Radiation Damage Studies of Silicon Photomultipliers for for the CMS HCAL Phase I Upgrade

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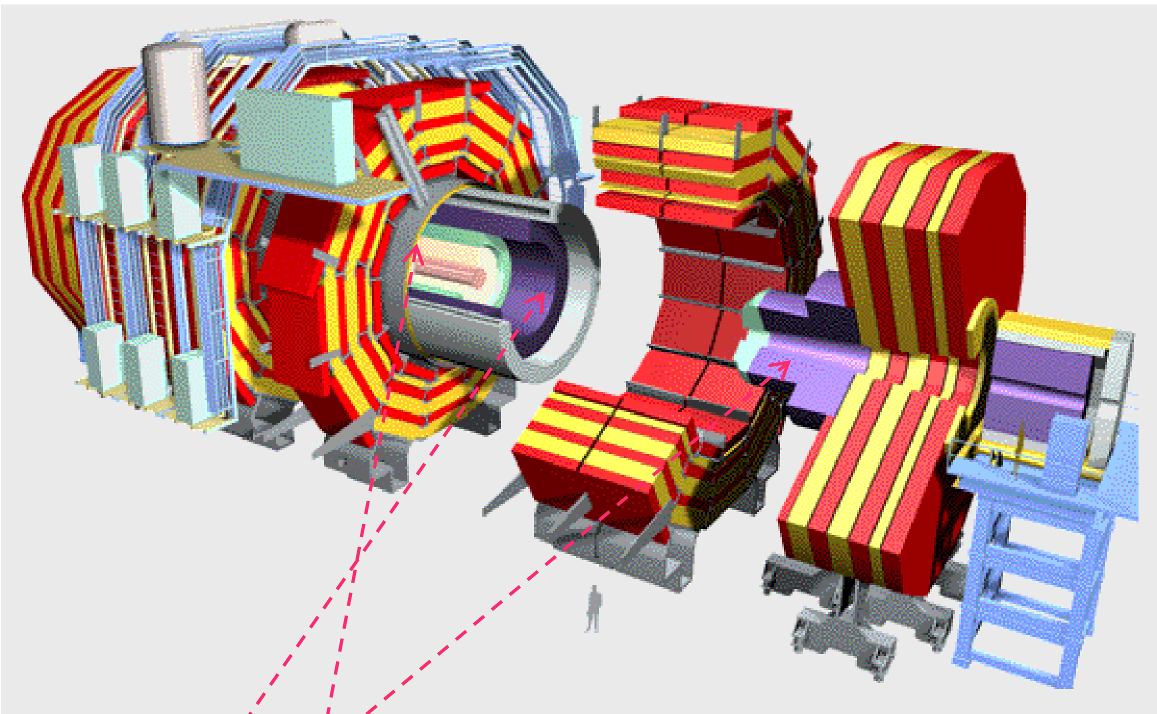
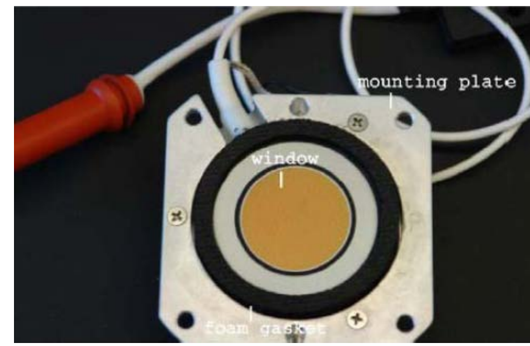
Outline

- The CMS Hadron calorimeter (HCAL) at the LHC
- Motivation for the photodetector upgrade
- SiPM requirements for the CMS HCAL Upgrade
- SiPM R&D goals and proposed solutions
- HPK, KETEK and FBK SiPM performances (developed for the CMS HCAL project in 2012)
- Irradiation results
- Discussion
- Summary

CMS Hadron Calorimeter (HCAL)





HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber readout, brass (steel for HO) absorber. HPD was selected as the CMS HCAL photodetector.

Motivation for the HB/HE photo-detector upgrade

1. SiPMs have better quantum efficiency, higher gain, and better immunity to magnetic fields than HPDs. Since SiPMs operate at relatively low voltages, they do not produce large pulses from high voltage breakdown that mimic energetic showers like HPDs do. These features of the SiPMs together with their low cost and compact size compared to HPDs enable several major changes to the HCAL.
2. Implementation of depth segmentation which has advantages in coping with higher luminosities and compensating for radiation damage to the scintillators. This is made possible by the use of SiPMs.
3. Use of timing to clean up backgrounds, made possible by the extra gain and better signal-to-noise of the SiPMs.

For more details see talk of A. Heering at NDIP-14:

Photo Sensors Replacement for the CMS HCAL for Phase I upgrade from HPD to SiPM

A. Heering
For the CMS Collaboration

Main CMS HCAL HB/HE SiPM requirements

- Area: ~Ø3 mm
- PDE(515 nm): > 15%
- Operating voltage: <90 V
- Gain: <700 000
- ENF: <1.3
- Optical X-talk between cells: <20%
- Temperature coefficient: <5%/°C
- Dynamic range: > 20 000 "effective" cells/SiPM
- Cell recovery time: <10 ns
- Dark current (T=24 °C, after $2*10^{12}$ n/cm^2): <1000 μA
- Fractional Gain*PDE (after $2*10^{12}$ n/cm^2): >65%
- Neutron sensitivity: low

> 5 years of R&D to improve SiPM radiation hardness

The goal of the R&D was to develop radiation hard SiPM for the CMS HCAL Upgrade with SiPM parameters after $2*10^{12}$ n/cm^2 :

PDE(515 nm)>15 %

Fractional Gain*PDE (in comparison to that before rad. damage) > 65 %

Dark Current <1 000 μA

ENC(50ns gate)<40 p.e.

Is this easy? The answer is: No!

Why it is difficult?

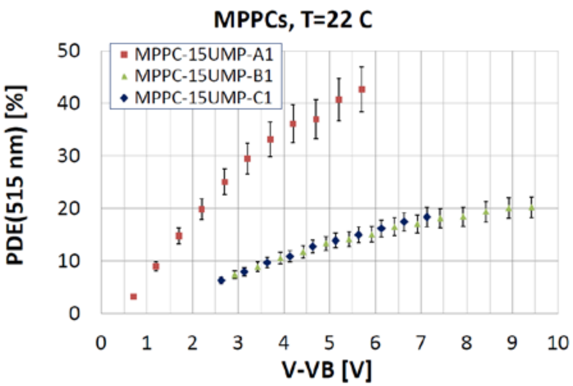
High neutron fluences → high dark noise → large size cells (we need them for high PDE!!) are permanently fired → V-VB approaches “0” → significant drop of the SiPM PDE and gain → SiPM has low PDE, gain and it is useless as a photodetector for the calorimetry…

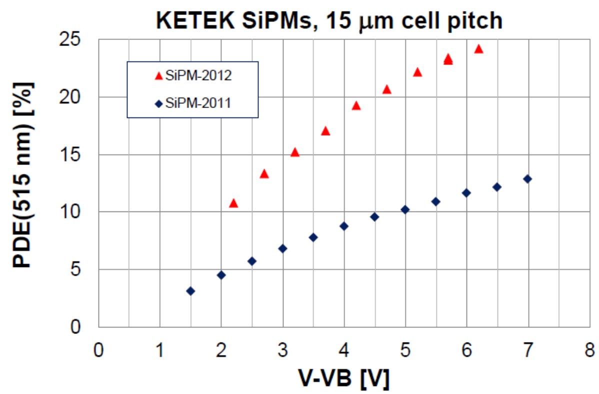
What can we try to do to achieve the goal? We proposed:

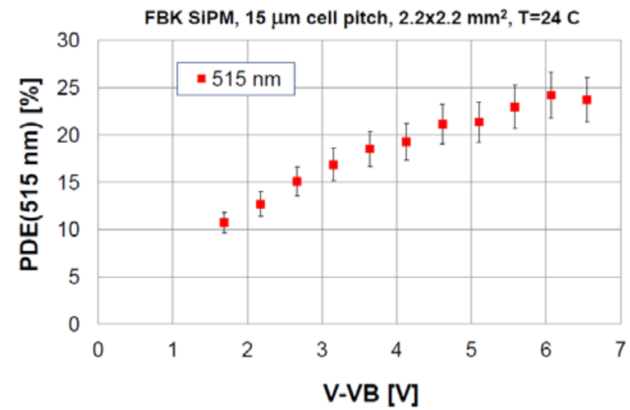
- Small cell size (<15 μm) → smaller dark noise generation rate (to avoid cell blocking effects);
- Fast cell recovery (<10ns) → 1/(dark count rate)<<cell recovery time → small PDE*Gain losses
- Improve SiPM’s geometric factor →High PDE (>15%) → better S/N ratio after irradiation
- “Thick” epitaxial layer and deep p-n junction → better PDE for green Y11 light → Small gain (700 000) → less dark current after irradiation
- small “parasitic” (parallel to R_q) capacitance → smaller gain→ smaller X-talk&afterpulsing→ smaller dark current and smaller noise after irradiation
- SiPM electric field engineering → smaller dark noise generation rate, faster noise reduction with temperature

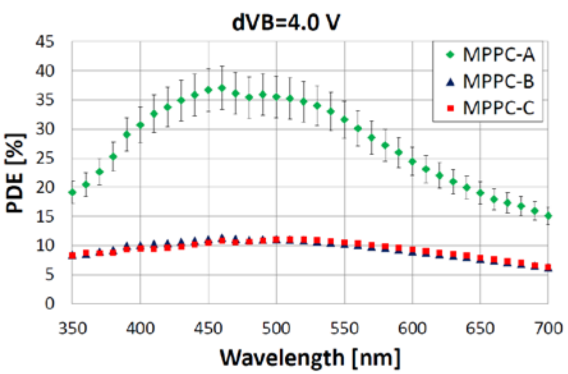
Many different SiPM structures were developed during >5 years of R&D performed by the CMS SiPM group and commercial companies (CPTA, Zecoteck, Hamamatsu, KETEK, FBK ---)

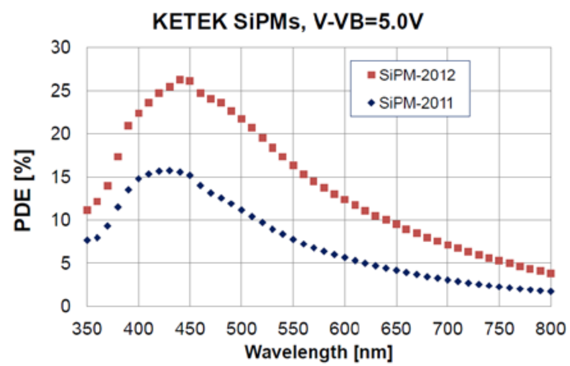
Progress in PDE for the 15 μm cell pitch HPK, KETEK and FBK SiPMs (2011-2012)

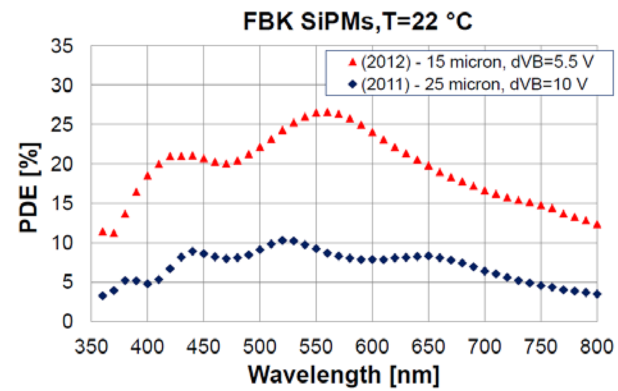












Significant improvement of PDE for all 3 developers during 2011-2012 R&D

But are these SiPMs rad.hard?

