation loop

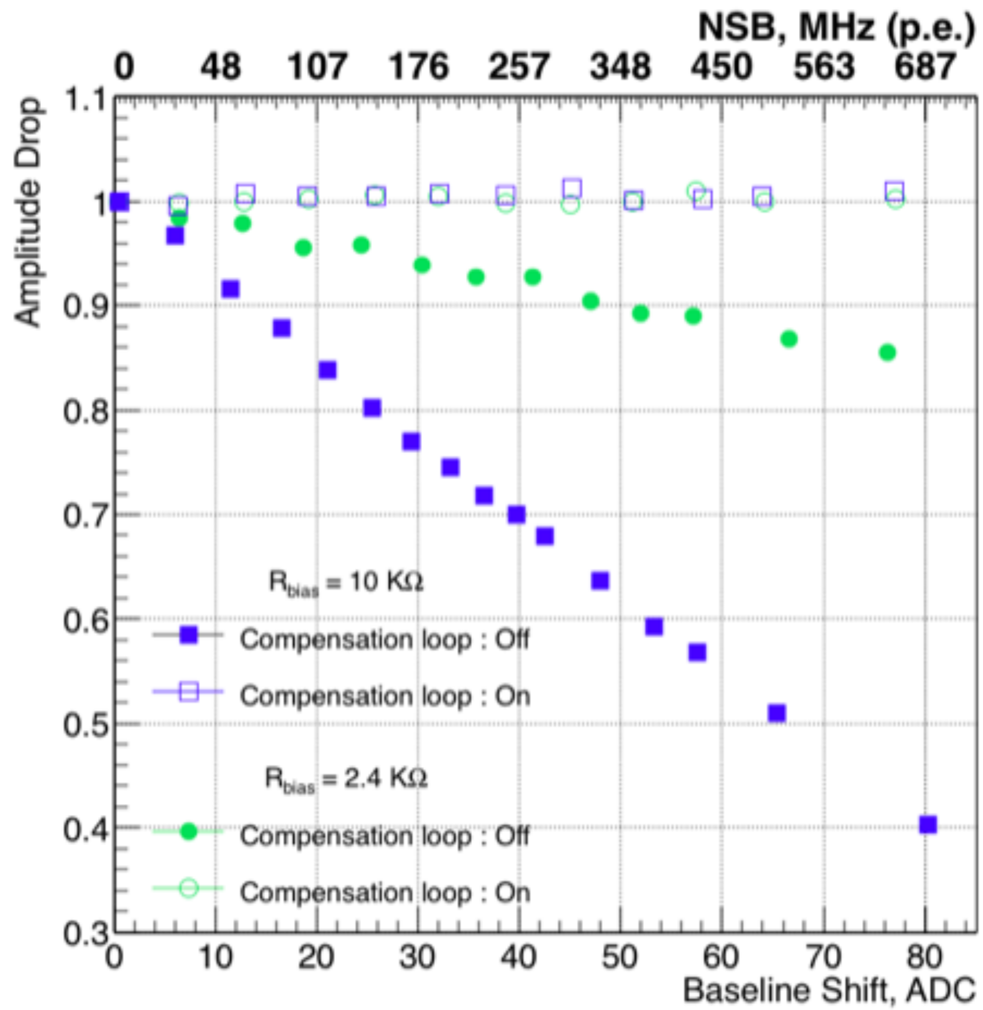
Transition time (100 ns) $NSB = 2 \times 10^9\ \gamma/s$



No voltage drop after transition time!

Voltage drop: compensation





By increasing V_{bias} constant ΔV can be achieved → Amplitude stability is ± 1.5 %

Calibration strategy for operation

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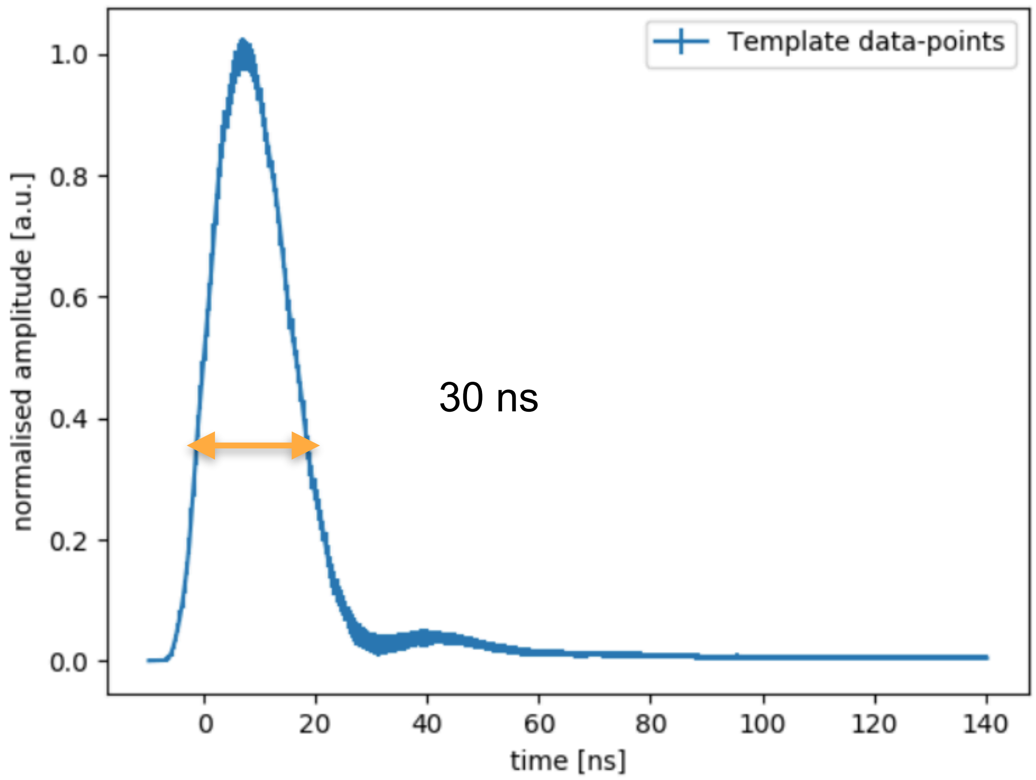
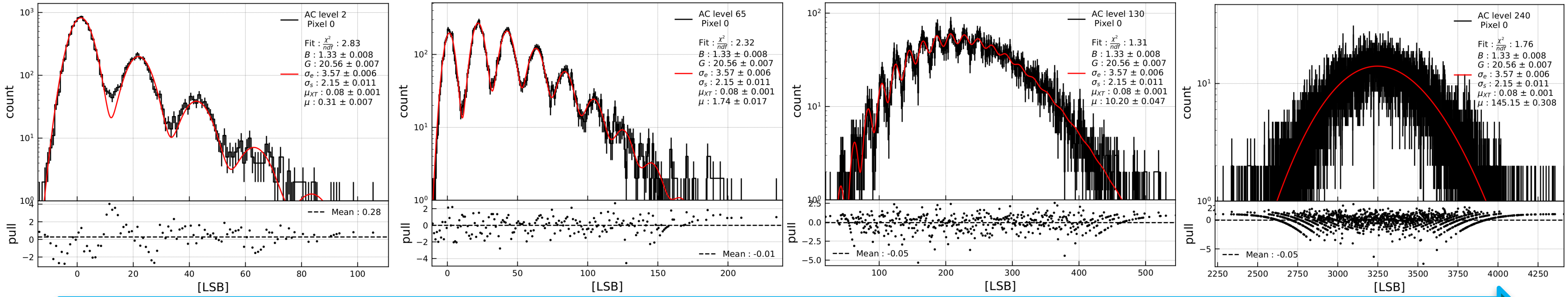
- Extraction of SiPM and readout parameters per pixel in the laboratory
  - gain, optical cross talk, dark count rate, noise, etc…
- Monitoring of these parameters during operations
  - Dark count run
  - Flasher runs
- Image reconstruction accounts for up to date calibration parameters

