Optimization of timing performance of large-area FBK SiPMs in the scintillation light readout.

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http://srs.fbk.eu

Overview of the SiPM technology at FBK

A. Gola

FBK technology evolution

Original technology 2006

2010-11

RGB-SiPM

(Red-Green-Blue SiPM)

- excellent breakdown voltage uniformity
- low breakdown voltage temperature dependence (gain variation < 1%/C)
- higher efficiency
- lower noise

2012

NUV-SiPM

(Near-UV SiPM)

- excellent breakdown voltage uniformity
- low breakdown voltage temperature dependence (gain variation < 1%/C)
- high efficiency in the near-ultraviolet
- very low dark noise

2012

RGB-SiPM_HD

(Red-Green-Blue SiPM – high density)

- small cell size with high fill factor:
  - high dynamic range
  - low excess noise factor

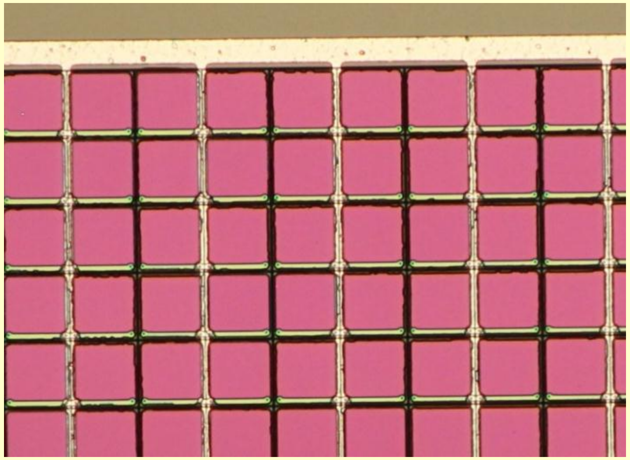
RGB-SiPM HD

Redesigned cell border, for obtaining small cells with high Fill Factor (FF).

The 15 um cell RGB-HD has the same FF of the 50 um cell RGB technology.

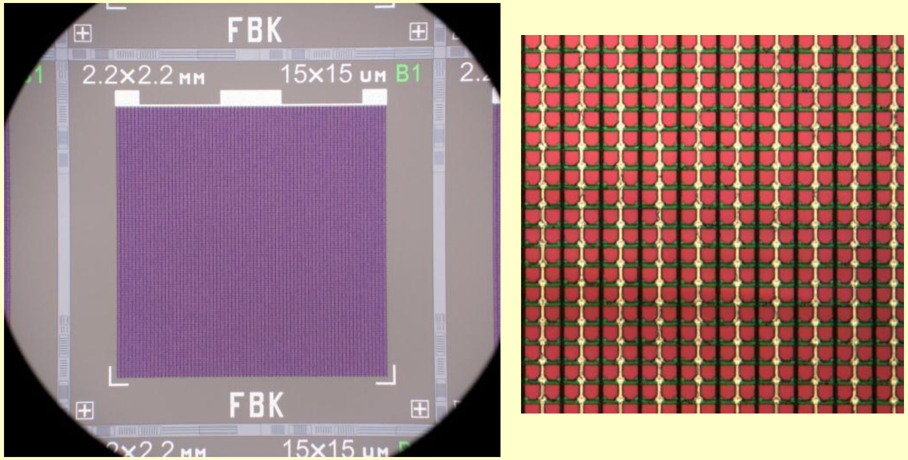
SiPM:
size: **4x4mm^2**
cell size: **30x30um^2**
cells: ~17000

Fill factor = 74%



SiPM:
size: **2.2x2.2mm^2**
cell size: **15x15um^2**
cells: 21316

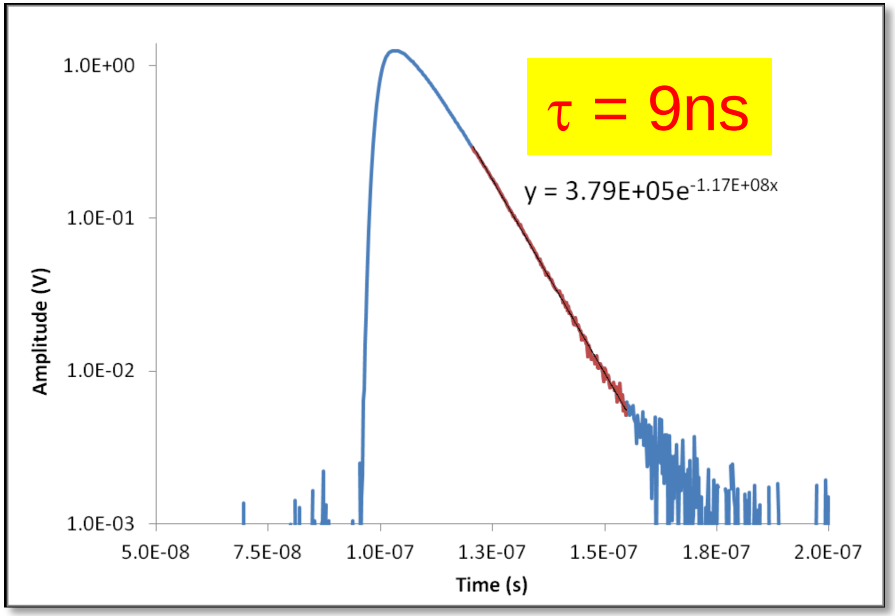
Fill factor = 48%



RGB-SiPM HD

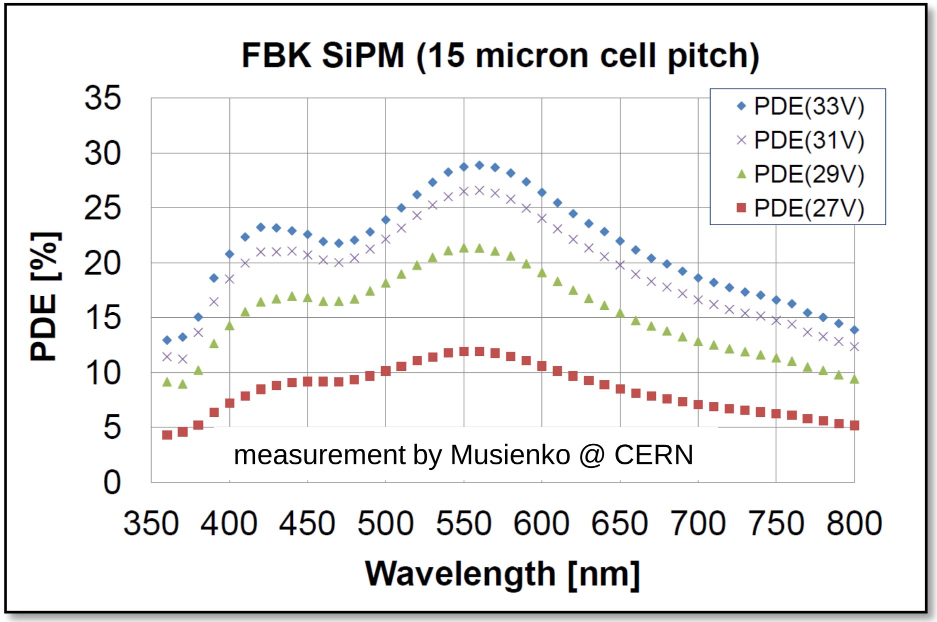
2.2x2.2mm^2 15um

Response to fast light pulse from LED



very short decay!!

Photo-detection efficiency

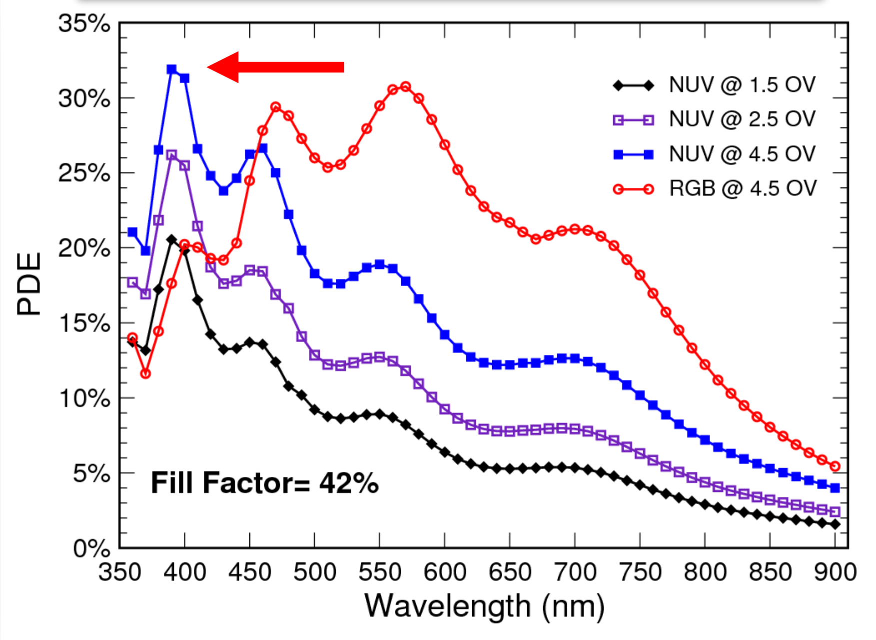


measurement by Musienko @ CERN

NUV-SiPM

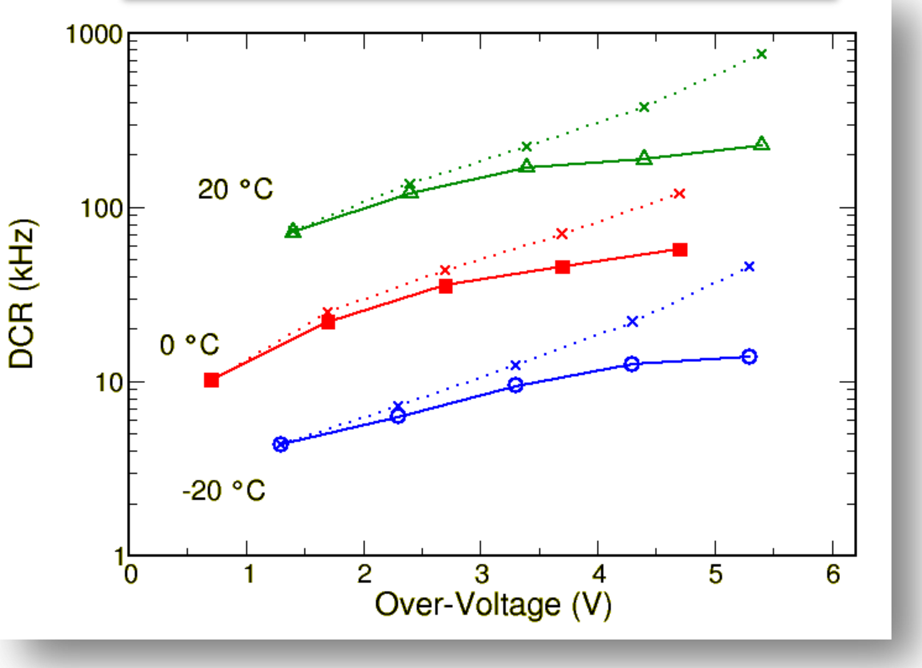
The NUV SiPM is based on a p-on-n junction, for increased PDE at short wavelengths.