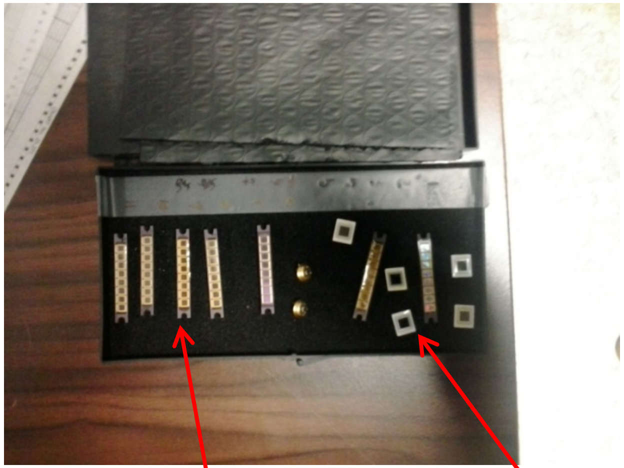
SiPMs irradiated up to $1*10^{12}$ p/cm^2 and irradiation facility

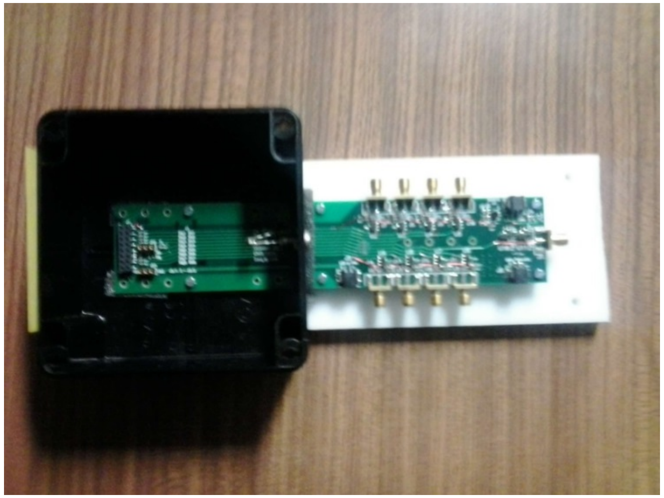
• Here we report on irradiation study of Hamamatsu, KETEK and FBK SiPMs:

- Hamamatsu SiPM (MPPC), 2.8 mm dia. (6.16 mm^2), 15 μm cell pitch
- KETEK SiPM, 2.5 mm dia. (4.91 mm^2), 15 μm cell pitch
- FBK SiPM, 2.2x2.2 mm^2 (4.84 mm^2), 15 μm cell pitch

SiPMs were irradiated with 62 MeV protons up to 1E12 p/cm^2 (~2E12 1/cm^2 1 MeV equivalent neutrons) at UCL (Université Catholique de Louvain), Belgium. After irradiation all the SiPMs were annealed (1000 min at 60 C) to stabilize their currents. The SiPM parameters were measured after irradiation at CERN APD Lab: Id vs. V, Noise vs. V, S/N ratio vs. V. Amplitude of the LED (λ=515 nm) pulse was the same for all the SiPMs (irradiated and non-irradiated): N_γ~4200 photons/pulse. Signal integration gate was 50 ns. Non-irradiated SiPMs were the “clones” of the irradiated SiPMs. All measurements were performed at T=23 C.

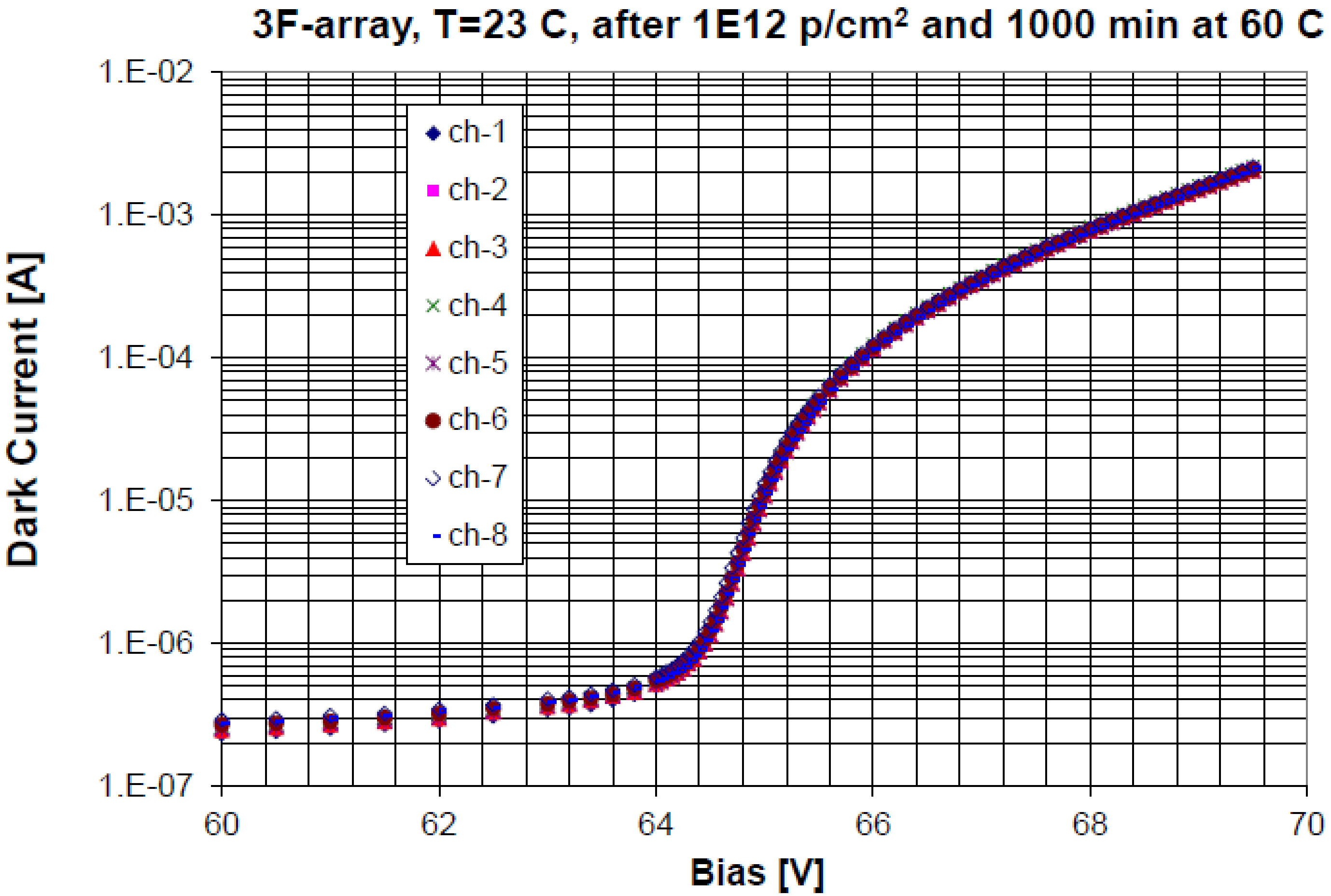
SiPMs and Irradiation Set-up





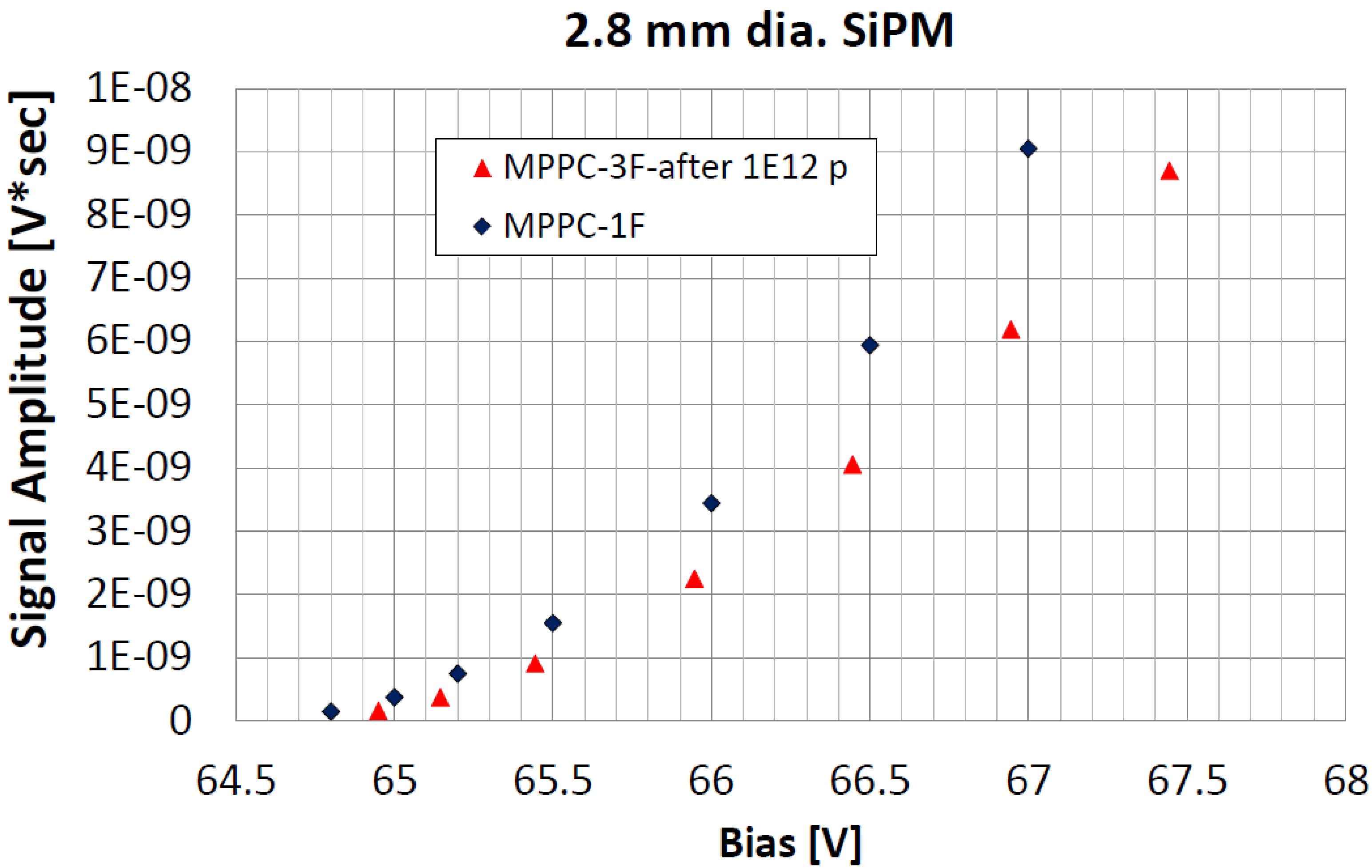
The SiPM dark currents were monitored during irradiation. Arjan worked hard to install a box with the SiPM arrays to the center of the proton beam. Do you see the damage produced by protons to the white plastic support plate?! CMS ECAL APDs were used to monitor the integral proton flux.

Dark current vs. bias (Hamamatsu MPPC)



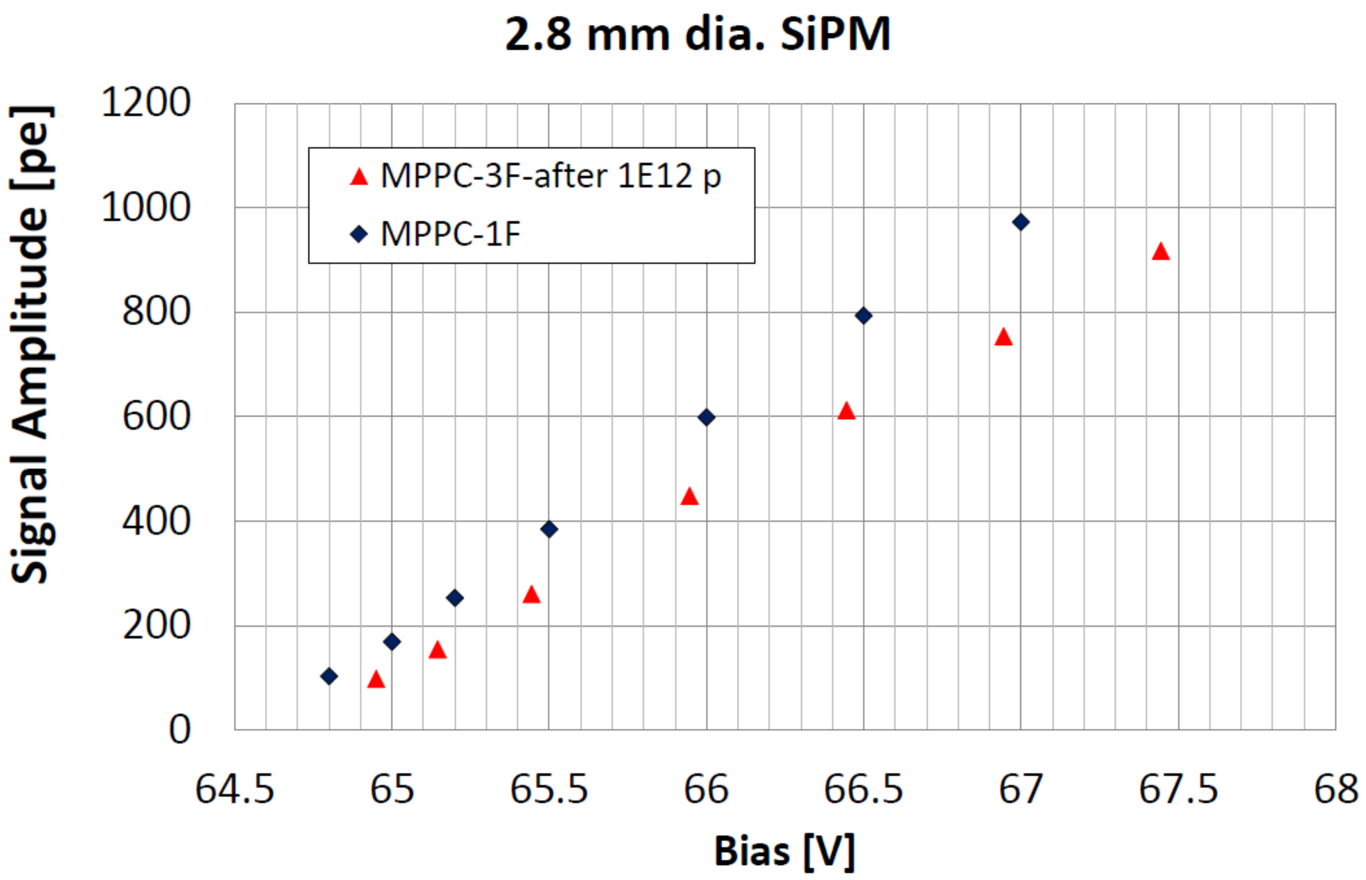
Irradiation was very uniform (dark currents vs. bias curves are identical)

