FONDAZIONE BRUNO KESSLER

Large area tiles of Position-Sensitive Silicon Photomultipliers
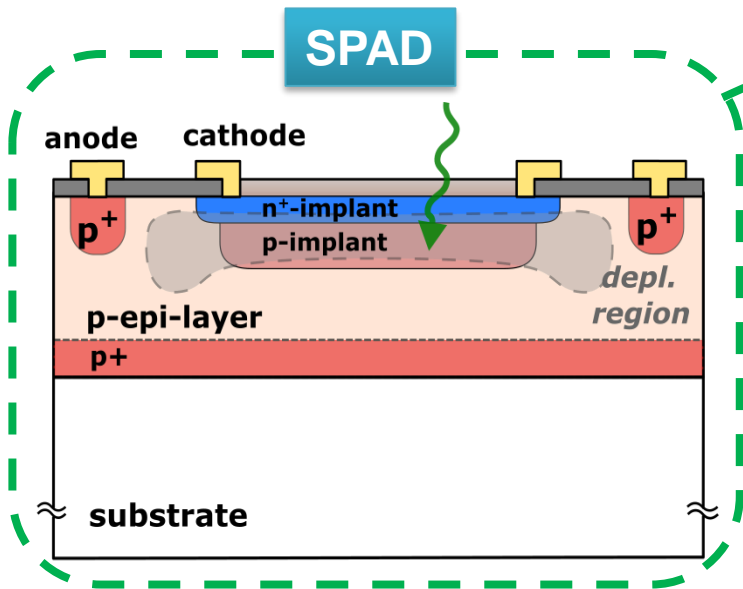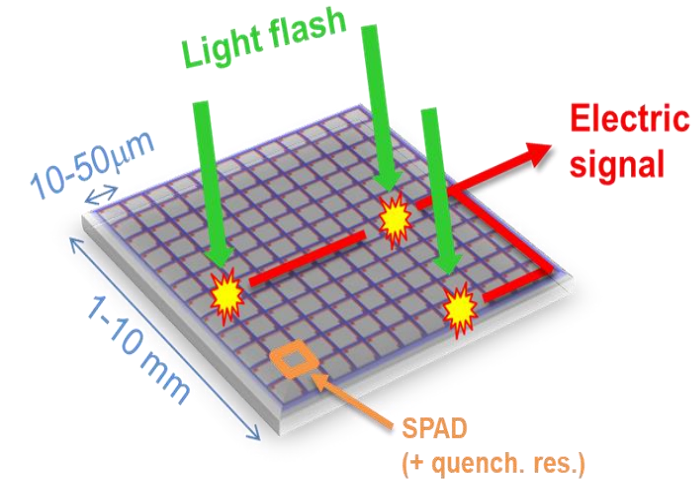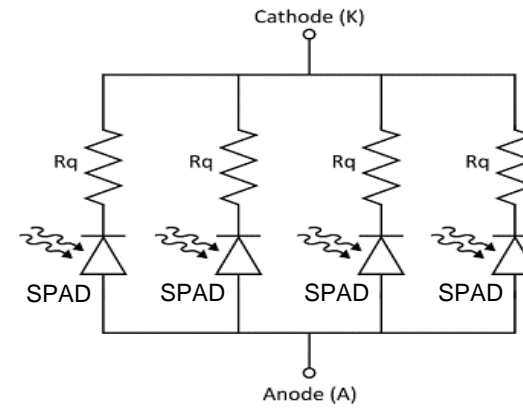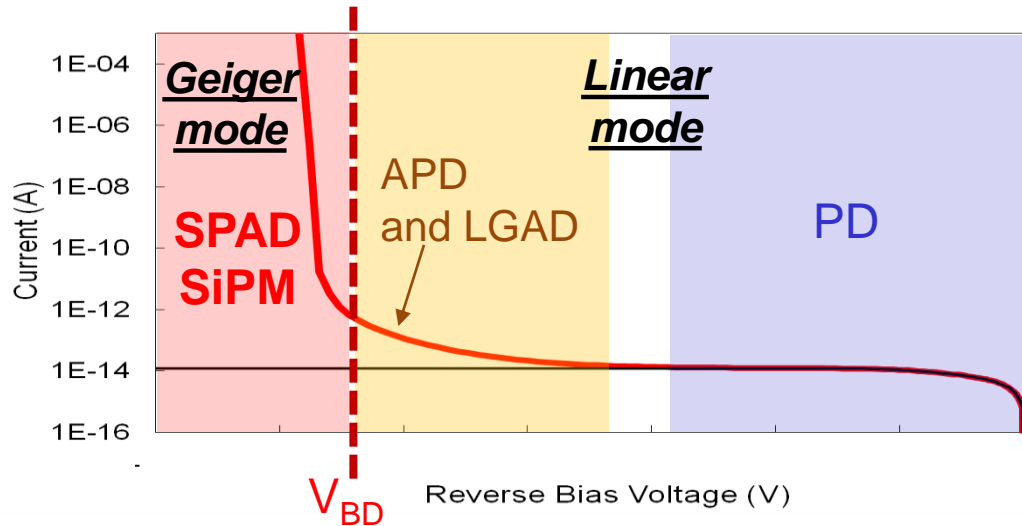
Fabio Acerbi[a], S. Merzi[a], A. Gola[a]

[a] Fondazione Bruno Kessler (FBK), Center for Sensors and Devices, Trento, Italy.
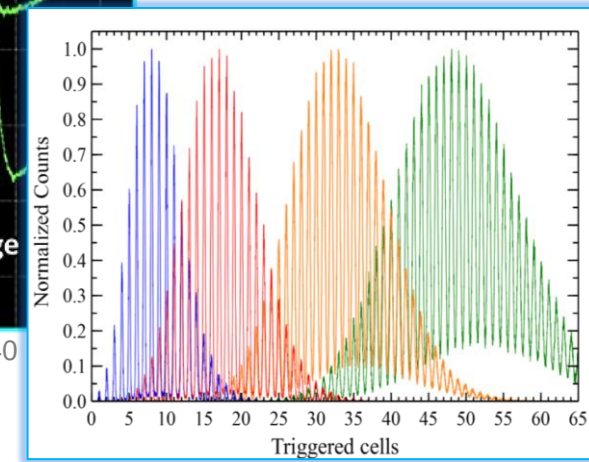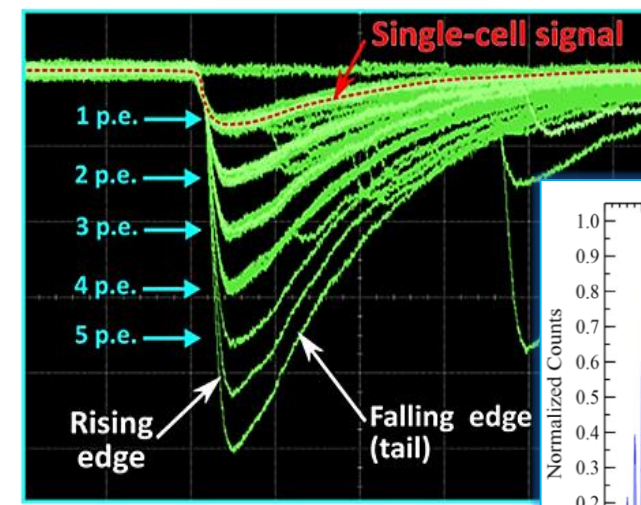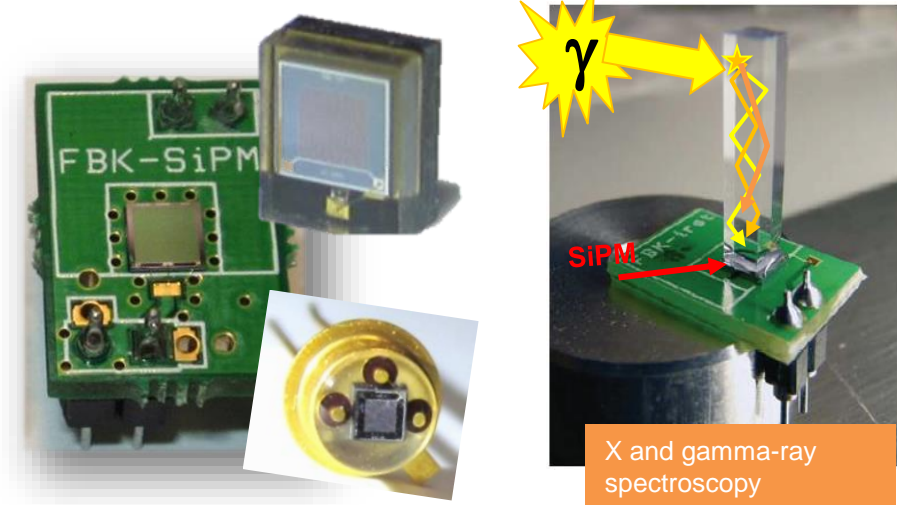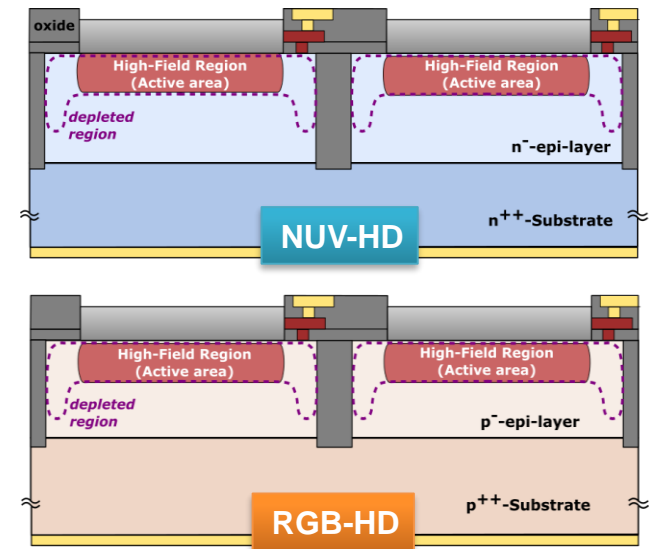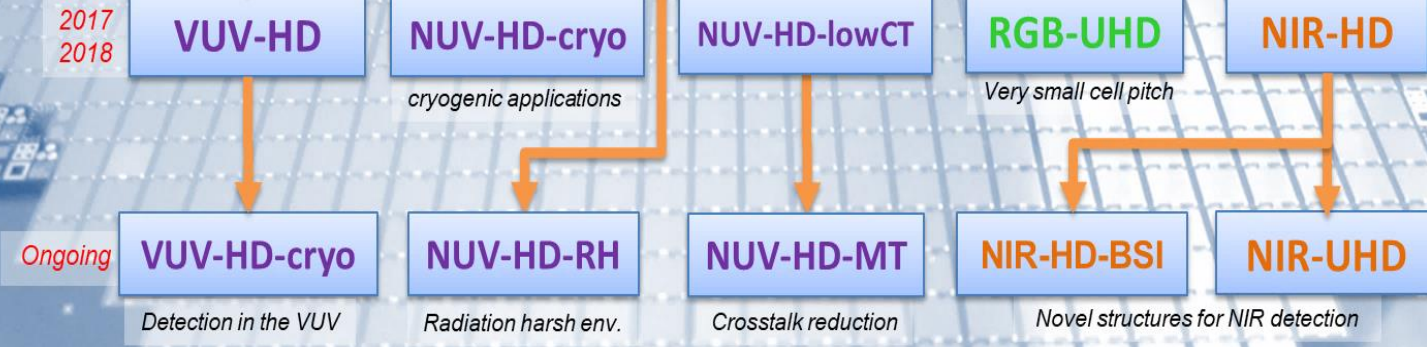
acerbi@fbk.eu

□ **SiPM: (analog) Silicon photomultiplier → thousands of SPADs in parallel**

Silicon Photomultipliers (SiPMs)

- Silicon Photomultiplier (SiPM):
  large-area, solid-state, single-photon sensitive detectors,
  with ph.-number resolution, and large dynamic range.

- Applications: medical imaging, high-energy physics,
                biotech, LiDAR, diffuse optics, others.

- Active areas: 1x1 mm^2 up to 10x10 mm^2

FBK-SiPM

γ

SiPM

X and gamma-ray spectroscopy

diffuse optics

DOI: 10.1117/1.NPh.3.4.045004

LiDAR

elettronicanews.it

CERN nEXO DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

High energy physics

Calorimeters - Particle Physics
Cherenkov light - LXe - LAr

Single-cell signal

1 p.e.
2 p.e.
3 p.e.
4 p.e.
5 p.e.

