Radiation hardness
Introduction

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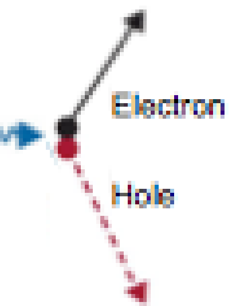
Relevance of radiation hardness in SiPM



Scientific motivation:

SiPMs is photo-sensor of choice in many upcoming experiments often applied in radiation hard environment

Examples:

Imaging calorimeters for collider experiments:

Hadronic calorimeter for ILC (CALICE)

➔ ~ 10^{10} n/cm^2 in the endcap region (after 500 fb^{-1})

Upgrade of hadronic calorimeter for CMS (HGCAL)

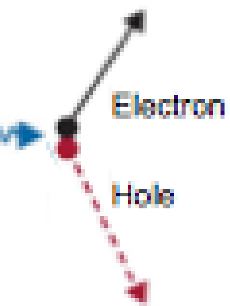
➔ 6x10^{13} n/cm^2 (after 300 fb^{-1})

Space experiments:

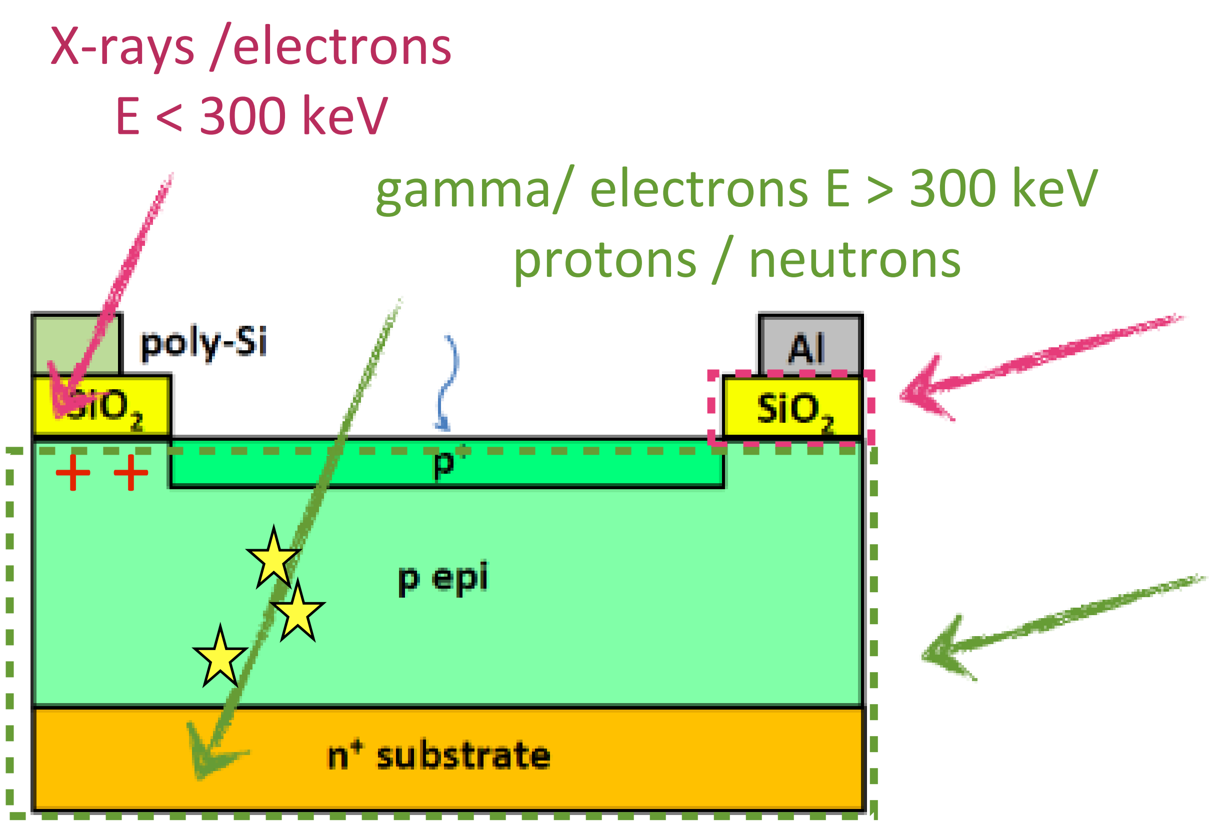
Very high radiation expected for detectors in space

5x10^{10} n/cm^2, AGILE gamma ray detector in geostationary orbit

Types of radiation damage



Gamma/X-rays/electrons with energies below the minimum threshold for bulk defects (~300 keV) generate only defects in the dielectrics, at the Si-SiO_2 interface and at the interface between dielectrics (~18 eV / e/h pair)