Increased PDE at low λ



PDE vs. wavelength for a NUV-SiPM and RGB-SiPM with 50x50um^2 cell, 42% fill factor.

Very low primary DCR



NUV-SiPM: 1x1mm^2 50x50um^2.*Total* and *primary* dark count rate at 0.5 phe.

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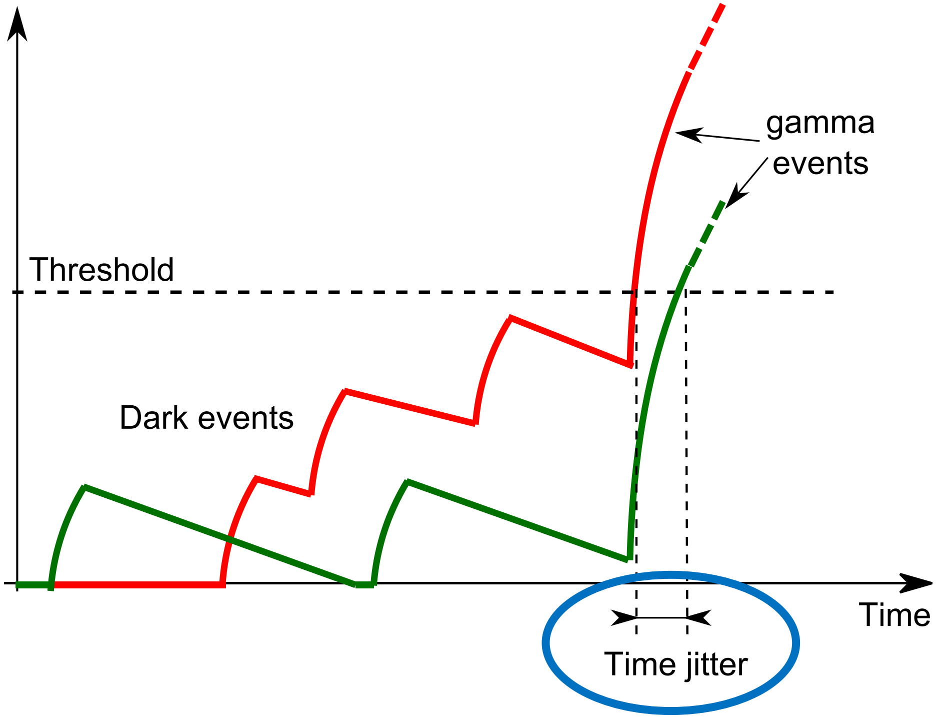
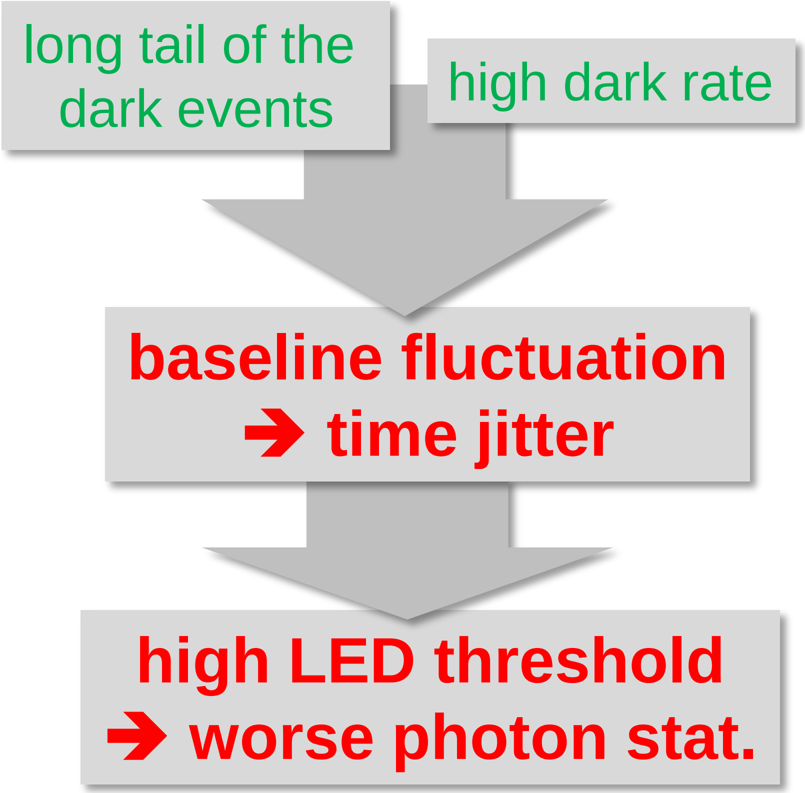
Effects of the SiPM noise: Dark Count Rate

Effect of dark noise in LED

Leading Edge Discriminator (LED) is commonly used for time pick-off with PMTs.





long tail of the dark events

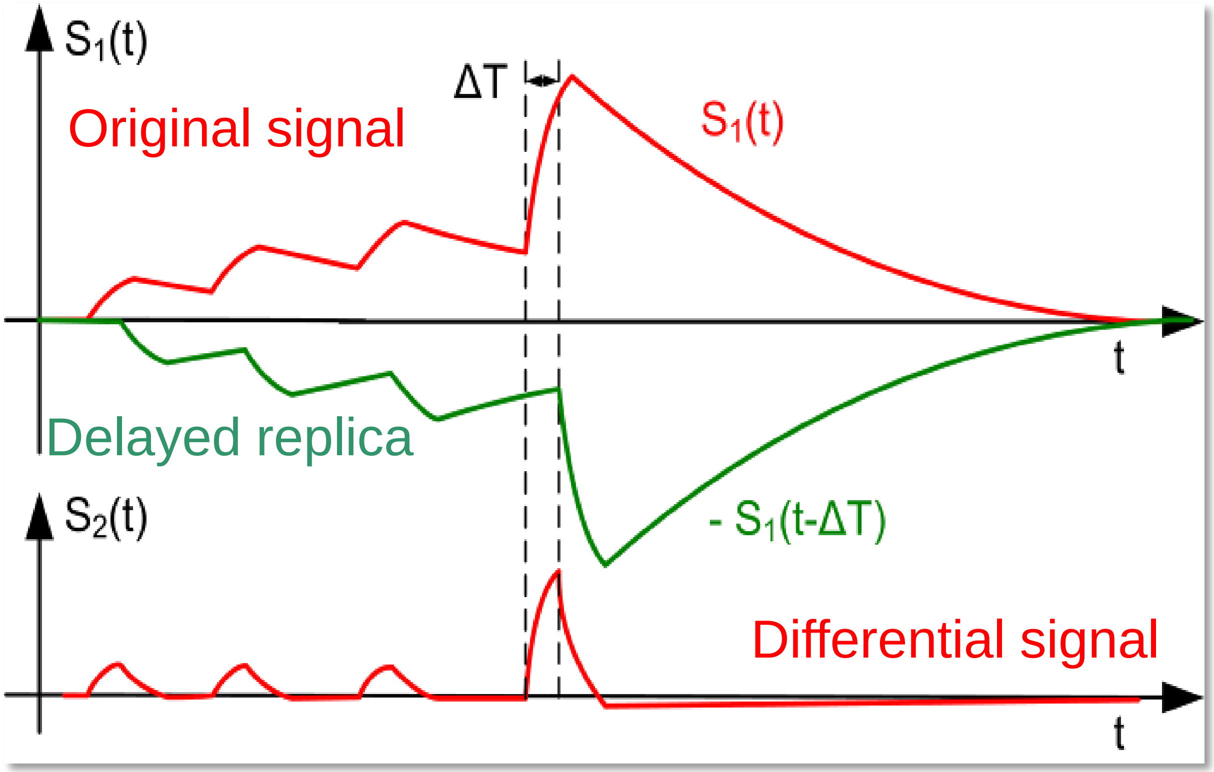
high dark rate

baseline fluctuation ➔ time jitter

high LED threshold ➔ worse photon stat.

In large area SiPMs the dark rate can be quite high and consequently also the effect described above.

SiPM Signal filtering: DLED



We exploit the difference between rise time and decay time to obtain a signal:

- **“free” from baseline fluctuations**
- **identical initial part of the gamma signal**

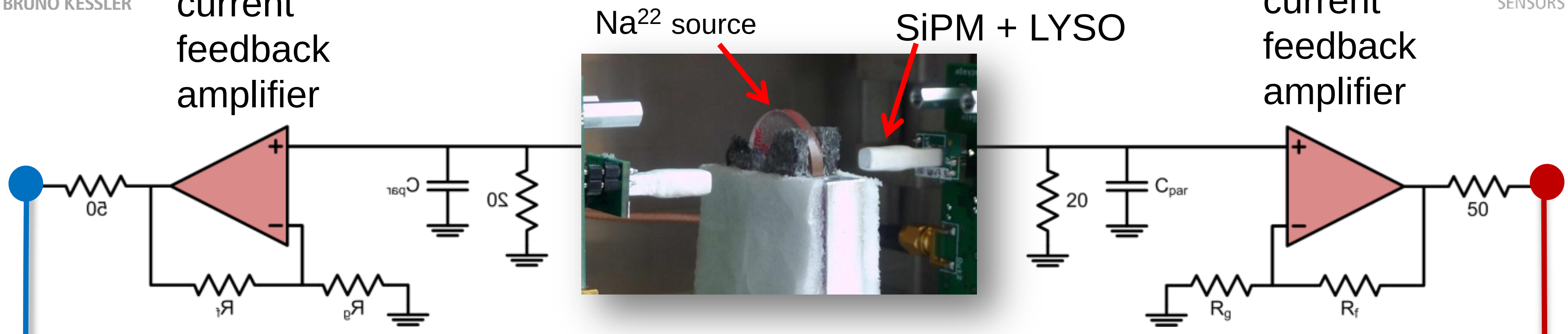
Then, we use the LED on the differential signal $s_2(t)$.

