Radiation damage on FBK SiPMs

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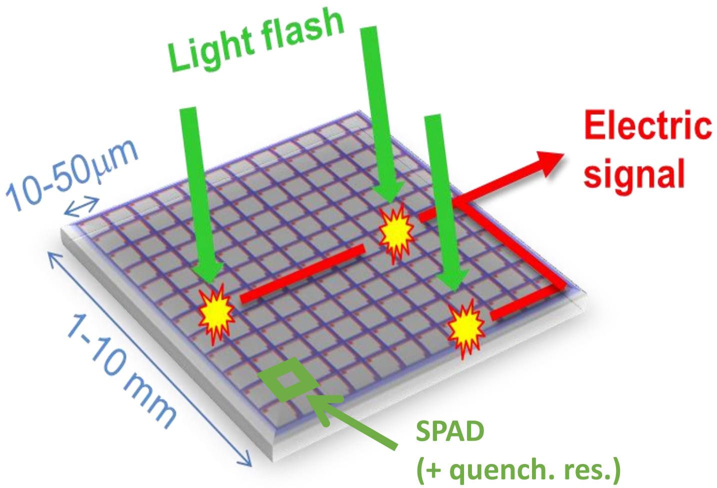
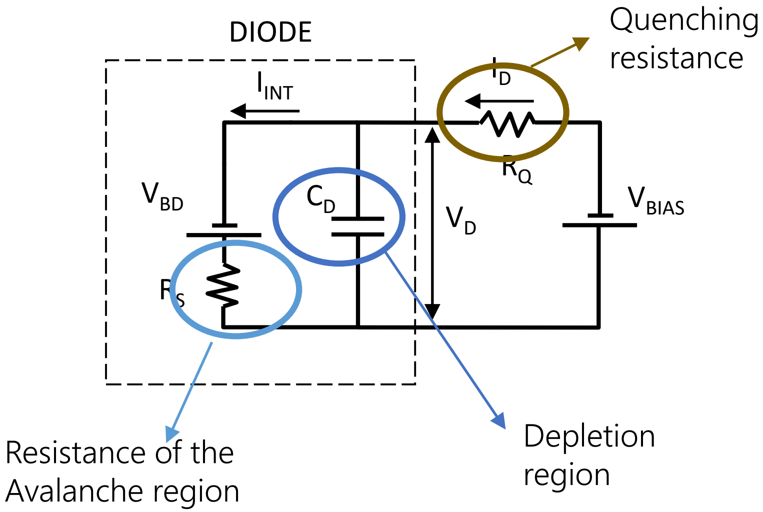
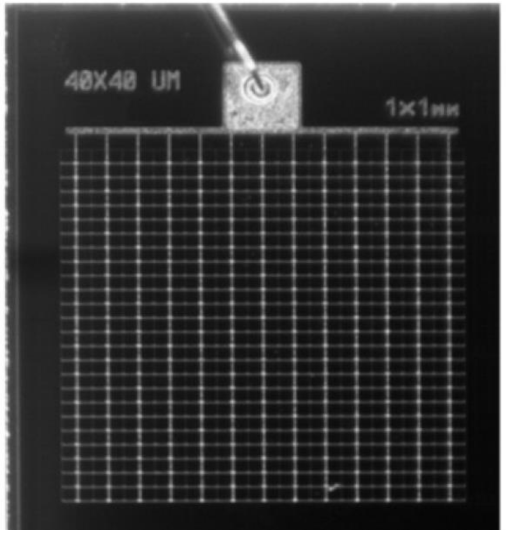
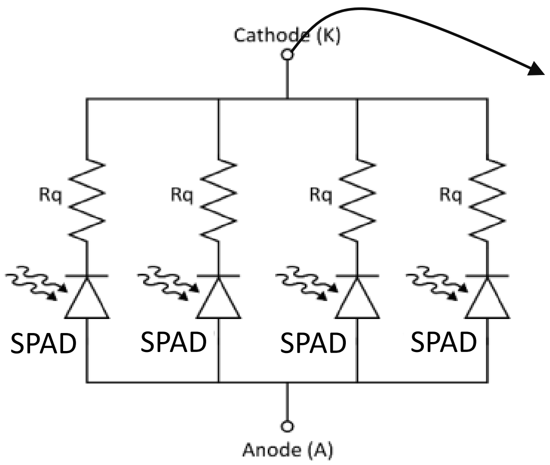
Silicon Photomultipliers

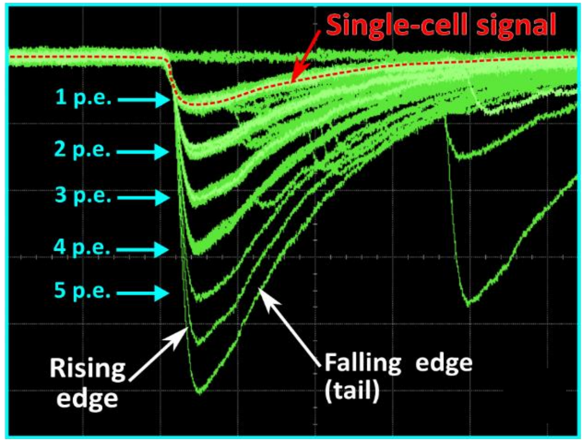
What is a SiPM?







