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Ionizing and non-ionizing radiation damage on Silicon Photomultipliers

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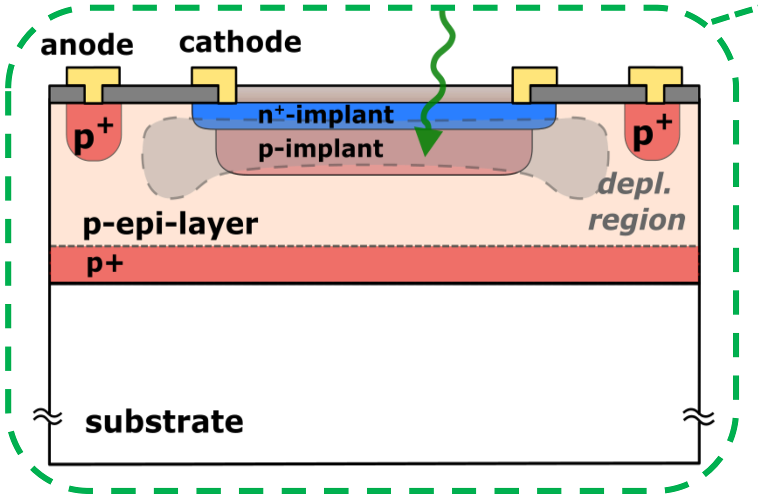
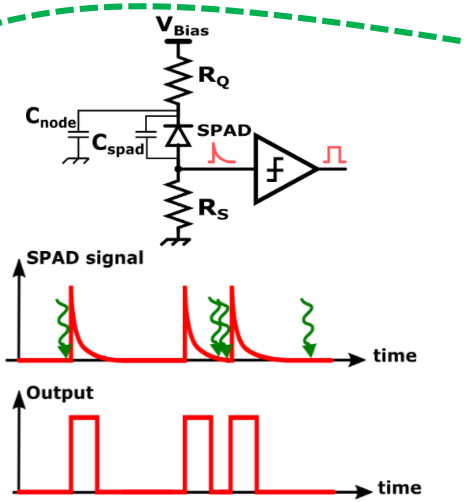
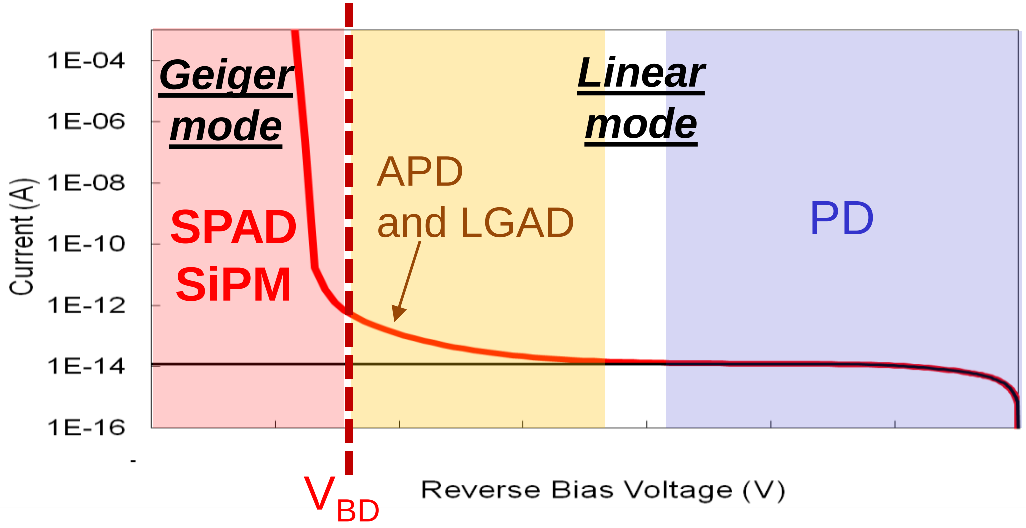
Single-photon avalanche diode (SPAD) & Silicon Photomultipliers (SiPM)

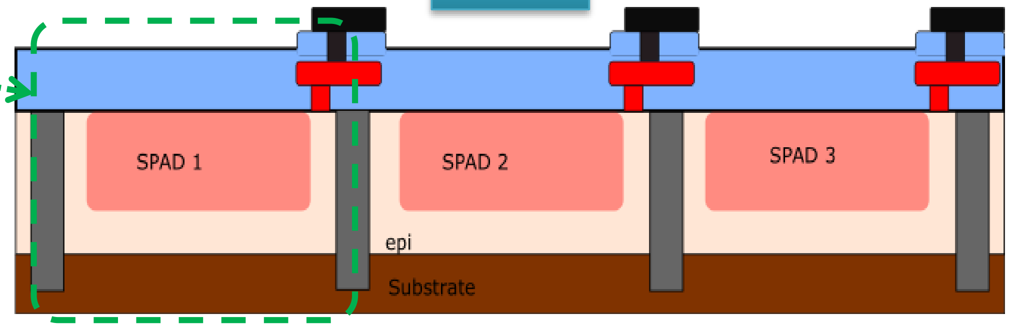
SPAD

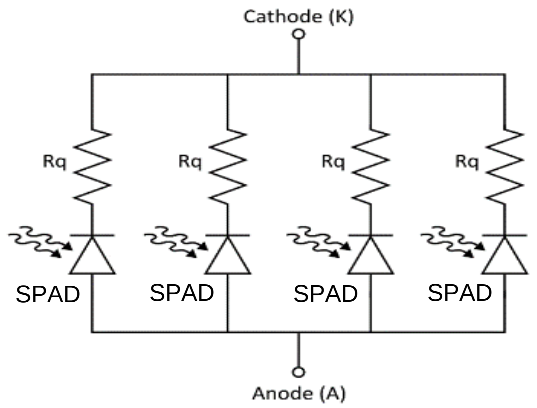


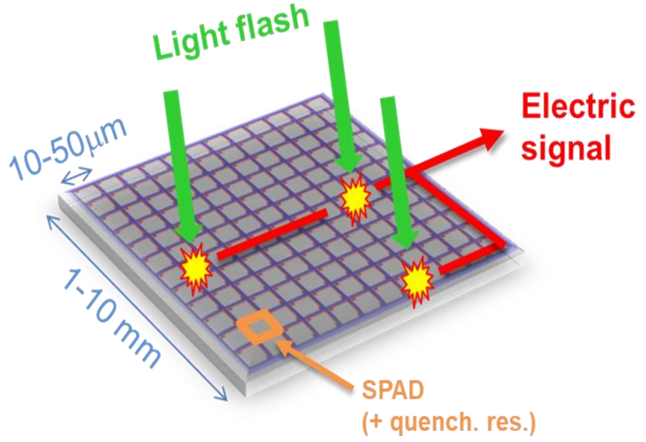




SiPM







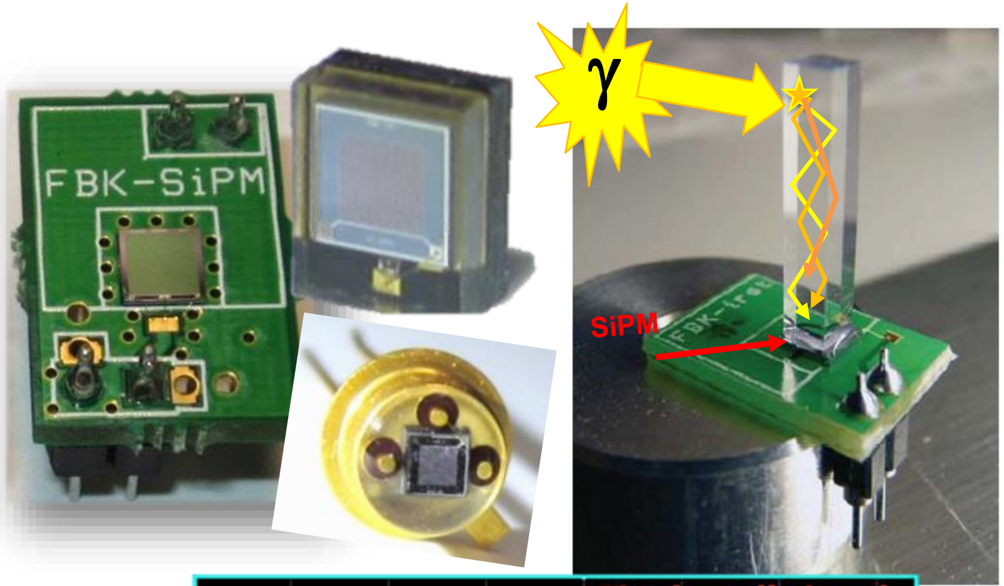
- **SiPM: (analog) Silicon photomultiplier → thousands of SPADs in parallel**

Silicon Photomultipliers (SiPMs)

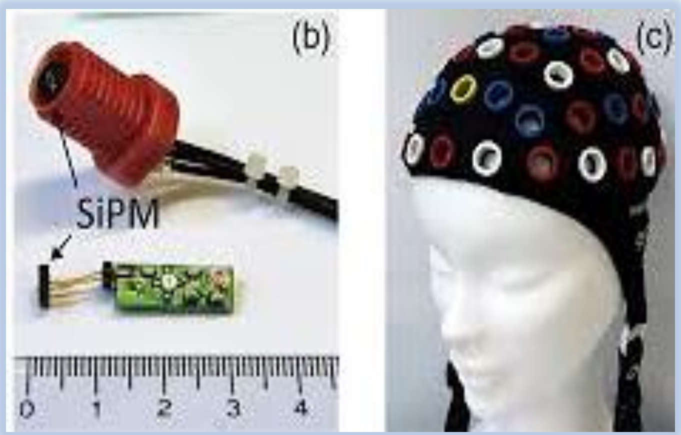
- Silicon Photomultiplier (SiPM):
  large-area, solid-state, **single-photon sensitive** detectors, with **ph-num. resolution**, and large dynamic range.

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

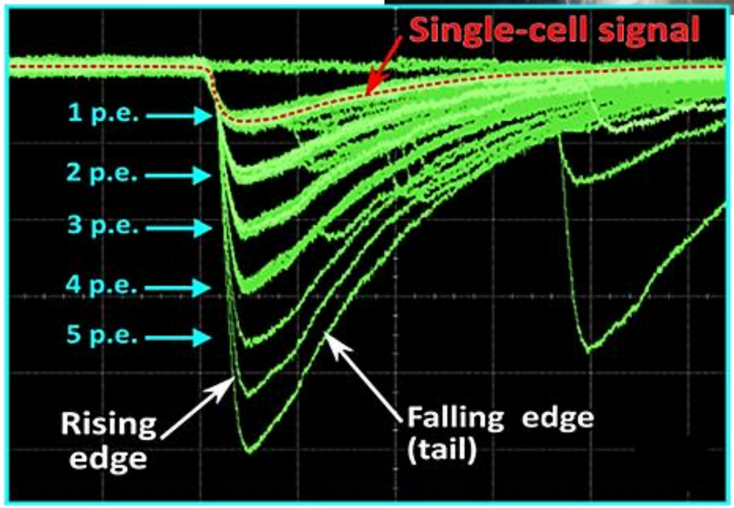
- Active areas: 1x1 mm^2 up to 10x10 mm^2



elettronicanews.it



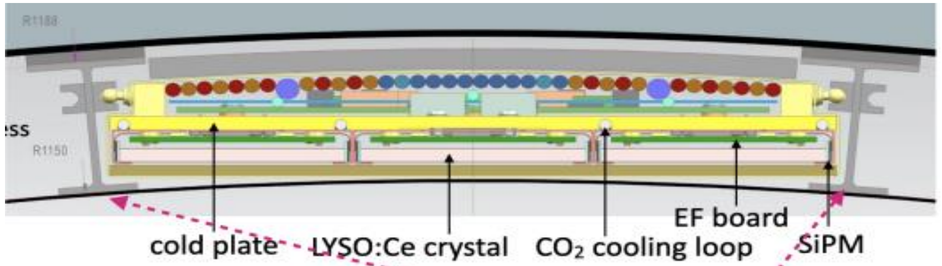
DOI: 10.1117/1.NPh.3.4.045004



DOI: 10.5772/intechopen.71940

SiPMs in harsh-radiation environments

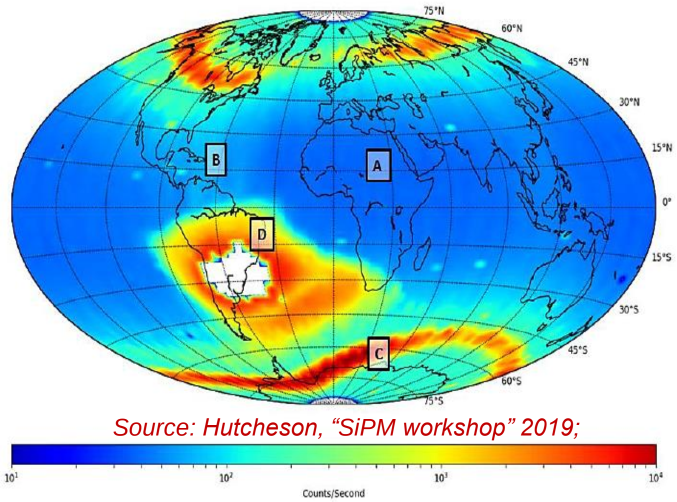
❑ High-energy physics (HEP) experiments
(e.g. calorimeters in CMS, LHCb, etc.)



