Functional performance of high-fill factor small-cell size SiPMs at FBK

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Outline

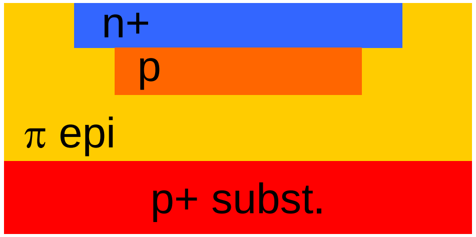
- Introducion
- Standard SiPM technology at FBK
- High-Density (HD) SiPM Technology
- HD-SiPM Functional Characterization
- Application Example: TOF-PET
- Conclusions

Standard SiPM technology at FBK

RGB Technology

N-on-P structure

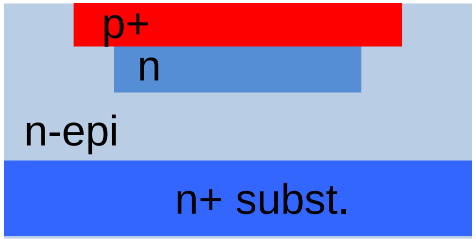
Peak sensitivity: Red-Green-Blue



NUV Technology

P-on-N structure

Peak Sensitivity: Near Utra Violet



Parameter	RGB	NUV
Breakdown voltage	28.5 V	26.5 V
Cell Size (Fill Factor)	40 µm (60%)	40 µm (60%)
DCR (20C)	<400 kHz/mm^2	100 kHz/mm^2
DiCT	20%	<10%
DeCT+AP	15%	40%
Max PDE band	480-600 nm	300-400 nm
Peak PDE	35%	35%

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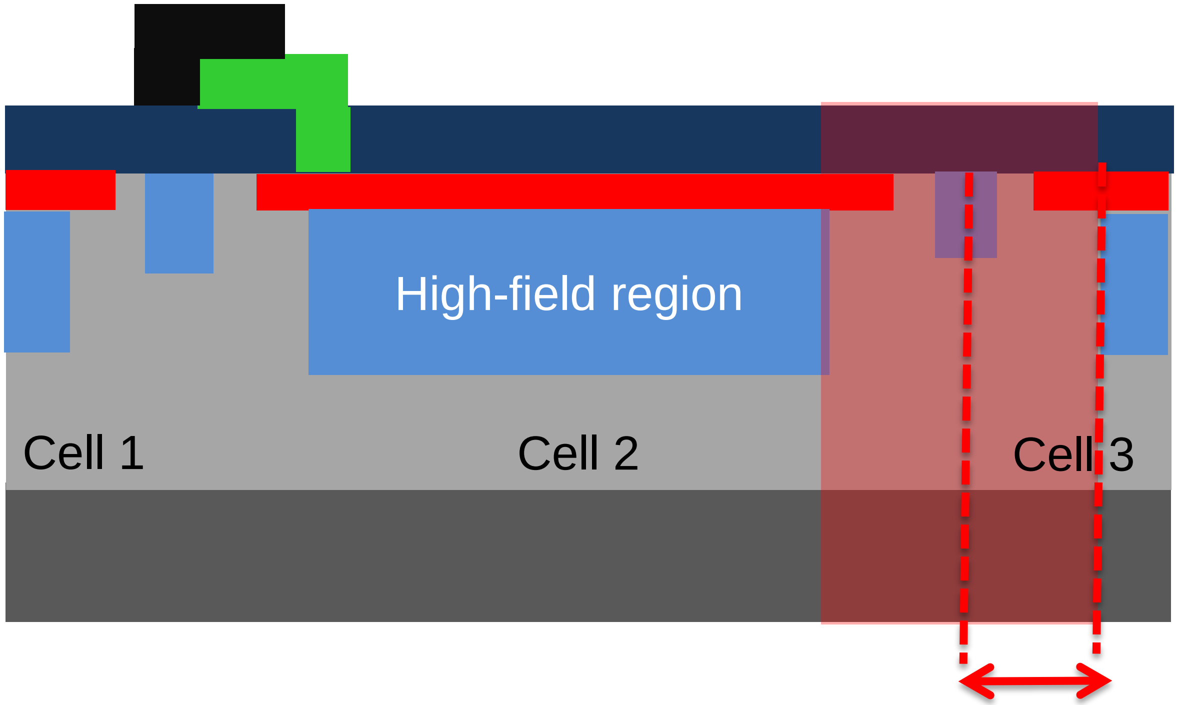
Standard RGB SiPM: limits

1. Limited fill factor → limited PDE



Dead border region around each SPAD deteriorates the active-to-total area ratio (FF).

The key-point to increase FF is the reduction of gap between high-field region and cell border

