Radiation Damage on SiPM for High Energy Physics Experiments in space missions

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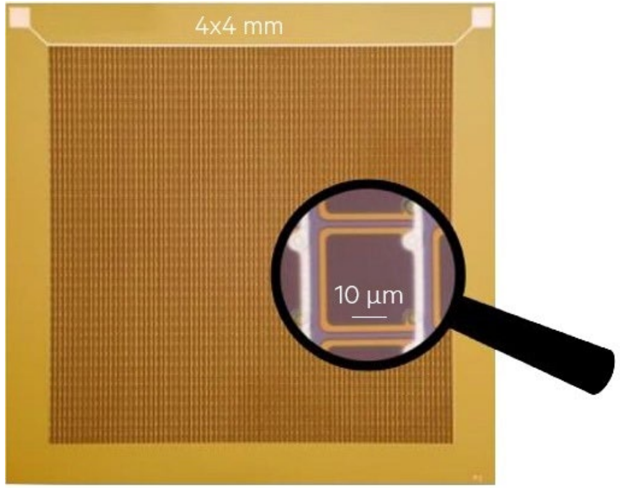
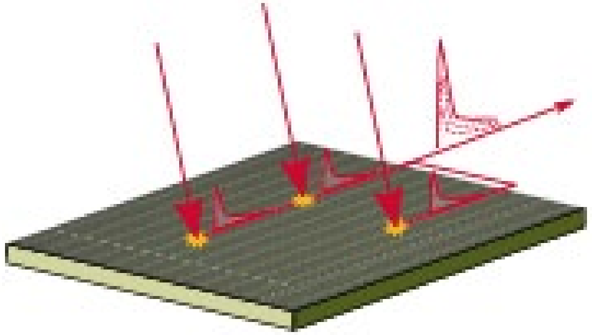
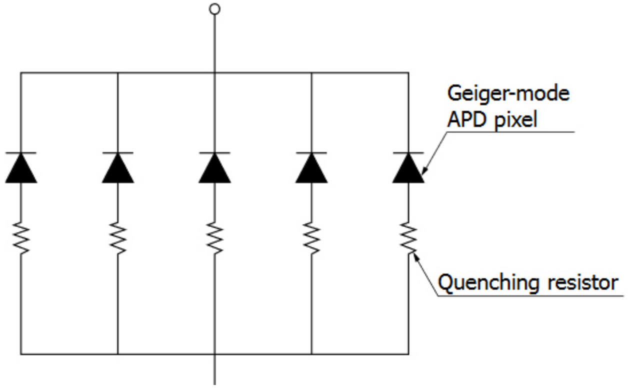
Silicon Photomultiplier (SiPM)

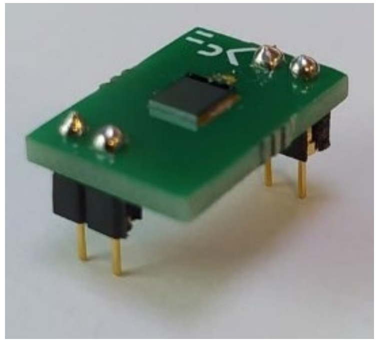
A SiPM consists of an array of cells (pixels) connected in parallel. Each cell is a SPAD (Singe Avalanche Photo Diode) operating in Geiger mode and is coupled with the others by a metal or polysilicon quenching resistor.



- Size of a microcell = from 10 µm to 100 µm ;
- Active areas ranging from to 1x1 mm^2 to 6x6 mm^2 ;
- Spectral sensitivities from UV to IR (350 nm – 650 nm).







Picture from Technology of Broadcom-SiPM and Hamamatsu Technical Note

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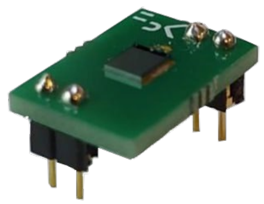
SiPMs in aerospace applications

Current and future space missions are starting to employ SiPMs instead of classical Photomultiplier Tubes to read out the scintillator light emission.



Why SiPMs?

- High gain → $(10^5\ to\ 10^7)$;
- Compactness;
- Operated with low bias → $25 - 70\ V$;
- Insensitive to magnetic fields → up to few T;
- Low cost.

In this work we tested FBK NUV-HD-low crosstalk SiPMs designed for the High Energy cosmic Radiation Detection (HERD) project, produced in 2022 by Fondazione Bruno Kessler (FBK) on Trento.

R&D and characterization of technologies for ground-based (CTA) and space applications (HERD, NUSES, APT…) on going since >10 years at INFN Bari.

