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10th Conference on PET, SPECT, and MR Multimodal Technologies, Total Body and Fast Timing in Medical Imaging

NUV-sensitive Deep-Junction (NUV-DJ) SiPMs, a new technology optimized for fast timing applications

O. A. Marti Villarreal[1,*], *Fabio Acerbi[1], Giovanni Paternoster[1], Michele Penna[1,2], Nicola Zorzi[1], and Alberto Gola[1]*

[1]Fondazione Bruno Kessler (FBK), Center for Sensors and Devices, Trento, Italy
[2]Politecnico di Torino *(POLITO), Torino, Italy*

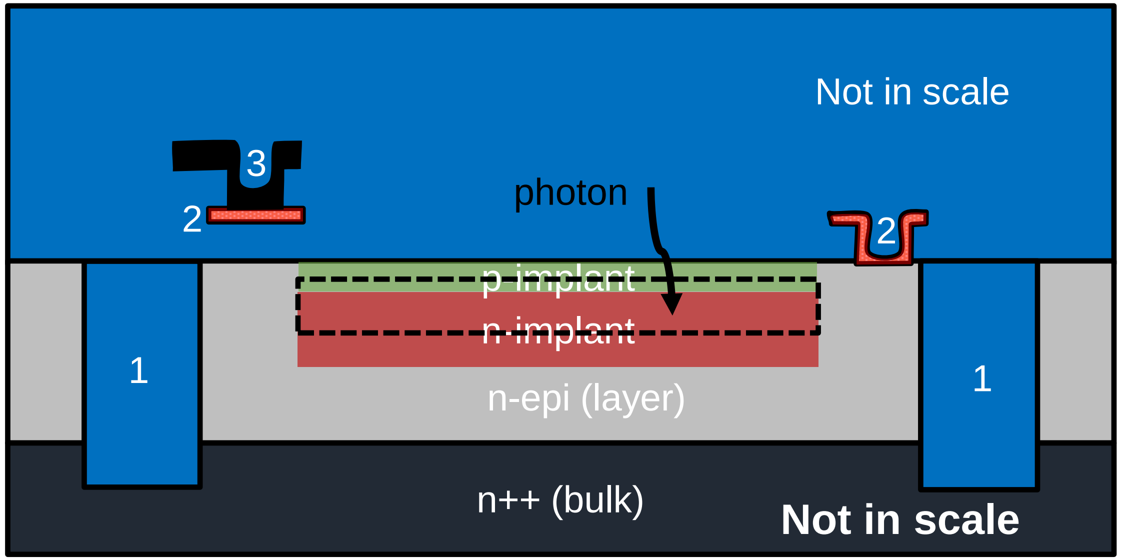
*omartivillarreal@fbk.eu

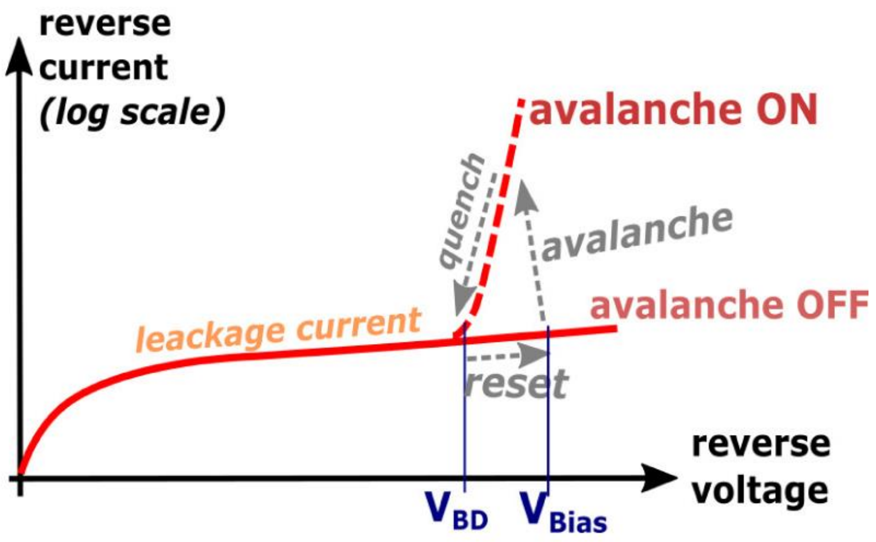
Outline

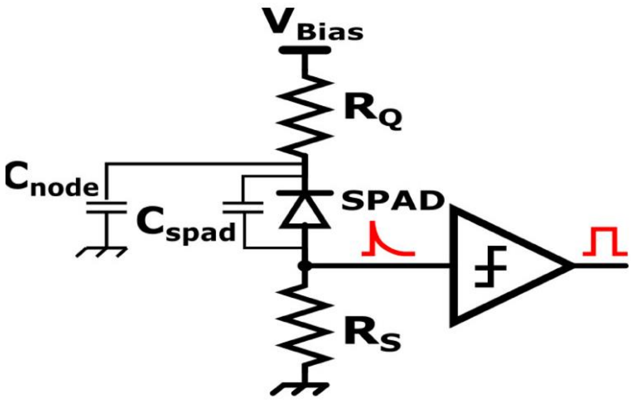
- Single Photon Avalanche Diode (SPAD) & Silicon Photomultipliers (SiPMs)
- SiPMs technologies on FBK
- Near-Ultraviolet sensitive Deep-Junction (NUV-DJ) SiPMs
- Experimental characterization of the first production of NUV-DJ technology
- Remarks and Conclusions

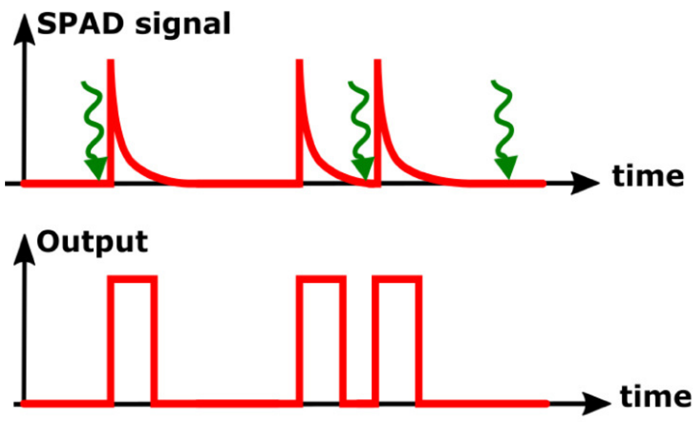
*omartivillarreal@fbk.eu

Single Photon Avalanche Diode (SPAD)







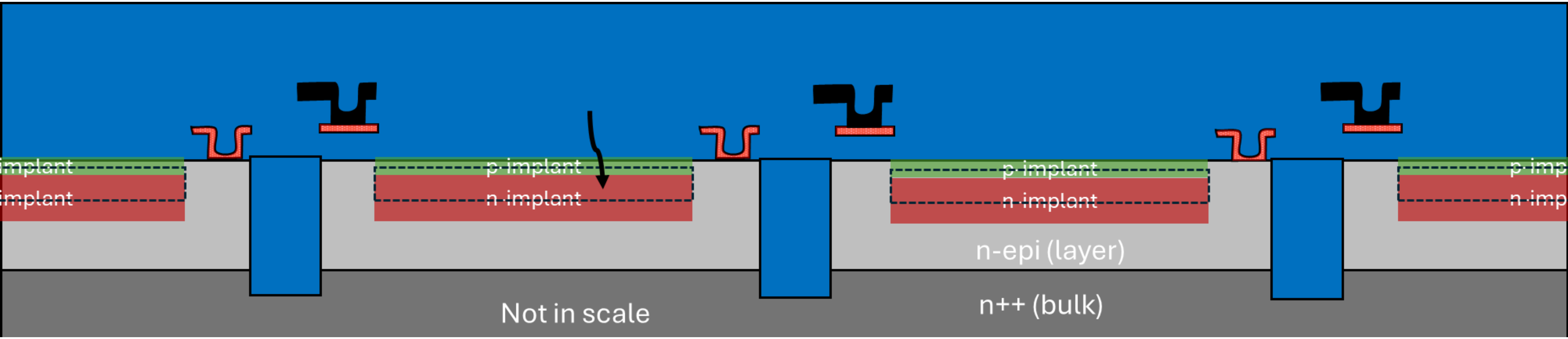


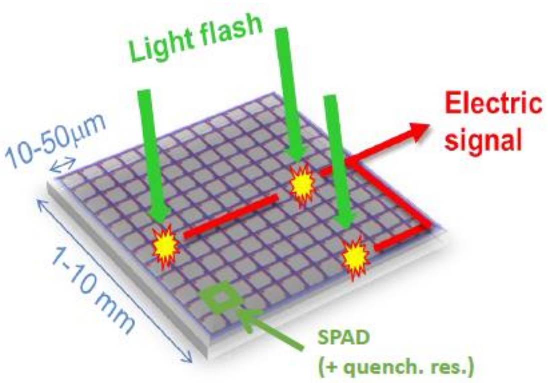
1-) Deep trench isolation
2-) Polysilicon quenching resistor
3-) Metal connection to the readout pad
High-field region

