Radiation damage study of SiPMs for the CMS BH HGCAL (SiPM-on-Tile CE-H HGCAL)

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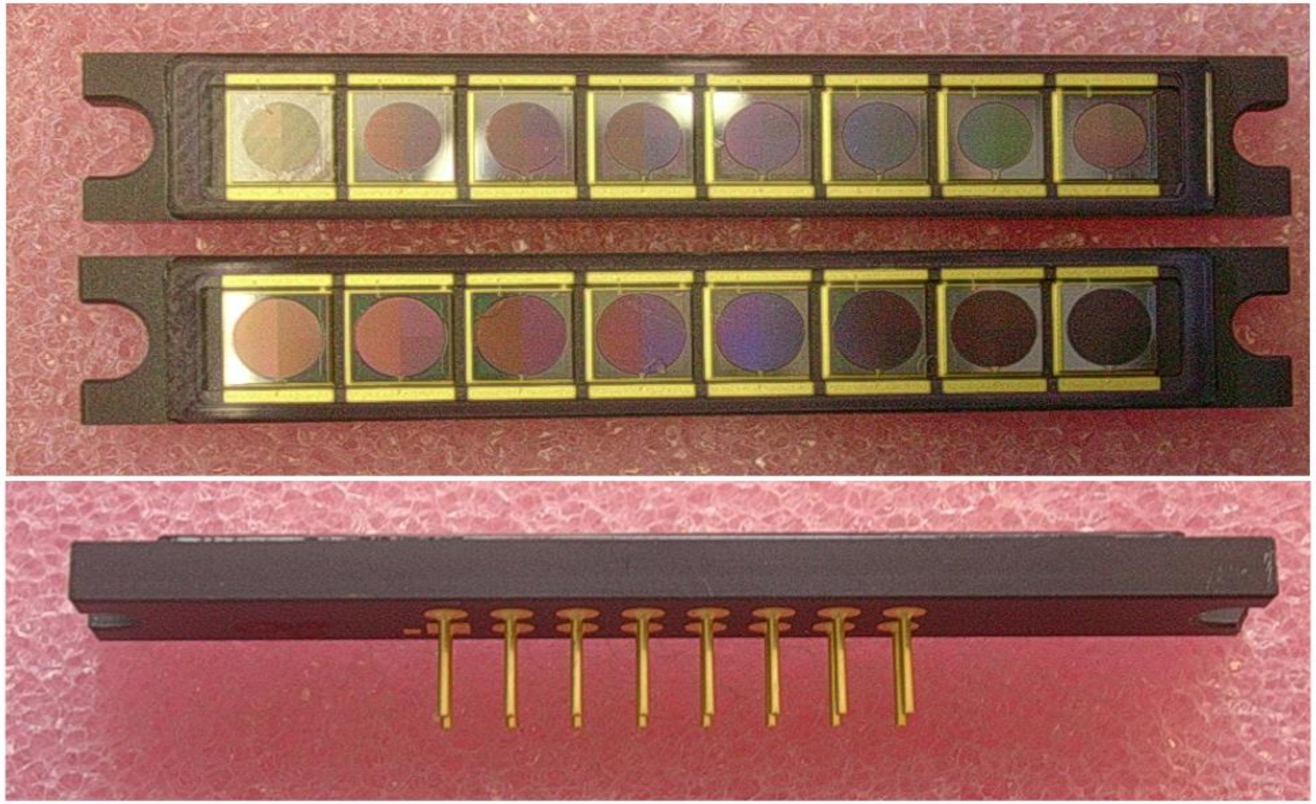
Outline

- Study of HE/HB SiPMs after 5E13 n/cm^2 (Ljubljana reactor)
- Irradiation and annealing study of the HPK SiPM irradiated at T=-30 °C
- HPK S13190-1015 TSV SiPM
- New HDR2 SiPMs from Hamamatsu

HE/HB SiPMs irradiation studies

- HE/HB SiPM irradiated up to 5E13 n/cm^2 (1 MeV neutron equivalent, Ljubljana reactor). It was sent to CERN inside cooler.
- I-V curves were measured (with help of J.Gonzalez) in b.28 inside freezer
- After that it was warmed to room T and was annealed at RT for 103 days
- Than it was placed inside our new freezer and measured its dark current and noise using 450 nm pulsed LED light $<N_{photons}>$=340 photons/pulse using recently built **new SiPM setup: metal box with optical connector and Peltier cooler, PT-100 temperature sensor, low noise fast amplifier. SiPM temperature is stabilized with a precision of 0.01 ^{o}C using Labview code developed by Anton.**
- ENC was calculated for 15 ns integration time (request of J.Virdee)

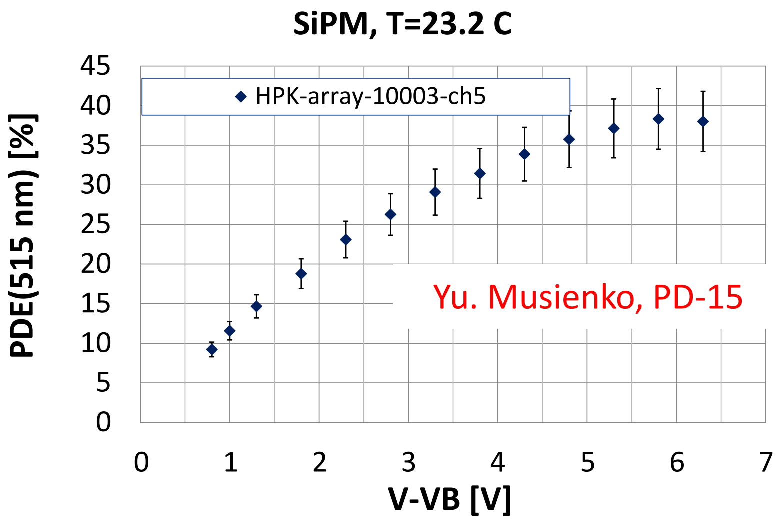
HE MPPC arrays (Ø2.8(3.3) mm SiPMs) and 3x3 mm^2 MPPCs (SMD package)

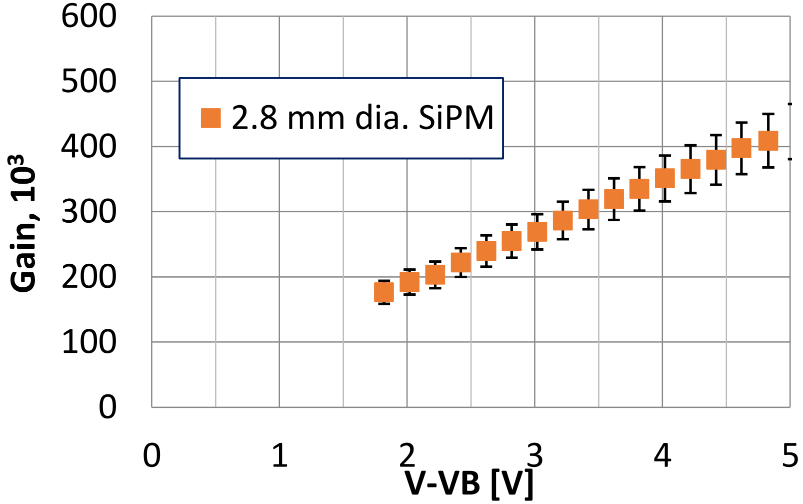


S10943-4732
S10943-4733

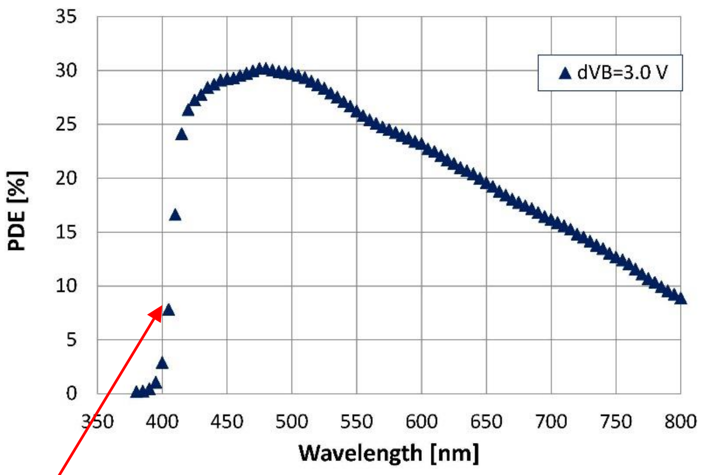
Parameter	HPK
Cell size [μm]	15
Sens. area [Ømm]	2.8
Operating temperature [°C]	24
VB [V]	~65
V_{op}-VB (V)	3.0
Dark Current [nA]	150
PDE(515 nm) [%]	27
Gain, x10^3	250
Capacitance [pF]	215
Recovery time [ns]	7-8
Excess Noise Factor	1.15
Optical Cross-Talk [%]	12
After-pulses [%]	<2
dVB/dT [mV/°C]	59

Large dynamic range SiPMs for the CMS HE/HB HCAL Upgrade

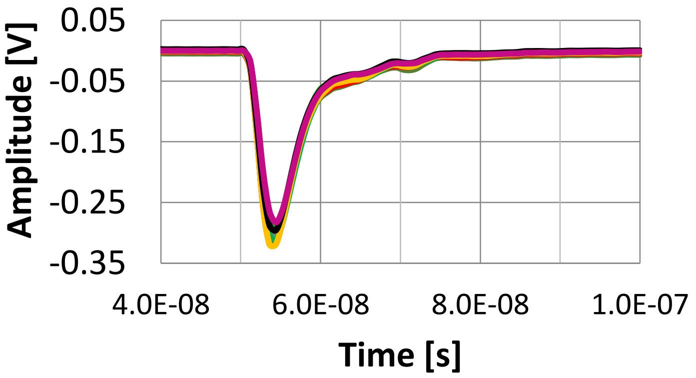




2100 SiPM arrays have been delivered to CERN during 2016 -2018



SiPM laser response



Recovery time 7-8 ns

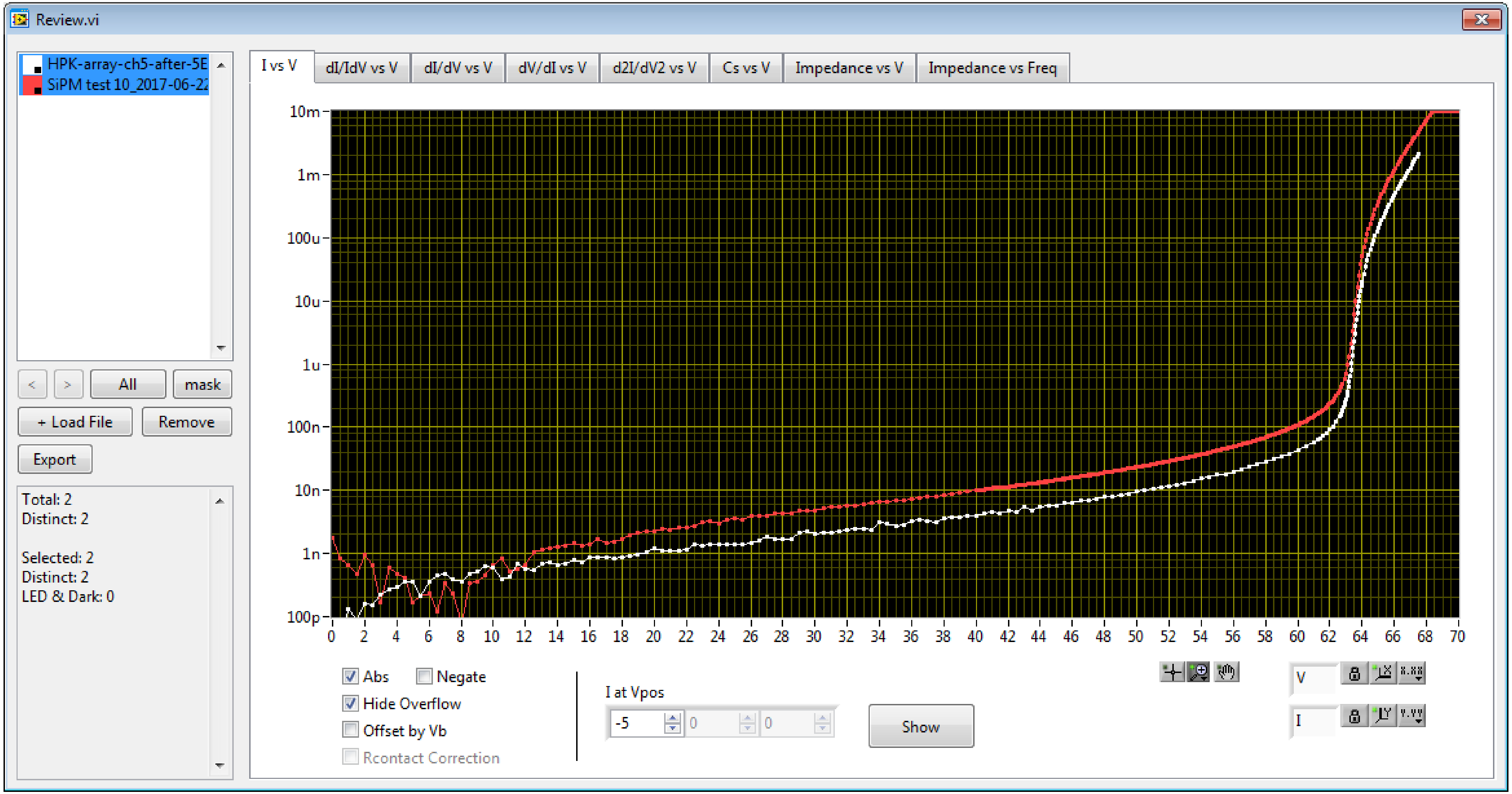
Quartz widow with special filter was designed by HPK to cut off UV light which can be produced by muons and hadrons in plastic fibers

Dark current comparison at T=-30 °C (before/after 103 days of annealing at RT)

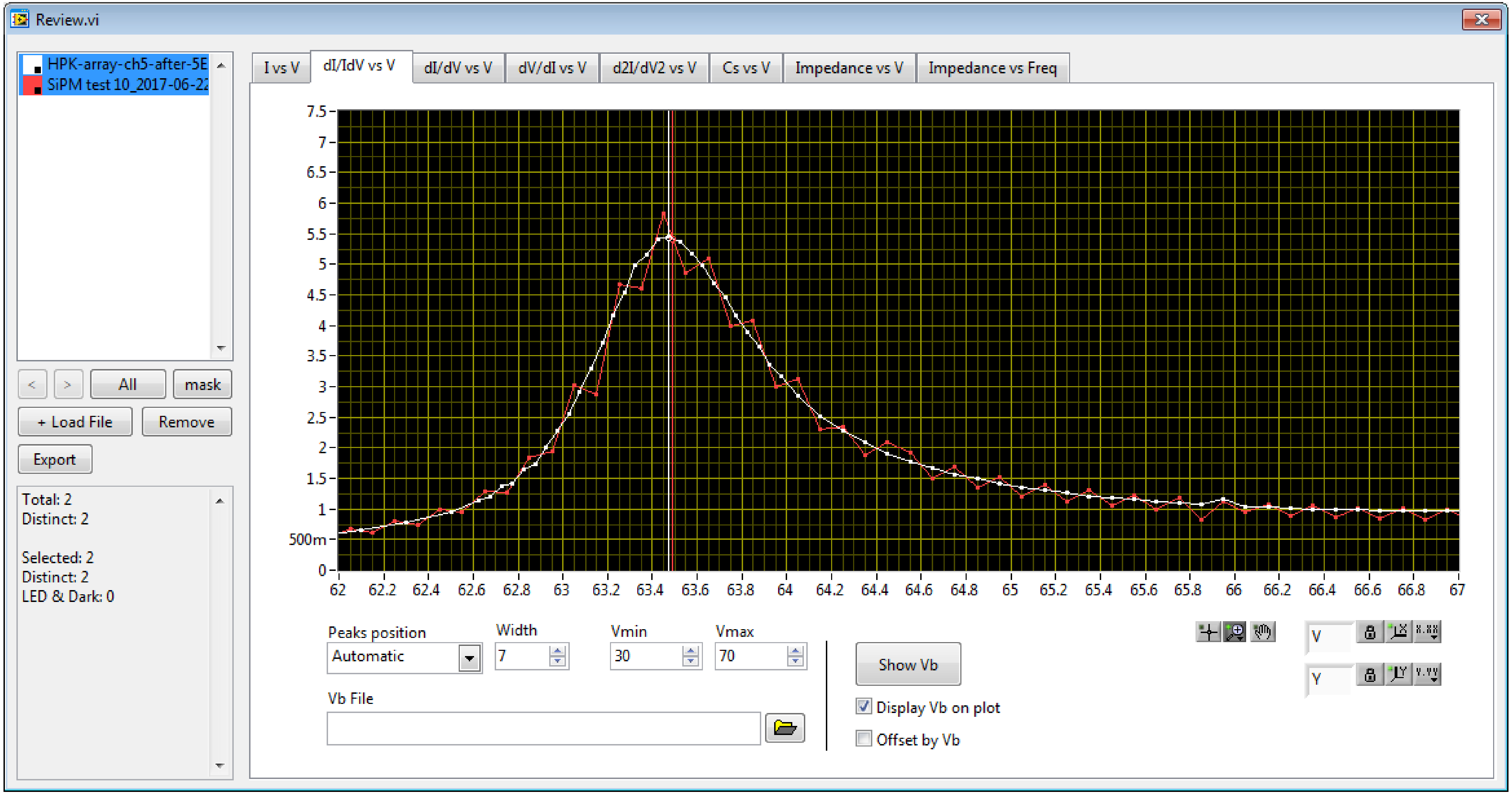
- HE-11064 SiPM (**2.8 mm dia. or 6.16 mm^2 in area**) was irradiated up to 5E13 n/cm^2 in Ljubljana. It was sent to CERN inside cooler.
- I-V curves were measured inside freezer at T=10 ^{o}C ÷ -40 ^{o}C
- After that it was warmed to room T and was annealed at RT for 103 days

I-V curves were measured again at T=-30 ^{o}C ÷ -40 ^{o}C .

Dark current vs. Bias (before/after annealing at RT)

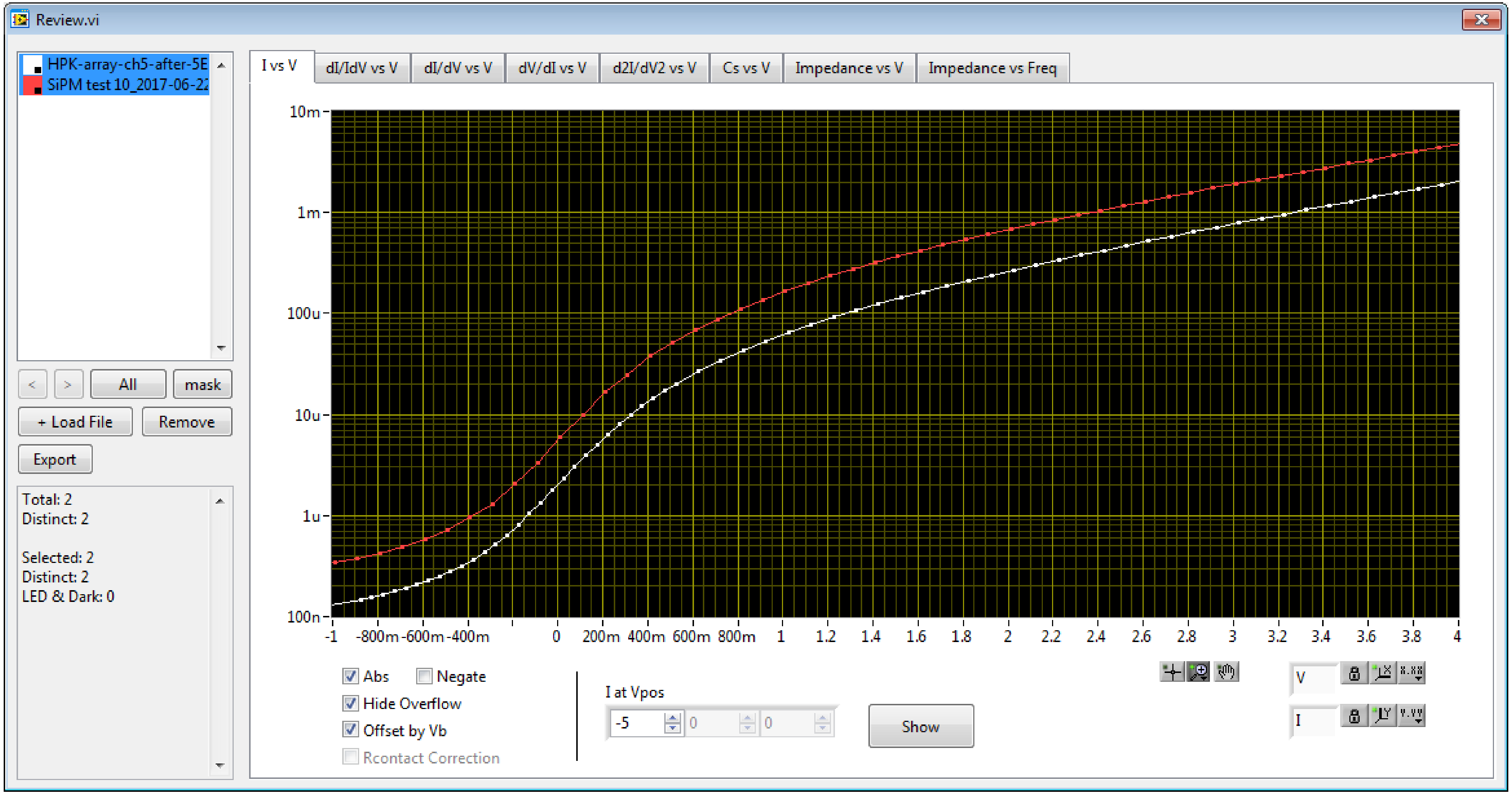


VBs (before/after annealing at RT)



Maximum of dlnI/dV method was used. The VB of the HE SiPM didn't change after RT annealing!