LED amplitude vs. bias (Hamamatsu)



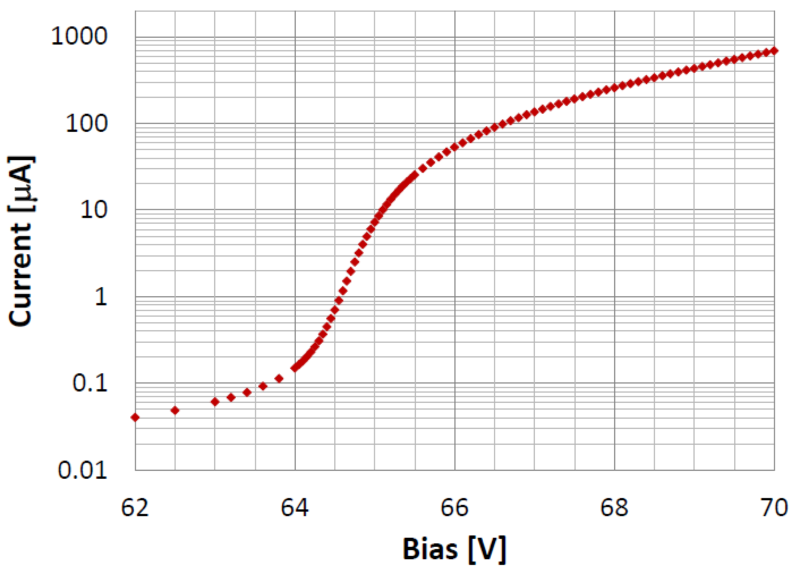
~30 % signal (Gain*PDE) reduction was measured for the irradiated HPK SiPM.
(< 15% signal reduction was measured for HPK SiPMs after 2E12 n/cm^2)

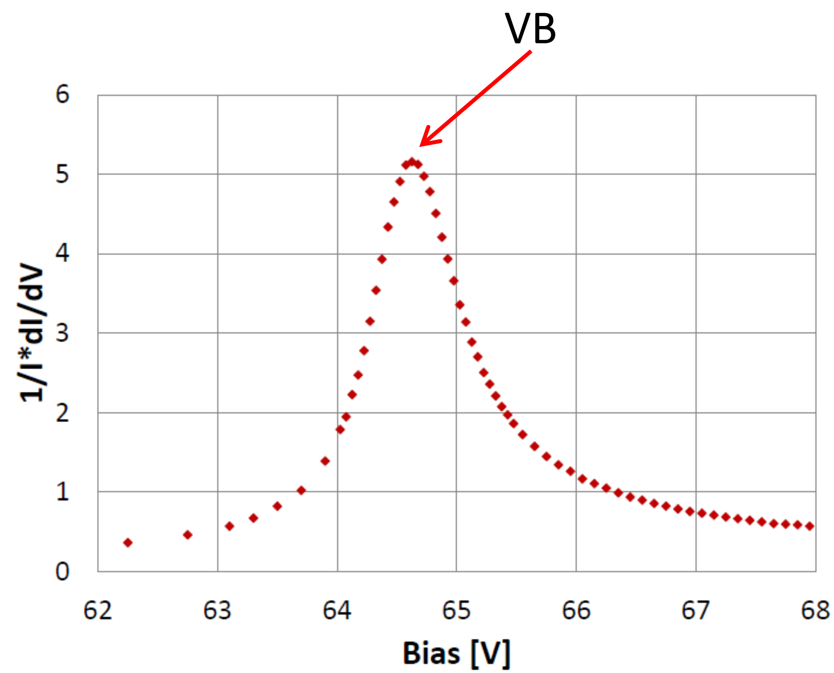
Number of photoelectrons vs. bias (Hamamatsu)



~22% PDE reduction was measured for the irradiated HPK SiPM (<10% change of PDE was measured for HPK SiPMs after 2E12 n/cm^2)

VB measurement for new and irradiated SiPMs

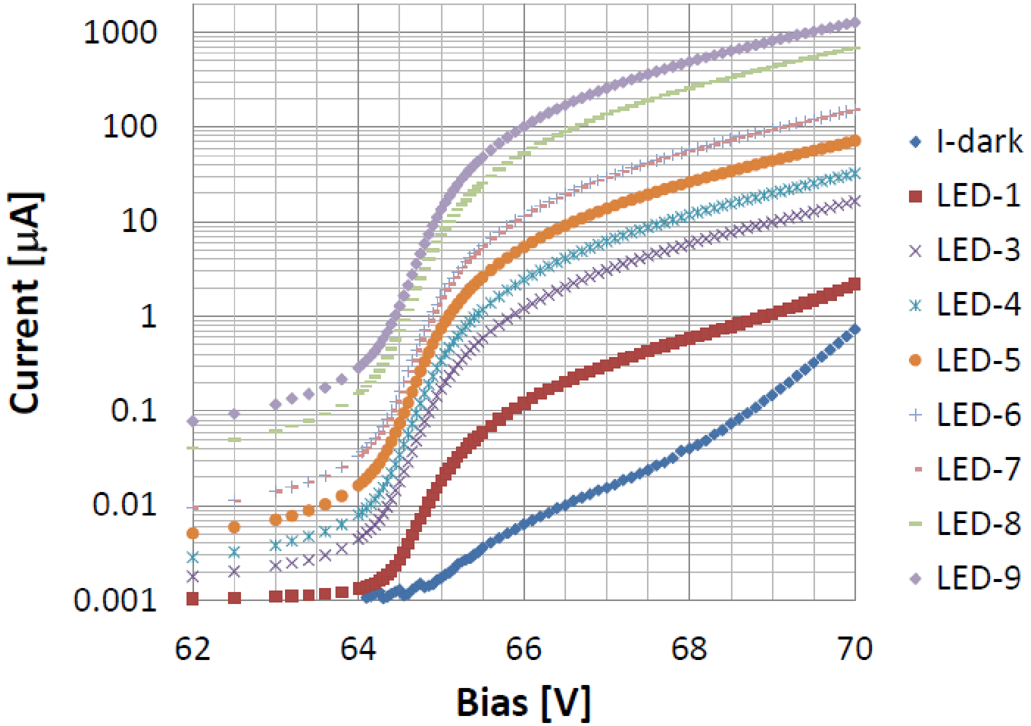




After irradiation standard method the SiPM VB measurement (intersection of the Gain vs. bias dependence with the bias axis) doesn't work. We need another way to measure VB!

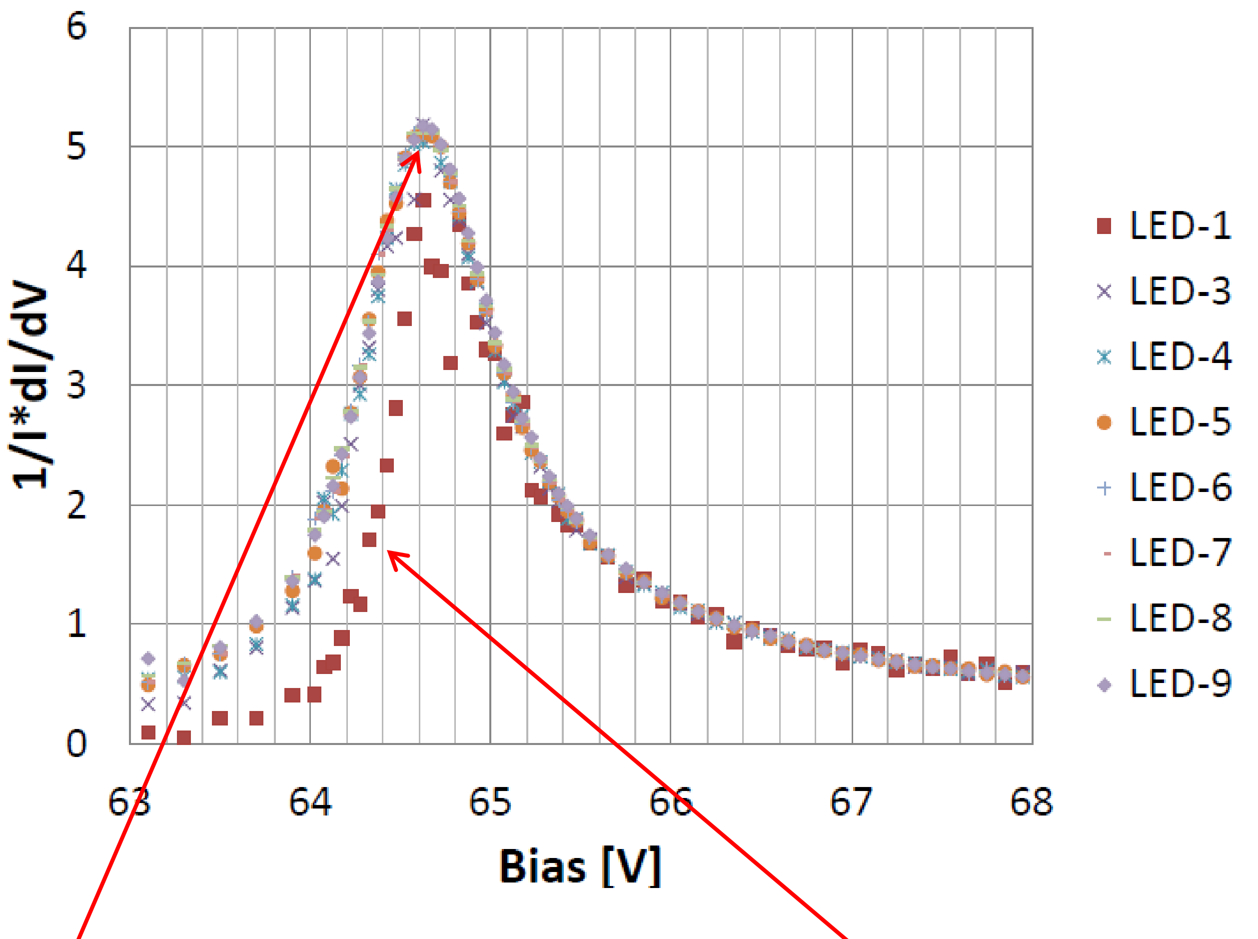
We illuminated SiPM with the LED continuous light and measured I-V dependence. We observed that maximum of the 1/I*dI/dV dependence on the bias voltage with a precision of ~30 mV coincides with the VB found by the standard method.

