Characterization of X-ray Damage of Silicon Photo-Multipliers

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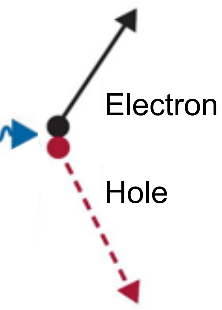
Relevance of radiation damage in SiPM



Scientific motivation:

- SiPMs considered as photo-sensor of choice in many upcoming experiments
- In literature some study report investigation of radiation damage in SiPM

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:

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

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Outline

- Radiation damage in silicon photo-multipliers (SiPM)
- Characterization of SiPM parameters
- Results: surface damage in SiPM
- Conclusion and outlook

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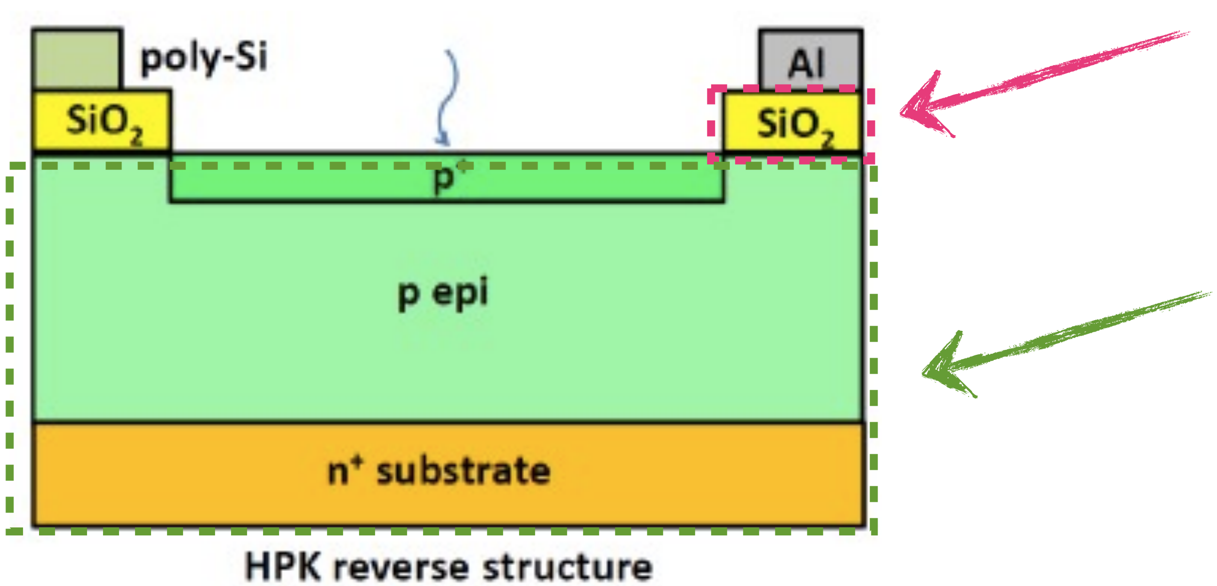
Radiation damage in silicon photo-multipliers

Types of radiation damage

Two types of radiation damage in detector materials:

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

- Surface damage due to Ionizing Energy Loss (IEL)
  - accumulation of charge in the oxide (SiO_2), traps at Si/SiO_2 interface

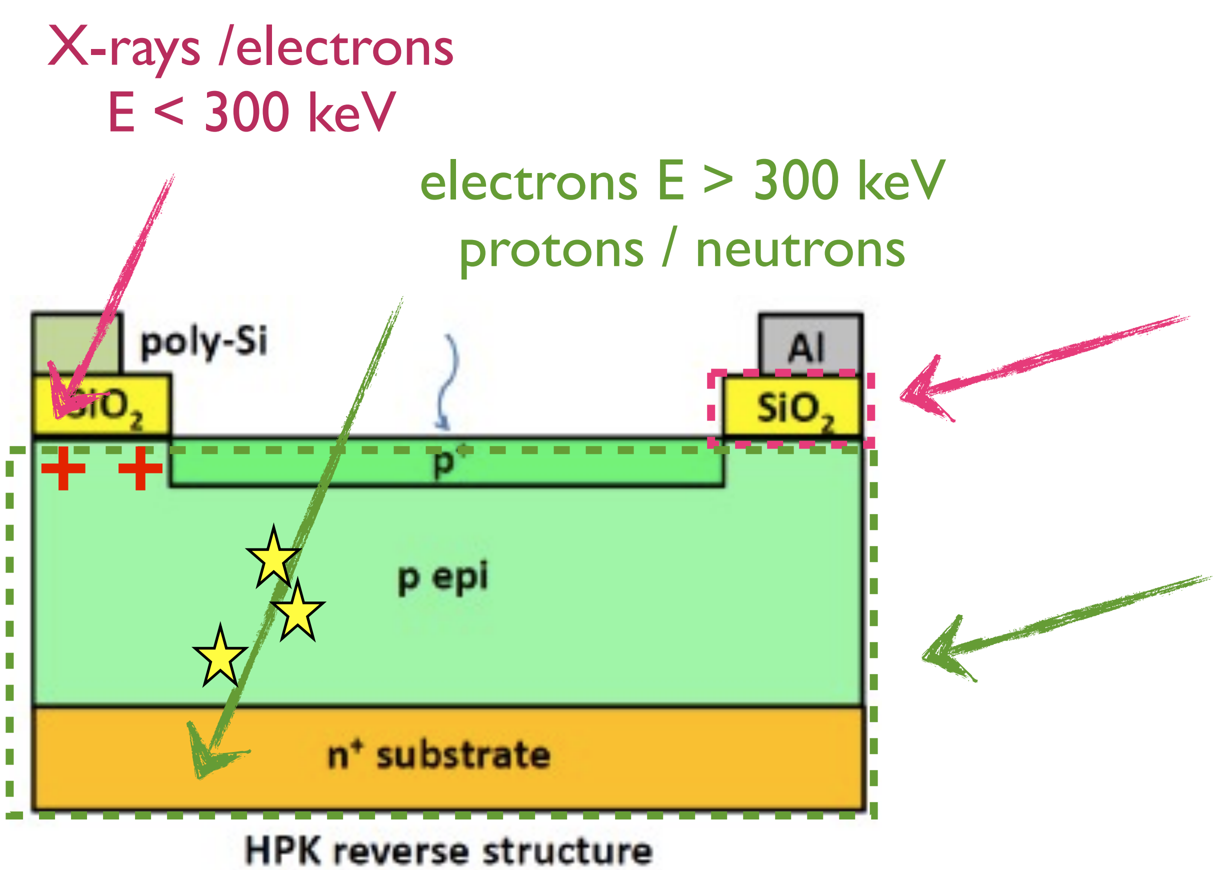


Region affected by ionizing energy loss
- surface damage

Region affected by non-ionizing energy loss
- bulk damage

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)



