SiPM Nuisance Parameters

Alberto Gola
On behalf of the Nuisance Parameters Topical Group

gola@fbk.eu

Nuisance Parameters Topical Group

7 Members, meeting by phone regularly since 3 months.

Alberto Gola

Johannes Breuer

Antonio Ciarlone

Gianmaria Collazuol

Eugen Engelmann

Elena Popova

Nepomuk Otte

Fabrice Retiere

Sergey Vinogradov

Results:

List of relevant topics

- Types of noise, experimental methods, special structures, alternative methods, effects on applications

General agreement in the group

- Apart from details or optional data processing

Presentations from the group on the most general topics

- Time is limited, allow some time for discussions

To Do:

In the paper that will be written

- Provide a final set of recommendations
- Analyze minor topics

Nuisance Parameters Topical Group

Presenter	Talk
A. Gola	Noise Sources in SiPM
S. Vinogradov	Statistical Modeling of SiPM Noise
E. Engelman	SiPM Noise Measurements with Waveform Analysis
D. Strom	Direct Measurement of Optical Crosstalk in SiPMs Using Light Emission Microscopy
F. Retiere	Experimental SiPM Parameter Characterization from Avalanche Triggering Probabilities
H. Tajima	Suppressing Optical Crosstalk in SiPMs
J. Breuer	Simulation of SiPM Noise

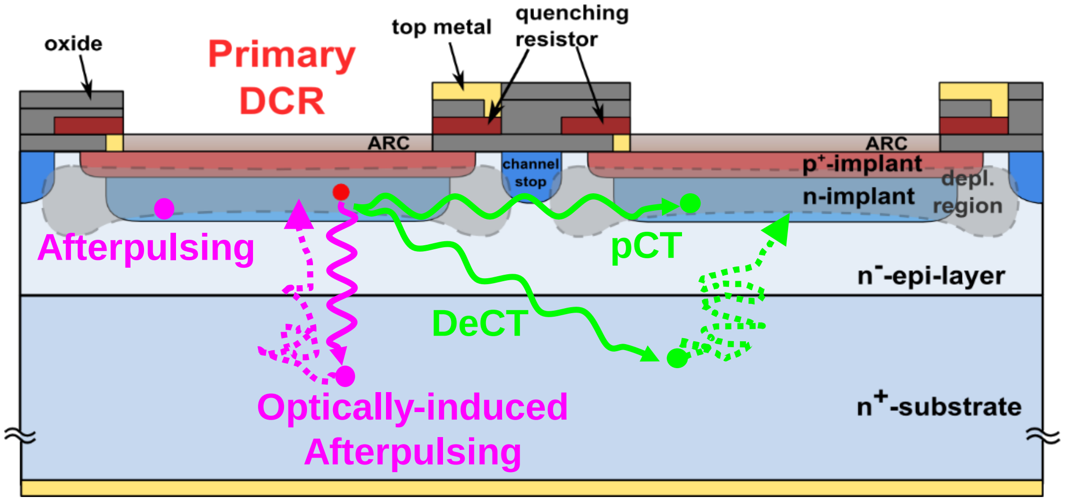
Noise Sources in Silicon Photomultipliers

Alberto Gola
On behalf of the Nuisance Parameters Topical Group

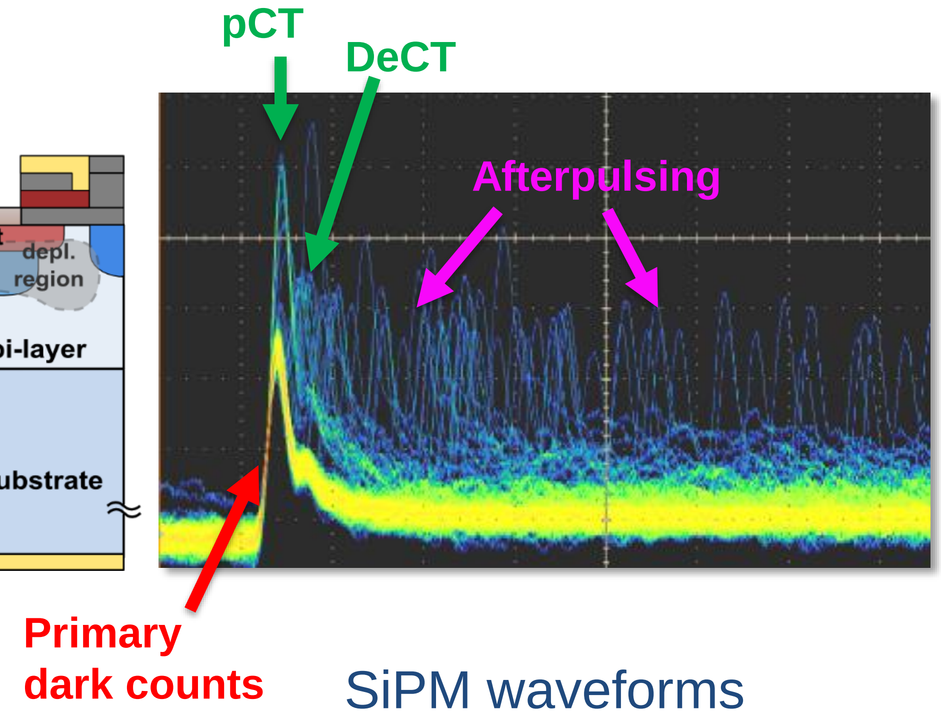
gola@fbk.eu

Noise in SiPMs

Different SiPM noise components are related to different physical phenomena.



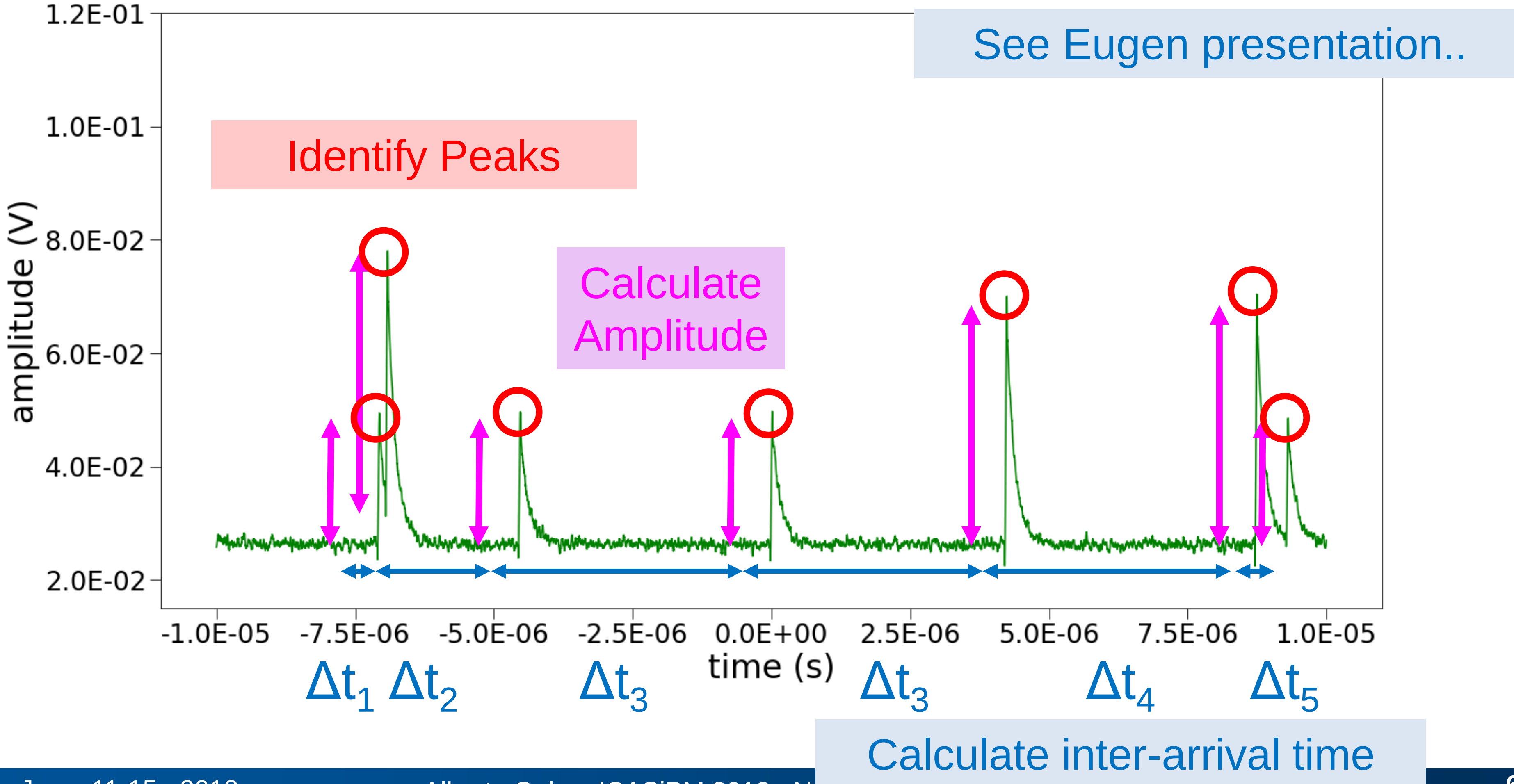
Cross-section of the SiPM microcells.



SiPM waveforms acquired with the oscilloscope

Typical Measurement Technique

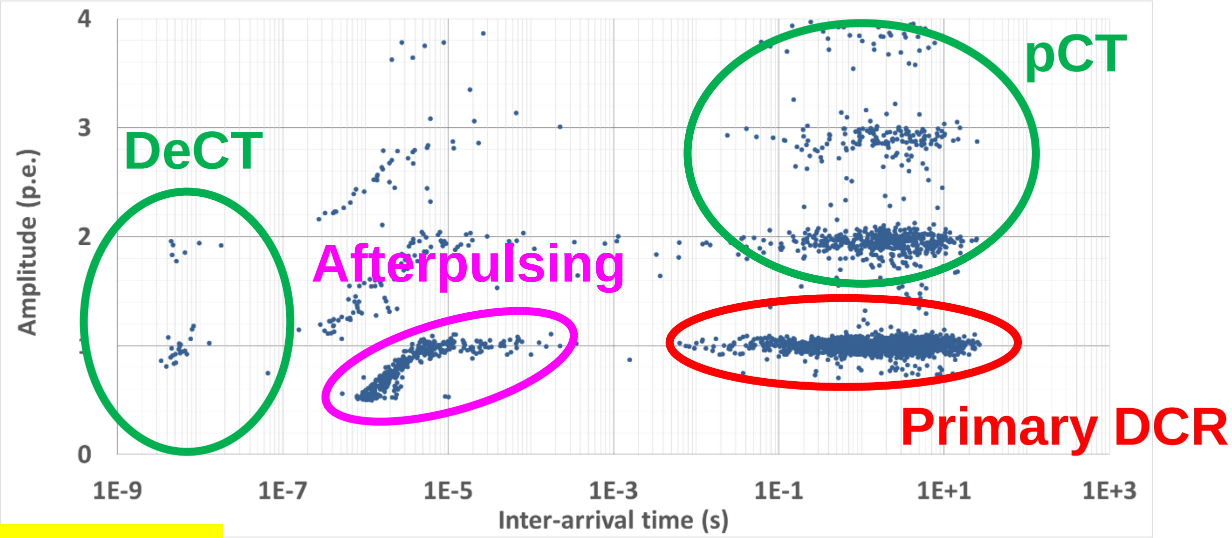
Acquire continuous waveform, filter and post-process data to identify peaks corresponding to dark counts. Then calculate inter-arrival times.



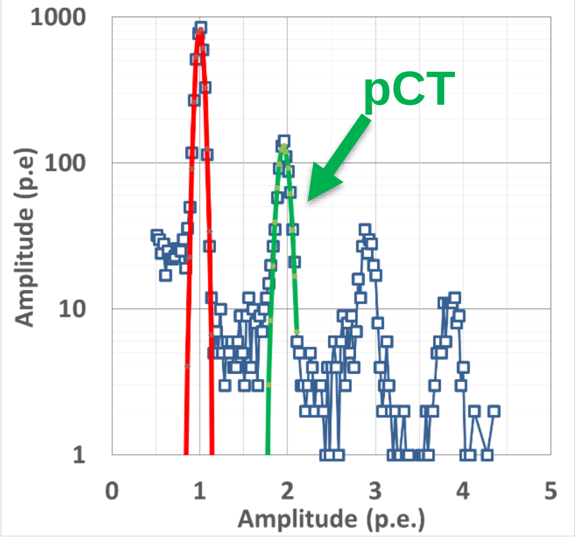
Scatter plot of different noise components