Photocurrent vs. bias (Hamamatsu non-irradiated MPPC)



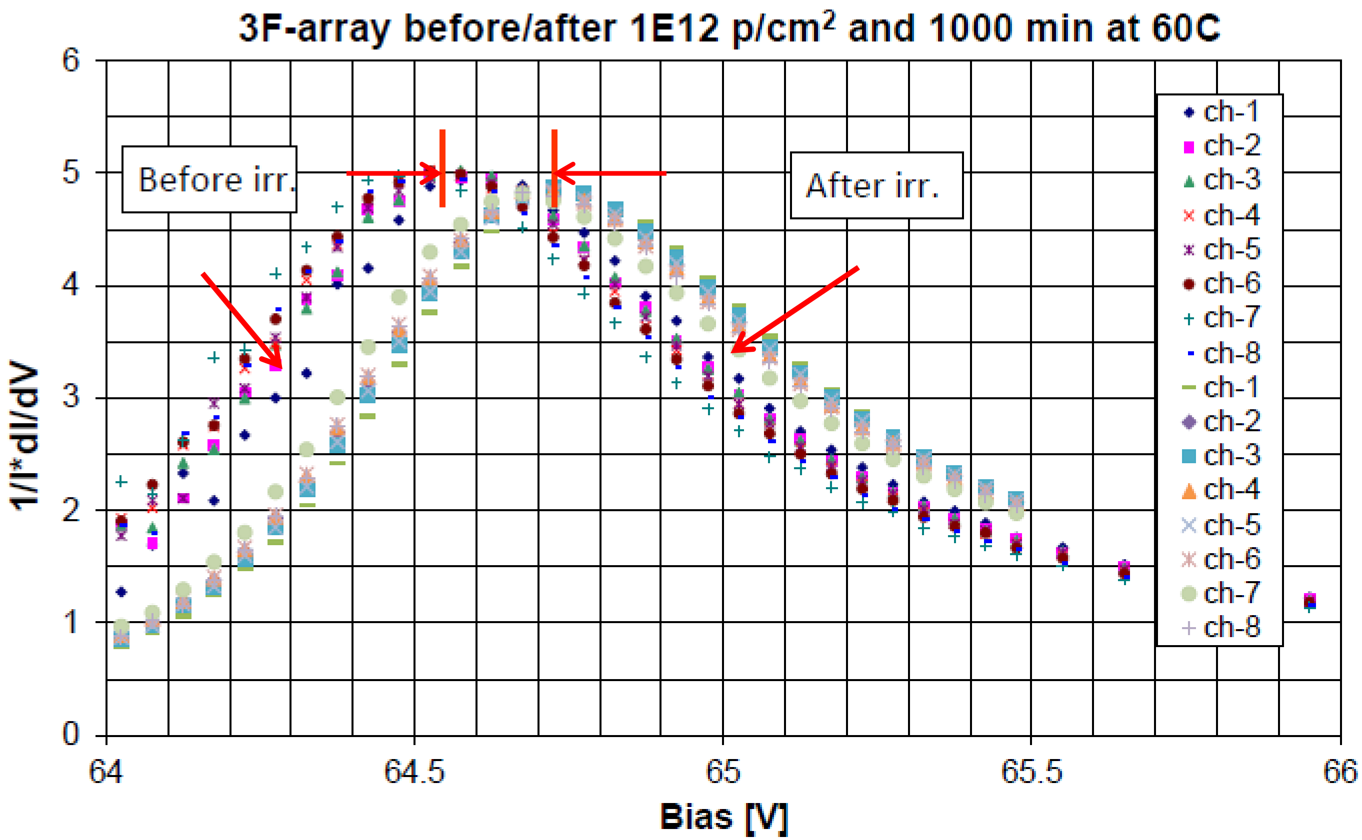
Does the VB value depend on the light intensity?

VB vs. light intensity



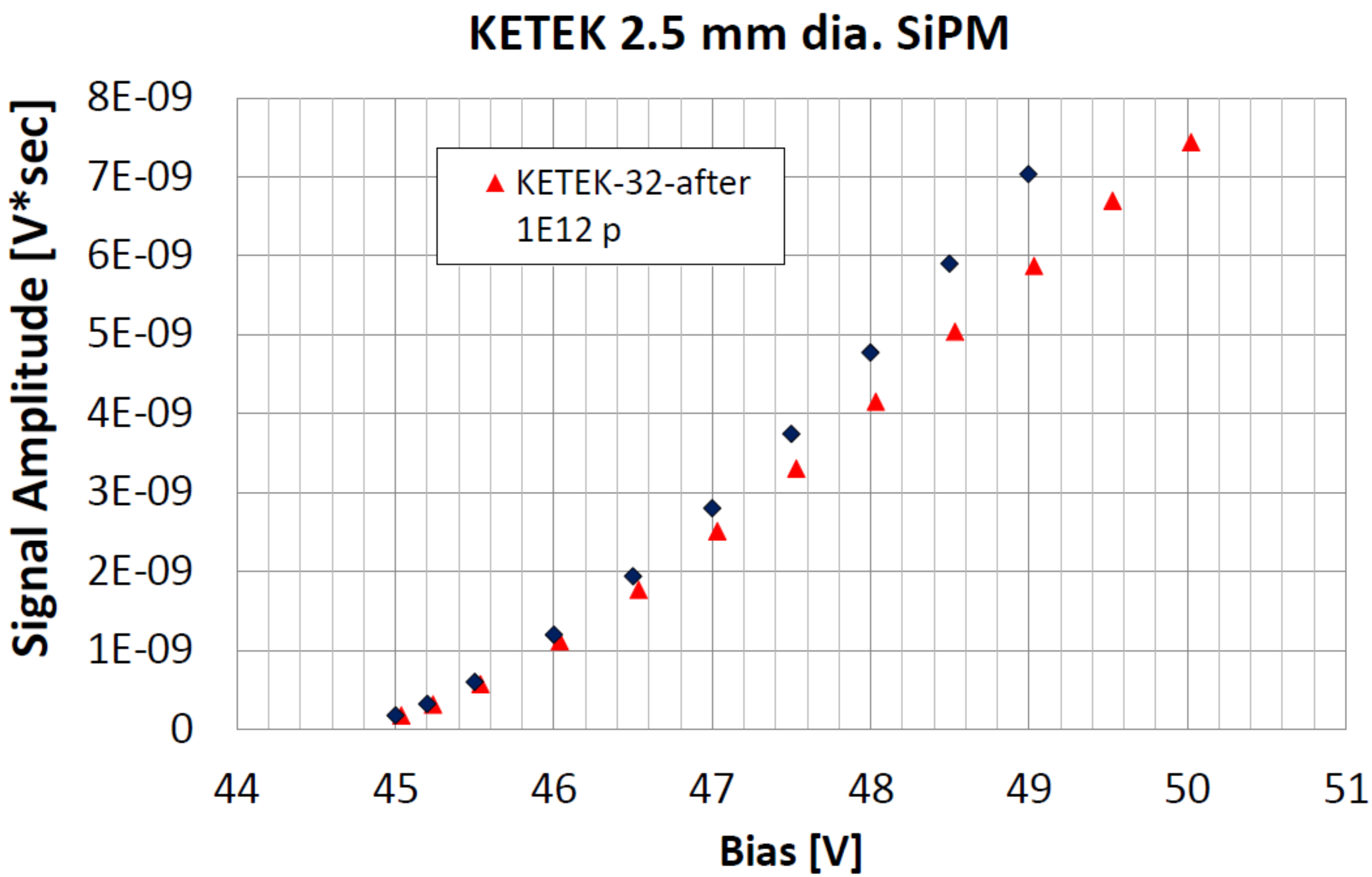
No, it doesn't! We should take into account that low intensity light doesn't guarantee a good precision.

1/I*dI/dV vs. bias (Hamamatsu)



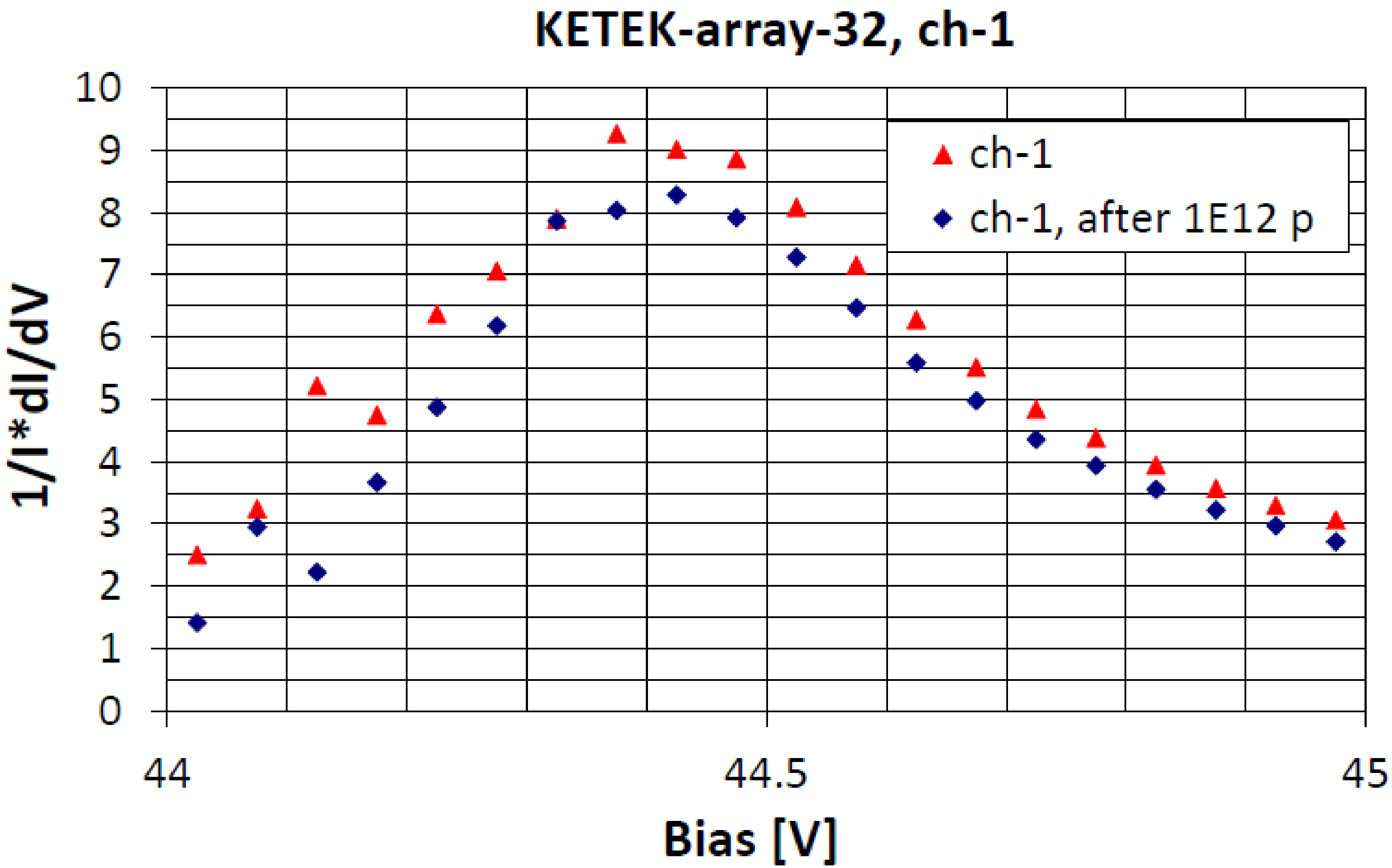
We measured 1/I*dI/dV curve maximum for HPK SiPM before and after irradiation. VB increase of 175 mV was observed for the HPK SiPM after 1E12 p/cm^2 and annealing. This shift explains 30% signal amplitude drop for irradiated SiPM.

SiPM amplitude vs. bias (KETEK)



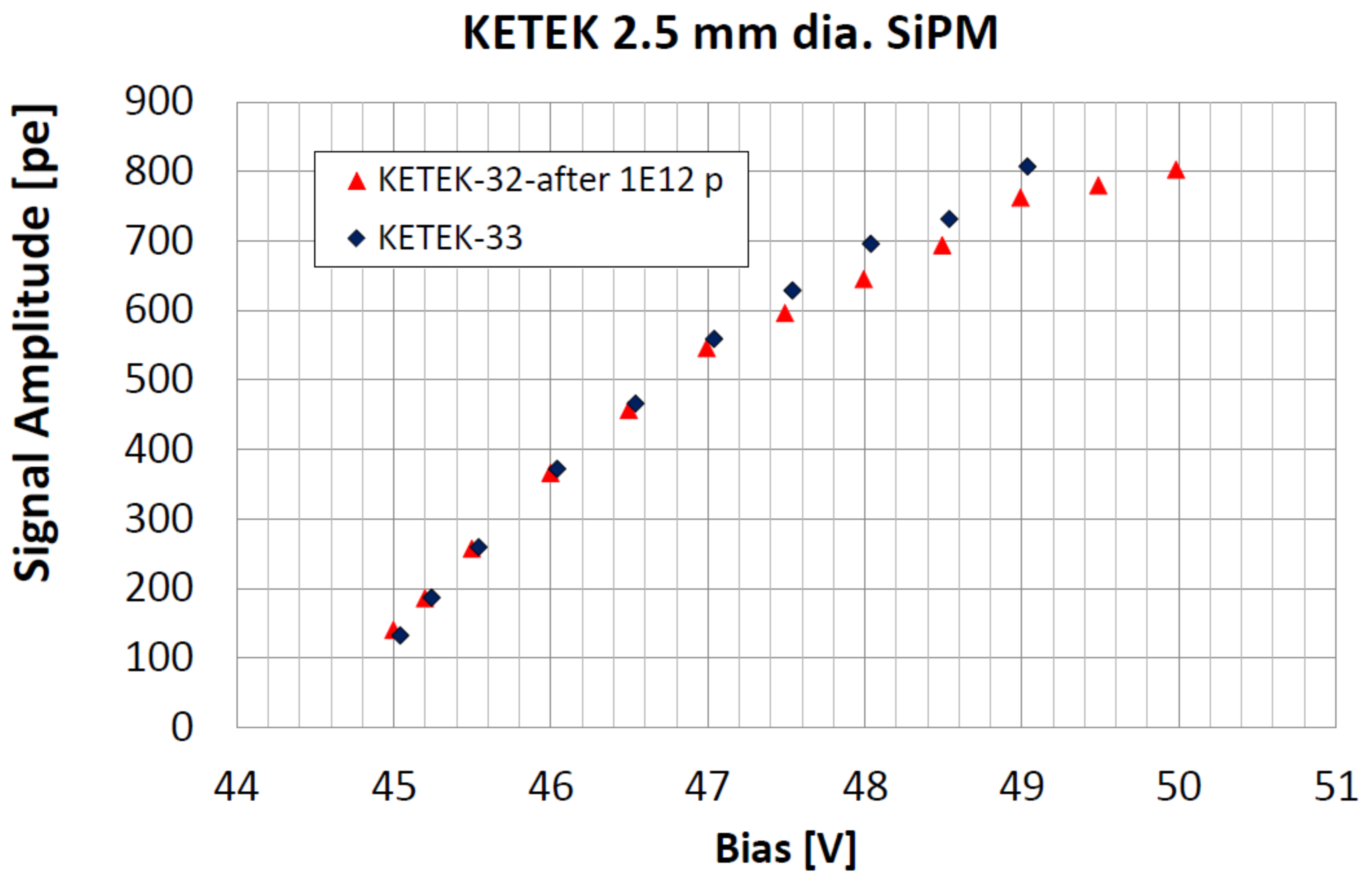
<15 % signal (Gain*PDE) reduction was measured for the irradiated KETEK SiPM (< 15% signal reduction was measured for KETEK SiPMs after 2E12 n/cm^2).

