SiPMs proton irradiation for POLAR-2

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NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Dose: 2.23 Gy

POLAR-2 project

POLAR-2 is a polarimeter, built to investigate the polarization of Gamma-Ray Bursts.

GRBs are the most energetic astrophysical events in the Universe known to man (energies up to 10^{53} erg).

POLAR-2, the successor to POLAR.

It will be launched to the China Space Station in 2024 or 2025 (at least 2 years mission).

- The polarimeter consists of 100 modules.
- Each module consists of 64 plastic scintillators.
- Each scintillator is read out by its own SiPM channel.

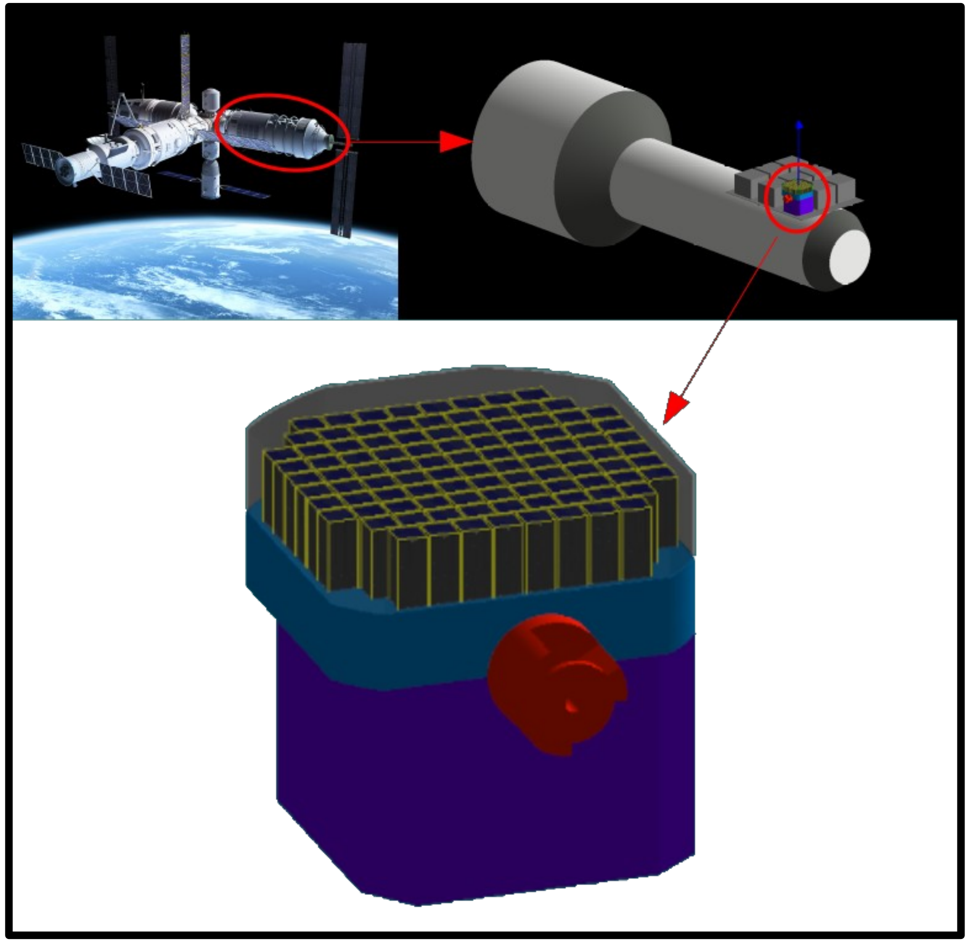


Fig. 1. Top left - 3D rendering of the CSS. Top right - a simplified version of the experimental module. Bottom - the full POLAR-2 instrument .

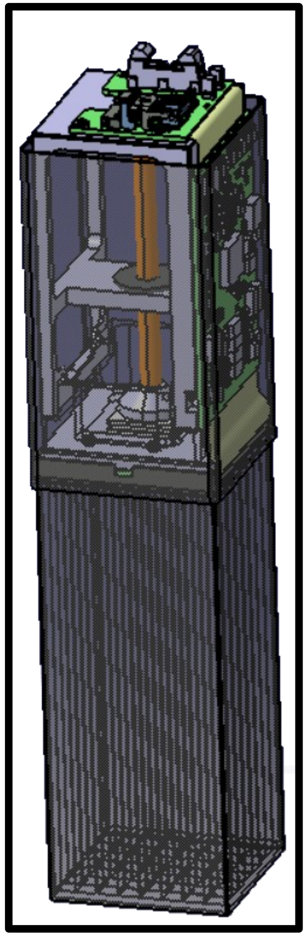


Fig. 2. The single polarimeter modul.

Monte-Carlo simulation

MC siulations - to obtain good estimate on radiation damage from background radiation.

Considering penetration depth, energy spectrum and deposition it is expected for protons to be the most contributing factor to deposit energy in the SiPM array.

Accounting for the South Atlantic Anomaly, their flux is at least two order of magnitudes higher than that of neutrons.

We use the AP-8 proton model during a solar maximum for protons with energies ranging from 100 keV to 400 MeV.

Simulation Setup	SiPM dose per year (Gy/yr)
Bare SiPM	9.84×10^{-1}
Bare SiPM + CSS	6.27×10^{-1}
Full instrument	7.65×10^{-2}
Full instrument + CSS	6.38×10^{-2}

Tab. 1. Radiation doses of a SiPM for four different scenarios. The most pessimistic scenario is the ’Bare SiPM’. The most realistic one is the ’Full Instrument + CSS’.

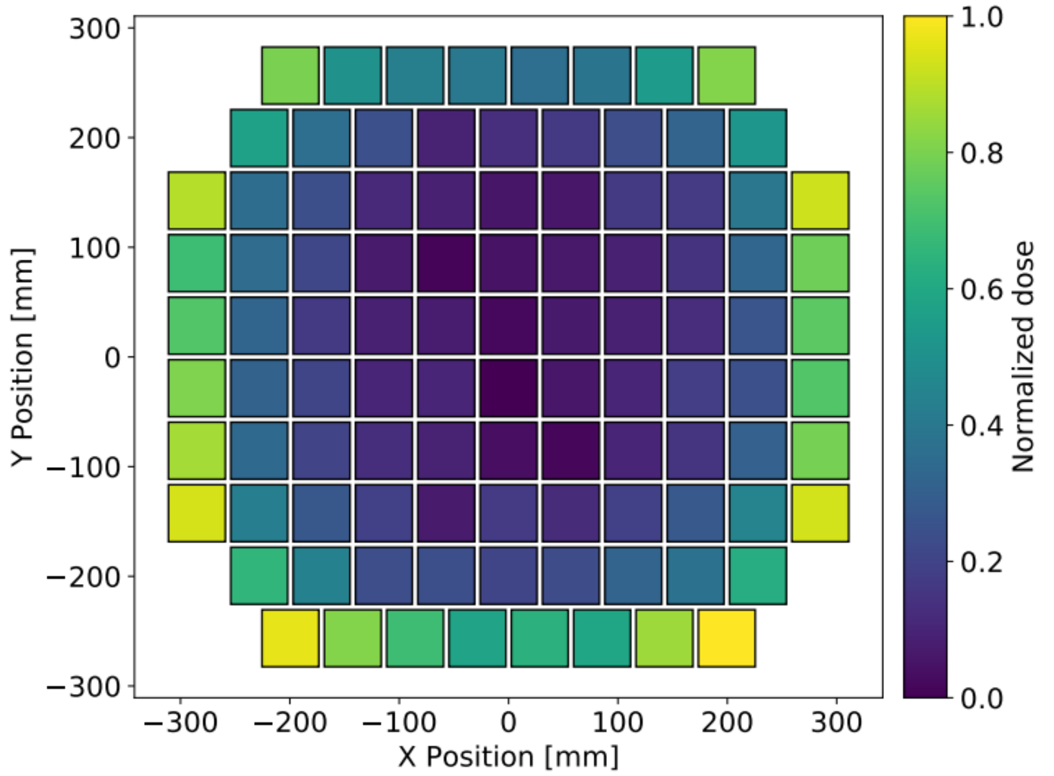


Fig. 3. Normalized dose distribution per detector module in the POLAR-2 instrument due to background radiation.

SiPMs irradiation at IFJ

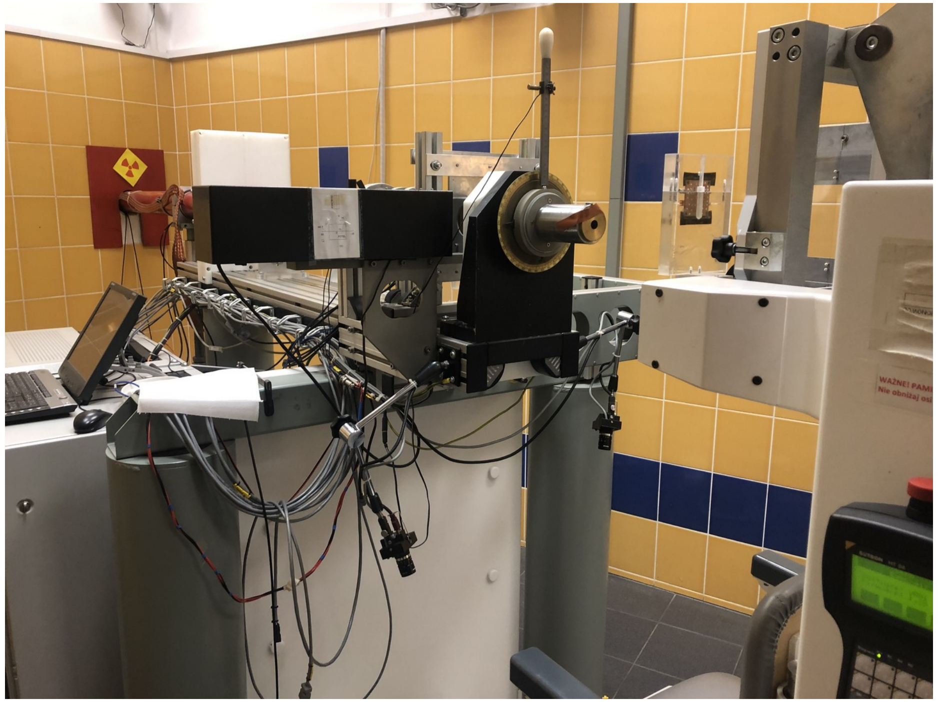


Fig. 4. The exit of proton beam line at IFJ.