FONDAZIONE BRUNO KESSLER

Noise Scatter plot

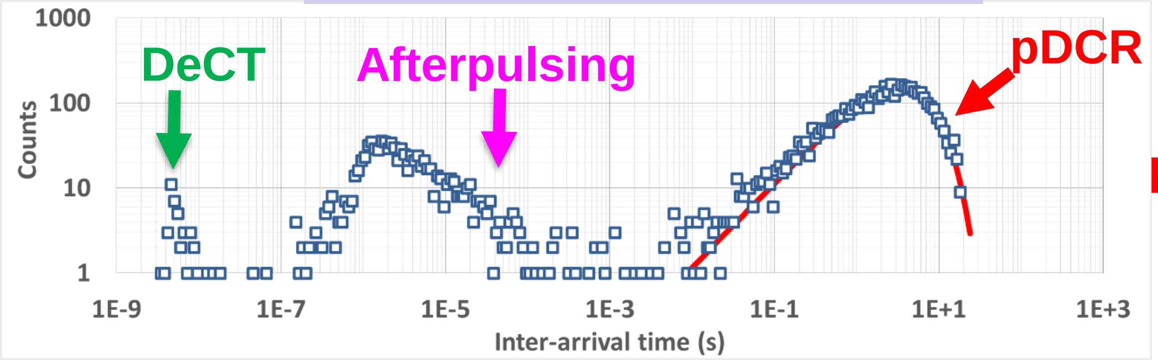


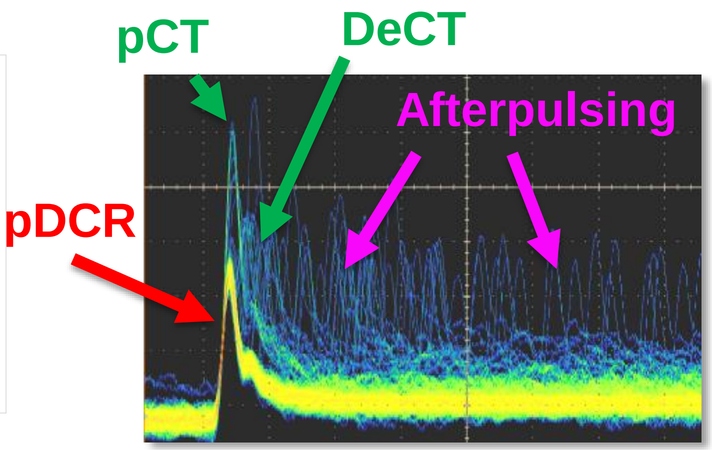
Amplitude histogram



77 K

Inter-arrival time histogram





← Sensitivity ≥ 12 orders of magnitude! →

Method proposed by C. Piemonte – NSS 2012 Conference Record

Primary, Poisson distributed DCR

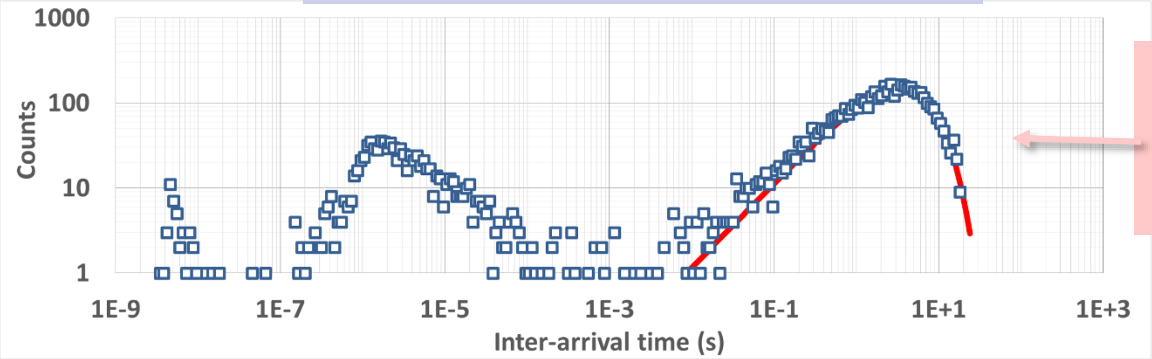
Primary Dark Counts occur when:

1. A couple of carriers is generated in the microcell because of thermal generation / tunneling
2. One of the two carriers is collected and passes through the high-field region
3. It triggers an avalanche

Generation and trigger of Dark counts are independent from each other

→ Primary DCR follows a Poisson distribution.

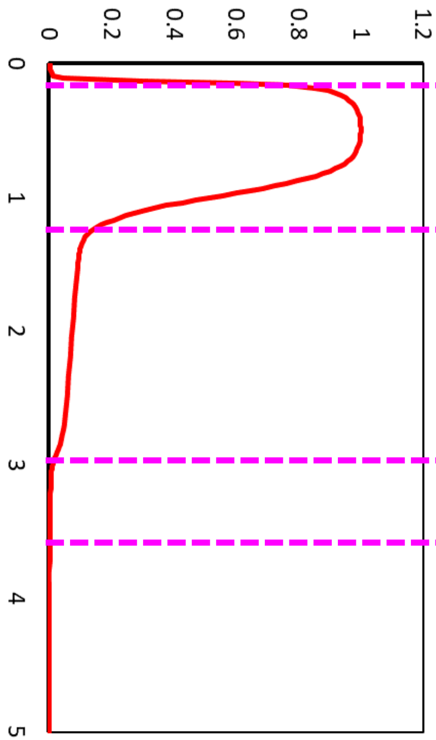
Inter-arrival time histogram



Exponential distribution of inter-arrival time (in bilog scale with log binning along X)

Sources of primary DCR

Electric Field



Entrance window (un-depleted) → Diffusion

Typically dominant at room T

High-Field region → Field-enhanced SRH; Band-to-band tunneling (dominant at low-Temp)

Drift Region → SRH generation

Un-depleted epi → Diffusion

Bulk → Diffusion

All these components have different dependence on device parameter and on temperature..

Primary DCR population

Primary DCR (pDCR) of a SiPM is the sum of the pDCRs of the single cells (SPADs), composing the SiPM.

SRH (field enhanced) is dominating at room T.

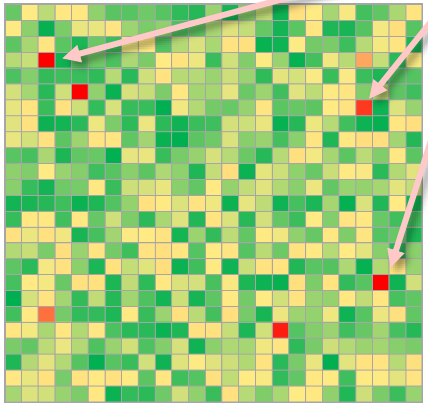
Factors affecting SRH (FE-SRH) in one SPAD:

- Contaminants
- Lattice defects
- (lithography defects)

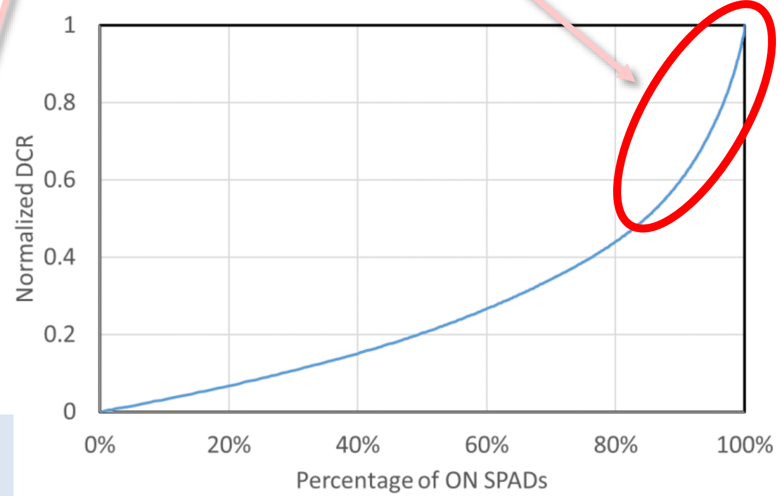
Local factors, affecting one cell at a time

There is a distribution of pDCR among SPADs composing a SiPM

Few «white» pixels can contribute significantly to the SiPM pDCR



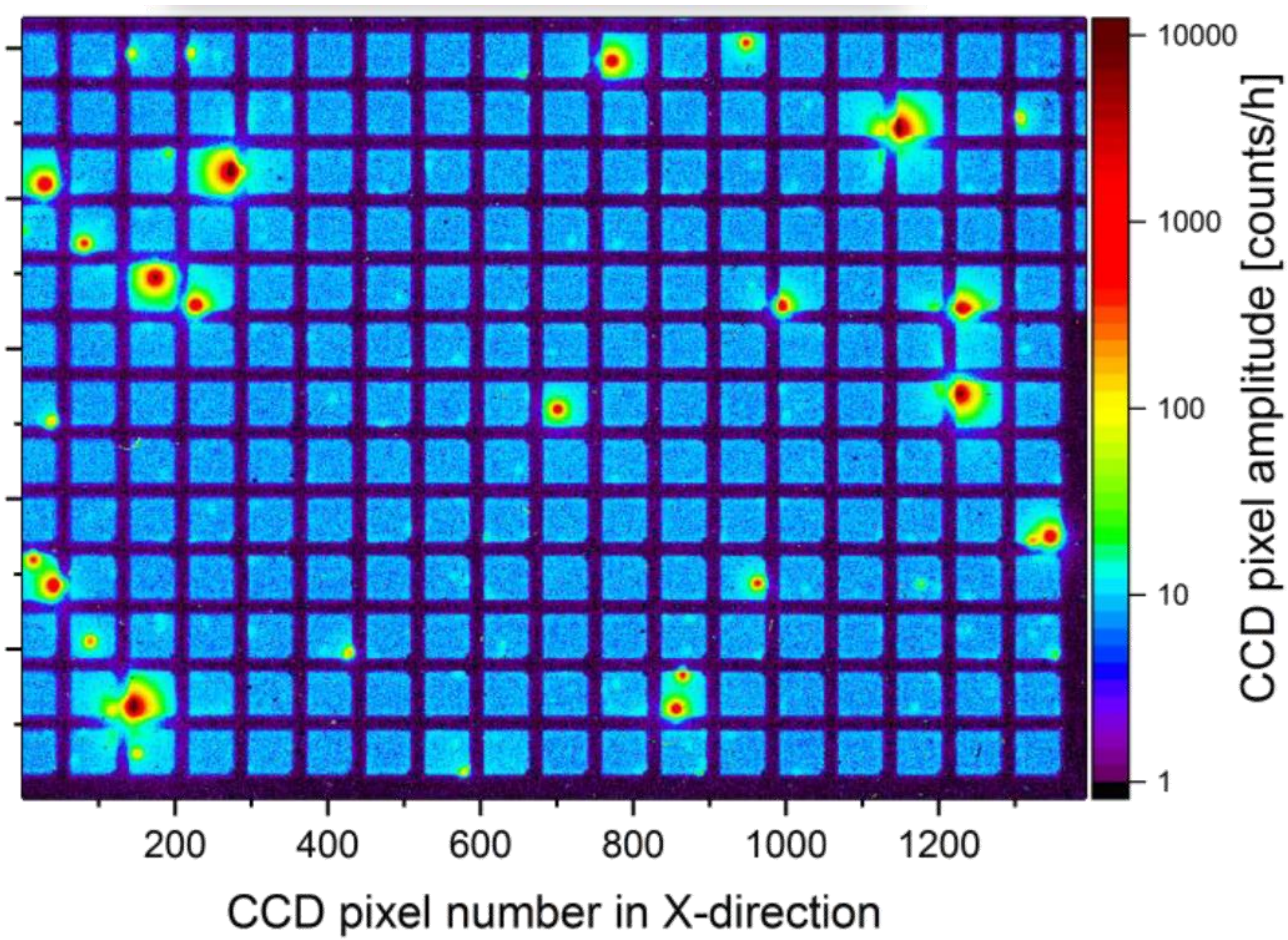
Simulated distribution of DCR in SPADs of one SiPM



Primary DCR population

Map of the white pixels can be measured experimentally.

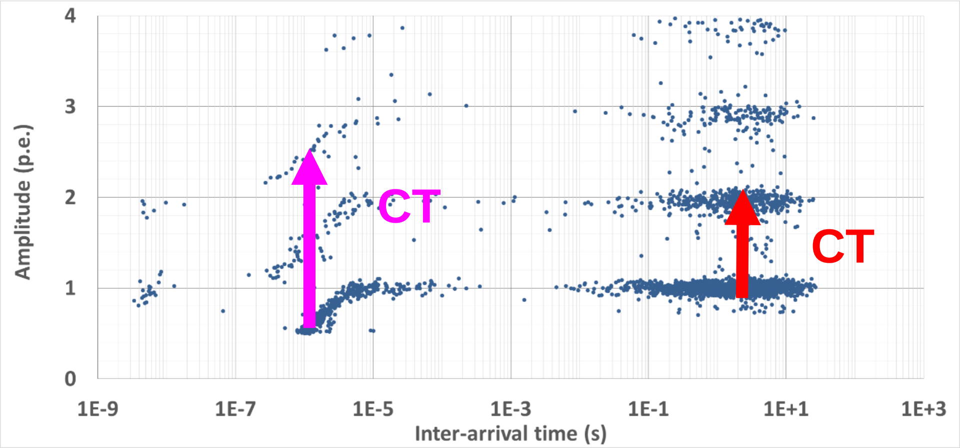
Measurement Setup:
- Andor cooled CCD camera
- Operating temperature: -55 °C
- Cost: ~ 20 k€

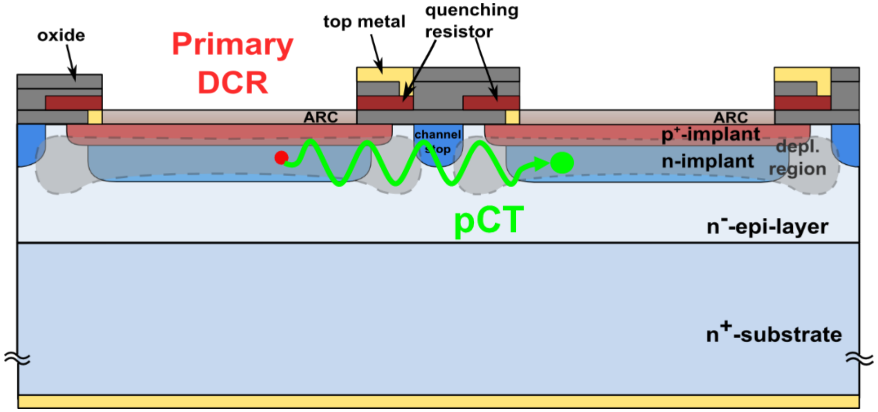


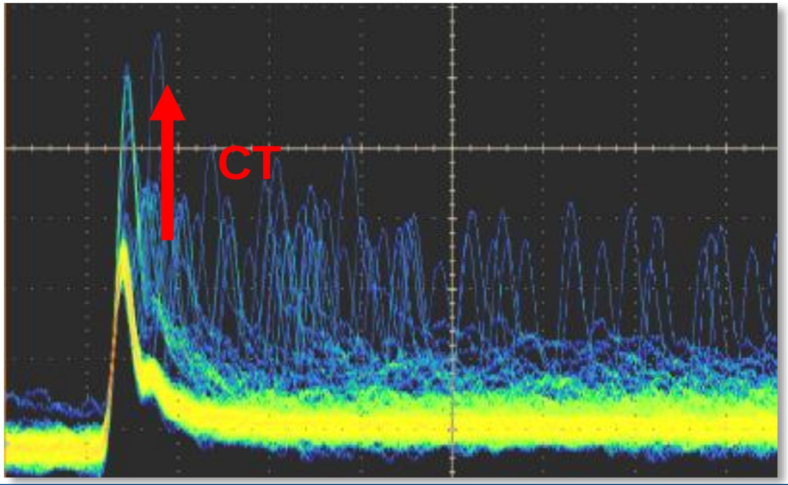
Prompt Optical Crosstalk (pCT)

Correlated noise events are additional events generated in the SiPM as a consequence of a primary event, either detection of light or another noise event.