Signal shape after preamplifier

Average SiPM pulse for all pixels in the camera
for a single photon equivalent (1 p.e.)



Calibrations in the lab



Increasing light level

Smeared generalized Poisson evaluated for a given light level *j*:

$$P(C_j = x) = \sum_{k=0}^{\infty} \frac{\mu_j(\mu_j + k\mu_{XT})^{k-1}}{k!} e^{-\mu_j - k\mu_{XT}} \frac{1}{\sqrt{2\pi}\sigma_k} e^{-\frac{(x-k\bar{G}-\bar{B})^2}{2\sigma_k^2}}$$

With $\sigma_k^2 = f\Delta t \sigma_e^2 + k\bar{G}\sigma_s^2$

f: sampling frequency

Δt: integration window

G: charge gain, i.e. pulse integral

B: residual charge

μ_{XT}: Cross talk fraction

σ_e : electronic noise

μ_j: average p.e. number

Maximum log-likelihood estimation per light level and per pixel:

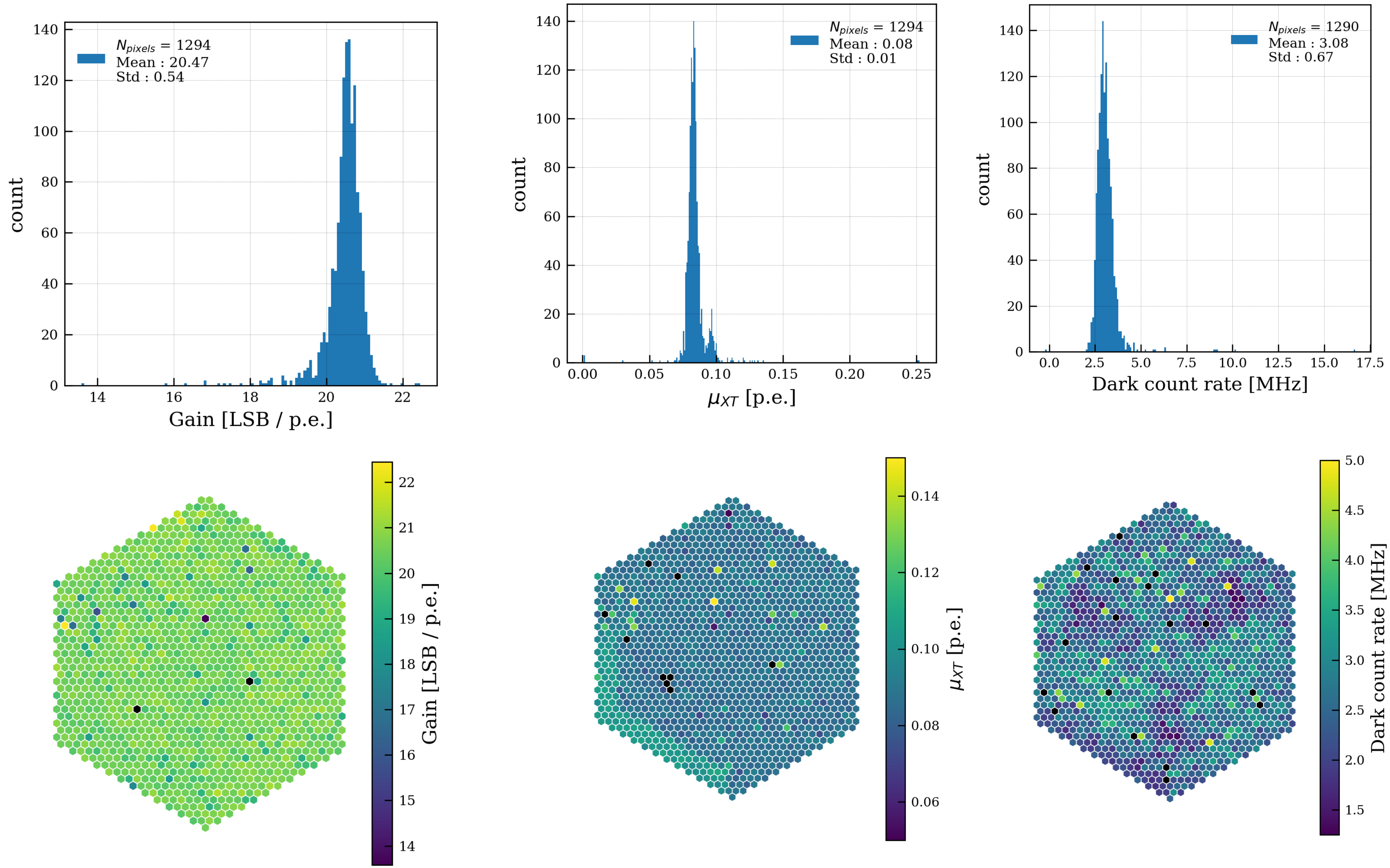
$$l(\vec{\theta}; C_j) = \frac{1}{N_w} \sum_{i=1}^{N_w} \ln \mathcal{L}(\vec{\theta}; C_{ij})$$

