SiPM development at FBK for highly irradiated environments

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Presentation Outline

- SiPMs in highly irradiated environments
- R&D on rad hard SiPMs for CMS-BTL
- Irradiation test with protons + functional testing
- Irradiation test with neutrons @ 1e13 n_{eq}/cm^2
- Packaging for rad hard SiPMs
- Future R&D on rad hard SiPMs

Near-UV technology: NUV-HD

Original technology 2005

Electric field engineering

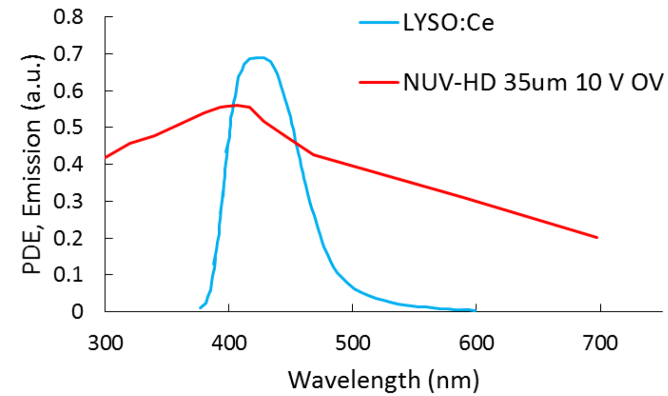
RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015



NUV-HD as baseline technology for LYSO readout

NUV-HD-Cryo | VUV-HD | RGB-UHD | NIR

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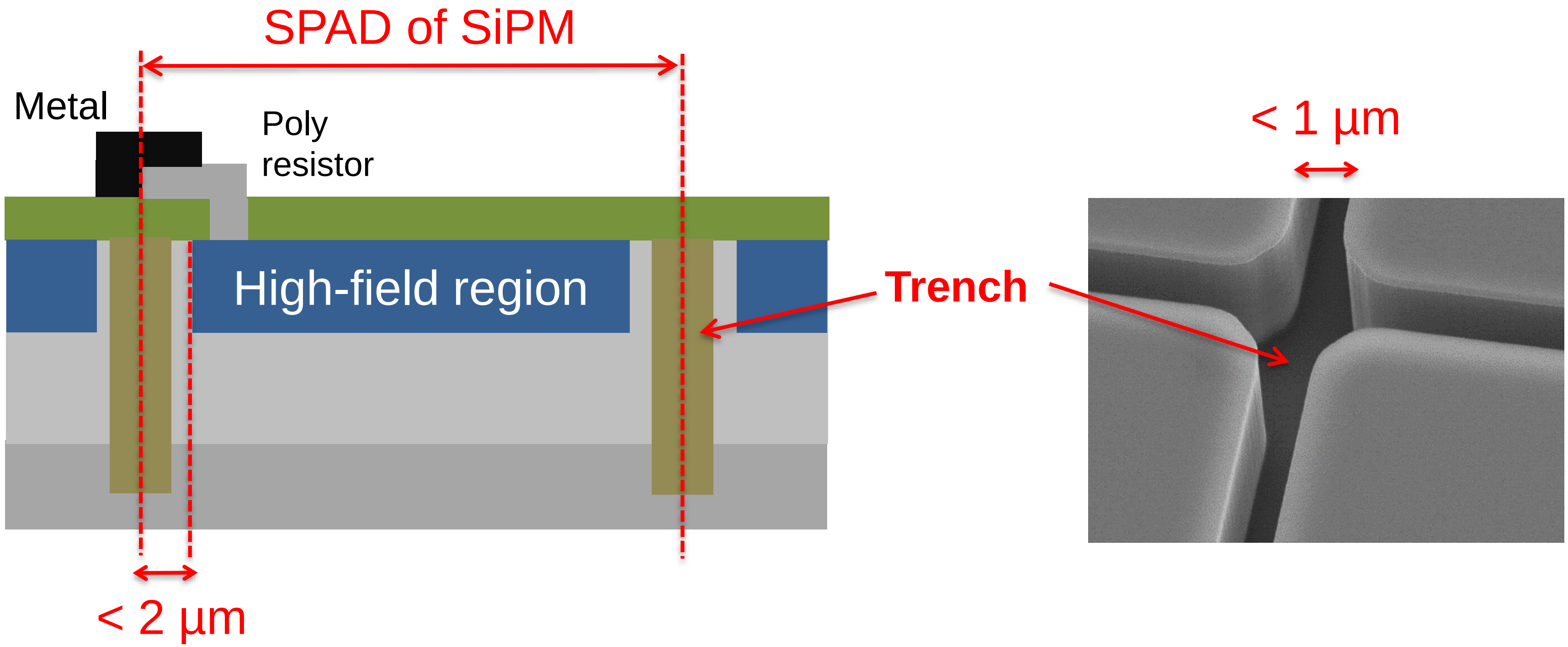
NUV-HD: technology



- p-on-n junction → higher Pt for UV light
- Narrow dead border region → Higher Fill Factor
- Trenches between cells → Lower Cross-Talk
- Make it simple: 9 lithographic steps

