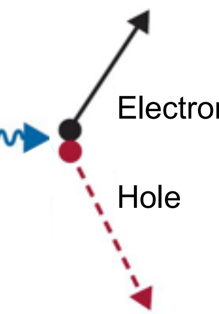
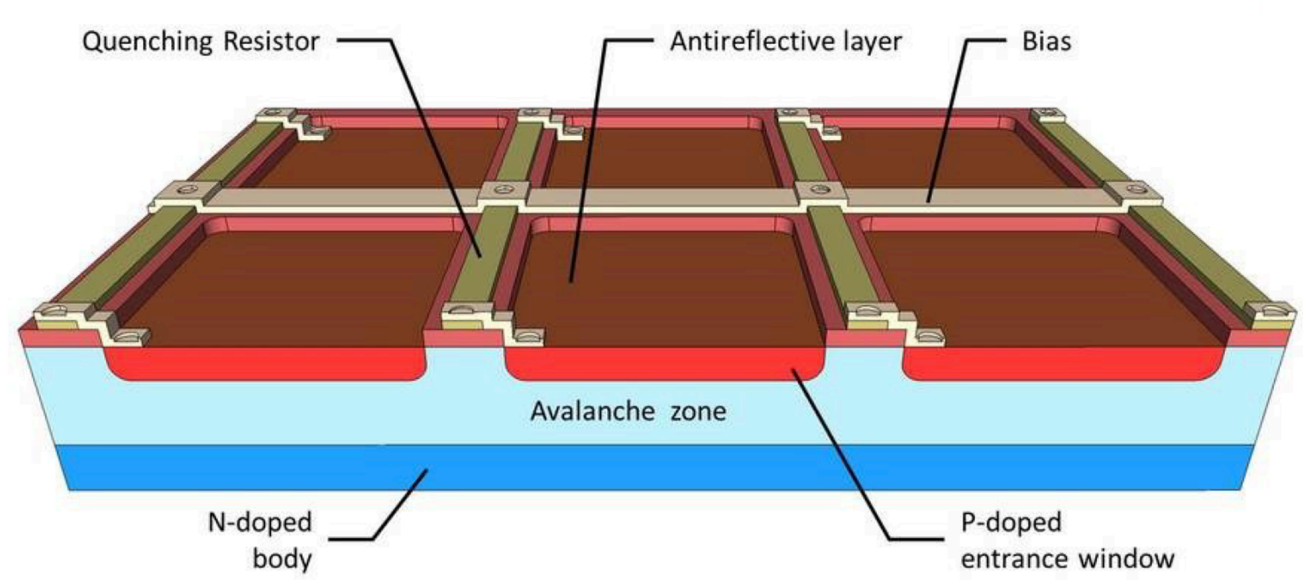
Radiation damage on silicon photo-multipliers

Erika Garutti

Silicon Photo-Multiplier

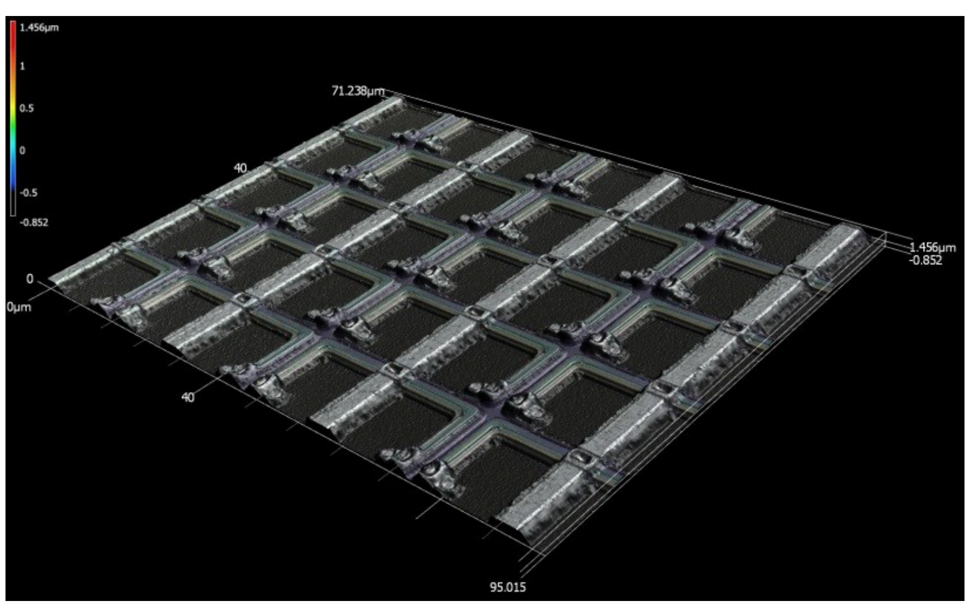


Matrix of single avalanche diodes operated in Geiger Mode (reverse $V_{Bias} > V_{Breakdown}$)



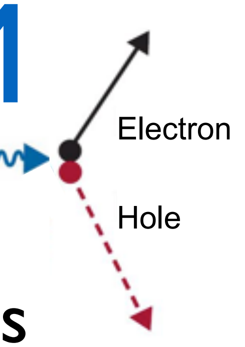
Single photons can trigger measurable charge avalanches

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

Relevance of radiation damage in SiPM



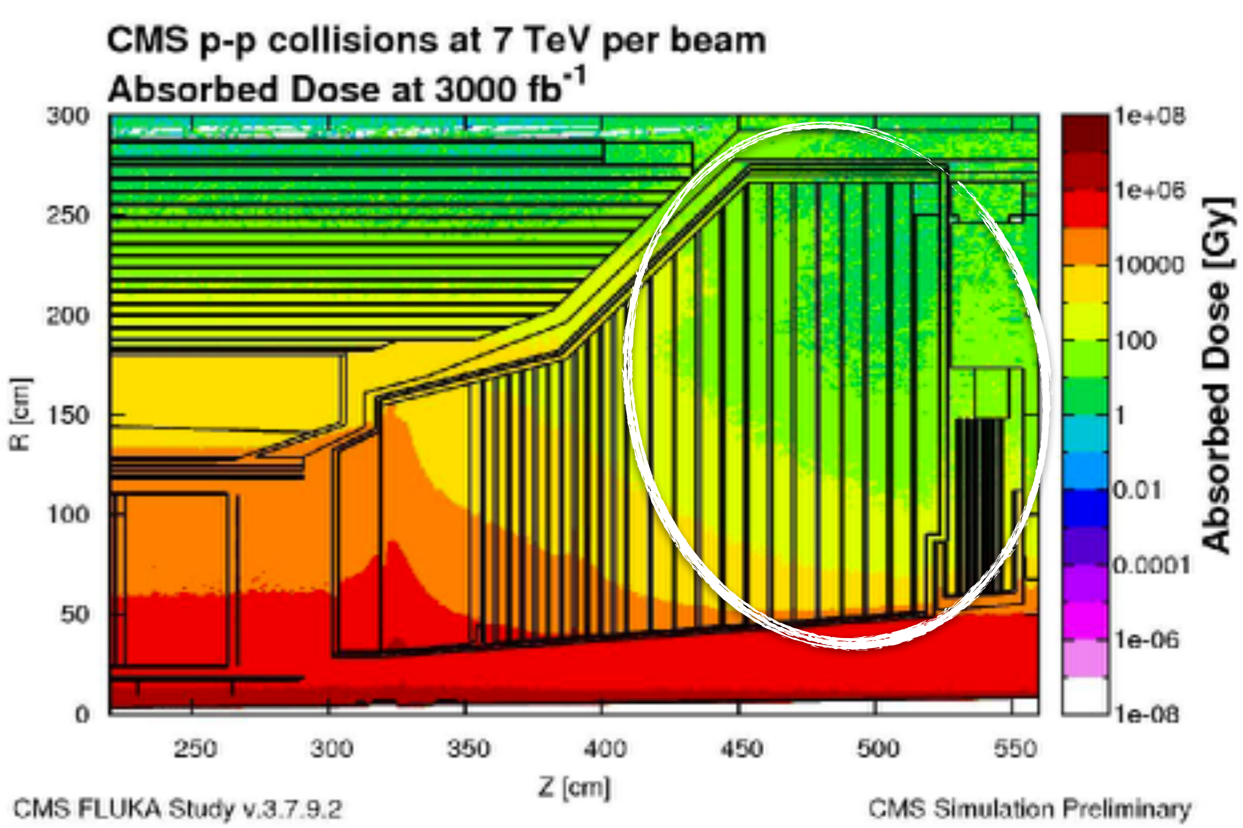
Scientific motivation:

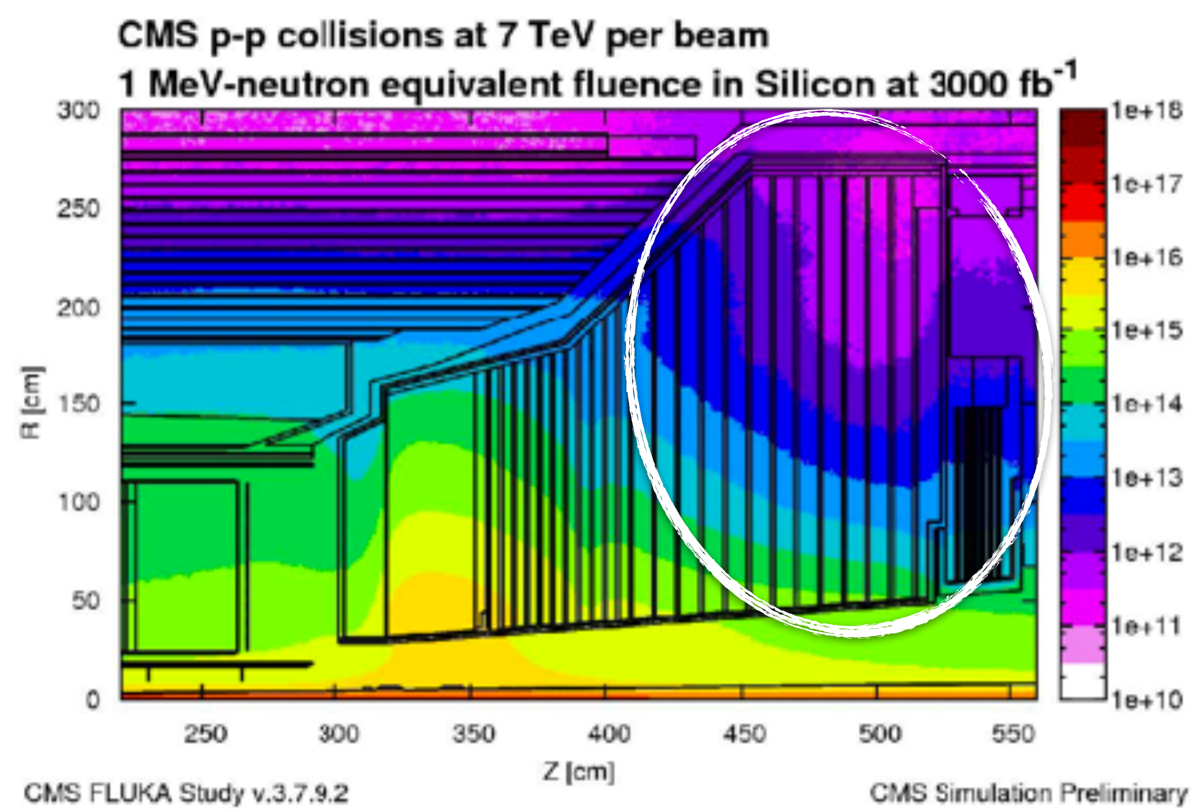
- SiPMs considered as photo-sensor of choice in many upcoming experiments
- Up to now limited investigation of radiation damage in SiPM is available

Imaging calorimeters for collider experiments:

- Hadronic calorimeter for ILC (CALICE)
  - ➔ ~ 10^{10} n/cm^2 in the end cap region (after 500 fb^{-1})
- Upgrade of hadronic calorimeter for CMS
  - ➔ ~ 10^{14} n/cm^2 (after 3000 fb^{-1})

see following two talks by Marcello Manelli & Gregor Kramberger





Outline

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

see also my talk at 9th Terascale Detector workshop 2016 (Freiburg)

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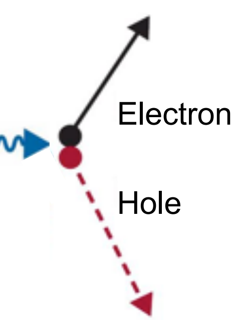
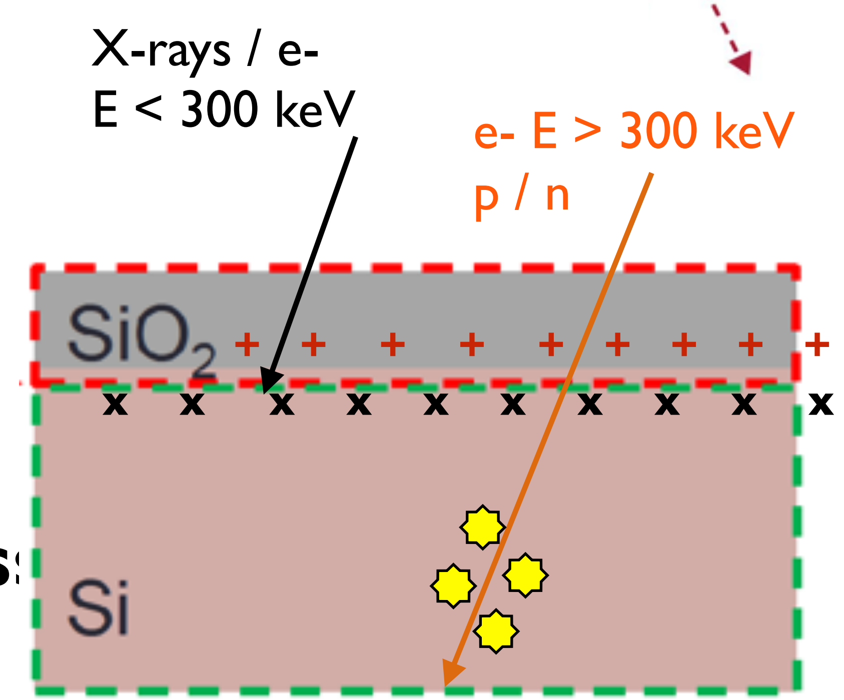
Radiation damage in Silicon



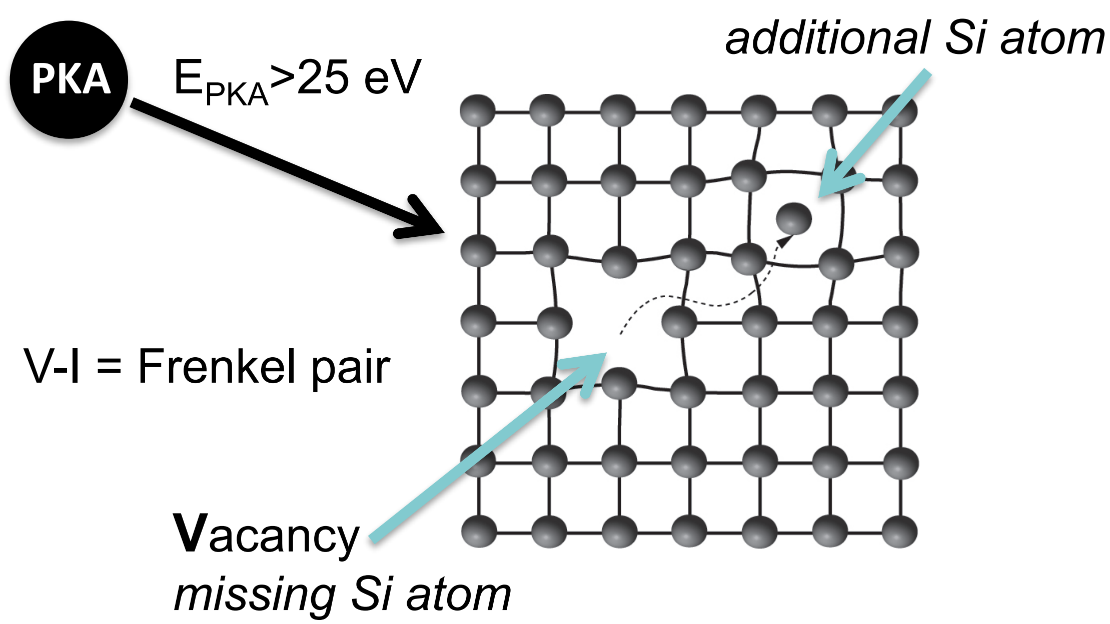
Two types of radiation damage in silicon detectors:

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



Primary Knock on Atom (PKA)

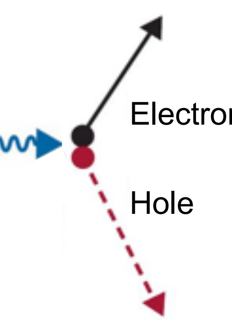


Energy threshold for bulk defects generation:

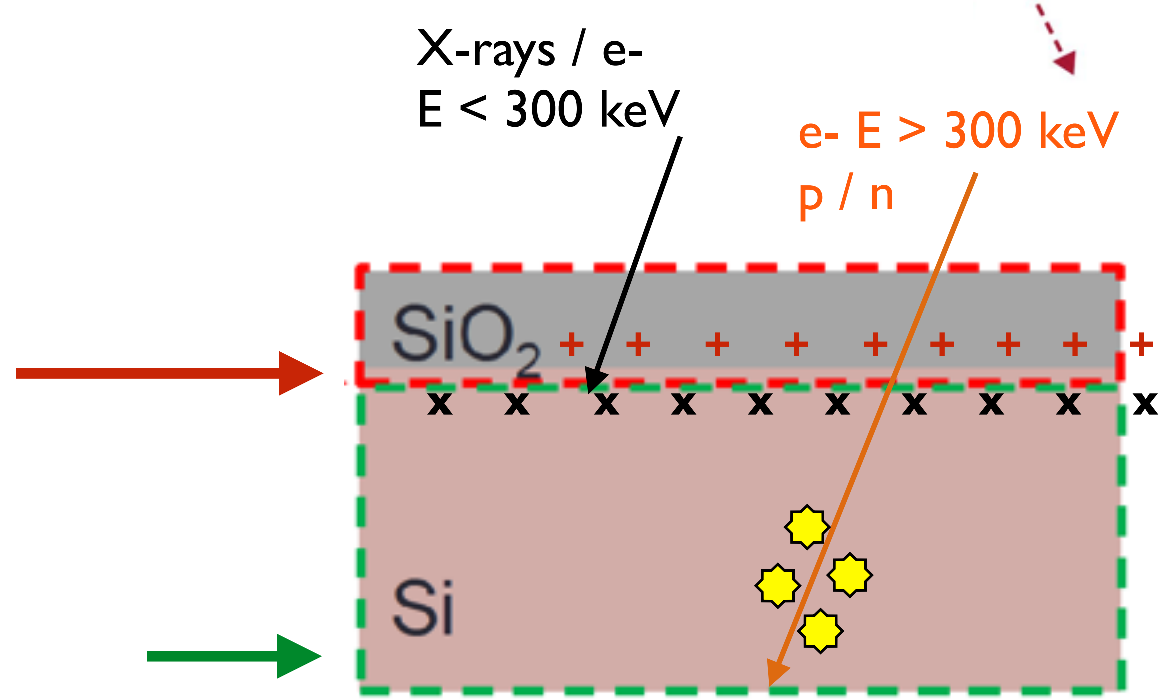
Particle	Gamma/ X-ray	Electron	Proton	Neutron
Frenkel pair	300 keV	255 keV	185 eV	185 eV
Cluster defects	-	8 MeV	35 keV	35 keV

Number of defects is proportional to the Non Ionizing Energy Loss (NIEL)

Radiation damage in SiPM

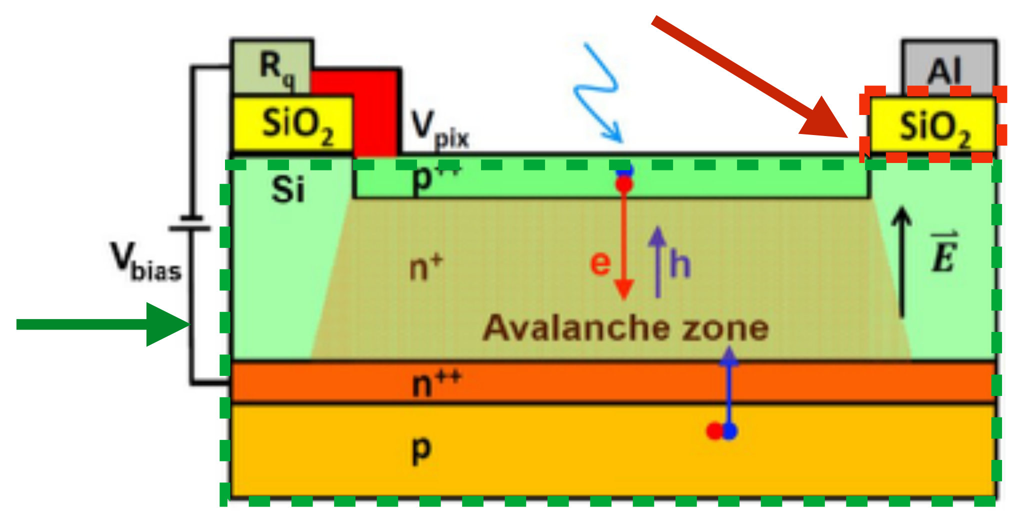


Effects on an SiPM:



Surface damage:
➔ Increase dark current

Bulk damage:
➔ Increase dark current and dark count
➔ Change of V-dependence of G and PDE (SiPM cell "blocking" effects due to high induced dark carriers generation-recombination rate)
➔ V_{bd}, G, PDE, AP change due to donor/acceptor concentration change
➔ Fatal damage above a certain absorbed dose



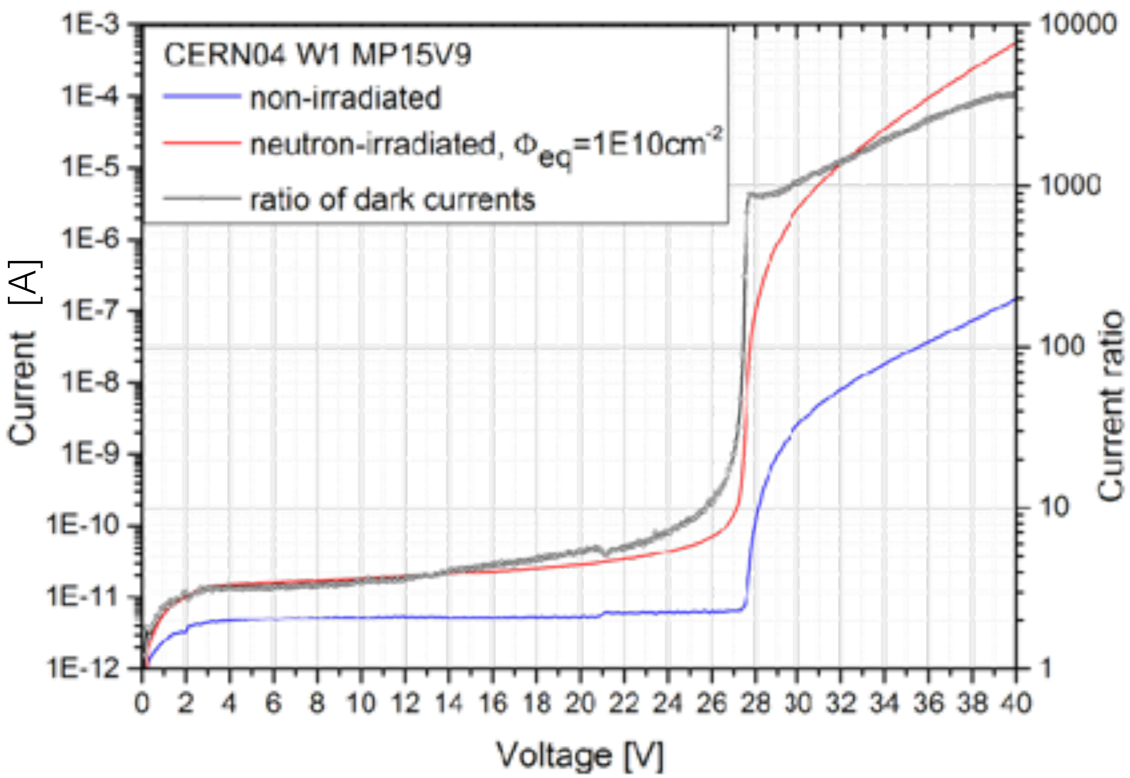
Cross-section of a single pixel of our SiPMs

