Change of SiPM parameters after very high neutron irradiation.

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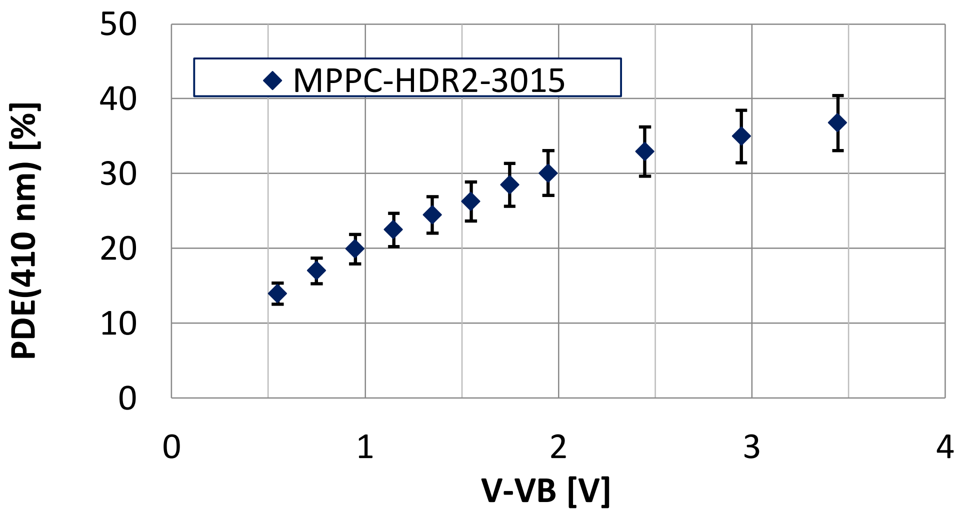
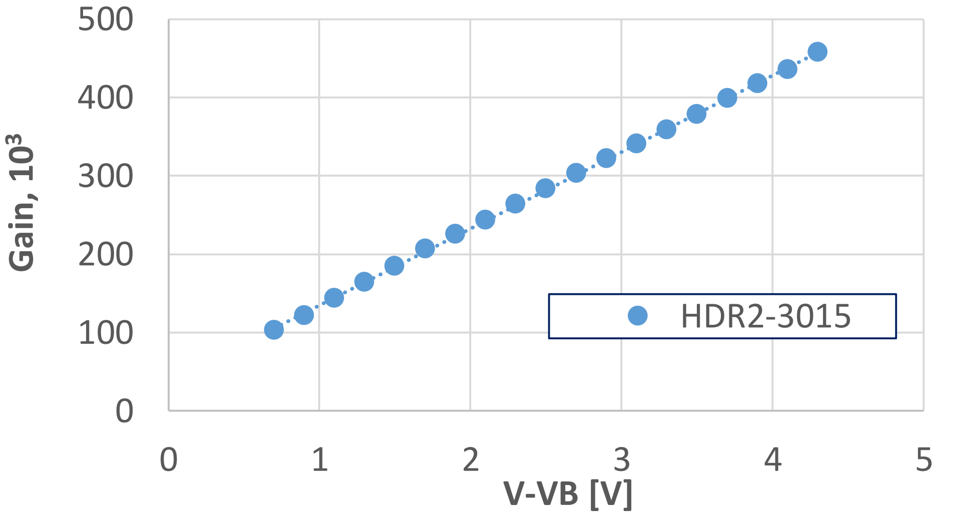
Introduction

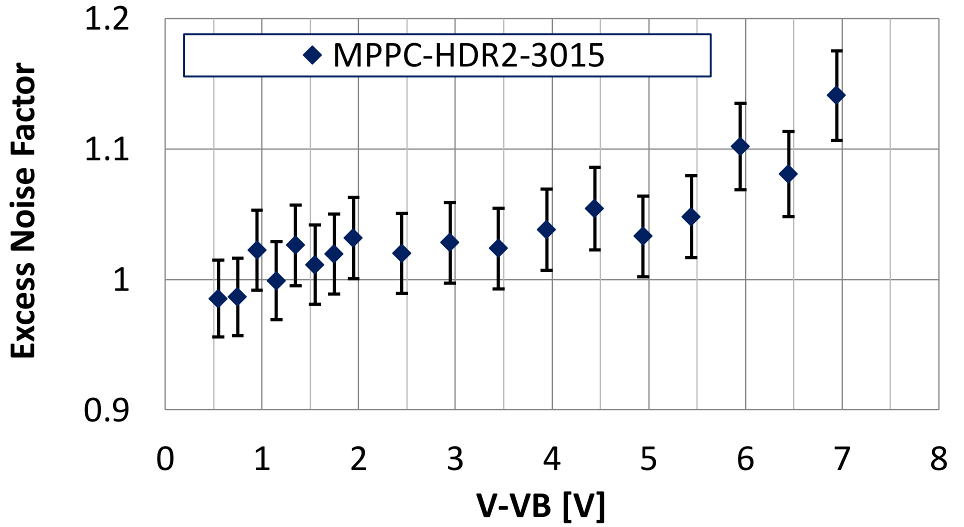
New detectors for the upgrade of the LHC experiments (CMS, LHCB) demand to operate SiPMs up to fluences of $10^{12} \div 10^{14}$ particles/cm^2. The design of the CMS phase II upgrade for the HL-LHC uses SiPMs for the Barrel Timing Layer (BTL) and the High Granularity HCAL detector (HGCAL). In both sub-detectors the SiPMs will see a 1 MeV equivalent dose of around 10^{14} particles/cm^2. To lower the noise in the SiPMs the design is to keep the SiPMs at a low temperature of −30 °C or lower. Recently developed high dynamic range Hamamatsu (HPK) and FBK SiPMs (3x3 mm^2, 15 um cell pitch, ~10 ns cell recovery time) were irradiated with reactor neutrons to a total dose of $2*10^{14}$ particles/cm^2 at the TRIGA reactor at the JSI in Slovenia. After irradiation they was kept in freezer, sent to CERN inside cold box.

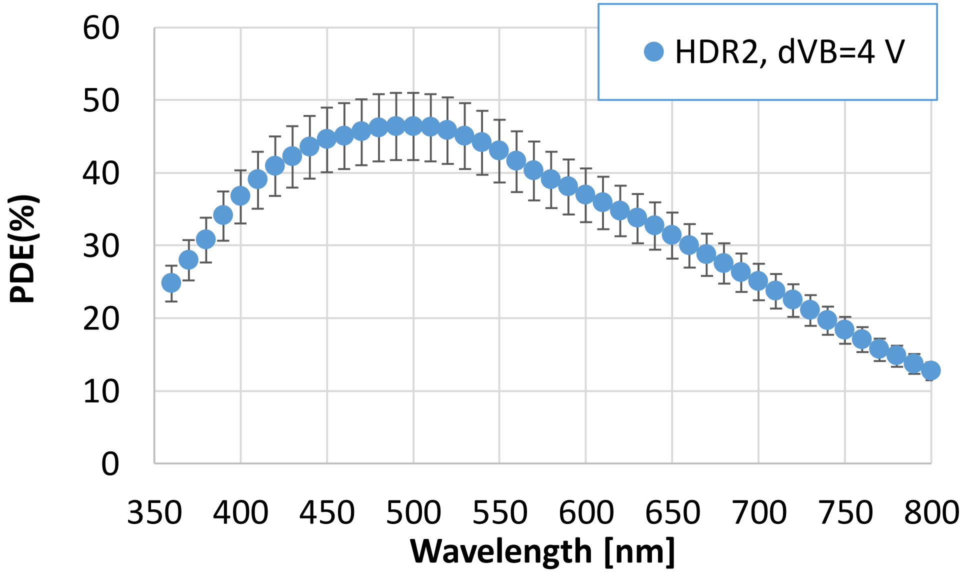
Measurements after irradiation were performed inside freezer (lab. 27) in dark and with LED pulsed and continuous light illumination (450 nm LED, box with temperature stabilization using TEC cooling). The same measurements were repeated with new HPK and FBK SiPMs.