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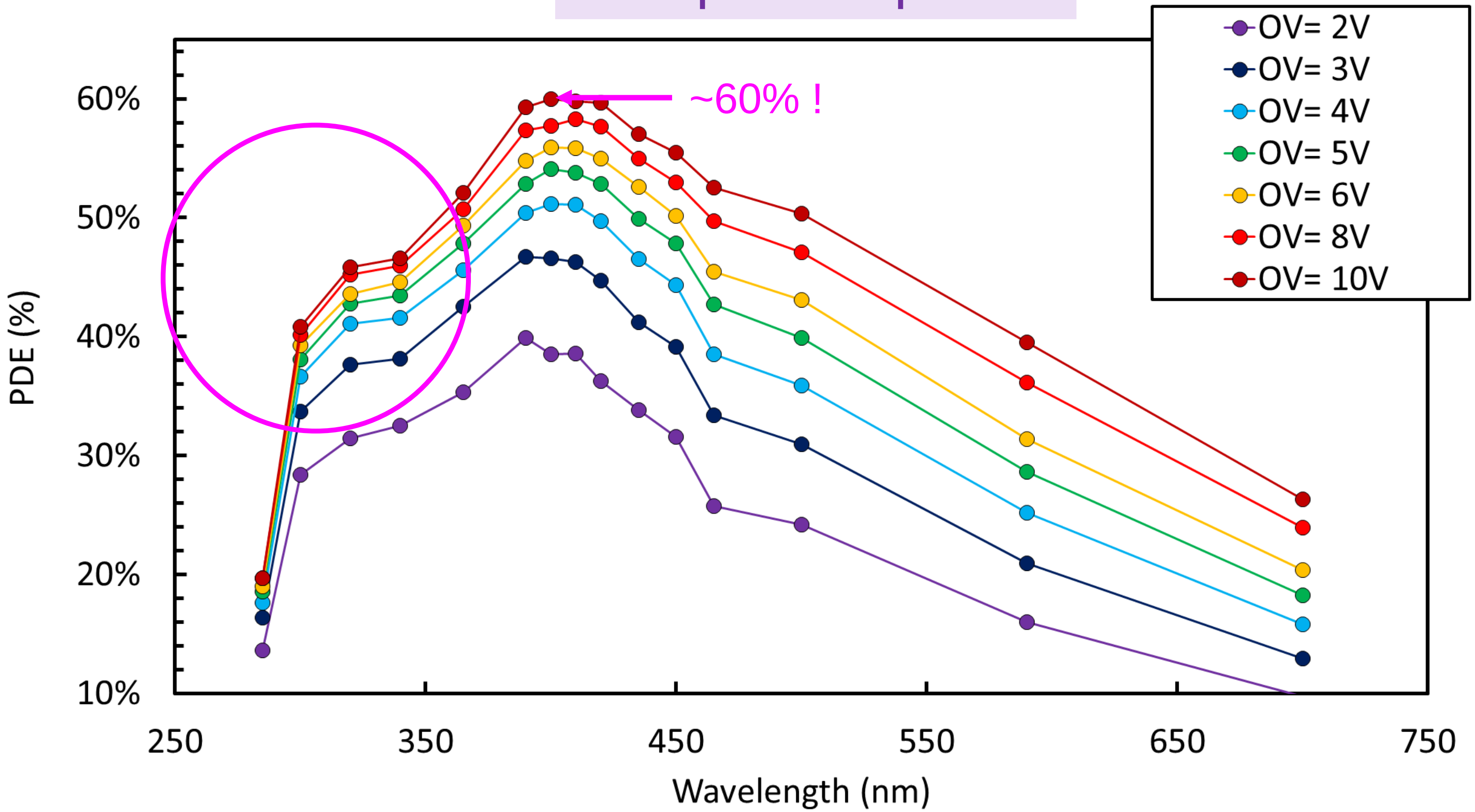
Photon detection efficiency

35 µm cell pitch



Gola, A et al. (2019). “NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler.” *Sensors*, *19*(2), 308.

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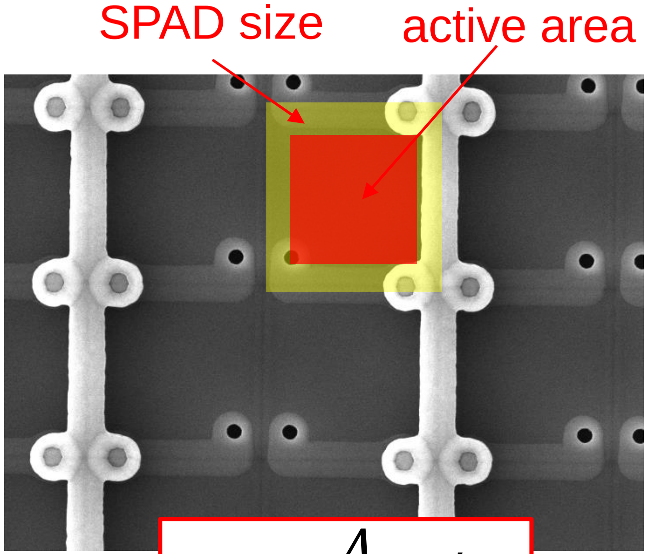
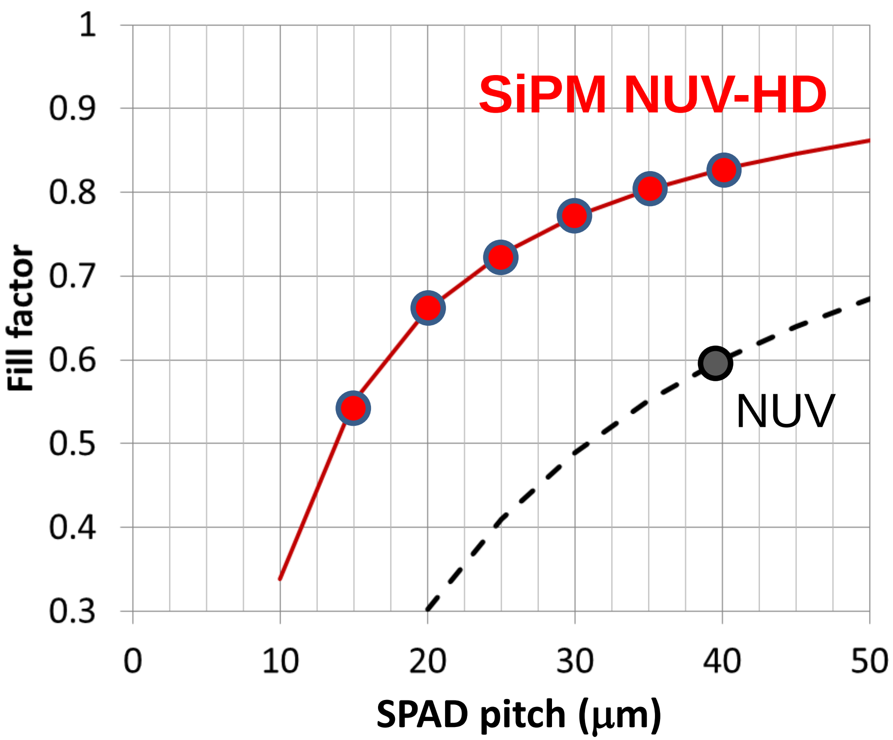
NUV-HD: Fill Factor



$$FF = \frac{A_{active}}{A_{total}}$$



SPAD Pitch	15 μm	20 μm	25 μm	30 μm	35 μm	40 μm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Fast recovery time (15–25 μm)

High PDE (35–40 μm)

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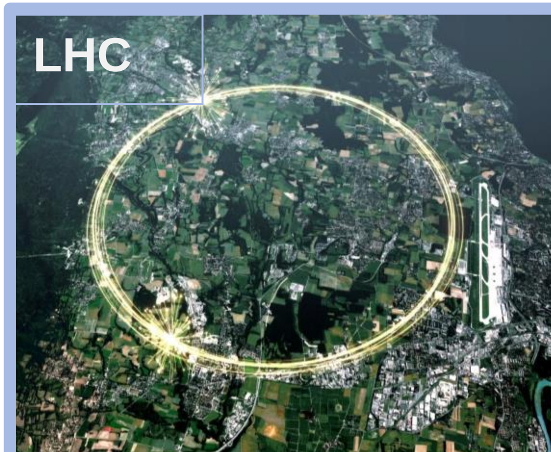
SiPMs in highly irradiated environments

Improving radiation hardness of SiPMs is *one of the next frontiers of development at FBK* for very important applications, both in big science experiments and in space.