Important: electronic noise is ~ √2 higher in differential signal so its effect must be negligible for DLED to be effective

Experimental set-up

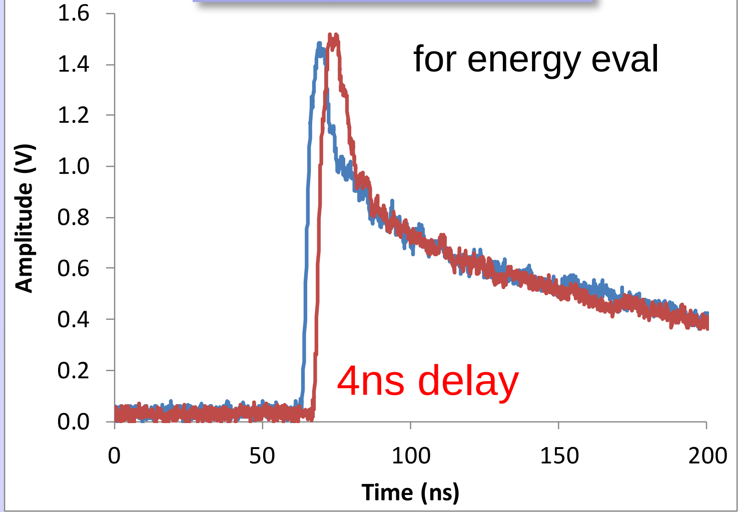
current feedback amplifier

current feedback amplifier



Digital scope (1GHz, 10GSa/s, 8 bit ADC)

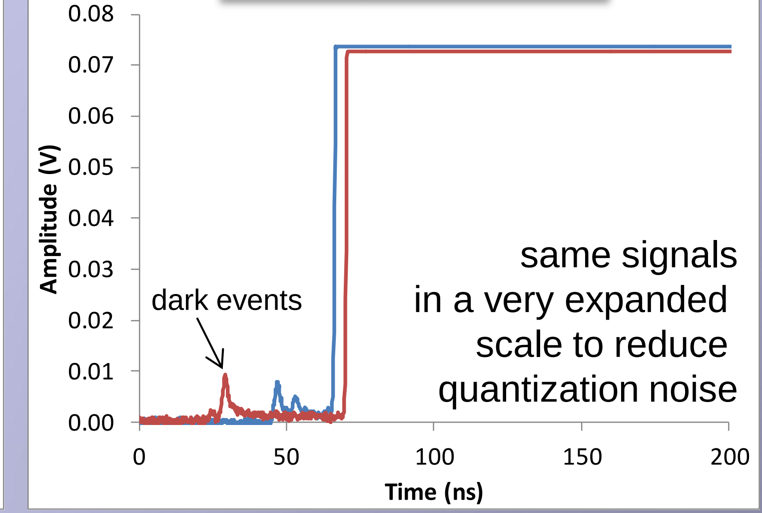
Energy channels



for energy eval

4ns delay

Timing channels



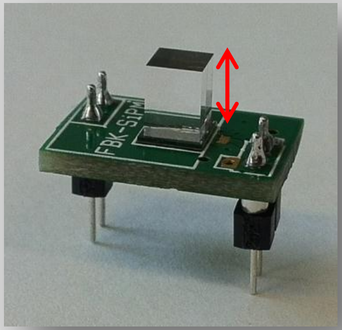
dark events

same signals in a very expanded scale to reduce quantization noise

Ch1 1MΩ Ch2 Ch3 50Ω Ch4

Detectors tested

Detector “cube”

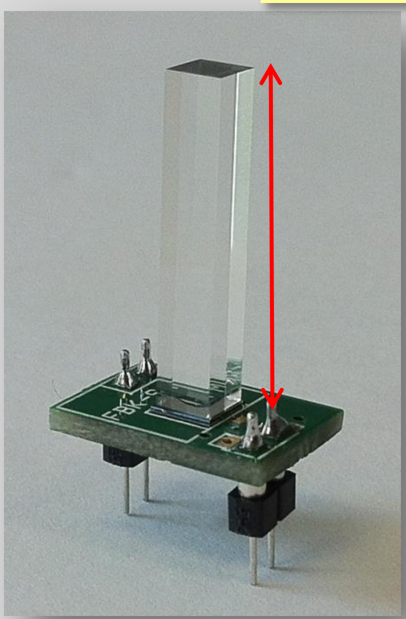


LYSO crystal 3x3x5mm^3

height ~ side

to test ultimate SiPM performance

Detector “PET”



LYSO crystal 3x3x15mm^3

height ~ 5 x side

real PET configuration (timing affected by light propagation in crystal)

SiPMs used

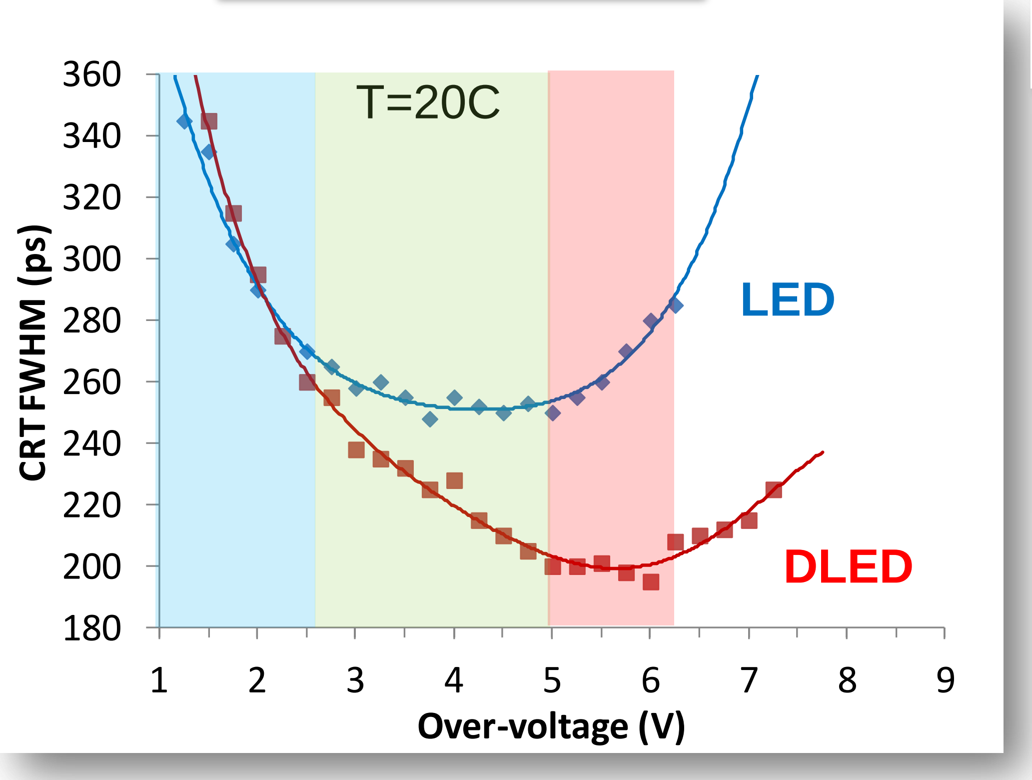
- **3x3mm^2**
- **4x4mm^2**

67um cell-size

produced by FBK, Trento

DLED vs. LED performance

Detector cube, 3x3mm² SiPM



DLED ΔT=500ps good up to 1ns

Low over-voltage:
low gain, low dark rate
➔ electronic noise dominates
➔ DLED slightly worse than LED

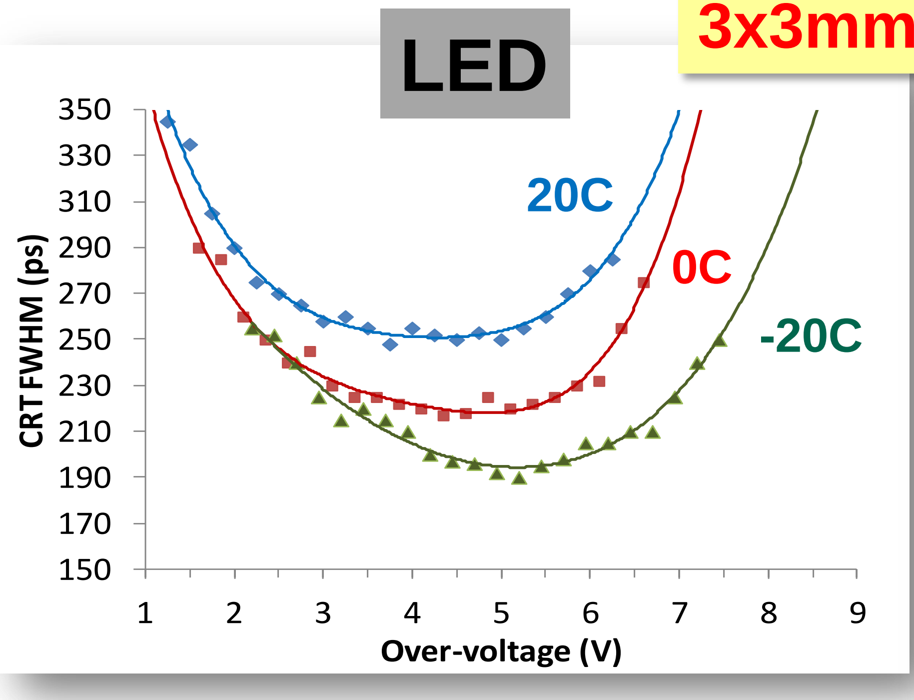
Medium over-voltage:
gain increases
dark noise ampl. > elect. noise
➔LED is flat (increase of PDE is compensated by increase of noise)
➔ DLED improves following PDE

High over-voltage:
high dark noise/rate
➔ LED starts deteriorating
➔ DLED still improves
for high PDE and
good noise compensation

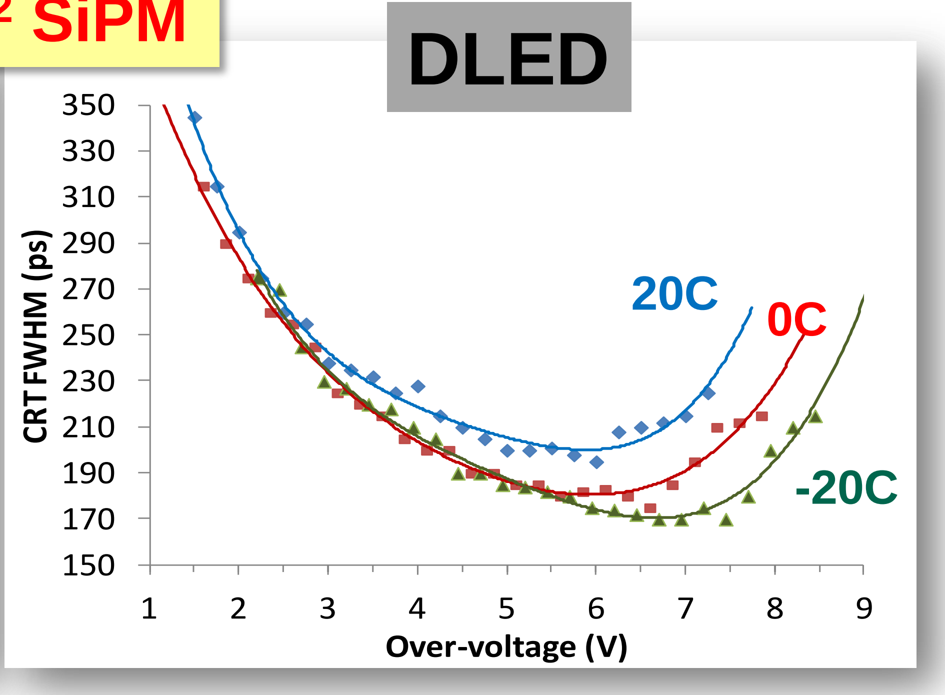
CRT vs. Temperature

Detector cube $3x3mm^2$ SiPM

LED



DLED



LED strongly improves with temperature because of noise (DCR) reduction.