Rising edge

Falling edge (tail)

DOI: 10.5772/intechopen.71940

FBK SiPMs technologies
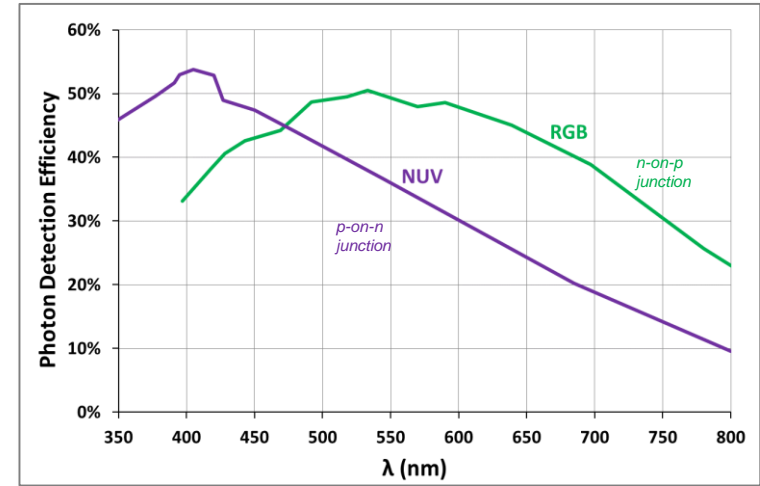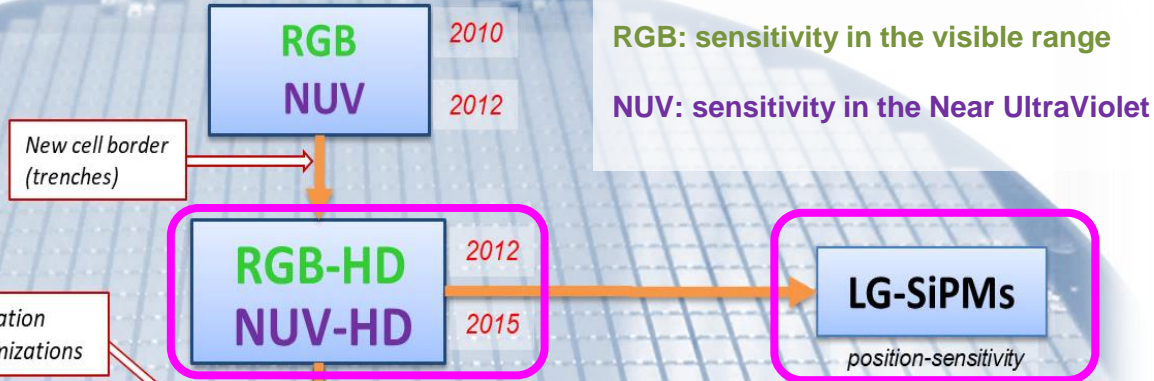
❑ Many different SiPM technologies, tailored for different applications

SiPM: large areas & pos. resolution
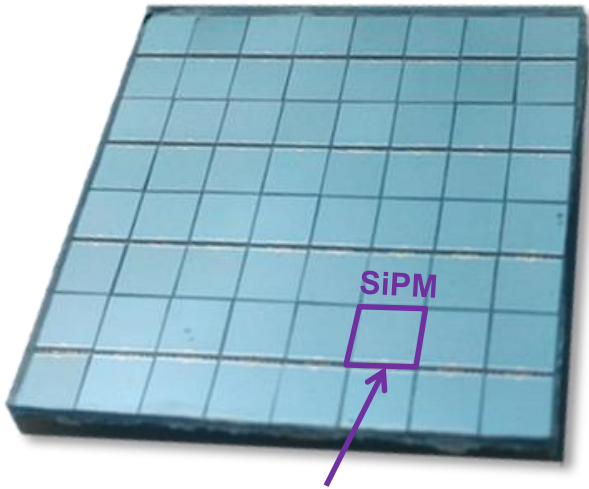

Doi: 10.1016/j.nima.2017.02.016

1 SiPM: 1 output
(chip size: 1÷4mm)
(pos. res.: 1÷4mm)

doi:10.1088/1361-6560/aaa707
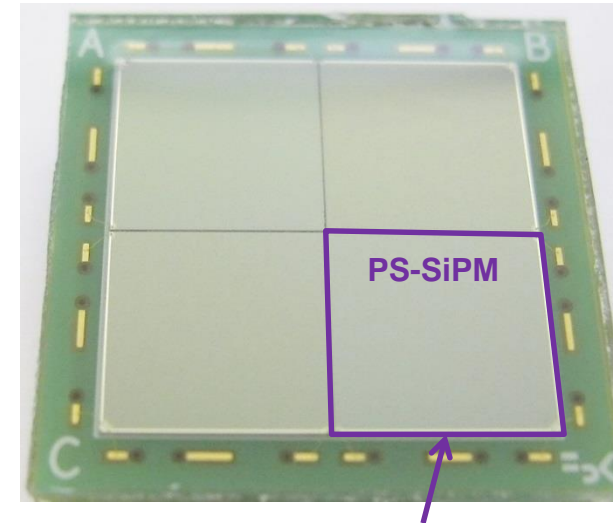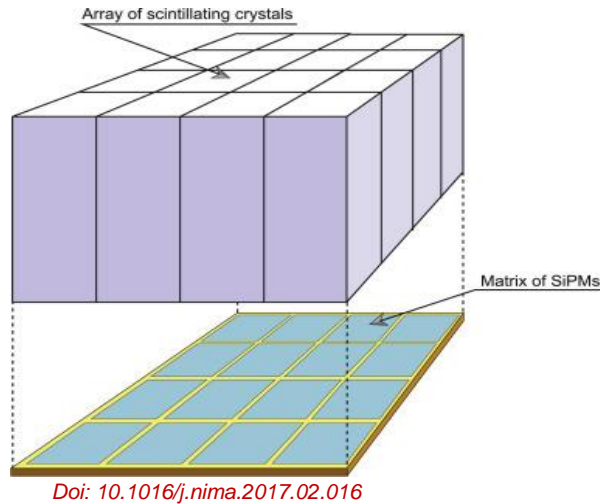
1 SiPM: 4 output
(chip size: 8÷10mm)
(pos. res.: <0.5mm)
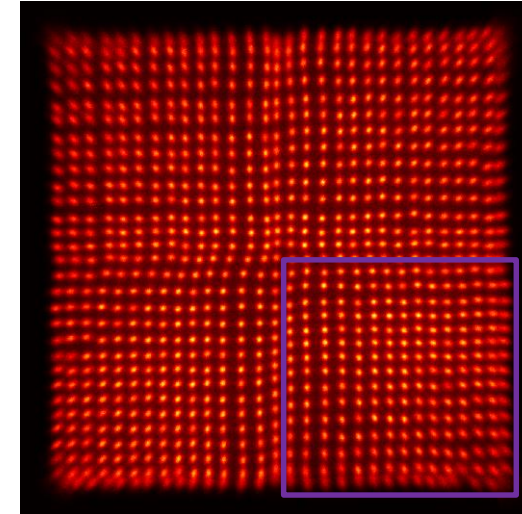
SiPM array

- Small/med. size chips (no pos. resolution)
  - Array position resolution: ~ chip size
- Many output channels (e.g. 8x8)
- Typ. ASIC readout (64 channels)

Position-sensitive (PS) SiPM

- Large area chips with position resolution(<0.5mm)
- Reduced number of channels.
  - Further #channels reduction techniques.
- *Slightly complex production process.*

SiPM: large areas coverage
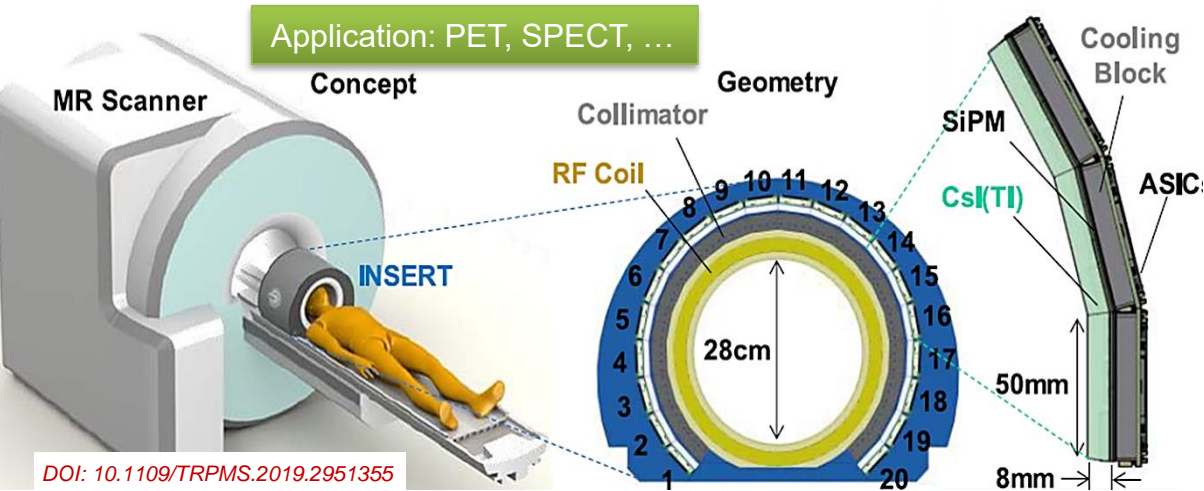
SiPM array

Application: PET, SPECT, …

DOI: 10.1109/TRPMS.2019.2951355

Application: γ-ray det. modules for space experiments

Hutcheson, "SiPM workshop" 2019;

Murphy, doi: 10.1007/s10686-022-09842-z

Position-sensitive (PS) SiPM

Application: small-animal PET

DOI: 10.2967/jnumed.115.170019
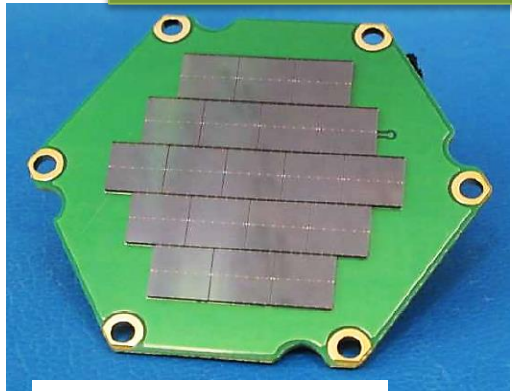
Application: TPC readout

arXiv:2009.05086v2

Application: compact γ cameras

DOI: 10.2967/jnumed.111.090464
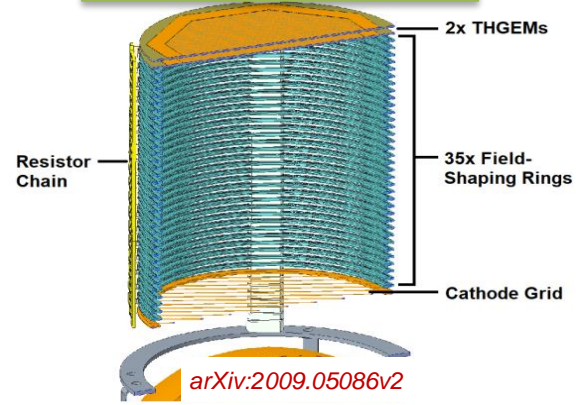
Position sensitive SiPM technologies

(1) SeSP

[1] Omidvari, N. and V. Schulz, IEEE Transactions on Nuclear Science, 2015. 62(3): p. 679-687.

(2) i-SiPM

[2] I., S., et al. IEEE SENSORS. 2013.

(3) *Resistive-network*
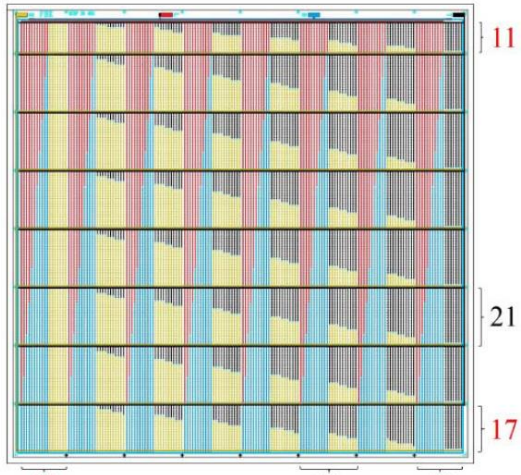

[3] J., P.S., et al., IEEE Transactions on Nuclear Science, 2014. 61(3): p. 1074-1083.