Detectors for HEP experiments:
from 10^{10} neq/cm² to $>10^{14}$ neq/cm²



FAIR
Facility for Antiproton
and Ion Research
in Europe GmbH

Geostationary orbit space experiments: $\sim 5 \cdot 10^{10}$ neq/cm²

1. Qualification of radiation tolerance of current SiPM technologies.
2. Study / modeling of the effects of radiation damage on SiPM characteristics, under different sources of radiation.
3. <u>Development of a highly customized SiPM technology</u> for optimal performance after irradiation is most likely needed

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Rad Hard SiPMs: small-cell SiPMs

ISSUE		MITIGATION
• Increase in the primary noise (DCR).		
• Increased afterpulsing (increased number of traps).	SMALLER CELLS →	Lower gain: reduction of afterpulsing (for a given number of traps).
• PDE loss due to cells busy triggering dark counts.	SMALLER CELLS →	More cells and faster recharge: less PDE loss.
• Increased power consumption due to higher DCR.	SMALLER CELLS →	Lower gain: less current (for a given DCR).

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Rad Hard SiPMs: E field engineering

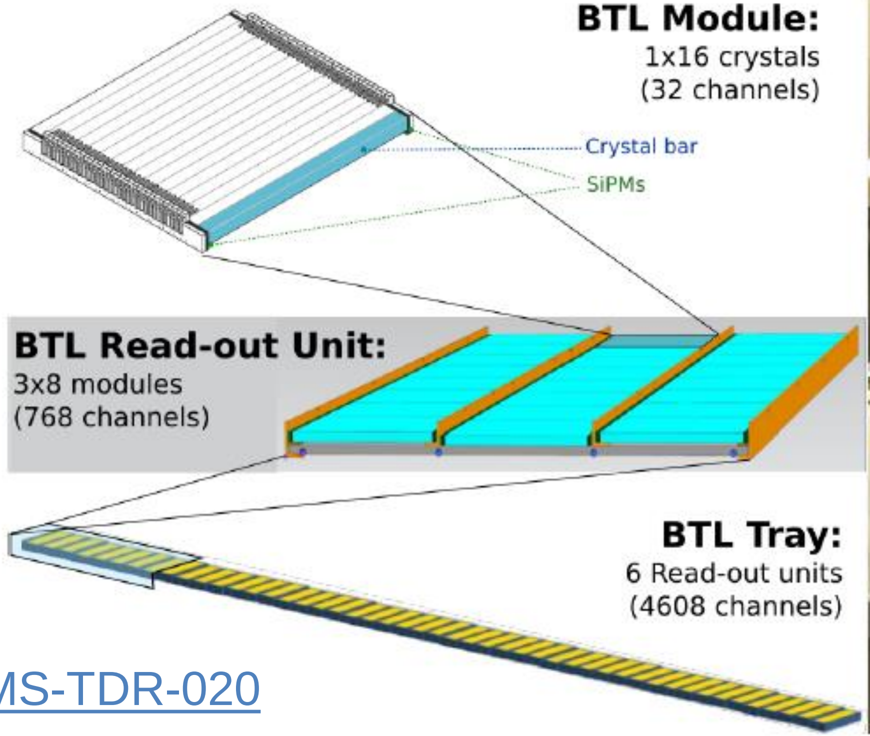
ISSUE		MITIGATION
Lower activation energy of DCR after irradiation.	E field engineering →	Possible reduction of DCR at low temperature. Effective DCR suppression with moderate cooling
Low triggering probability at small excess bias.	E field engineering →	Process with faster increase of PDE vs. bias (less tunneling)
Need to increase PDE at a fixed microcell gain	E field engineering →	Higher PDE at small Gain

Barrel Timing Layer of CMS

MIP timing detector of CMS: development for the Phase2 Upgrade

- Endcaps Timing Layer: LGADs
- Barrel Timing Layer: scintillators with SiPM readout

Radius: ~1.15 m, length: ~5.00 m, max thickness ~40 mm
Operating temperature: ~ –30°C
Radiation tolerance for BTL: 30 kGy, ~2×10^{14} 1 MeV n_{eq}/cm^2



CMS-TDR-020

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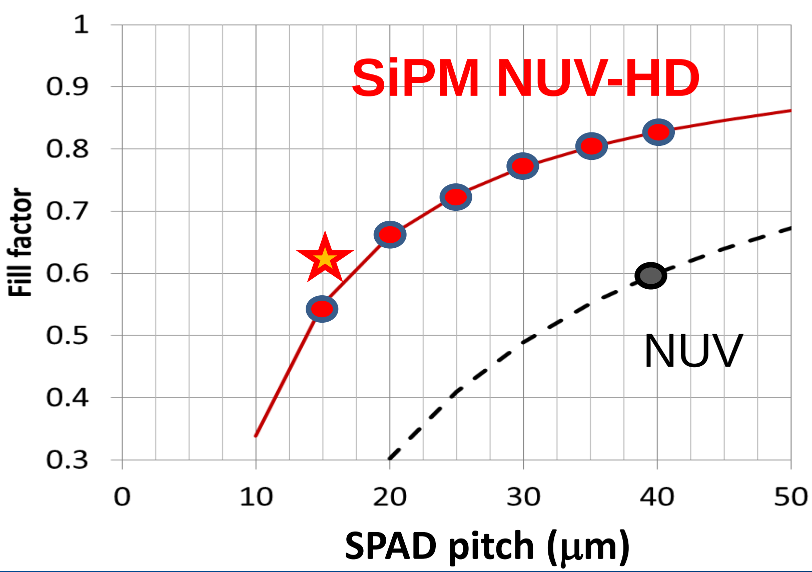
SiPM R&D at FBK for CMS-BTL

Small cells + electric field engineering **with high PDE**

Process and layout combined optimizations

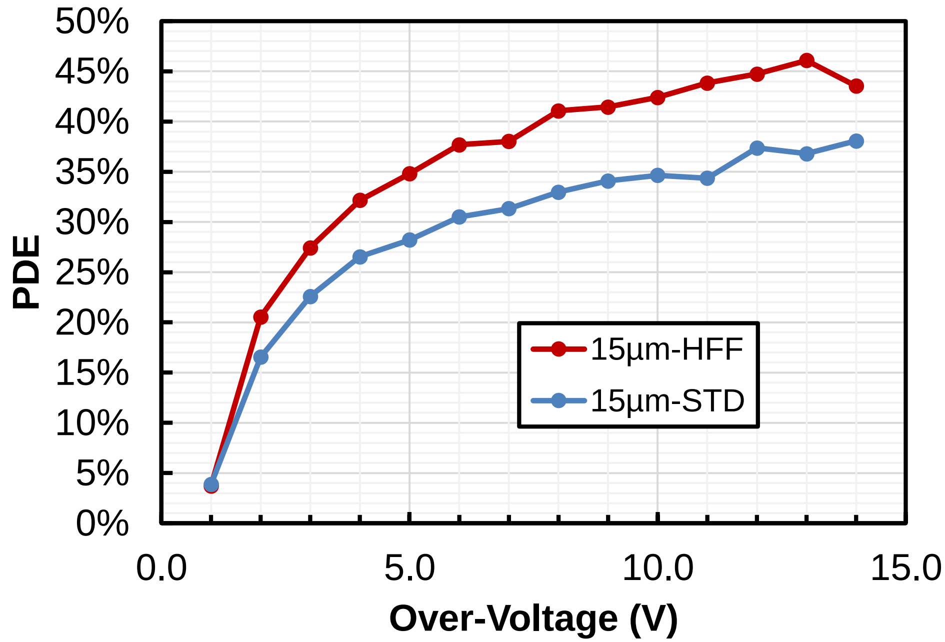
Layout versions
STD: standard NUV-HD design rules
HFF: increased microcell fill factor

