Radiation hardness of SiPMs

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- Radiation damage effects in SiPMs
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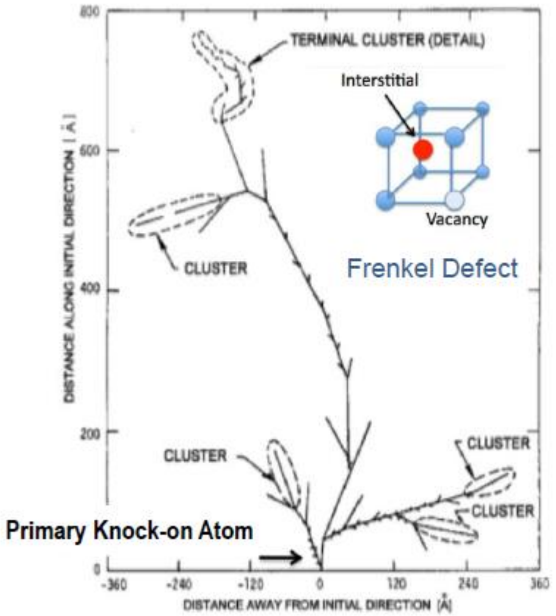
- Results on heavily irradiated SiPMs
- Annealing of the radiation damage
- Radiation damage of SiPMs at reduced temperature
- Approaches to develop radiation harder SiPMs
- Conclusion

Introduction

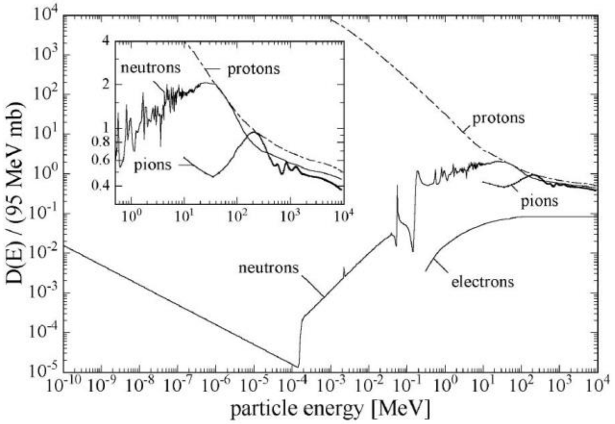
New detectors for the upgrade of the LHC experiments (CMS, LHCB) demand to operate SiPMs up to fluences of $10^{12} \div 10^{14}$ particles/cm^2. Application of SiPMs in this experiments requires understanding of the effects caused by different types of irradiation on SiPM parameters. This review is an attempt to summarize the current knowledge of radiation damage of SiPMs.

Radiation induced damage in silicon

Radiation induced damage in Silicon



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings



Bulk damage:

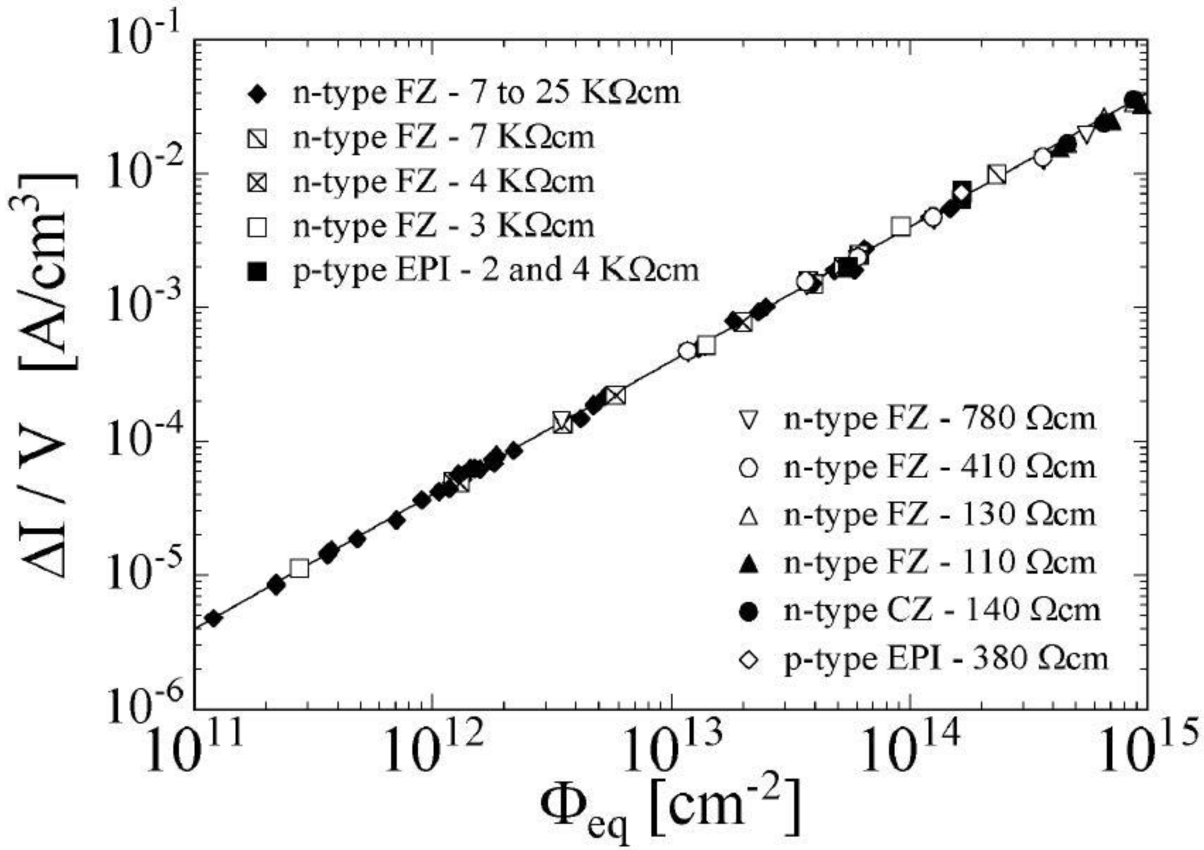
- Incoming particle transfers a certain amount of energy to atom
- If the energy transferred to the atom is large than the binding energy of a silicon atom (~190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy → single point or cluster defects
- Number of defects is proportional to the Non Ionizing Energy Loss (NIEL) – depends on incoming particle type and its energy

Surface damage:

- Low energy X-rays can produce surface damage affecting the SiO_2/Si_3N_4 layer
- Ionizing particles can produce charging up effects affecting the internal fields inside the device

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation induced damage in Silicon: dark current increase



Measured after 80 min annealing at 60 °C

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Dark current increase is proportional to the neutron fluence and depleted volume of silicon in a wide range of fluences ($10^{11} \div 10^{15}$):

$$\Delta I = \alpha \, \Phi_{eq} \, V$$

$$\alpha(80\,\mathrm{min}, 60°\mathrm{C}) = (3.99 \pm 0.03) \times 10^{-17} \mathrm{A/cm}$$

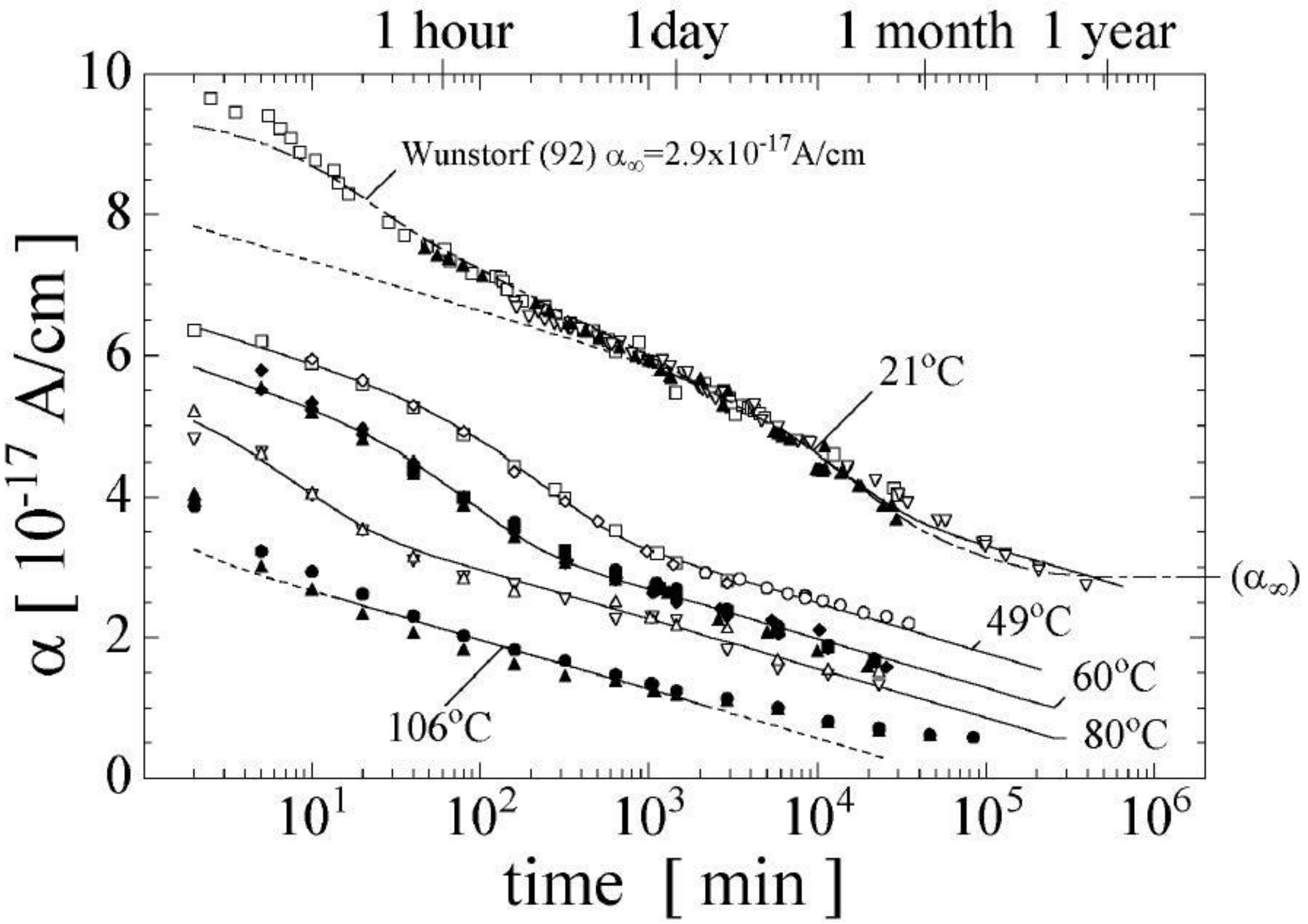
Dark current generation rate depends on temperature:

$$I_{gen} \propto T^2 e^{-\frac{E_a}{kT}}$$

Activation energy E_a = 0.605 eV is close to the middle of the silicon bandgap

A. Chilingarov, Temperature dependence of the current generated in Si bulk, Journal of Instrumentation 8 (10) P10003.

Radiation induced damage in Silicon: dark current annealing



High temperature can significantly speed up process of dark current annealing in irradiated silicon devices

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation induced damage in Silicon: doping concentration change

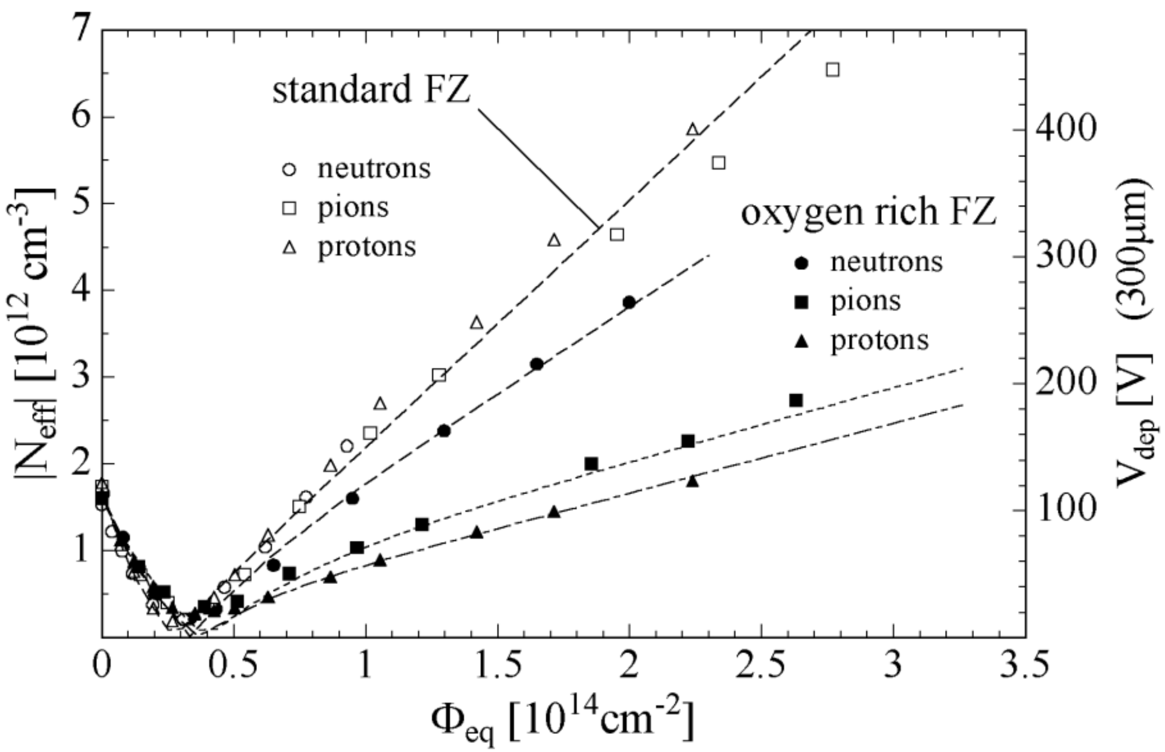


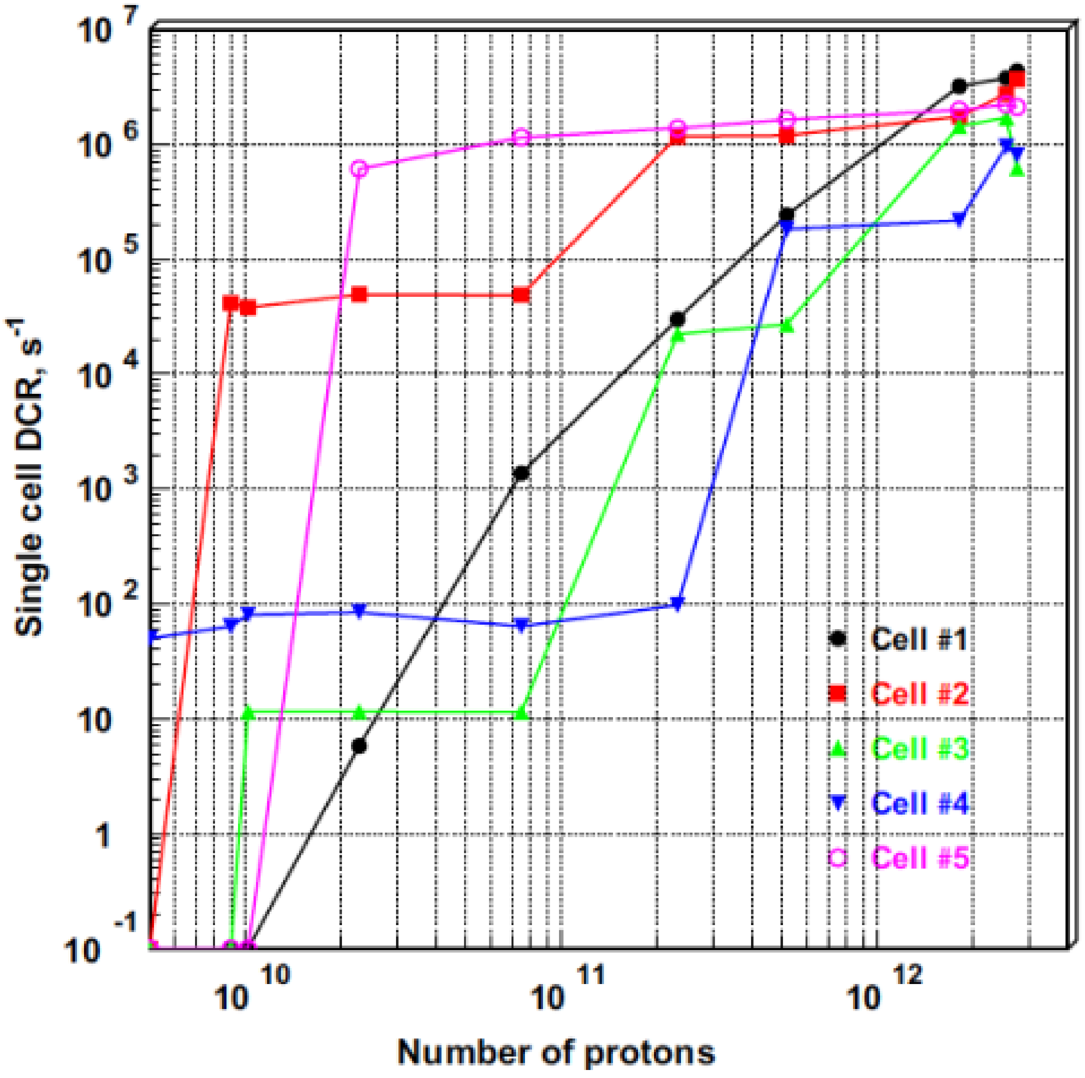
Figure 5.21: Dependence of N_{eff} on the accumulated 1 MeV neutron equivalent fluence Φ_{eq} for *standard* and *oxygen enriched* FZ silicon irradiated with reactor neutrons

Under hadron irradiation doping concentration in silicon detectors changes due to acceptor creation (donor removal) processes.

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation damage effects in SiPMs (hadrons)

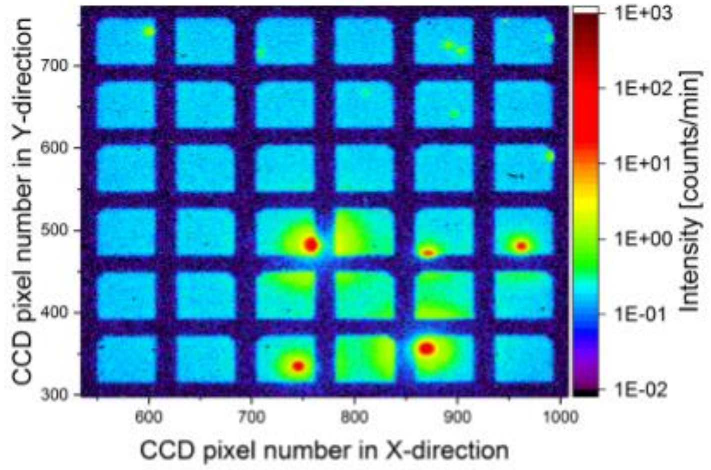
The dark count rate of individual cells of a Philips DSiPM as a function of total accumulated dose.