SiPMs irradiation at IFJ

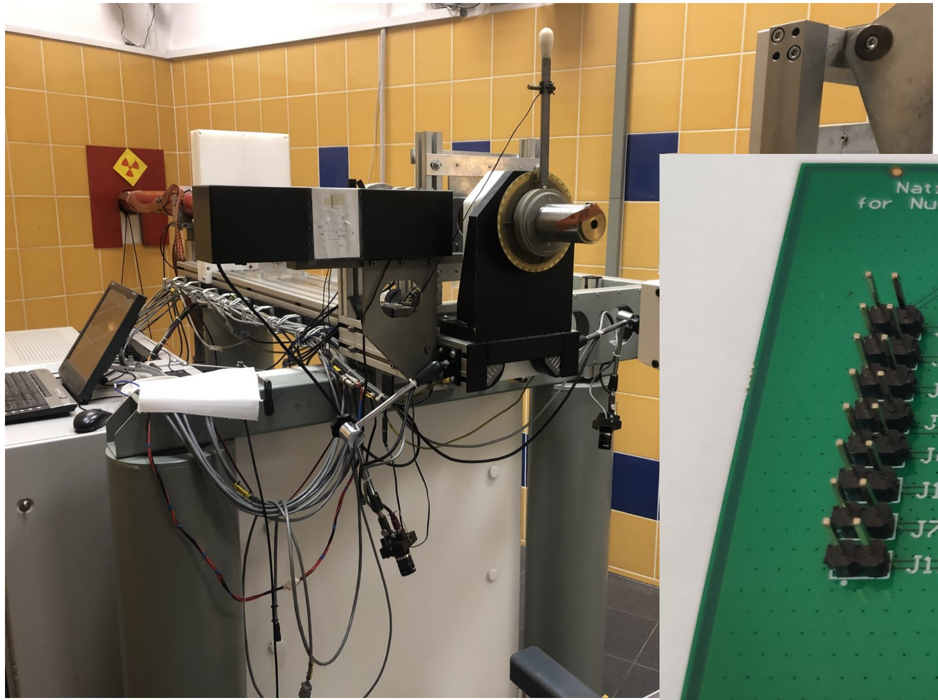


Fig. 4. The exit of proton beam line at IFJ.

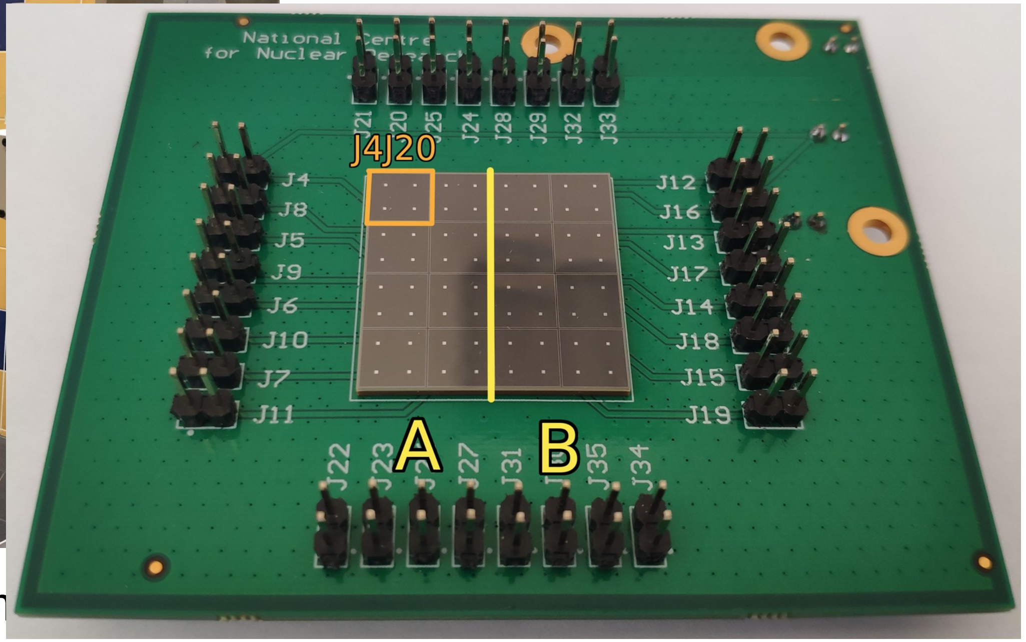


Fig. 5. The Hamamatsu MPPC S13361-6075NE-04 (or S14161-6050HS-04) array mounted on PCB plate.

SiPMs irradiation at IFJ

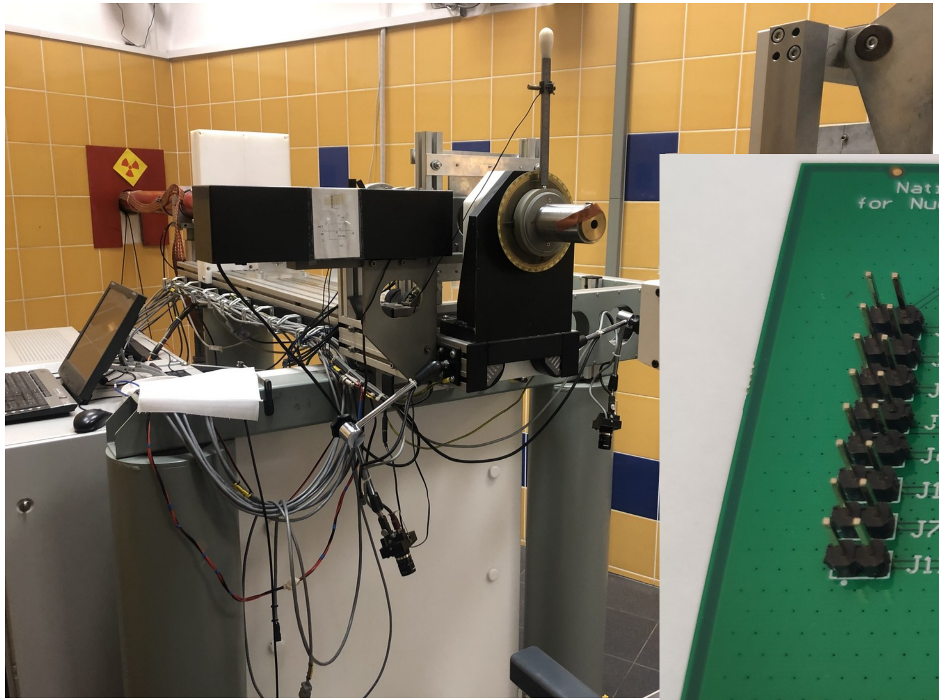


Fig. 4. The exit of proton beam
line at IFJ.

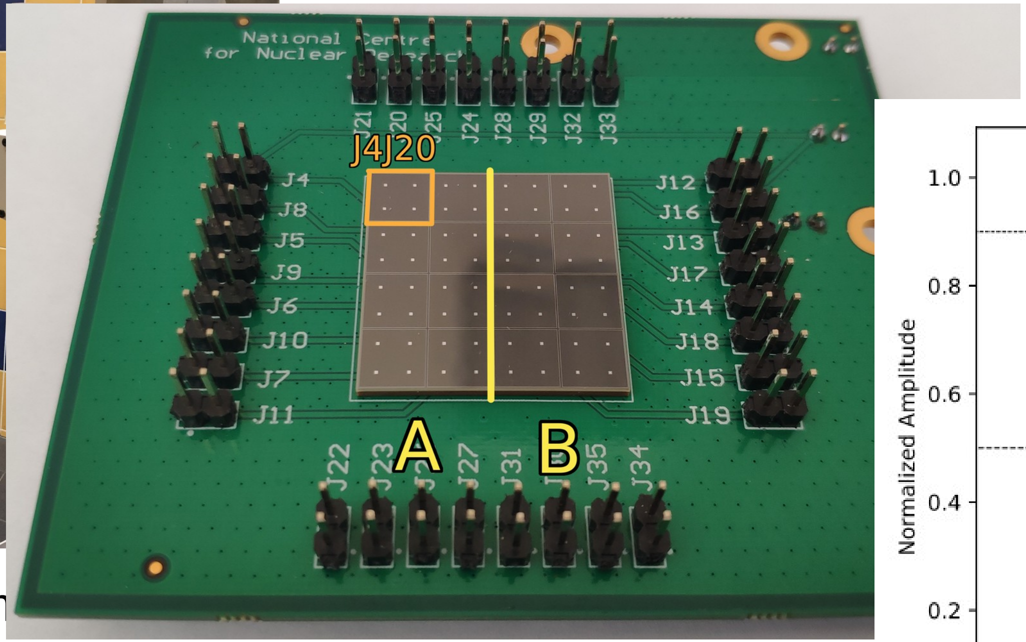


Fig. 5. The Hamamatsu MPPC S13361
6075NE-04 (or S14161-6050HS-04)
mounted on PCB plate.

