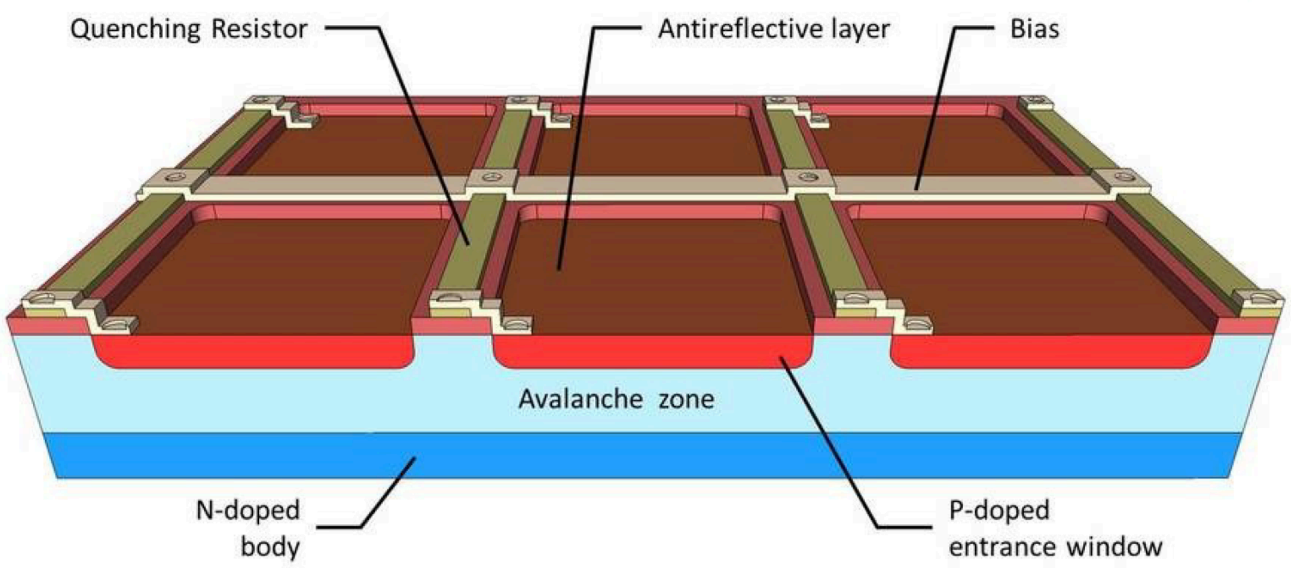
Radiation damage on silicon photo-multipliers

Erika Garutti

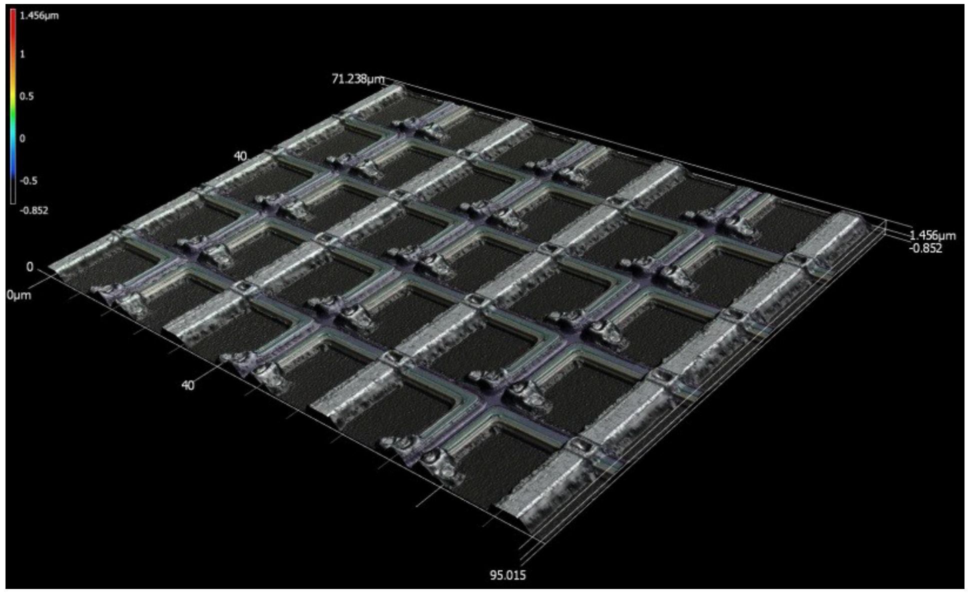
Silicon Photo-Multiplier

Matrix of single avalanche diodes operated in Geiger Mode (reverse $V_{Bias} > V_{Breakdown}$)



Single photons can trigger measurable charge avalanches

Advantages (compared to PMT):
Smaller, cheaper, V_{Bias} < 100 V, B-field insensitive, single photon resolution
Disadvantages:
Higher dark count rate, after-pulses + cross-talk, worse radiation hardness



laser microscope image of a KETEK SiPM

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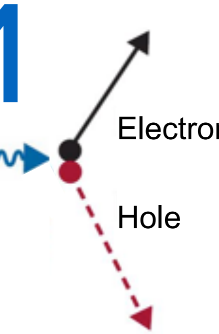
Relevance of radiation damage in SiPM



Scientific motivation:

- SiPMs considered as photo-sensor of choice in many upcoming experiments
- Up to now limited investigation of radiation damage in SiPM is available

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
  ➔ 6×10^{13} n/cm^2 (after 3000 fb^{-1})

Space experiments:

- Very high radiation expected for detectors in space
  5×10^{10} n/cm^2, AGILE gamma ray detector in geostationary orbit

Outline

- Radiation damage in silicon
- Surface damage in silicon photo-multipliers
- Bulk damage in silicon photo-multipliers
- Impact on SiPM parameters

Radiation damage in Silicon

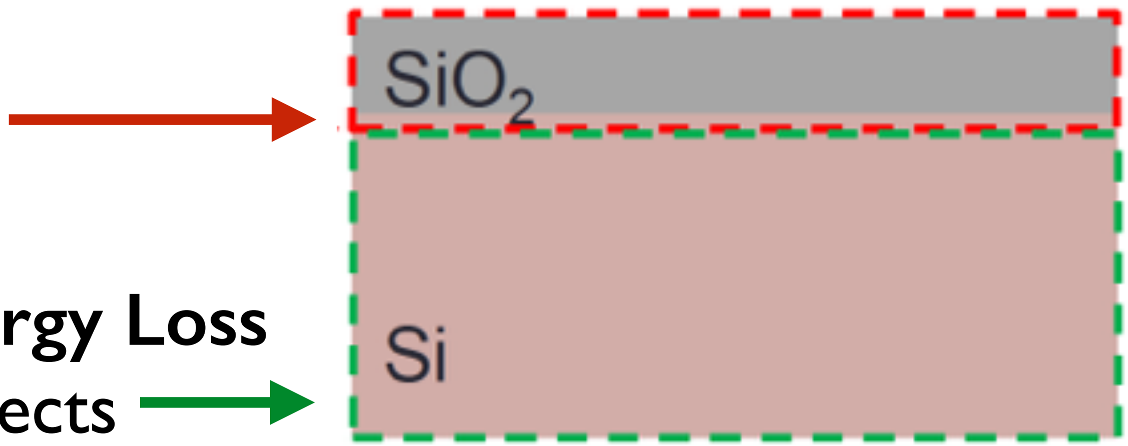
Two types of radiation damage in silicon detectors:

Surface damage due to **Ionizing Energy Loss**

- Accumulation of charge in the oxide (SiO_2),
- traps at Si/SiO_2 interface

Bulk/Crystal damage due to **Non-Ionizing Energy Loss**

- Displacement damage, build-up of crystal defects



Radiation damage in Silicon

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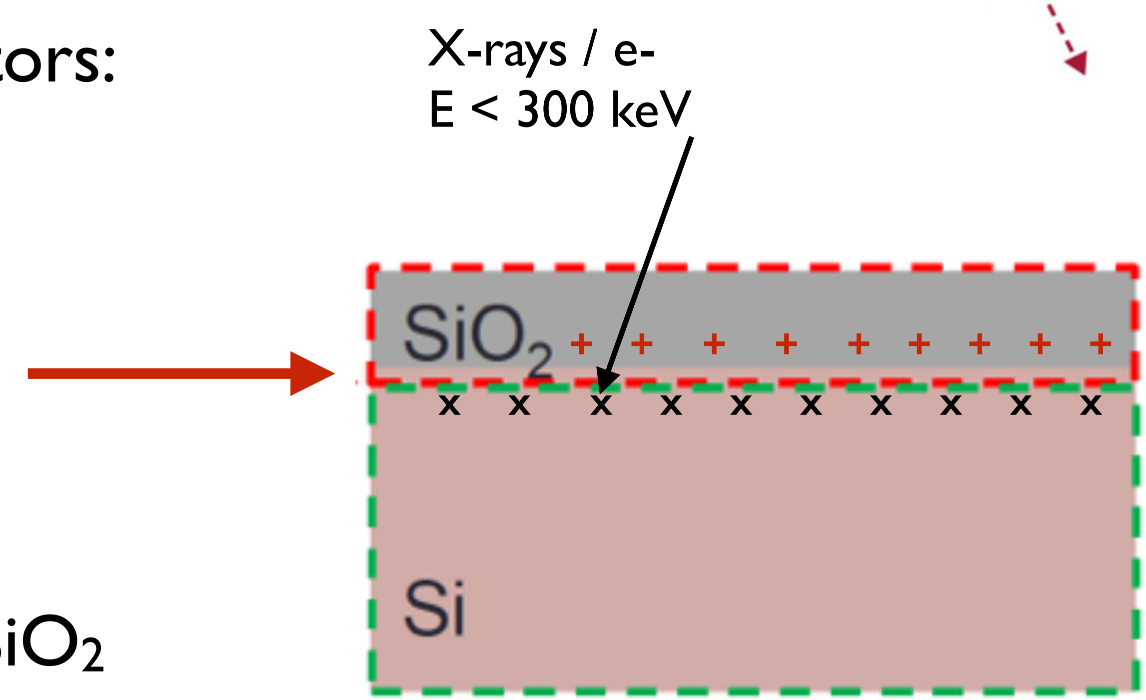