Challenges:

- **Radiation hardness!**

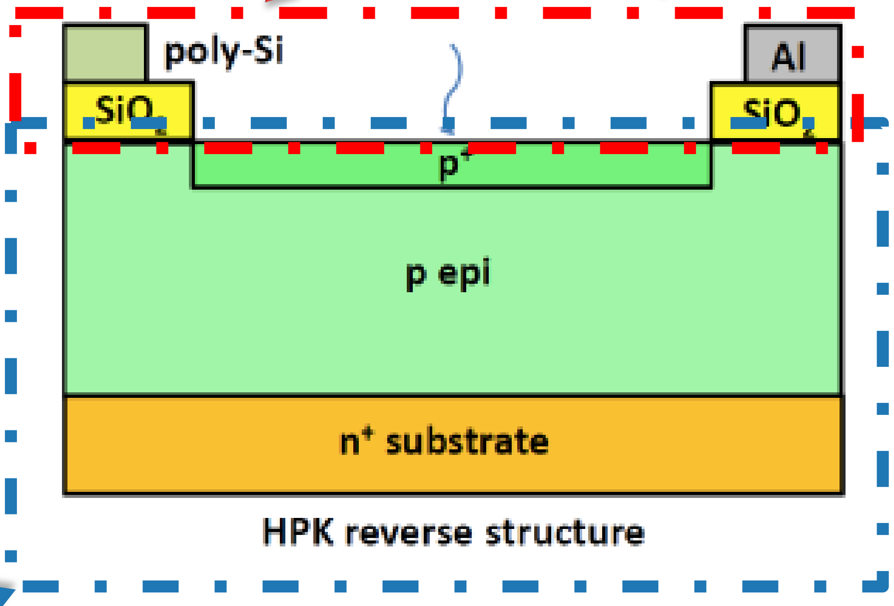
Radiation damage in silicon

Two types of radiation damage in silicon:

- **Surface damage** due to Ionizing Energy Loss (IEL):
  accumulation of charge in the oxide (SiO2), traps at Si-SiO2 interface

  Generate traps at the Si-SiO_2 interface. Fixed positive oxide charge (Nox):
  ➔Change in the electric field (Vbd)
  ➔Accumulation layers
  ➔**Increase in leakage current** by additional surface current.

X-Ray/ electrons
E < 300 keV



- **Bulk damage:** Bulk (Crystal) damage due to Non-Ionizing Energy Loss (NIEL):
  displacement damage, built up of crystal defects.

  Locally distorted Si lattice with new energy states
  ➔ Add donor and acceptor levels
  ➔ **Increase DCR**
  ➔ **Increase after-pulsing**
  ➔ **Change in charge collection**