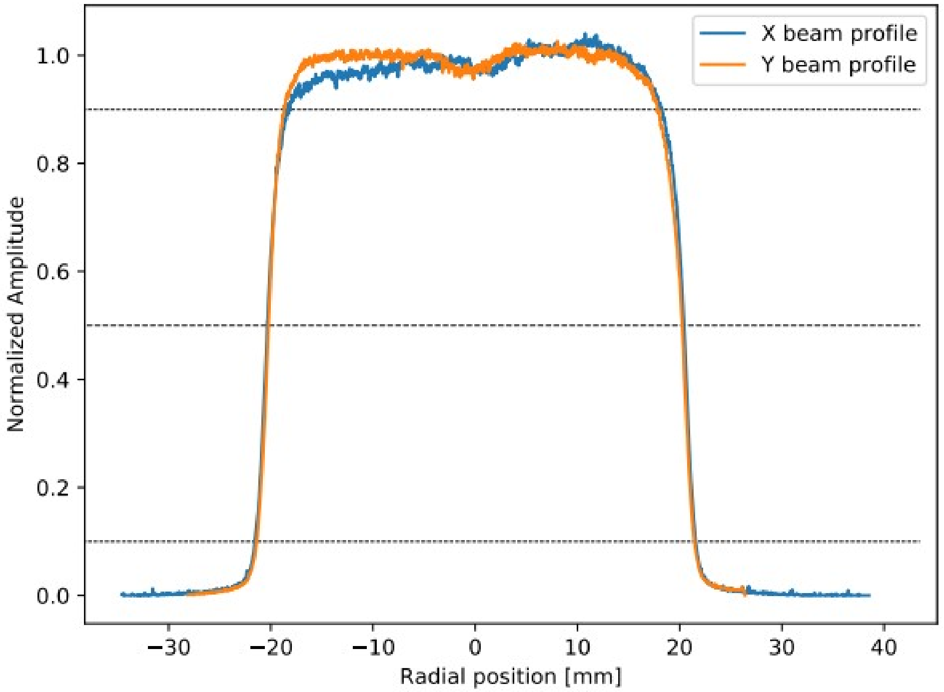


Fig. 6. Scaled beam profile (to its average) of
58 MeV protons along the x-axis and y-axis.

SiPMs irradiation at IFJ

MPPC Type	Fluence $(\frac{protons}{cm^2})$	Dose (Gy)	Equivalent Years in Space for POLAR-2	
			’Full Instr. + CSS’	’Bare SiPM’
S13361-1 sec. A	2.00×10^8	0.267	4.19	0.271
S13361-1 sec. B	6.10×10^8	0.815	12.8	0.828
S13361-2 sec. A	1.64×10^9	2.19	34.4	2.23
S13361-2 sec. B	3.73×10^9	4.96	78.1	5.04
S14161-1 sec. A	1.90×10^8	0.254	3.98	0.258
S14161-1 sec. B	1.73×10^9	2.31	36.2	2.35
S14161-2 sec. A and B	1.73×10^9	2.31	36.2	2.35

Tab. 2. An overview of SiPM elements irradiated, their corresponding dose and equivalent time in space for a ’Full Instrument + CSS’ and ’Bare SiPM’ scenarios

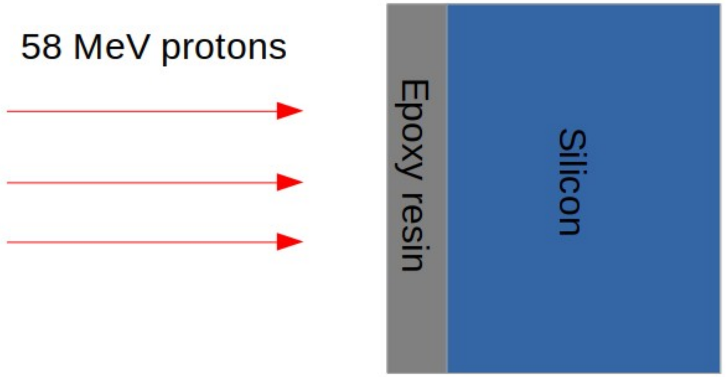
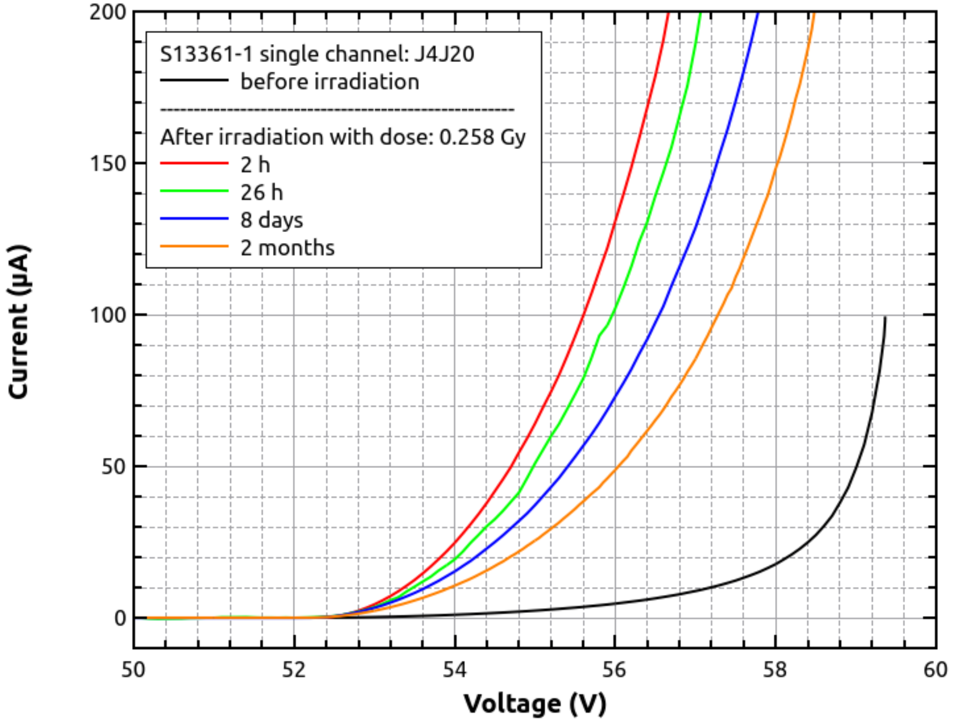


Fig. 7. The model of SiPM single channel used for different dose calculations: 100 μm of epoxy resin and 450 μm of silicon.

Experimental results: I-V characteristics

S13361-6075NE-04

Dose: 0.258 Gy



Dose: 4.96 Gy

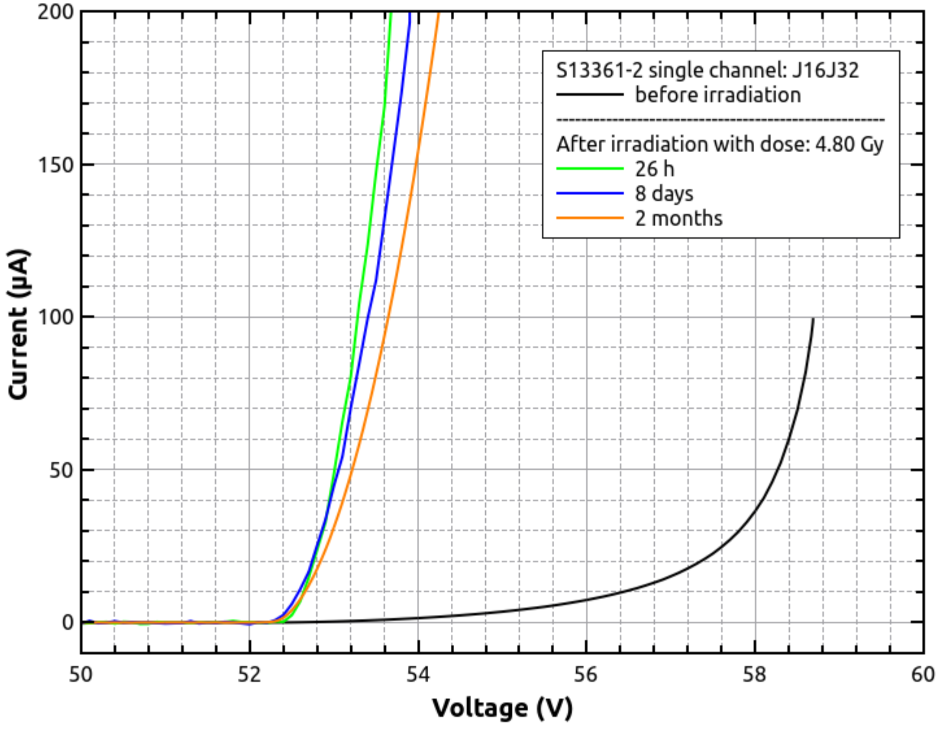


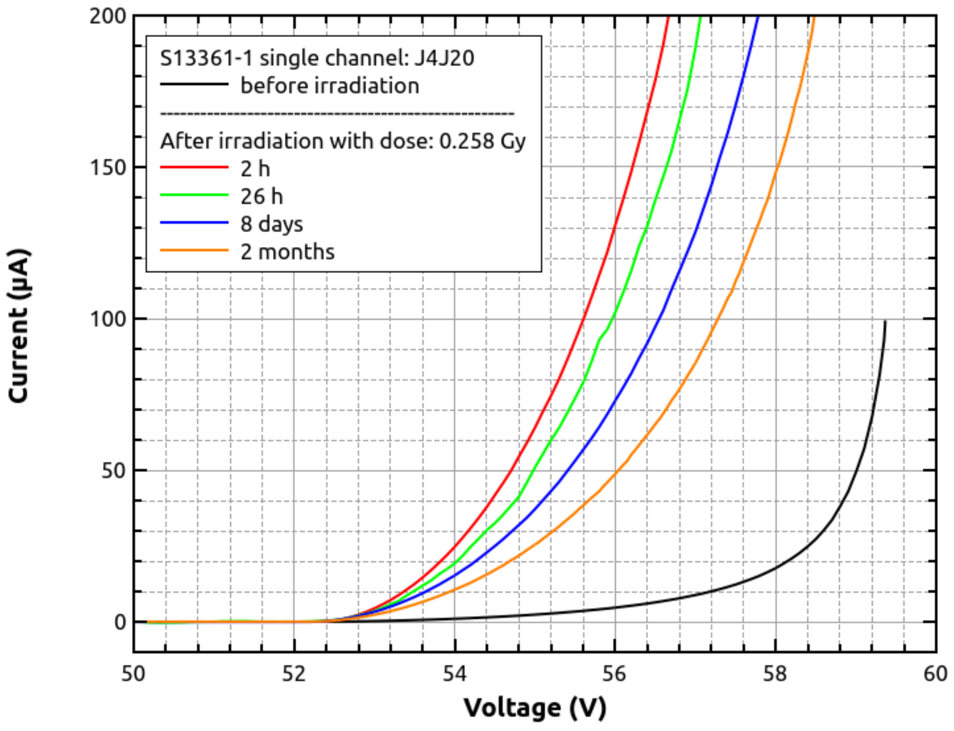
Fig. 8. Current-voltage single channel characteristics for S13361 single module for different time after proton irradiation. Left - the dose of 0.258 Gy. Right – the dose of 4.80 Gy