1/I*dI/dV vs. bias (KETEK)



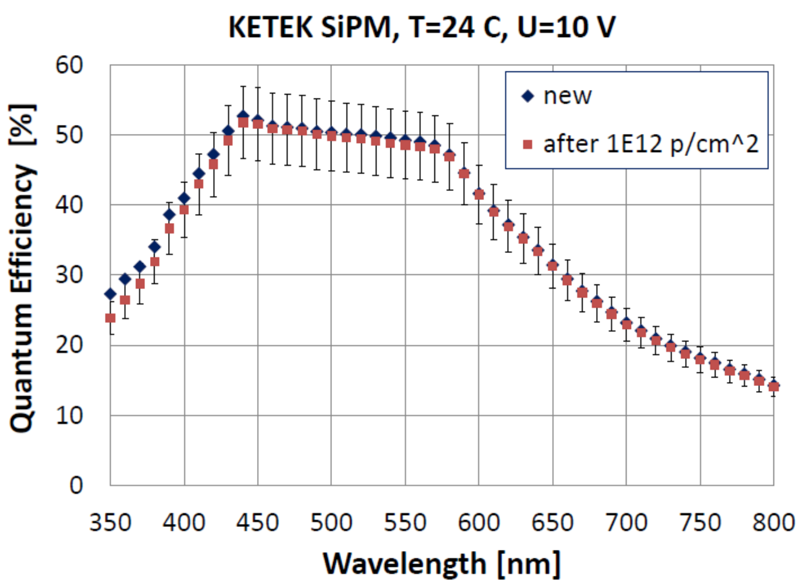
VB change is <50 mV!

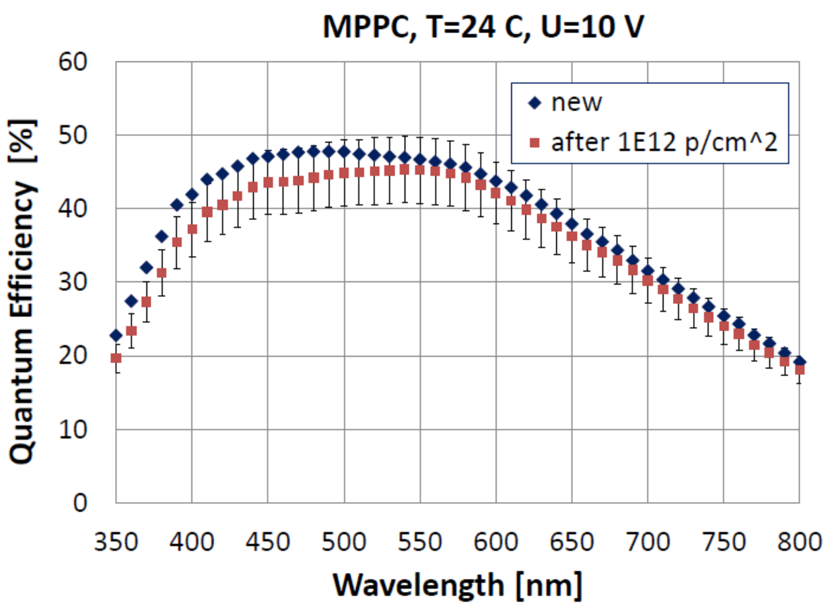
Number of photoelectrons vs. bias (KETEK)



<10% PDE reduction was measured for the irradiated KETEK SiPM (<10% change of PDE was measured for KETEK SiPMs after 2E12 n/cm^2)

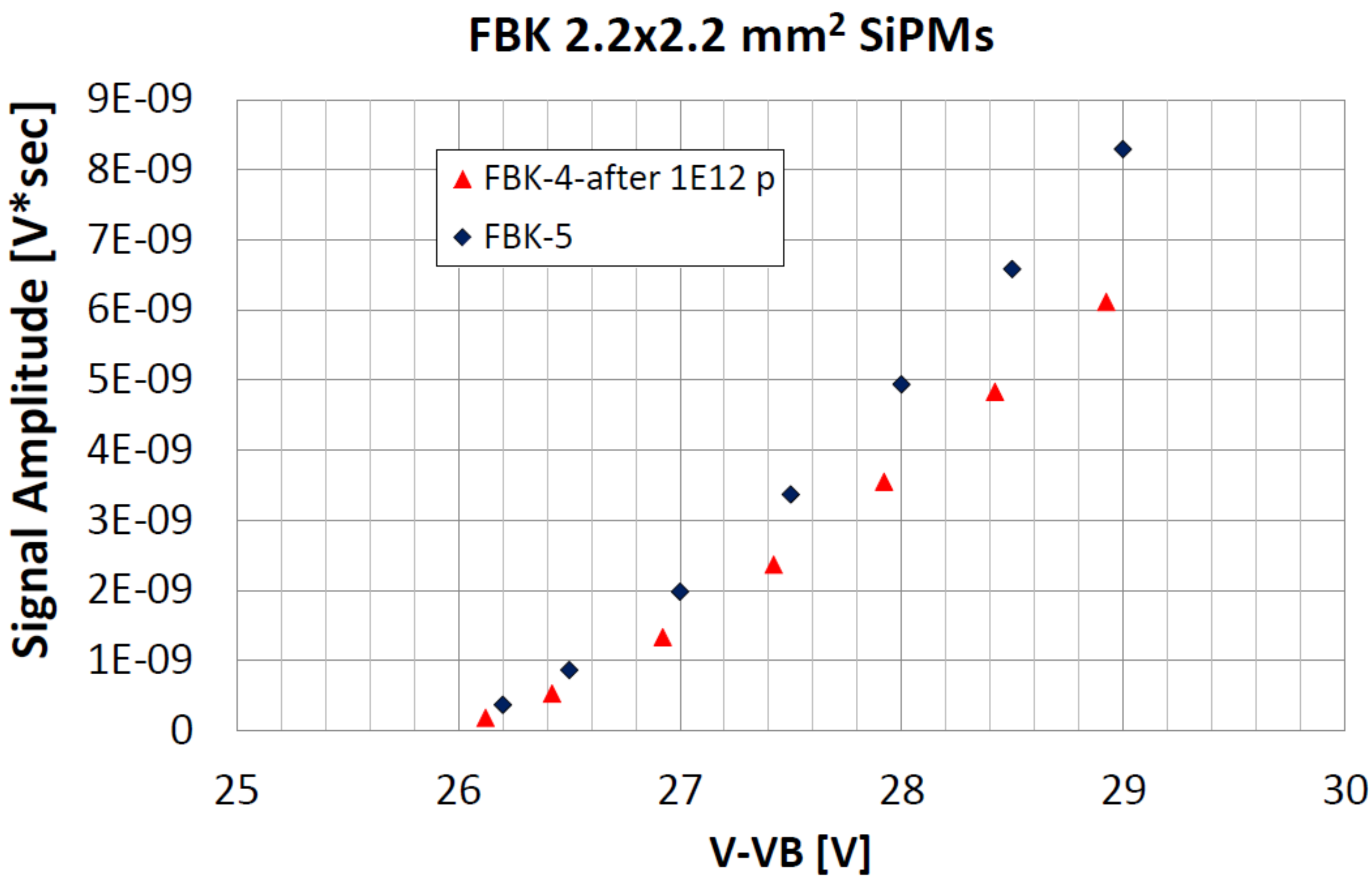
QE vs. wavelength measured at 10 V for the HPK and KETEK SiPMs before and after irradiation





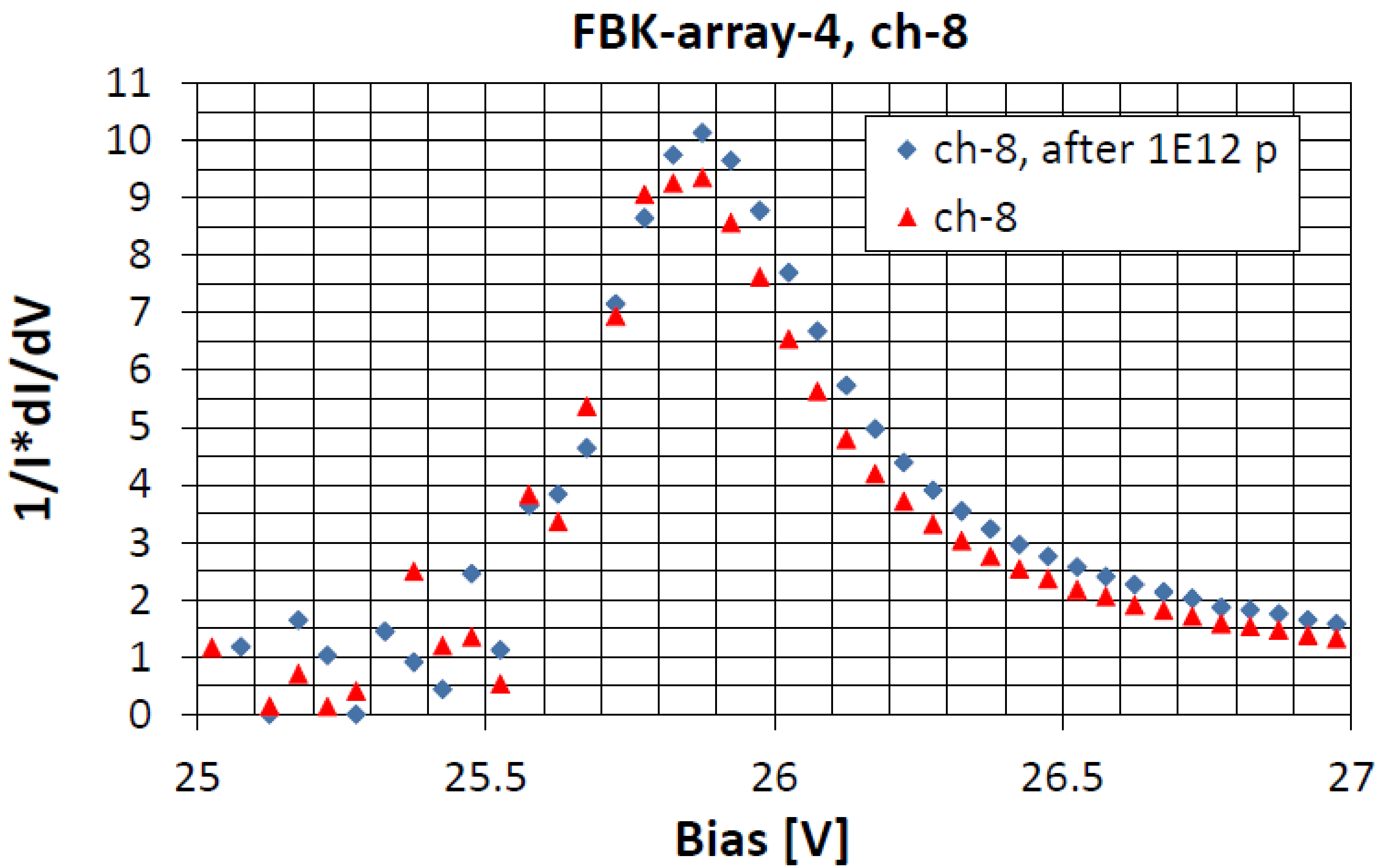
No change of QE for the KETEK SiPM and <10 % QE reduction for the HPK MPPC (400-800nm).

