

# 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  
NUV

2010

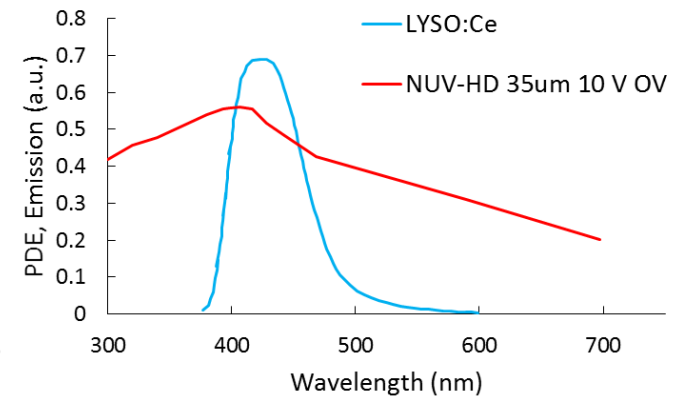
2012

*New cell border  
(trenches)*

RGB-HD  
**NUV-HD**

2012

2015



**NUV-HD as baseline technology  
for LYSO readout**

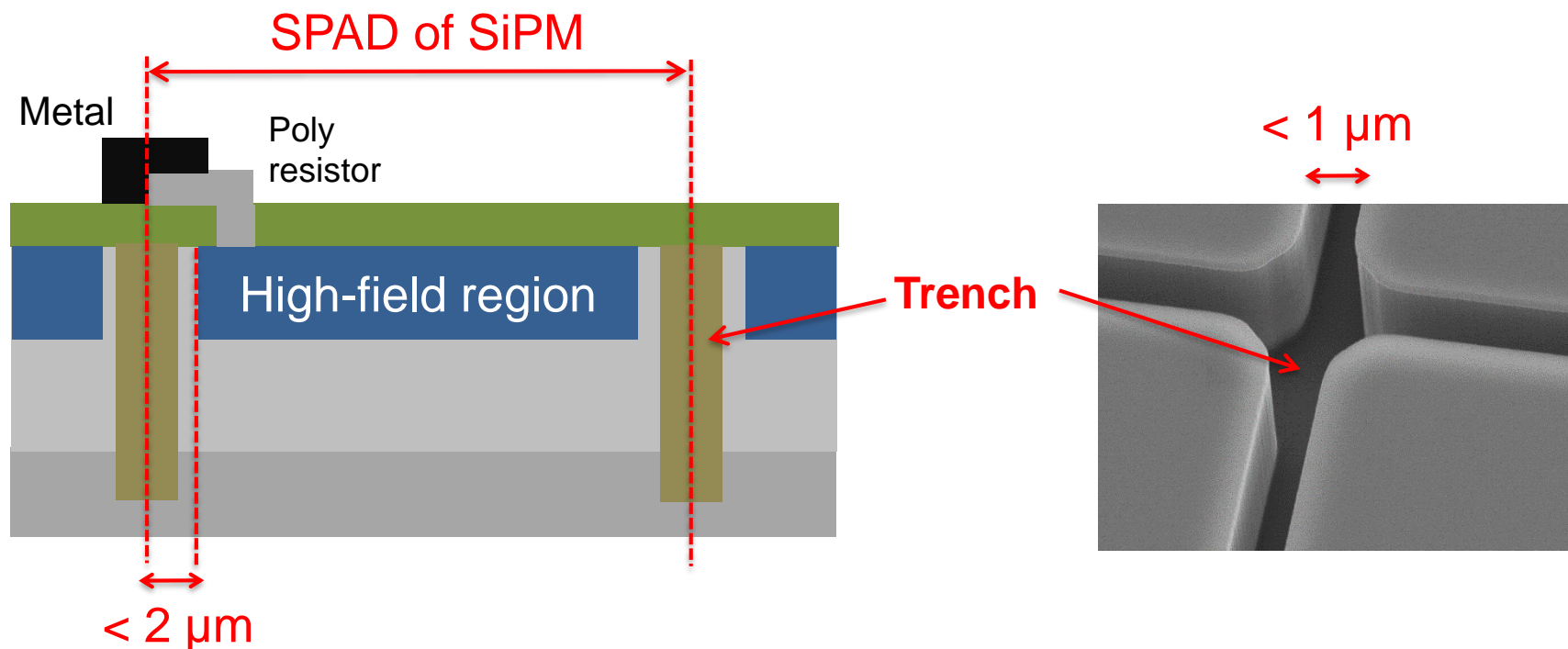
NUV-HD-Cryo

VUV-HD

RGB-UHD

NIR

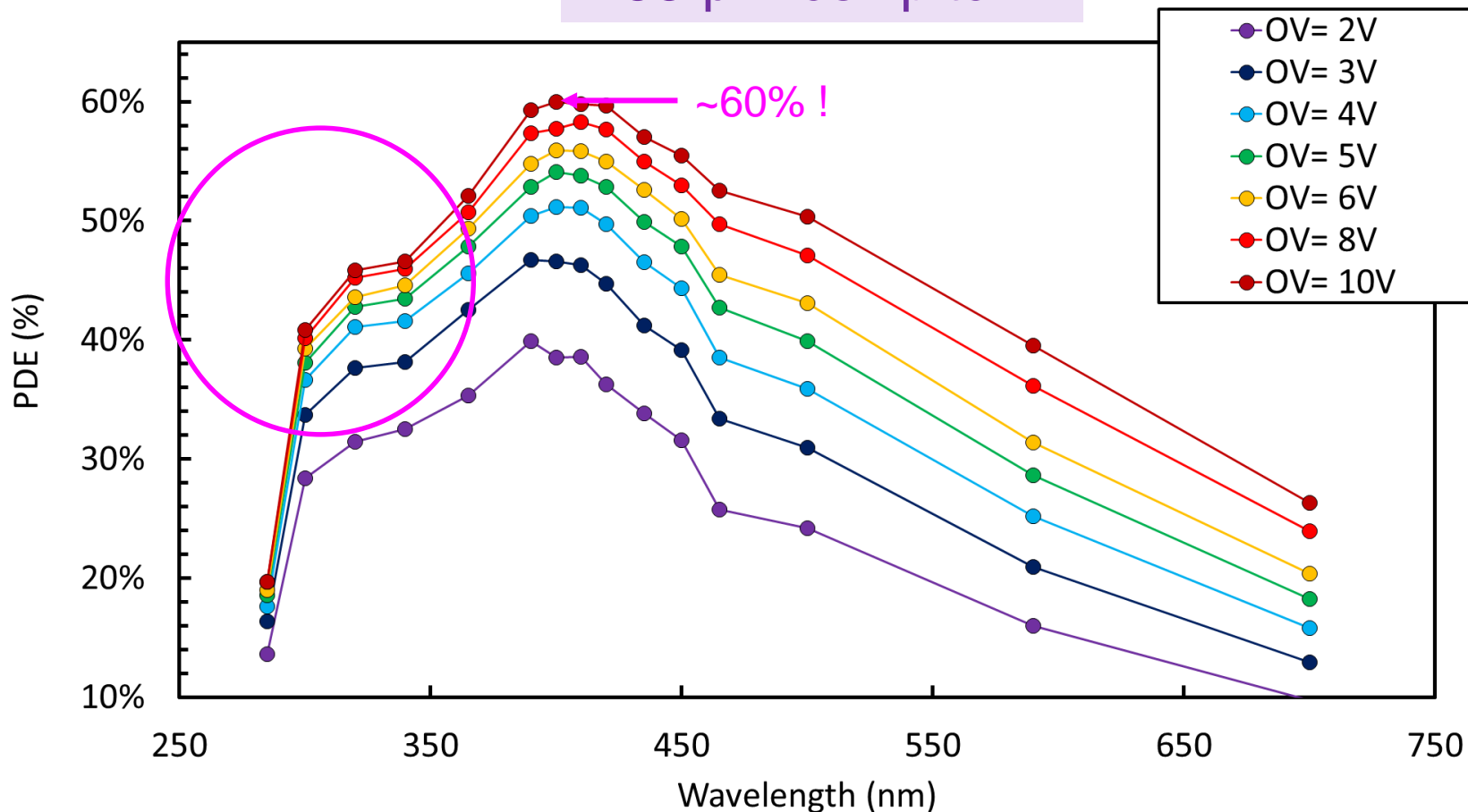
# NUV-HD: technology



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

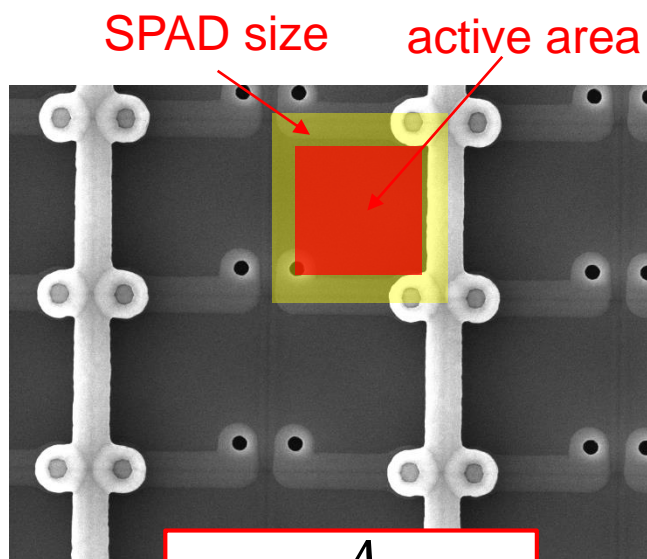
# Photon detection efficiency

35  $\mu\text{m}$  cell pitch

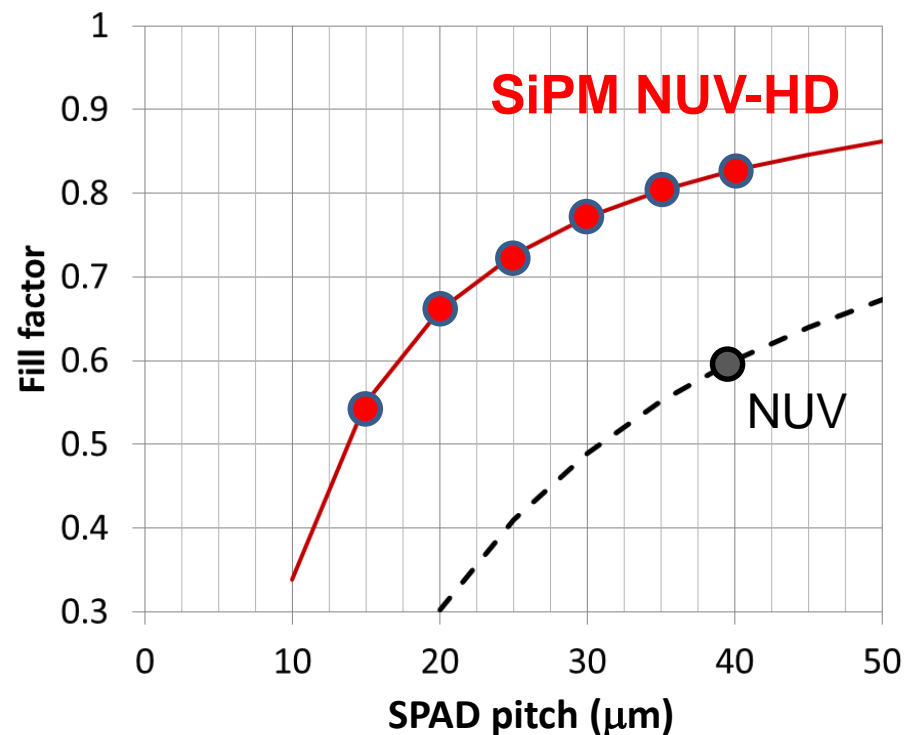


Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, 19(2), 308.

# NUV-HD: Fill Factor



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



SPAD Pitch	15 $\mu\text{m}$	20 $\mu\text{m}$	25 $\mu\text{m}$	30 $\mu\text{m}$	35 $\mu\text{m}$	40 $\mu\text{m}$
Fill Factor (%)	55	66	73	77	81	83
SPAD/ $\text{mm}^2$	4444	2500	1600	1111	816	625

High Dynamic Range, Fast recovery time

High PDE

# 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/cm<sup>2</sup> to  $>10^{14}$  neq/cm<sup>2</sup>



**Geostationary orbit space experiments:**  $\sim 5 \cdot 10^{10}$  neq/cm<sup>2</sup>

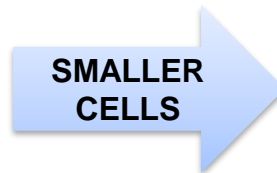
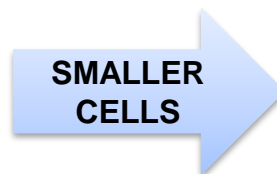
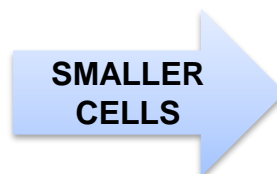