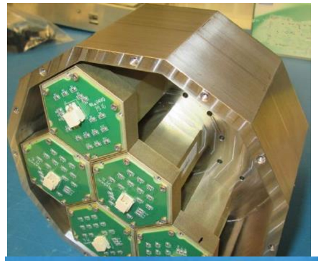
Source: Nan Lu, ICHEP 2020

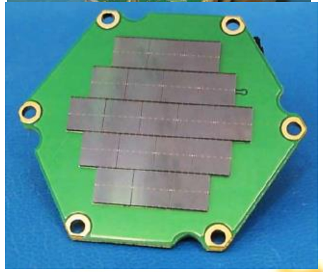
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab⁻¹: $2 \times 10^{14}\ n_{eq}/cm^2$

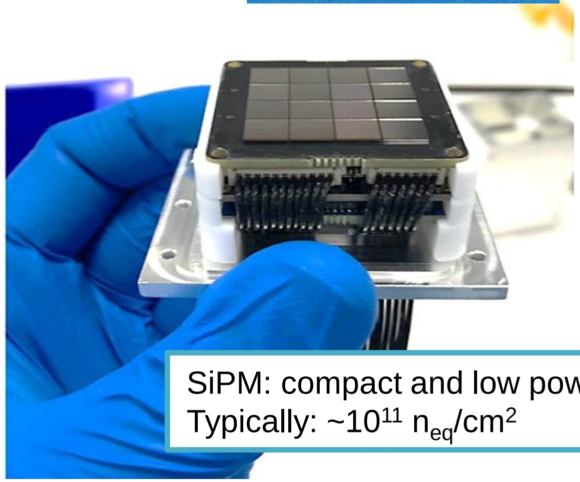
❑ X- and γ-ray detectors for space experiments
(e.g. SIRI2, GMOD, GRID, AMEGO, …)



Source: Hutcheson, "SiPM workshop" 2019;





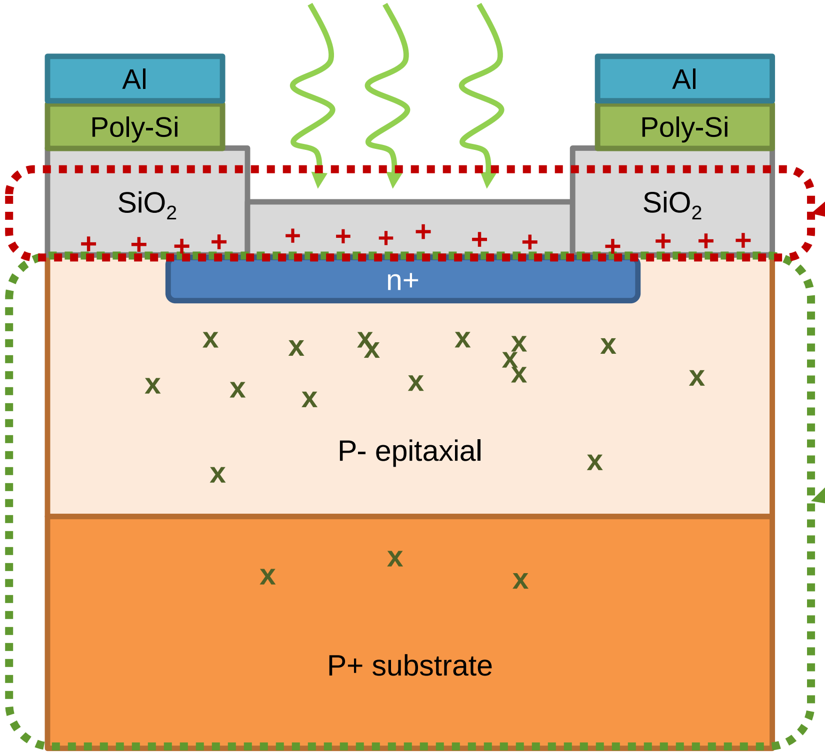


SiPM: compact and low power
Typically: ~$10^{11}\ n_{eq}/cm^2$

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

Radiation damage in silicon detectors

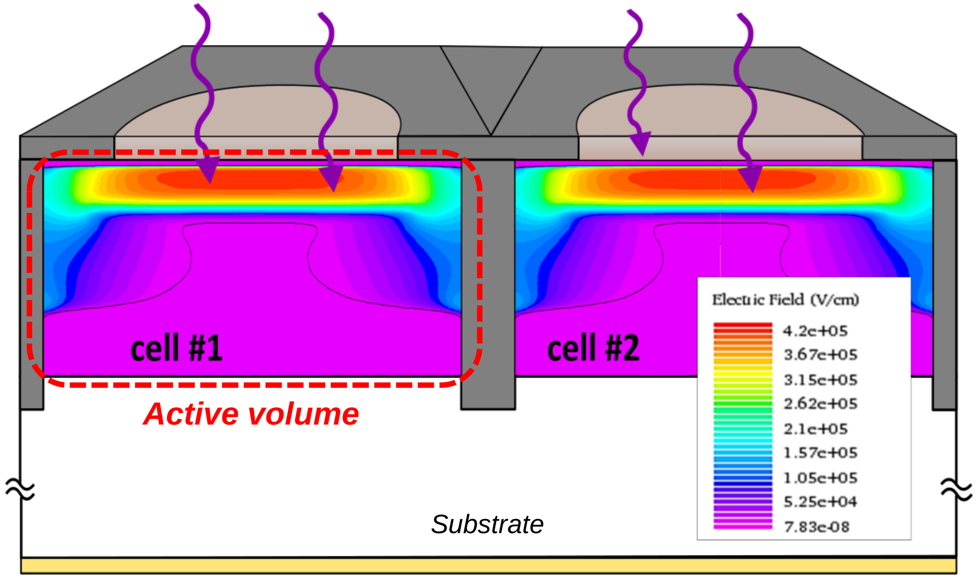
- **Bulk (crystal) damage ← non-ionizing energy loss (NIEL)**
  - Displacement damage → crystal defects, interstitials, vacancies, clusters → *increased noise.*
- **Surface damage ← ionizing energy loss (IEL)**
  - Accumulation of charge in the dielectrics; damage of dangling bonds.



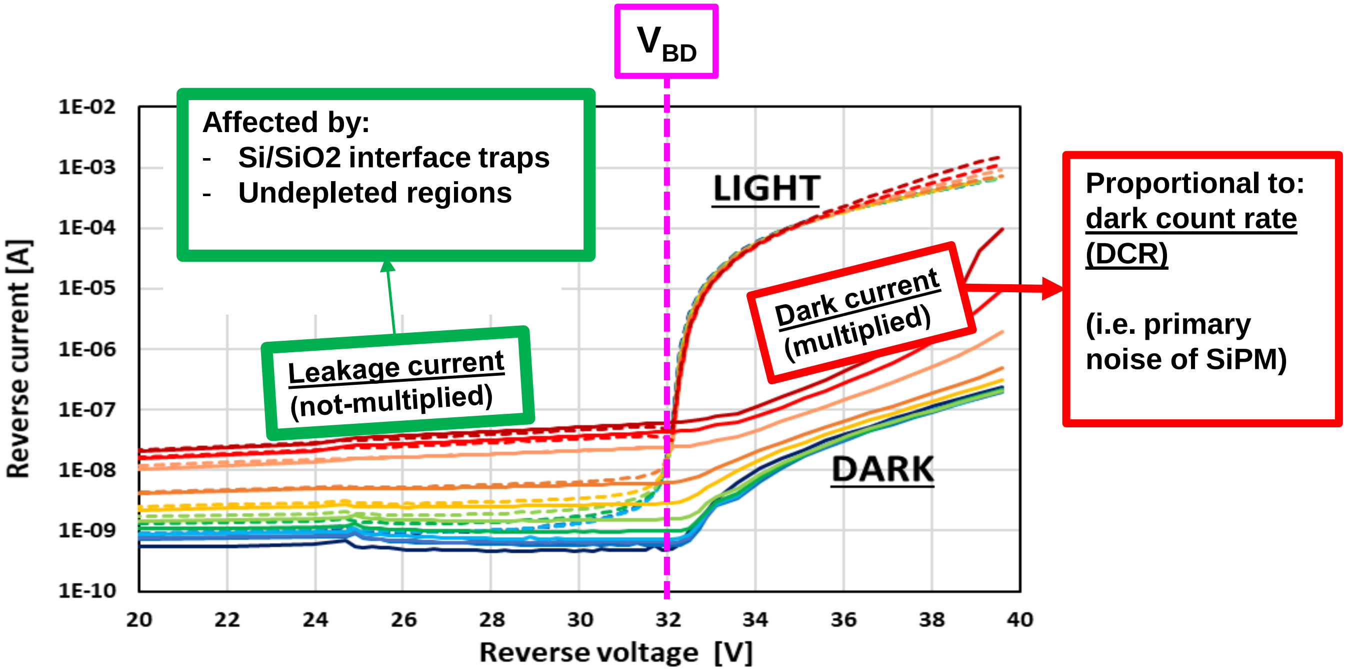
Top dielectrics: (ionizing energy loss) ("surface" damage)

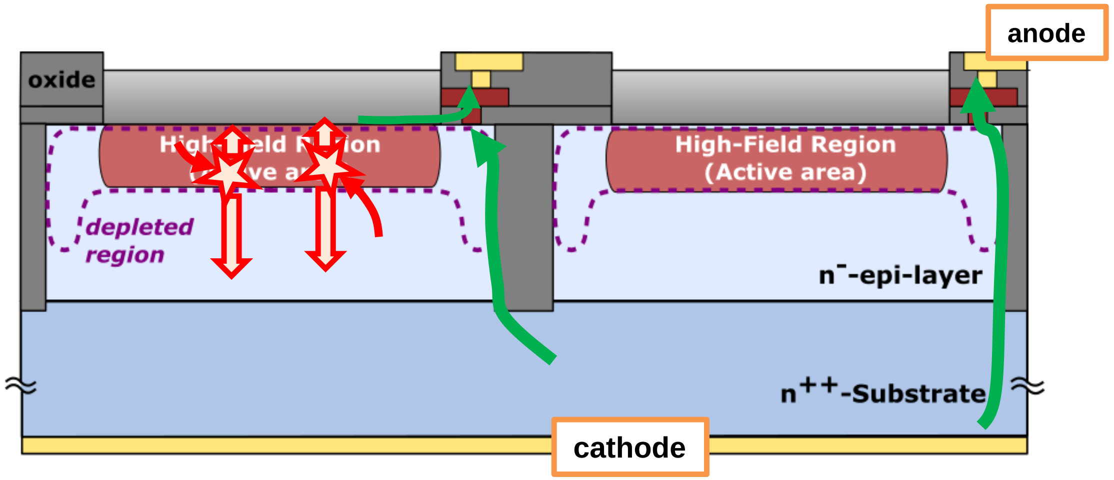
Epi-layer and substrate: (non-ionizing energy loss) (bulk damage)

- **But: SPADs, SiPMs have:**
  - *High Internal gain (~10^6).*
  - *High electric fields (~$4 \cdot 10^5$ V/cm).*