Other name: Direct Crosstalk







Photon transit time, carrier collection time and trigger of second avalanche are so fast that the two events cannot be separated from signal analysis.

Amplitude increased by an integer multiple of single cell amplitude.

Same time distribution as the primary event.

Optical Crosstalk Probability

Photons are emitted by the hot carriers during the avalanche.

Number of carriers passing through the high-field region during avalanche

$$P_{CT} \cong Gain(OV) \cdot \alpha \cdot \gamma \cdot P_t(OV)$$

Emission coefficient of photons by the hot carriers: Approximately 1-3x10^{-5}

Collection efficiency of crosstalk photons by neighboring cells. Depends on:

- Spectrum of crosstalk photons
- SiPM geometry
- Optical isolation between cells
- Boundary conditions (e.g. optical properties of package, system..)

Triggering probability of CT photons. Depends on:

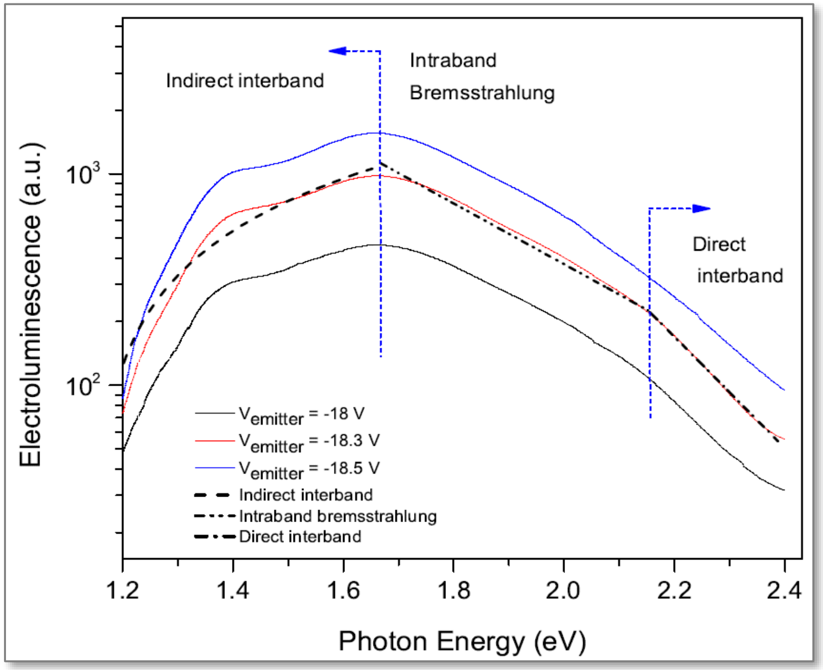
- Spectrum of CT photons
- Excess bias of SiPM

Main approximation: saturation effects are negligible.

Optical Crosstalk Emission Spectrum

The spectrum of emitted photons is very important to study CT properties and, possibly, optimizing SiPM design.

No agreement between data measured and reported in literature



Example of measurement of avalanche emission (FBK) fitted with multi-mechanism emission mode (Akil 1999).

Measurement difficult because:

- Faint light emission
- Possible differences between different devices (Efield, depth of junction, etc..)
- Self-absorption of silicon
- Effect of ARCs
- …

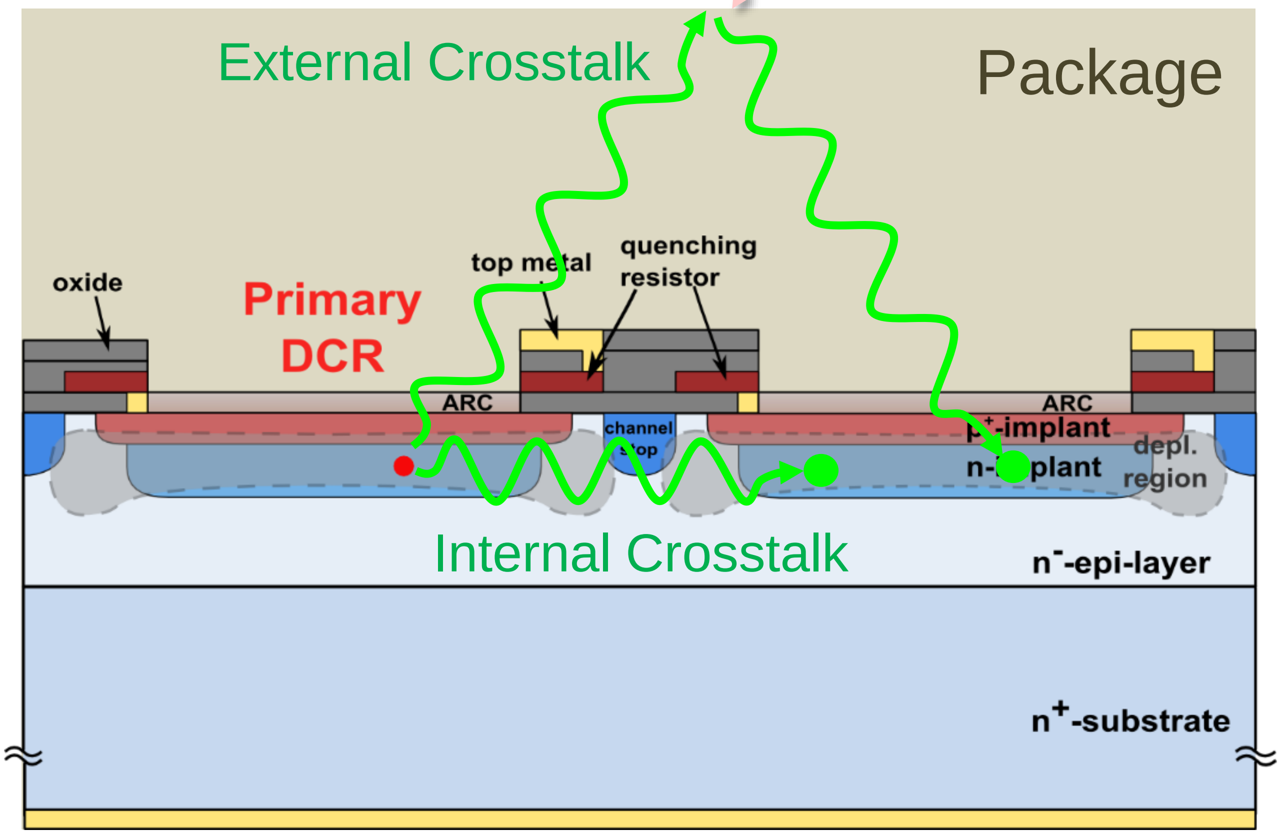
Different physical processes are considered to explain photon emission:

- Indirect / direct interband (recombination)
- Indirect intraband (e.g. Bremsstrahlung)
- Direct intraband

Internal and External Crosstalk

Optical crosstalk photons can travel either inside the silicon or exit the SiPM surface, be reflected and re-enter in another cell..

Reflections can be caused either by the SiPM package or by the environment in which the SiPM is operated

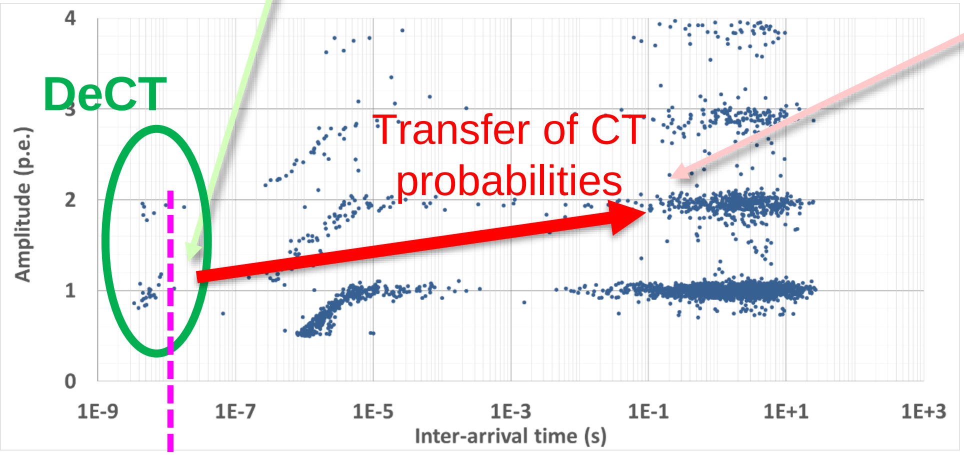


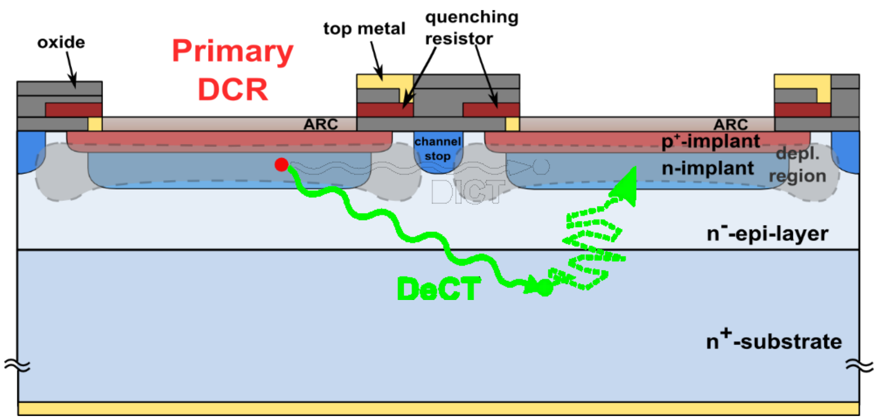
Delayed Optical Crosstalk (DeCT)

Crosstalk photons can also be absorbed in the un-depleted region below cells and generate minority carriers that diffuse to the depleted region.

Diffusion time can be enough to separate DeCT from primary event (depends also on amplifier bandwidth)

If DeCT happens too close in time to the primary event, it is interpreted as a pCT (transfer of CT probabilities)
Effect depends also on BW of amplifier and SiPM output cap



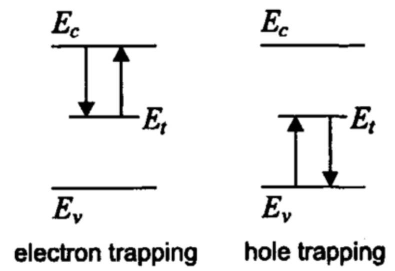


Maximum DeCT time-delay depends on minority lifetime in the un-depleted region:
- un-depleted part of epitaxial layer
- Un-depleted bulk

Minority lifetime:
Bulk: from 10 to 100 ns
Epi Layer: up to 100 us / few ms

Afterpulsing

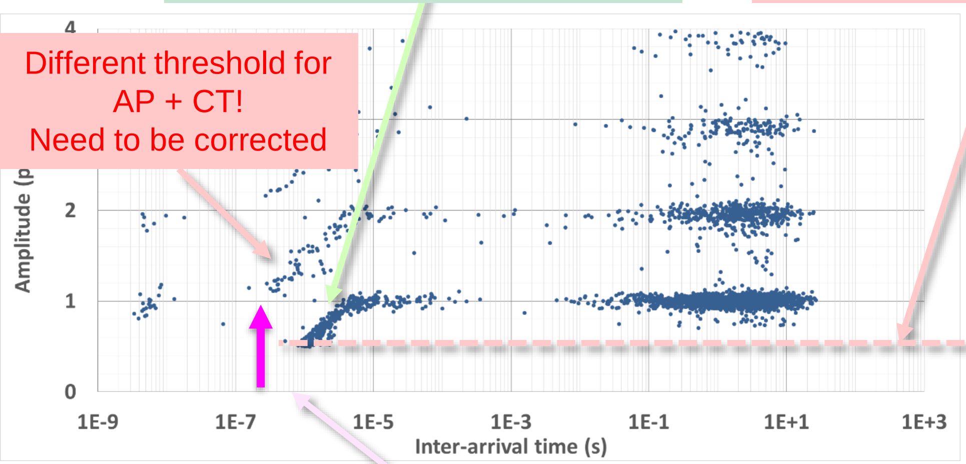
Normal afterpulsing is generated by capture and delayed emission of carriers by trapping centers in semiconductor lattice.