(4) EQR Tetra-Lateral PS SiPM

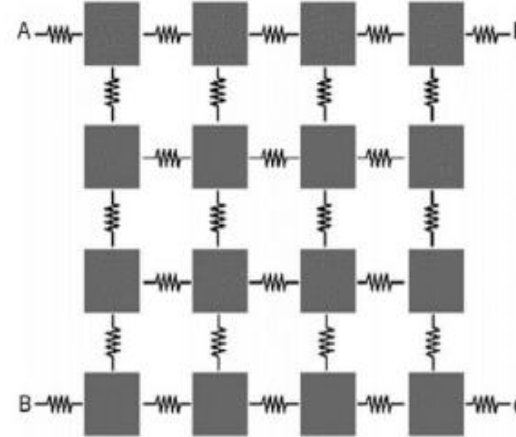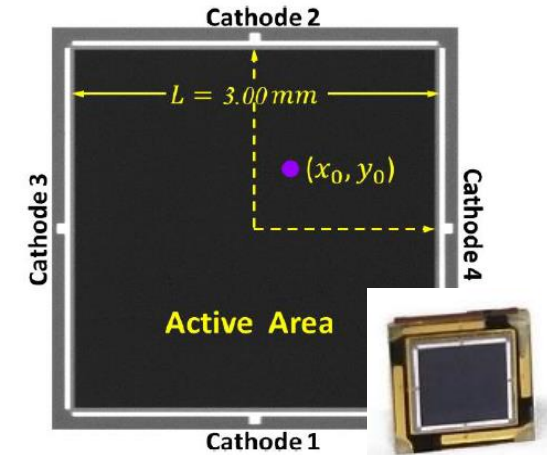[5] Zhao, T., et al., IEEE Electron Device Letters, 2017. 38(2): p. 228-231.

- "Sensitivity-encoding" or "interpolating" position-sensitive SiPM
- Based on scintillation light-sharing among micro-cells or SiPM regions
- Scaling: not straightforward

- Based on resistive-network
- Parasitic effects / signal shape might depend on SiPMs size
- Scaling: difficult

- Based on common cathode and epitaxial quenching resistor (EQR)
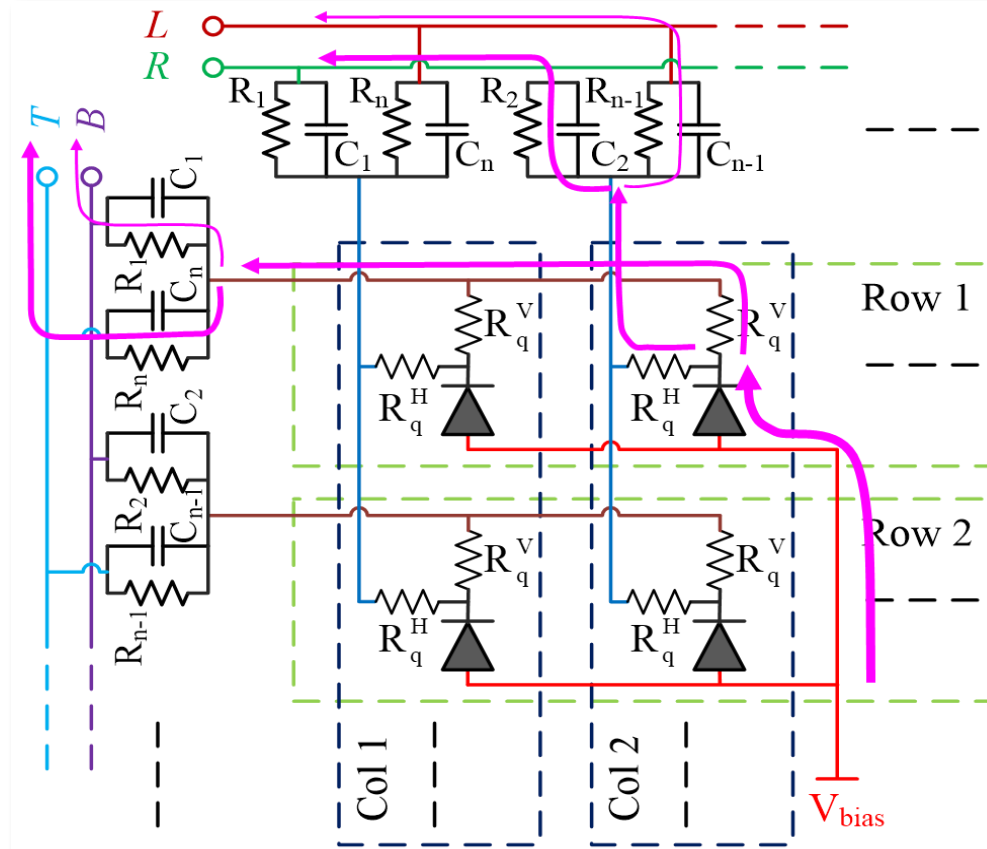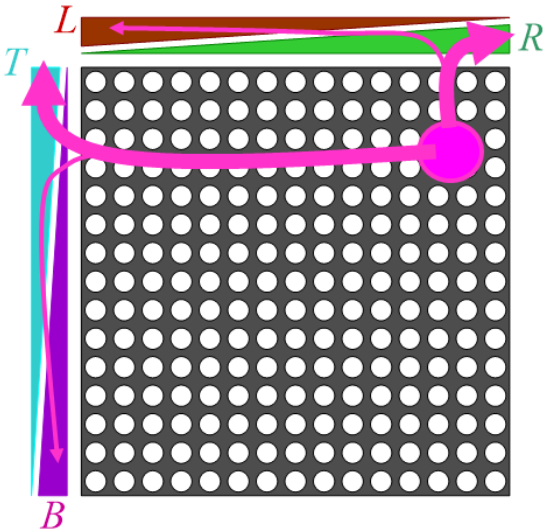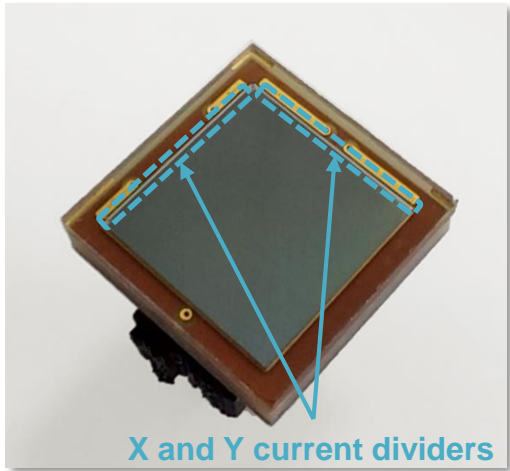- Limited freedom in cell-pitch and SiPM dimension
- Scaling: not straightforward

# FBK approach : Linearly-graded (LG) SiPM

X and Y current dividers

- **Each micro-cell: 2 quenching resistor** connected to **2 current dividers**

- Every column (every row) of cells is connected to the same current divider

- Current split between **2 outputs** for the **vertical** position and **2 outputs** for the **horizontal** position

- Difference between the currents flowing through the two arms (amplitude or total charge) of the divider **changes linearly** with the horizontal and vertical position.

LG-SiPM approach:
✓ **Based on a charge-sharing method**
✓ **Discretization: almost at the single micro-cell level**
✓ **Highly scalable → large tiles, with very few channels**

FBK approach: Linearly-Graded (LG) SiPM
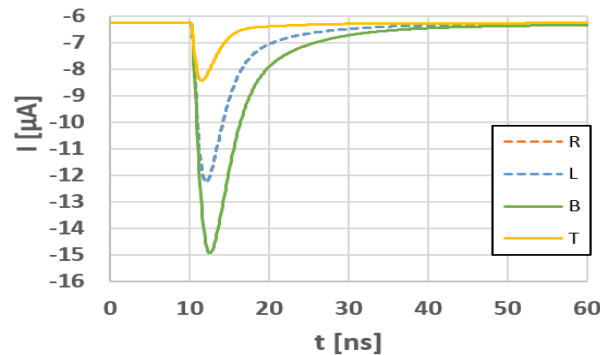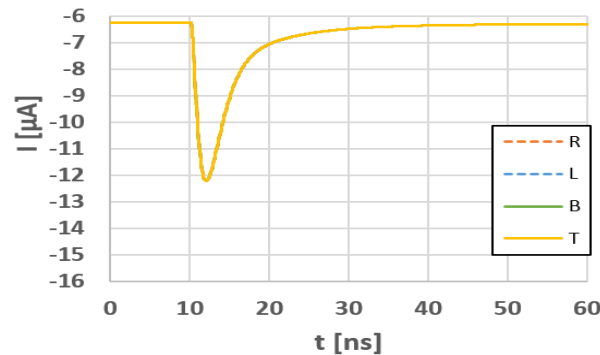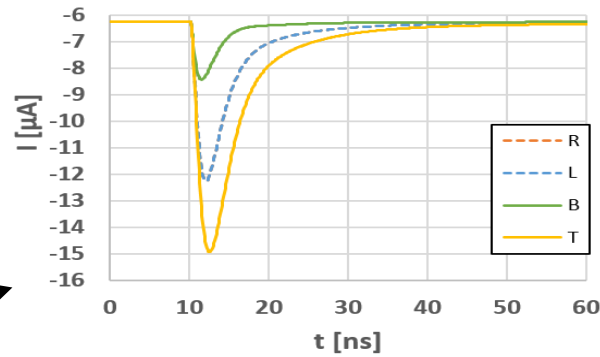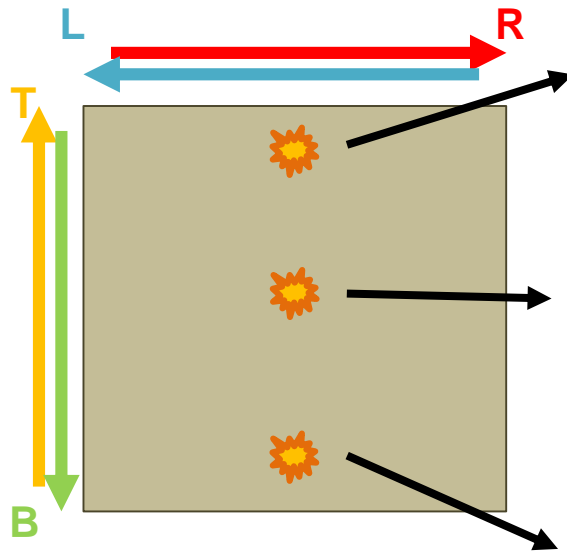
- Single cell signal split into **4 outputs**

$$I_{cell} = I_R + I_L + I_T + I_B$$

- Ratio of the outputs (amplitude and charge) **depend on the position of the triggered cells**

- Event position: reconstructed through **center of mass** calculation:

$$\mathbf{X} = \frac{\boldsymbol{I_R - I_L}}{\boldsymbol{I_R + I_L}} \qquad \mathbf{Y} = \frac{\boldsymbol{I_T - I_B}}{\boldsymbol{I_T + I_B}}$$

- Total event energy: sum of all the signals:

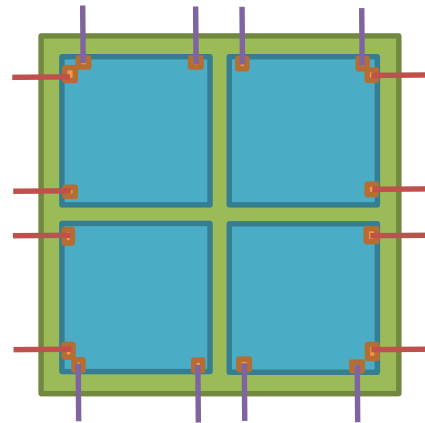$$\boldsymbol{E_{event} = E_R + E_L + E_T + E_B}$$

Channel reduction configurations

Std SiPM array
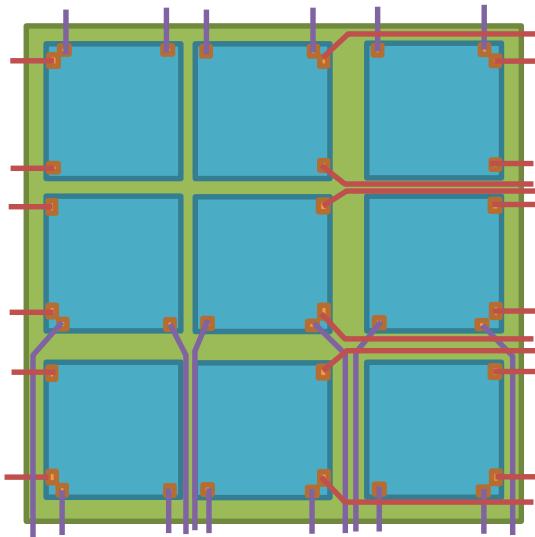
20x20 mm² (pitch 1mm) Approx. 400 ch.

