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Characterization of performance parameters

in irradiated SiPMs

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HIGH-D

Radiation damage effects

for SiPMs

Radiation damage is a major concern when operating SiPMs in harsh radiation environment

Main effect:

Increase of dark current (I_{dark})/ dark count rate (*DCR*) proportionally to fluence that leads to:

- **loss of single photoelectron resolution**
- **decrease in response,**
  which could be attributed to either:

$$I_{photo} = q_0 \cdot \mu \cdot G \cdot PDE \cdot (1 + CN)$$

CN: Correlated Noise

  - **decrease of *G*** (gain)

$$G = \frac{1}{q_0} C_{pix} \cdot (V_{bias} - V_{bd})$$

  - **decrease of *PDE*** (photon detection efficiency)

$$PDE \propto (V_{bias} - V_{bd})$$

  - V_{bd} shift induced by change in E-field and **self-heating effect** due to high power dissipation (high I_{dark})

} unclear which effect dominates or if all three are relevant

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  - V_{bd} shift induced by change in E-field and **self-heating effect** due to high power dissipation (high I_{dark})

Solution (this talk):

- study radiation effects on a dedicated test structure
- gain and PDE of irradiated SiPM are best investigated on one single-cell readout separately from the others

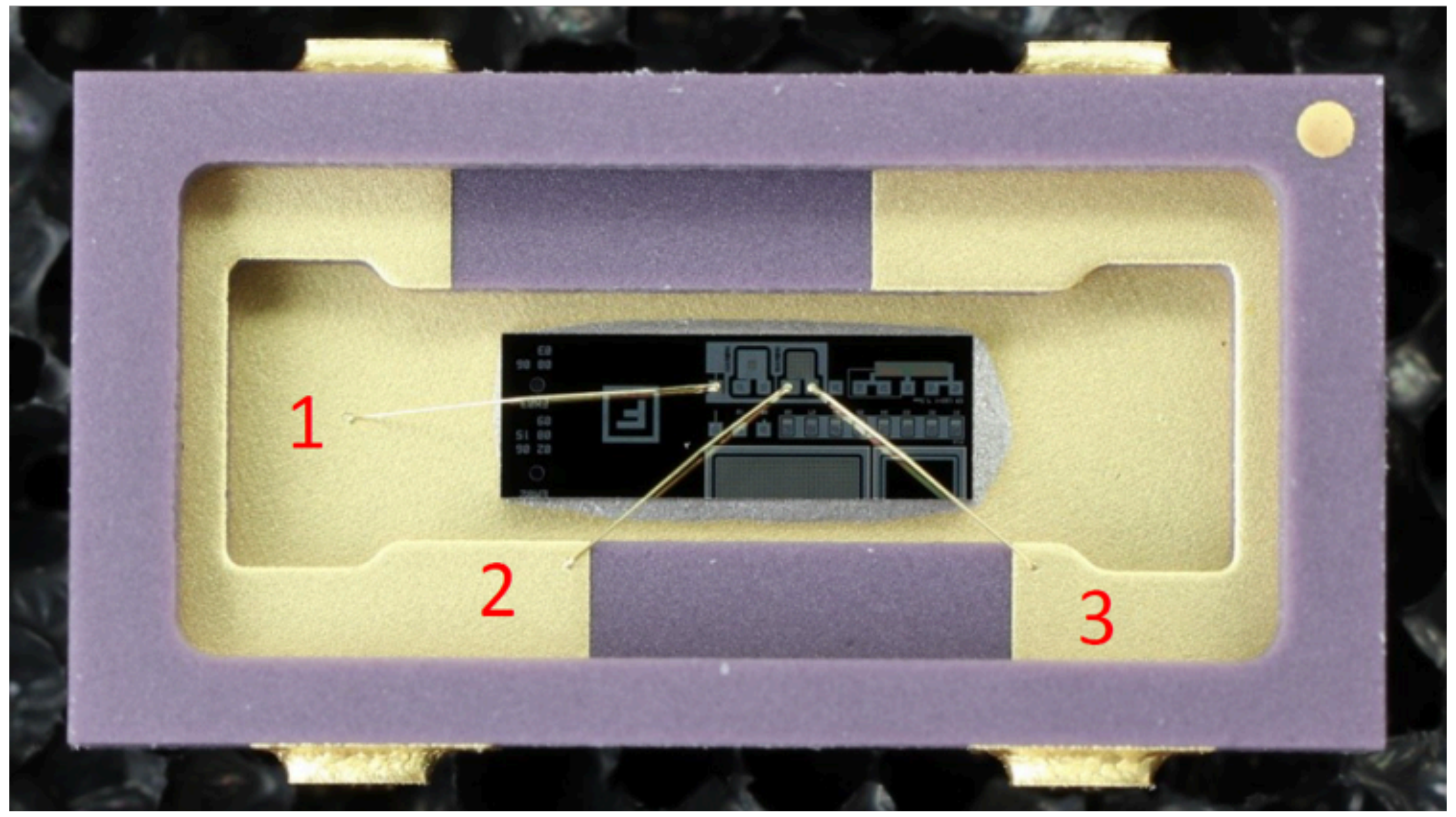
Device under test

Hamamatsu S14160-15UM-SMPTS

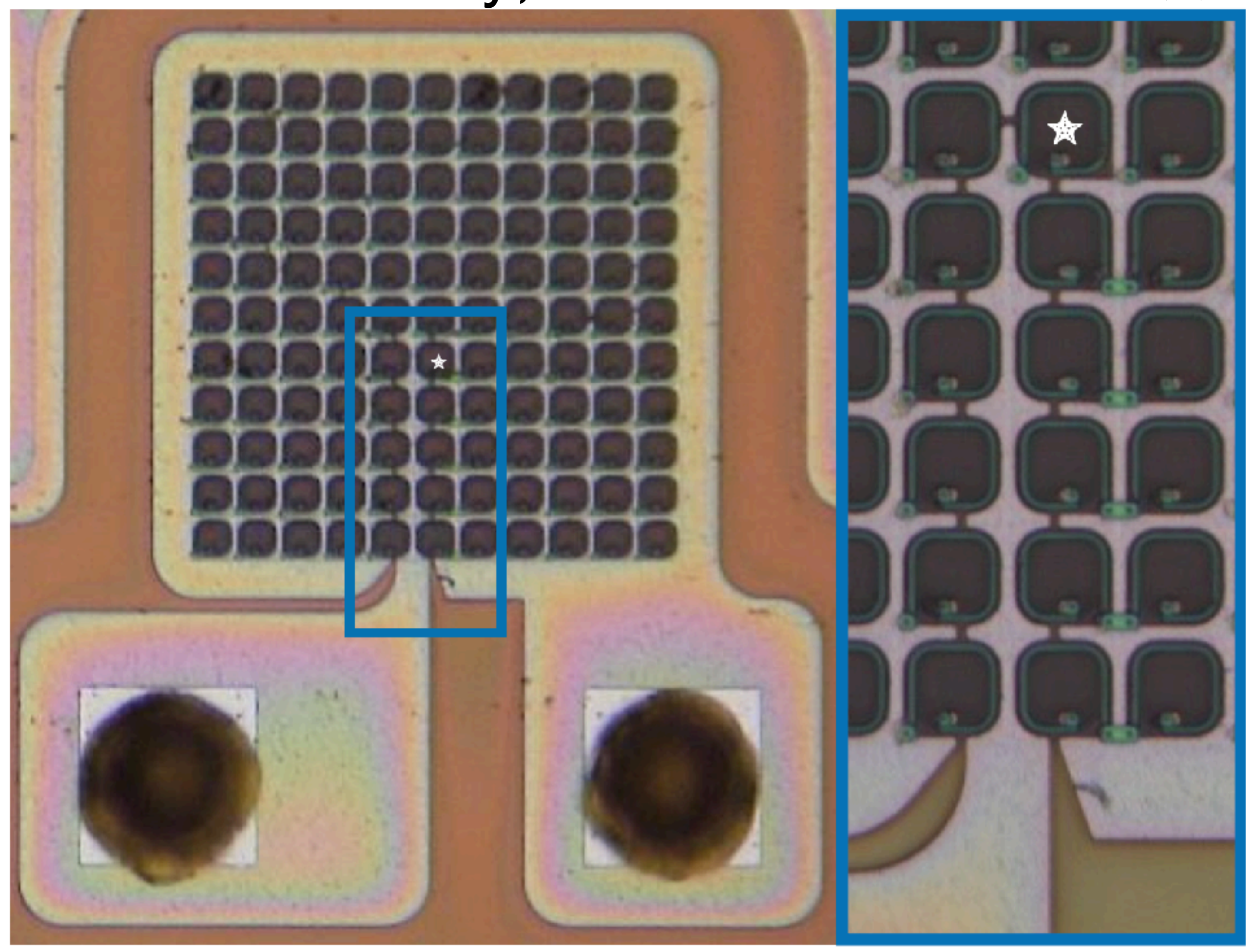
After discussion with Hamamatsu special test structures were provided:

- DUT on cut of silicon wafer in ceramic package
- Array of 11x11 cells with 15 μm pitch
- One cell in the centre of array disconnected from the others
  - 1 – common cathode
  - 2 – anode of 1 cell
  - 3 – anode of 120 cells
- Irradiated at Lubljana neutron reactor
  (with kind help of Y. Musienko and A. Heering)