Hamamatsu SiPM parameters before irradiation

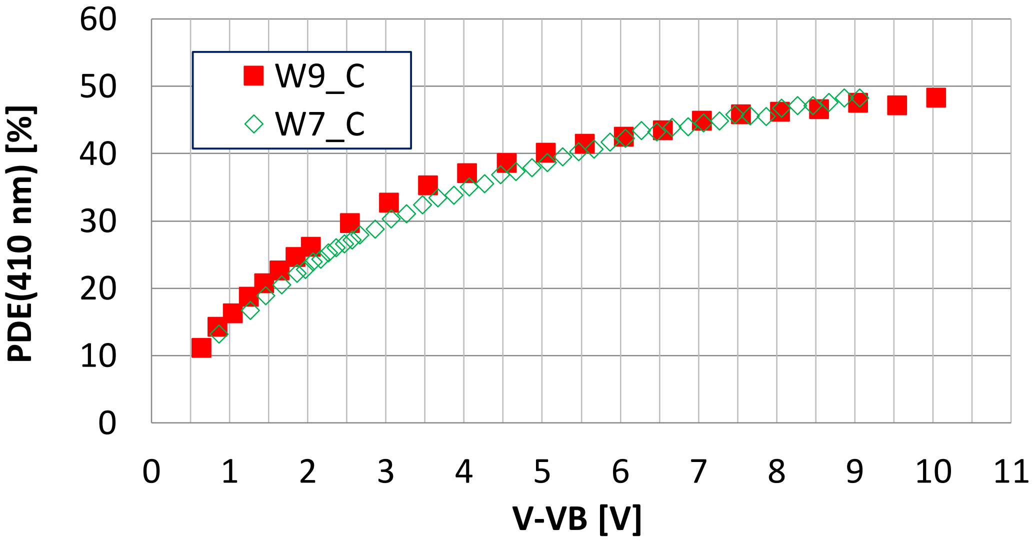


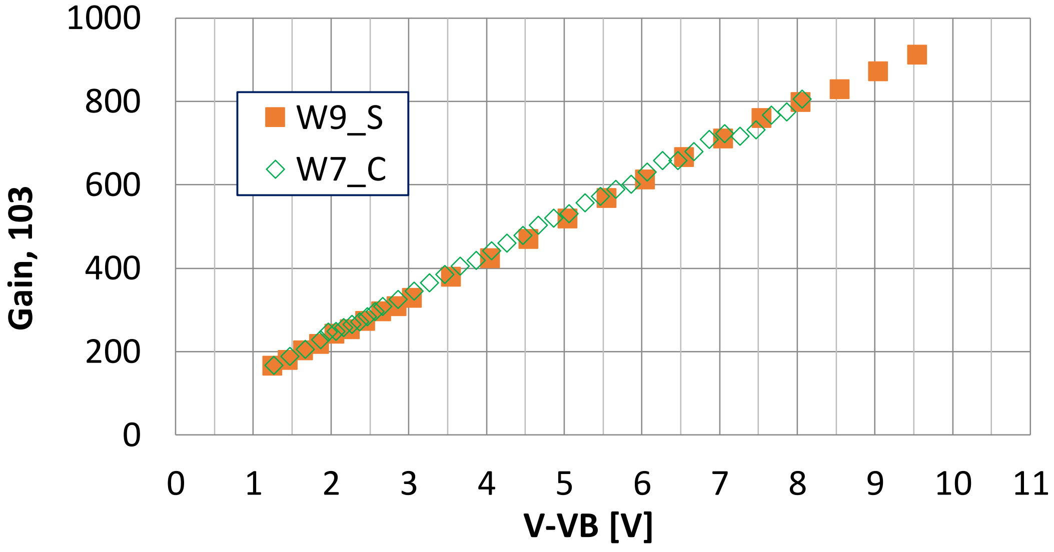


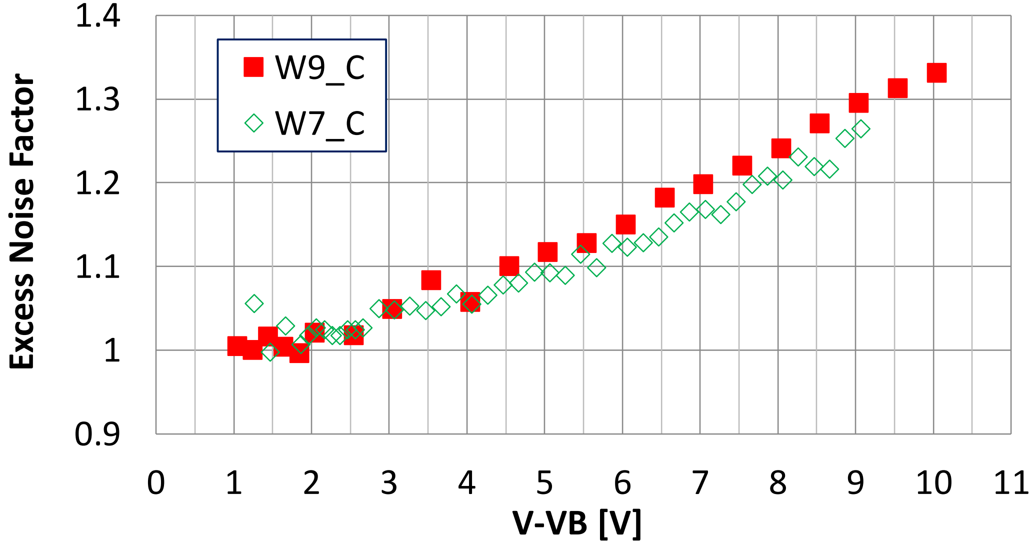


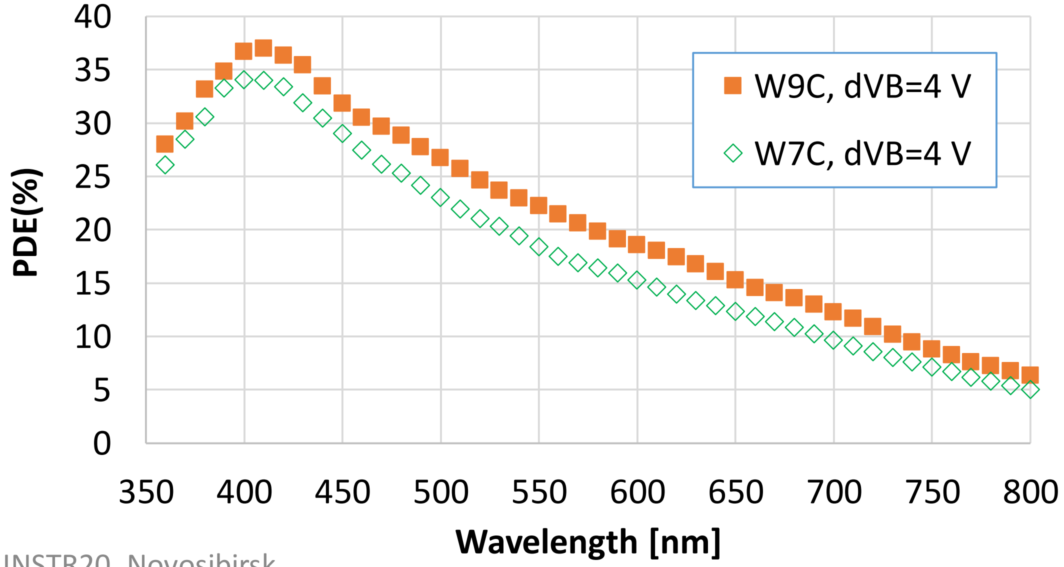


FBK SiPM parameters before irradiation





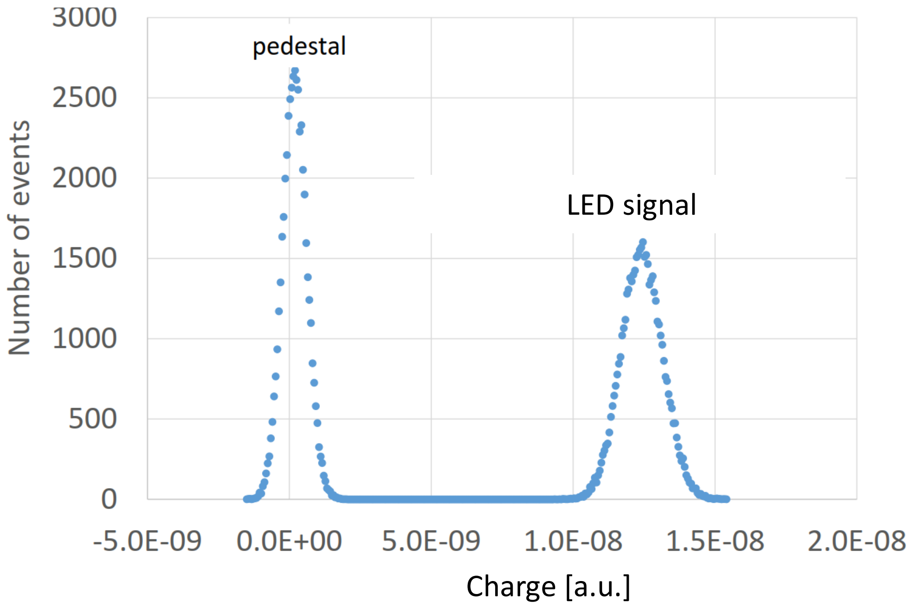




SiPMs: new and after 2E14 n/cm^2. Measurements with the 450 nm LED pulsed and DC light (T=-30 °C and T=-37 °C).

After arrival to CERN SiPMs dark current dependences on the bias were measured at -30 C. After that the SiPM were annealed 80 min at 60 °C. The annealing factor of ~2.1 was measured for all SiPMs. Measurements of SiPM parameters were performed inside freezer in dark and with LED pulsed and continuous light illumination (450 nm LED, box with temperature stabilization using TEC cooling). The same measurements were performed with the new HPK and FBK SiPMs.

Example of measured LED spectra and pedestal



<u>Approach:</u>

Gain and average number of photoelectrons in an LED pulse can be calculated from RMS of the LED and pedestal spectra:

Gain(rms)=<A-ped>/N(rms)/ECF , where N(rms)=ENF*<A-ped>^{2}/(RMS(A)^2-RMS(ped)^2) – average number of photoelectrons in a LED pulse.

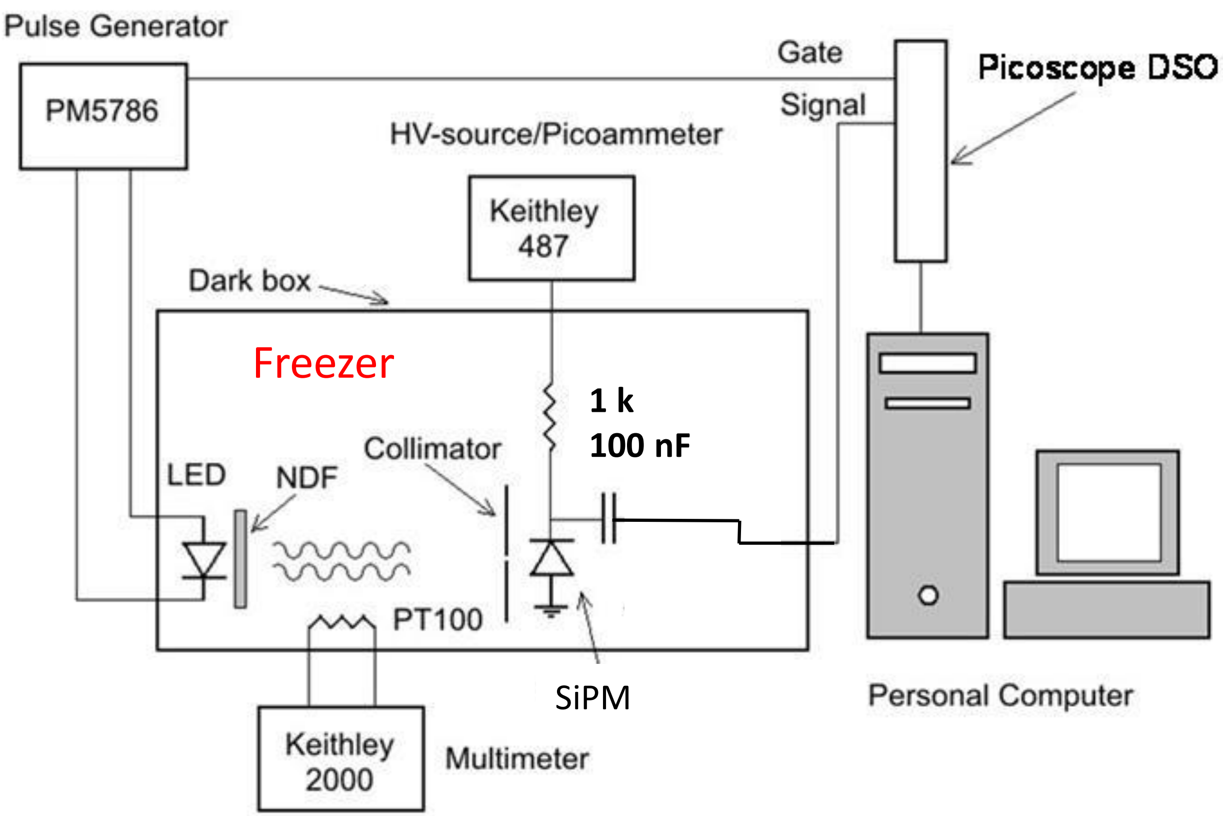
DCR = Idark/Gain(rms)/1.6E-19

ECF=ENF=1 for low dVBs. Amplifier wasn’t used in these measurements.

Measurement set-up

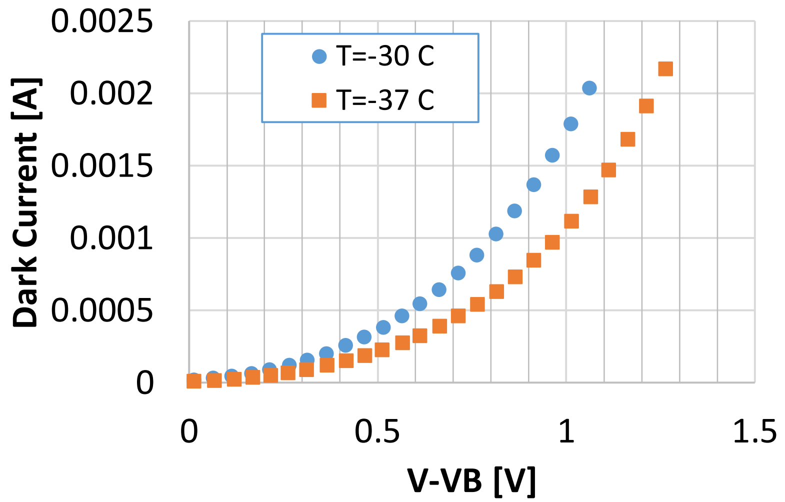
- Measurement box with SiPM was placed inside GFL laboratory freezer (80 l)
- SiPMs were illuminated with parallel light from LED through 2 mm diameter collimator
- Light intensity is selected to be in SiPM linear range (<5% non-linearity)
- Average pulse amplitude (in photons) is measured using calibrated new SiPM
- LED with peak emission of 450 nm was used in these measurements
- Temperature of the measurement box is controlled by TEC and monitored using Pt-100 resistor
- Currents were measured using Kethley-487 source-meter
- Drop of the bias voltage due to HV resistor (1 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 was developed to run DAQ and analyze data