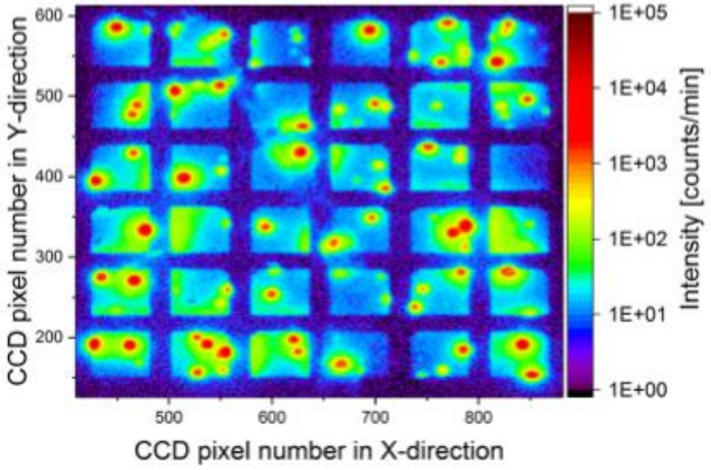
Barnyakov et. all have investigated the radiation damage of digital SiPMs exposed to 800 MeV protons. In a digitalSiPM, the DCR of every individual cell can be monitored separately. The step-like increase of the DCR indicates that a single interaction of a proton with a Si atom may result in a drastic DCR increase and that the increase may differ by orders of magnitude for each proton interaction. Most likely this effect is linked to the formation of cluster-like defects in one pixel.
SiPMs help to understand radiation induced defects in silicon!

(M. Yu. Barnyakov et. all, NIM A824 (2016) 83)

Using IR light emission to study neutron irradiated SiPMs



(a) Reference sample, $t_{exp} = 2$ h



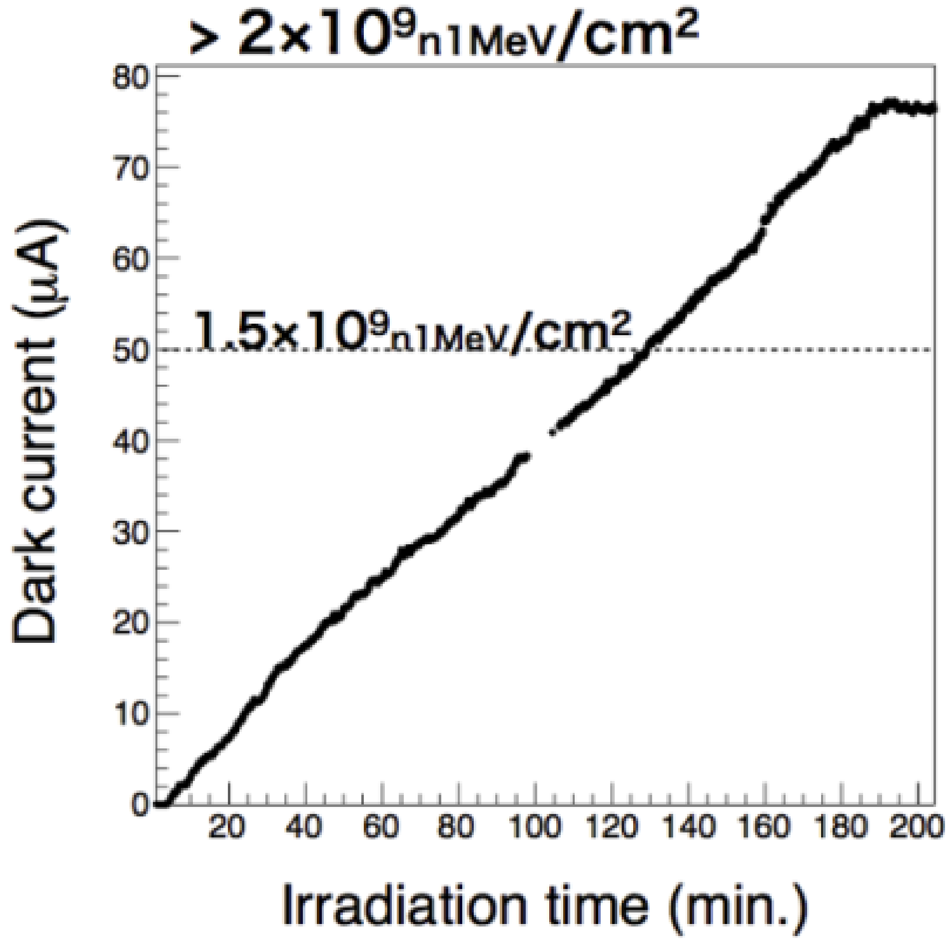
(b) Neutron irradiated sample, $t_{exp} = 2$ min

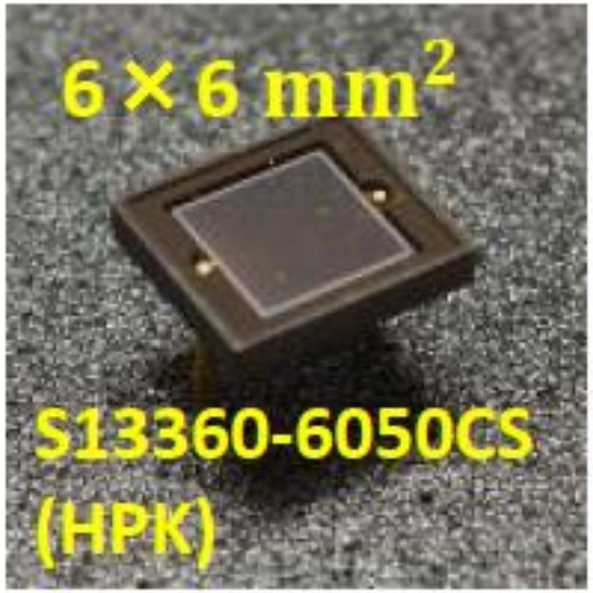
Light intensity images for a non-irradiated (a) and a neutron irradiated SiPM test structure (b), operated at $\Delta V = 4$ V. The irradiated SiPM was exposed to $\Phi_{eq} = 10^{10}$ cm^{-2} and no annealing was applied. The effect of radiation in increasing the number of hot-spots is evident in these images.

Every Geiger discharge emits a certain number of optical and IR photons produced in the high field region. For randomly distributed DCR on the SiPM volume, the light emission is expected to be homogeneous. In the case of local defects in silicon, hotspots can form, which are more likely to generate Geiger avalanches in the dark.

(*E. Engelmann, Dark count rate of silicon photo-multipliers, Ph.D. thesis, Universitt der Bundeswehr Mnchen (2018))*

Dark current increase with neutron fluence for Hamamatsu S13360-6050CS MPPC (dVB=3.0 V)

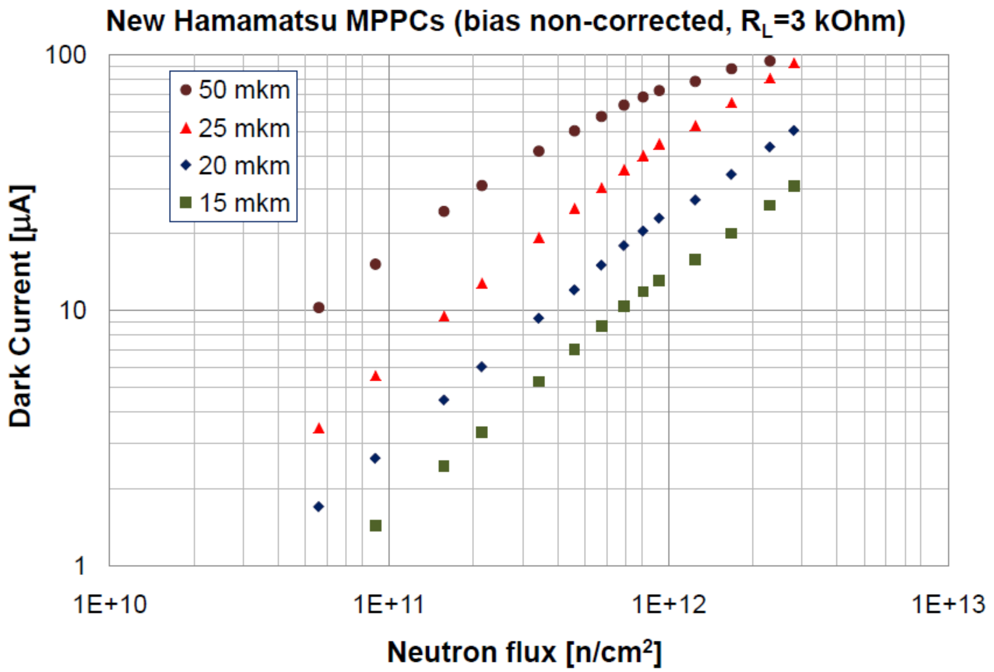




Dark current linearly increases with fluence

(Nobuhiro Shimizu, Upgrade of the Cesium Iodide calorimeter for the KOTO experiment., PD18, Tokyo)

Dark current vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



(Yu. Musienko, A. Heering, NDIP-2011, Lyon, France)

High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

$I_d \sim \alpha * \Phi * V * M * k$,

α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – "effective" silicon volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~$4*10^{-17}$ A*cm after 80 min annealing at T=60 °C (measured at T=20 °C)
Damage produced by 40 neutrons (1 MeV) in 1 µm thick Si → 1 dark count/sec at 20 °C

Thickness of the epi-layer for most of SiPMs is in the range of 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-Frenkel effect) play significant role in the origin of SiPM's dark noise.

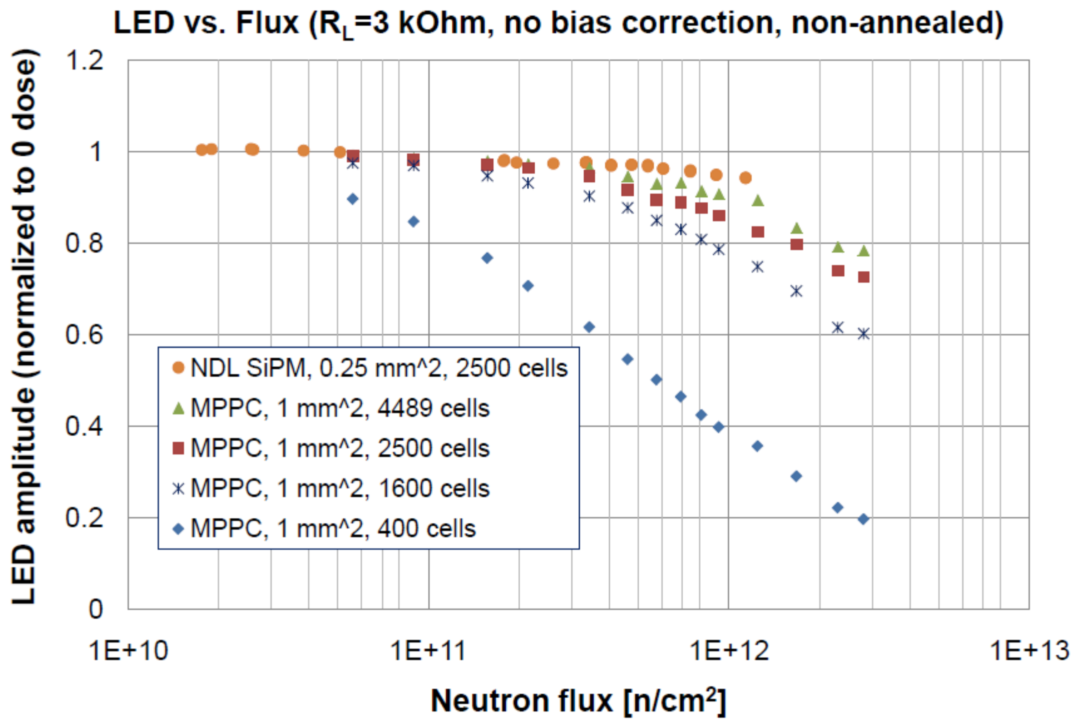
$V \sim S*G_f*d_{eff}$,
S - area
G_f - "effective" geometric factor
d_{eff} - "effective" thickness

SiPM radiation damage by neutrons: signal reduction

Radiation may cause:

- Fatal SiPMs damage (SiPMs are broken and can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPM cell "blocking" effects due to high induced dark carriers generation-recombination rate)
- Breakdown voltage increase, PDE, Gain reduction due to donor/acceptor concentration change

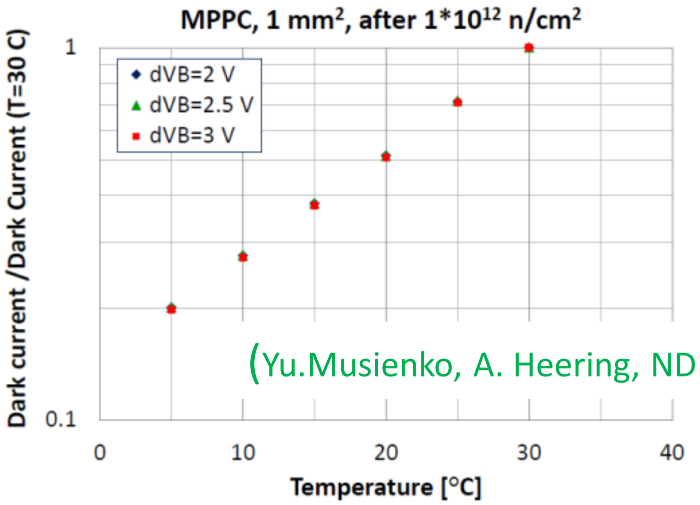
Relative response to LED pulse vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



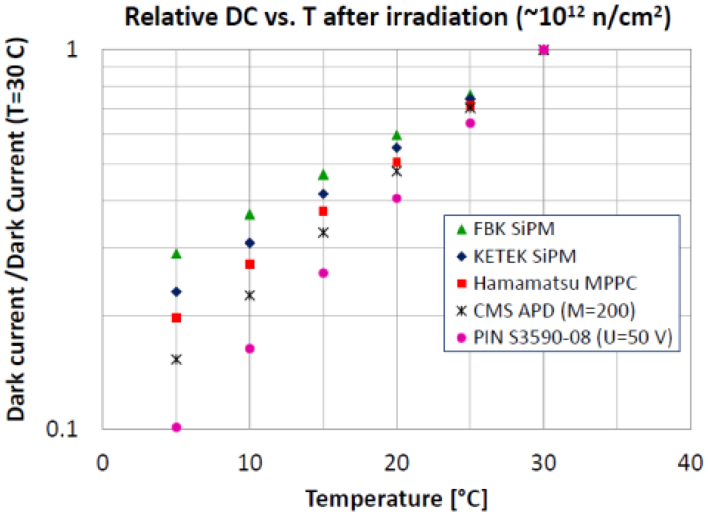
(Yu. Musienko, A. Heering, NDIP-2011, Lyon, France)

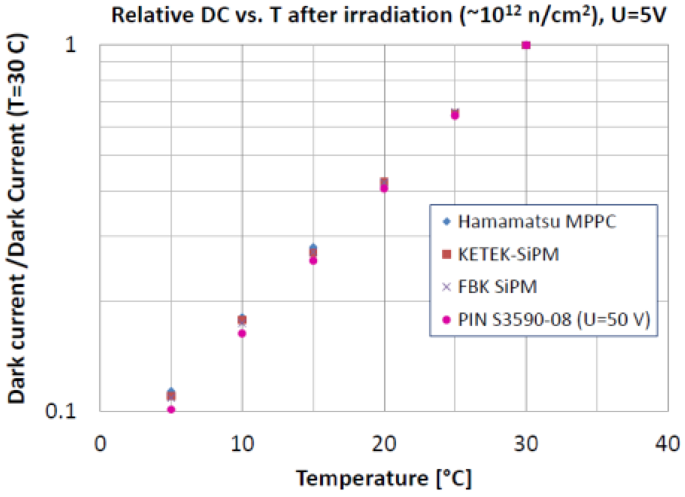
SiPMs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm^2 (gain change is< 25%).

Dependence of the SiPM dark current on the temperature (after irradiation)



(Yu.Musienko, A. Heering, NDIP-2014)

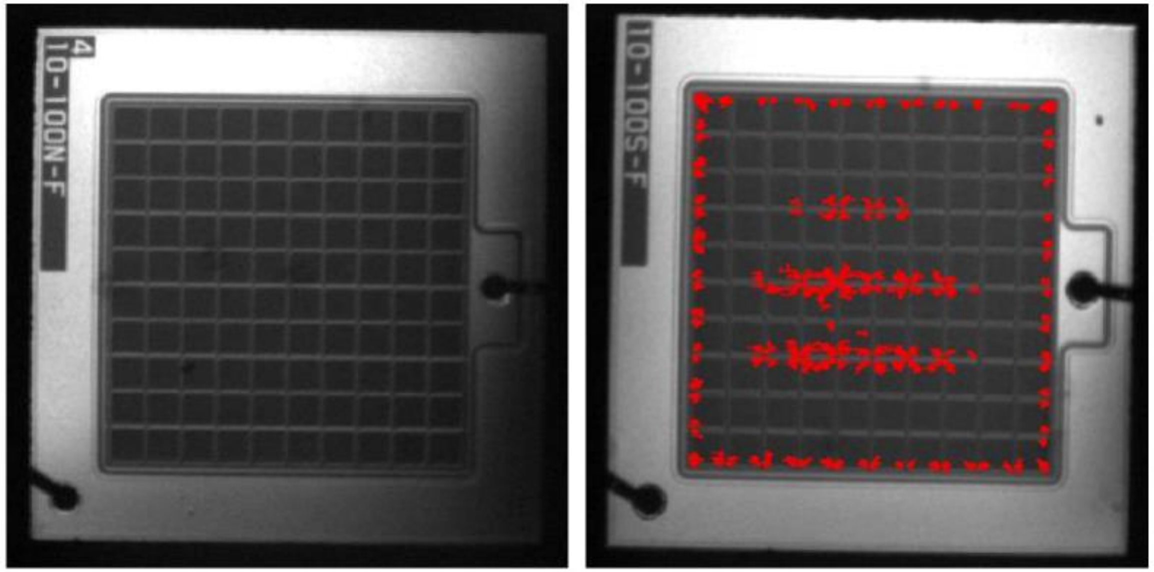




It was observed a rather weak dependence of the SiPM's dark current decrease with temperature on the dVB value. SiPM dark currents at low voltage (5V) behave similar with temperature to that of the PIN diode. However we observed significant difference of this dependence for differenet SiPM types when they operate over breakdown! General trend is that SiPMs with high VB value have faster dark current reduction with the temperature.