DLED improves less with temperature and only at high over-voltages.

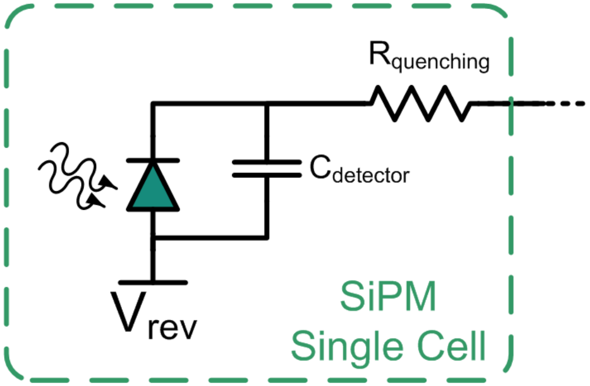
LED@-20C is almost equivalent to DLED@20C

Hardware Implementation

The DLED is difficult to integrate in an ASIC → Pole-Zero Compensation.

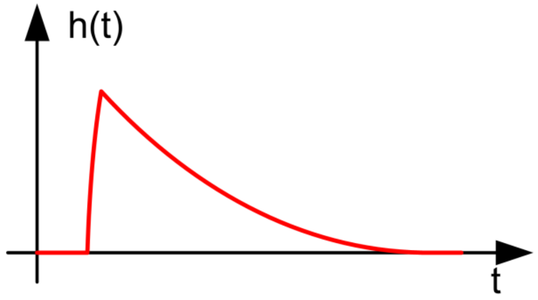
The passive recharge of the cells of the SiPM corresponds to a single real pole in the pulse response of the detector in the frequency domain.

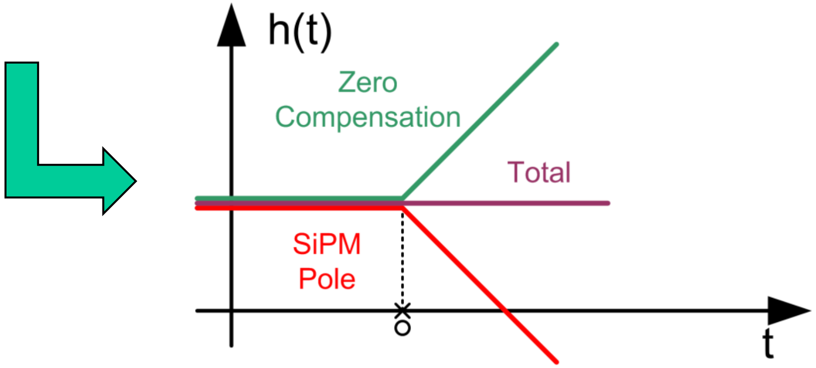
→ Pole cancellation through a zero at the same frequency in the front end.



$$\tau = R_q C_d$$

Non Compensated

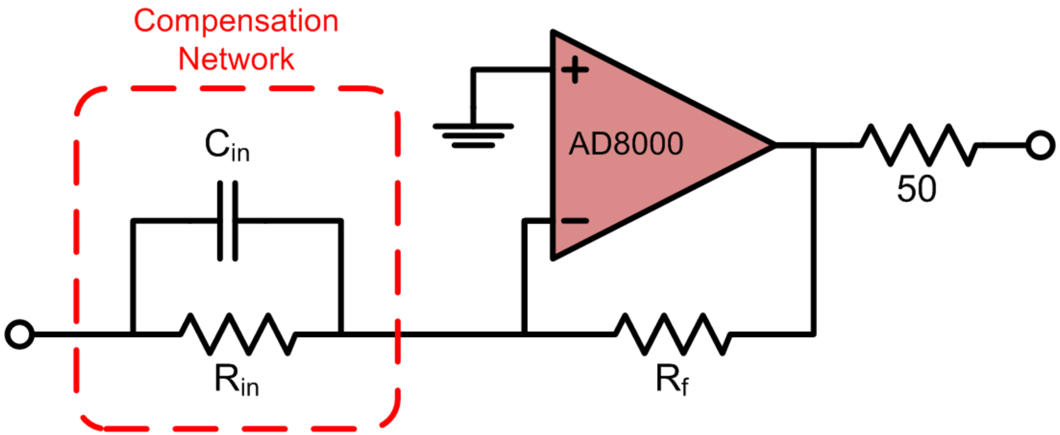




Compensated

The PZ in the Time Domain

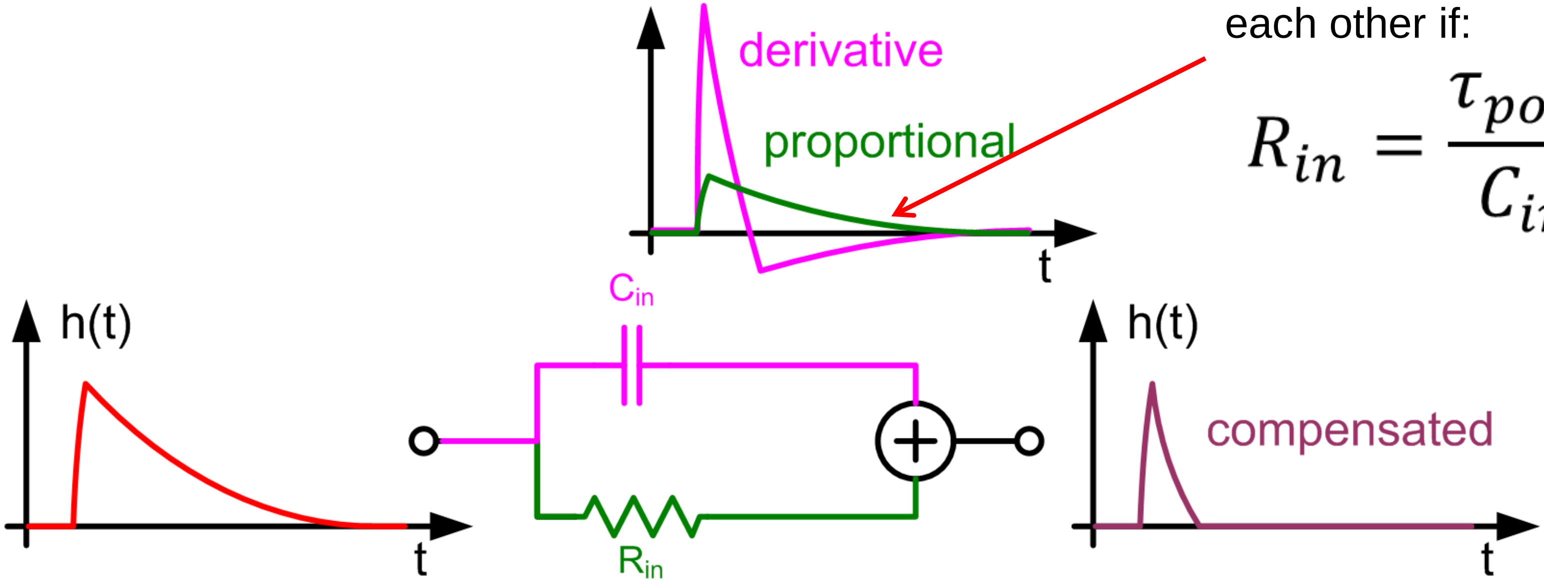
$$\tau_{in} = R_{in} C_{in}$$



Simple circuit implementation of the PZ method.