($\vec{\theta}$: fit parameters)

All fitting parameters are independent of the light level (LL), aside from μ_j => all light levels are combined for the fitting (N_{LL}+4 instead of 5 x N_{LL} free parameters):

$$\hat{l}(\vec{\theta}; C) = \frac{1}{N_w N_{AC}} \sum_{j=1}^{N_{AC}} \sum_{i=1}^{N_w} \ln \mathcal{L}(\vec{\theta}; C_{ij})$$

Verification of performance with prototype in the lab



Verification of performance with prototype in the lab

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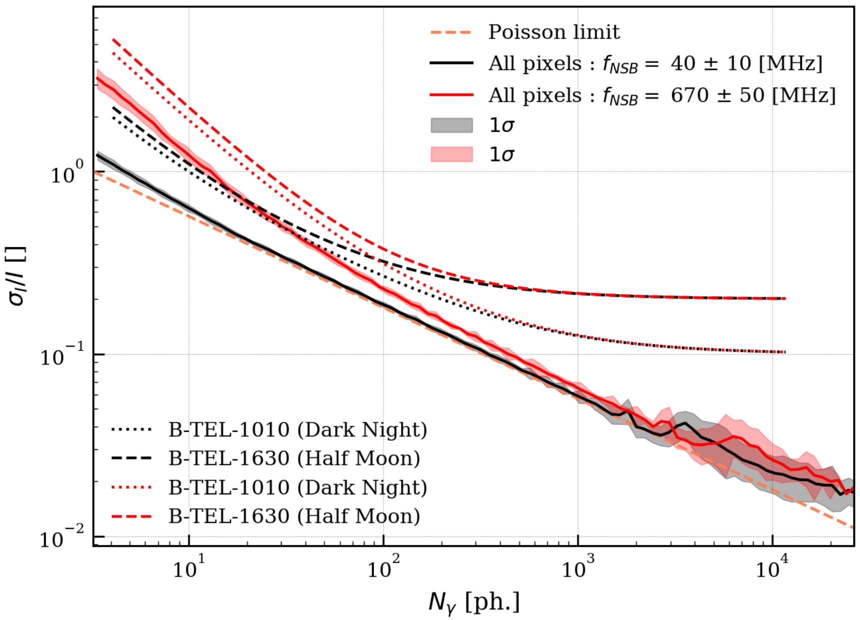
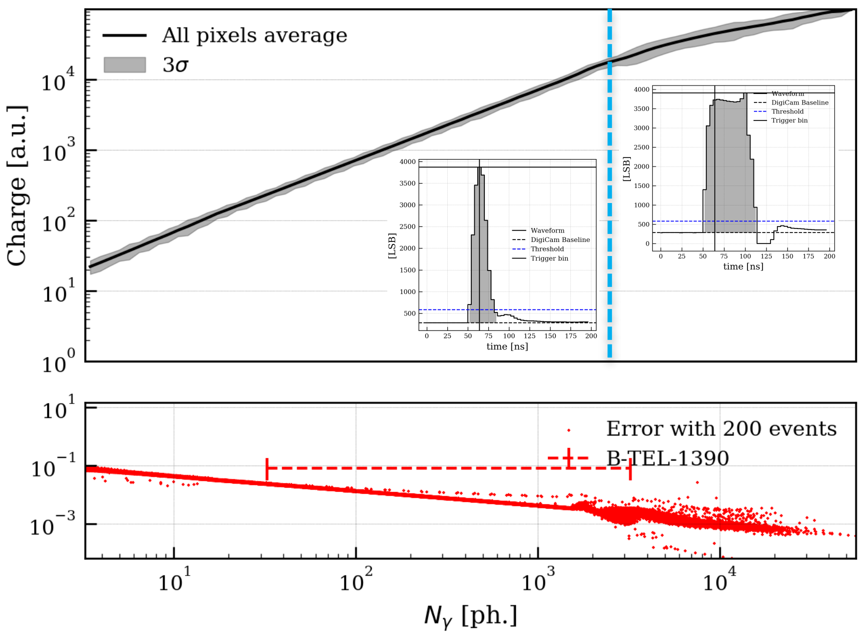
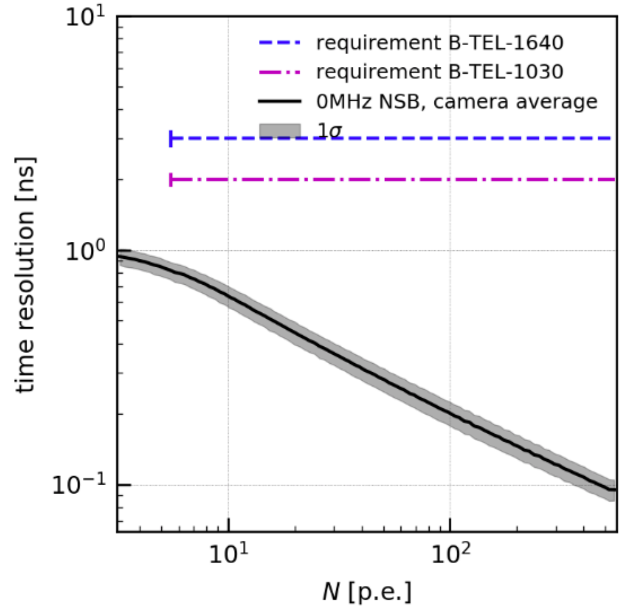
Charge resolution