Radiation damage effects in SiPMs (X-rays and gammas)

“Early” SiPMs under Co-60 gamma ray irradiation



Infrared pictures of a new sample and the irradiated with 240 Gy dose. Infrared light is emitted due to heat produced by high leakage current (red points).

Matsubara and co-authors in have irradiated a prototype SiPM from Hamamatsu (Type No. T2K-11-100C) under bias up to 240 Gy of 60-Co γ-rays and measured the dark current, dark-count rate, gain, and cross talk. Whereas gain and cross talk did not significantly change with dose, large dark count pulses and localized spots with leakage current along the outer edge of the active region and the bias lines were observed for about half an hour after irradiation for doses above 200 Gy

T. Matsubara, H. Tanaka, K. Nitta, M. Kuze, Radiation damage of MPPC by gamma-ray irradiation with Co-60, PoS PD07 (2007) 032.

Effects of X-rays irradiation on recent SiPMs

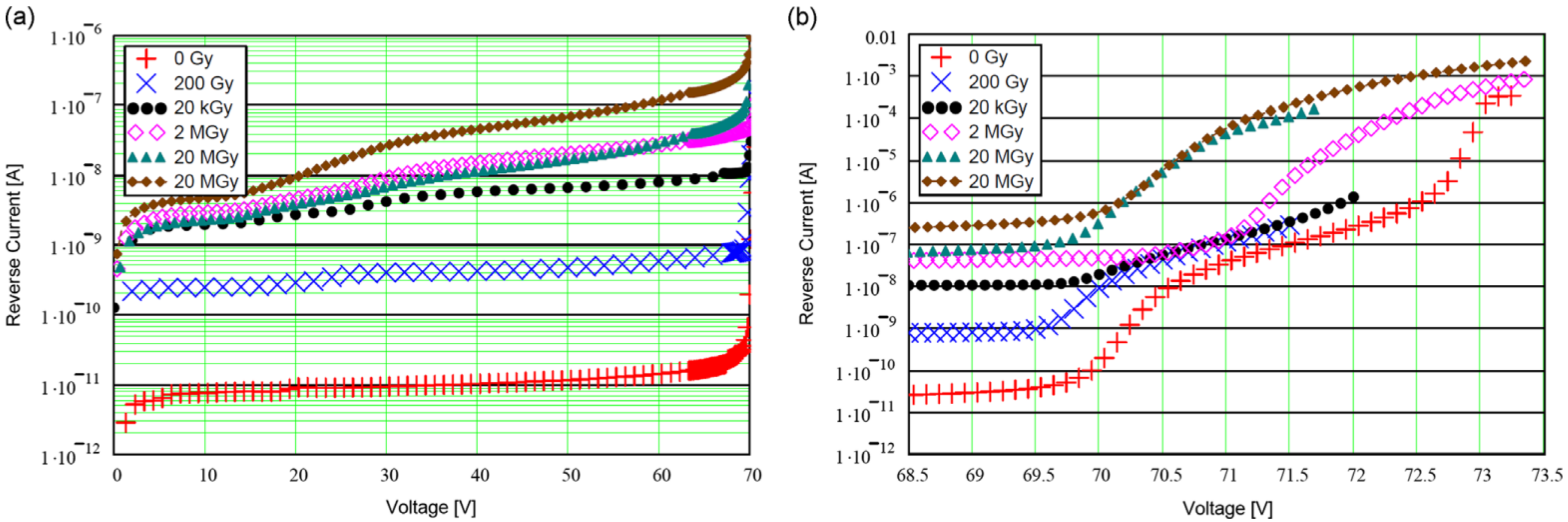


Fig. 6. Reverse currents of SiPMs as a function of voltage before, and after irradiation with X-rays to 200 Gy 20 kGy, 2 MGy, and 20 MGy (a) below the breakdown voltage, and (b) in the region of and above the breakdown voltage.

The X-ray irradiations up to 20 kGy were performed at an X-ray tube (PW 2273/20 from PANalytical). The X-ray irradiations to 2 MGy and 20 MGy were performed with X-rays of 8 keV in the P11 beam line of PETRA III.

(C. Xu, R. Klanner, E. Garutti, W.-L. Hellweg, NIM A762 (2014) 149)

Dark-count and X-talk vs. dVB after X-ray irradiation

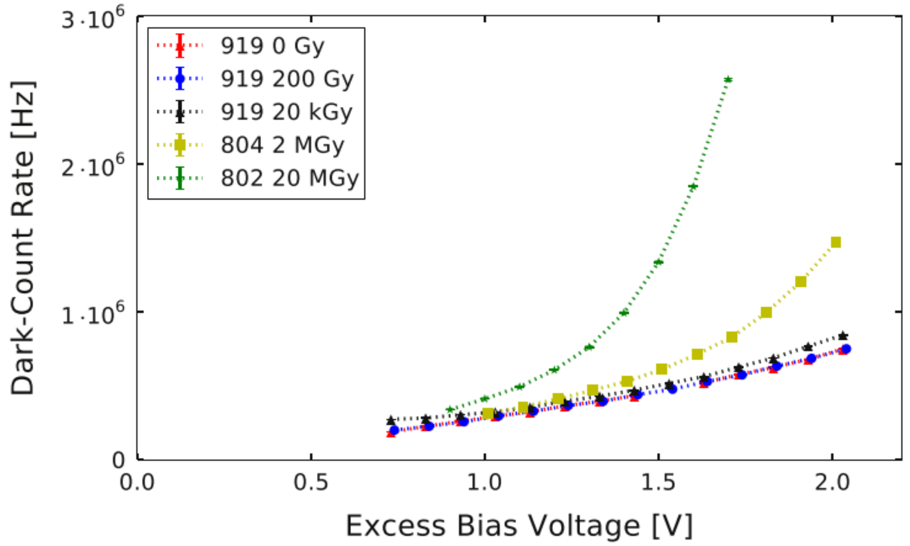


Fig. 14. Dark-count rate for several SiPMs as a function of the excess bias voltage, $V_{op} - V_{bd}$, before and after irradiation to 200 Gy, 20 kGy, 2 MGy, and 20 MGy.

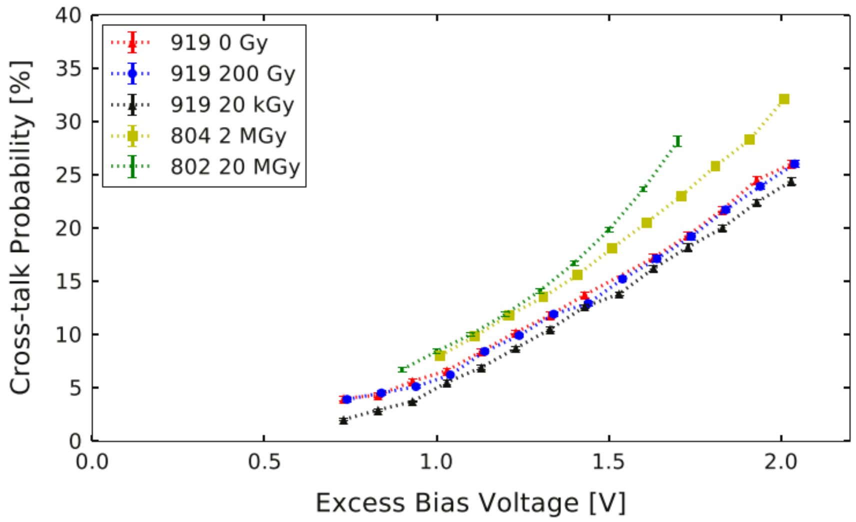


Fig. 15. Cross-talk probability for several SiPMs as a function of the excess bias voltage, $V_{op} - V_{bd}$, before and after irradiation to 200 Gy, 20 kGy, 2 MGy, and 20 MGy.

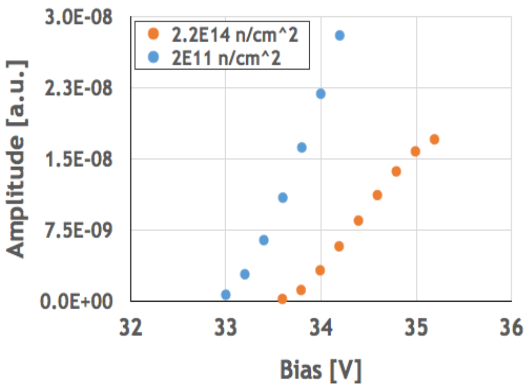
(C. Xu, R. Klanner, E. Garutti, W.-L. Hellweg, NIM A762 (2014) 149)

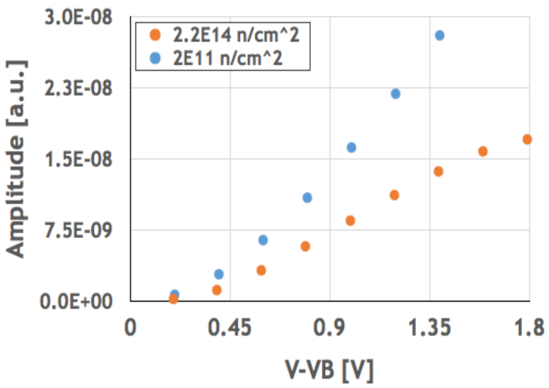
The effects of X-ray irradiation to doses of 0, 200 Gy, 20 kGy, 2 MGy, and 20 MGy investigated on the Hamamatsu silicon-photomultiplier (SiPM) S10362-11-050C. The SiPMs were irradiated without applied bias voltage using. From current–voltage, capacitance/conductance–voltage, capacitance/conductance–frequency, pulse-shape, and pulse-area measurements, the SiPM characteristics below and abovebreakdown voltage were determined. Up to a dose of 20 kGy the performance of the SiPMs is hardly affected by X-ray radiation damage. For doses of 2 and 20 MGy the SiPMs operate with hardly any change in gain, but with a significant increase in dark count rate and cross-talk probability.

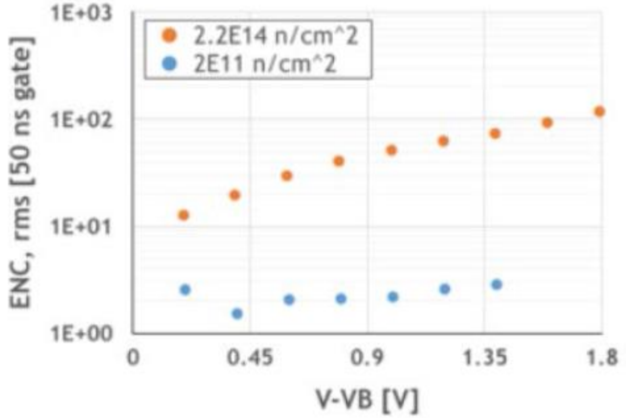
Results on heavily irradiated SiPMs

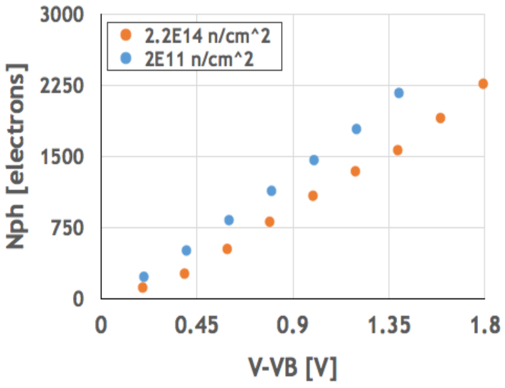
SiPM irradiated up to 2.2*10^{14} n /cm^2

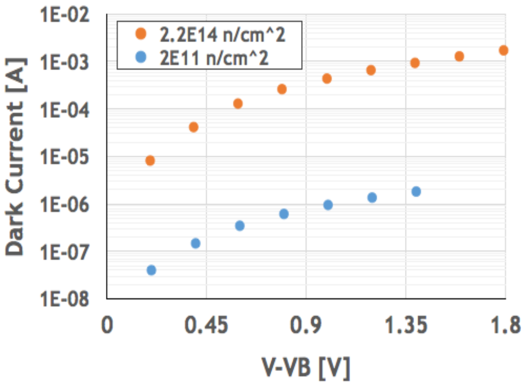
Can SiPM survive very high neutron fluences expected at high luminosity LHC? FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to 2.2*10^{14} n /cm^2 (1 MeV equivalent).











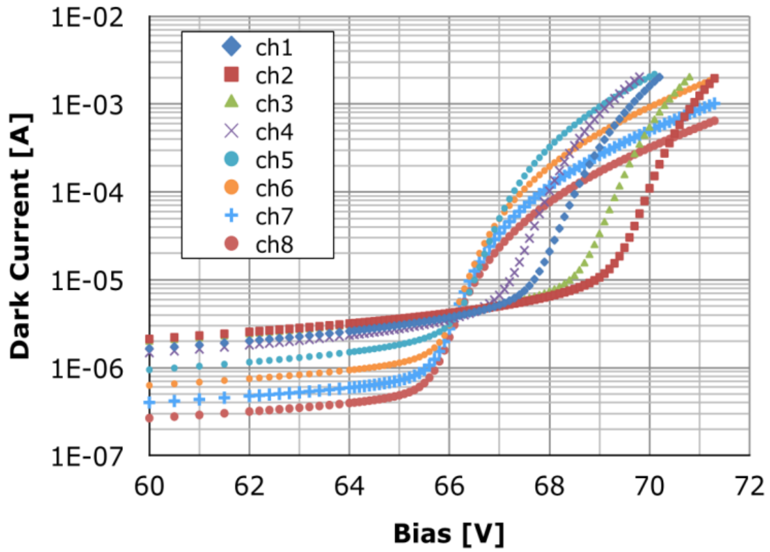
(A.Heering et al., NIM A824 (2016) 111)

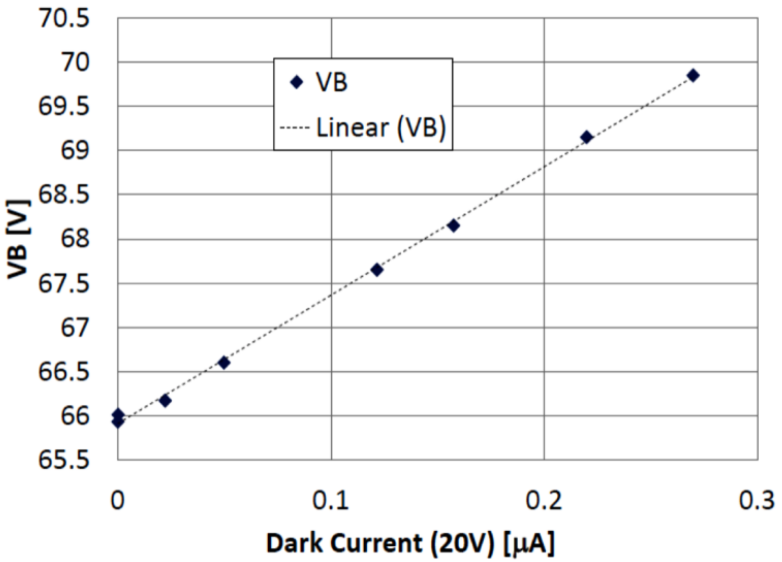
The authors found:

- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

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

2.8 mm dia., 10 um cell pitch Hamamastu MPPCs irradiated up to 2.2E14 n/cm^2





(a) Dark current vs. bias voltage. (b) VB shift vs. dark current at gain 1

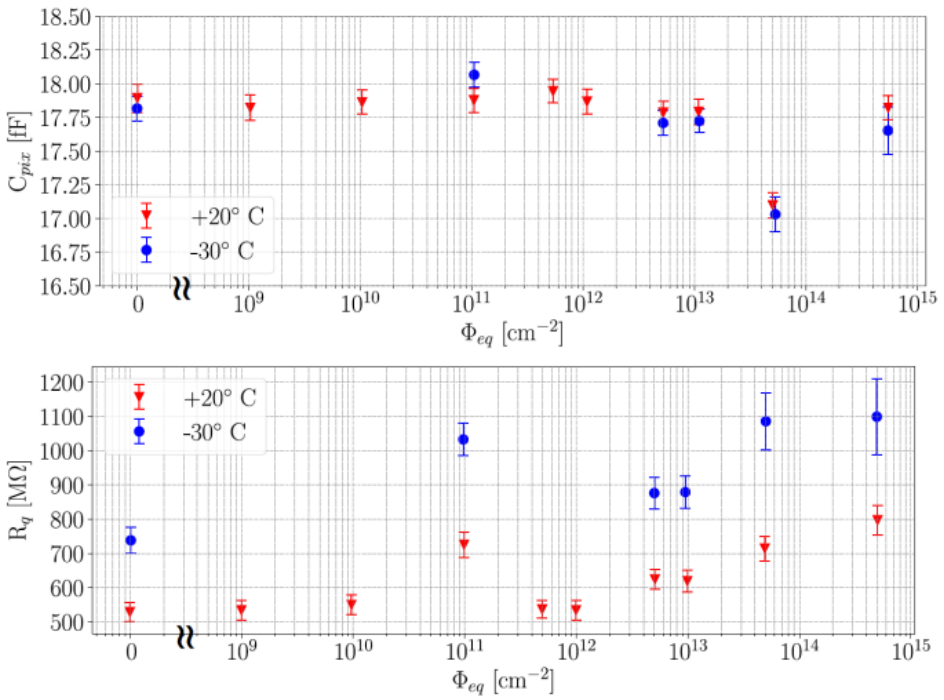
The same type as S12572-010C MPPC. 8-ch. array developed for the CMS HCAL Phase I Upgrade project. Non-uniform irradiation with 24 GeV protons (5 mm dia. Spot size).

Change of the doping concentration: VB shift with fluence reaches 4 V at 2.2E14 n/cm^2. SiPMs with thicker depletion region has larger VB shift in comparison to the "thin" SiPMs.

Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm^2)
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm^2)

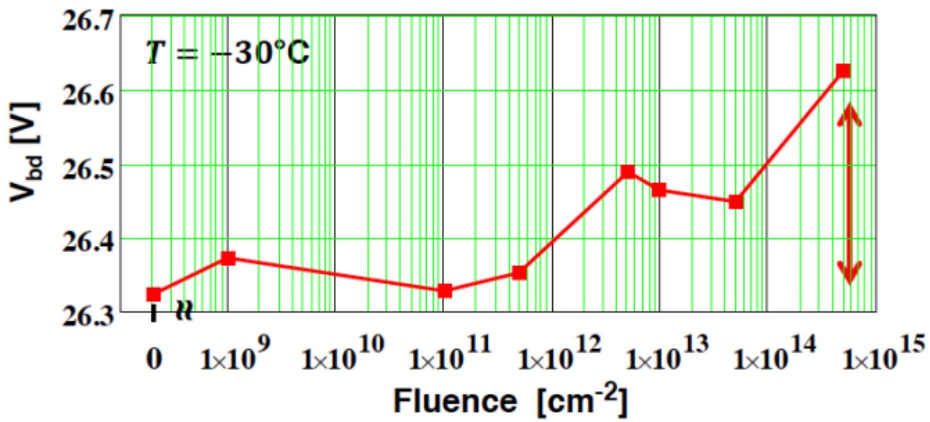
(A.Heering et al., NIM A824 (2016) 111)

KETEK SiPM after high neutron irradiation



SiPM electrical parameters of a KETEK SiPM (15 µm pixel size) as the function of neutron fluence measured at +20 °C and -30 °C . (Top) Pixel capacitance, Cpix, and (bottom) quenching resistance, Rq.