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

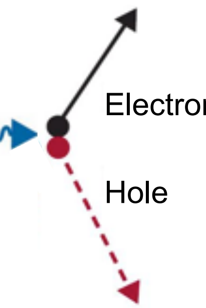
➔ Increase DCR

Increase after-pulsing

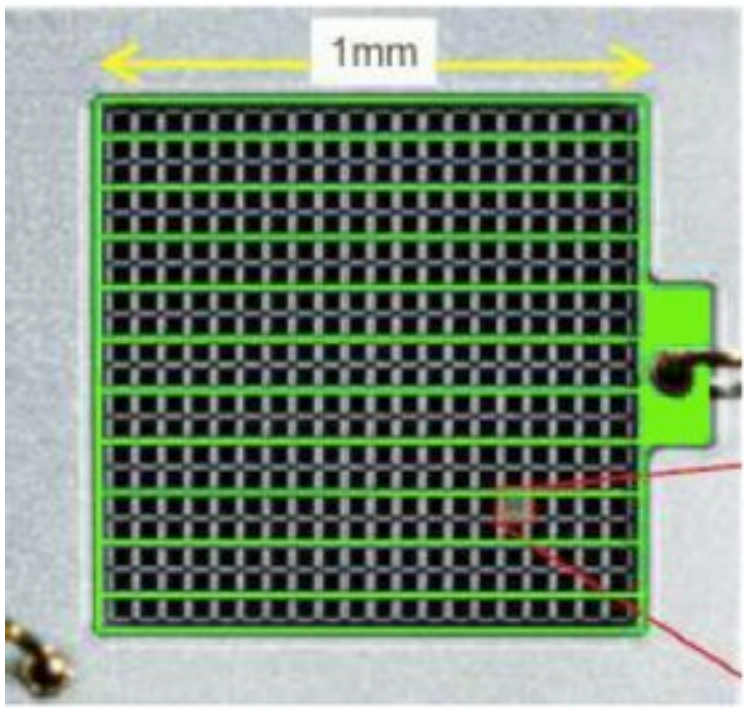
➔ Change in charge collection

Investigated devices

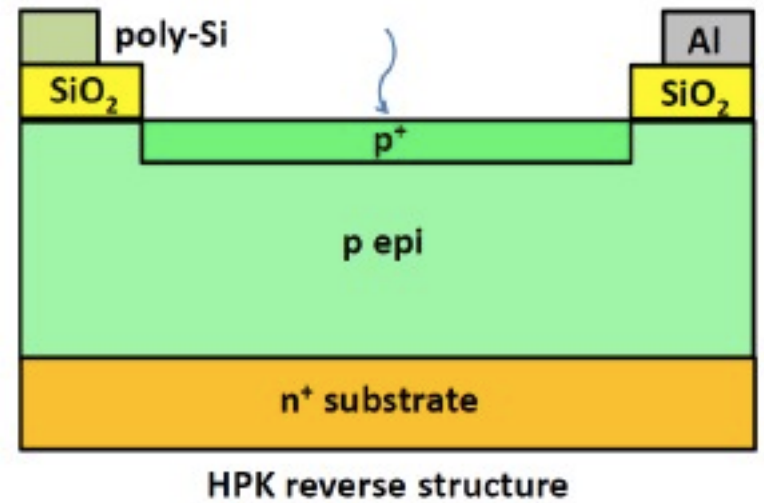
Investigated devices



Hamamatsu MPPC S10362-11-050C



20 x 20 pixels, size 50µm x 50µm

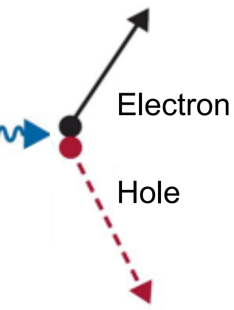


From capacitance measurements we estimate a depth of the p-epi layer ~2.3µm

K.Yamamoto et al., 2007 POS (PD07) 004

Characterization of silicon photo-multipliers parameters

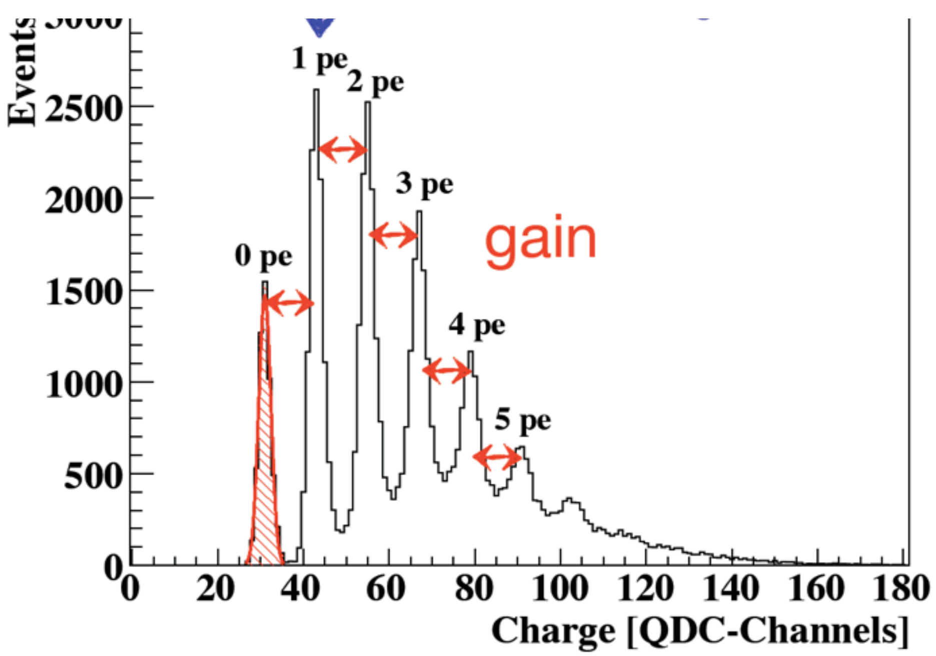
Static vs dynamic characteristics



Dynamic characteristics:

- Set SiPM in operation ($V_{bias} > V_{bd}$)
- Determine operation parameters (gain, V_{bd}, C_{pix}, DCR, XT, AP, ...) and their (V,T) dependence

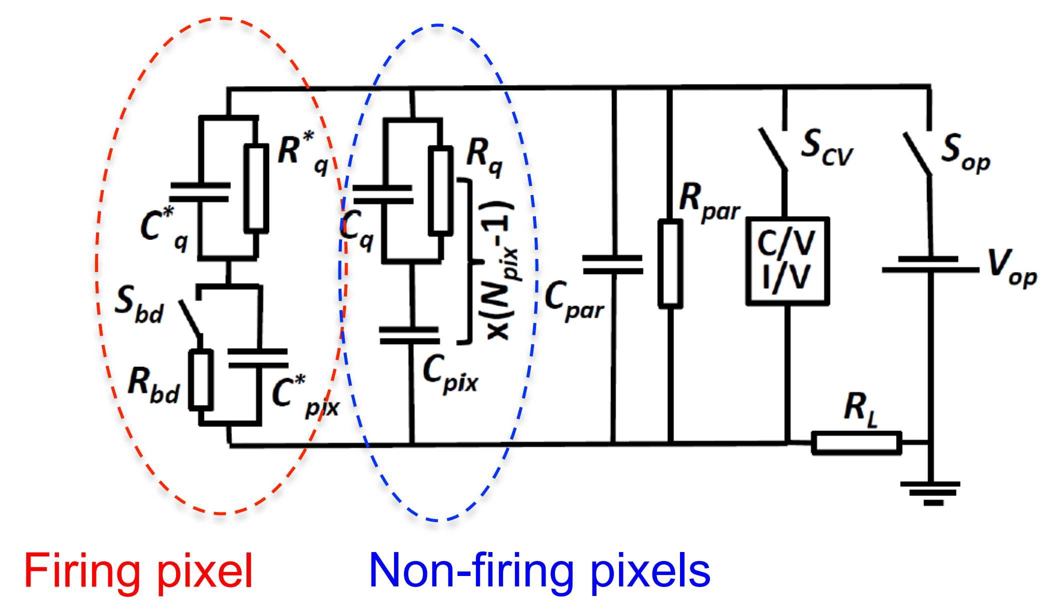
- Investigate the variation after irradiation



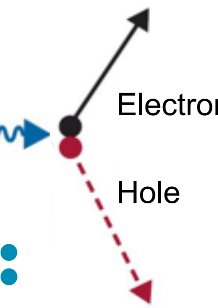
Static characteristics:

- Determine the components of the equivalent circuit of a SiPM (C_{pix}, C_q, R_q, V'_{bd}, ...)
- Compare to dynamic values