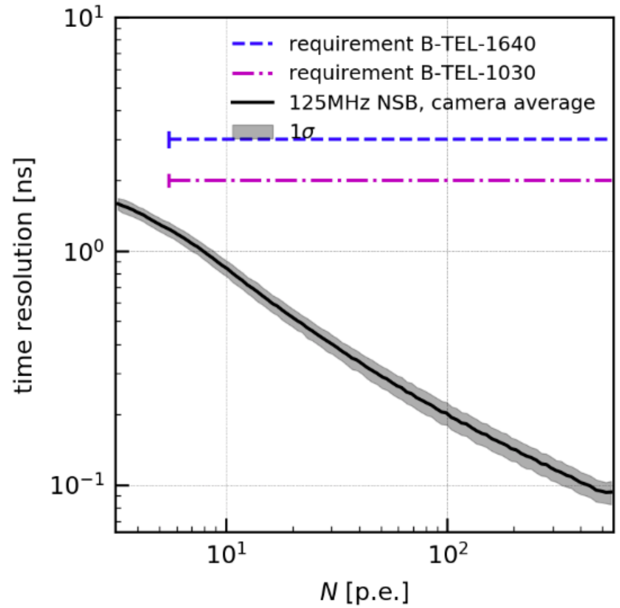
Response linearity



Dark conditions

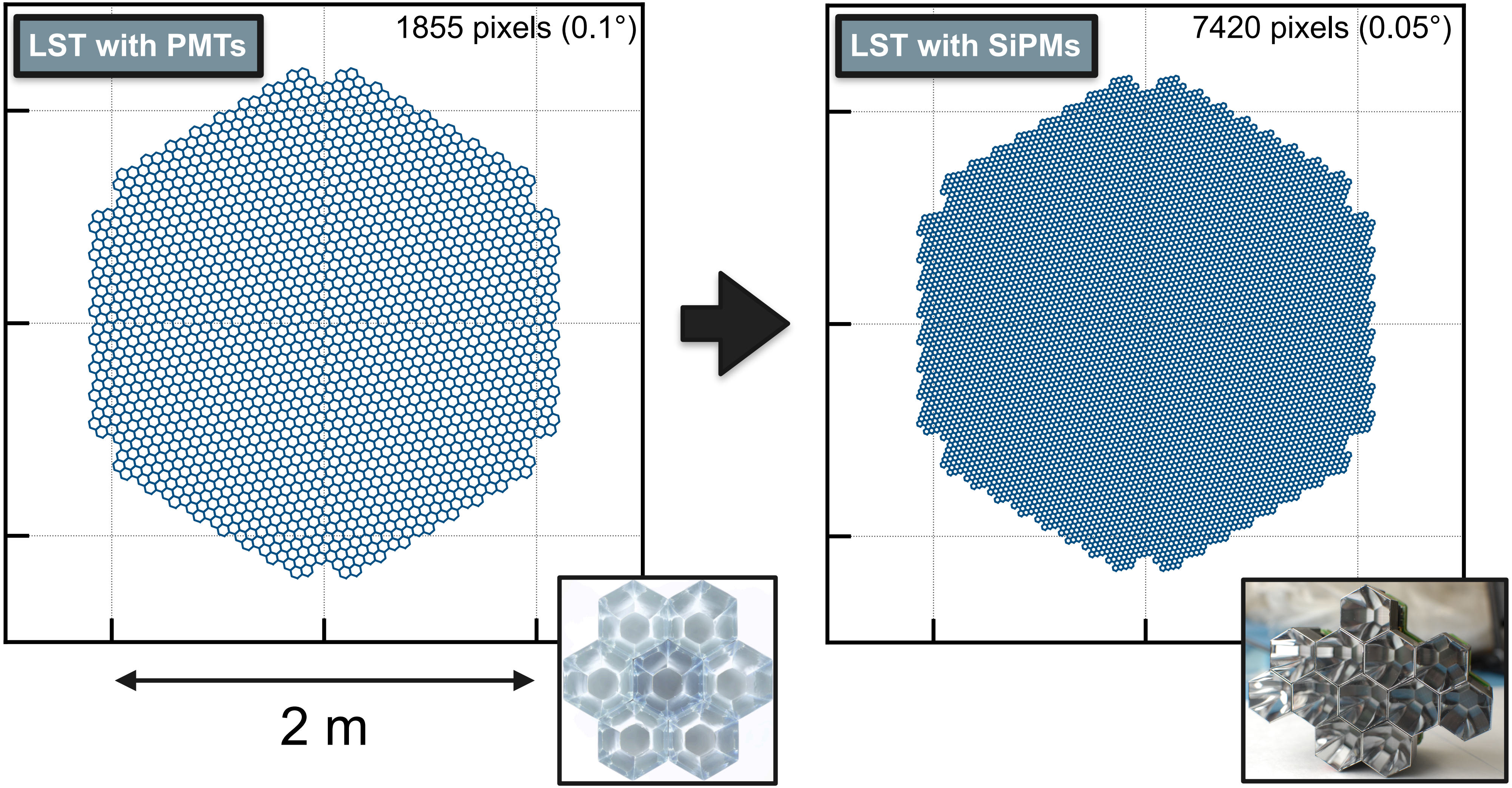


125 MHz/pixel NSB



A vision of the future

- Apply the same pixel technology to larger cameras, e.g. the LST camera for the CTA project