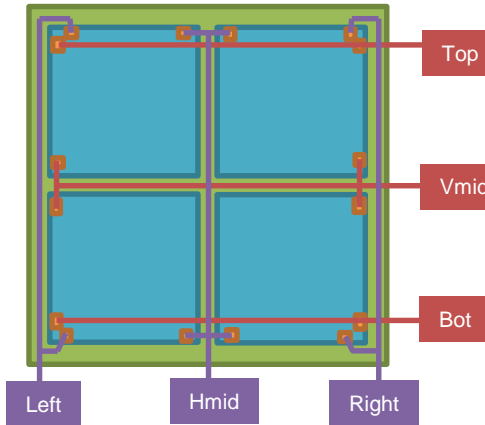30x30 mm² (pitch 1mm) Approx. 900 ch.

LG-SiPM: Std array readout

2x2 array

20x20 mm²
16 ch.

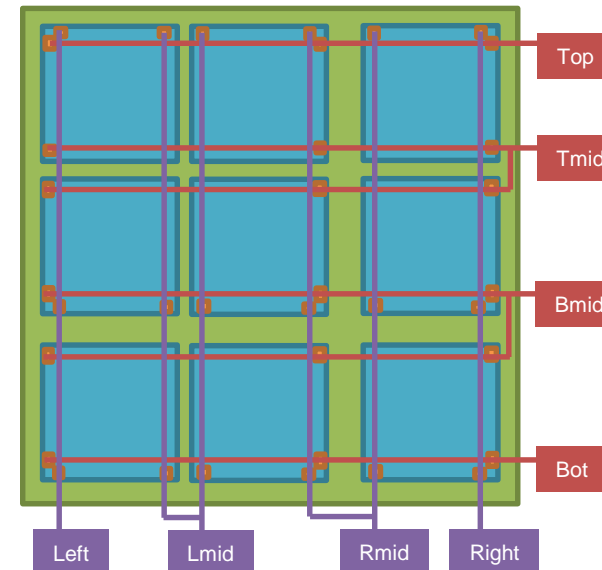**3x3 array**

30x30 mm²
36 ch.

LG-SiPM: Advanced #ch-reduction config.

2x2 array

20x20 mm²
6 ch.

Still with nominal pos. res. <0.5mm

Top

Vmid

Bot

Left   Hmid   Right

$$X = \frac{I_R - I_L}{I_R + I_{Hmid} + I_L}$$

$$Y = \frac{I_T - I_B}{I_T + I_{Vmid} + I_B}$$

3x3 array

30x30 mm²
8 ch.

Still with nominal pos. res. <0.5mm

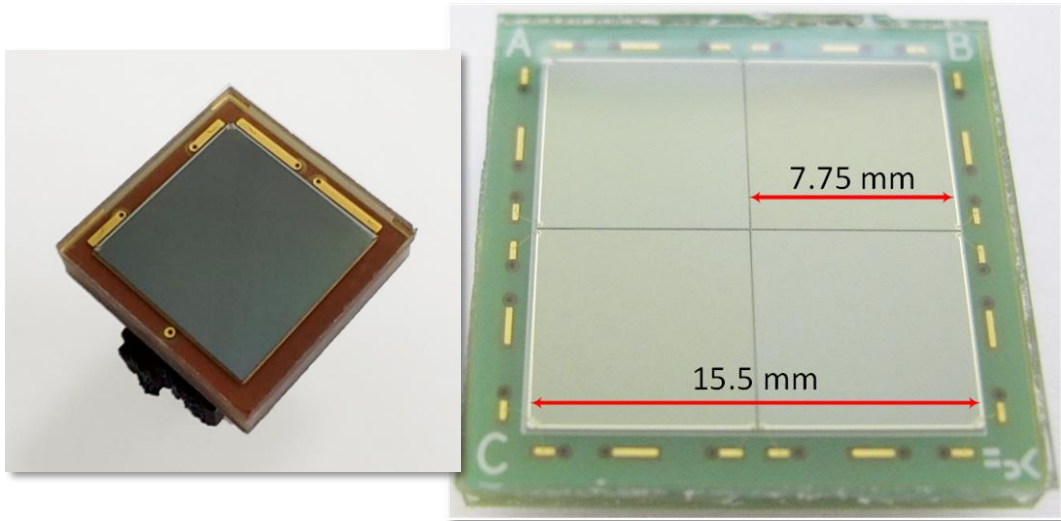Top

Tmid

Bmid

Bot

Left   Lmid   Rmid   Right

$$X = \frac{I_R + 0.33 \cdot I_{Rmid} - 0.33 \cdot I_{Lmid} - I_L}{I_R + I_{Rmid} + I_{Lmid} + I_L}$$

$$Y = \frac{I_T + 0.33 \cdot I_{Tmid} - 0.33 \cdot I_{Bmid} - I_B}{I_T + I_{Tmid} + I_{Bmid} + I_B}$$
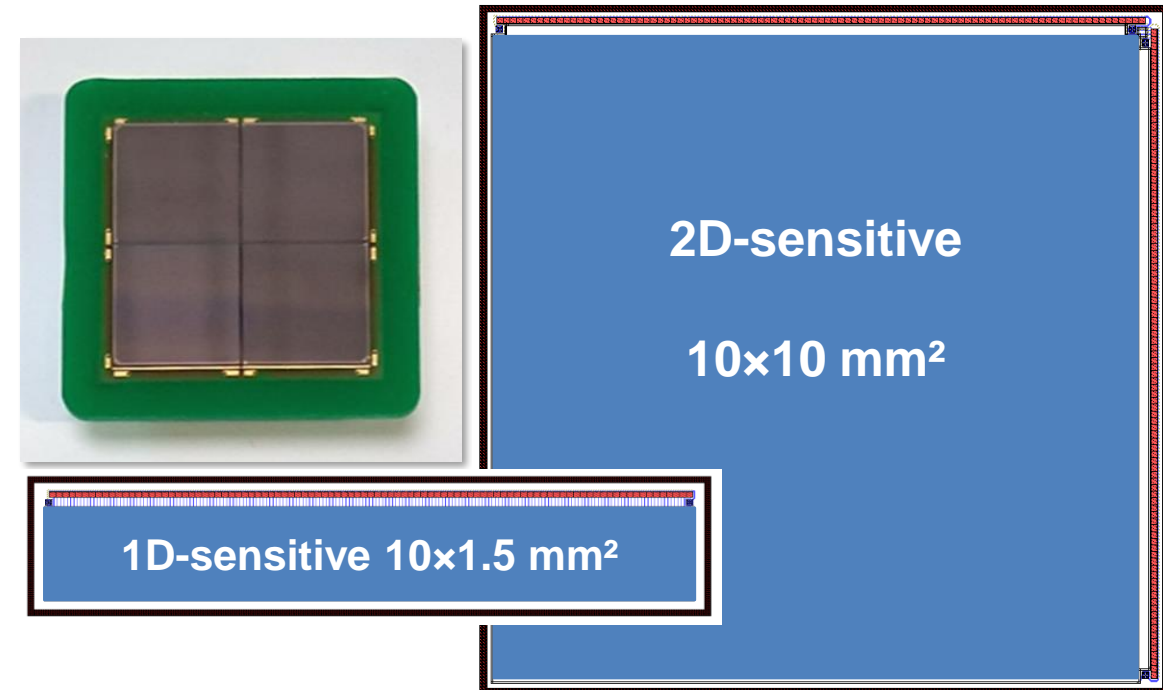
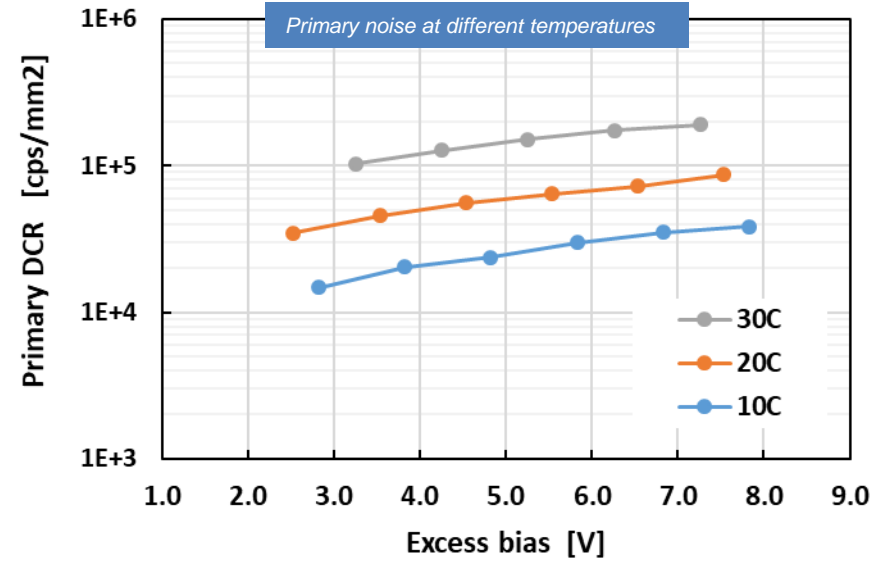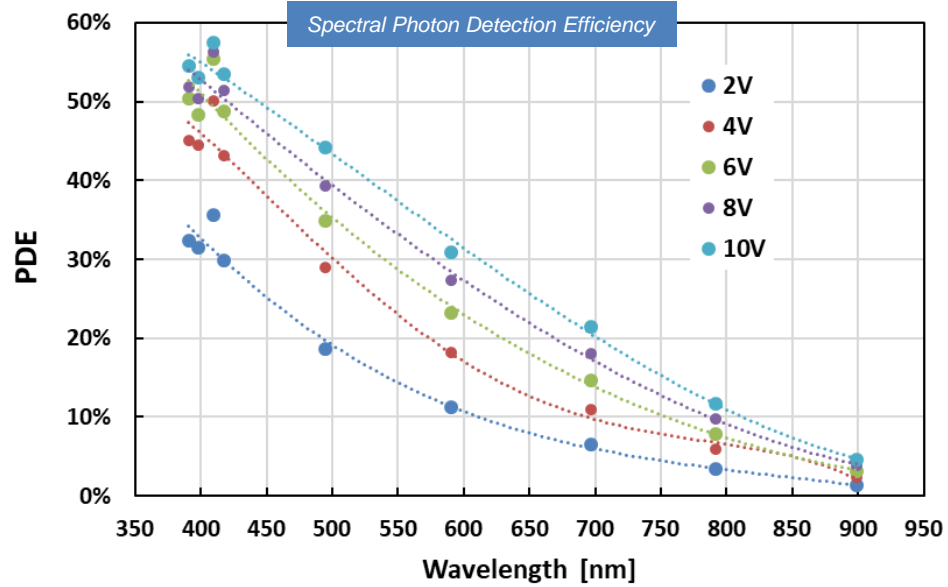# FBK approach: Linearly-Graded (LG) SiPM

RGB-HD LG-SiPM

- Chip nom. size: 8×8 mm²
- Active area: 7.75×7.75 mm²
- Cell pitch: 20 µm
- Peak PDE: 550nm
- DCR: ~300 kcps/mm² @ V_{ex}=5V

NUV-HD LG-SiPM

- Chip Nom. size: 10×10 mm²
- Active area: 9.75×9.75 mm²
- Cell pitch: 25 µm
- Peak PDE: 420nm
- DCR: 30÷60 kcps/mm² @ V_{ex}=5V