Experimental results: I-V characteristics

S13361-6075NE-04

See also Nicolas De Angelis talk (12:00)

Dose: 0.258 Gy



Dose: 4.96 Gy

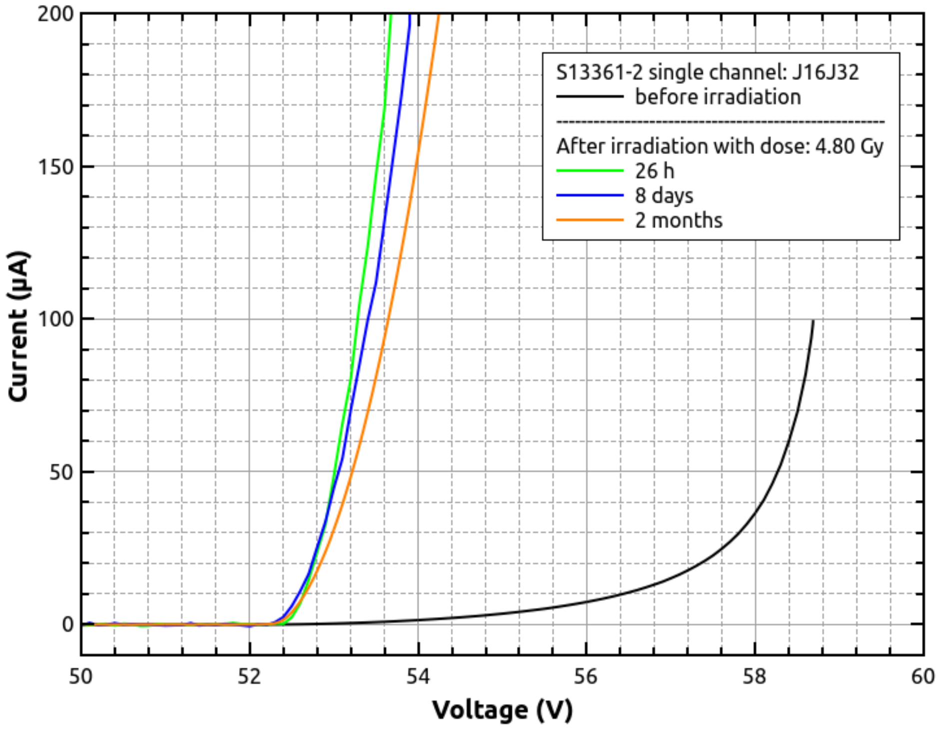
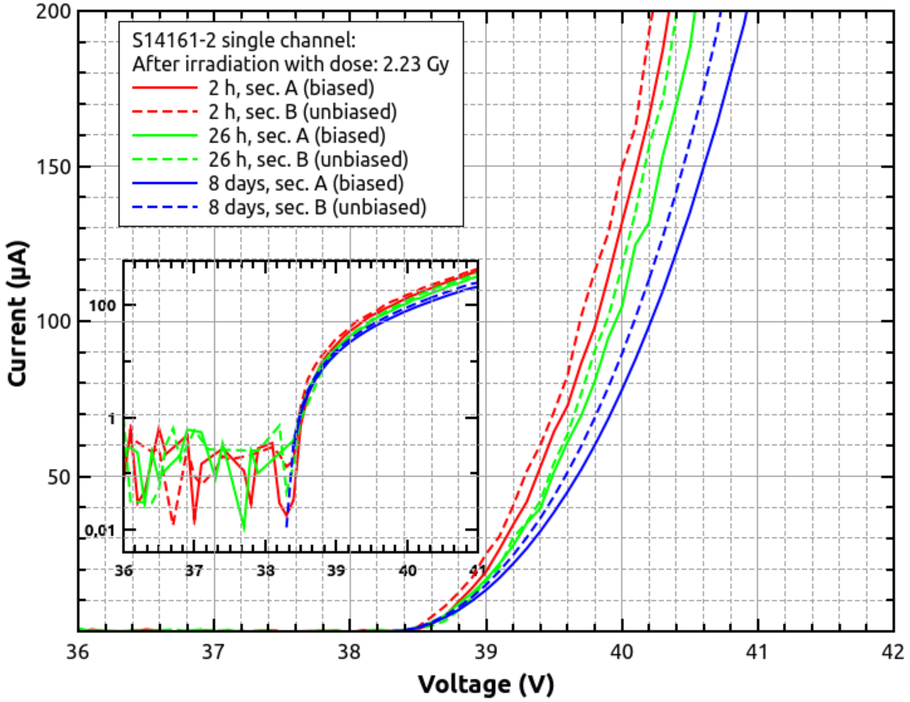


Fig. 8. Current-voltage single channel characteristics for S13361 single module for different time after proton irradiation. Left - the dose of 0.258 Gy. Right – the dose of 4.80 Gy

Experimental results: I-V characteristics

S14161-6050HS-04   Dose: 2.23 Gy

Biased and unbiased channel.



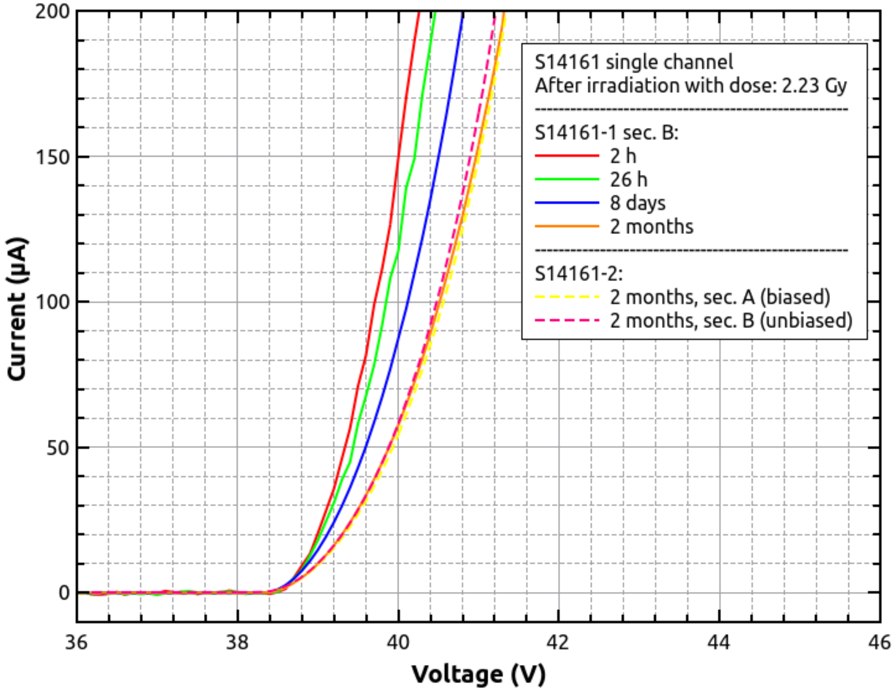


Fig. 9. Current-voltage single channel characteristics for biased (channel: J4J20) and unbiased (channel: J16J32) S14161 subarray irradiated with dose 2.31 Gy for different time after proton irradiation. Left - the inset shows the breakdown voltage region in y-log scale. Right - compares also two S14161 arrays (two single channels unbiased, one biased) two months after irradiation.