A vision of the future

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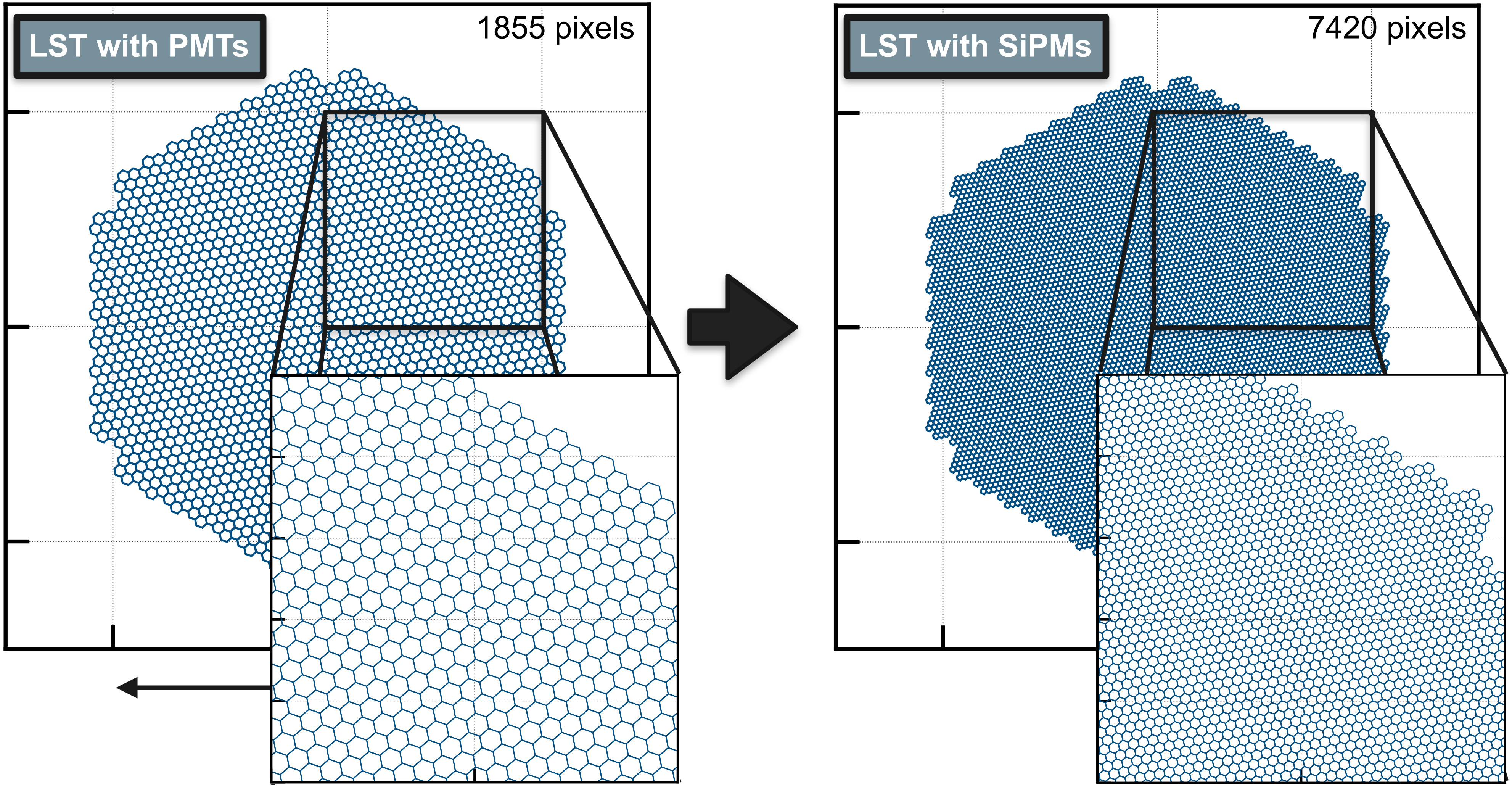

Application of ASICs: CITIROC

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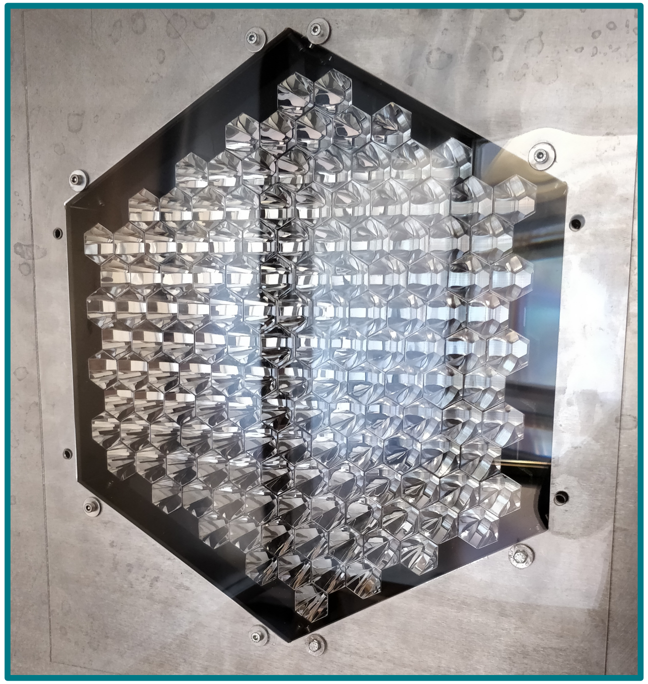
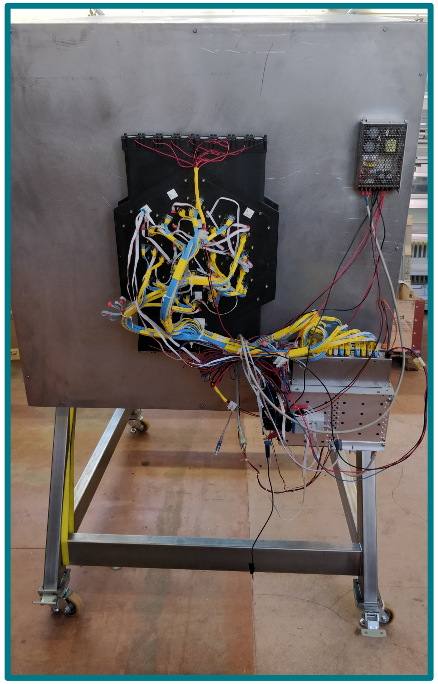
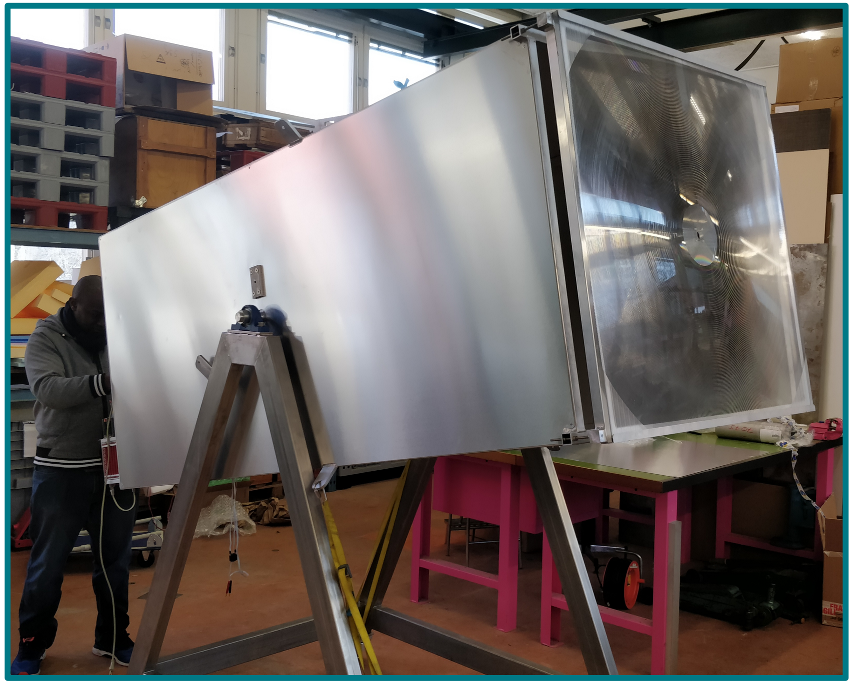
- Combine Front End Boards based on the CITIROC ASIC (Weeroc) and developed at UniGe for the BabyMind experiment with the optical modules developed for the SST-1M camera to build a 144 pixels camera for atmospheric showers detection