Exponential recharge of microcells (in log scale)

0.5 p.e. typical threshold to avoid electronic noise

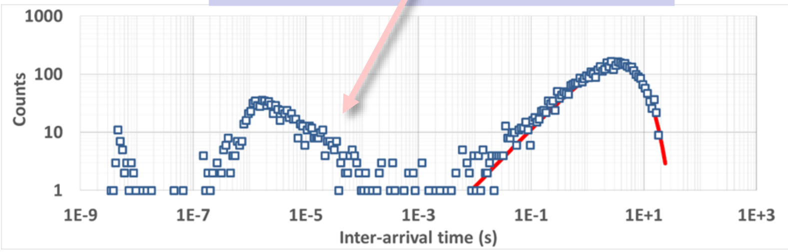
Different threshold for AP + CT! Need to be corrected

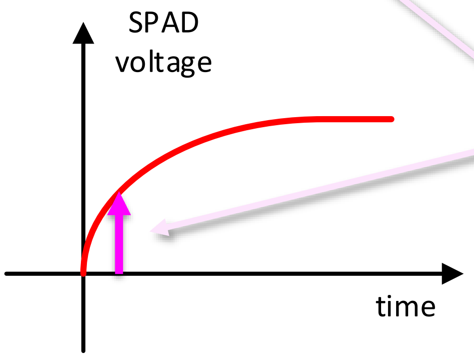


$$P_{AP} \cong Gain(OV) \cdot P_{trap} \cdot P_{trigger}(OV)$$

AP is the part in excess of pDCR but slower than DeCT

Inter-arrival time histogram

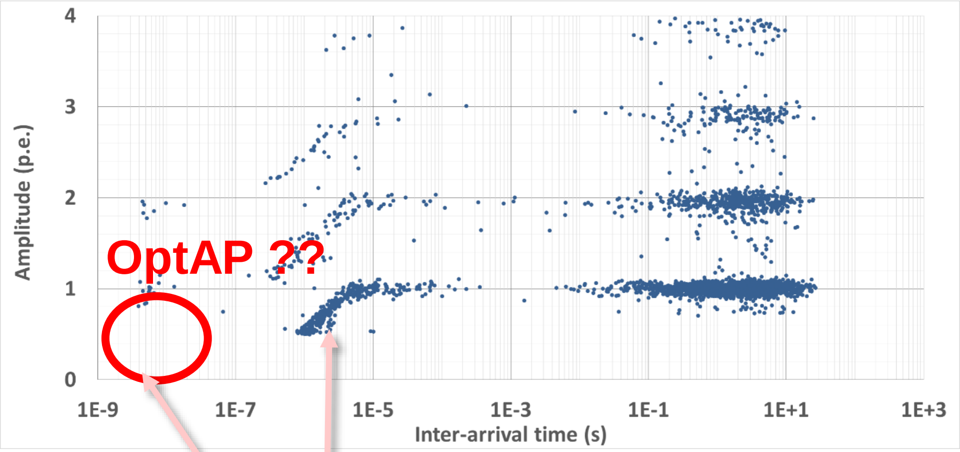


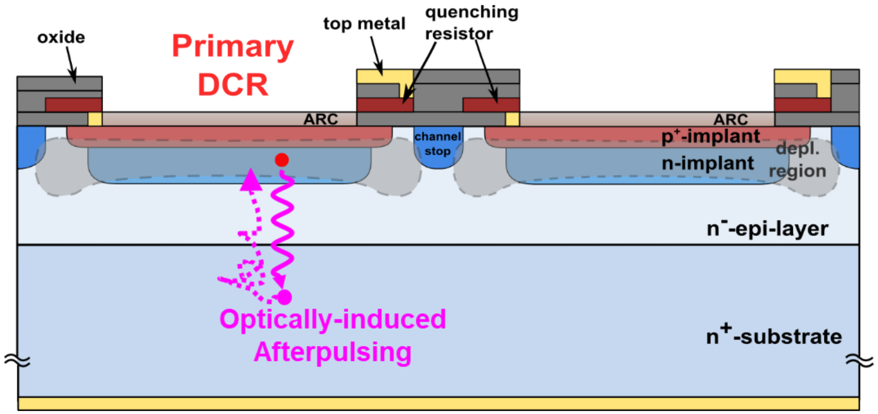


Carriers emitted shortly after primary event have very low probability of generating an afterpulse because SPAD is still discharged.

Optically-induced Afterpulsing (OptAP)

Photons generated during the avalanche can be also absorbed in the un-depleted region below cells and generate minority carriers that diffuse to the depleted region of the same cell.





In many cases, Optical Afterpulsing is difficult to observe because charge reaches the same cell when it is still almost completely discharged.

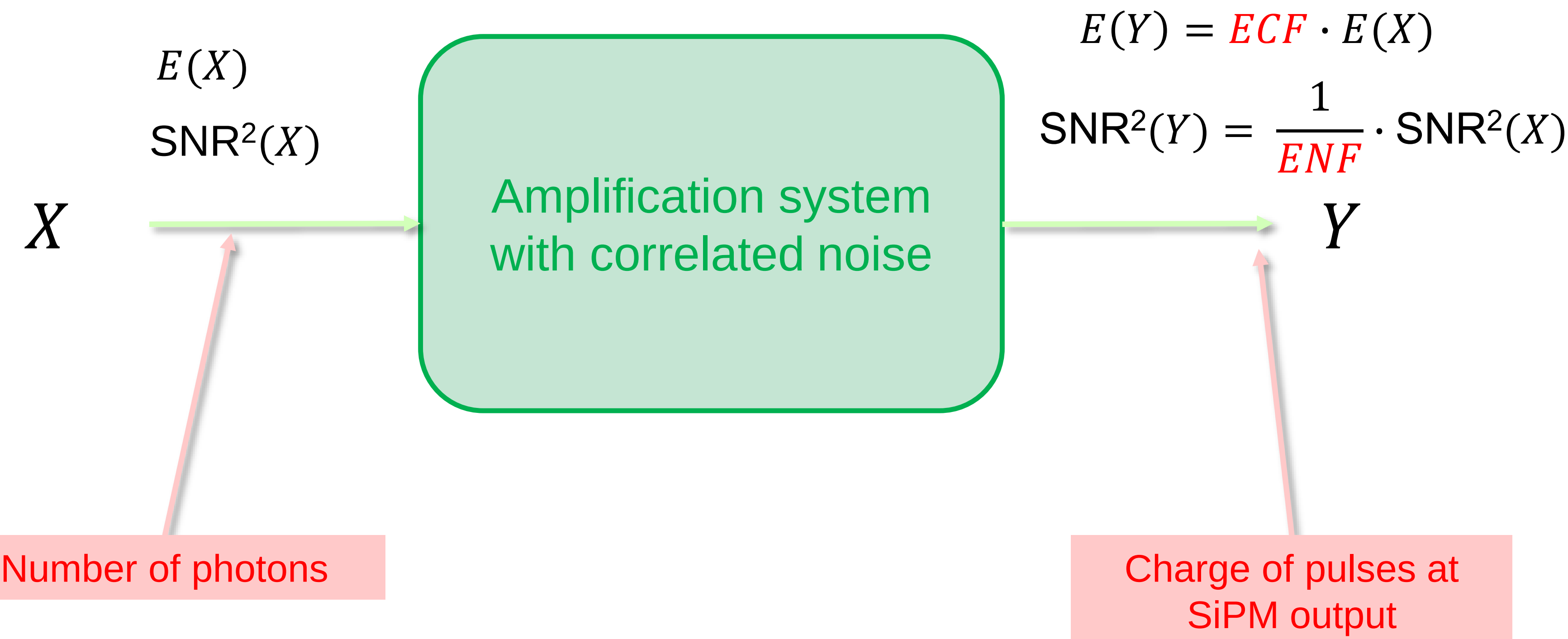
It may be relevant in the following cases:

- ultra-fast recharge of cells in new technologies
- "very long" minority carrier lifetime in bulk

It should be noted that the number of carriers diffusing from the bulk is higher than in DeCT because of favorable geometry.

Excess Charge Factor (ECF) and Excess Noise Factor (ENF)

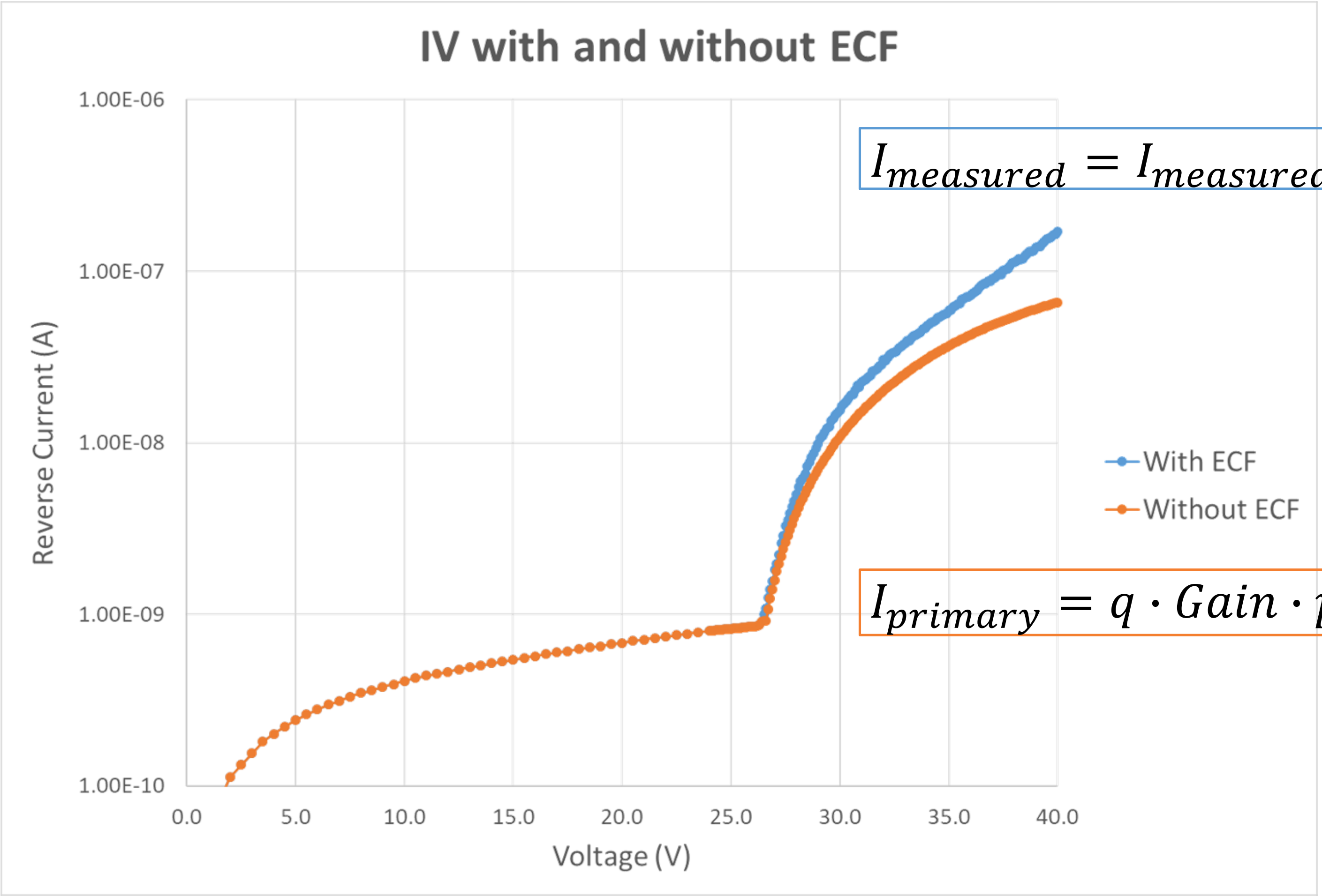
They are a convenient, synthetic representation of the effects of the correlated noise on the first and second moment statistics (variance) of the detected photons.



See Sergey presentation..

Rev IV analysis

By combining rev IV measurements and pDCR measurements, we obtain a direct measurement of the ECF.



$$I_{measured} = I_{measured} \cdot ECF$$

$$I_{primary} = q \cdot Gain \cdot pDCR$$

Divergence of SiPM correlated noise and "second breakdown"

Divergence of the correlated noise

Afterpulsing probability depends on Cell gain and, thus, overvoltage.

$$P_{AP}(OV) \cong Gain(OV) \cdot P_{trap} \cdot P_{trigger}(OV, \tau_{trap})$$

Number of carriers passing through the junction during an avalanche

$$P_{AP}(OV) \cong OV \cdot C_{SPAD} \cdot \alpha(OV, \tau_{trap})$$

For every SiPM technology, there is a value of over-voltage such as the probability of having a correlated noise event approaches one.

Crosstalk and afterpulsing effect are interacting:
→ Combined correlated noise probability determines divergence

Divergence of the correlated noise

The number of avalanches generated by a primary event, either dark count or photon detection, can be expressed by:

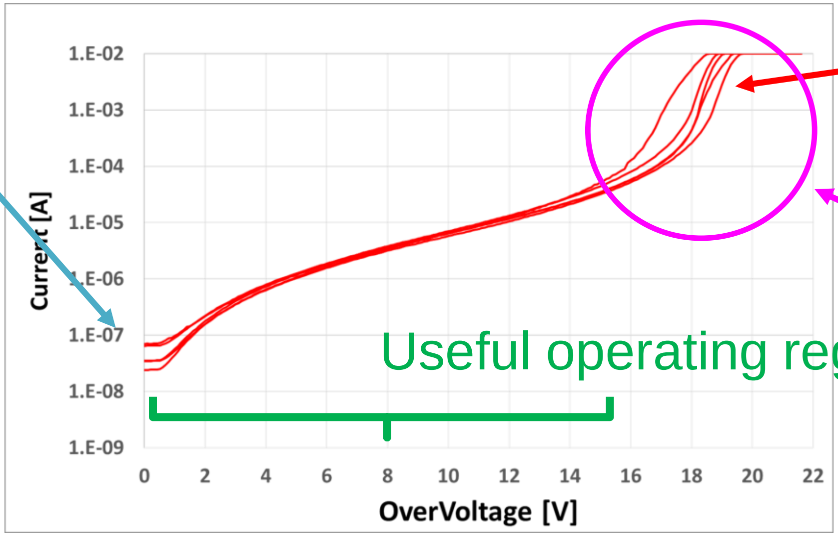
$$ECF \cong \frac{1}{1-P_{CN}} = \frac{1}{1-p'_{CN}(OV)\,Gain(OV)}$$

Geometric series approximation

Excess Charge Factor

Above a certain over-voltage the number of dark counts and, thus, the reverse current diverge.