- Investigate the variation after irradiation



Dynamic characterization

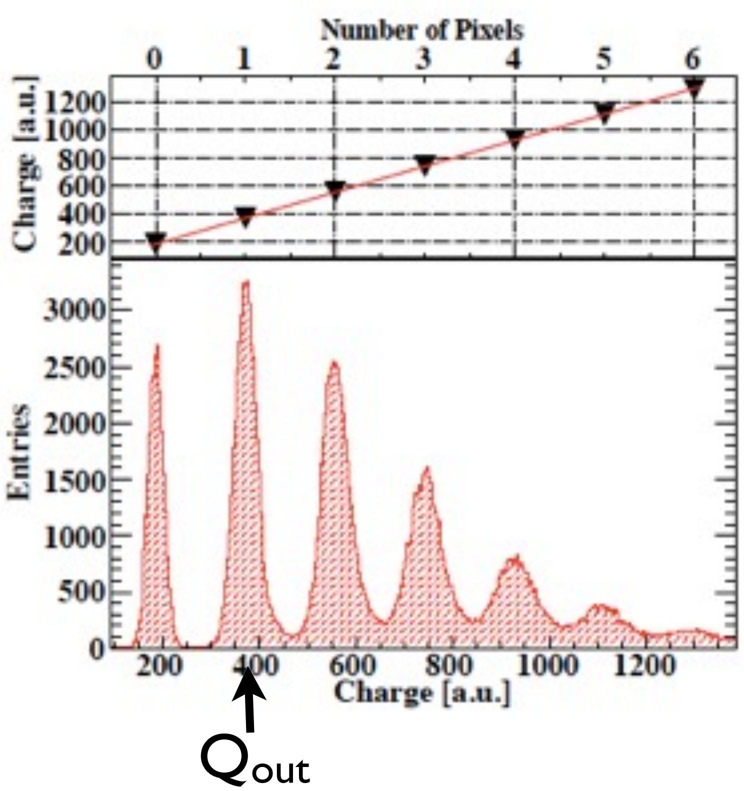


Gain & V_{bd} determination:

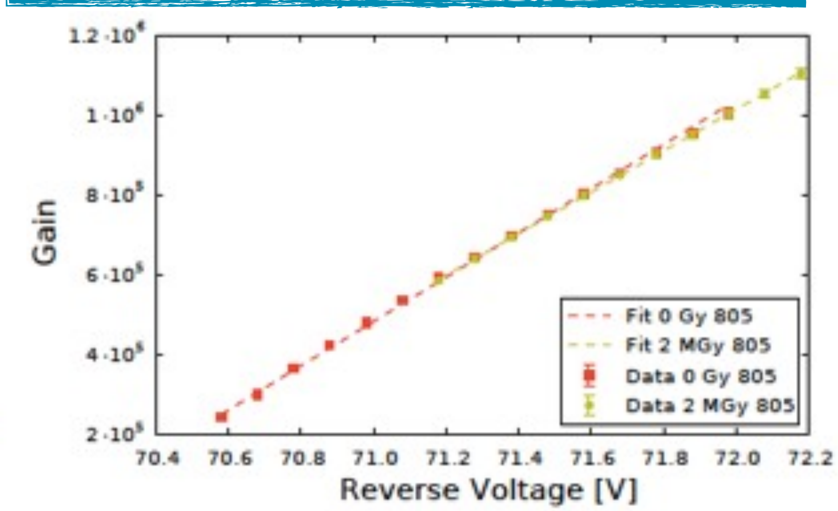
- set SiPM in operation ($V_{bias} > V_{bd}$)
- LED pulse: λ=405 nm
- integrate charge: gate 100 ns
- identify single peak spectra & fit a linear regression
- Reproducibility error on Gain~1-2 %
- V_{bd} from linear fit to voltage dep.
- V_{bd} error ~ 50 mV

DCR & XT determination:

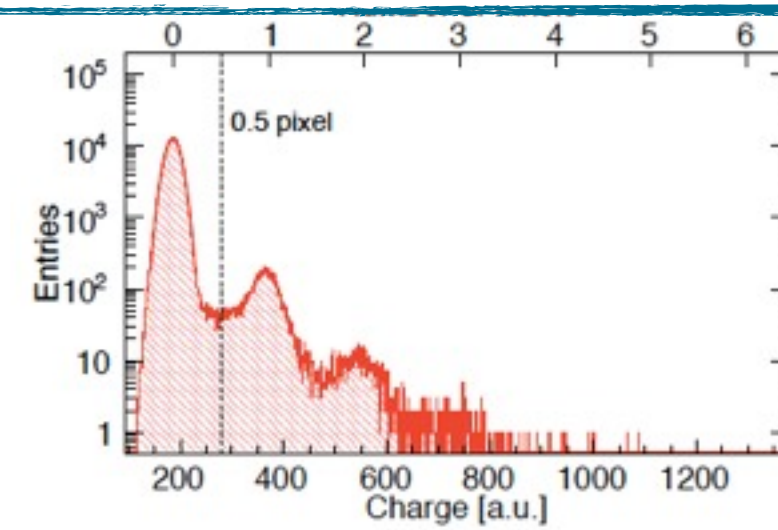
- set SiPM in operation ($V_{bias} > V_{bd}$)
- random trigger (no light)
- integrate charge: gate 100 ns
- use Poisson statistics to determine DCR (λ) from occupation of zero peak (<0.5 pixels)
- XT = $N_{>1.5}$ / $N_{>0.5}$



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



$$P_0(\Delta t) = e^{-\lambda \cdot \Delta t} \rightarrow \lambda = -\frac{\ln(P_0(\Delta t))}{\Delta t}$$



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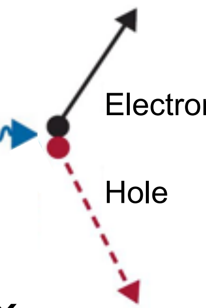
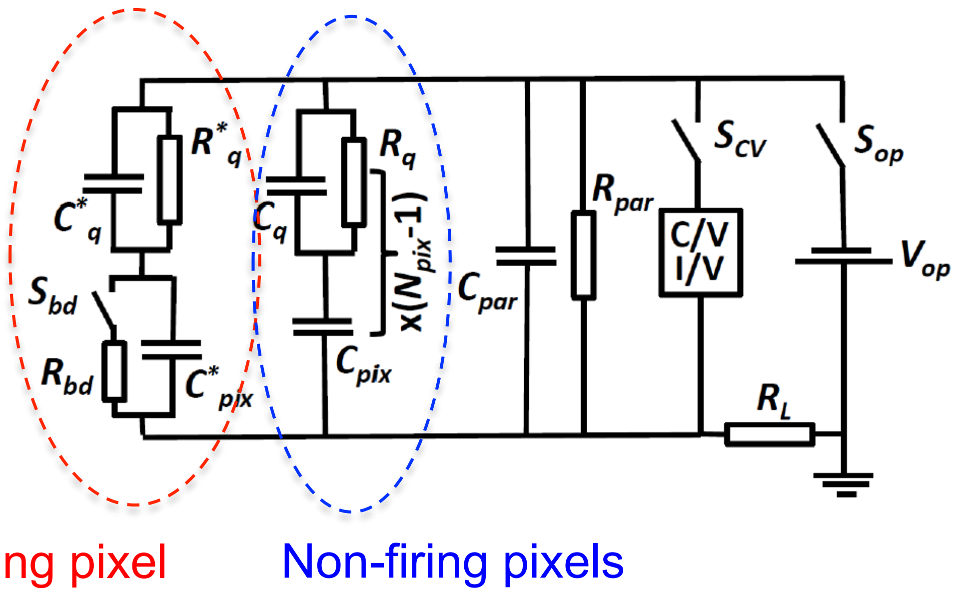
Static characteristics