VB shift vs. accumulated neutron fluence



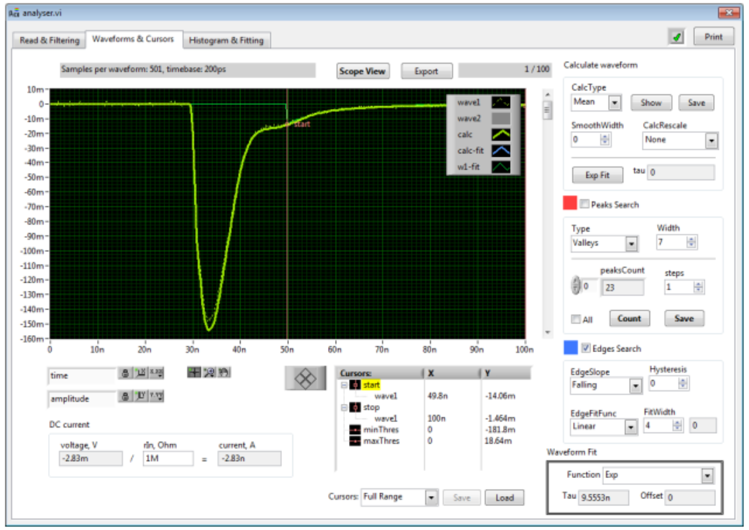
S. Cerioli, E. Garutti, R. Klanner, D. Lomidze, S. Martens, J. Schwandt, M. Zvolsky, Characterisation of radiation-damaged sipms, International Conference on the Advancement of Silicon Photomultipliers, ICASiPM 2018.

From the C-V measurements below the breakdown voltage, which were taken at 25 frequencies between 100 Hz and 2 MHz, the SiPM electrical parameters have been determined using a simple R-C model. It is found that the value of Cpix neither depends on temperature nor on neutron fluence, whereas the value of Rq increases for $\Phi eq > 10^{12}$ cm^{-2}. As expected for a poly-Si resistor, Rq increases with increasing temperature

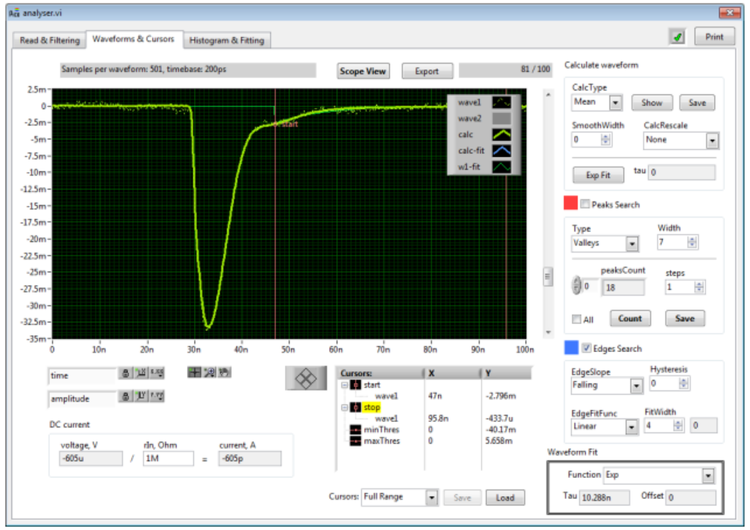
Laser response of the CMS HE SiPM after irradiation with 5E13 n/cm²

R_{load} = 16.7 Ohm, average of 100 waveforms

New



After 5E13 n/cm²



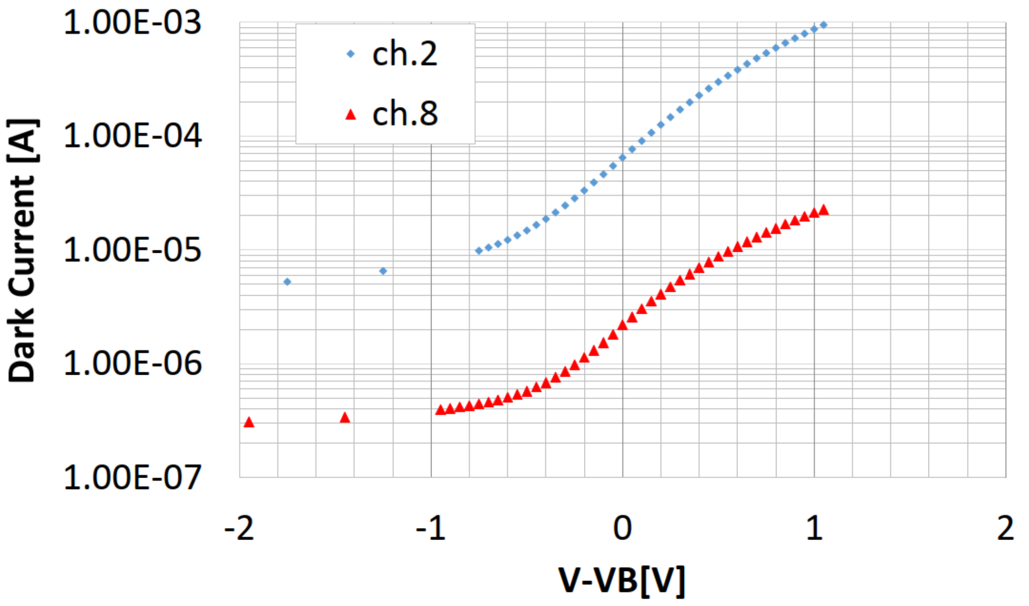
- HE 2.8 mm dia., 15 cell pitch SiPMs
- Laser 405 nm, 25 psec FWHM
- Quartz fiber 2 m long
- Picoscope 6404D, BW=500 MHz, 5 Gs/sec
- Loads: 50 Ohm, 25 Ohm, 16.7 Ohm

(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

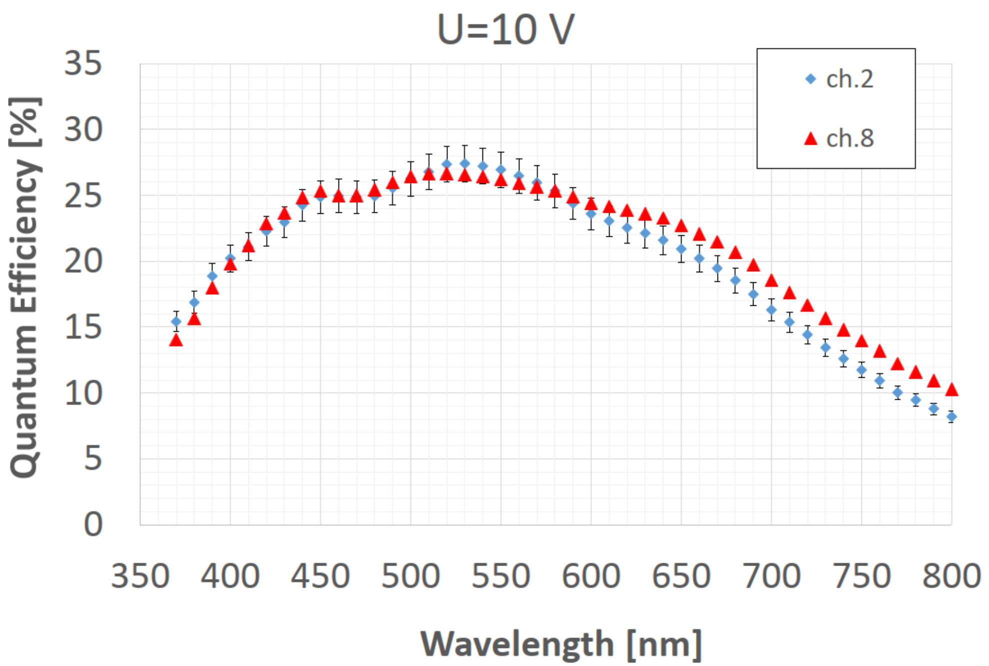
S10943-4732, 15 micron pixels, no trenches similar to S12572-015C SiPM

The SiPM response remains unchanged after 5E13 n/cm² (irradiated at Ljubljana reactor)

S12572-010C (quartz window) MPPC: dark currents and spectral response after irradiation



S12572-010C MPPC: dark currents vs. V-VB

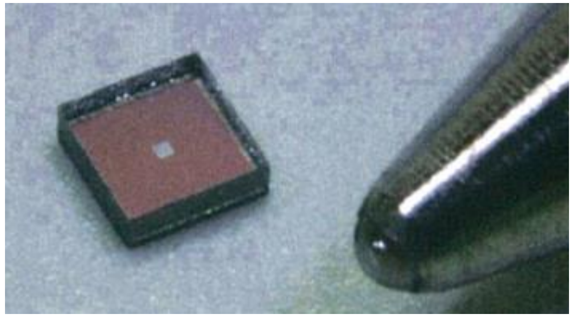


S12572-010C MPPC: QE(10 V) s vs. wavelength

Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm^2)
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm^2)

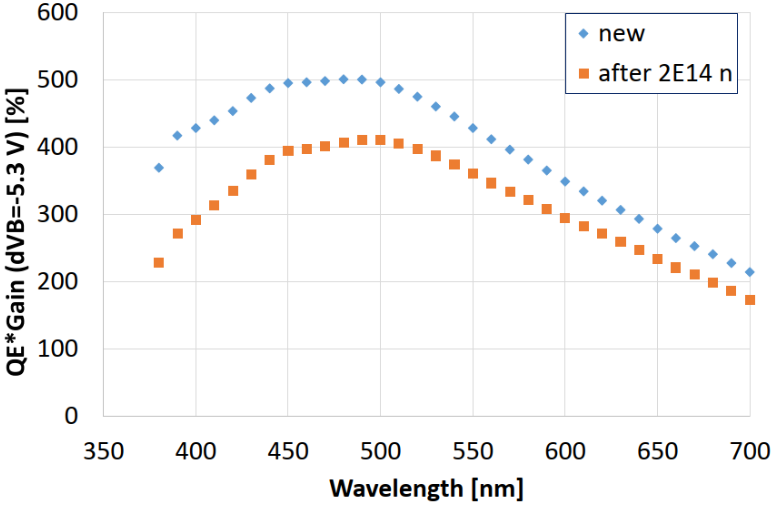
(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

S13190-1015 TSV MPPC: spectral response after 2E14 n/cm^2

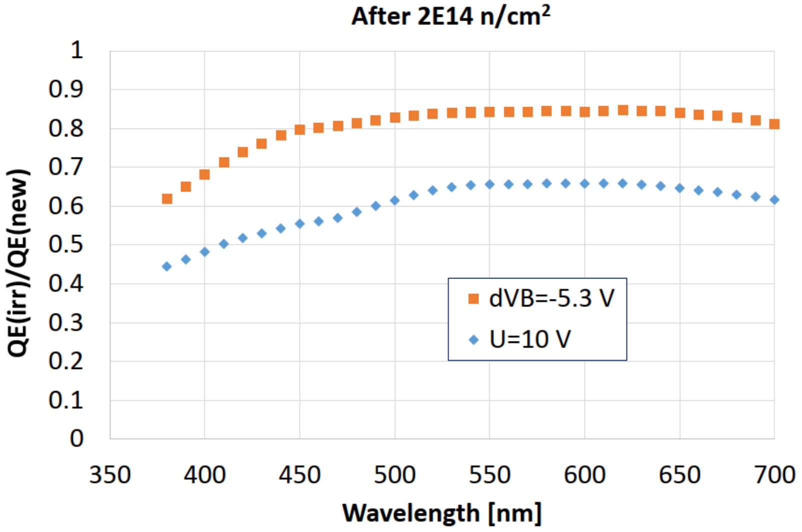


TSV design, SiPM is protected by ~300 um thick glass window

(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)



*QE*Gain vs. wavelength (new and irradiated)*



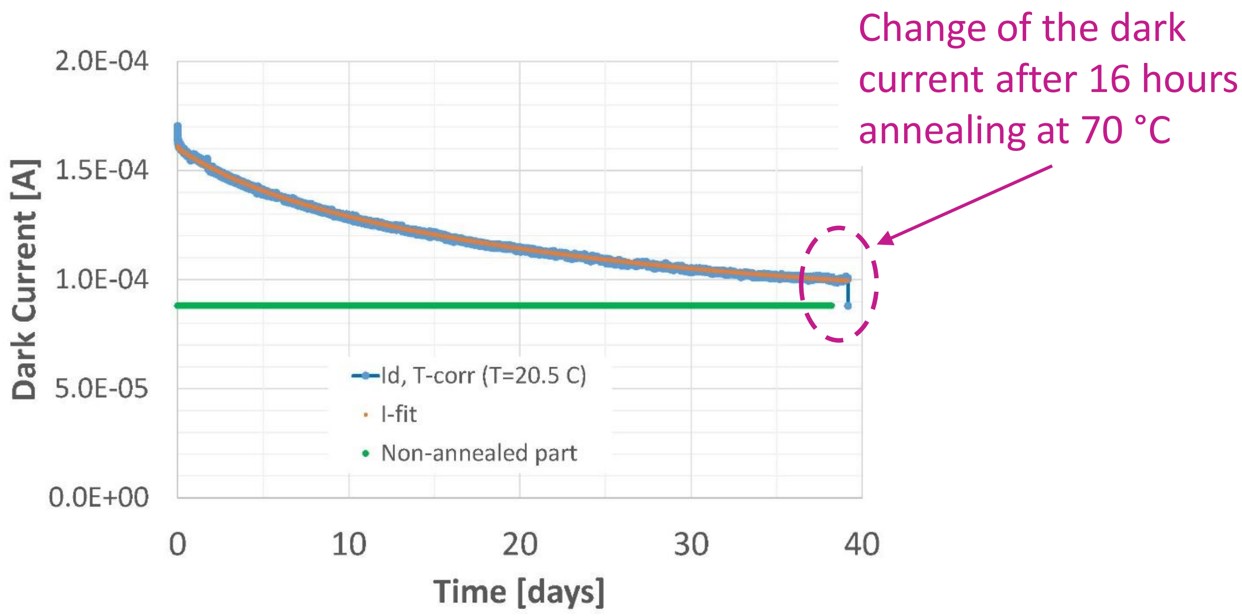
QE(irr.)/QE(new) vs. wavelength (new and irradiated)

20% ÷ 30 % loss of the QE after irradiation is probably due to darkening of the entrance glass window after irradiation

Annealing of the radiation damage

SiPM dark current annealing after irradiation

S10943-4732, 15 micron pixels, no trenches similar to S12572-015C SiPM



HE-P-10935 array (2.8 mm dia., 15 μm cell pitch) was passively irradiated at CHARM up to 1.4E12 n/cm^2 (1 MeV equivalent, CHARM calibration!!). Irradiation took ~5 days. Annealing study (at T=20.5 °C) started 1 day after end of irradiation.

- SiPM bias - 66.8 V (dVB=0.98 V)
- T=20.5 °C
- Duration of measurement – 39.2 days

After that SiPM was annealed at T=70 °C during 16 hours. I-V curves were measured before and after annealing.

After 39.2 days of annealing at T=20.5 °C the SiPM dark current reduced from 160 mA to 100.5 mA. Additional 16 hours annealing at 70 °C reduced the SiPM dark current from 100.5 mA to 88 mA (~13 %).

6 days after irradiation the dark current vs. time annealing can be described by 3 time components:

(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

τ = 4 days	τ = 23.5 days	Non-anneal. part	Total (I(0)=160 uA)
0.069	0.382	0.549	1.000

Dark current annealing at elevated temperature

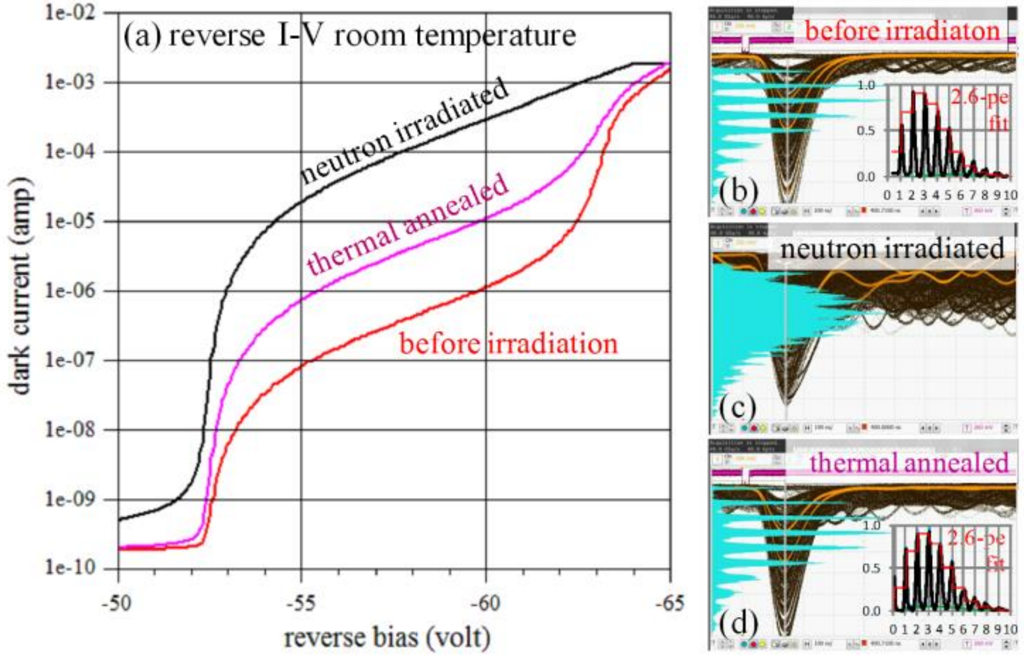


Figure 3. (a) Representative reverse I–V characteristic of SiPM at room temperature, and its cumulative collection of the photoelectron histogram sampled at the peak of the time-gated single photoelectron charge signal pulses at ~ 3 volt over-voltage (b) before irradiation, (c) after neutron irradiation to a dosage of 10^9 n/cm^2, and (d) followed by 250°C thermal annealing, respectively. Single photoelectron histograms are in cyan, insets in (b) & (d) are the corresponding Poisson fitted photon number resolving histograms to ~ 2.6 photoelectrons (red).