Experimental results: Dark Counts analysis

Before proton irradiation T=25°C, V_{ov}=3.5 V

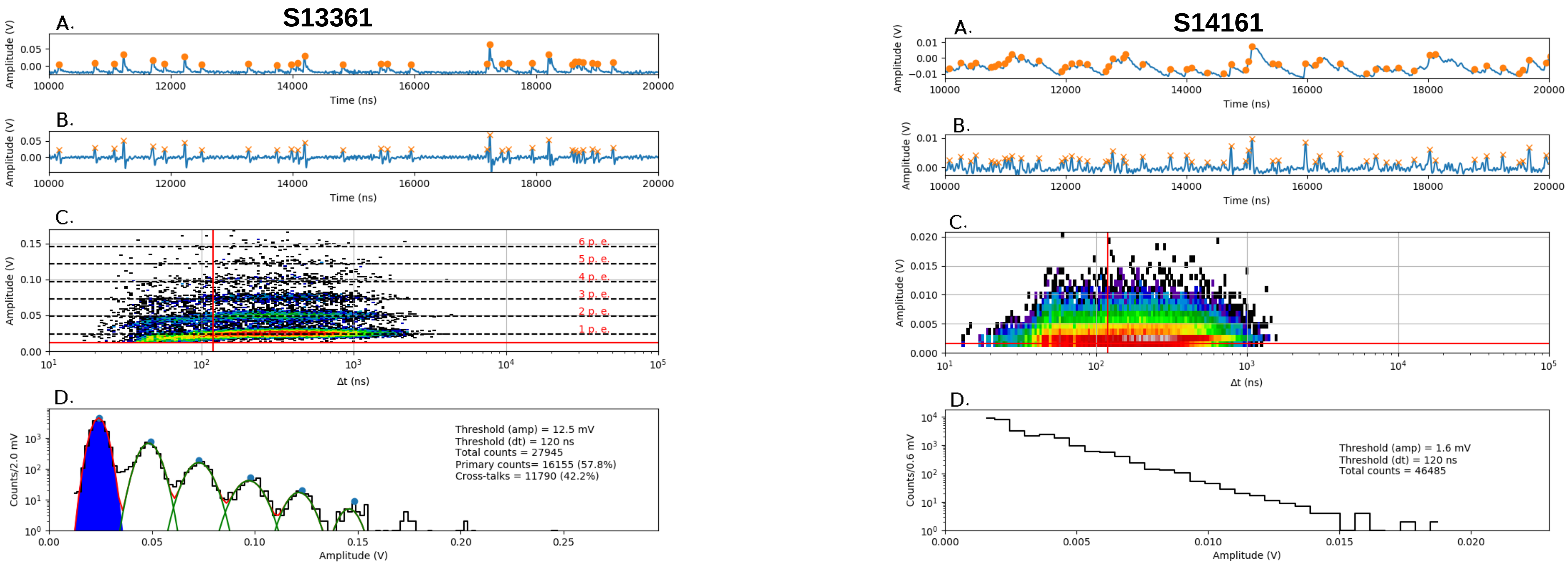


Fig. 10. An example of a single channel waveform analysis of S13361 (left) and S14161 (right), measured at temperature 25°C before proton irradiation. A - a part of 10 ms waveform, B – transformed waveform with peak identification, C - 3D distribution of dark pulse amplitudes as a function of time difference between two subsequent events. D - projection of the dark counts with amplitude and time cut conditions. Blue color describes 1 p.e. position and primary counts (not visible in the S14161 case).

*Method originally presented by Claudio Piemonte, doi: 10.1109/NSSMIC.2012.6551141.

Experimental results: Dark Counts analysis

Before proton irradiation, S13361

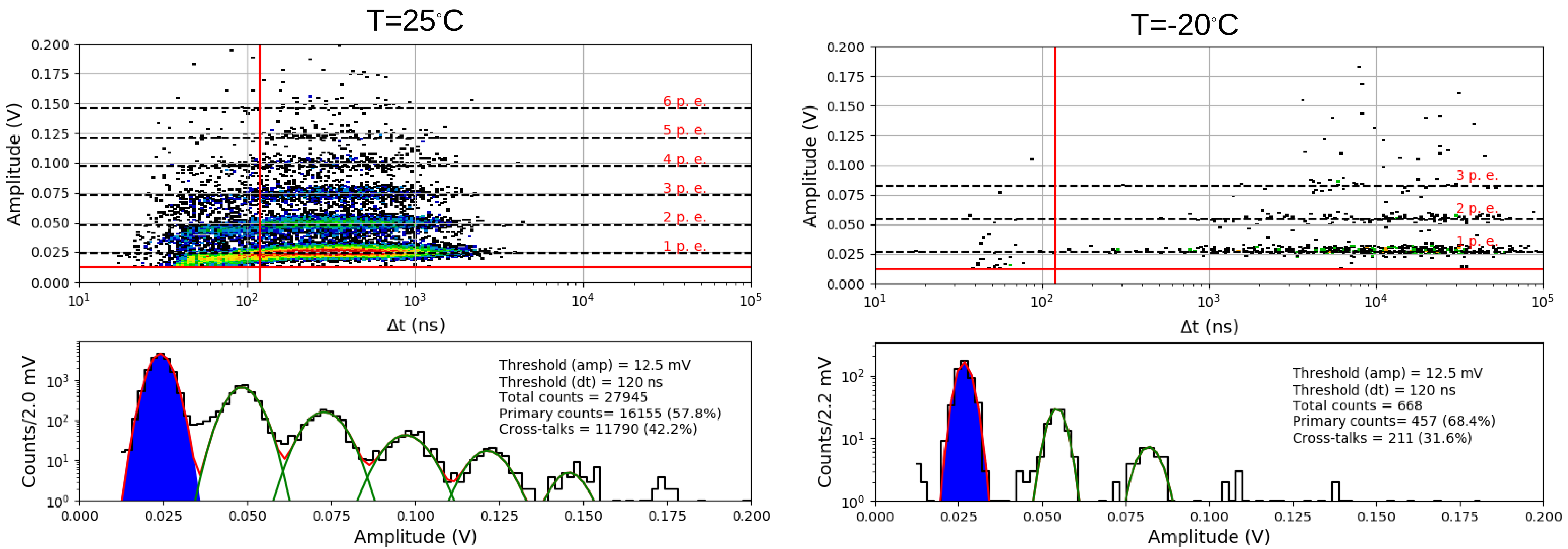


Fig. 11. S13361 single channel DC spectra measured before proton irradiation for various temperatures and the same V_{ov}=3.5 V. Left: 25°C and right: -20°C.

Experimental results: Dark Counts analysis

Before proton irradiation

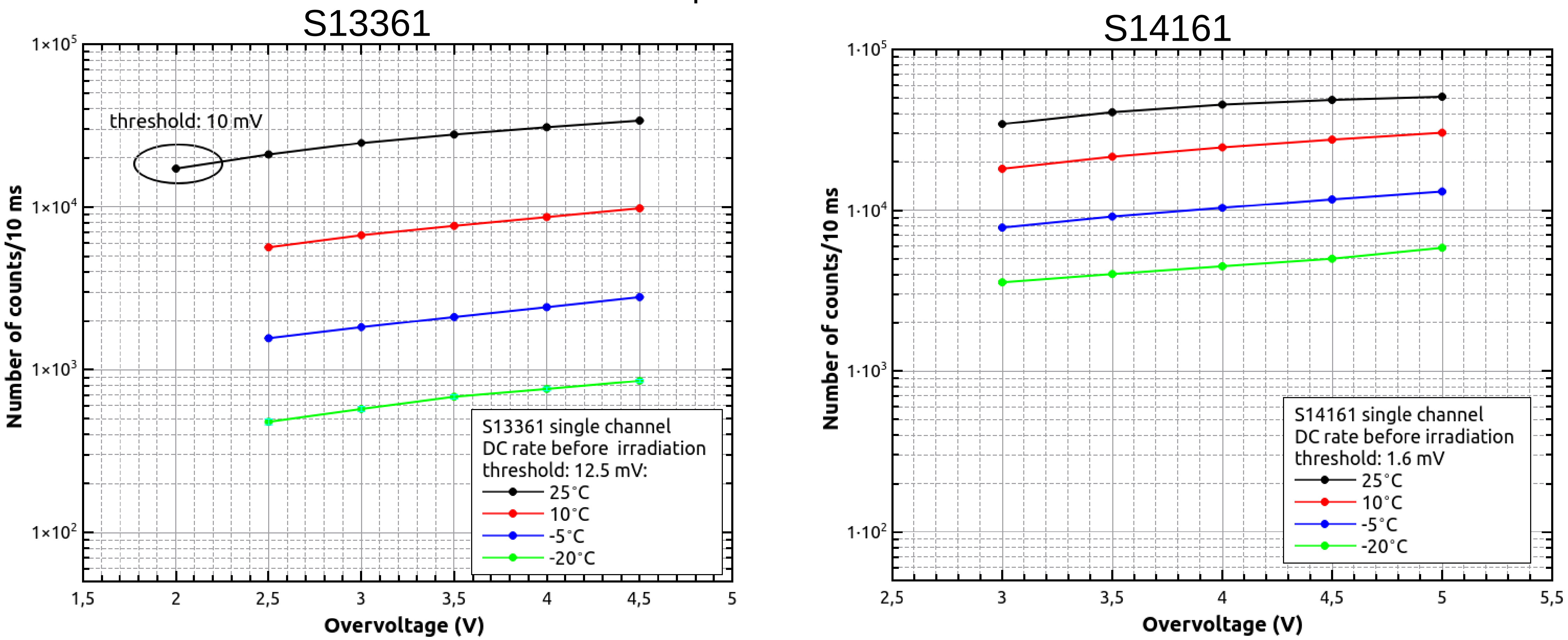


Fig. 12. The number of DC measured for a single channel of S13361 (left) and S14161 (right) array for chosen overvoltage ranges at different temperatures.