Dark Current

The largest impact of radiation damage is on the Dark Current (DC)

Eugen Engelmann, PhD thesis, KETEK

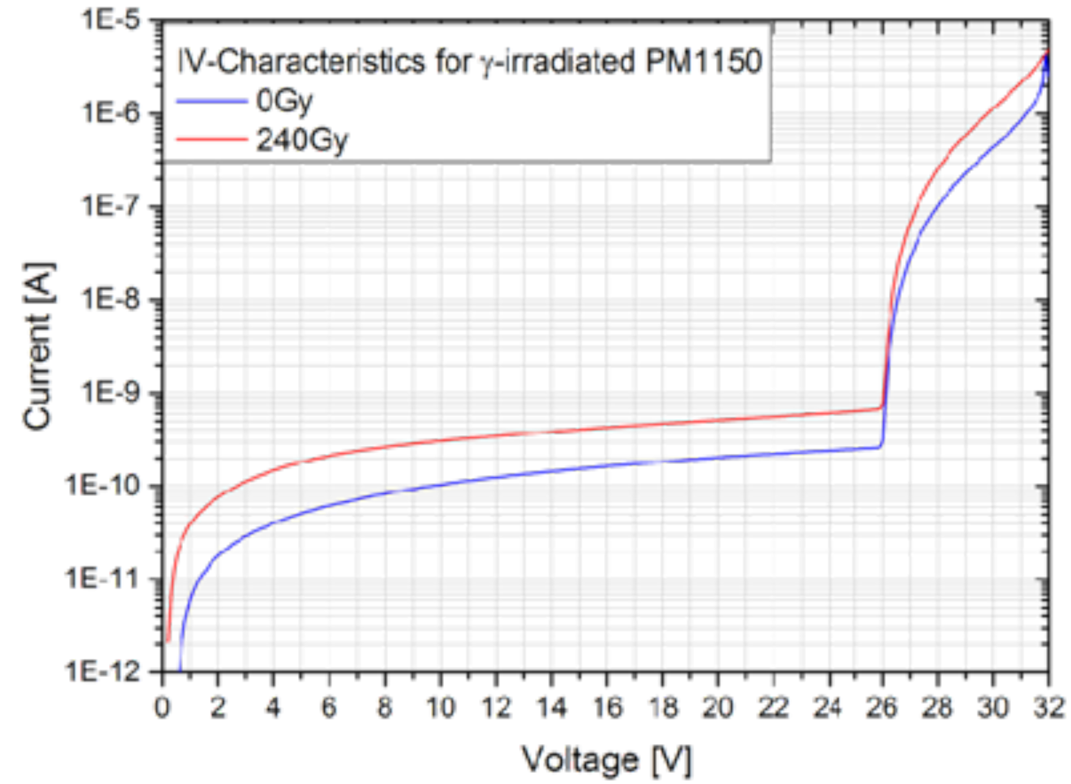
Bulk damage



KETEK SiPM, type: MP15V9
4384 µ-cells, 15µm pitch

- V < V_{bd}: DC increases by factor ~3-5
- V > V_{bd}: DC increases by factor ~1000-4000
- determination of DCR not possible by conventional methods

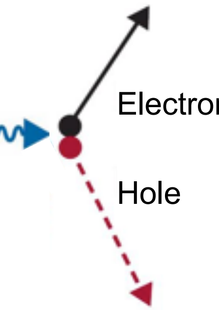
Surface damage



KETEK SiPM, type: PM1150
400 µ-cells, 50µm pitch

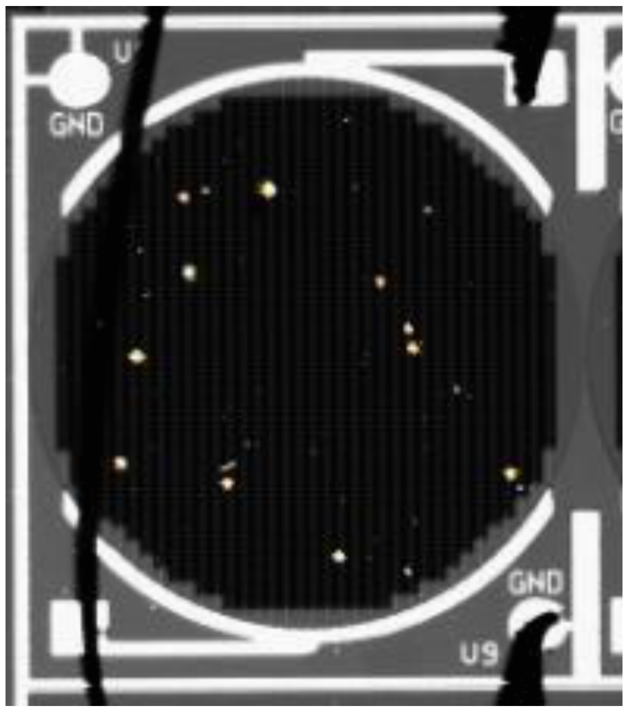
- DC is increased by factor ~3

Dark Current

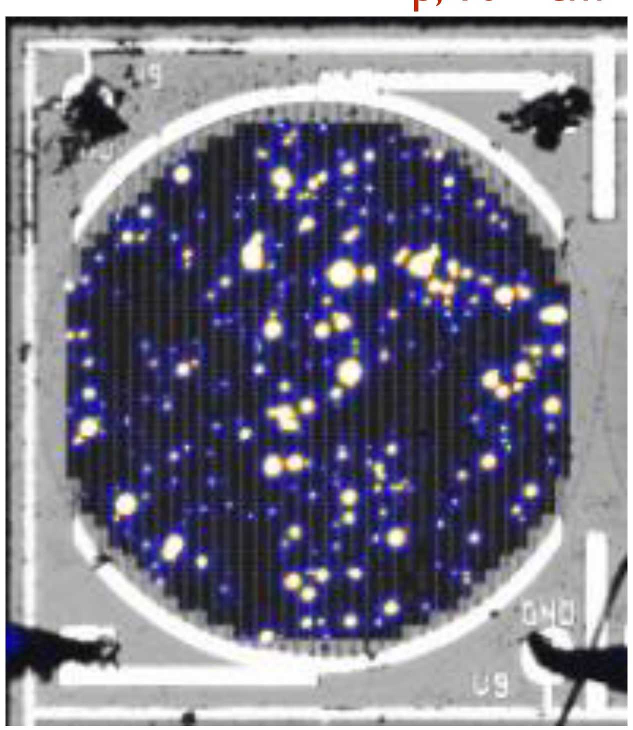


Eugen Engelmann, PhD thesis, KETEK

non-irradiated



p, 10^{10} cm^{-2}

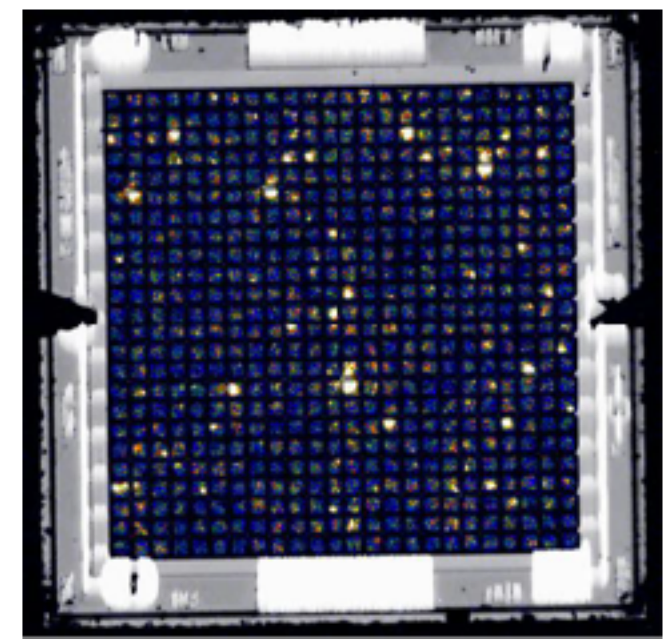


MP15V9

Investigation of micro-plasma emission with low light level CCD camera (in NIR)