Standard RGB SiPM: limits

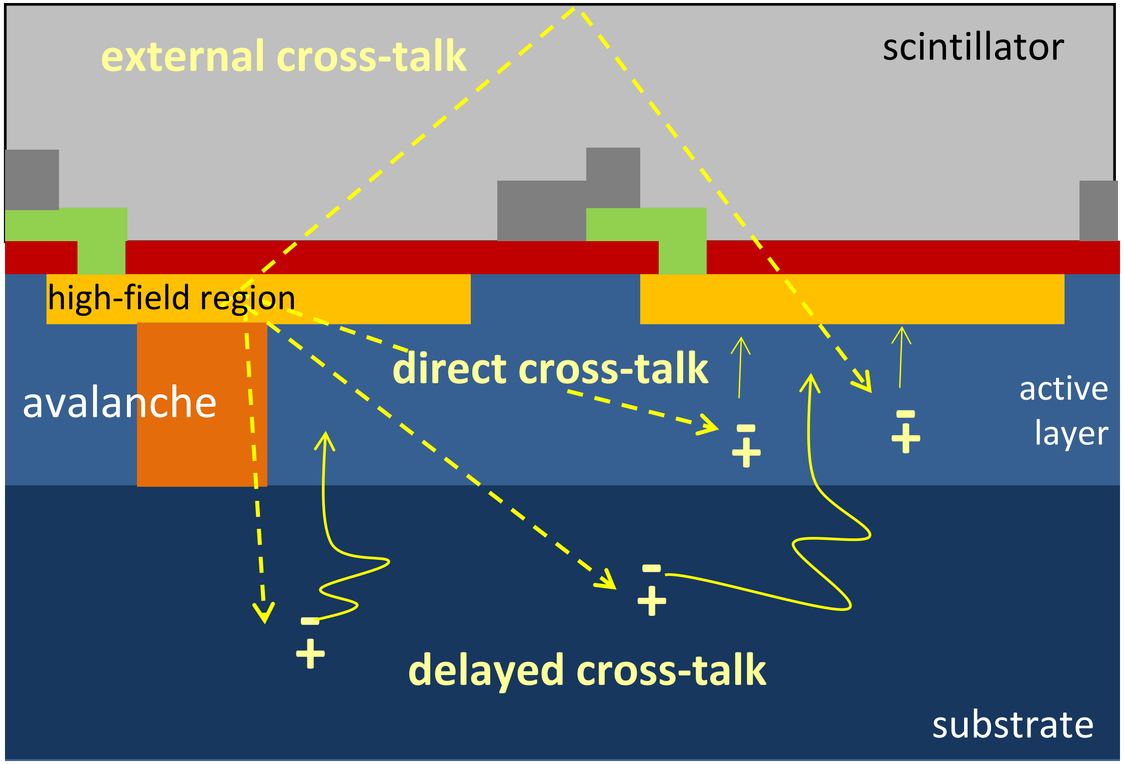
2. Correlated noise

❖ **Optical Cross-talk**

CT can be reduced:
→ with proper optical isolation structures;
→ **reducing the gain.**

❖ **After-pulsing**

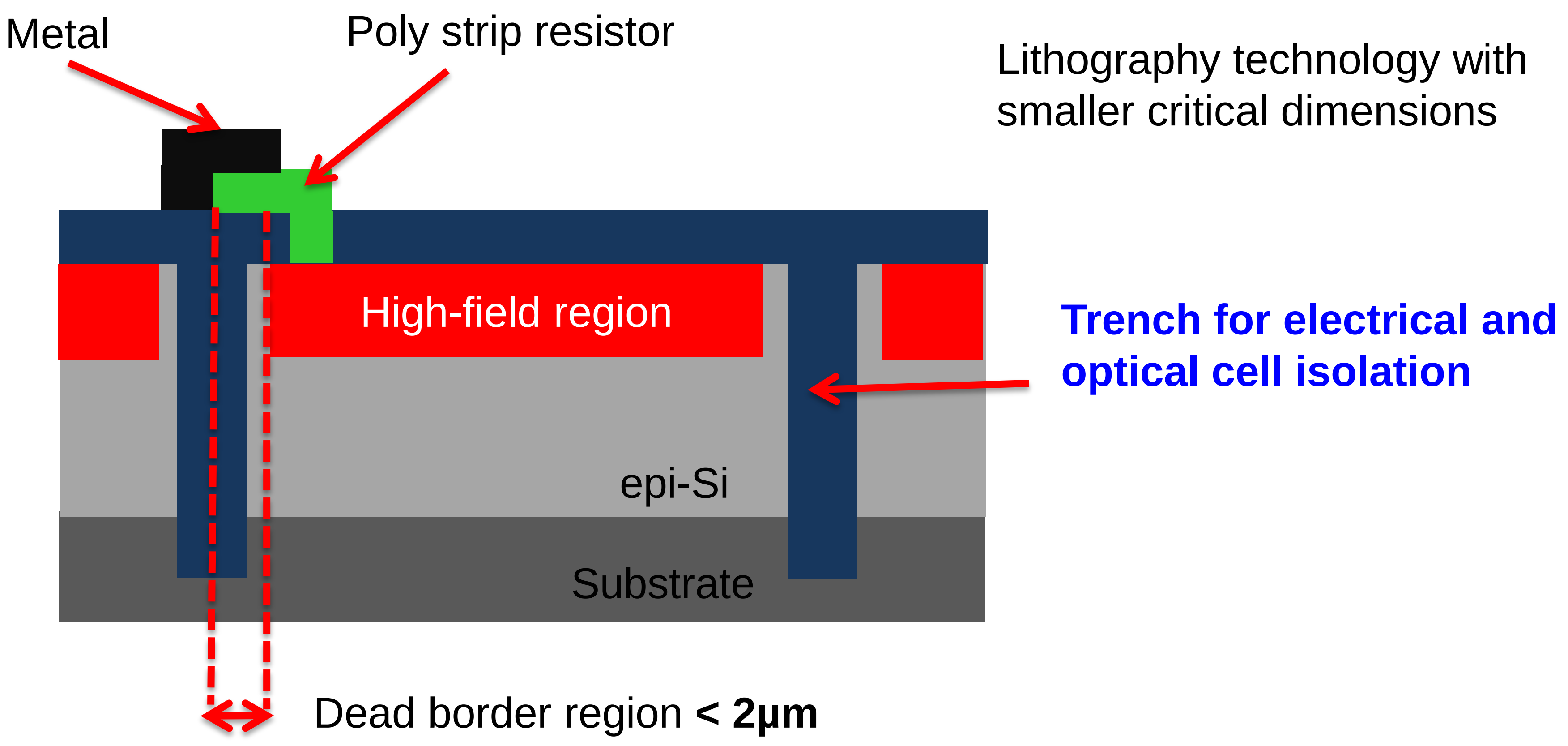
It can be reduced:
→ reducing the carrier trapping centers;
→ **reducing the gain.**



One way to reduce the gain is to reduce the Cell Size

RGB-HD SiPM technology

Keeping the same active area of the Std. RGB technology, we redesigned the border structure to increase the FF



