New developments in high-density (HD) SiPM technology at FBK.

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Outline

- Motivation for HD SiPMs
- SiPM-HD technology and characterization
- Radiation Damage on HD-SiPMs
- Ongoing «HD» developments
- RGB-HD for SPECT
- RGB-HD for TOF-PET

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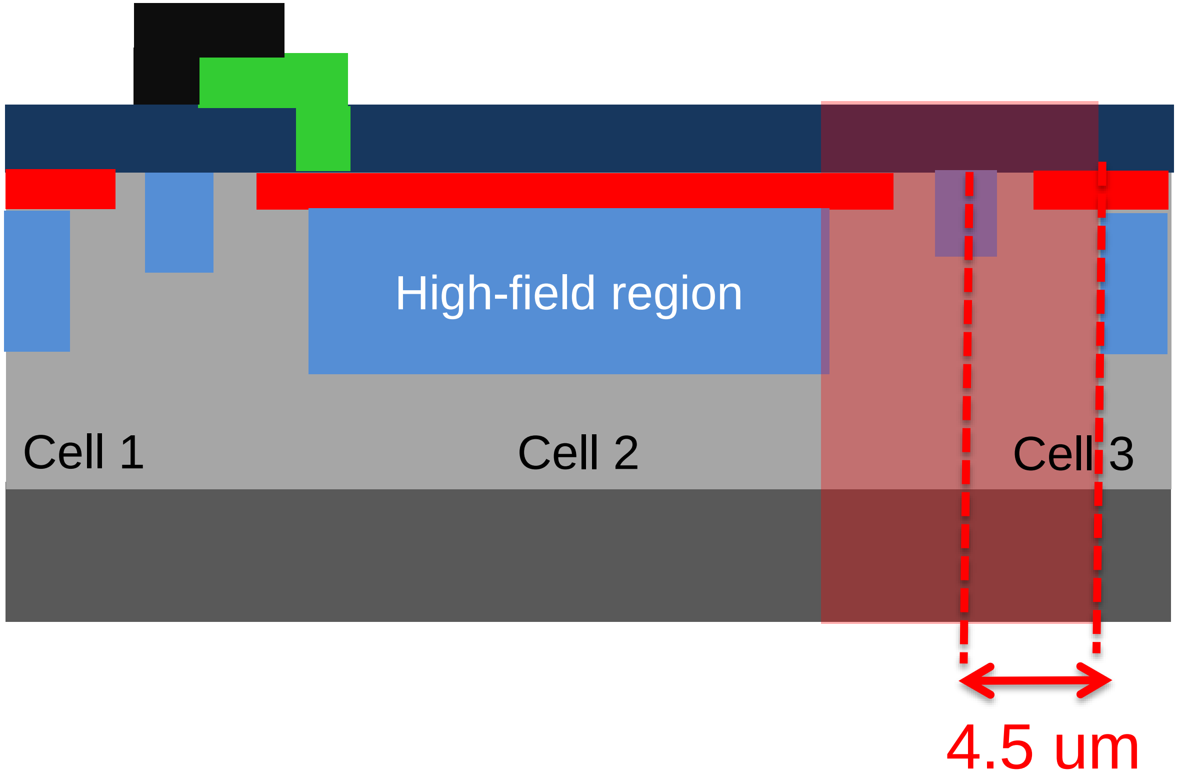
Standard (non HD) SiPM: limits I

1. Limited Fill Factor (FF) → limited PDE



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

Max 60% FF for 40um microcell (SPAD)

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

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Standard SiPM: limits II

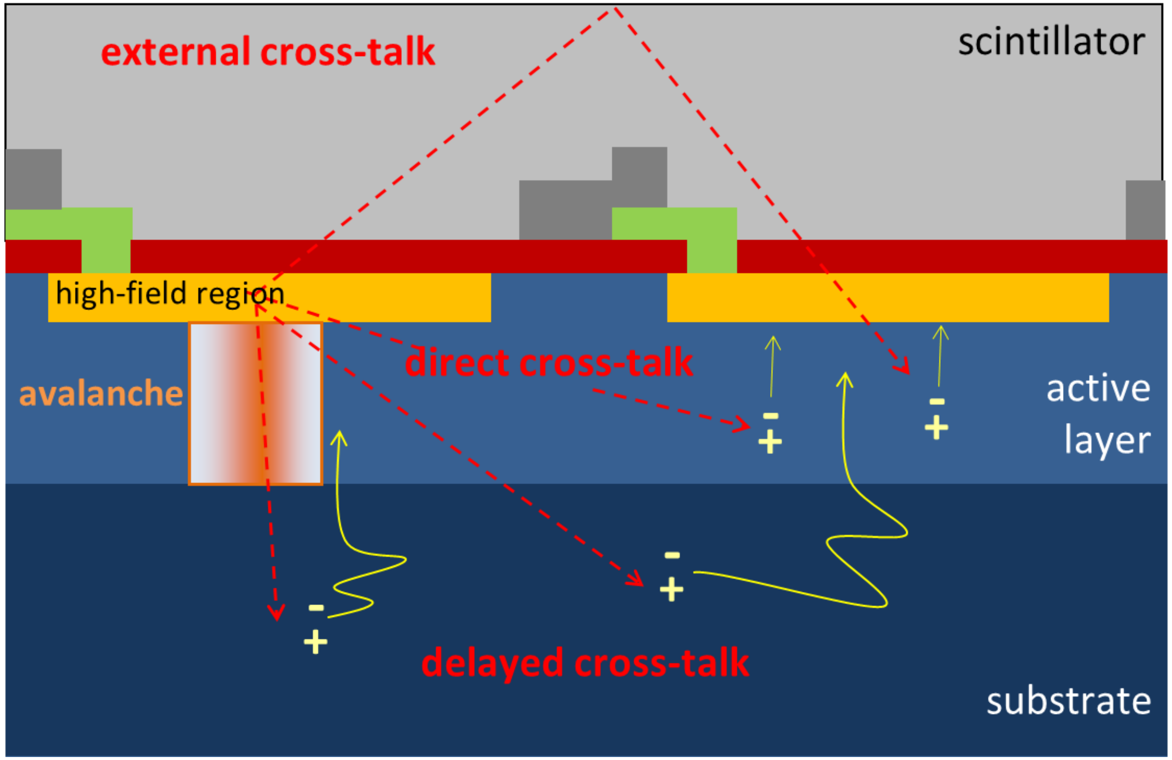
2. Correlated noise

❖ **Optical Cross-talk**

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

❖ **After-pulsing**

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



Different cross-talk paths

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

Advantages of Small Cell Size

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

2. **Larger dynamic range** → improved 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

…good, but only if we have a high fill factor!!

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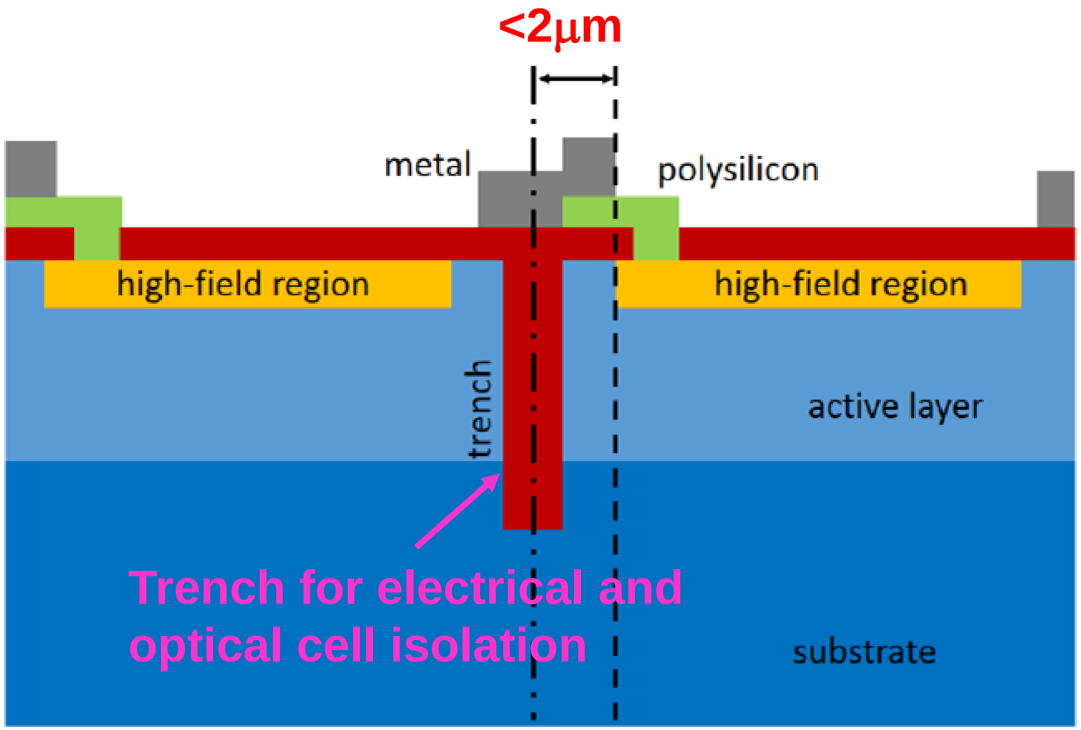
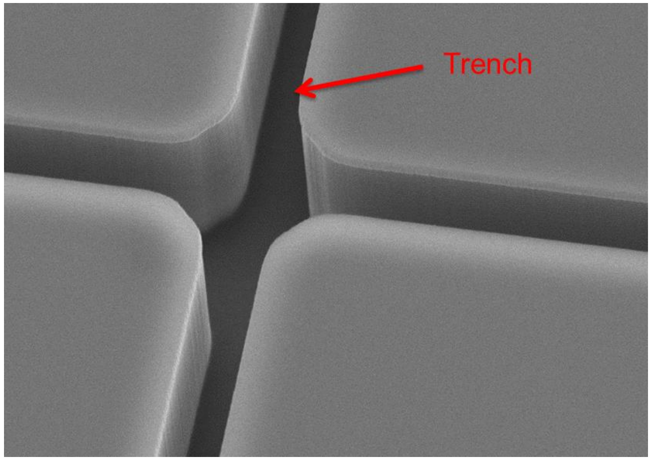
HD technology