Dark Currents vs. dVB

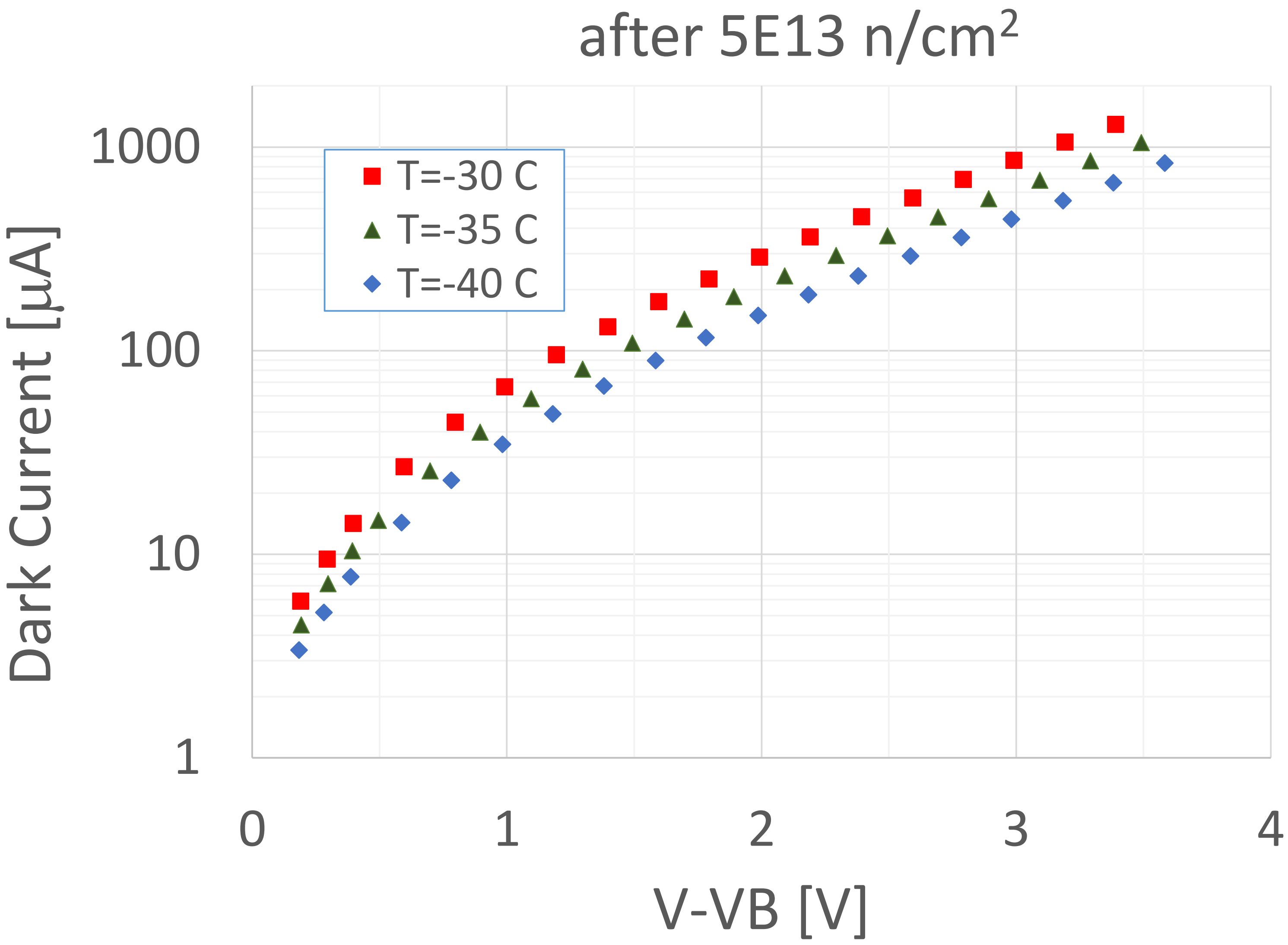


Dark current comparison (before/after 103 days of annealing at RT)

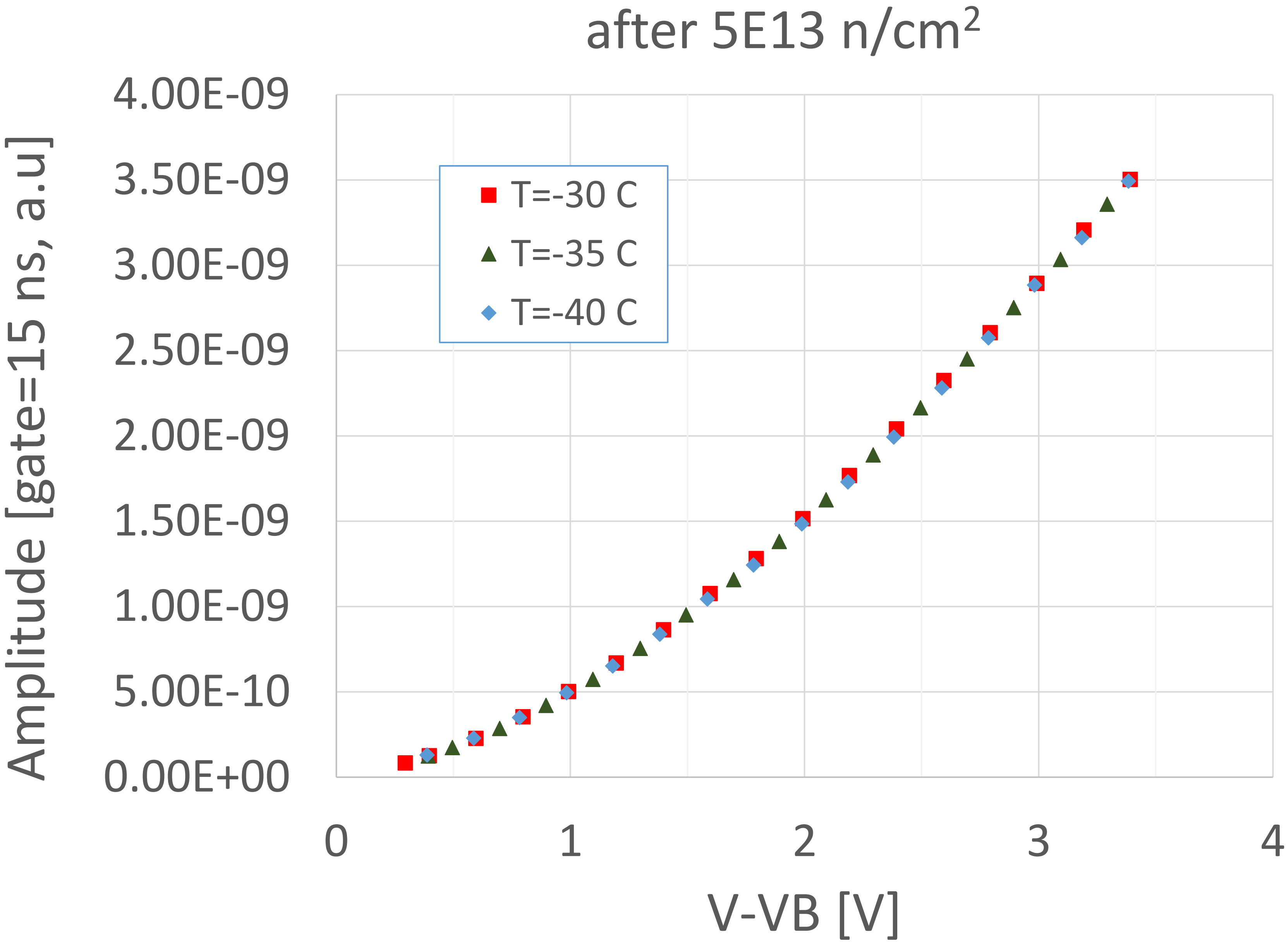
V-VB, V	Idark-before, uA	Idark-after, uA	Ratio
-5	0.07635	0.03055	2.499182
-3	0.1248	0.04894	2.550061
-1	0.3393	0.1299	2.612009
0.5	49.27	18.6	2.648925
1	162.5	61.84	2.627749
1.5	365.2	138.5	2.636823
2	675.1	262.3	2.57377
2.5	1154	460.7	2.504884
3	1877	768.6	2.442103

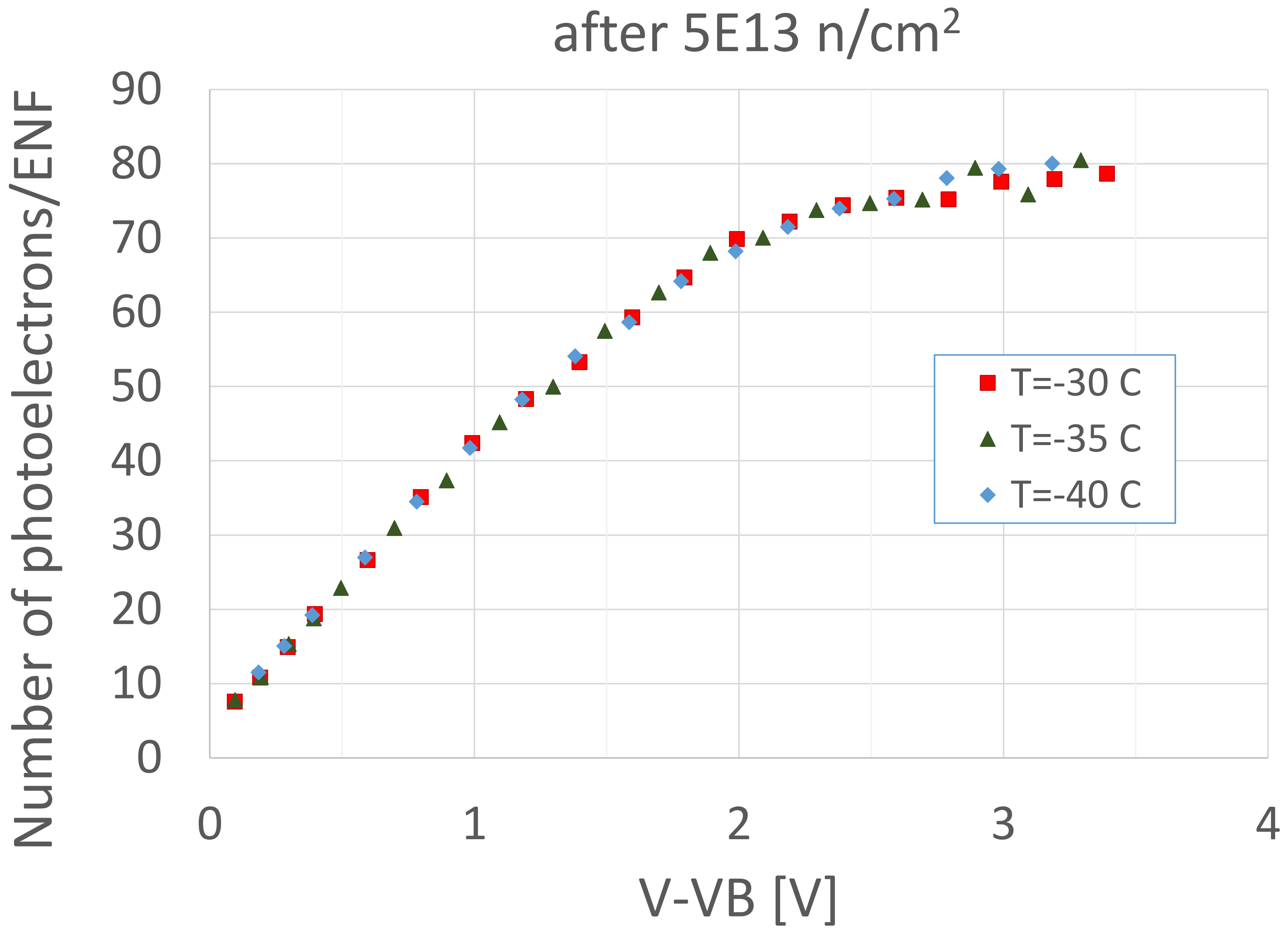
The HE SiPM dark currents were reduced by a factor of 2.5 in comparison to ones measured before room temperature annealing.

Pulsed LED (450 nm) measurements at T=-30 °C ÷ -40 °C (<$N_{photons}$>=340 photons/pulse)

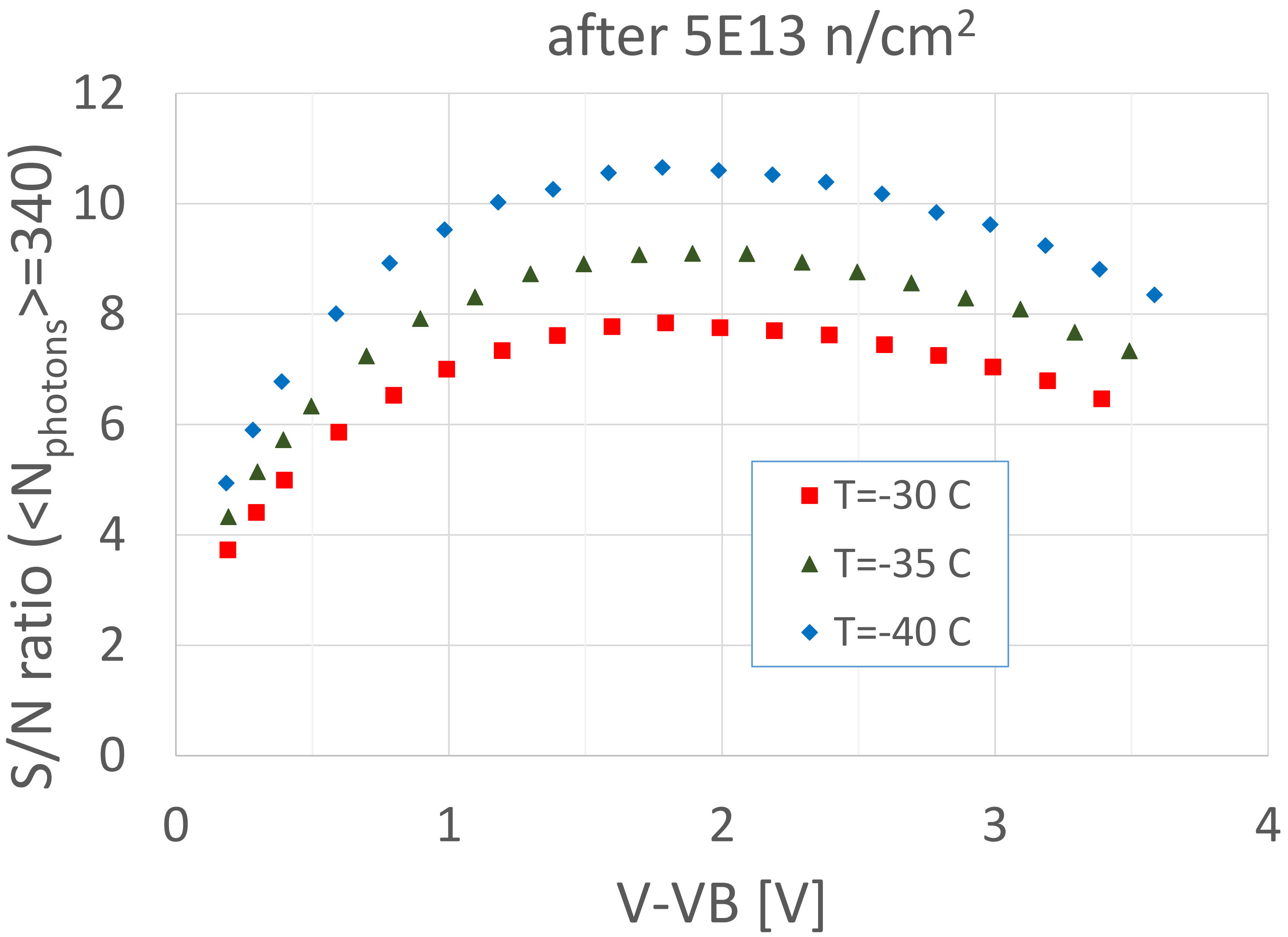


I_{dark}(-30 ^{o}C)/I_{dark}(-40 ^{o}C)=1.93 at dVB=1÷3 V (or x1.068 ^{o}C)

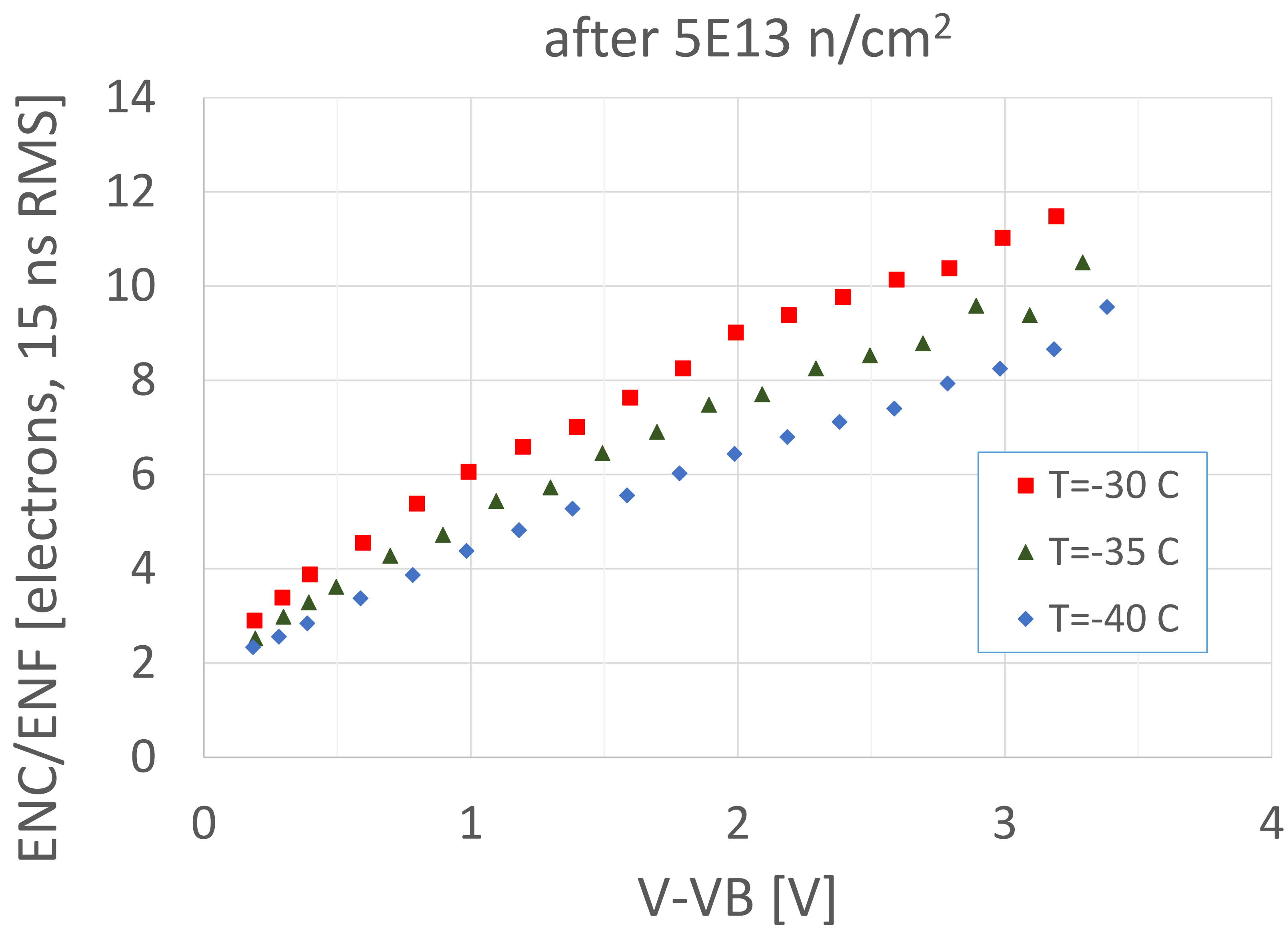

after 5E13 n/cm2
Amplitude [gate=15 ns, a.u]
4.00E-09
3.50E-09
3.00E-09
2.50E-09
2.00E-09
1.50E-09
1.00E-09
5.00E-10
0.00E+00
0
1
2
3
4
V-VB [V]
T=-30 C
T=-35 C
T=-40 C



No blocking effects observed: cell occupancy is low. Self-heating effects reduced by proper heat removal.



Maximum of S/N ratio is reached at dVB=1.5 ÷ 2.5 V



ENC/ENF = 9.8 pe RMS at dVB=2.4 V

Discussion

Can we use these results to calculate signal to noise ratio for 25 pe MIP signal and 1 mm^2 **HE SiPM** irradiated/annealed at T=-30 ^oC?

For 1 mm^2 **HE SiPM** irradiated/annealed at T=-30 ^oC dark current will be 6.16/2.5=2.46 lower in comparison to the 2.8 mm diameter HE SiPM annealed at room temperature ➔ ENC(dVB=2.4 V)~9.8/SQRT(2.46)=6.25 pe (RMS)

S/N ratio 25 pe MIP is expected to be S/N=25/6.25=4

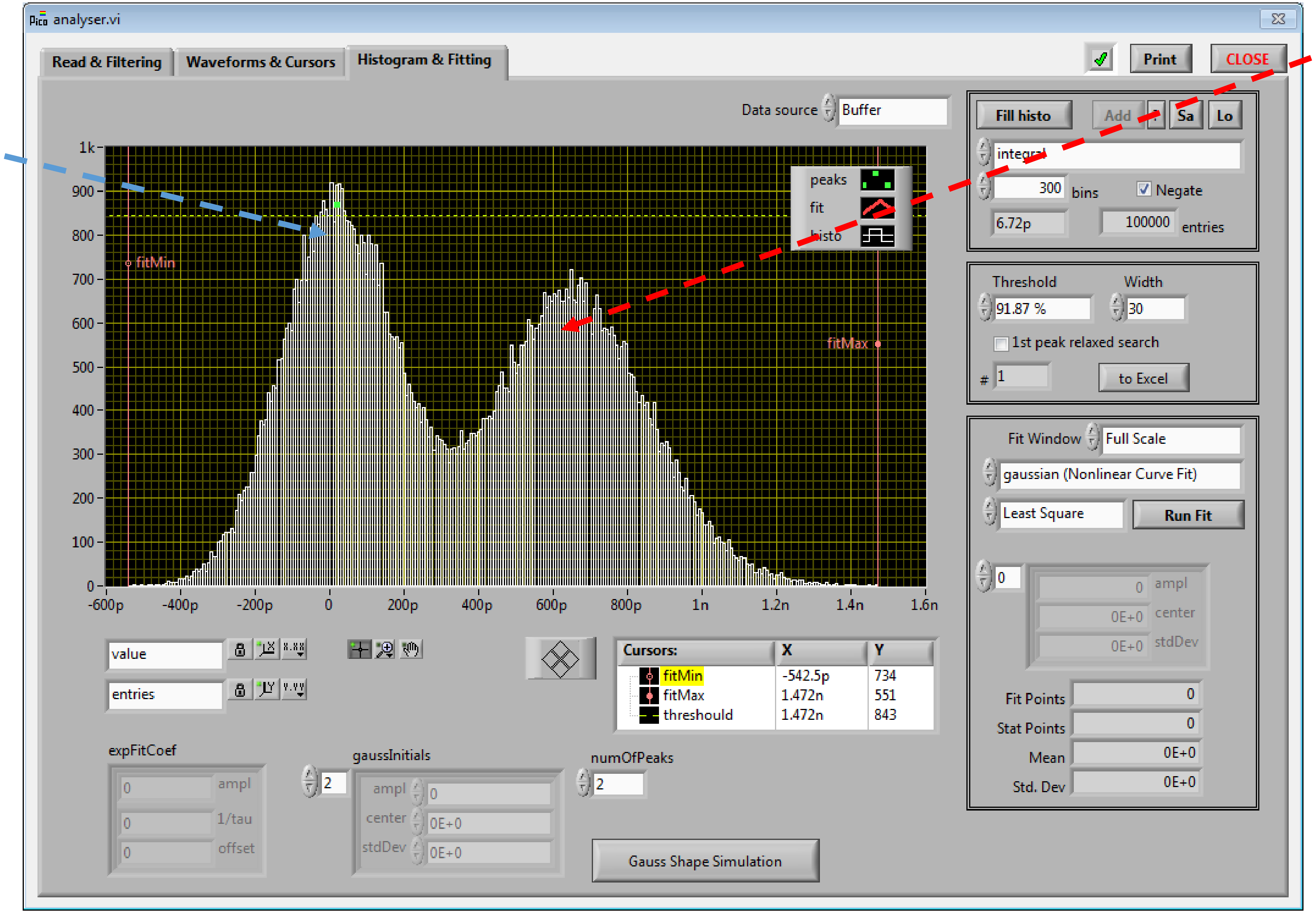
For the HE SiPM dark current at T=-44 ^oC dark current will be a factor of 2.5 lower in comparison to T=-30 ^oC.

We can simulate this situation setting the average LED amplitude to 25 pe and measuring noise and amplitude spectra at T=-44 ^oC

T=-44 °C

LED signal $\langle N_{pe} \rangle$=25

ENC~6.3 p.e.

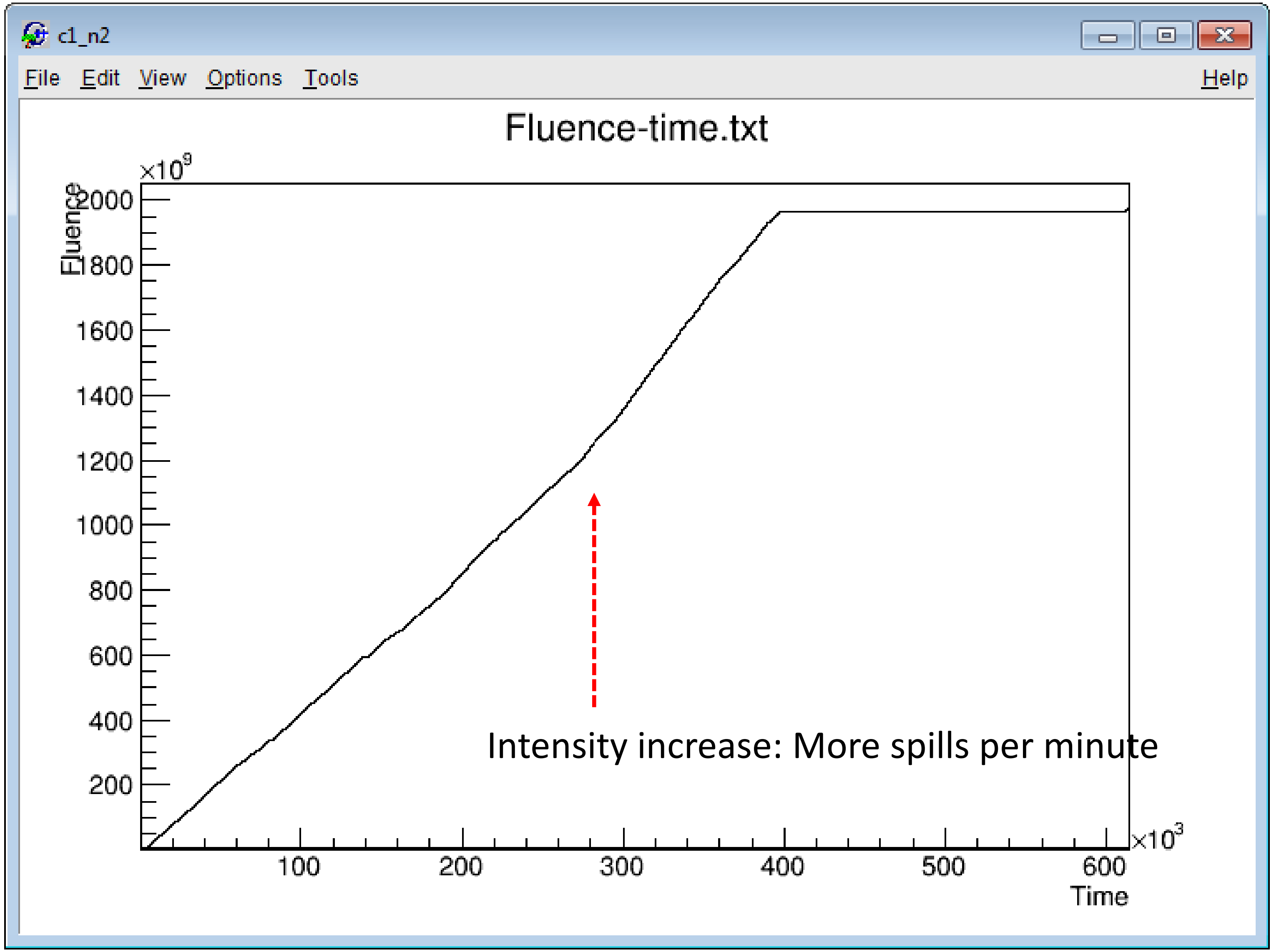


Sig/Noise~4

HPK 1 mm^2 SiPM irradiated at T=-30 °C. Annealing studies at low temperature.