Cell layout	Fill factor
15 µm STD	52%
15 µm HFF	61%



Process splits
4 process splits for electric field optimization
Capacitance and $P_{trigger}$ vs. OV

Impact of HFF layout: microcell fill factor and PDE



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SiPM R&D at FBK for CMS-BTL

16x1 SiPM array for scintillation crystal (LYSO) readout at both ends
SiPM active area: 3.0x2.4 / 3.0x3.0 / 3.0x3.75 mm^2

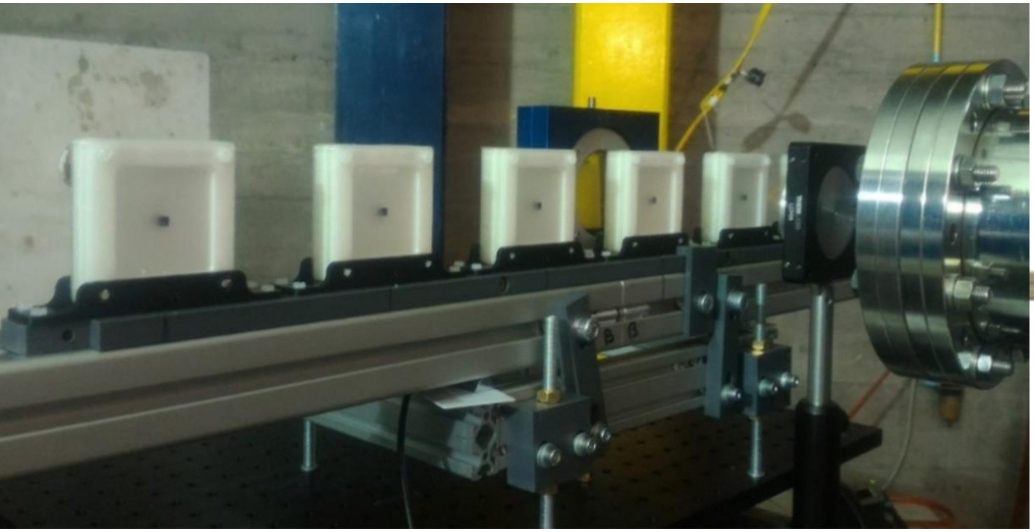
SiPM Specifications		FBK SiPM
Cell pitch	< 20 µm	15 µm
Recovery time	< 10 ns	< 8 ns
Capacitance	< 600 pF/ch	530 pF/ch
Cell density	> 20k/ch	42k/ch
ENF	< 1.1	< 1.05

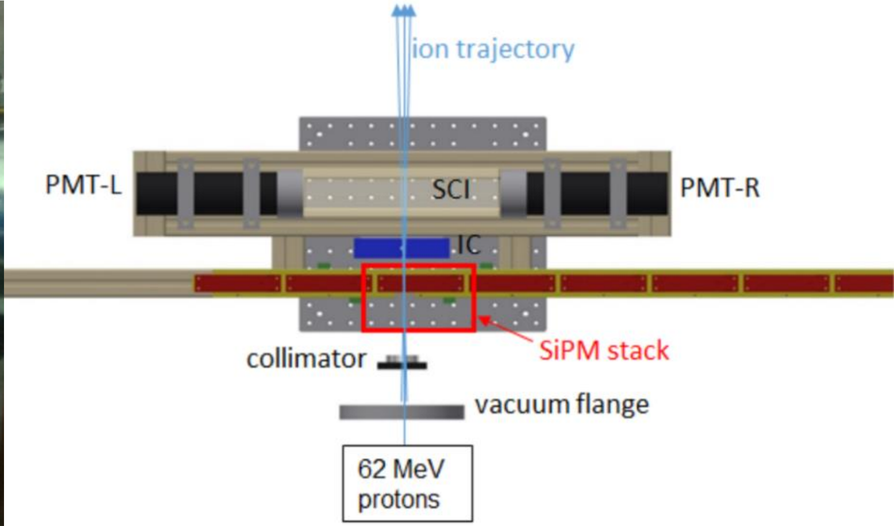
After 3000 fb^{-1}		FBK SiPM
Optimal OV	> 1 V	1.6 V
$dV_{BD}/10^{13}\ n_{eq}$	≤ 0.2 V	< 0.1 V
Cell gain	≥ 1.3×10^5	2×10^5
SNR	≥ 2.0	2.3
Power/ch	≤ 50 mW	50 mW

FBK has developed a candidate technology for the BTL of CMS
SiPM arrays under qualification @ CERN
to study technology and package reliability

p^+ irradiation of FBK SiPMs, variable fluence

SiPM irradiation with protons, 62 MeV @ INFN-LNS
Test SiPMs with 1x1 mm^2 active area, microcell optimized for BTL
Rev bias IV curves after irradiation @ +20°C, ~1 month RT annealing