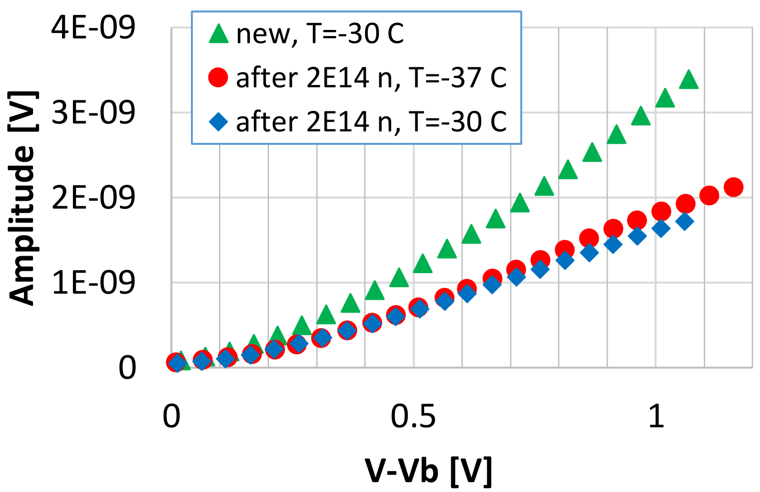
Measurement set-up (II)

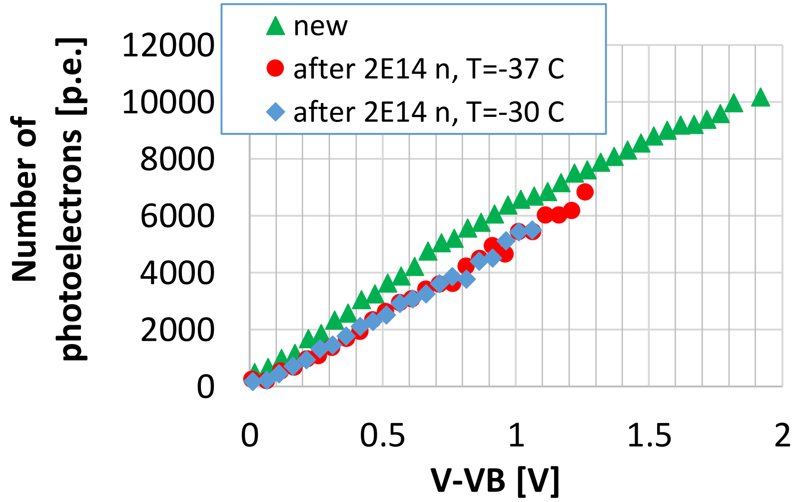


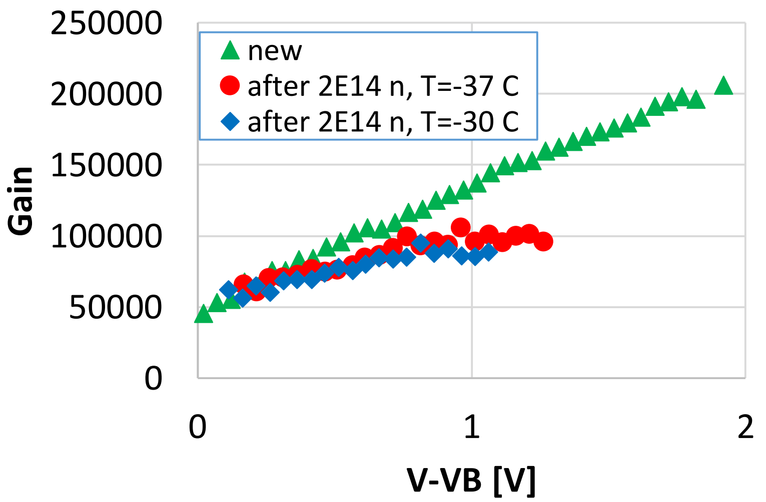
HDR2 SiPMs after 2E14 n/cm^2. Measurements with the 450 nm LED pulsed light (T=-30 °C and T=-37 °C, ~30 k photons/pulse, 120 ns integration gate).