gamma/ electrons
E > 300 keV
protons / neutrons

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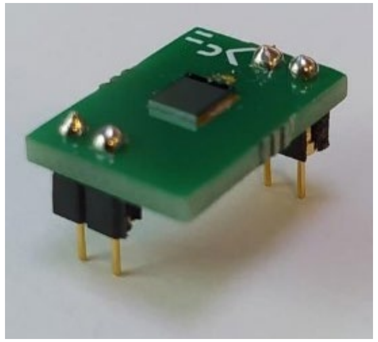
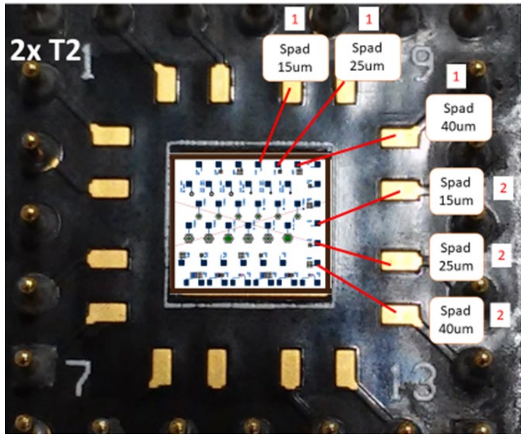
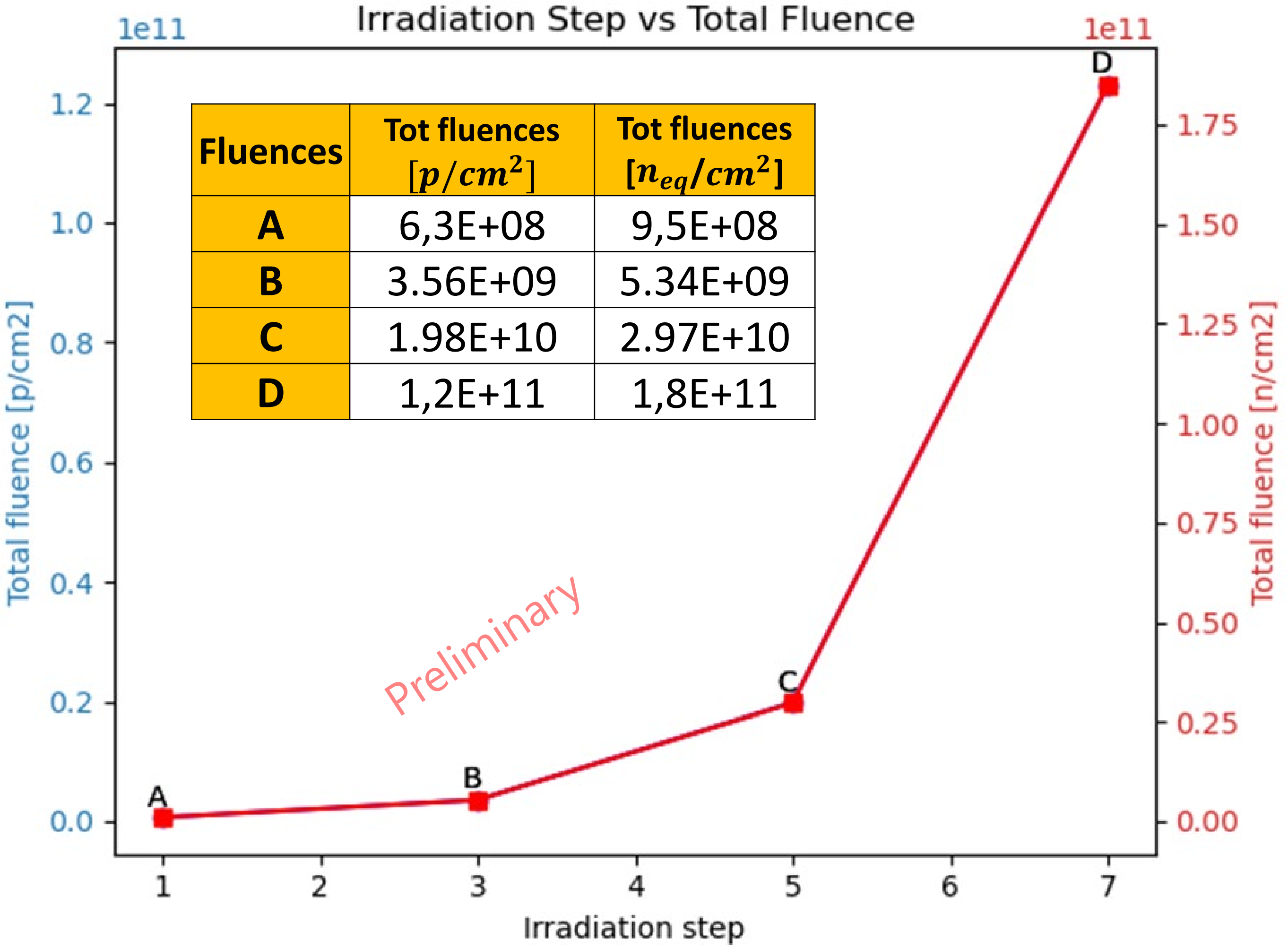
Radiation Testing on SiPMs

We report the effect on SPADS and SiPM of the irradiation with protons with four fluence levels up to $1\text{x}10^{11}$ p/cm^2 on SiPMs NUV-HD-lowCT technology, with different cell pitch (40µm and 15µm).



https://arxiv.org/abs/2405.07191





Fluences	Tot fluences $[p/cm^2]$	Tot fluences $[n_{eq}/cm^2]$
A	6,3E+08	9,5E+08
B	3.56E+09	5.34E+09
C	1.98E+10	2.97E+10
D	1,2E+11	1,8E+11

Steps of the total fluences doses of protons at wich SiPM and SPADs under test have been exposed (up to $1\text{x}10^{11}$ p/cm^2*).*