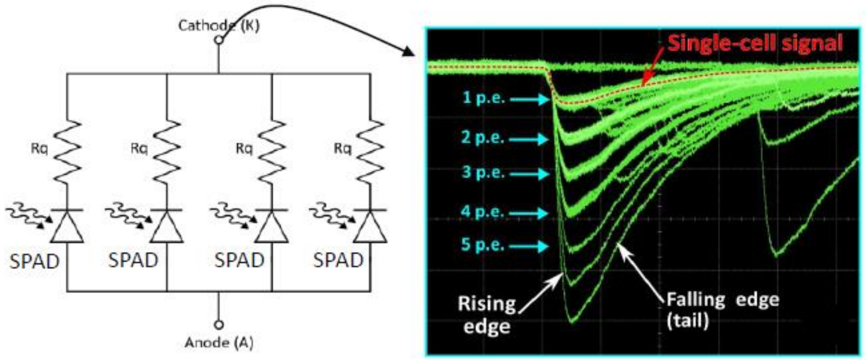
*Acerbi, Fabio, and Stefan Gundacker. "Understanding and simulating SiPMs." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 926 (2019): 16-35.

*omartivillarreal@fbk.eu

Silicon Photomultipliers (SiPMs)







Silicon Photomultiplier (SiPM) main features:

- Single-photon sensitive detectors with an excellent Single photon time resolution (few tens of ps)
- Can cover large-areas (1x1 mm^2 up to 10x10 mm^2)
- Low bias voltage (Lower power consumption)
- Compactness and Robustness
- Insensitive to magnetic fields

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

*omartivillarreal@fbk.eu

SiPM application in ToF-PET systems

Time-Of-Flight PET (ToF-PET) systems

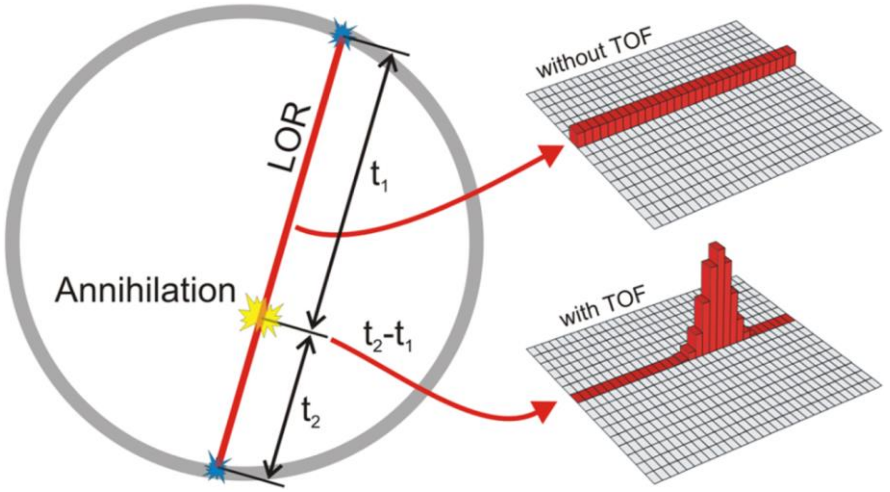
-Improved spatial resolution compared to standard PET systems

- Faster acquisition
- Lower dose to the patient
- Better diagnosis

SiPM detector main requirements:

-Fast timing (Coincidence time resolution (CTR)) (< 100 ps)

-High Photon Detection Efficiency (PDE) (> 60%) for a scintillator peak wavelength emission of 420 nm (For LYSO scintillators)



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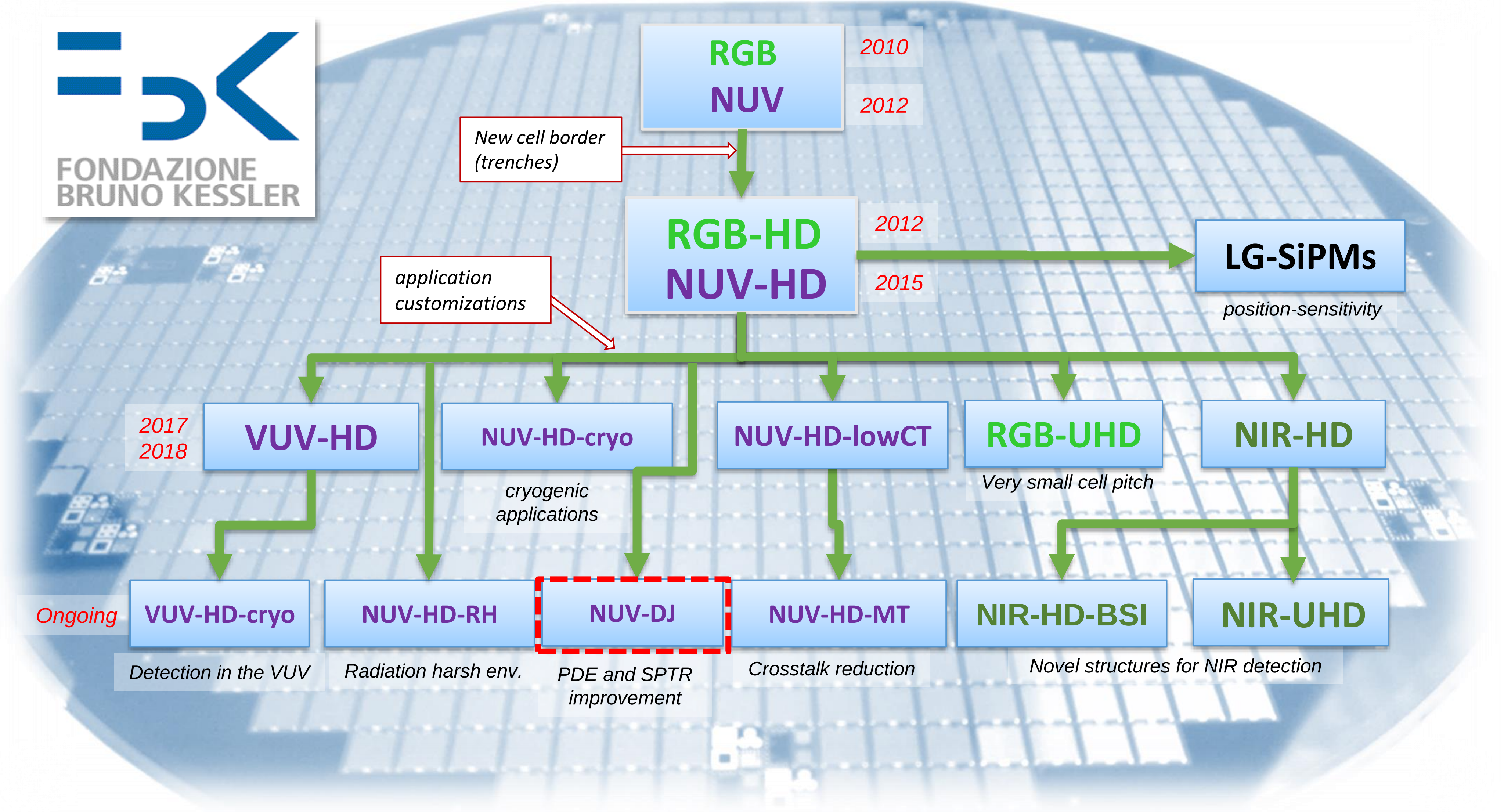
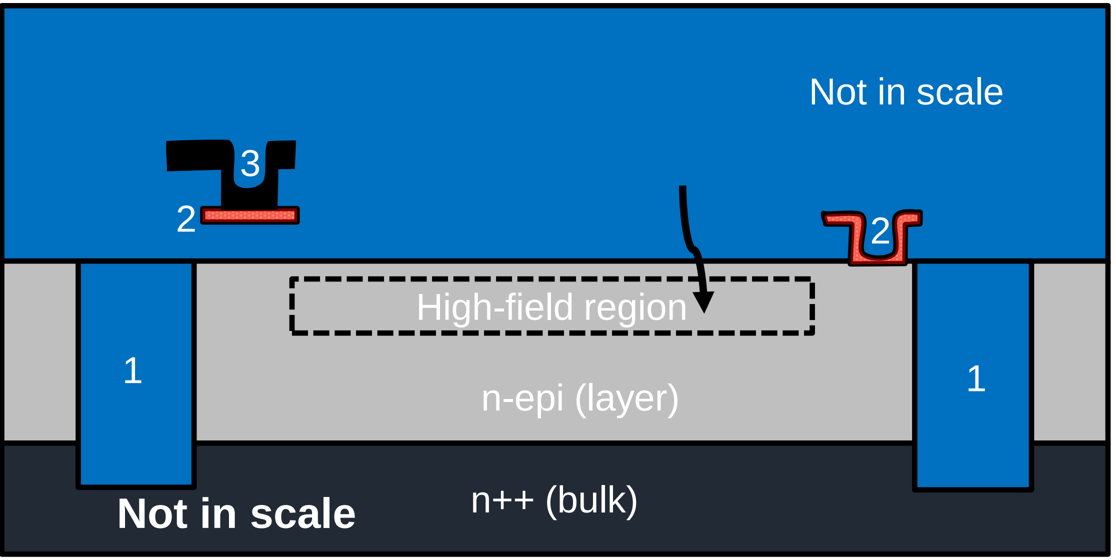
SiPMs technologies on FBK