Hamamatsu SiPM test structure of S14160 series



11x11-cell array; 1 disconnected cell ★

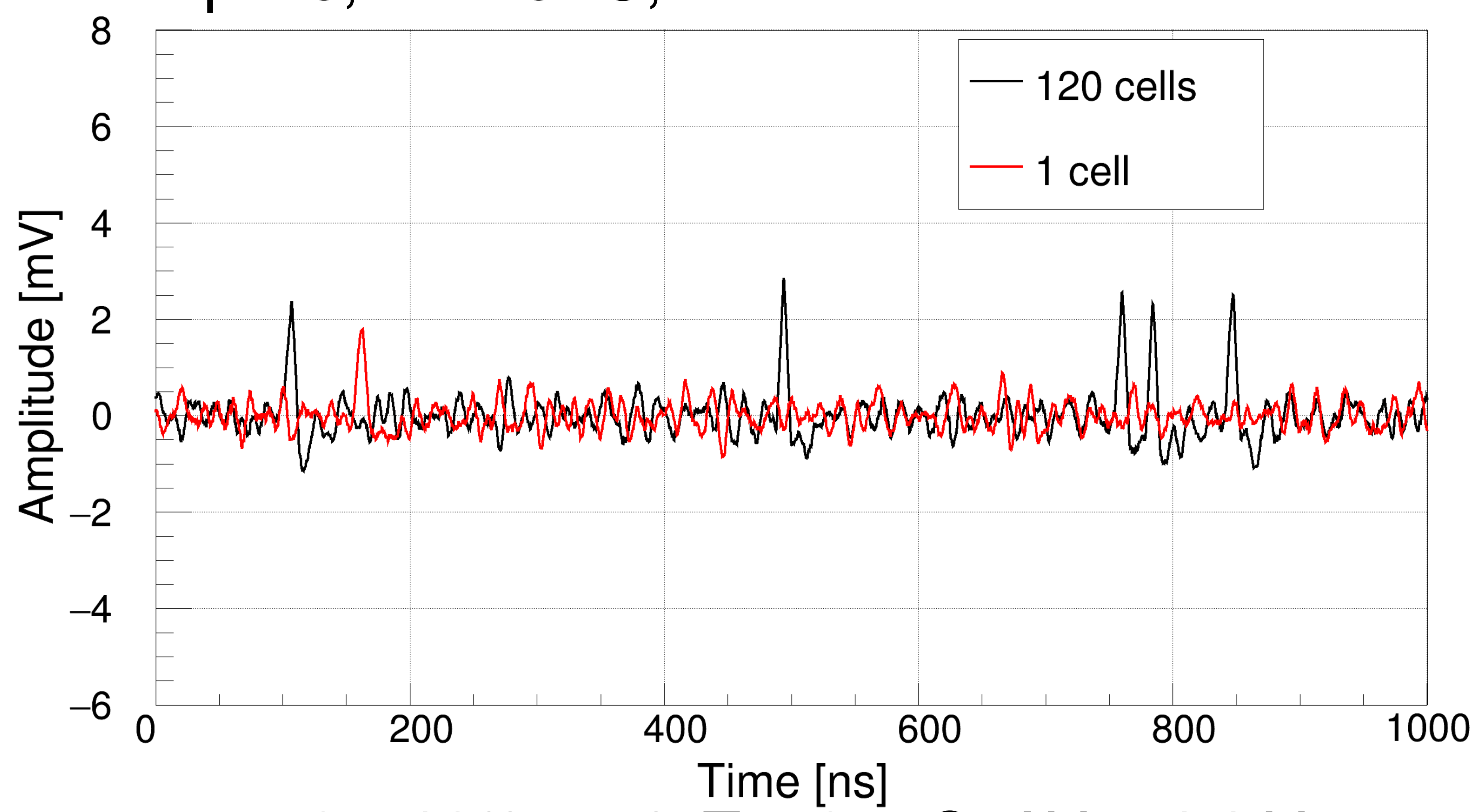


Test samples	
#	ϕ [cm^{-2}]
10, 11, 13	0E+00
5	2E+12
6	1E+13
7	5E+13

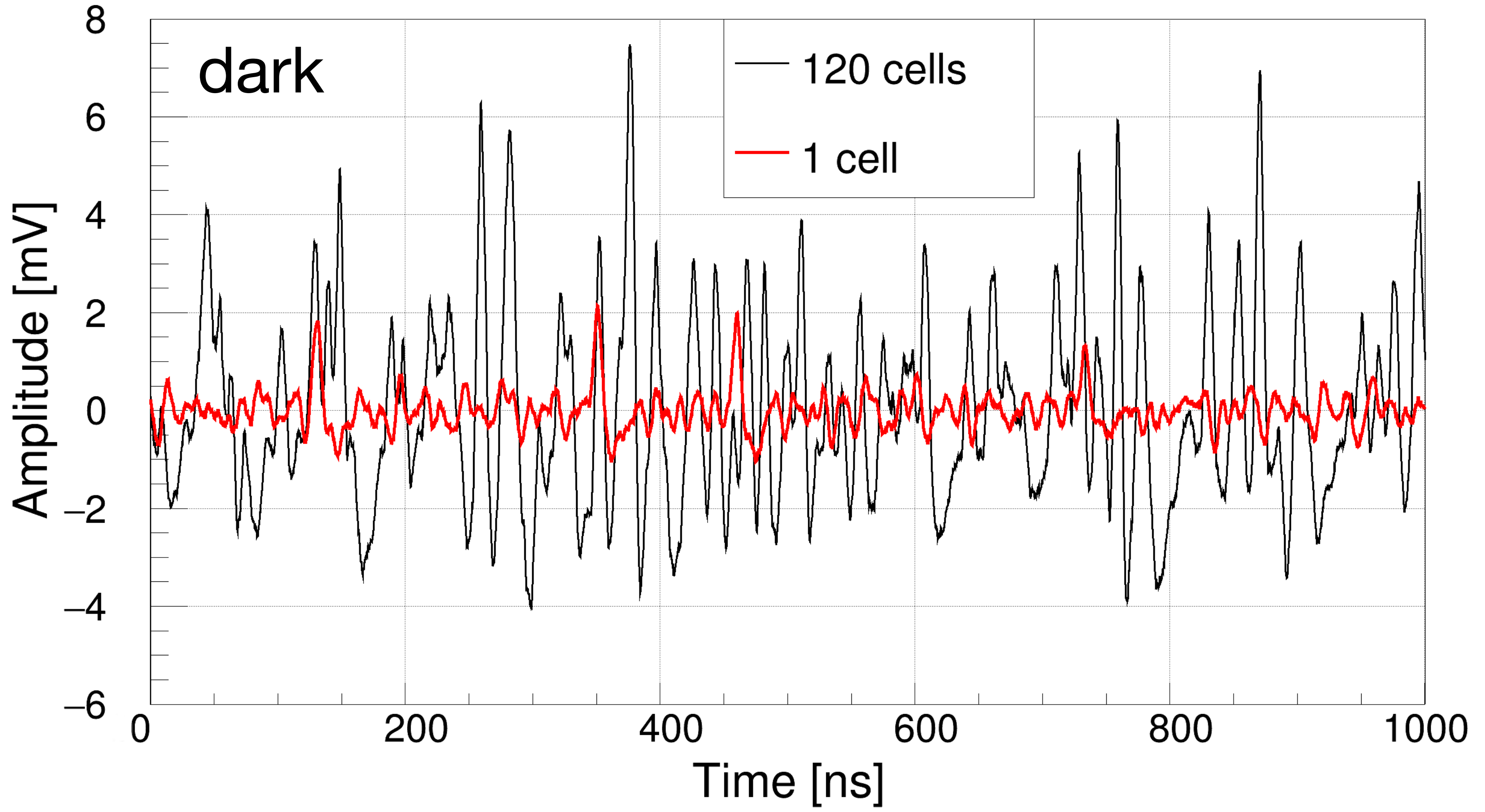
Waveforms

before and after irradiation

$\phi = 0$, T = 25 °C, $\Delta V = 4.1$ V



$\phi = 2 \cdot 10^{12}$ cm^{-2}, T = 25 °C, $\Delta V = 4.1$ V



Before irradiation:

- single photon pulses visible in 120 cells as well as 1 cell

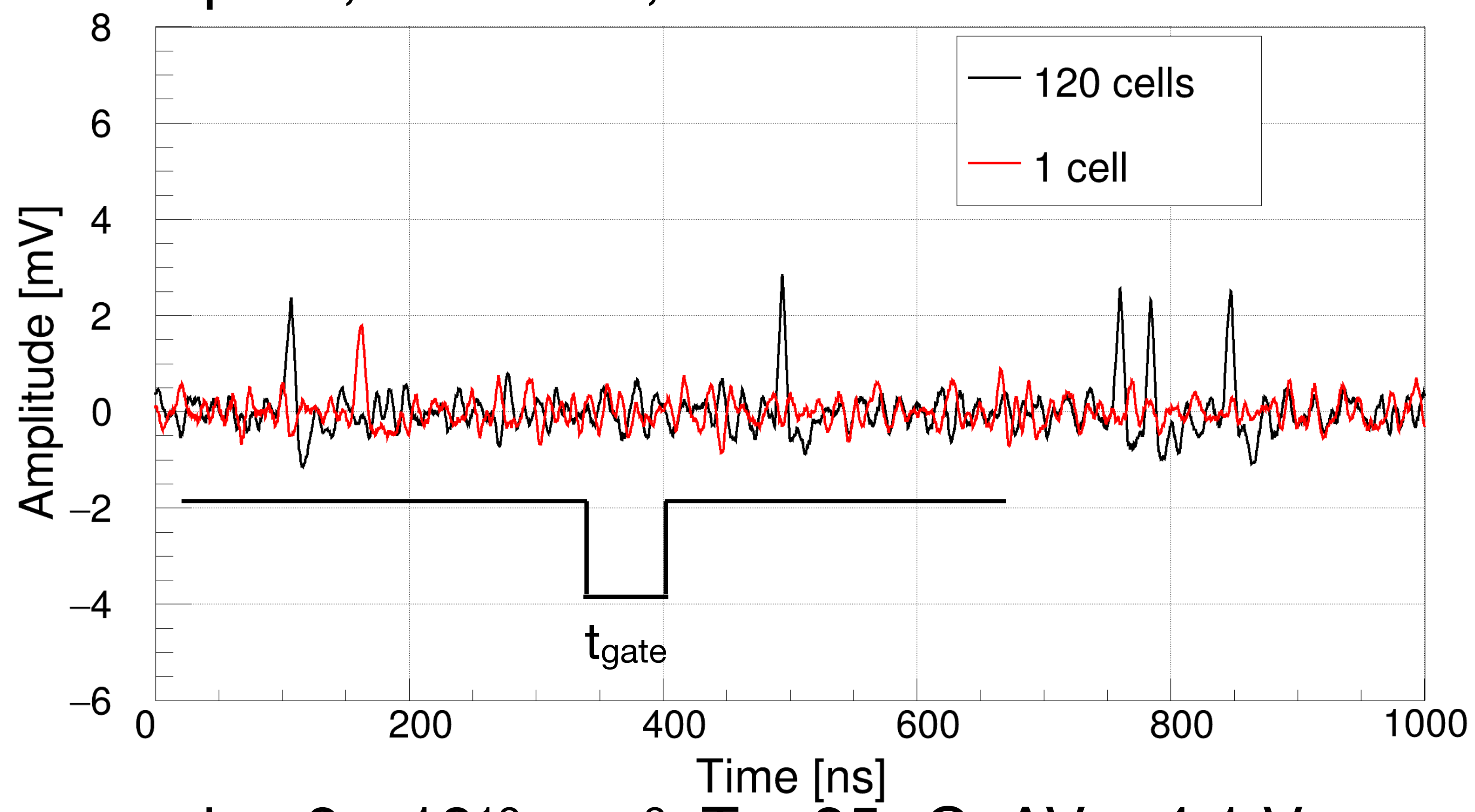
After $\phi = 2 \cdot 10^{12}$ cm^{-2} :