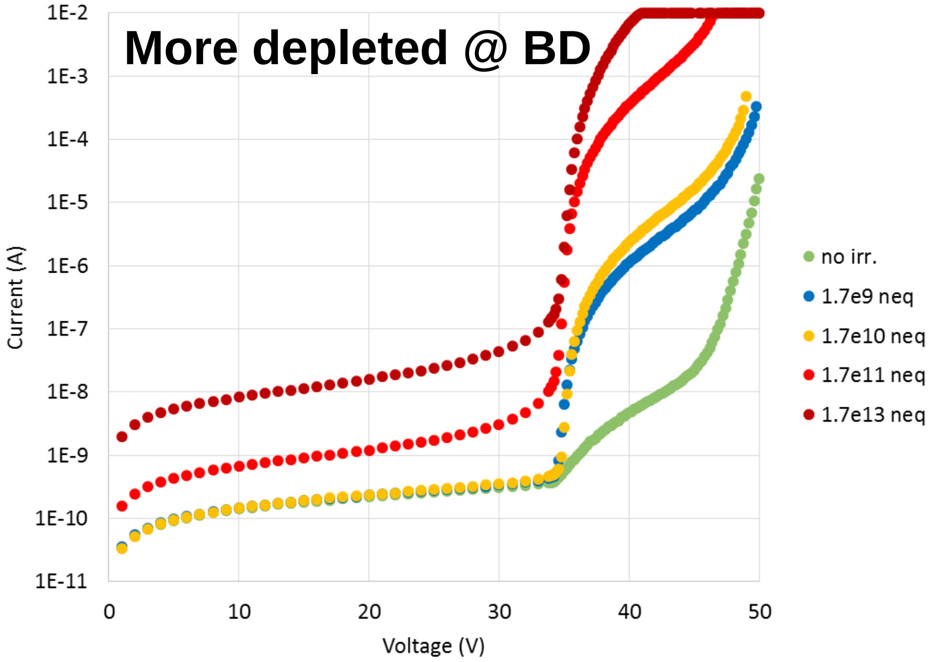


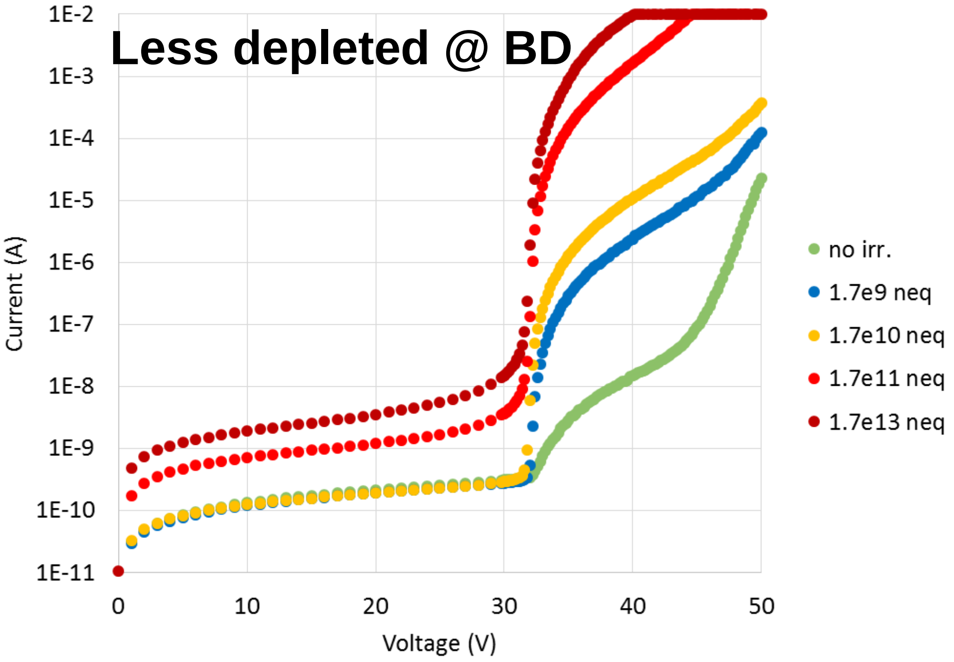


Results from collaboration with GSI
A. R. Altamura et al. arXiv:2106.12344

p^{+} irradiation of FBK SiPMs, variable fluence

Impact of process split: op. range and performance after irradiation



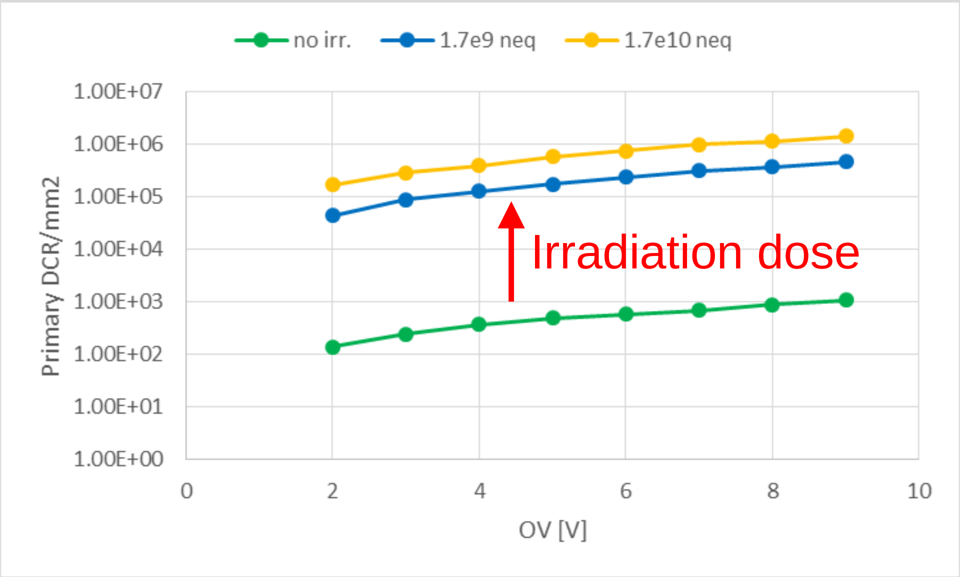


Wider operating range after irradiation

Results from collaboration with GSI

A. R. Altamura et al. arXiv:2106.12344

p+ irradiation of FBK SiPMs, variable fluence



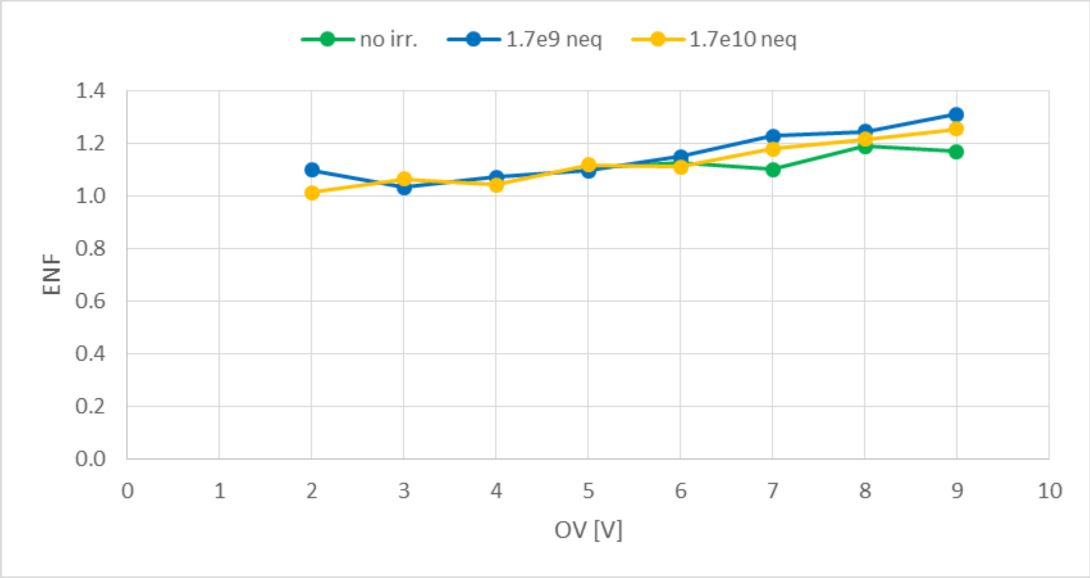
Functional characterization of SiPMs after irradiation: waveform analysis