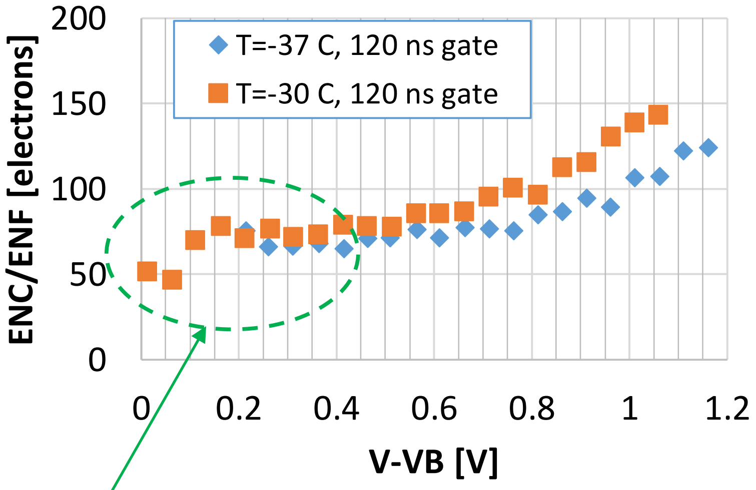
HDR2: T = -30 °C and -37 °C

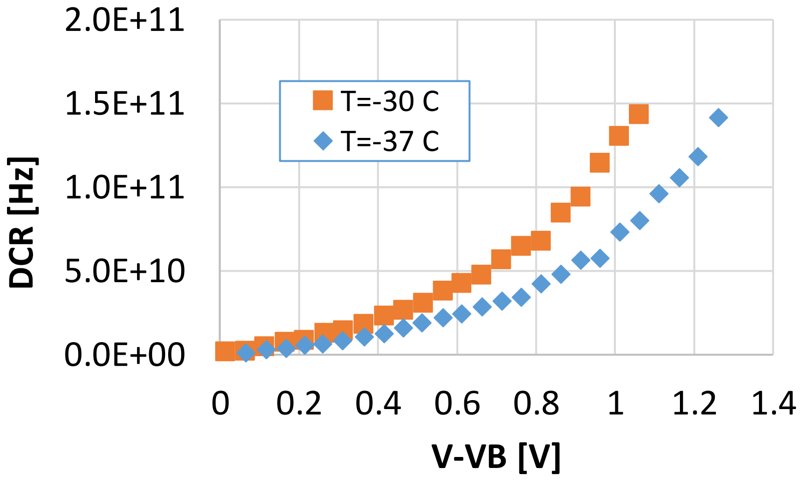






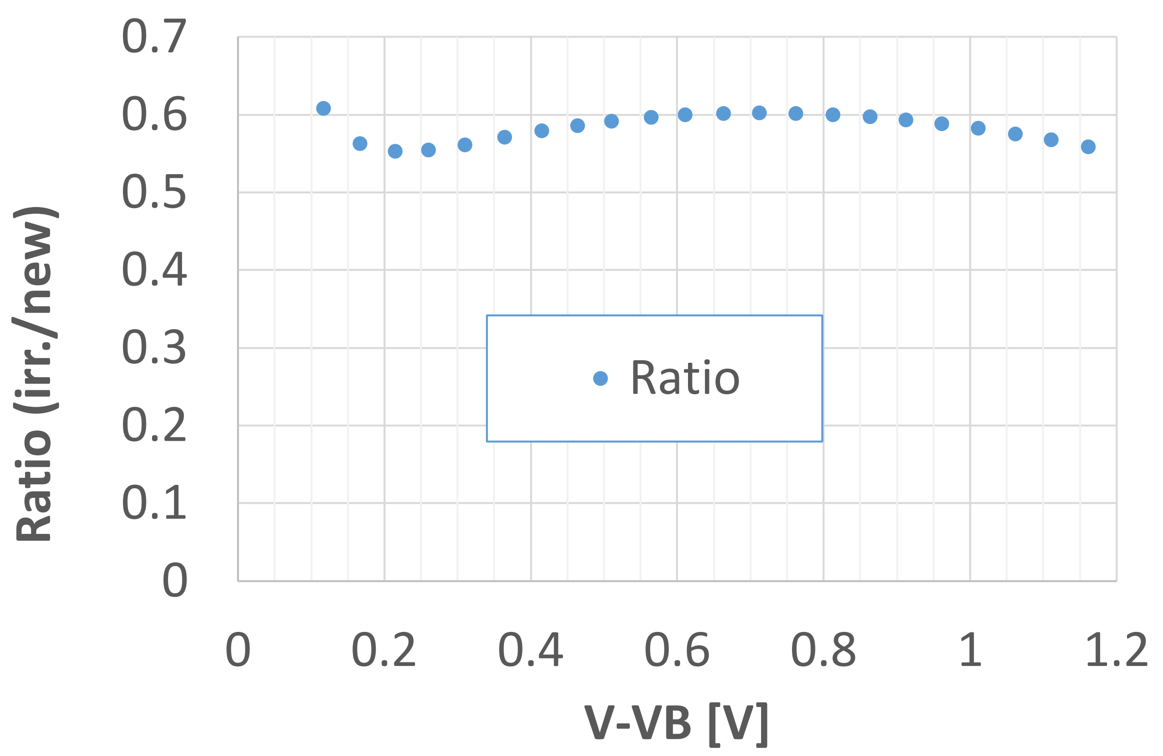


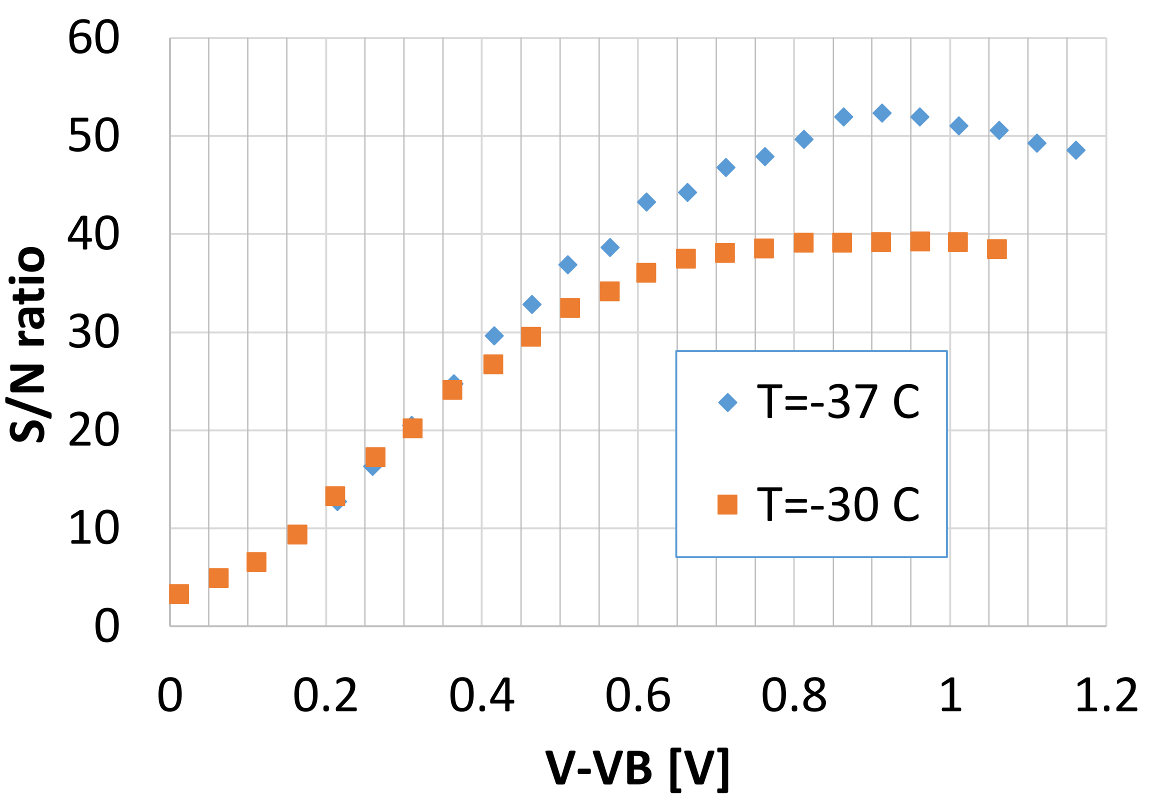




Noise is dominated by readout electronics noise

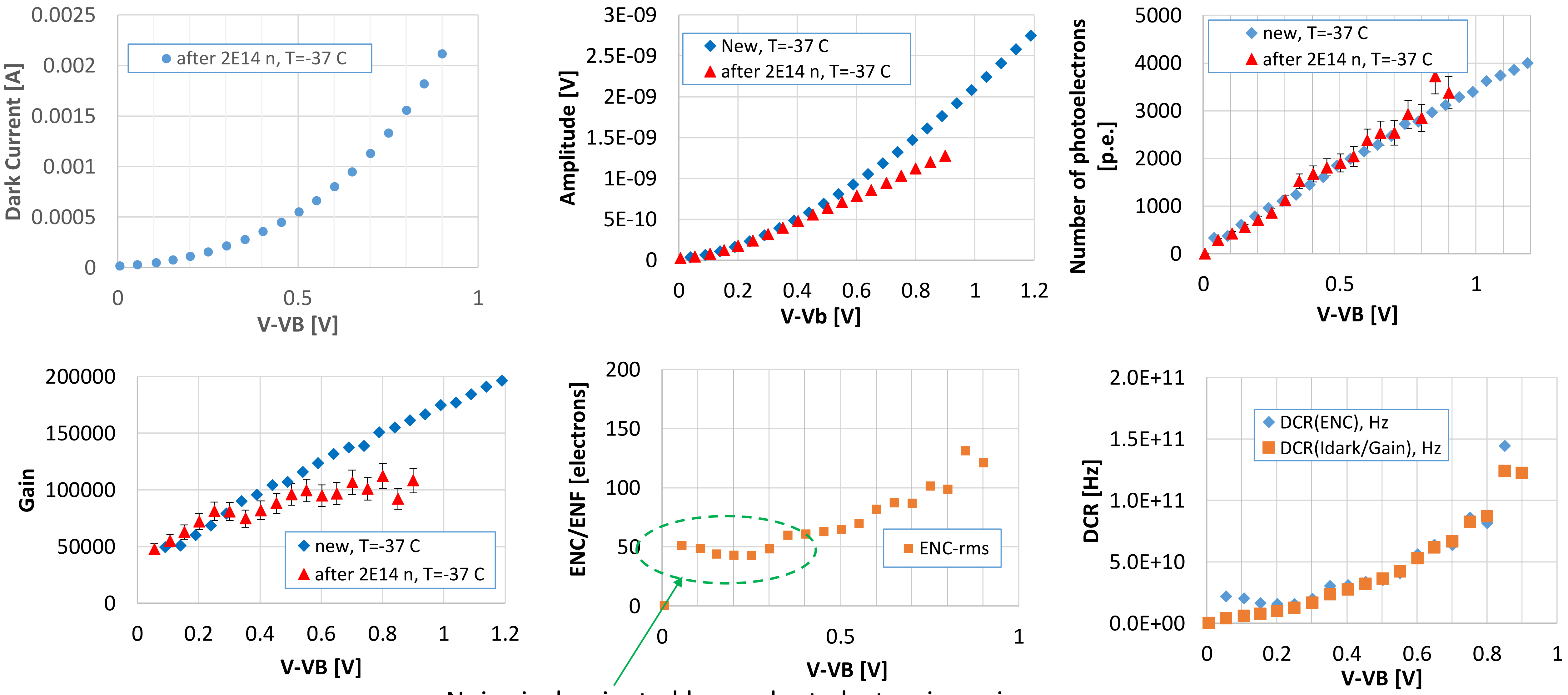
HDR2 SiPM: LED amplitude ratio (irr./new) at T =-37 °C, S/N ratio vs. dVB