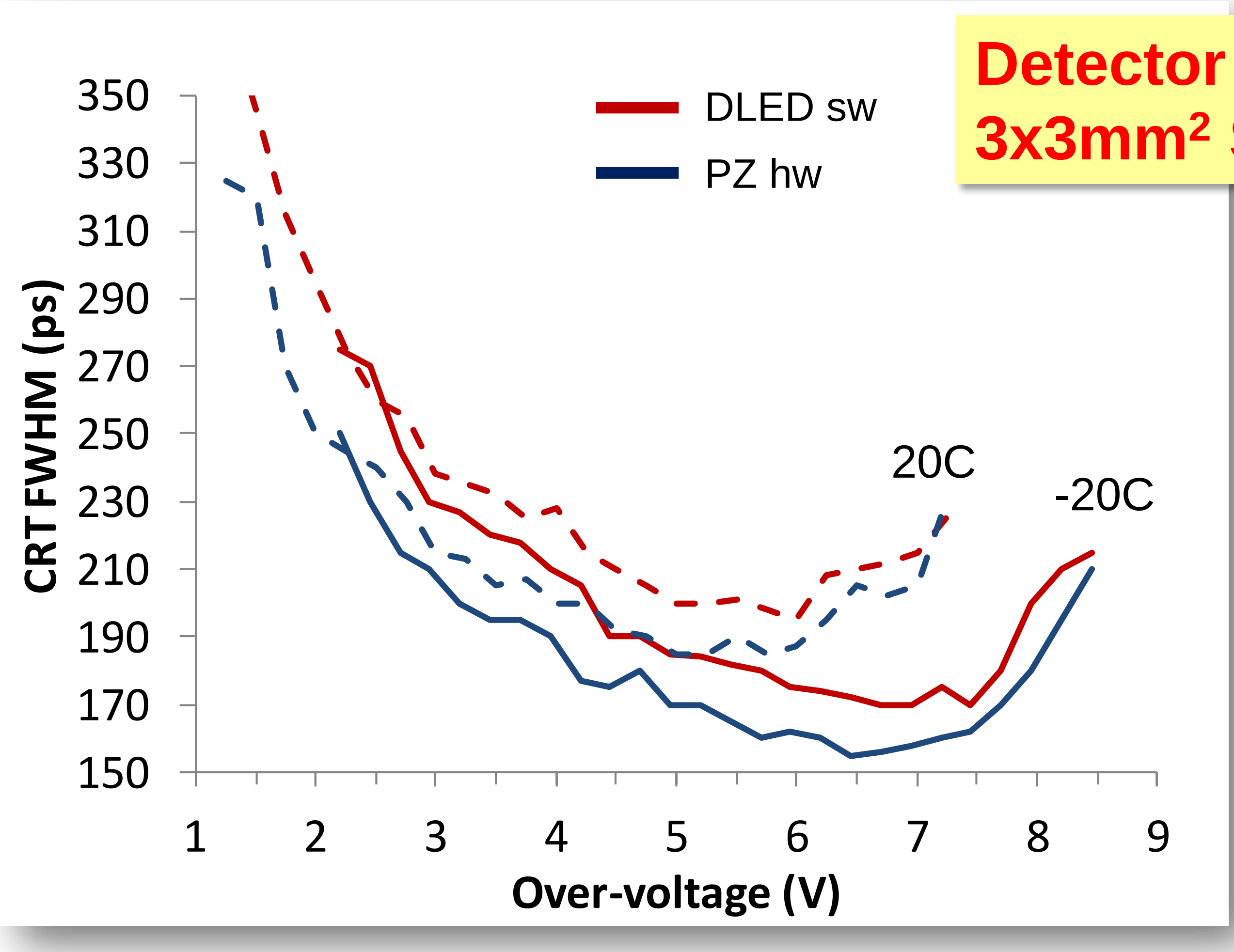
The tails have equal amplitudes and cancel each other if:

$$R_{in} = \frac{\tau_{pole}}{C_{in}}$$



CRT with PZ

The results are comparable or slightly better with the PZ method than with DLED → less noise without numerical differentiation.

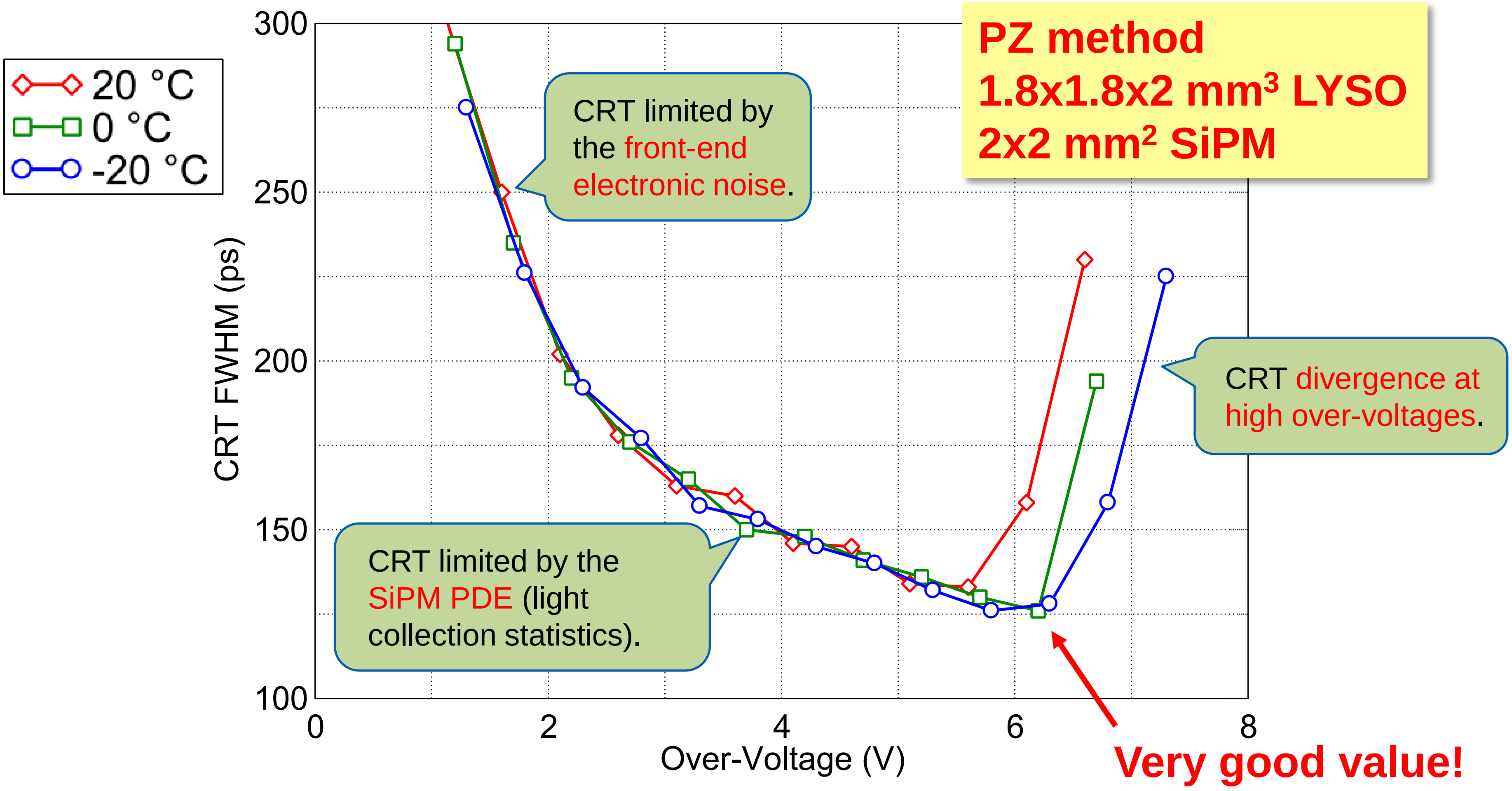


Detector cube 3x3mm^2 SiPM

Effects of the SiPM noise:
Optical Cross-talk Amplification

CRT limit at high over-voltage

With Pole-Zero noise compensation and smaller detectors we observe almost no dependence of the measured CRT on the DCR of the detector → timing resolution should be limited by PDE of the device only.



PZ method
1.8x1.8x2 mm^3 LYSO
2x2 mm^2 SiPM

CRT limited by the front-end electronic noise.

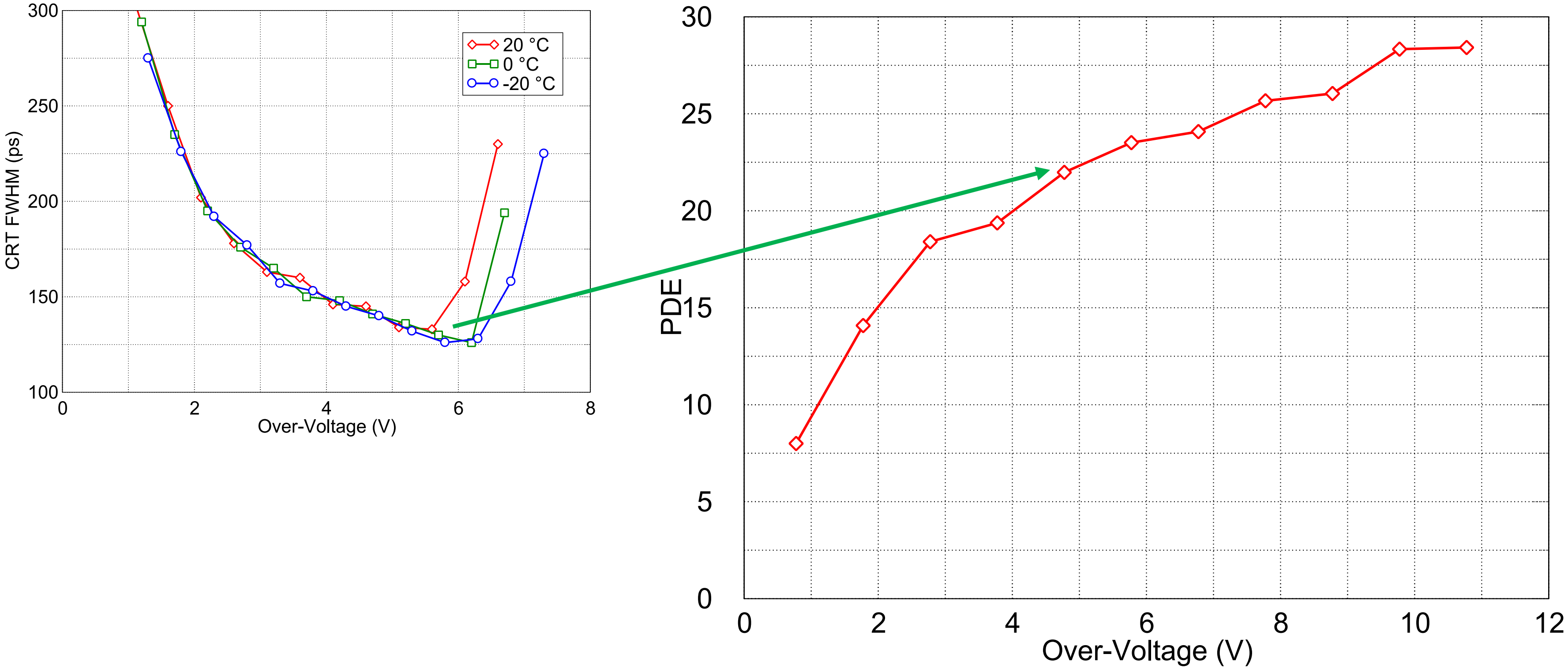
CRT limited by the SiPM PDE (light collection statistics).

CRT divergence at high over-voltages.

Very good value!