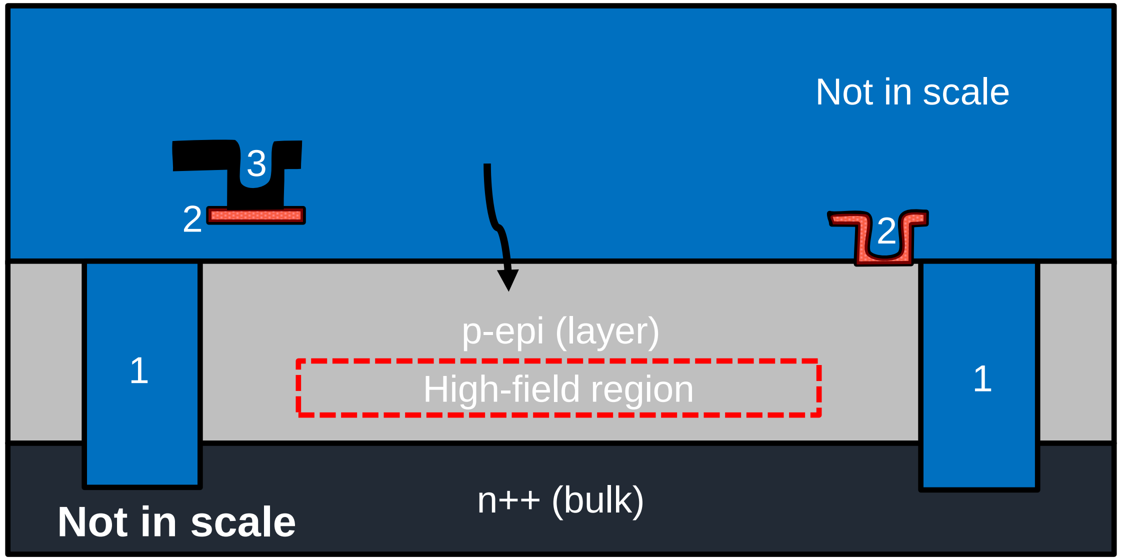
*omartivillarreal@fbk.eu

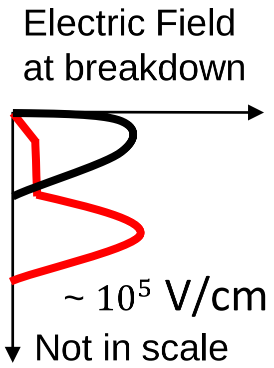
Near-Ultraviolet sensitive Deep-Junction (NUV-DJ) SiPMs*

Microcell (SPAD) of FBK NUV-HD technology



Microcell (SPAD) of FBK new NUV-DJ technology





1-) Deep trench isolation
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3-) Metal connection to the readout pad

NUV-HD (SPAD)

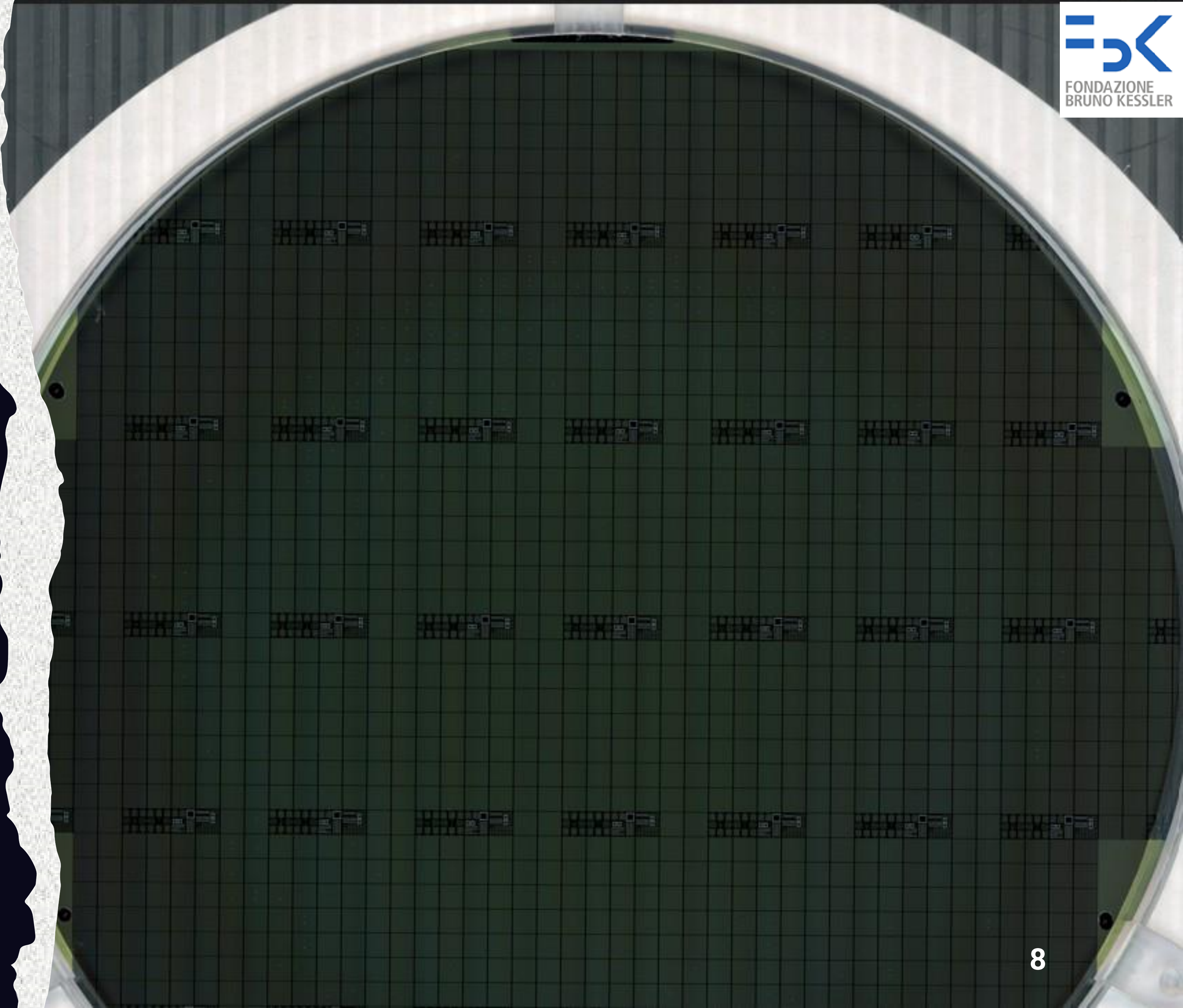
NUV-DJ (SPAD)

*The illustration of the Electric Field at breakdown for both technologies is only illustrative

*omartivillarreal@fbk.eu

General description of the first production (It was used an external silicon foundry)