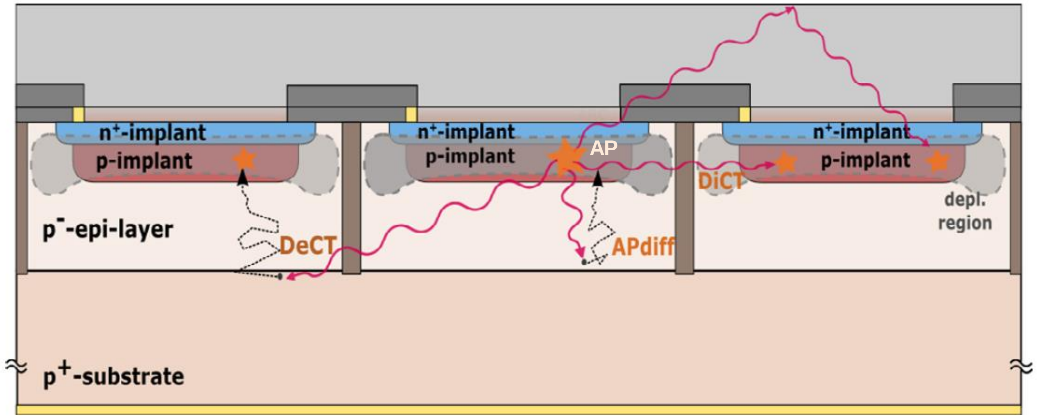


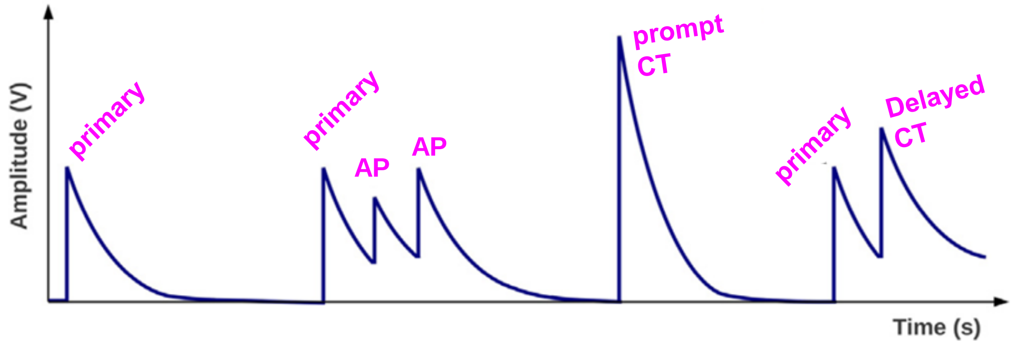
SiPM: IV and noise source



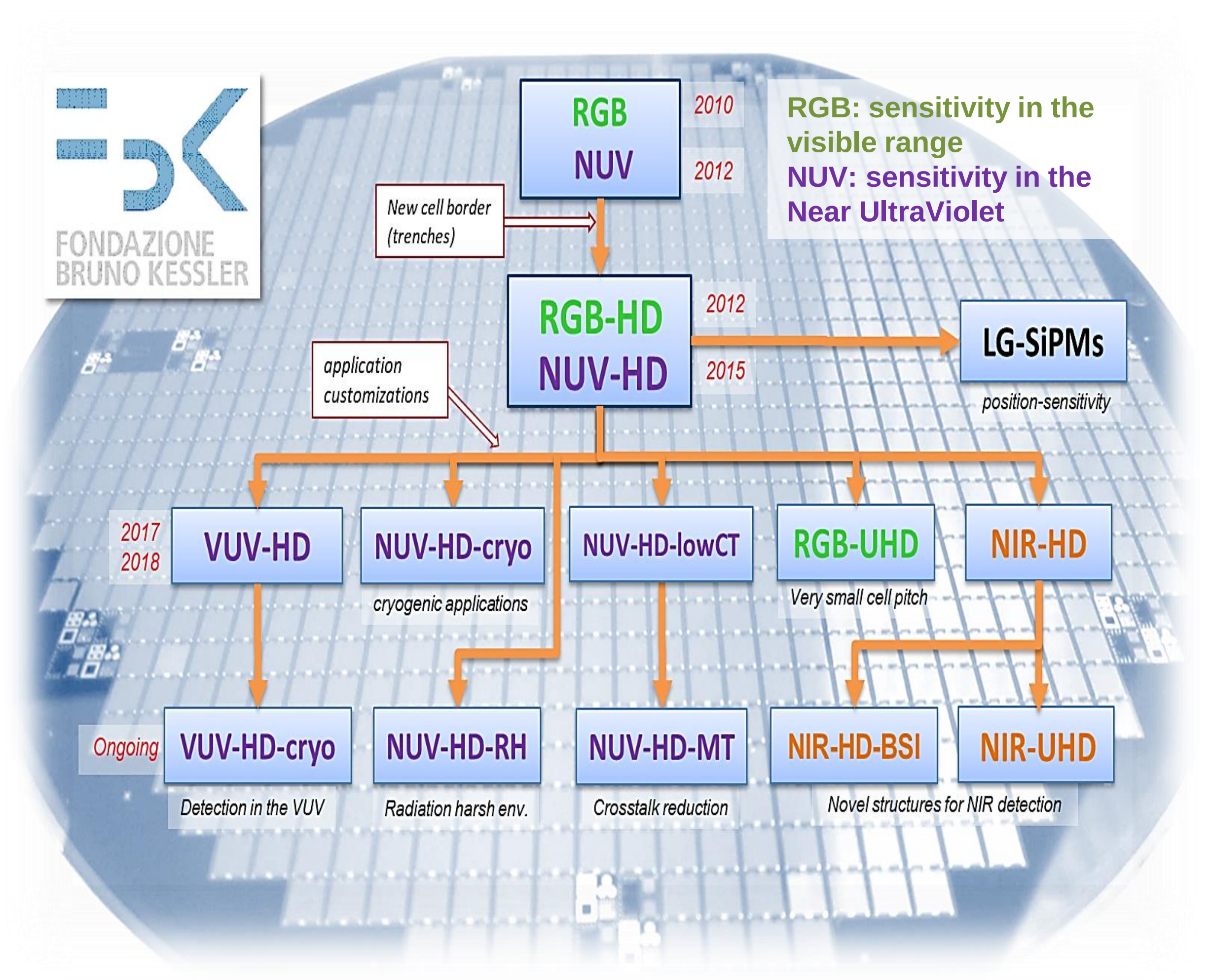


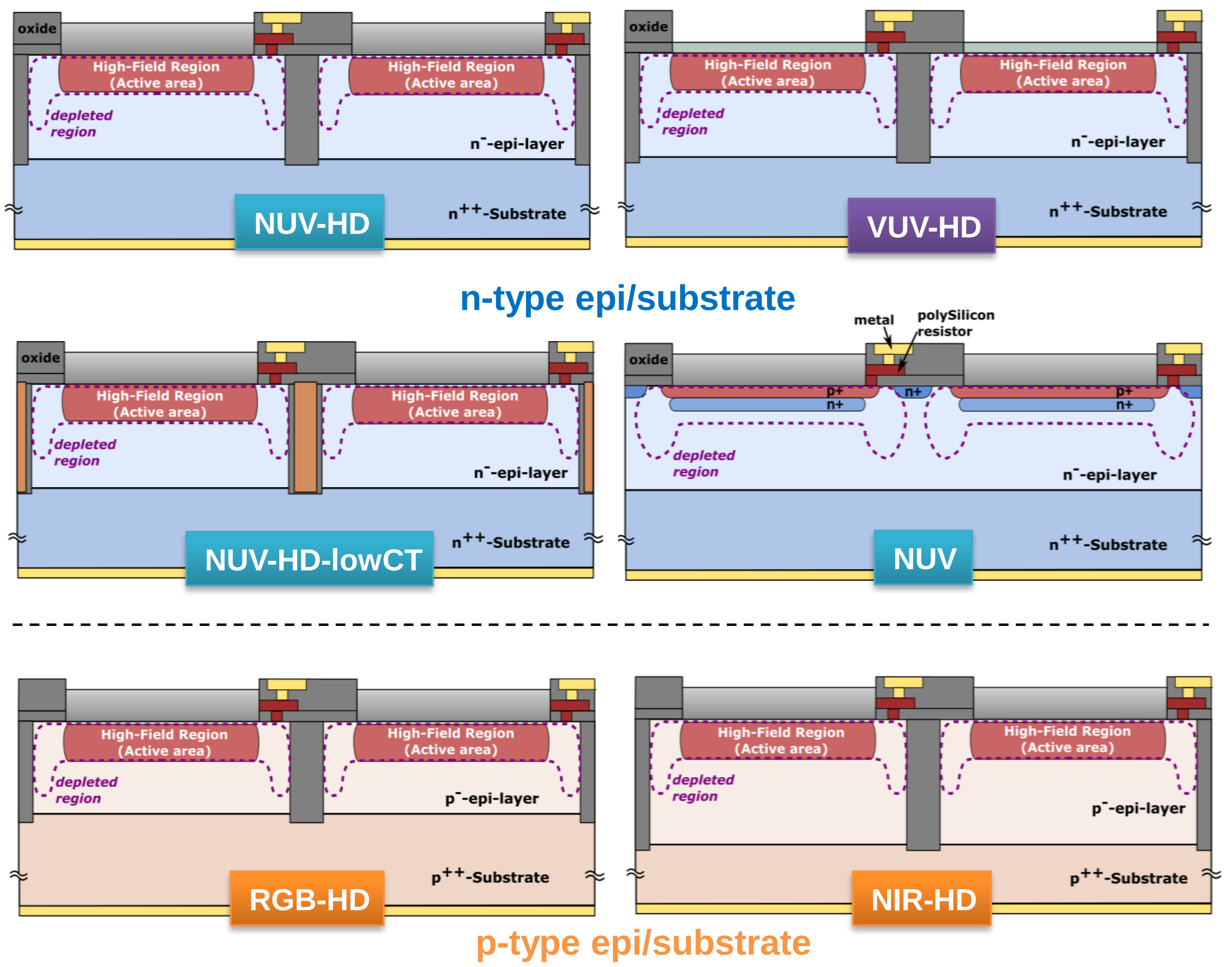
- **Not only primary noise (DCR),** but also "***correlated noise***"
  - Afterpulsing (trapping/de-trapping & optical)
  - Optical crosstalk between pixels





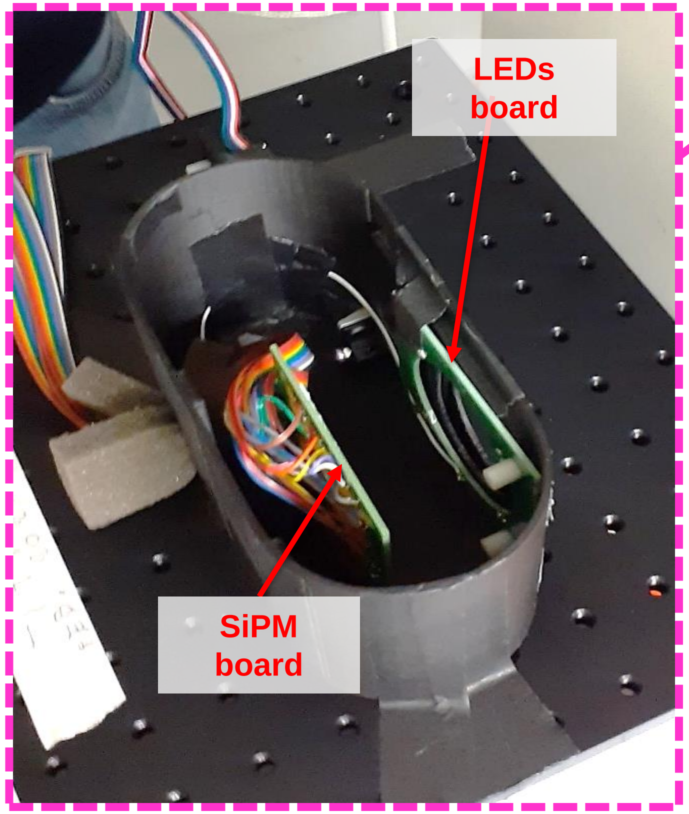
FBK SiPMs technologies → irradiated and tested

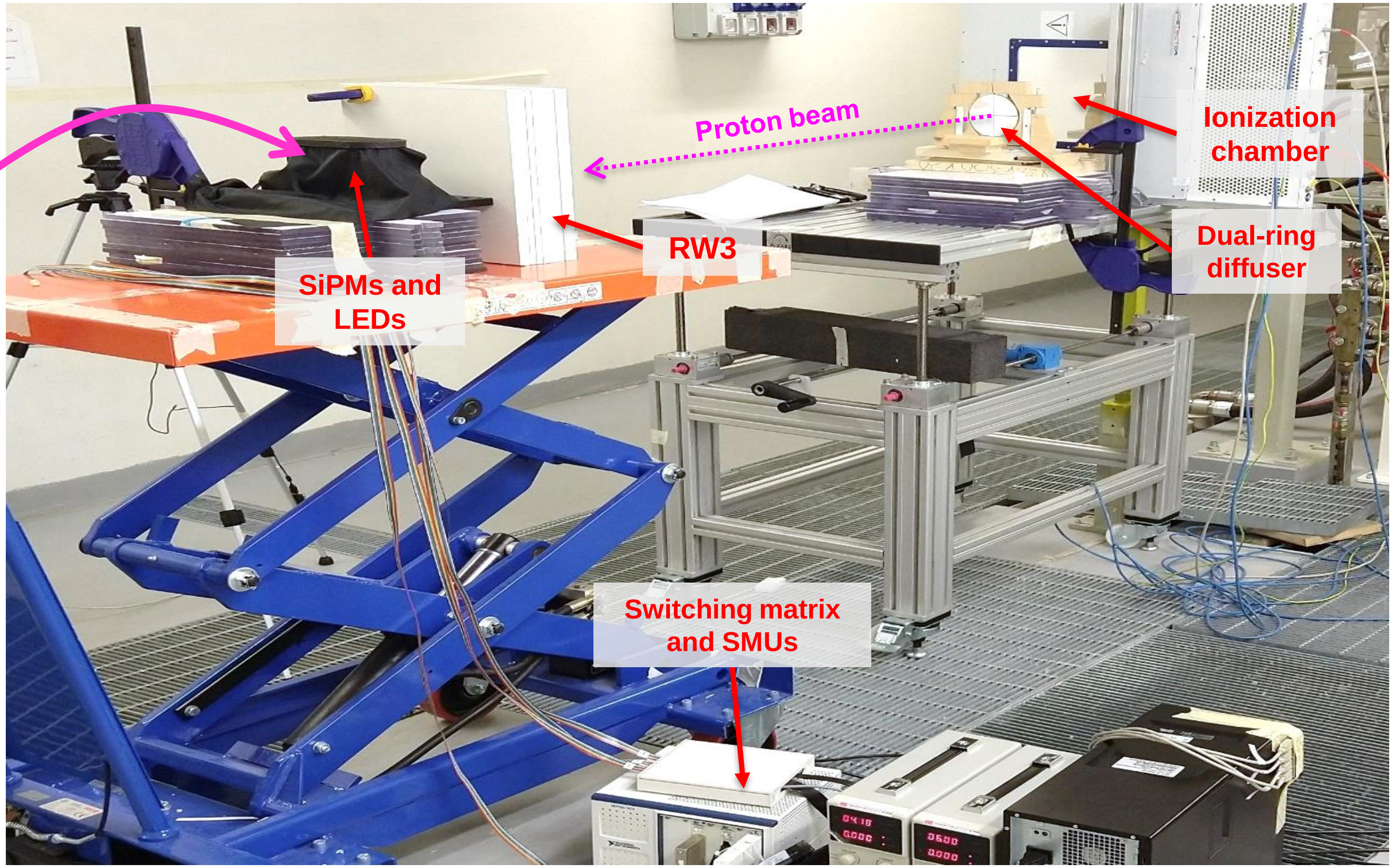




- Many different SiPM technologies, tailored for different applications → **interesting to compare radiation effects**.