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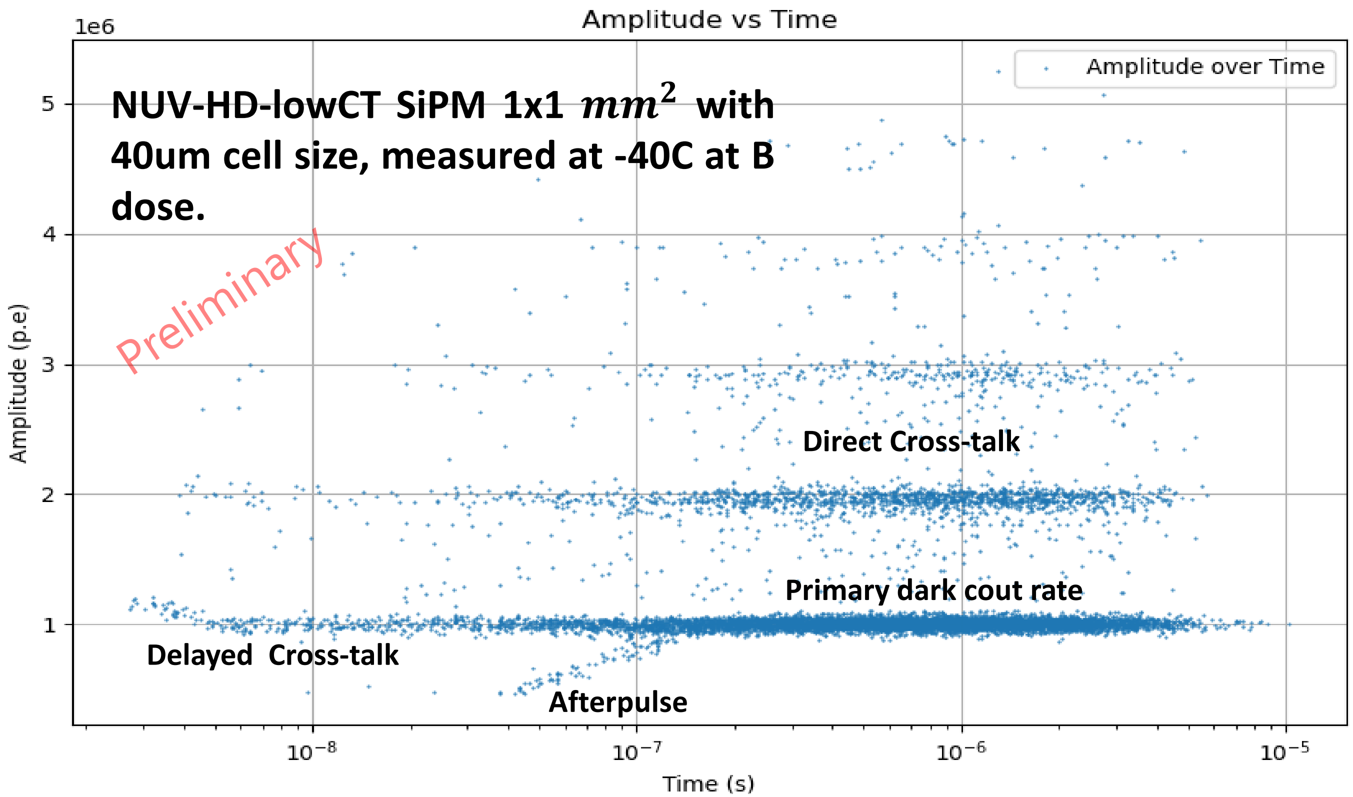
SiPM NUV-HD-lowCrossTalk



SiPM 1x1 40µm at B dose: scatter plot of the pulse amplitude as a function of t its distance from the preceding event at 6V over-voltage.

Noise components :

- ➔ **Direct Cross-talk (DiCT)**
- ➔ **Delayed Cross-talk (DeCT)**
- ➔ **After-pulsing**
- ➔ **Primary dark count rate(DCR)**

Fluences	Tot fluences $[p/cm^2]$	Tot fluences $[n_{eq}/cm^2]$
A	6,3E+08	9,5E+08
B	1,9E+10	2,9E+10
C	3,5E+09	5,3E+09
D	1,2E+11	1,8E+11

Functional tests on the irradiated samples (SPADs and SiPM) confirmed an increment with a fluence of primary DCR and excluded significant variation in breakdown voltage (V_{BD}).