SiPM amplitude vs. bias (FBK)



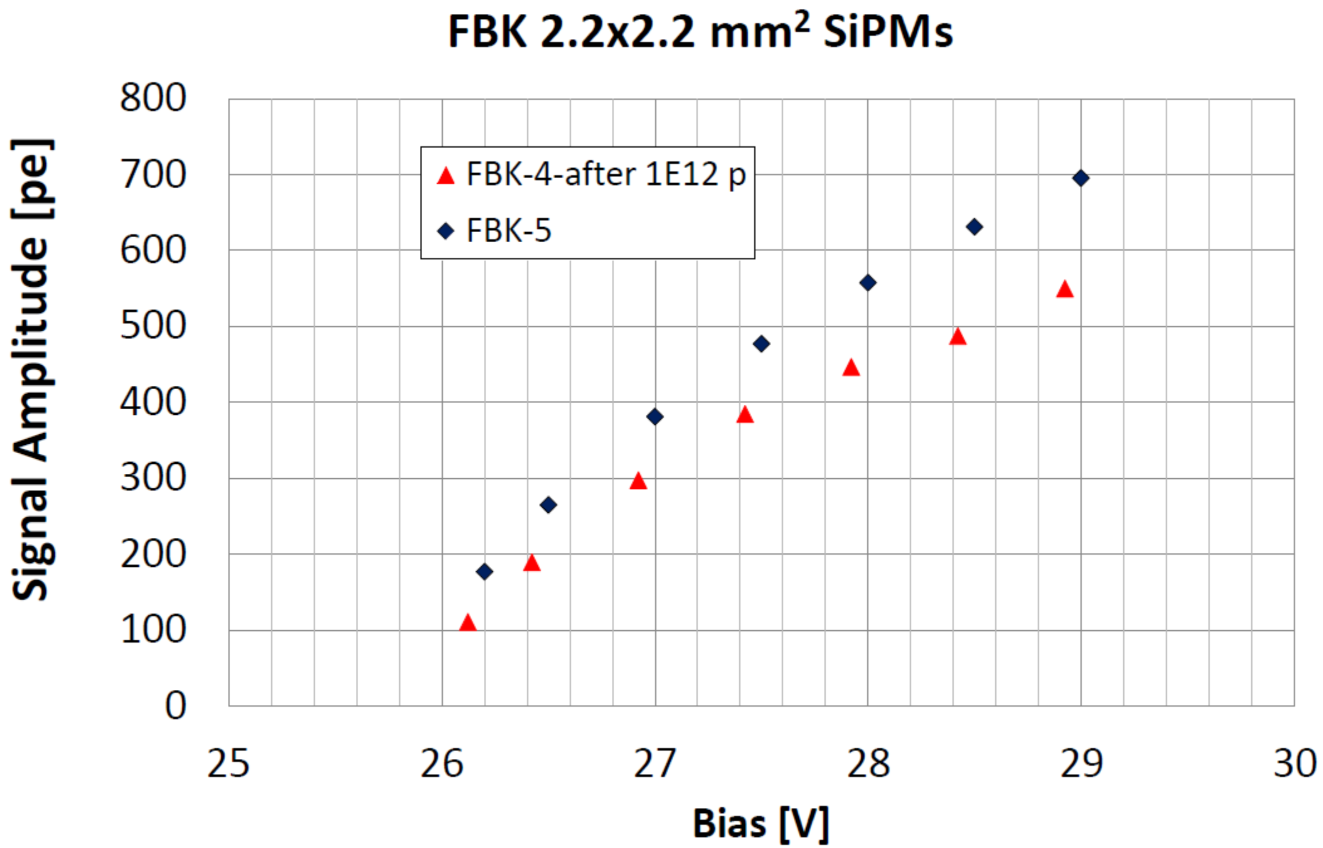
~28 % signal (Gain*PDE) reduction was measured for the irradiated FBK SiPM (< 15% signal reduction was measured for FBK SiPMs after 2E12 n/cm^2).

1/I*dI/dV vs. bias (FBK)



VB change is <50 mV!

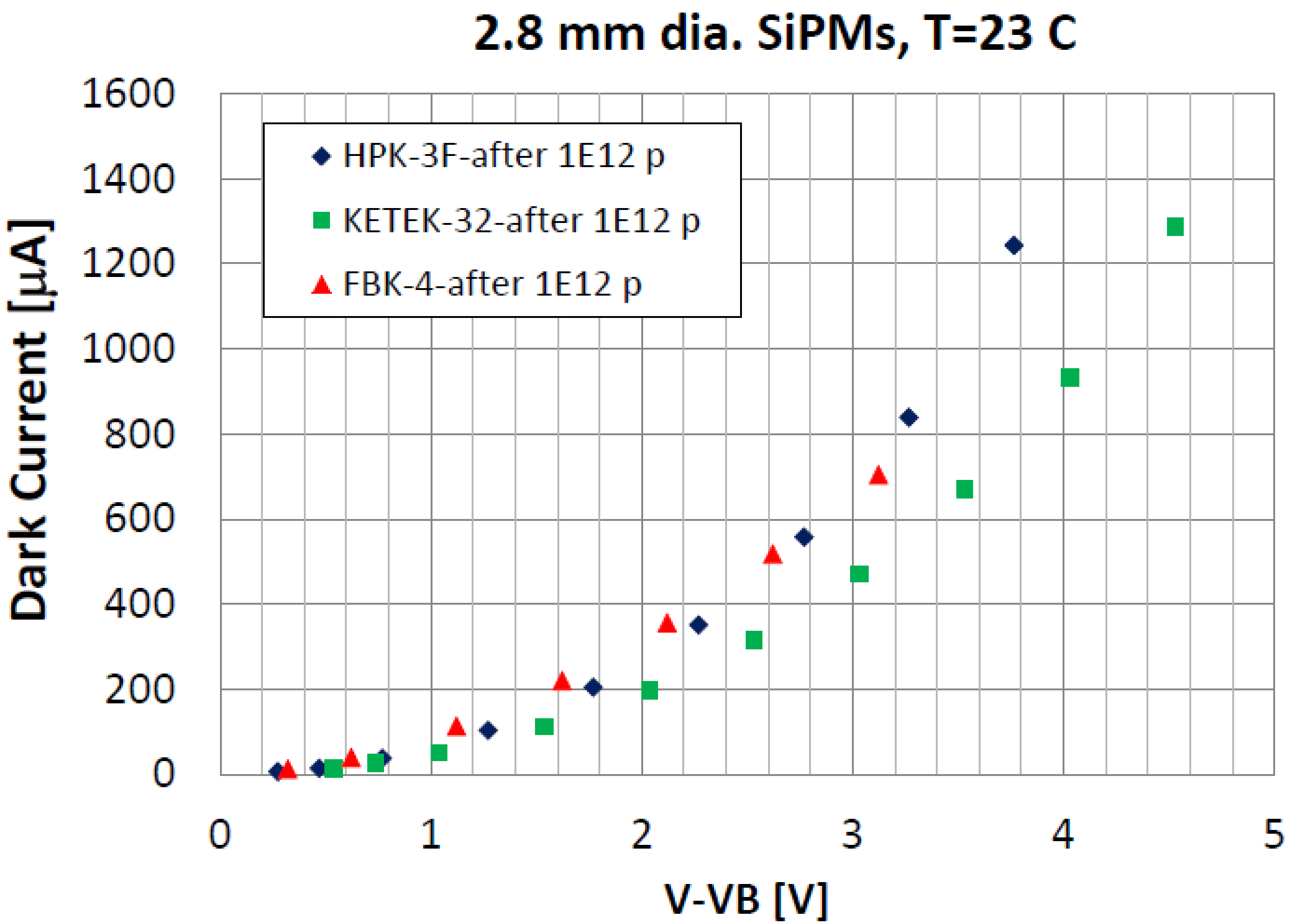
Number of photoelectrons vs. bias (FBK)



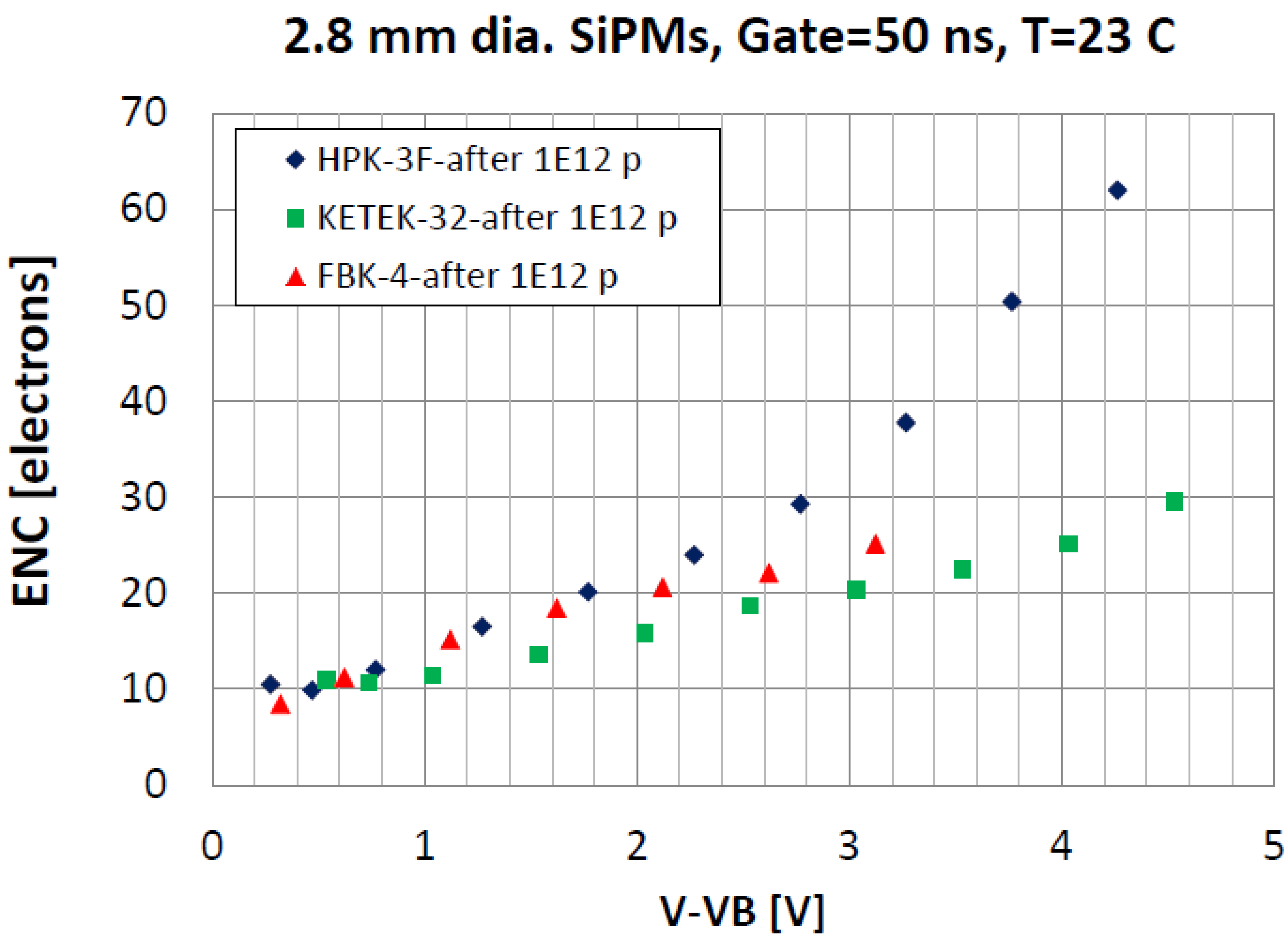
~25 % signal PDE reduction was measured for the irradiated FBK SiPM (< 15% PDE was measured for FBK SiPMs after 2E12 n/cm^2). <u>Being transparent before proton irradiation the Epotek epoxy became yellow!</u> The SiPM epoxy protection was not properly done. We should admit our mistake.

SiPM measured dark currents and noise after irradiation were corrected for a difference in neutron fluences (< 12 %) and SiPMs active area: recalculated for an active area of 2.8 mm in dia.