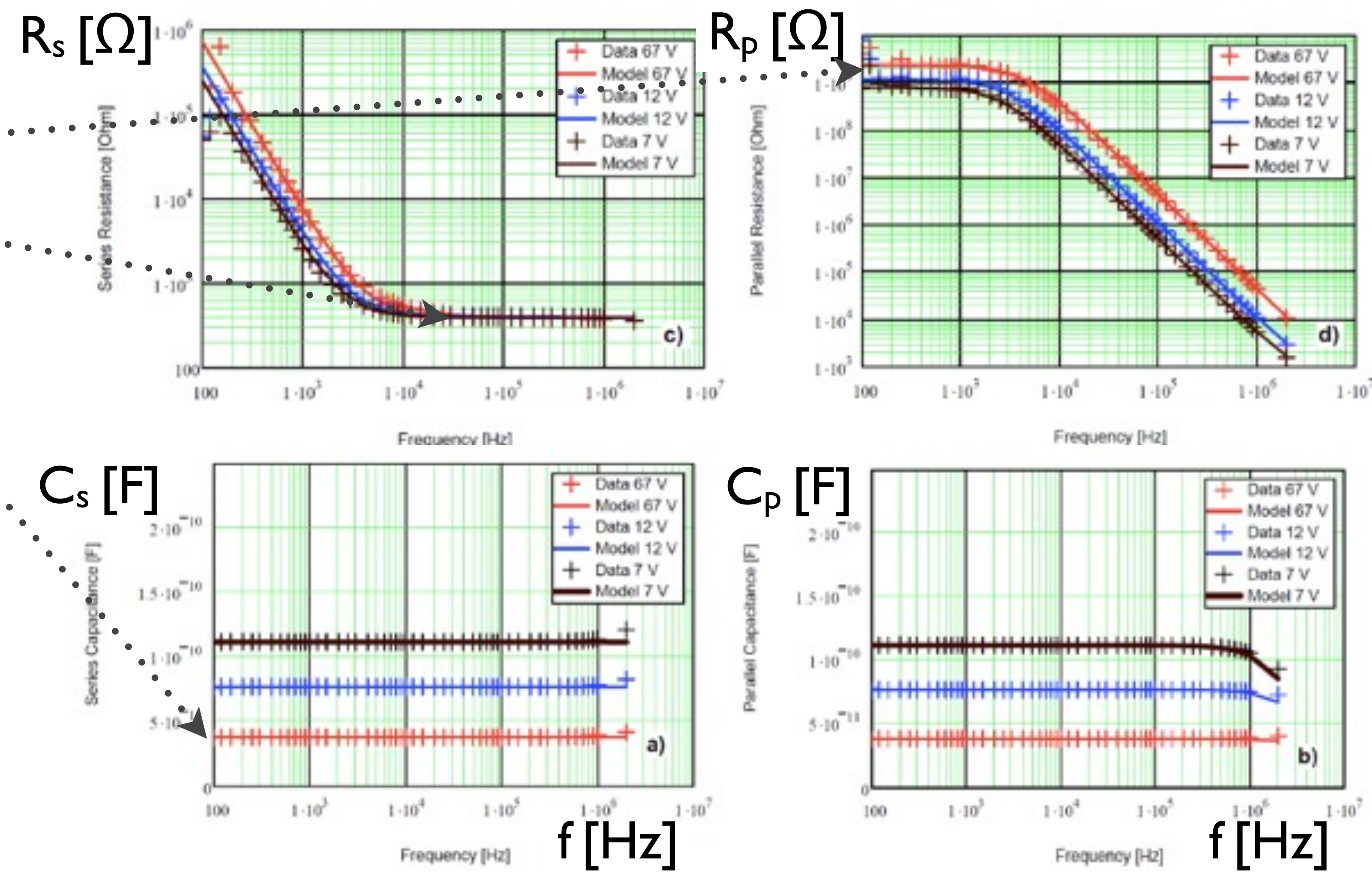


The complex resistance of a SiPM with N_{pix} pixels below the breakdown voltage is given by:

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

Measure freq. dependent parallel R and C on an LCR meter, and extract serial R and C

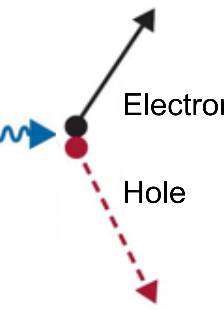
Dose	0 Gy
R_{par} [MΩ]	$2\,100 \pm 100$
R_q^{Cf} [kΩ]	125 ± 5
C_{pix}^{Cf} [fF]	94.0 ± 1.5
$R_q^{Cf} \cdot C_{pix}^{Cf}$ [ns]	11.8 ± 0.6