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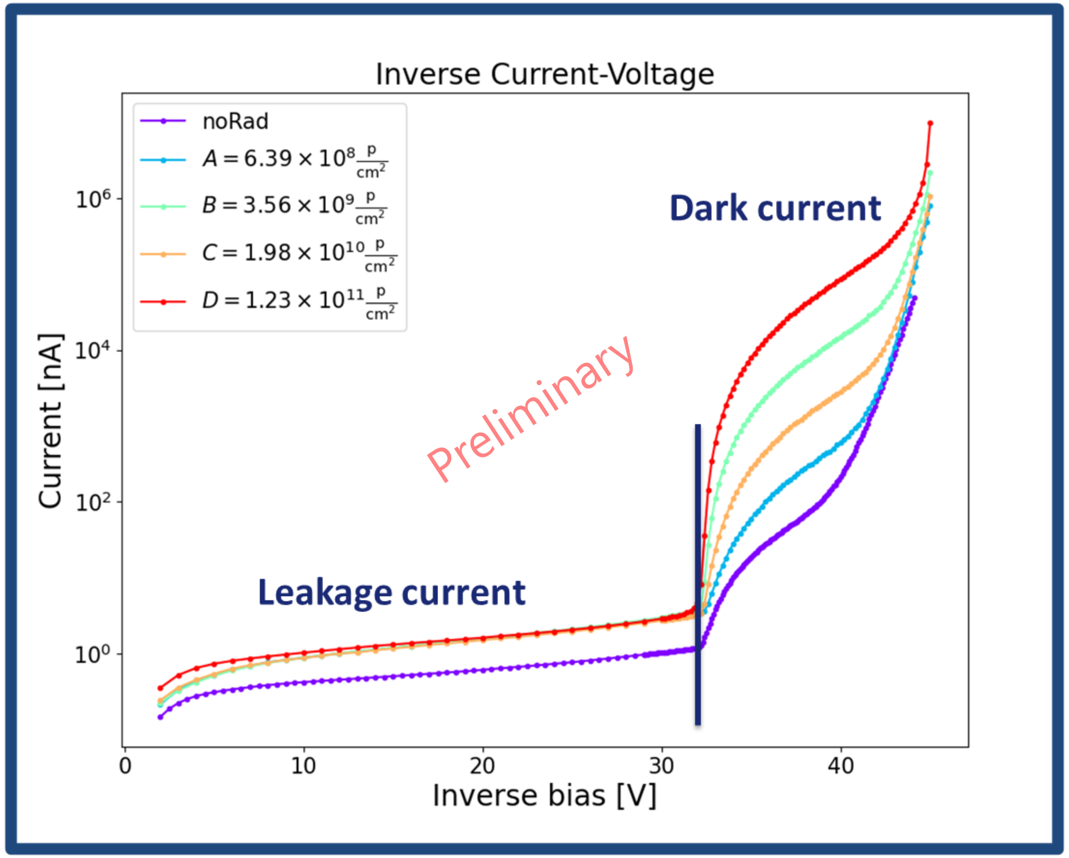
SiPM NUV-HD-lowCrossTalk



Measured reverse current-voltage curves of NUV-HD SiPM, with 15µm cell size, at different proton irradiation fluences.

Breakdown voltage marks the border between the leakage current and the dark current.

- **leakage current** is considered as current below the breakdown voltage
- **dark current** is the current above the breakdown.

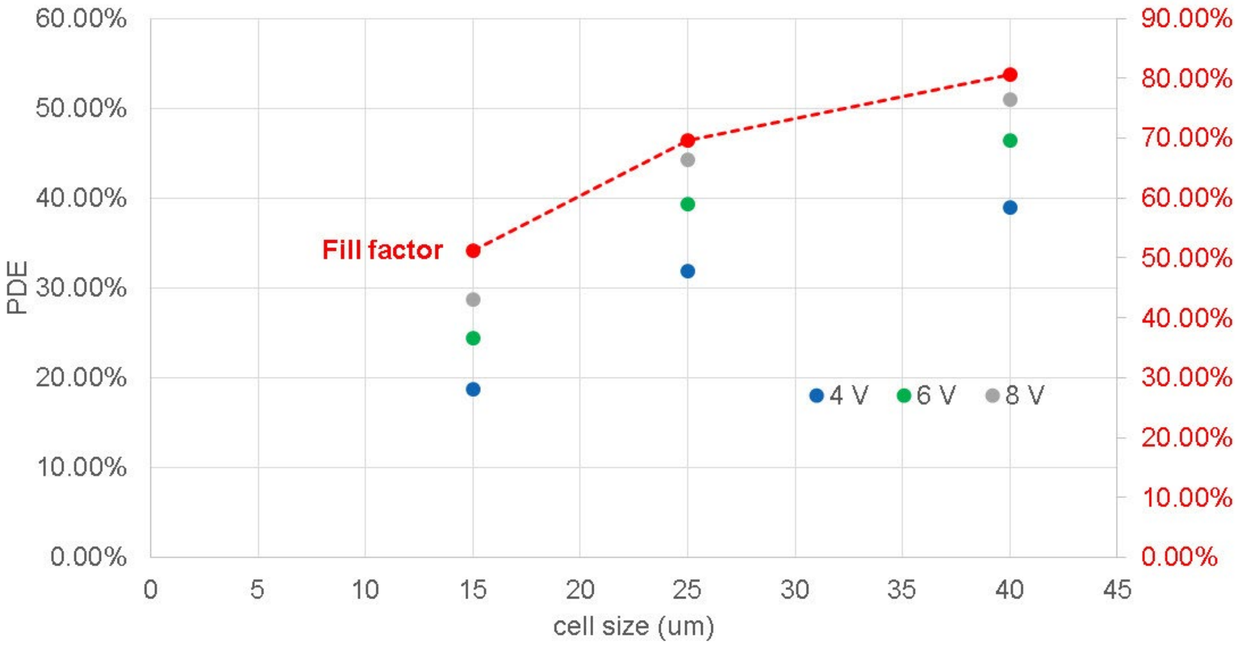
Visible increment of **dark current** (primary noise) with dose. No change in **leakage current**.