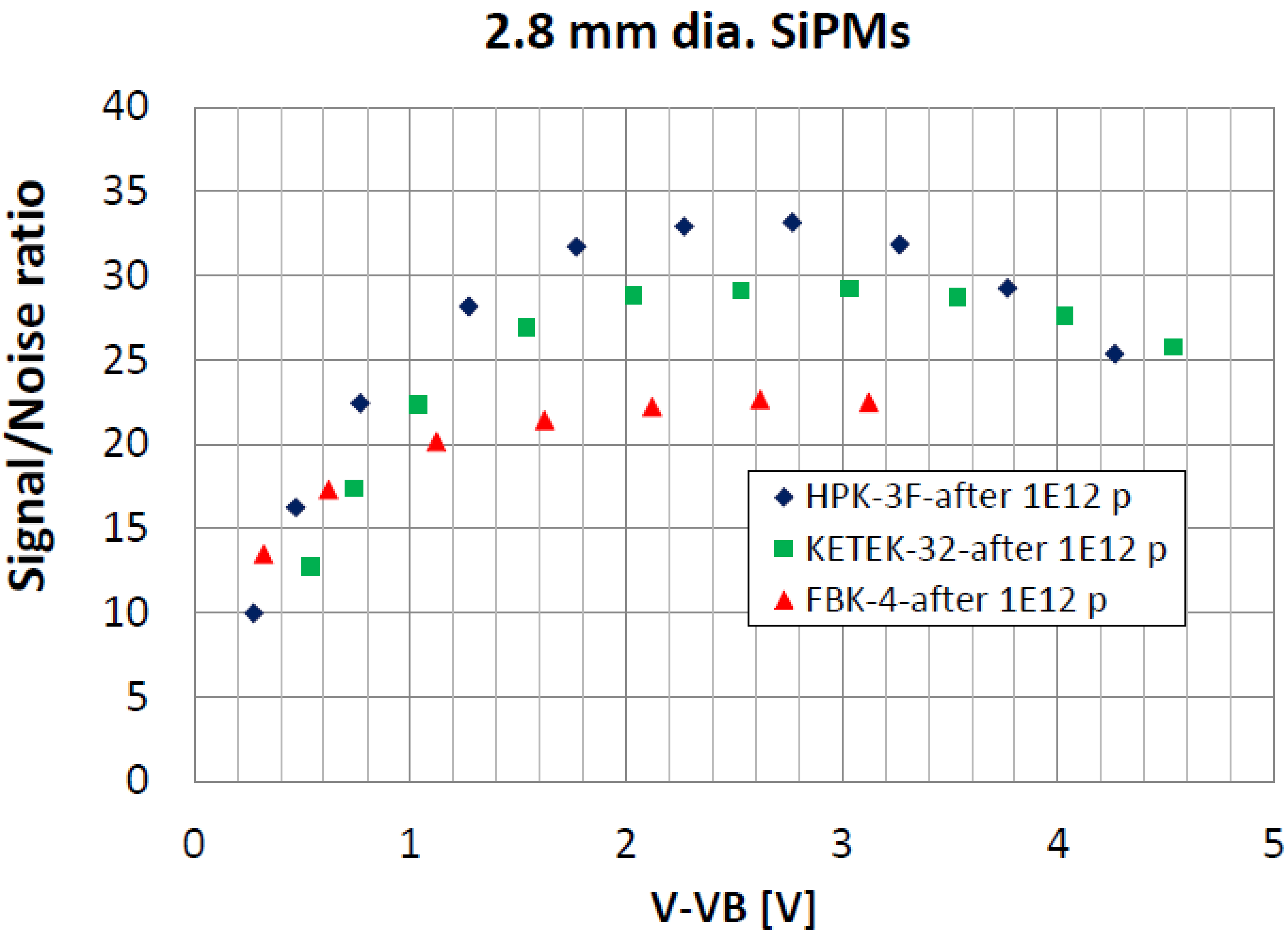
Dark Current vs. V-VB, T=23 C



Noise vs. V-VB, Gate=50 ns

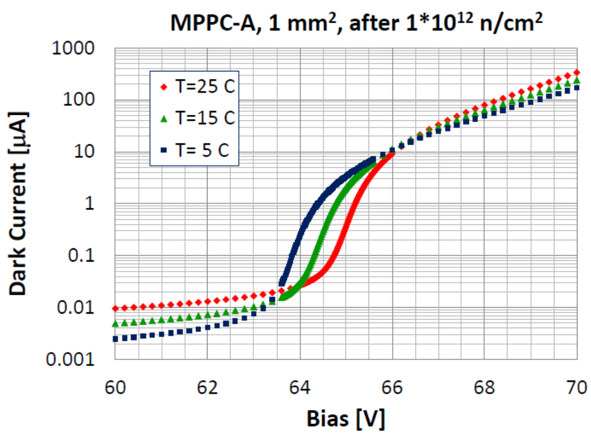


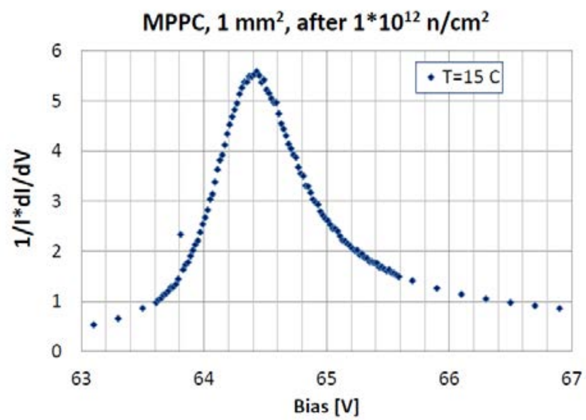
Signal/Noise Ratio vs. V-VB – 515 nm LED (N_γ~4200 photons/pulse)

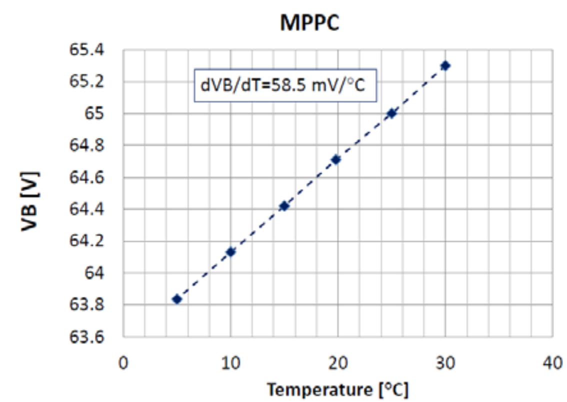


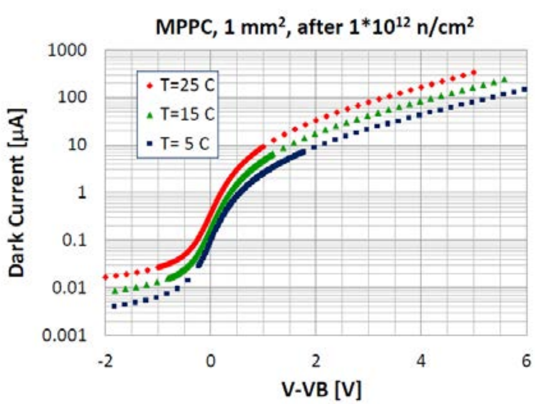
Dark Current vs. temperature study (HPK. KETEK, FBK SiPMs, CMS ECAL APD and HPK PIN photodiode)

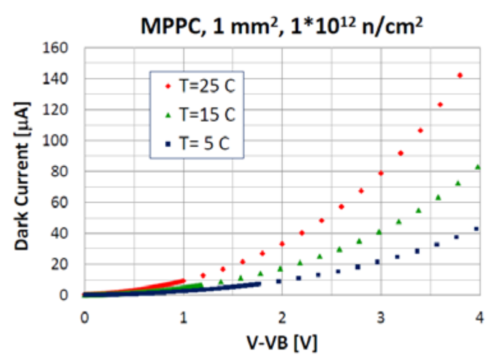
Dependence of the SiPM dark current on the temperature (example: HPK MPPC)

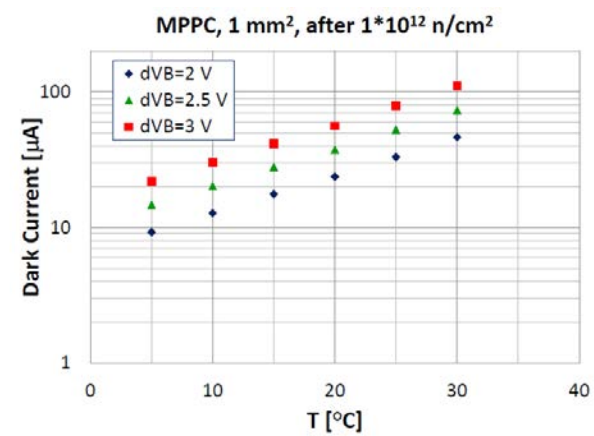




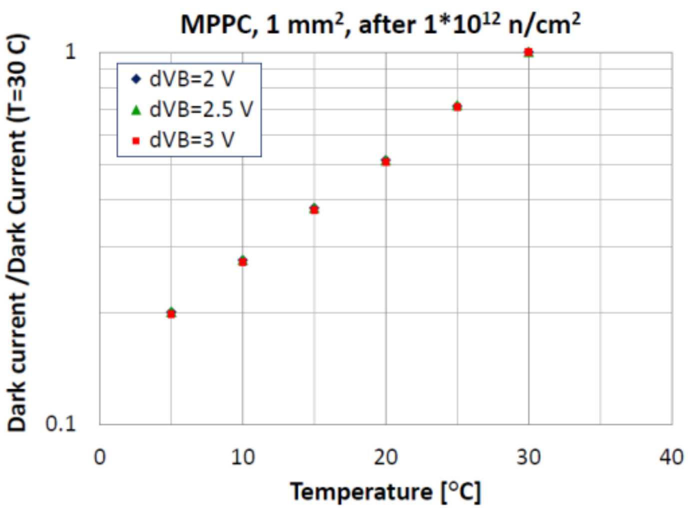


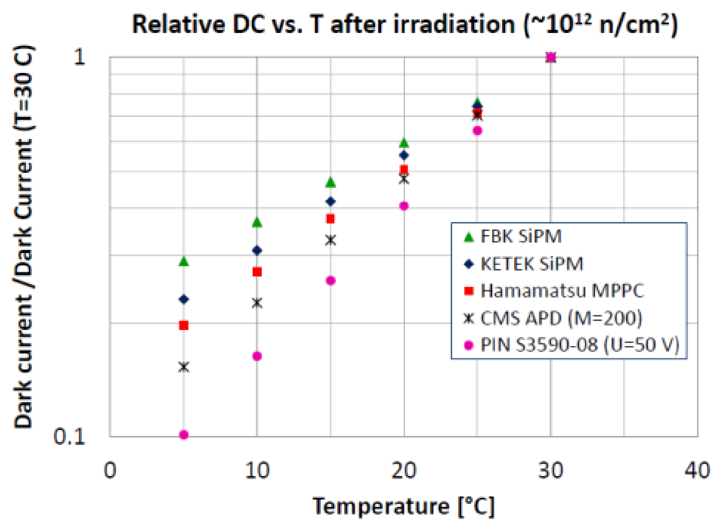


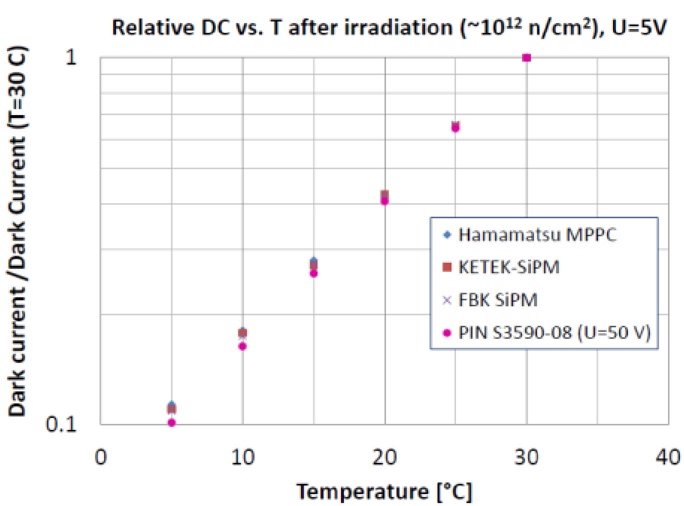




Dependence of the SiPM dark current on the temperature (FBK, KETEK, HPK SiPMs, CMS APD, and PIN photodiode)







We observed a very weak dependence of the SiPM's dark current decrease with temperature on the dVB. SiPM dark currents at low voltage (5V) behave similar with temperature to that of 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.