HPK reverse structure

Surface damage:

Generate traps at the Si-SiO_2 interface

Fixed positive oxide charge (N_{ox}):

➔ Change in the electric field (V_{bd})

➔ Accumulation layers

➔ Increase in leakage current by additional surface current (J_{surf})

Bulk damage:

Locally distorted Si lattice with new energy states

Add donor and acceptor levels

➔ Increased DCR

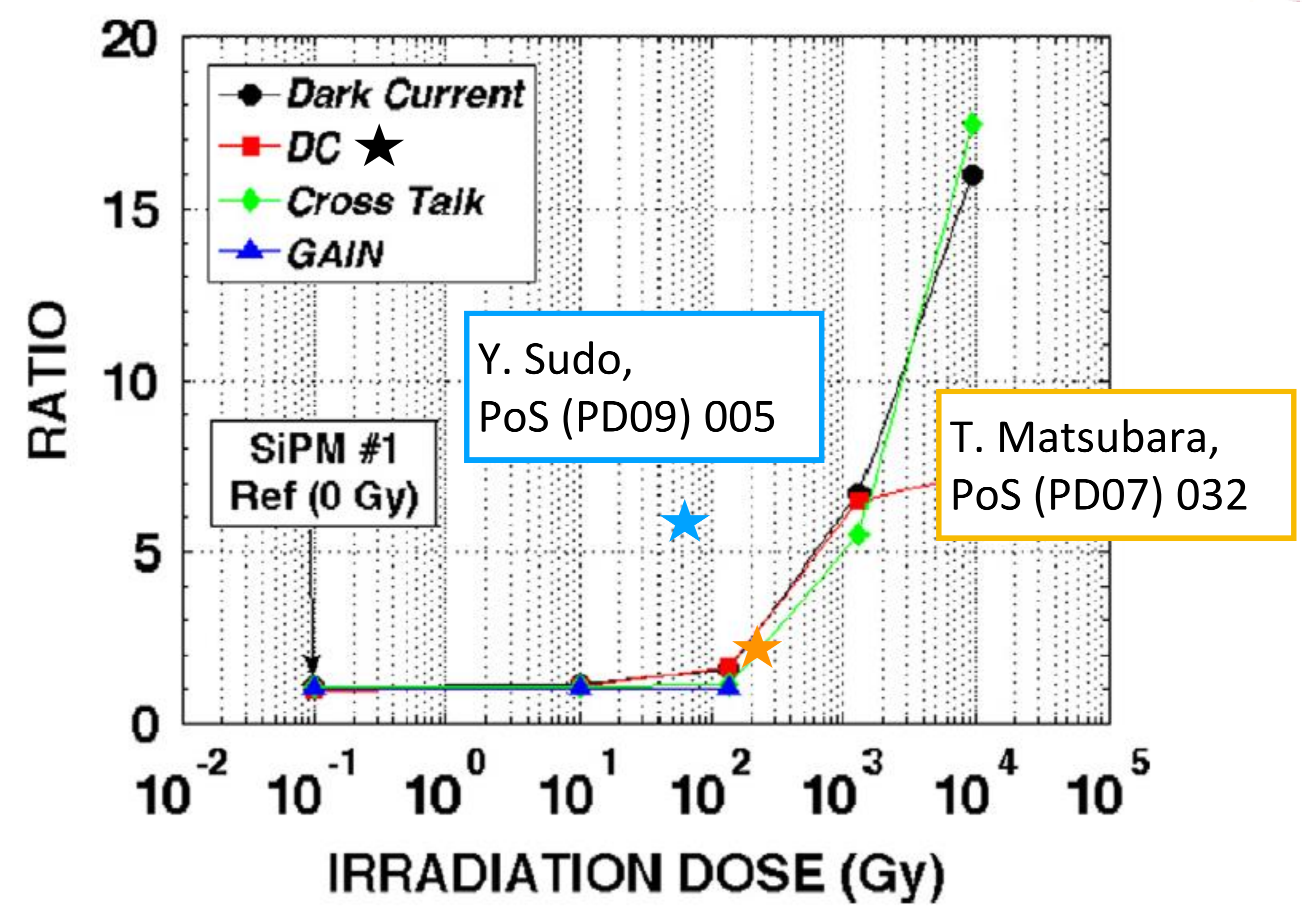
Increased after-pulsing

➔ Change in charge collection efficiency

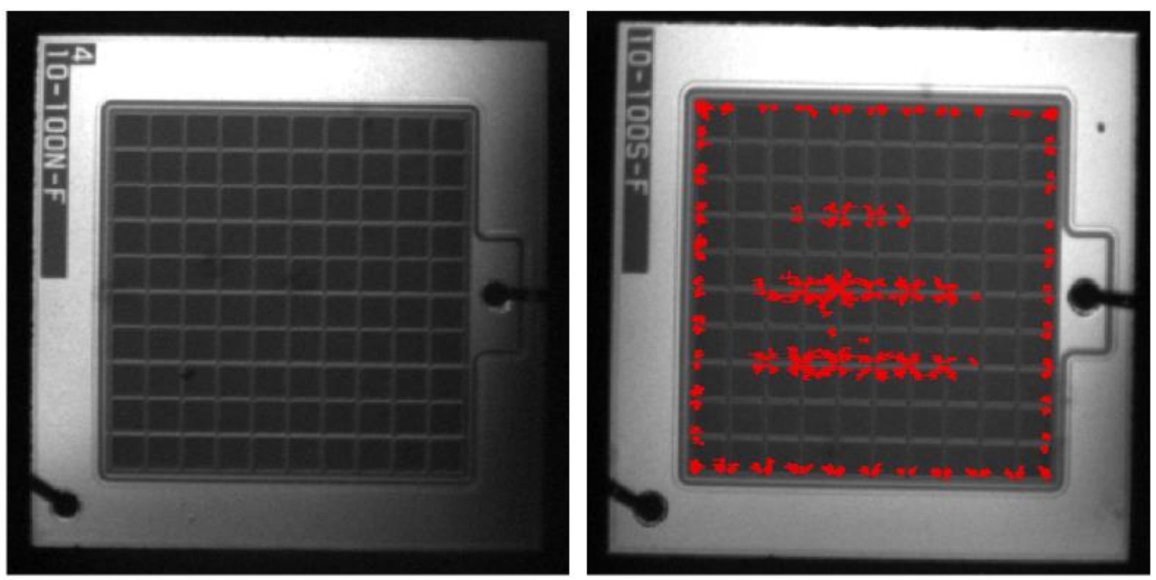
Irradiations with gamma / electrons

Main effects observed:

- all SiPM are operational after irradiation
- loss of single photoelectron resolution for dose > 1 kGy
- significant increase of dark count / current
- point-like defects along readout lines



. Ratio of the measured quantities vs. irradiation dose at $\Delta V = 3V$ ($\Delta V \approx 11\%$).



Infrared pictures of a non-irradiation sample (left) and the irradiated sample (right).
Infrared light is emitted due to the Joule heat cause by passage of leakage current (red points).

Pagano, Lombardo, Palumbo, Sanfilippo, Valvo, Fallica, Libertino,
”Radiation hardness of silicon photomultipliers under ^{60}Co γ-ray irradiation”,
NIM A767, p347-352 (2014) doi:10.1016/j.nima.2014.08.028

Matsubara, Tanaka, Nitta, Kuze,
"Radiation damage of MPPC by gamma-ray irradiation with Co-60”
PoS, PD07 p032 (2006)

Irradiations with X-ray

Main effects observed:

- all SiPM were operational after irradiation
- loss of single photoelectron resolution for dose > 1 kGy
- factor 1000 increase of DC at 20 MGy
- static parameters not affected