- baseline fluctuation in 120 cells larger than single photon pulse amplitude
- single photon pulses still visible in 1 cell

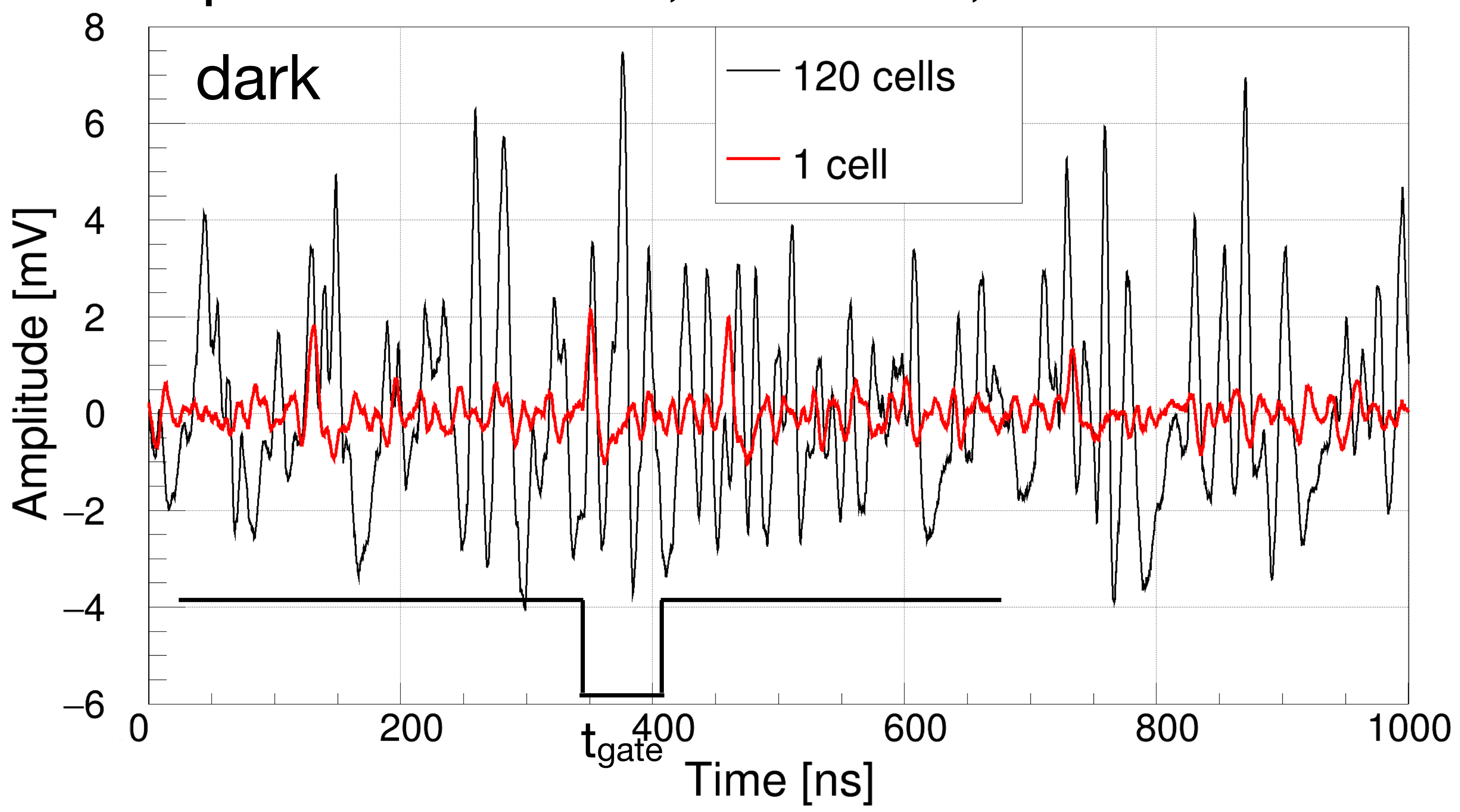
Waveforms integrals

before and after irradiation

ϕ = 0, T = 25 °C, ΔV = 4.1 V



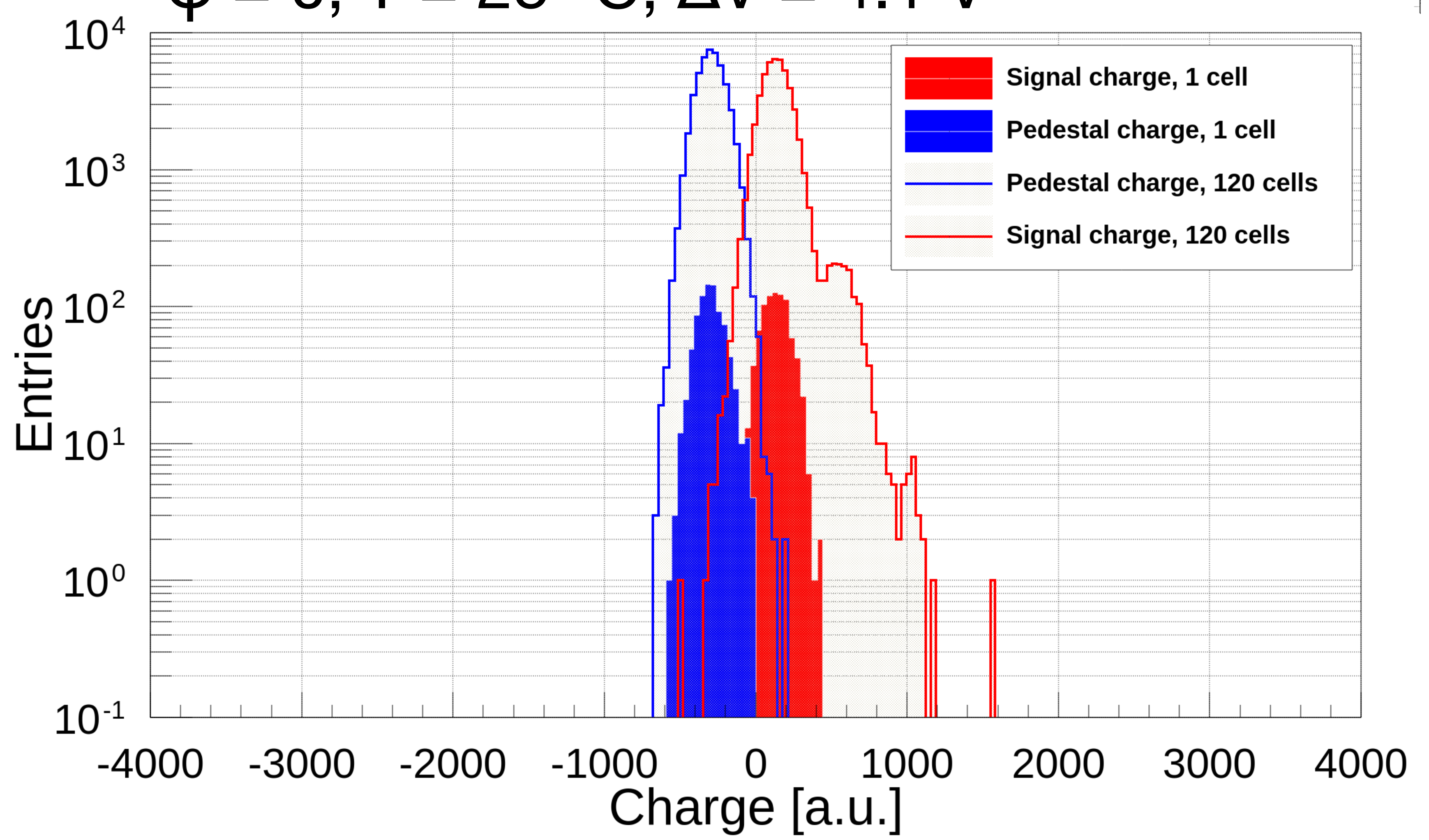
ϕ = 2 · 10^{12} cm^{-2}, T = 25 °C, ΔV = 4.1 V



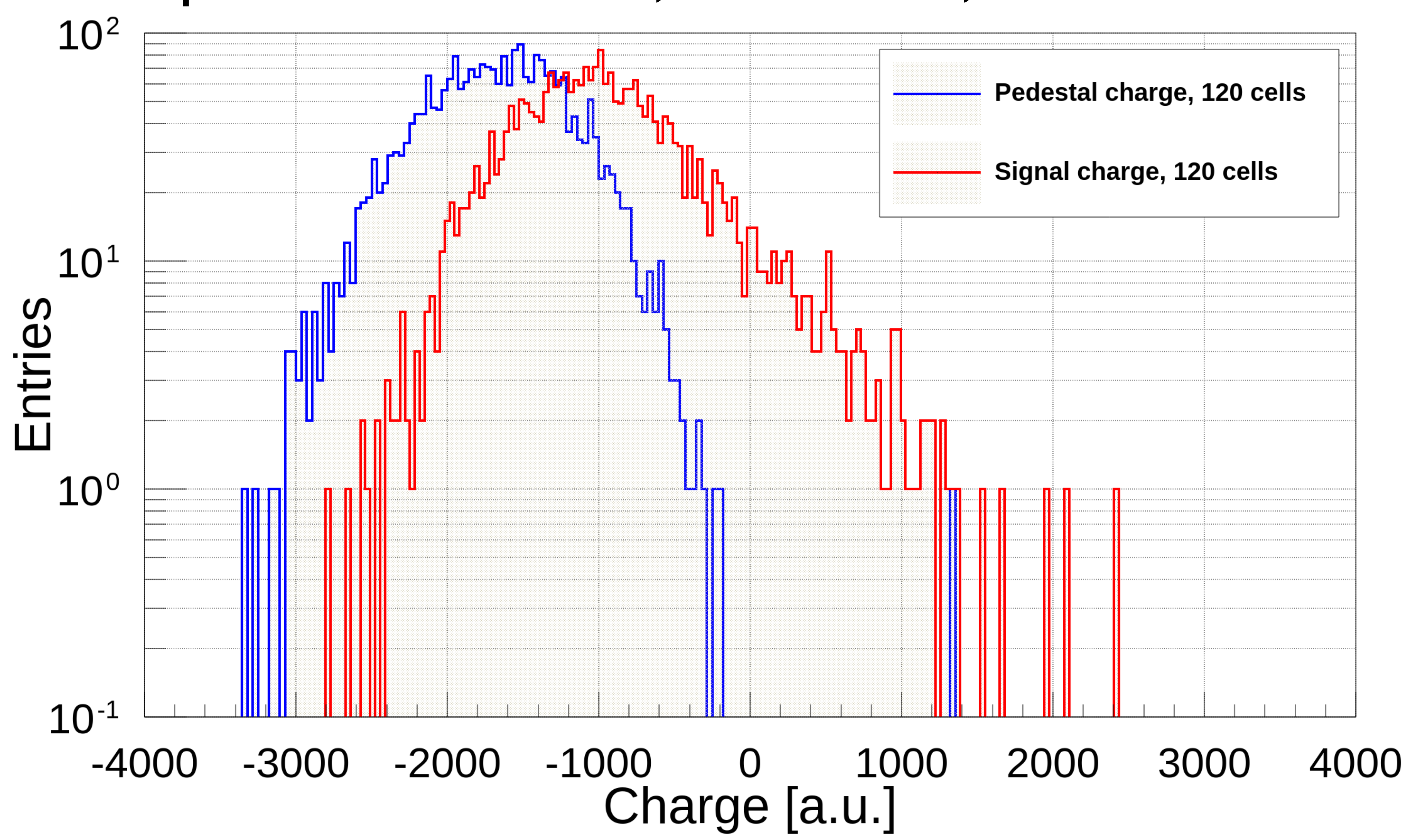
Integration time:

t_{gate} = 60 ns

ϕ = 0, T = 25 °C, ΔV = 4.1 V



ϕ = 2 · 10^{12} cm^{-2}, T = 25 °C, ΔV = 4.1 V



Gain

from single cell

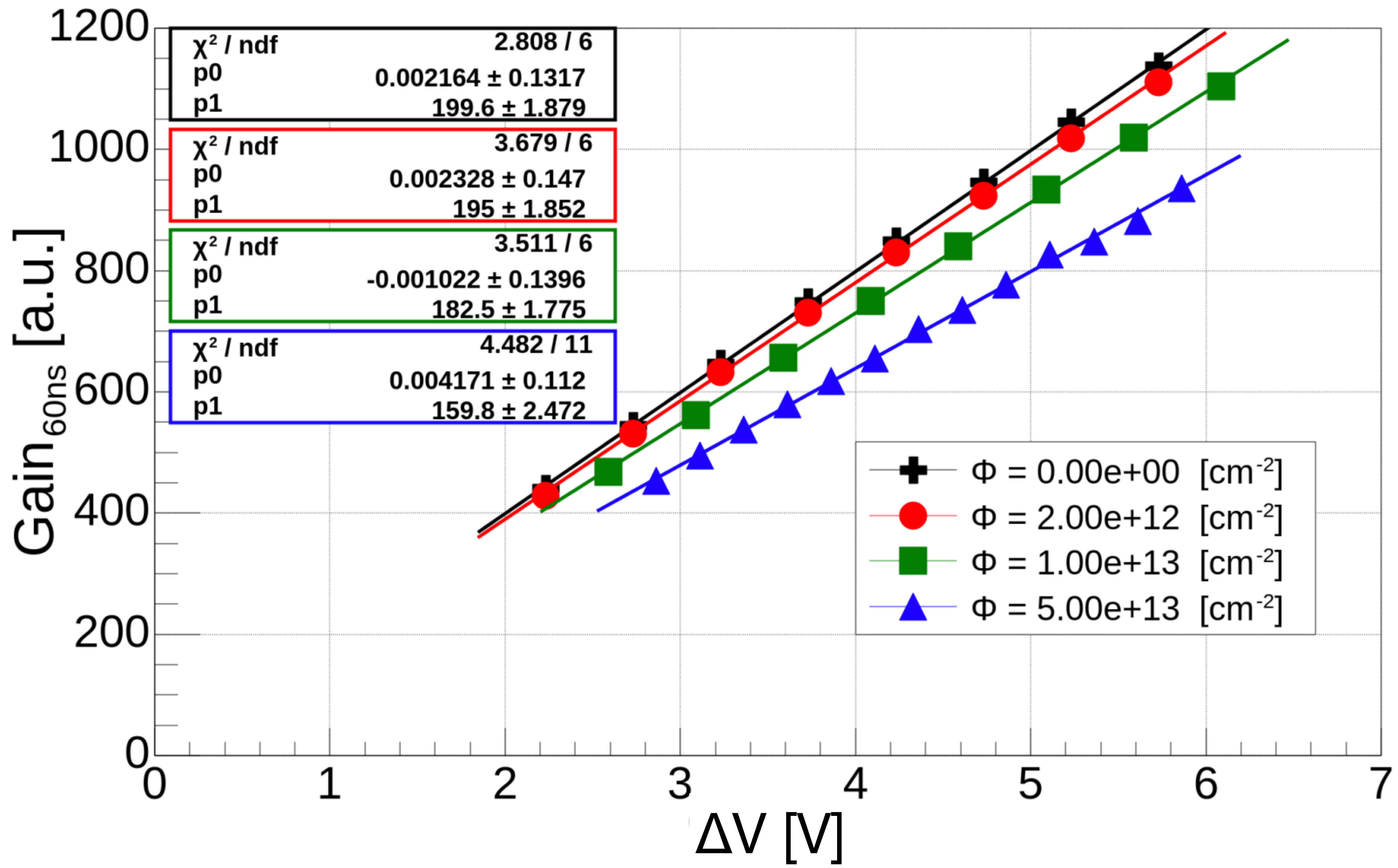
First **direct gain measurement** of irradiated SiPMs with single-cell readout

Garutti et al. "Radiation hardness study using SiPMs with single-cell readout" (2021) https://doi.org/10.48550/arXiv.2111.00483

For the highest fluence ($\phi = 5\ 10^{13}\ cm^{-2}$):

- gain reduction of 19%
- increase of $V_{bd}^{G} = V_{off}$ by ~0.5 V

Φ [cm^{-2}]	V_{off} [V]	G/G_0
0e00	35.25±0.04	1.00
2e12	35.26±0.04	0.98
1e13	35.41±0.04	0.92
5e13	35.74±0.05	0.81



Hamamatsu S14160-15UM-SMPTS

Open questions

from gain analysis

- Does the increase in dark current induce self-heating in the DUT?
- Is the difference between V_{bd}^{G} and V_{bd}^{IV} fluence dependent?
  - $V_{bd}^{G} = V_{off}$: breakdown voltage from G-measurements, so called turn-off voltage, it indicates the voltage at which the Geiger discharge **stops**
  - V_{bd}^{IV} : breakdown voltage from IV-measurements, it indicates the voltage at which the Geiger discharge **starts**
  - in the following the overvoltage is $\Delta V = V_{bias} - V_{bd}^{IV}$
- Is the radiation damage uniform? Does 1 cell represent the 120 cells average?

Answers from analysis of IV-measurements of the same test structures

IV-measurements

before and after irradiation

Bychkova et al. "Radiation damage uniformity in a SiPM" (2022), proceeding to VCI2022, submitted to NIMA

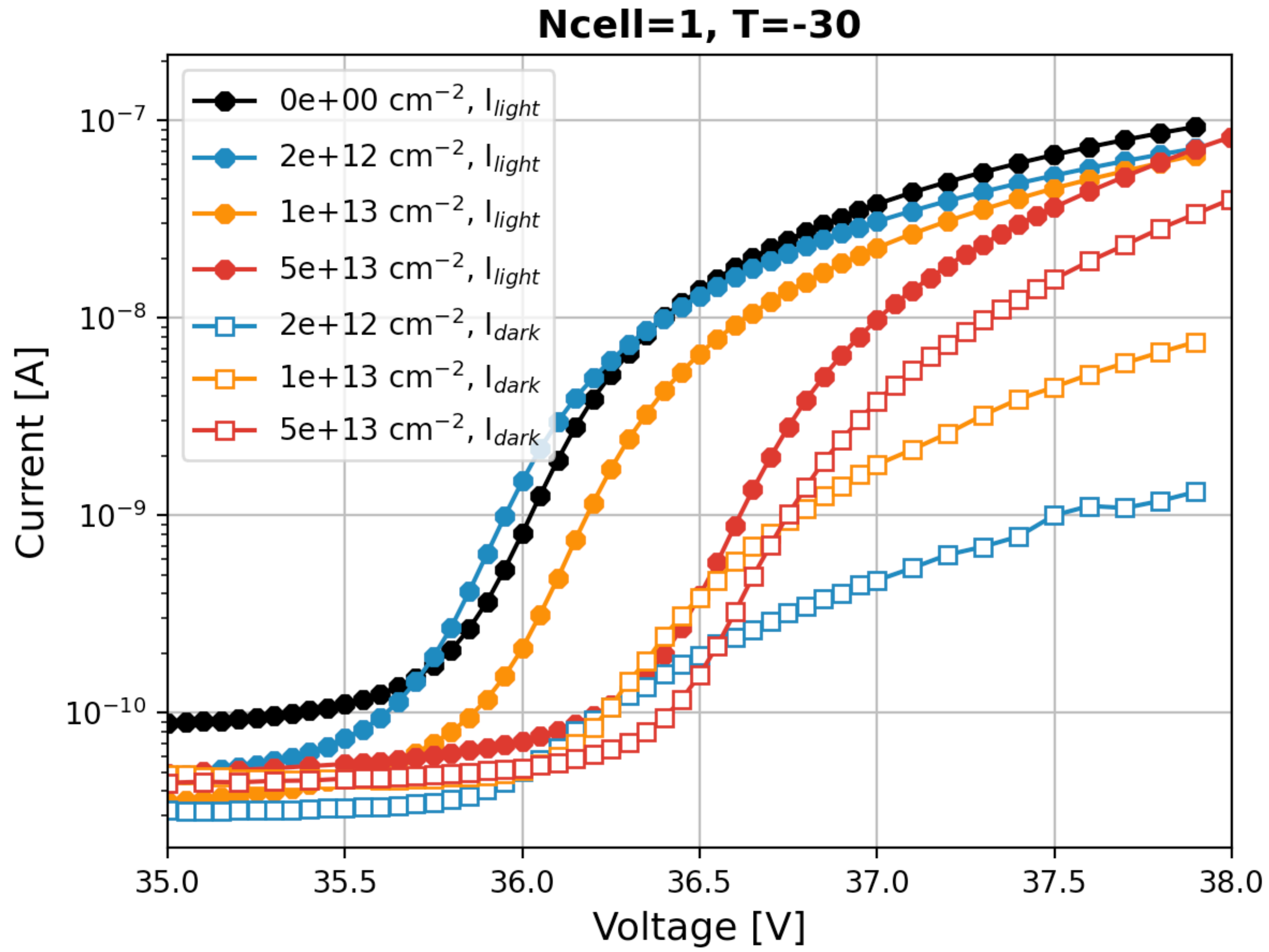
Measurements of IV-curves for 1 cell and 120 cells:

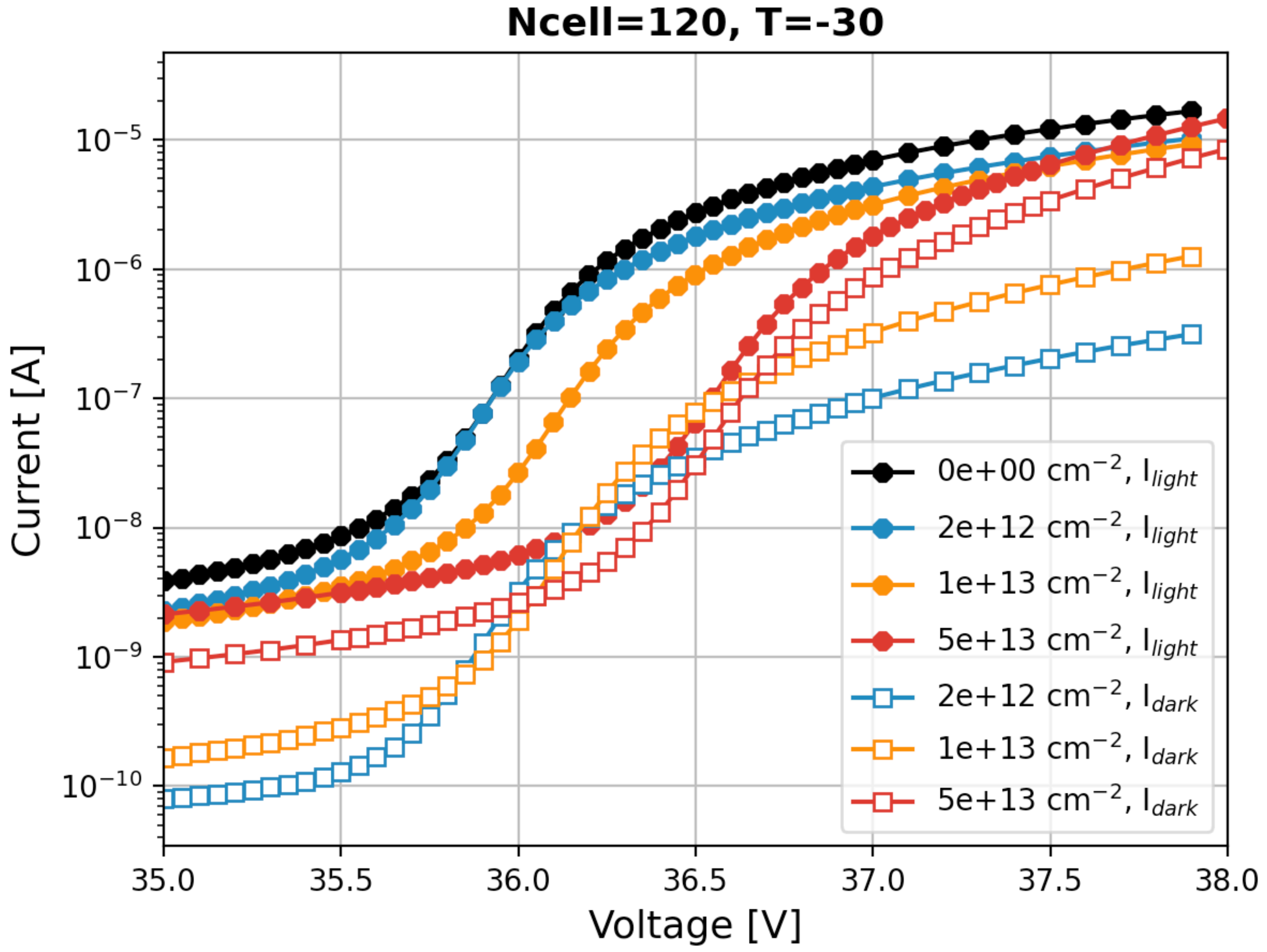
- at T = -30 °C
- with and without illumination
- in a voltage range V_{bd}^{IV} - 2V < V_{bias} < V_{bd}^{IV} + 2V

I_{dark} — dark current

I_{photo} — photocurrent

$I_{light} = I_{dark} + I_{photo}$ — light current





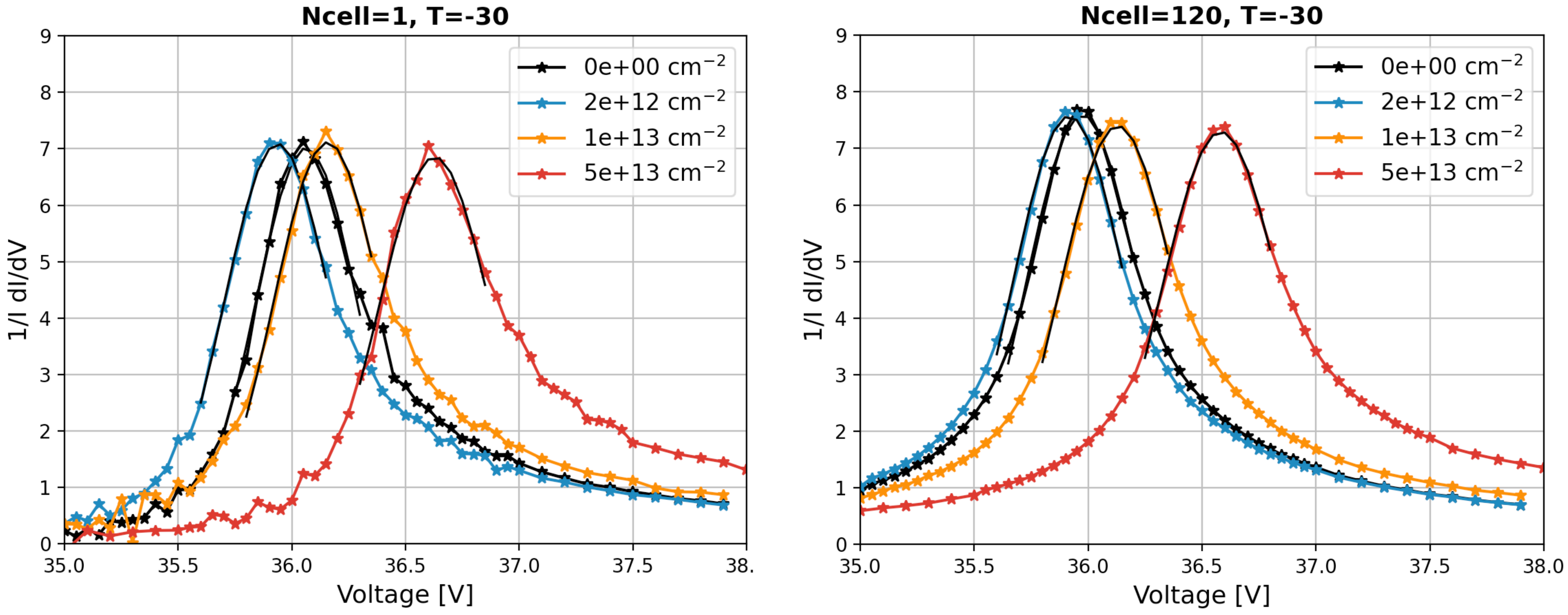
Breakdown voltage

V_{bd}^{IV}

Logarithmic Derivative method used to determine breakdown voltage:

- using of logarithmic derivative of I_{light}
- maximum approximated as mean from Gauss fit

Musienko et al, “Radiation damage of prototype SiPMs for the CMS HCAL Barrel phase I upgrade”, NIMA 912, 21 (2018) 359-362.

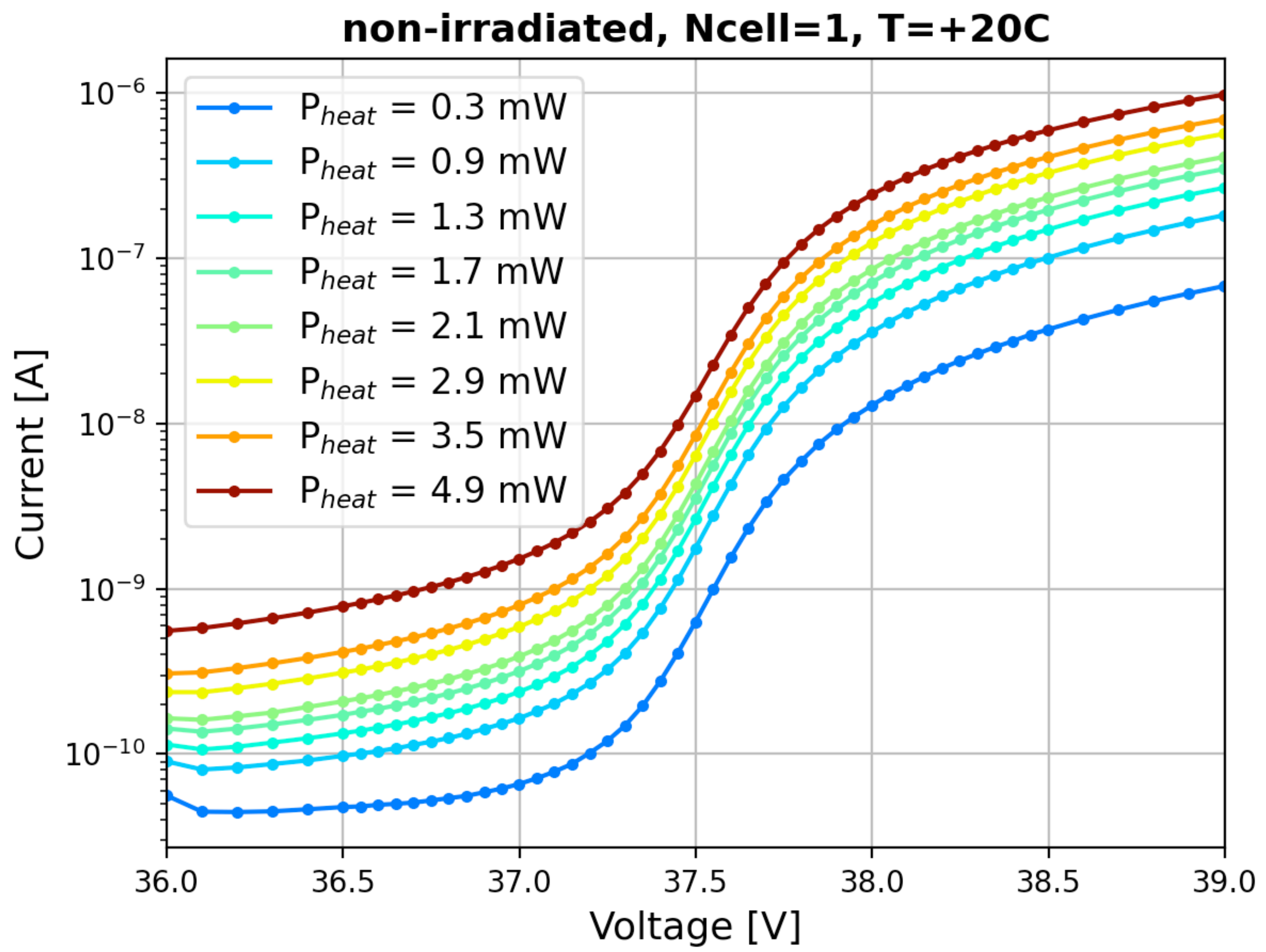


DUT	V^{IV}_{bd} [V] at -30C	
ϕ [cm^{-2}]	1 cell	120 cells
0E+00	35.98 ± 0.03	35.94 ± 0.03
2E+12	35.93 ± 0.02	35.91 ± 0.03
1E+13	36.16 ± 0.03	36.13 ± 0.03
5E+13	36.62 ± 0.02	36.58 ± 0.03