- non-irradiated
- exposure time of 2h
- expected number of hotspots is observed (~10-15 mm^{-2})

γ, 240 Gy



PM1150

- photon-irradiated: 240 Gy dose
- large amount of minor-hotspots is introduced

- neutron-irradiated: fluence of 10^{10} cm^{-2}
- exposure time of 5 min
- observed number of hotspots is increased dramatically
- introduced defects are not homogeneously distributed

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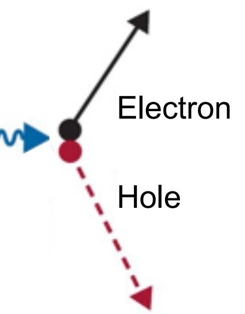
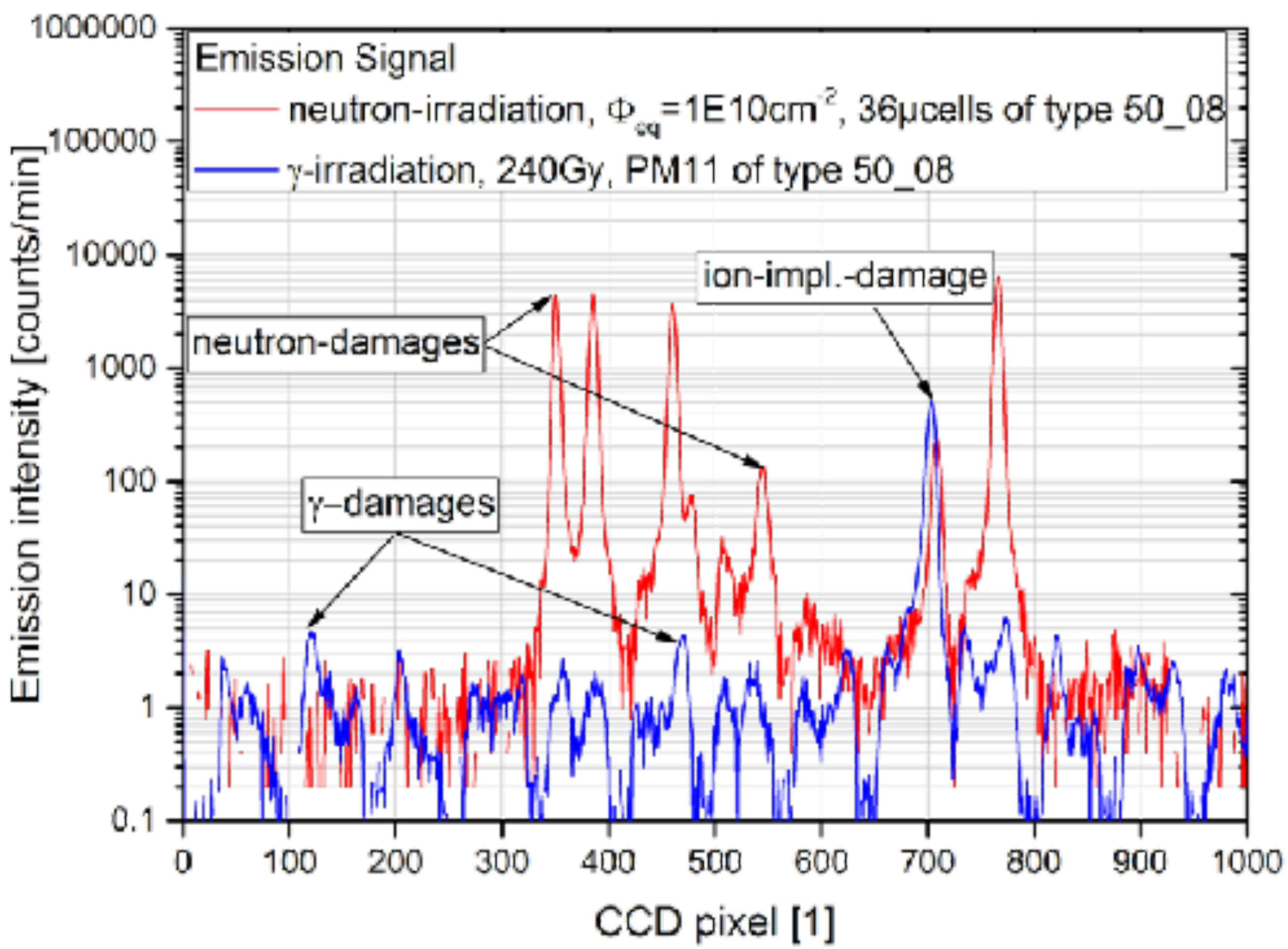
Dark Current



From the analysis of the intensity spectrum of the CCD camera

Eugen Engelmann, PhD thesis, KETEK



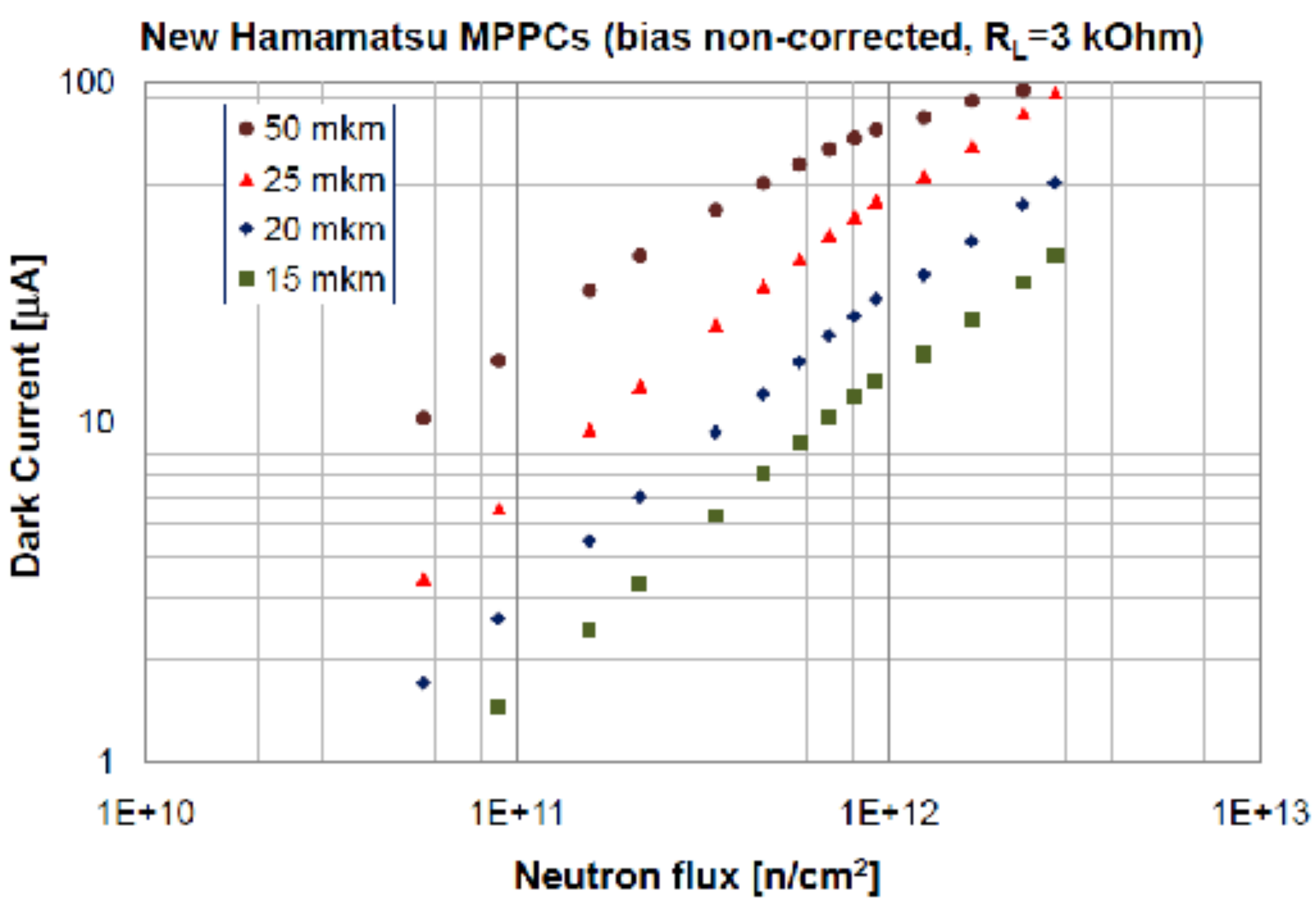
- intensities of hotspots induced by different sources are compared
- 2-3 order of magnitude higher emission intensity for neutron-induced damages w.r.t. γ-induced damages
- in rare cases damages from ion-impl. (after annealing) can reach intensities of neutron-induced damages (before annealing)