Surface damage due to **Ionizing Energy Loss**

- Accumulation of charge in the oxide (SiO_2),
- traps at Si/SiO_2 interface

Simplified model:

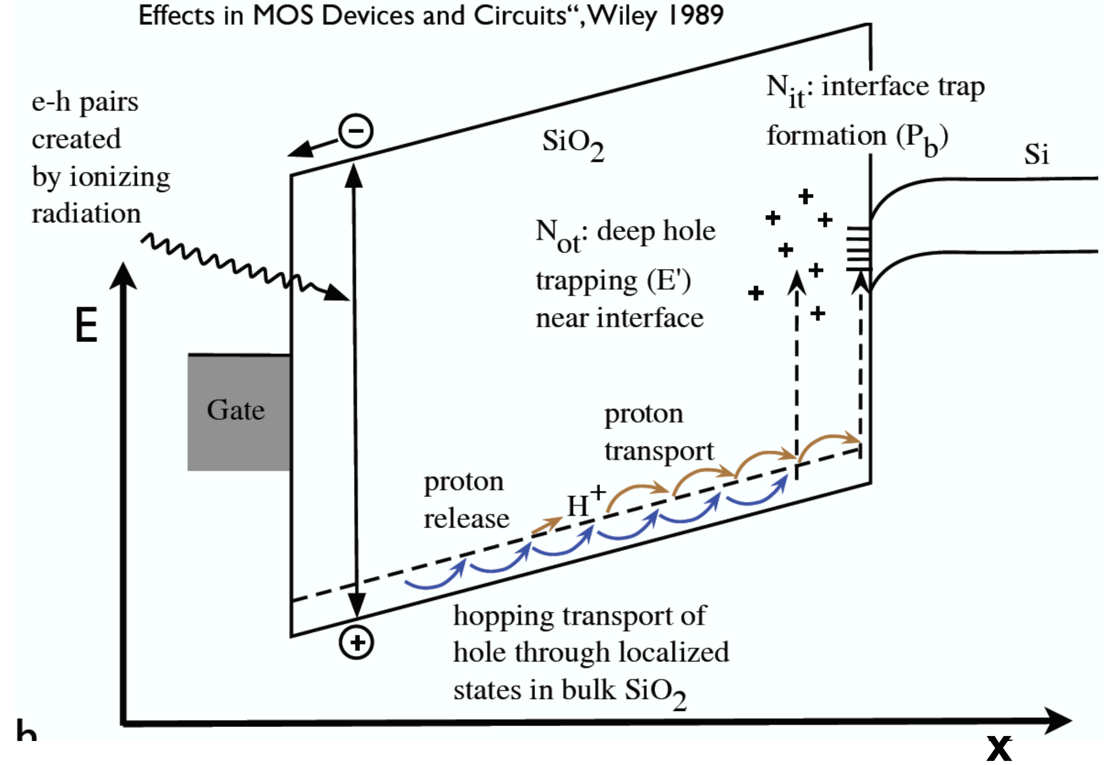
- X-rays or ionizing rad. produce e-h pairs in SiO_2
- Fraction of electron-hole pairs recombine
- Remaining electrons escape from SiO_2
  $[\mu_e \sim 20\ cm^2/(Vs)]$
- Remaining holes move toward the $Si\text{-}SiO_2$ interface
  $[\mu_h \sim 5 \times 10^{-5}\ cm^2/(Vs)]$

The trapped holes generate:

- Fixed oxide charges: N_{ox}
- Interface traps: N_{it}, $D_{it}(E)$

which in turn lead to additional surface current

from T.P. Ma and Paul V. Dressendorfer, „Ionizing Radiation Effects in MOS Devices and Circuits“, Wiley 1989



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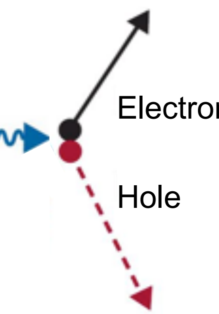
Radiation damage in Silicon



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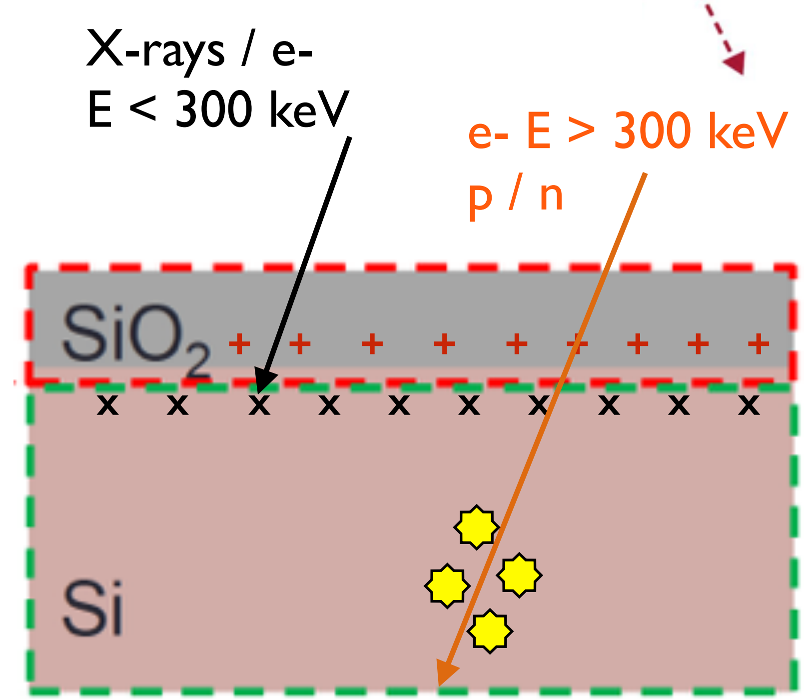
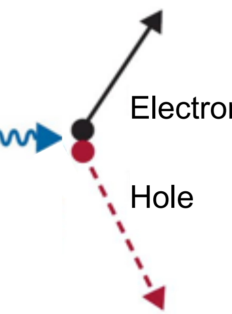


Radiation damage in Silicon



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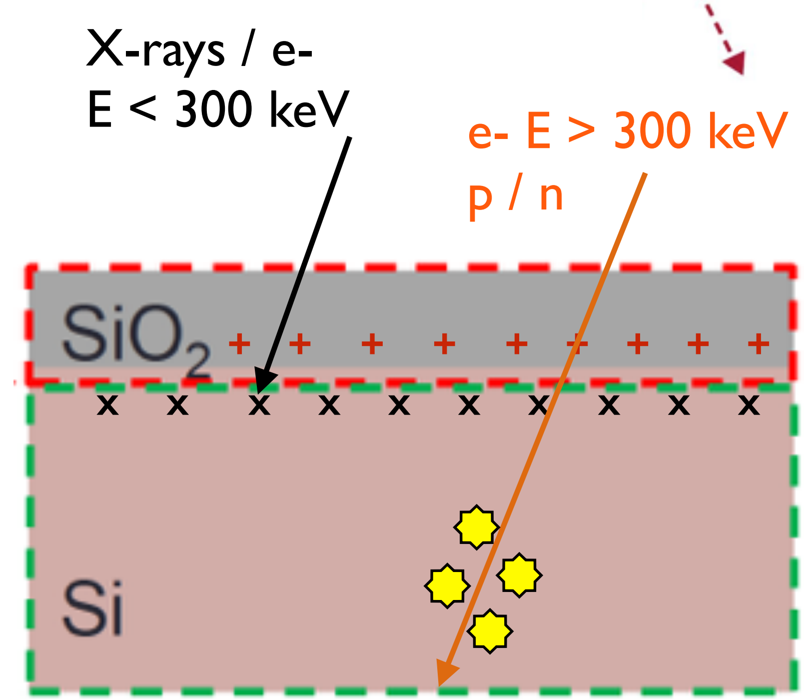
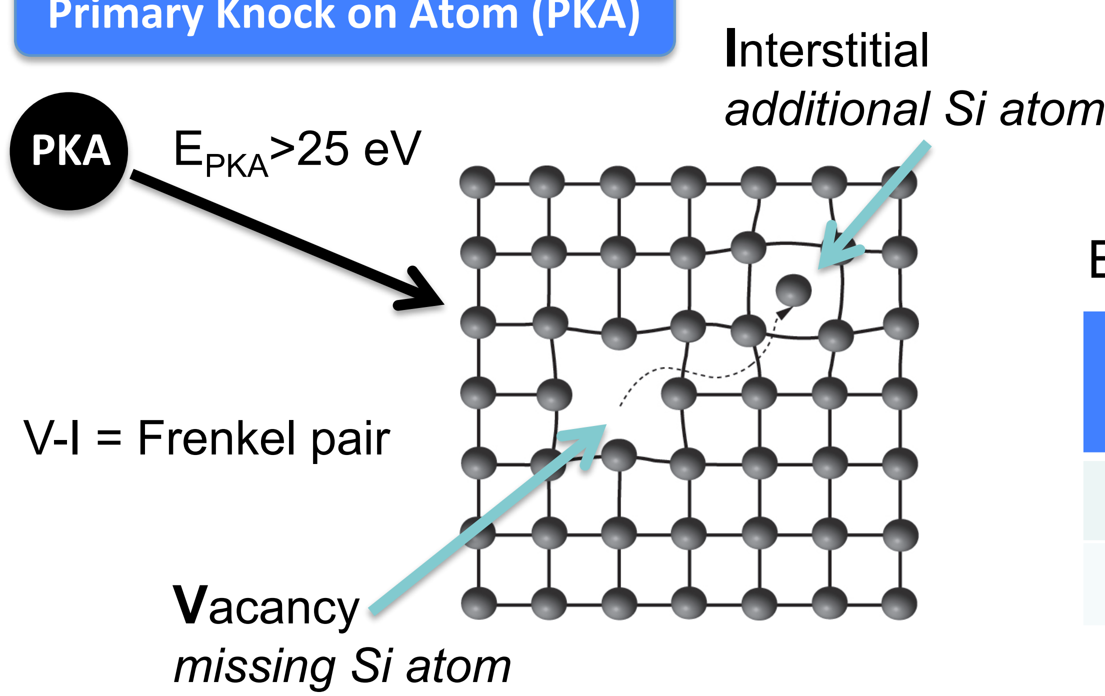


Primary Knock on Atom (PKA)