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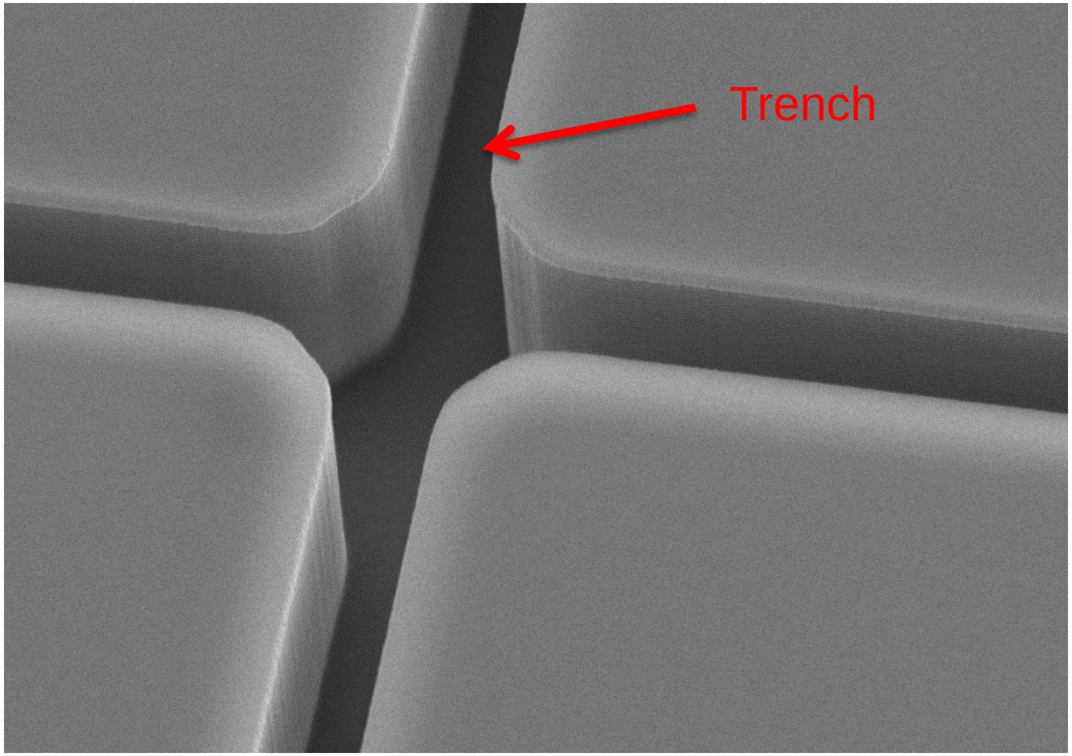
RGB-HD SiPM technology



Trench characteristics:

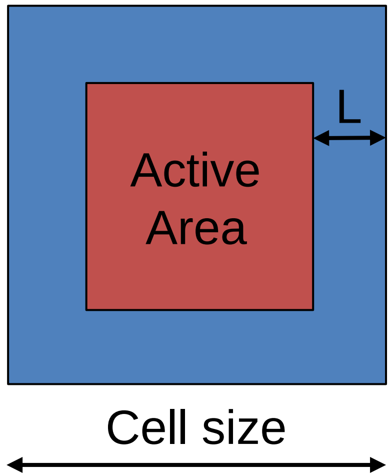
- Narrow (< 1 µm)
- High aspect-ratio (depth > 5 µm)
- Low roughness sides -> low induced defects

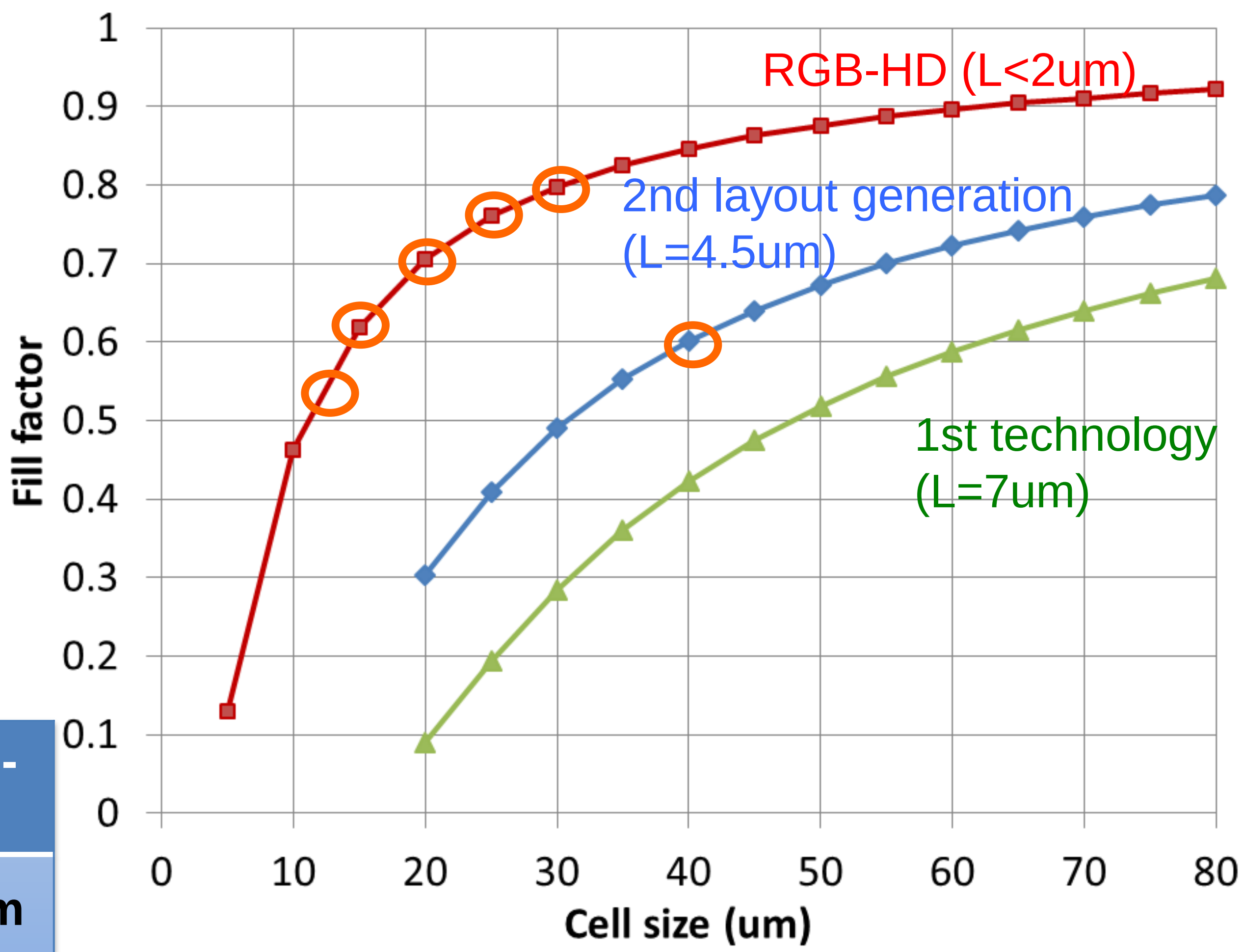
Advantages:

- Optical isolation -> Reduced Direct and Delayed Cross talk
- Electrical isolation with reduced dead border width –> Small Cell Size without FF reduction

RGB-HD SiPM technology

SiPM Cell, top view





	Std. SiPM RBG	RGB-HD
CS	40 μm	15 μm
FF	60 %	62 %

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Advantages of Small Cell Size

1. Lower correlated noise, because of lower gain (lower C_d):
- lower afterpulsing
- lower direct and delayed CT
- lower external Optical CT (with scintillator).