7.75 mm

15.5 mm

2D-sensitive

10×10 mm²

1D-sensitive 10×1.5 mm²

NUV-HD LG-SiPM: functional characterization

Spectral Photon Detection Efficiency

Primary noise at different temperatures

Measured on 1x1mm2 SiPMs (at different temperatures) and on LG-SiPM 1D
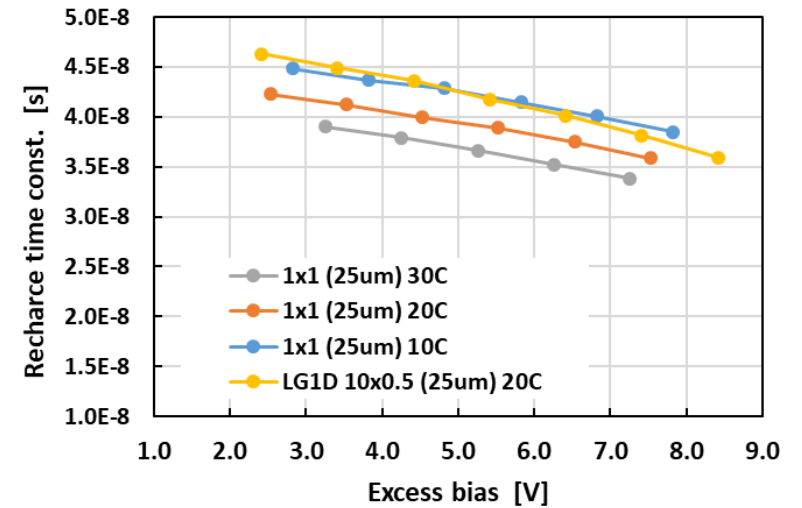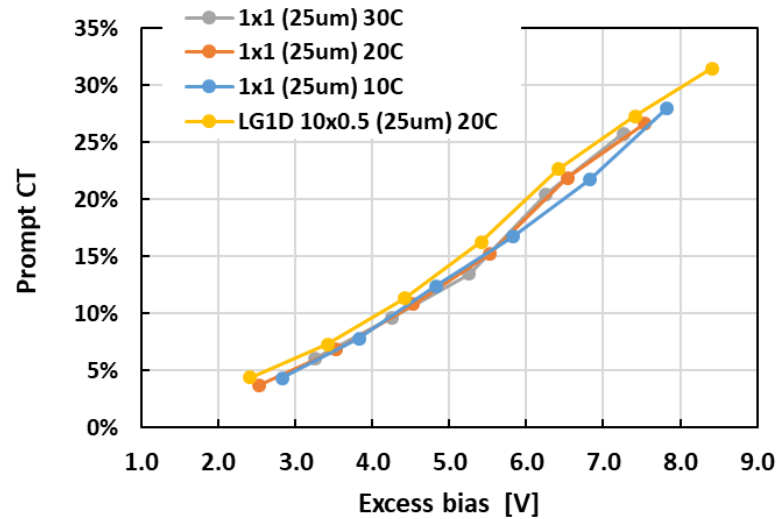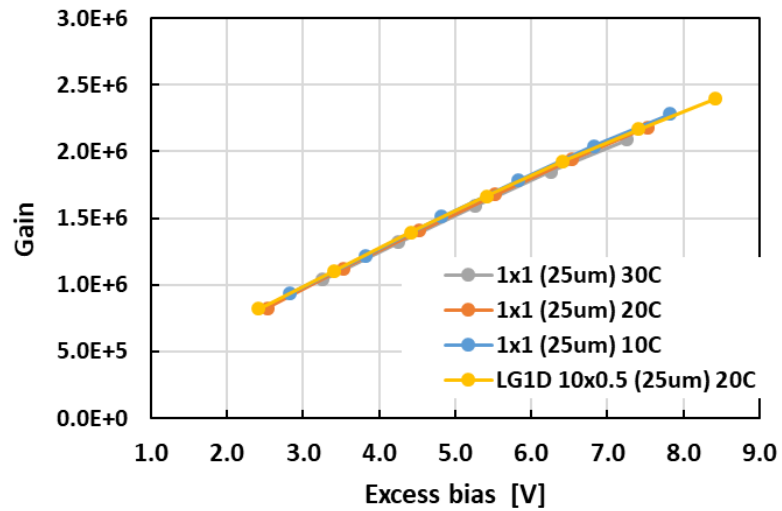
Position resolution tests: setup and devices

Climatic chamber

Multi-ch tras-imp. amplifier
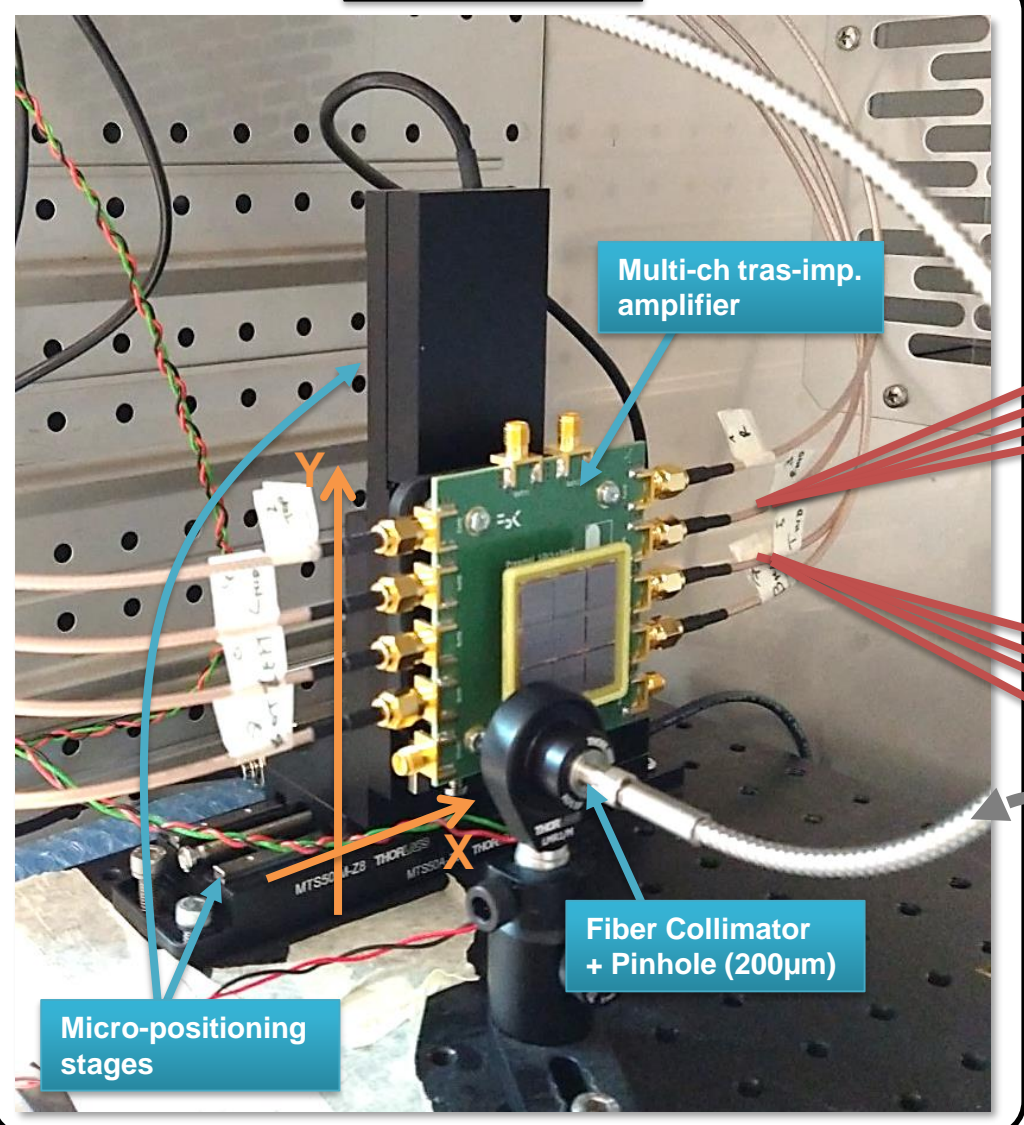
#2 Synchronized oscilloscopes
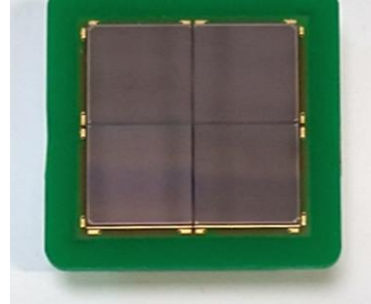
Y

X

Fiber Collimator + Pinhole (200µm)

Micro-positioning stages

Pulsed LED

sync

1chip (LG-SiPM) 4 ch.

2105 LG10
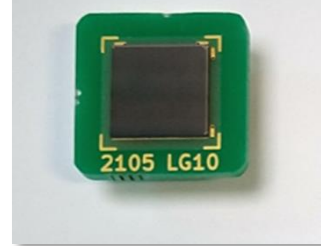
Tile 2x2 (LG-SiPM) 6 ch.

Tile 3x3 (LG-SiPM) 8 ch.