Energy threshold for bulk defects generation:

Particle	Gamma/ X-ray	Electron	Proton	Neutron
Frenkel pair	300 keV	255 keV	185 eV	185 eV
Cluster defects	-	8 MeV	35 keV	35 keV

Radiation damage in SiPM

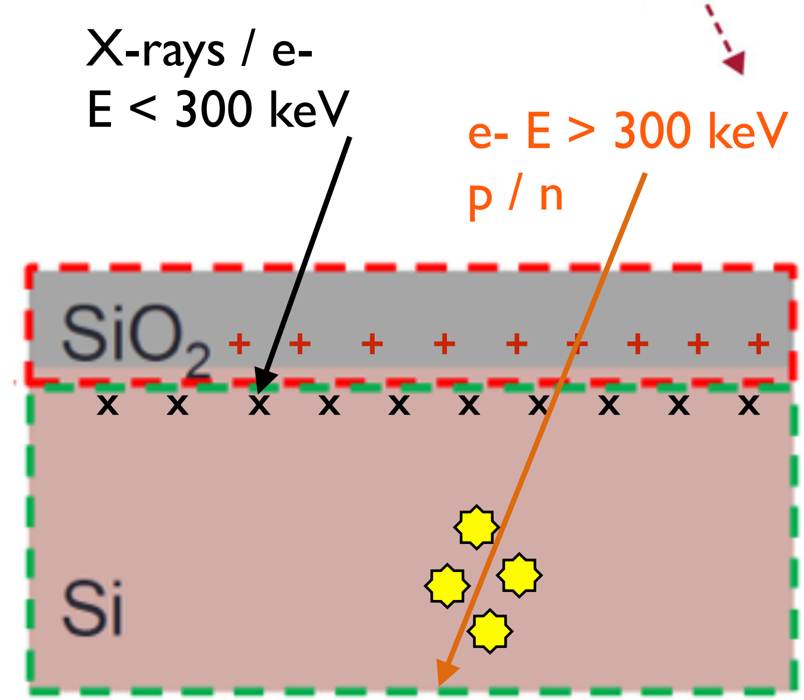
Two types of radiation damage in silicon detectors:

Surface damage due to **Ionizing Energy Loss**

- Accumulation of charge in the oxide (SiO_2),
- traps at Si/SiO_2 interface

Bulk/Crystal damage due to **Non-Ionizing Energy Loss**

- Displacement damage, build-up of crystal defects



Effects on an SiPM:

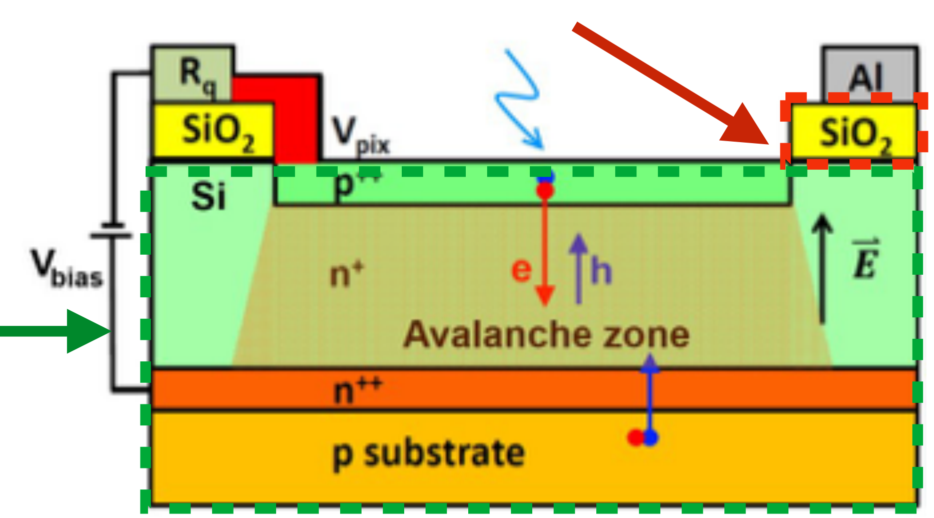
Surface damage:

➔ Increase in leakage current

Bulk damage:

➔ Increase in leakage current

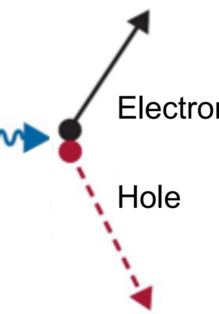
➔ Increase in after-pulse and cross-talk



Cross-section of a single pixel of our SiPMs

is there any effect of the field, i.e. on V_{bd} and PDE?

Investigation of leakage current



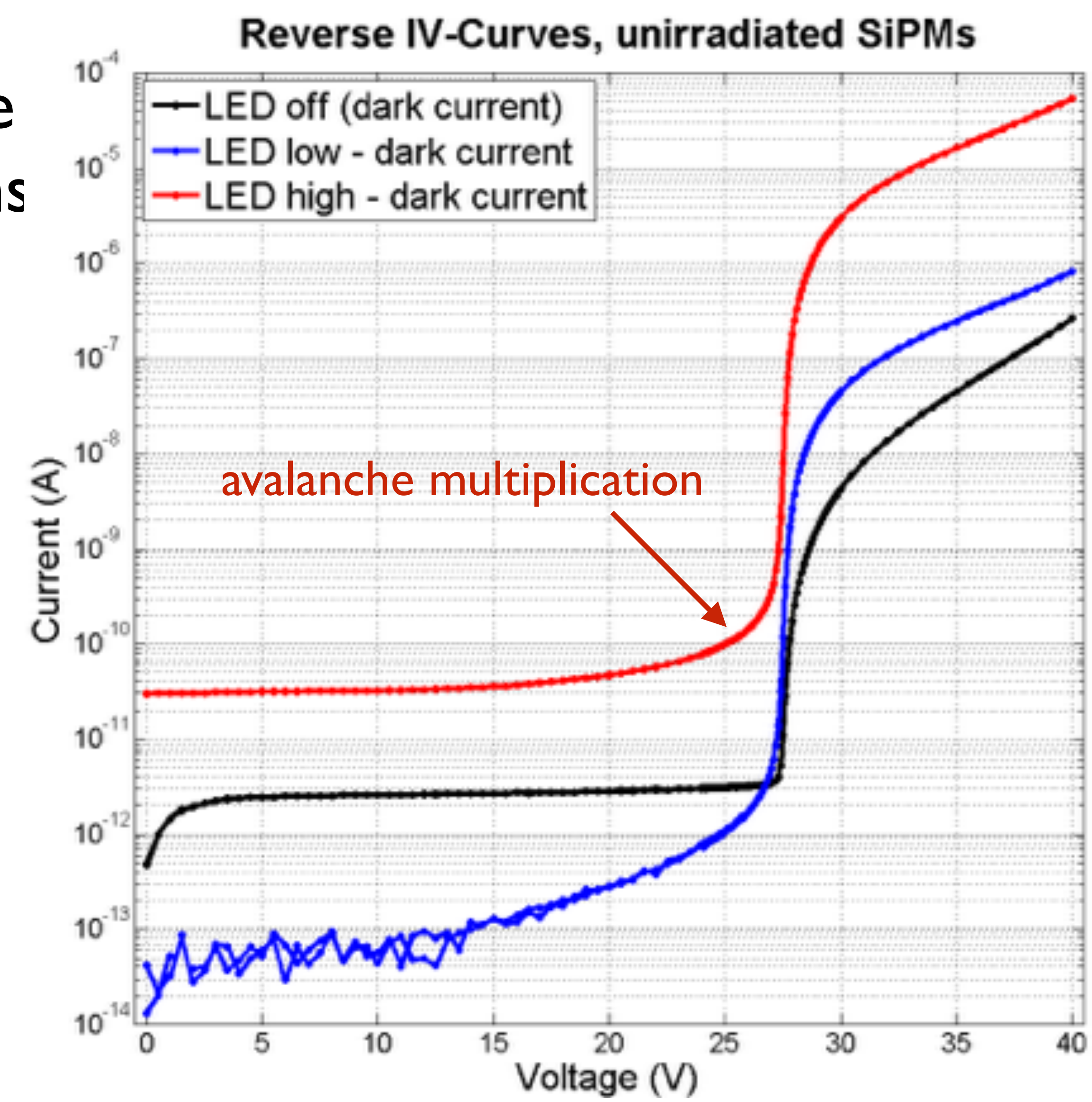
Compare I-V curves w/ and w/o light

Below breakdown: Avalanche multipl. range

- Surface current and first impact ionizations increase with voltage
- Nearly no multiplication for dark current („misses" avalanche region)
  ➔ Sharp rise at breakdown
- Avalanche multiplication for curves with light
  ➔ Less abrupt rise at breakdown

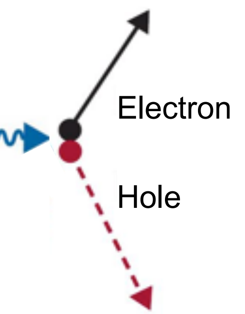
Above breakdown: Geiger mode

- Current increases due to increase in gain, breakdown-probability, cross-talk and after-pulses



KETEK SiPM (~4300 pixels, 15 μm pitch, 1 mm^2)
LED 470 nm, attenuation length ~0.5 um