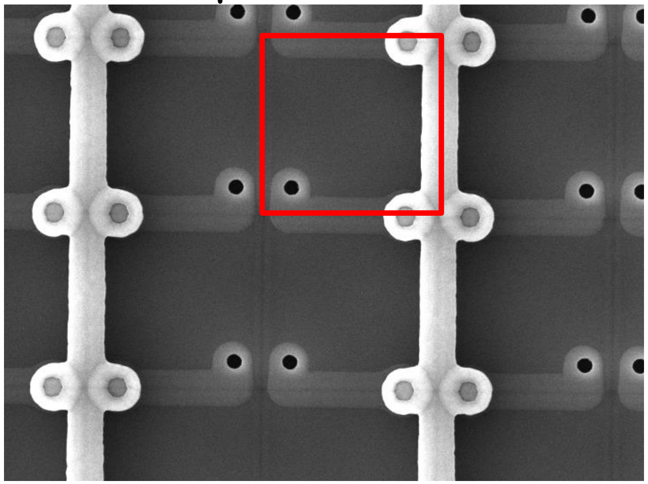
Lithography technology with smaller critical dimensions + use of trenches.

Narrow border region around each SPAD

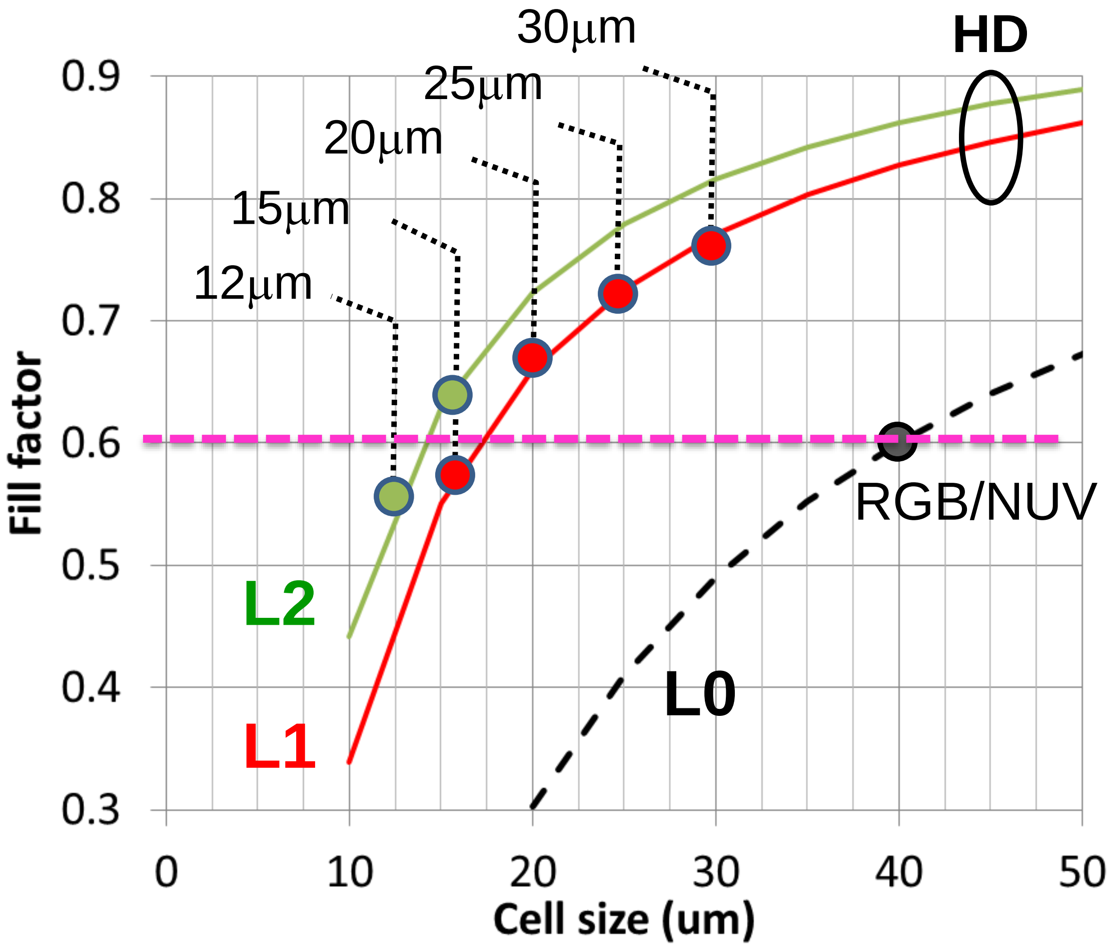


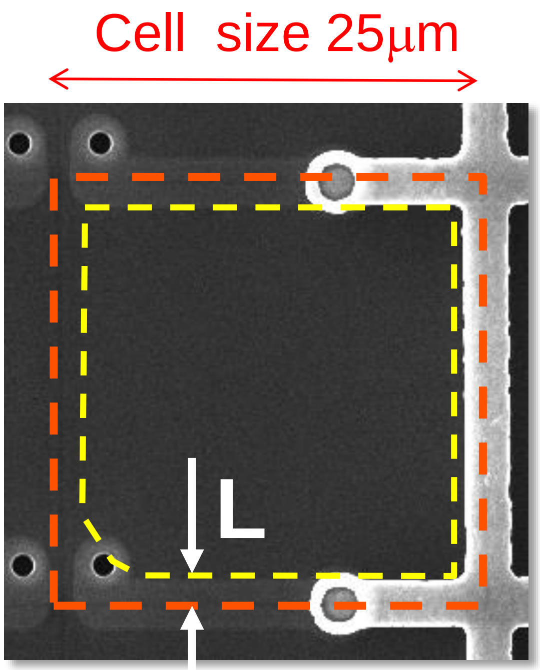


15x15μm² SPAD size



HD Fill Factor





L0 = 4.5μm

L1 ~ 1.7μm

L2 ~ 1.4μm

Application of HD technology

RGB SiPM	NUV SiPM
SPAD size: 40μm	SPAD size: 40μm
Fill factor: 60%	Fill factor: 60%
Peak PDE: 33%	Peak PDE: 40%
Max PDE @ 550nm	Max PDE @ 400nm
ENF: ~1.7	ENF: ~1.5
DCR ~ 300 kHz/mm^2	DCR: < 100kHz/mm^2