- 8-inch wafers
- Total wafers: few tens
- Layout split: 26
- Process split: >10 (different implants energies, doses, and thermal budget)
- Three different epi thicknesses: few micrometers
- n++ bulk: low resistivity
- p-type epitaxial layer: high resistivity
- SPAD pitch: 40 μm
- SiPM dimension: 4x4 mm^2, 1x1 mm^2
- Some test structures were added with different geometries



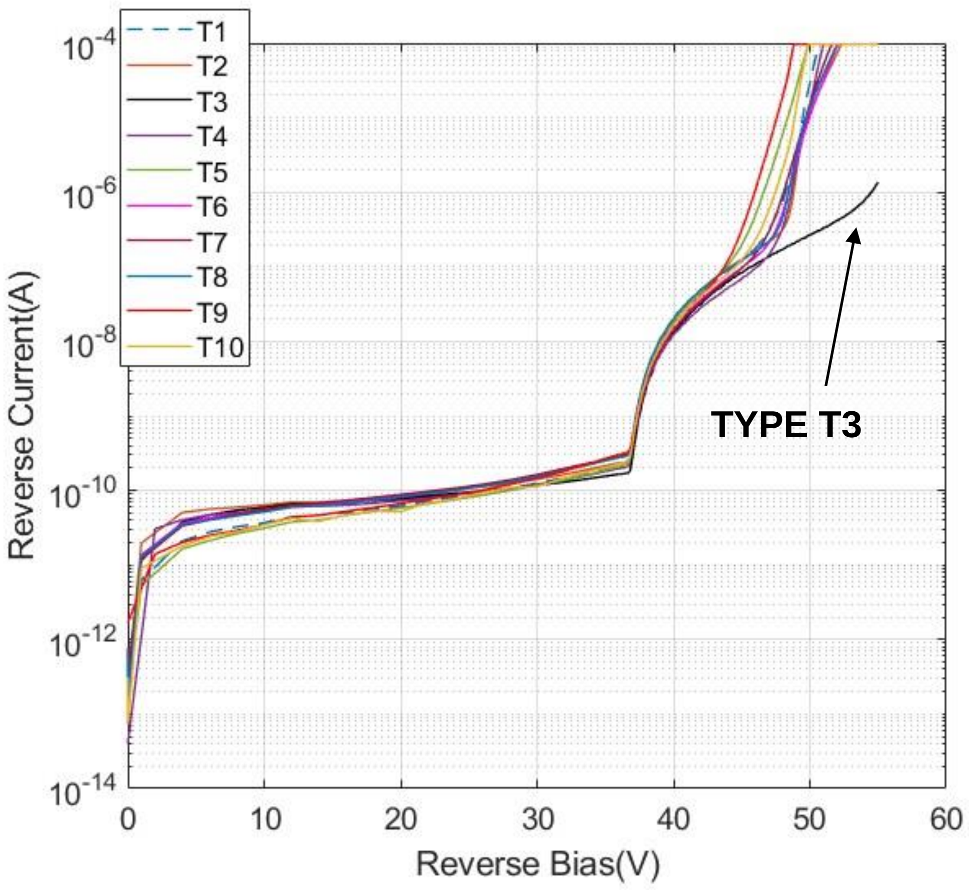
Experimental characterization of the first production of NUV-DJ technology

Main process split

Process split	Epi (p-type) thickness	High-Field region depth (D1 < D2, etc...)	Deep implant (DI) dose
1	Thin	D1	Low
2	Thin	D1	Medium
3	Thin	D1	High
4	Thin	D2	Low
5	Thin	D2	Medium
6	Thin	D2	High
7	Thick	D3	Medium
8	Thick	D4	Medium

Design*	Total	Nominal Fill Factor (%)
Aggressive	10	80.8
Moderate	8	76.9
Safe	8	72.9

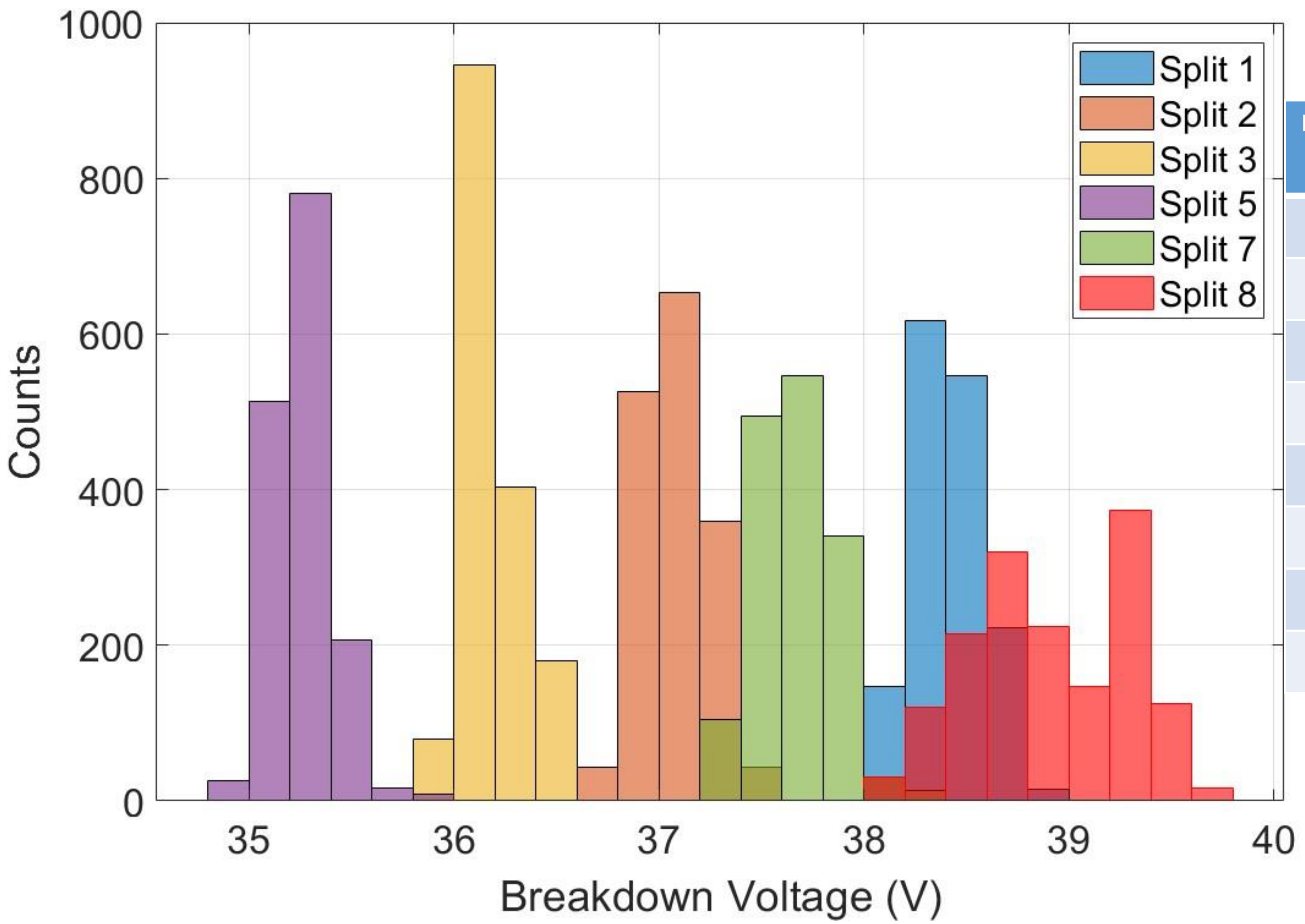
Example of I(V) for the Aggressive design (Split 2)



*Distance from the High-Field region to the Trench

*omartivillarreal@fbk.eu

Breakdown Voltage (24 °C)



Process split	Epi (p-type) thickness	High-Field region depth (D1 < D2, etc...)	Deep implant (DI) dose
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2	Thin	D1	Medium
3	Thin	D1	High
4	Thin	D2	Low
5	Thin	D2	Medium
6	Thin	D2	High
7	Thick	D3	Medium
8	Thick	D4	Medium

Yield> 90% (All splits)