Investigation of leakage current



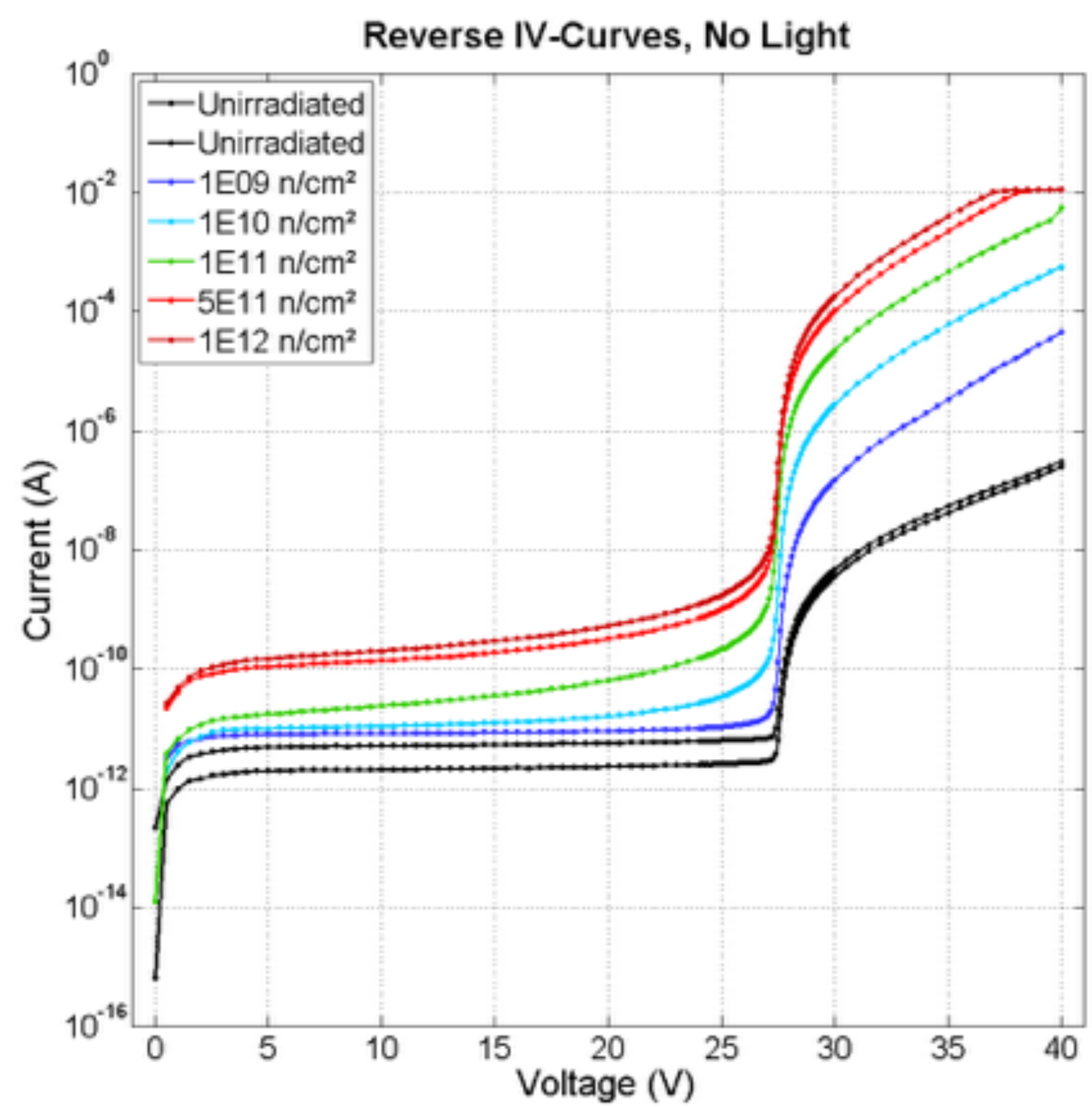
Neutron irradiation to 10^9 to 10^{12} 1 MeV neq/cm²

Below breakdown: Linear avalanche range

- leakage current increases by x10^2
- avalanche multiplication visible
  ➔ Dark current after irradiation originates mainly from avalanche zone

Above breakdown: Geiger mode

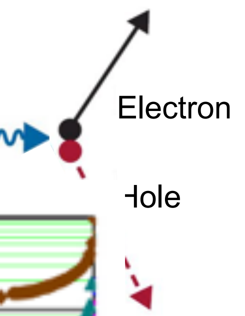
- Current increases by > x10^4
- V_{bd} remains unchanged (accuracy 50 mV)



KETEK SiPM (~4300 pixels, 15 µm pitch, 1 mm²)

Neutron irradiation @ Ljubljana reactor
No annealing performed

Investigation of leakage current



X-ray irradiation < 300 keV only surface damage

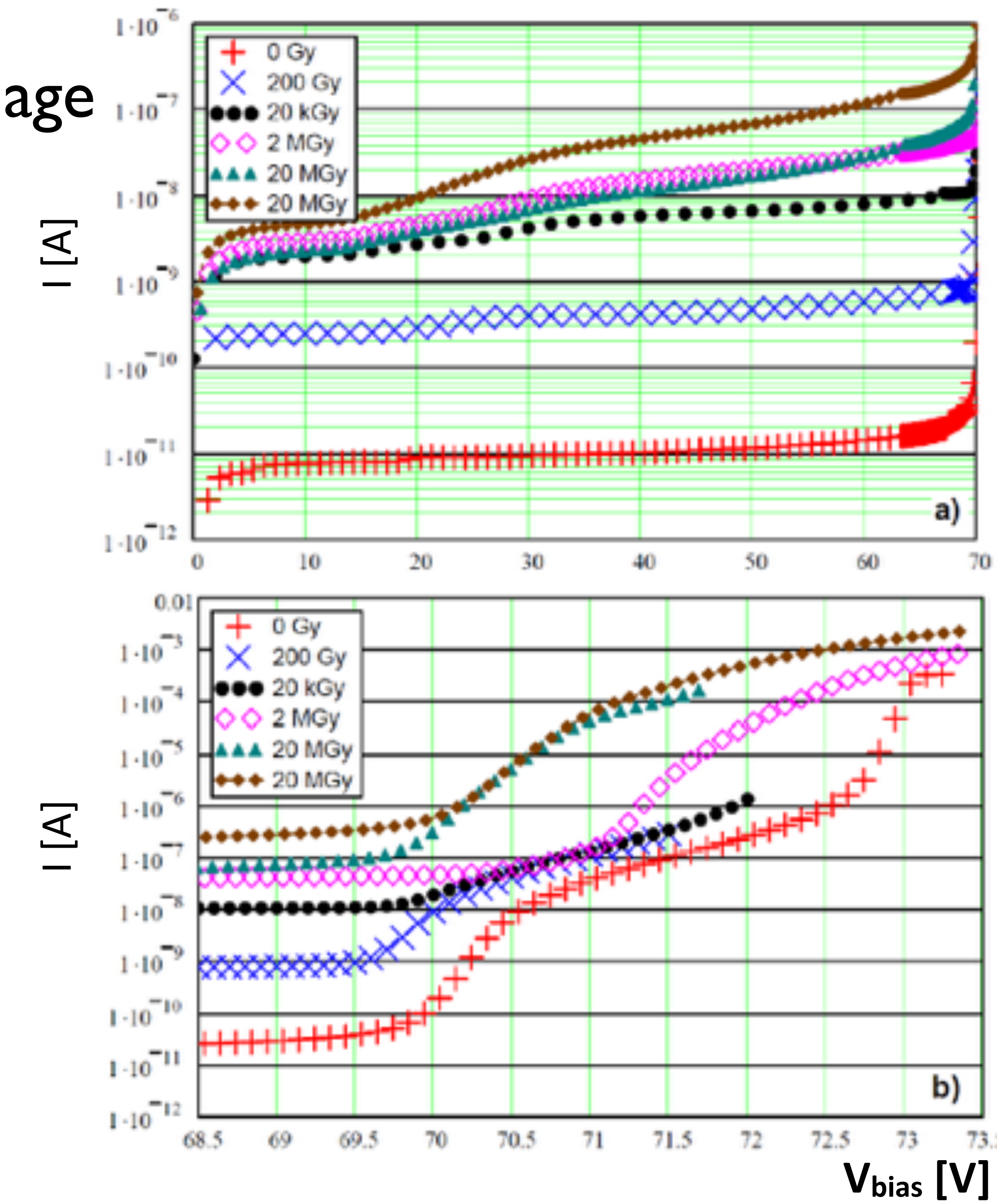
Below breakdown: Linear avalanche range

- leakage current increases by $\times 10^4$

Above breakdown: Geiger mode

- Current increases by x2 from 0 - 200 kGy and by $\times 10^3$ above 20 MGy
- V_{bd} remains unchanged (accuracy 50 mV)

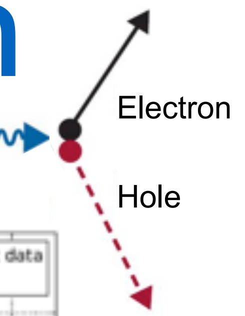
C. Xu, W. L. Hellweg, E. Garutti, and R. Klanner, "Influence of X-ray Irradiation on the Properties of the Hamamatsu Silicon Photomultiplier S10362-11-050C", NIMA 762 (2014) 149-161.



Hamamatsu SiPM (MPPC 50um pitch, 1 mm^2)

200 Gy - 20 kGy from X-ray tube (Mo target)
2 - 20 MGy at PETRA III
No annealing performed

Parenthesis on “V_{bd}“ determination



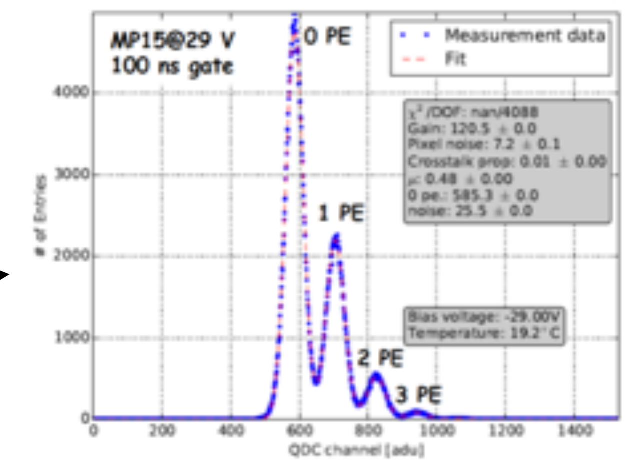
There are several “breakdown voltages”

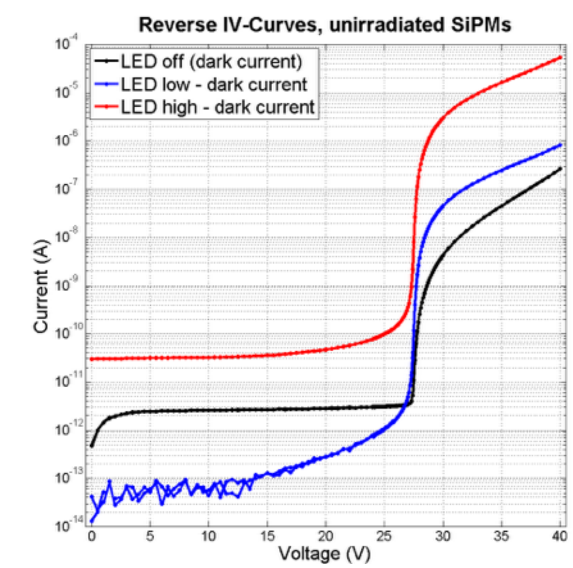
Experimentally determined parameters:

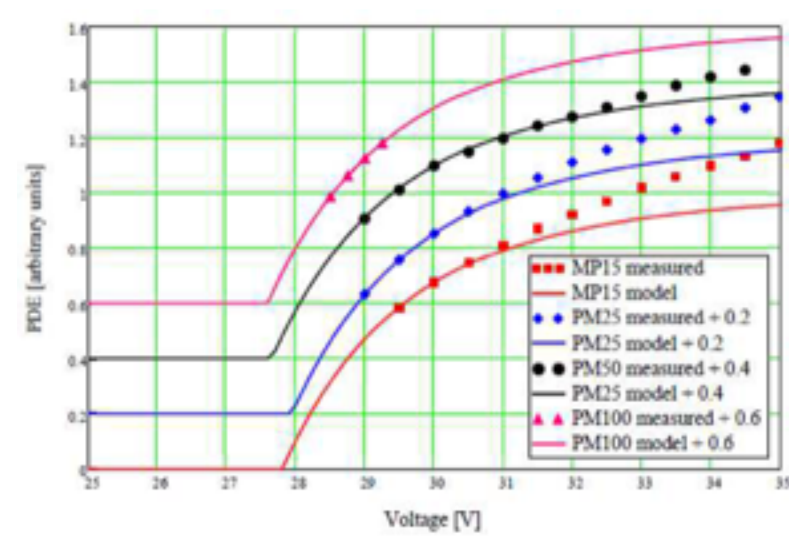
- Gain breakdown voltage V_{Gain}
- Current breakdown voltage V_I
- PDE start voltage V_{PDE}

Model parameters:

- Pixel breakdown voltage V_{bd}
- Geiger discharge turn-off voltage $V_{turn\text{-}off}$







V. Chmill, E. Garutti, R. Klanner, M. Nitschke, and J. Schwandt “Study of the breakdown voltage of SiPMs”, Proceeding to VCI 2016, Submitted to NIMA.

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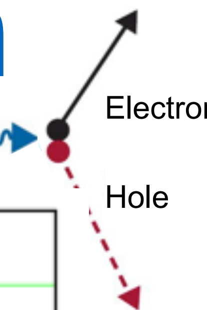

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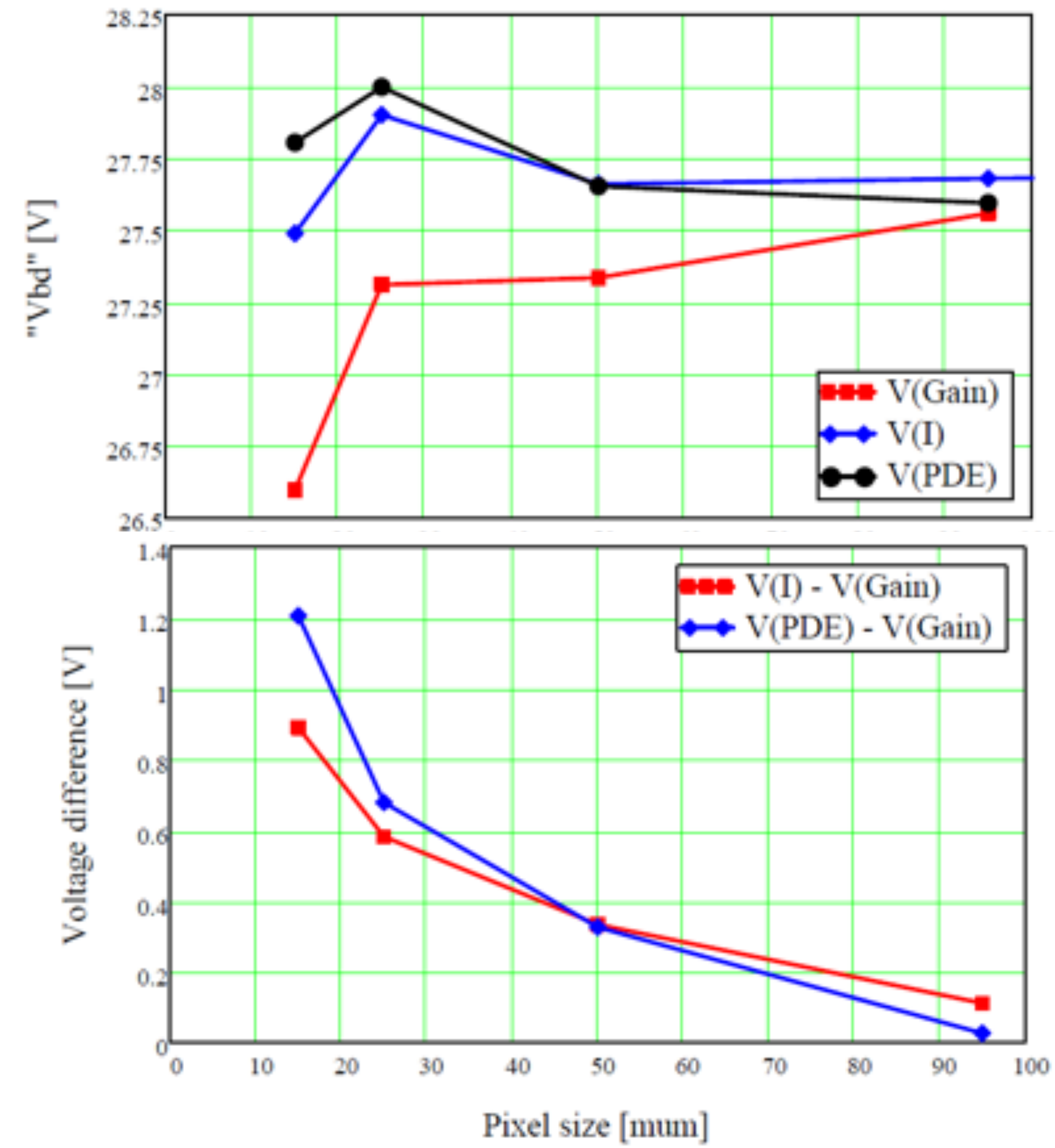

Experimentally determined parameters:

- Gain breakdown voltage V_{Gain}
- Current breakdown voltage V_{I}
- PDE start voltage V_{PDE}

We observe:

- $V_I \approx V_{PDE} \neq V_{Gain}$ [$V_{bd} = V_I = V_{PDE}$]
- $(V_I - V_{Gain}) > 0$, and decreasing with pixel pitch [$V_{turn\text{-}off} \neq V_{Gain}$]

Relevant for the SiPM user:

- V_{Gain} is the relevant parameter $Q \sim (V_{bias}\text{-}V_{Gain})$ with $V_{Gain} \neq V_{bd}$
- I(V) measurement **does not** give V_{Gain}

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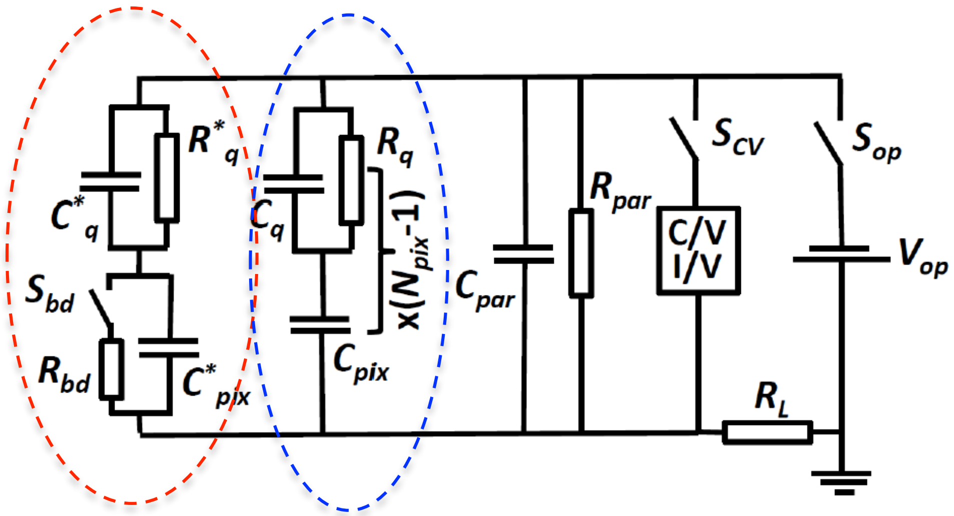
Investigation of C-f curve