Breakdown voltage



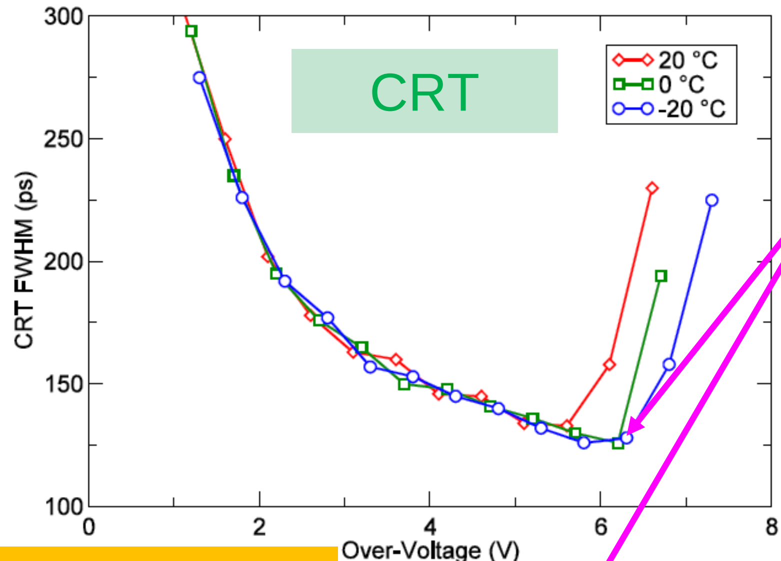
Divergence of correlated noise

SiPM cannot be operated here

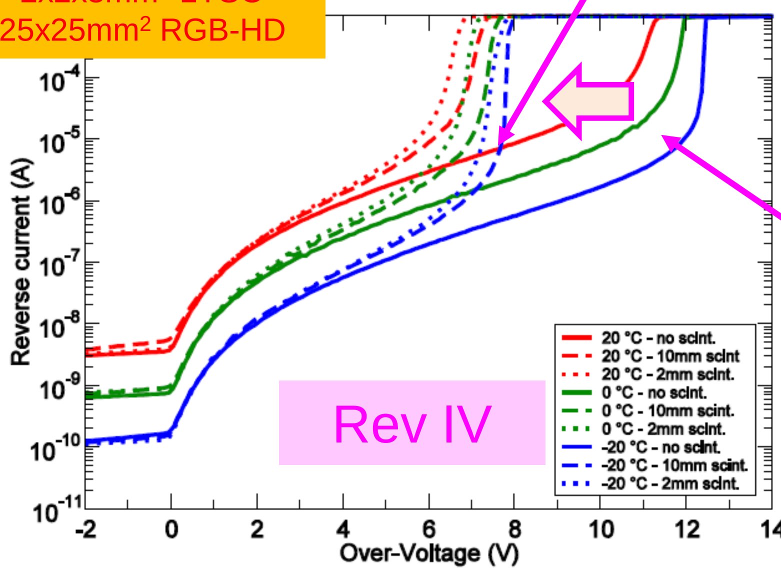
Also value of quenching resistor not high enough can generate IV divergence

Change of SiPM noise when the detector is placed in a system

ECF in presence of scintillator



2x2x3mm³ LYSO
25x25mm² RGB-HD

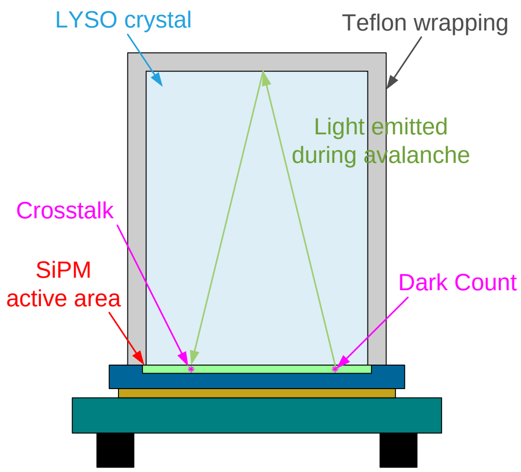


Maximum bias and, thus, maximum PDE are limited by the divergence of the correlated noise.

$$ECF \cong \frac{1}{1-P_{CT}} = \frac{1}{1-p'_{CT}(OV)\,Gain(OV)}$$

Excess Charge Factor

Crosstalk probability is increased by the presence of the scintillator



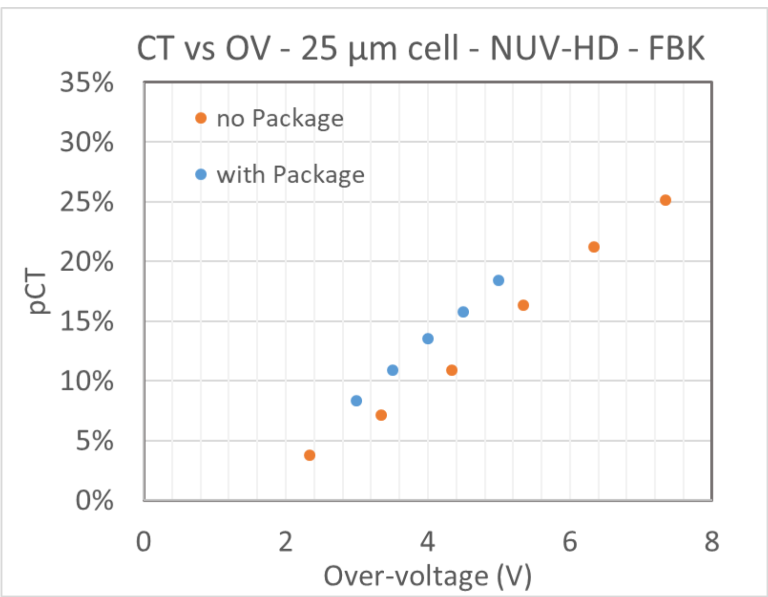
Gola, A., et al. "SiPM optical crosstalk amplification due to scintillator crystal: effects on timing performance". *PMB 2014*

Noise in presence of package

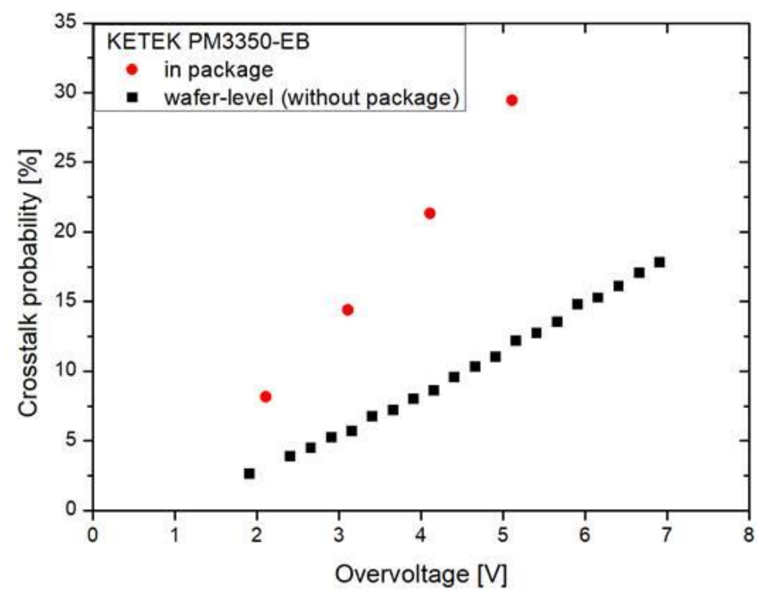
Although the effect of placing a scintillator on top of the SiPM is the most noticeable, also the use of package can affect correlated noise.

Wafer-level measurements may be not fully representative of the correlated noise of device in package

Difference depends on:
- Package type
- Cell size
- Level of Internal CT (IntCT)



Example of pCT measured on a 25 um cell FBK SiPM

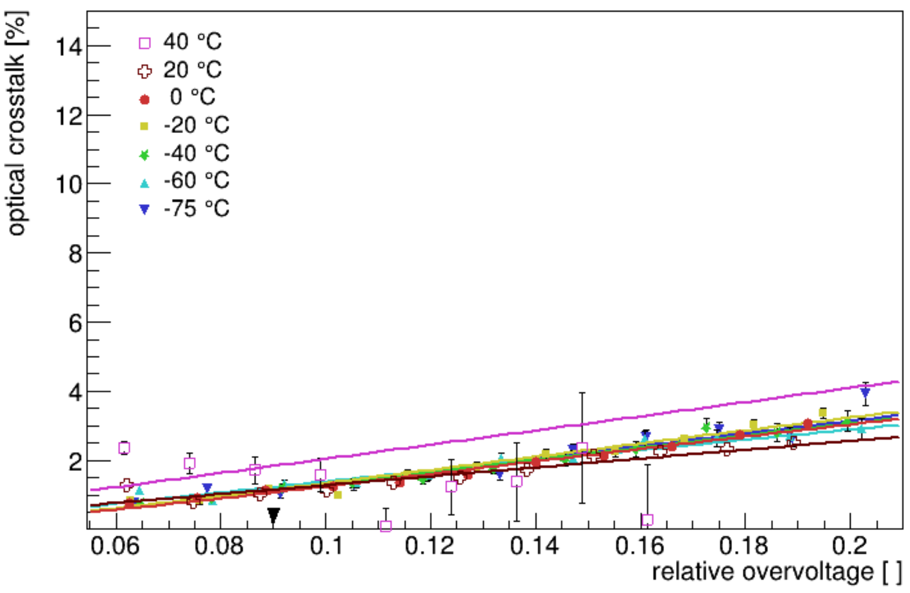


Example of pCT measured on a 50 um cell Ketek SiPM

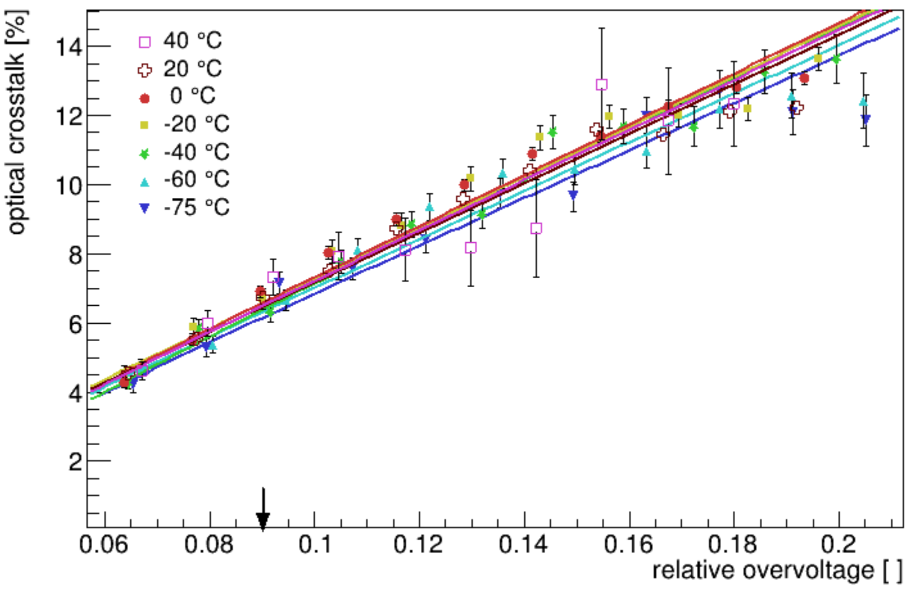
Noise in presence of package

The difference with and without package is even more important when the IntCT is strongly suppressed by the use of metal trenches.