RGB-HD SiPM

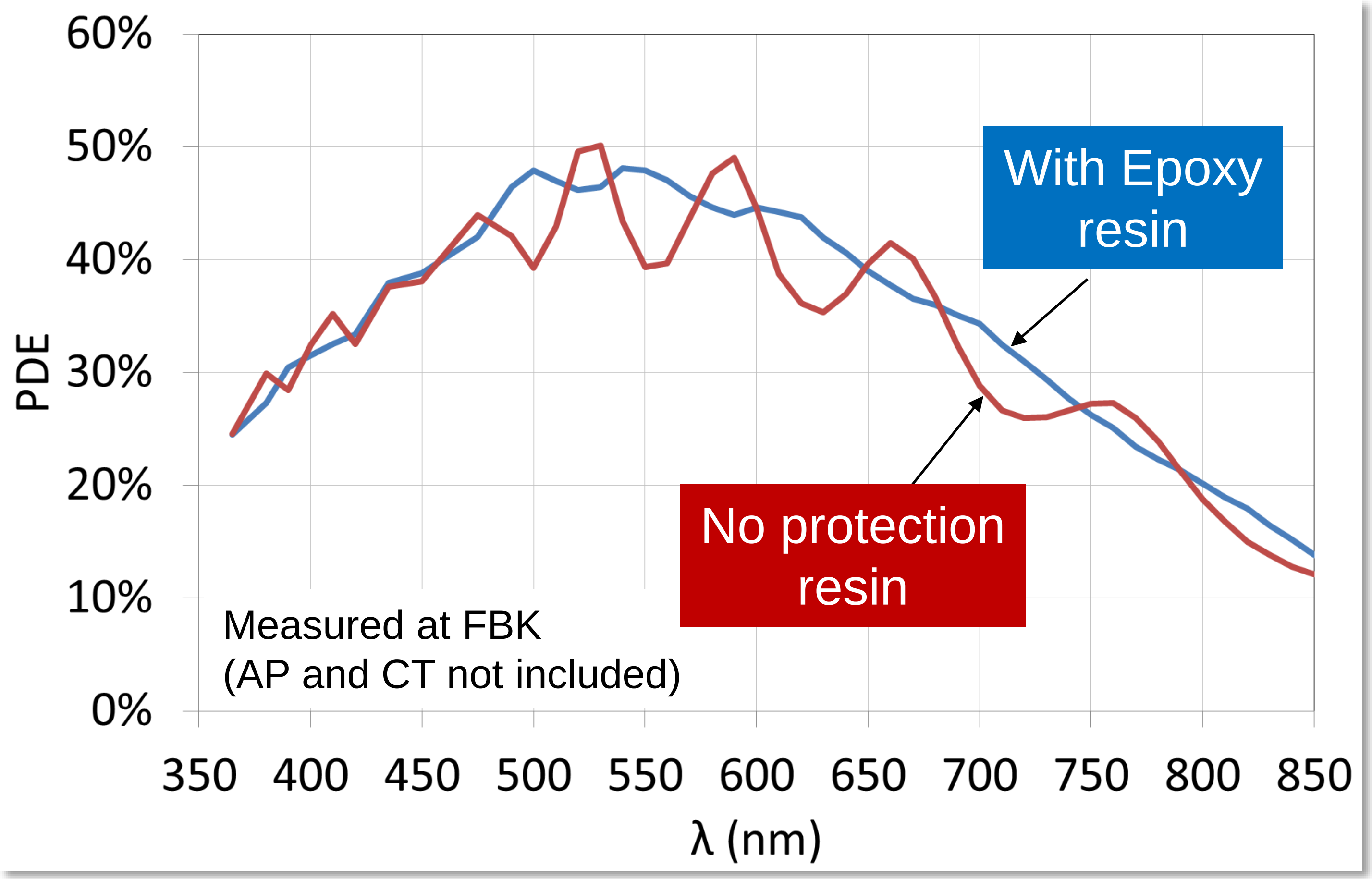
advanced development

NUV-HD SiPM

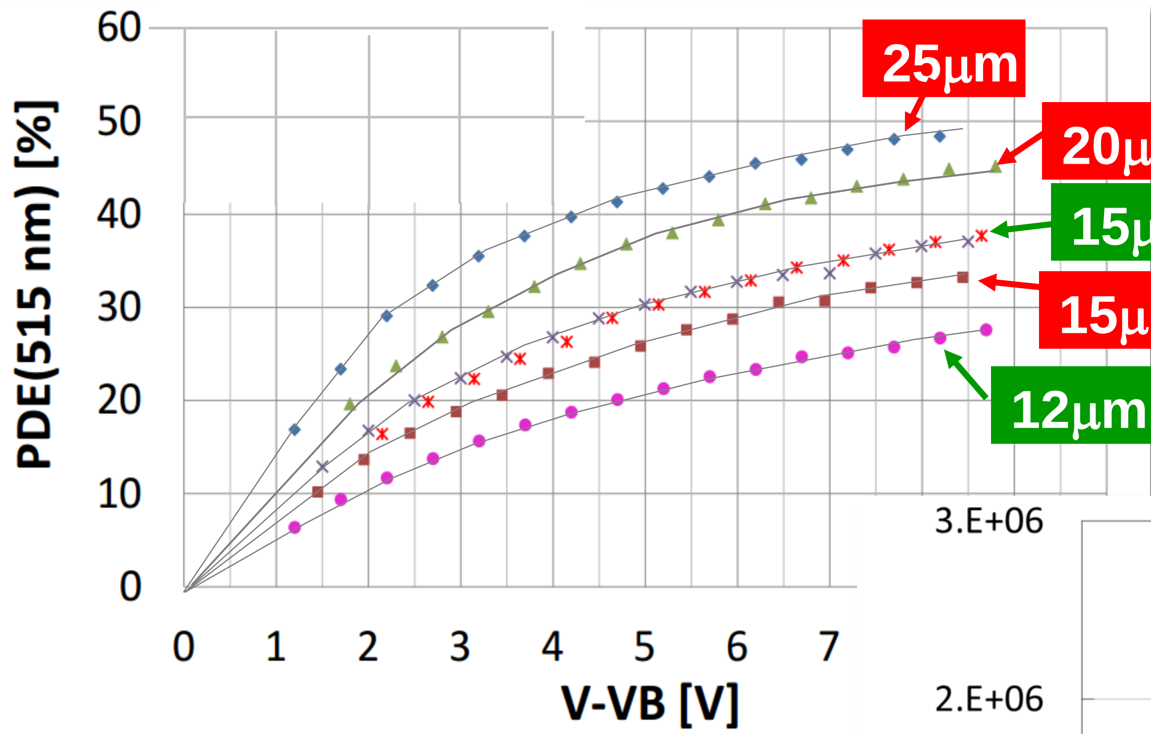
first prototypes

RGB-HD: PDE vs λ

- RGB-HD 25µm
- Over-voltage = 9 V



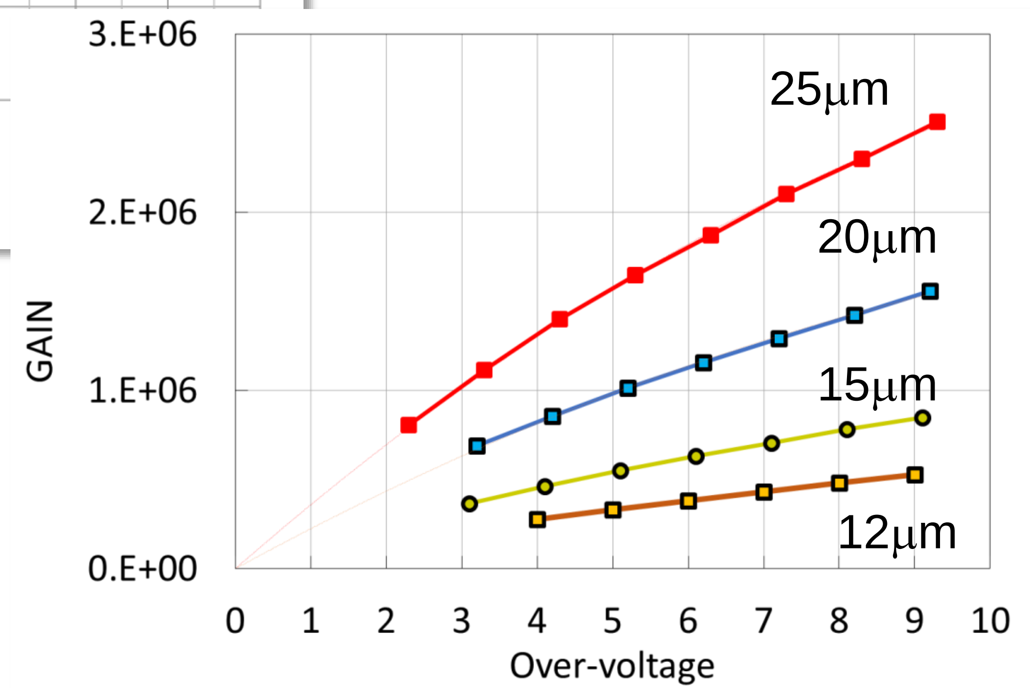
RGB-HD: PDE, GAIN



Measurements by Y. Musienko (CERN)