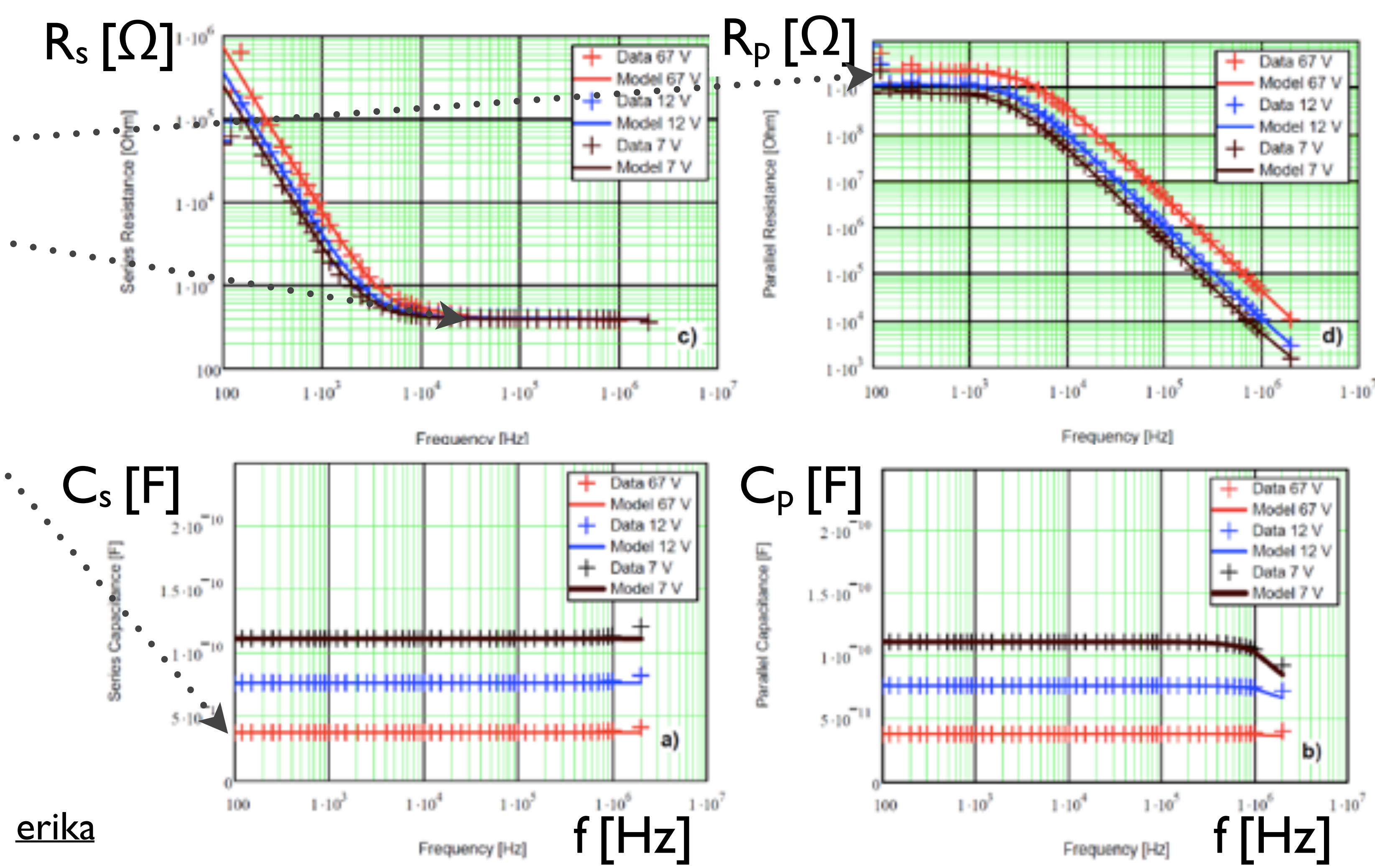
Firing pixel   Non-firing pixels

The complex resistance of a SiPM with N_{pix} pixels below the breakdown voltage is given by:

$$\left(\frac{1}{R_{par}} + i\omega C_{par} + N_{pix} \cdot \left(\frac{1}{i\omega C_{pix}} + \frac{R_q}{1 + i\omega C_q R_q}\right)^{-1}\right)^{-1}$$

Measure freq. dependent parallel R_p and C_p on an LCR meter, and extract serial R_s and C_s

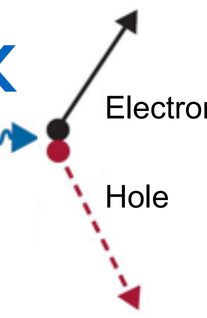
Dose	0 Gy
R_{par} [MΩ]	$2\,100 \pm 100$
R_q^{Cf} [kΩ]	125 ± 5
C_{pix}^{Cf} [fF]	94.0 ± 1.5
$R_q^{Cf} \cdot C_{pix}^{Cf}$ [ns]	11.8 ± 0.6



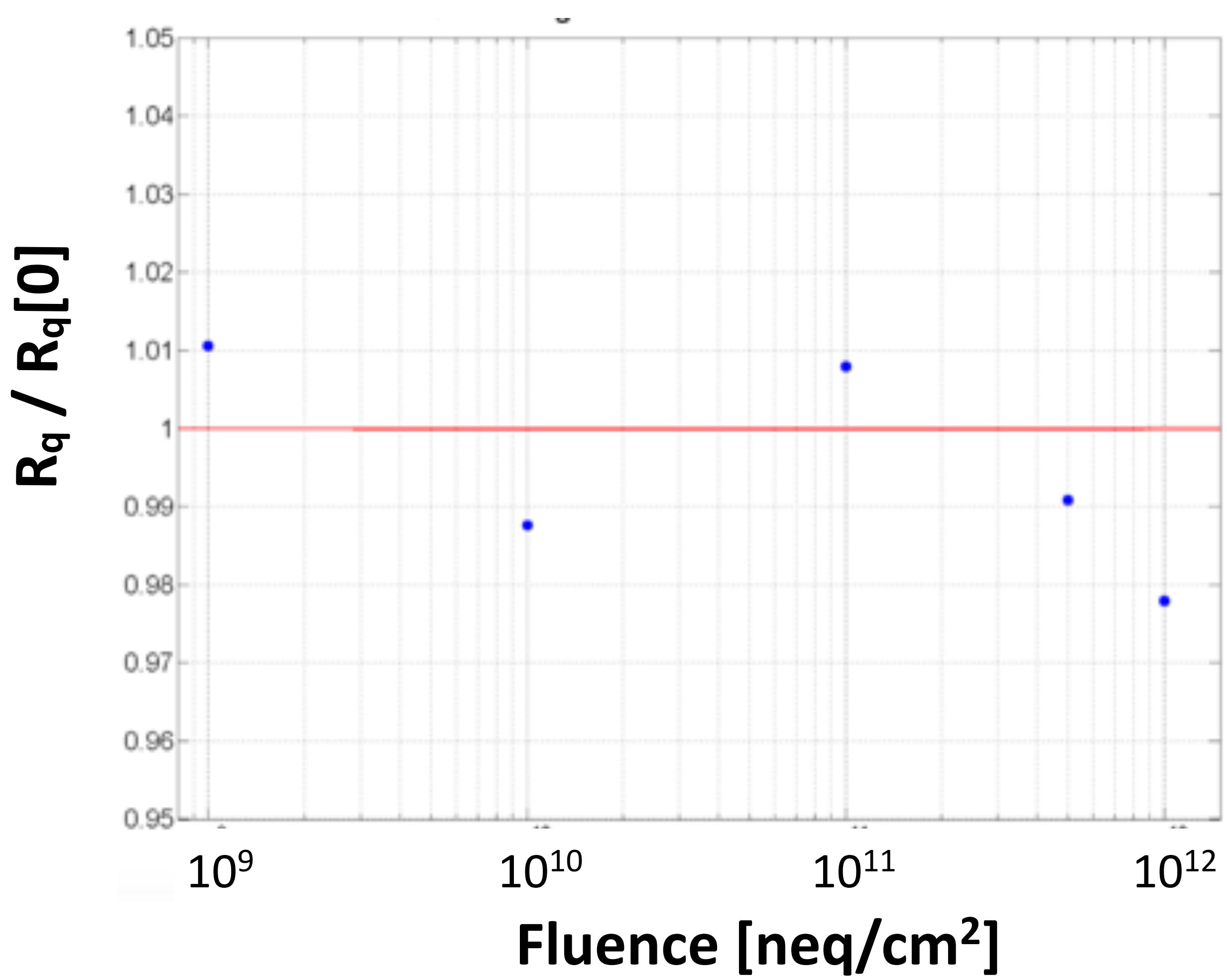
$$Z = R_s + 1/(i\, 2\pi f\, C_s) =$$
$$= (1/R_p + i\, 2\pi f\, C_p)^{-1}$$

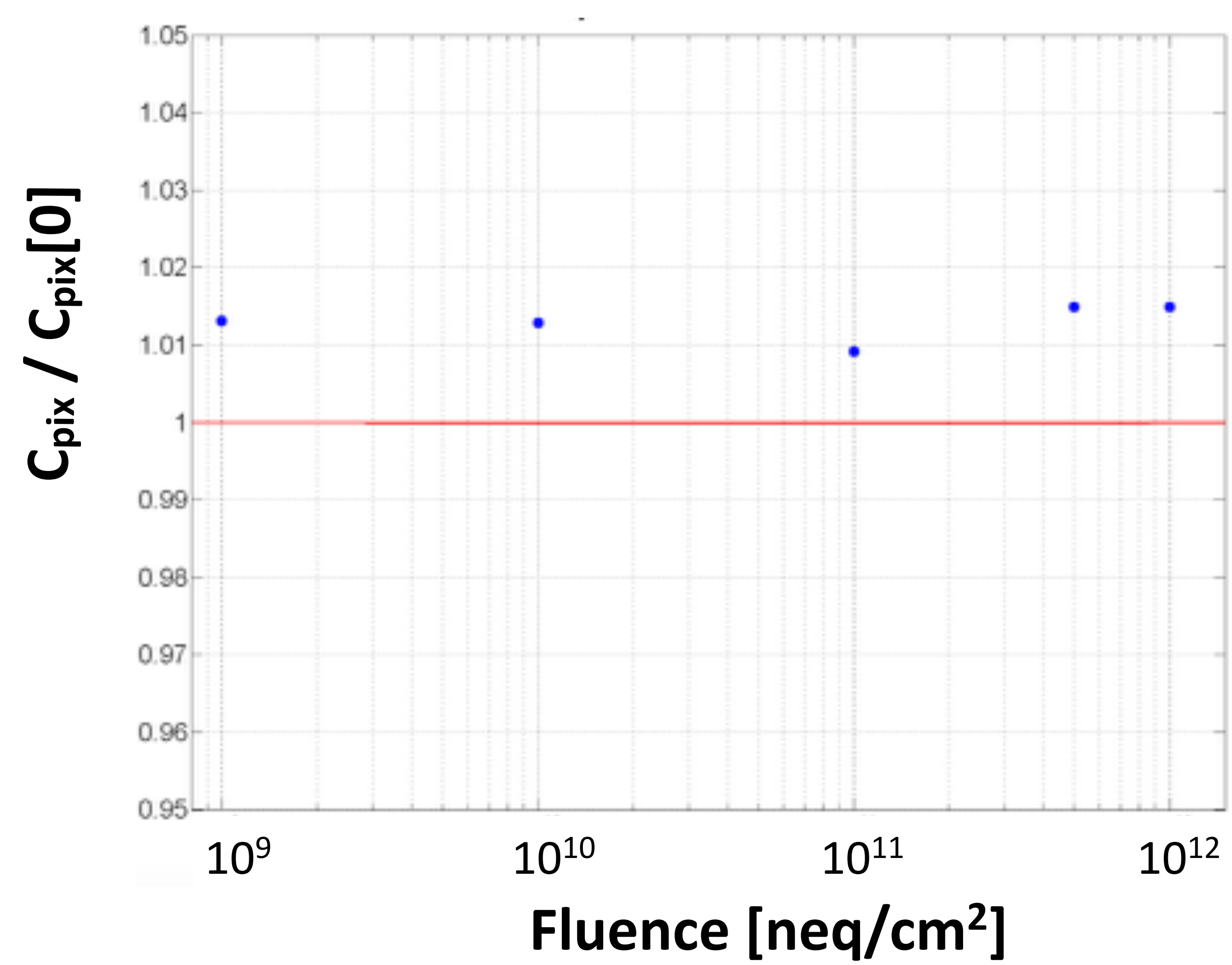
erika

Impact on SiPM parameters: R_q, C_{pix}



Neutron irradiation to 10^9 to 10^{12} 1 MeV neq/cm²



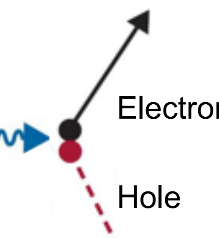


Quenching resistor and pixel capacitance do not change after neutron (and X-ray) irradiation