$Z = R_s + 1 / (i\, 2\pi f\, C_s) =$

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

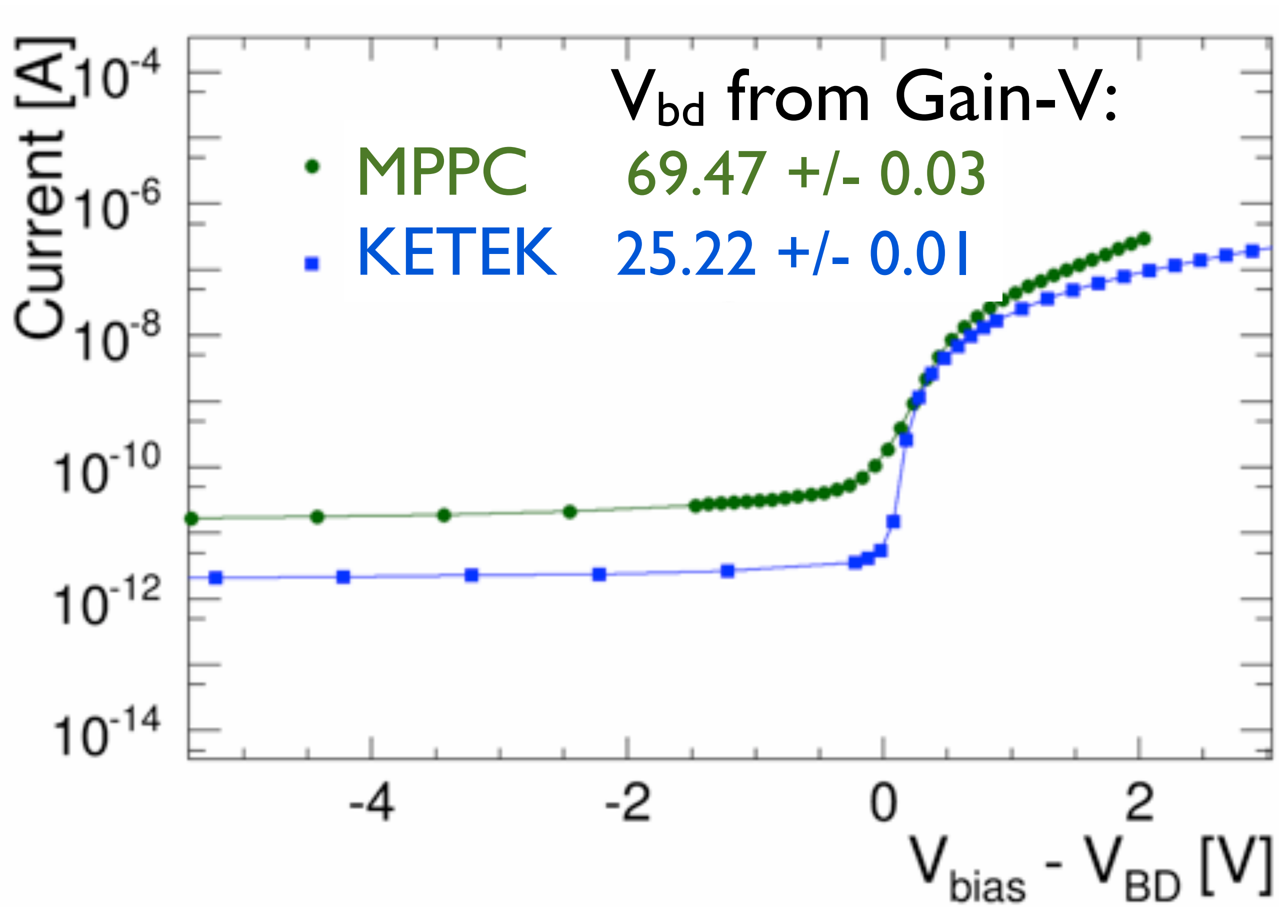
Static characteristics: V_{bd}

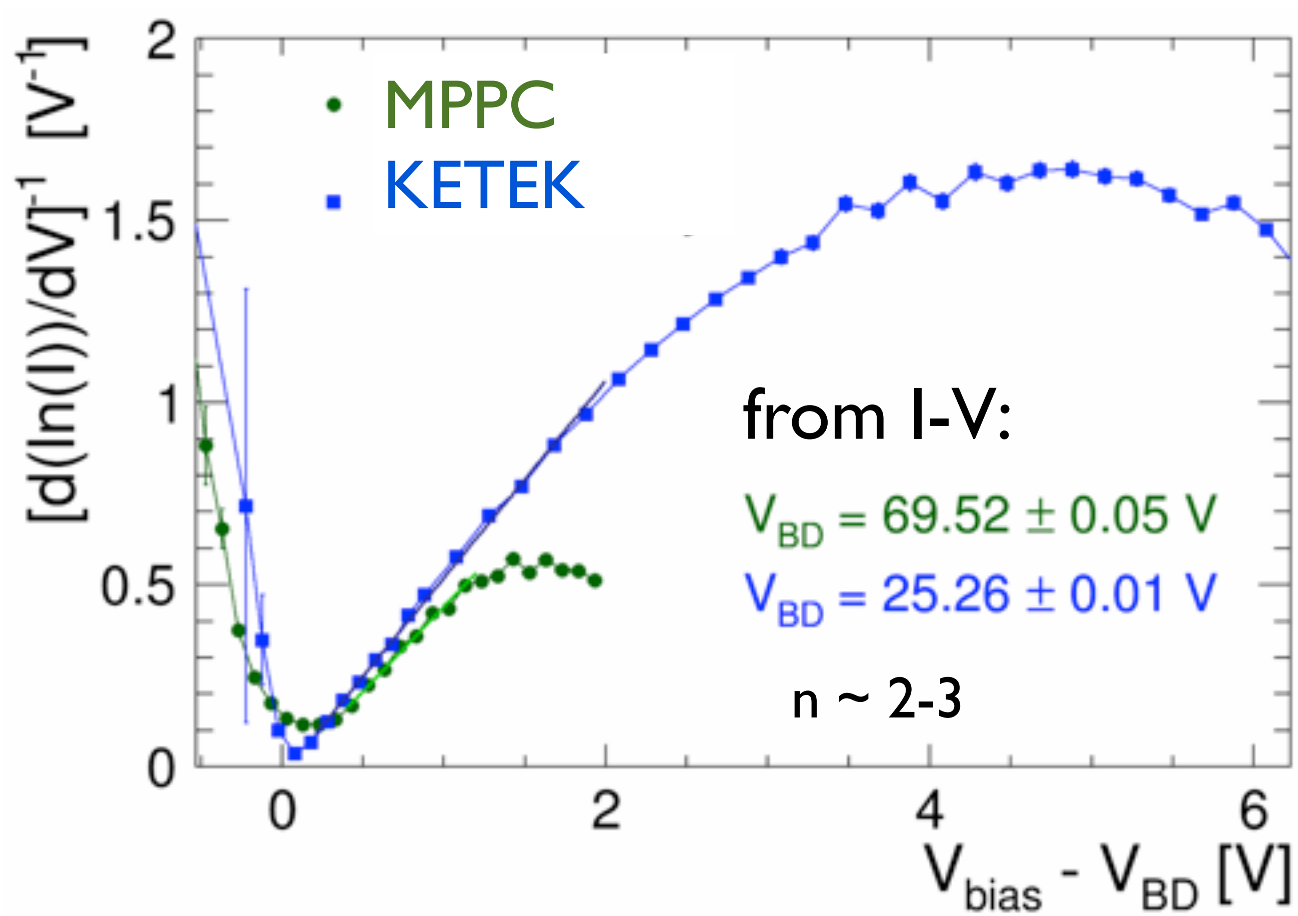


Determine V_{bd} from the I-V curve assuming: $I = \alpha(V - V_{bd})^n$

therefore:

$$\left[\frac{d\ln(I)}{d}\right]^{-1} = (V - V_{bd})/n$$



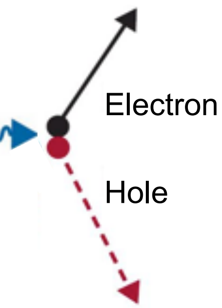


V_{bd} can be determined either from Gain-V or I-V measurements (at least for non irradiated devices !!!)

Results on surface damage in silicon photo-multipliers

“Influence of X-ray Irradiation on the Properties of the Hamamatsu Silicon Photomultiplier S10362-11-050C", E. Garutti, W.–L. Hellweg, R. Klanner, and C. Xu, accepted for publication in NIM A, DOI: 10.1016/j.nima.2014.05.112

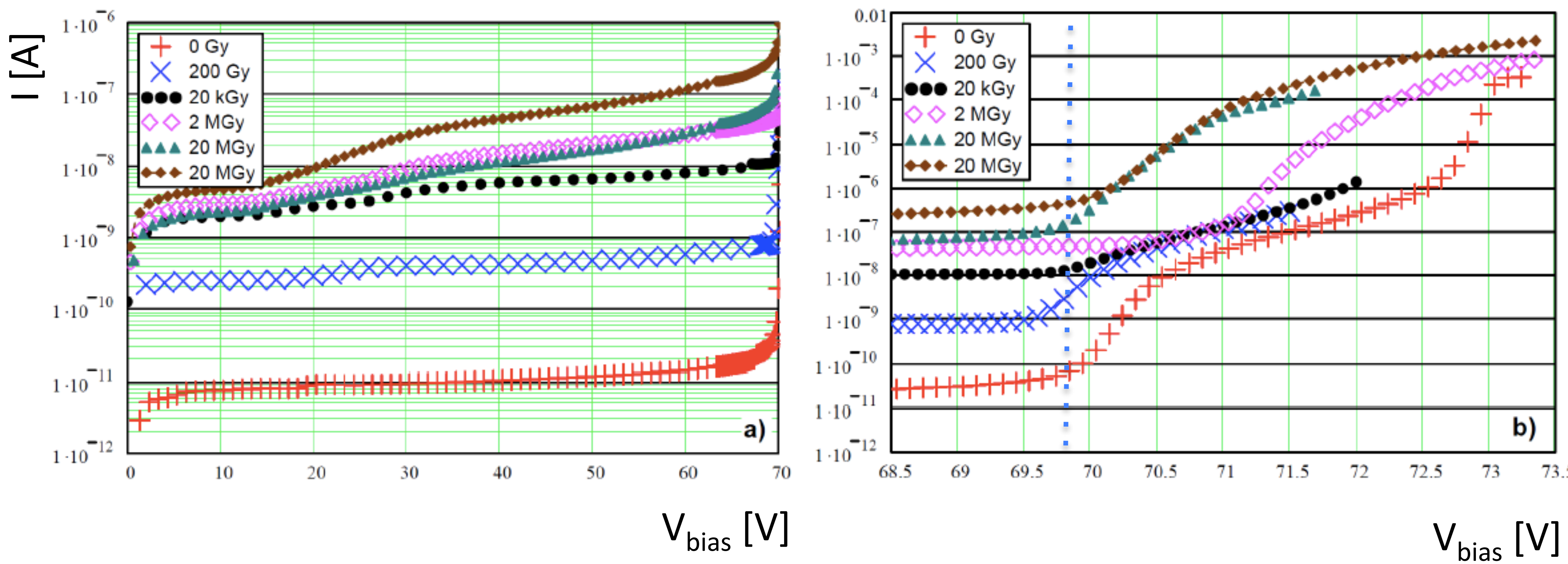
Dark current



Hamamatsu SiPM (MPPC 50 µm pixel) irradiated, not biased:

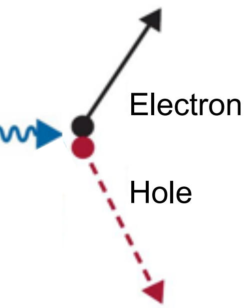
- 200 Gy and 20 kGy at X-ray tube (Mo target)
- 2 and 20 MGy at PETRA III (8 keV)

X-ray < 300 keV only surface damage ➜ N_{ox} and J_{surf}



Below V_{bd}: I increases by x10^4 at 20 MGy **Above V_{bd}:** I increases x2 from 0 - 200 kGy and by x10^3 above 20 MGy