1. Qualification of radiation tolerance of current SiPM technologies.
2. Study / modeling of the effects of radiation damage on SiPM characteristics, under different sources of radiation.
3. Development of a highly customized SiPM technology for optimal performance after irradiation is most likely needed

# Rad Hard SiPMs: small-cell SiPMs

## ISSUE

- 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

**Lower gain:** reduction of afterpulsing (for a given number of traps).

**More cells and faster recharge:** less PDE loss.

**Lower gain:** less current (for a given DCR).

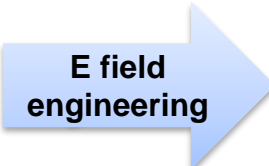


# Rad Hard SiPMs: E field engineering

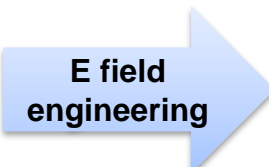
## ISSUE

- Lower **activation energy** of DCR after irradiation.
- Low **triggering probability** at small excess bias.
- Need to increase PDE at a fixed **microcell gain**

E field  
engineering



E field  
engineering



E field  
engineering



## MITIGATION

Possible reduction of DCR at **low temperature**.  
Effective DCR suppression **with moderate cooling**

**Process** with faster increase of PDE vs. bias (less tunneling)

Higher PDE at **small Gain**

# Barrel Timing Layer of CMS

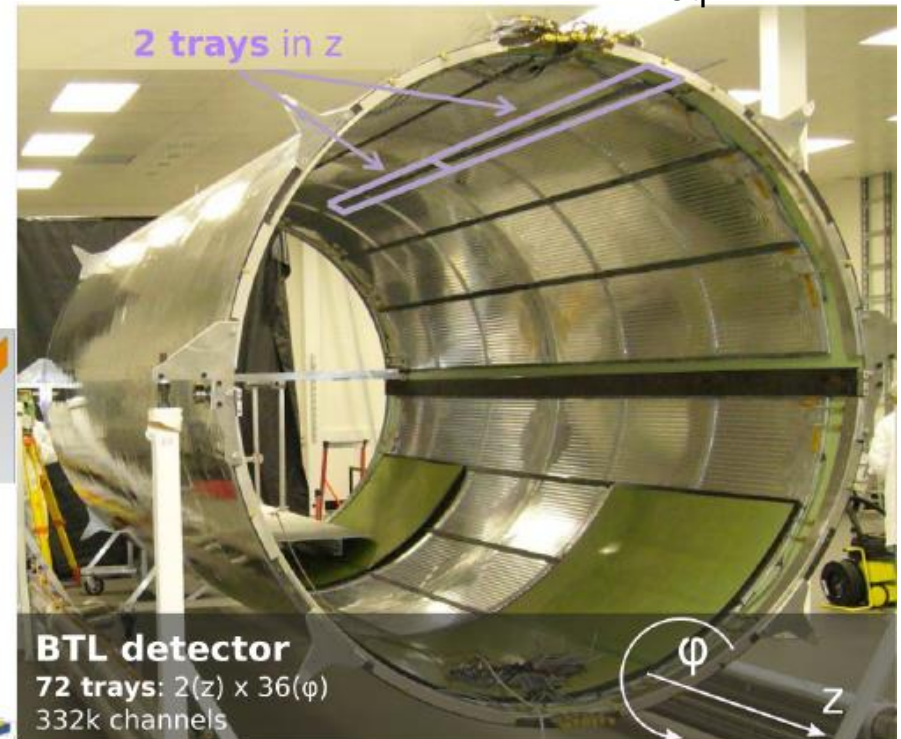
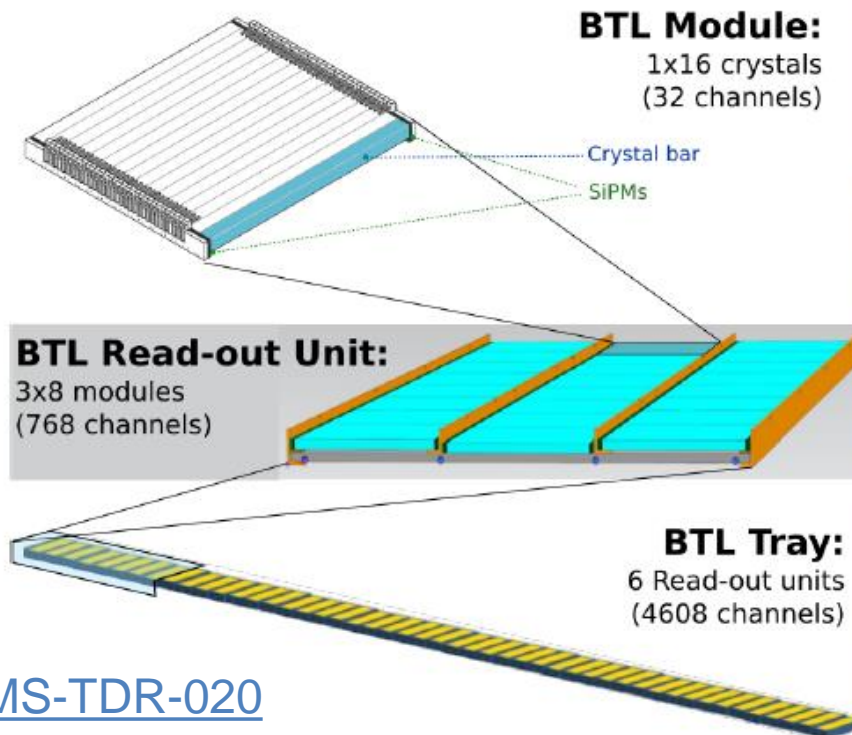
MIP timing detector of CMS: development for the Phase2 Upgrade

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

Radius:  $\sim 1.15$  m, length:  $\sim 5.00$  m, max thickness  $\sim 40$  mm

Operating temperature:  $\sim -30^\circ\text{C}$

Radiation tolerance for BTL: 30 kGy,  $\sim 2 \times 10^{14}$  1 MeV  $n_{\text{eq}}/\text{cm}^2$