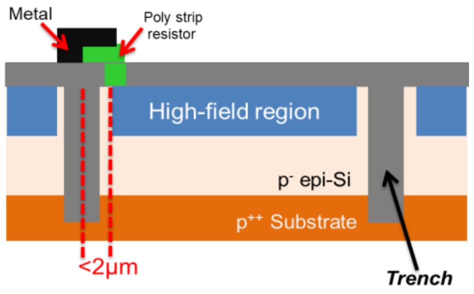




FBK SiPM technologies

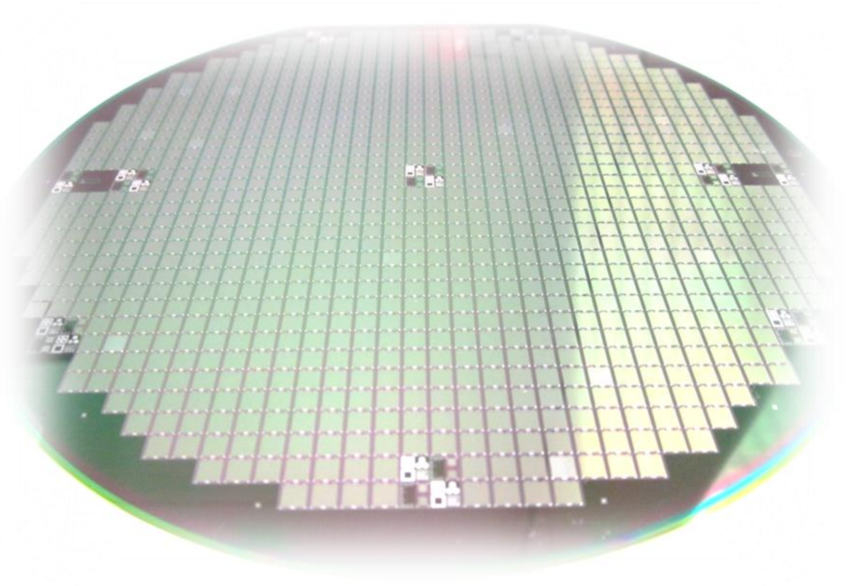
RGB

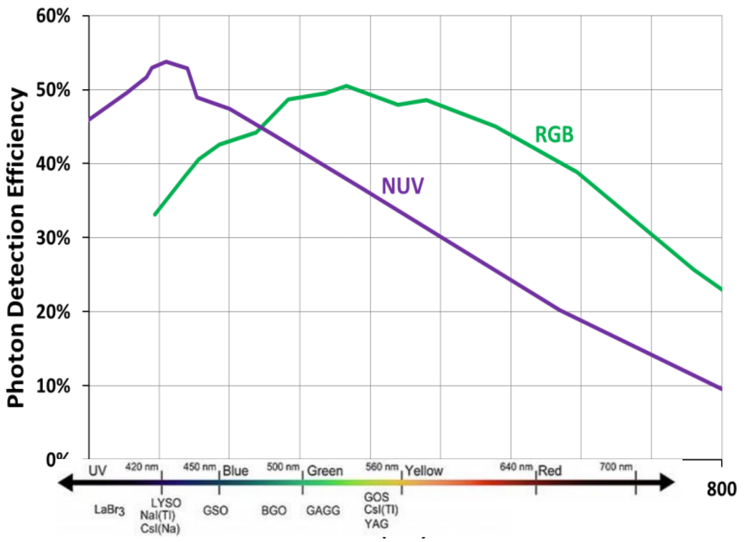
RGB-HD



RGB-UHD

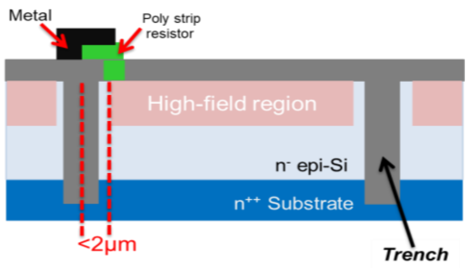
Optimized for cryogenic applications





NUV

NUV-HD

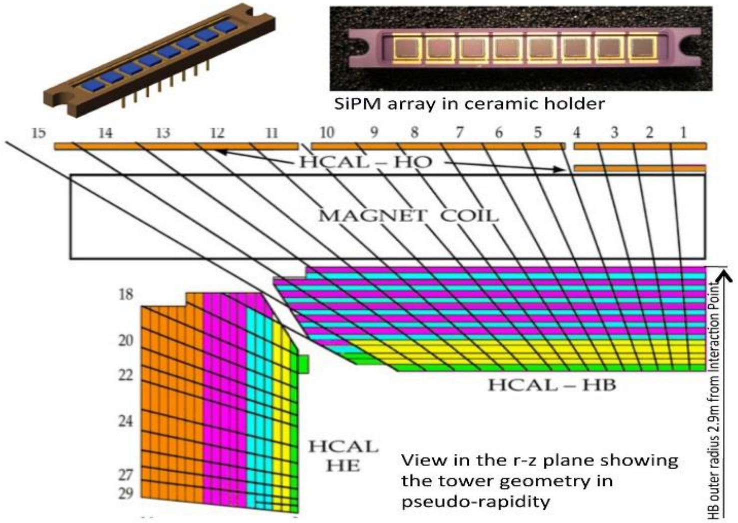


NUV-HD-LF

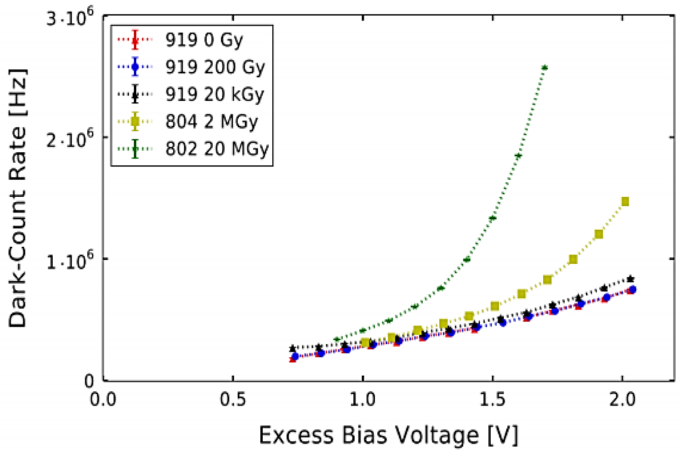
Ultra high cell density (Very small cells)

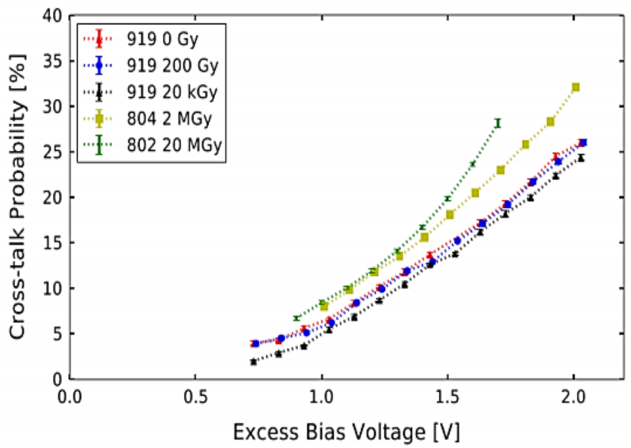
SiPM and radiation damage

High fluences in HEP experiments …



Example: CMS – ECAL upgrade





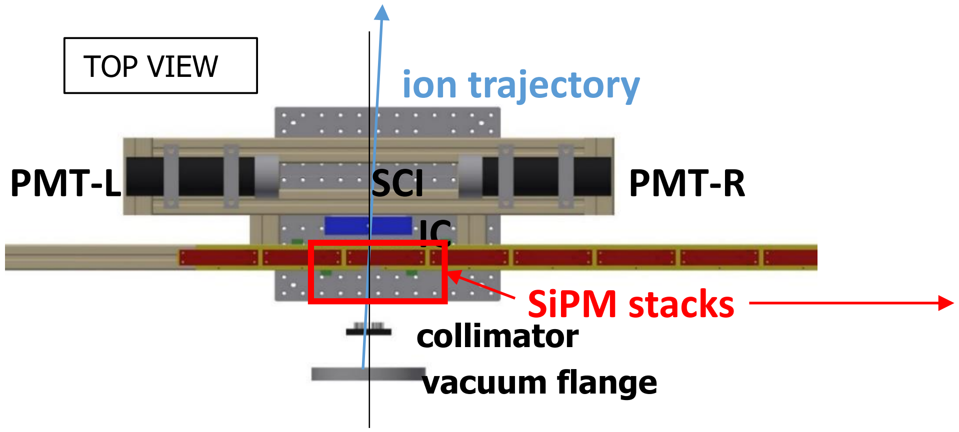
… but losing performance in sensors

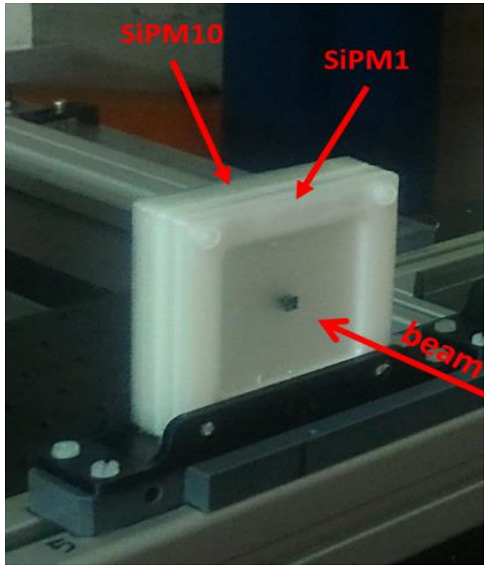
Irradiation test to check SiPMs radiation hardness