Gain and breakdown voltage



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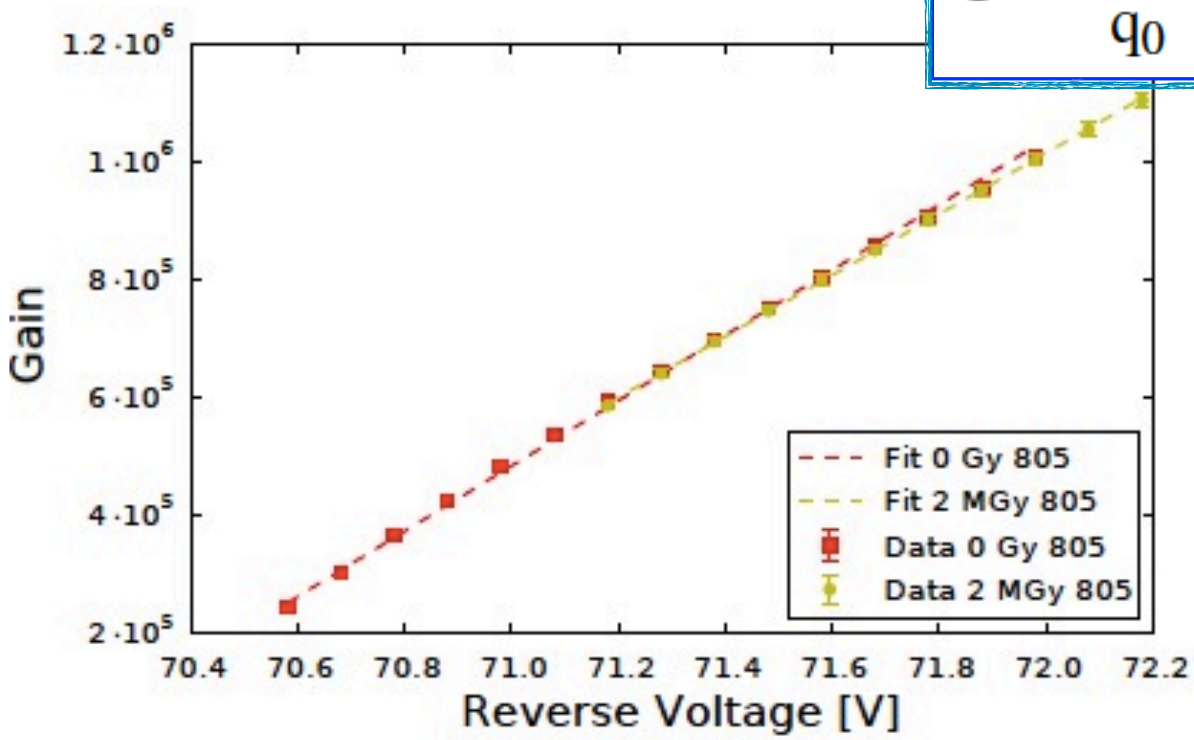
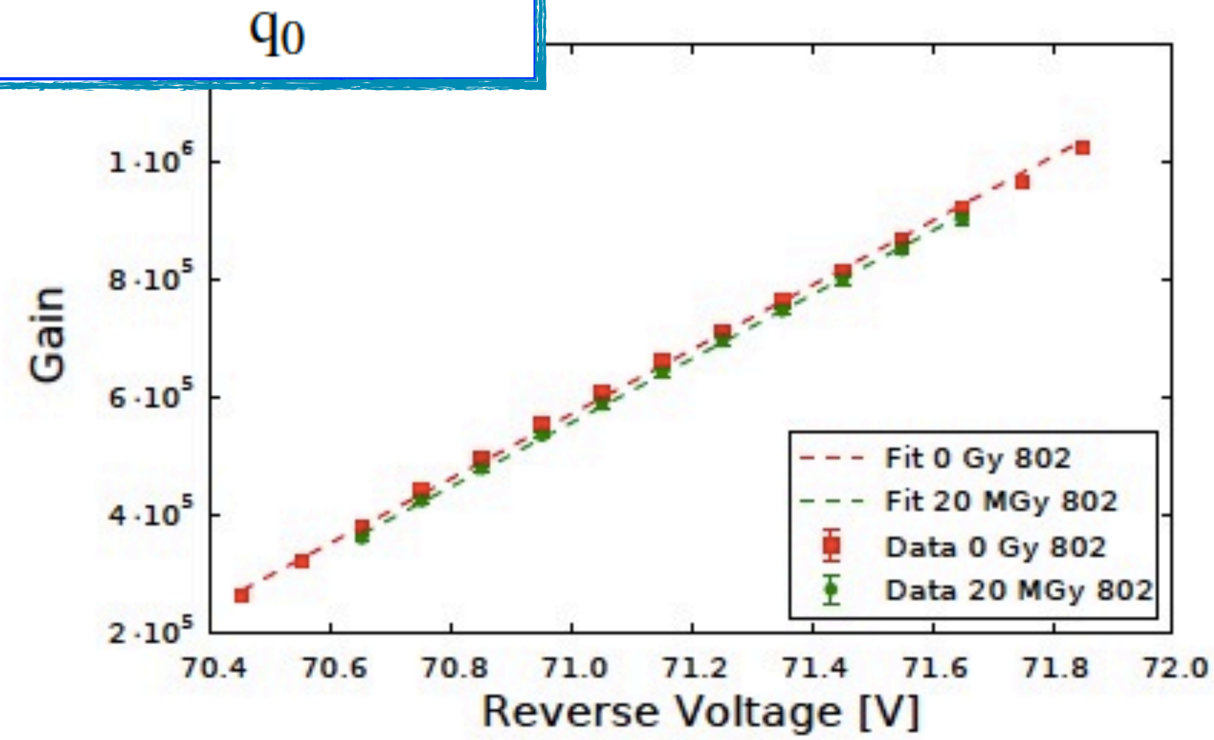
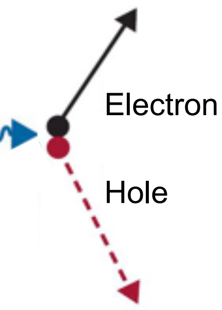




V_{bd}: changes < 50 mV for 0 – 20 MGy (compatible within T-dependence)

Gain: changes < 5% for 0 – 20 MGy (small reduction)