L1 = 1.7µm

L2 = 1.4µm

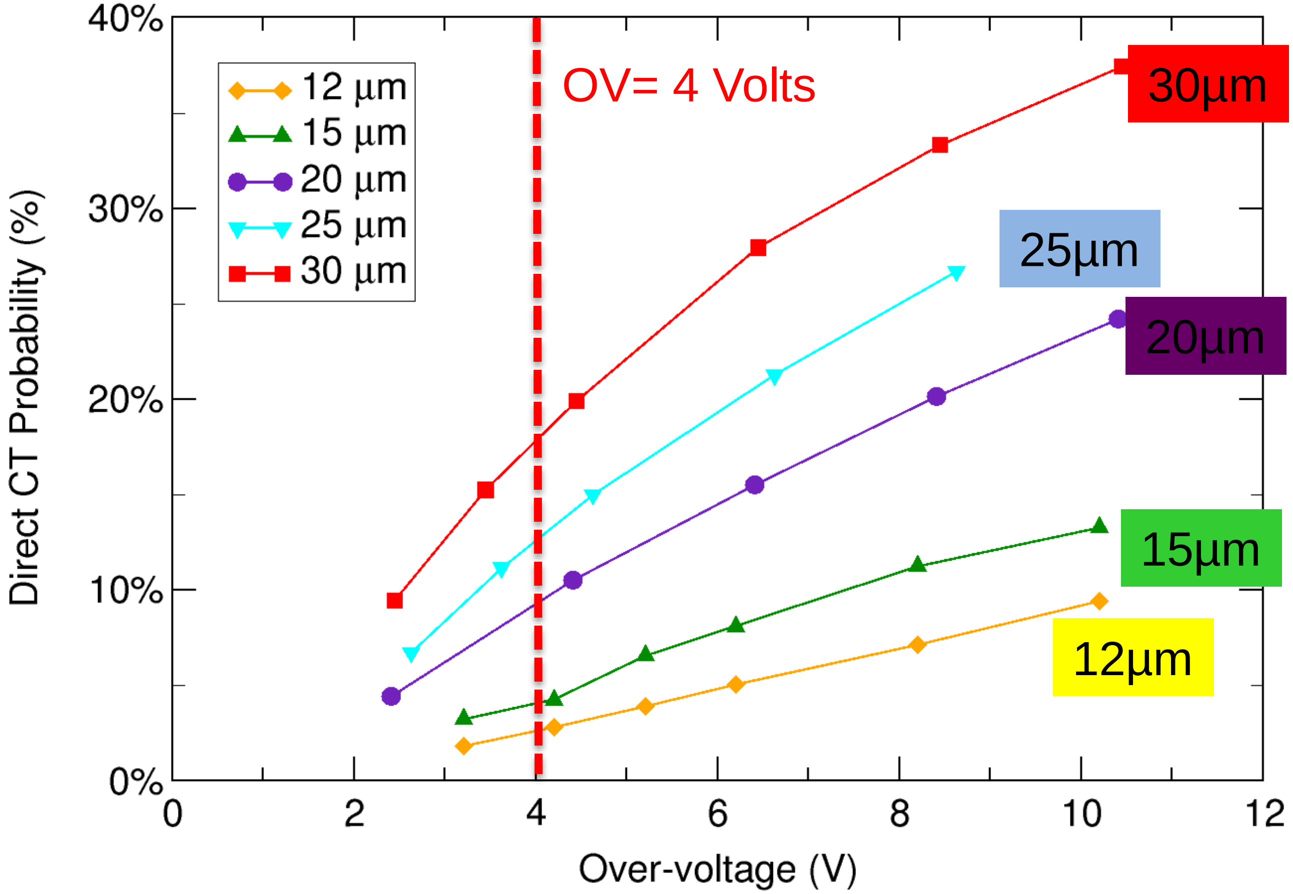


Crosstalk Probability

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

RGB-HD (15µm)
CT < 5 %
FF = 62 %

20°C
Over-voltage = 4 V



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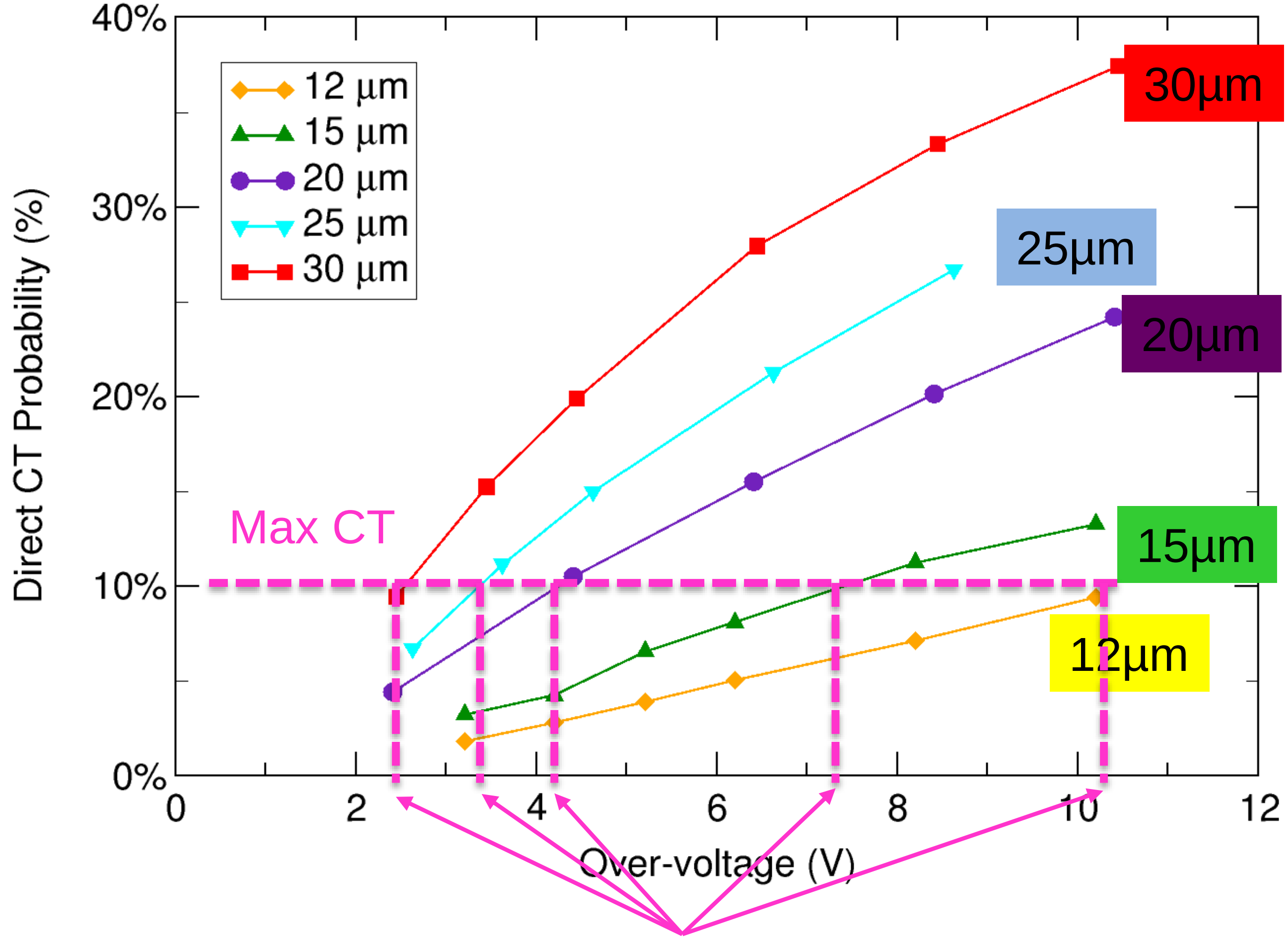
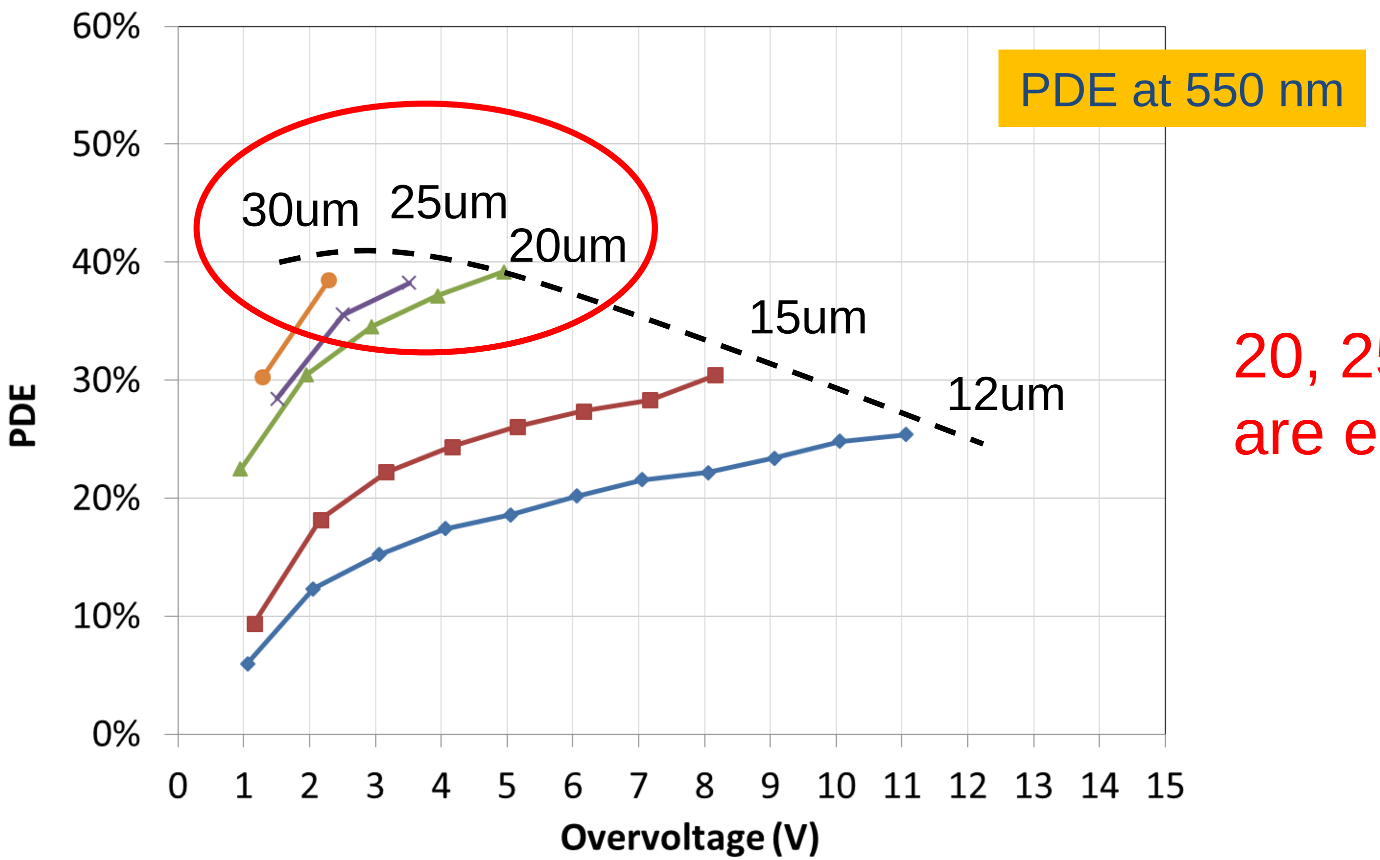


Different maximum over-voltage

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



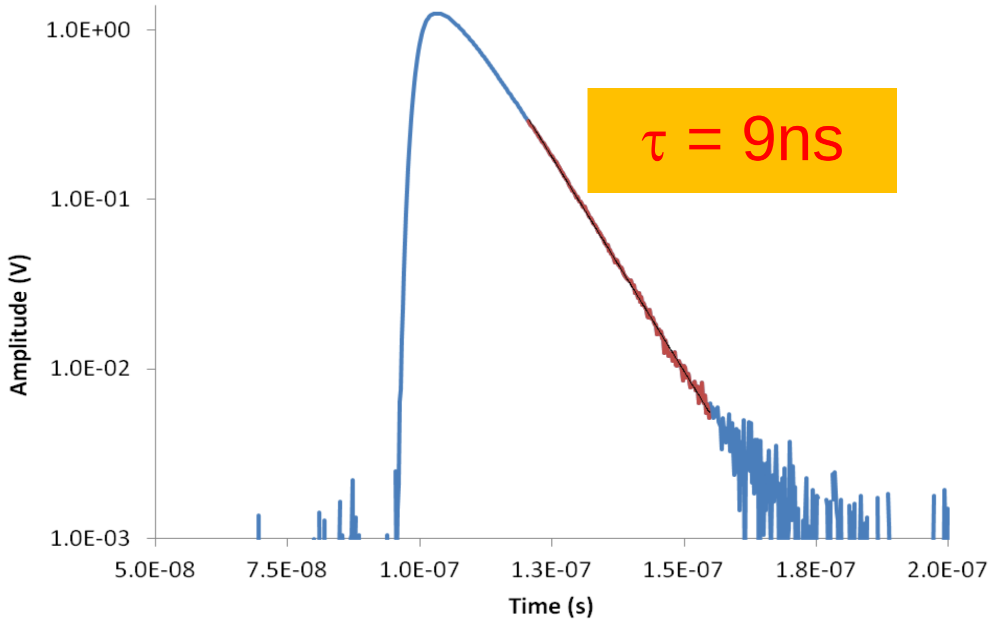
20, 25, 30 um cells are equivalent!