144 pixels camera



Readout system



Telescope structure

Application of ASICs: CITIROC

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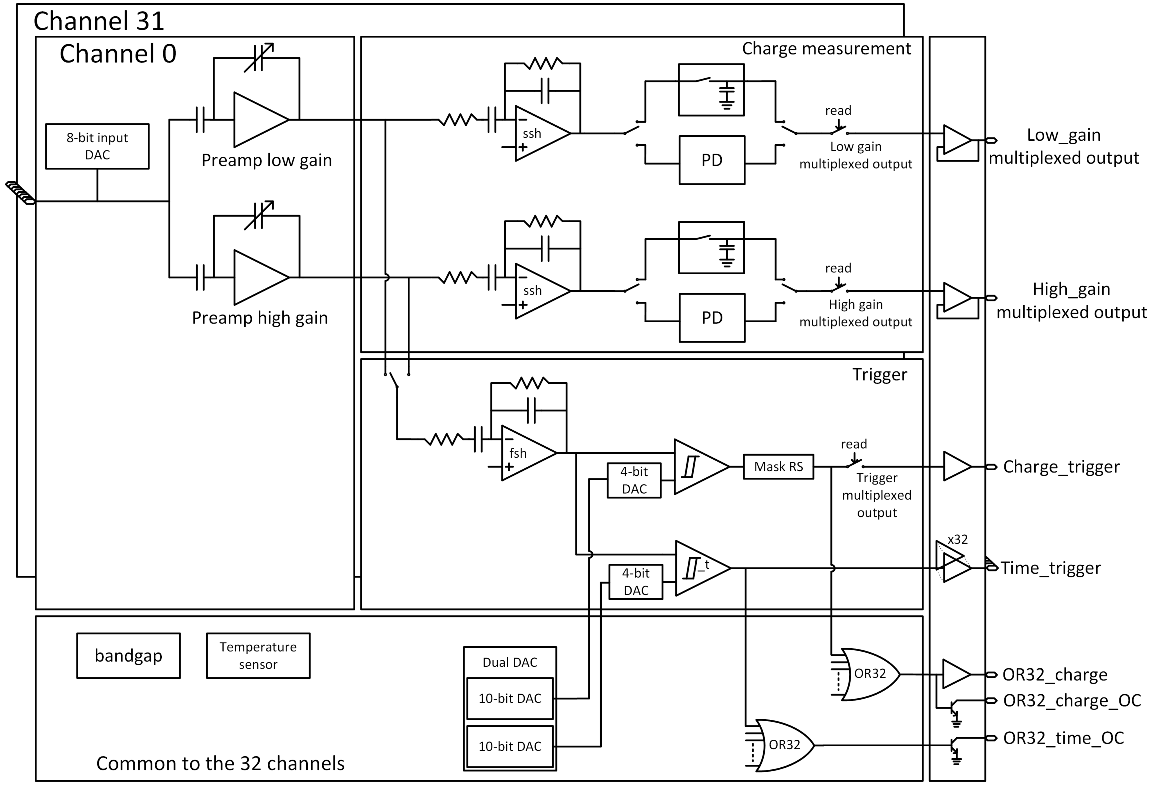