Dark spectra



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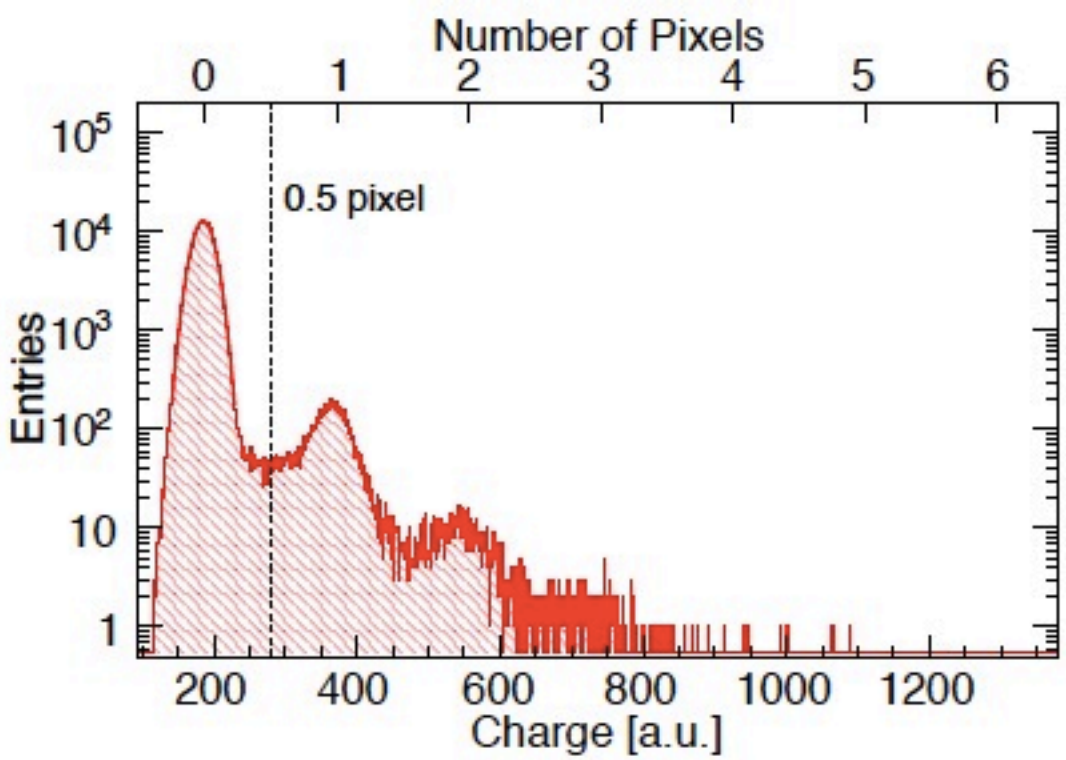
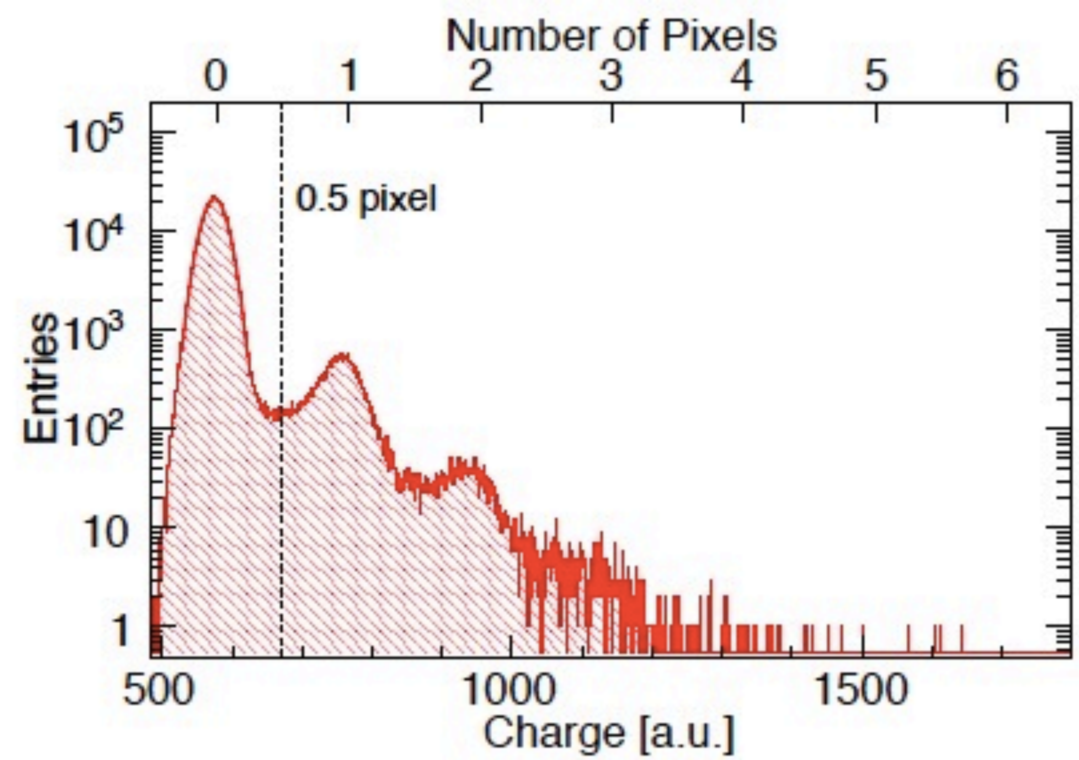


Un-irradiated (0 Gy) dark spectra



Irradiated (20 MGy) dark spectra

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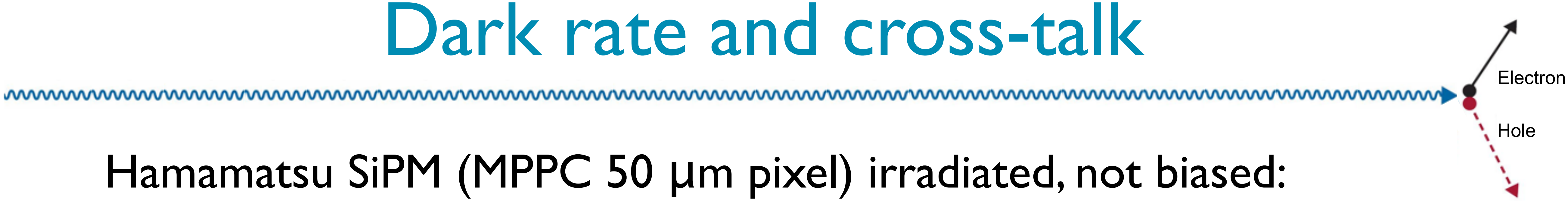
Dark rate and cross-talk



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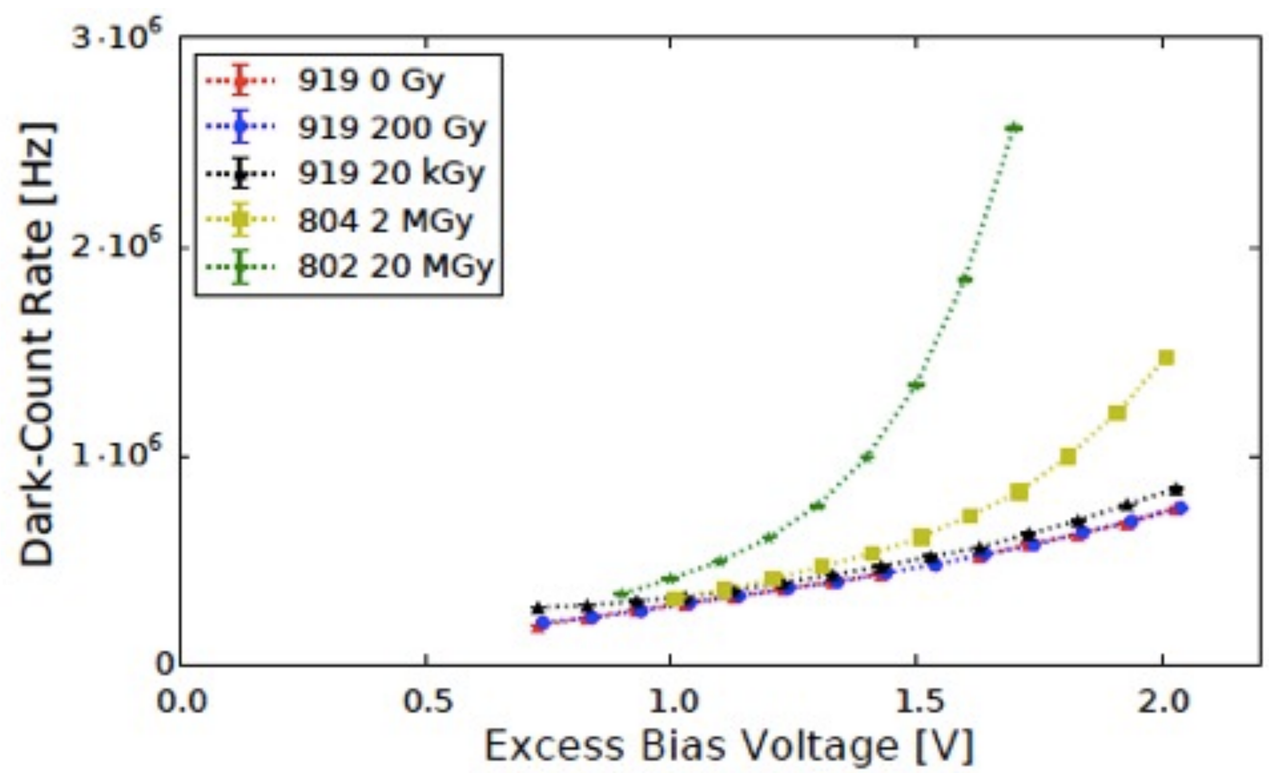
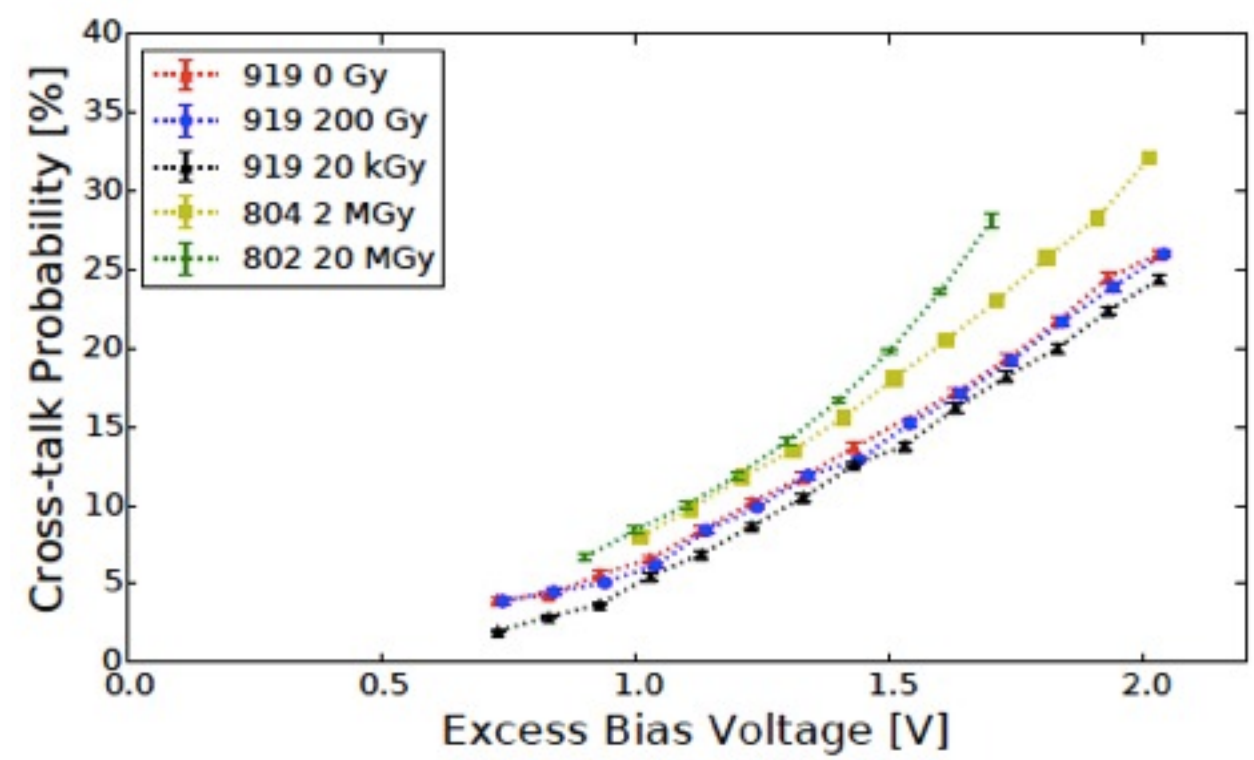