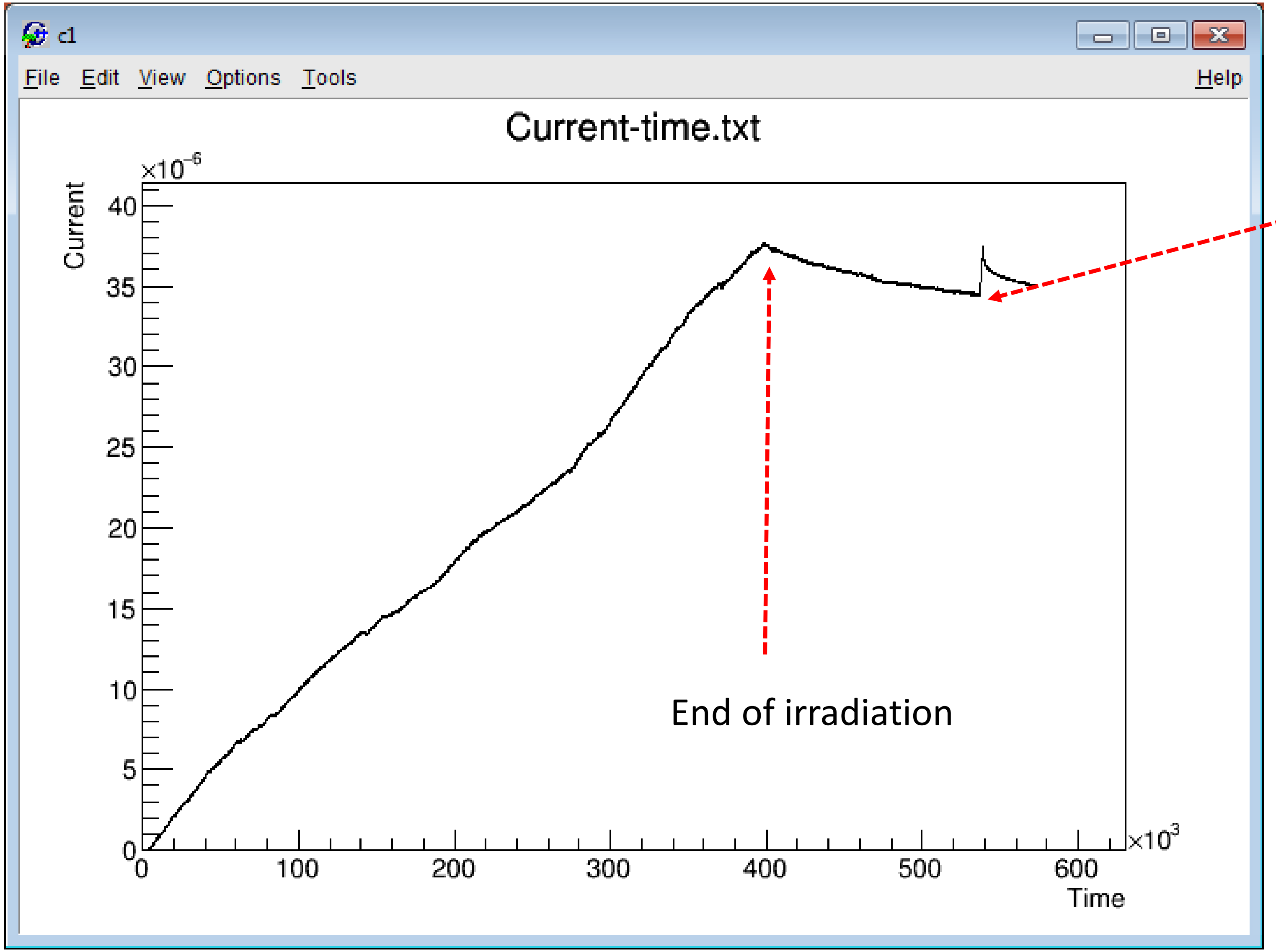
HPK 1 mm^2, 15 um cell pitch SiPM (HE/HB type) was irradiated in cold (T=-30 °C, Peltier cooler) at CERN CHARM facility. Set-up was located close to the point where 24 GeV proton beam hits the wall – backscattered neutrons (also gammas, pions, protons). "LHC like neutron energy spectra". SiPM was irradiated with $2.0*10^{12}$ n/cm^2 (1 MeV neutron equivalent) total neutron fluence. After irradiation SiPM was kept in cold to study annealing at low temperatures.

Fluence [1 MeV eq. n/cm^2] vs. Time [sec]



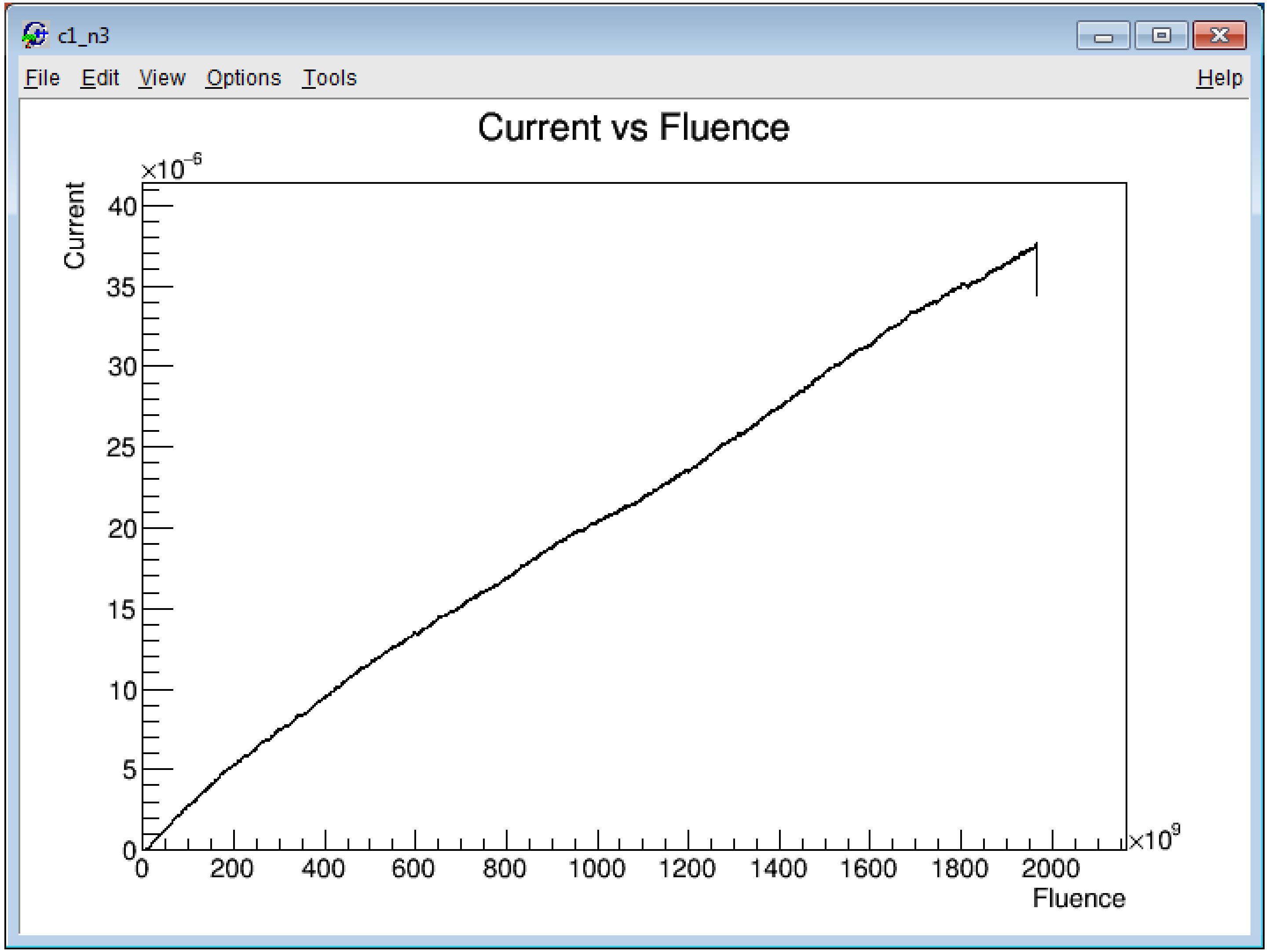
2E12 n/cm^2 (1 MeV equivalent) in ~4.6 days of irradiation

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

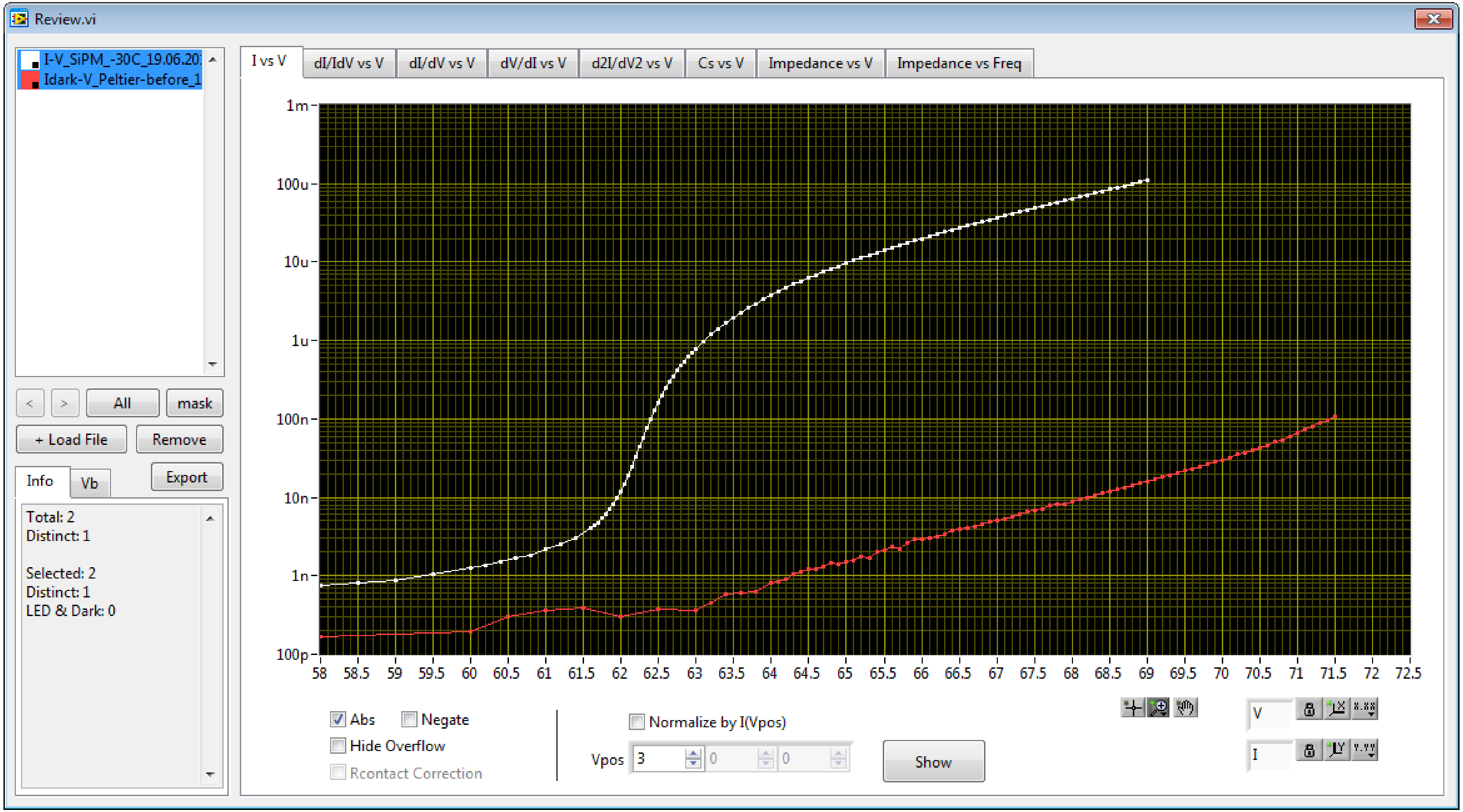


Bias was set OFF and set to 67 V again

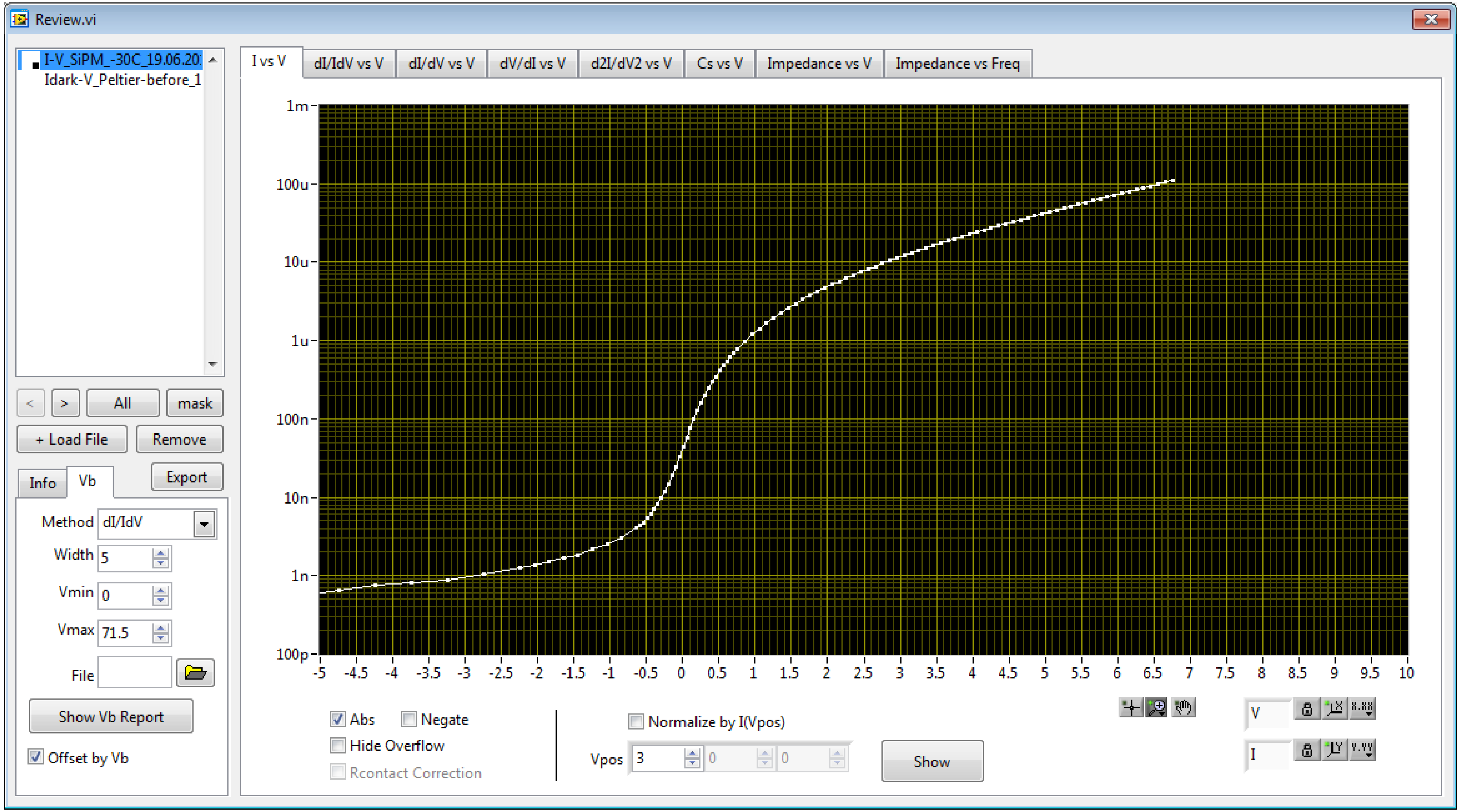
I_{dark} vs. Fluence, T=-30 °C, U=67.0 V (dVB=4.76 V)



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

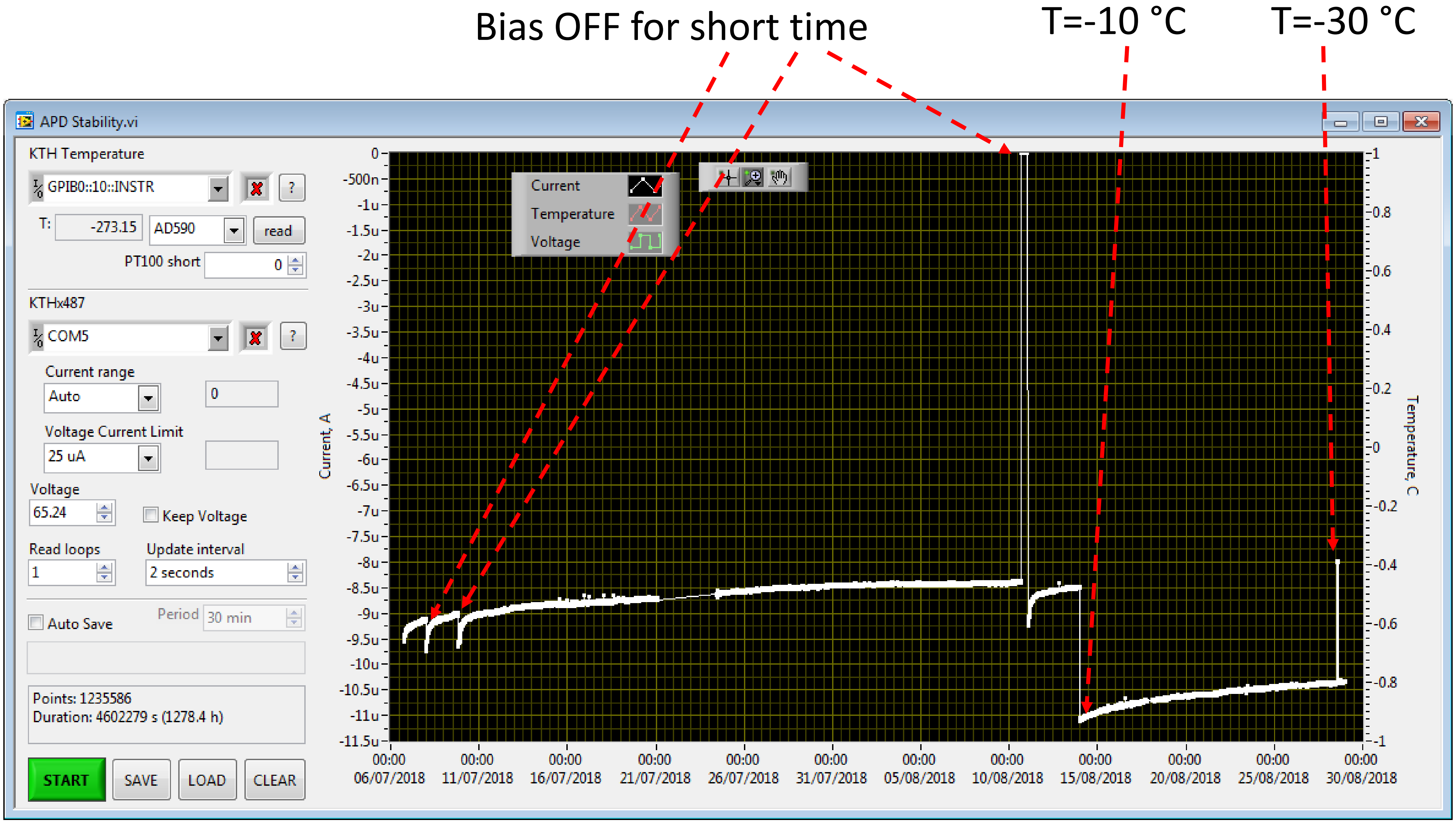


Idark vs. dVB, T=-30 °C



At dVB = 3.0 V Idark = 11.71 uA/mm^2 after 2E12 n/cm2 agrees with the dark current of the HE SiPM irr. up to 5E13 n/cm2 in Ljubljana Idark=305 uA/mm^2 (dVB=3 V, T=-30 °C)

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



HPK S13190-1015 SiPMs (TSV)

Model	Pixel size	Active area	Pixels	Vbd @ +25C	I_{dak}
S13190-1015	15 um	1 x 1 mm^2	4356	~ 64 V	~9nA at Vbd + 5V
S13615-1025	25 um	1 x 1 mm^2	1600	~ 52 V	~12nA at Vbd + 4V

Table 1: Specifications of the measured samples.

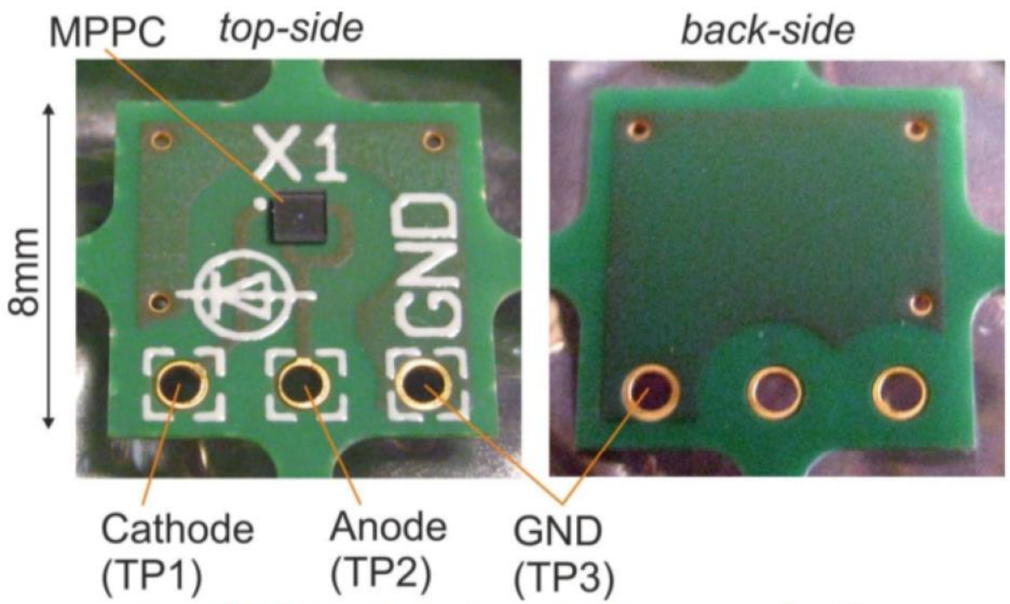


Fig. 1: MPPC Prototyping Board top-side (left) and bottom-side (right).

HPK S1390-1015, 1 mm^2, 15 um cell pith TSV SiPMs (internal structure is the same as the structure of the HE/HB SiPMs) were recently received from Hamamatsu. They were irradiated up to 2E12 n/ n/cm^2 , 5E13 n/cm^2 , 2E14 n/ n/cm^2 in Ljubljana. They were kept in a freezer after irradiation → sent to CERN inside a "beer" box → placed inside our new freezer (T=-30 °C) → removed from the freezer for 10 min to solder pins → placed in our new set-up (with Peltier cooler) inside the freezer → I-V curves measured for T= -10 °C ÷ -40 °C. Preliminary results look encouraging.