Measurements on Hamamatsu SiPMs with metal filled trenches



Without package



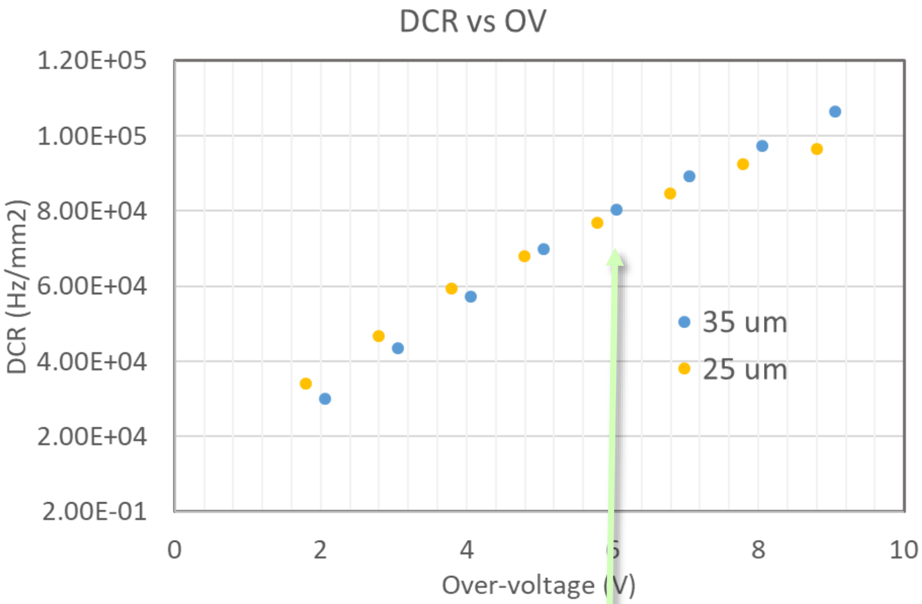
With package

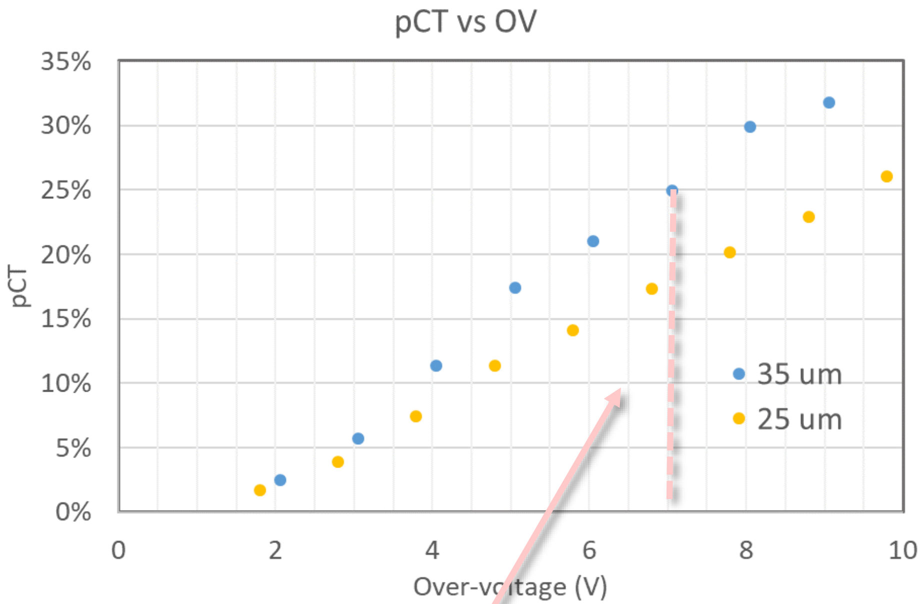
How to compare different SiPM technologies / cell sizes

Noise vs. Over-voltage

Standard way of performing and, thus, plotting noise figures is with respect to over-voltage.

Example of comparison of different cell sizes of FBK NUV-HD SiPMs





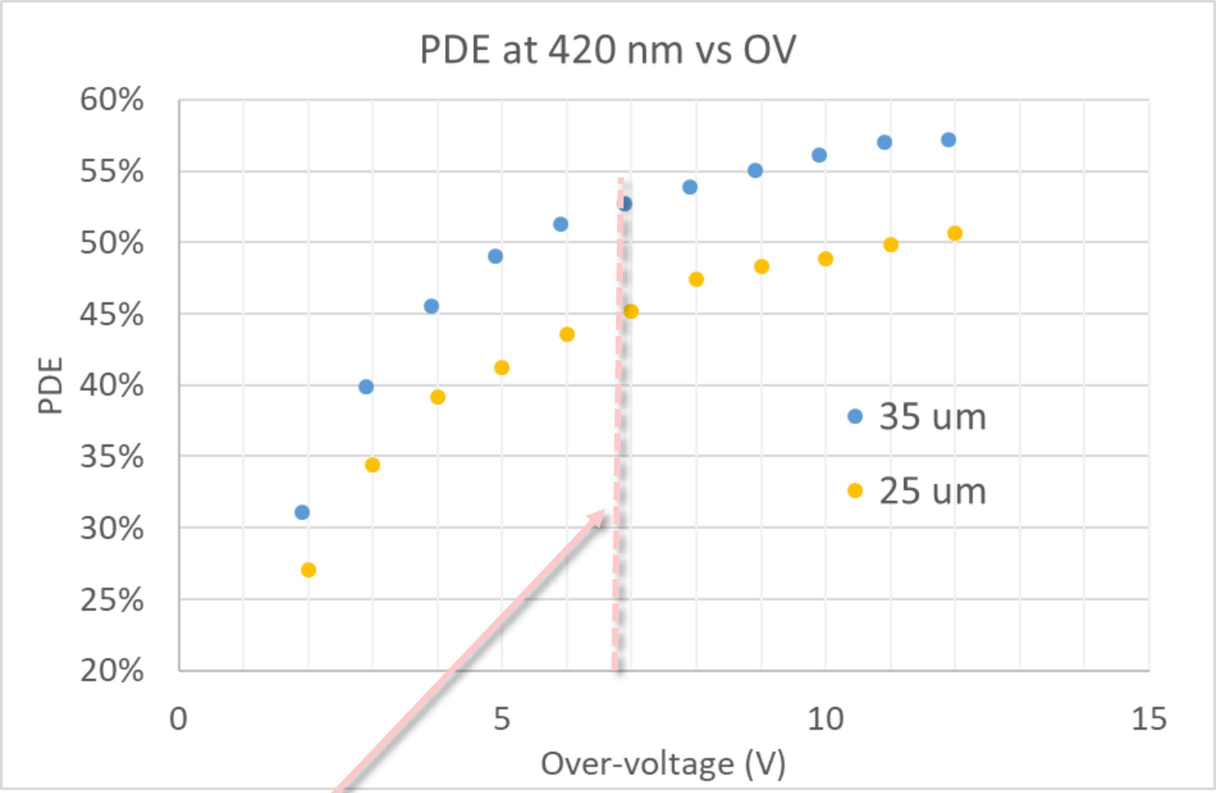
The noise per unit area is very similar for 25 um and 35 um cells

Because correlated noise is proportional to microcell gain, larger cells feature higher level of correlated noise at the same OV.

20 °C measurements

PDE vs. Overvoltage

However, different cell size also have a very different PDE at the same overvoltage.



FBK NUV-HD SiPMs

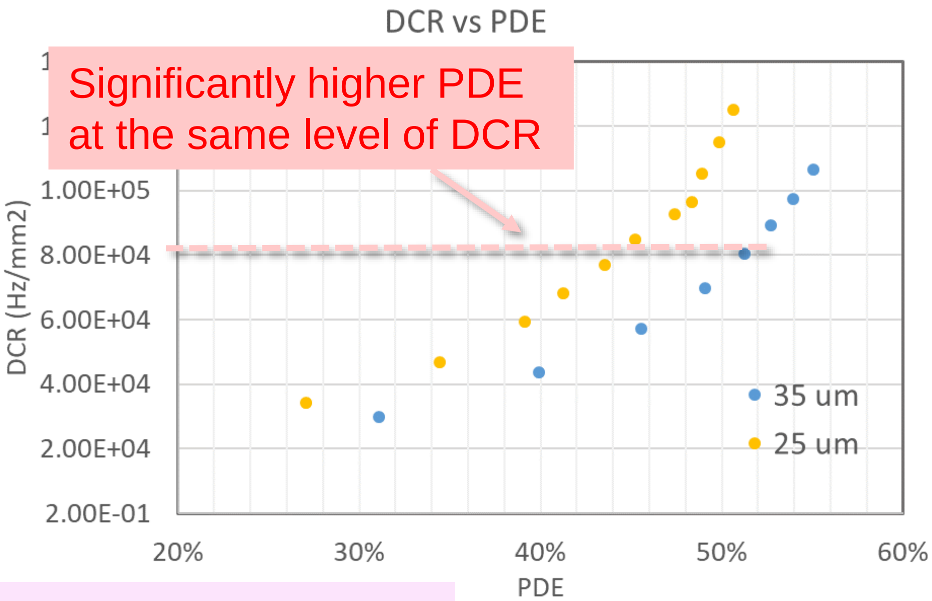
Larger cells feature higher PDE at the same over-voltage, because of the larger fill factor.

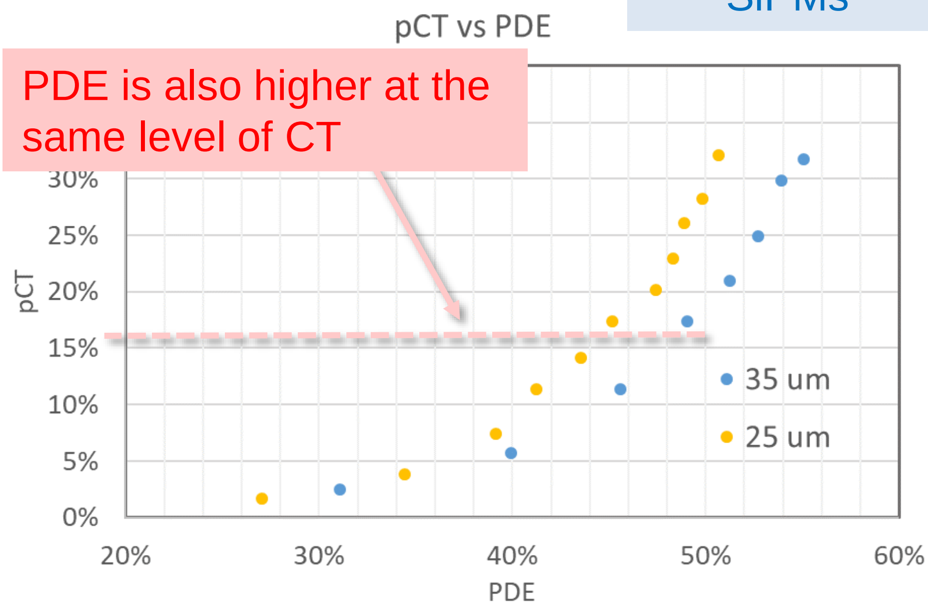
We are not comparing apples to apples!

Noise vs. PDE

We can select a wavelength of interest for a specific application and then plot the noise as a function of that PDE.

FBK NUV-HD SiPMs





20 °C measurements

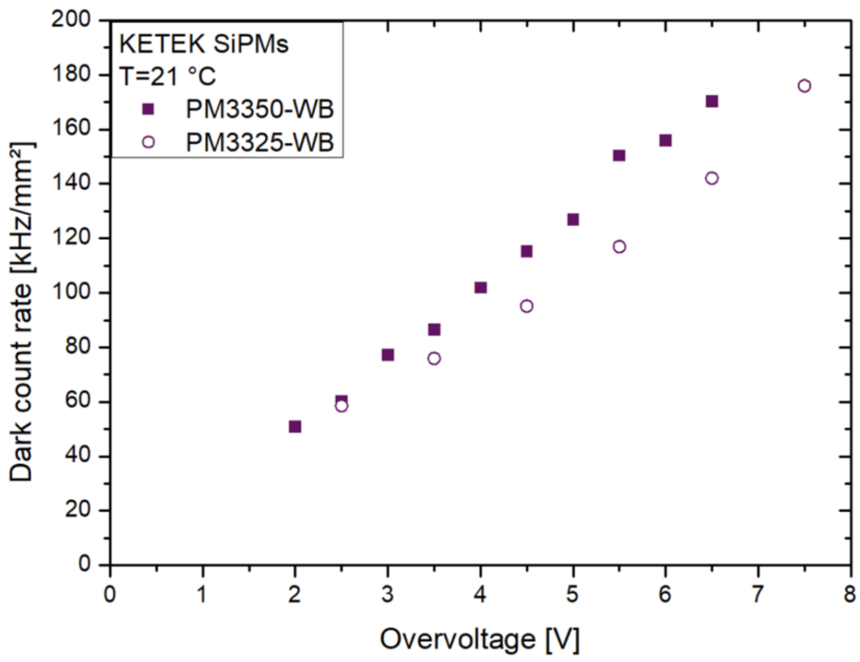
These are standard parameters, which can be included in a data sheet.

See Sergey presentation for the use of the ENF as a tool to generate proper FoM (related to SNR) and compare performance in a specific application.