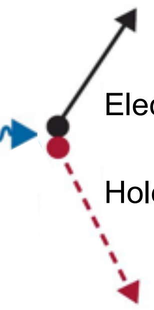


- small increase ~10% for 0-20 kGy
- increase by x3 for ΔV >1.5 V and 20 MGy
- rapidly increasing with ΔV
  ➜ maximum useful gain limited

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

Note: this definition of XT includes partially after-pulse

Pulse shape



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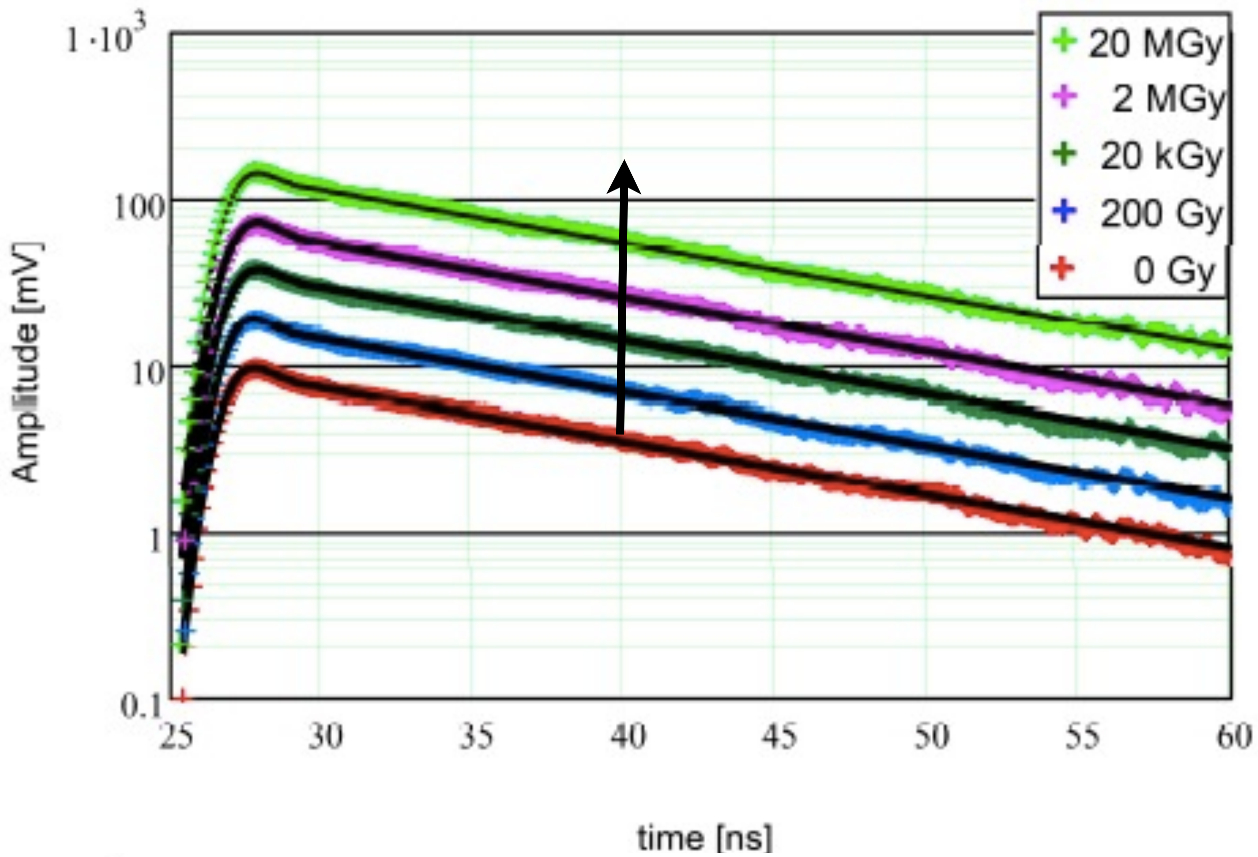
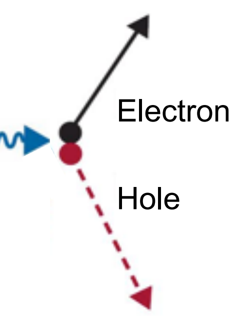


SiPMs operated at a gain of 7.5 x10^5

No change in pulse shape

Dose	0 Gy	200 Gy	20 kGy	2 MGy	20 MGy
τ_d [ns]	13.6 ± 0.5	13.6 ± 0.5	13.7 ± 0.5	13.3 ± 0.5	13.8 ± 0.5
Fraction fast signal [%]	5.3 ± 0.5	5.4 ± 0.5	5.2 ± 0.5	5.8 ± 0.5	5.1 ± 0.5

Conclusions and Outlook



Conclusions:

- Detailed characterization of MPPC S10362-11-050C below and above V_{bd}
- Characterized SiPM parameters (quench resistor, pixel capacitance, dark-count rate and pulse shape) as a function of X-ray dose in different ways.
- The study shows that the MPPC S10362-11-050C can be operated after X-ray irradiation to a dose of 20MGy.
- First step by the group towards a systematic investigation of radiation effects on SiPMs.

Outlook:

- Study the sensor performance during and shortly after X-ray irradiation, where large pulses and currents have been observed previously.
- Investigate the influence of environmental conditions like humidity.
- Extend the study to SiPMs from different producers.