- generation of cluster defects with neutrons
- no cluster generation with photons (only Frenkel pairs)

Dark Current

DC increase with **Neutron** irradiation dose: not strongly dependent on cell size

Yu. Musienko, INSTR-17, Novosibirsk



Dark current is given by

$$I_{dark} \propto \alpha \cdot \Phi \cdot V \cdot G \cdot k$$

α = damage constant

$\alpha_{Si} \approx 4\ 10^{-17}\ A\ cm^{-1}$
T = 20°C, 80 min @ 60°C

Φ = particle flux [cm^{-2}]

$$V \approx S \cdot G_f \cdot d_{eff}$$

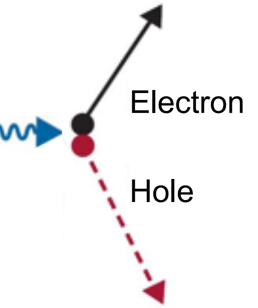
S - area
G_f - geometric factor
d_{eff} - effective thickness

G = SiPM gain

k = NIEL coefficient

- Thickness of the epi-layer for most of SiPMs is ~1-2 µm, however d_{eff} ~ 4÷50 µm for different SiPMs.
- High electric field effects, such as phonon assisted tunneling and field enhanced generation (Pool-Frenkeleffect) play significant role in the origin of DC

Dark Count Rate



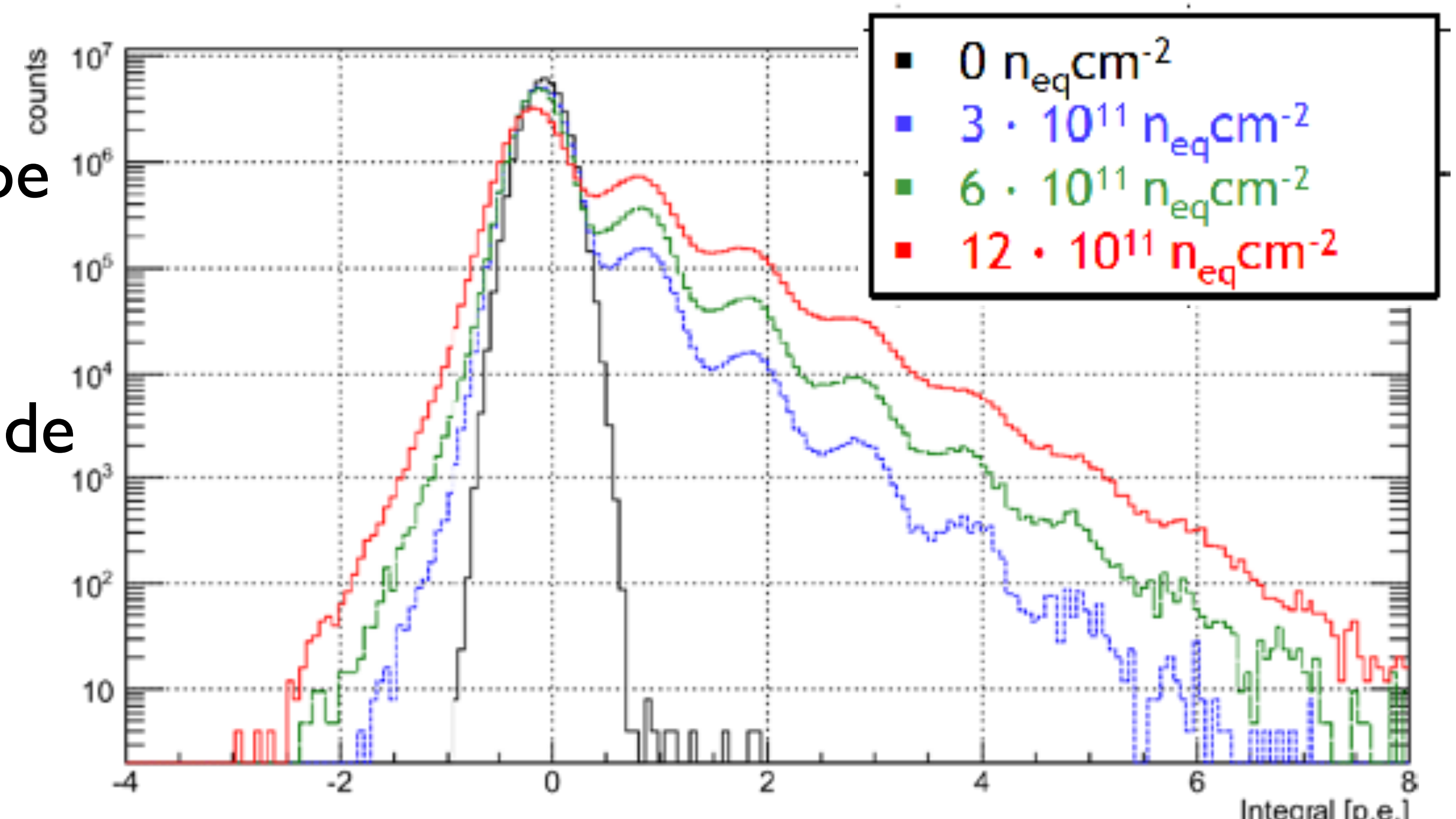
Neutron irradiation up to 1.2 x10^{12} neq/cm²

T = -40°C

PACIFIC shaper output spectrum integrated for 25ns with oscilloscope

Dark count rate (DCR):

- increase by >6 orders of magnitude



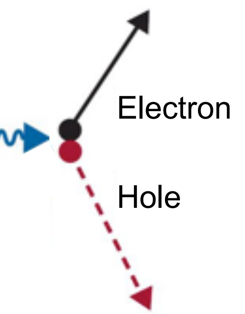
Detector still functional after irradiation
Single photon sensitivity with fast readout and at T = -40°C

David Gerick (Uni. Hei.) for the LHCb Collaboration, DPG Frühjahrstagung 2016

Hamamatsu S10943-3183 (custom made - LHCb)

128 ch. with each 4x24 pixels (62.5x57.5 μm²)