- DCR: Orders of magnitude increase
- Correlated noise nearly independent on irradiation dose

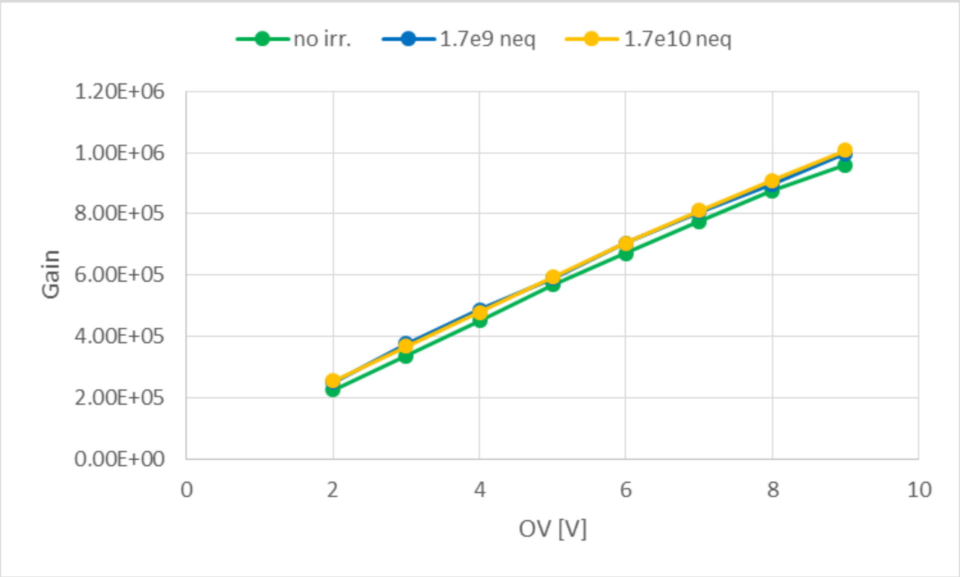
Results obtained on HFF devices
Selected process split

Measurements at +20°C

At higher fluences,
waveform analysis not possible



p^{+} irradiation of FBK SiPMs, variable fluence



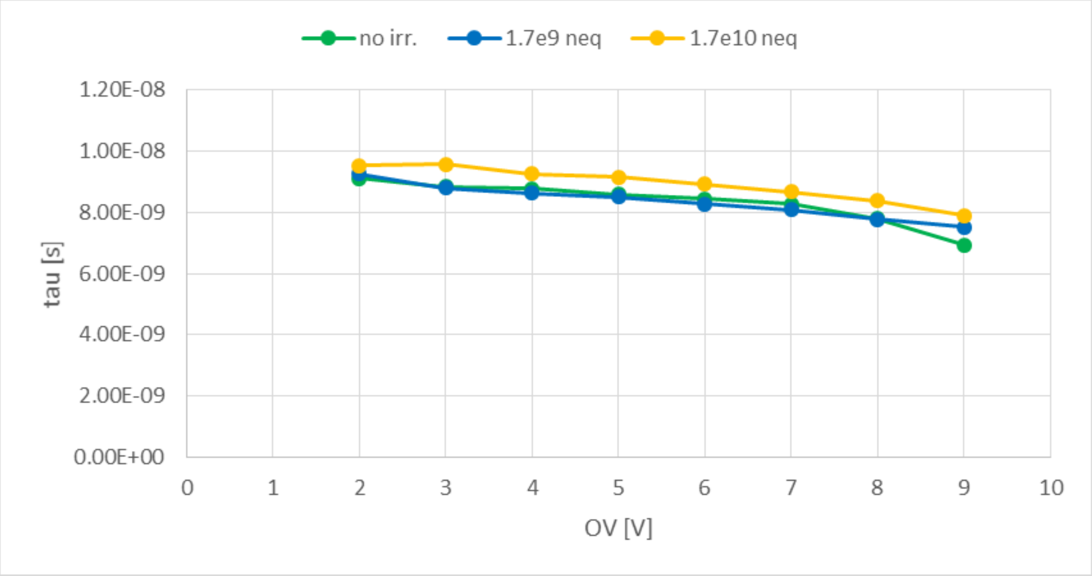
Microcell **gain** and signal amplitude independent on irradiation dose

Microcell **recovery time** independent on irradiation dose
< 10 ns recharge
to minimize cell occupancy