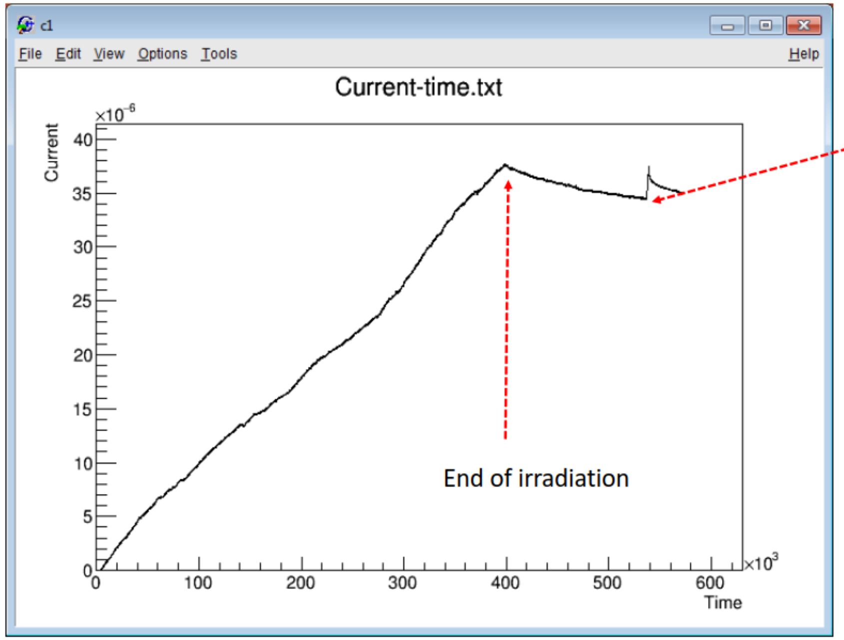
T. Tsang et. all performed annealing at +250 °C, using forward bias with the SiPM current reaching 10 mA. A remarkable effect of this high temperature annealing was demonstrated: >20 fold reduction of the dark current. Single photo-electron resolution was recovered after this procedure for devices irradiated up to $\Phi_e q = 10^{12}$ cm^{-2} with cooling them to about -50 °C.

T. Tsang, T. Rao, S. Stoll, C. Woody, Neutron radiation damage and recovery studies of sipms, Journal of Instrumentation 11 (12) (2016) P12002.

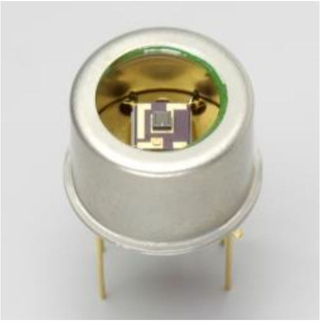
Studies of radiation damage to SiPMs at low temperatures

Dark Current vs. Irradiation Time&Neutron Fluence

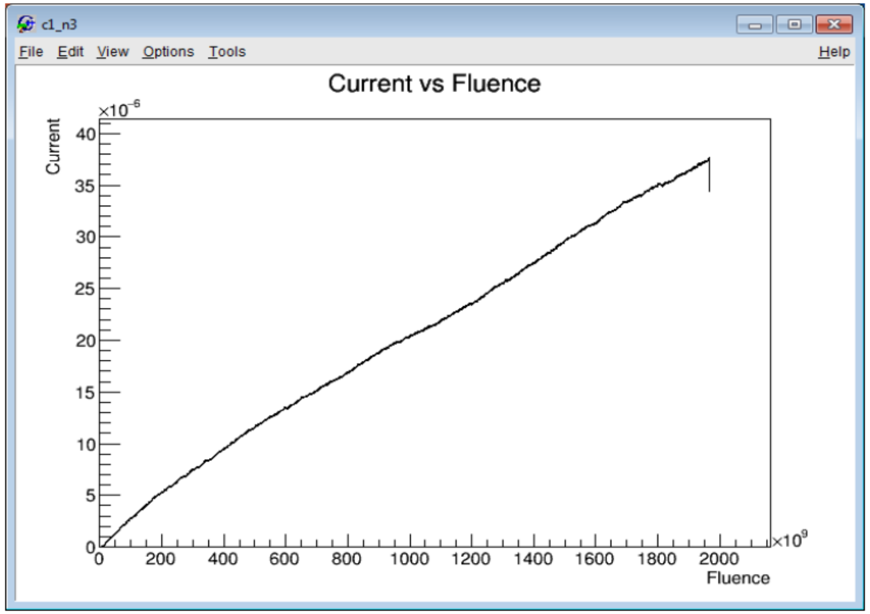
I_{dark} vs. Time, T=-30 °C, U=67.0 V (dVB=4.76 V)



Bias was set OF and set to 67 V again



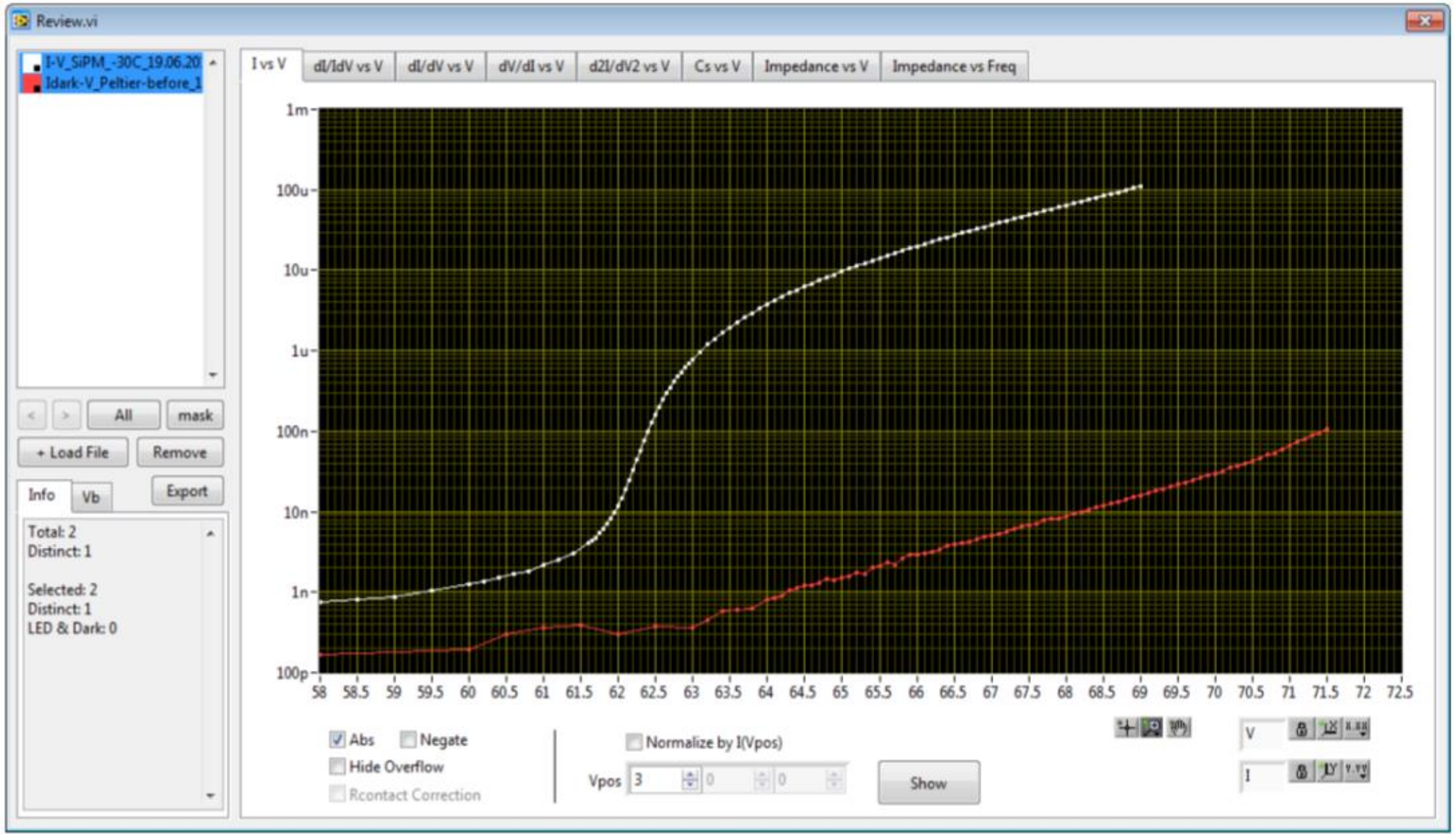
I_{dark} vs. Fluence, T=-30 °C, U=67.0 V (dVB=4.76 V)



HPK 1 mm^2, 15 um cell pitch SiPM (HE/HB type) was irradiated under bias (U=67 V, dVB=4.76 V) in cold **(T=-30 °C, Peltier thermoelectric cooler)** at CERN CHARM irradiated facility up to **2.E12 n/cm^2** (1 MeV neutron equivalent) total fluence. The SiPM dark current was monitored during irradiation.

Dark Current vs. Bias (before/after irradiation, T=-30 C)

I_{dark} vs. Bias (before/after irradiation)

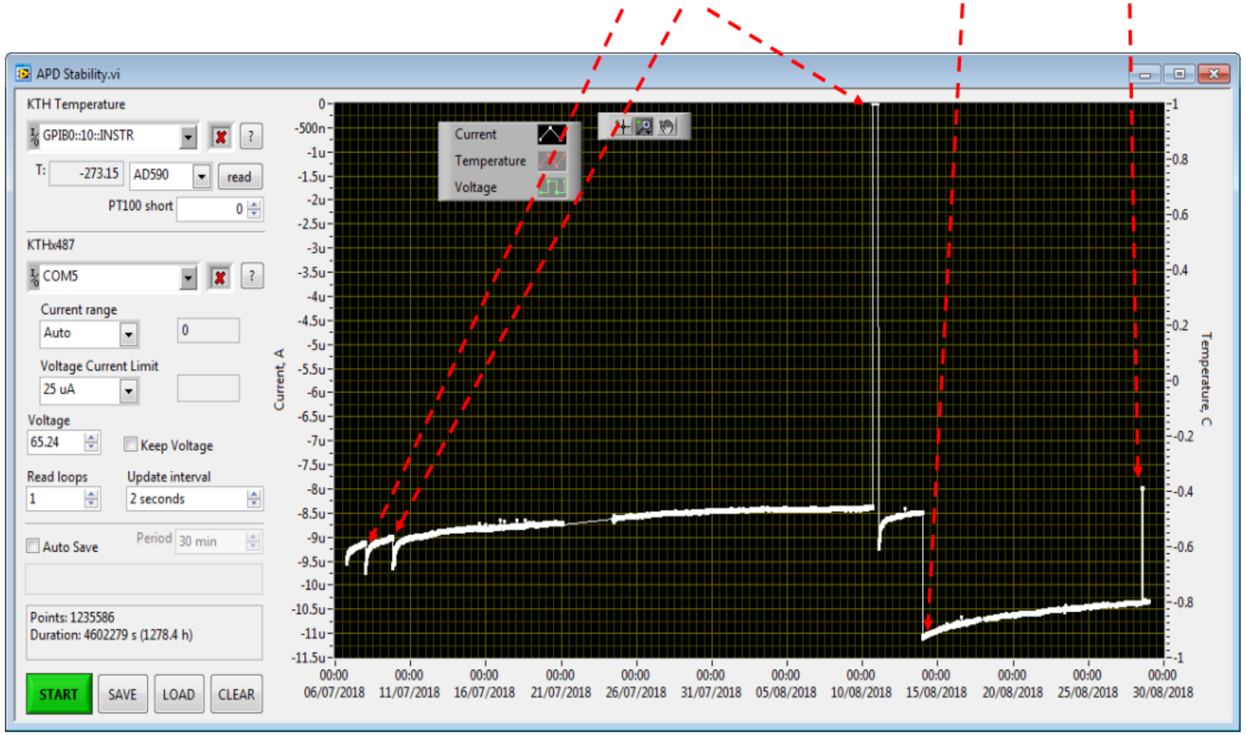


At the end of irradiation Idark=11.7 uA was measured at dVB=3.0 V. This result agrees well with our previous result on the HE SiPM dark currents measured after irradiation at Ljublana reactor (~12 uA after recalculation for the 1 mm^2 area and 2E12 n/cm^2).

Dark Current annealing at T=-30 °C and -10 °C

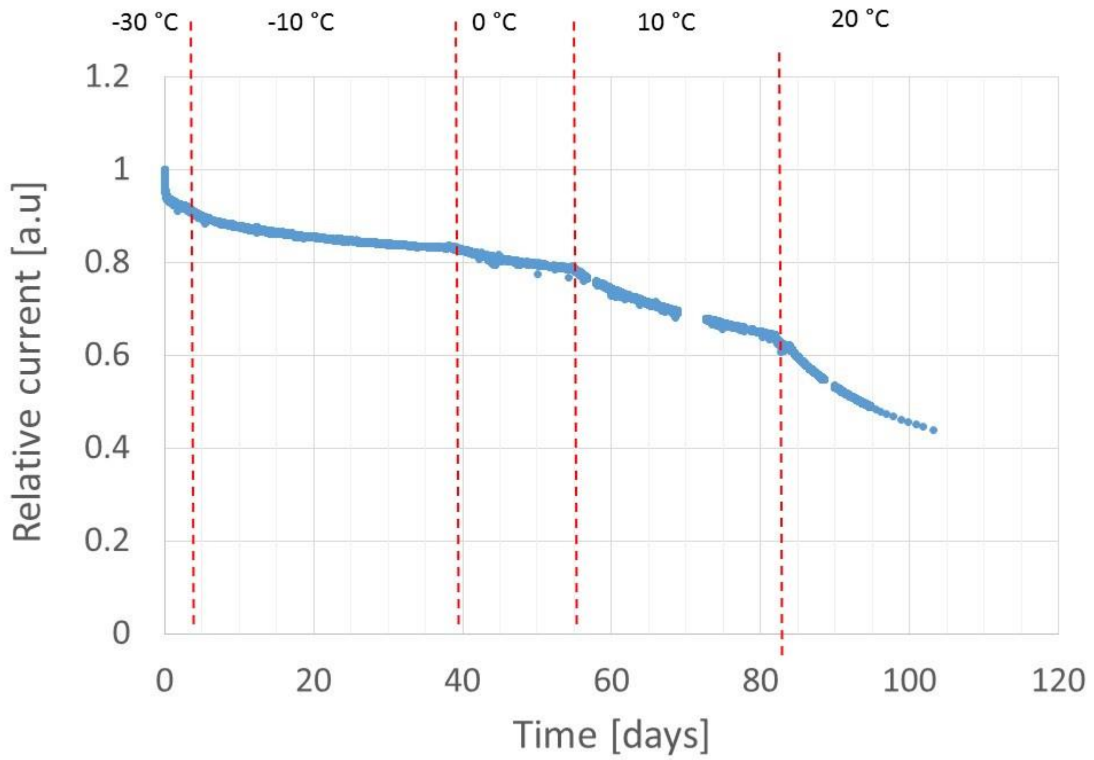
Dark Current annealing at U=65.24 V (T=-30 °C and T=-10 °C)

Bias OFF for short time T=-10 °C T=-30 °C



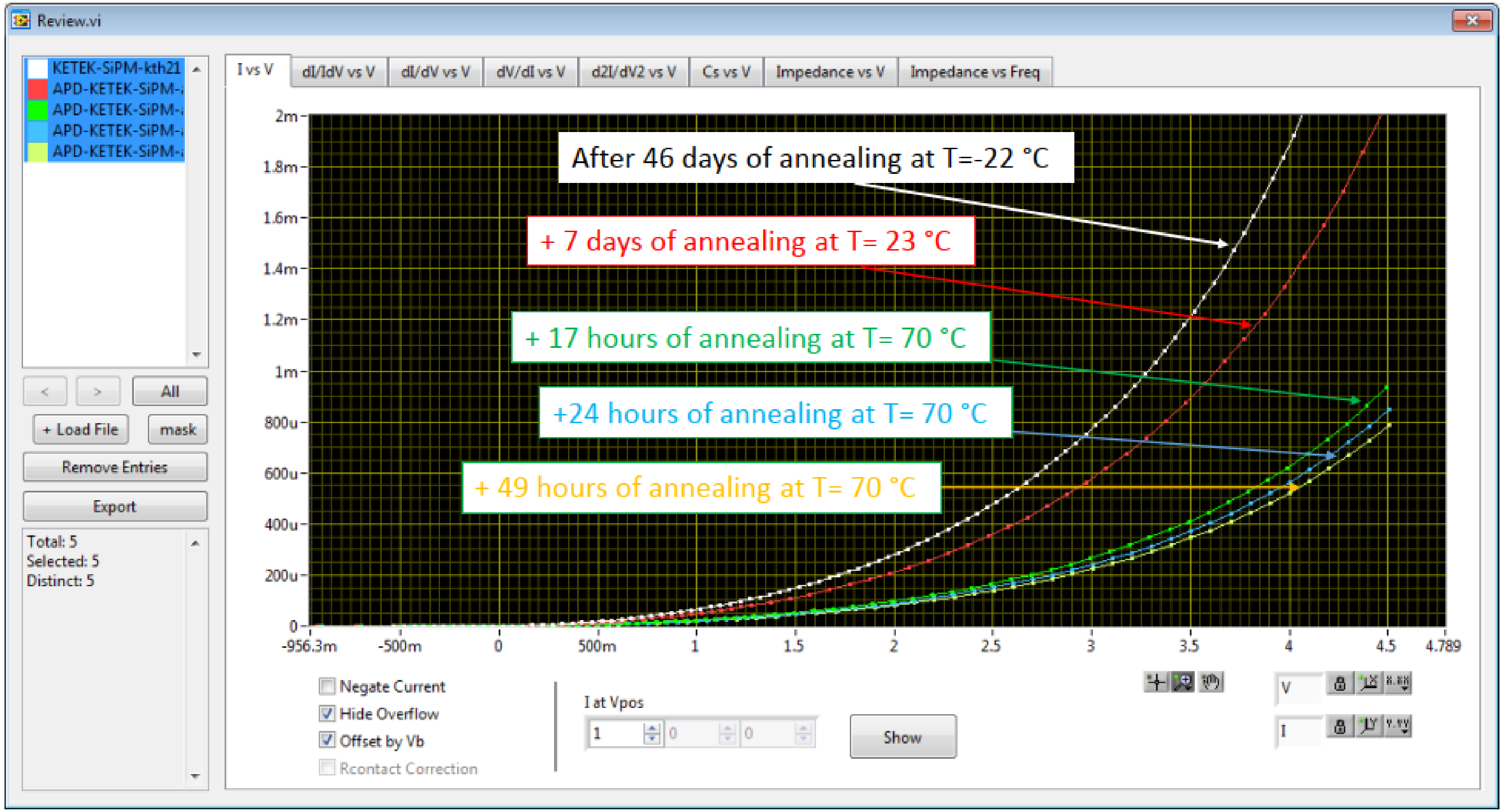
We also studied annealing of the dark current at T=-30 °C during >38 days. Less than 25% of the dark current annealed at this temperature. We increased the temperature up to -10 °C and found another 7% reduction of the dark current after 2 weeks of annealing at this temperature.