V_{bd}^{IV} from 1 and 120 cells structure agree within errors

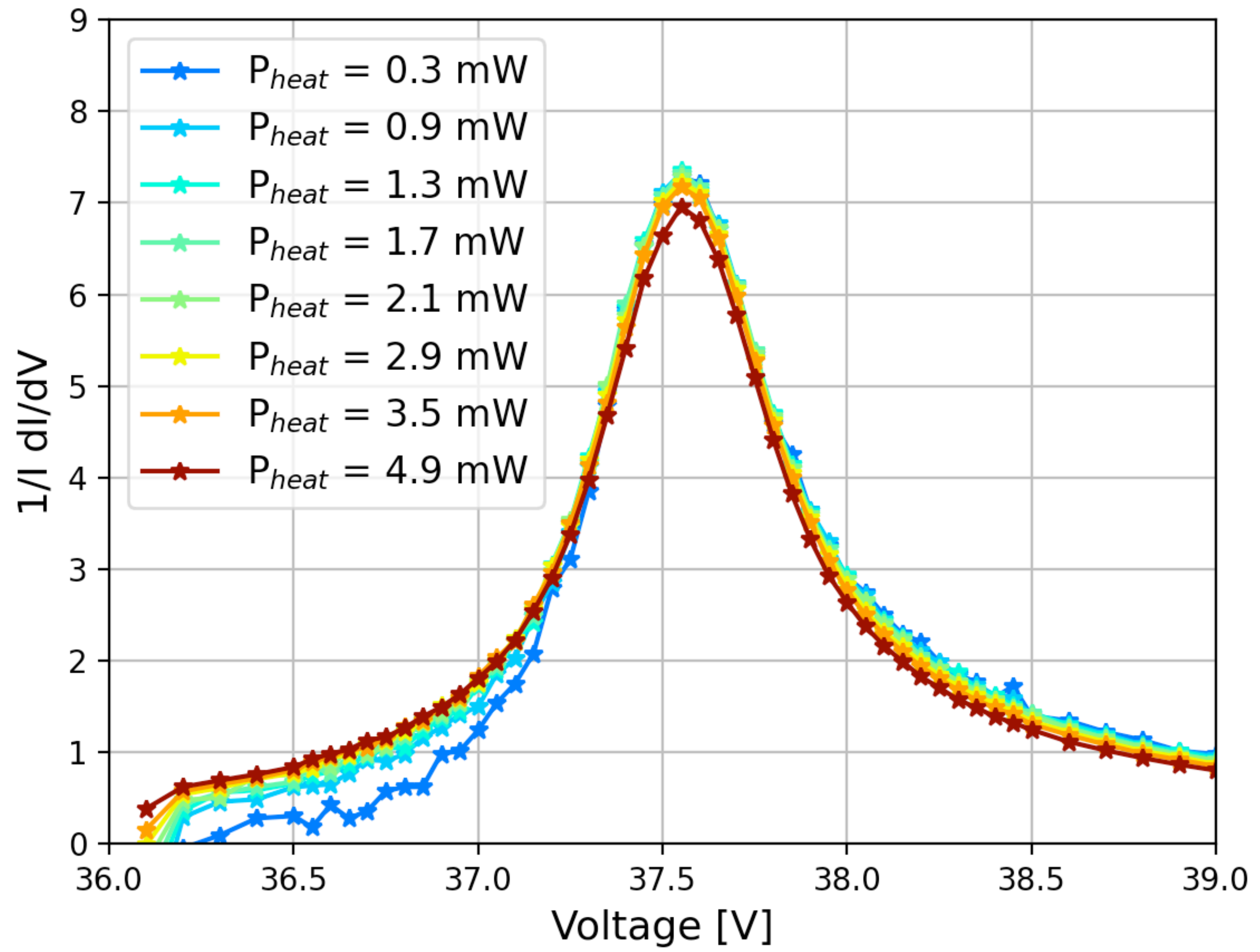
Self-heating effect

studied with non-irradiated structure



Highest heat power observed in the irradiated structure:
P = 1.9 mW (120 cells, ϕ = 5 10^{13} cm^{-2}, T = -30 °C, ΔV= 4 V)

Study self-heating effect by reproducing the same power by light intensity on a non-irradiated structure
(120 cells, ϕ = 0, T = +20 °C, ΔV = 1.5 V)



- 120 cells serve as a heater
- 1 cell serves as a temperature sensor since V_{bd}^{IV} strongly depends on SiPM temperature

no shift in V_{bd}^{IV} observed up to 4.9 mW
‣ self-heating effect is negligible in this study

Comparison of breakdown voltages

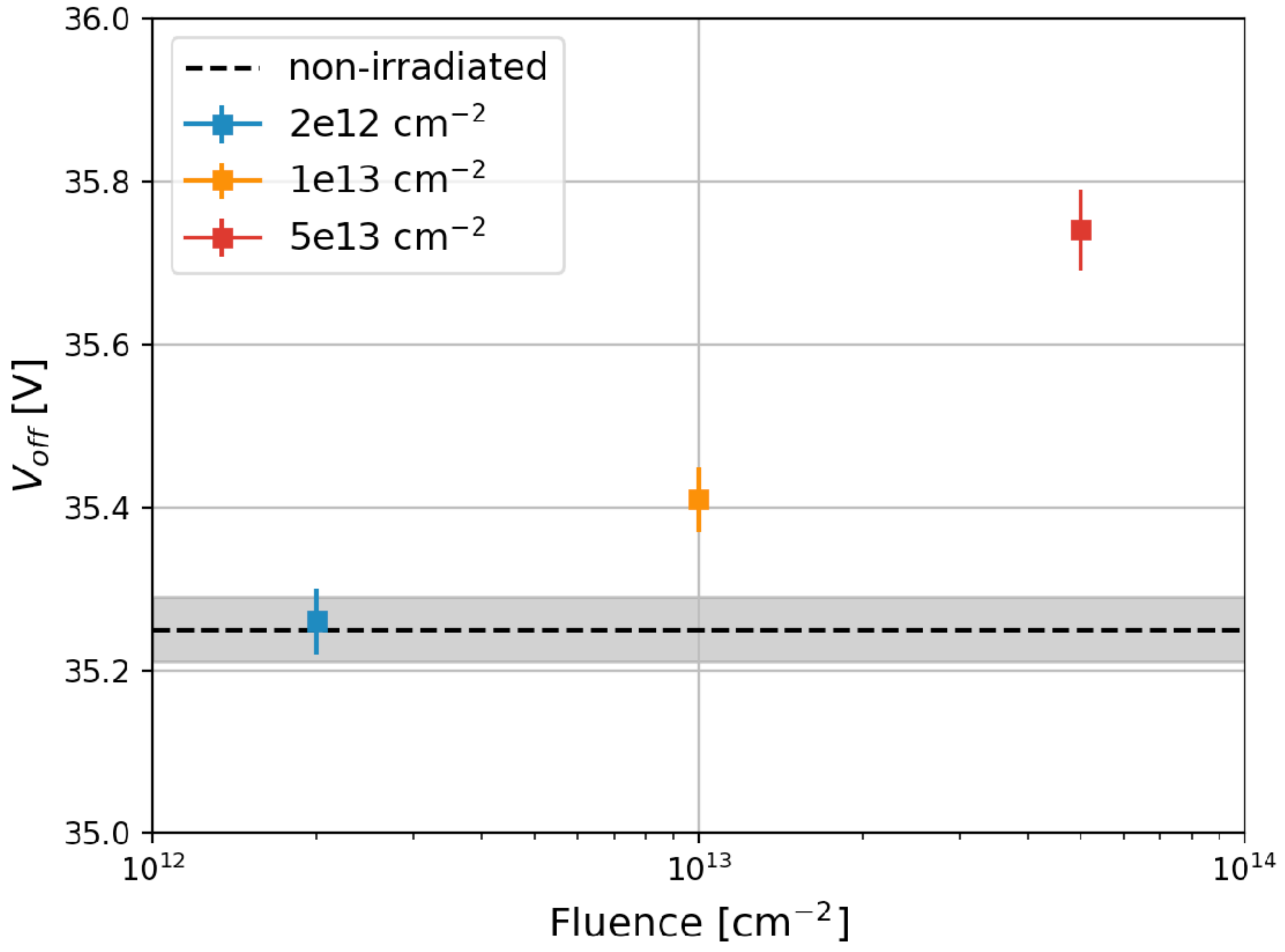
and fluence dependence

Observation for the highest fluence (ϕ = 5 10^{13} cm^{-2}):