PDE - Photo-Detection Efficiency

The **Photo-Detection Efficiency** is defined as the probability that a SiPM detects an incoming photon.

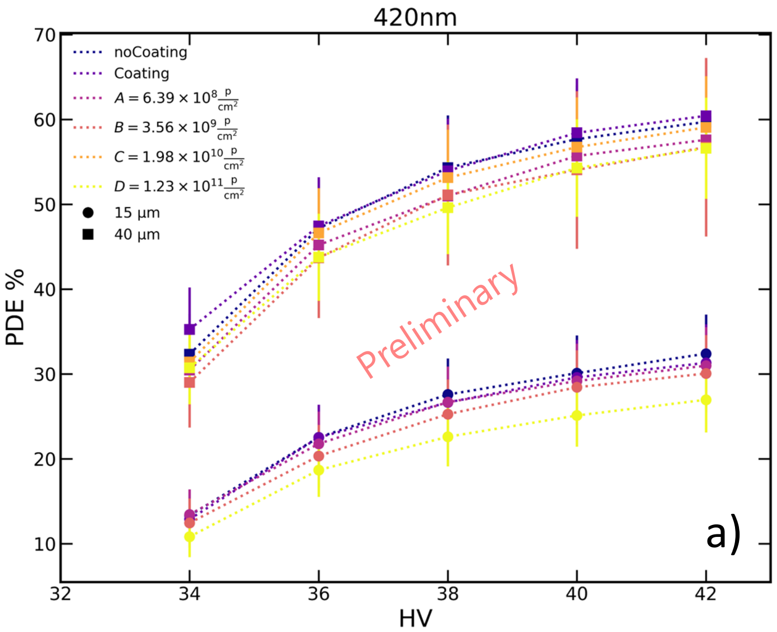
$$\mathrm{PDE} = \mathrm{FF} \times \mathrm{QE} \times T_P$$

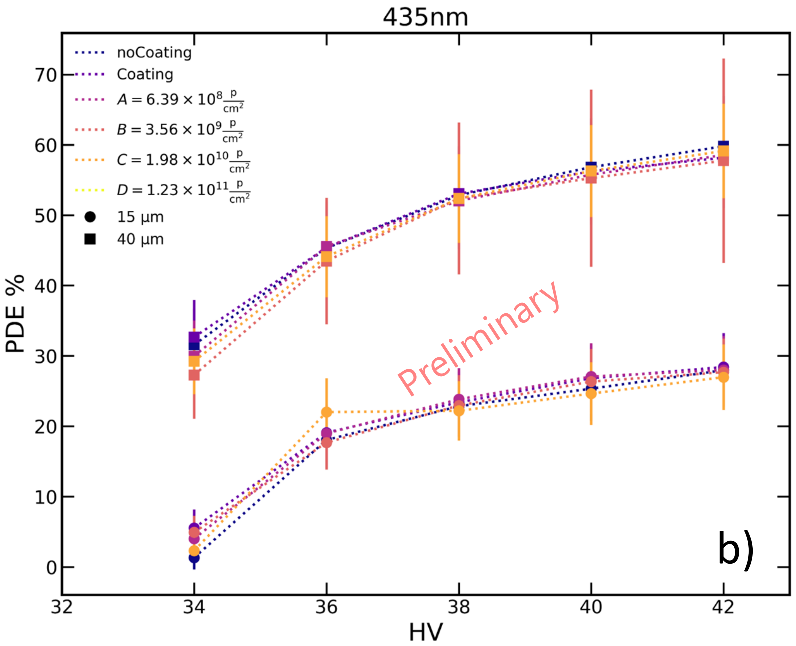
- **FF → Fill Factor**, the geometrical ratio between the active and the total area;
- **QE → Quantum Efficiency**, the probability that a photon creates an electron-hole pair in a position in silicon from which a carrier can reach the high electric field region;
- **TP → PTriggering**, the probability for a primary carrier to trigger an avalanche in the cell. Each term depends on other physical quantities.