Experimental results: Dark Counts analysis

After proton irradiation (~26 h)

Dose: 0.267 Gy

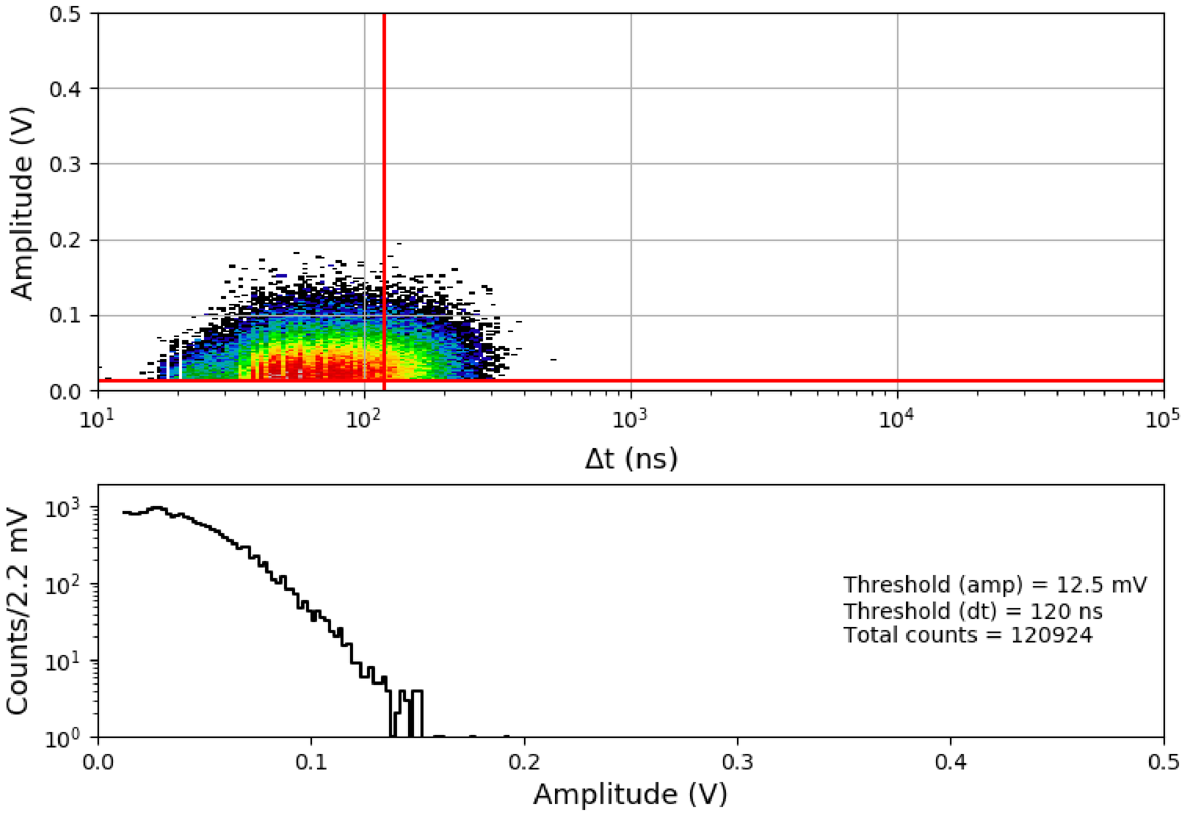
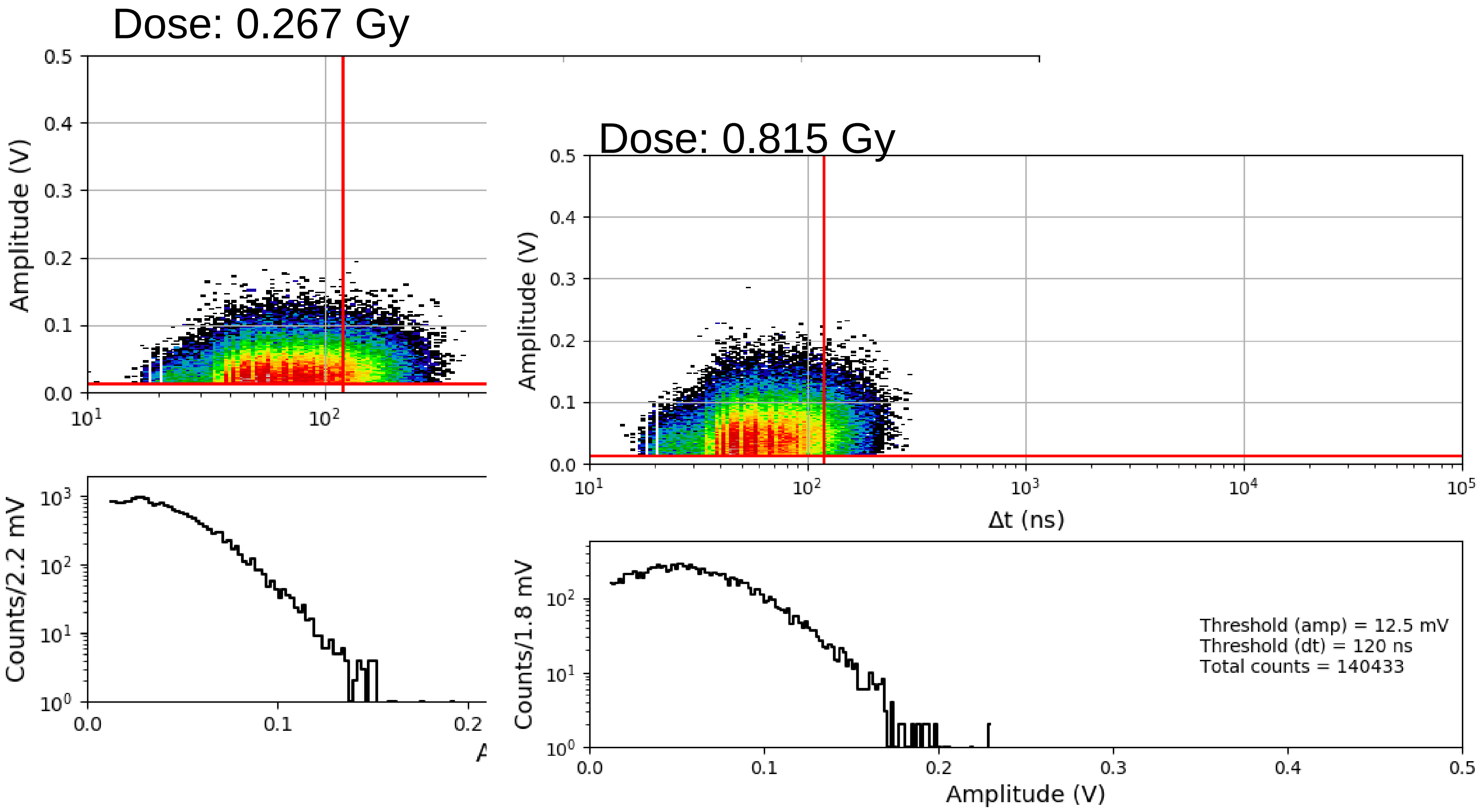


Fig. 13. An example of waveform analysis for data taken about 26 hours after irradation for S13361 single channel measured at 27°C for doses (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

After proton irradiation (~26 h)



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Experimental results: Dark Counts analysis

After proton irradiation (~26 h)

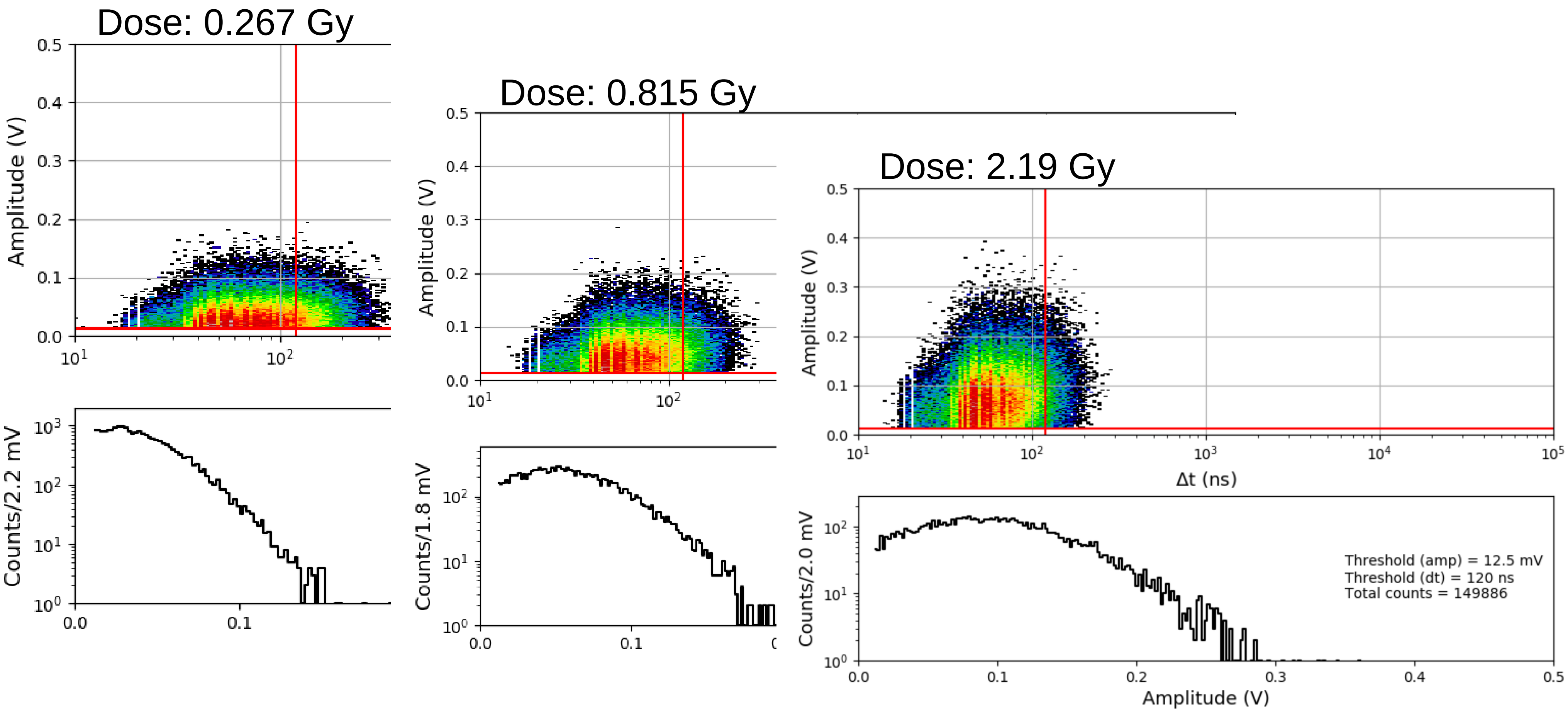


Fig. 13. An example of waveform analysis for data taken about 26 hours after irradation for S13361 single channel measured at 27°C for doses (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