# 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

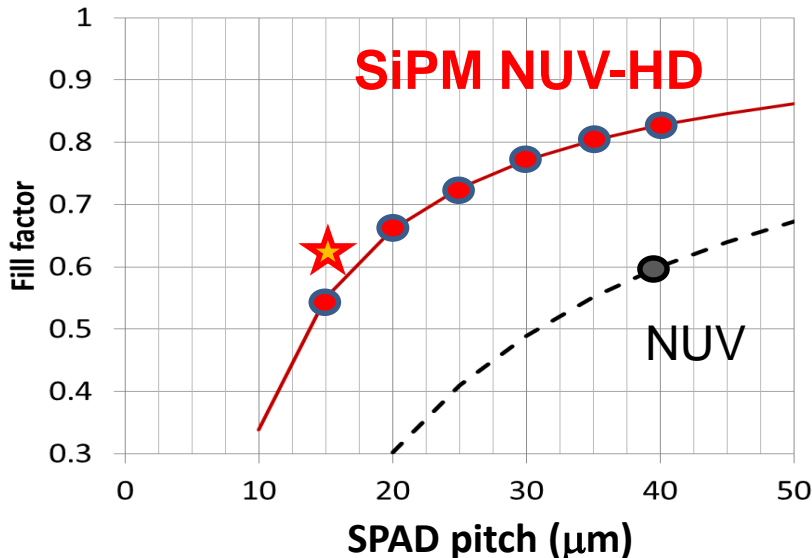
HFF: increased microcell fill factor

Process splits

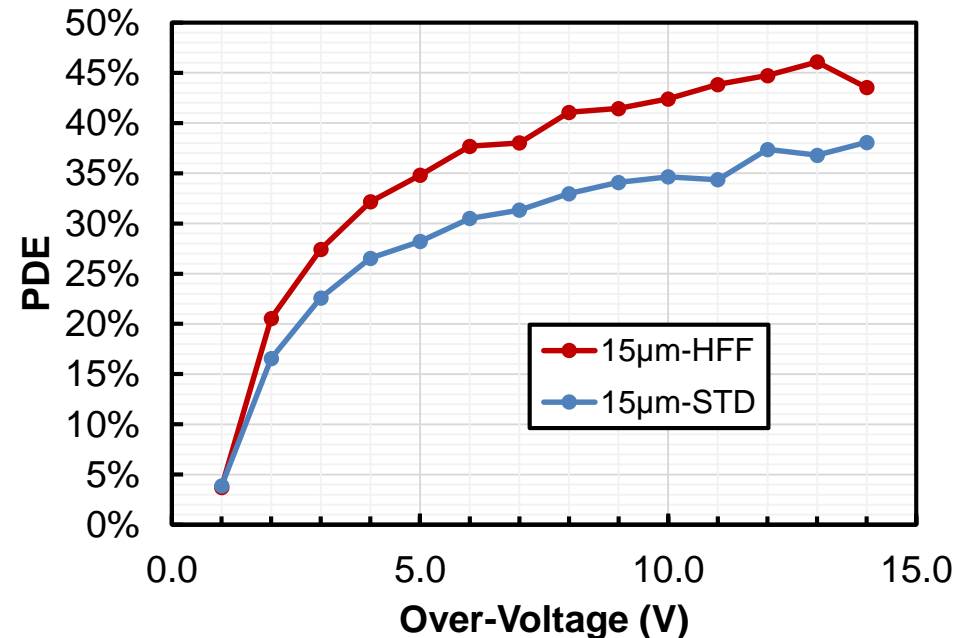
4 process splits for electric field optimization

Capacitance and  $P_{\text{trigger}}$  vs. OV

Cell layout	Fill factor
15 $\mu\text{m}$ STD	52%
15 $\mu\text{m}$ HFF	61%



**Impact of HFF layout:  
microcell fill factor and PDE**



# SiPM R&D at FBK for CMS-BTL

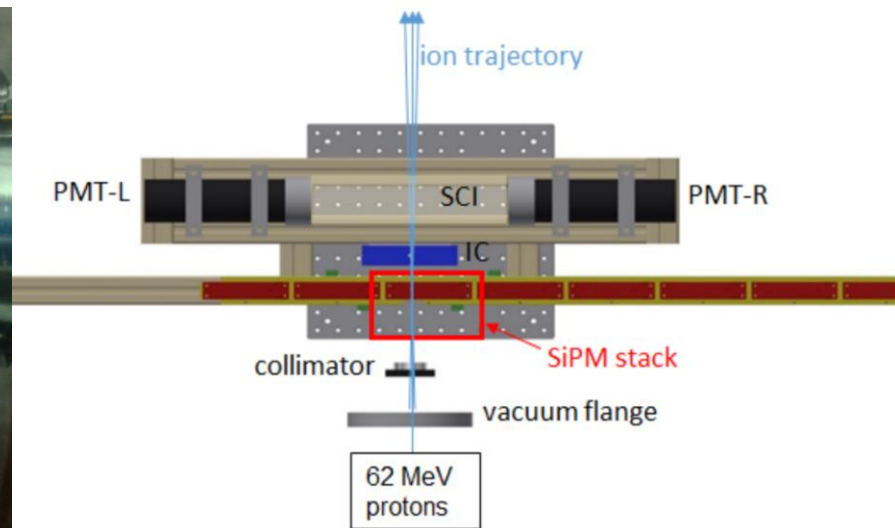
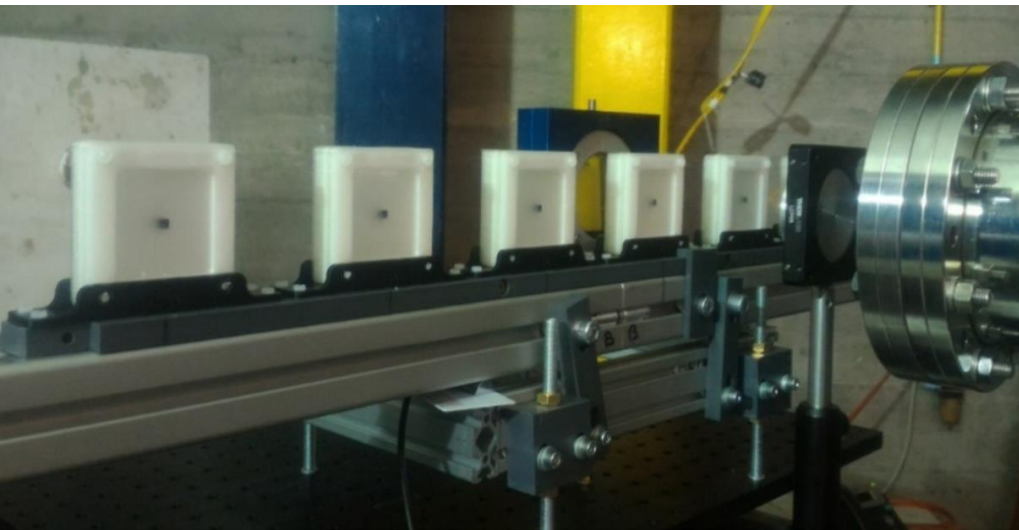
**16x1 SiPM array** for scintillation crystal (LYSO) readout at both ends  
 SiPM active area: 3.0x2.4 / 3.0x3.0 / 3.0x3.75 mm<sup>2</sup>