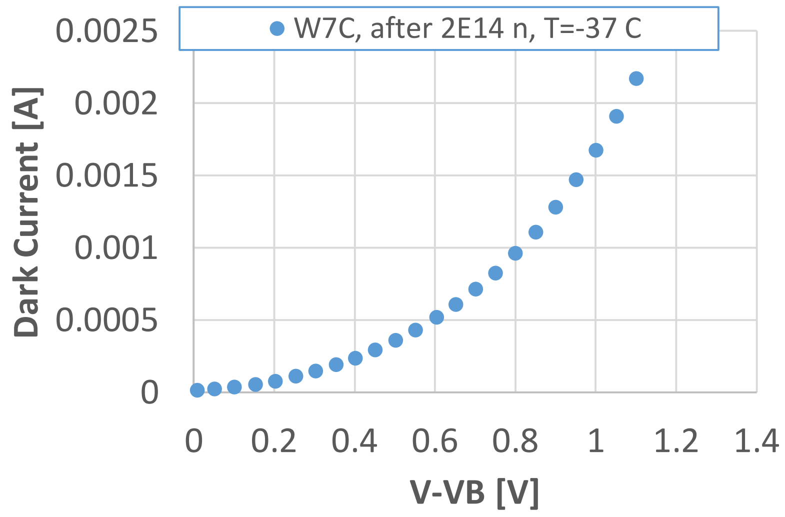
W9C and W7C FBK SiPMs after 2E14 n/cm^2, T=-37 °C, 450 nm pulsed LED, N(photons)~30 k, 120 ns integration gate

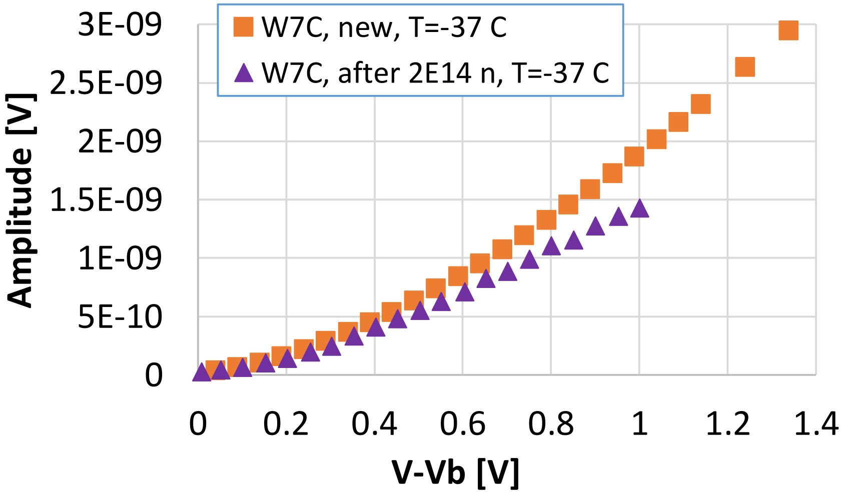
FBK W9C SiPM: T = -37 °C

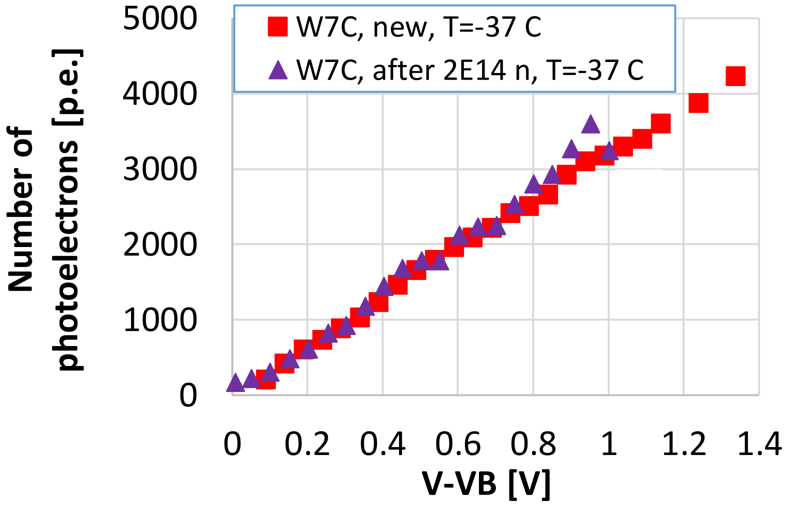


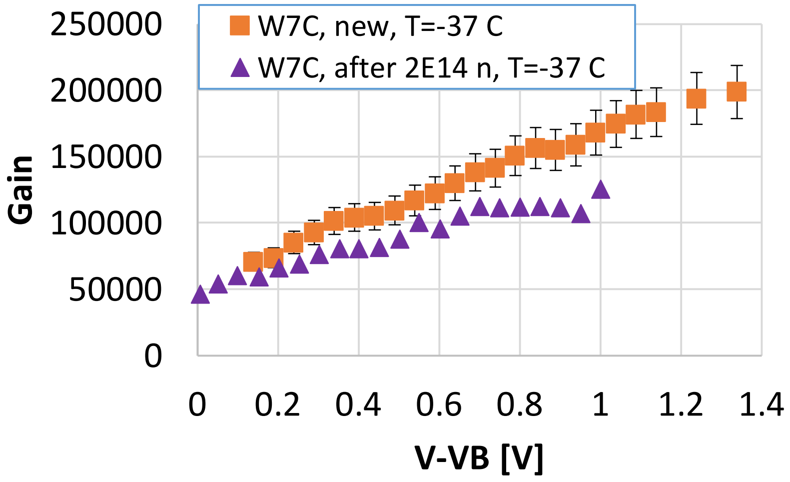
Noise is dominated by readout electronics noise