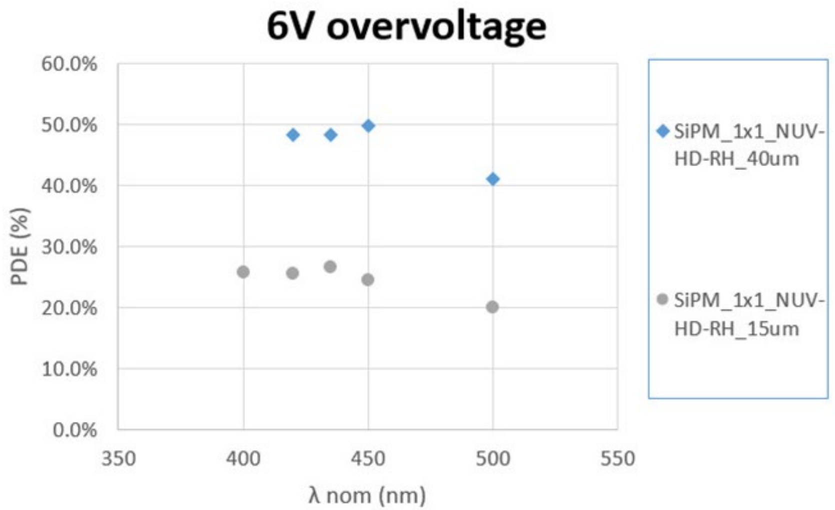


PDE -Results

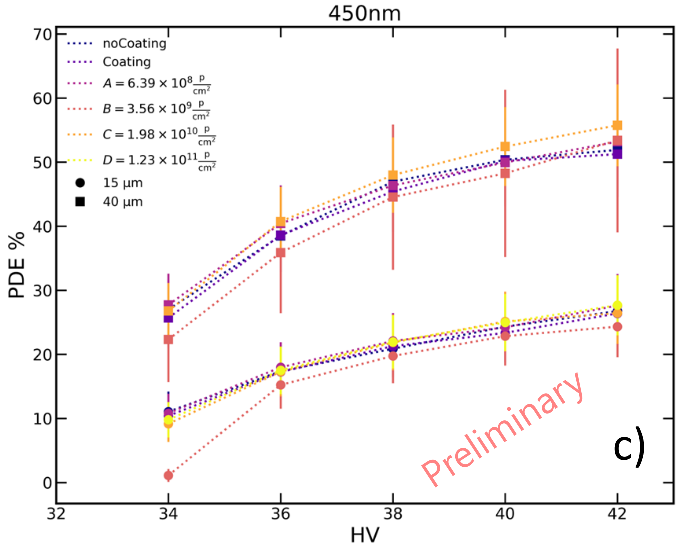
PDE of non irradiated SiPMs at different wavelenghts. We have tested the PDE in a wavelength range close to the one of plastic scintillators.







PDE measured on non-irradiated SiPM with 15 μm and 40 μm cell size at T_{amb} at different wavelengths.



PDE measured on NUV-HD SiPMs with 15 μm and 40μm cell size at 420nm(a), 435nm(b), 450nm(c) at T amb (~20°C) for different proton doses and no irradiated with and without coating.

PDE of irradiated SiPMs does not change with dose.