Pos. Res. tests: RGB-HD LG-SiPM

Scan points

Histogram of Total energy

LED: 591nm, ~400det.ph/pulse
Temp: 20°C, Vex: ~4V

SCAN:
Range: -3.0 ÷ +3.0 mm,
Step 0.5mm

Area Map 1

Reconstructed map

3D view

Reconstructed map - Stretched X and Y scales

Y-axis projection
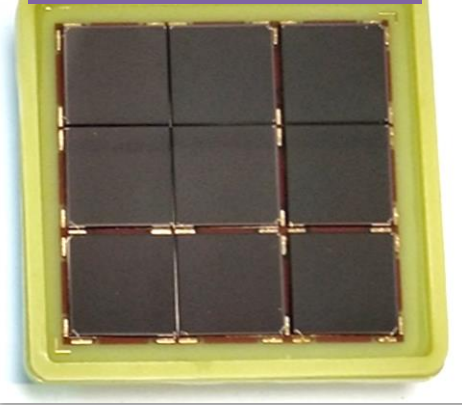
Position res.:
σ=0.054÷0.065mm
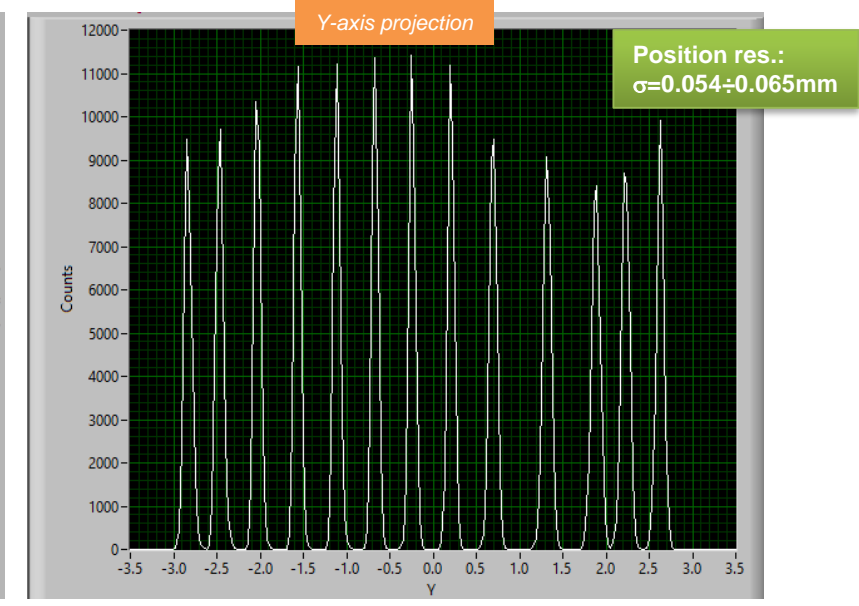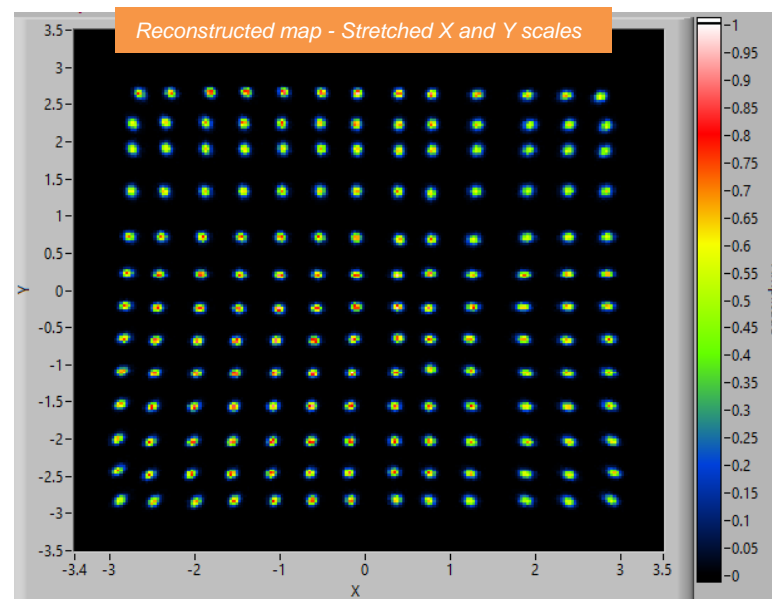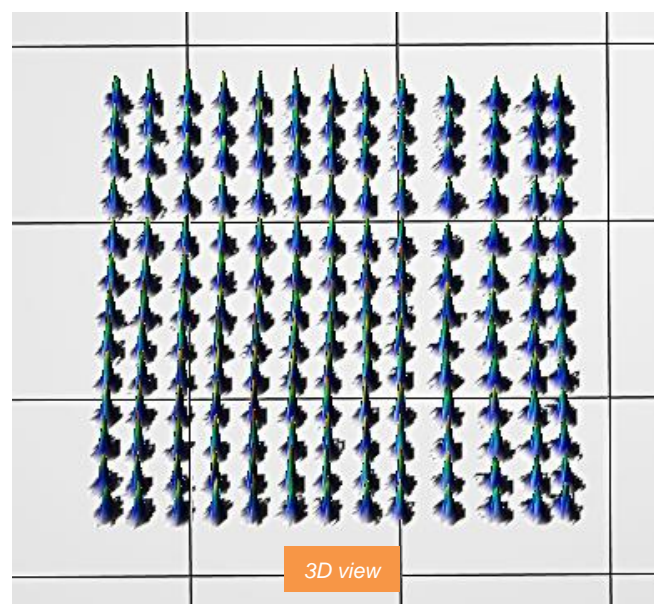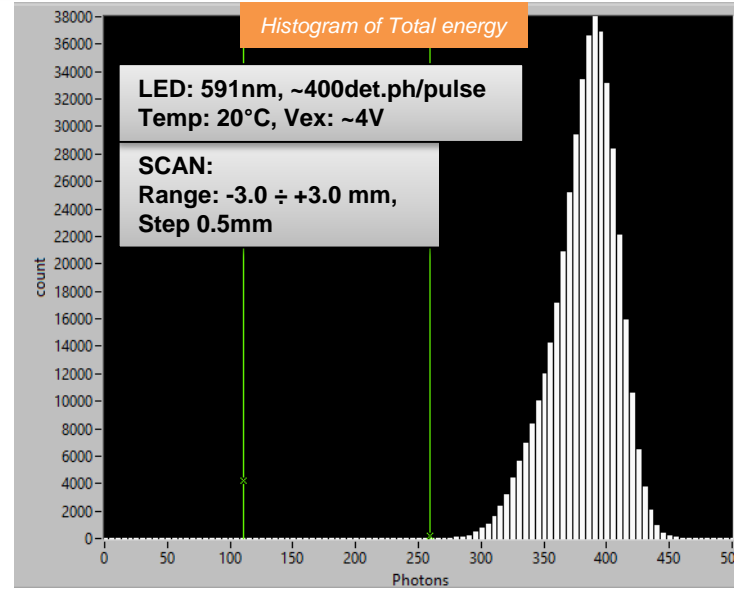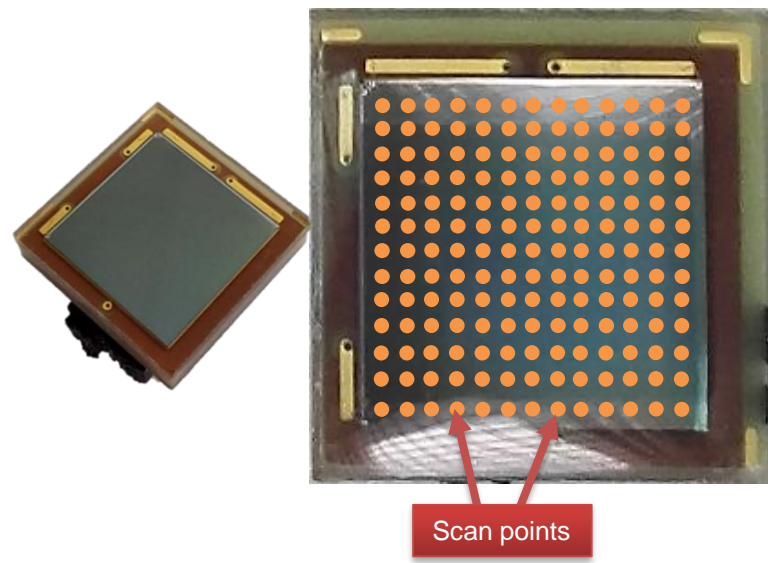
Pos. Res. tests: RGB-HD LG-SiPM TILE 2x2

67mm

22mm
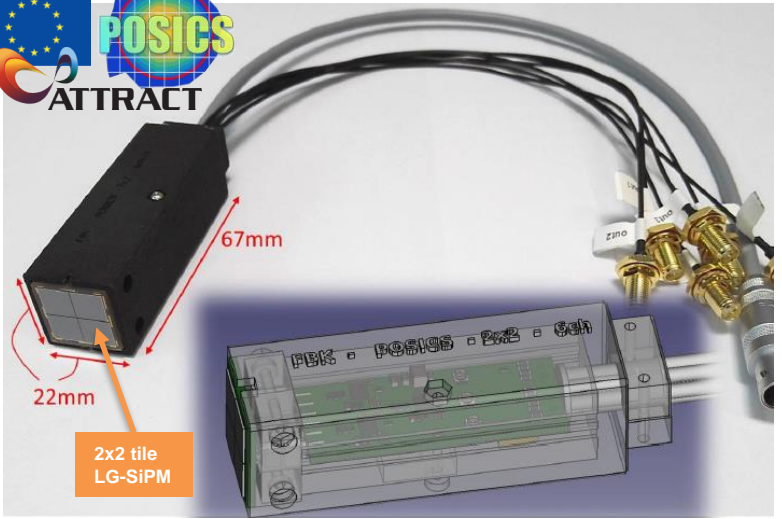
2x2 tile LG-SiPM

2x2 Tile of LG-SiPM (with only 6 channels), *in a compact module*

Area Histogram 1

Histogram of Total energy

LED: 591nm, ~400det.ph/pulse
Temp: 20°C, Vex: ~4V

SCAN:
Range: -7.5 ÷ +7.5 mm,
Step 1.0mm

Area Map 1
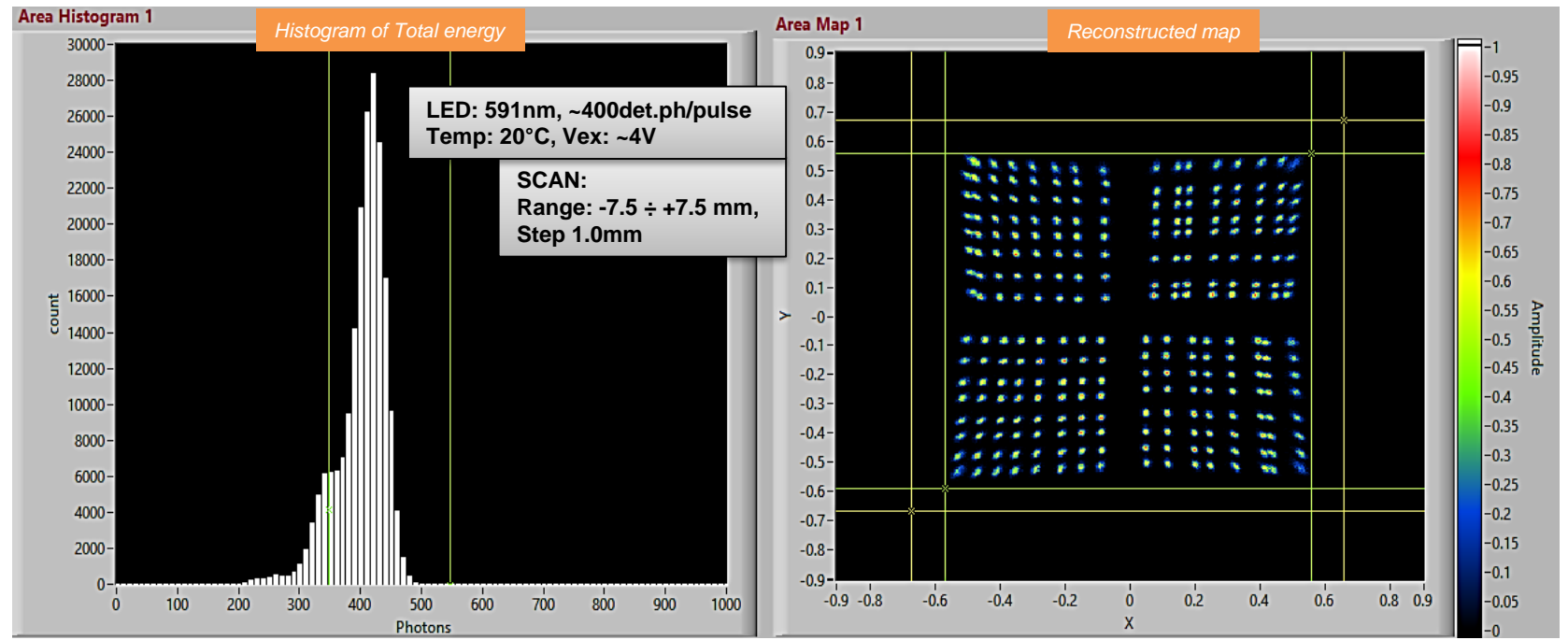
Reconstructed map

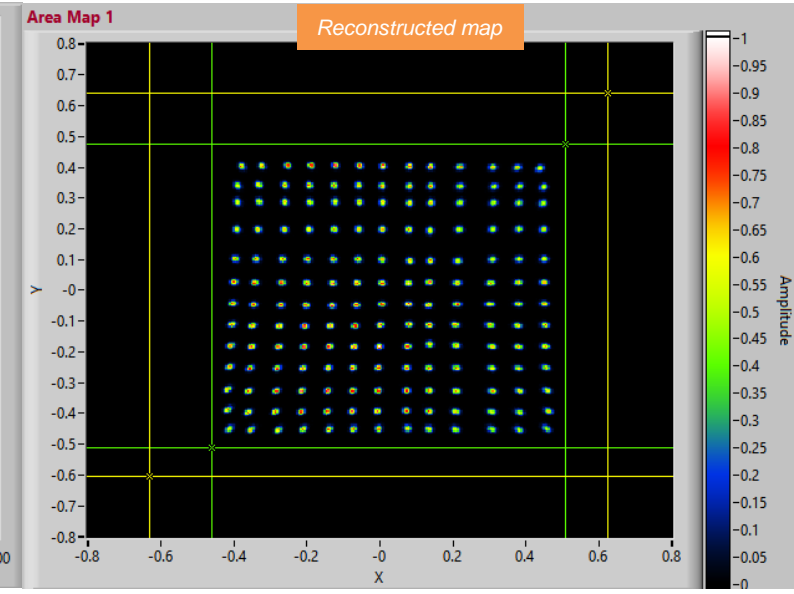- **Effect of SiPM noise** when increasing temperature: worsening of the position resolution

Temp: 20°C

Temp: 30°C

Temp: 40°C
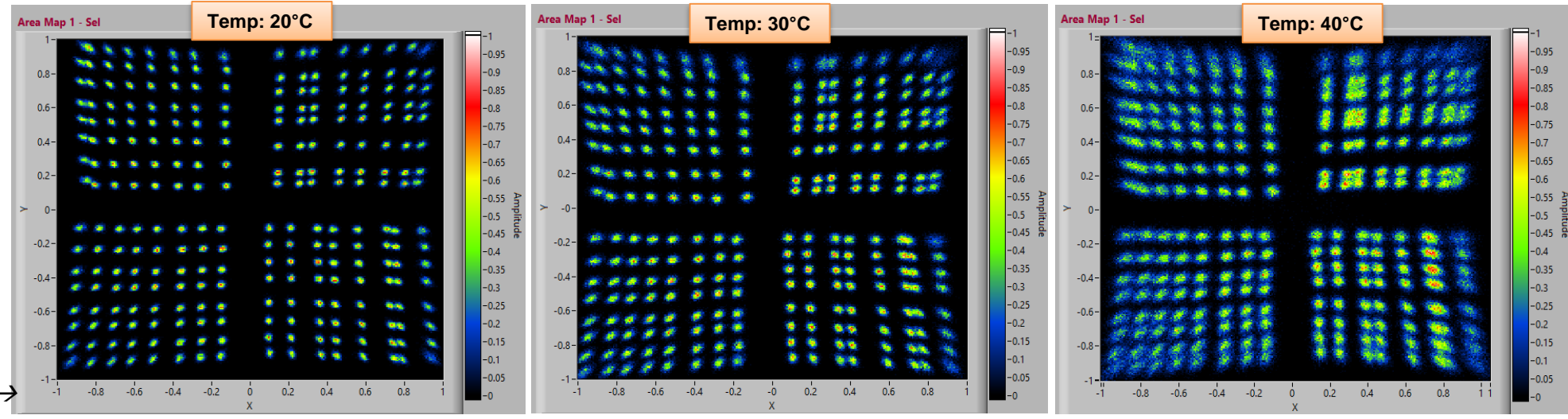
Normalized X and Y scales →

Pos. Res. tests: NUV-HD LG-SiPM

1chip (LG-SiPM) 4 ch.