↓ Cell Size
↓ Gain (10^5)
↓ Correlated Noise

2. Larger dynamic range, higher linearity
3. Faster recharge time
   - reduced pile-up
   - useful with «slow» scintillators (CsI) for further dynamic range
4. Operation at higher over-voltage for
   - better temperature stability
   - better gain uniformity

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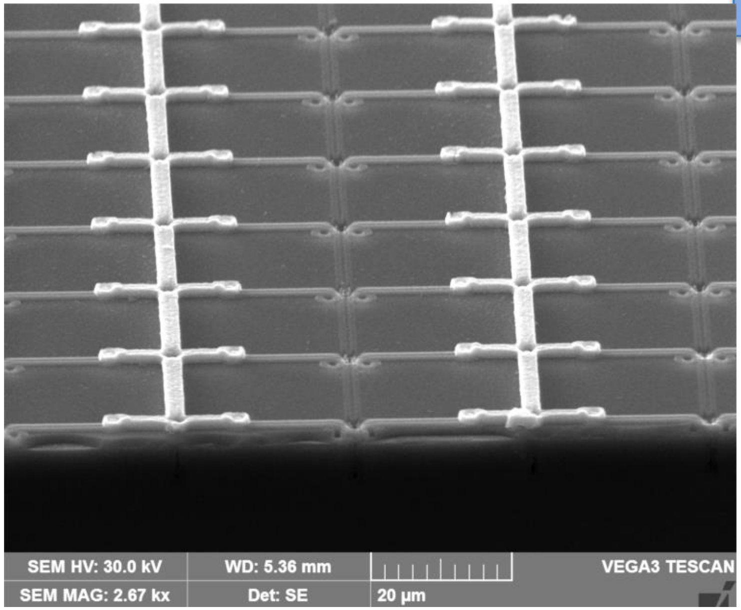
New SiPM-HD prototypes

Devices with five different CS have been produced and tested !

CS	Nominal FF	Cell Density
12 × 12 μm^2	52 %	7056 cells/mm^2
15 × 15 μm^2	62 %	4624 cells/mm^2
20 × 20 μm^2	66 %	2500 cells/mm^2
25 × 25 μm^2	72 %	1600 cells/mm^2
30 × 30 μm^2	77 %	1156 cells/mm^2



SiPM with 15 μm cell size

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RGB-HD SiPM Functional Characterization

Main Parameters

- Gain
  - Number of electrons produced per detected photon
- Correlated Noise
  - after-pulsing, optical cross-talk
- Primary Noise (DCR)

  - Thermal+Tunneling generated events
- Photo-detection efficiency (PDE)
  - Number of detected photons over total incident photons

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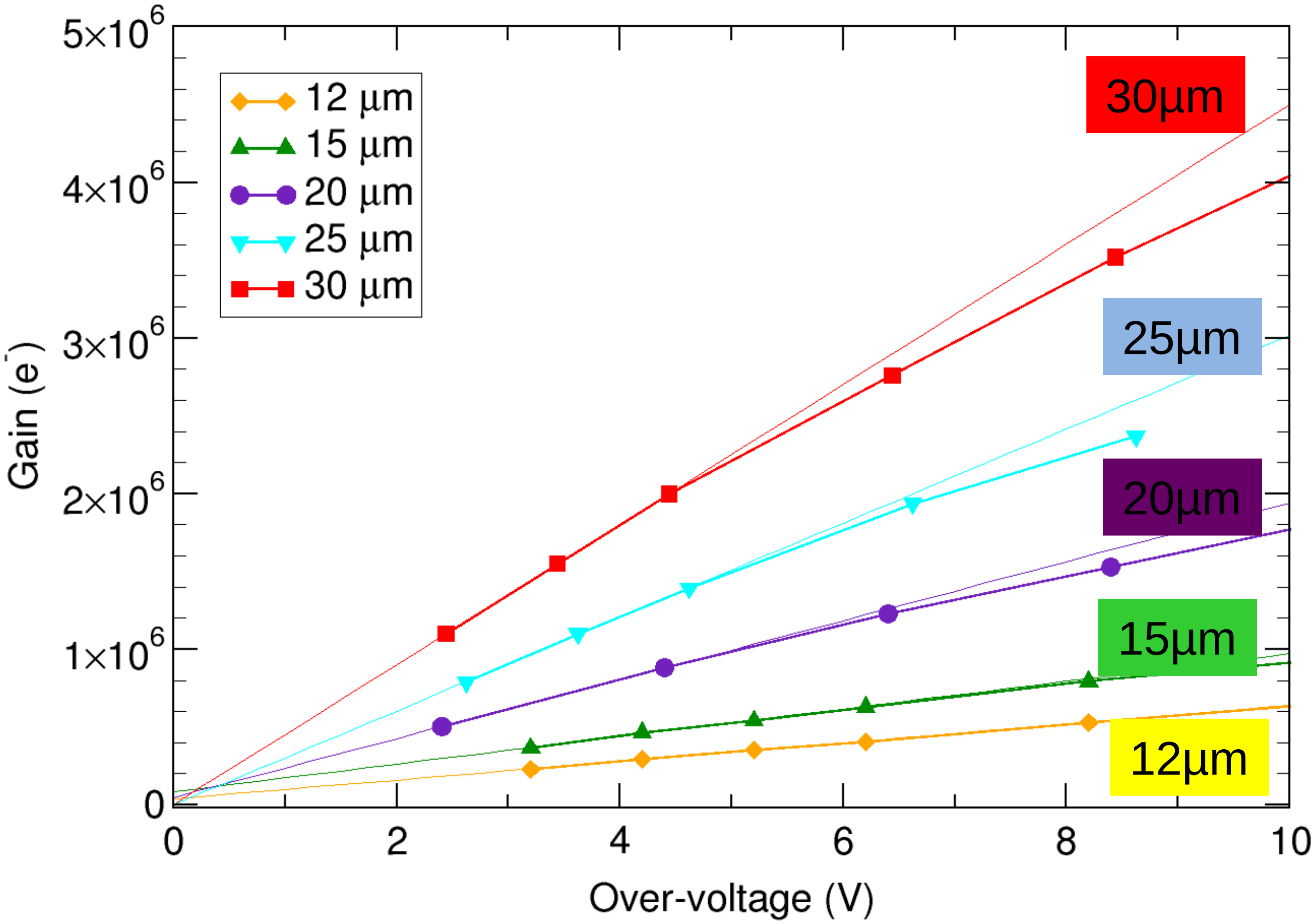
RGB-HD SiPM Functional Characterization:

GAIN

Std. SiPM RBG (CS 40 µm)
Gain = 4 10^6
FF 60 %

RGB-HD (CS 15µm)
Gain = 4 10^5
FF = 62 %



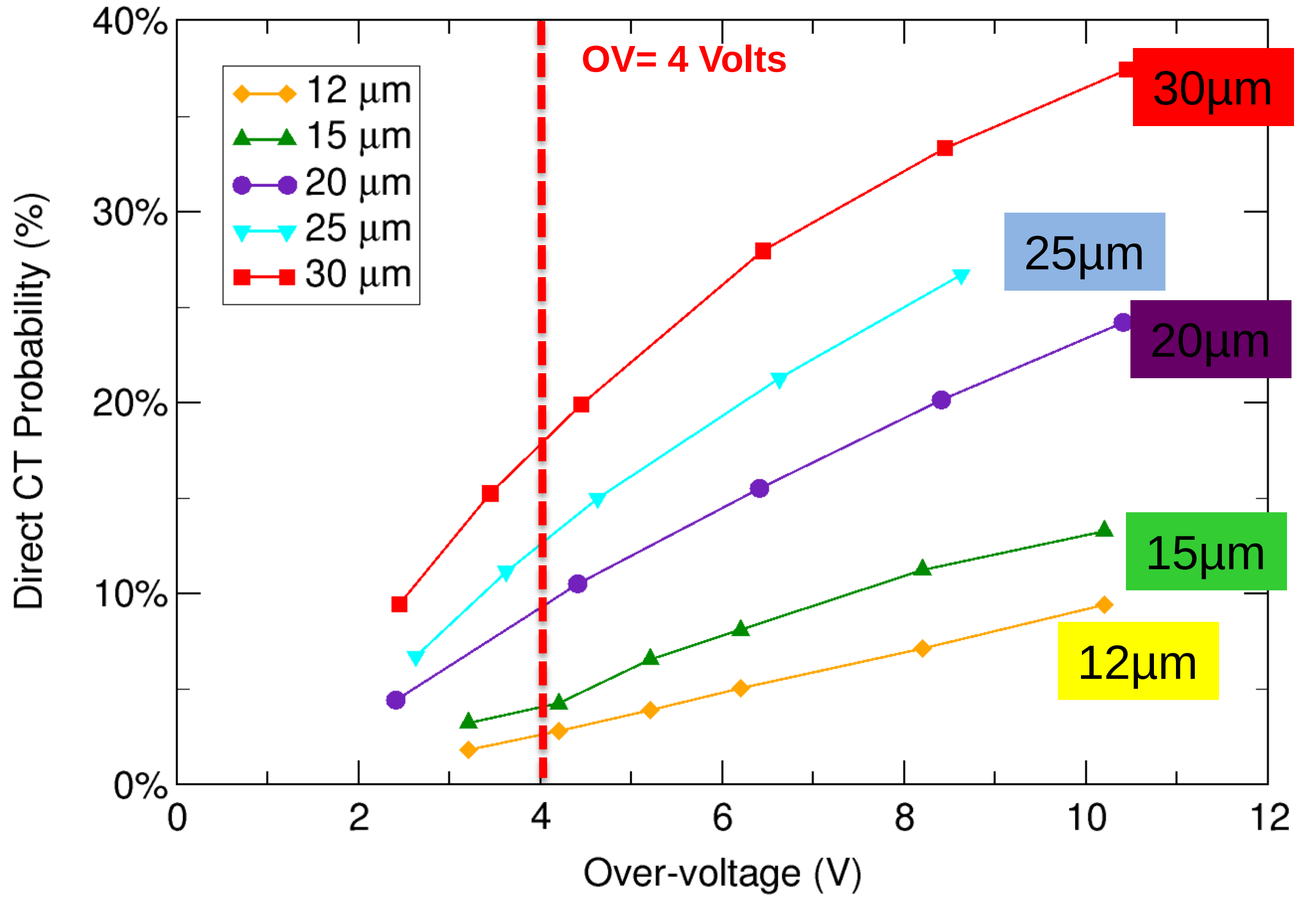
20°C, OV= 4 Volts

RGB-HD SiPM Functional Characterization:

Crosstalk Probability

Std. SiPM RBG (40 µm)
CT = 20 %
FF = 60 %

RGB-HD (15µm)
CT < 5 %
FF = 62 %



20°C, OV= 4 Volts

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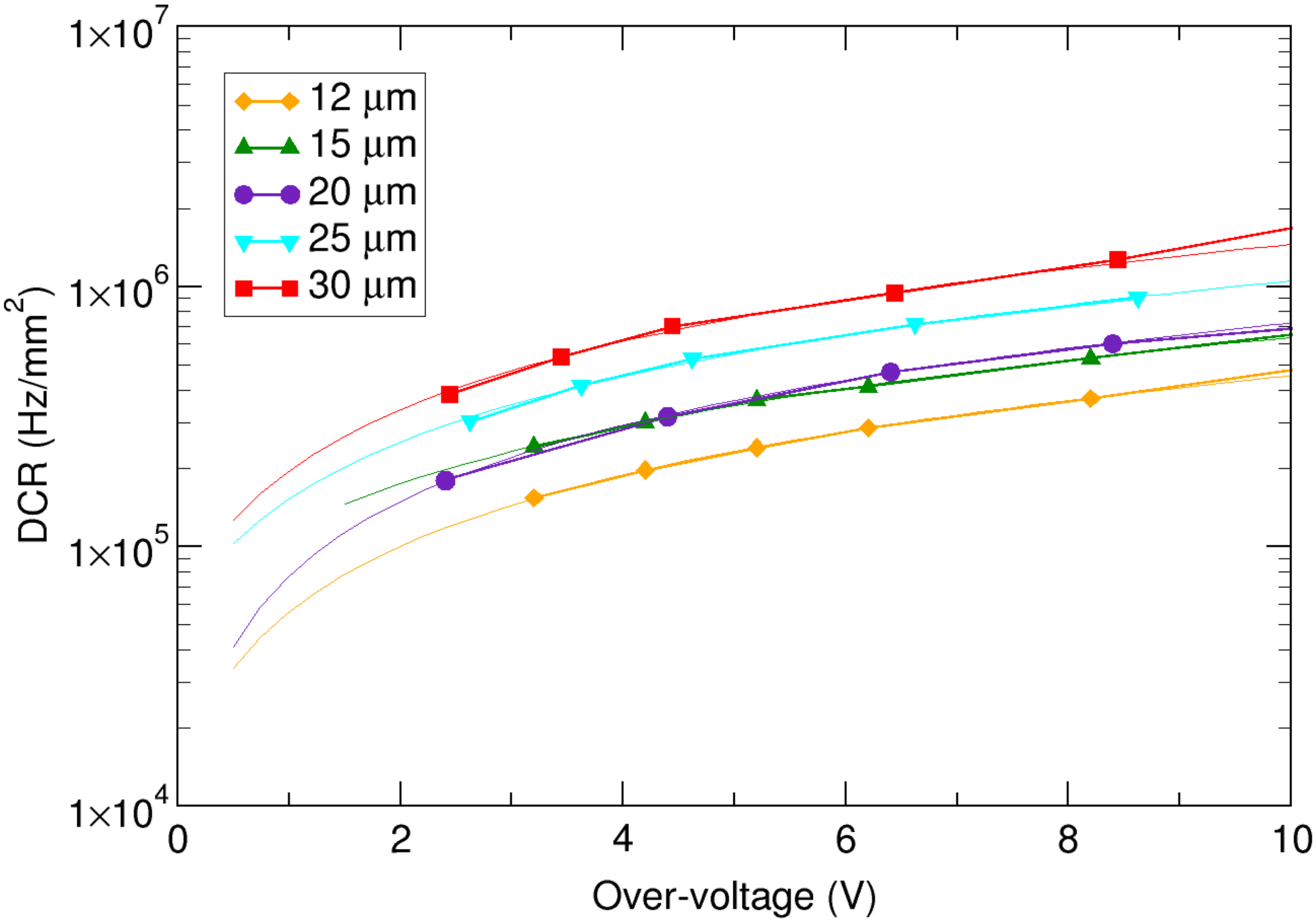
RGB-HD SiPM Functional Characterization:

Dark Count Rate (DCR)

Std. SiPM RBG (40µm)
DCR = 200-400 kHz/mm²
FF 60 %

RGB-HD (15µm)
DCR= 250 kHz/mm²
FF = 62 %



20°C, OV= 4 Volts

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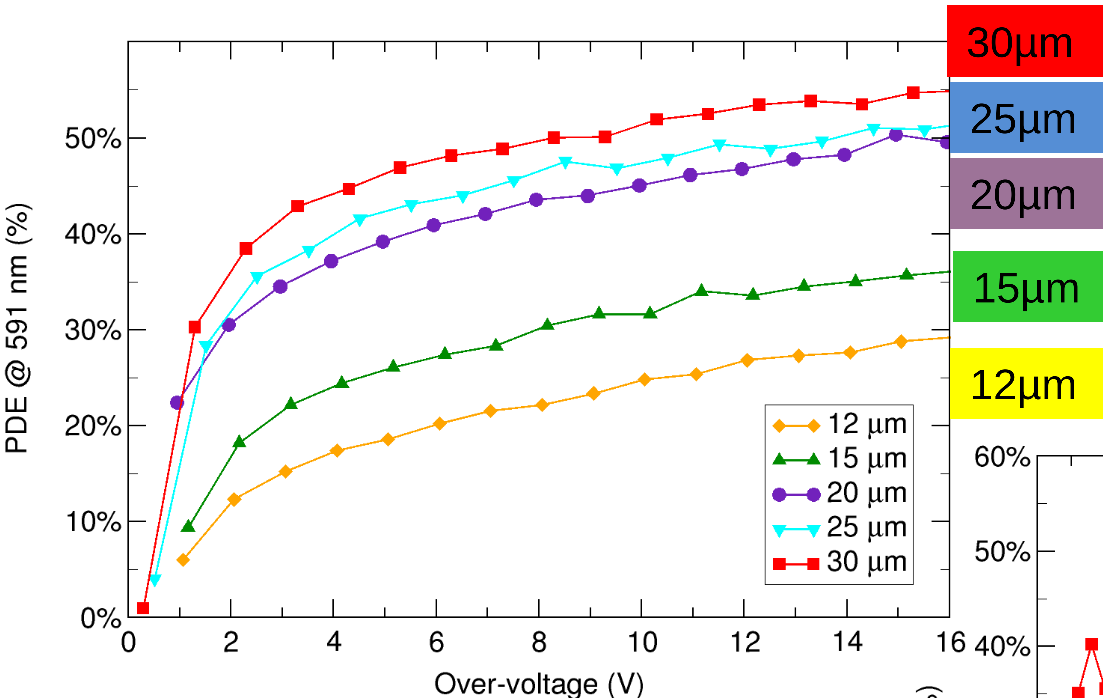
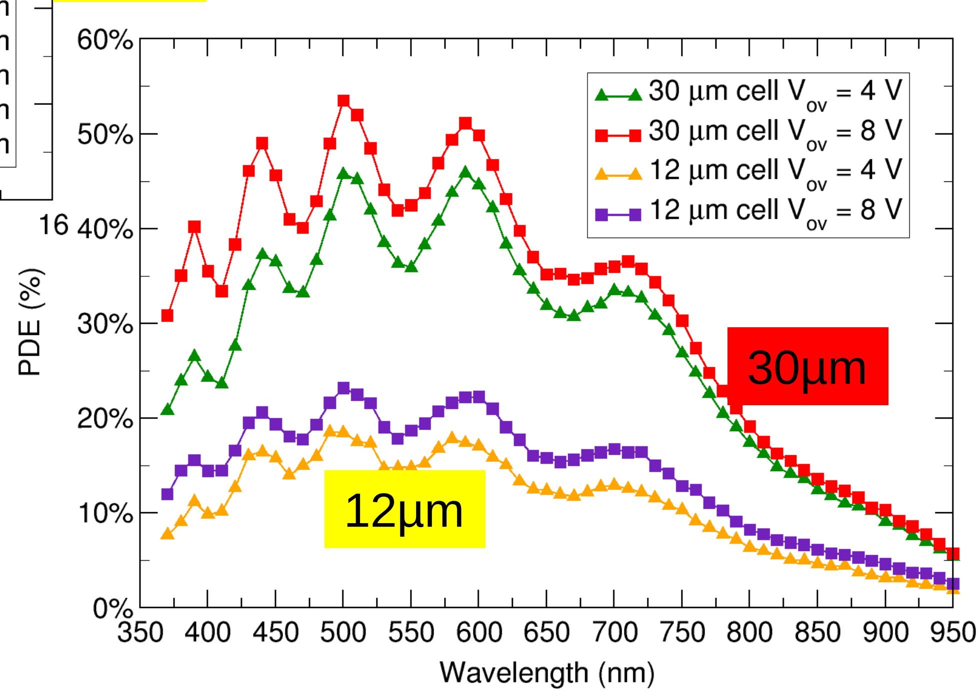
RGB-HD SiPM Functional Characterization:

Photo Dection Efficiency (PDE)



λ = 590 nm



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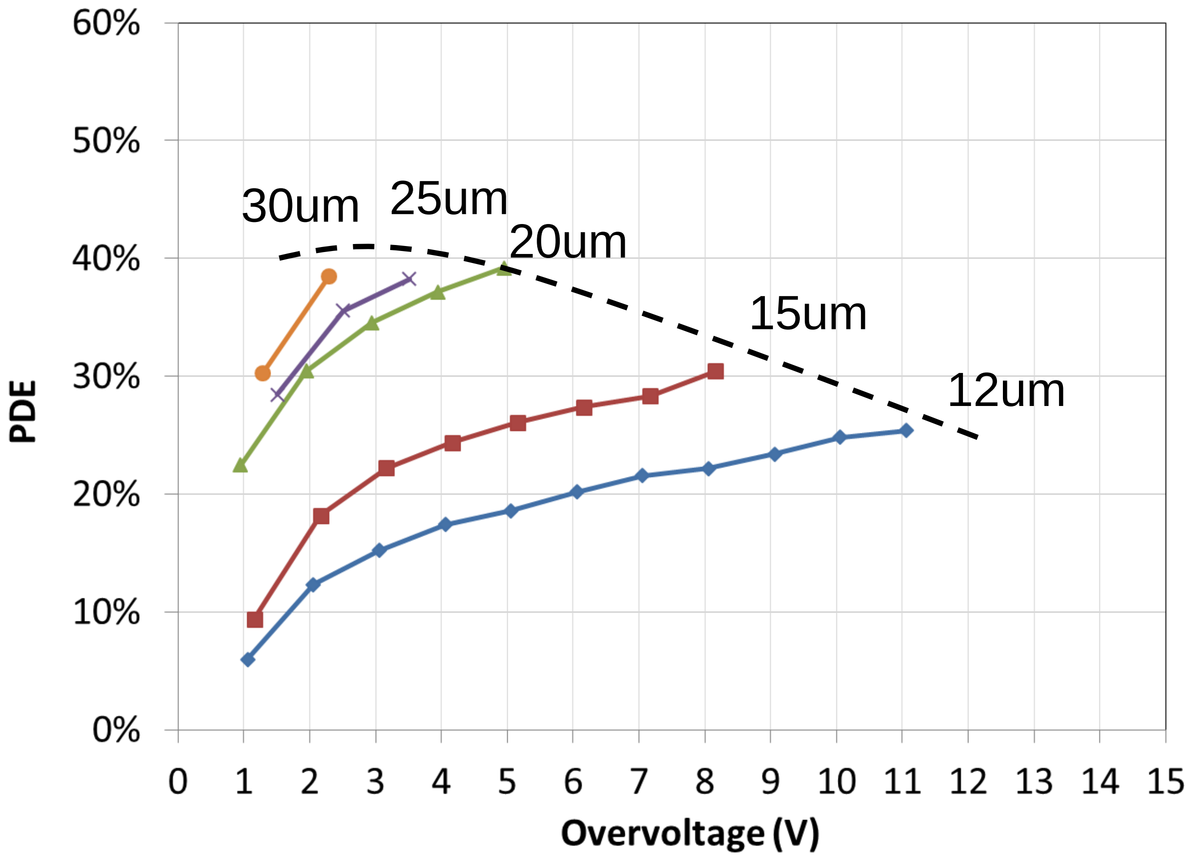
Max Photo Detection Efficiency with Cross-talk & after-pulsing < 10%



20,25,30um cells are equivalent!