SiPM Specifications		FBK SiPM	After 3000 fb <sup>-1</sup>		FBK SiPM
Cell pitch	< 20 μm	15 μm	Optimal OV	> 1 V	1.6 V
Recovery time	< 10 ns	< 8 ns	dV <sub>BD</sub> /10 <sup>13</sup> n <sub>eq</sub>	≤ 0.2 V	< 0.1 V
Capacitance	< 600 pF/ch	530 pF/ch	Cell gain	≥ 1.3×10 <sup>5</sup>	2×10 <sup>5</sup>
Cell density	> 20k/ch	42k/ch	SNR	≥ 2.0	2.3
ENF	< 1.1	< 1.05	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

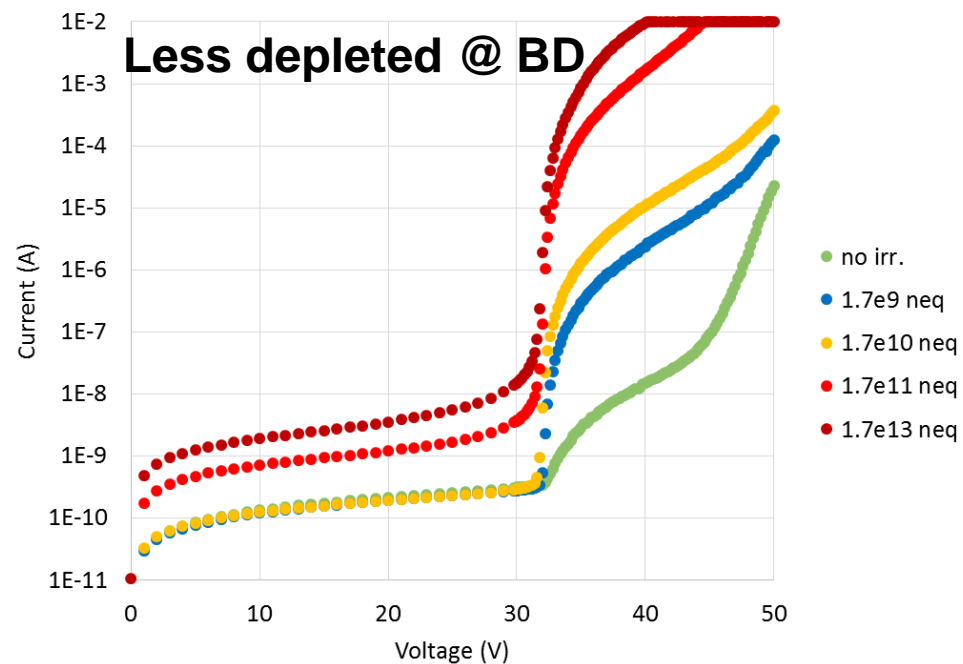
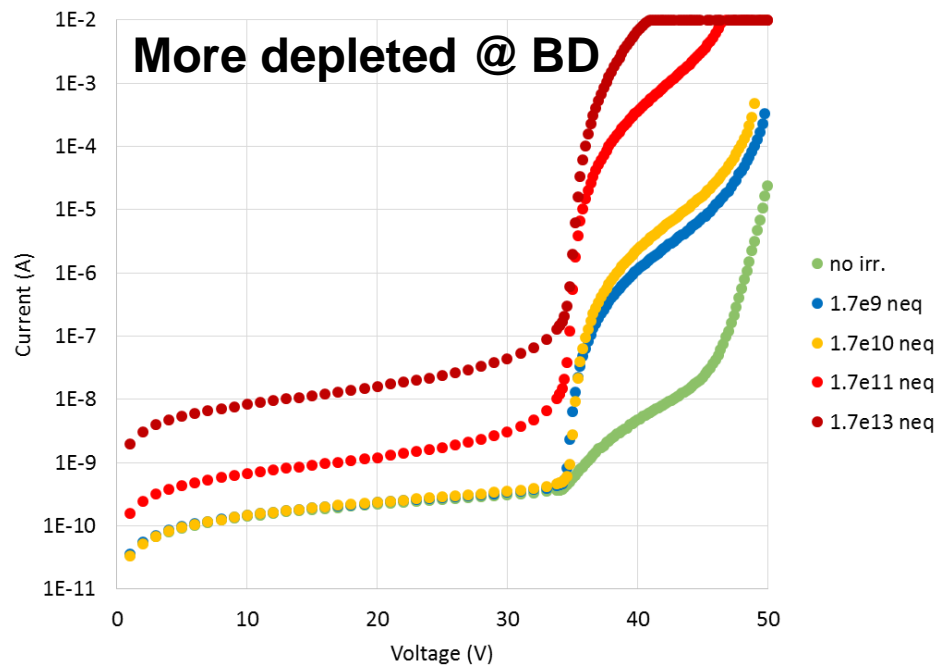
SiPM irradiation with protons, 62 MeV @ INFN-LNS  
 Test SiPMs with  $1 \times 1 \text{ mm}^2$  active area, microcell optimized for BTL  
 Rev bias IV curves after irradiation @  $+20^\circ\text{C}$ ,  $\sim 1$  month RT annealing



Results from collaboration with GSI  
 A. R. Altamura et al. [arXiv:2106.12344](https://arxiv.org/abs/2106.12344)