Proton irradiation: irradiation setups





- **Proton-therapy center in Trento** → IBA cyclotron
- "**Dual ring setup**": 98% uniformity on ~6 cm diameter. → 148 MeV source + inhibitor → **74 MeV protons**
- Fluences: $3 \cdot 10^{7}$ n_{eq}/cm^2, … … , **$6.4 \cdot 10^{11}$ n_{eq}/cm^2**

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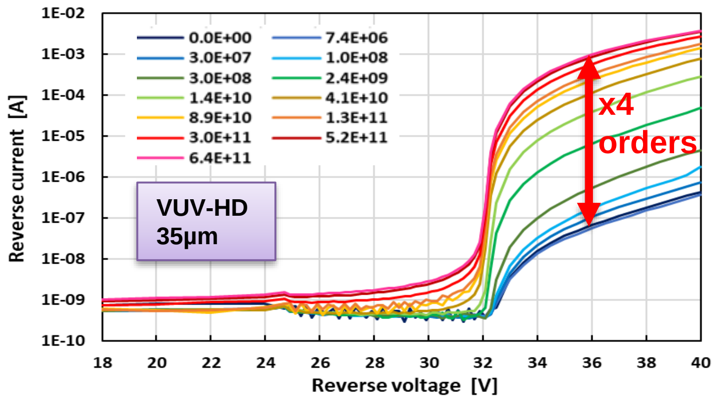
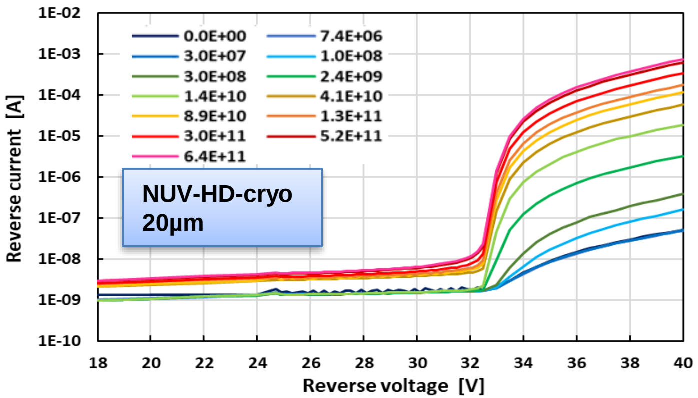
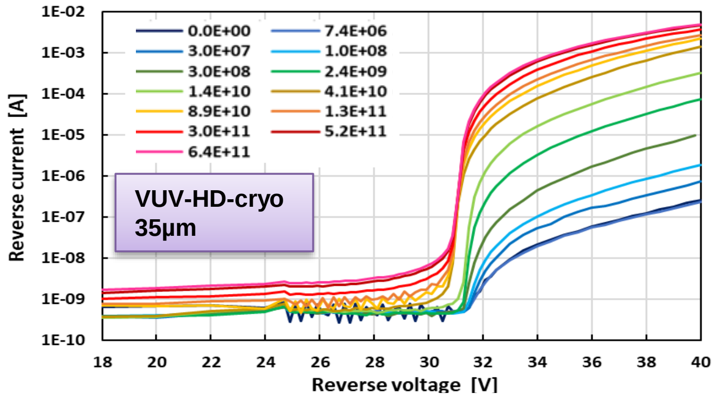
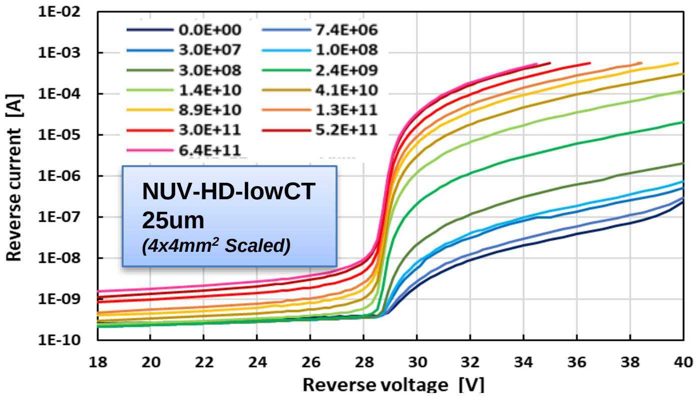
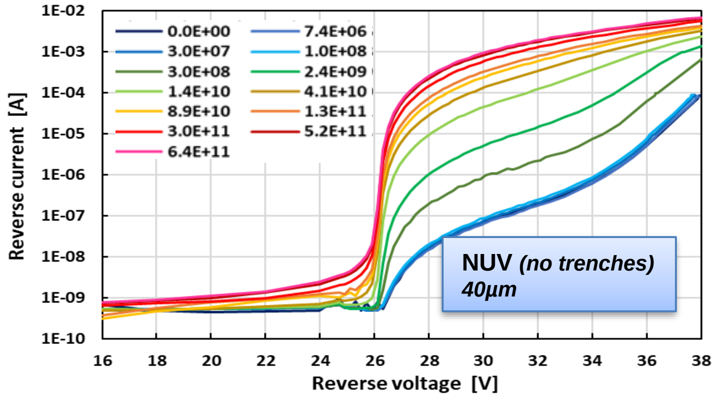
Proton irradiation: online IV measurements (in dark)

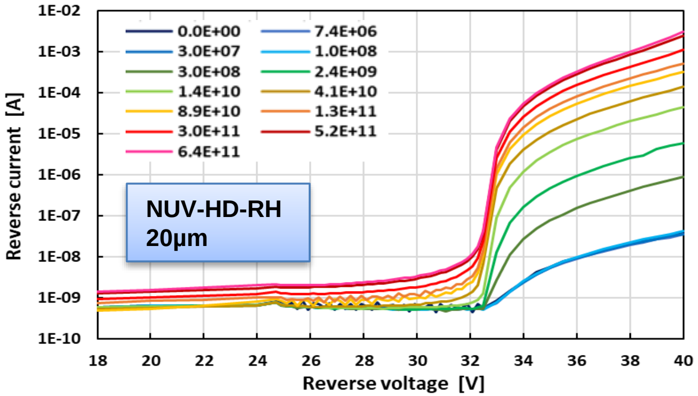


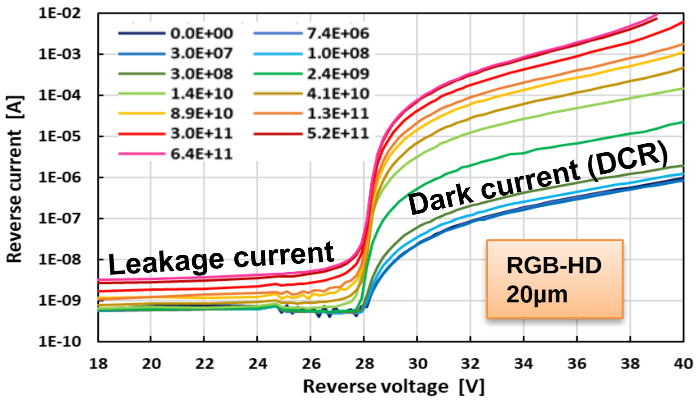


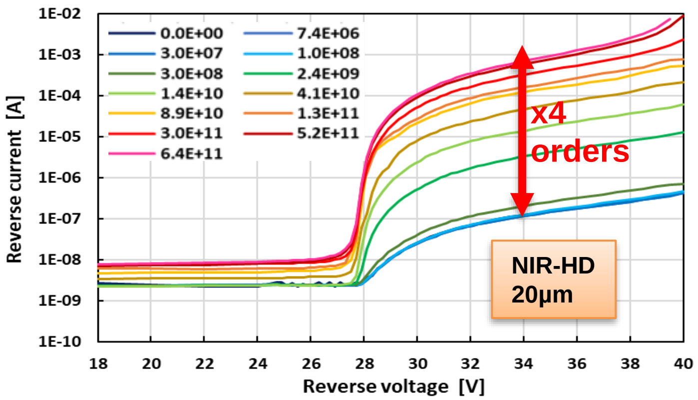








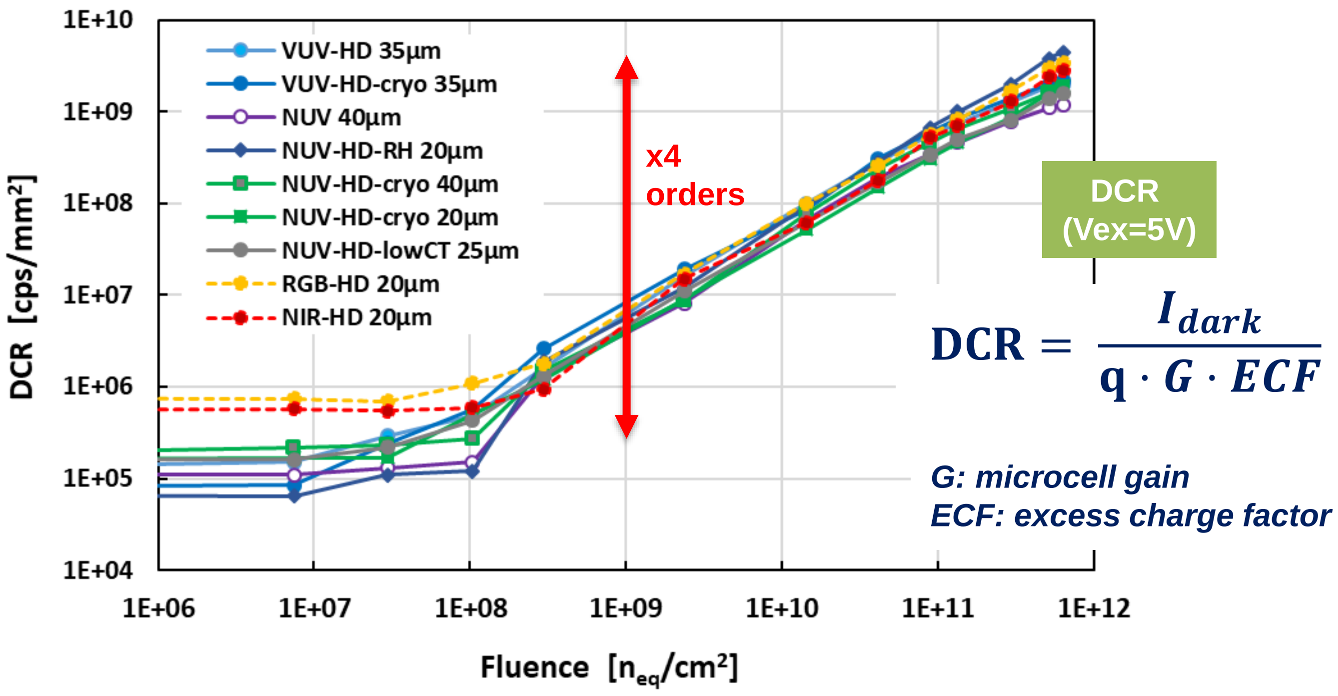




Neutron-eq. fluence:

- 0.0E+00
- 3.0E+07
- 3.0E+08
- 1.4E+10
- 8.9E+10
- 3.0E+11
- 6.4E+11
- 7.4E+06
- 1.0E+08
- 2.4E+09
- 4.1E+10
- 1.3E+11
- 5.2E+11
- Ann.