Fluence	I_{dark}, DCR	GAIN	PDE	Rq	V_{bd}
Medium $\phi < 10^{12}\,cm^{-2}$	x(↑)				
High $\phi > 10^{12}\,cm^{-2}$	x(↑)	x(↓)	x(↓)	x (↑)	x (↑)

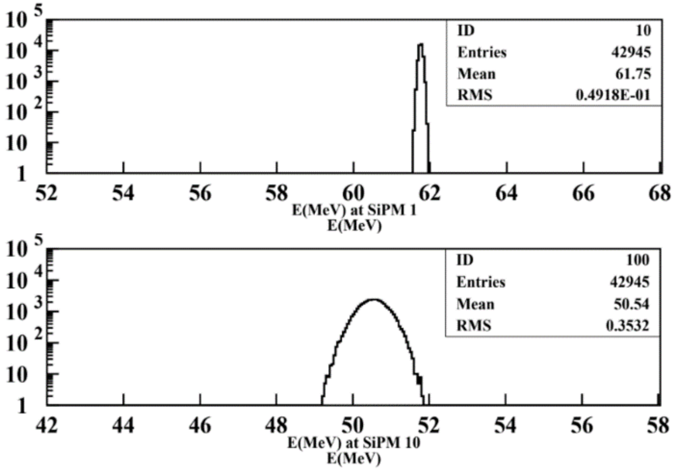
Irradiation tests with protons

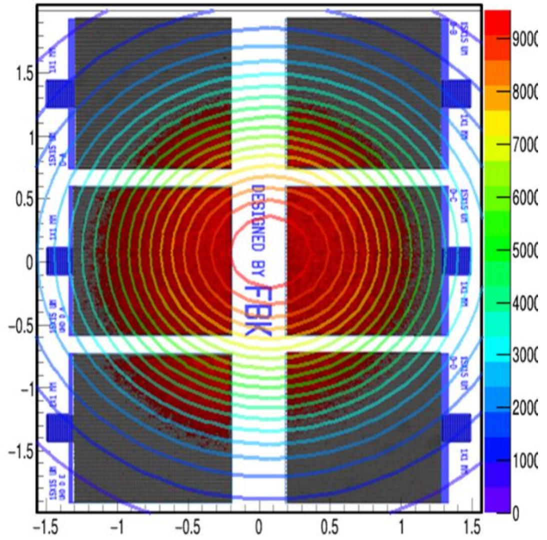
Proton irradiation tests
→ 2019, LNS Catania (Italy)





Gaussian beam at 61MeV with a non uniform irradiation along the sensors surface





Energy shift between the first and the last SiPM in the block

Irradiation tests with protons

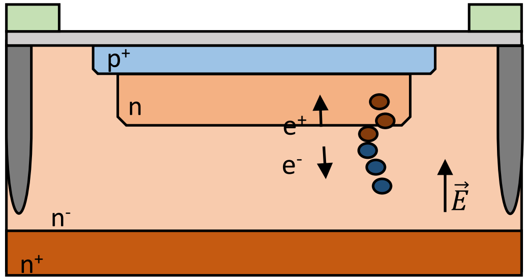
- 10 technologies in a fluence range $(1.7\times10^{8} \div 1.7\times10^{12})$ n_{eq}/cm^{2}

- SiPM type:
  - $1x1mm^{2} \div 1.75mm^{2}$ active area
  - Placed on bigger chip (test chip)
  - Different pitches

- All SiPMs have been annealed at room temperature for ~1month before measurement

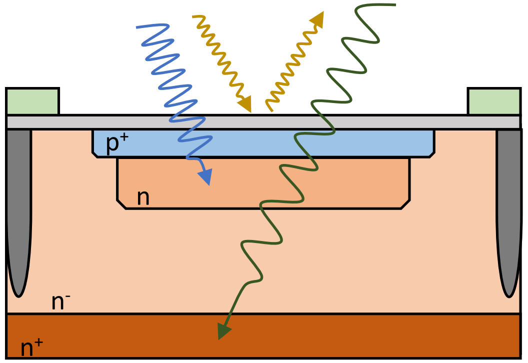
TECHNOLOGY	Characteristics	Cell pitch [µm]									
RGB – HD 2016	P-type substrate. Peak sensitivity 550nm.					20	25	30	35		
NUV – HD lowCT 2015	N-type substrate. peak sensitivity 400nm.						25	30	35	40	
RGB – UHD LF 2017	Ultra high density. Lower electric field.	7.5	10	12	15						
NUV-HD ULF 2019	Lower electric field. Small cell pitch.			12	15						

Main investigation parameters



CURRENT

- **Leakage**: pre-breakdown current
- **Dark current**: post-breakdown current

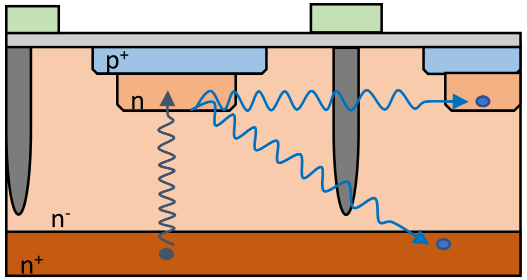


PHOTON **D**ETECTION **E**FFICIENCY

PDE = Q_e x P_t x FF

DARK **C**OUNT **R**ATE

<u>Primary noise</u> due to deep-levels into the silicon, thus crucially affected by the damage