Photon irradiation is probably not one of the main worry

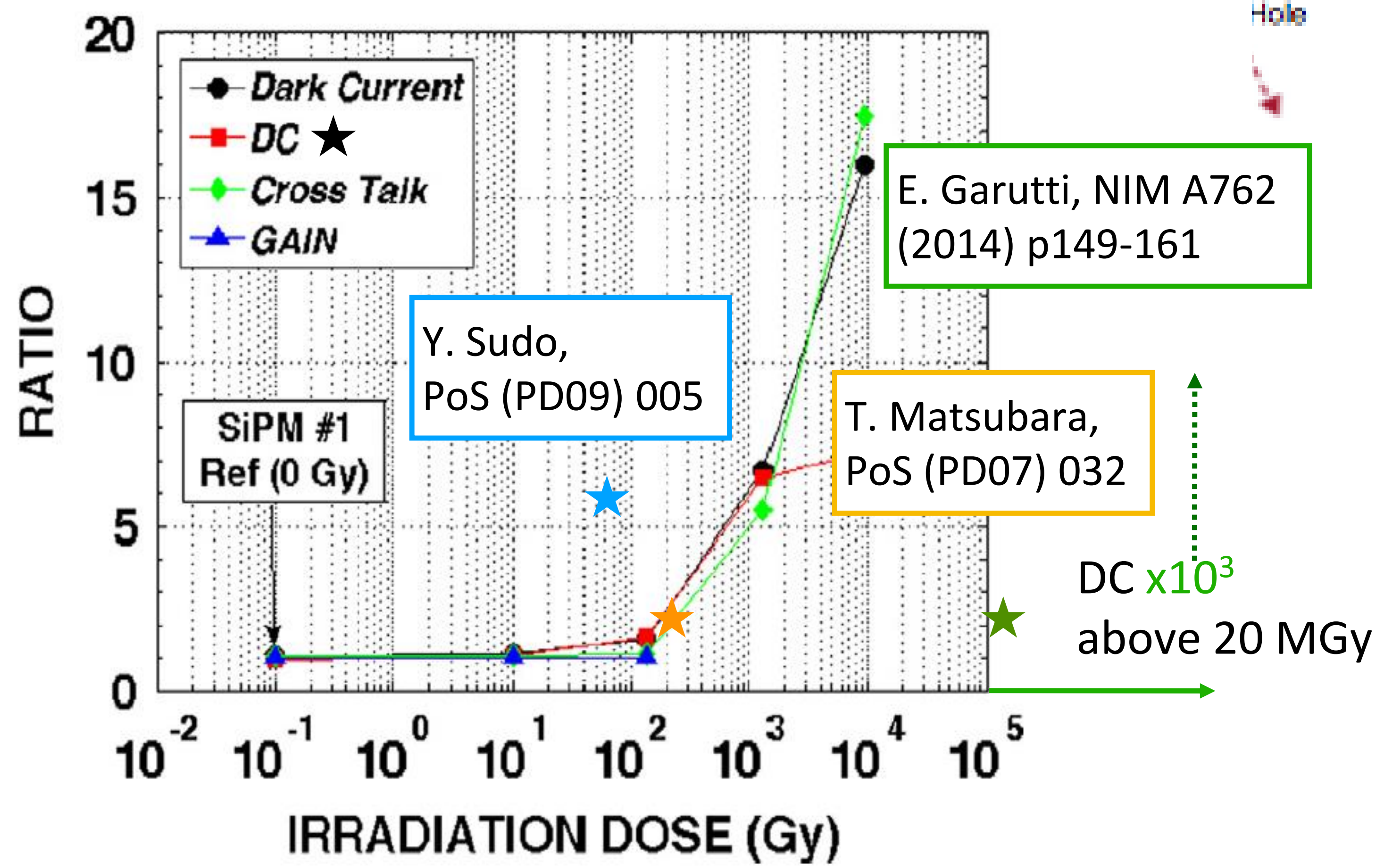


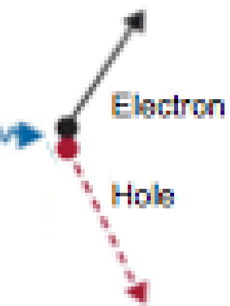
Fig. 7. Ratio of the measured quantities vs. irradiation dose at $\Delta V = 3V$ ($\Delta V \approx 11\%$).

Dose	0 Gy	200 Gy	20 kGy	2 MGy	20 MGy
R_{par} [MΩ]	$2\,100 \pm 100$	$2\,000 \pm 100$	$1\,600 \pm 80$	275 ± 50	75 ± 20
R_q^{Cf} [kΩ]	125 ± 5	116 ± 5	112 ± 5	110 ± 5	108 ± 5
C_{pix}^{Cf} [fF]	94.0 ± 1.5	93.8 ± 1.5	93.5 ± 1.5	93.0 ± 1.5	93.5 ± 1.5
$R_q^{Cf} \cdot C_{pix}^{Cf}$ [ns]	11.8 ± 0.6	10.9 ± 0.6	10.5 ± 0.6	10.2 ± 0.6	10.1 ± 0.6

R_q from forward I-V is systematically higher

Xu, Klanner, Garutti, Hellweg, Wolf-Lukas, "Influence of X-ray Irradiation on the Properties of the Hamamatsu Silicon Photomultiplier S10362-11-050C"
NIM A762, p149-161 (2014),
doi:10.1016/j.nima.2014.05.112

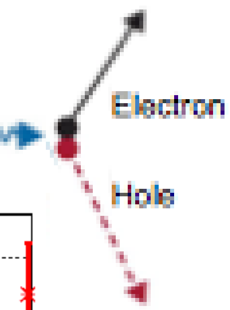
Irradiation with hadrons



- No studies dedicated to distinction between proton/neutron effects
- NIEL hypothesis: rad. damage proportional to non-ionizing energy loss
- Fluences often quoted in 1 MeV neutron equivalent / cm^2 using hardness factor to scale particles and energy