CITIROC block diagram

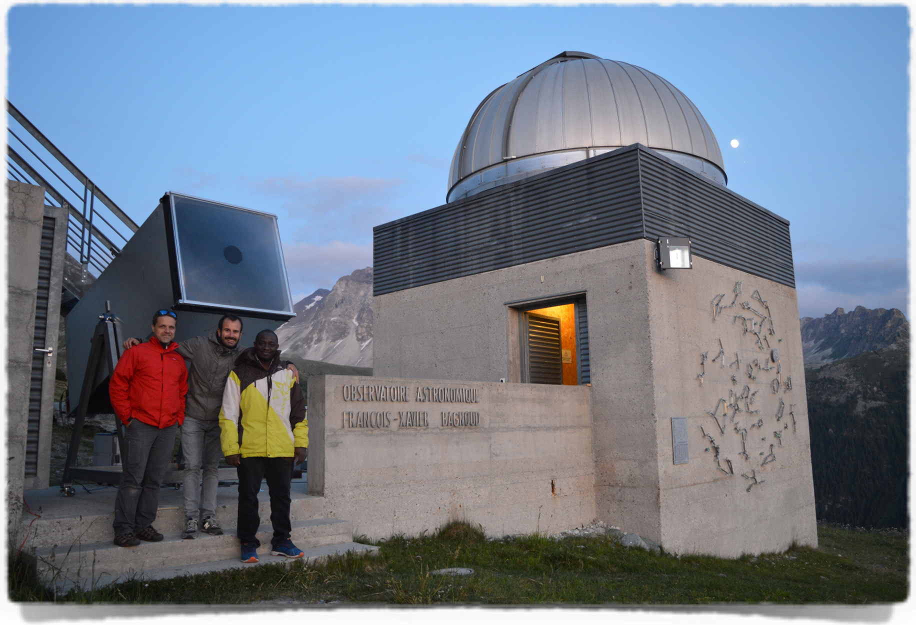
Main advantages:

- Dual gain + ToT
  ➡ Large dynamic range
- Variable gain preamplifier per channel
  ➡ Gain equalisation

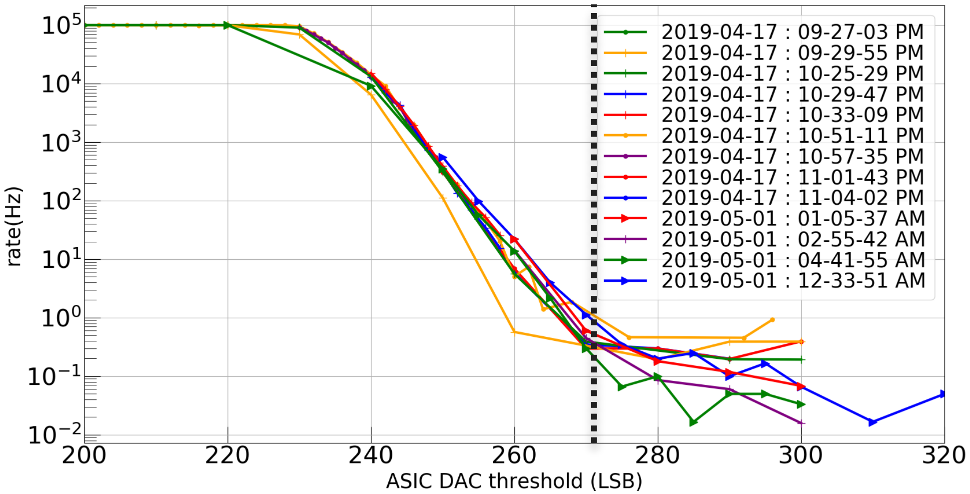
Main drawbacks:

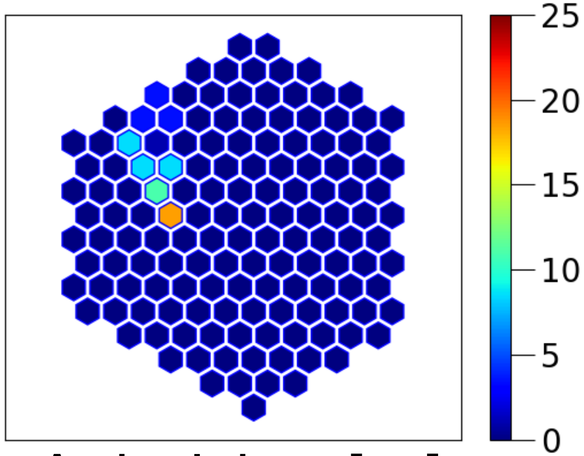
- Multiplexed amplitude readout
  ➡ Deadtime of 9.12 μs to read one event
- Different shaper for amplitude and trigger
  ➡ Single channel calibration

Application of ASICs: CITIROC

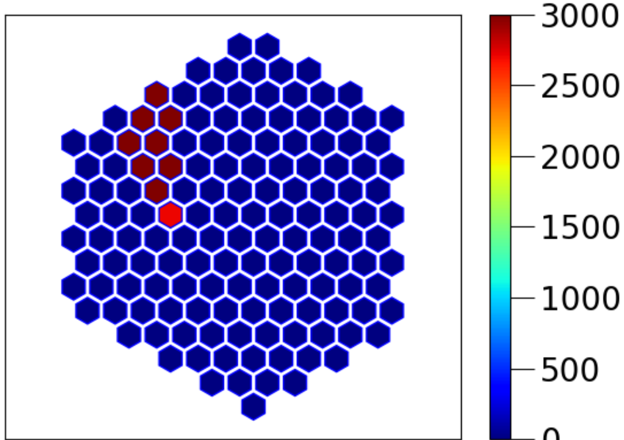


- Observation campaign @ OFXB in Saint Luc (Valais, Switzerland)
- Trigger rate scan to determine acquisition threshold

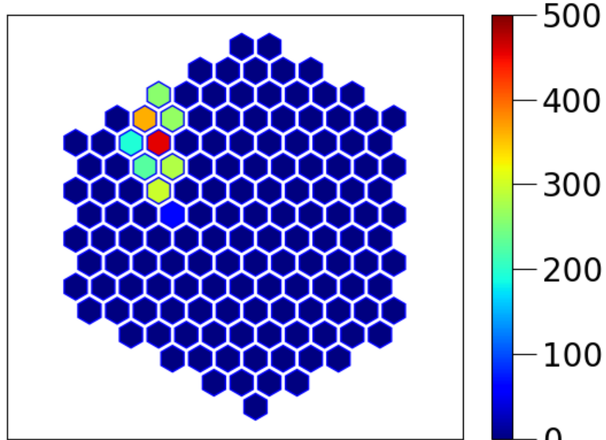




Arrival time [ns]