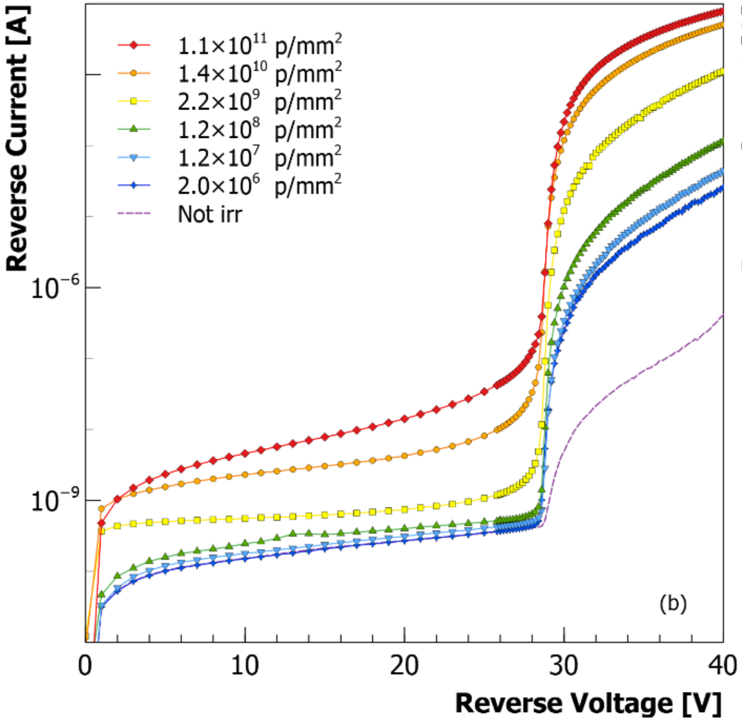


CORRELATED NOISE

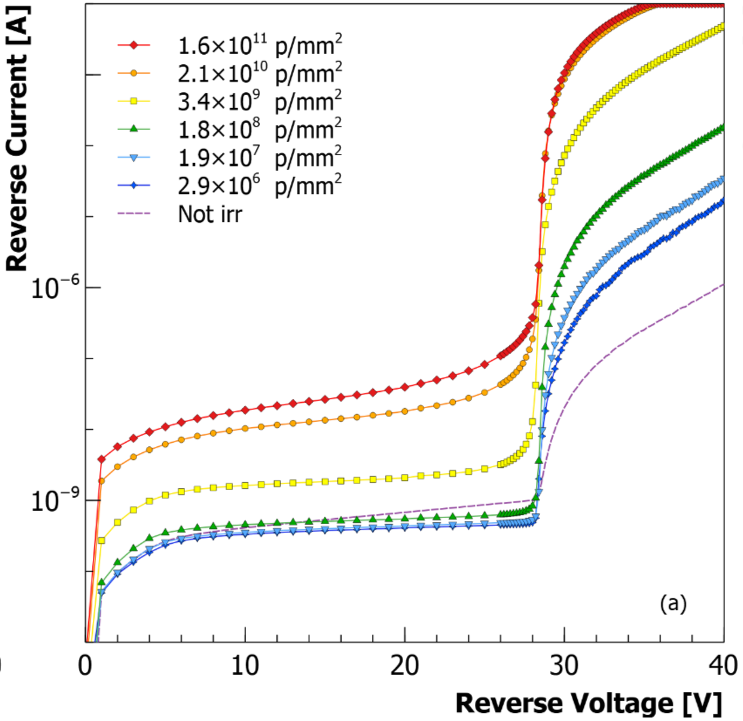
- **Cross-Talk (optical) between cells**
- **Afterpulsing**

Results – Current

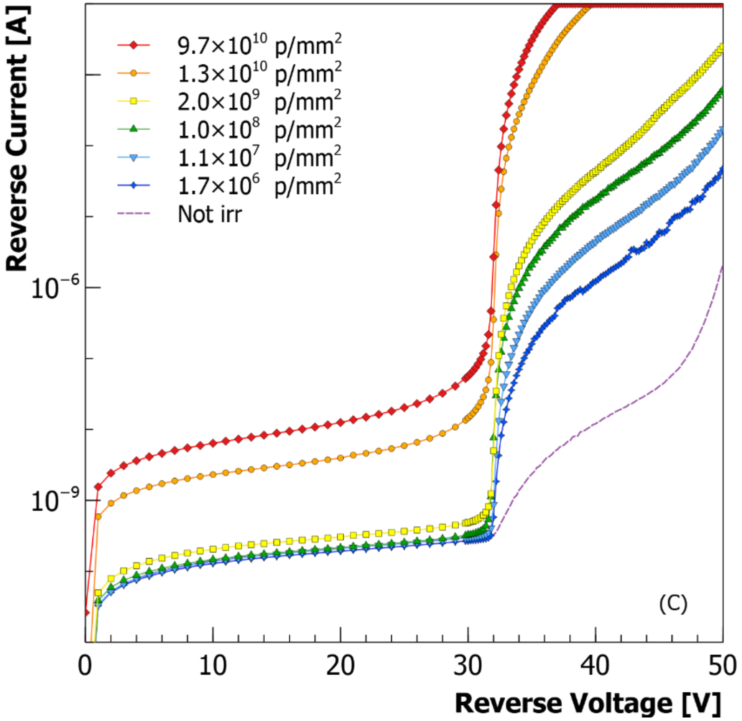
NUV-HD



RGB-HD



NUV-HD ULF



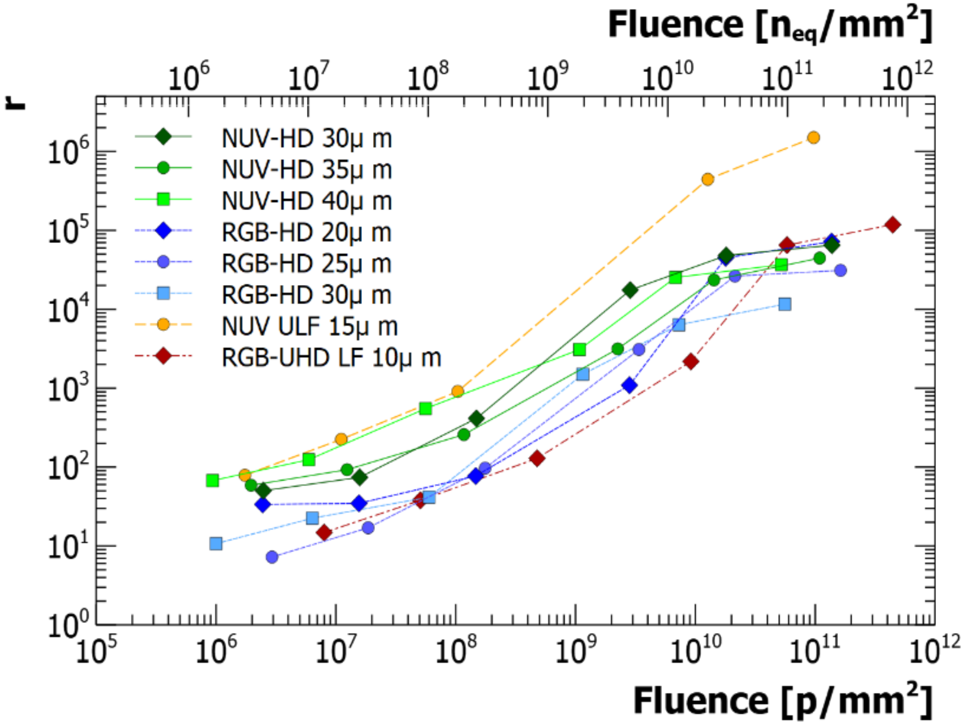
- Significant increase from 1×10^9 p/cm^2
- Dark current increasing of 2.5 decades after 1×10^{11} p/cm^2