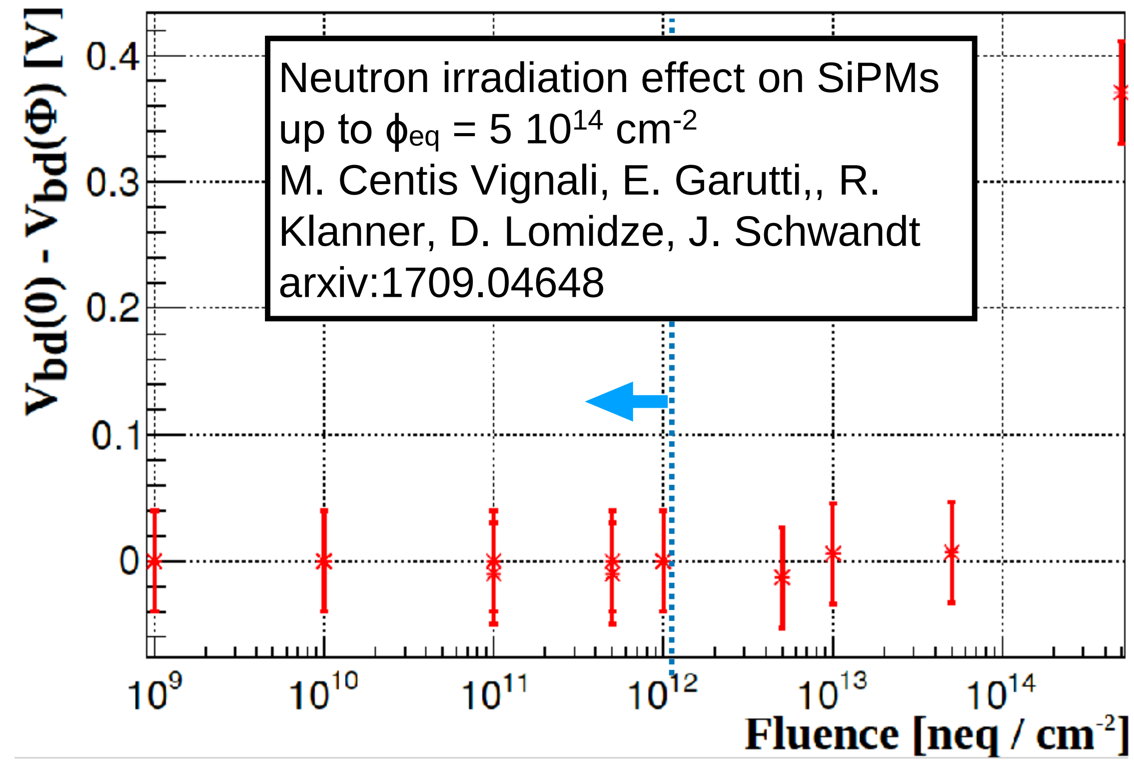
- Studies divided in two categories:
  - medium-low fluences: $\phi_{eq} < 10^{12}$ cm^{-2}
  - high fluences: $\phi_{eq} > 10^{12}$ cm^{-2}

Irradiation with hadrons: $\phi_{eq} < 10^{12}\ cm^{-2}$

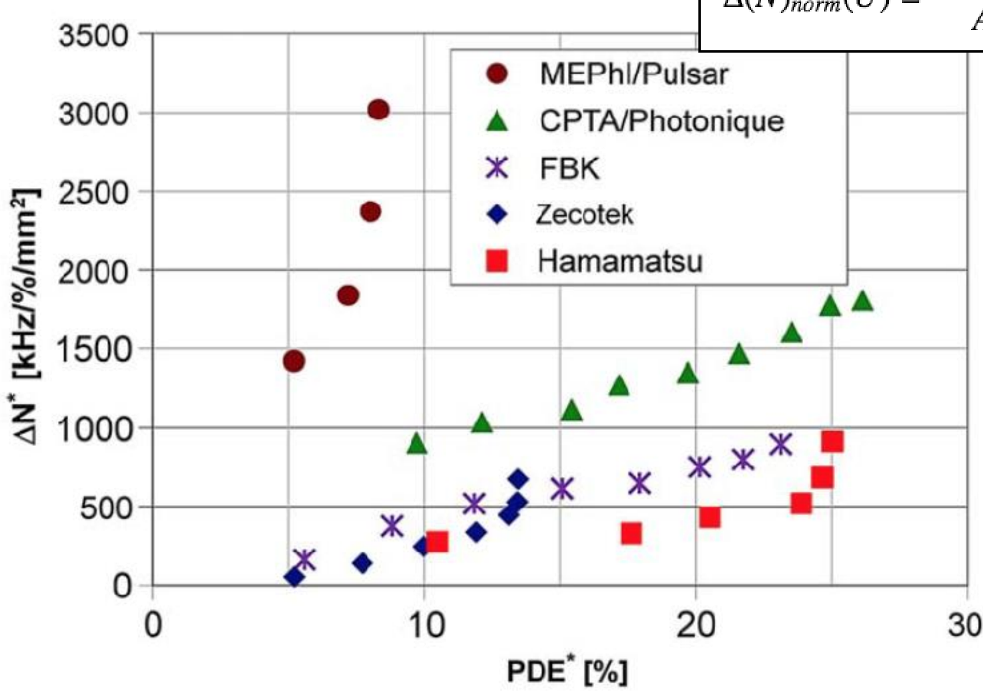


Main effects observed:

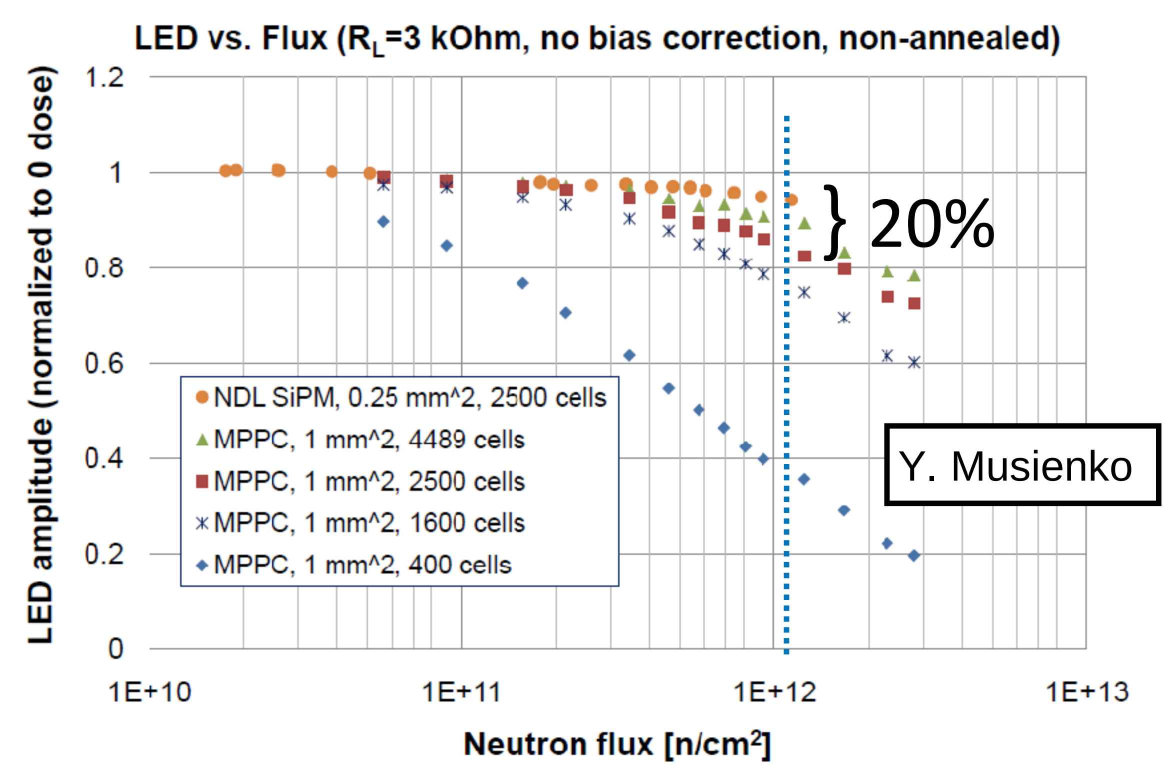
- all SiPM were operational after irradiation
- loss of single photoelectron resolution for $\phi_{eq} > 10^{10}\ cm^{-2}$ @ -30°C
- no change in static parameters (R_q, C_{pix}, V_{bd})
- small changes in G, PDE, CN (~10%)
- significant increase in DCR / DC
  small cells (small C_{pix} / fast recovery time / small G) are more favorable