Dark Current annealing at T=-30 °C and 20 °C



We calculated relative dark current change with time: ~60 % of dark anneals if temperature changes from -30 °C to +20 °C.

KETEK 2.8 mm dia. (15 um cell pitch) SiPM irradiated at -22 °C with 1.4E12 n/cm2 : accelerated annealing study



Similar result was obtained with the KETEK SiPM irradiated in cold

Approaches to develop radiation harder SiPMs

❖ Dark noise reduction

Optimization of the electric field profile (especially for smaller cell size) to get uniform electric field across the cell (no regions with higher or lower electric field values). Reduction of the maximum electric field value (trap-assisted tunneling, Pool-Frenkel effect), while keeping thickness of the depletion layer thin to reduce generation volume

❖ Cell occupancy reduction

Cell occupancy can be reduce developing SiPMs with small cell size and small recovery time

❖ Power consumption reduction

Reduction of SiPM gain (smaller cell size, smaller cell capacitance) and dark current generation

❖ Breakdown voltage increase minimization

It can be reduced by reducing the thickness of the depletion region. Compromise with the electric field reduction is required.

❖ Reduction of the damage in SiPM entrance window

Optimization of the $SiO_2/S_3N_4/Si$ interface to reduce light losses in an entrance window and avoid trapping in front SiPM layer

❖ Optimization of SiPM package

Package of SiPM has to allow:

✓ SiPM operation in wide range of temperatures (-50 °C ÷ 200 °C);

✓ Easy heat removal (to reduce SiPM self-heating)

✓ Integrated temperature sensor (can be integrated on the same chip as SiPM)

✓ Integrated heater?

Summary

This review is an attempt to summarize the current knowledge of radiation damage of SiPMs. The main issues with heavily irradiated SiPMs are the increase of dark count rate and Gain&PDE reduction due to high cell occupancy and self-heating effects caused by high currents of irradiated SiPMs. Recently developed SiPMs from several producers demonstrated they ability to operate up to 1E14 n/cm^2. R&D on radiation hard SiPMs continue. Approaches to develop radiation harder SiPMs are defined.

I would like to thank all the people whose slides (shown at PhotoDet-2012, NDIP-2014, PhotoDet-2015, VCI-2016, Elba-2015, 2nd SiPM Advanced workshop-Geneva-2014, CPAD-2016, RICH-2016, IEEE-NS/MIC-2016, INSTR-2017, SENSE-2018, ICASiPM-2018 conferences etc.) are used in this presentation.

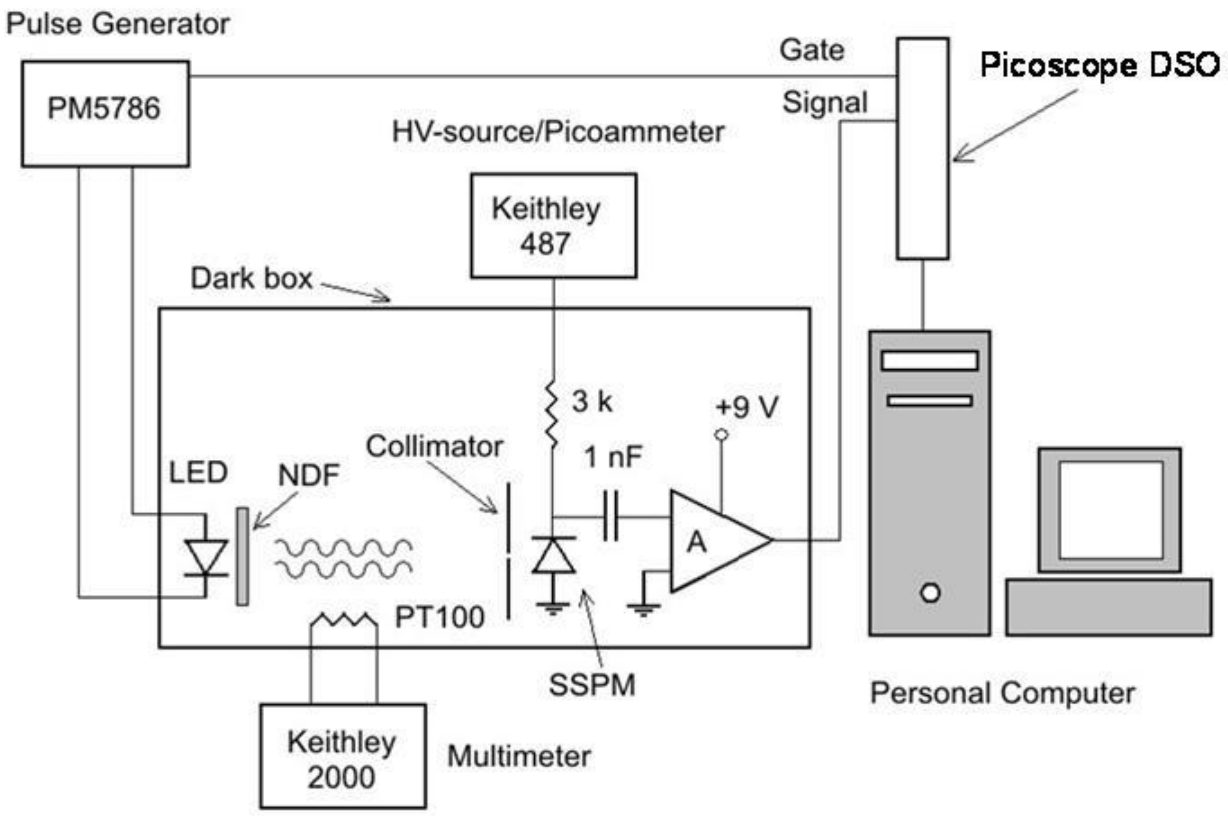
Back-up

Characterization methods for irradiated SiPMs

Set-up (I)

- SiPMs (or XP2020 PMT) are illuminated with the parallel light from LED through 0.7 mm (or 2 mm) diameter collimator
- Light intensity is selected to be in SiPM linear range (<5% non-linearity)
- SiPMs were connected to a fast linear transimpedance amplifier (gain~50)
- Average pulse amplitude (in photons) is measured using calibrated XP2020 PMT
- Mechanical system allowed precise positioning (<50 μm) of the SiPM and PMT in all 3 dimensions
- SiPM can be easily replaced with the XP2020 PMT for light calibration
- LED with the peak emission of 300 nm – 670 nm can be used in these measurements
- LED spectral response is measured using @Optometrix@ monochromator
- Temperature - monitored using Pt-100 resistor
- Currents were measured using Kethley-487 source-meter
- Drop of the bias voltage due to HV resistor (1.9 kOhm) is corrected using values of dark current during this measurement
- Signals (50 k – 100 k of waveforms) are digitized by Picoscope 6404D DSO, BW=500 MHz, 5Gs/sec, 2 Gb
- Labwiev based software to run DAQ and analyze data

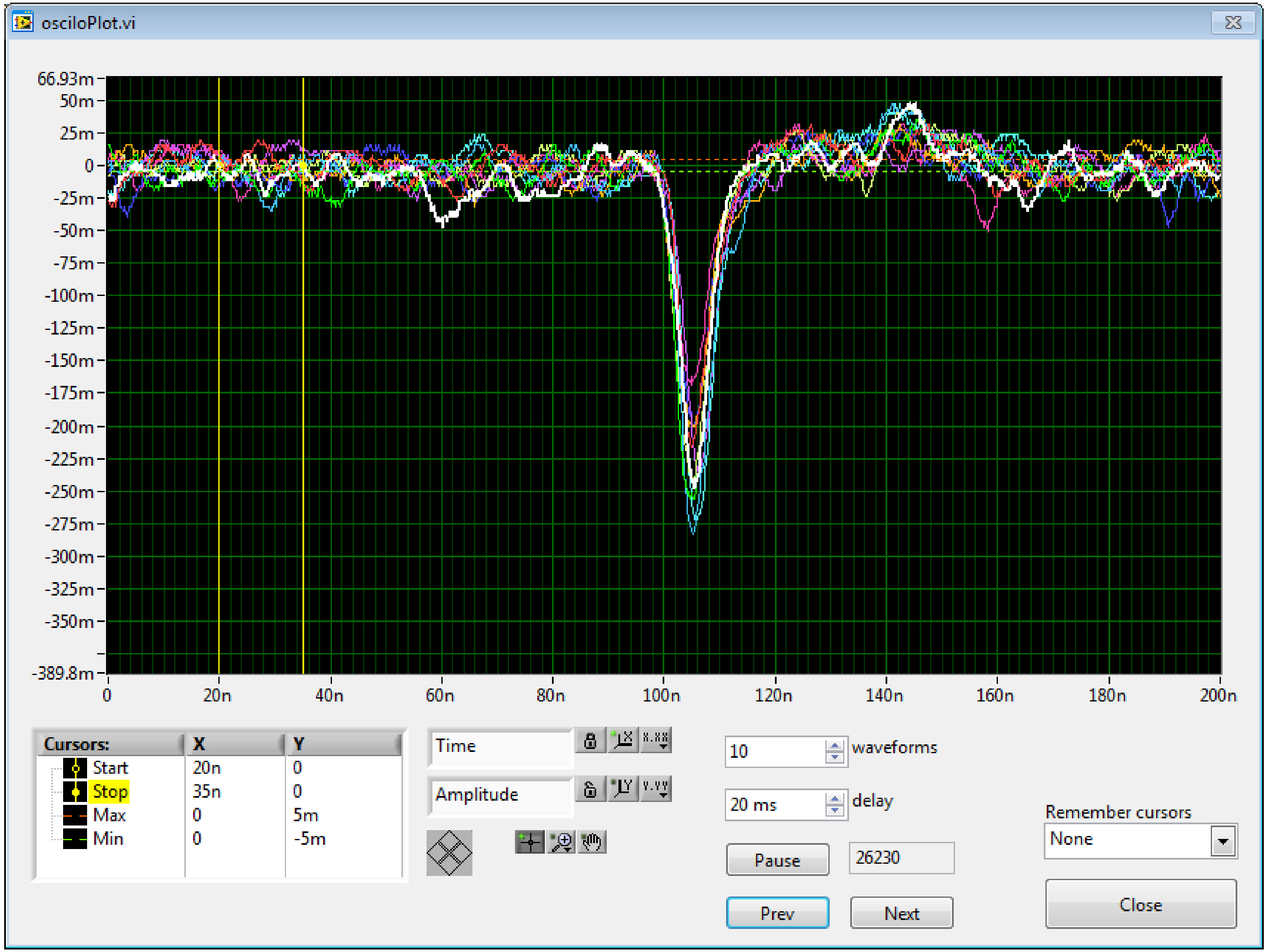
Set-up (II)



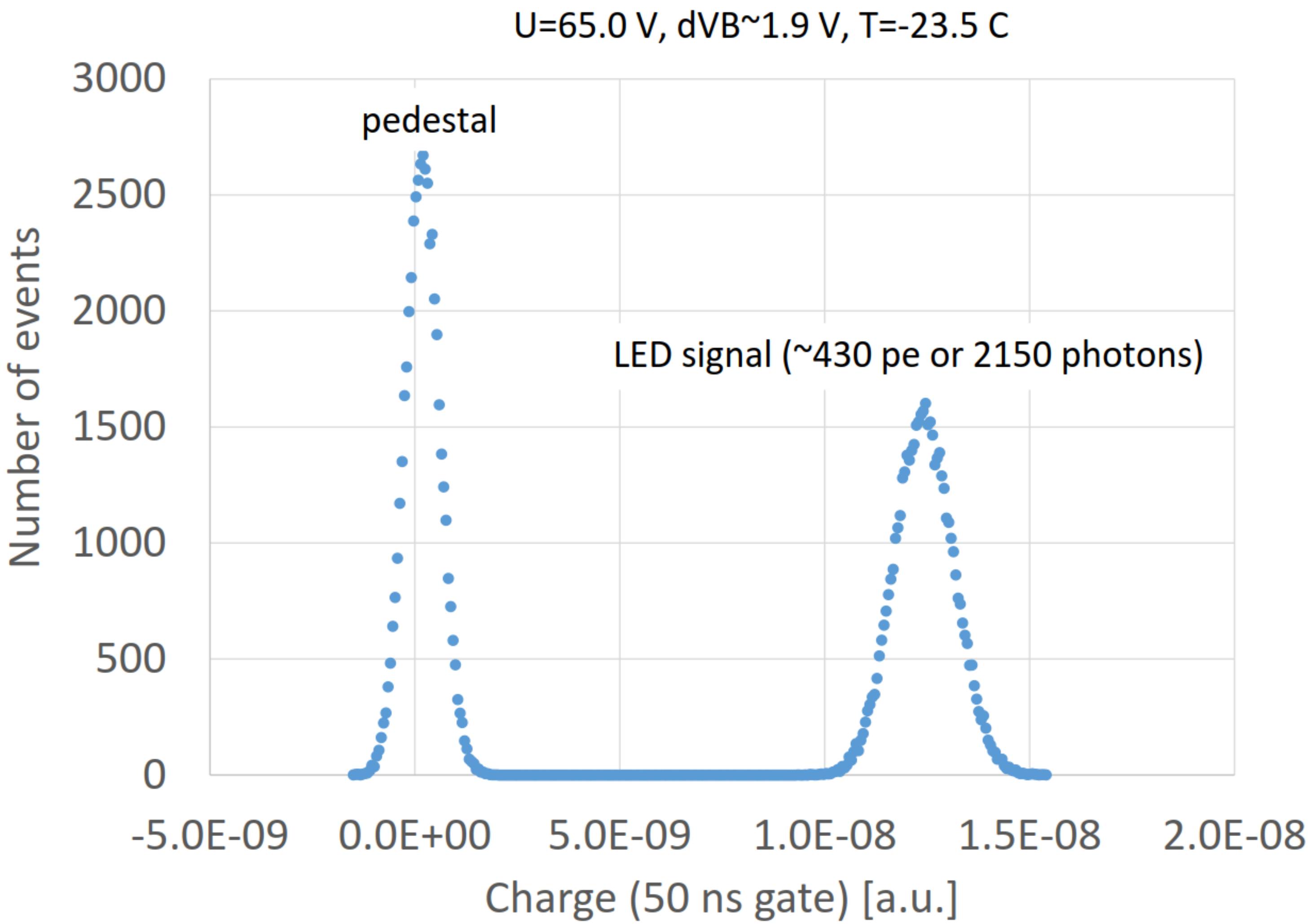
Pulse Generator
PM5786
Gate
Signal
Picoscope DSO
HV-source/Picoammeter
Keithley
487
Dark box
3 k
+9 V
Collimator
1 nF
LED
NDF
A
PT100
SSPM
Personal Computer
Keithley
2000
Multimeter

DSO measurement (Signal)

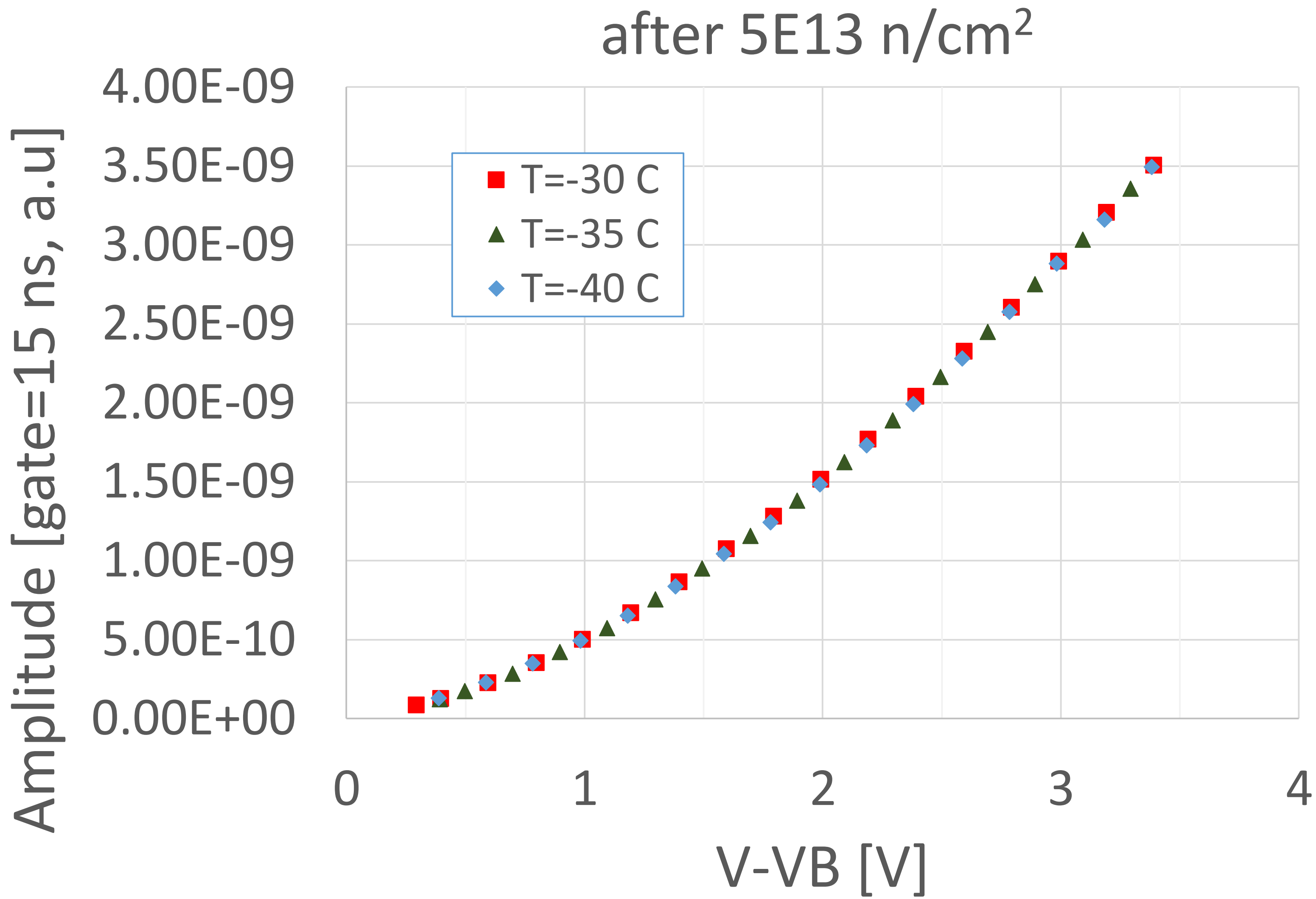
DSO measurement (pedestal)