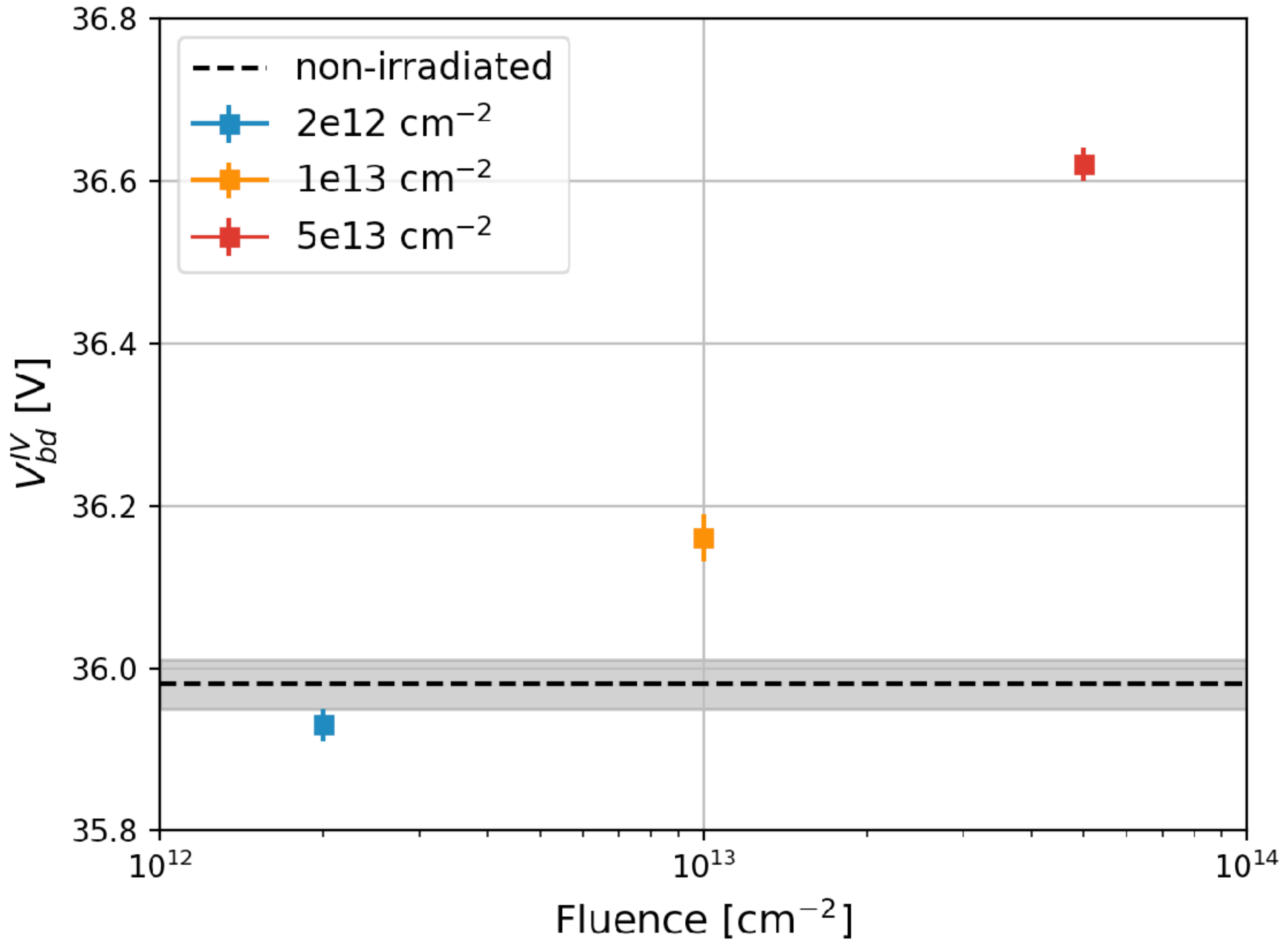
- increase of V_{off} by ~0.5 V
- increase of V_{bd}^{IV} by ~0.6 V
- difference between V_{bd}^{IV} and V_{off} ~0.9 V

DUT	V_{off} [V]	V^{IV}_{bd} [V]
ϕ [cm^{-2}]	1 cell at -30C	
0E+00	35.25 ± 0.04	35.98 ± 0.03
2E+12	35.26 ± 0.04	35.93 ± 0.02
1E+13	35.41 ± 0.04	36.16 ± 0.03
5E+13	35.74 ± 0.05	36.62 ± 0.02

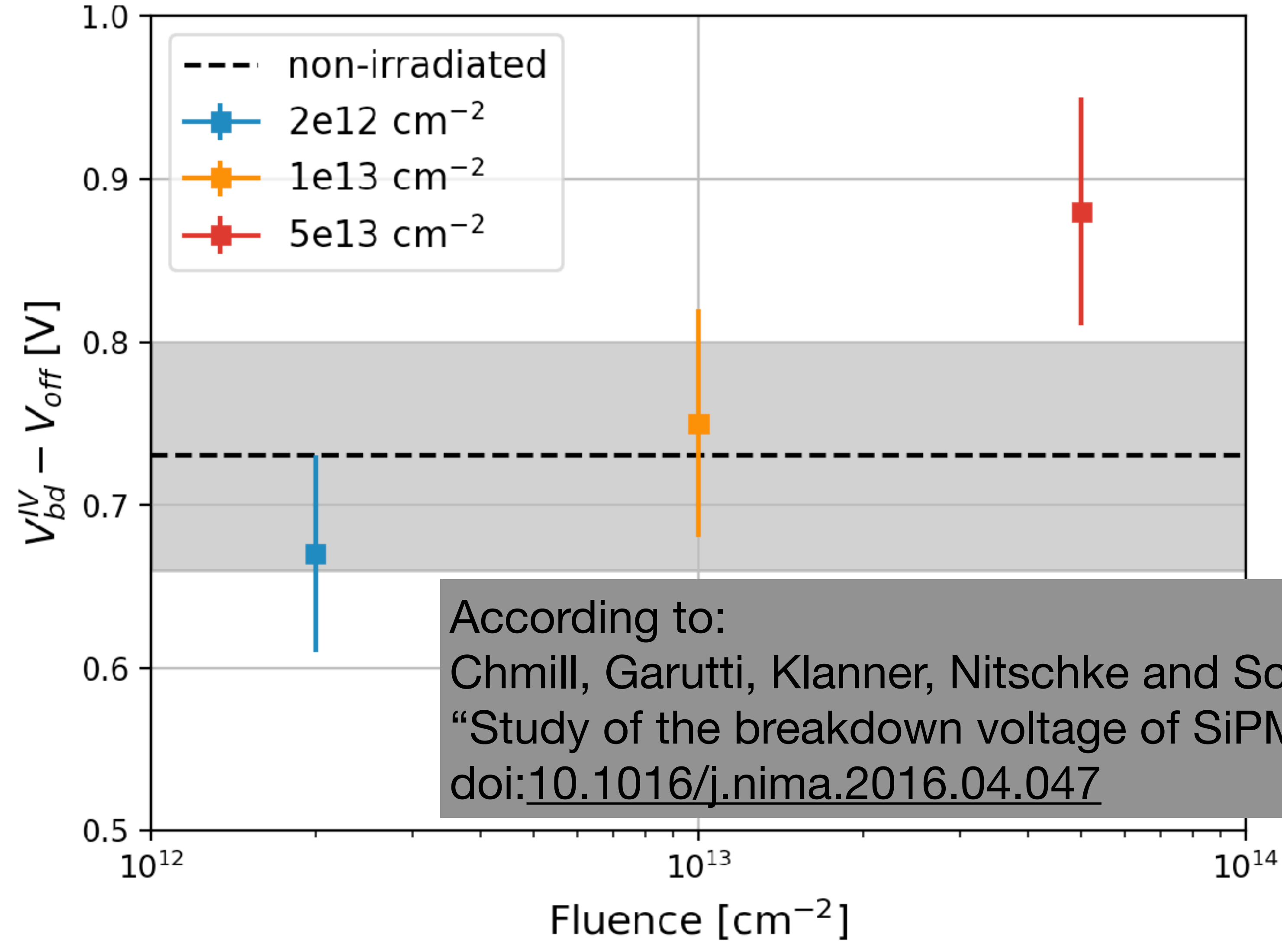
$$V_{bd}^{G} = V_{off}$$



$$V_{bd}^{IV}$$



$$V_{bd}^{IV} - V_{bd}^{G}$$



According to:
Chmill, Garutti, Klanner, Nitschke and Schwandt,
"Study of the breakdown voltage of SiPMs"
doi:10.1016/j.nima.2016.04.047

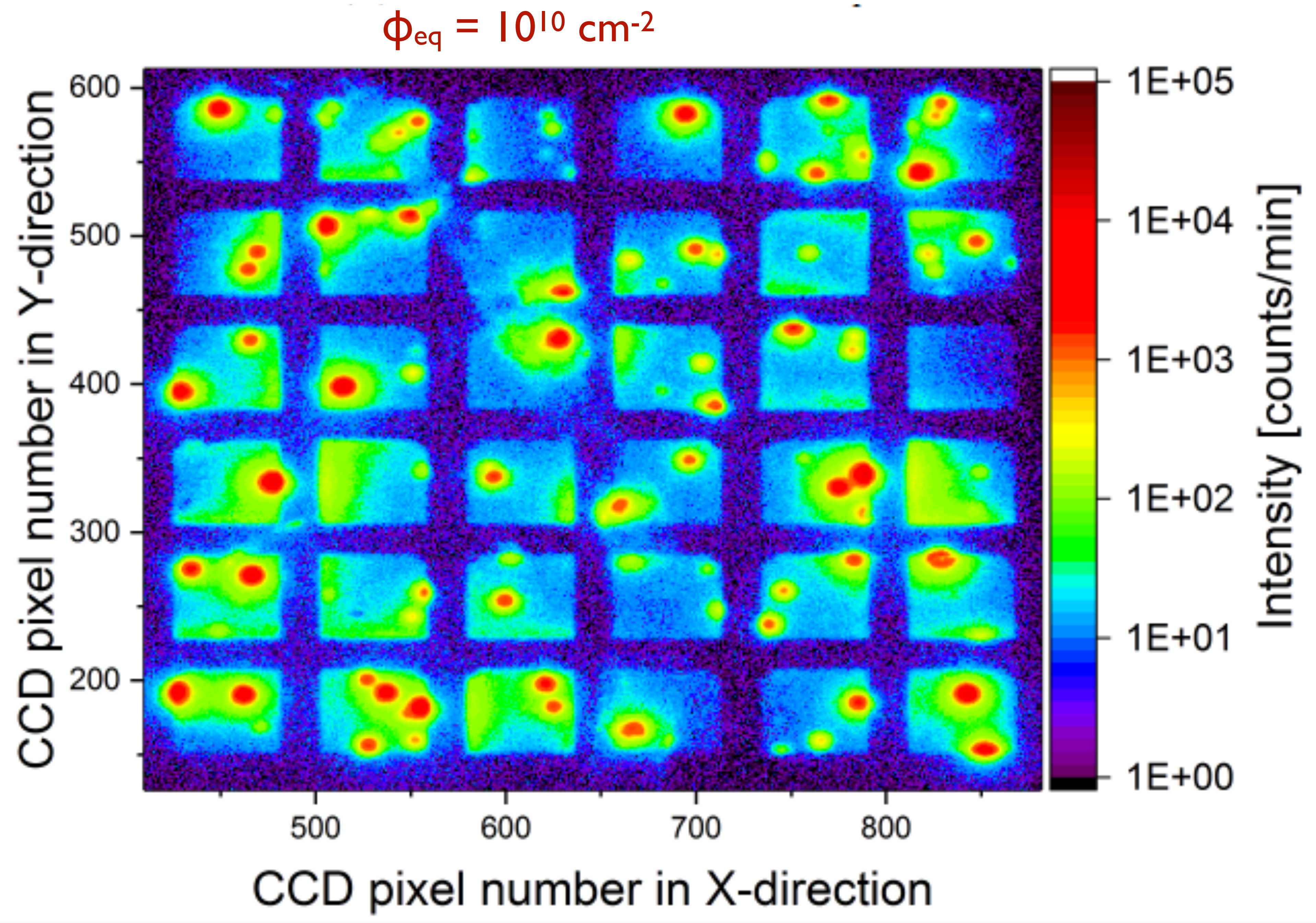
Radiation damage uniformity

Radiation damage may produce local "hot spots" with size smaller than or similar to a cell.