KETEK SiPM (~4300 pixels, 15 µm pitch, 1 mm²)

Neutron irradiation @ Ljubljana reactor
No annealing performed

Impact on SiPM parameters: DCR, XT



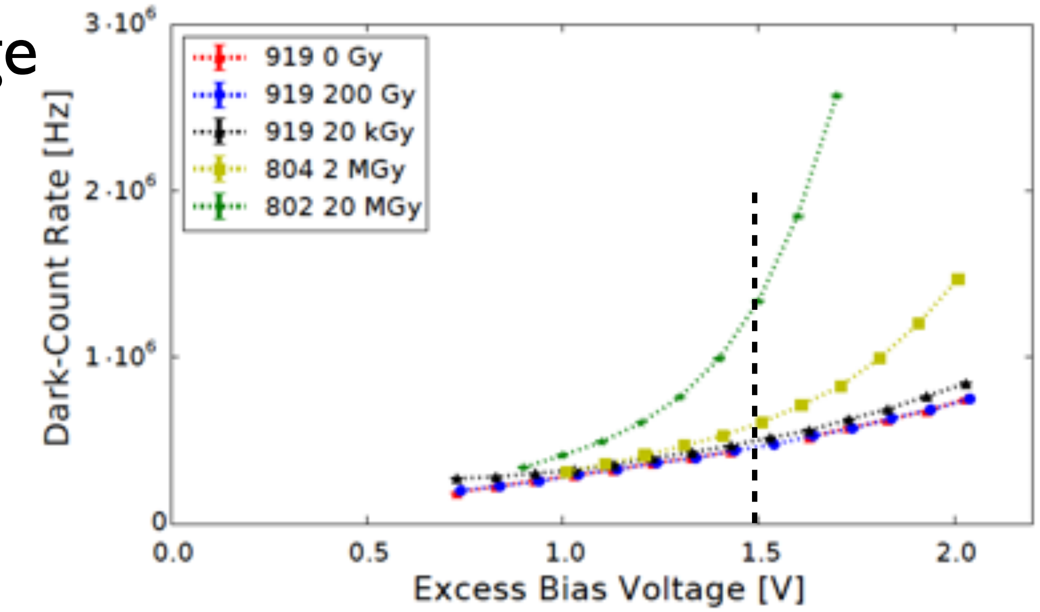
X-ray irradiation < 300 keV only surface damage

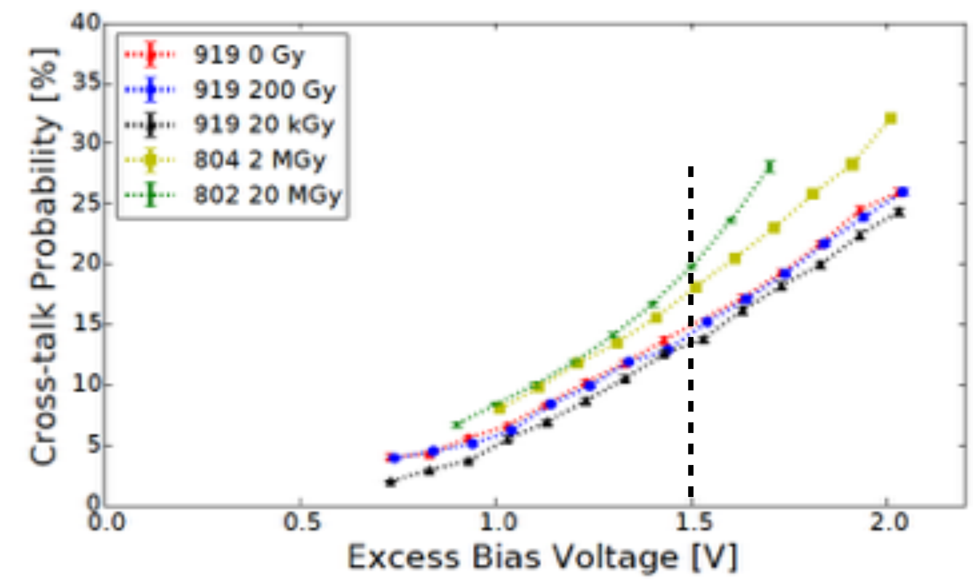
Dark count rate (DCR):

- small increase ~10% for 0-20 kGy
- increase by x3 for ΔV > 1.5 V and 20 MGy
- rapidly increasing with ΔV
  ➔ maximum useful gain limited

Cross-talk (XT):

- negligible change for 0-20 kGy
- unexpected increase for > 2 MGy





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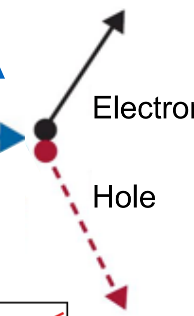
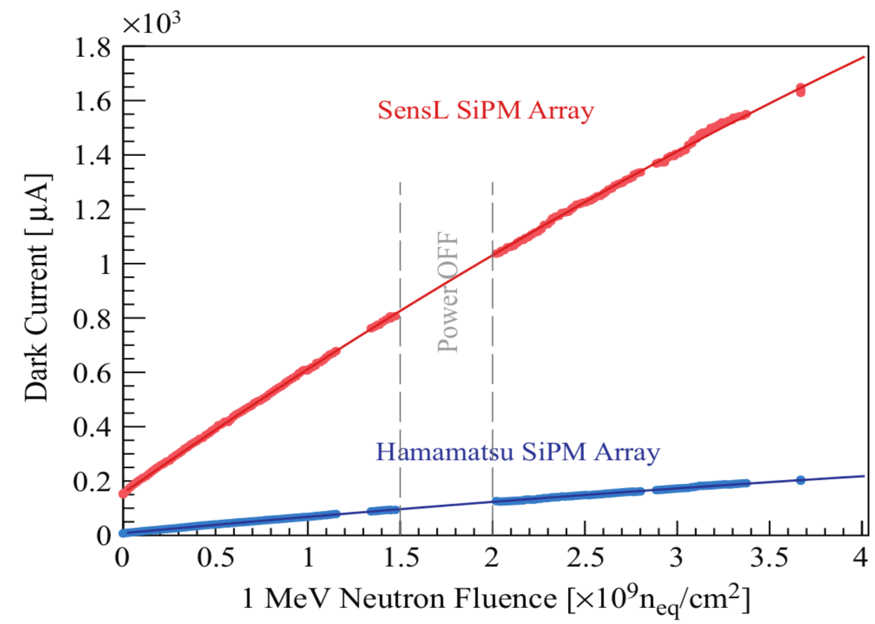
Impact on SiPM parameters: DCR, A



Neutron irradiation to 3.7 x10^{9} neq/cm^{2}

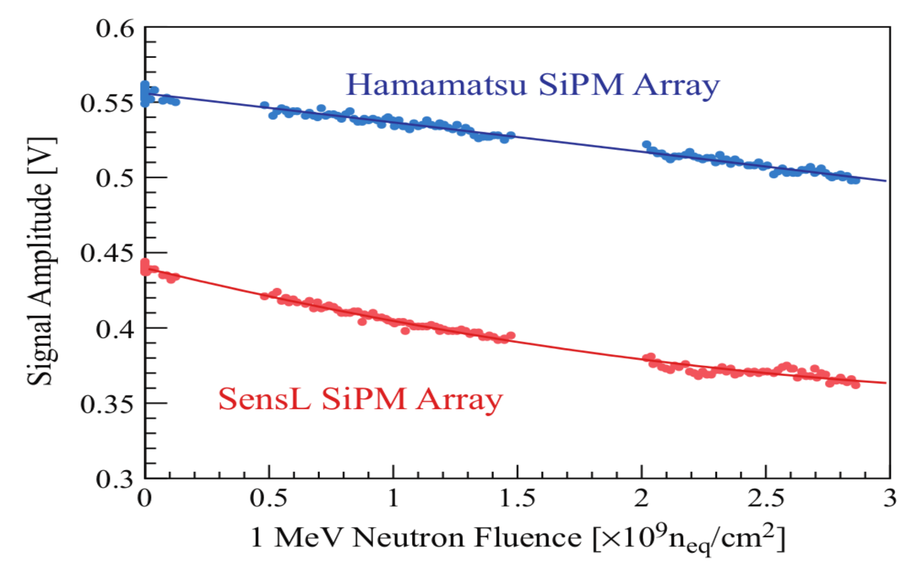
Dark count rate (DCR):

- increase by x8-10



Signal amplitude:

- 10-15% signal loss

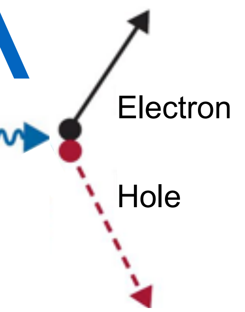


Hamamatsu & SensL SiPM

Monitored during irradiation
Operated at fixed gain of 0.75 x 10^{6}
Neutron irradiation @ JLAB with 1 GeV e- on Pb