Dark Count Rate



Neutron irradiation up to 1.0 x10^{12} neq/cm^2

T = 20°C

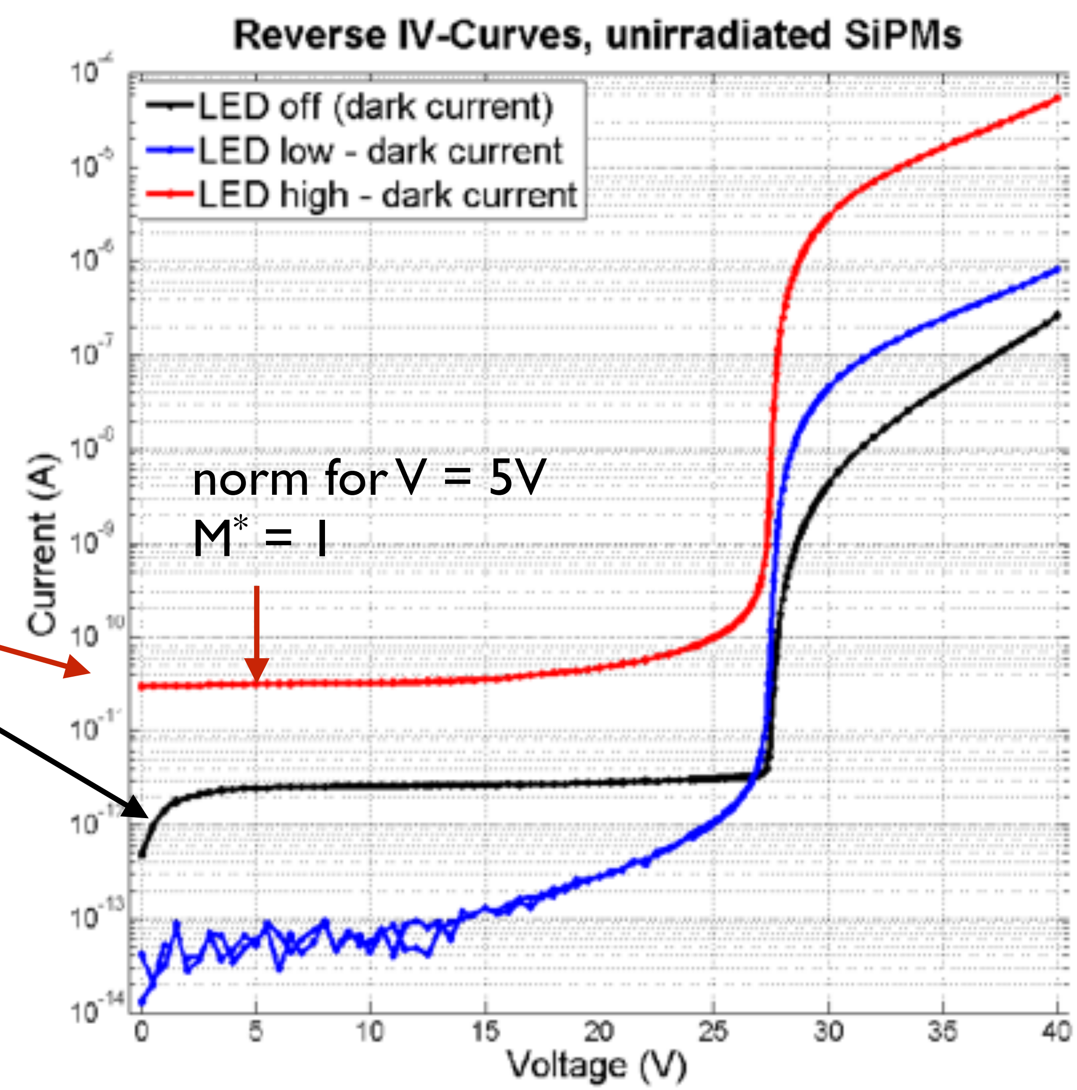
Determination of DCR at room T without single photo-electron peak spectrum

$$I_{dark} = q_0 \; DCR \; G(1 + CN)$$

$$I_{LED}^{norm} = A_{prob}^{*} \; G(1 + CN)$$

$$\frac{1}{q_0} \frac{I_{dark}}{I_{LED}^{norm}} = \frac{DCR}{A_{prob}^{*}} \qquad V > V_{bd}$$

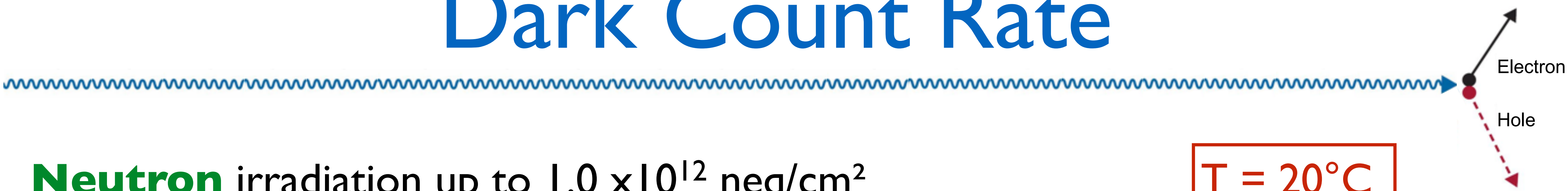
CN = correlated noise (XT, AP)
A$^*_{prob}$ = avalanche prob. for LED light (~90%)



$$I_{LED} = \begin{cases} N_\gamma M^* q_0 & V < V_{bd} \\ N_\gamma A_{prob}^{*} G(1 + CN) q_0 & V > V_{bd} \end{cases}$$

Matteo Centis-Vignali et al., (Uni. HH), NSS/MIC IEEE 2016

Dark Count Rate



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↓

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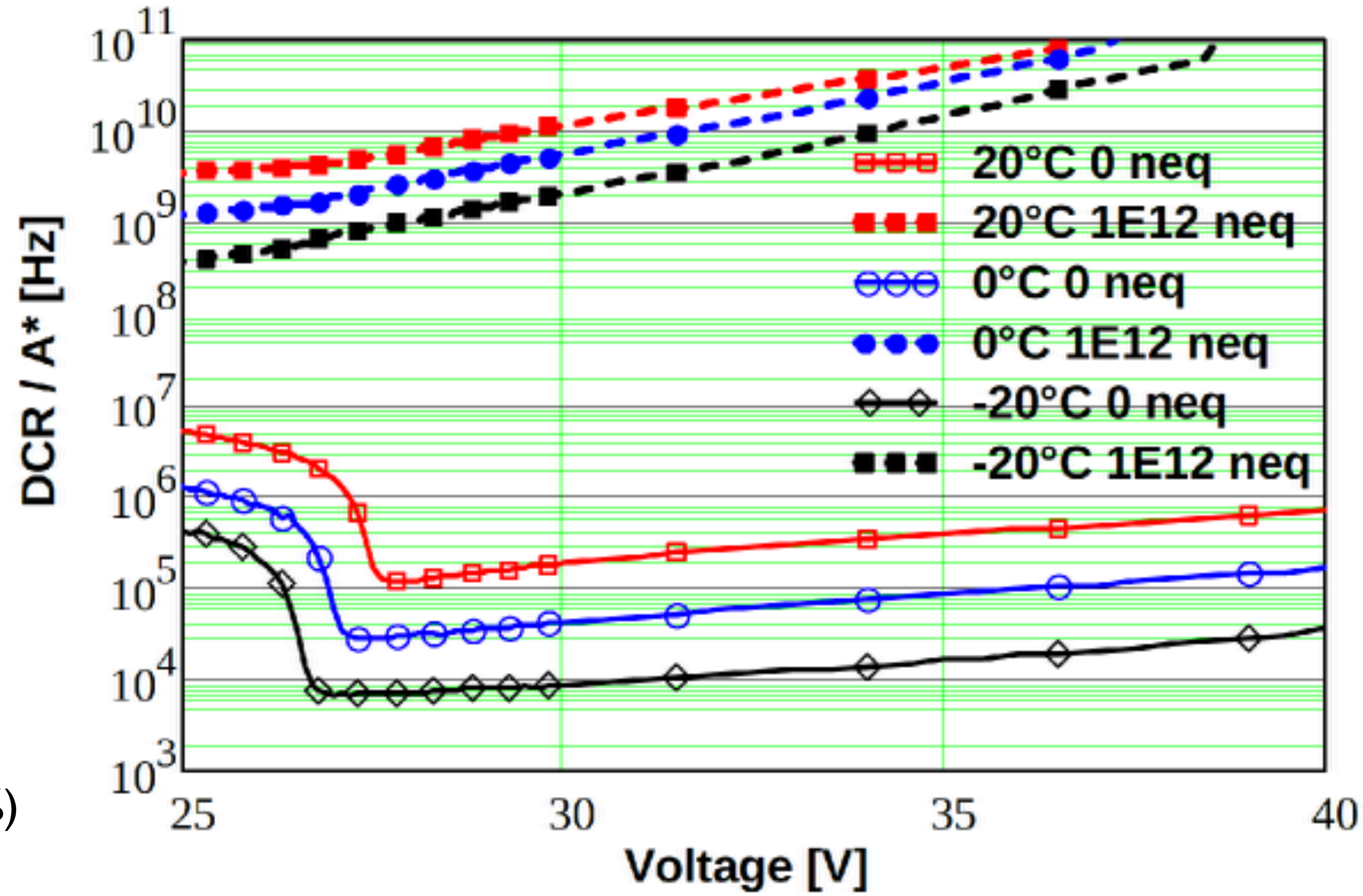
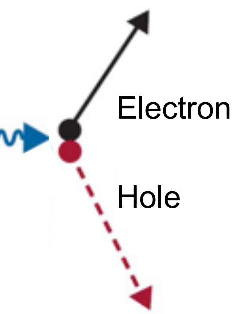