- the probability to find a hot spot in the single cell depends on the fluence and the cell size
- our study is based on the measurements of four single cells → results could be subject to large fluctuations due to the presence of "hot spots”
- one has to compare the 1 cell results to the average results of few cells

Technique described in:
Engelmann, Popova, Vinogradov, Spatially resolved dark count rate of SiPMs (2018). arXiv:1807.04113
Plot from Engelmann PhD thesis.

Light emission image of KETEK PM3350T STD, $\Delta V = 5.4$ V



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

Radiation damage uniformity

comparison of dark and photocurrents

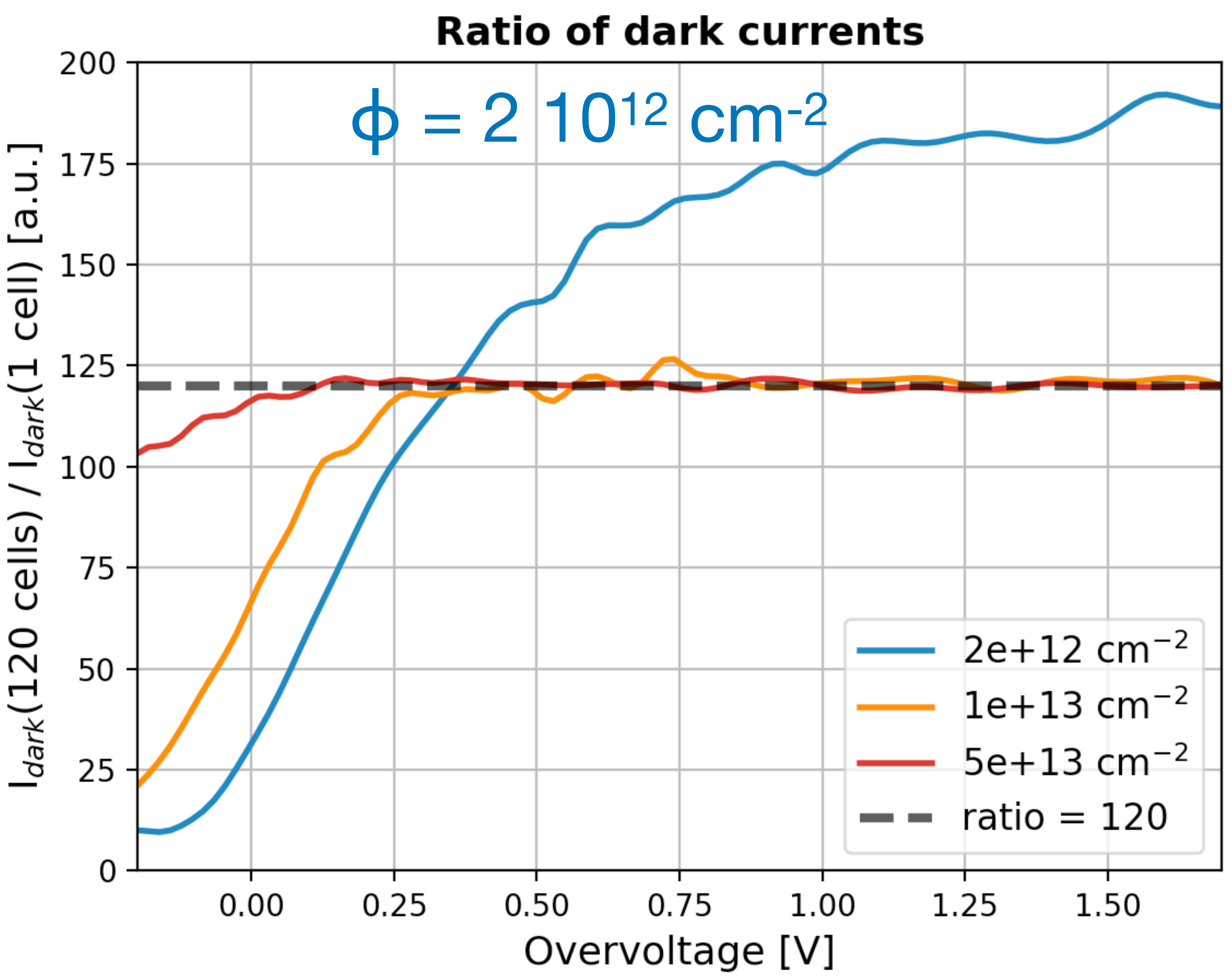
Ratio of currents for 120 / 1 cell structures expected to equal 120

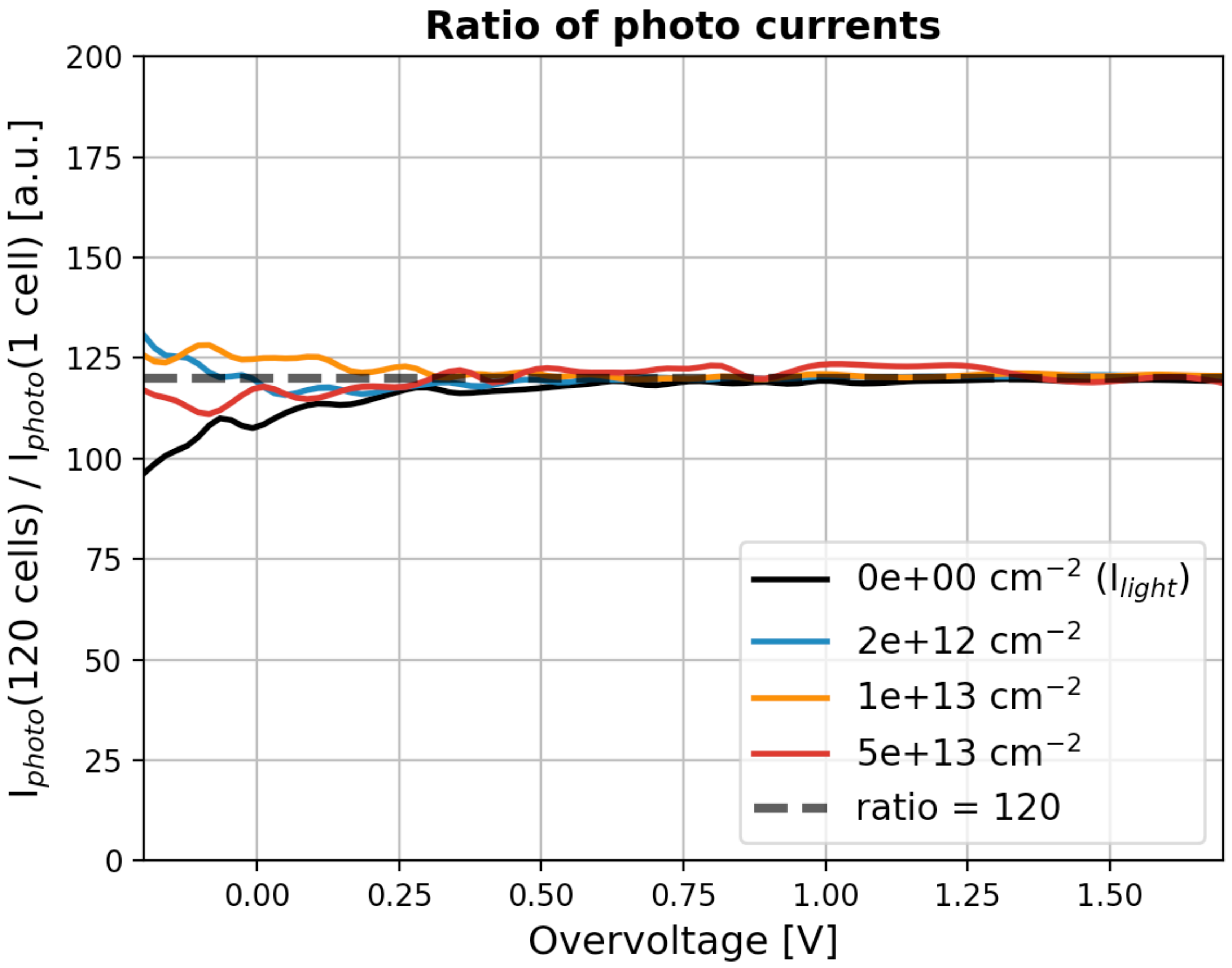
True for most samples except for I_{dark} of samples at $\phi = 2\ 10^{12}\ cm^{-2}$

possible reasons:

- radiation damage non-uniformity
- limited accuracy of low current measurements

Radiation damage of single cell comparable to the average of 120
‣ good damage uniformity in terms of effects on dark current, and on *PDE*G*(1+CN)*





Summary

- The radiation hardness study using SiPMs with single-cell readout is ongoing
- First observations from waveform analysis:
  - gain reduction of 19% for $\phi = 5\ 10^{13}$ cm^{-2}
  - increase of V_{off} by ~0.5 V for $\phi = 5\ 10^{13}$ cm^{-2}
- IV-measurements were carried out for the same test samples to address the questions:
  - self-heating effect
    - negligible in this study
  - fluence dependence of the difference between V_{off} and V_{bd}^{IV}
    - no visible dependence within the uncertainties for $\phi = [0.2, 1]\ 10^{13}$ cm^{-2}
    - increase from 0.7 to 0.9 V for $\phi = 5\ 10^{13}$ cm^{-2}
  - radiation damage uniformity
    - for most samples radiation damage of 1 and 120 cells is comparable
    - good damage uniformity on dark current change, and PDE*G*(1+CN)

BACKUP SLIDES

Extraction of IV curves ratio

- determine breakdown voltage for each IV curve
- scale IV curves x-axis to overvoltage
- perform spline interpolation
- compute the ratio
- evaluate the effect of V_{bd}^{IV} uncertainty (± 50-60 mV) on the ratio:
  - for 120 cells curve — fix V_{bd}^{IV} value → V_{bd}^{IV} = 36.58 V
  - for 1 cell curve — vary V_{bd}^{IV} with 10 mV step within the errors → V_{bd}^{IV} = [36.57..36.67] V
  - take the ratios and evaluate the result
    - plateau is expected above the breakdown → violet curve V_{bd}^{IV} = 36.63 V (10 mV difference with measured one)
    - extrema at V_{ov} = 0 V mean that the IV-curves are inconsistent → yellow and greenish curves