New HDR2 MPPCs from Hamamatsu (with trenches)

New HDR2 MPPCs received from Hamamatsu 3 weeks ago:

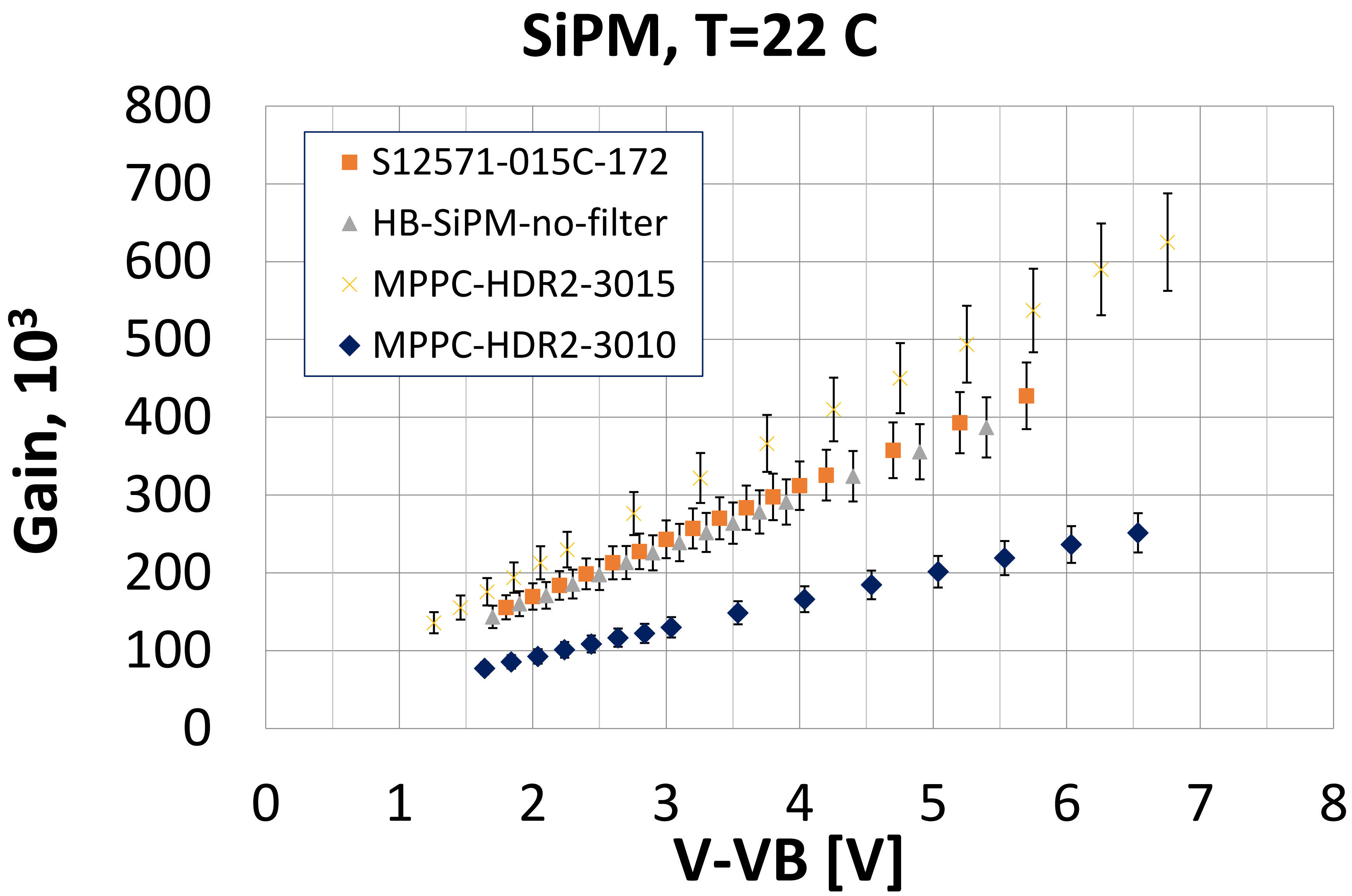
- MPPC-HDR2-3015: 15 um cell pitch, 3x3 mm^2;
- MPPC-HDR2-3010: 10 um cell pitch, 3x3 mm^2;

  Breakdown voltages~38 V, **PCB package**

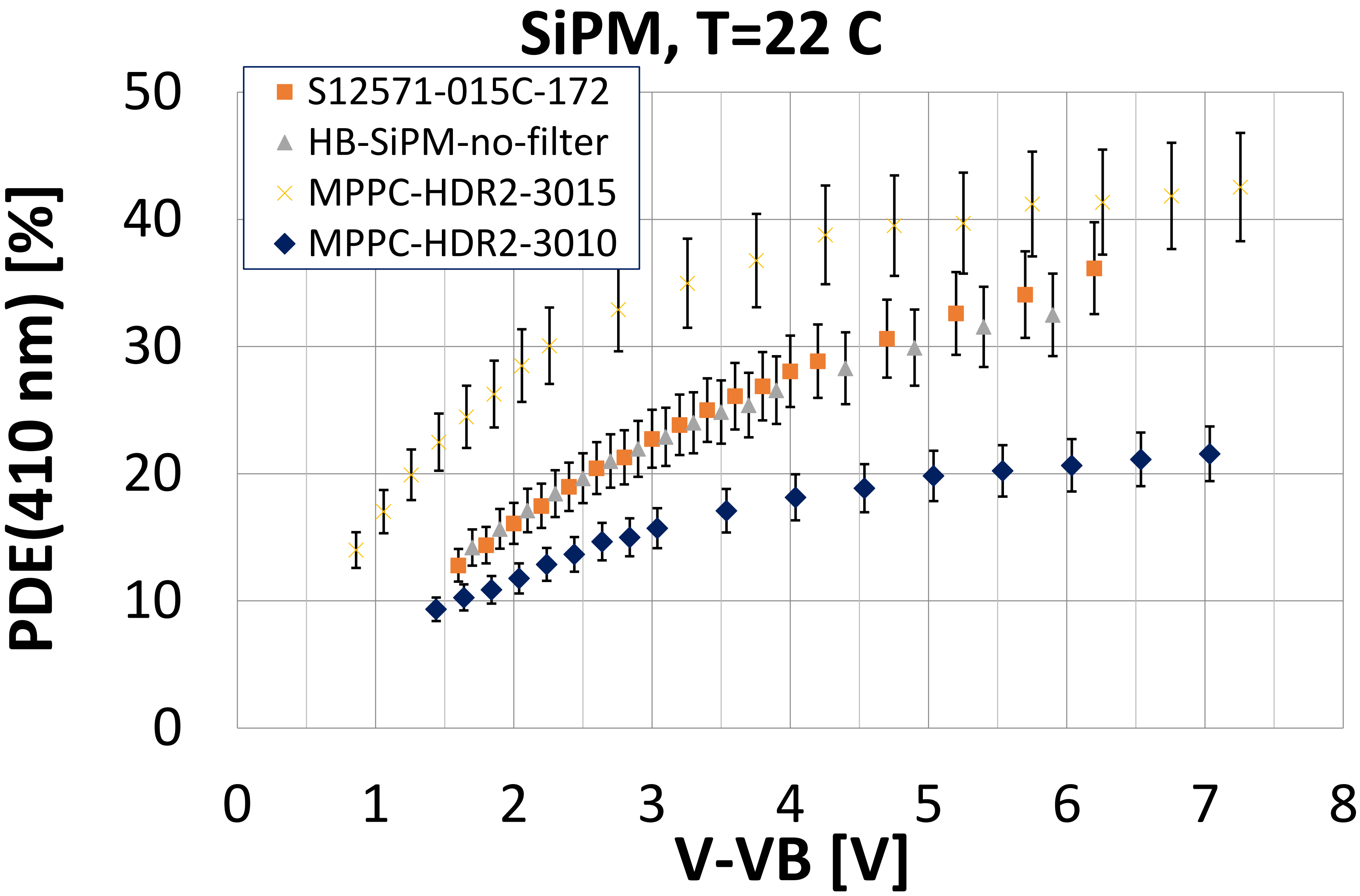
Some of their parameters were measured in our Lab (b.27)

Two HDR2 SiPMs (together with HB-no-filter-SiPM-array, 3.3 mm dia., 15 um cell pitch, **ceramic package**) were irradiated at CHARM (1÷2E12 n/cm^2 – to be confirmed next week). The SiPMs were annealed 80 min at 60 C. Their parameters (I-V, ENC/ENF …) were measured using fast 410 nm LED pulsed light (~3400 photons/pulse) at room temperature.

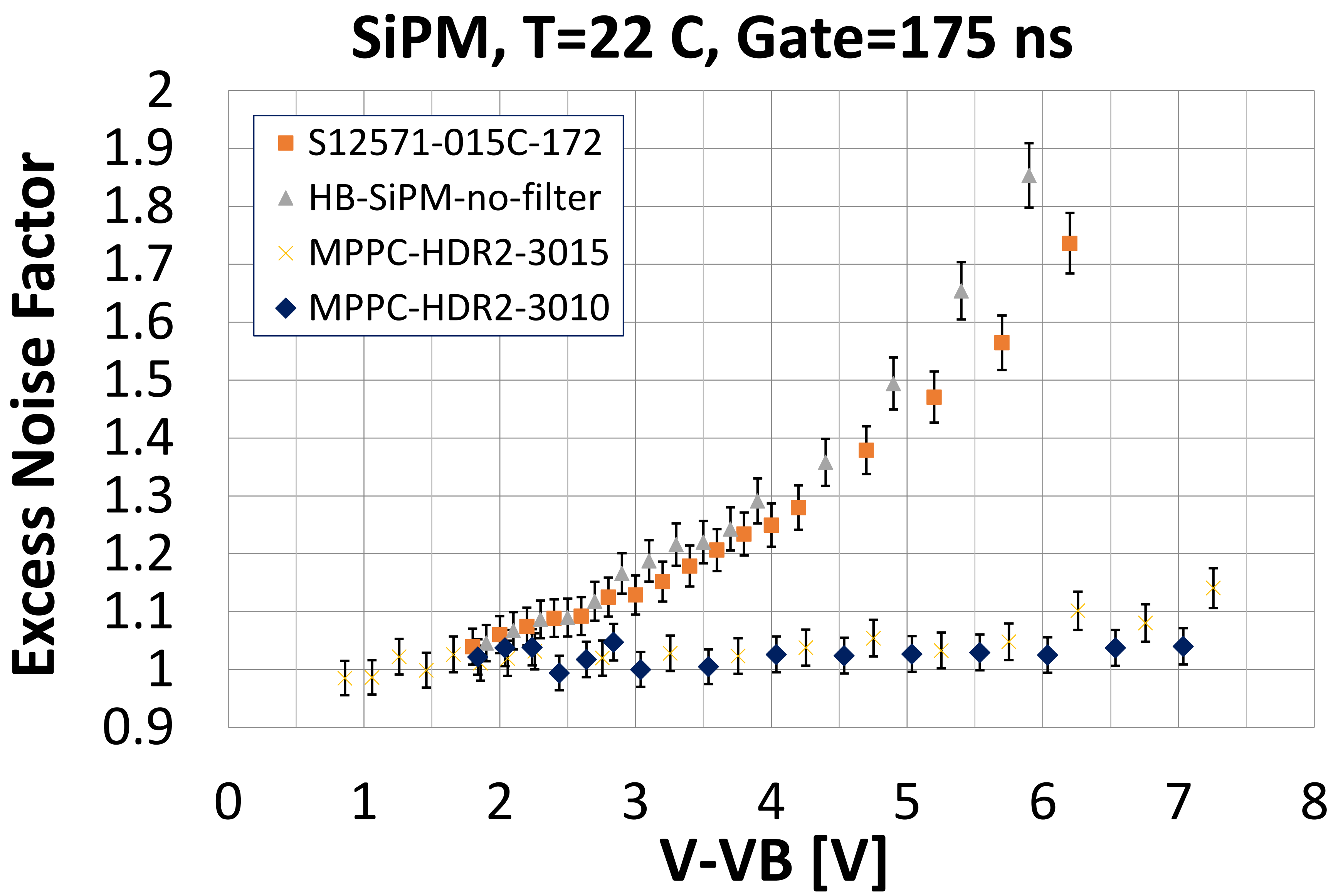
Gain vs. dVB


SiPM, T=22 C
800
700
600
500
400
300
200
100
0
Gain, 10³
S12571-015C-172
HB-SiPM-no-filter
MPPC-HDR2-3015
MPPC-HDR2-3010
0
1
2
3
4
5
6
7
8
V-VB [V]

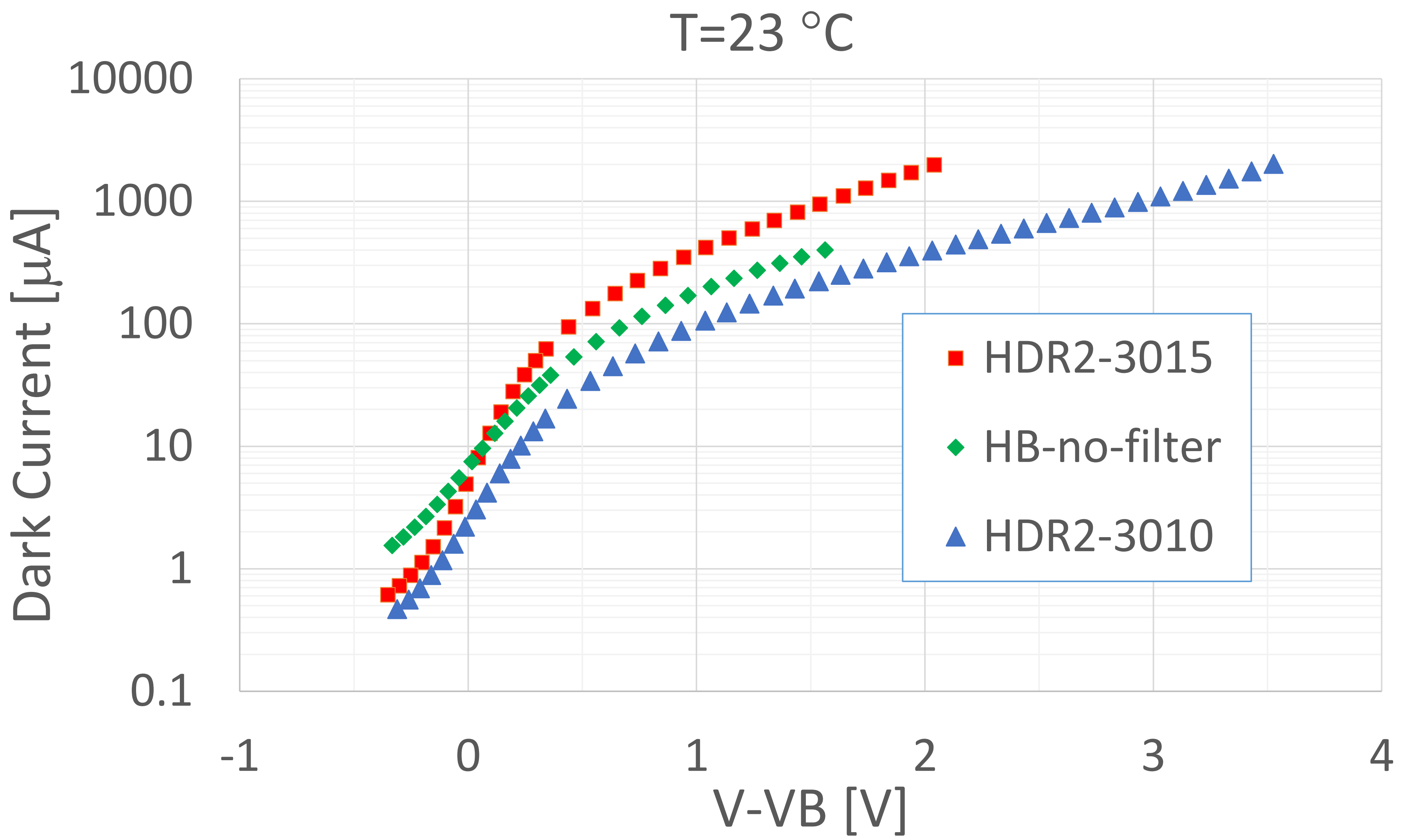
PDE(410 nm) vs. dVB



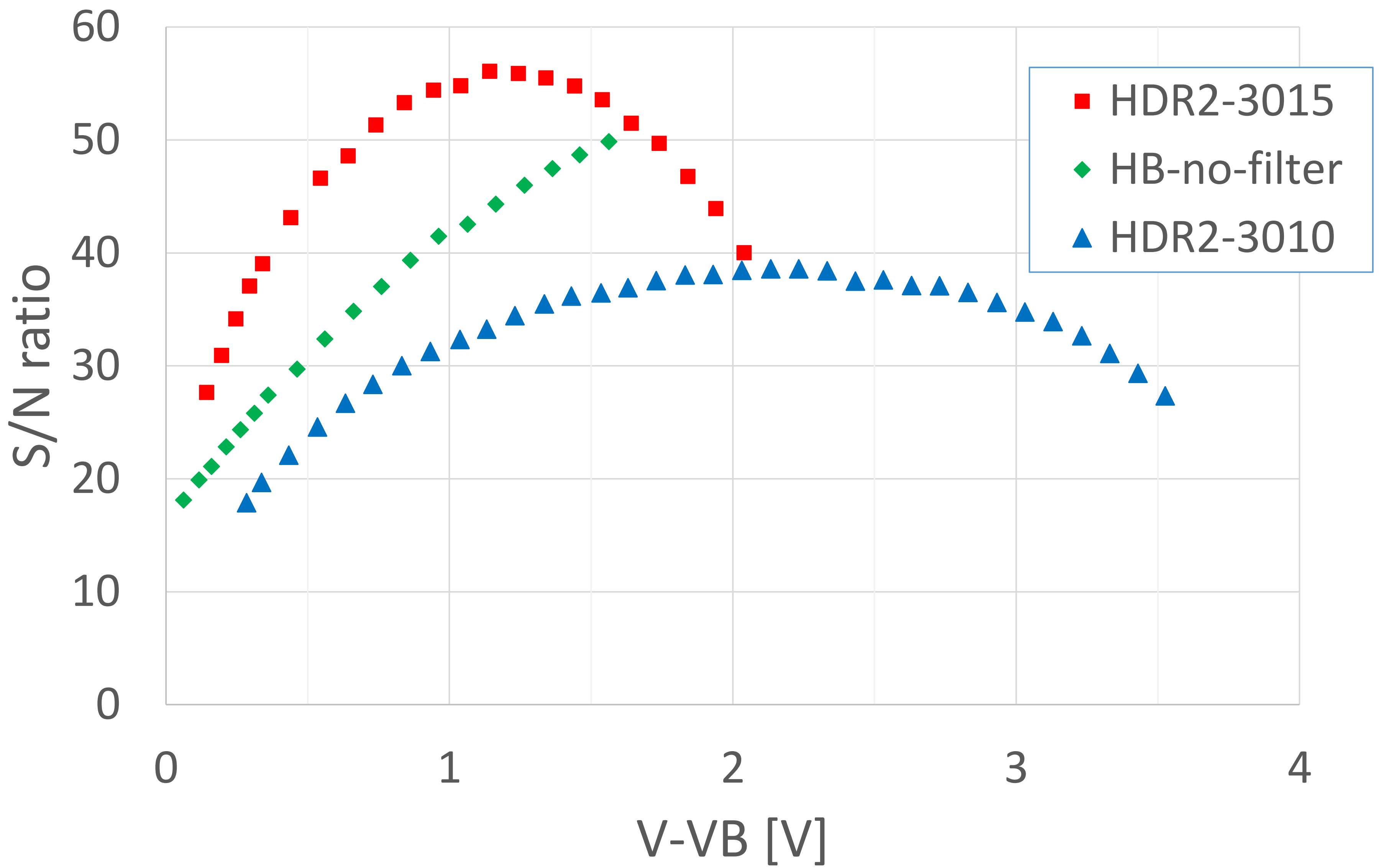
ENF vs. dVB


SiPM, T=22 C, Gate=175 ns
Excess Noise Factor
V-VB [V]
S12571-015C-172
HB-SiPM-no-filter
MPPC-HDR2-3015
MPPC-HDR2-3010
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0
1
2
3
4
5
6
7
8

Dark current vs. dVB, T=23 °C (after 1÷2×E12 n/cm^2)



S/N ratio vs. dVB, T=23 °C, LED 410 nm, ~3 400 photons/pulse



Summary

- HE-11064 SiPM (**2.8 mm dia. or 6.16 mm^2 in area**) was irradiated up to 5E13 n/cm^2 in Ljubljana. It was sent to CERN inside cooler.
- I-V curves were measured inside freezer at T=10 °C ÷ -40 °C
- After that it was warmed up to a room temperature and annealed at RT for 103 days

I-V curves were measured again at T=-30 °C ÷ -40 °C . The HE SiPM dark currents were reduced by a factor of 2.5 in comparison to ones measured before room temperature annealing. The VB of the HE SiPM didn't change after RT annealing!

- SiPM was placed again inside freezer and its dark current and noise was mesaured using 450 nm pulsed LED light $\langle N_{photons} \rangle$=340 photons/pulse using recently built **SiPM setup: metal box with optical connector and Peltier cooler, PT-100 temperature sensor, low noise fast amplifier. SiPM temperature is stabilized with a precision of 0.01 °C using Labview code.**
- ENC was calculated for **15 ns** integration time (request of J.Virdee)

For a LED signal of $\langle N_{photons} \rangle$=340 photons/pulse (for dVB=2.4 V (PDE~24%) this corresponds to 81 pe/pulse) an optimal S/N ~7.6 ÷ 8 was found to be in the range of dVB=1.5 V ÷ 2.5 V. No blocking effects observed at T=-30 ºC ÷ -40 ºC: cell occupancy is low. Self-heating effects reduced by proper heat removal.

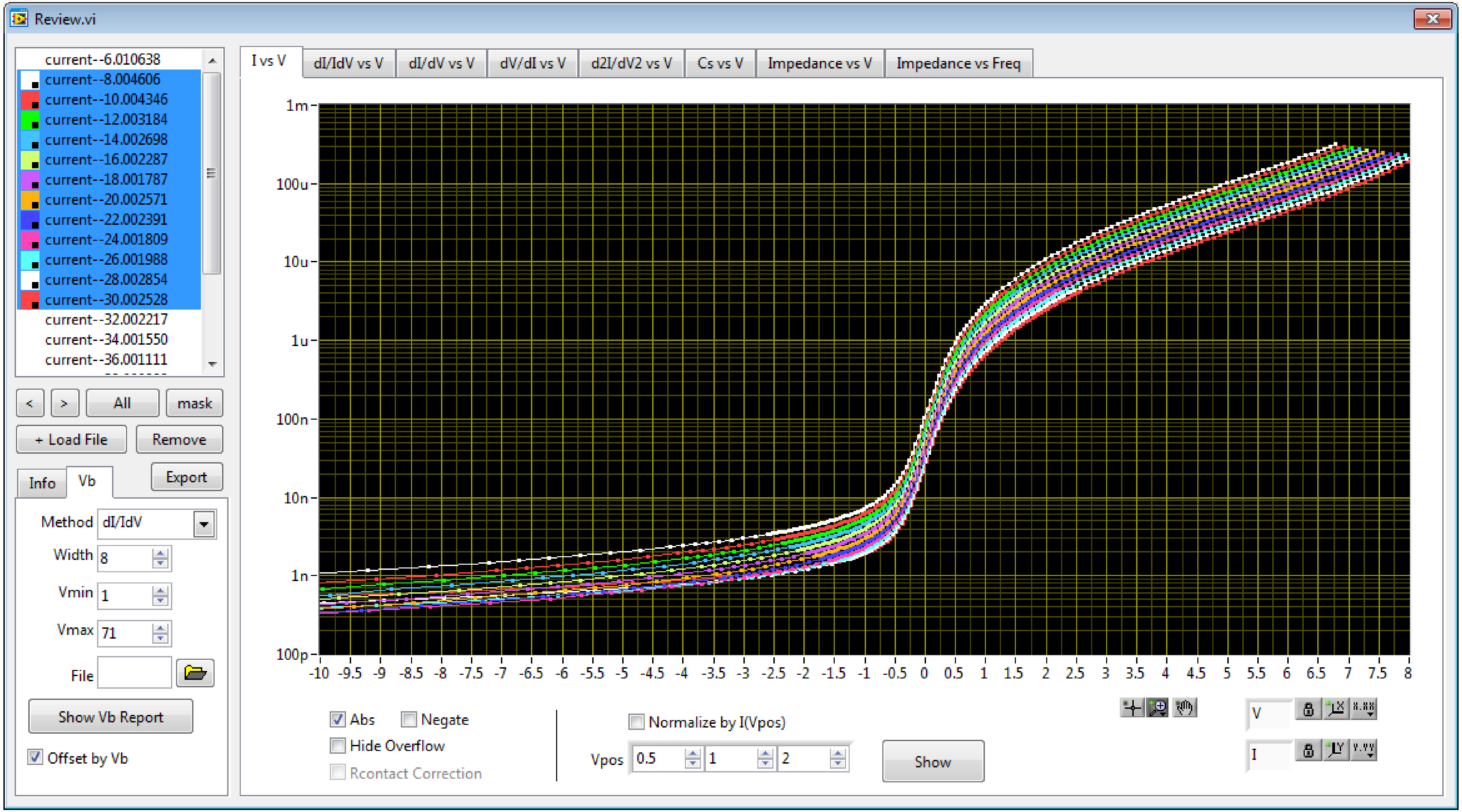
To simulate a 1 mm^2 HE SiPM irradiated and operated at T= -30°C, the HE SiPM's (2.8 mm dia.) temperature was reduced to -44°C and charge spectra were recorded at dVB=2.4 V. For an average LED signal of 25 pe (104 photons) a S/N=4 was measured for 15 ns integration time.