Devices working at high OV have higher temperature stability.

Fast Signal

15 um cell

Response to fast light pulse from LED



$$\tau = C_d \cdot R_q$$

Microcell recharge time constant

Very fast single cell response (SCR)

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Radiation Damage in HD-SiPMs

The main effects of radiation damage, in SiPMs, are:

- Increase in the primary noise (DCR).
- Increased afterpulsing (increased number of traps).
- PDE loss due to cells busy triggering dark counts.
- Increased power consumption due to higher DCR.

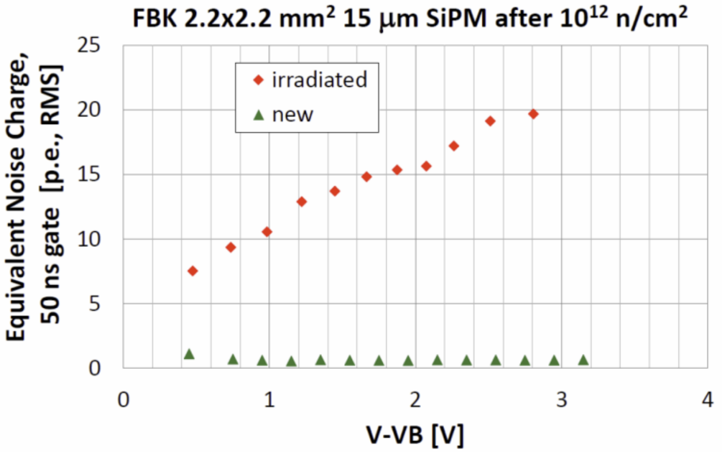
Mitigation of the effects of rad. damage with HD SiPM technology:

- E field engineering allows a faster reduction of DCR with cooling.
- Low gain reduces afterpulsing (for a given number of traps).
- Many, smaller cells with faster recharge are less sensitive to the phenomenon.
- Lower gain means less current (for a given DCR).

Measurements after Irradiation

First measurements carried out by Y. Musienko and A. Heering @CERN, with a dose of 10^{12} n/cm^2.

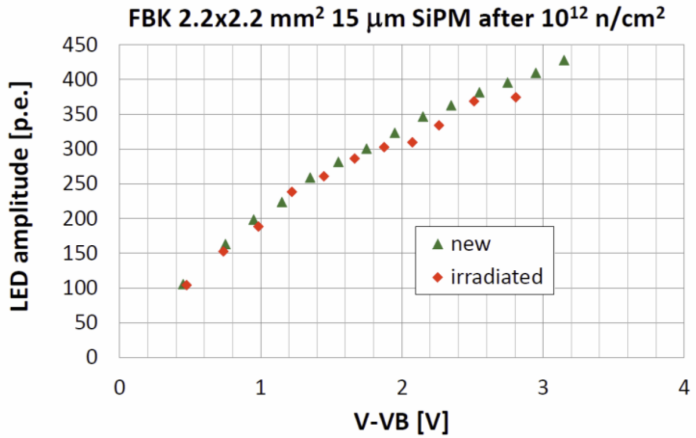
15 um cell



Noise increase

After irradiation:

- Dark current increased up to 450 µA
- Gain*PDE change is < 10%
- PDE change is < 10%
- ENC(50ns gate) ~ 20 p.e. RMS



PDE loss

Parameters measured at V_{OV}=2.7 V (PDE(515 nm)=15%)

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- Ongoing «HD» developments:
  - LOW ENF HD technology
  - NUV-HD
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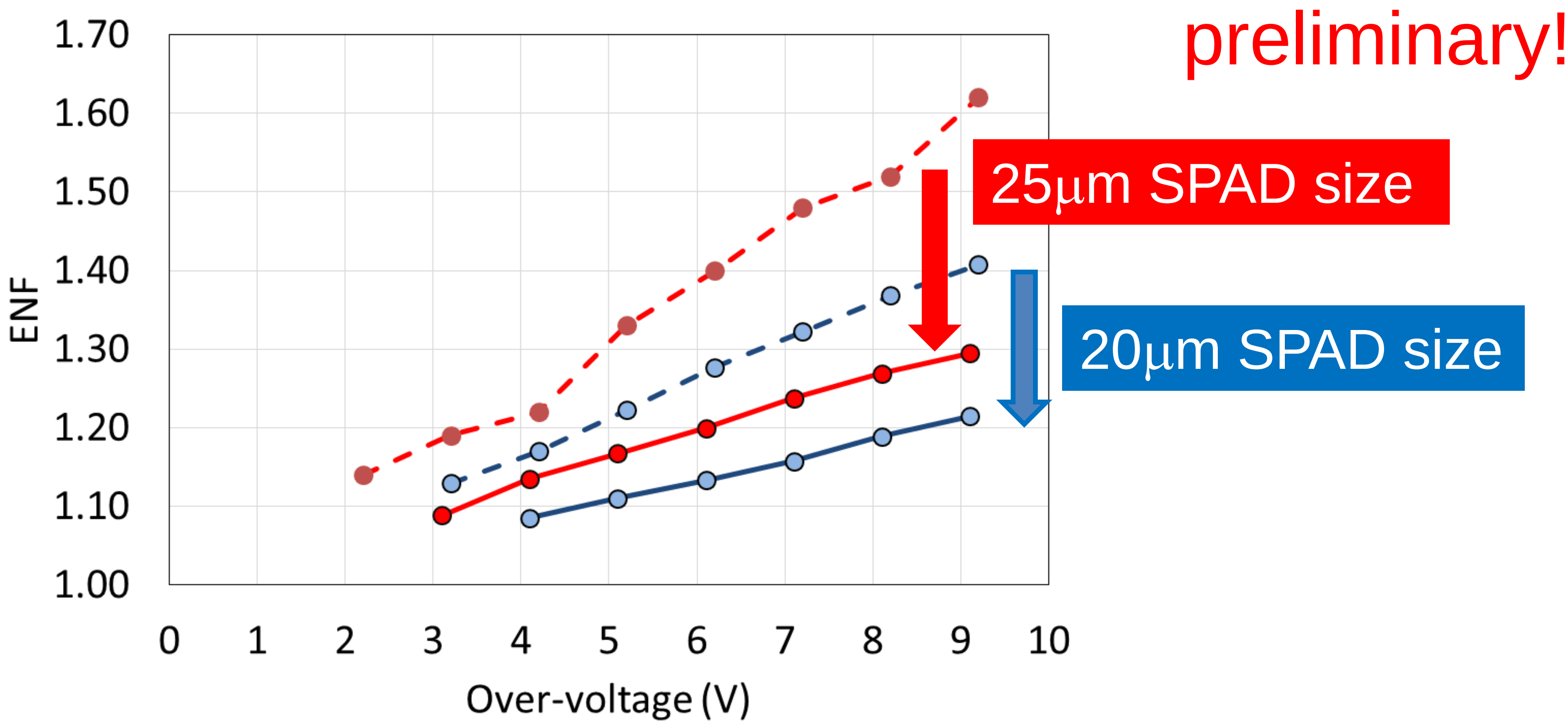
LOW-ENF **HD** technology

New trench technology featuring improved optical isolation.