CRT limit at high over-voltage

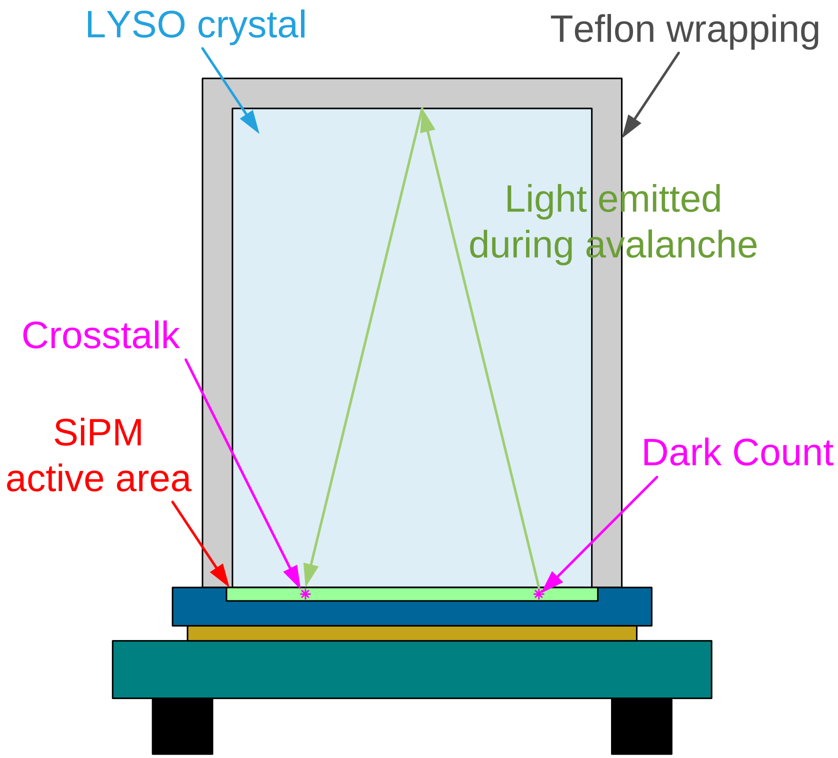
The optimum CRT value is not obtained at maximum PDE.



There is some other effect that prevents to operate the device at higher over-voltage and PDE.

Optical Cross-talk Amplification

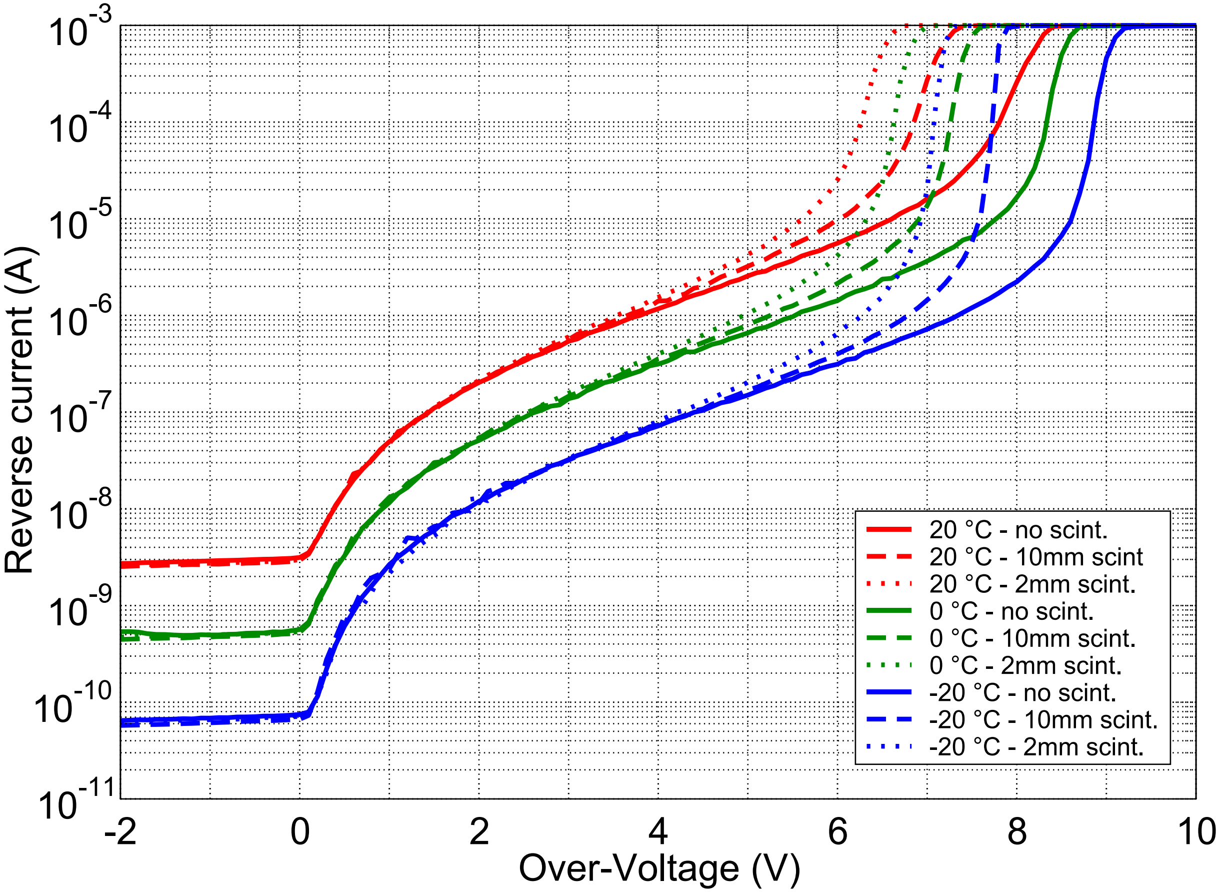
The scintillator reflects the photons emitted by the hot carriers during the avalanche.



Increase in the collection efficiency of the optical cross-talk photons.

Reverse SiPM Current

The phenomenon can be easily observed from the reverse current of the device, measured with and without the scintillator.



3 cases:

- **No scintillator**
- **2x2x2 mm³ LYSO**
- **2x2x10 mm³ LYSO**

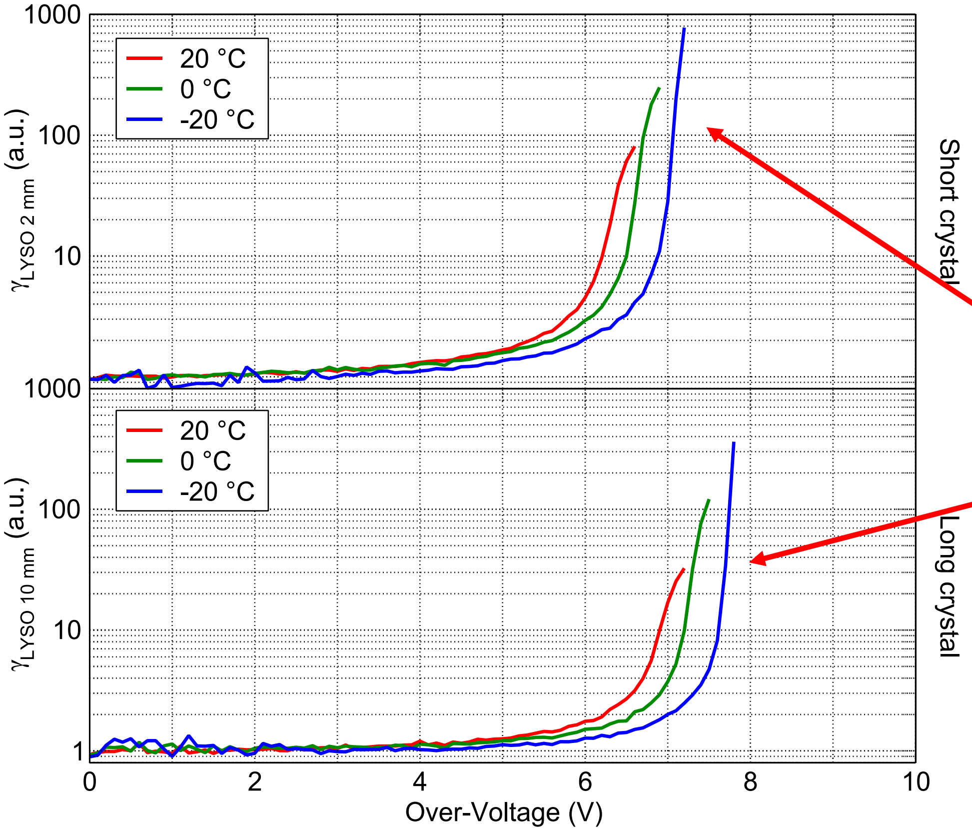
3 temperatures:
20°C, 0°C, -20°C

The current increase is larger for the shorter scintillator.

DCR amplification

It is possible to define a DCR amplification coefficient due to the scintillator enhanced cross-talk.

$$\gamma(V_{OV}) = \frac{I_{scint}(V_{OV})}{I_0(V_{OV})} = \frac{DCR_{scint}(V_{OV})}{DCR_0(V_{OV})}$$



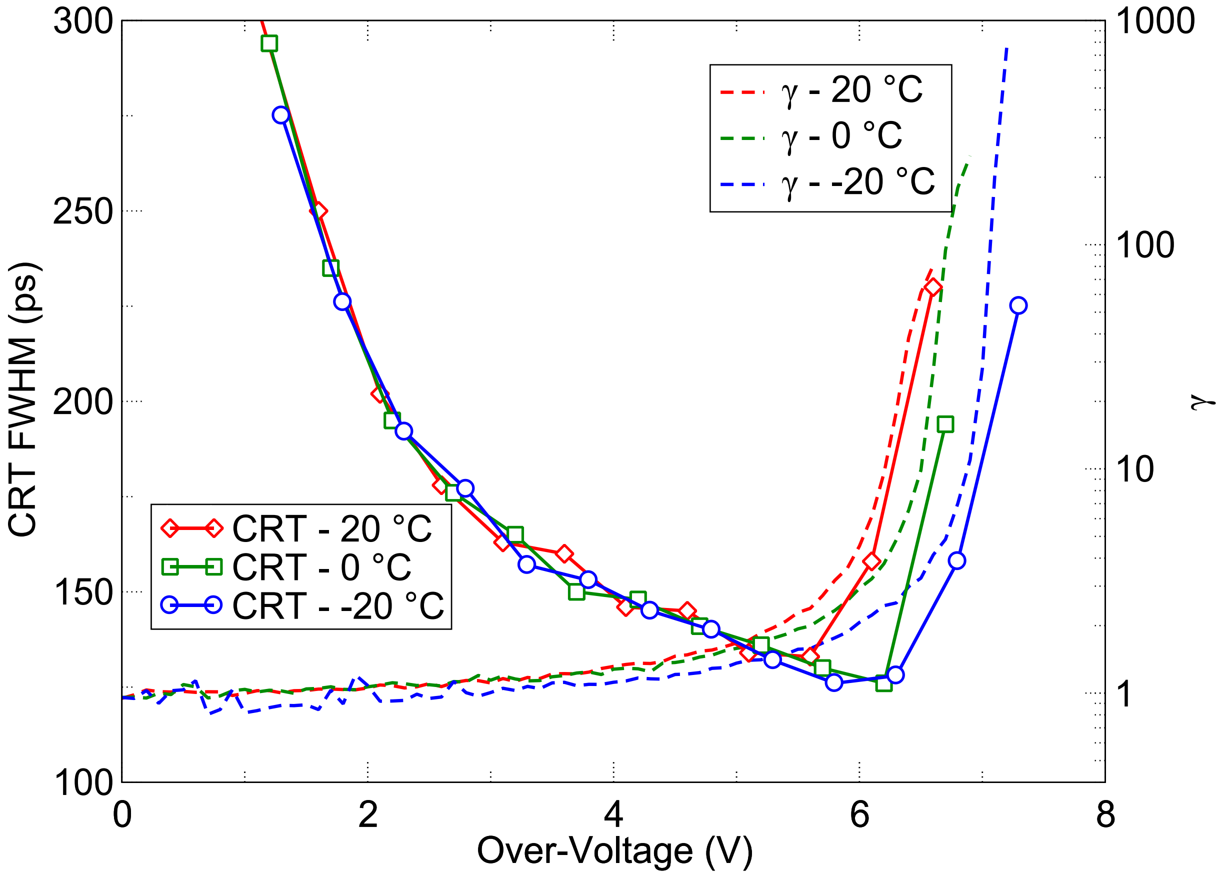
There is no amplification if the LYSO top face is covered with black paint.