Summary (continued)

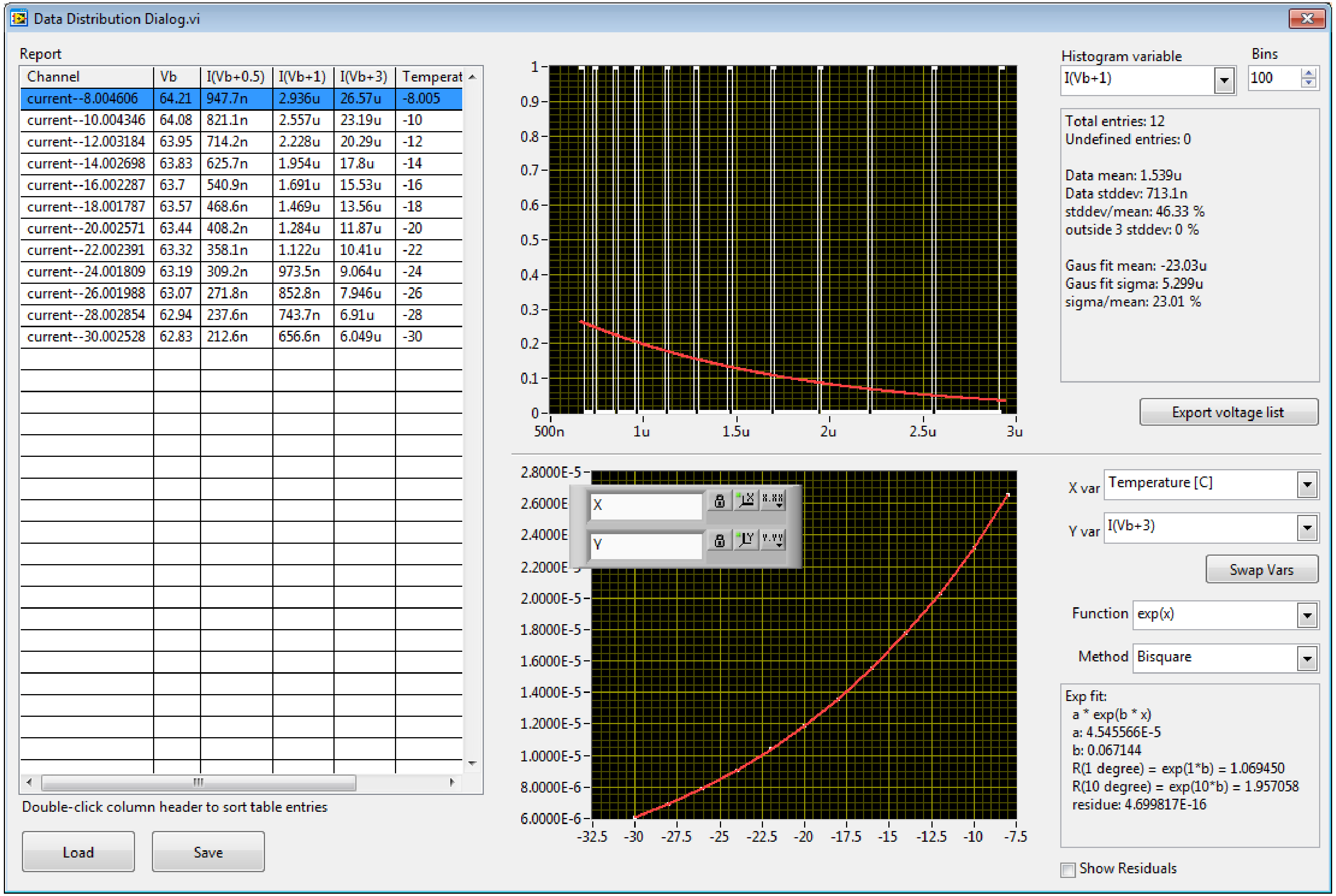
- HPK 1 mm^2, 15 um cell pitch SiPM (HE/HB type) was irradiated under bias (U=67 V, dVB=4.76 V) in cold (T=-30 °C, Peltier thermoelectric cooler) at CHARM irradiated facility up to $2.0*10^{12}$ n/cm^2 (1 MeV neutron equivalent) total neutron fluence.
- The SiPM dark current was monitored during irradiation. 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). 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.
- HPK S1390-1015, 1 mm^2, 15 um cell pith TSV SiPMs (internal structure is the same as the structure of the HE/HB SiPMs) were recently received from Hamamatsu. They were irradiated up to 2E12 n/ n/cm^2 , 5E13 n/cm^2 , 2E14 n/ n/cm^2 in Ljubljana. Preliminary results look encouraging. **It was demonstrated that this SiPM can be selected as a baseline solution for the HB HGCAL.**
- New HDR2 MPPCs received from Hamamatsu 3 weeks ago (MPPC-HDR2-3015: 15 um cell pitch, 3x3 mm^2; MPPC-HDR2-3010: 10 um cell pitch, 3x3 mm^2). Their parameters were measured at CERN APD/SiPM lab. The PDE of these SiPM was significantly increased (and ENF was reduced) in comparison to the previous similar HPK SiPMs. Preliminary irradiation results look very promising. More studies are needed to consider them as candidates for the HB HGCAL.

Back-up

15 um SiPM after 2E12n/cm^2: Id vs dVB

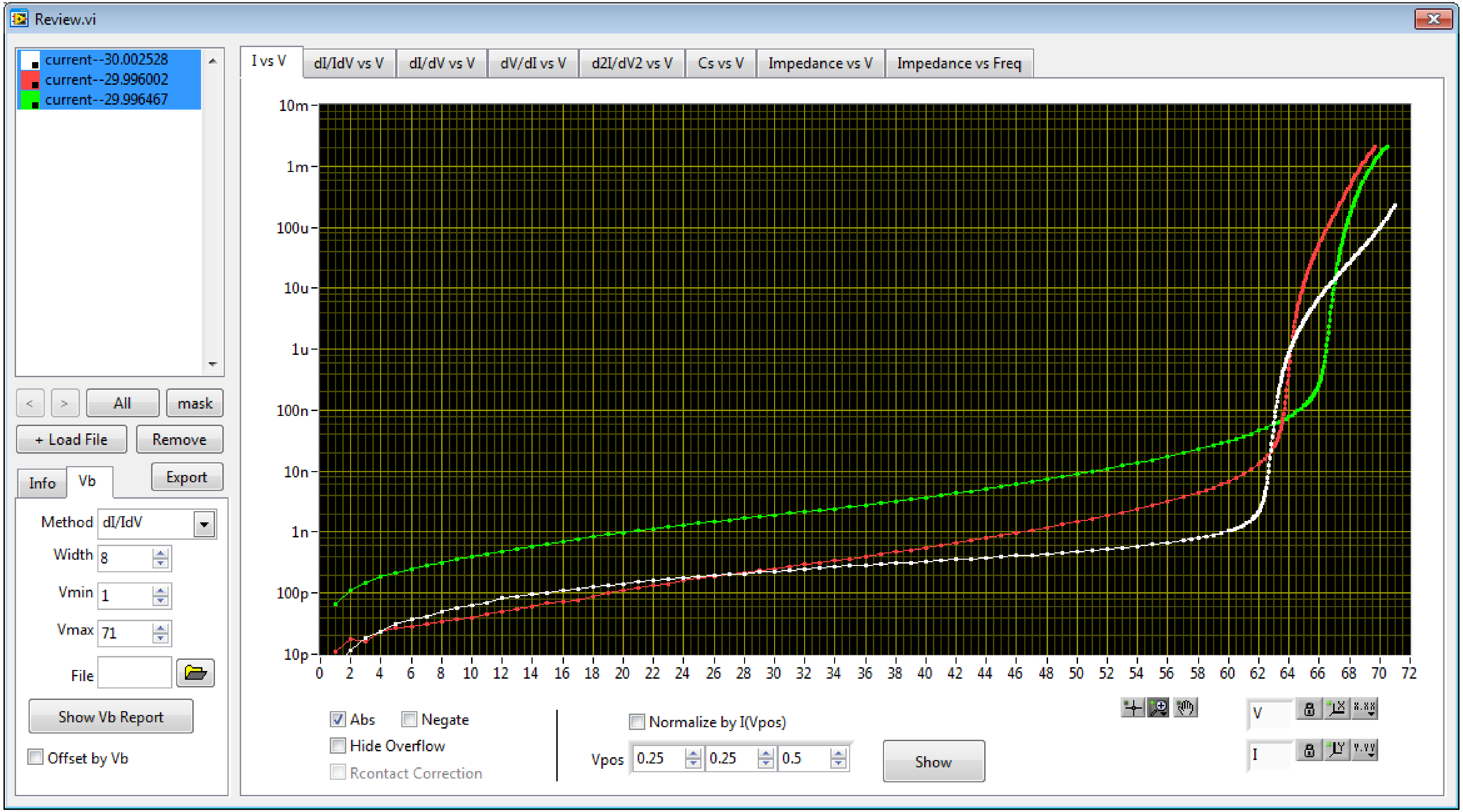


15 um SiPM after 2E12n/cm^2, dVB=3.0 V: Id vs T

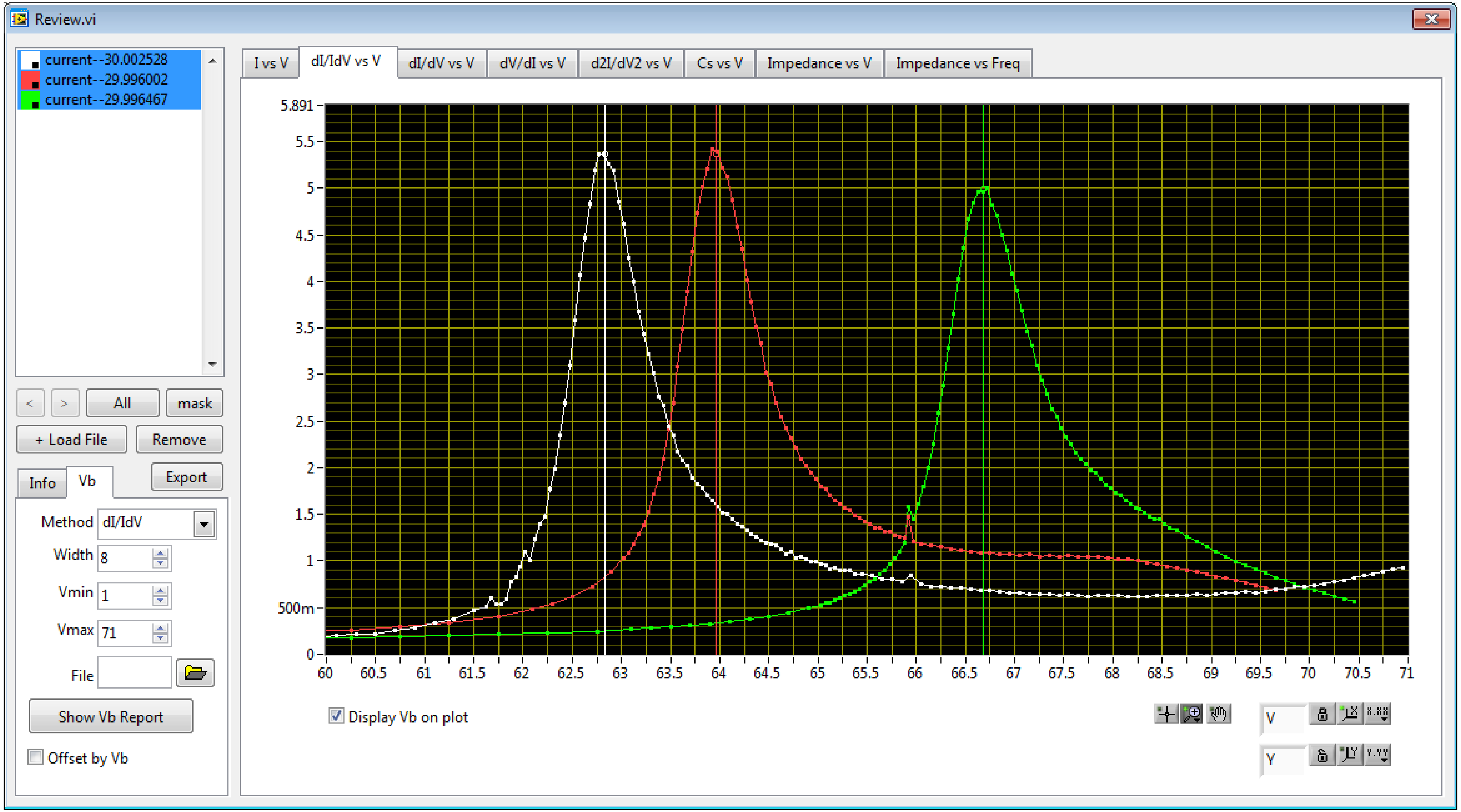


Ratio = 1.96 per 10 °C

15 um SiPM: Id vs V, T=-30 C after 2E12 n/cm^2, 5E13 n/cm^2, 2E14 n/cm^2

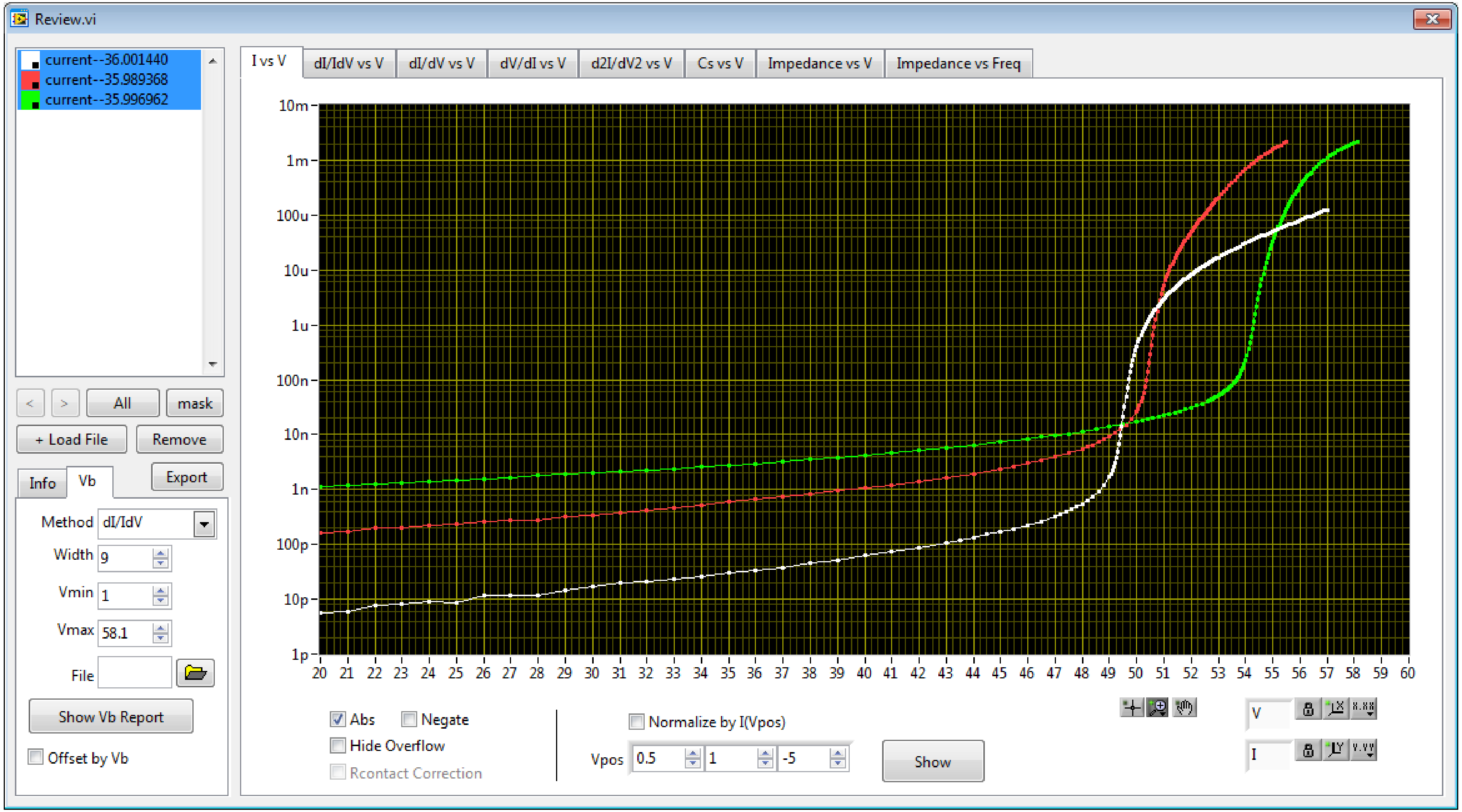


15 um SiPM:VBs at T=-30 °C after 2E12 n/cm^2, 5E13 n/cm^2, 2E14 n/cm^2



VB shift: 1.1 V after 5E13 n/cm^2, 3.9 V after 2E14 n/cm^2

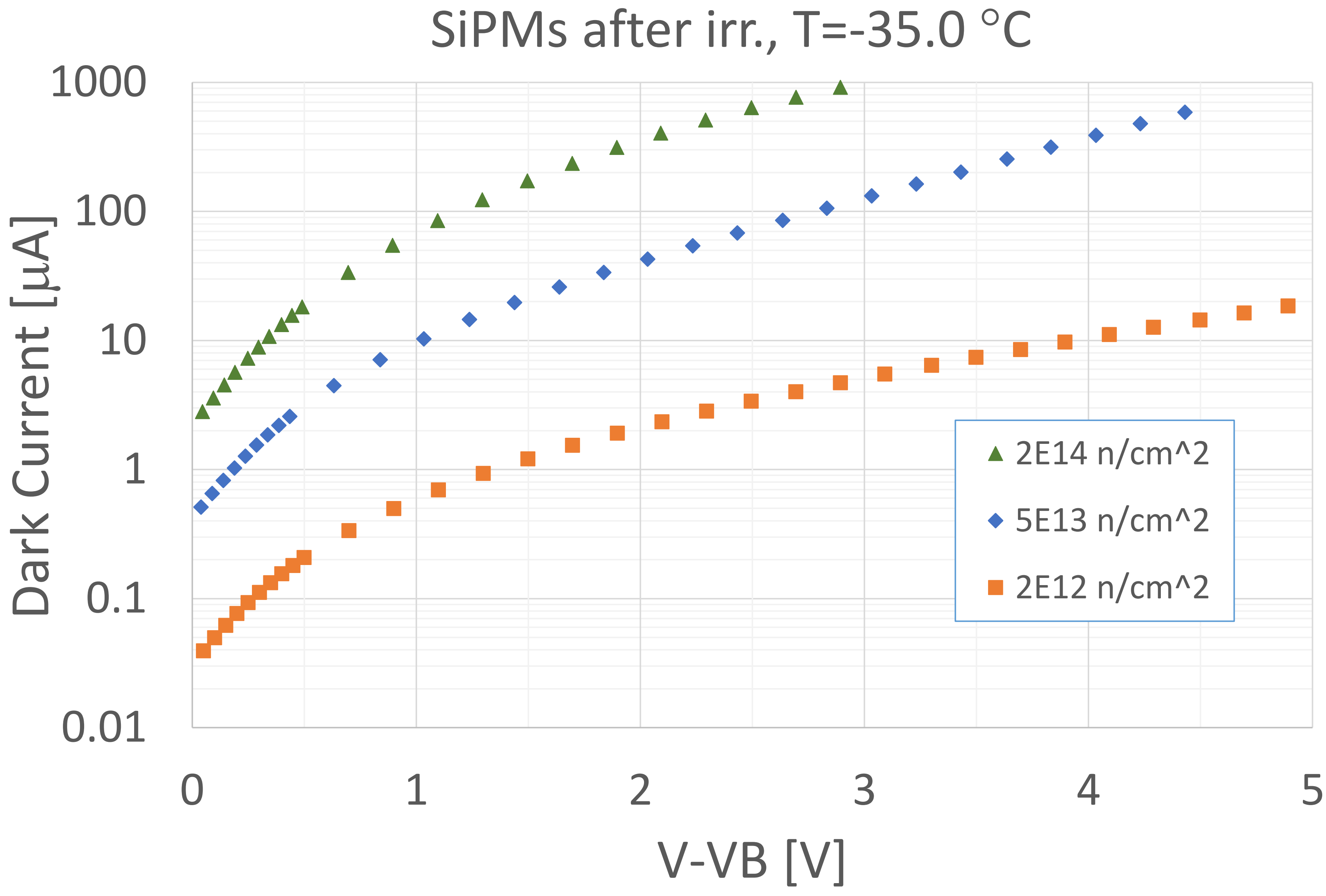
25 um SiPM: Id vs V, T=-36 C after 2E12 n/cm², 5E13 n/cm², 2E14 n/cm²



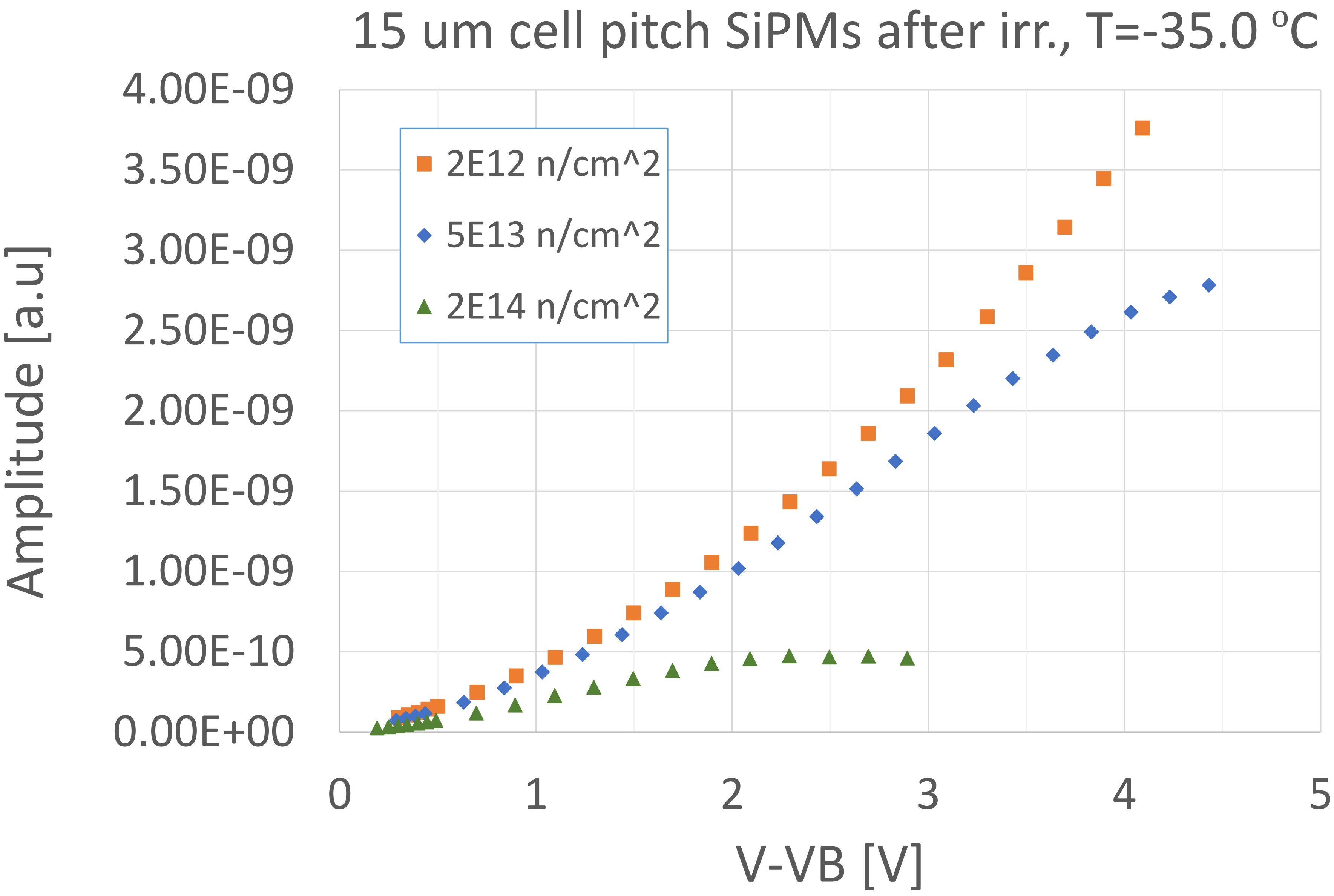
Measurements with pulsed LED light

- Measurements were done inside a new cold box (+Peltier stabilization)
- T=-20 ^{o}C ÷ -40 ^{o}C, PT-100 temperature sensor
- LED 410 nm, 10 ns pulse width FWHM, $<N_{photons}>$~270&315 photons/pulse, at T=22 ^{o}C, 1 mm^2 quartz fiber ➔ cold box
- Fast current amplifier, gain~50, 2 ns rise time
- Keithley 487 picoammeter/voltage source
- Picoscope 6404D
- Integration time = 15 ns