Matteo Centis-Vignali et al., (Uni. HH), NSS/MIC IEEE 2016

DCR strongly affected by irradiation
Using I-V, rates higher than 10^{7} Hz are accessible

How about all other parameters?



- In Matteo Centis-Vignali et al., (Uni. HH), NSS/MIC IEEE 2016 we reported no change in PDE, G, V_{bd}, C_{pix}, R_q for KEKEK SiPMs exposed to **neutron** irradiation up to 1.0×10^{12} cm^{-2}

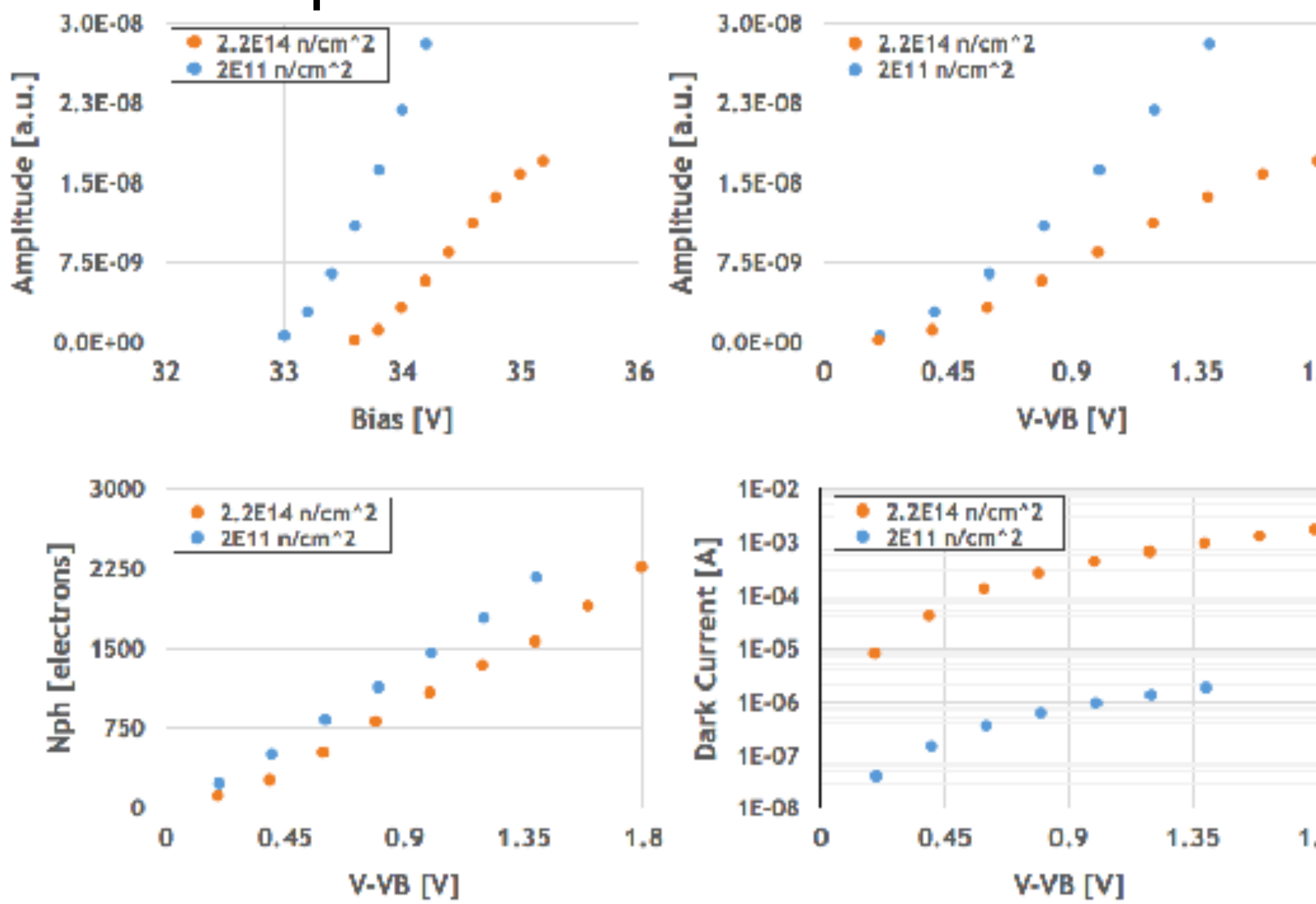
New studies

- FBK SiPM irradiated with 62 MeV **protons** up to 2.2×10^{14} /cm^{-2}

Results:

- V_{bd} increases by ~ 0.5 V
- Response decrease ~ 2 times
- PDE from 10% to 7.5 %
- Increase of DC to ~1mA at ΔV=1.5 V

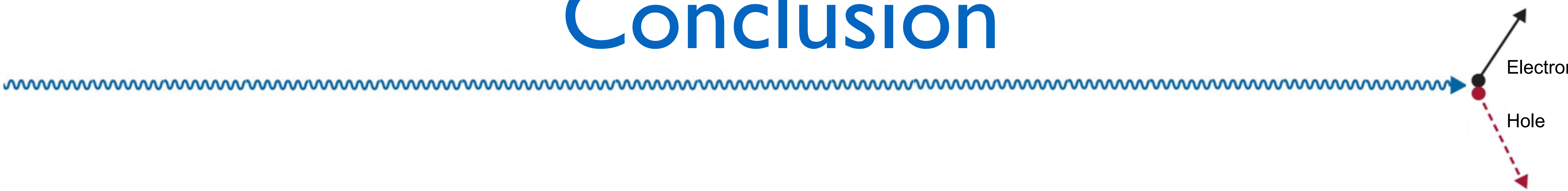
The main result is that SiPM survived this dose of irradiation and can be used as photon detector!



FBK SiPM (1mm^2, 12µm cell pitch)

A.Heeringet al., NIM A824 (2016) 111

Conclusion



- SiPMs remain efficient photodetectors after irradiation with (X-rays &) hadrons
- After hadron damage calibration using single PE not applicable
  → different calibration methods to be developed

- Observed increase of DCR (on different SiPM types):
  - I_{dark} ~ nA before irradiation
  - I_{dark} ~ 10 μA (1 μA) after 10^{11} cm^{-2} neutron (proton) irradiation
  - I_{dark} ~ 0.1 mA after 10^{12} cm^{-2} neutron irradiation
  - I_{dark} ~ 1 mA after 10^{14} cm^{-2} proton irradiation

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