Example of measured LED spectra and pedestal



Amplitude (a.u.) vs. dVB (determined using maximum dln(I)/dV method



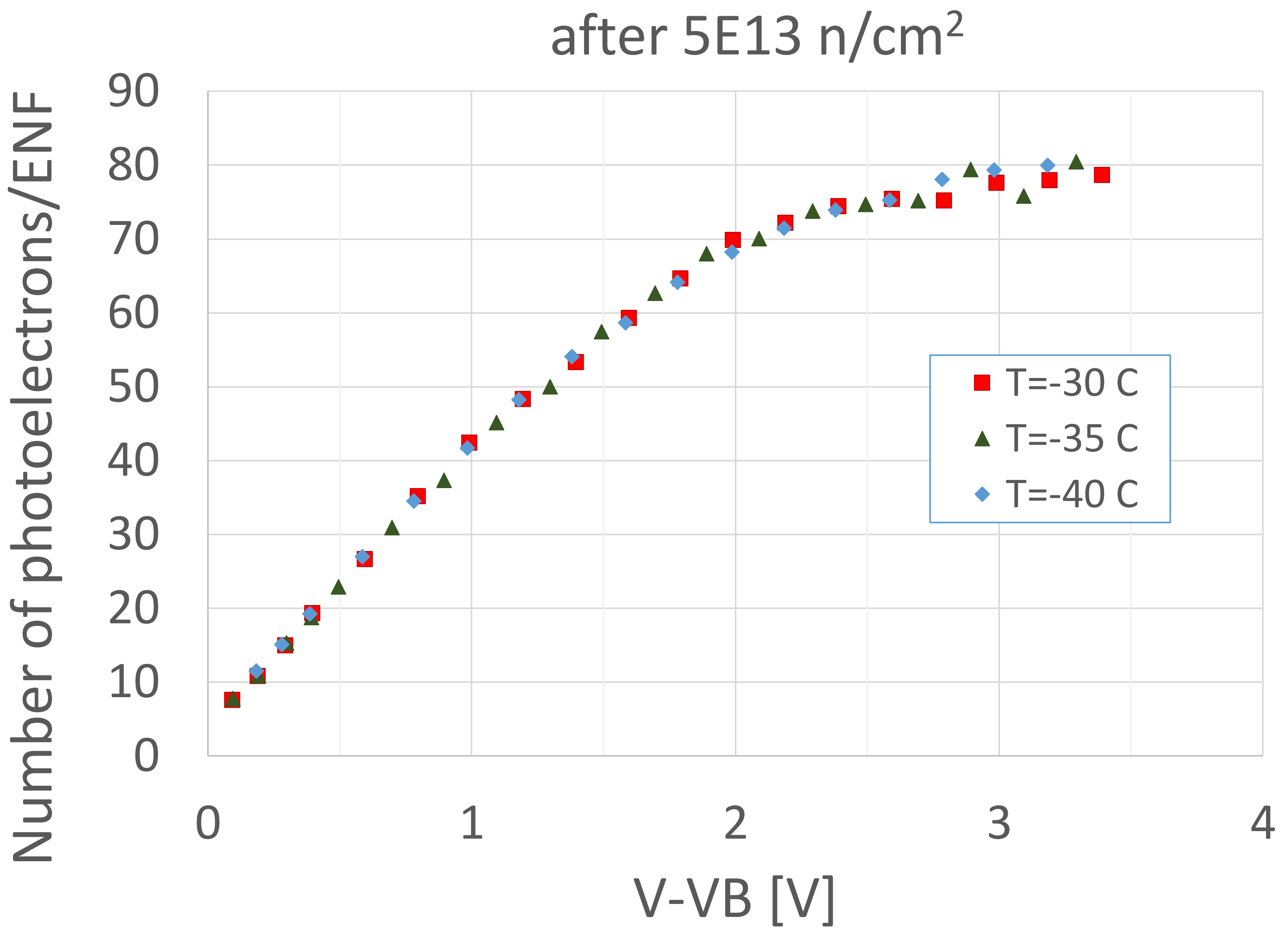
PDE* calculation

- Average number of photons in LED pulse is measured using XP2020 calibrated: PMT (QE(410 nm)=25.0 %, ENF=1.15), 100 k of waveforms recorded by DSO: N_γ
- Replace PMT with SiPM+amplifier
- Record ~ 50 k of waveforms for dVB= -1V ÷ +5 V, step 0.1 V ÷ 0.2 V
- Calculate average signal amplitude (A), signal rms (rms(A), pedestal (P), pedestal rms (rms(ped))
- Number of photoelectrons/ENF is calculated using Poisson statistics:

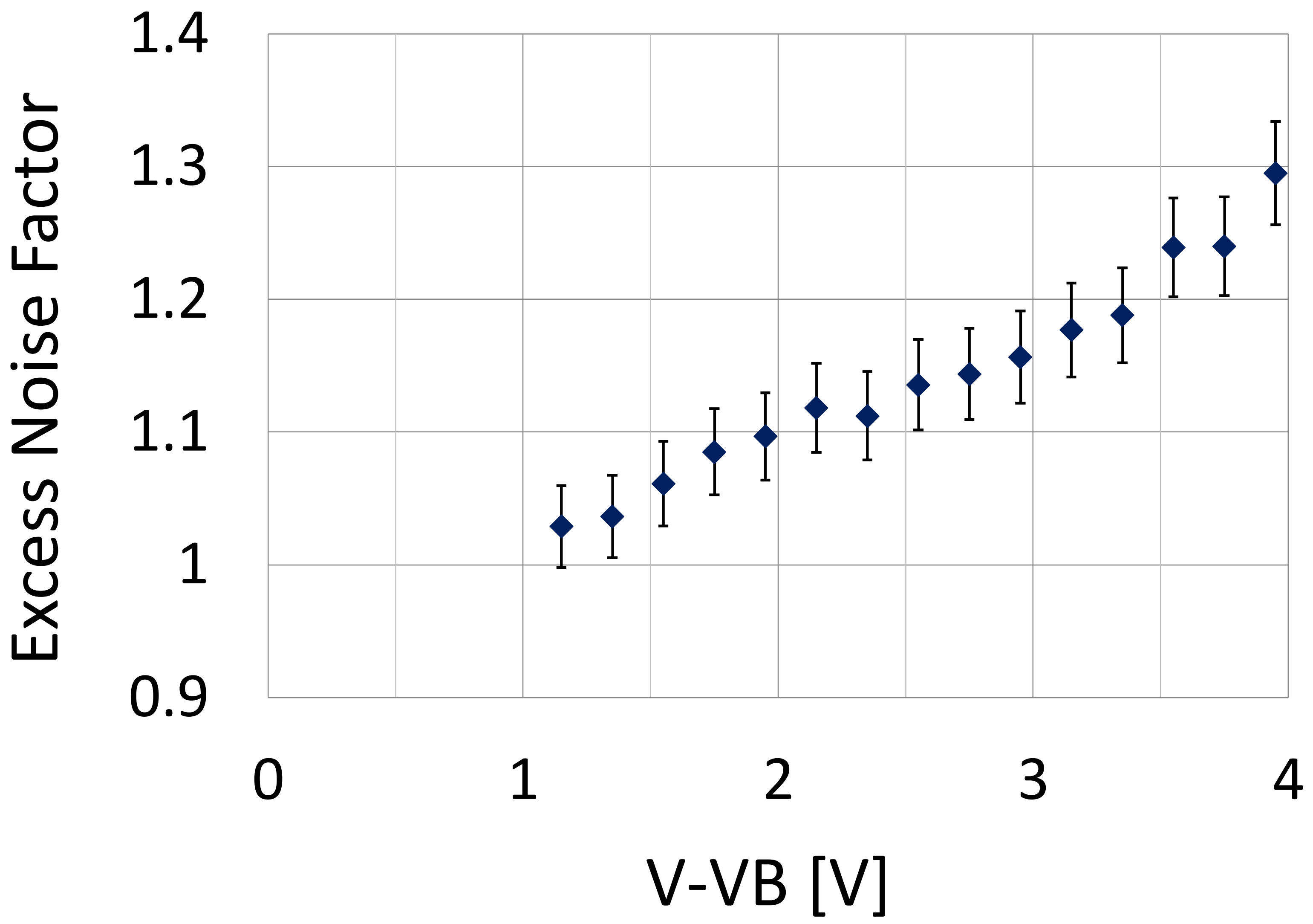
  $N_{pe}/ENF=(A\text{-}ped)^2/(rms(A)^2\text{-}rms(ped)^2)$
- PDE* is calculated using:

  $PDE^*=PDE/ENF= (N_{pe}/ENF)/N_\gamma$

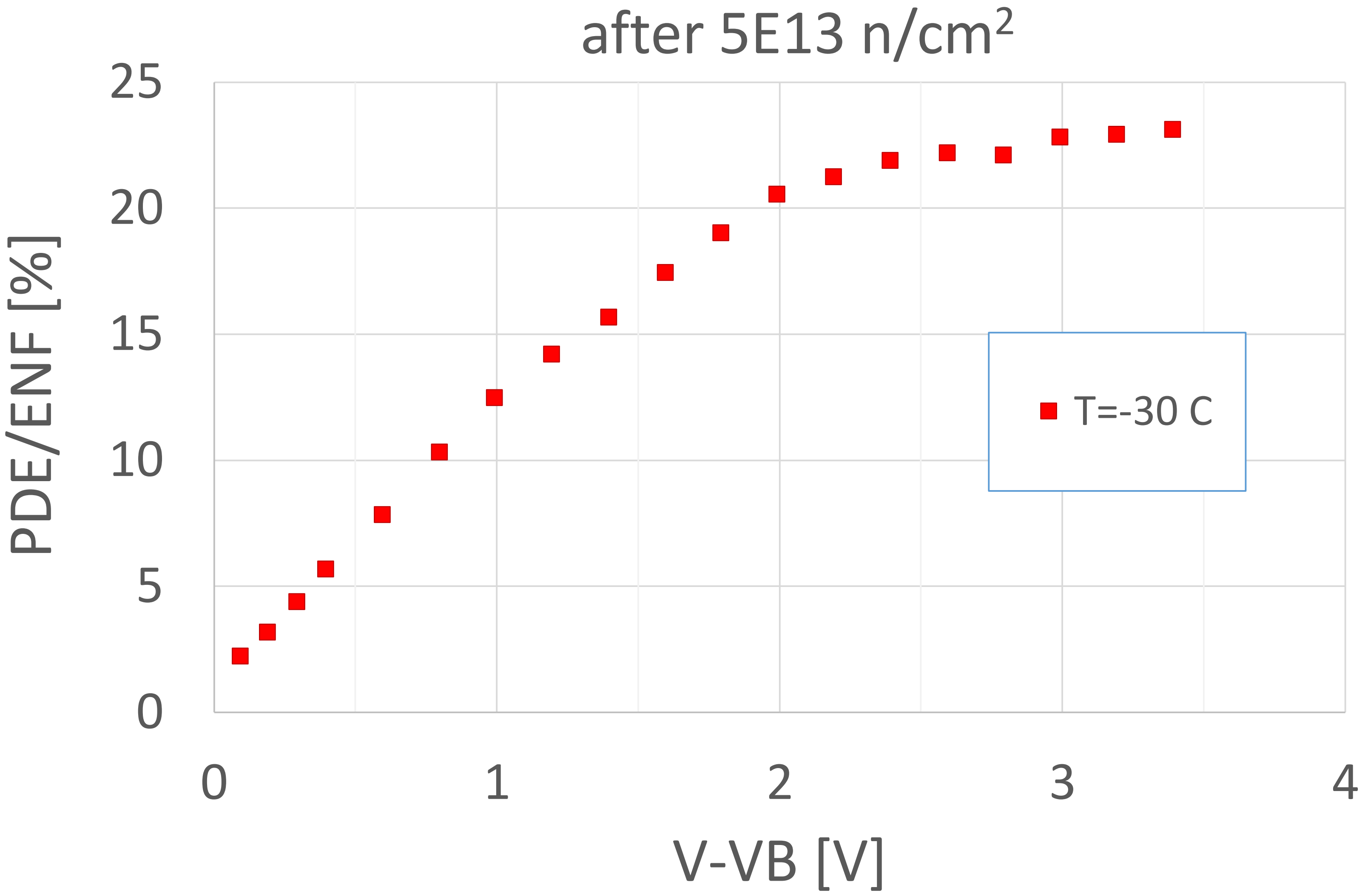
Number of photoelectrons



HE SiPM: ENF vs. dVB before irradiation



PDE* vs. dVB



Equivalent Noise Charge (ENC*) - calculation

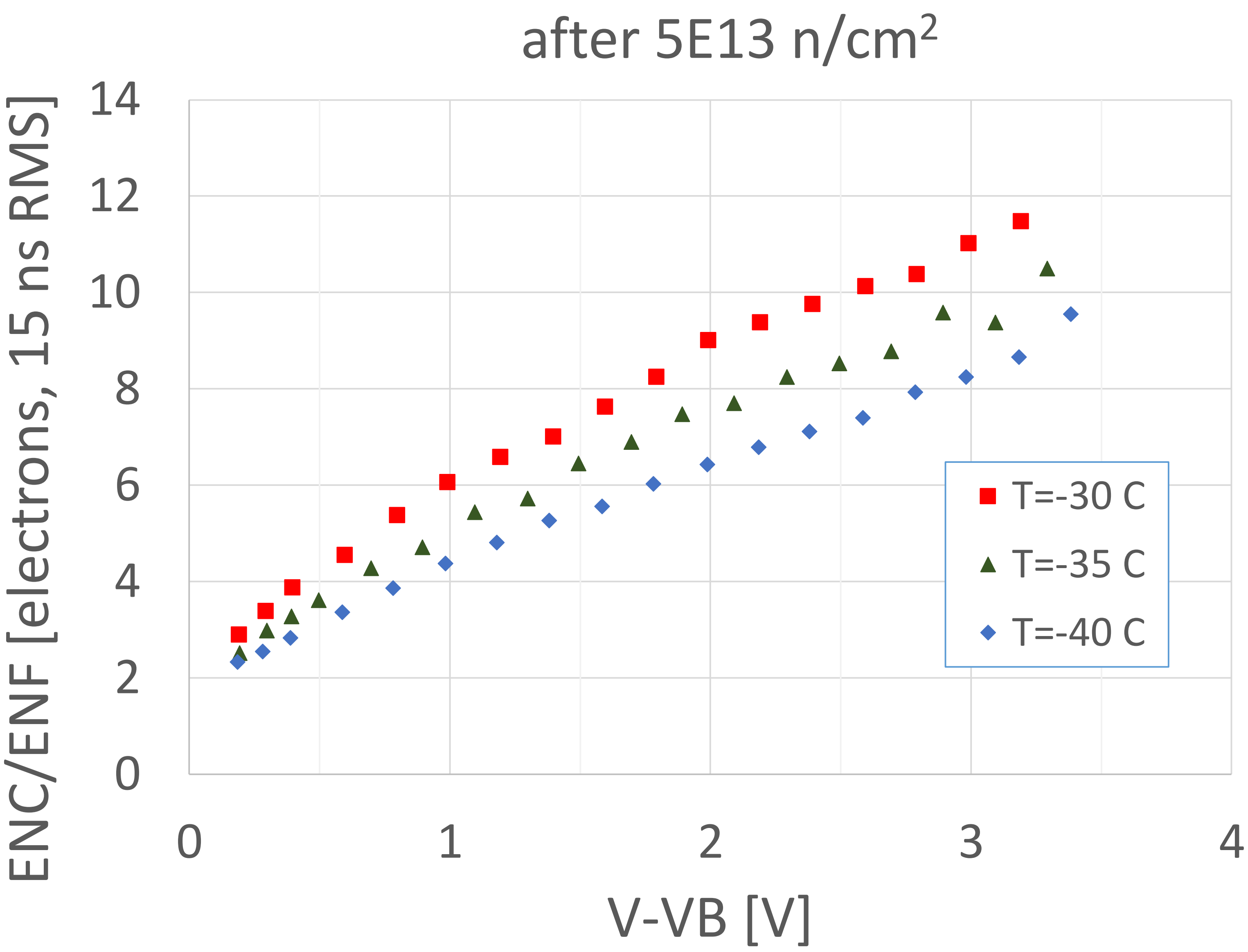
- Calibration of amplitude scale in (photo)electrons (k_{pe}) for each SiPM voltage:

$$k_{pe}(V)=(N_{pe}(V)/ENF(V))/(A(V)-ped(V))$$

- ENC* calculation:

$$ENC^*(V)=ENC(V)/ENF(V)=rms(ped)(V)^*\ k_{pe}(V)$$

ENC* vs dVB

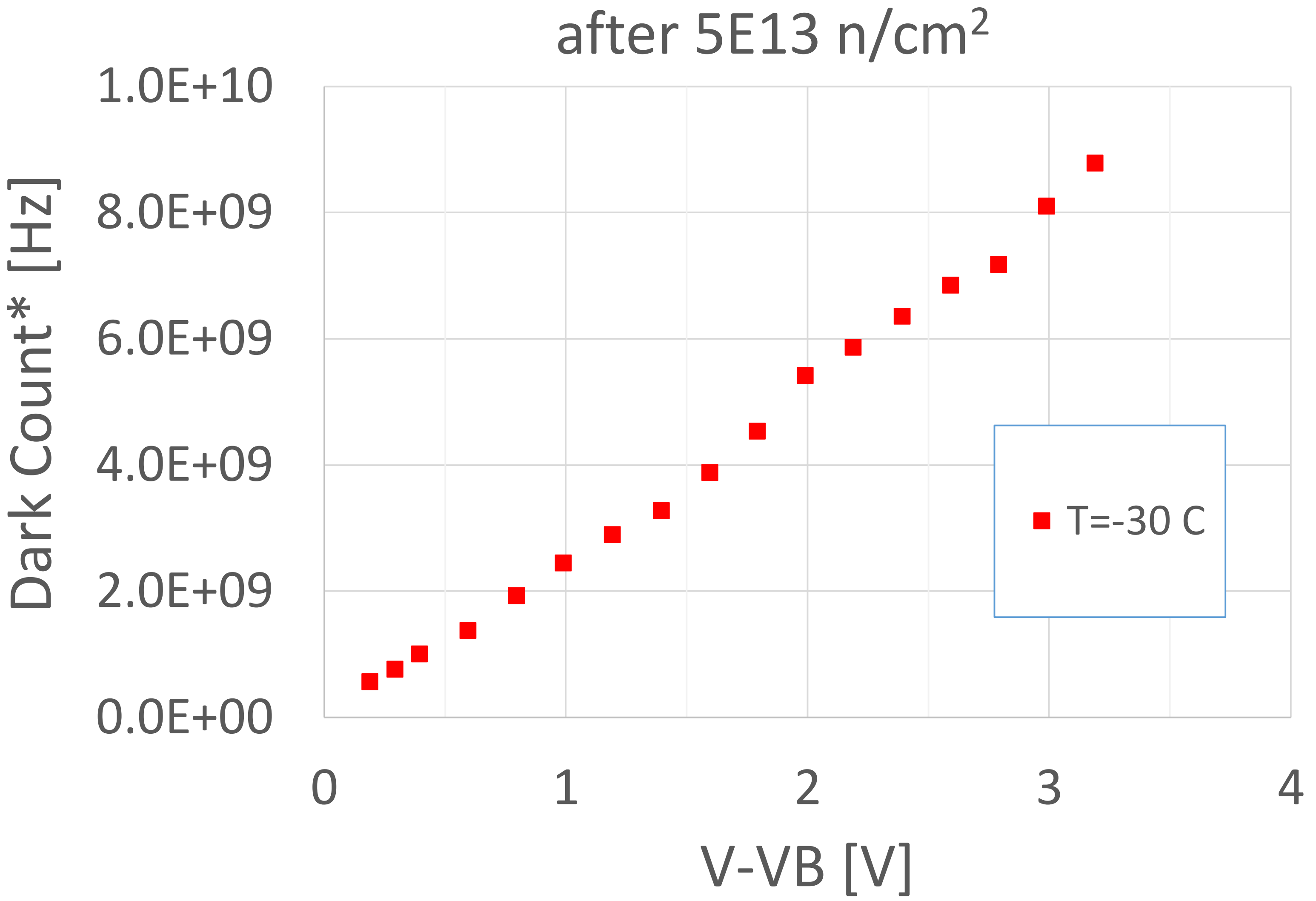

after 5E13 n/cm2
ENC/ENF [electrons, 15 ns RMS]
14
12
10
8
6
4
2
0
0
1
2
3
4
V-VB [V]
T=-30 C
T=-35 C
T=-40 C