2105 LG10

Histogram of Total energy

LED: 410nm, ~200det.ph/pulse
Temp: 20°C, Vex: ~4.5V

SCAN:
Range: -4.5÷+4.5 mm,
Step 1.0mm

Reconstructed map

Map of total energy (avg value)
Int. time 200ns

Map of total energy (Standard deviation)
Int. time 200ns

Map of position resolution

Position res.:
$\sigma=0.046÷0.056$mm

Pos. Res. tests: NUV-HD LG-SiPM

1chip (LG-SiPM) 4 ch.

2105 LG10

Area Map 1 - Sel   Int. Time = 100ns

Area Map 1 - Sel   Int. Time = 800ns

Area Map 1 - Sel   Int. Time = 1200ns

- *Small **pincushion effect** on reconstructed map.*
- Worse when increasing integration time.
  (Note: no corrections in our measurements)

- *Might be related to parasitic inductances in the large-area SiPM chips, combined with non-zero input impedance of readout electronics.*

- *SPICE simulation will be performed to better understand the issue.*

Pincushion Distortion Correction in Position-Sensitive Avalanche Photodiodes
DOI: 10.1109/NSSMIC.2005.1596732
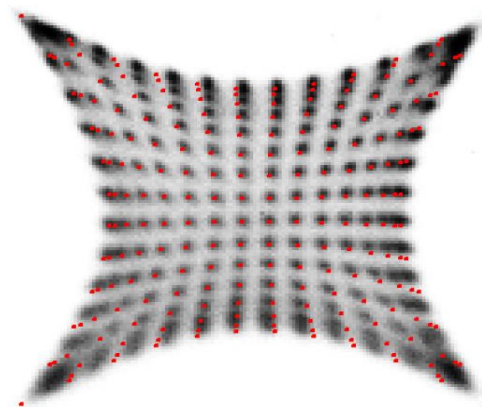
Fig. 3.   The raw ^{99m}Tc flood image of the crystal array with superposed dots obtained from simulation (red dots).

Evaluation of Large-Area Silicon Photomultiplier Arrays for Positron Emission Tomography Systems
  DOI: 10.3390/electronics10060698

Unideal signal source output impedance and DPC termination impedance are potential sources of the pincushion distortion and resolution degradation at the edges and corners

(b)
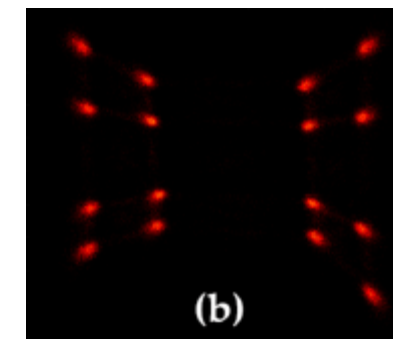
Pos. Res. tests: NUV-HD LG-SiPM TILE 2x2

Tile 2x2 (LG-SiPM) 6 ch.

Histogram of Total energy

Area Histogram 1

LED: 410nm, ~200 det.ph/pulse
Temp: 20°C, Vex: ~4.5V

SCAN:
Range: -10 ÷ +10 mm,
Step 1.0mm

Reconstructed map

Area Map 1

Map of total energy (avg value)

Int. time 400ns

Map of total energy (Standard deviation)
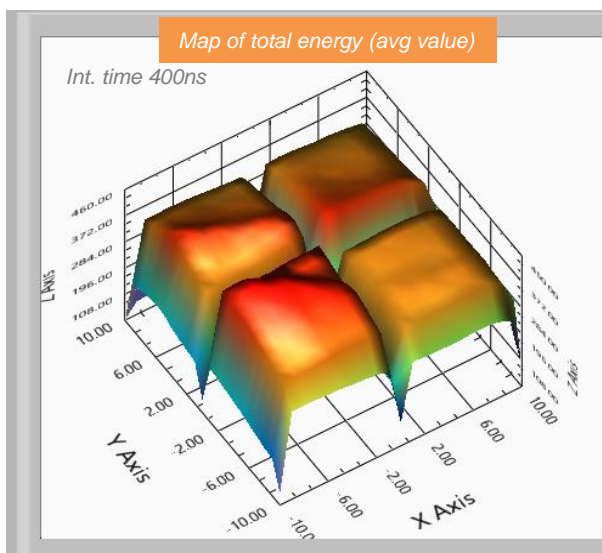
Int. time 400ns

Map of position resolution

Int. time 150ns

Position res.:
σ=0.110 ÷ 0.115 mm

3x3 tile LG-SiPM

8 output channels

32mm

https://attract-eu.com/wp-content/uploads/2022/07/ATTRACT-RDI_POSICS-2-project.pdf
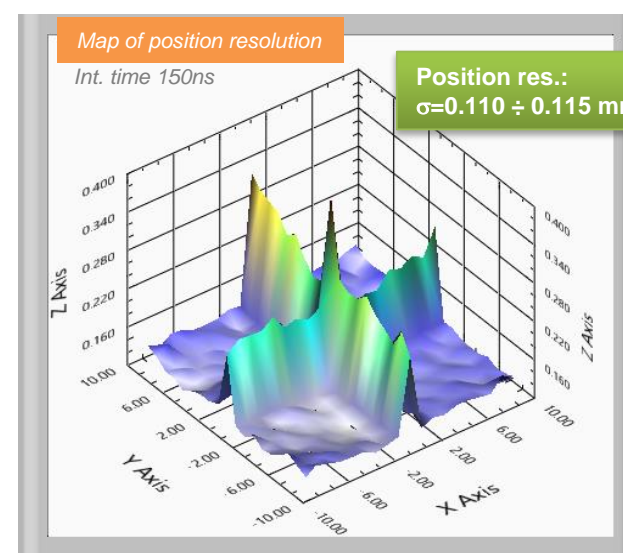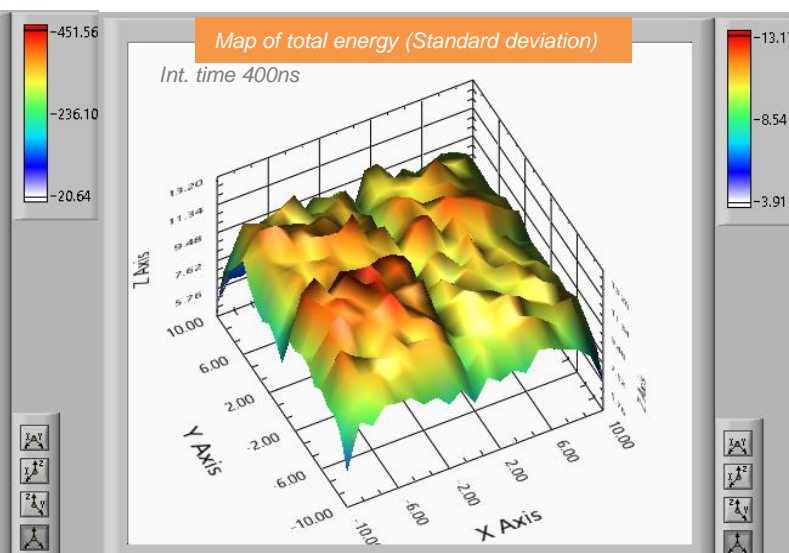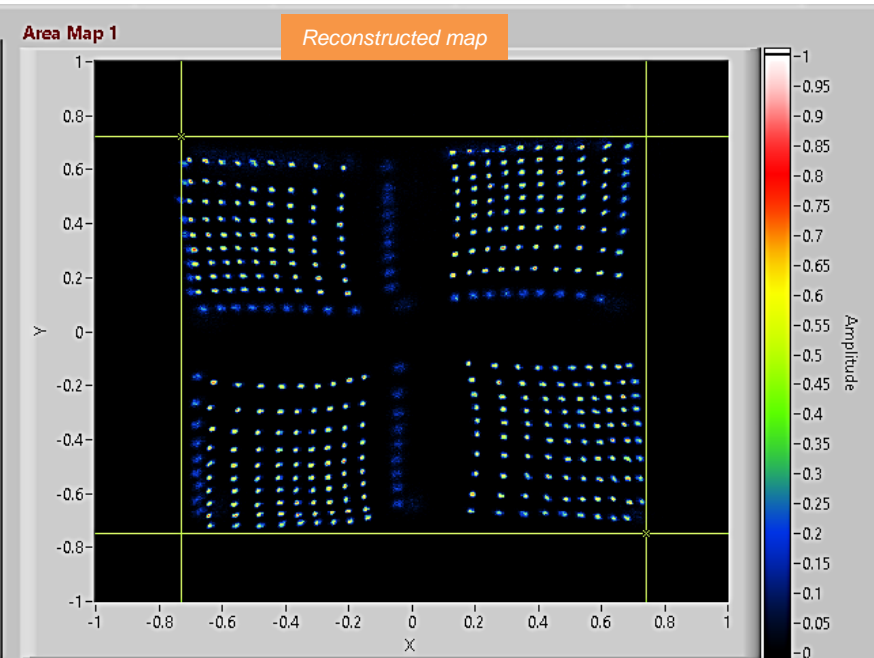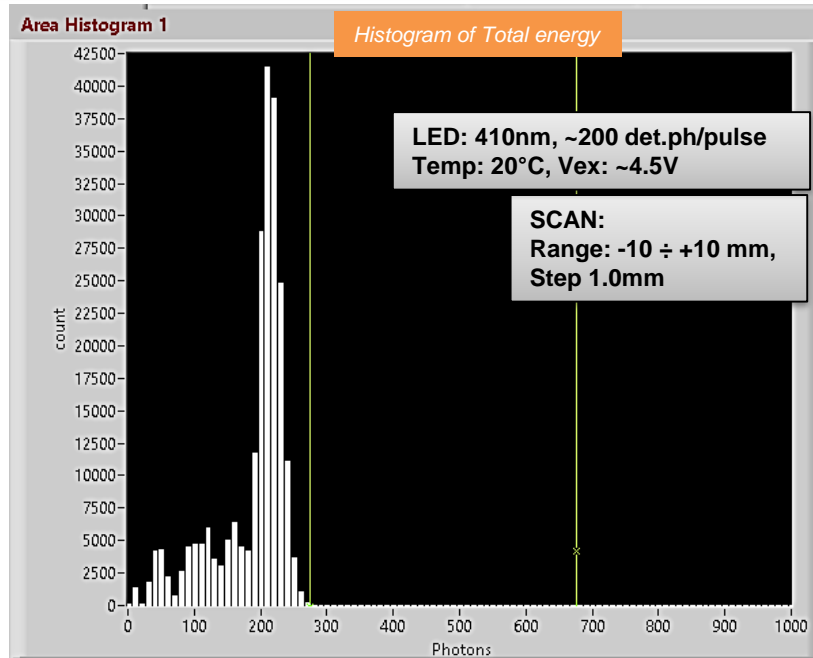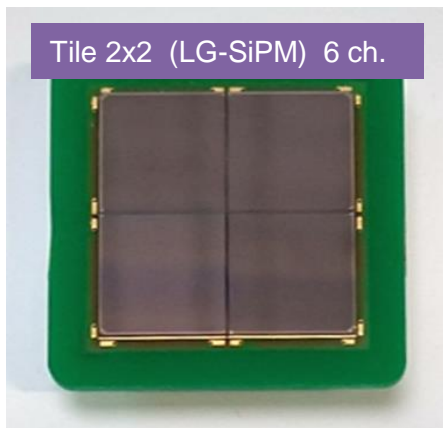
POSICS-2 project