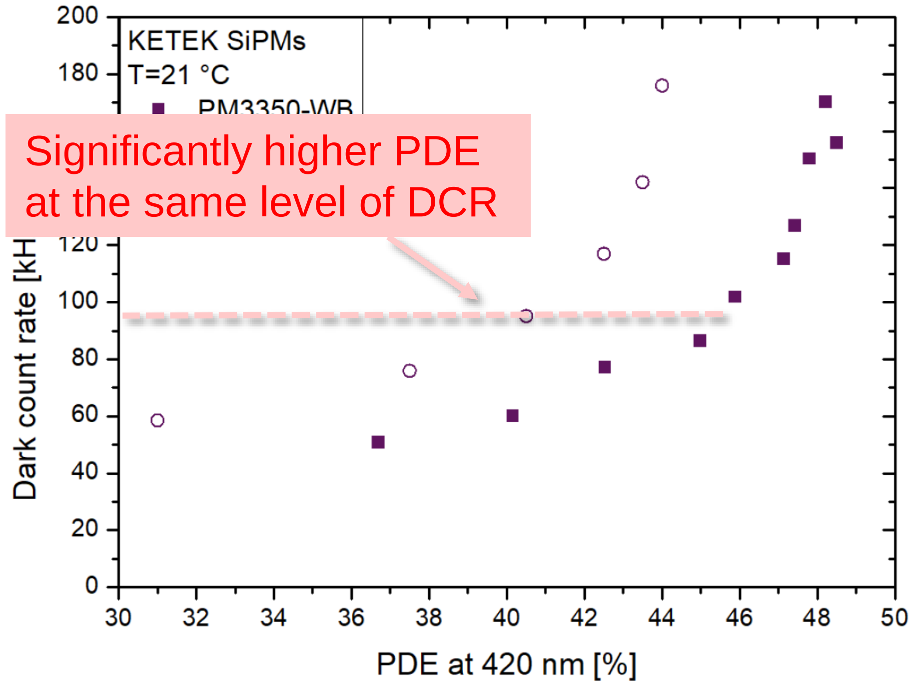
Noise vs. PDE

Similar behavior can be observed also with SiPMs from other manufacturers

25um and 50 um cell SiPMs from Ketek



pDCR vs. Overvoltage

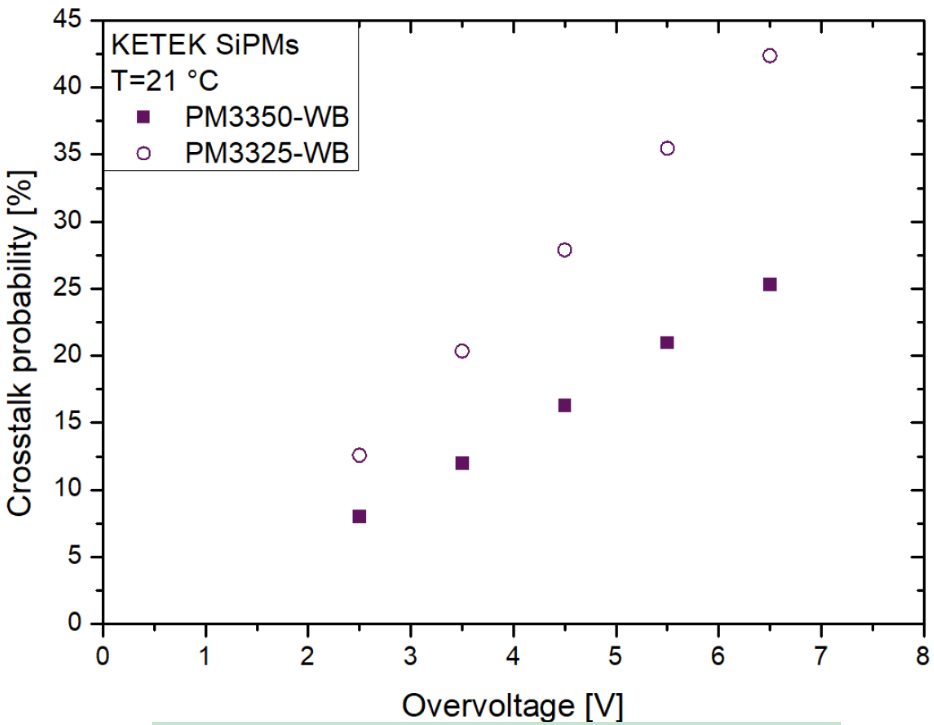


pDCR vs. PDE

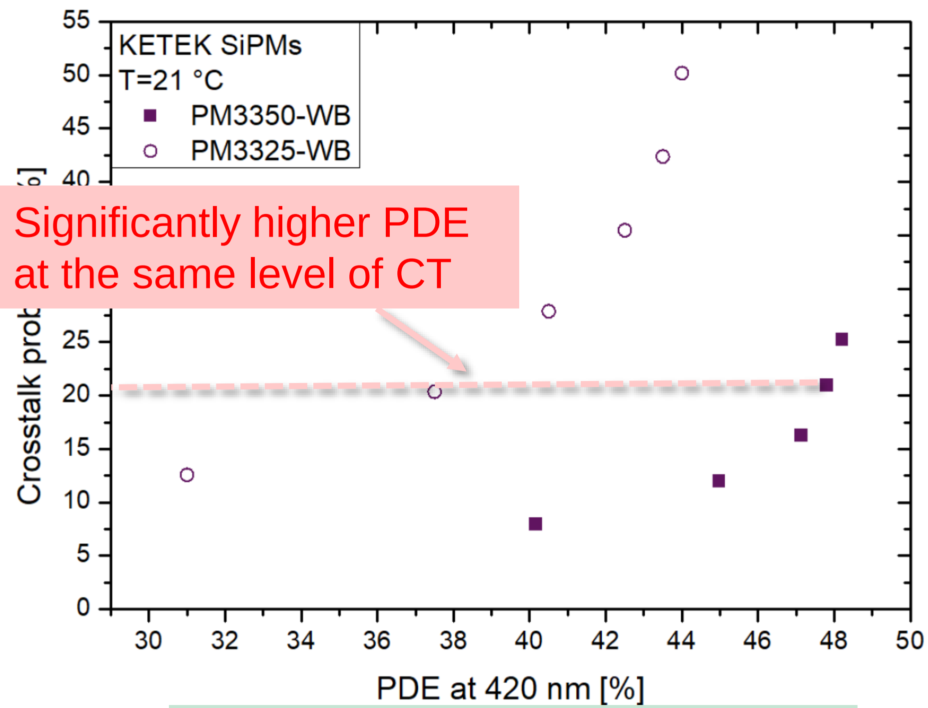
Noise vs. PDE

Similar behavior can be observed also with SiPMs from other manufacturers

25um and 50 um cell SiPMs from Ketek



CT vs. Overvoltage



CT vs. PDE

FONDAZIONE BRUNO KESSLER

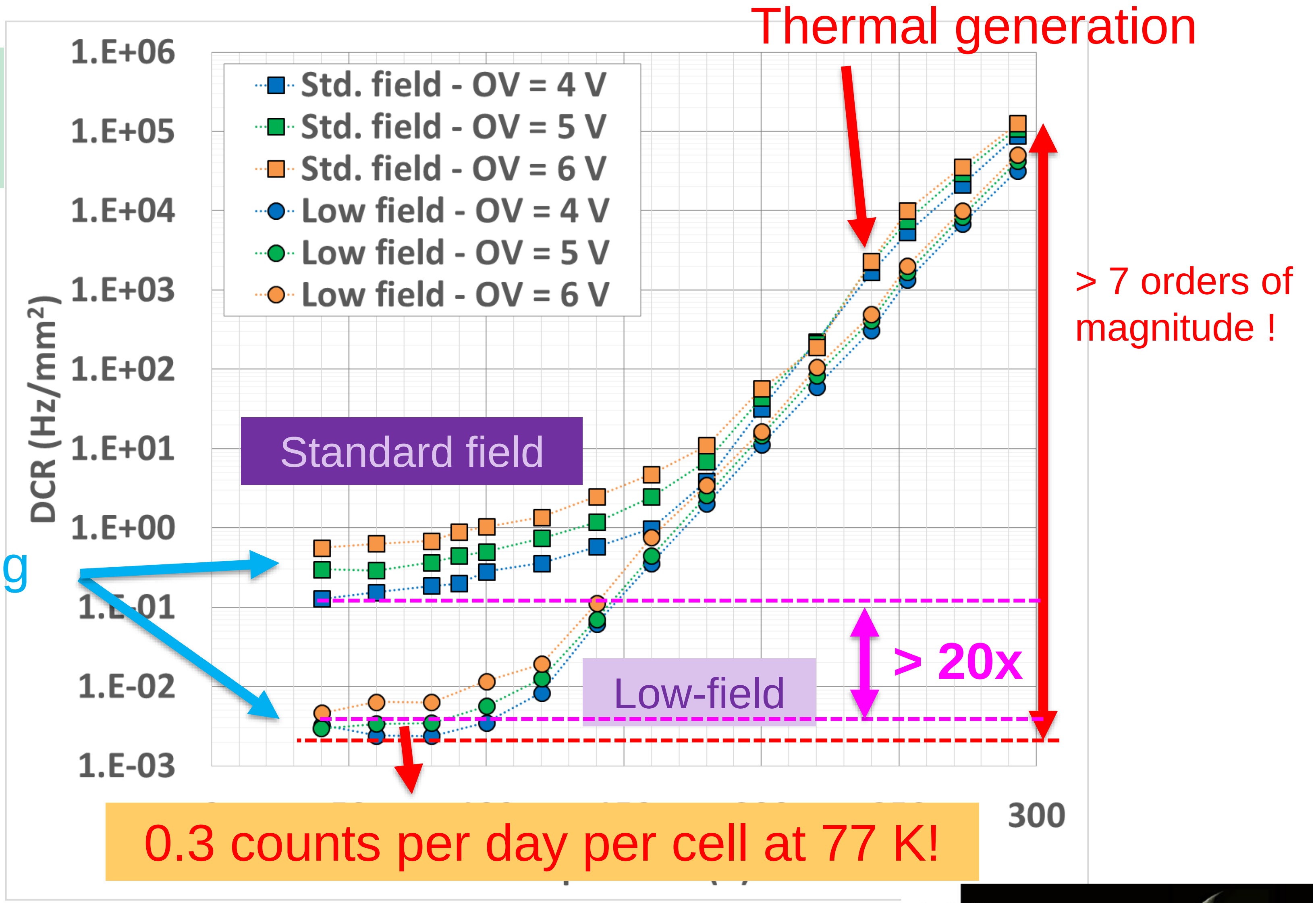
Thank you!

Backup slides

Change of noise with temperature

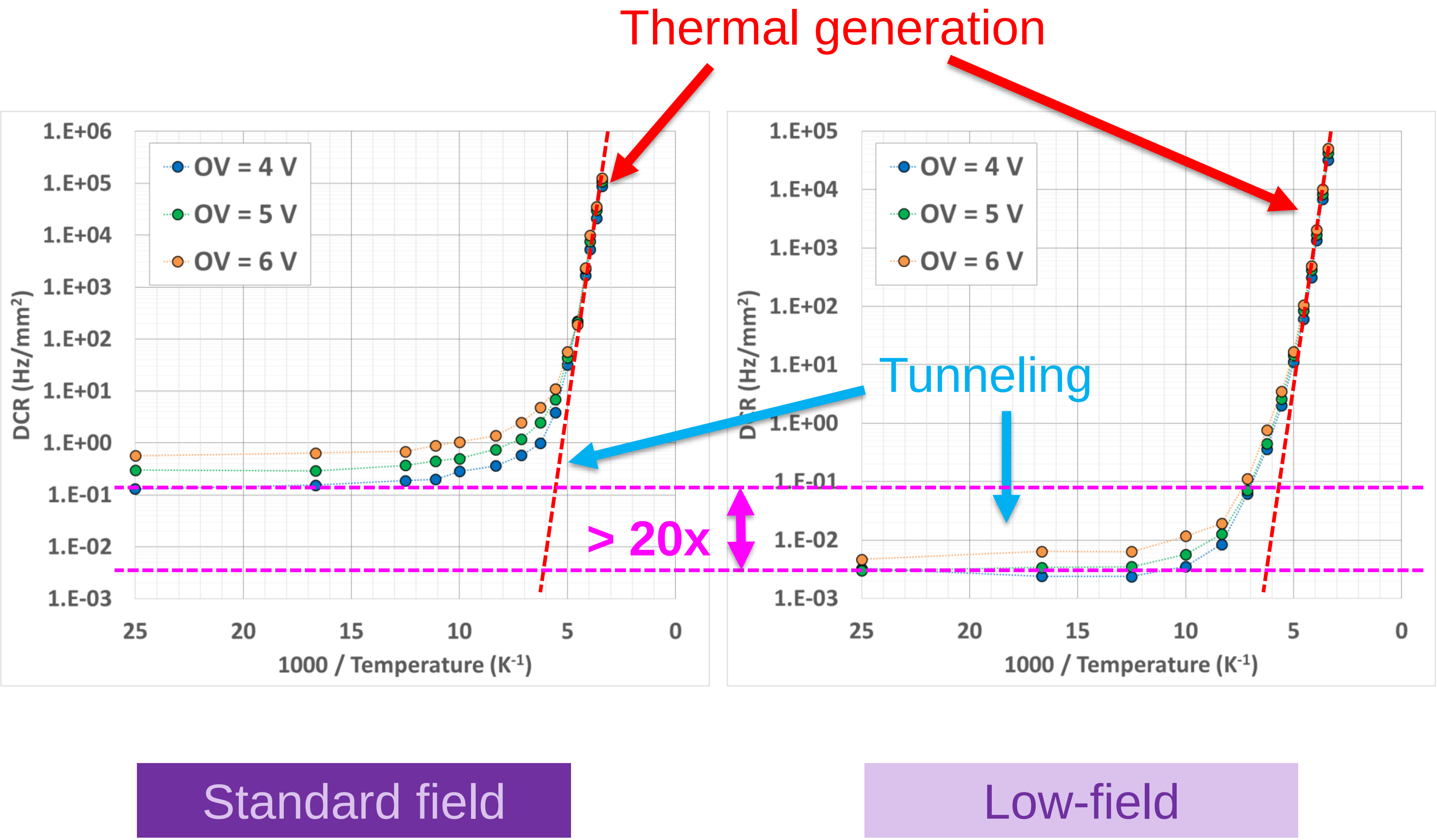
Reduction of DCR with temp: limit due to tunneling

25 um cell



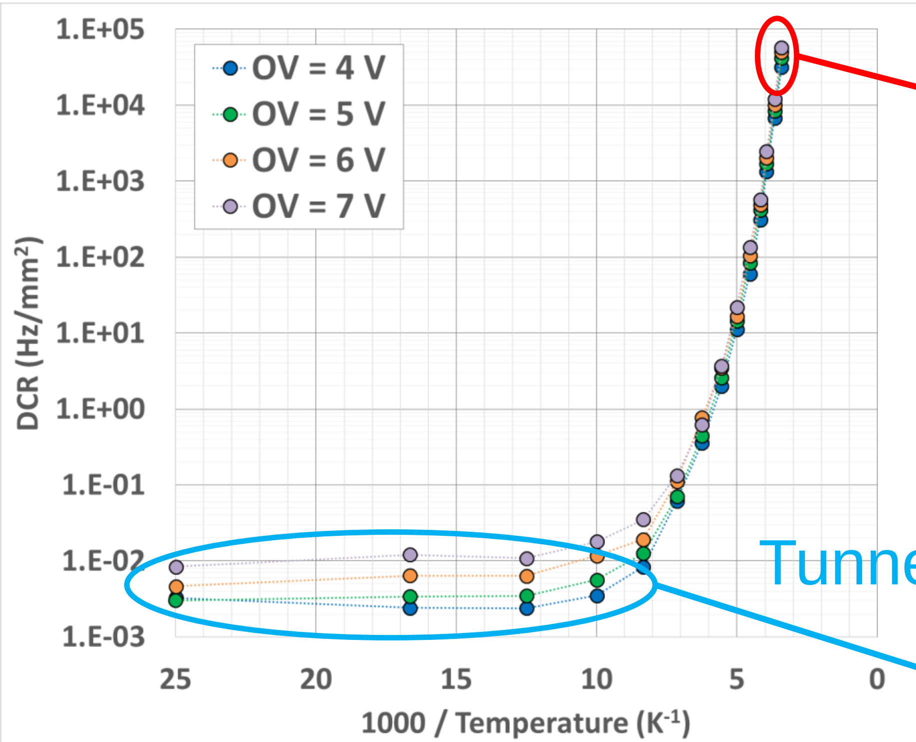
0.3 counts per day per cell at 77 K!