Proton irradiation: dark current and DCR variation

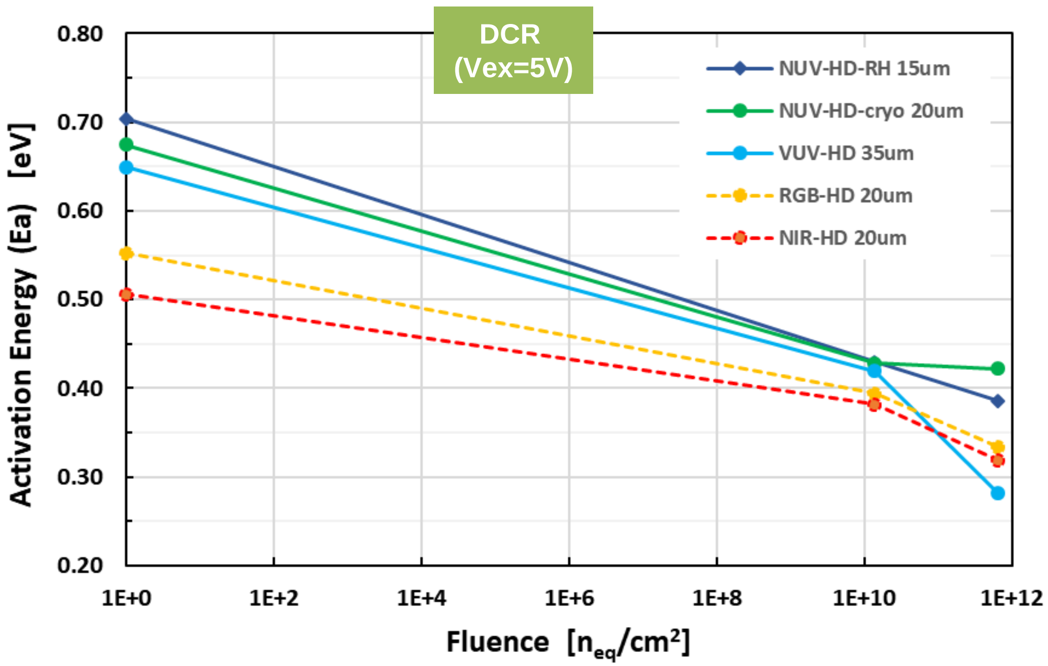


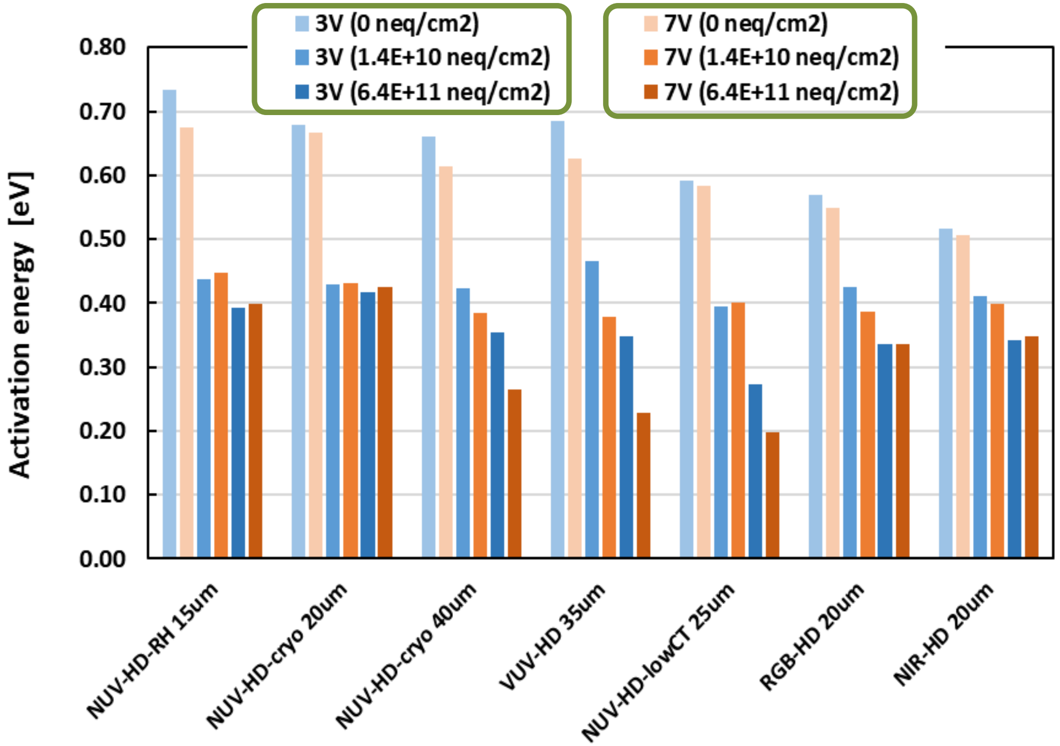
$$DCR = \frac{I_{dark}}{q \cdot G \cdot ECF}$$

G: microcell gain
ECF: excess charge factor

- **DCR (primary SRH generation from the bulk) → estimated from the reverse current:**
  we considered ECF and Gain not changing with irradiation (verified up to $1{\cdot}10^{11}$ n_{eq}/cm^2)
- **Random fluctuations starting at $10^7 \div 10^8$ n_{eq}/cm^2**
- **increment of ~4 orders of magnitude at $6{\cdot}10^{11}$ n_{eq}/cm^2 → DCR: $10^9 \div 10^{10}$ cps/mm²**
  (~10^6 cps/SPAD)

Proton irradiation: DCR activation energy





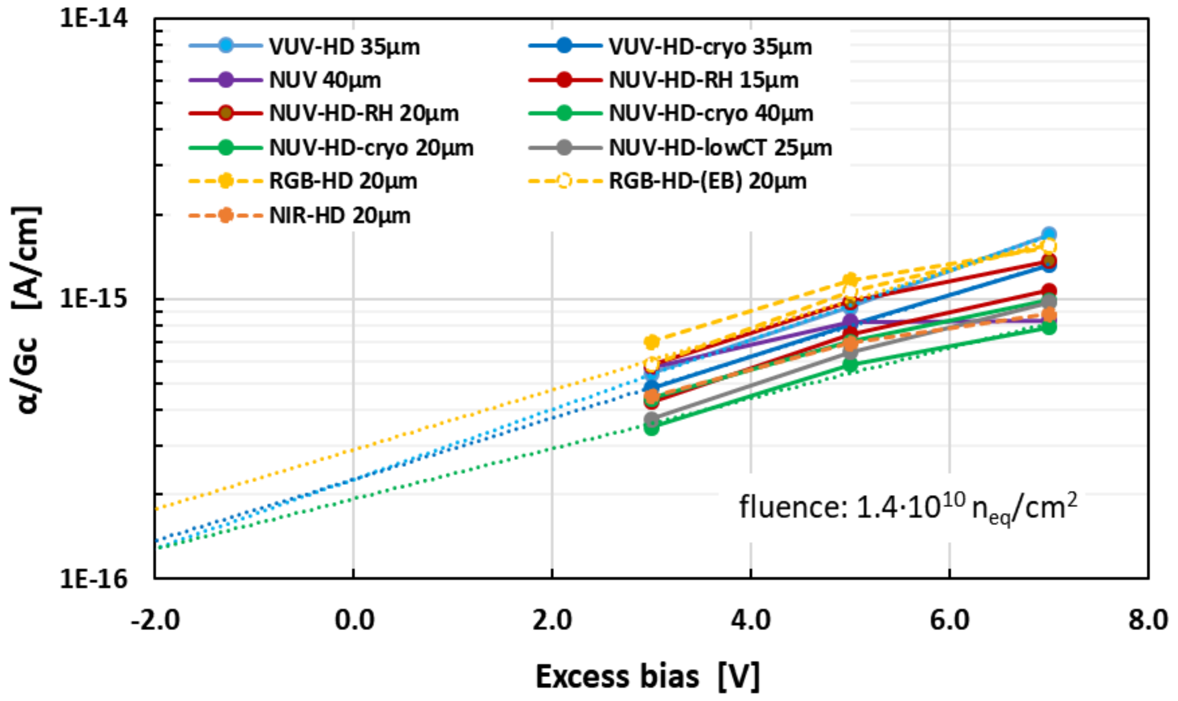
- **Reverse IV measured in the temperature range [-30°C, +30°C]**
  1. Samples not irradiated
  2. PCB-A (irrad at $1.4\cdot10^{10}$ n_{eq}/cm^2 + annealing)
  3. PCB-B (irrad at $6.4\cdot10^{11}$ n_{eq}/cm^2 + annealing)

- **Reduction of temperature dependence (activation energy) with fluence**

  → temperature needed to halve the DCR: from ~8°C to ~15°C.

- **Dependence of activation energy on excess bias → effect of electric field + possible saturation effects**

Proton irradiation: "damage factor"



- *Data for sample w/o annealing.*
- *Measured at room temperature*

- To quantify the damage in the bulk: "Current related damage factor" (α)
  - valid for detectors without gain

$$\alpha = \frac{\Delta I}{\Phi_{eq} V}$$

$\Phi = fluence\ (1MeV\ neutron\ eq.)$
$V = depleted\ volume$

- **But: variation for SiPM** *(Geiger-mode , with internal gain):*
  - normalization by Current gain (G_C)

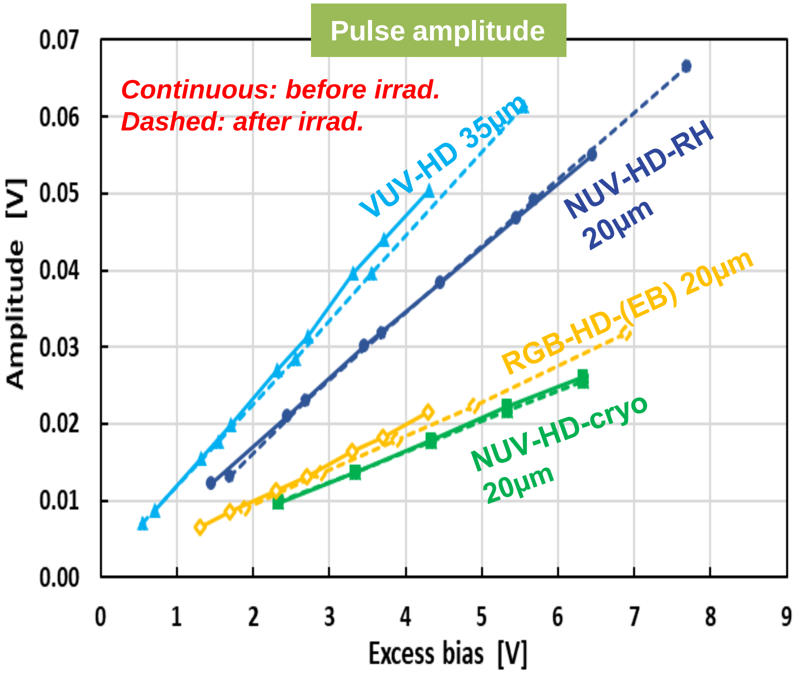
$$\frac{\alpha}{G_C} = \frac{\Delta I}{\Phi_{eq} \cdot V \cdot G \cdot ECF} = \frac{\Delta I}{\Phi_{eq} \cdot V \cdot G_c} \approx \frac{\Delta DCR * q}{\Phi_{eq} V}$$

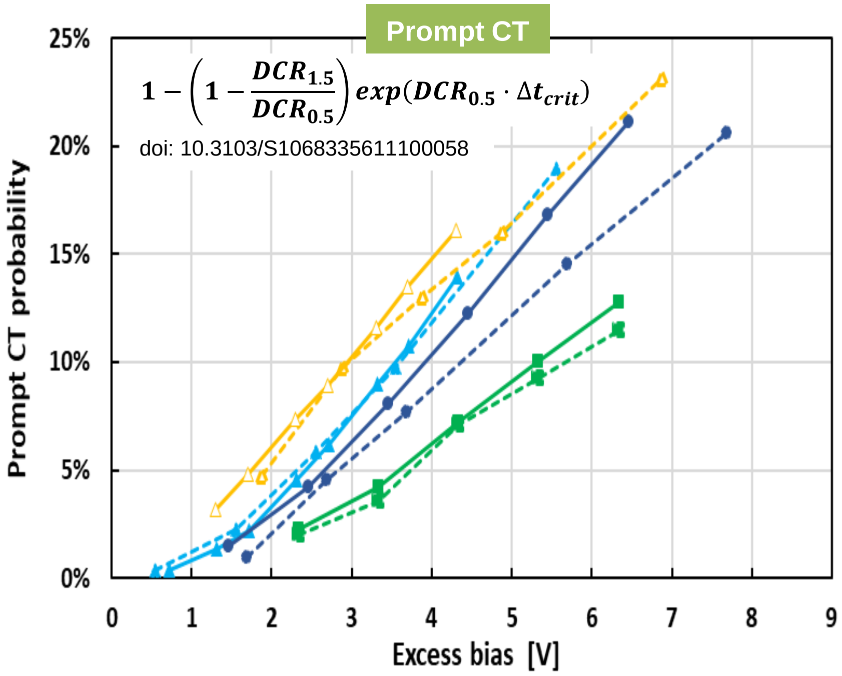
$ECF = Excess\ charge\ factor$
G = microcell gain
$G_c =$ "current gain"