Devices working at high OV have higher temperature stability

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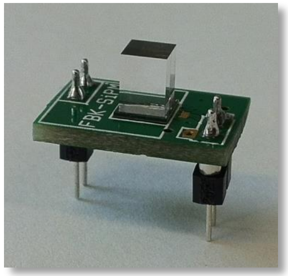
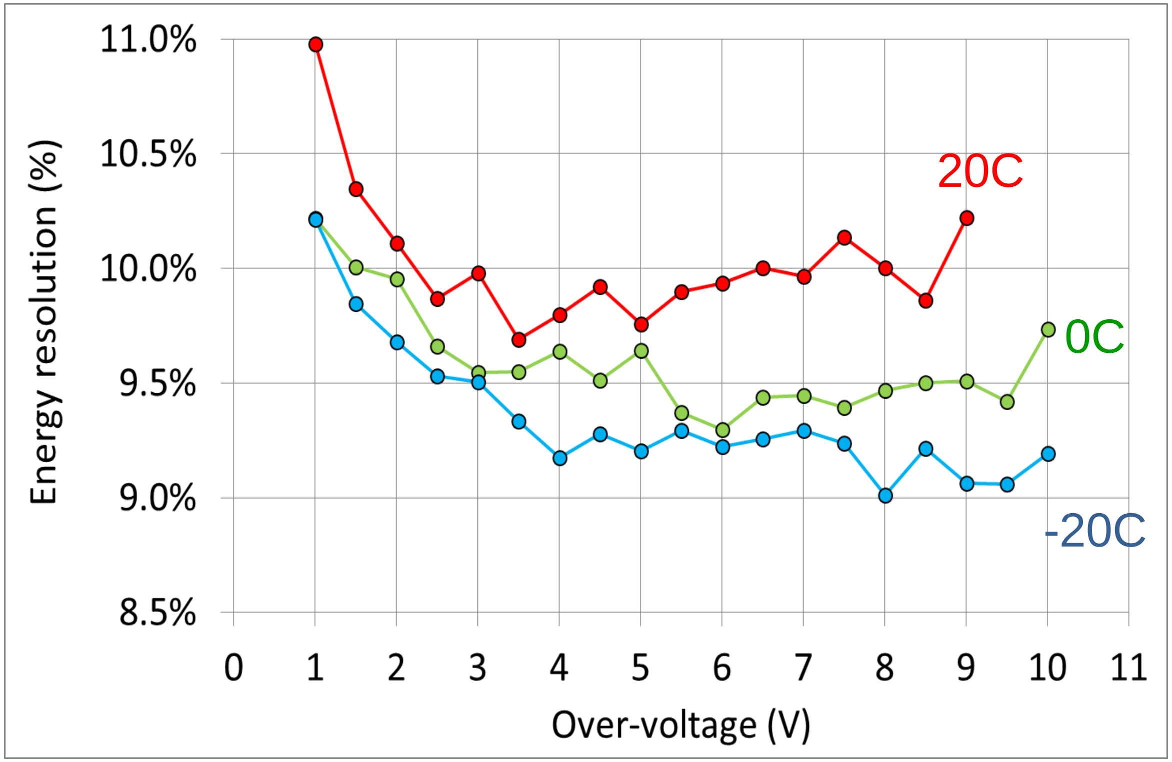
RGB-HD for TOF-PET (1)

Energy Resolution @ 511keV



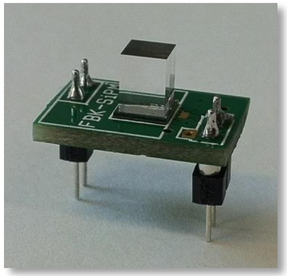
4x4mm² SiPM-HD with 25μm cell coupled to **3x3x5mm³ LYSO (teflon wrapped)**



Excellent energy resolution (corrected for non-linearity)

RGB-HD for TOF-PET (2)

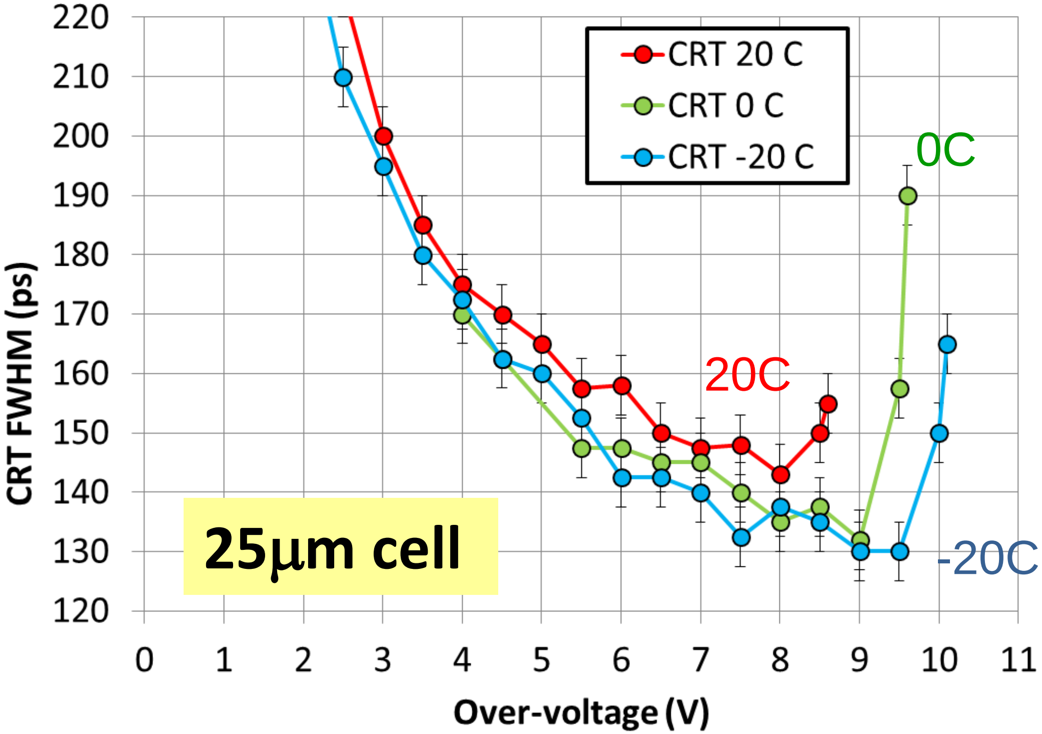
Coincidence Time Resolution



- **2 4x4mm² SiPMs-HD** each coupled to
- **3x3x5mm³ LYSO (teflon wrapped)**

in coincidence

- **Leading edge discriminator**



RGB-HD shows impressive time resolution because of high PDE

RGB-HD (CS=25µm)
CRT @-20°C = 130 ps
CRT @ +20°C = 145 ps

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Conclusion

- A new border structure in cell design allowed to obtain SiPM with **small CS** and **high FF**.
- The new devices have been characterized in terms of PDE and noise characteristics
- Very promising results with **HD technology** in terms of **PDE** and **Correlated noise.**
- Very promising results for **TOF-PET** applications **(**good **energy resolution** and **coincidence time resolution)**

Future Development

- We're already implementing **new technological features** to further increase FF and reduce the crosstalk.

- Development of **NUV-HD** technology SiPM with PDE peaked in UV region

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Thanks for your attention !!!

… and thanks to all collaborators

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