# $p^+$ irradiation of FBK SiPMs, variable fluence

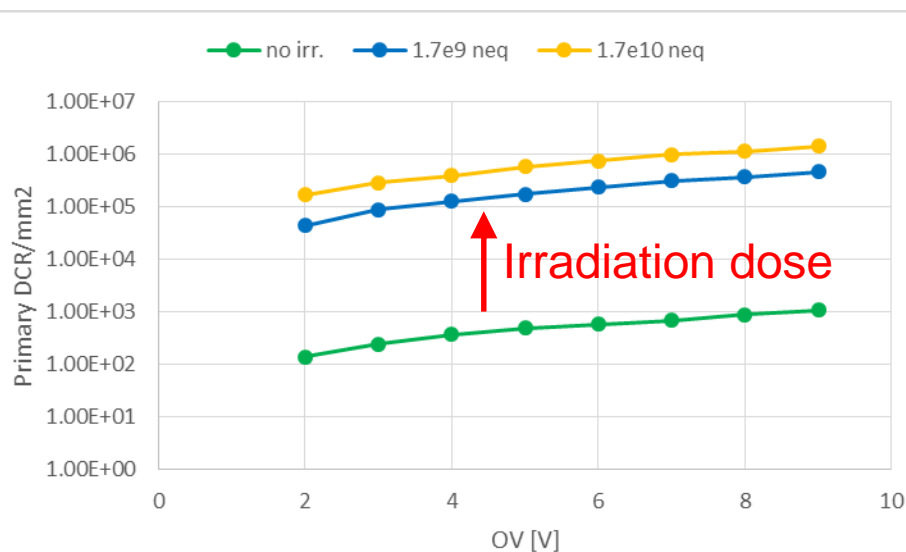
## Impact of process split: op. range and performance after irradiation



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



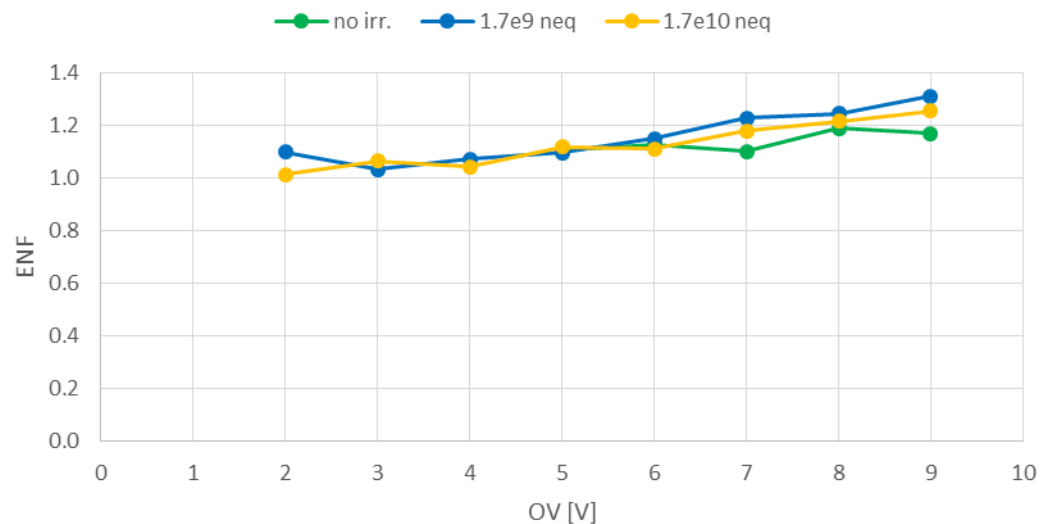
## Functional characterization of SiPMs after irradiation: waveform analysis

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

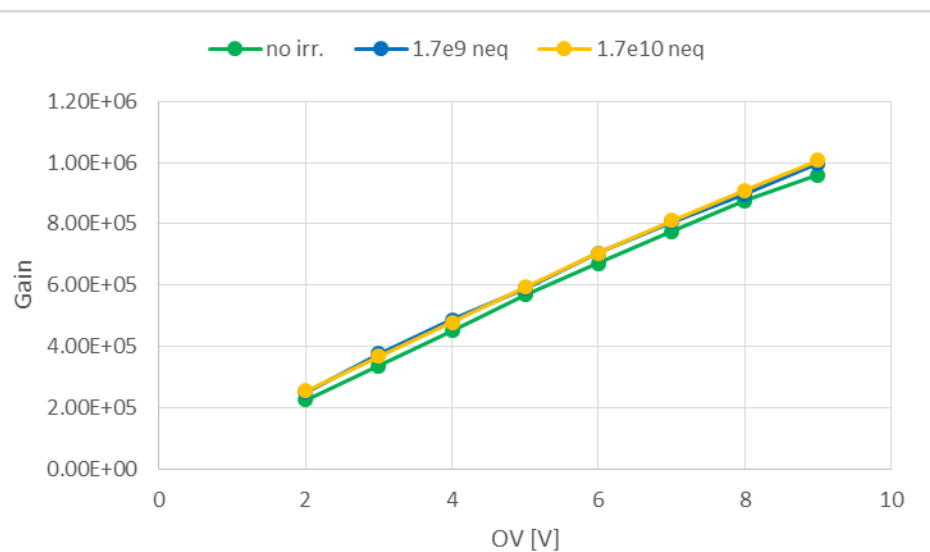
Results obtained on HFF devices  
Selected process split

Measurements at +20°C

At higher fluences,  
waveform analysis not possible



# $p^+$ irradiation of FBK SiPMs, variable fluence



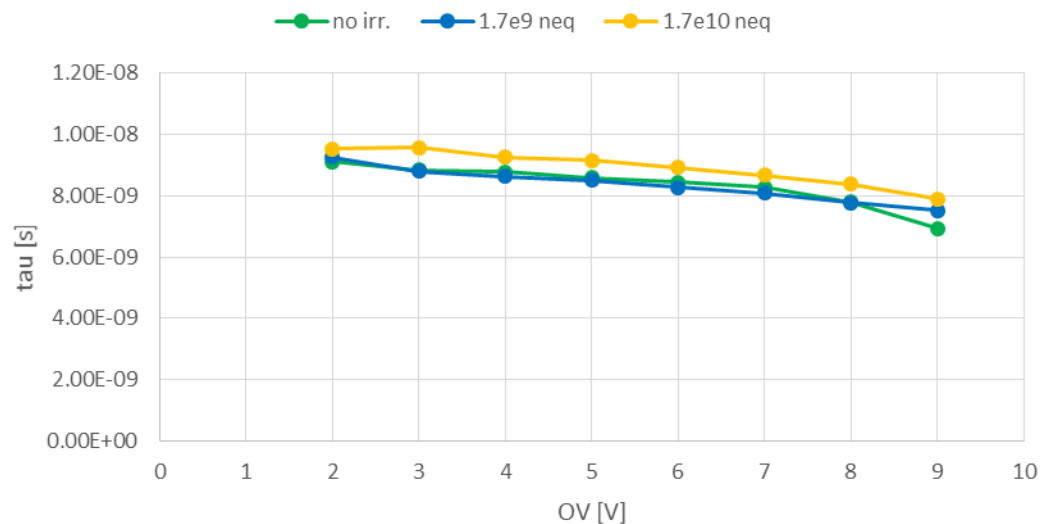
Microcell **gain** and signal amplitude independent on irradiation dose