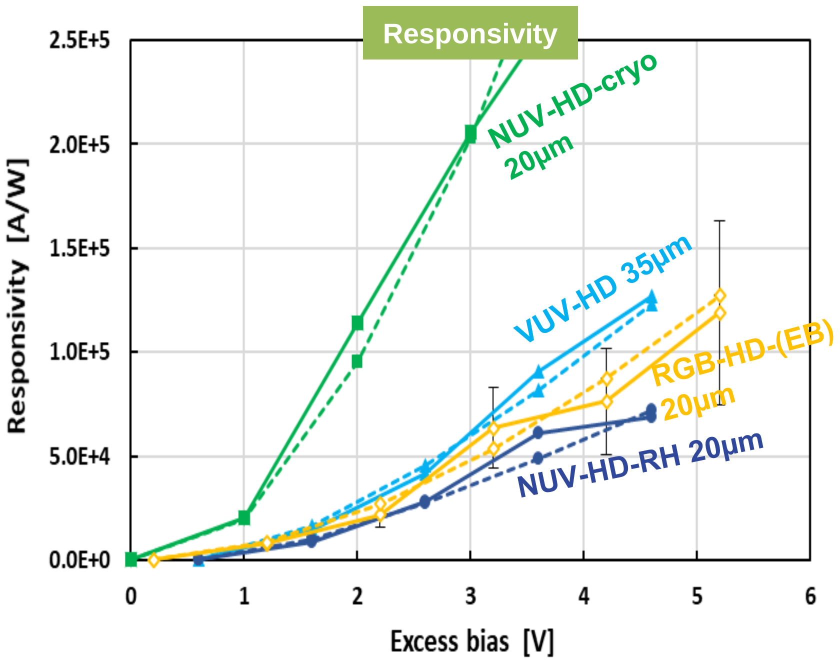
- Intercept at low biases (low Electric field) → *more in agreement with literature*

[1] M. Moll (2018) https://doi.org/10.1109/TNS.2018.2819506

Proton irradiation: functional parameters





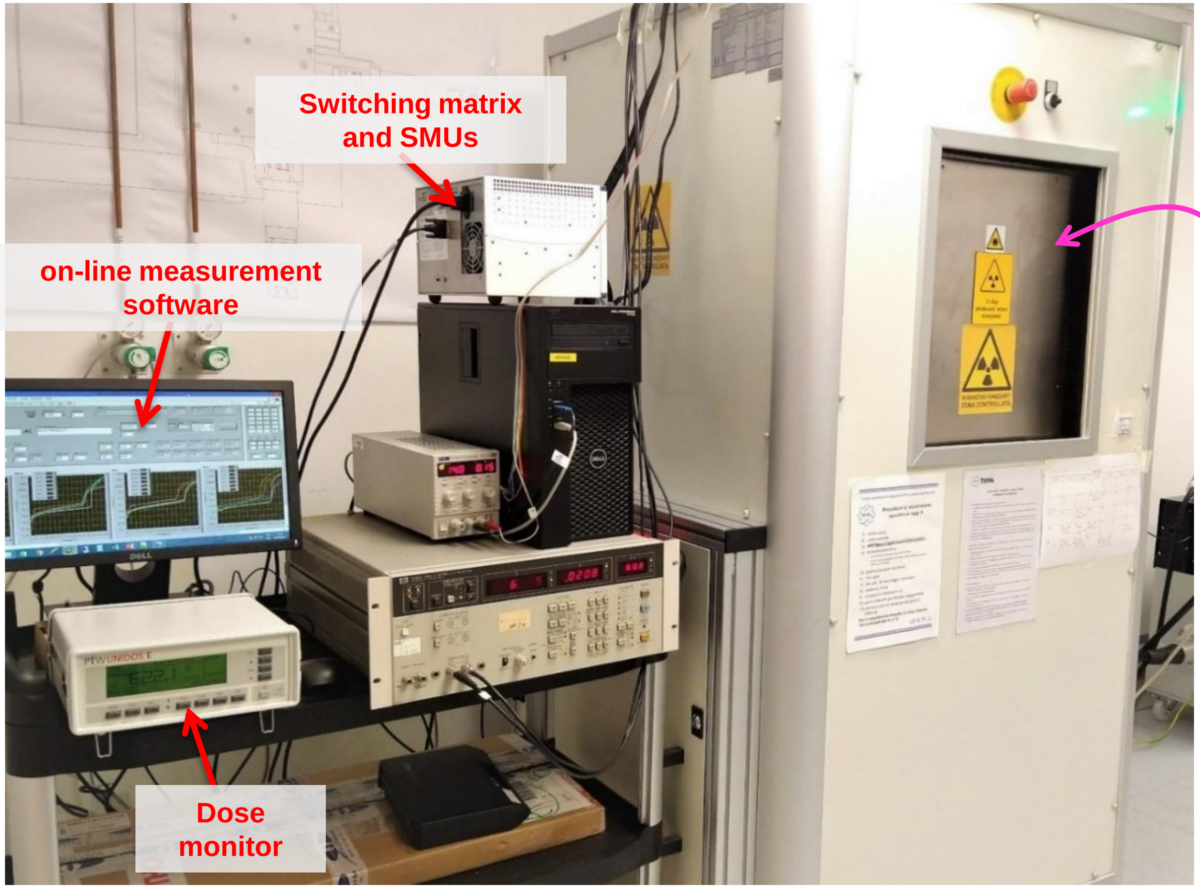


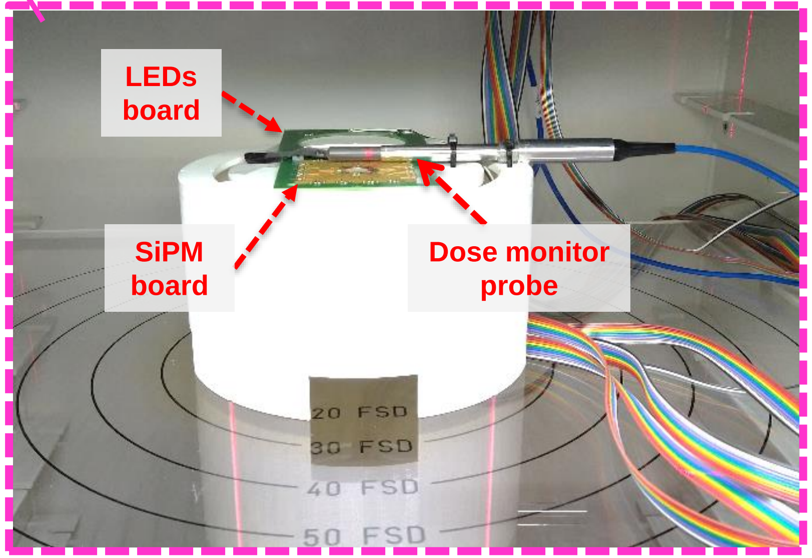
- **Functional measurements @ -40°C**
  - Pulse amplitude;
  - Prompt crosstalk probability *(calculated considering the pile-up effect at high DCR):*
  - Responsivity *(detection efficiency)*

→ *no relevant variations (up to the investigated fluence)*

But: after irradiation
→ high noise → loss of ph. num. resolution

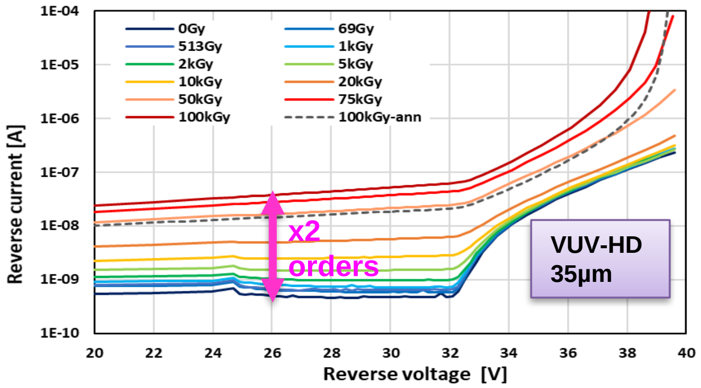
X-ray irradiation: irradiation setups

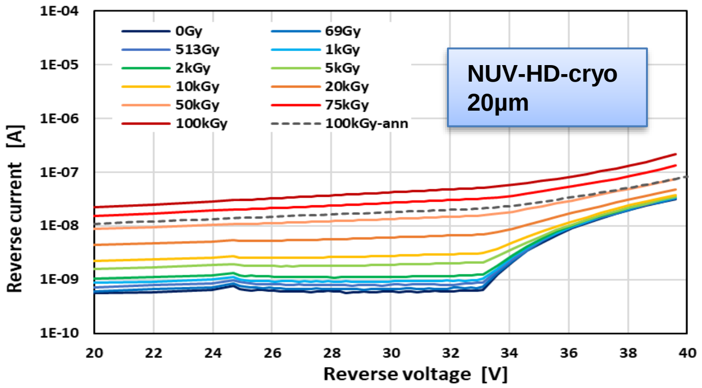


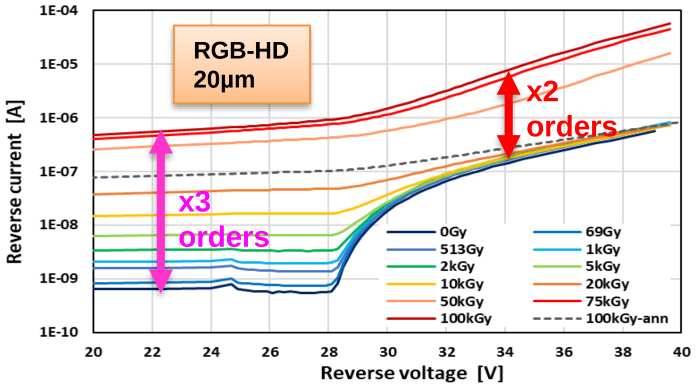


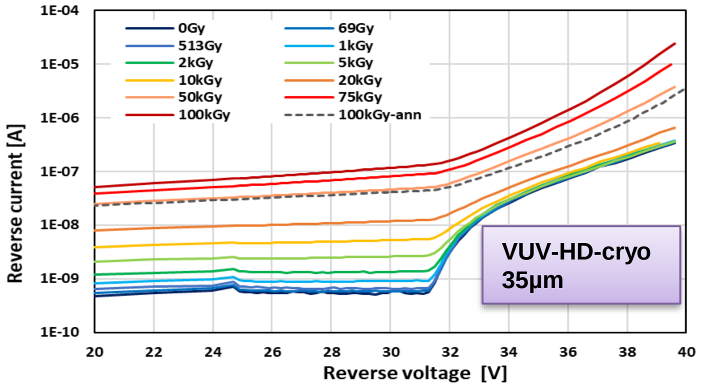
- **X-ray machine at TIFPA center in Trento**
  - W-anode + Al filter (180um): emission up to 40kV → peaks:7.6 - 12 keV
- Doses: 69 Gy, … … , 100 kGy *(in Silicon)* *[dose monitor pre-calibrated in a different setup]*

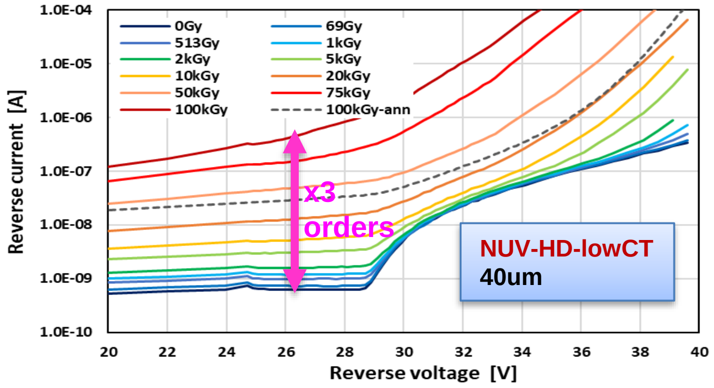
X-ray irradiation: online IV measurements (in dark)