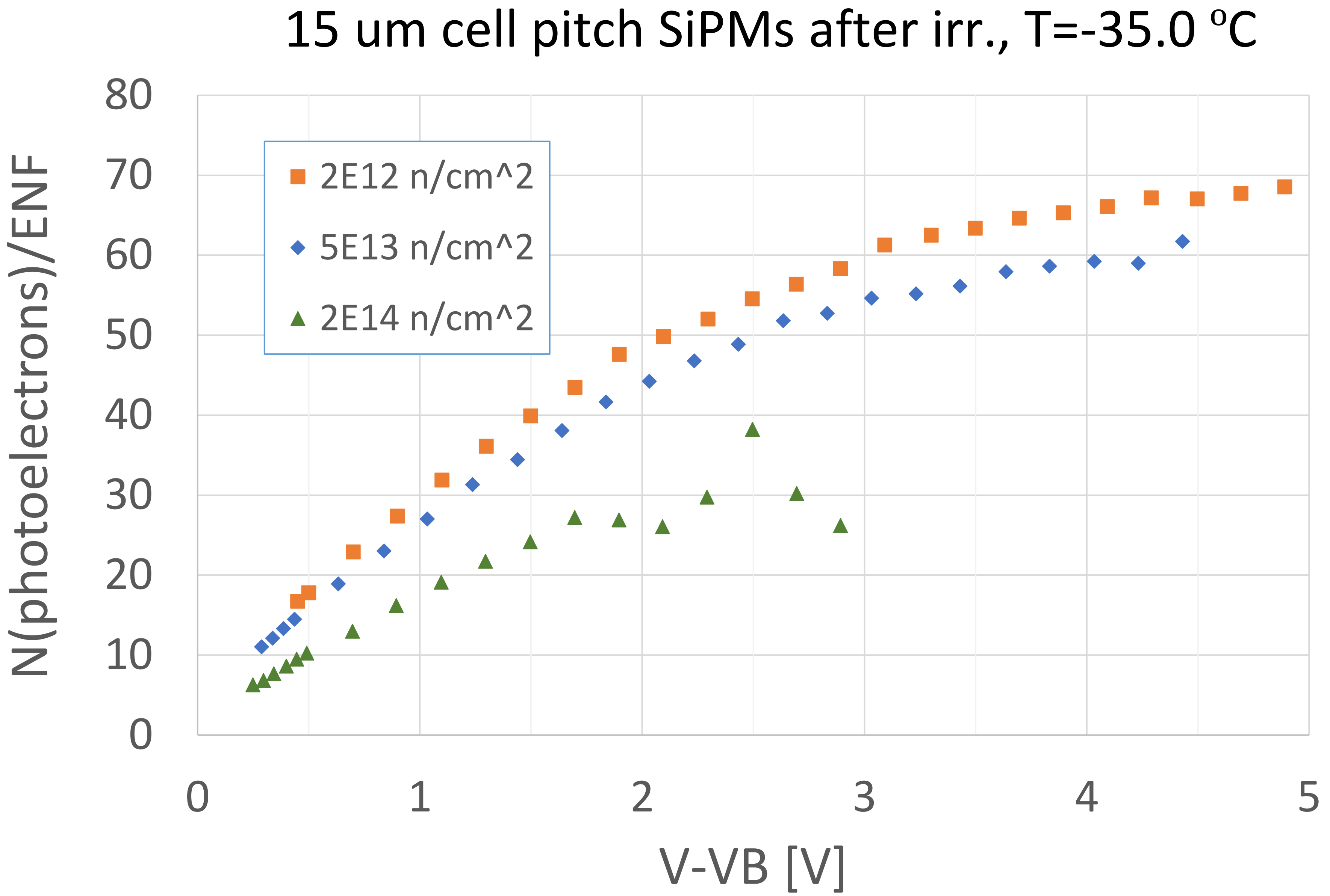
1 mm^2, 15 um cell pitch HPK TSV SiPMs (after 2E12 n/cm^2, 5E13 n/cm^2, 2E14 n/cm^2) at T=-35.0 C

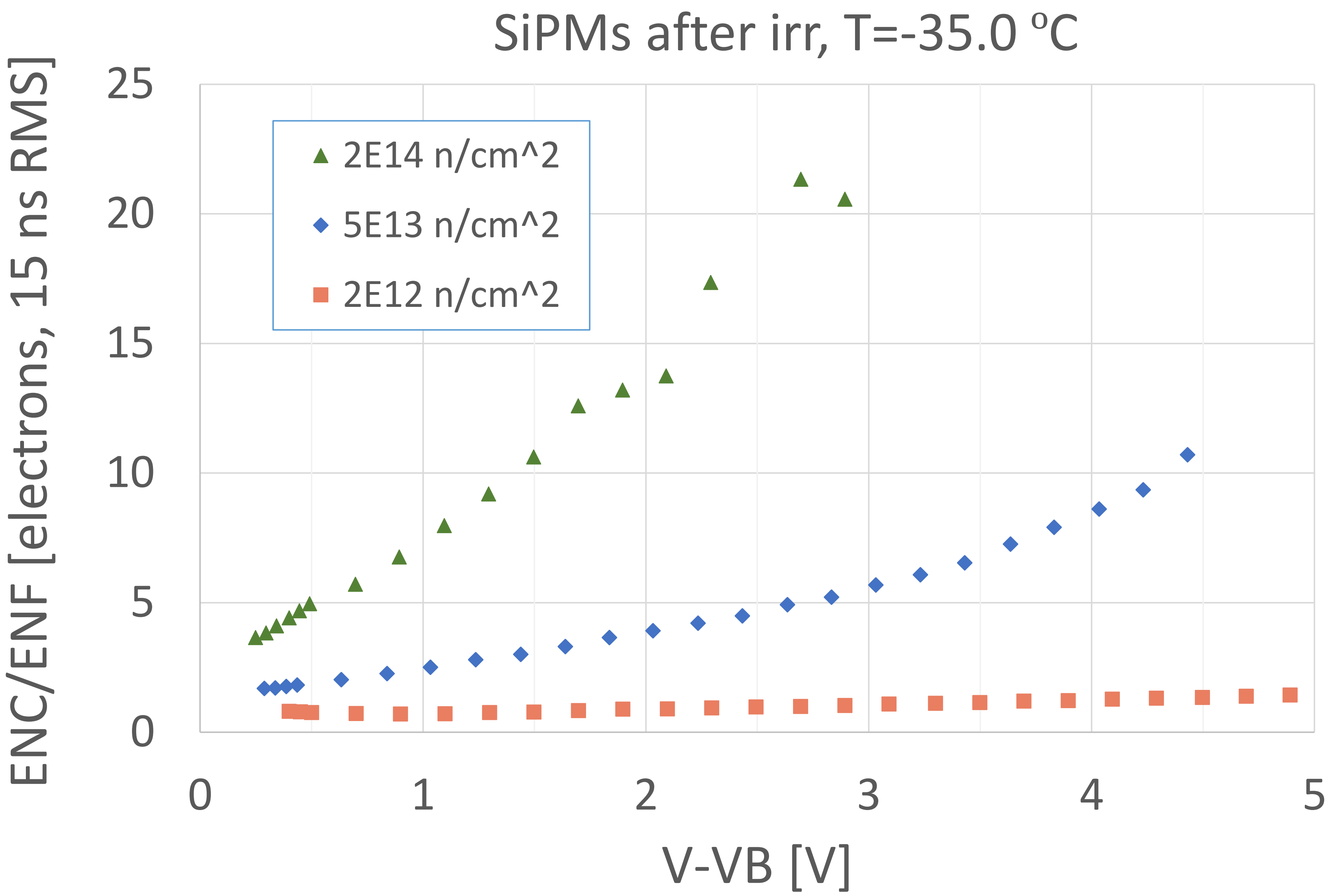


SiPMs after irr., T=-35.0 °C
Dark Current [µA]
1000
100
10
1
0.1
0.01
0
1
2
3
4
5
V-VB [V]
2E14 n/cm^2
5E13 n/cm^2
2E12 n/cm^2



15 um cell pitch SiPMs after irr., T=-35.0 °C
Amplitude [a.u]
4.00E-09
3.50E-09
3.00E-09
2.50E-09
2.00E-09
1.50E-09
1.00E-09
5.00E-10
0.00E+00
0
1
2
3
4
5
V-VB [V]
2E12 n/cm^2
5E13 n/cm^2
2E14 n/cm^2


15 um cell pitch SiPMs after irr., T=-35.0 °C
80
70
60
50
40
30
20
10
0
N(photoelectrons)/ENF
2E12 n/cm^2
5E13 n/cm^2
2E14 n/cm^2
0
1
2
3
4
5
V-VB [V]


SiPMs after irr, T=-35.0 °C
ENC/ENF [electrons, 15 ns RMS]
25
20
15
10
5
0
0
1
2
3
4
5
V-VB [V]
2E14 n/cm^2
5E13 n/cm^2
2E12 n/cm^2

Summary - II

- For 15 um cell pitch (irradiated with 5E13 n/cm^2) SiPMs dark current (at the same dVB=3V) drops faster (x1.96 per 10 C) in comparison to 25 um cell pitch SiPM (x1.82 per 10 C)
- After 5E13 n/cm^2 (2E14 n/cm^2) ~1 V (3.9 ÷ 5) VB increase was measured for 15 um and 25 um SiPMs
- For the same LED (410 nm) light irradiated 15 um cell pitch SiPM has better S/N ratio in comparison to 25 um cell pitch SiPM (especially for high neutron fluences: 5E13 n/cm^2 and 2E14 n/cm^2)
- Losses of the signal response are seen for the 25 um cell pitch SiPMs at dVB>3 V after 5E13 n/cm^2 (high cell occupancy&self-heating effects)
- After 5E13 n/cm^2 optimum S/N ratio for the 15 um (25 um) cell pitch is in the range of 1.2 V ÷ 2.4 V (0.8 V ÷ 2 V)
- SiPMs irradiated with 2E14 n/cm^2 show significant reduction of PDE (damage in glass window, dead layer creation?)

Outline

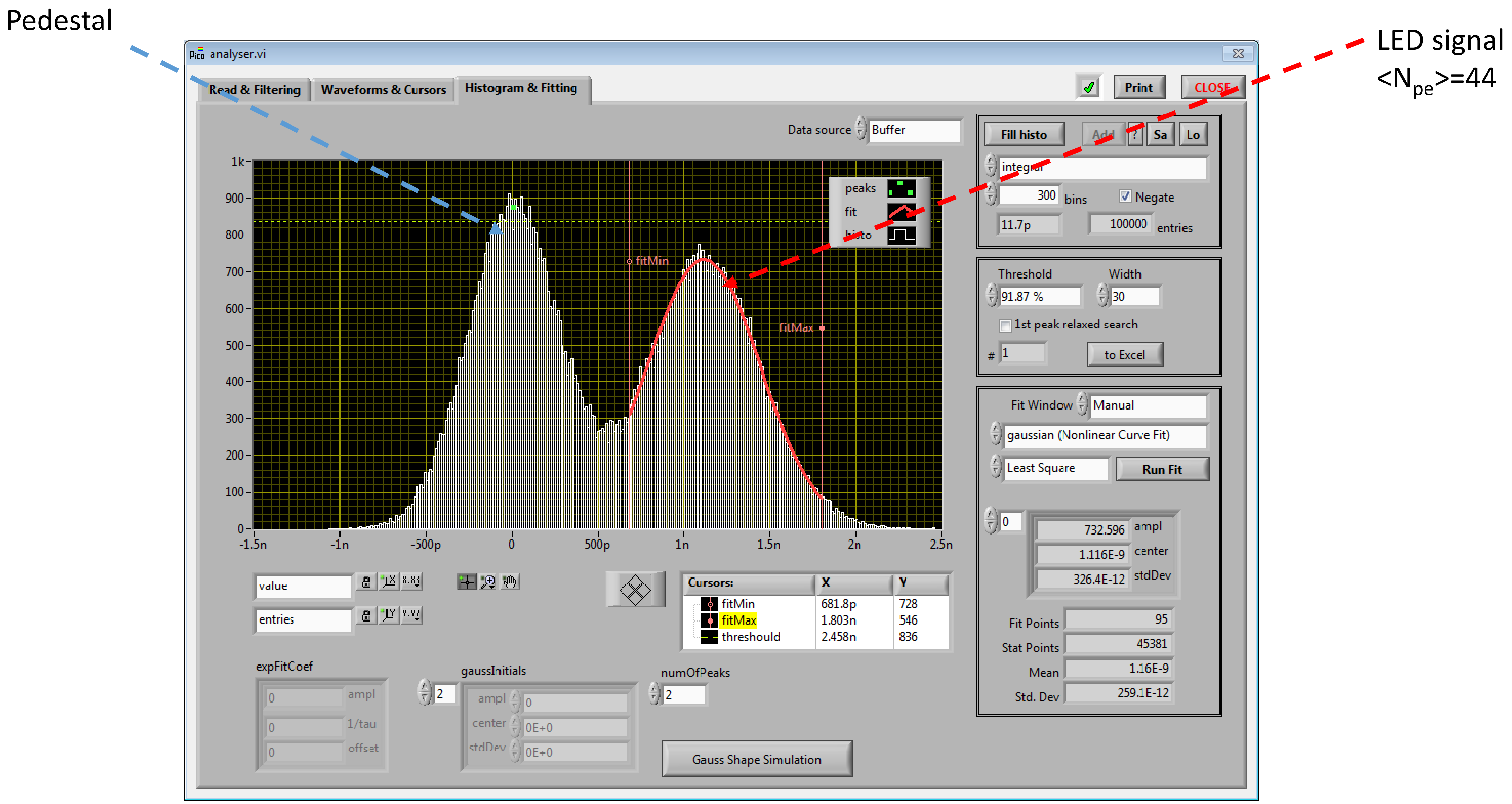
1) Irradiation of SiPMs:
a) CERN
- CHARM facility: 1÷4E12 n/cm^2 1 MeV equivalent (LHC like spectra)
- PS beam 24 GeV protons – up to 2E14 p/cm^2

b) Ljubjana – reactor neutrons – up to 1E15 n/cm2, 1 MeV equivalent
c) JINR (Dubna) – IBR-2 reactor, fast neutrons – up to 5E14 n/cm2, 1 MeV equivalent
2) Study of SiPM irradiation and annealing in cold
3) ”Spikes” in SiPMs: CHARM facility
4) Study irradiated SiPMs/APDs with different internal structure to understand influence of electric field on the dark current generation (trap assisted tunnelling, Pool-Frenkel effect …)

Summary - III

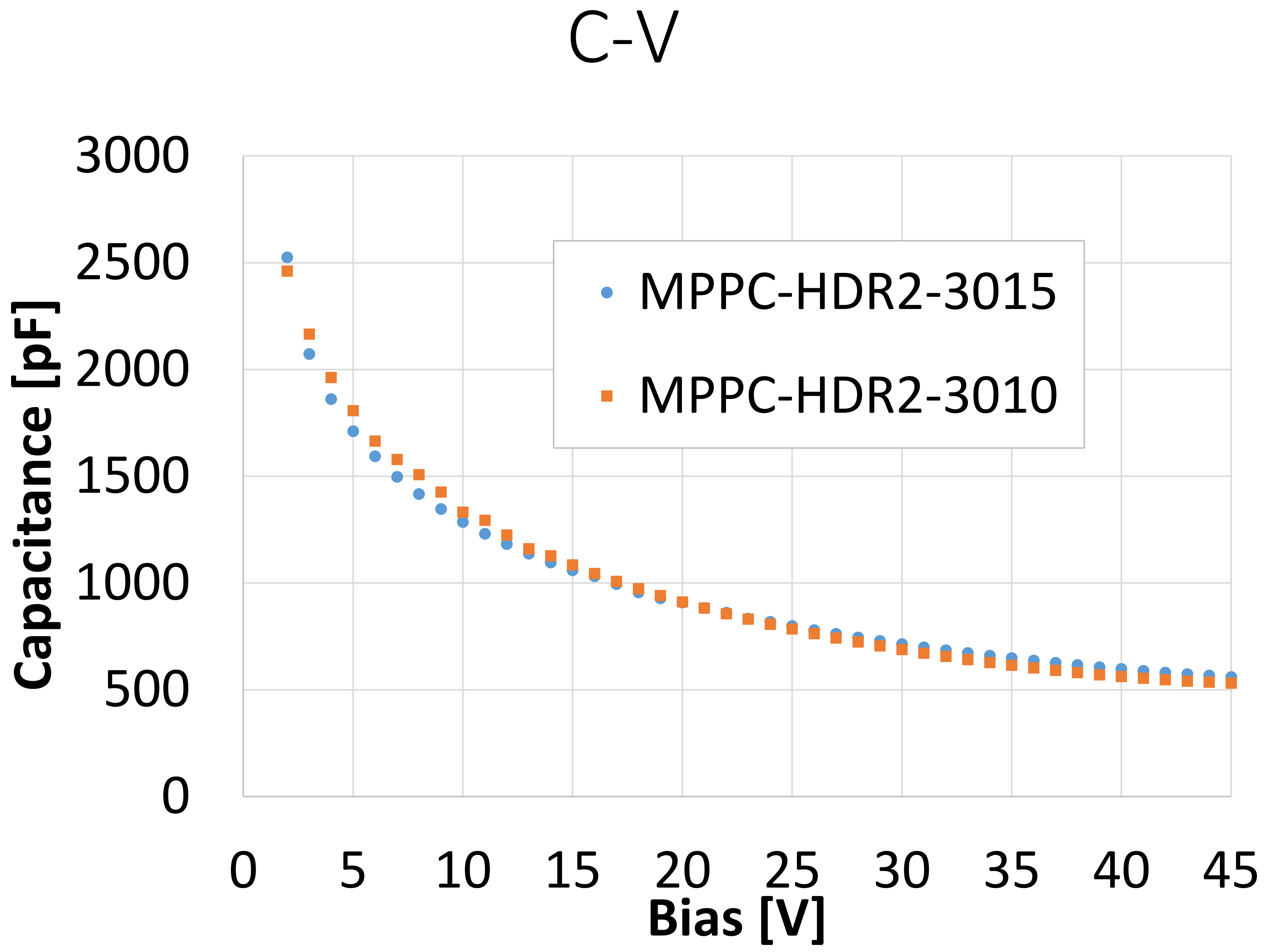
HPK 1 mm^2, 15 um cell pitch SiPM (HE/HB type) was irradiated under bias (U=67 V, dVB=4.76 V) in cold (T=-30 °C, Peltier thermoelectric cooler) at CHARM irradiated facility up to $2.0*10^{12}$ n/cm^2 (1 MeV neutron equivalent) total neutron fluence.
The SiPM dark current was monitored during irradiation. At the end of irradiation Idark~37 uA was measured at dVB=4.76 V and Idark~12 uA at dVB=3.0 V. This current is a factor of 2 higher than the dark current of similar SiPM which was irradiated up to the same fluence in Ljublana. This is not a surprise for us as we always see a factor of 2 difference in dark currents of SiPMs irradiated in Ljubljana and CHARM. We can't also exclude some annealing effects during transportation from Ljublana to Hamburg and CERN.
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.


osciloPlot.vi
118.1m
100m
75m
50m
25m
0
-25m
-50m
-75m
-100m
-125m
-150m
-175m
-200m
-225m
-250m
-275m
-315m
0
20n
40n
60n
80n
100n
120n
140n
160n
180n
200n
Cursors: X Y
Start 102n 0
Stop 117n 0
Max 0 5m
Min 0 -5m
Time
Amplitude
20 waveforms
20 ms delay
Pause
3420
Prev
Next
Remember cursors
None
Close



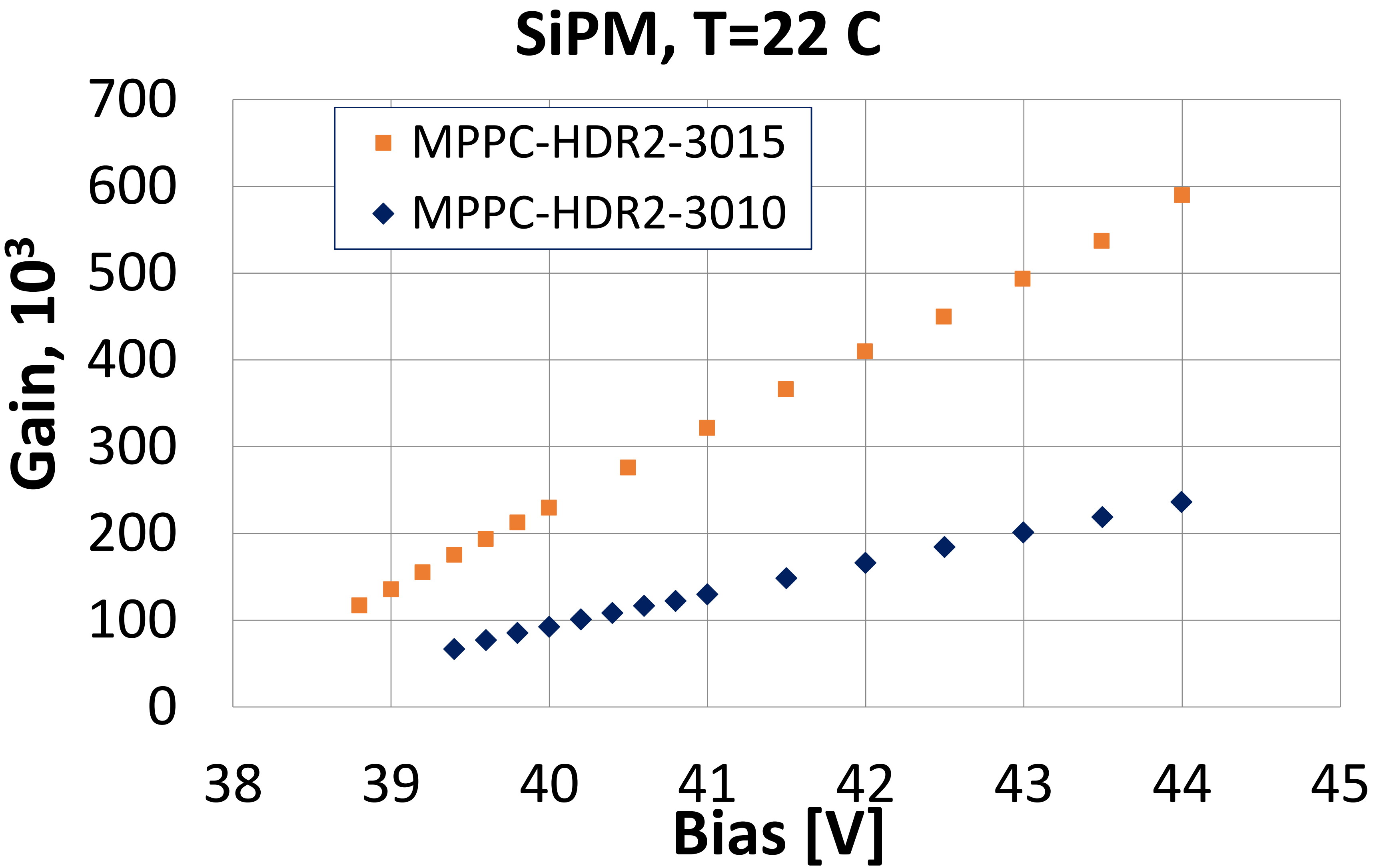
Pedestal
LED signal
$<N_{pe}>=44$
analyser.vi
Read & Filtering
Waveforms & Cursors
Histogram & Fitting
Print
CLOSE
Data source
Buffer
Fill histo
Sa
Lo
integral
300
bins
Negate
11.7p
100000
entries
Threshold
Width
91.87 %
30
1st peak relaxed search
to Excel
Fit Window
Manual
gaussian (Nonlinear Curve Fit)
Least Square
Run Fit
732.596
ampl
1.116E-9
center
326.4E-12
stdDev
Fit Points
95
Stat Points
45381
Mean
1.16E-9
Std. Dev
259.1E-12
peaks
fit
histo
fitMin
fitMax
value
entries
Cursors:
X
Y
fitMin
681.8p
728
fitMax
1.803n
546
threshould
2.458n
836
expFitCoef
ampl
1/tau
offset
gaussInitials
center
stdDev
numOfPeaks
Gauss Shape Simulation