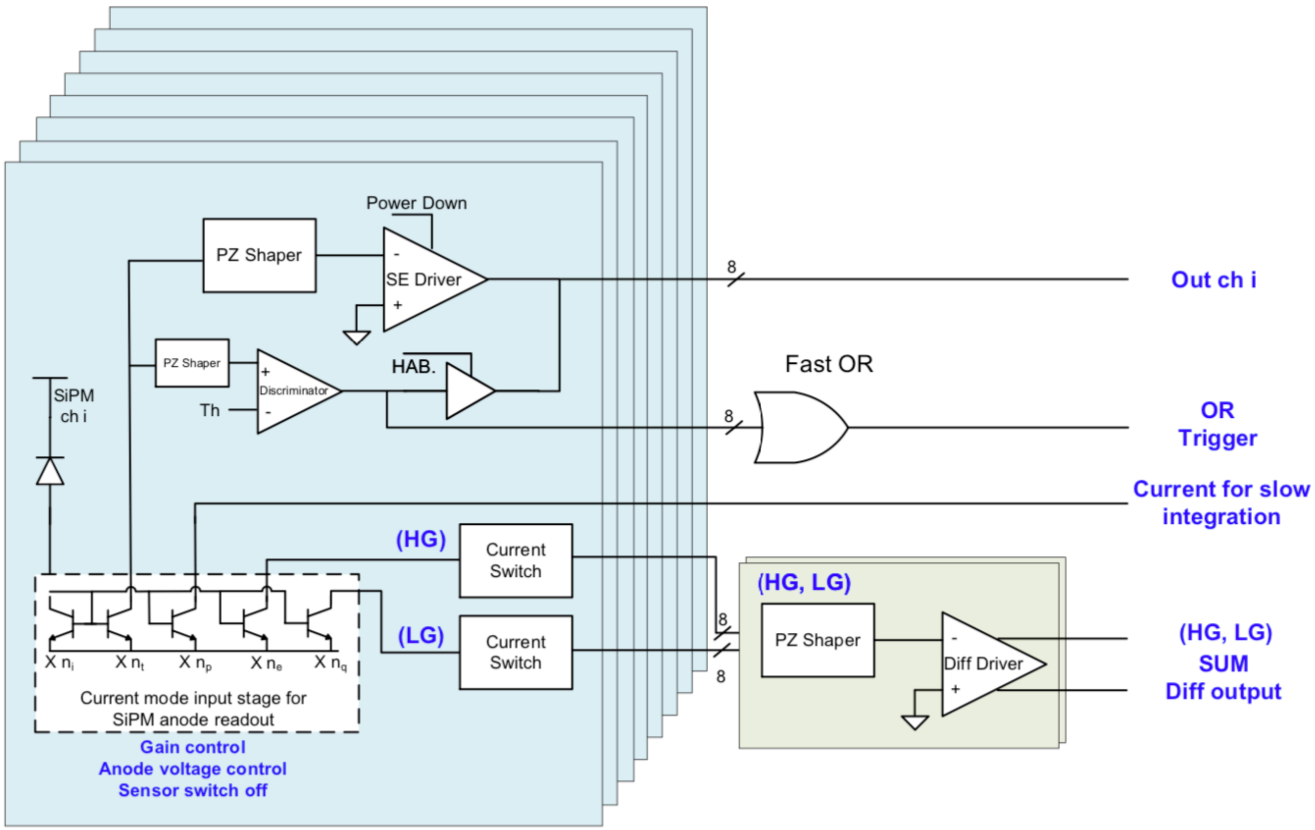
ADC counts HG



ADC counts LG

Application of ASICs: MUSIC

- The MUSIC ASIC (ICC-UB) intends to tackle large SiPM surfaces by offering a summation path



MUSIC block diagram

Main advantages:

- Dual gain
  ➡ Large dynamic range
- Variable gain preamplifier per channel
  ➡ Gain equalisation
- Pole Zero Cancelation
  ➡ Shorter pulses
- Summation of channels
  ➡ Larger pixels readout, trigger output for group of pixels

Main drawbacks:

- Current version has only 8 channels

Application of ASICs: MUSIC

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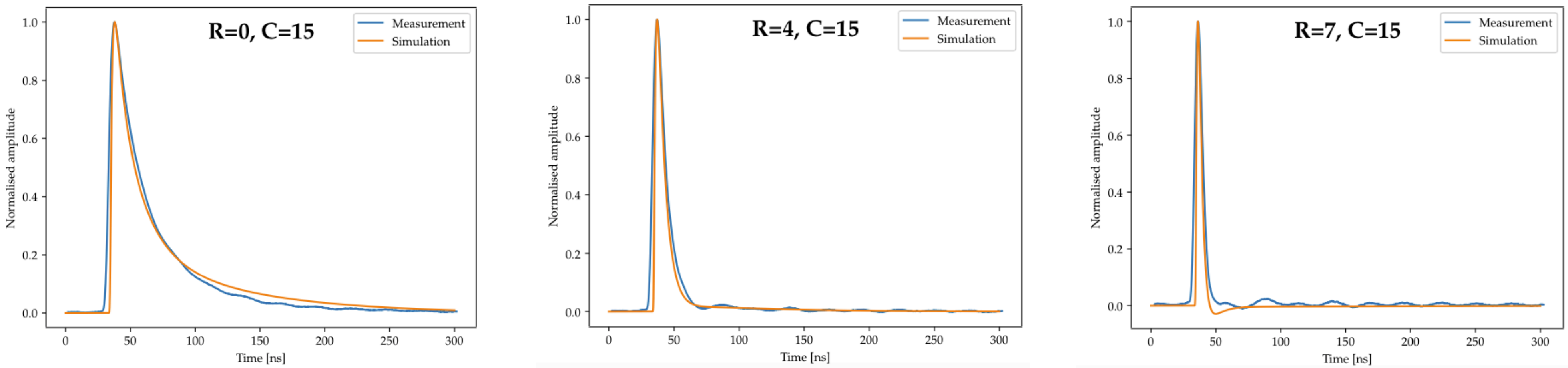
- The MUSIC response has been be fully simulated by the ICC-UB group and shows great agreement with measurements

Example with LVR3 6x6 mm²

N. De Angelis CERN-THESIS-2019-084



Example with LCT5 3x3 mm²