Results – Dark current increment

Useful information from the increase of dark current at excess bias 5V at +20C

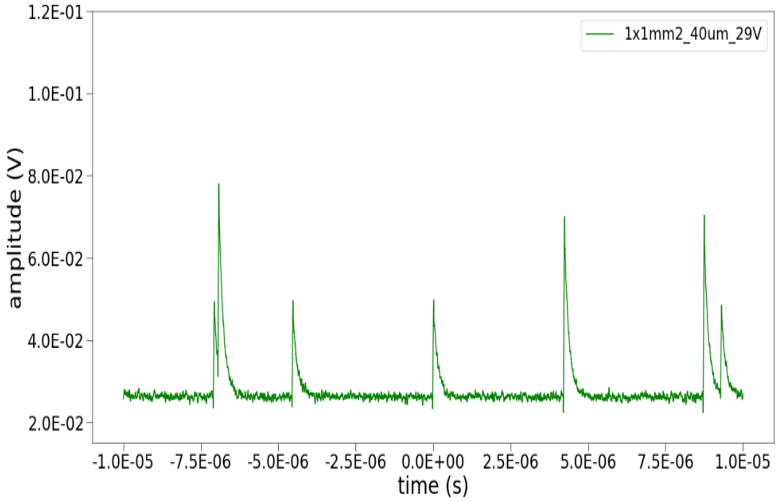
$$r = \frac{I_{after}}{I_{before}}$$

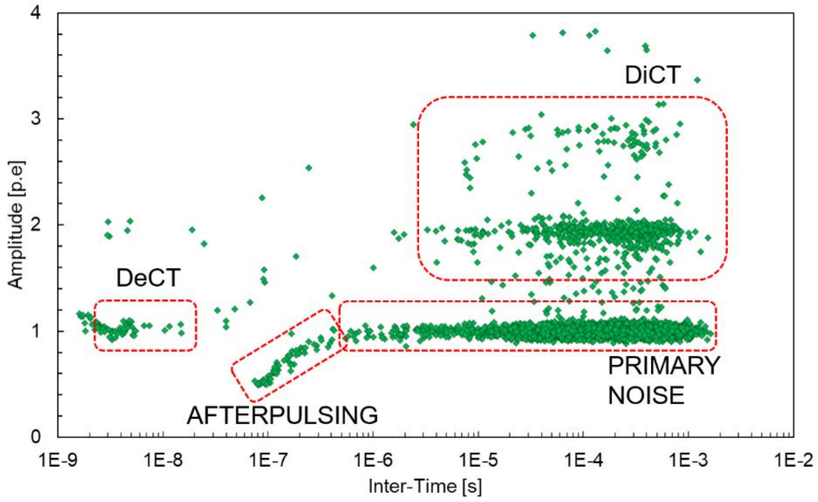
- Linear, then more than linear increment.
- Saturation at high fluences.
- More than factor 10^5 increment in noise at 10^{11} proton/mm^2



Results – Dark Count Rate (primary noise)

Method → analysis of pulses: Inter-arrival times





- Peaks identification
- Amplitude calculation
- Inter-arrival time estimation

Method widely used in SiPM characterization,
BUT no longer usable when pulses are no more clearly distinguishable!

Results – Dark Count Rate (primary noise)

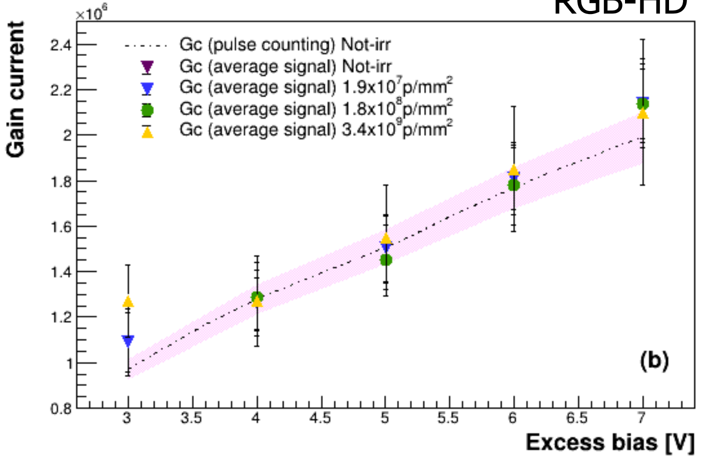
Current method

$$DCR\ (V) = \frac{I_{dark}(V)}{q \times G(V) \times ECF(V)} = \frac{1}{q}\frac{I_{dark}(V)}{G_c(V)}$$

- Pulsed 420nm LED connected to a fiber at -20C
- Charge integration Q
- Number of photons counting

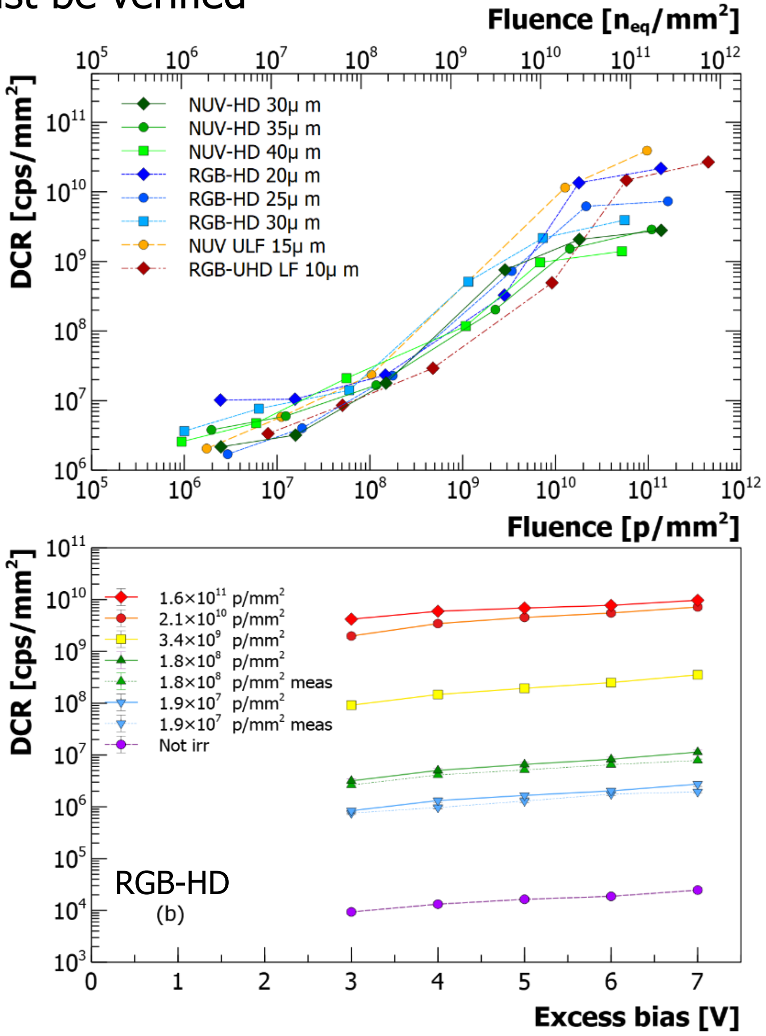
$$n_{ph} = \frac{Q}{PDE\ \times G_c}$$

RGB-HD

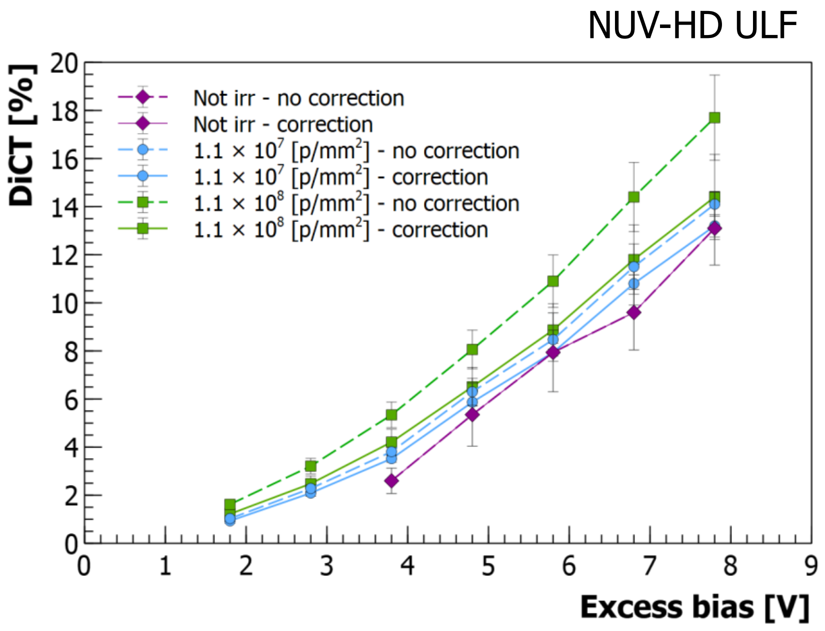


G_c steady up to 3.4x10^9 p/mm^2 at least
Proved effectiveness of the current method