Y. Quiang et al., Radiation hardness test of SiPMs for the J-Lab Hall D Barrel Calorimeter, Nucl. Inst. And Meth. A 698 (2013) 234-241

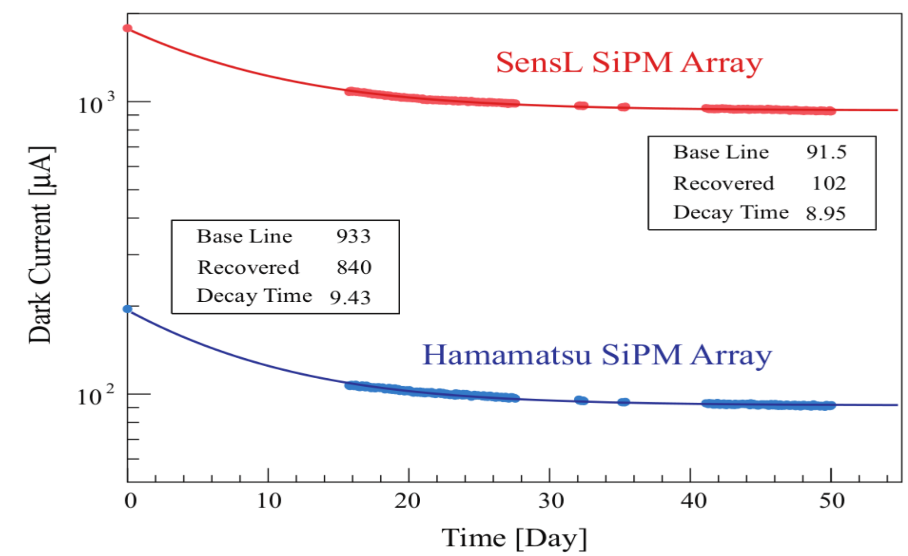
Impact on SiPM parameters: DCR, A



Neutron irradiation to 3.7 x10^9 neq/cm^2

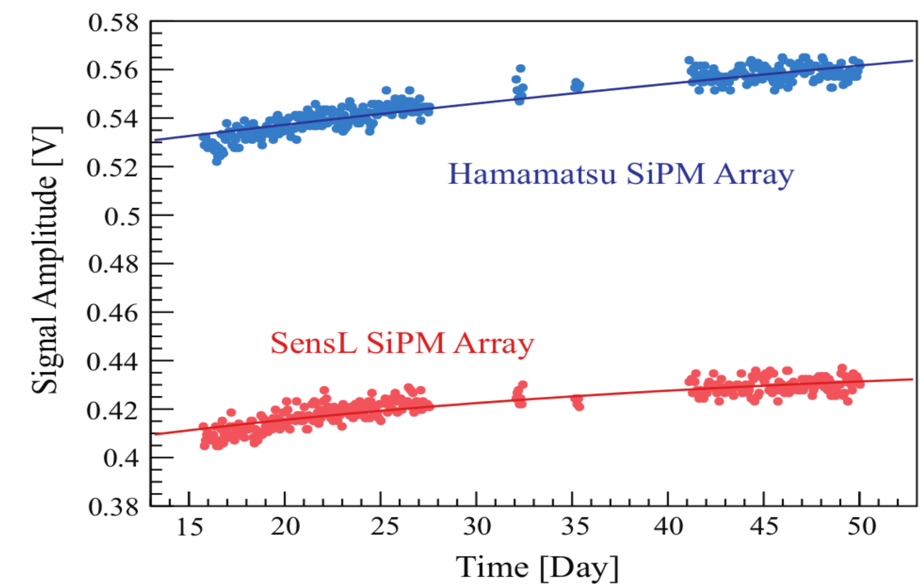
Dark count rate (DCR):

- increase by x8-10
- only 50% restored after 50 h room T annealing



Signal amplitude:

- 10-15% signal loss
- 100% restored after 50 h room T annealing



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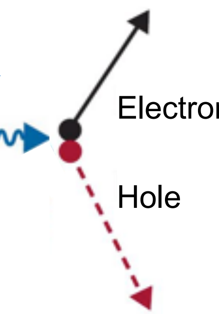
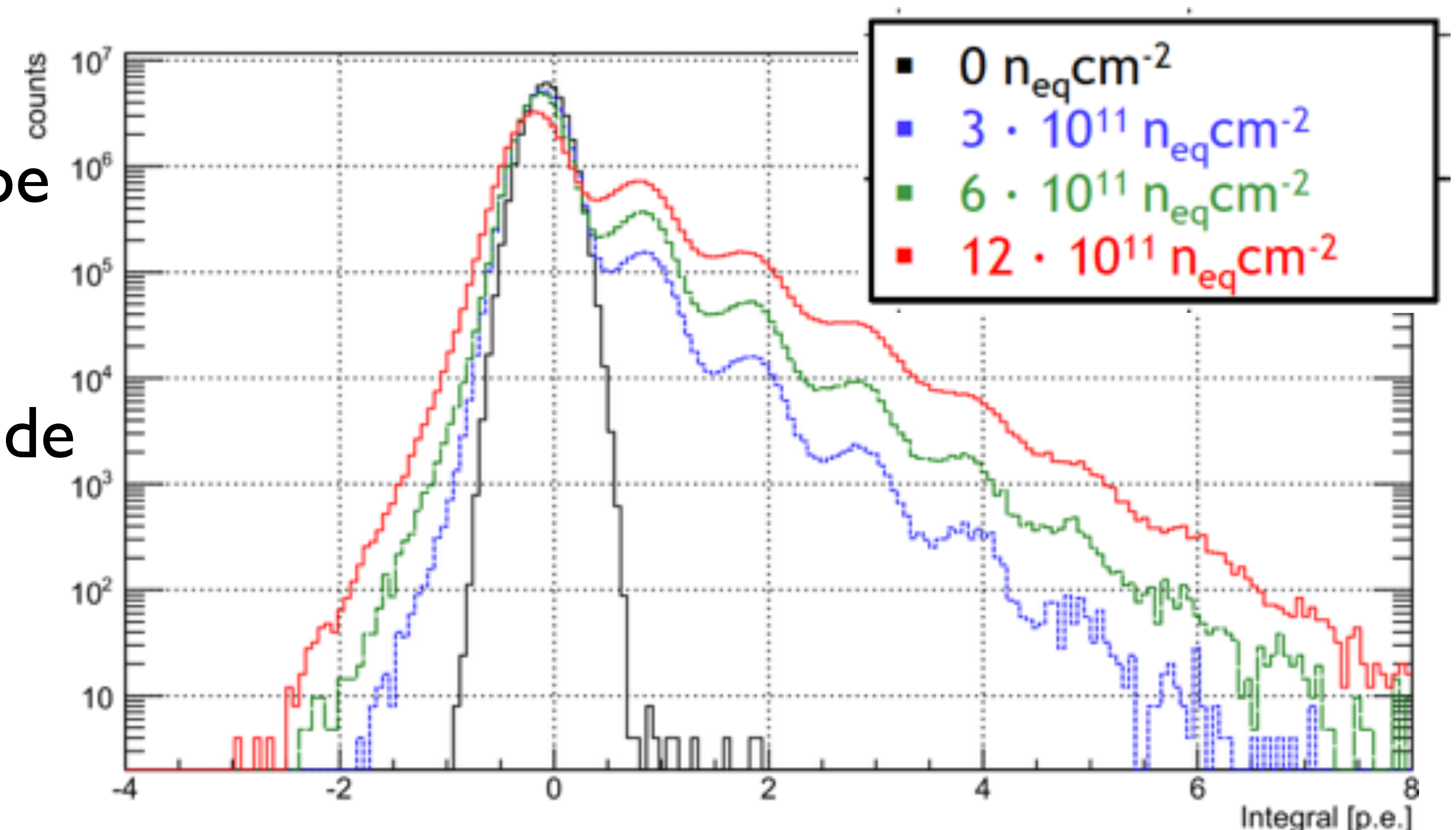
Impact on SiPM parameters: DCR



Neutron irradiation up to 12 x10^{11} neq/cm^2

PACIFIC shaper output spectrum integrated for 25ns with oscilloscope



Dark count rate (DCR):

- increase by >6 orders of magnitude

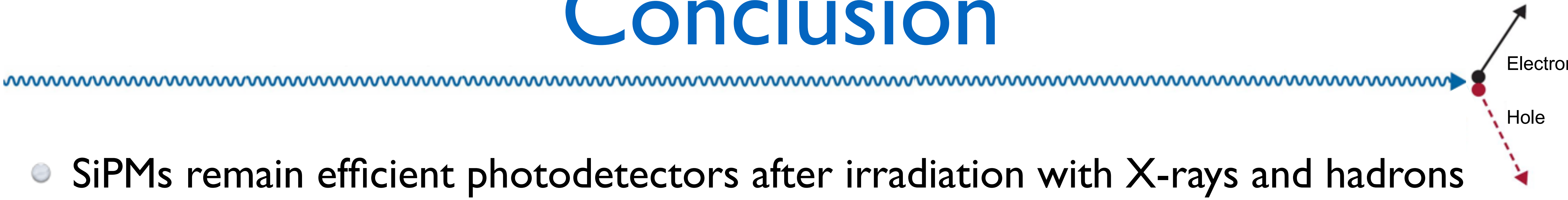
Detector still functional after irradiation
Single photon sensitivity with fast readout and at -40°C

Hamamatsu S10943-3183 (custom made - LHCb)

128 ch. with each 4x24 pixels (62.5x57.5 μm^2)
Operated at T = -40°C

David Gerick (Heidelberg University) for the LHCb Collaboration, DPG Frühjahrstagung 2016

Conclusion



- SiPMs remain efficient photodetectors after irradiation with X-rays and hadrons
- Detection efficiency and gain hardly affected by radiation damage
- After hadron damage (dependent on T) calibration using single PE not applicable
  ➔ different calibration methods to be developed

- Observed increase of DCR (on different SiPM types):
  - factor x10 after 3.7 x10^9 neq/cm² neutron irradiation
  - factor > x10^6 after 1.2 x10^{12} neq/cm² neutron irradiation
  - factor x3 for 20 MGy X-ray irradiation
  - only partially recovered with annealing

Wished studies for the future:

- Consistent series of studies for various SiPMs
- Investigation of exact cause of DCR increase
- Disentangling surface and bulk damage effects