Results obtained on HFF devices
Selected process split

Measurements at +20°C

At higher fluences,
waveform analysis not possible



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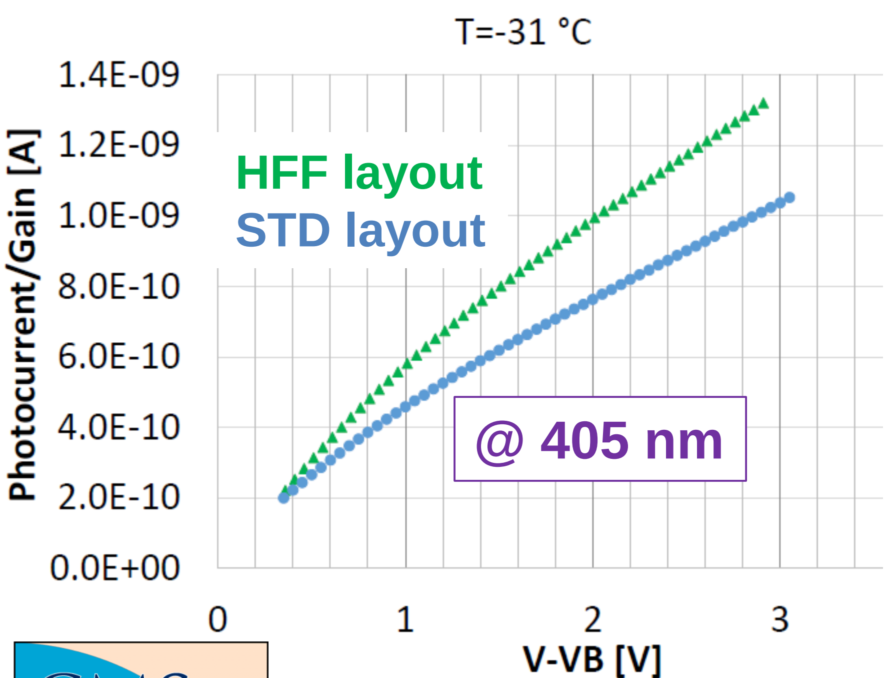
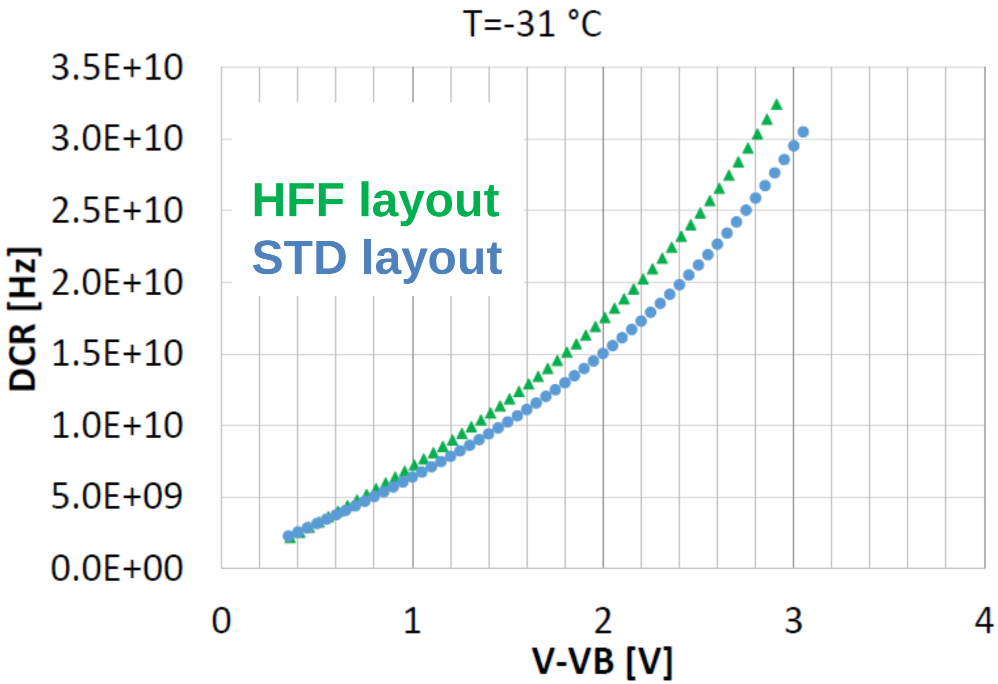
Neutron irradiation of FBK SiPMs 1e13 neq/cm^2

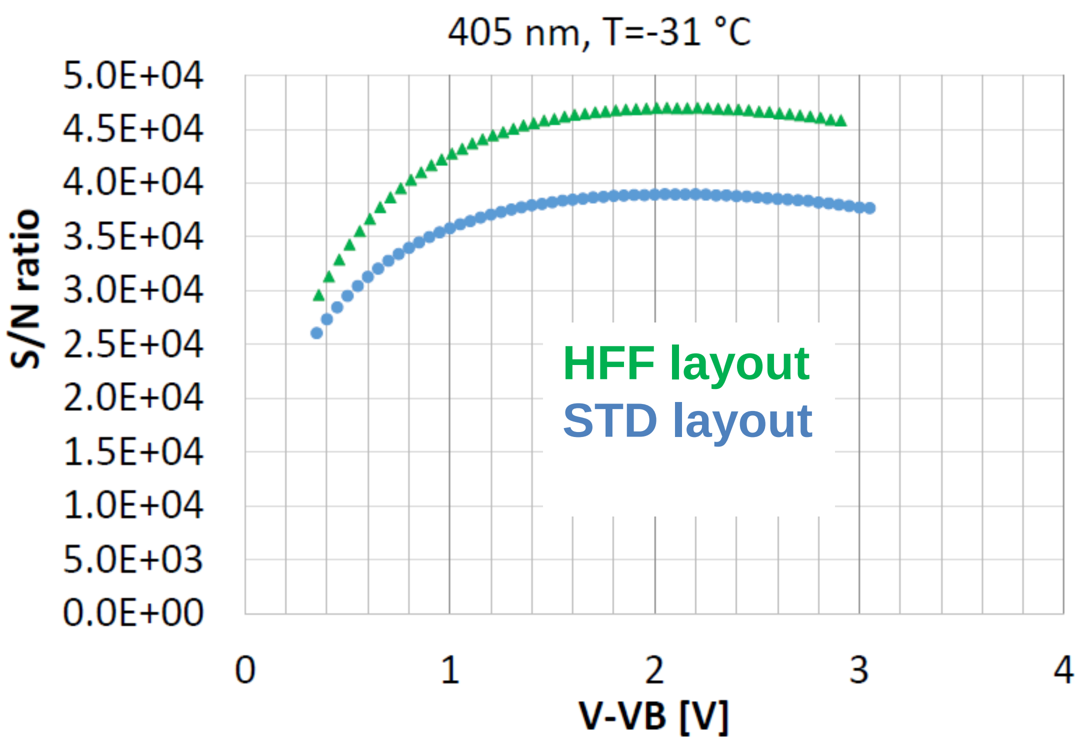
SiPM irradiation with neutrons 1 MeV 1e13 neq/cm^2 @ JSI
SiPMs with 3x3 mm^2 active area, microcell optimized for BTL
Measurements @ –30°C, annealing 80 min +60°C
(Results from CMS collaboration: A. Heering, Y. Musienko, M. Lucchini et al.)





Results obtained on selected process split
HFF provides significantly higher photon detection, with moderate increase of DCR