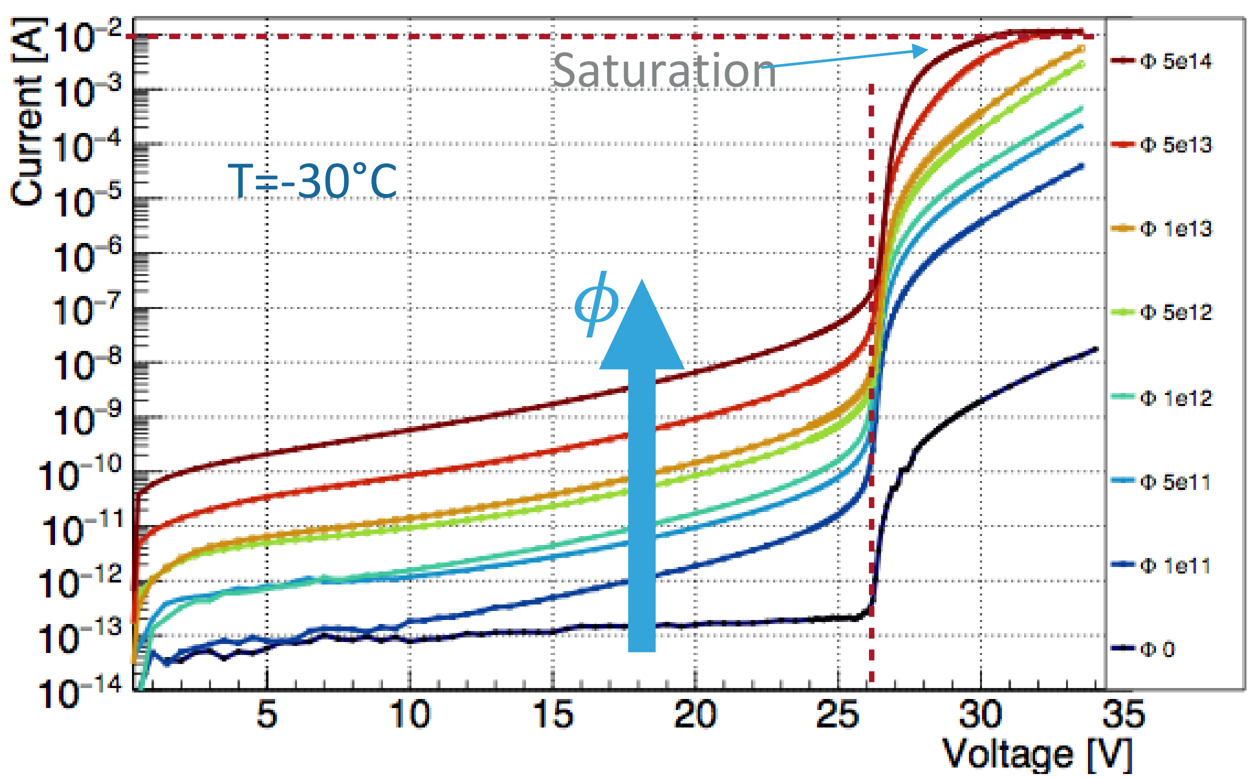
$$\Delta(N)_{norm}(U) = \frac{N_{after}(U) - N_{before}(U)}{A \cdot PDE_{515nm}(U)}$$