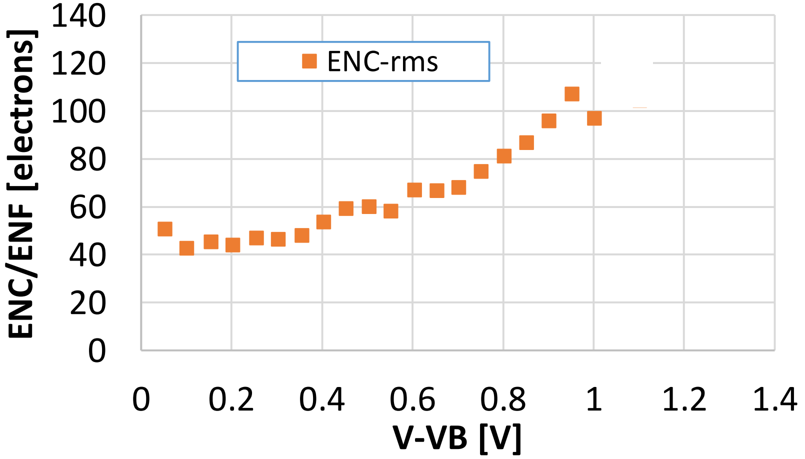
FBK W7C SiPM: T = -37 °C

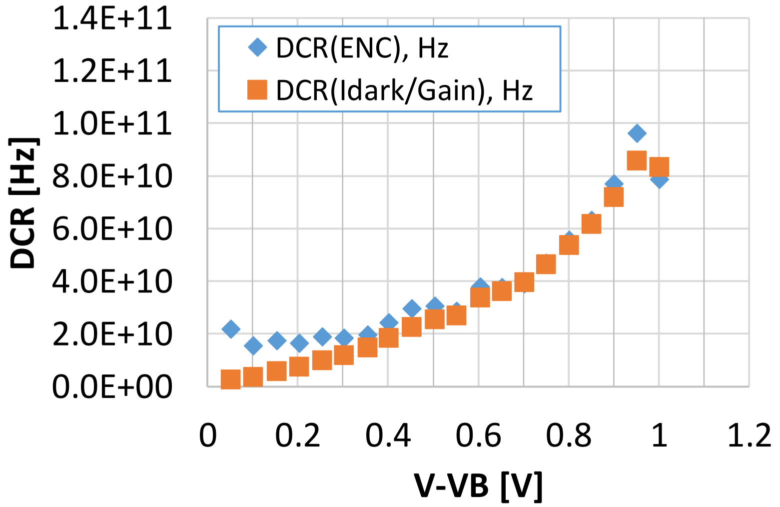




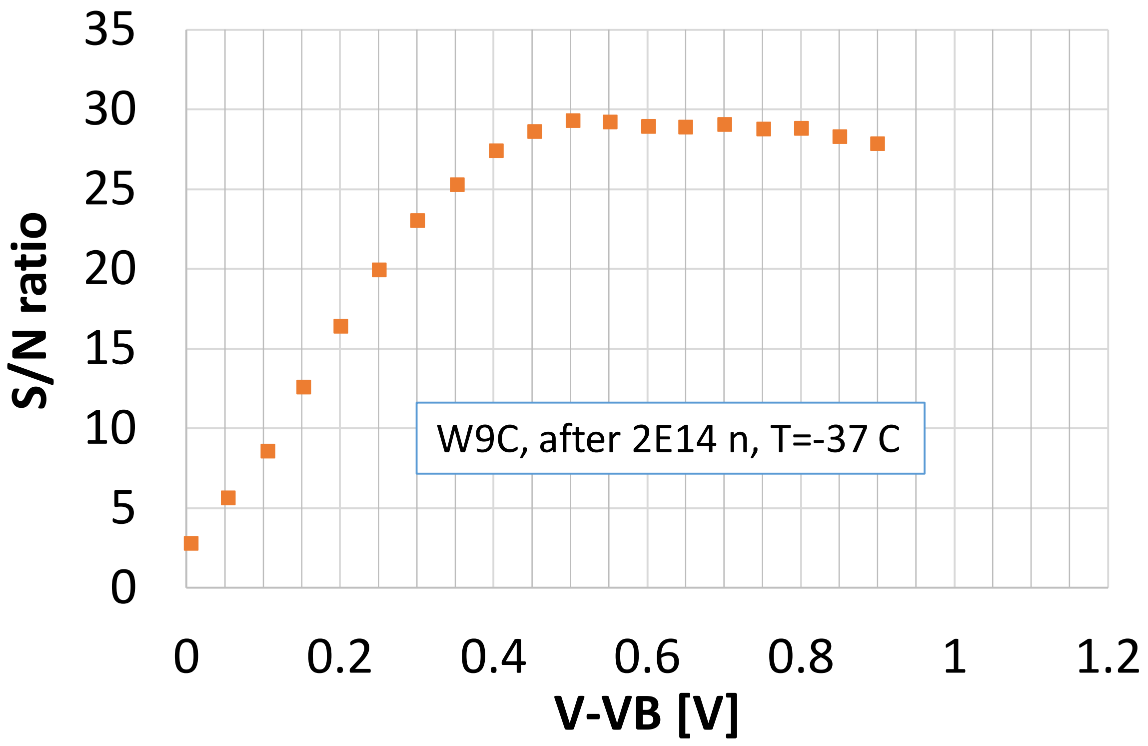


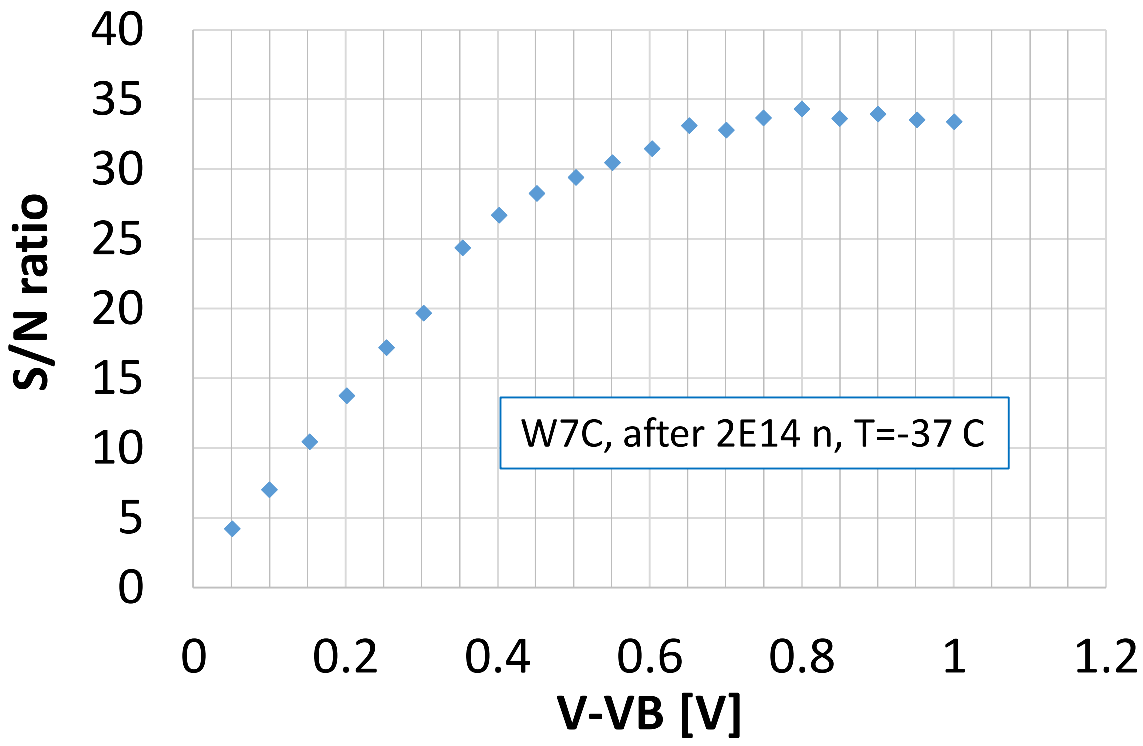




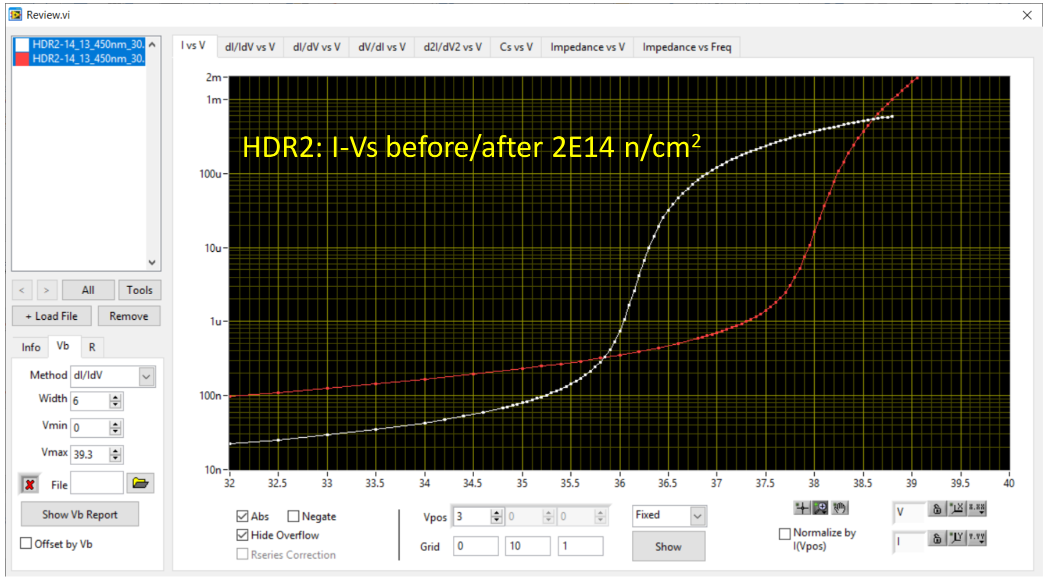


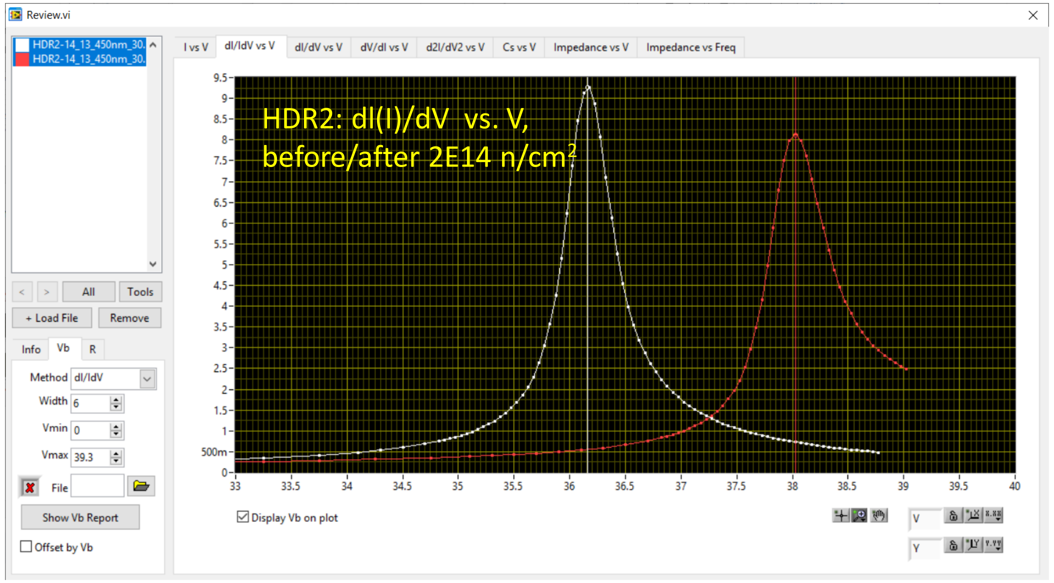
FBK SiPMs : S/N ratio vs. dVB at T =-37 °C

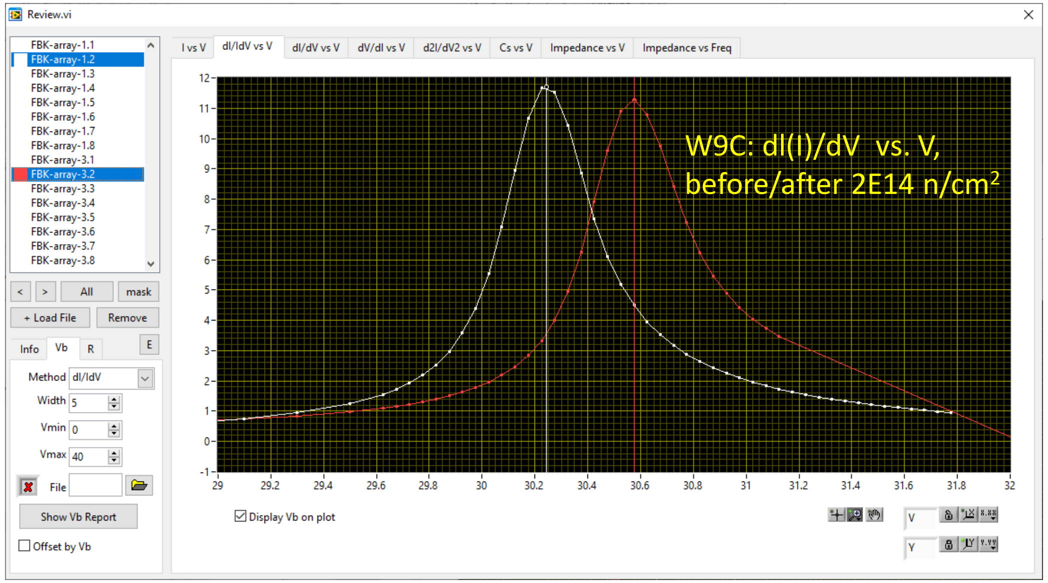


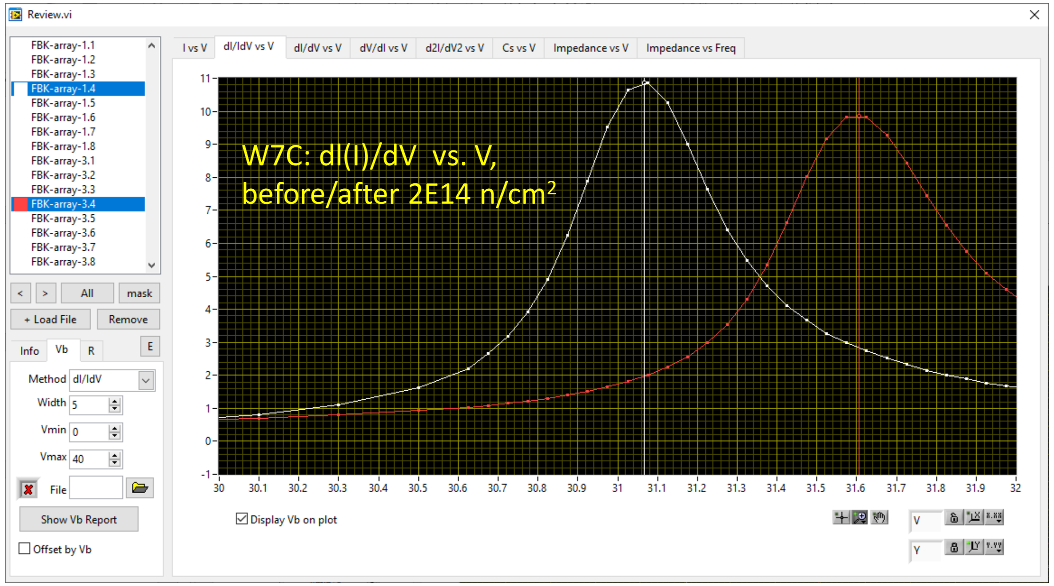


VB increase after 2E14 n/cm², T=-30 °C (max dln(I)/dV method)









I-V curves were measured under 450 nm LED continuous light illumination

VB increase after 2E14 n/cm², T=-30 °C (summary table)

SiPM	VB-shift at -30 °C, V
FBK W9C	0.34
FBK W7C	0.56
HPK HDR2	1.9
HPK HB/HE	~4

Summary of results and discussion

- The HPK HDR2, FBK W9C and W7C SiPMs are still operational after 2E14 n/cm^2.
- Best S/N ratio is reached at 0.6 V ÷ 1.0 V for all 3 SiPMs. It can be improved by lowering the SiPM temperature. Special precautions should be taken to reduce SiPM self-heating effects at high values of their leakage currents.
- The main limitation in improving SiPM S/N ratio is high power dissipation in SiPM that increases p-n junction temperature and causes VB shift and additional dark current increase.