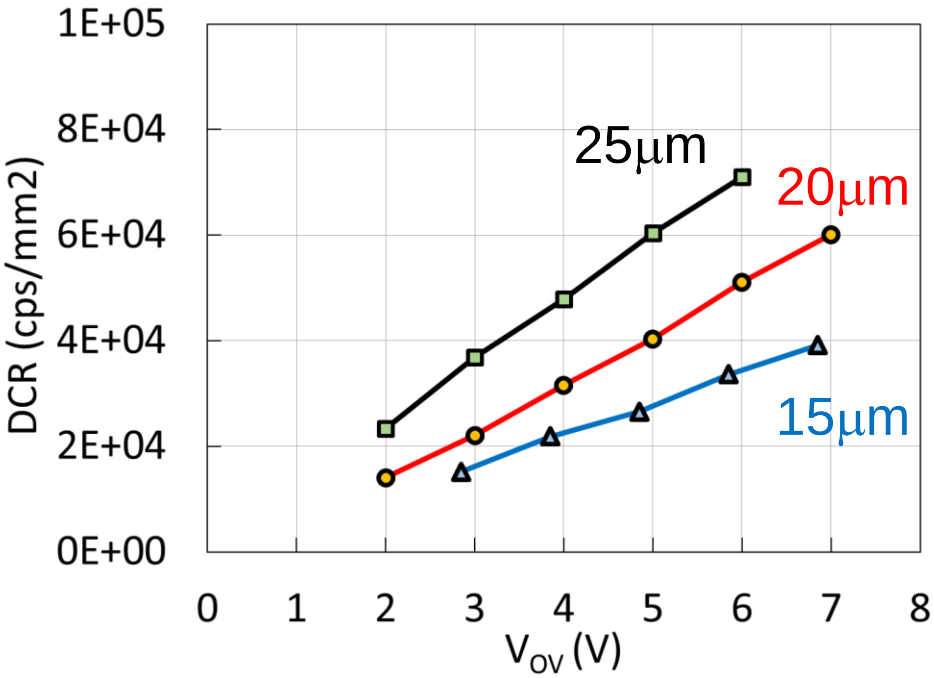


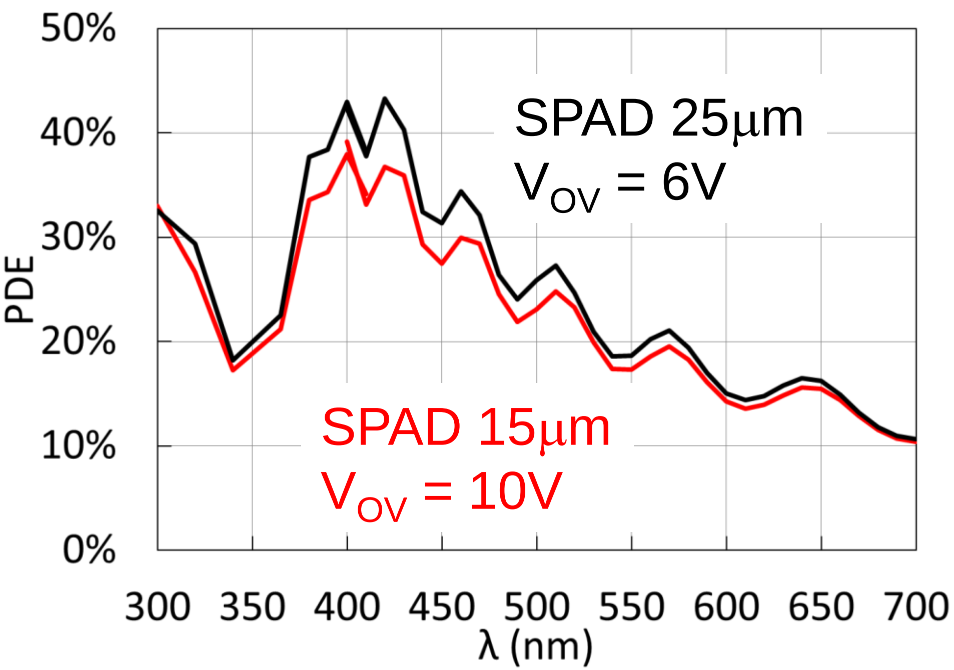
Same fill factor of first HD version but much lower ENF.

NUV-**HD** technology

We produced the first 1x1mm^2 prototypes.

preliminary!

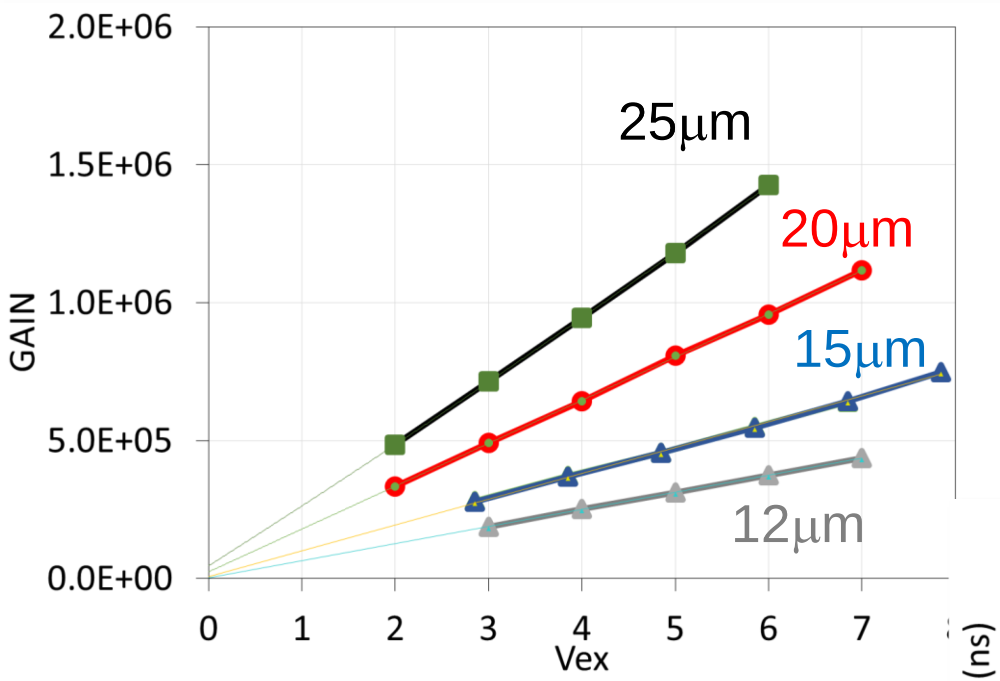




Very low DCR as in standard NUV.

Efficiency peaked in blue/near-UV

NUV-**HD** technology



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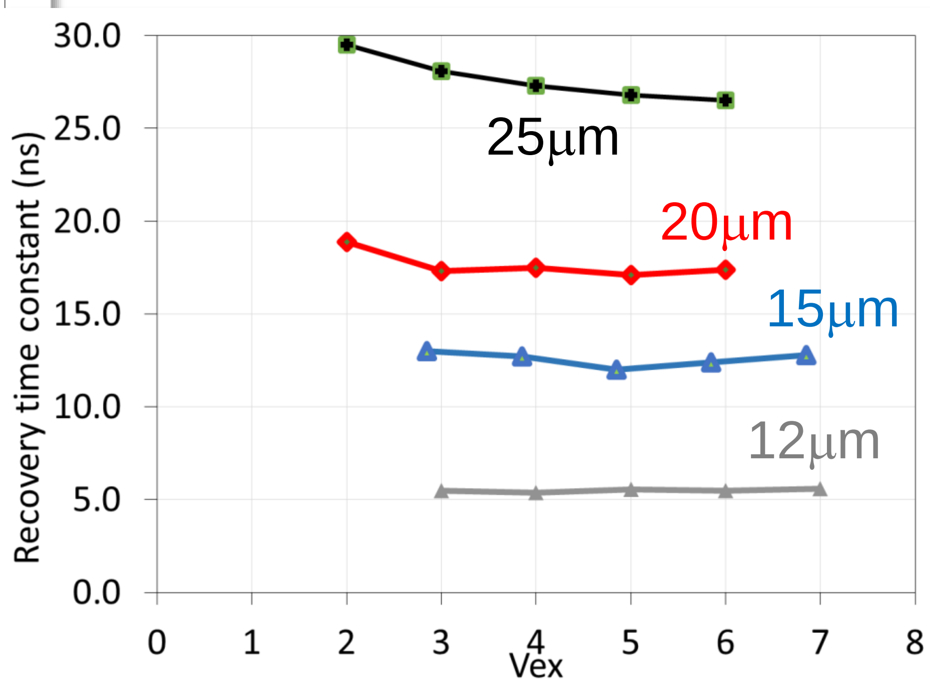