Dark Count* - calculation

Dark count is calculated using simple Poisson assumption: measured noise is produced by independent dark pulses of the same amplitude. Then:

$$\text{Dark Count}^* = \text{ENC}^{*2}/\text{Int. time}$$

Dark Count* vs. dVB



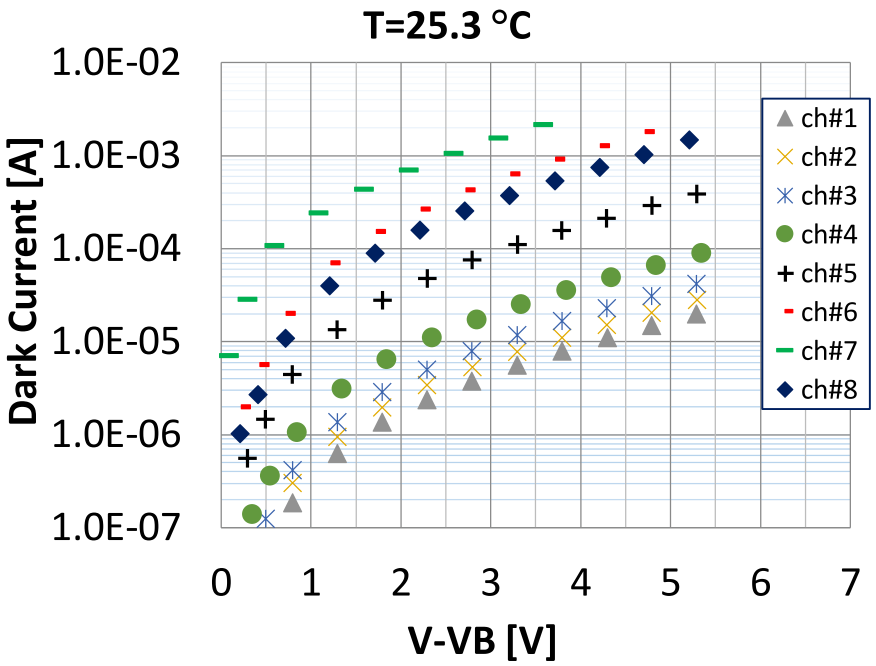
Does ENF changes with irradiation?

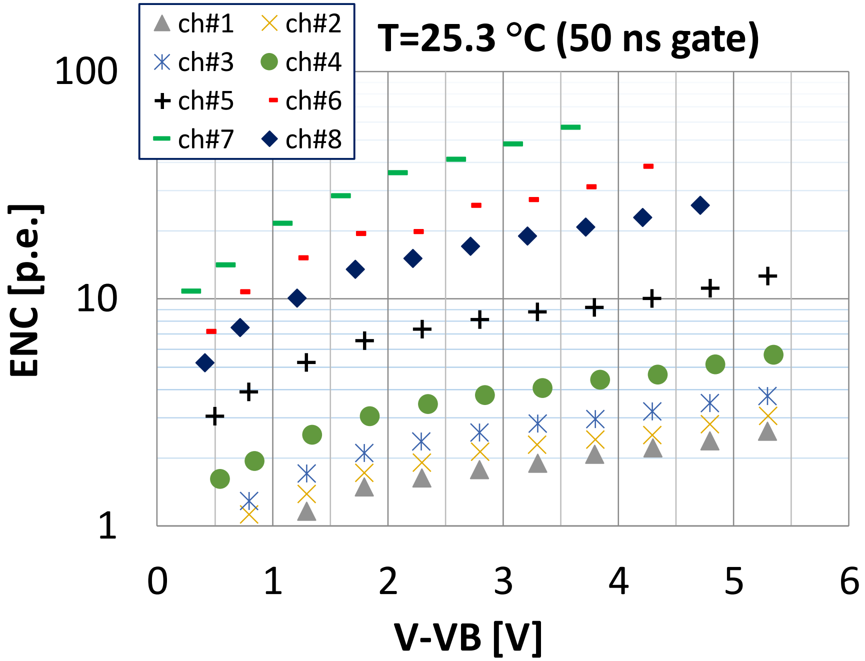
- HE arrays(8 channel) was irradiated in the IRRAD facility at CERN with 24 GeV protons
- Dosage was independently monitored using APDs
- Dosage across each array was position dependent due to the profile of the beam – this effect is very evident in the data
- Peak dosage of nearly 5E12 neutrons/cm^2 (ch# 7)

Estimated dose per channel number – Array 35

ch#	Fluence, n/cm^2
1	2.33E+10
2	3.42E+10
3	5.21E+10
4	1.12E+11
5	4.82E+11
6	3.05E+12
7	5.00E+12
8	1.70E+12

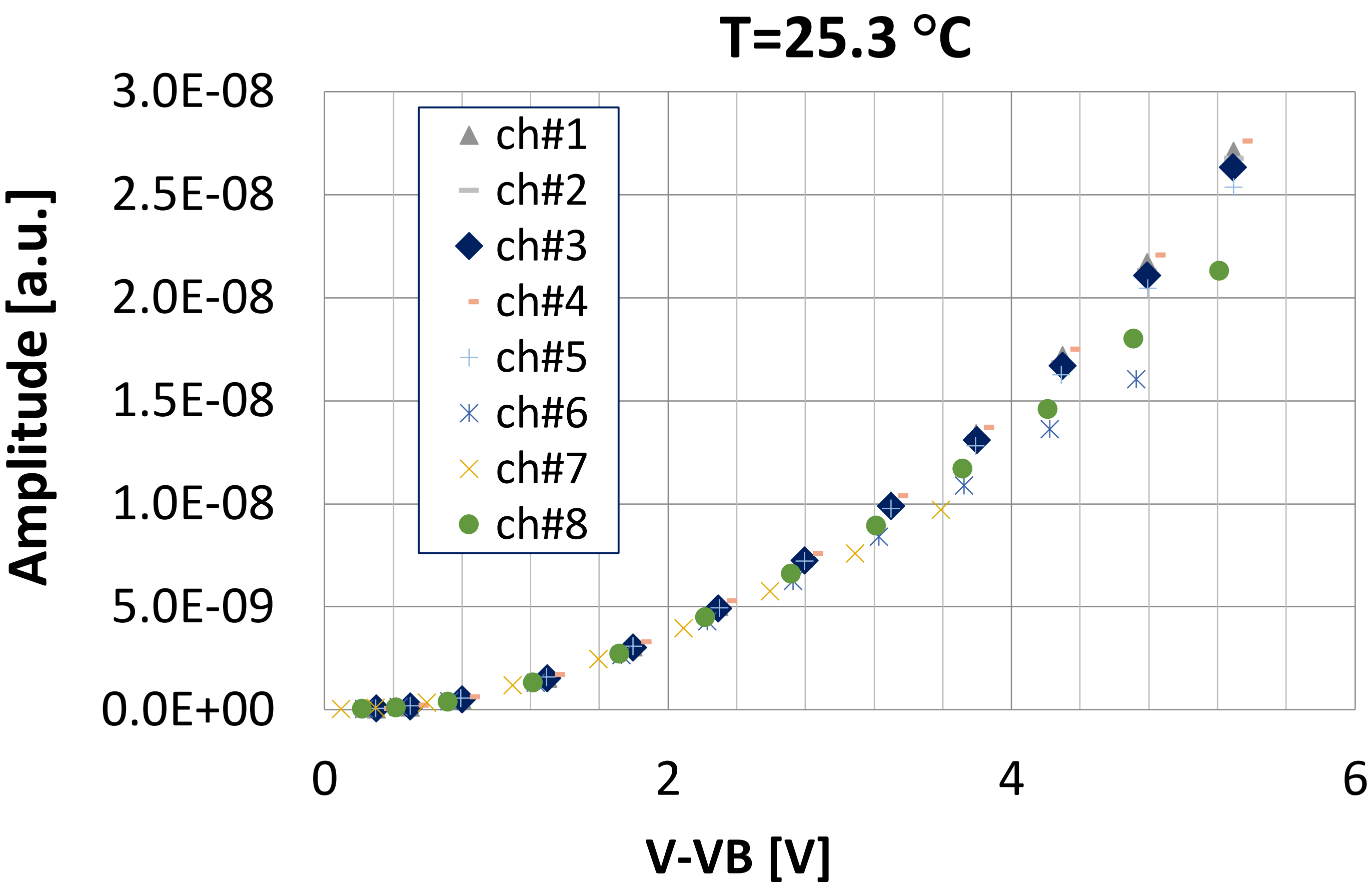
Dark current and equivalent noise charge for each channel after irradiation



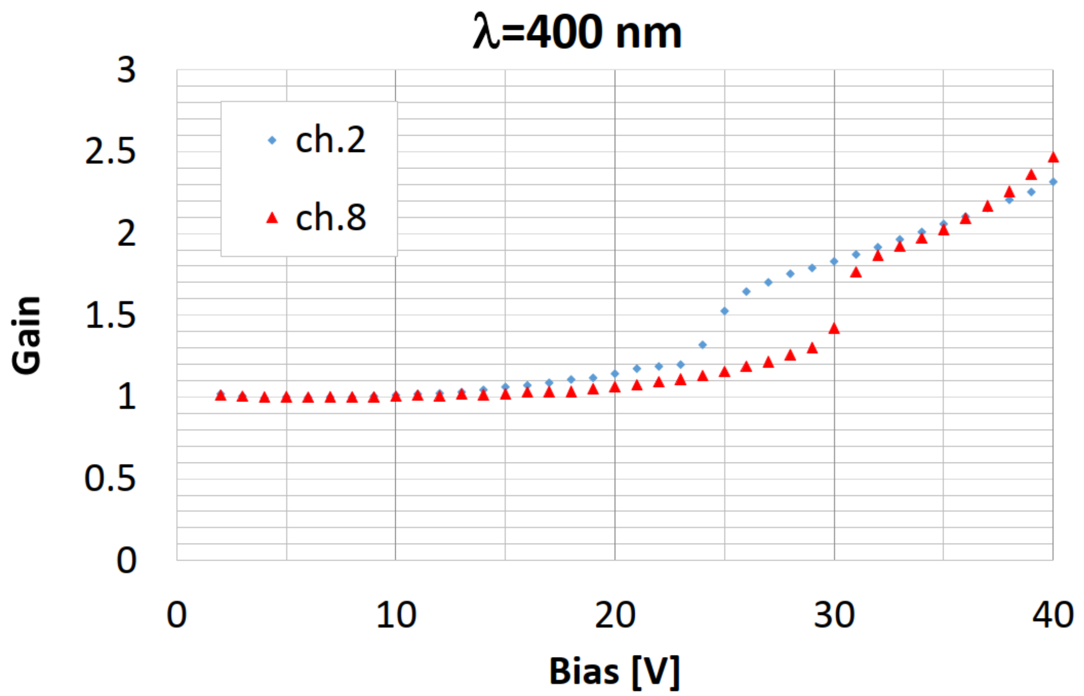


Channel 8 current corresponds to ~5E13 n/cm^2 at T=-30 °C

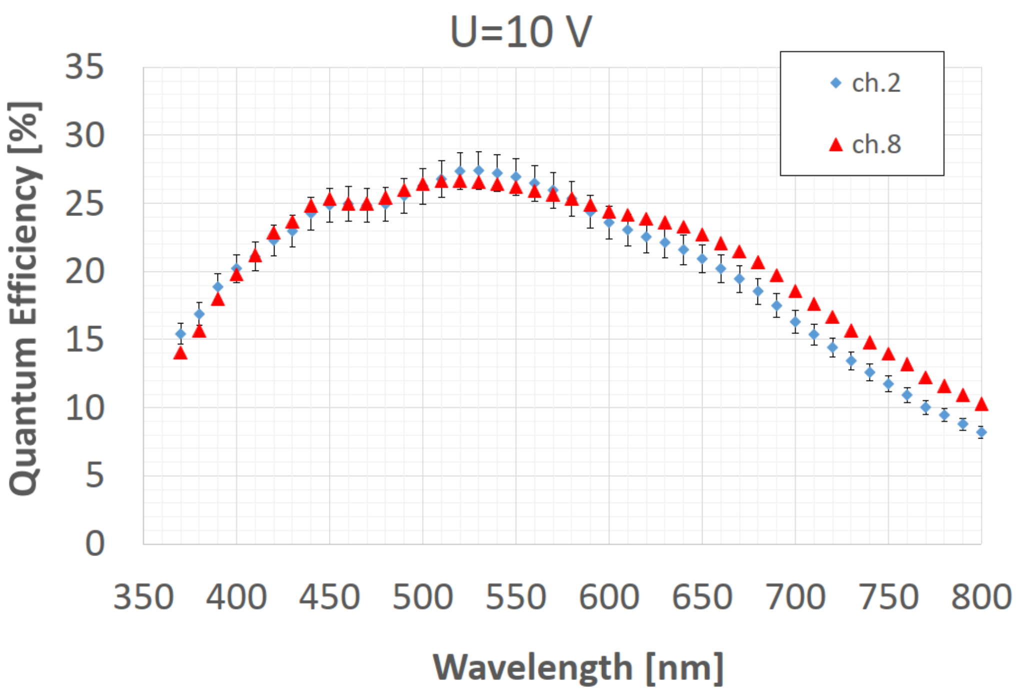
Relative amplitude for each channel after irradiation



T

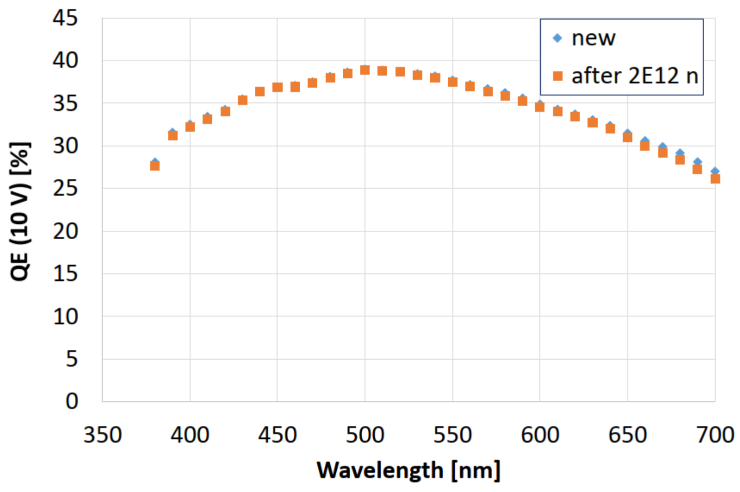


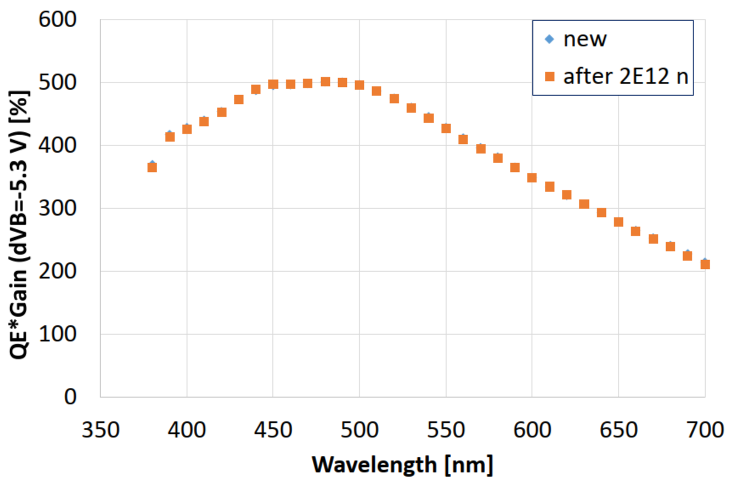
λ=400 nm
Gain
Bias [V]
ch.2
ch.8
0
0.5
1
1.5
2
2.5
3
10
20
30
40

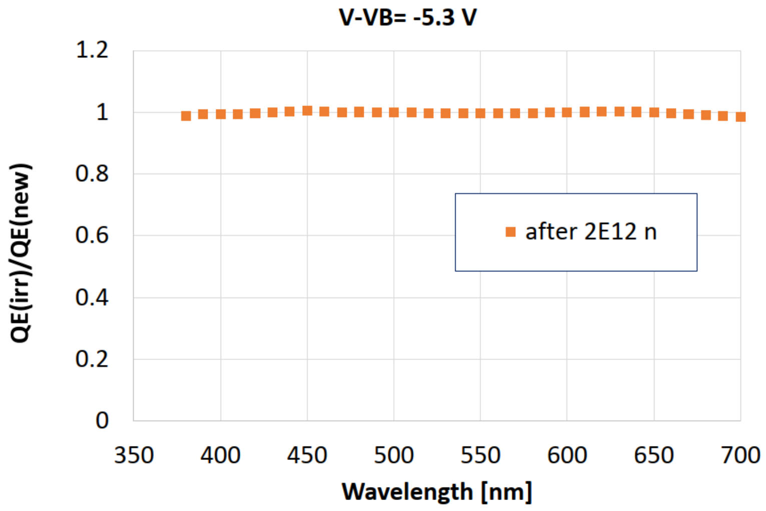


U=10 V
Quantum Efficiency [%]
Wavelength [nm]
ch.2
ch.8
0
5
10
15
20
25
30
35
350
400
450
500
550
600
650
700
750
800

After 2E12 n/cm2







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