Breakdown Voltage (V) study

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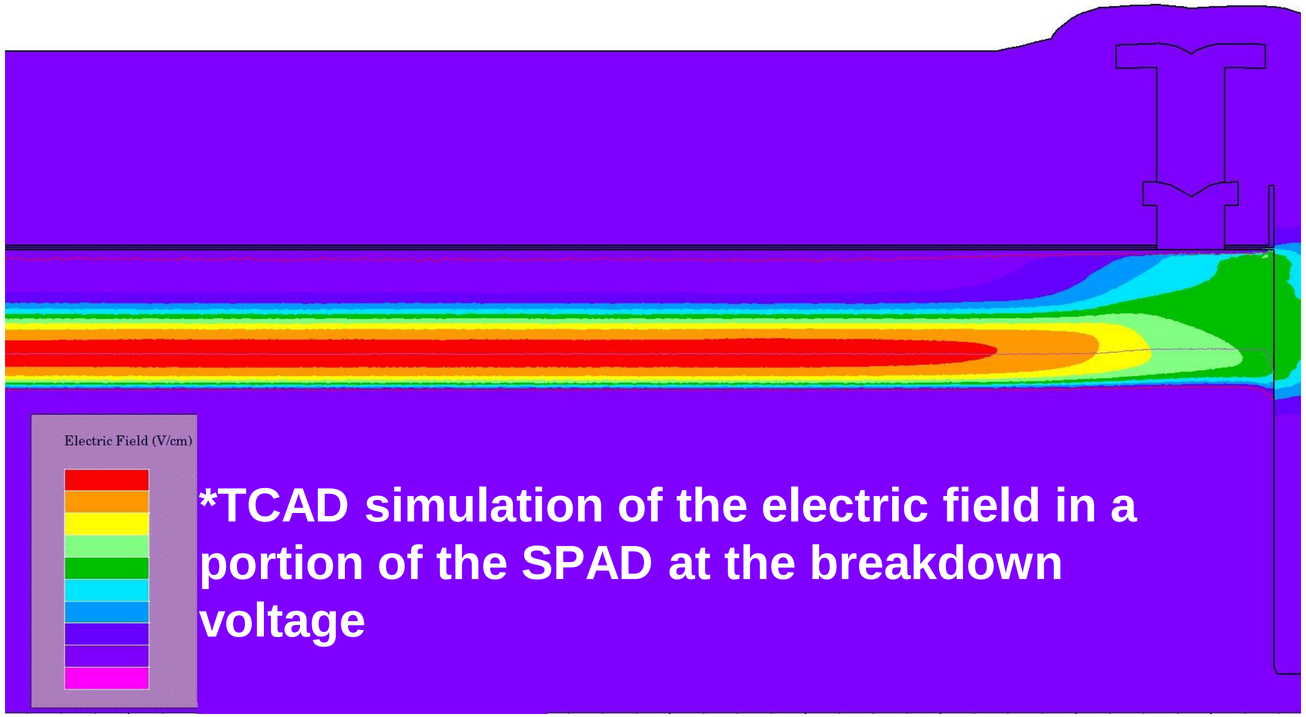
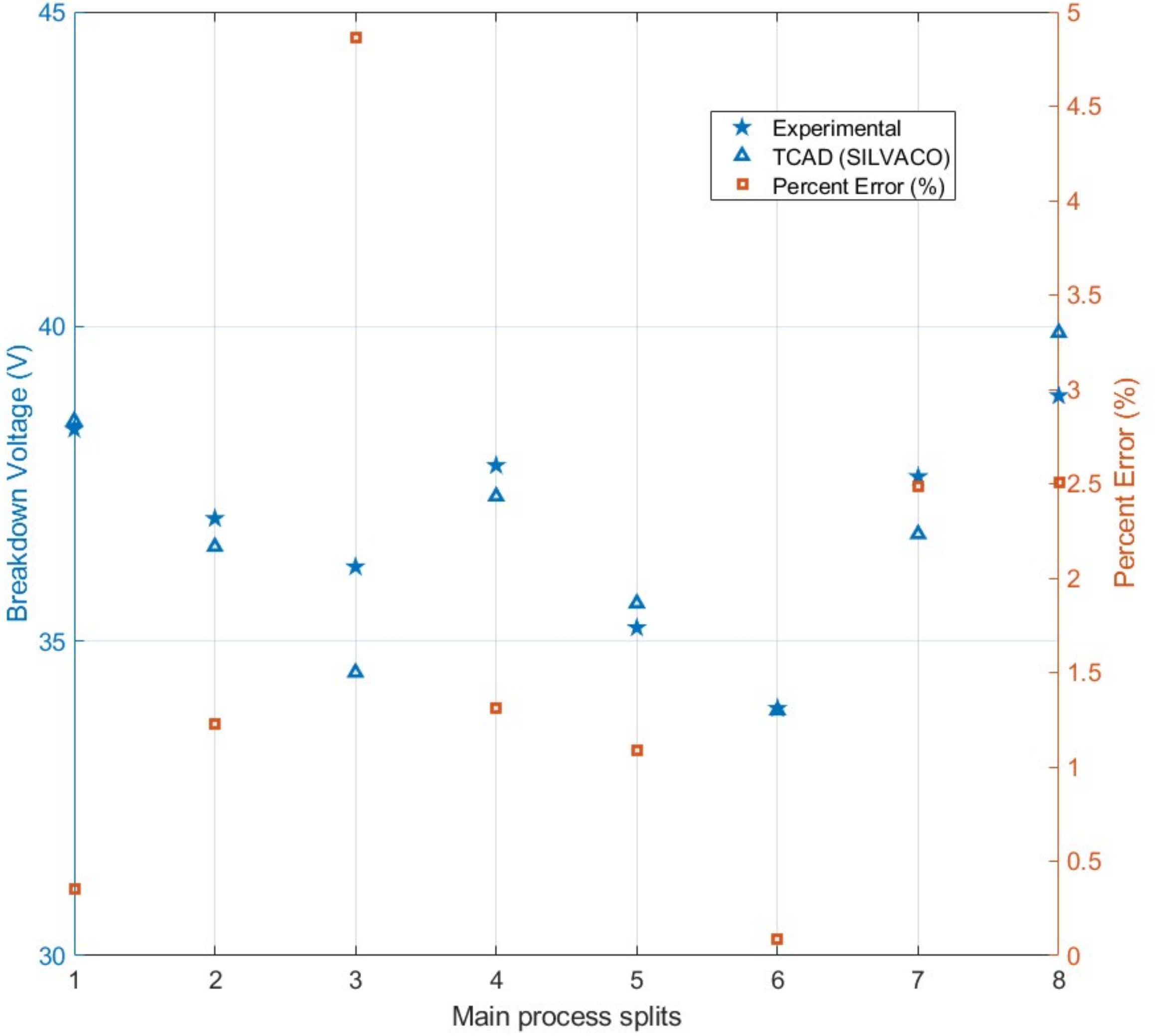