To estimate DCR from I_{dark} the assumption of G_c not changing with fluence must be verified



Results – Optical Crosstalk between cells



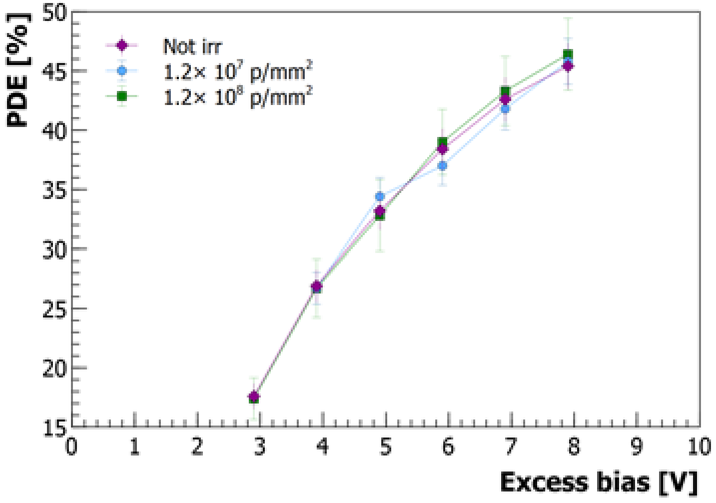
- Evidence of a slight increase of the DiCT due to the high noise
- Low efficiency in the program for highly damaged SiPM
- Correction factor useful to fix the issue

$$p = 1 - \left[1 - \frac{DCR_{1.5}}{DCR_{0.5}}\right] \cdot \exp(DCR_{0.5} \cdot \tau)$$

- Clear improvement visible in the results

Results – Photon Detection Efficiency

NUV-HD



PDE constant up to $1.2x10^8$ p/mm^2

Still no efficient method for estimation of PDE at high fluences due to the noise

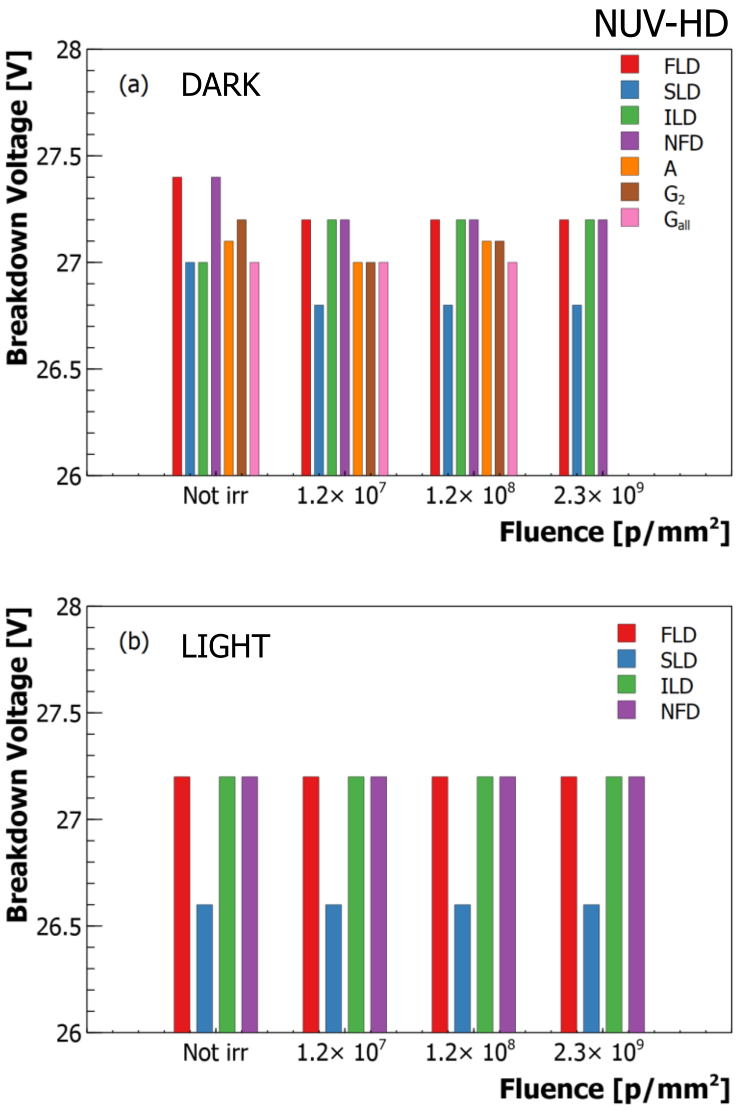
From Gc measure PDE not changing with fluence up to ~10^9p/mm^2

Results – Breakdown voltage

Interesting to determine if breakdown voltage is changing after irradiation:
used several methods to identify V_{bd}

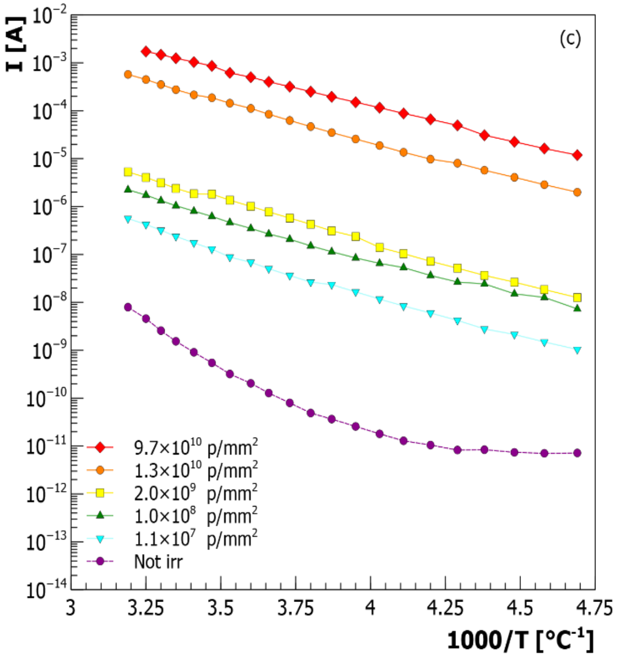
1. Maximum of First Logarithmic Derivative (FLD)
2. Maximum of Second Logarithmic Derivative (SLD)
3. Minimum of Inverse Logarithmic Derivative (ILD)
4. Maximum of Normalized First Derivative (NFD)
5. Bias at Amplitude equal to zero (A)
6. Bias at Gain equal to zero with only two points (G_2)
7. Bias at Gain equal to zero with all points (G_{all})