Summary

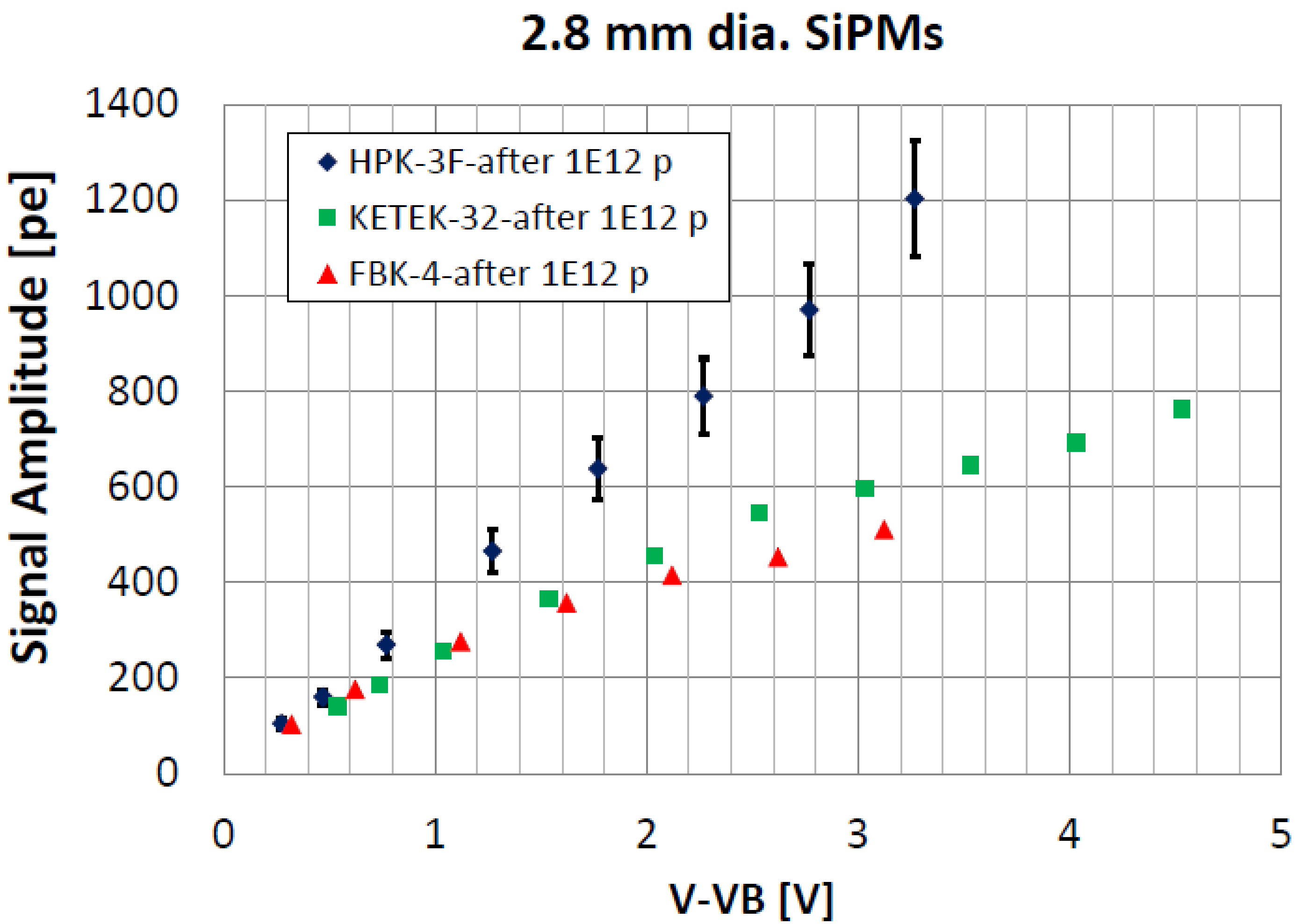
The CMS HCAL Upgrade SiPM candidates (made by HPK, KETEK and FBK) were irradiated with $1*10^{12}$ 1/cm^2 62 MeV protons ($2*10^{12}$ n/cm^2 1 MeV equivalent). All SiPMs survived this irradiation. Signal/noise ratio was found to be the best for the HPK SiPM. However a change of VB (~175 mV) was measured for these SiPMs after irradiation/annealing. The change of VB causes a 30% Gain*PDE reduction while keeping SiPM voltage stable. The SiPM Gain and PDE can be recovered by bias voltage increase. No change of VB was measured for the KETEK and FBK SiPMs after irradiation and annealing.

Summary (cont.)

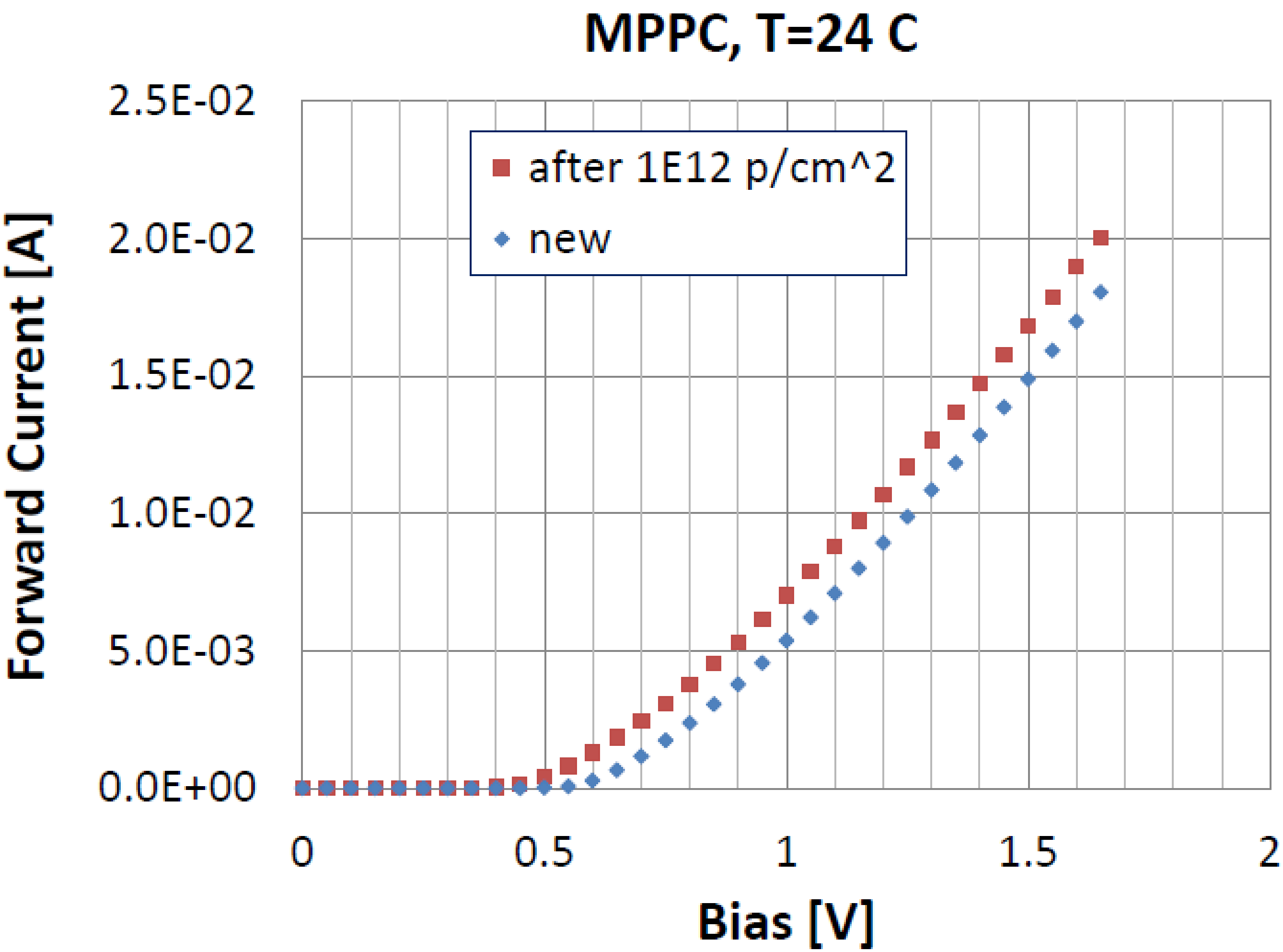
Dependence of dark currents of irradiated SiPMs (operated over VB) on the temperature is different from that measured at low voltages (in photodiode mode). We think that SiPM electric field shape is responsible for this effect → dark current vs. temperature dependence of SiPMs with higher VB (and lower peak electric field) are closer to that of PIN (low electric field) diodes. One of the explanations is that generation-recombination process in silicon (which is responsible for SiPM dark current generation) can have significant dependence on the peak value of the p-n junction electric field strength → SiPM electric field engineering may significantly reduce dark current/noise of irradiated SiPMs especially at low temperatures.

Back-up

Number of photoelectrons vs. V-VB

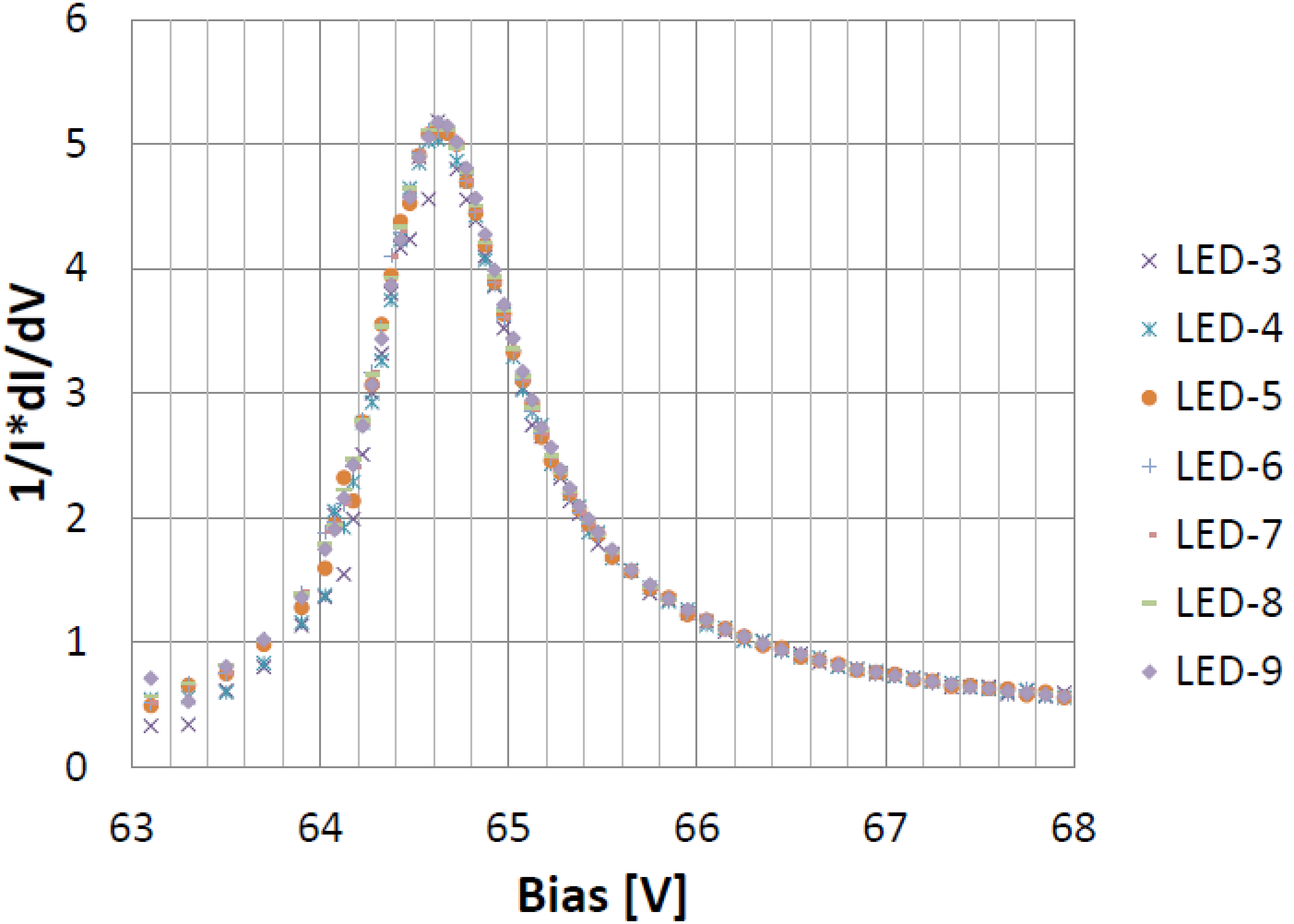


Summary



MPPC, T=24 C
2.5E-02
2.0E-02
1.5E-02
1.0E-02
5.0E-03
0.0E+00
Forward Current [A]
after 1E12 p/cm^2
new
0
0.5
1
1.5
2
Bias [V]

VB vs. light intensity



Summary