Extremely high values!

The process rapidly diverges.

Correlation with Timing

The γ coefficient shows an almost perfect correlation with the CRT.



The PZ filter can no longer compensate for the detector noise.

Reduction of the effective PDE, due to cells busy with DCR.

Basically, the SiPM stops working.

Possible Solutions

For reaching higher over-voltage and PDE, it is necessary to reduce the amount of cross-talk:

- Color filters in the scintillator
  - Suppression of external cross-talk
- Optical Trenches and Double Junction
  - Suppression of internal cross-talk (total CT is determined by both internal and external components)
- Smaller cells with smaller gain but same fill-factor
  - Updated fabrication technology and cell-edge layout

Conclusion

We have demonstrated that the effect of dark noise on timing measurements with SiPM coupled to LYSO crystal can be largely compensated.

The baseline compensation can be implemented with a simple, ASIC compatible, analog circuit.

Once the effects of the DCR are removed, we can observe a different phenomenon, limiting the timing resolution of the SiPM, related to the optical cross-talk, increased by the scintillator.

Possible solutions are under investigation, however the HD technology seems a very promising option.

Acknowledgments

HyperImage project

SUBLIMA project

FBK-INFN MEMS2 agreement

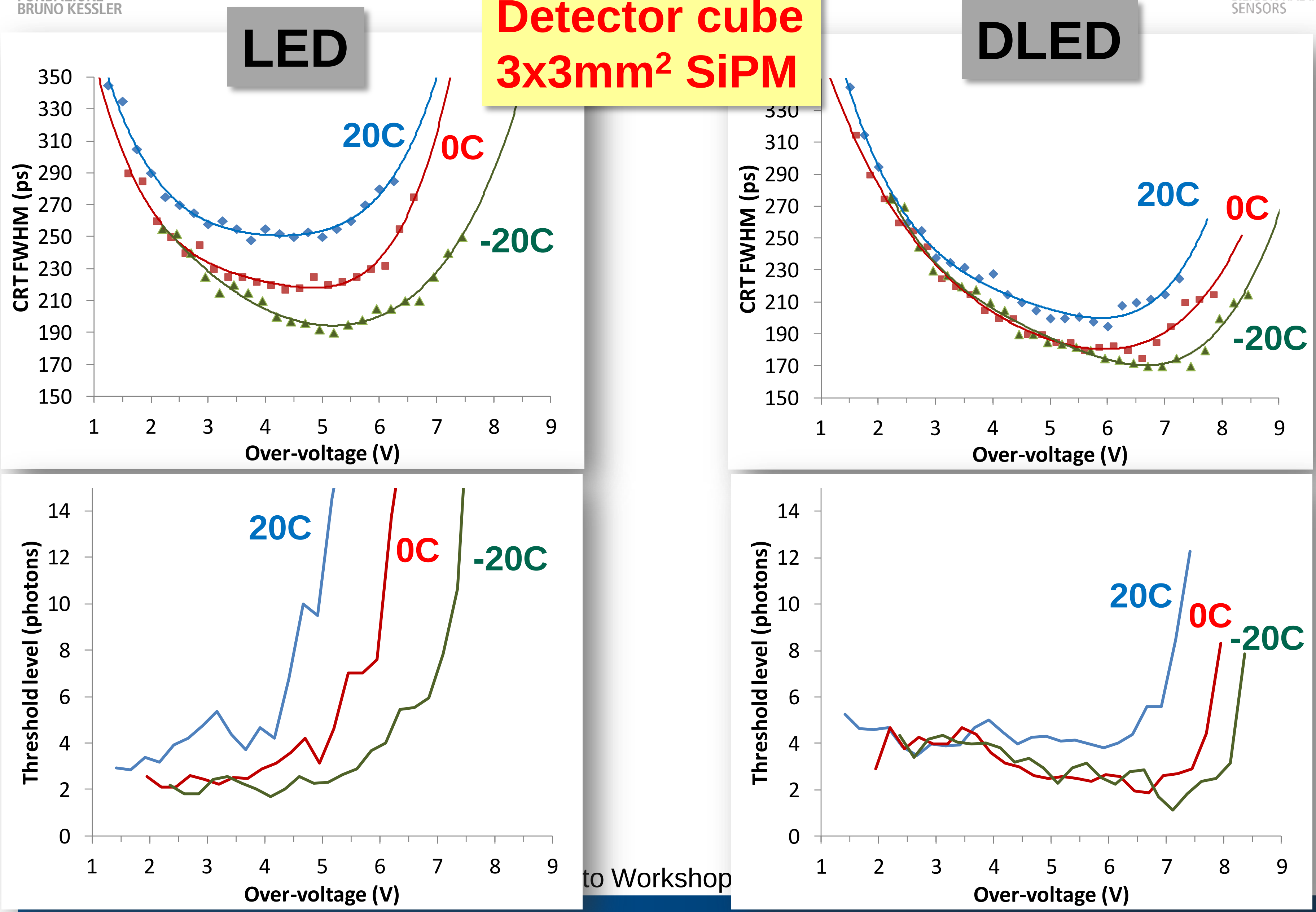
Back-up slides

In the next slides:

- CRT vs Temperature
- Threshold level
- crystal height
- SiPM size

Optimum Threshold level

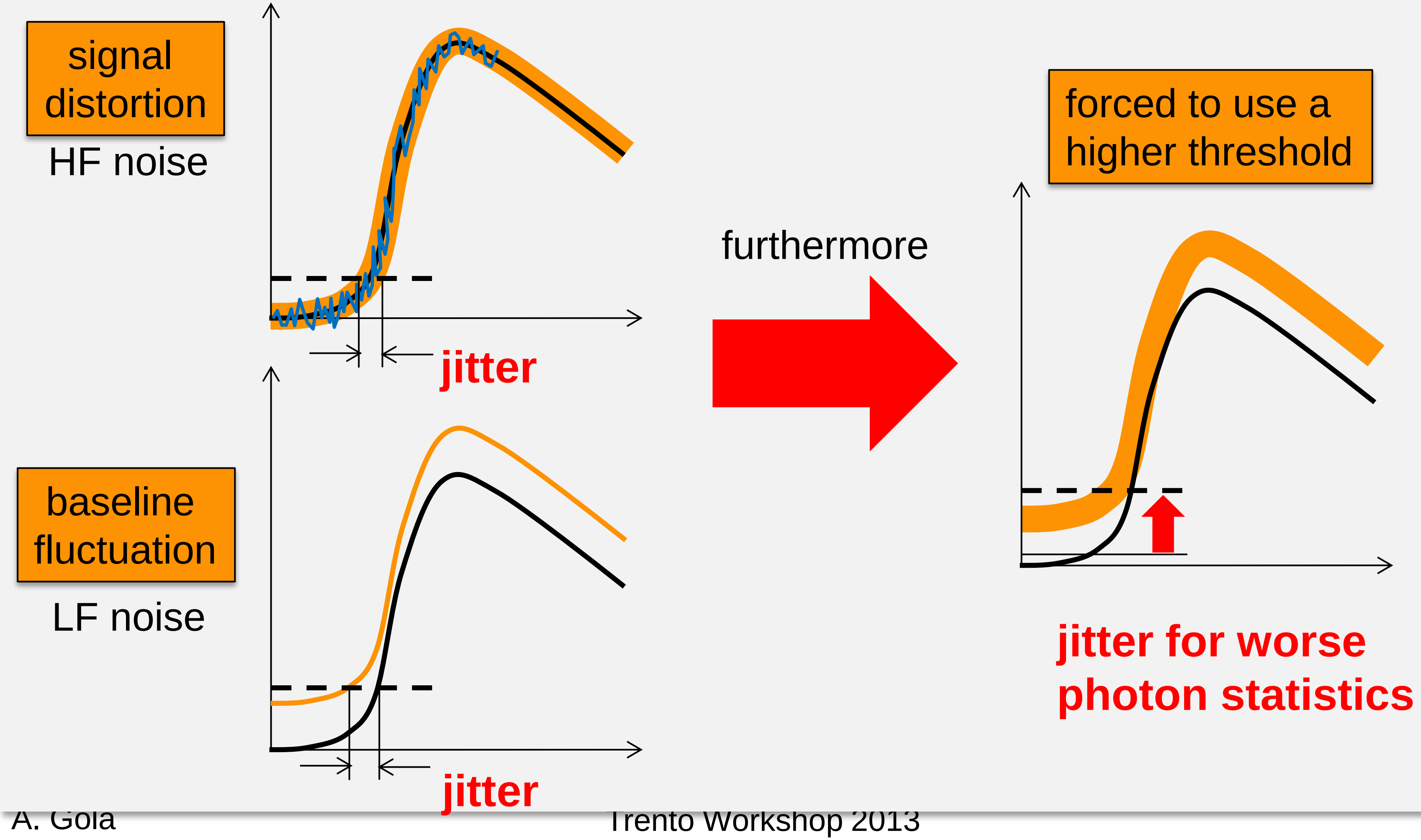
Detector cube
3x3mm^2 SiPM



Leading Edge Discriminator

LED is widely used in PMT-based systems

What is the effect of noise on timing?