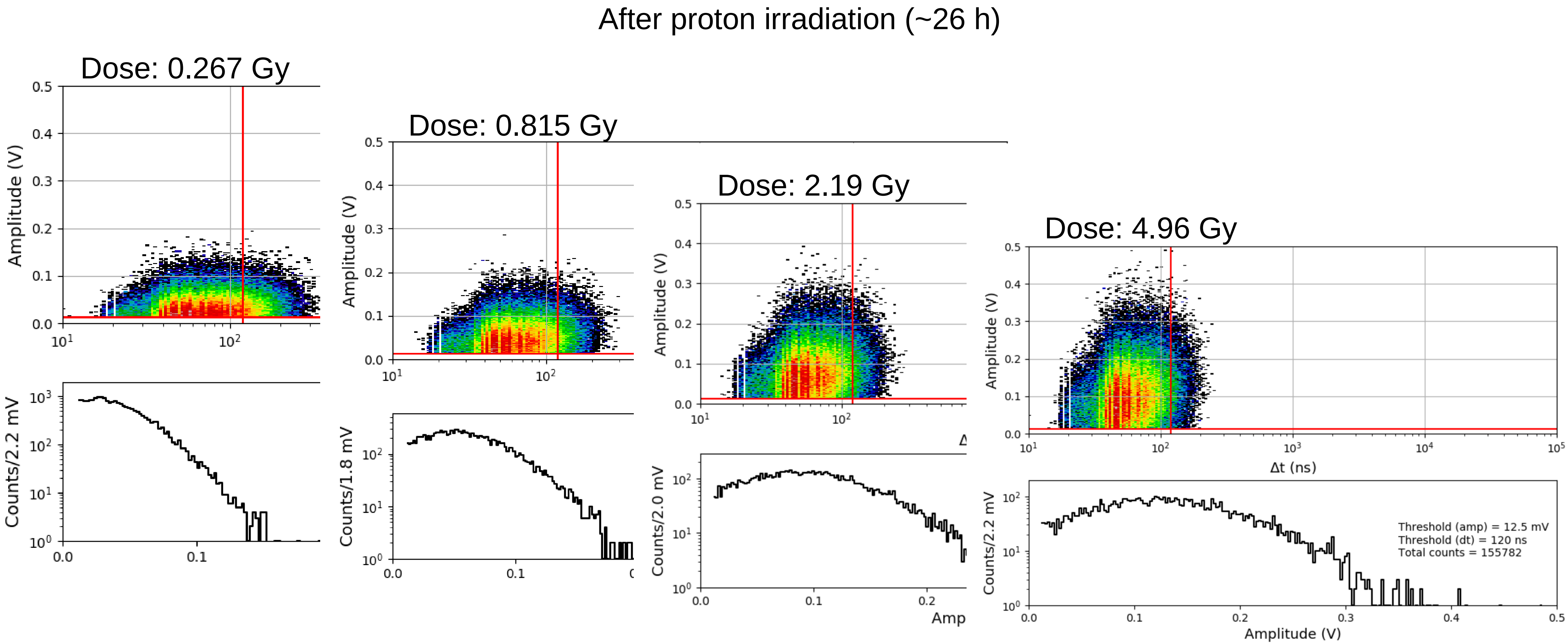


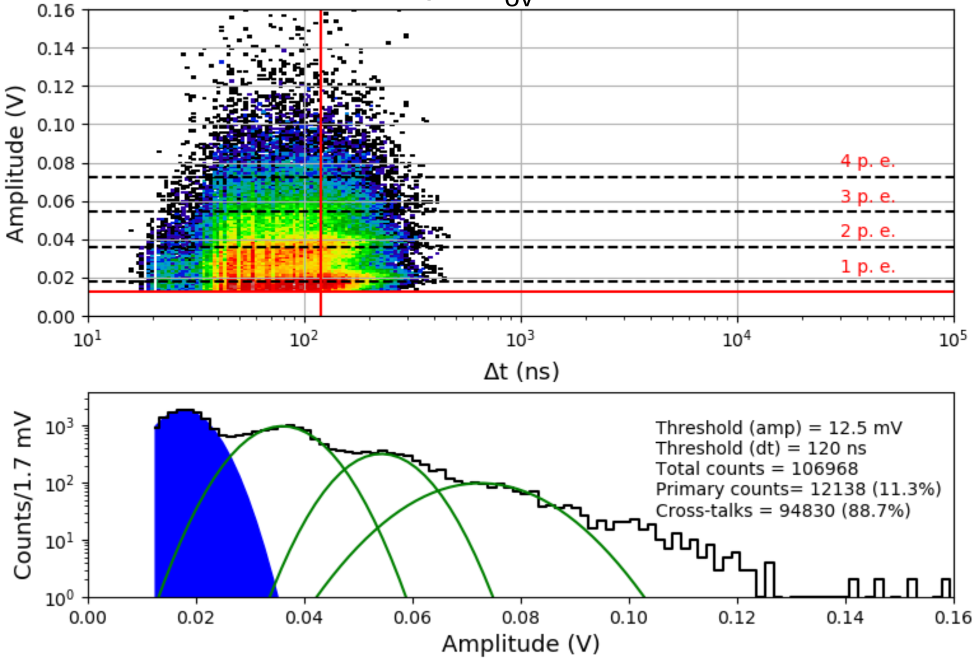
Fig. 13. An example of waveform analysis for data taken about 26 hours after irradation for S13361 single channel measured at 27°C for doses (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

After proton irradiation (2 months)

T=25°C

Dose: 0.267 Gy, V_{ov} = 2.8 V



Dose: 0.815 Gy, V_{ov} = 2.8 V

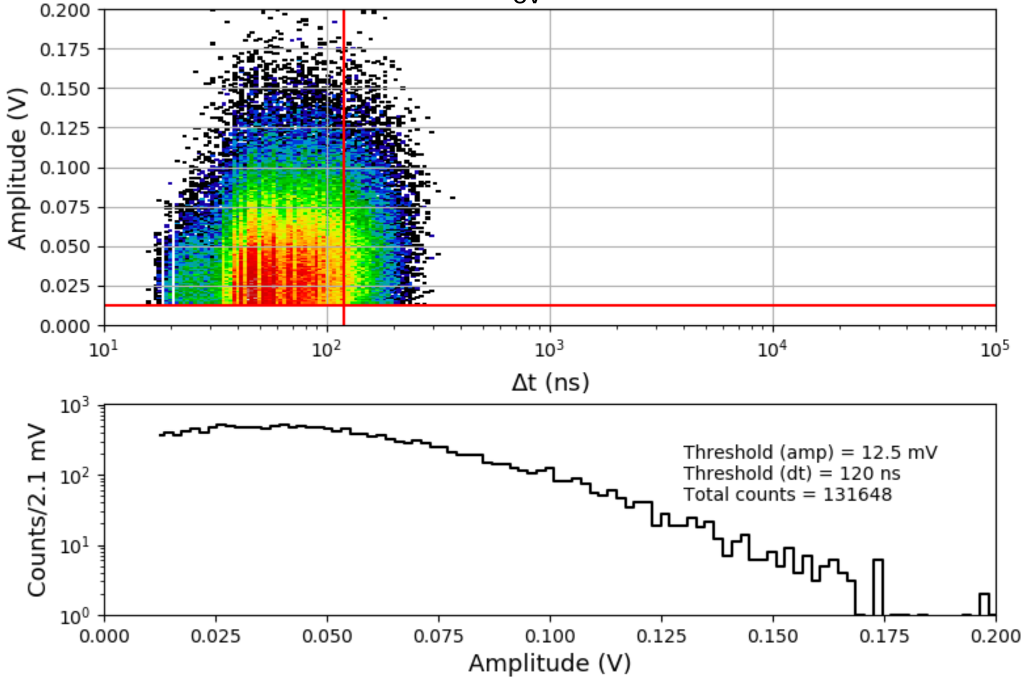


Fig. 14. An example of waveform analysis for data taken two months after irradation for S13361 single channel measured at 25°C and -20°C for different doses (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

After proton irradiation (2 months)