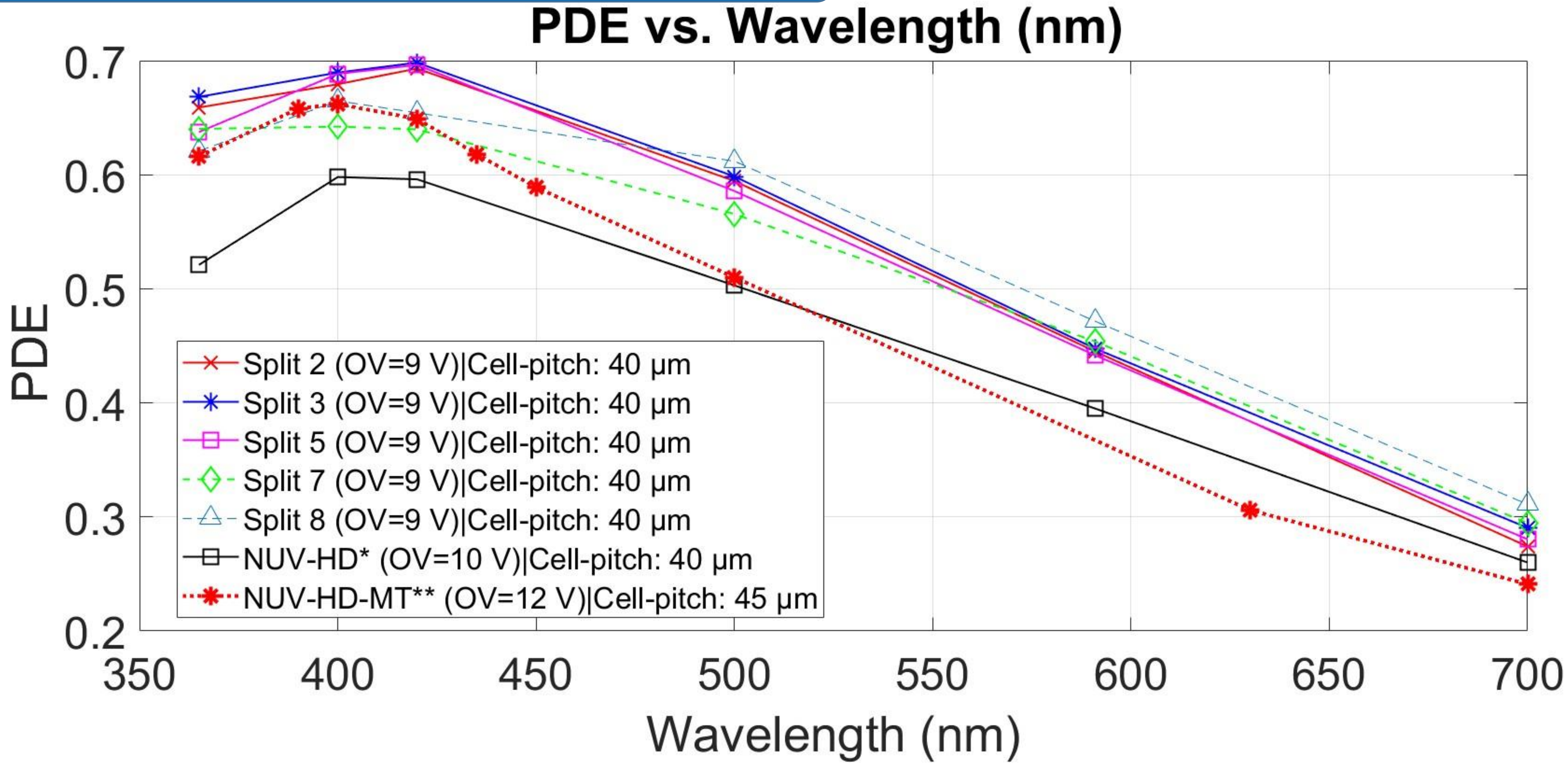
*TCAD simulation of the electric field in a portion of the SPAD at the breakdown voltage



Process split	Breakdown Coefficient (mV/℃)	Activation Energy (Ea) at 5 V of overvoltage
2	34.09	0.632
5	44.50	0.638
6	37.09	0.649

*omartivillarreal@fbk.eu

Photon detection efficiency (PDE) (Room temperature)



*Gola, Alberto, et al. "NUV-sensitive silicon photomultiplier technologies developed at Fondazione Bruno Kessler." *Sensors* 19.2 (2019): 308.
**Merzi, Stefano, et al. "Nuv-hd sipms with metal-filled trenches." Journal of Instrumentation 18.05 (2023): P05040.

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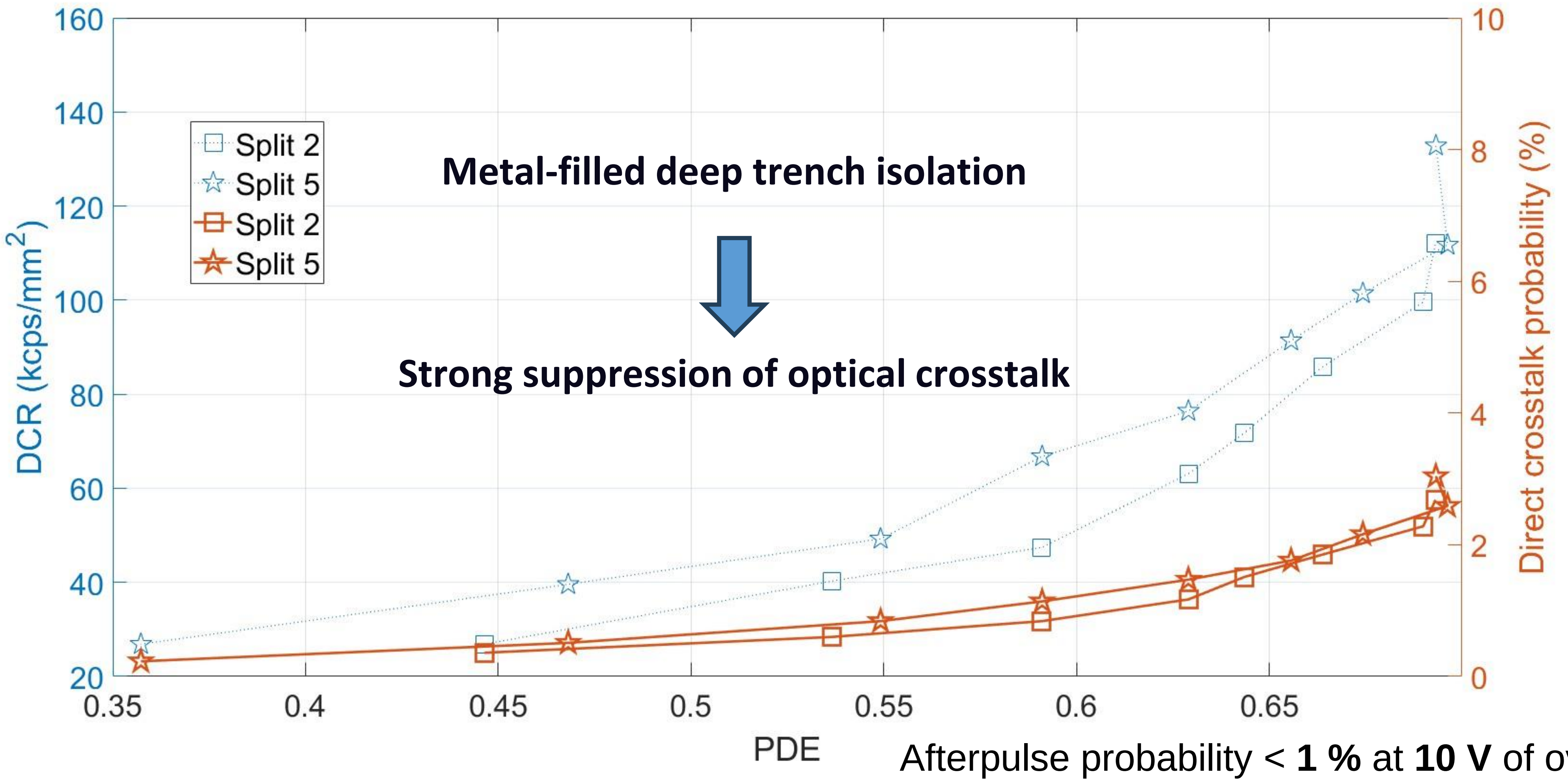
Noise parameter as function of the PDE