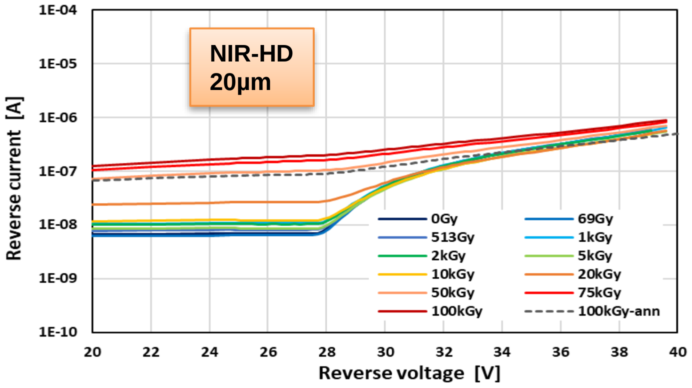


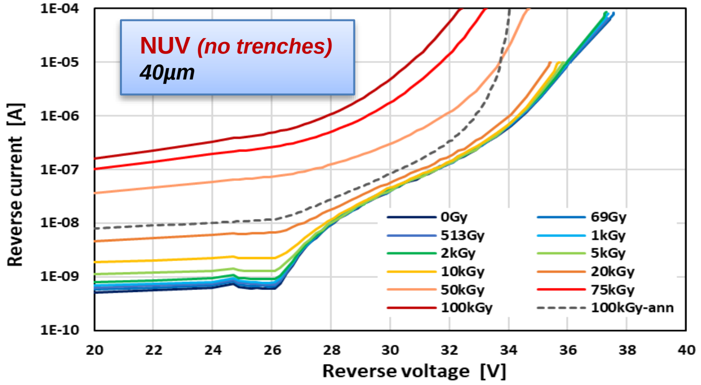


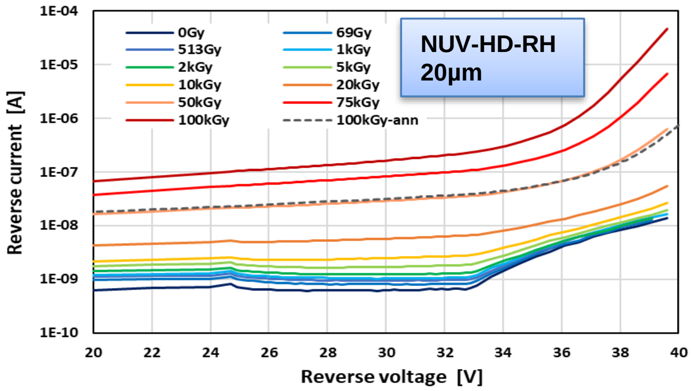








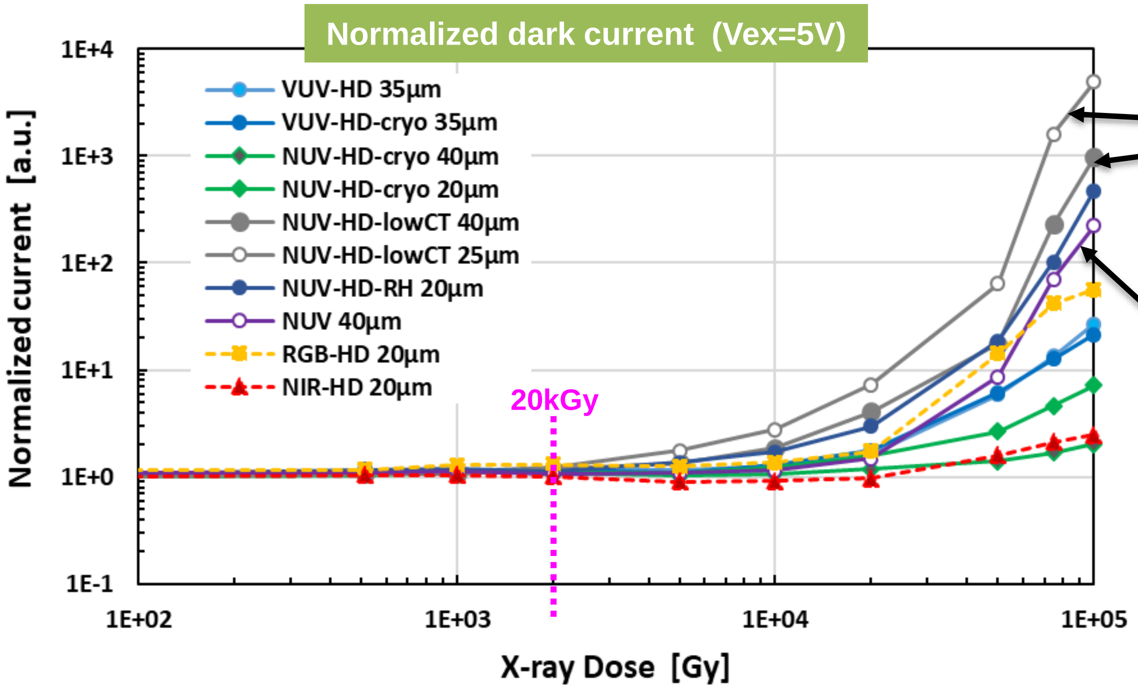


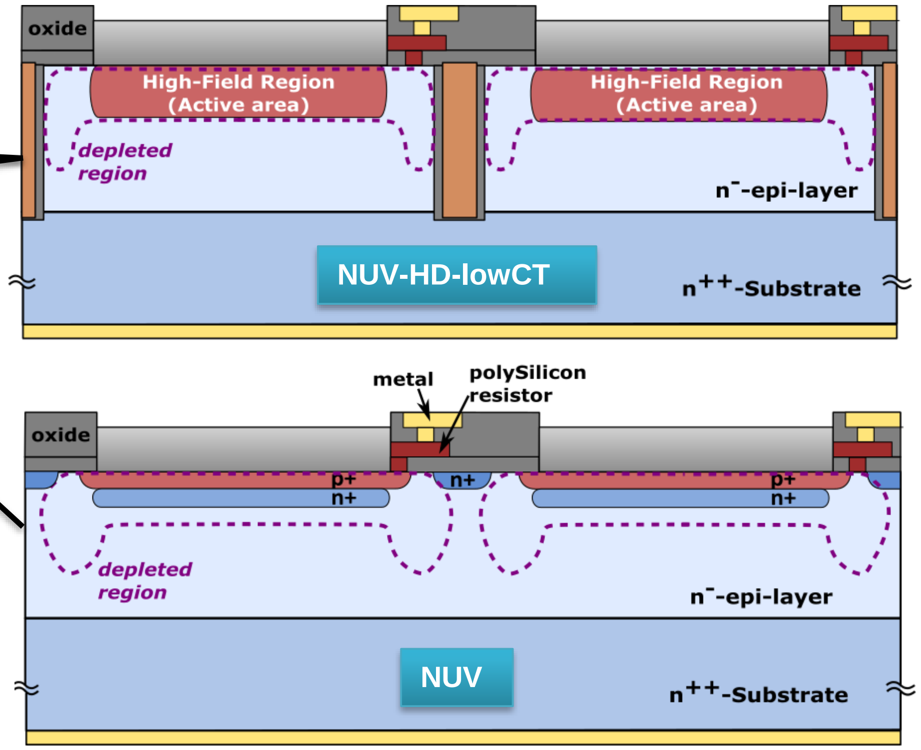


X-ray dose (in Silicon):

- 0Gy
- 69Gy
- 513Gy
- 1kGy
- 2kGy
- 5kGy
- 10kGy
- 20kGy
- 50kGy
- 75kGy
- 100kGy
- 100kGy-ann

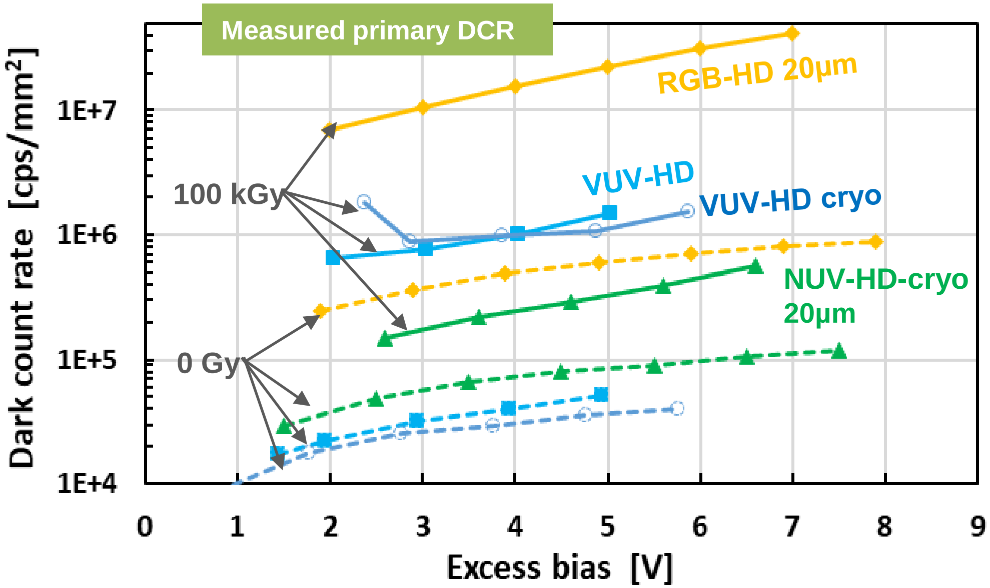
X-ray irradiation: dark current

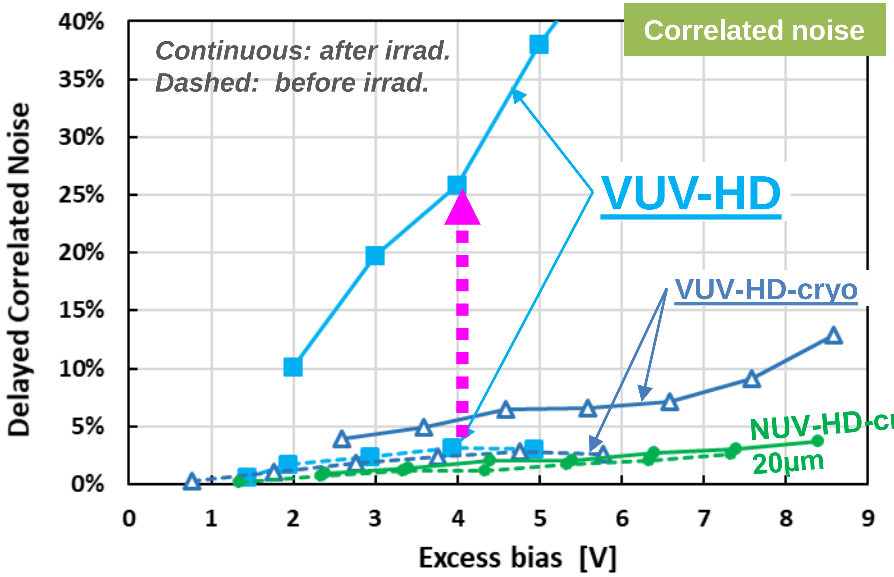


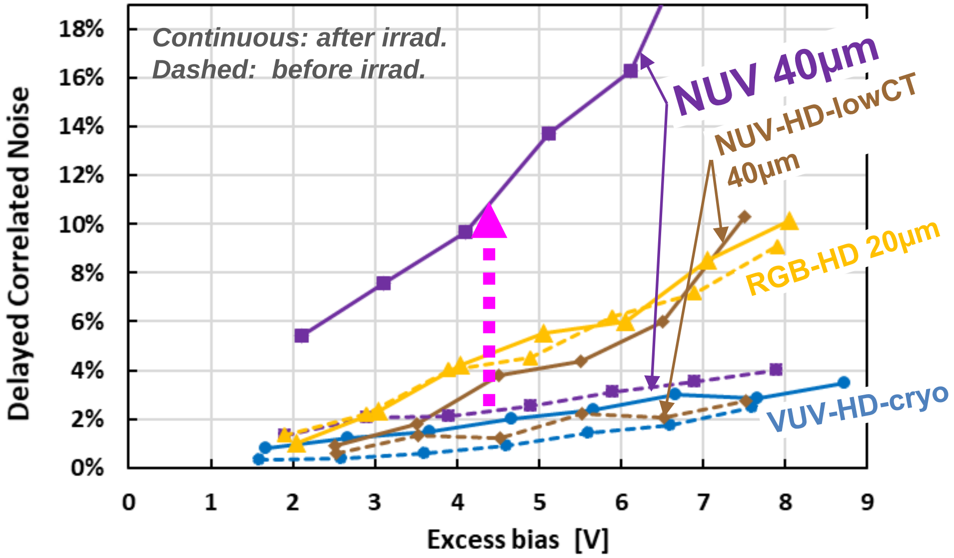


- **Biggest variations on IV curves:**
  - NUV-HD-lowCT (with abs material in trench)
    - → *Electric field modification at the border of AA*
  - NUV (w/o trench)
    - → *Loss of isolations between cells and/or modification of edge electric fields*