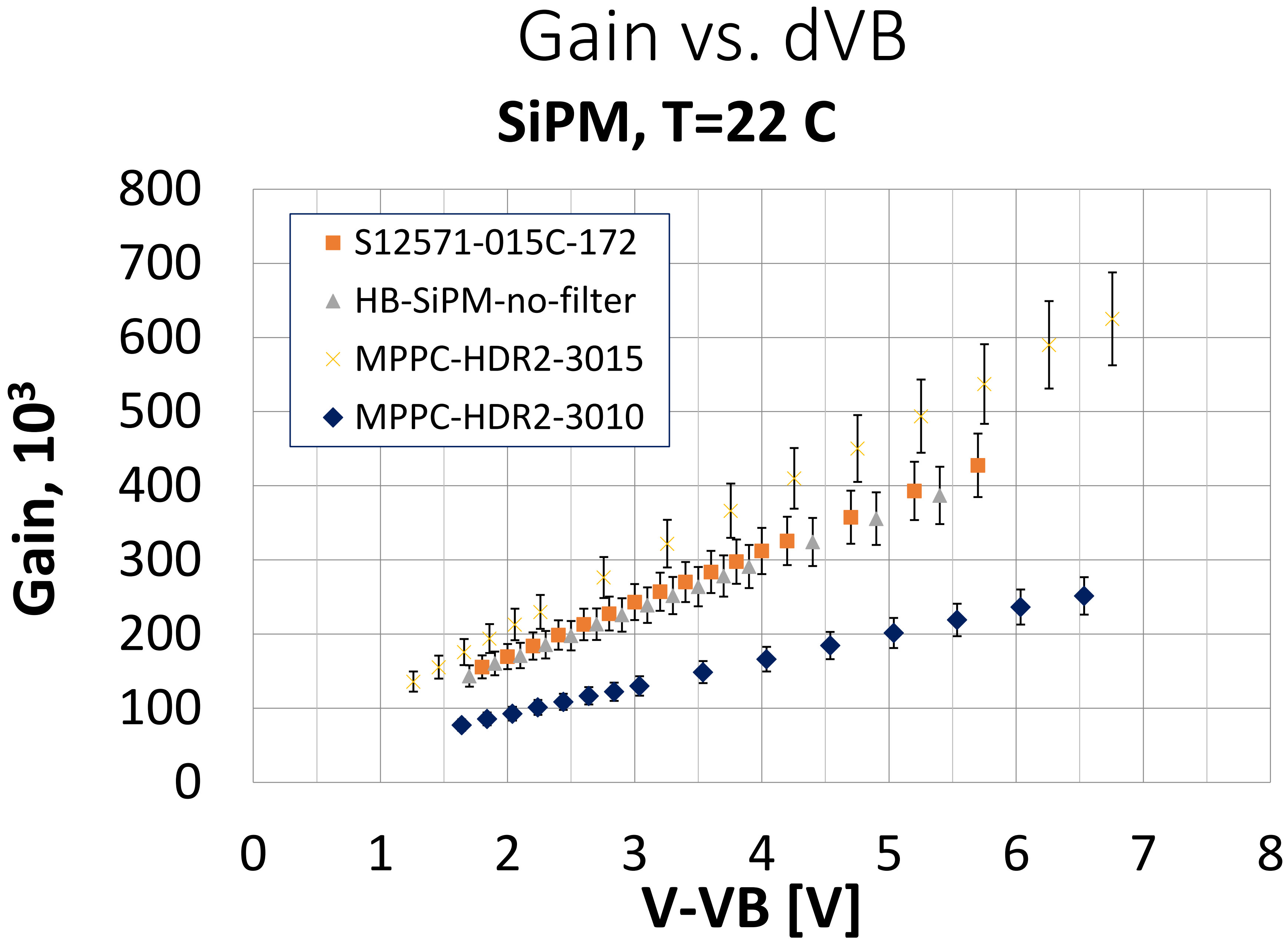
New HDR2 MPPCs



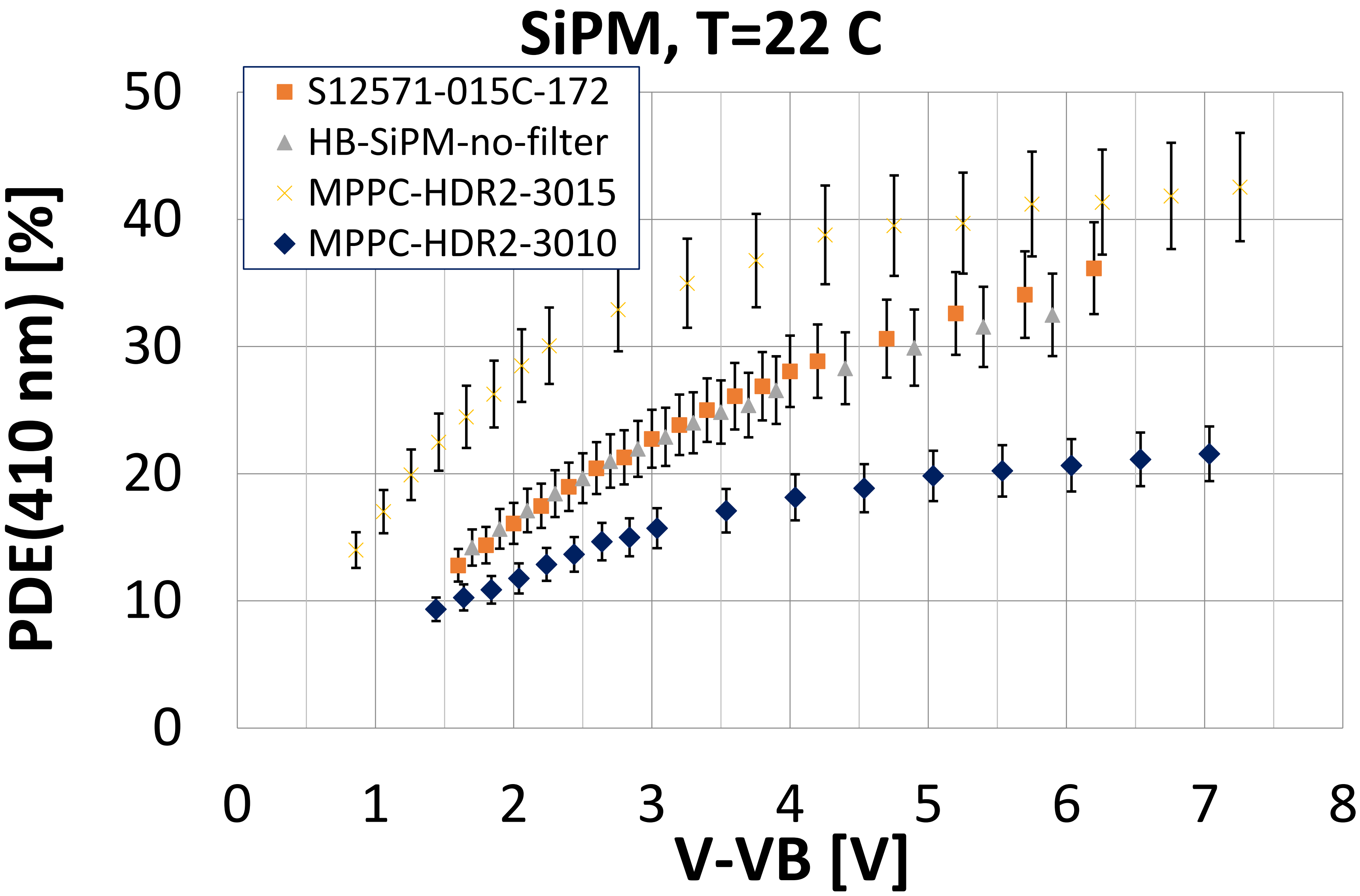
C-V
3000
2500
2000
1500
1000
500
0
Capacitance [pF]
0
5
10
15
20
25
30
35
40
45
Bias [V]
MPPC-HDR2-3015
MPPC-HDR2-3010

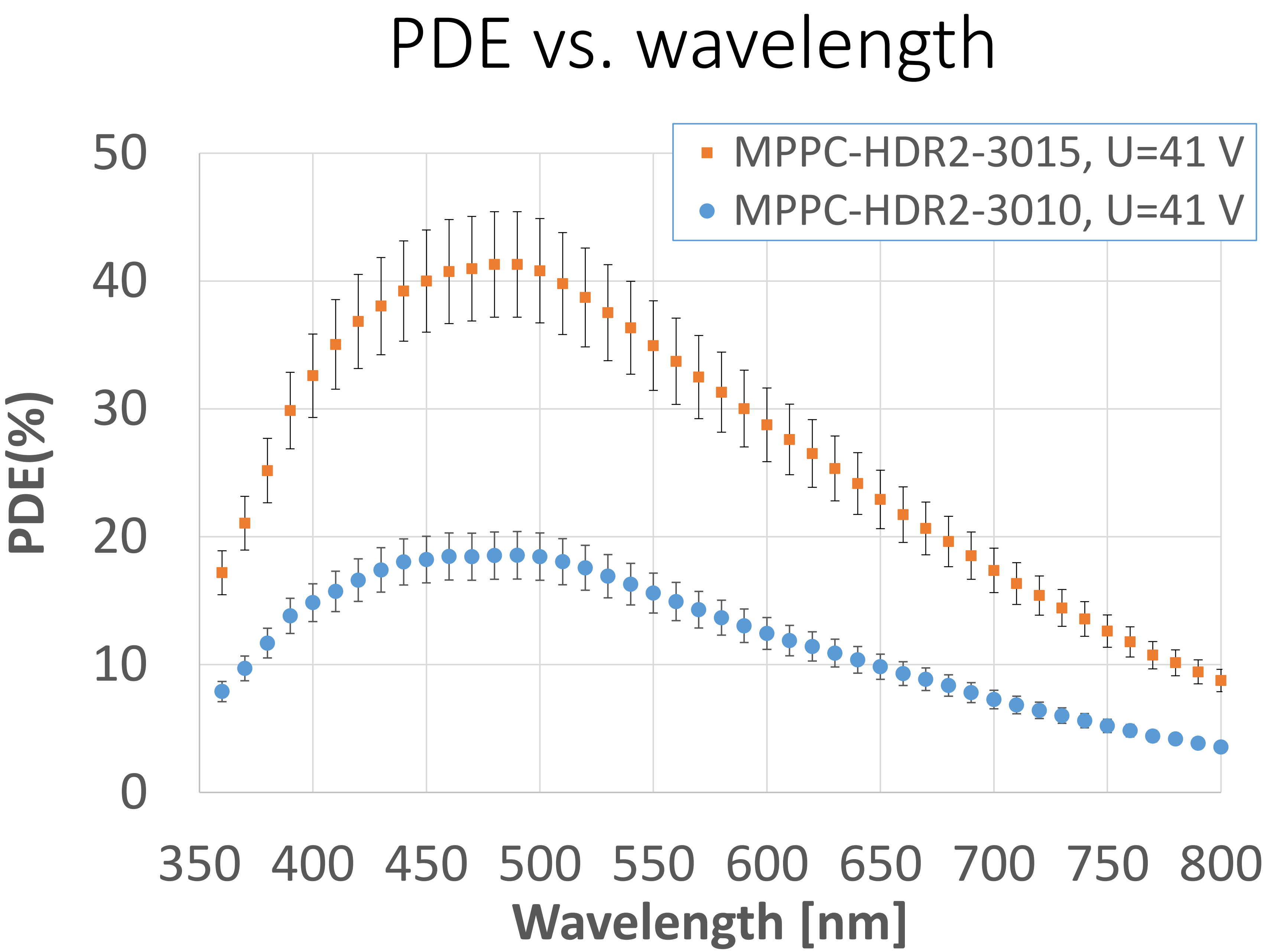
Gain vs. voltage



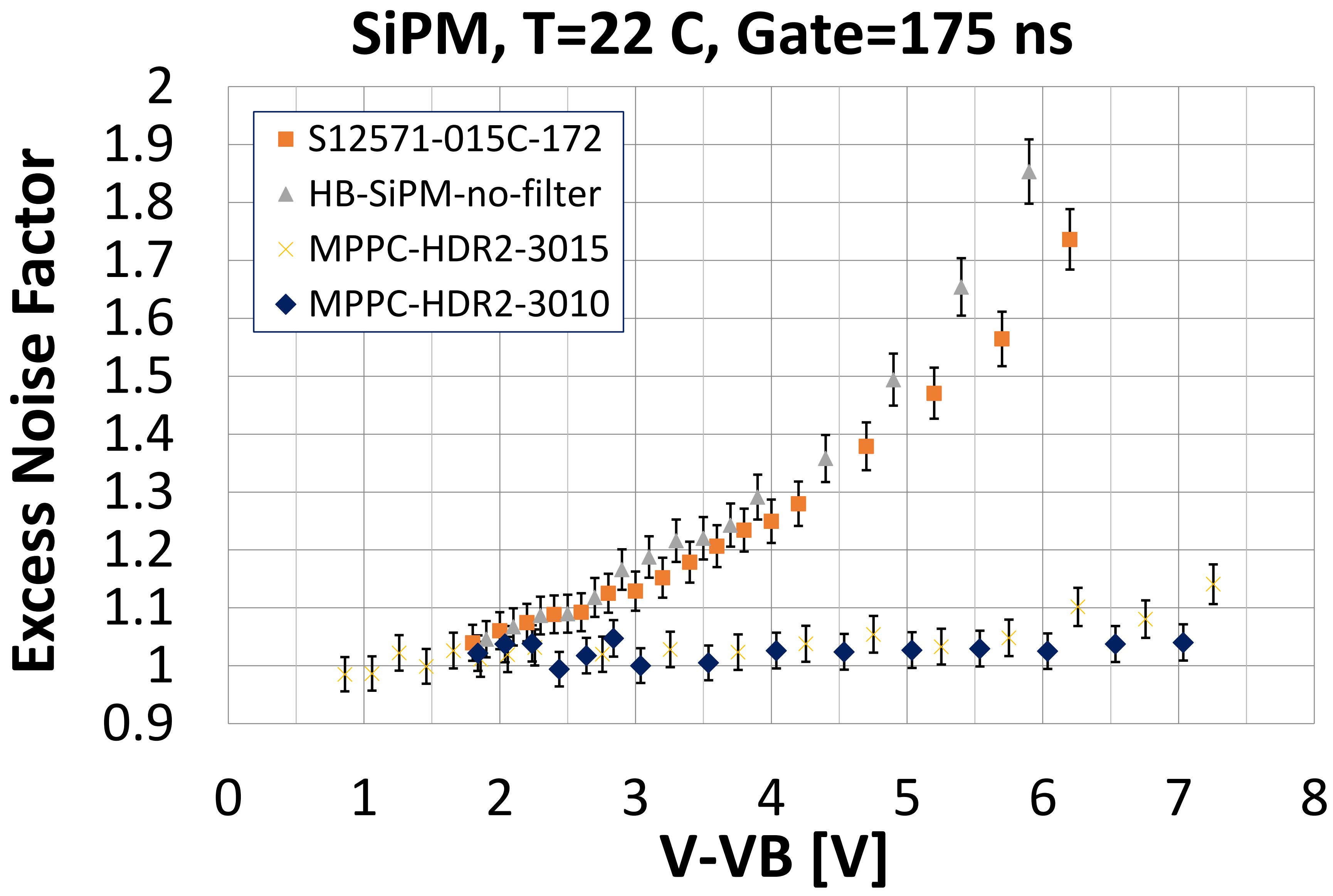

Gain vs. dVB
SiPM, T=22 C
S12571-015C-172
HB-SiPM-no-filter
MPPC-HDR2-3015
MPPC-HDR2-3010
Gain, 10^3
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
V-VB [V]

PDE(410 nm) vs. dVB

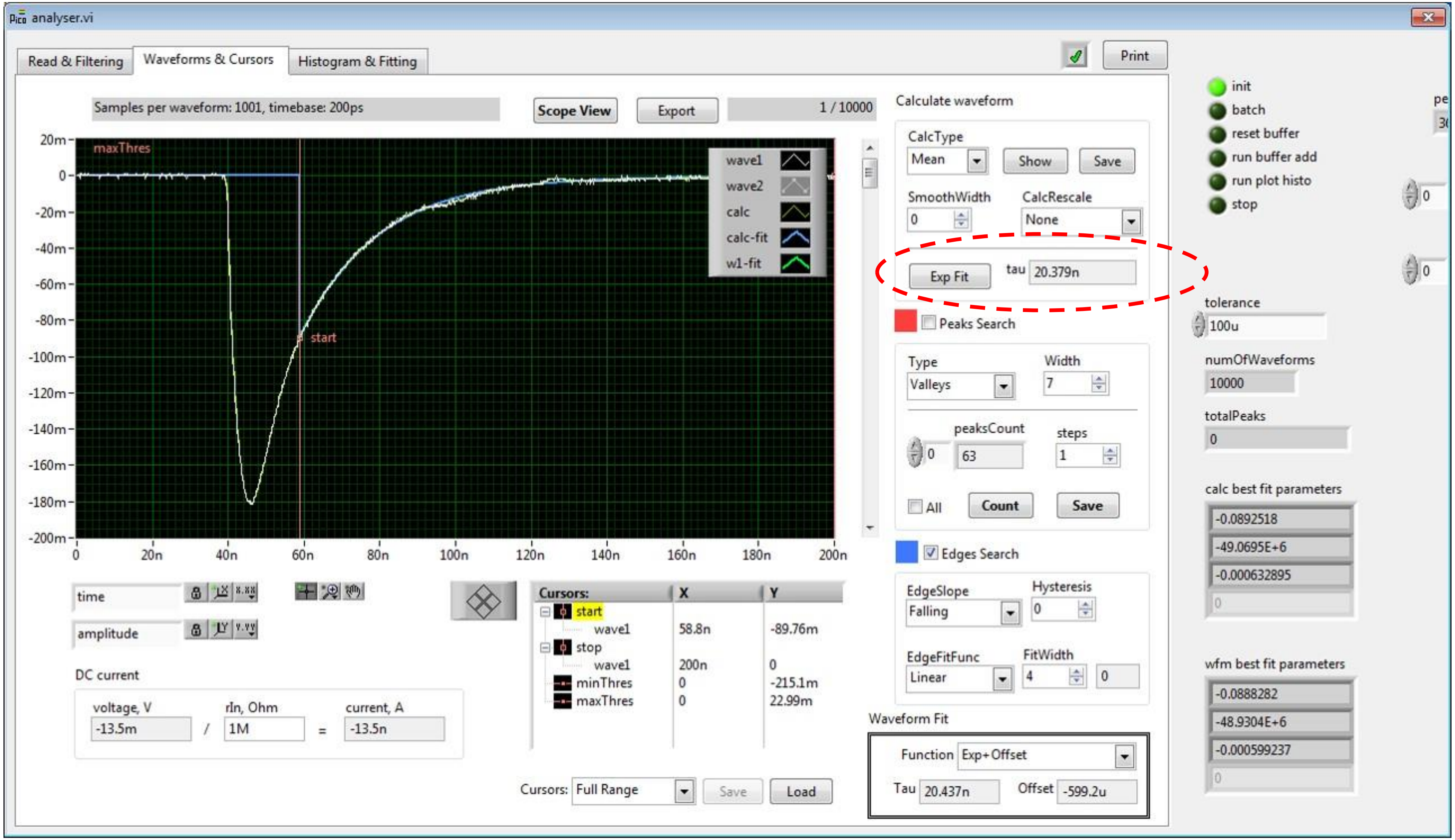



PDE vs. wavelength
MPPC-HDR2-3015, U=41 V
MPPC-HDR2-3010, U=41 V
PDE(%)
0
10
20
30
40
50
350
400
450
500
550
600
650
700
750
800
Wavelength [nm]

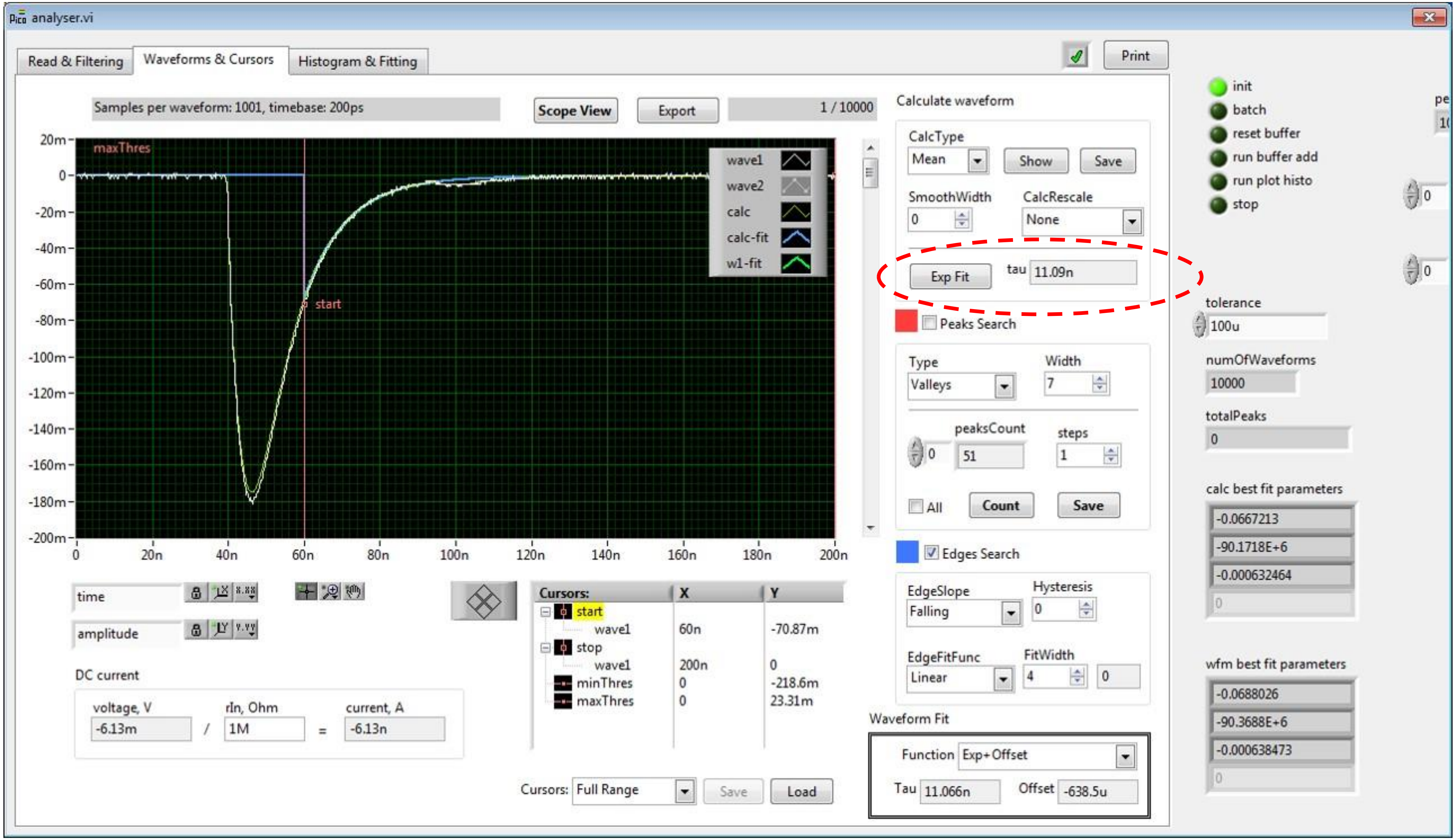
ENF vs. dVB


SiPM, T=22 C, Gate=175 ns
Excess Noise Factor
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0
1
2
3
4
5
6
7
8
V-VB [V]
S12571-015C-172
HB-SiPM-no-filter
MPPC-HDR2-3015
MPPC-HDR2-3010

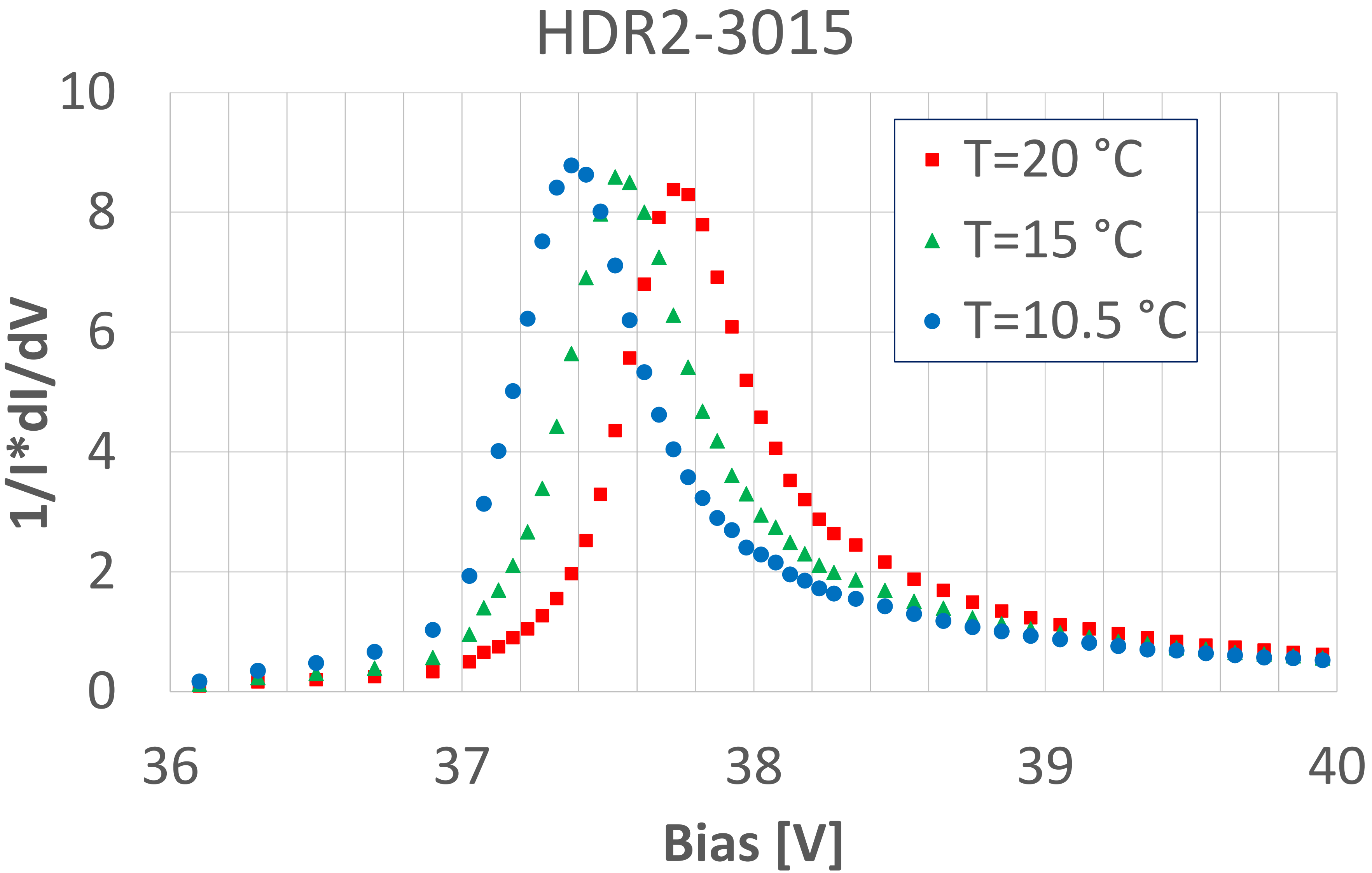
MPPC-HDR2-3015, 405 nm laser response, R_{load}=17 Ohm