- POSICS aims at realizing a cheap, handle-able, wireless, compact and light *gamma camera, for Radio-Guided-Surgery (RGS).*

- Based on LG-SiPM 3x3 array
  → reduced #channels
  → low-power consumption

- *Breakthrough approach in the intra-operative practice*, moving away from the current probe approach.
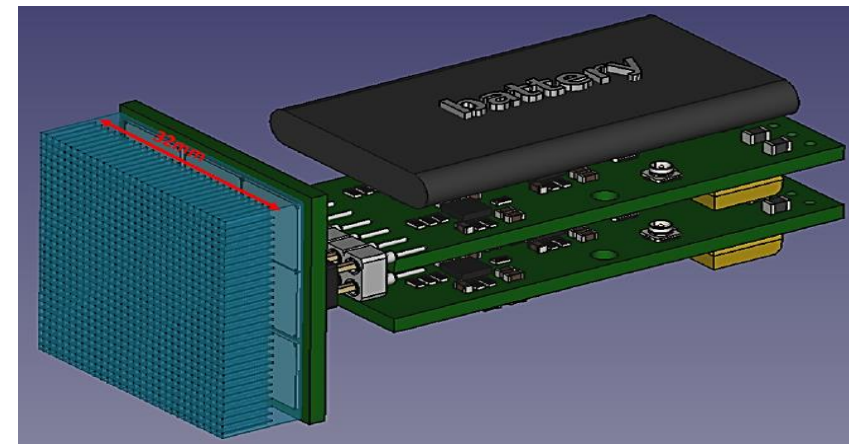
LED: 410nm, ~400 det.ph/pulse
Vex = 4V

SCAN:
Range: -14.25 ÷ +14.25 mm, Step 1.5mm

Temp: 20°C

Temp: 30°C

Map of total energy (avg value)

Int. time 150ns

Map of position resolution

Position res.:
σ=0.180 ÷ 0.210 mm
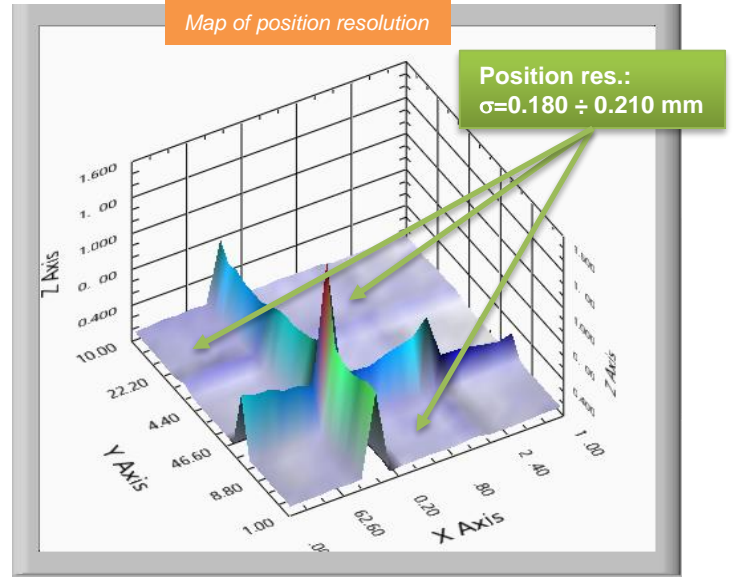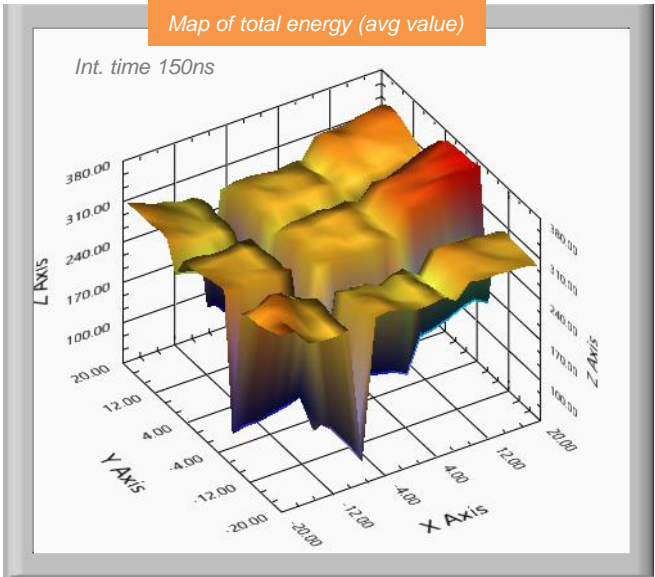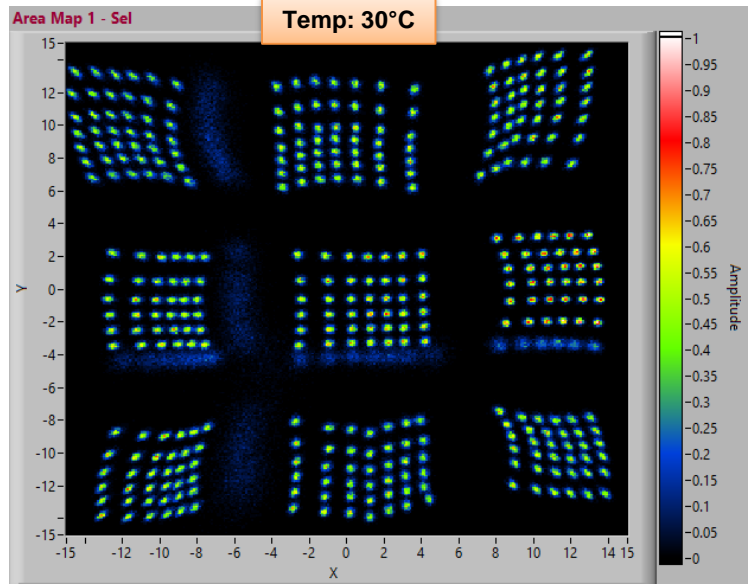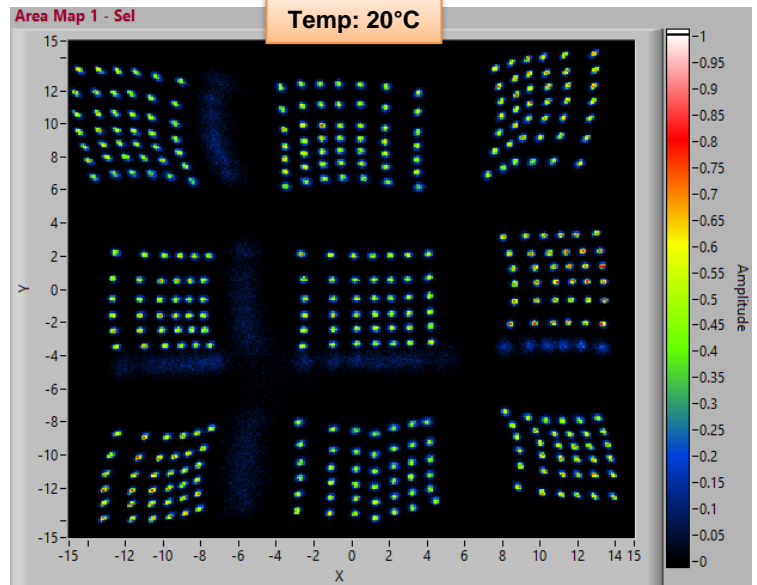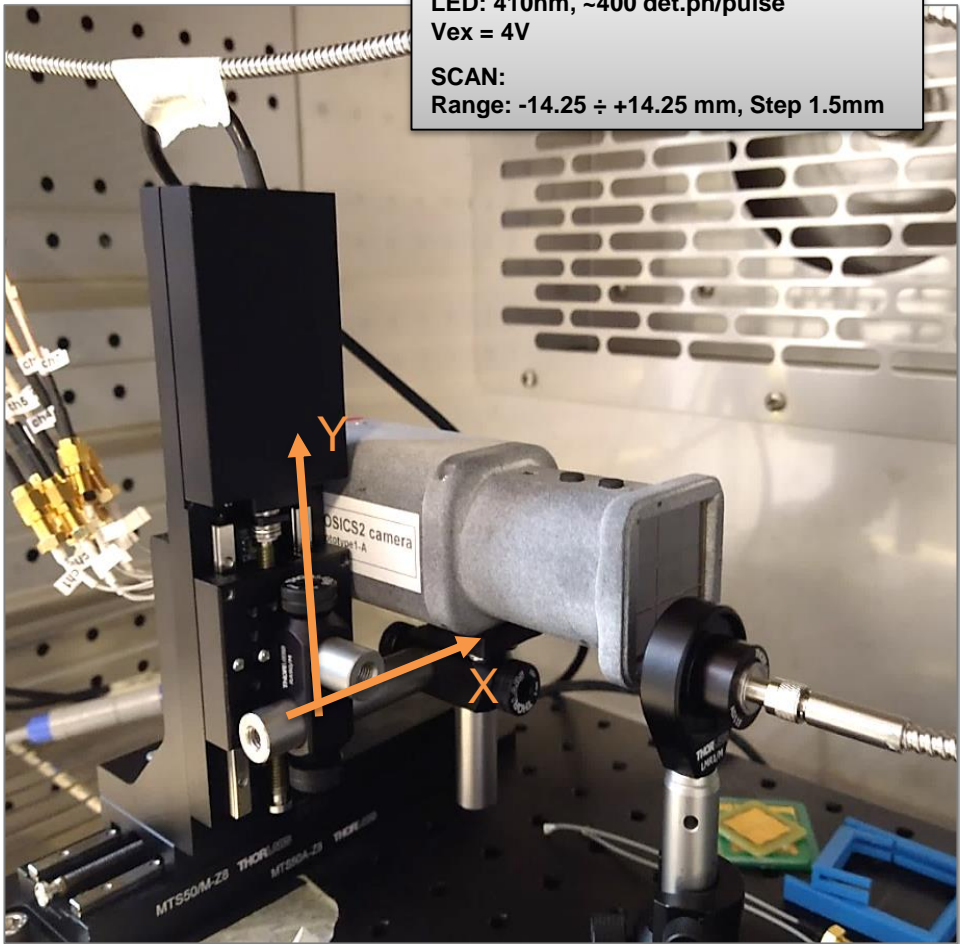
Conclusions

- We developed and improve the FBK LG (position sensitive) SiPM technology
  - **New NUV-sensitive large-area (10x10mm^2) devices**
  - 1D and 2D position sensitive version

- Development of **"smart" channel-reduction scheme**
  - Only 6 output channels for 2x2 tiles of SiPMs
  - Only 8 output channels for 3x3 tiles of SiPMs
  - Still preserving <0.5mm position resolution

- Functional characterization:
  - PDE: peaked at 410nm, reaching 45% at 4V, 55% at 8V excess bias.

- **Good position resolution**, also when SiPM chip combined in TILEs
  - Position resolution σ = ~0.05 mm for 1 SiPM chip (10x10mm^2)
  - Position resolution σ = ~0.12 mm for 2x2 SiPM tile (tot 20x20mm^2)
  - Position resolution σ = ~0.21 mm for 3x3 SiPM tile (tot 30x30mm^2)

- LG-SiPM used in many applications, e.g. **compact gamma-camera for RGS** (POSICS project)

FONDAZIONE BRUNO KESSLER

Large area tiles of Position-Sensitive Silicon Photomultipliers

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