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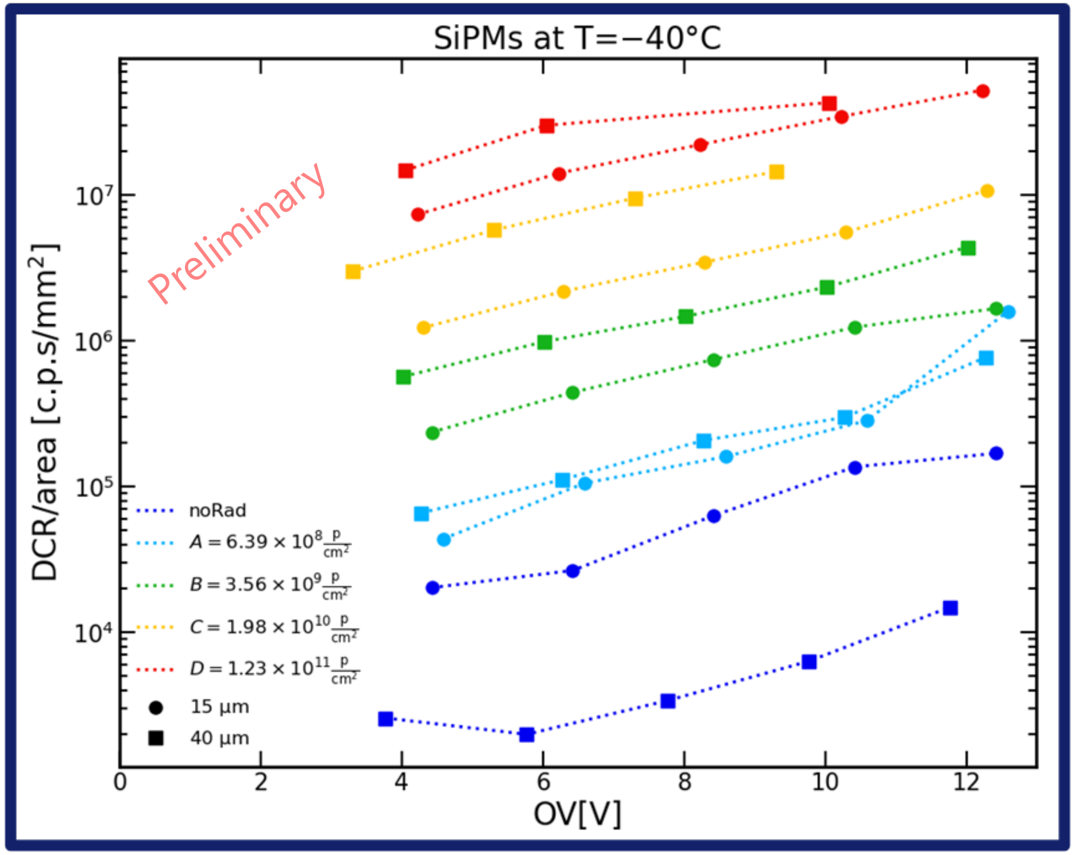
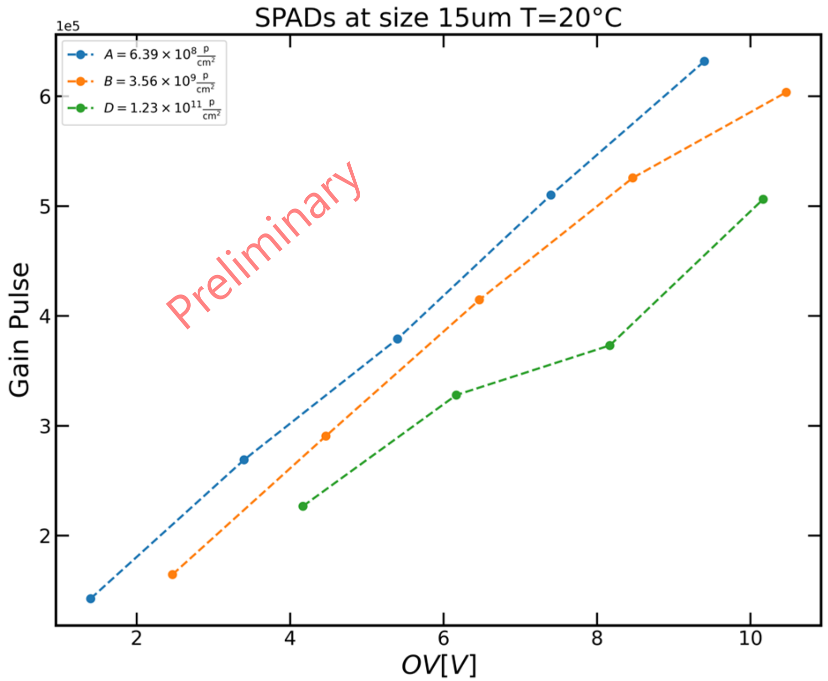


DCR increases with dose and it is slightly dependent on single cell size. For 15 µm SPADs the SIPMs DCR value increases of up to 10^2 when the doses increases from 0 to $1.23e^{11}$ p/ cm^2, due to the increase of the DCR of every single SPAD, which composes the SiPM.

DCR normalized at $1\mathrm{mm}^2$ for the NUV-HD SiPM with 15µm and 40 µm cell size.



Gain amount of charge flowing per each avalanche, small changes in gain observed.

Conclusion

We performed functional tests on the irradiated samples (SPADs), with Protons up to 1x10^{11} p/cm^2 which confirmed that:

- Primary DCR increment;
- No relevant modification of all other SiPM functional parameters.

Next step

Study of IEL damage **X-ray irradiation** (energy up to 40 keV) was performed at different doses, up to 100 kGy (in silicon).

Thank you for attention.

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