Neutron irradiation of FBK SiPMs 1e13 neq/cm^2



HFF provides higher SNR compared to STD layout

Optimal operating point after 1e13 neq/cm^2 irradiation ~2.0 V

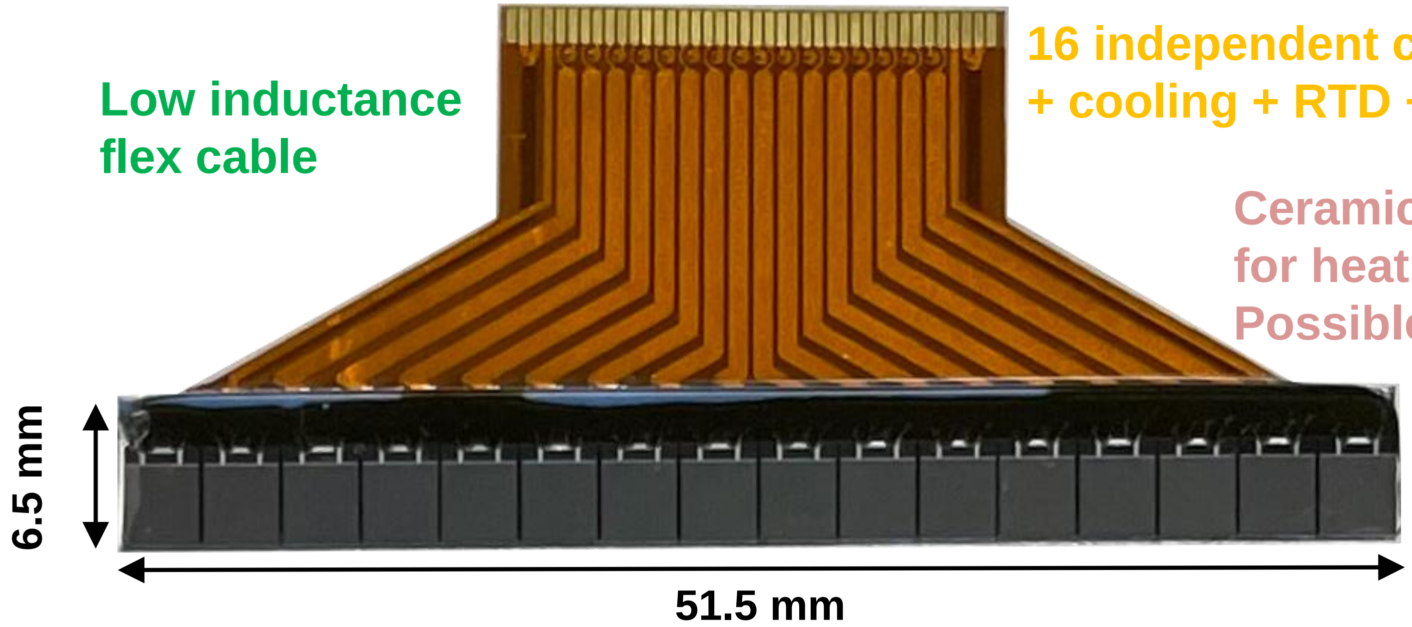
(Results from CMS collaboration:

A. Heering, Y. Musienko, M. Lucchini et al.)

Based on this result, further R&D is in progress

to improve SNR after irradiation

Rad hard SiPM packaging



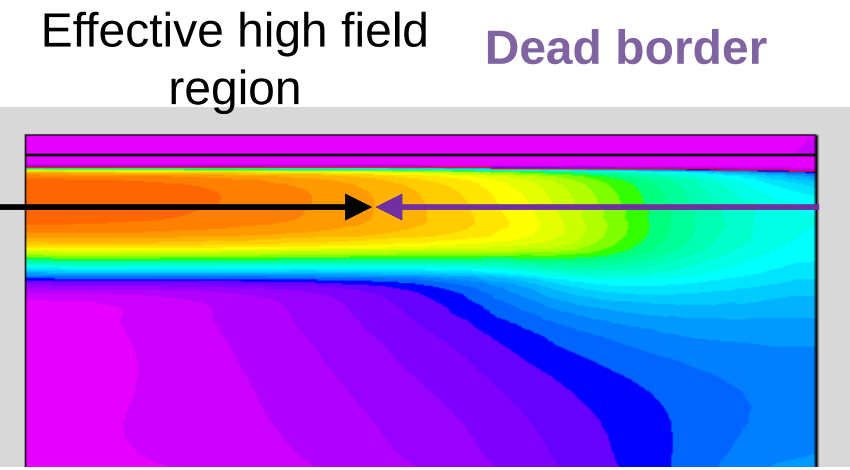
Specific R&D activity on rad-hard materials for SiPM encapsulation

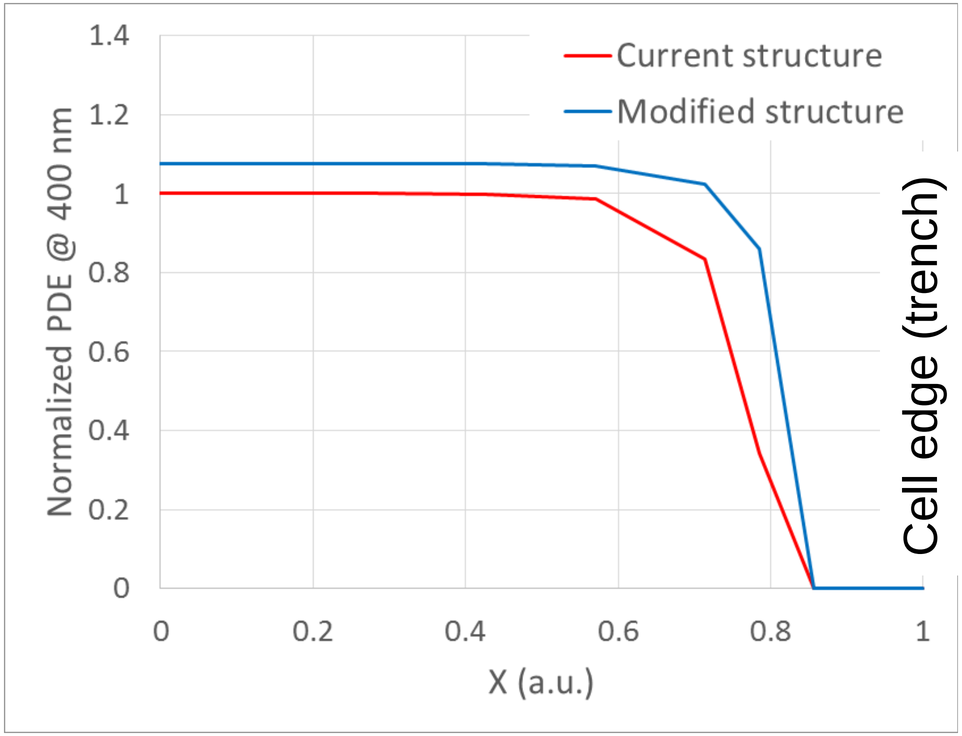
- Minimize transmittance losses
- Optimize optical coupling with scintillator (thickness and refractive index)
- Scalable process for series production

Future R&D on rad hard SiPMs @ FBK

R&D still in progress on the electric field profile:

- Narrower dead border at small OV
- Faster increase of PDE vs OV





Simulated PDE @ 400 nm vs normalized distance from cell center

FBK is expanding fabrication capabilities for next-generation SiPM technologies

Thank you!

Thanks to:

- **C. Nociforo (GSI)** for the proton irradiation tests
- **CMS-BTL collaboration** for commissioning this R&D and for neutron irradiation

All the members of the team working on custom SiPM technology at FBK:

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- **Giacomo Borghi**
- **Andrea Ficorella**
- **Alberto Franzoi**
- **Alberto Gola**
- **Alberto Mazzi**
- **Stefano Merzi**
- **Elena Moretti**
- **Giovanni Palù**
- **Laura Parellada Monreal**
- **Giovanni Paternoster**
- **Maria Stella Ruzzarin**
- **Tiziano Stedile**
- **Nicola Zorzi**