X-ray irradiation: noise and correlated-noise

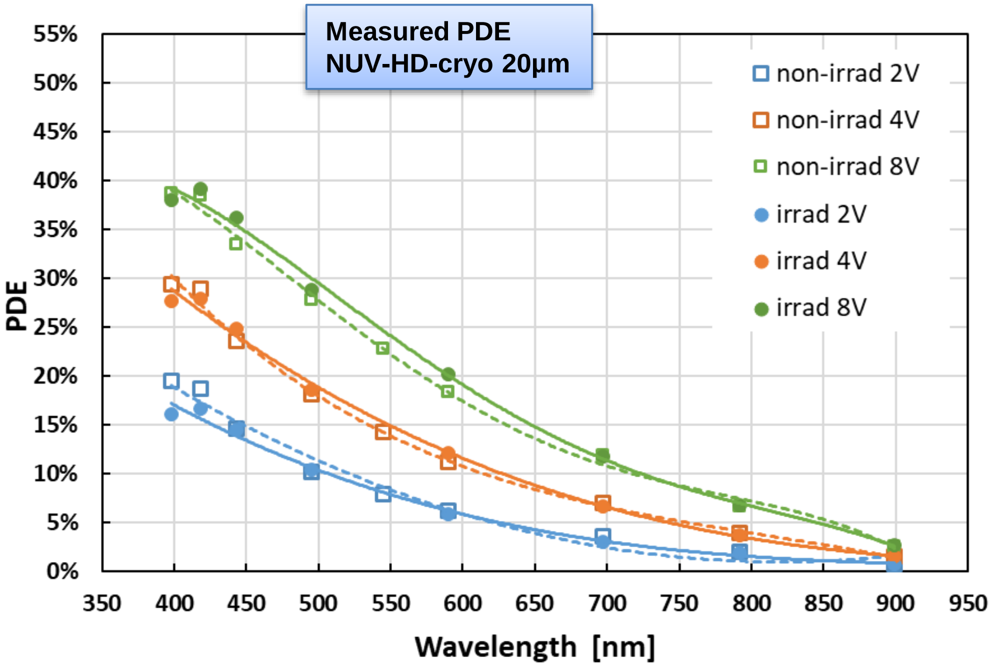


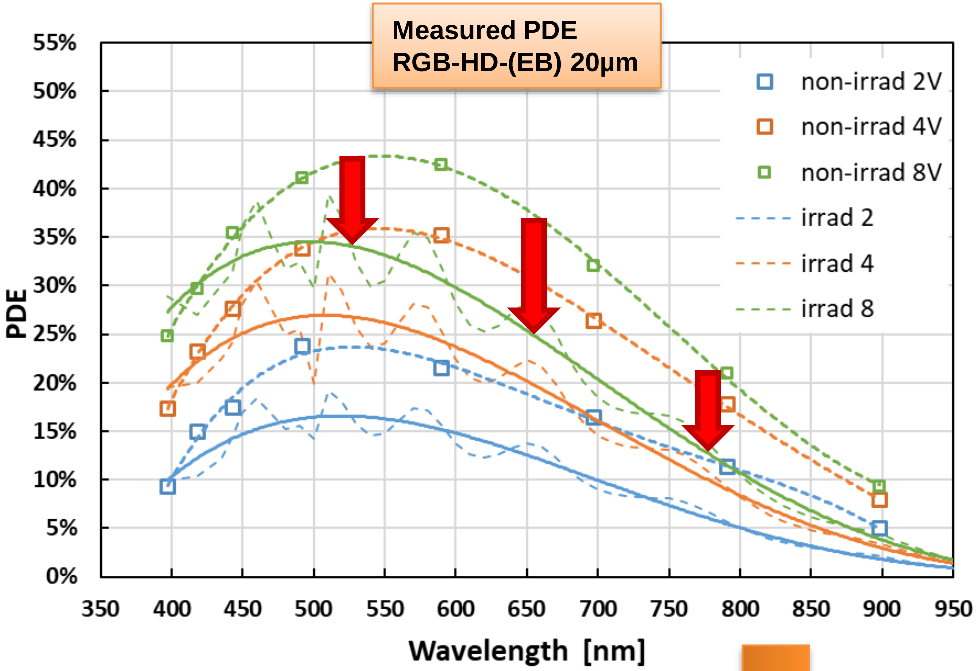


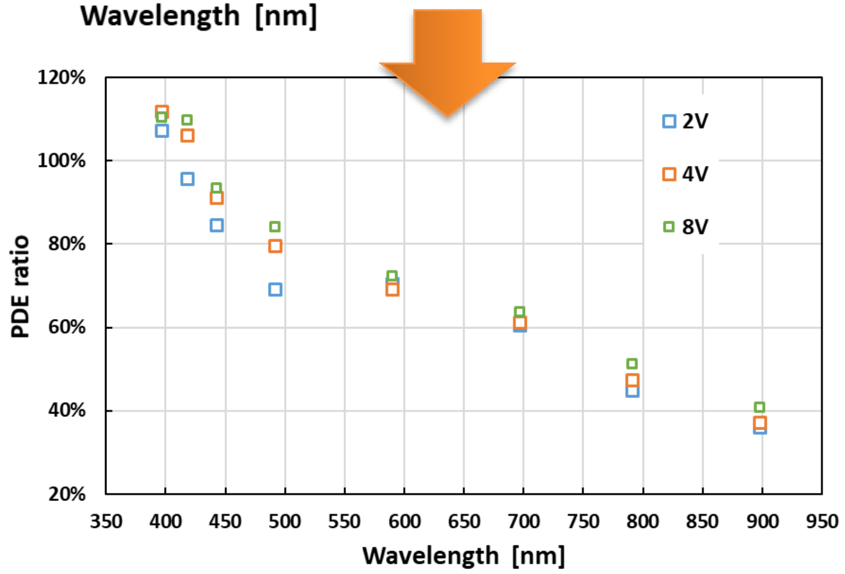


- **Primary DCR increment → large spread among tech.**
  - 0.5 ÷ 2.5 orders of magnitude
- **Big increment of correlated noise (in some SiPMs)**
  - NUV (w/o trench) and VUV-HD (modified ARC)

X-ray irradiation: detection efficiency

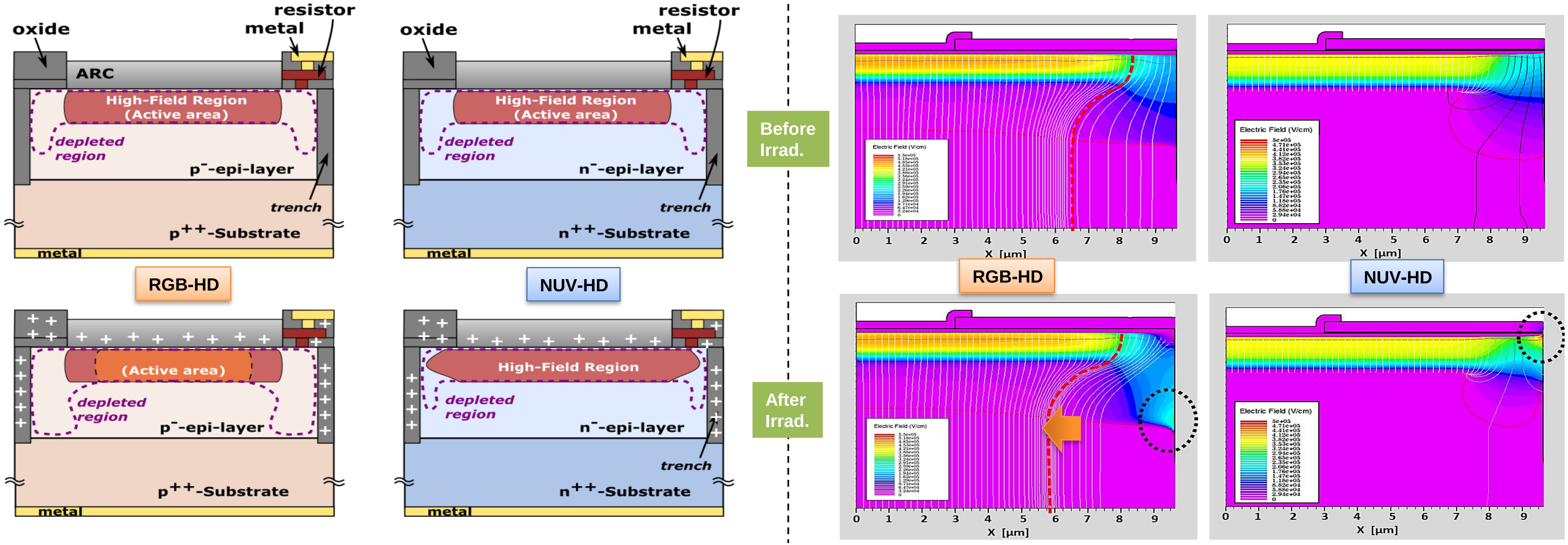






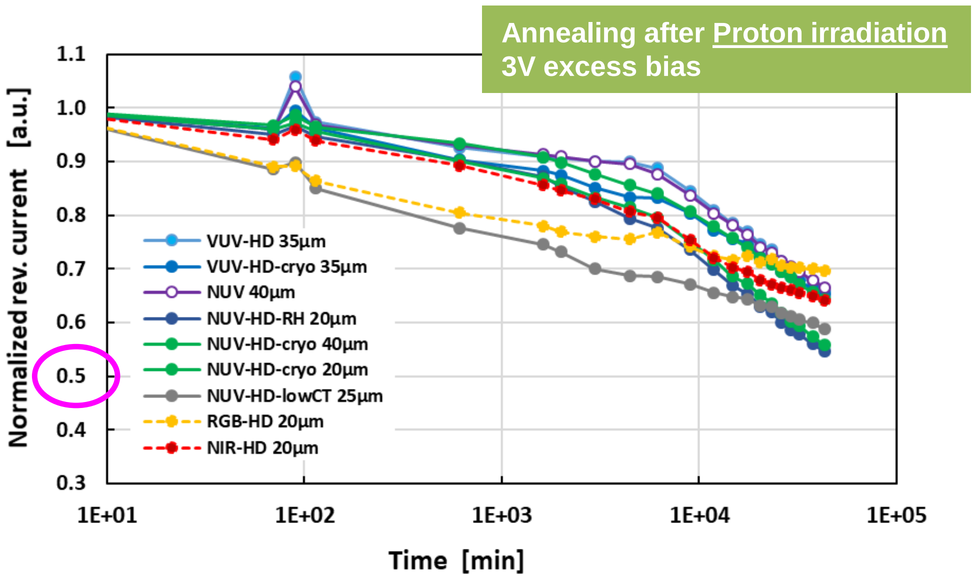
- **Measurements of the photon detection efficiency (PDE)**
  - No variation in the NUV-HD SiPMs (n-type epi/sub.)
  - Important variation in the RGB-HD (p-type epi/sub.)
    → More important at high wavelengths

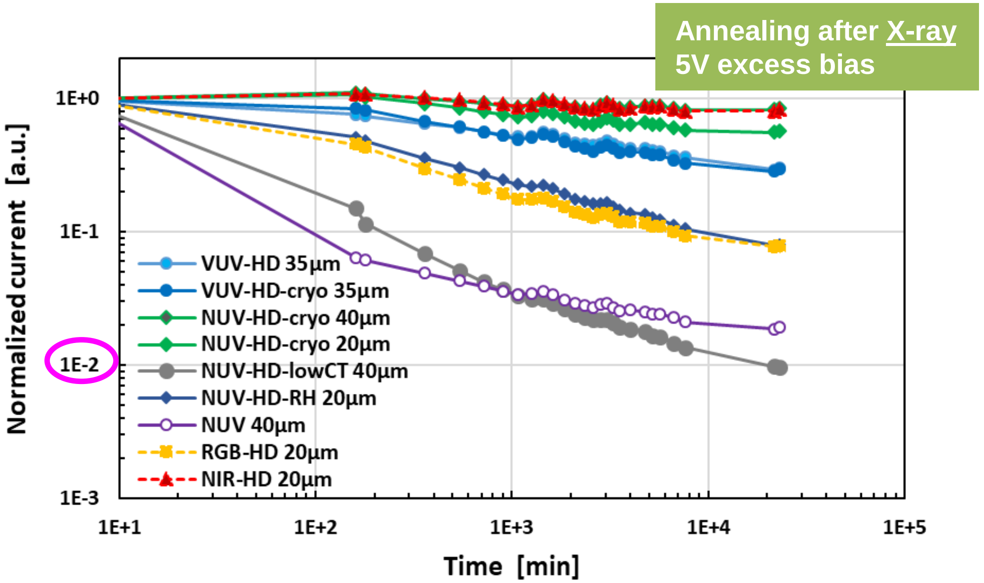
X-ray irradiation: structure modifications



- **Effect of X-ray irradiation → positive charge trapped in dielectric layers (e.g. SiO_2)**
  - **P-type epi →** additional electric field peak in depth
    → enhanced border region → lower effective FF
  - **N-type epi →** enhanced electric field close to the trenches (defective region)
    → possible higher DCR and Afterpulsing

Room temperature annealing



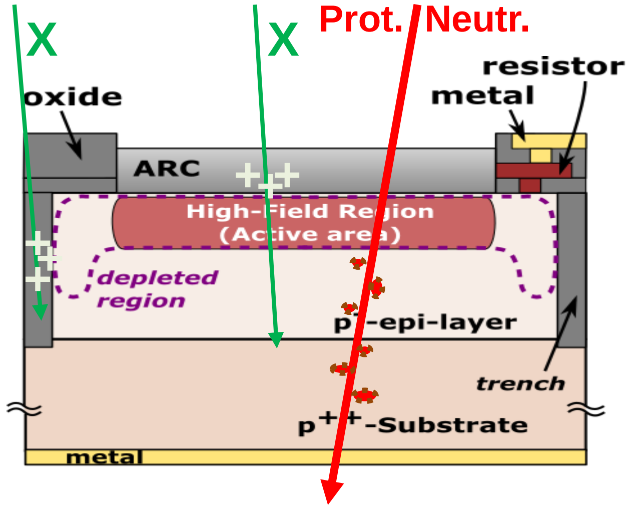


- ***Studied room-temperature annealing*** *(Measured 2 times per day for several weeks)*
- **Proton irradiation: exponential decrease (2 slopes)**
  - Max factor 0.5 recovery → need high temperatures
- **X-ray irradiation: exponential decrease (1 slopes)**
  - Much higher DCR recovery

Conclusions

- **Tested the effect of Ionizing and non-ionizing radiation**
  - Fluencies/doses compatible with experiments working in space environments

- **Protons at 74 MeV, up to $6 \cdot 10^{11}$ n_{eq}/cm^2**
  - more than 4 orders of magnitude increment on primary DCR
  - Reduction of activation energy → cooling less effective
  - No relevant modification of all other SiPM functional parameters



- **X-ray at 40 keV, up to 100 kGy**
  - Moderate increment of primary noise (DCR),
  - Important modification of the internal electric field profiles and functional parameters of SiPMs:
    - N-type epi/sub structures (p-on-n junction) → increment of DCR and afterpulsing probability
    - P-type epi/sub structures (n-on-p junction) → reduction of effective AA, thus of PDE

Ionizing and non-ionizing radiation damage on Silicon Photomultipliers

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