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

Results obtained on HFF devices  
 Selected process split

Measurements at  $+20^\circ\text{C}$

At higher fluences,  
 waveform analysis not possible

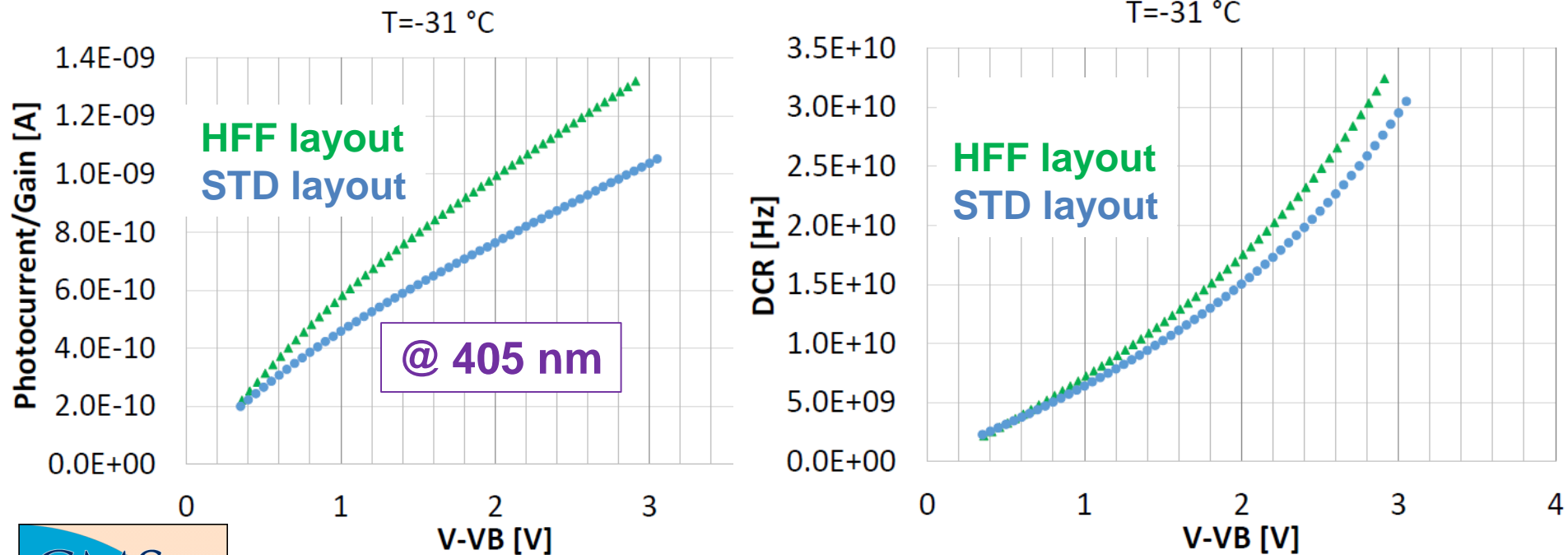




# Neutron irradiation of FBK SiPMs $1e13$ neq/cm<sup>2</sup>

SiPM irradiation with neutrons 1 MeV  $1e13$  neq/cm<sup>2</sup> @ JSI  
 SiPMs with  $3 \times 3$  mm<sup>2</sup> active area, microcell optimized for BTL  
 Measurements @  $-30^\circ\text{C}$ , annealing 80 min  $+60^\circ\text{C}$

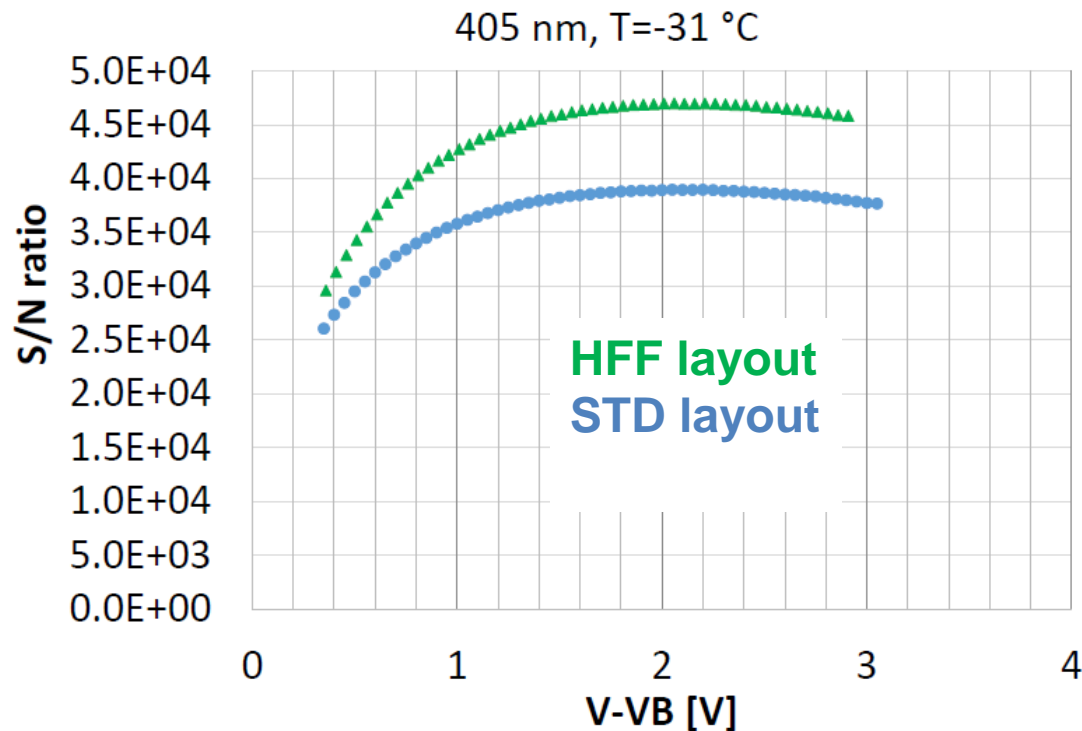
(Results from CMS collaboration: A. Heering, Y. Musienko, M. Lucchini et al.)