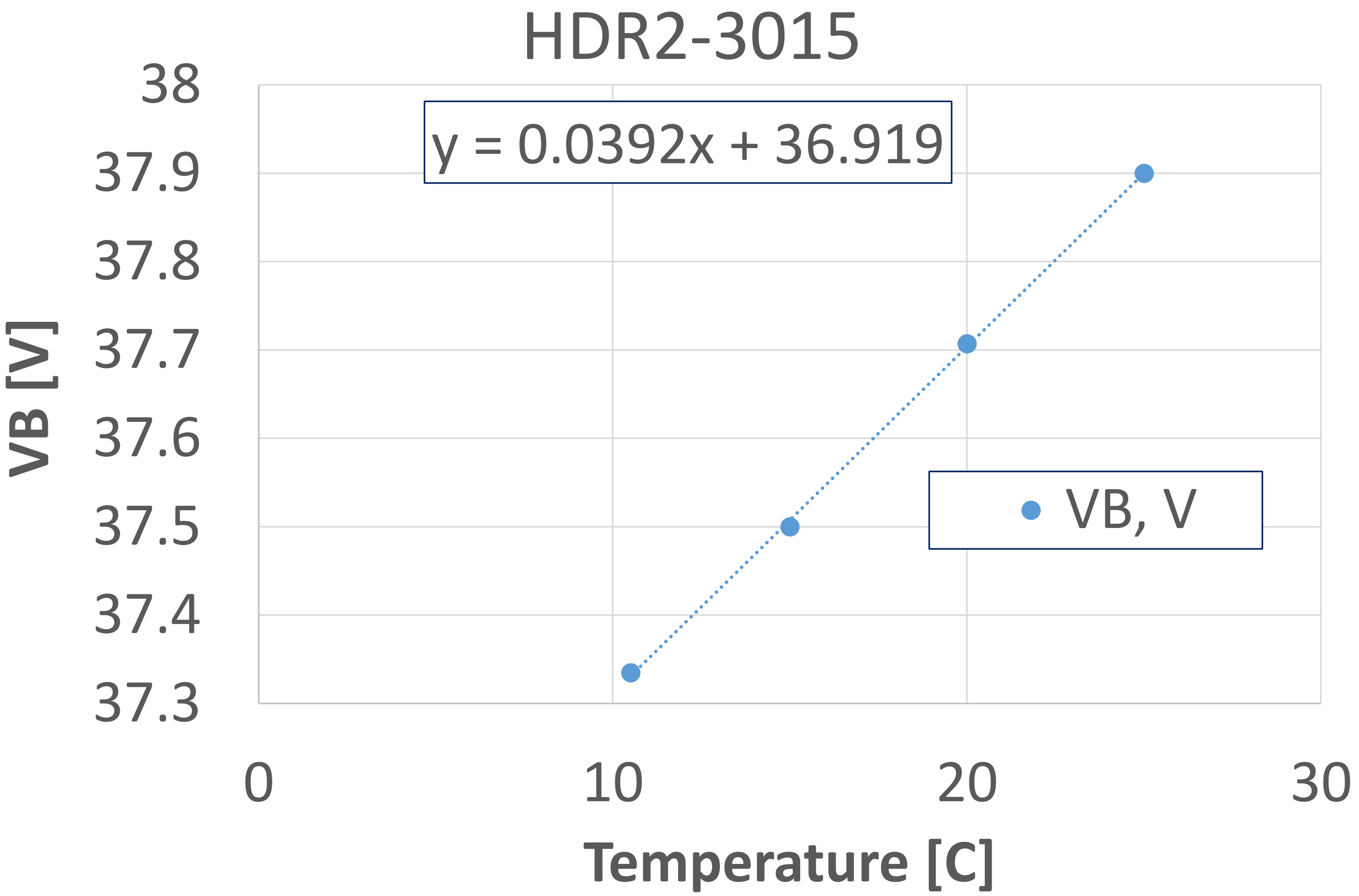
MPPC-HDR2-3010, 405 nm laser response, R_{load}=17 Ohm



VB vs. Temperature

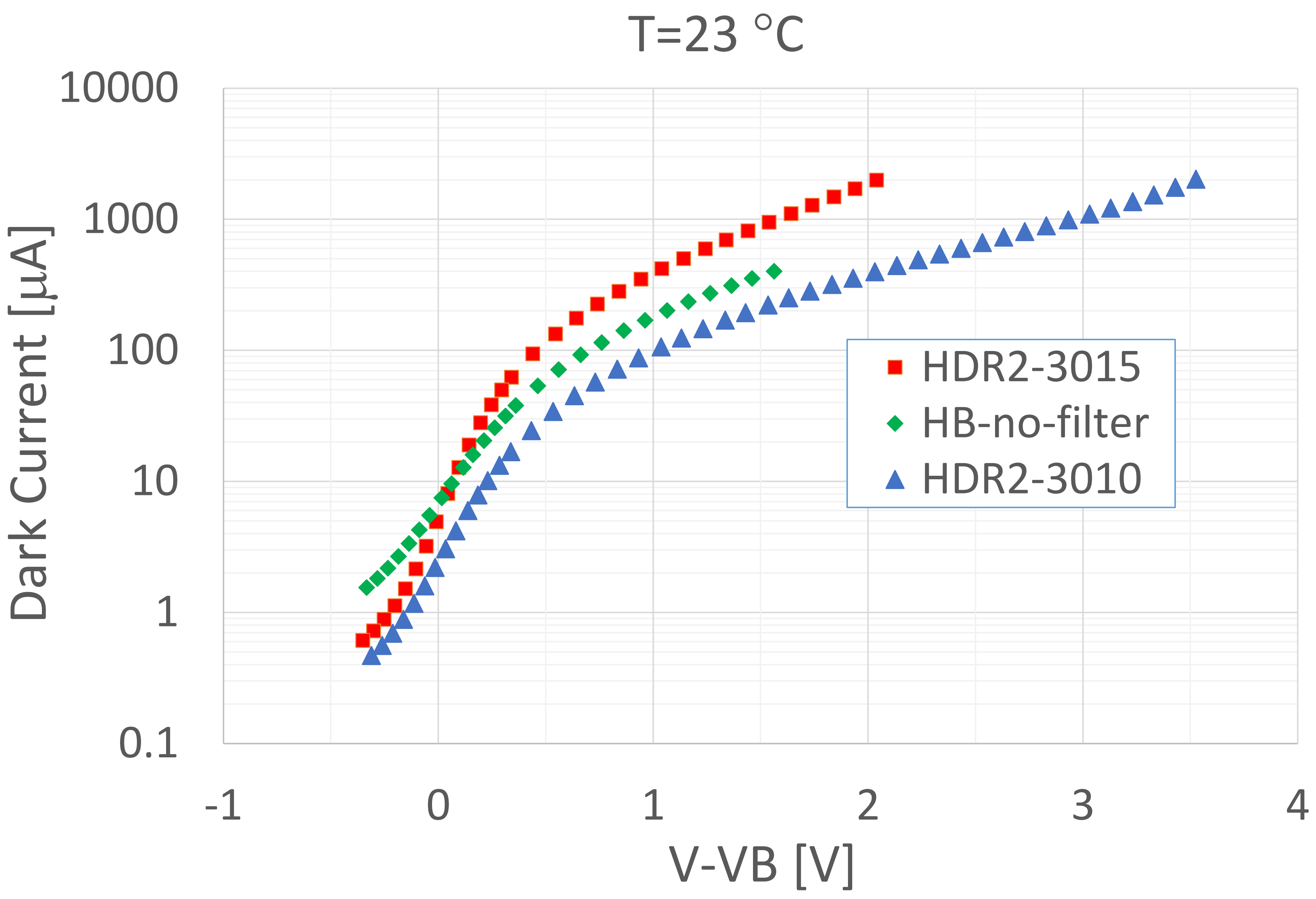


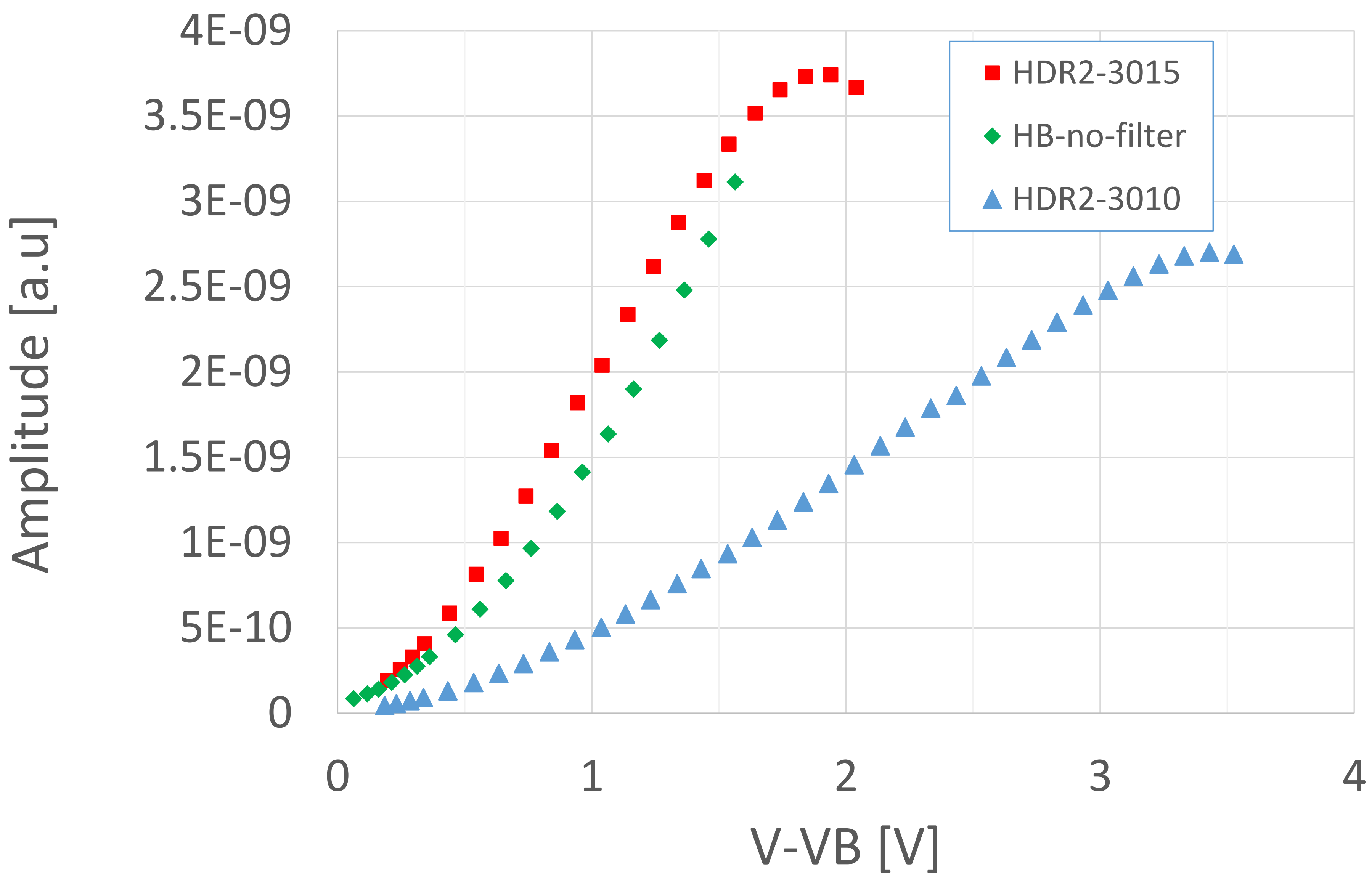
VB vs. Temperature



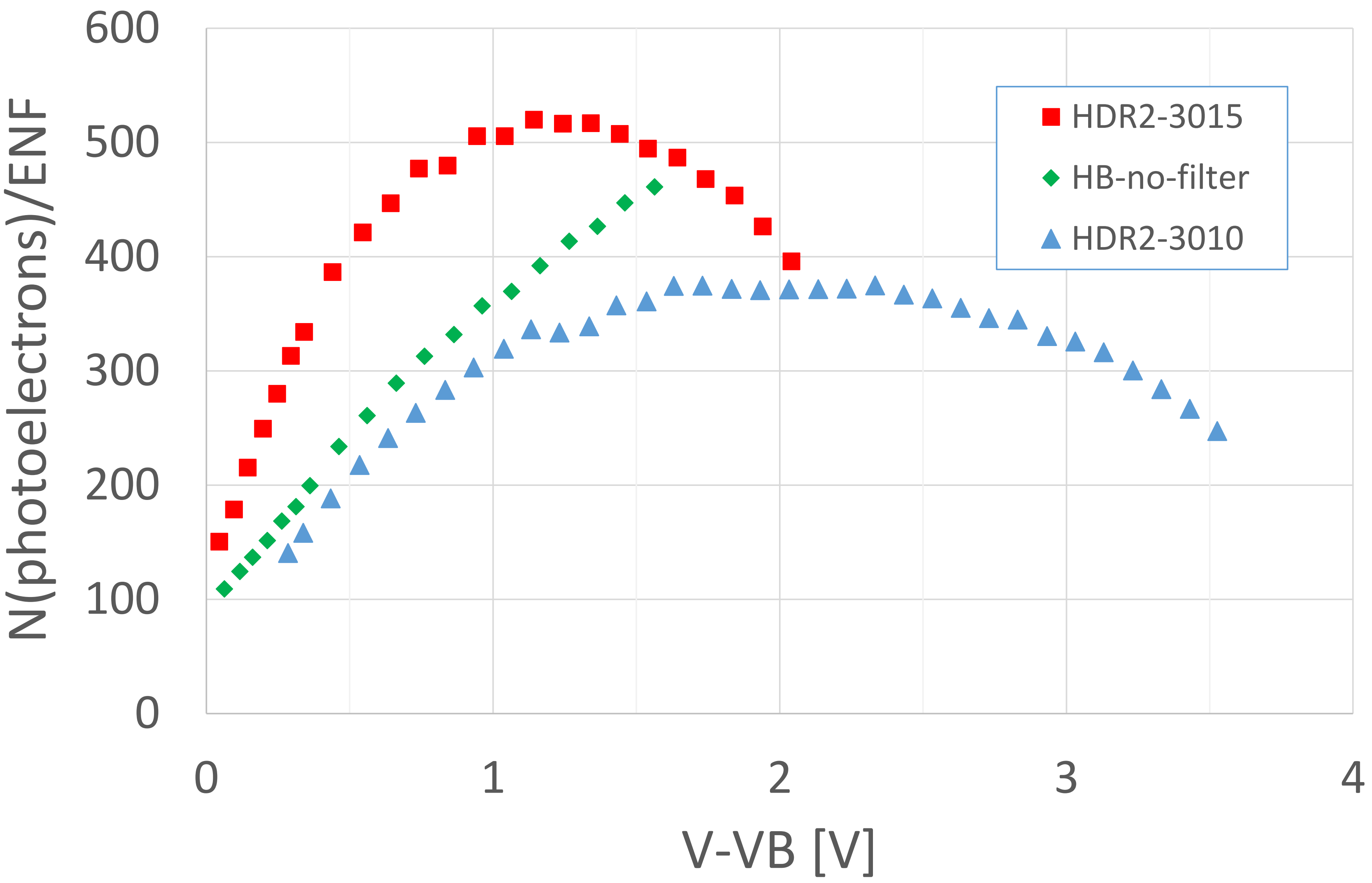
dVB/dT ~ 39 mV/°C

HDR2 and HB-no-filter SiPM after irradiation at CHARM (preliminary!)

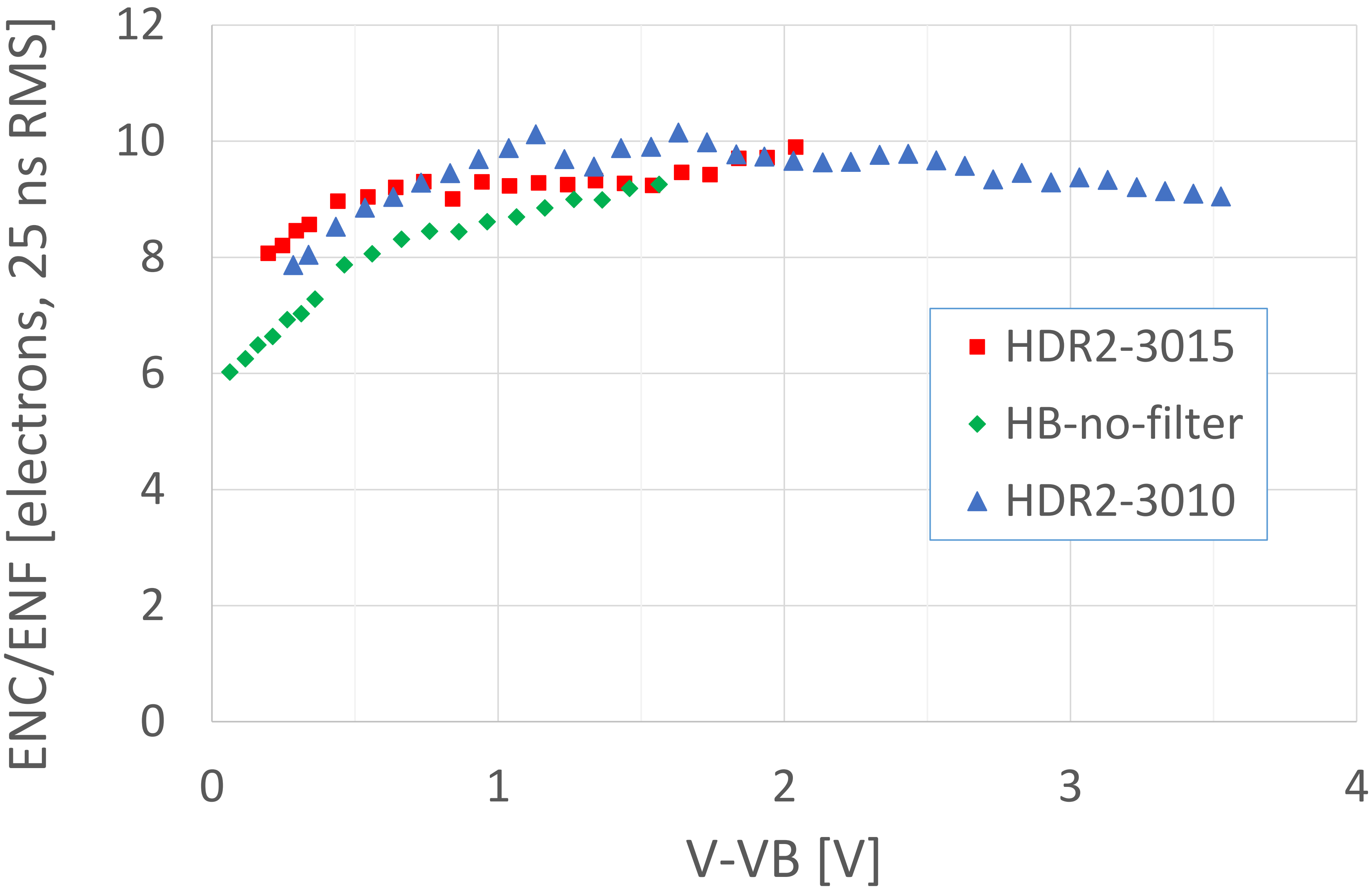

T=23 °C
Dark Current [µA]
10000
1000
100
10
1
0.1
-1
0
1
2
3
4
V-VB [V]
HDR2-3015
HB-no-filter
HDR2-3010



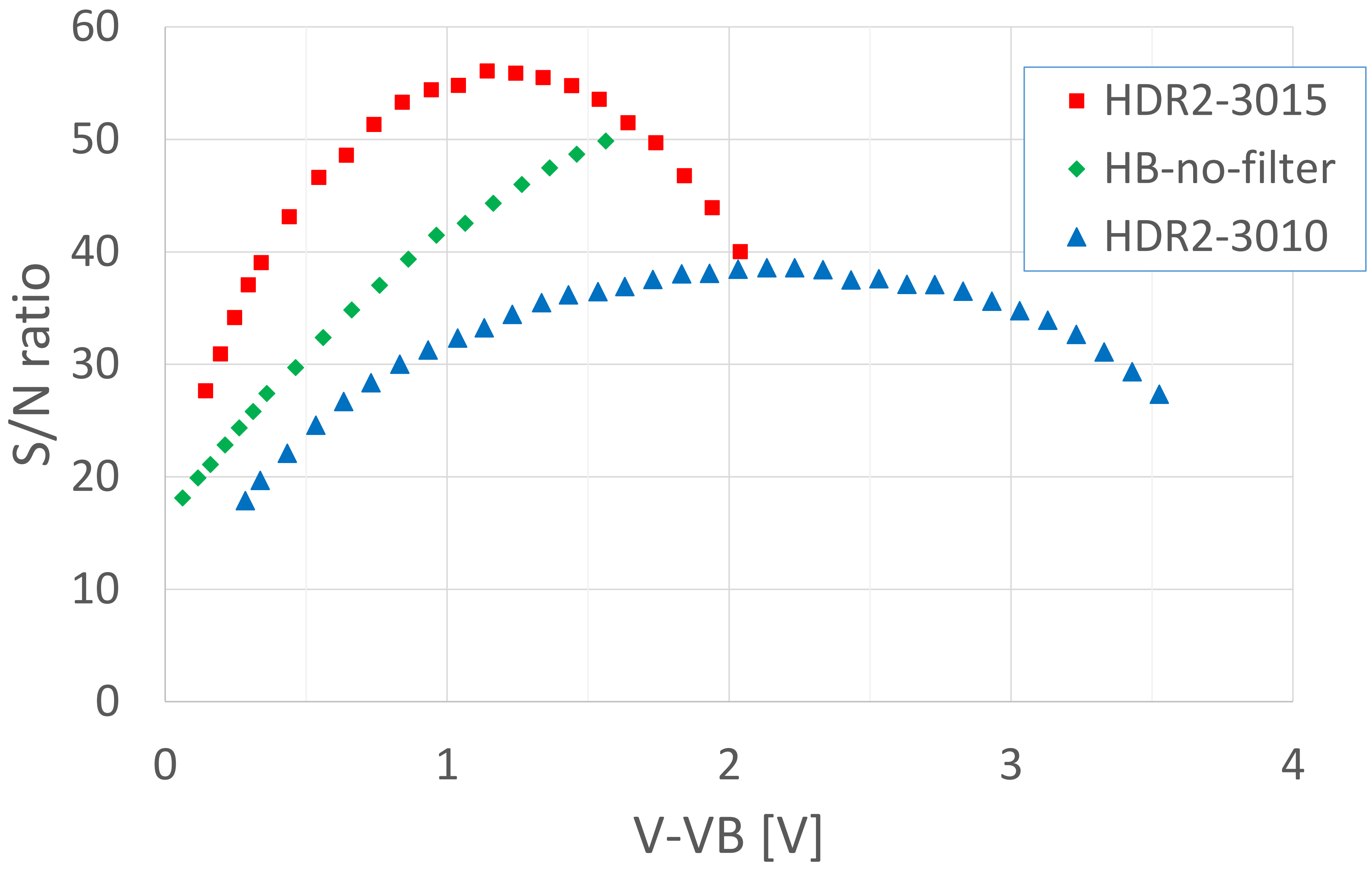
4E-09
3.5E-09
3E-09
2.5E-09
2E-09
1.5E-09
1E-09
5E-10
0
Amplitude [a.u]
0
1
2
3
4
V-VB [V]
HDR2-3015
HB-no-filter
HDR2-3010



$\langle N_{photons} \rangle$ ~3400 photons/pulse



ENC/ENF [electrons, 25 ns RMS]
12
10
8
6
4
2
0
0
1
2
3
4
V-VB [V]
HDR2-3015
HB-no-filter
HDR2-3010


60
50
40
30
20
10
0
S/N ratio
0
1
2
3
4
V-VB [V]
HDR2-3015
HB-no-filter
HDR2-3010

Summary - IV

HDR2-3015 and HDR2-3010 MPPCs have much better PDE and lower ENF, X-talk in comparison to the previous 10 um and 15 um HPK SiPMs. Preliminary irradiation results look very promising. More studies needed: noise dependence on the temperature, irradiation with 5E13 n/cm^2 in cold **– good thermal conductivity of the package is required!!!**