- We measured ~40 % reduction of the HDR2 SiPM response to 450 nm nm pulsed LED light at dVB=0.8 V and T=-37 °C (in comparison to the new SiPM). Similar SiPM response reduction was found for the irradiated windowless HDR2 SiPM.
- The response reduction can be explained by both gain (~20%) and PDE (~20%) reduction after irradiation. We think that PDE reduction is due to the photoelectrons recombination in non-depleted p^+ layer of the HDR2 SiPM.
- We also measured ~20 % reduction of the FBK W9C and W7C SiPM response to 450 nm pulsed LED light at dVB=0.8 V and T=-37 °C (in comparison to the new SiPMs). It is mainly due to gain reduction of irradiated SiPM. The change of the PDE vs. voltage dependence is not significant (<5 %) for 0.5 V ÷ 1.0 V dVB range.
- We measured dark count rates of 42 GHz, 54 GHz and 87 GHz for the 3x3 mm^2 HDR2, W7C and W9C SiPMs (respectively) at dVB=0.8 V and T=-37 °C .
- The SiPM VBs increased by 1.9 V, 0.56 V and 0.34 V for the irradiated HDR2, W7C and W9C SiPMs.

These effects can be partially mitigated by:

- Operating the SiPMs at lower temperature
- Annealing periodically (annealing at elevated temperature is preferred)
- Reducing recovery time to lower cell occupancy
- SiPM packages with excellent thermal conductivity are required

CMS SiPM group continues R&D work to develop radiation tolerant SiPMs with both companies