Afterpulse probability < **1 %** at **10 V** of overvoltage

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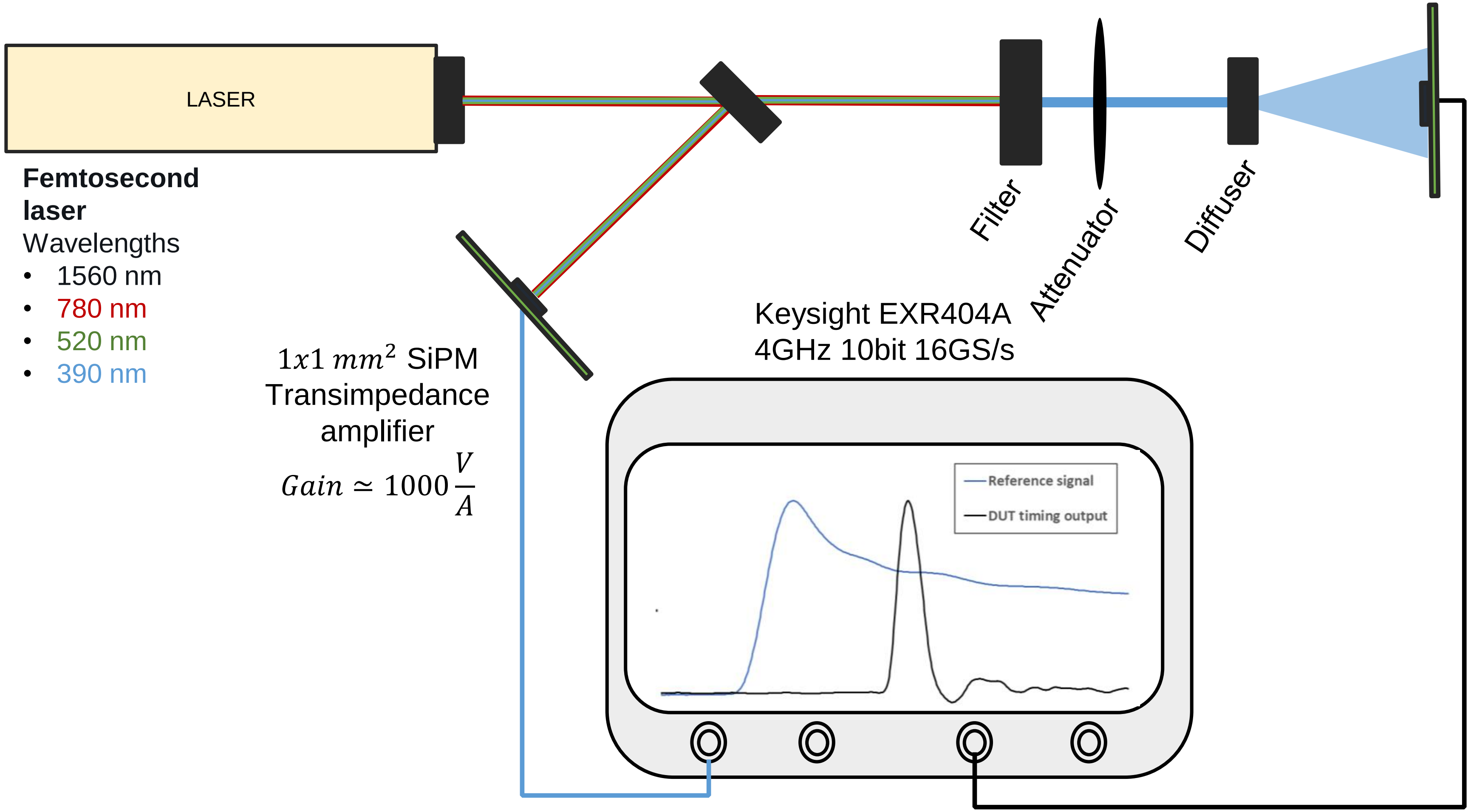
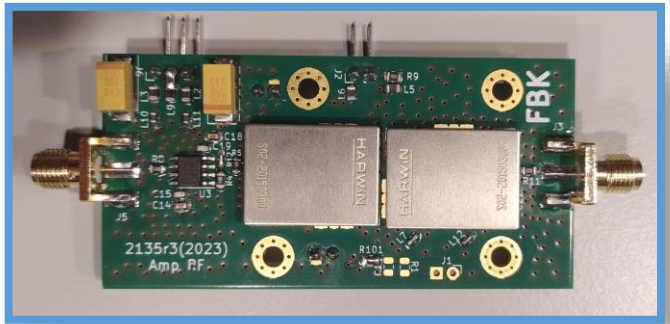
Single Photon Time Resolution (SPTR)

Experimental setup



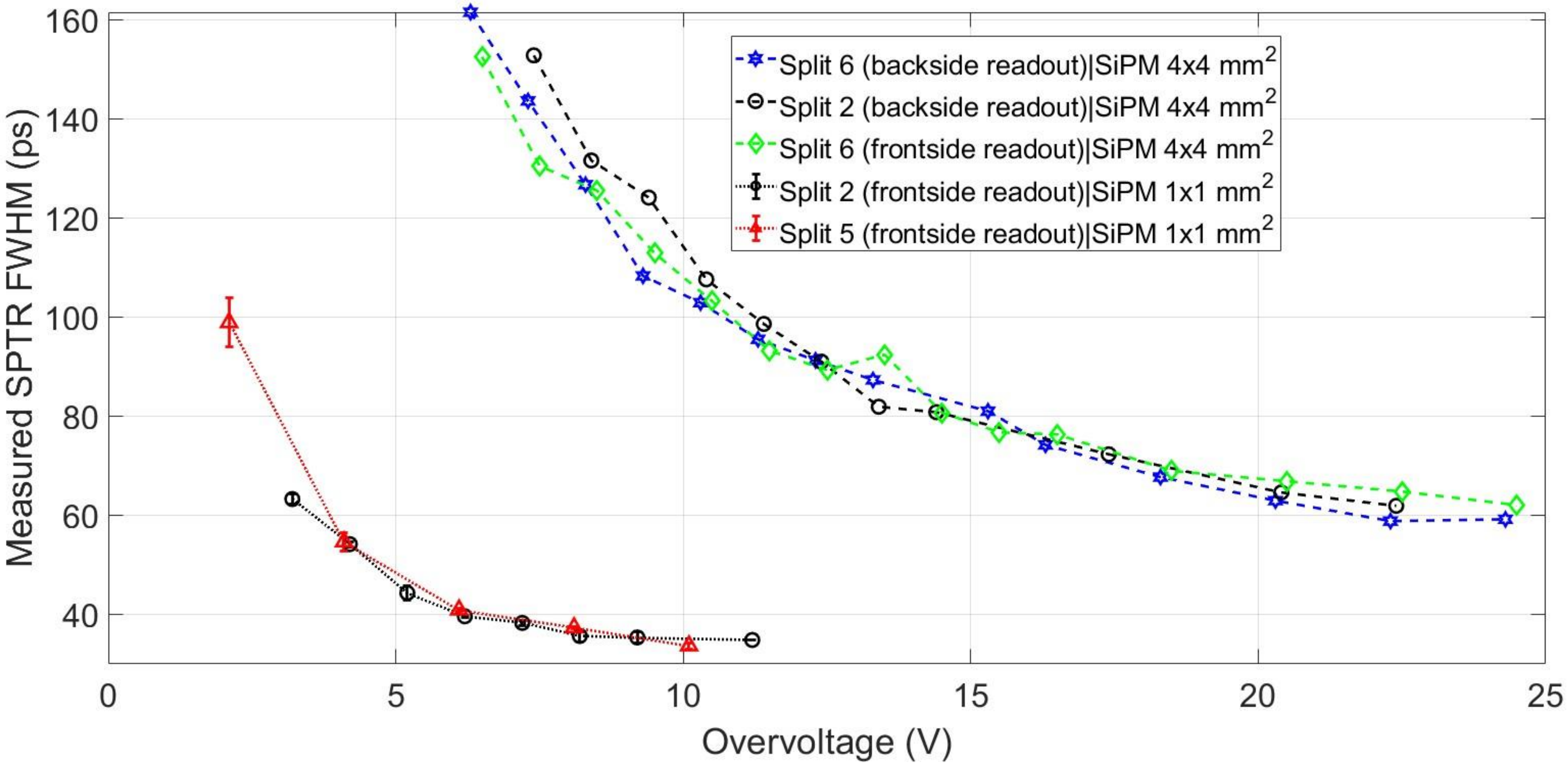
HF readout developed at FBK
Implemented with BGA61



SPTR measurements have been performed with blue light (390nm)