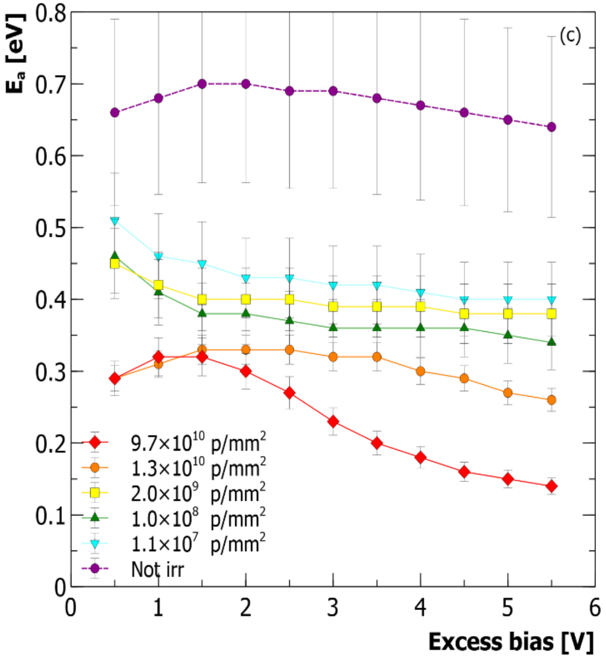
V_{bd} constant up to 2.3×10^9 p/mm^2

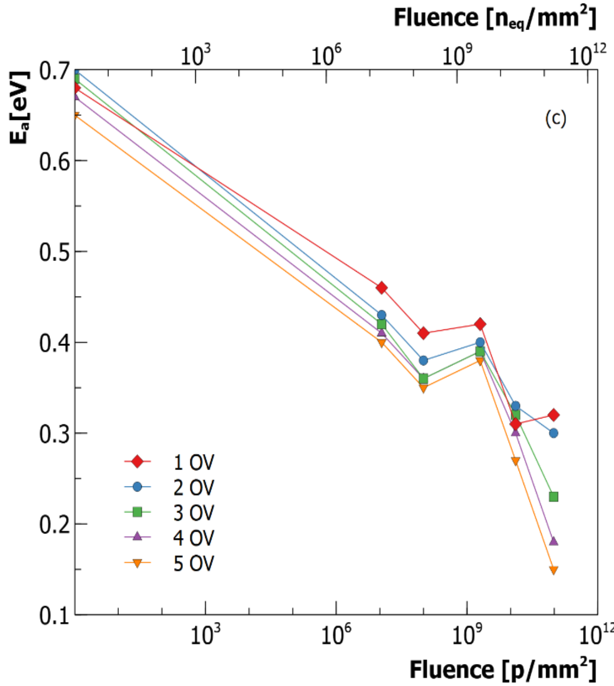


Results – Arrhenius plot and Activation Energy

NUV-HD ULF







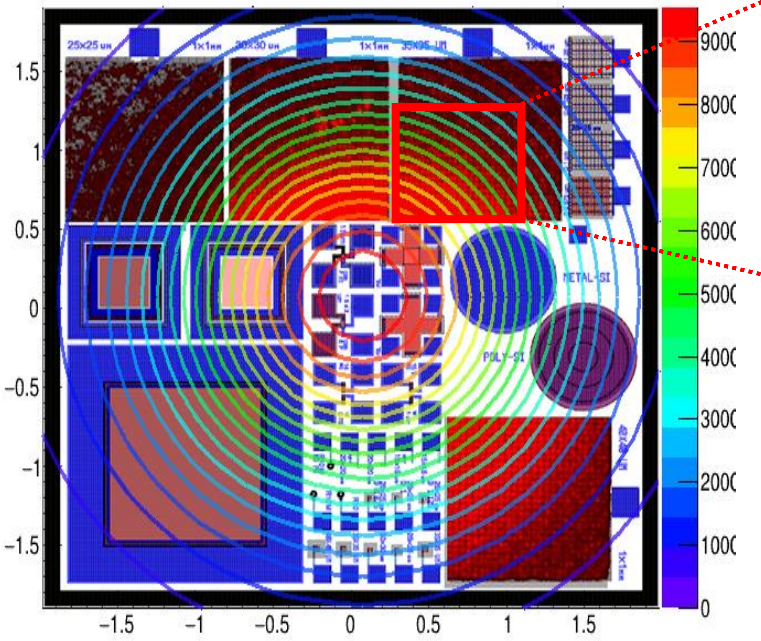
Activation energy extracted from linear fit of Current vs 1000/T in range (-15÷15)⁰C

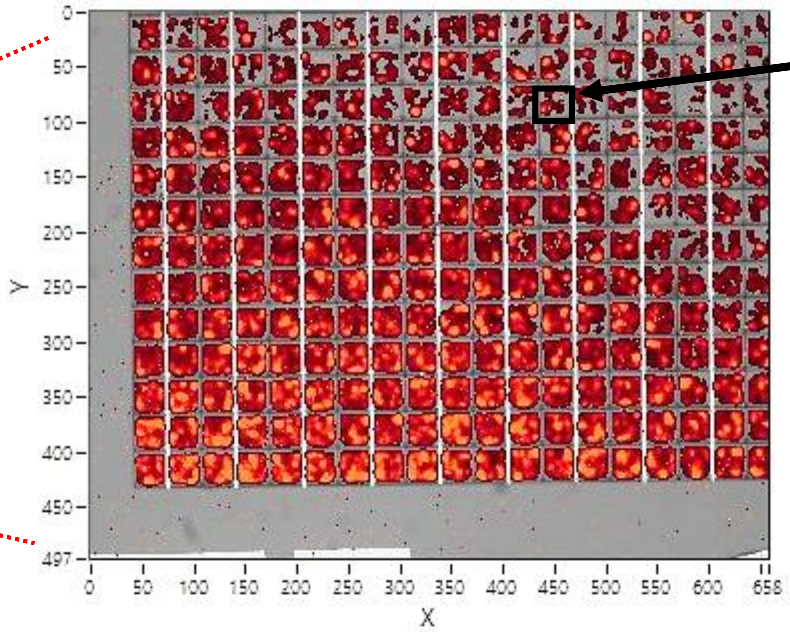
At least two E_a levels and clear saturation effects