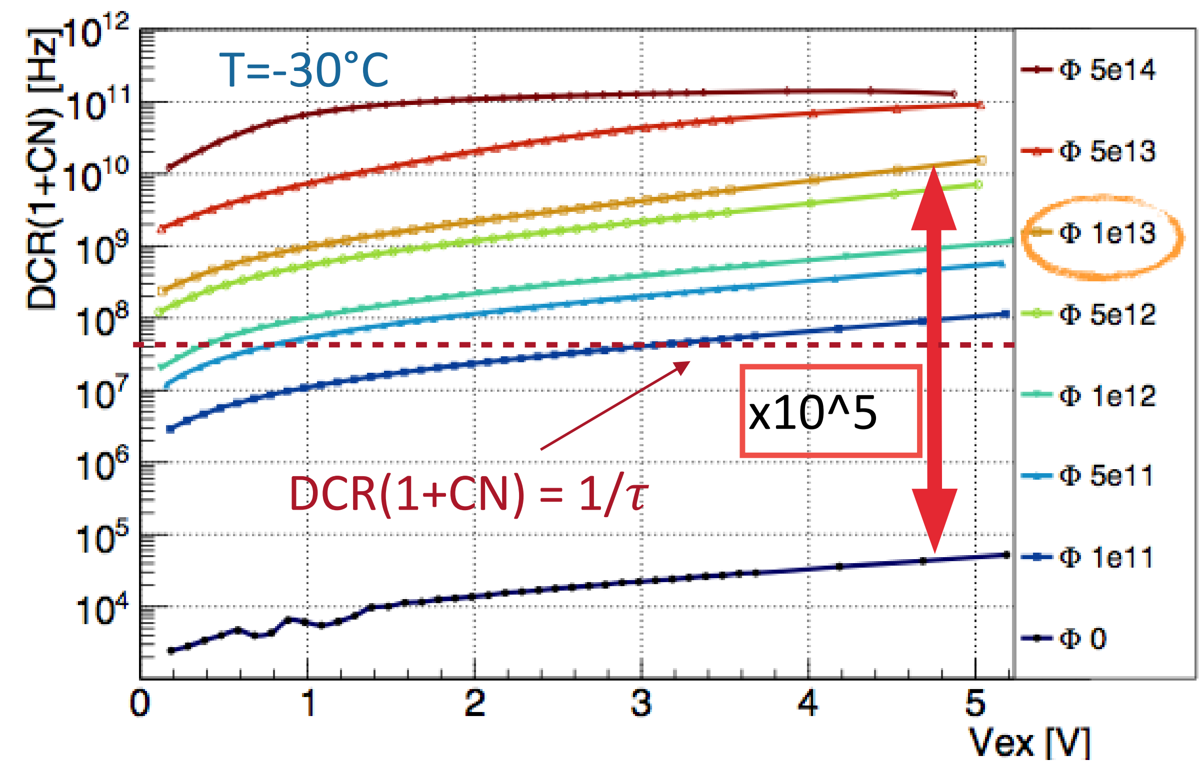


Y. Musienko et al.
NIM A 610 (2009) 87–92



Irradiation with hadrons: $\phi_{eq} > 10^{12}$ cm^{-2}

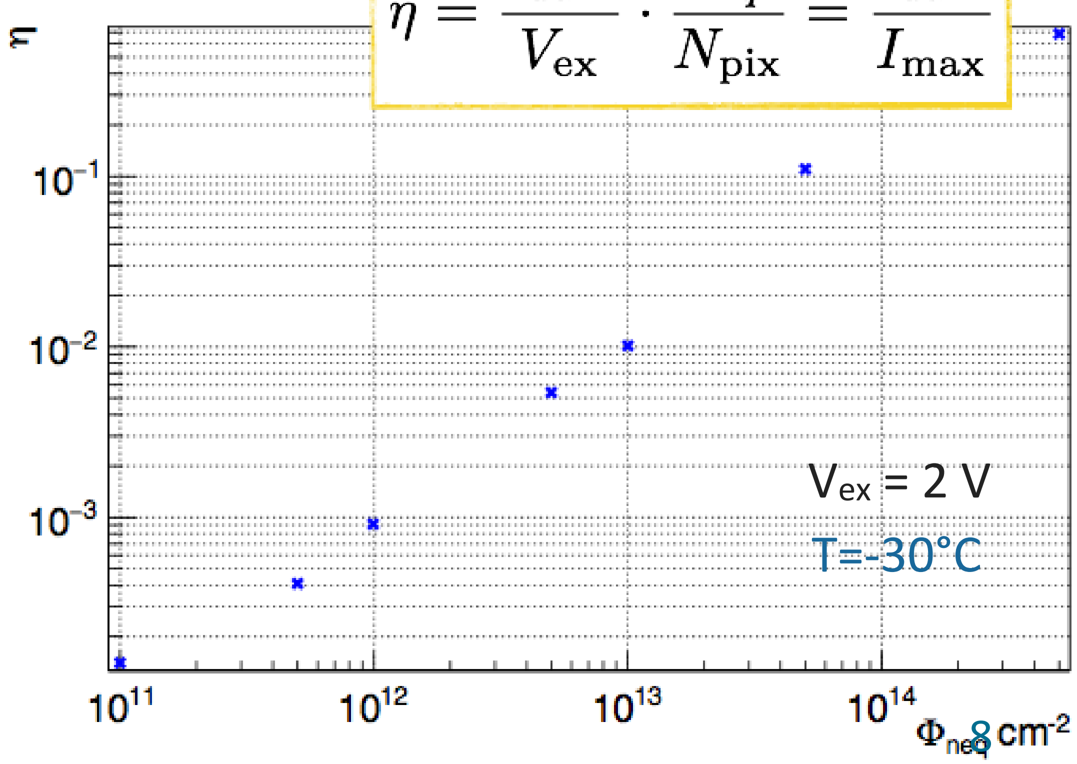




$$\mathrm{DCR}\cdot(1+\mathrm{CN}) = \frac{I_{\mathrm{dark}}}{q_0\cdot G}$$

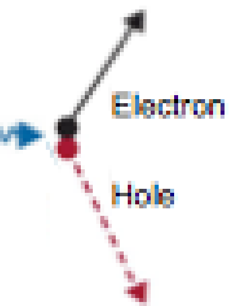
$$G = \frac{C_{pix}\cdot(V - V_{bd})}{q_0}$$

$$\eta = \frac{I_{\mathrm{dark}}}{V_{\mathrm{ex}}}\cdot\frac{R_q}{N_{\mathrm{pix}}} = \frac{I_{\mathrm{dark}}}{I_{\mathrm{max}}}$$



- Huge increase of dark current with irrad: 10 kHz before irrad, 2 GHz at ϕ=1x10^{13}
- increase in pixel occupancy η > 1%
- self-heating effect = increase of V_{bd} = reduction of G at fix V_{op}

Radiation hardening?



1. Significant increase of dark current (DCR)
2. $<10^{12}$ n/cm^2, generally no significant change on many paramters
3. $>10^{12}$ n/cm^2, observable change in many paramters
4. high dark current → self heating → apparent δV_{bd} → possibly device failure

What can we do after SiPMs are radiation damaged?
Can we radiation hard SiPMs?

- Study radiation effects on SiPMs
- Find engineering solutions
- Find physics solutions

Let's find out from our colleagues