*omartivillarreal@fbk.eu

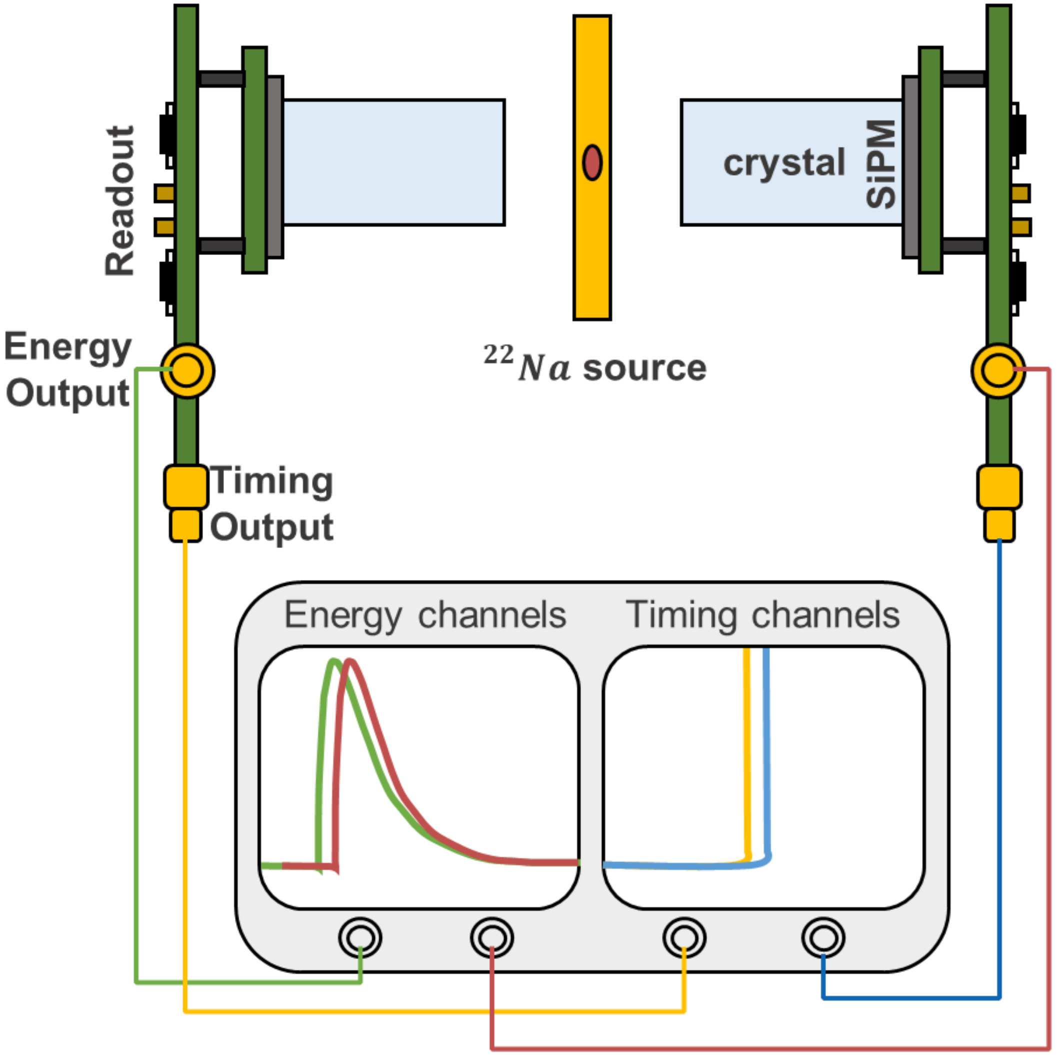
Single Photon Time Resolution (SPTR)



*omartivillarreal@fbk.eu

Coincidence time resolution (CTR)

Experimental setup



- Two SiPMs coupled with 2.76 x 2.76 x 18 mm^3 LYSO:Ce crystal
- The crystals were wrapped in Teflon and glued on the SiPMs with optical glue Meltmount (n = 1.58)
- Motorized steppers for alignment in two axis
- A High Frequency readout was used [1,2]
- A standard readout electronics with pole-zero implementation was also used [3]

[1] J. W. Cates *et al,* ''Improved single photon time resolution for analog SiPMs with front end readout that reduces the influence of electronic noise'', 2018, Phys. Med. Biol. **63** 185022

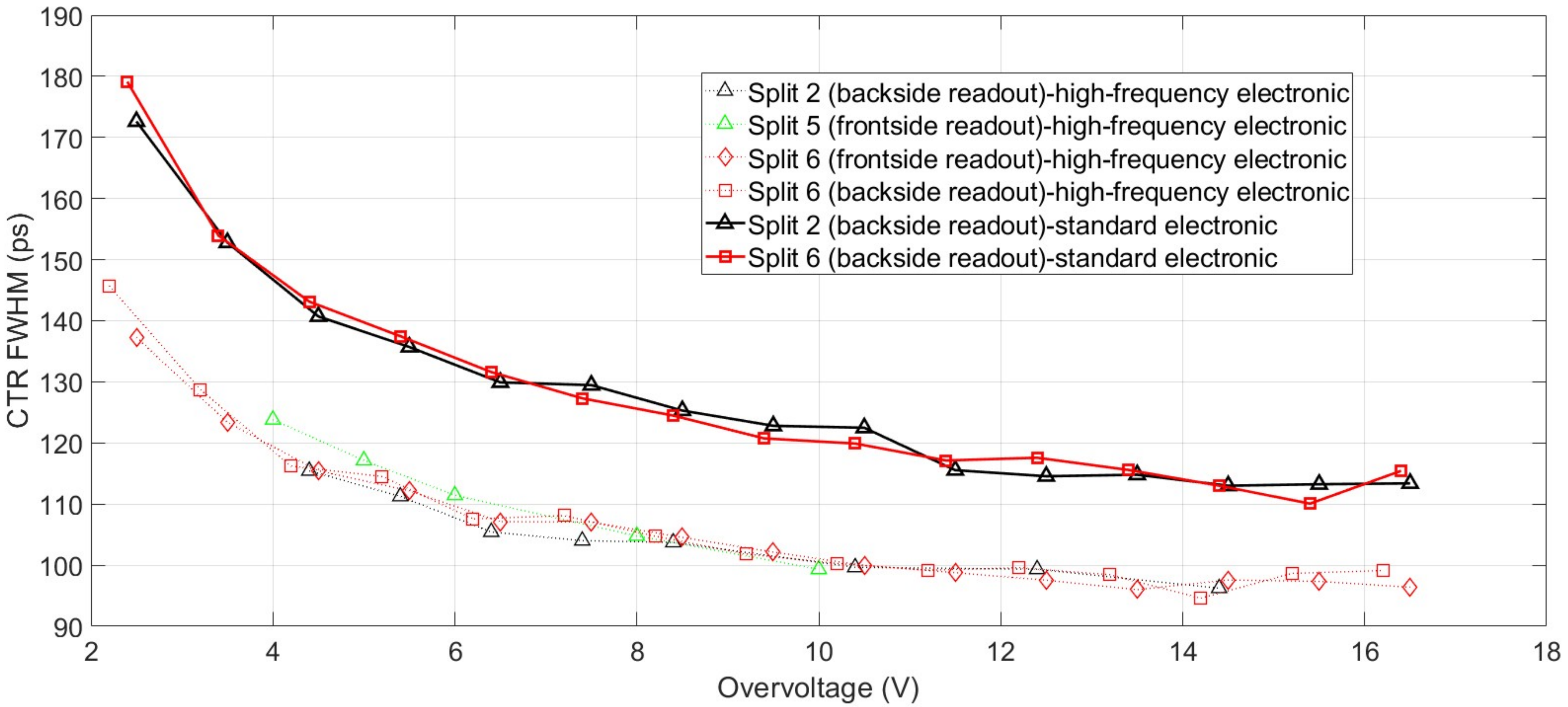
[2] S Gundacker *et al*, 'High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET '' 2019, Phys. Med. Biol. 64 055012

[3] Gola, Alberto et al. "Analog Circuit for Timing Measurements With Large Area SiPMs Coupled to LYSO Crystals". IEEE Transactions on Nuclear Science 60 (2011): 1296-1302

*omartivillarreal@fbk.eu

Coincidence time resolution (CTR) using a SiPM of 4x4 mm^2 of active area

2.76x2.76x18 mm^3 LYSO:Ce crystal



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Remarks and Conclusions

- A new Near-Ultraviolet sensitive Deep Junction (NUV-DJ) SiPMs technology is under development on FBK
- Several 8-inch wafers were manufactured in an external silicon foundry and the main layout and process split were tested in the laboratory
- The measured breakdown voltage in all the wafers was aligned with the expected values from the TCAD simulations with a percent error less than 5%
- For the process split 2, the DCR at 20 °C was less than 80 kcps/mm^2 for 65% PDE at 420nm which correspond of about 6 V of overvoltage (OV)
- The direct crosstalk probability for split 2 and 5 was less than 2% for 65% PDE, confirming the effectiveness of the new SPAD structure and the good optical isolation between microcells

*omartivillarreal@fbk.eu

Remarks and Conclusions

- The PDE showed unprecedented values of about 70% (including a nominal fill factor of 80.8%), at 420 nm of wavelength and 9 V of excess bias for Thin epi thicknesses
- Moreover, we measured a SPTR of 60 ps FWHM at 20 V of excess bias, for a 4x4 mm^2 SiPM and a CTR of less than 100 ps FWHM with a High Frequency readout using a 2.76x2.76x18 mm^3 LYSO:Ce crystal at 10 V of excess bias
- The measured CTR using standard readout electronics showed excellent values (about 115 ps FWHM at OV greater than 10 V)
- These results are state-of-art as regards timing and PDE, thus very interesting for ToF-PET applications or in an experiment where a high PDE in the NUV region is a requirement

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