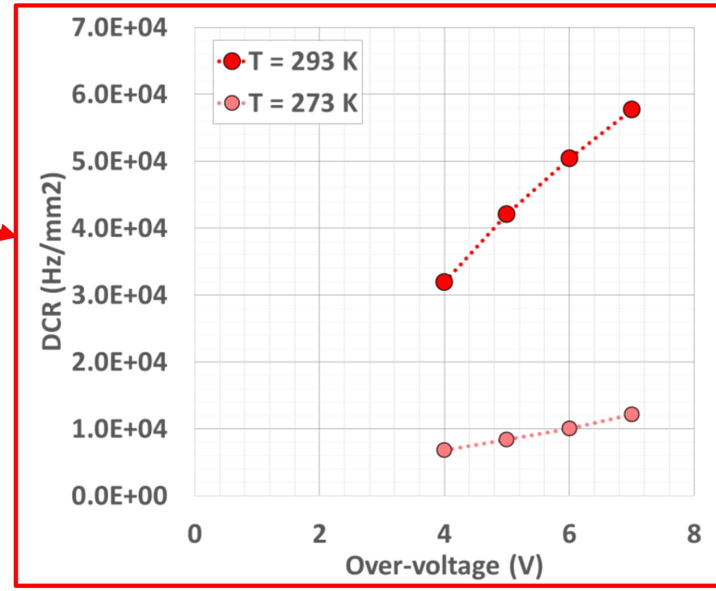
DCR / mm² – Arrhenius plot



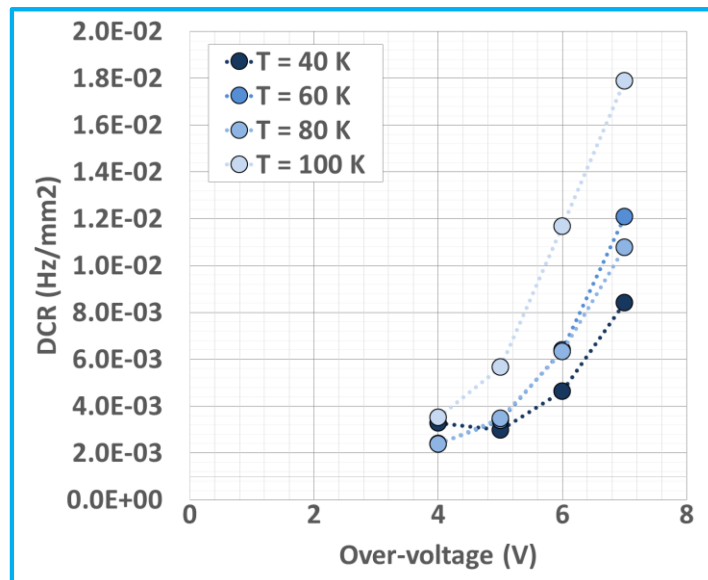
DCR / mm² vs. Over-voltage

Thermal generation



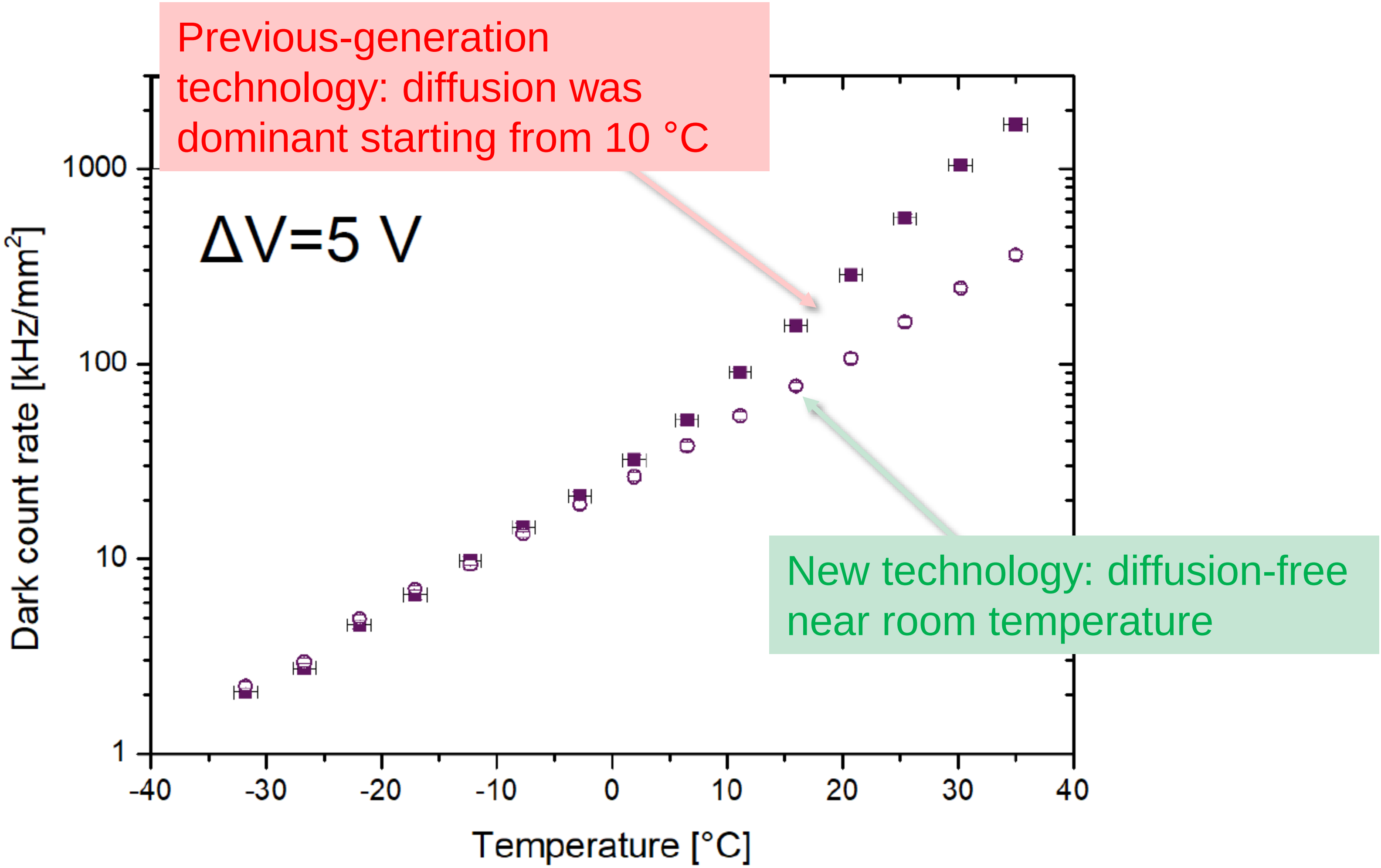


Tunneling



NUV-HD Low-field

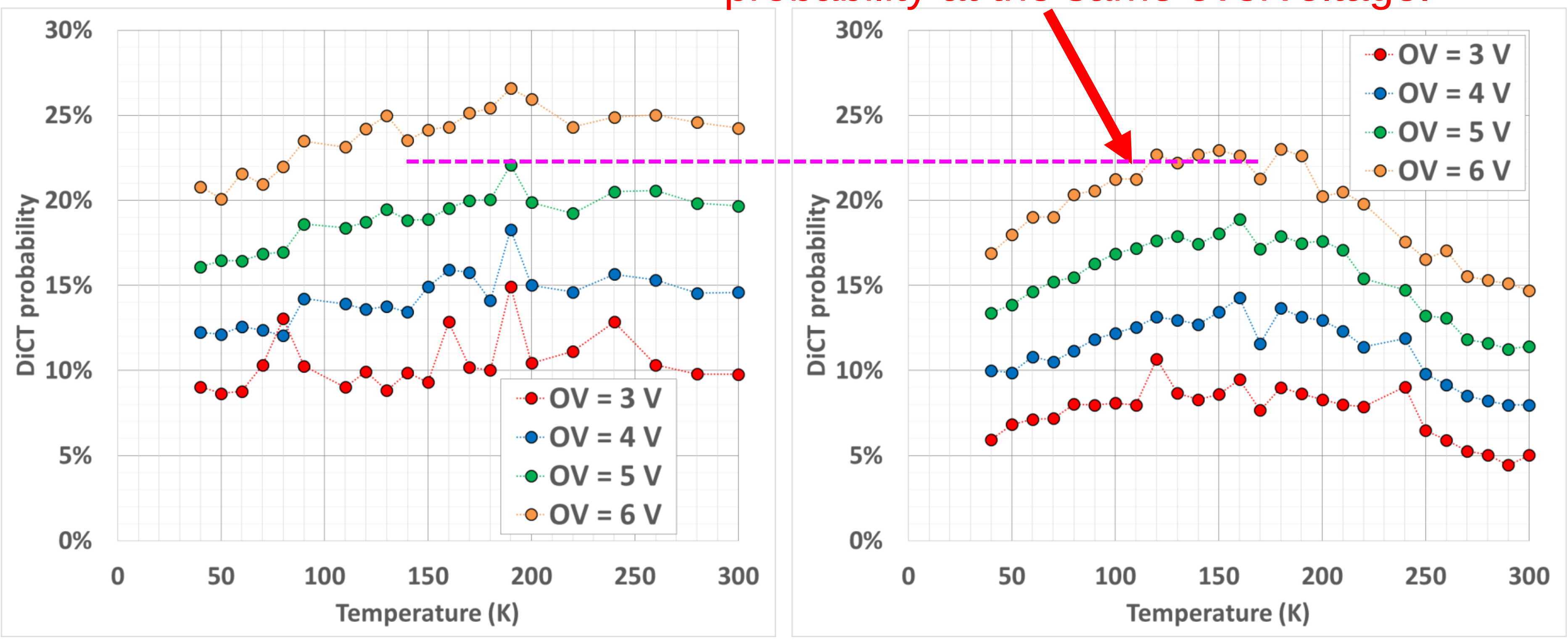
Increase of DCR with temp: diffusion component



pCT vs. Temperature

The direct crosstalk probability has only minor variations with respect to temperature.

Slightly lower gain and triggering probability at the same overvoltage.

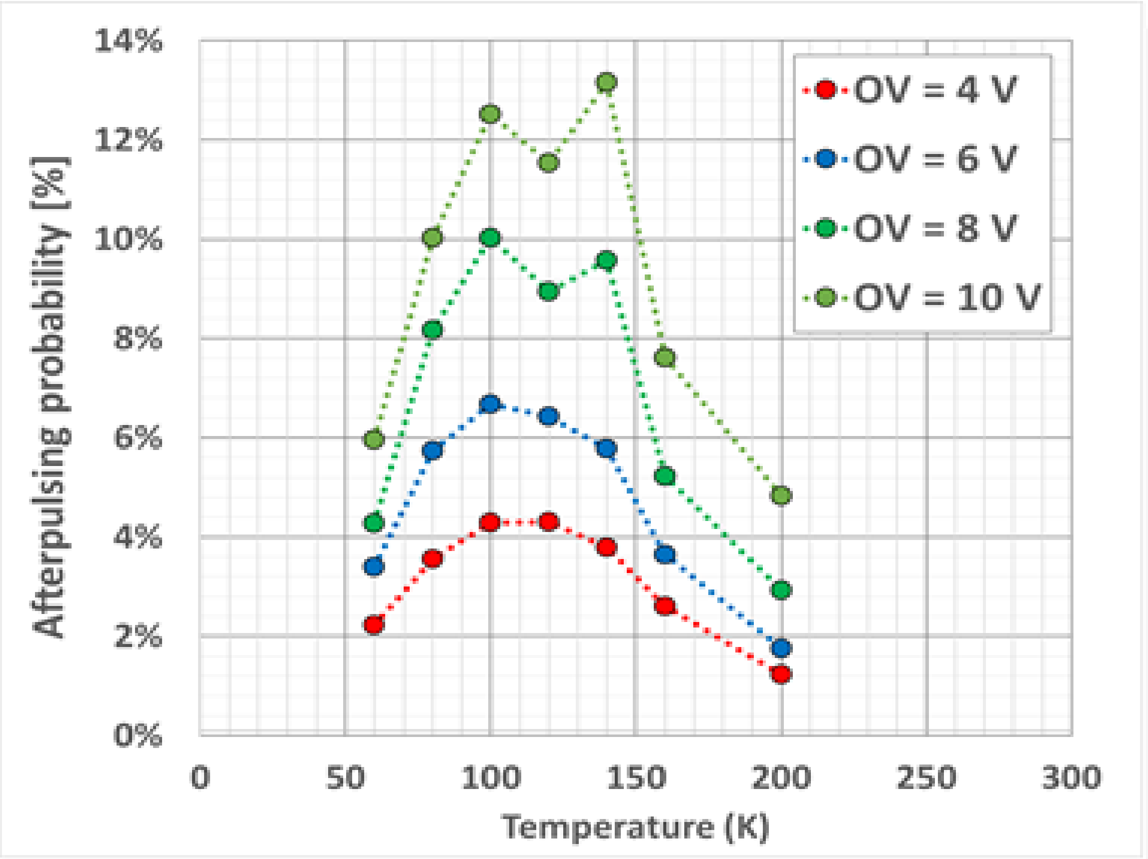


Standard field

Low-field

Afterpulsing vs. Temperature

The increase of the microcell recharge time constant helps reducing the afterpulsing at low temperature.



LowAP NUV-HD SiPM technology
(300 ns recharge time constant)