Fast recovery time

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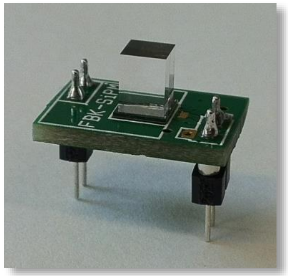
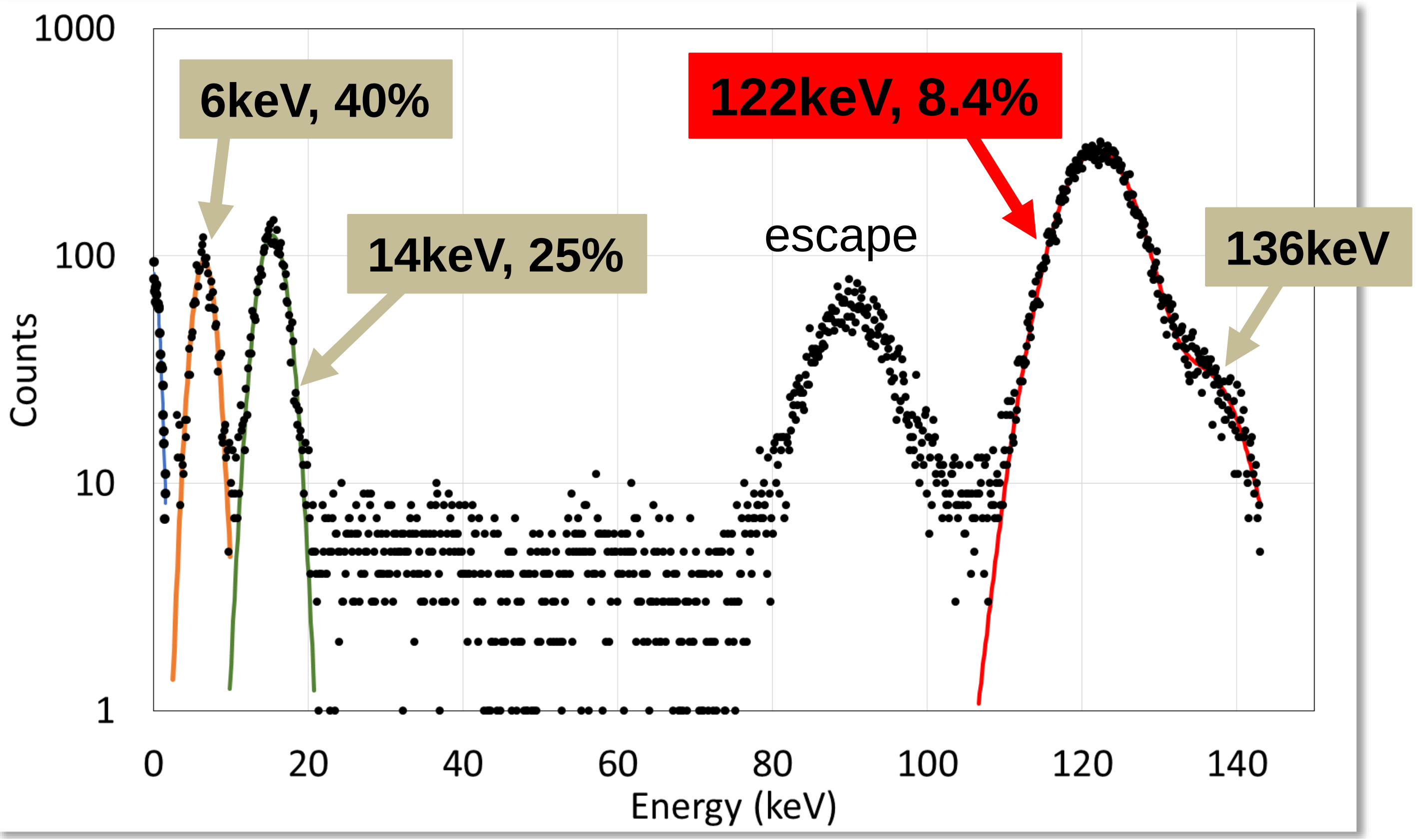
RGB-HD: ^{57}Co spectrum

- **4x4mm² 25x25μm² RGB-HD** SiPM
- 3x3x10mm³ **CsI (Tl)** (Hilger)



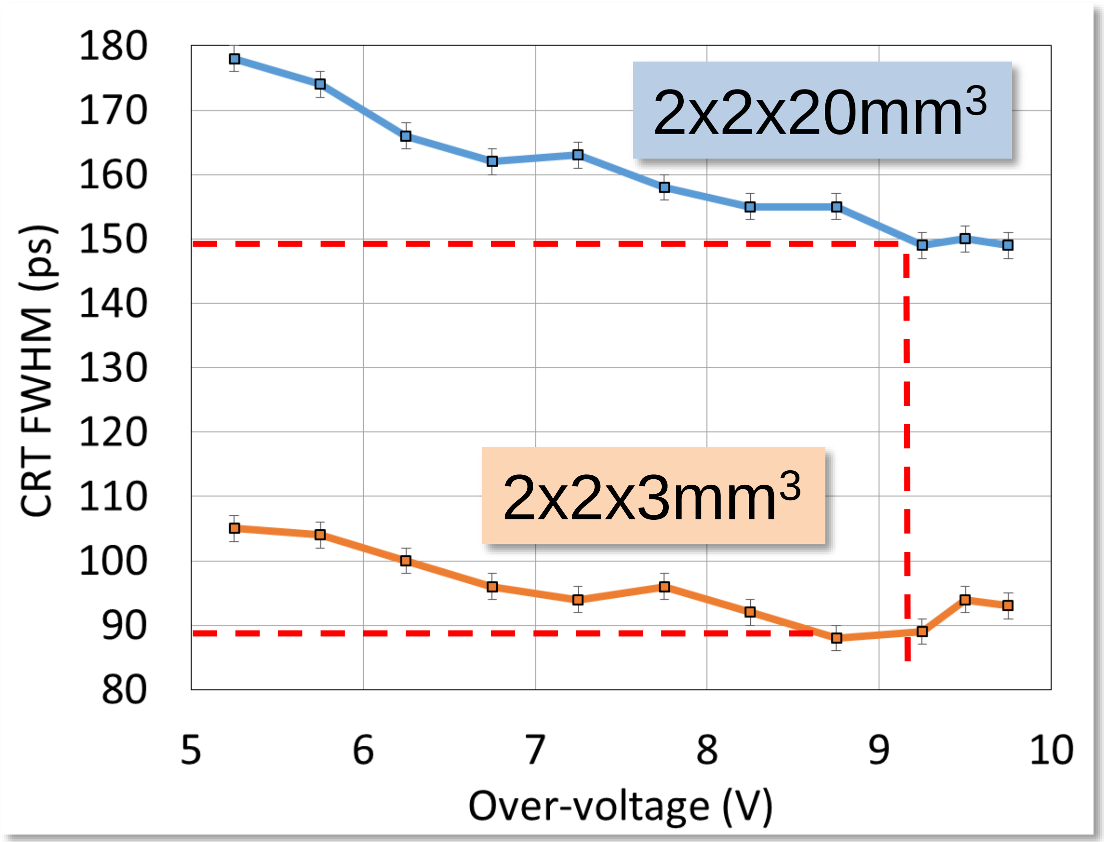
SiPM + scintillator



- T = 20 C
- T_{int} = 12μs

High PDE
+
Low ENF
(with scintillator)

RGB-HD: TOF-PET application



- $4x4mm^2$ RGB-HD 25μm SPAD size
- LSO:Ce codoped 0.4%Ca
- T = 8 C
- 511 keV photons

Low correlated noise (with scintillator) allows us to bias the detector at high excess bias (high PDE).

measurement performed at CERN with NINO chip

Conclusions

- **HD** technology was applied to **RGB SiPMs** investigating many SPAD sizes.

- **Very good results** were obtained with different scintillators and application conditions.

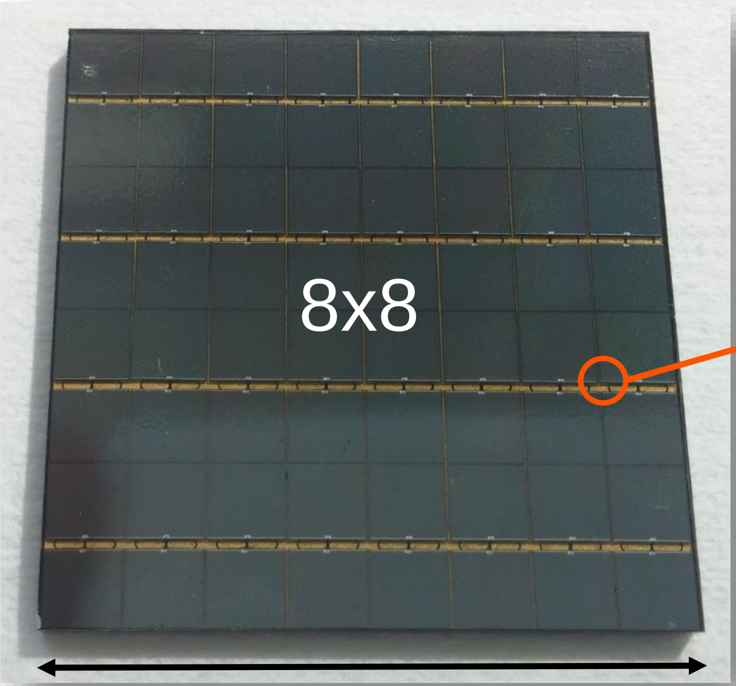
- HD technology provides interesting features to **mitigate the effects of radiation damage**.

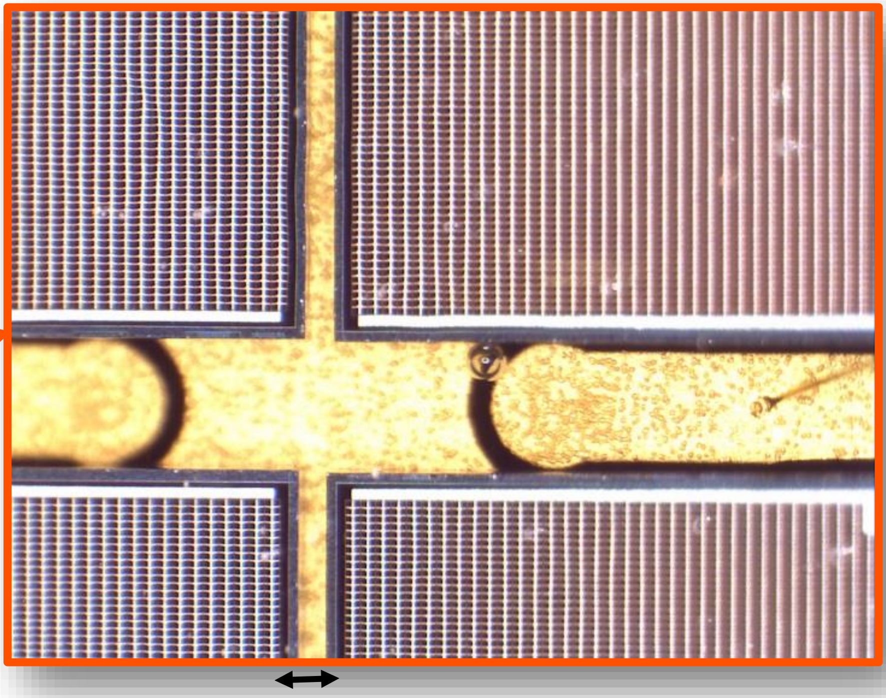
- HD technology roadmap:
  - **lower ENF;**
  - **blue/NUV peak light sensitivity.**

Thank you!