signal distortion

HF noise

jitter

baseline fluctuation

LF noise

jitter

furthermore

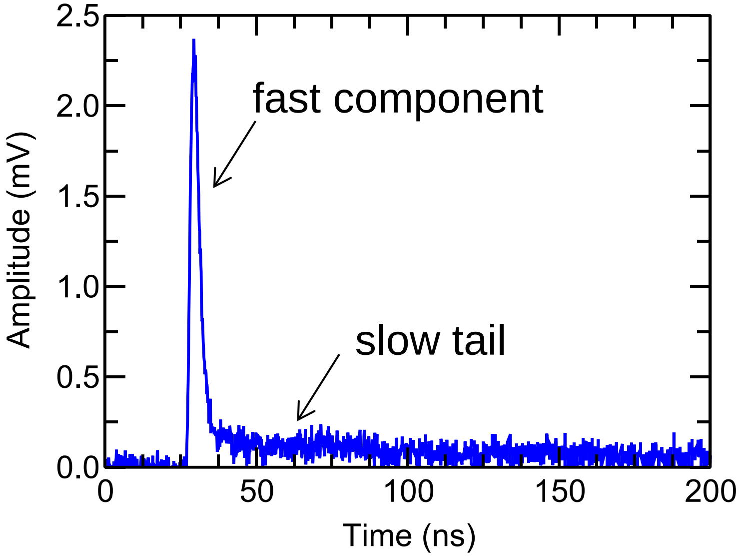
forced to use a higher threshold

jitter for worse photon statistics

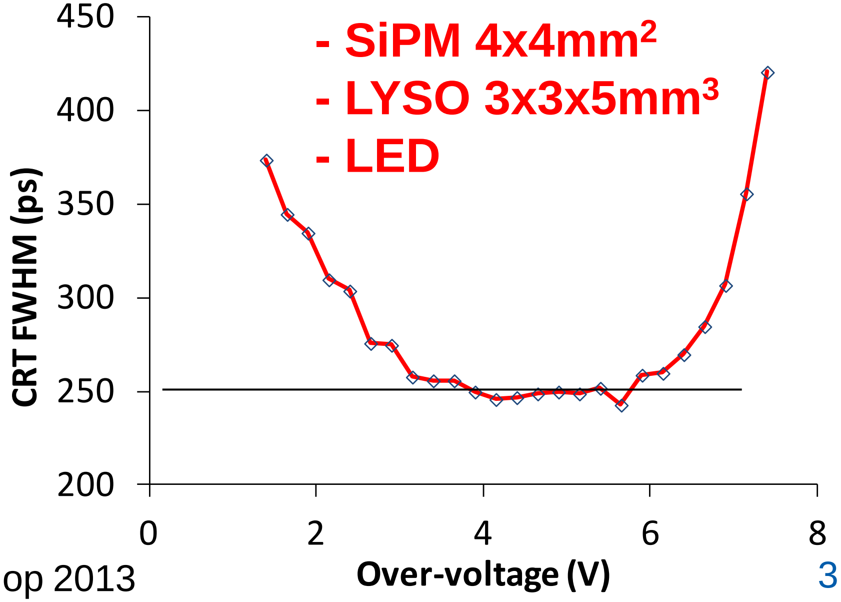
First approach: SiPM signal shape

In this case we increase both the quenching resistor and the quenching capacitor in order to enhance the fast component and decrease the slow one.

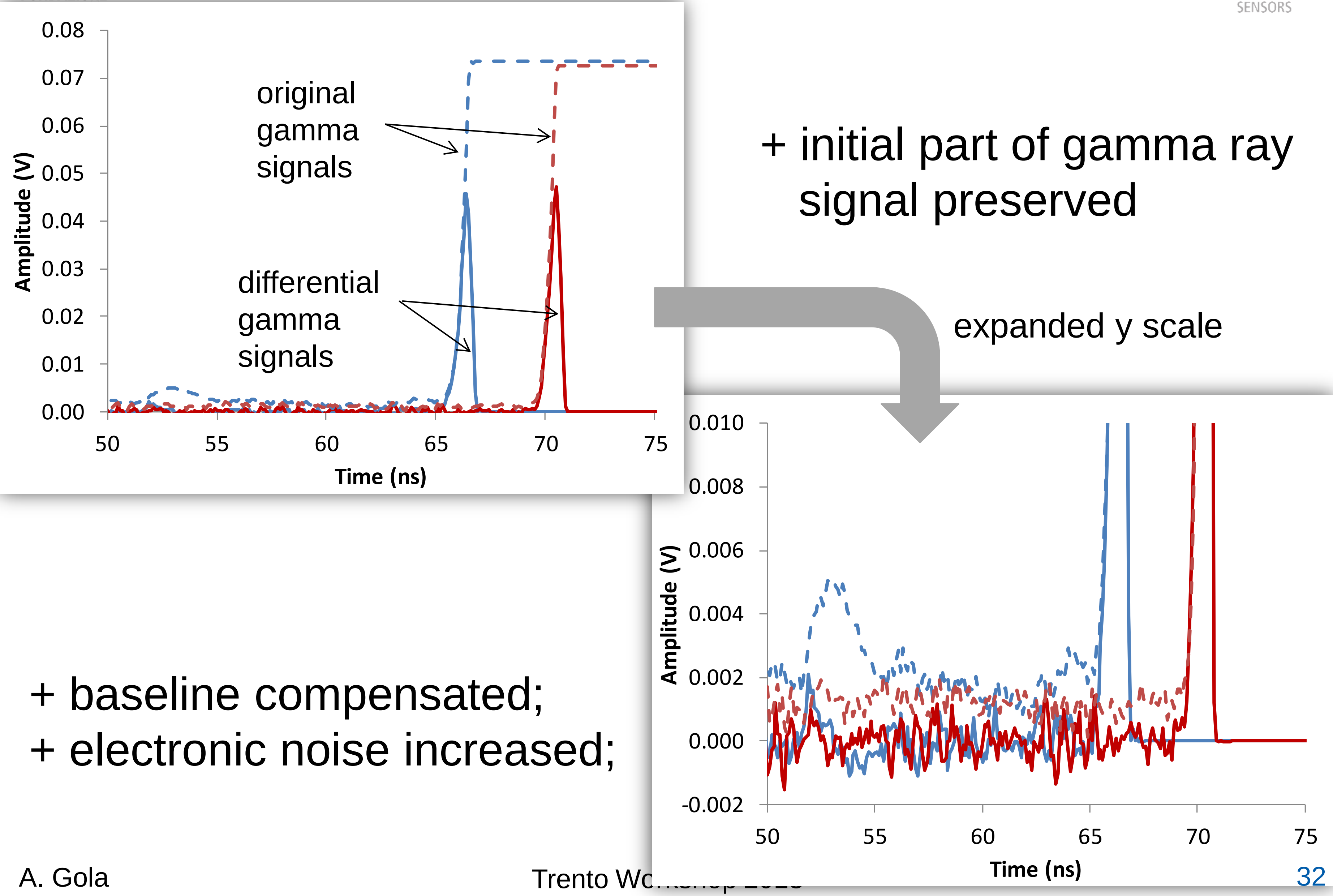
SCR of a 4x4mm^2 SiPM



Steeper rising edge of the gamma pulse and lower baseline fluctuation



Example



expanded y scale

+ initial part of gamma ray signal preserved

+ baseline compensated;

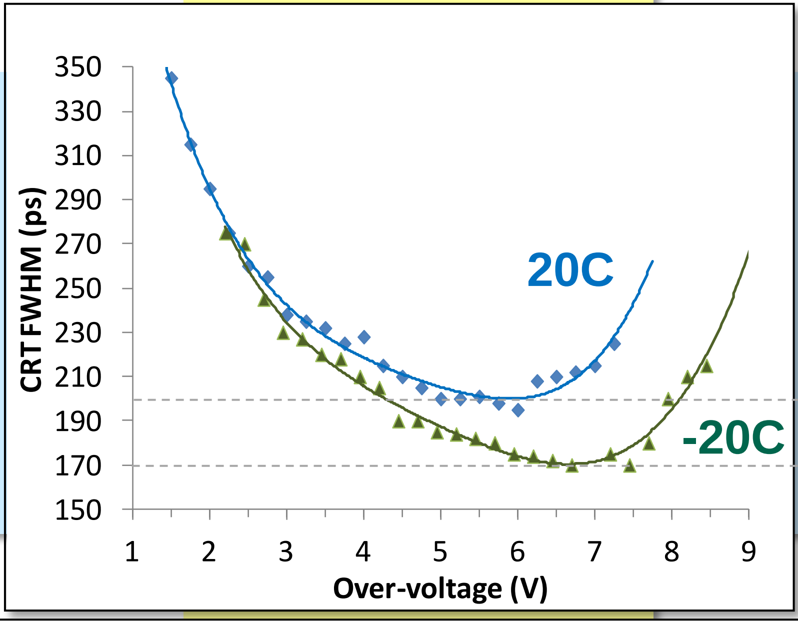
+ electronic noise increased;

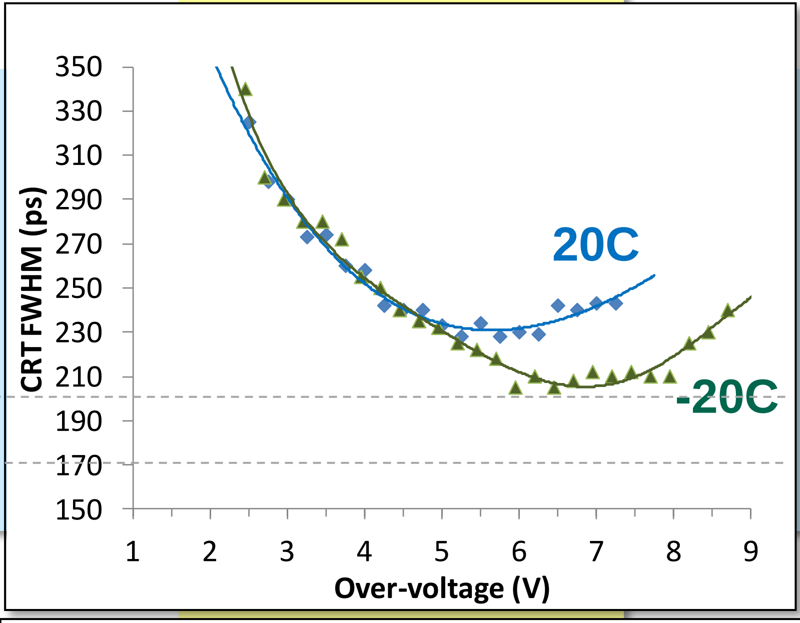
DLED – comparison

Detector cube

Detector PET

SiPM 3x3mm^2





SiPM 4x4mm^2