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<sup>2</sup>



HFF provides higher SNR compared to STD layout

Optimal operating point after  $1e13$  neq/cm<sup>2</sup> irradiation  $\sim 2.0$  V

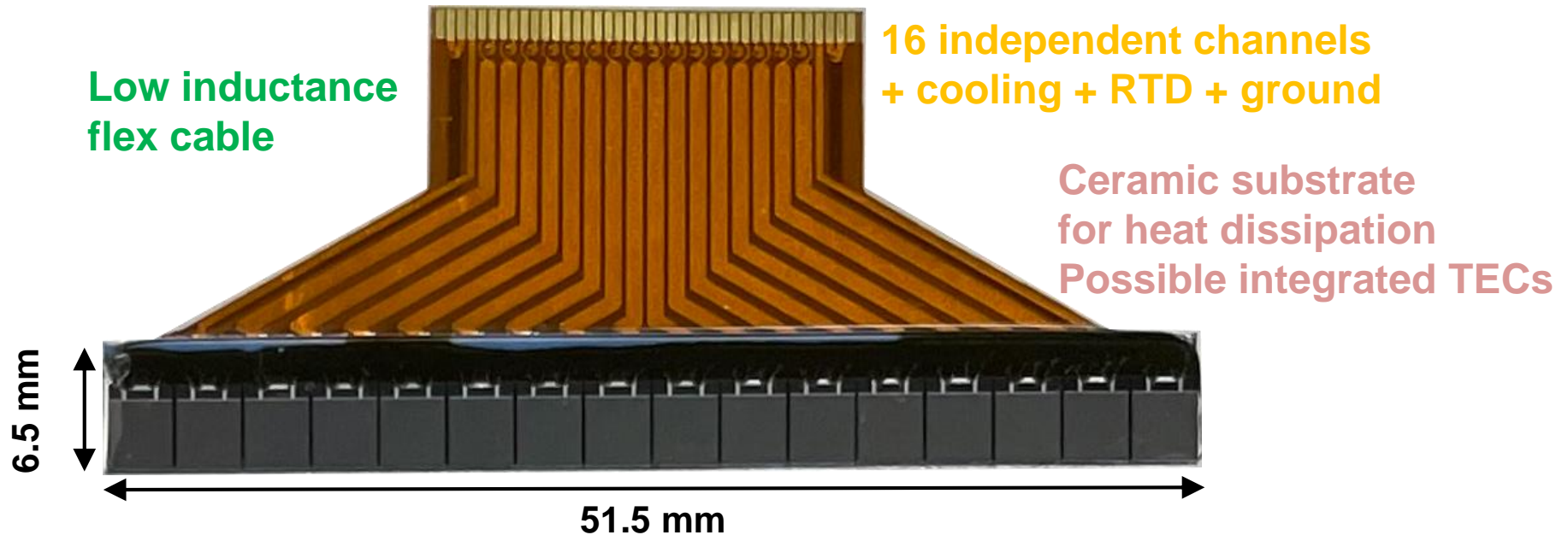
(Results from CMS collaboration:

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

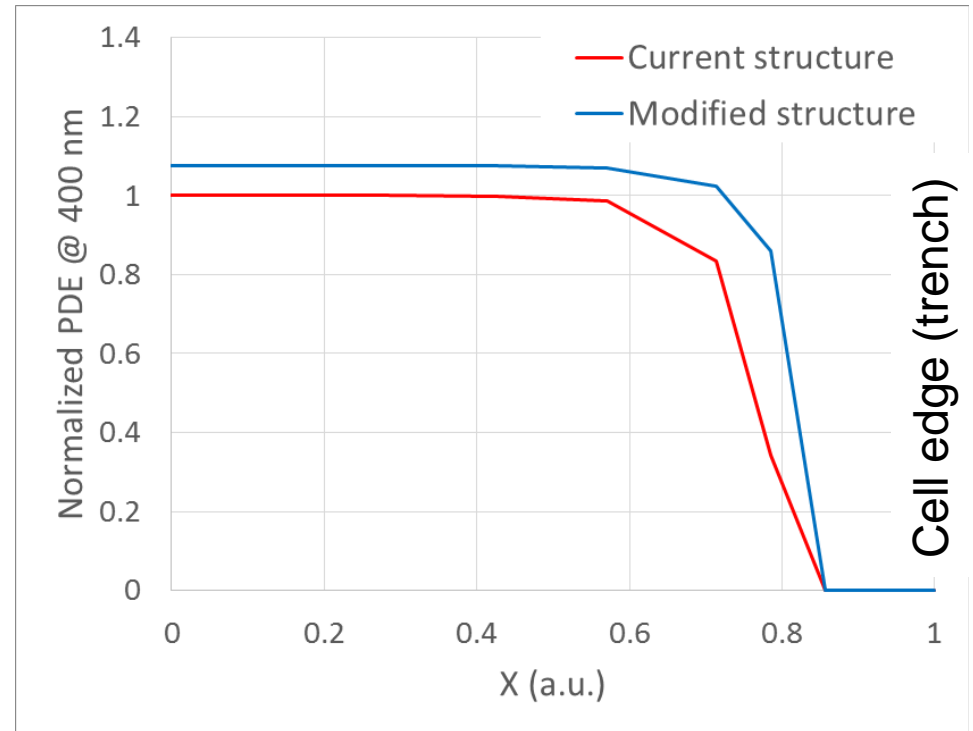
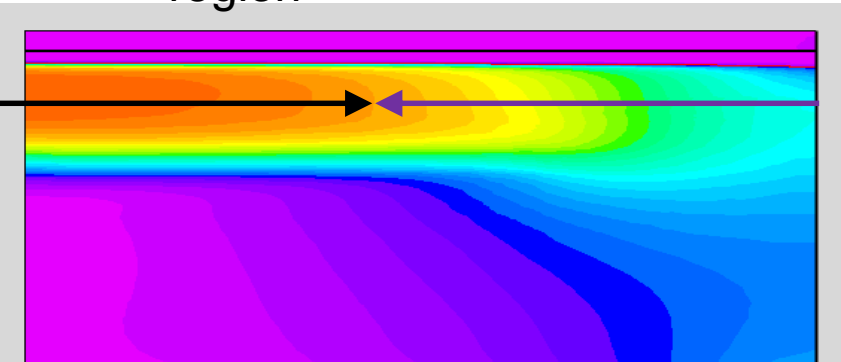
- Minimize transmittance losses
- Optimize optical coupling with scintillator (thickness and refractive index)
- Scalable process for series production

# 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

Effective high field region      Dead border



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:

- Fabio Acerbi
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- 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