Backup Slides

TOF-PET Tile



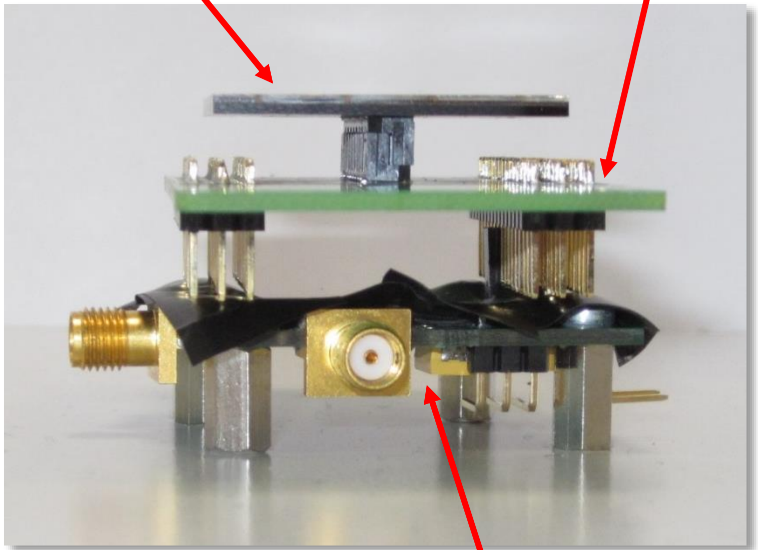


- 4mm pitch in x and y
- 85% fill factor
- Single-ended and differential implementations
- SiPMs: RGB-HD 25μm

TOF-PET tile: test set-up

SiPM Tile

Adapter board

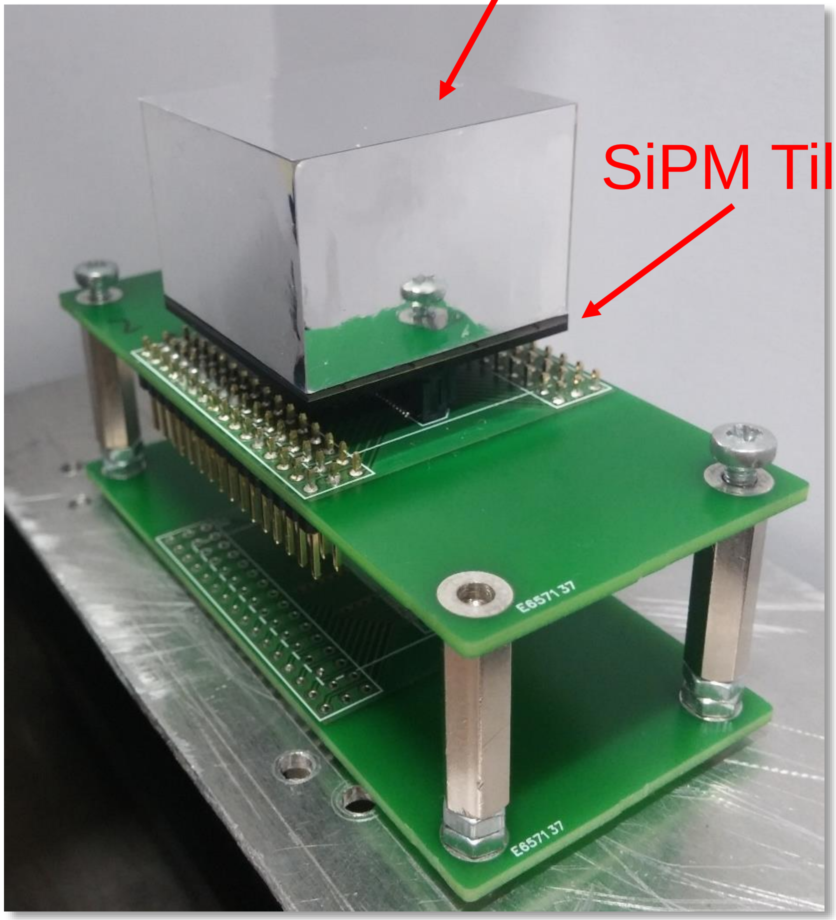


Discrete amplifier

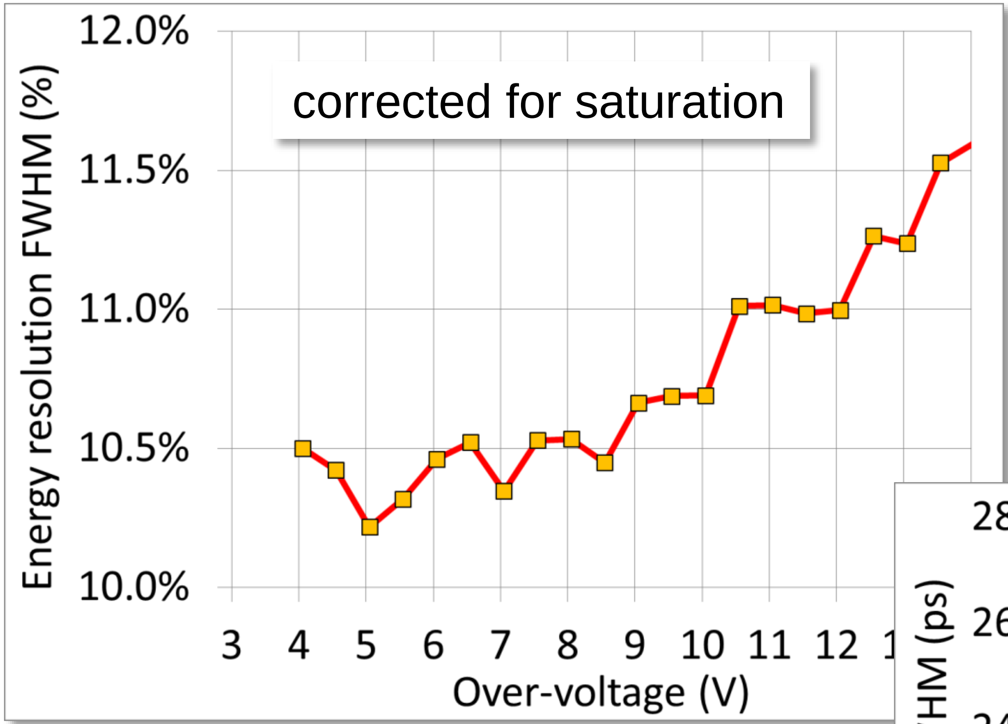
8x8 LYSO array

4x4x22mm^2 pixel

SiPM Tile

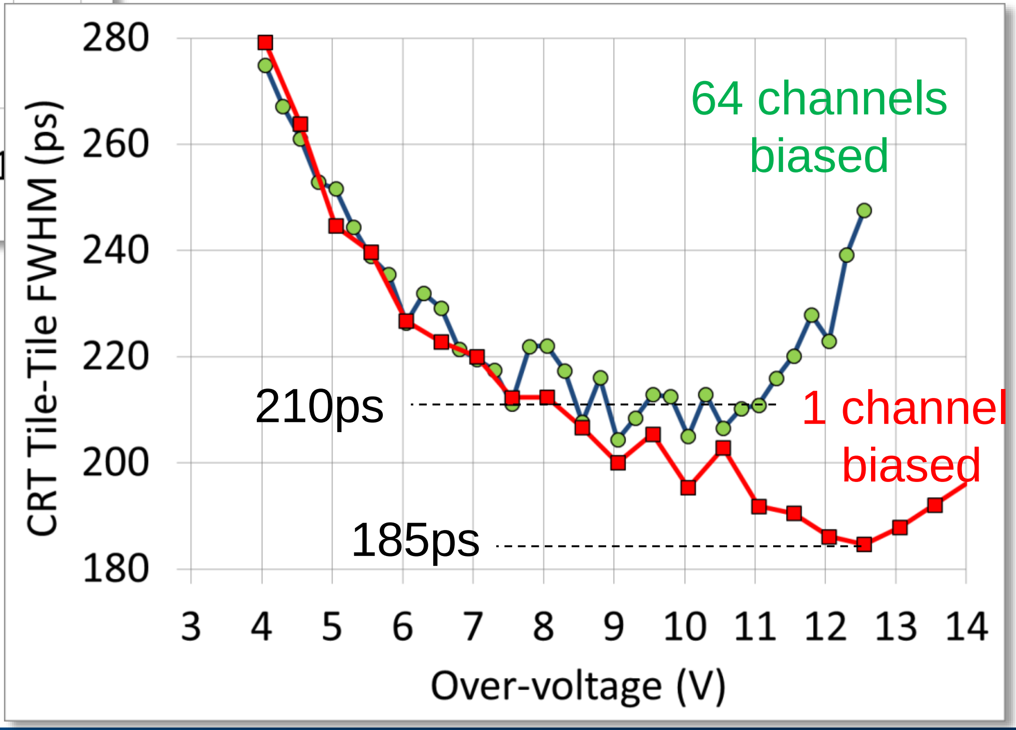


TOF-PET tile performance



Test conditions:

- ^{22}Na source
- T = 10 C
- $4x4x22mm^3$ LYSO pixel



- Tile in coincidence with single channel reference
- Tile CRT unfolded