Results – Emission Microscopy

Secondary photons emission

NUV-HD 35um





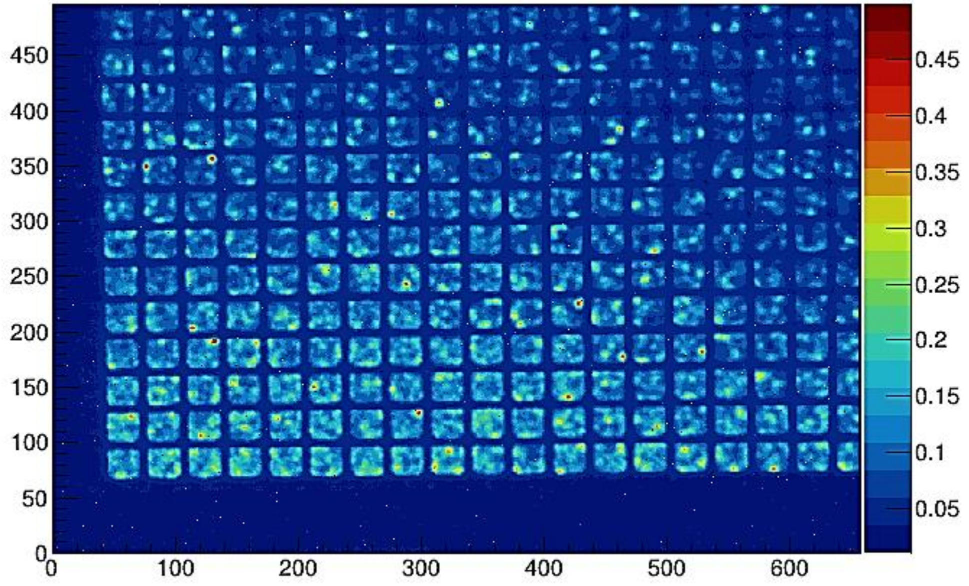
Single cell
35µm x 35µm

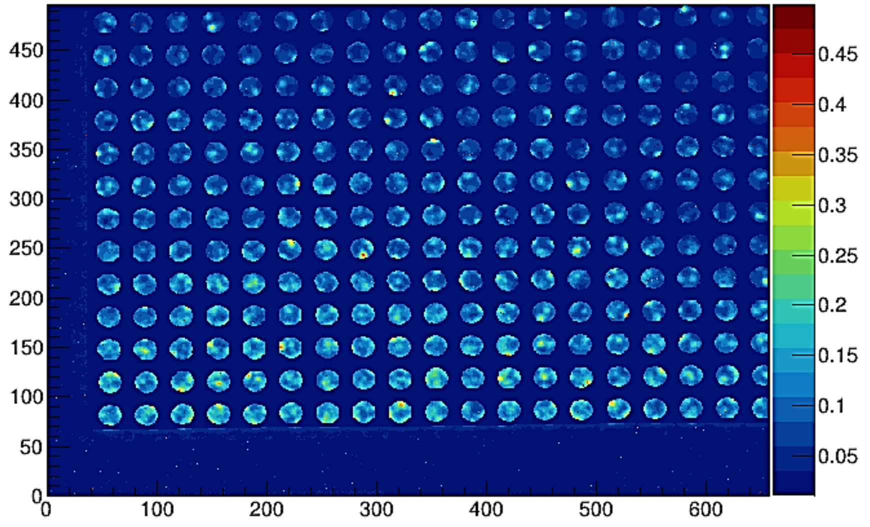
Hot carrier luminescence (HCL) due to accelerated carriers suddenly losing their energy in high electric field regions.

In SPADs secondary photons emission in avalanche multiplication process.

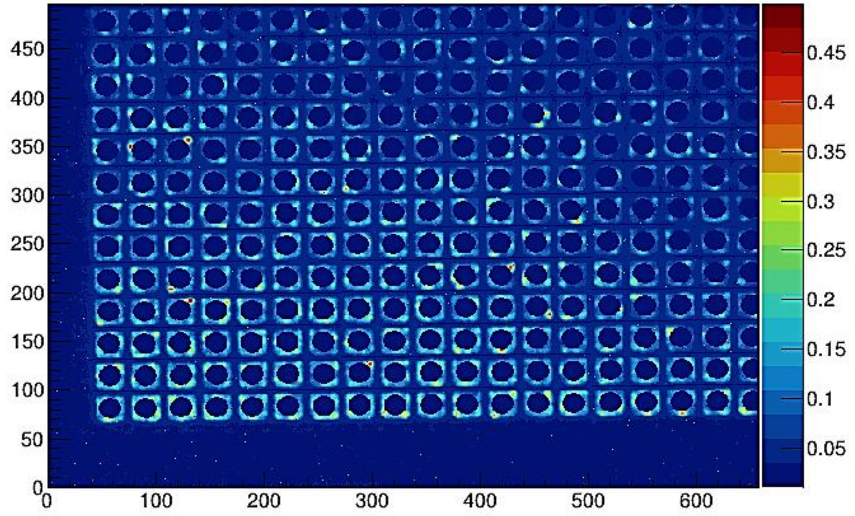
Results – Emission Microscopy

NUV-HD 35um





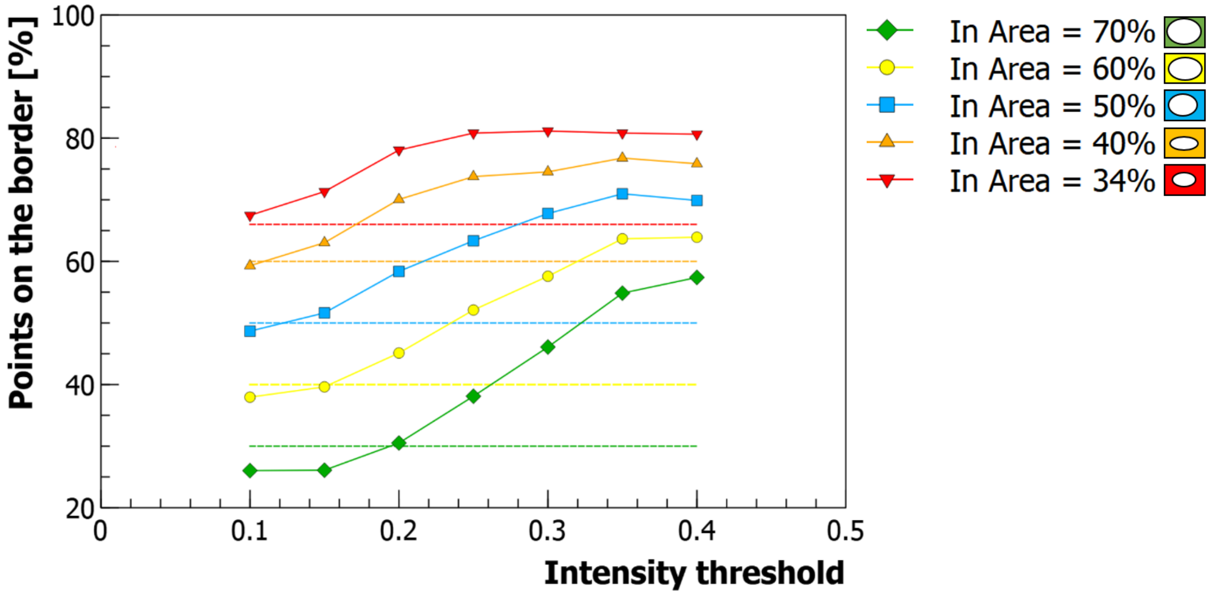
CENTER @50% area



BORDERS @50% area

Counting of points inside and outside the internal circle changing the intensity thresholds

Results – Emission Microscopy



- Hotspots mostly located on the border of the cells
- Further upgrades of the study will hopefully lead to a full localization of the defects in the cell

Conclusions

- Significantly worsening of the **CURRENT** between 10^8 and 10^{11} p/mm^2
- Trend of I_{after}/I_{before}
  - No linearity with fluence I_{after}/I_{before}
  - Possible saturation effect starting between 10^{10} and 10^{11} p/mm^2
- Increase of the **DCR** as expected from literature
  - Up to 6 order of magnitude increment between 0 –10^{11} p/mm^2
  - Significant bulk damage
  - No changes in gain current
- No significant changes in **DiCT, V_{bd}** and **Gain**
  - No significant variation in doping concentrations.
- Decrease of the activation energy with some saturation effects at high fluences
- High defect concentration on the border of the cells from EMMI measurement

THANK YOU