Dose: 0.267 Gy, V_{ov} = 2.8 V

Dose: 0.815 Gy, V_{ov} = 2.8 V

T=25°C

T=-20°C

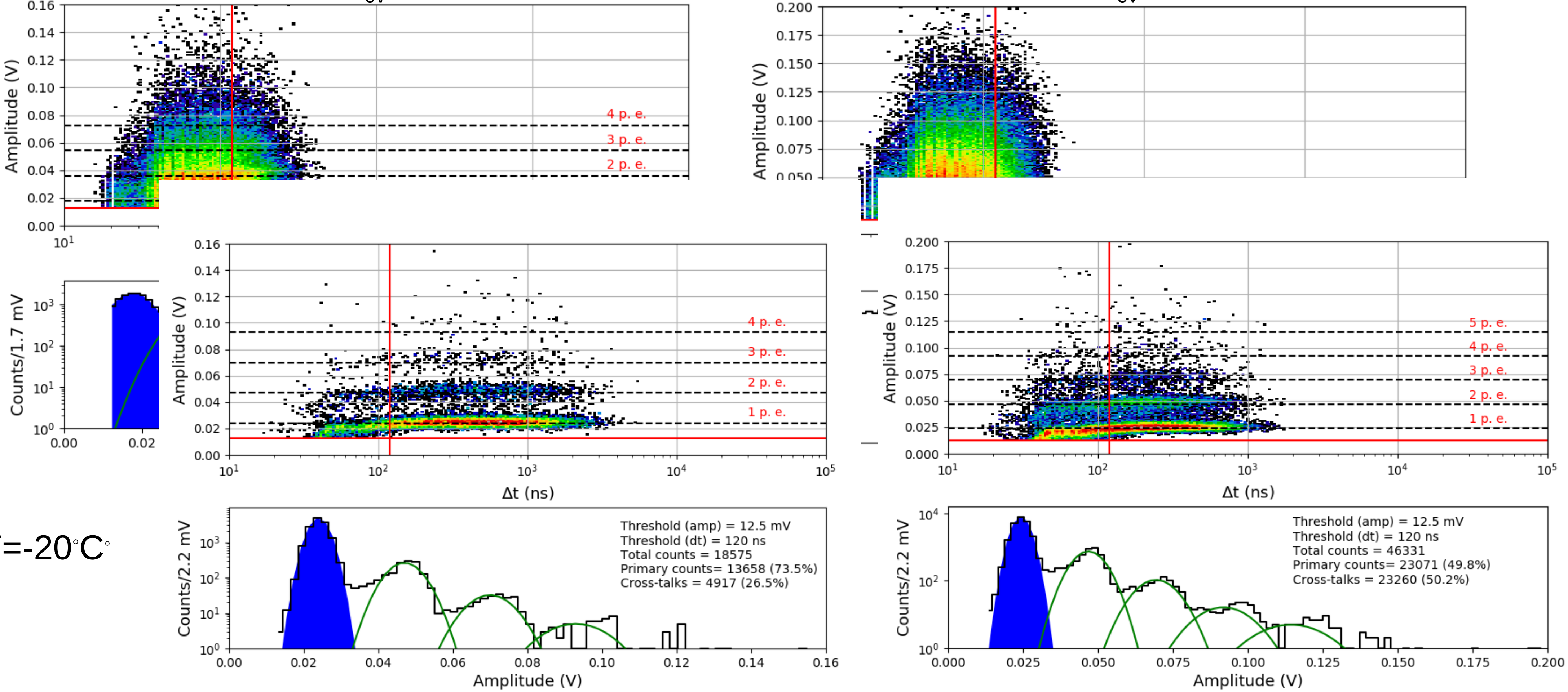


Fig. 14. An example of waveform analysis for data taken two months after irradation for S13361 single channel measured at 25°C and -20°C for different doses (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

After proton irradiation (2 months)

T=-20◦C, V_{ov} = 2.8 V◦

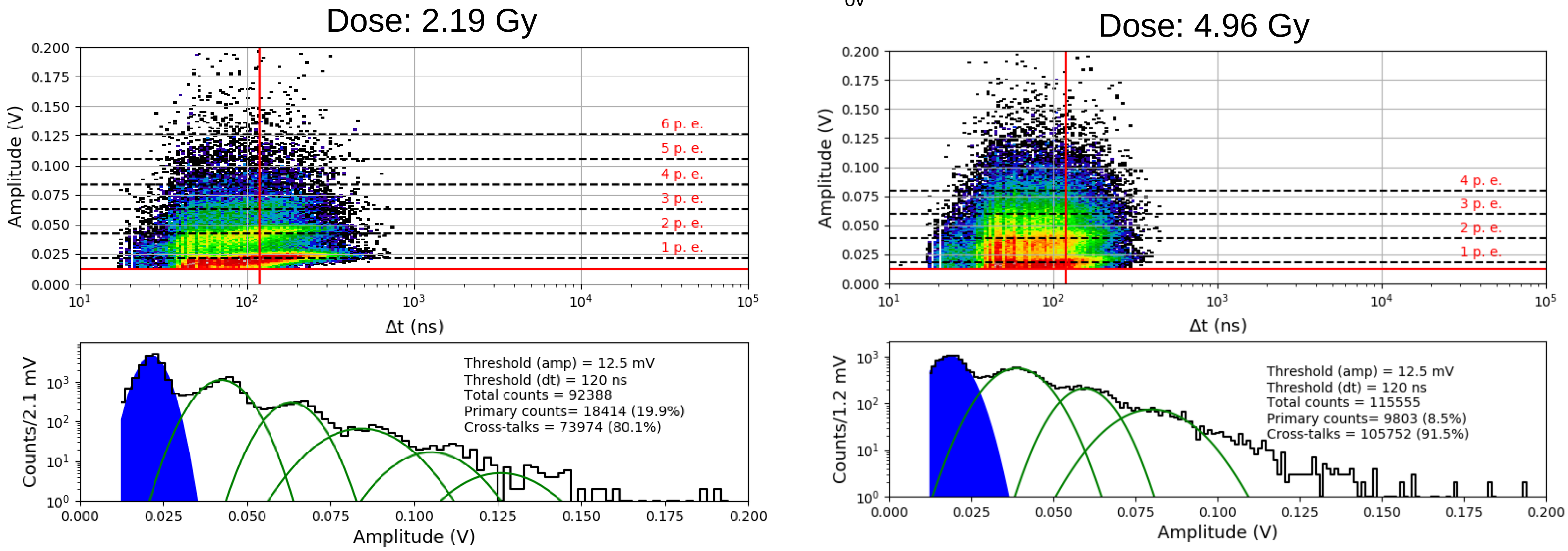


Fig. 15. An example of waveform analysis for data taken two months after irradation for S13361 single channel measured at -20◦C for doses 2.19 Gy and 4.96 Gy (V_{ov}=2.8 V).

Experimental results: Dark Counts analysis

S13361

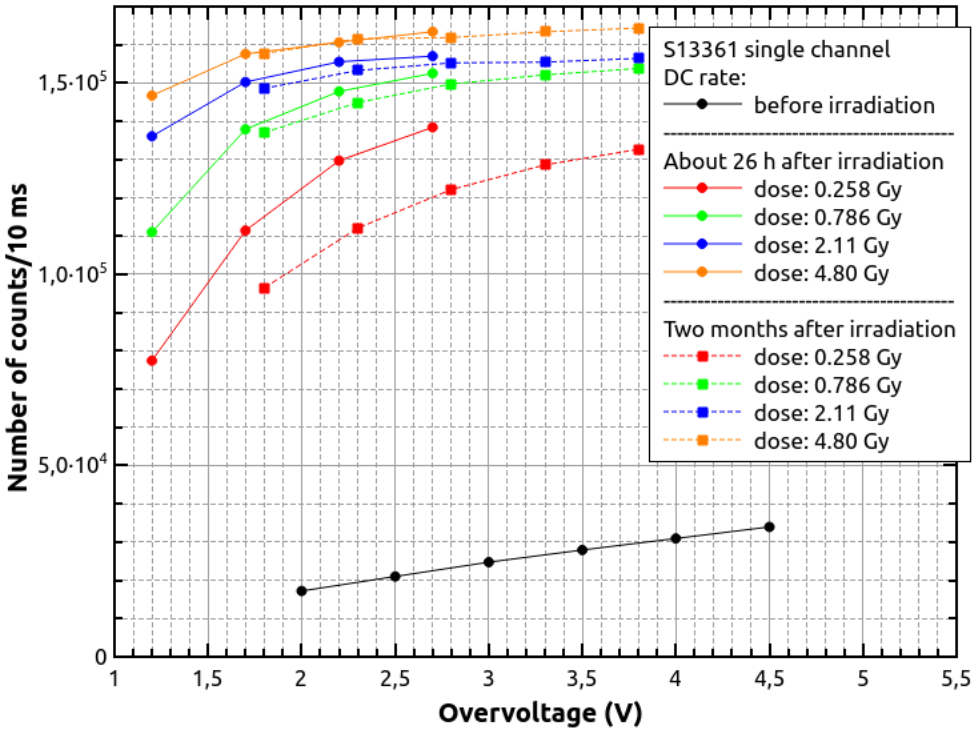


Fig. 16. The number of dark counts per 10 ms interval time measured at room temperature for S13361 before irradiation, 26 h and two months after.

Experimental results: Dark Counts analysis

S13361

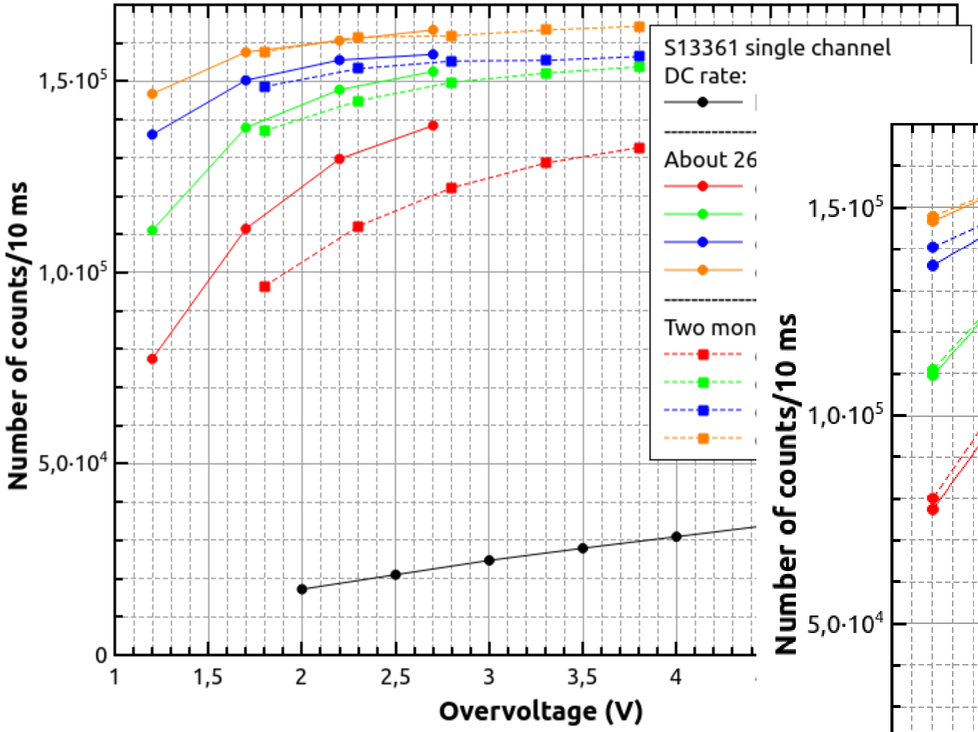


Fig. 16. The number of dark counts interval time measured at room te for S13361 before irradiation, 26 months after.

S13361

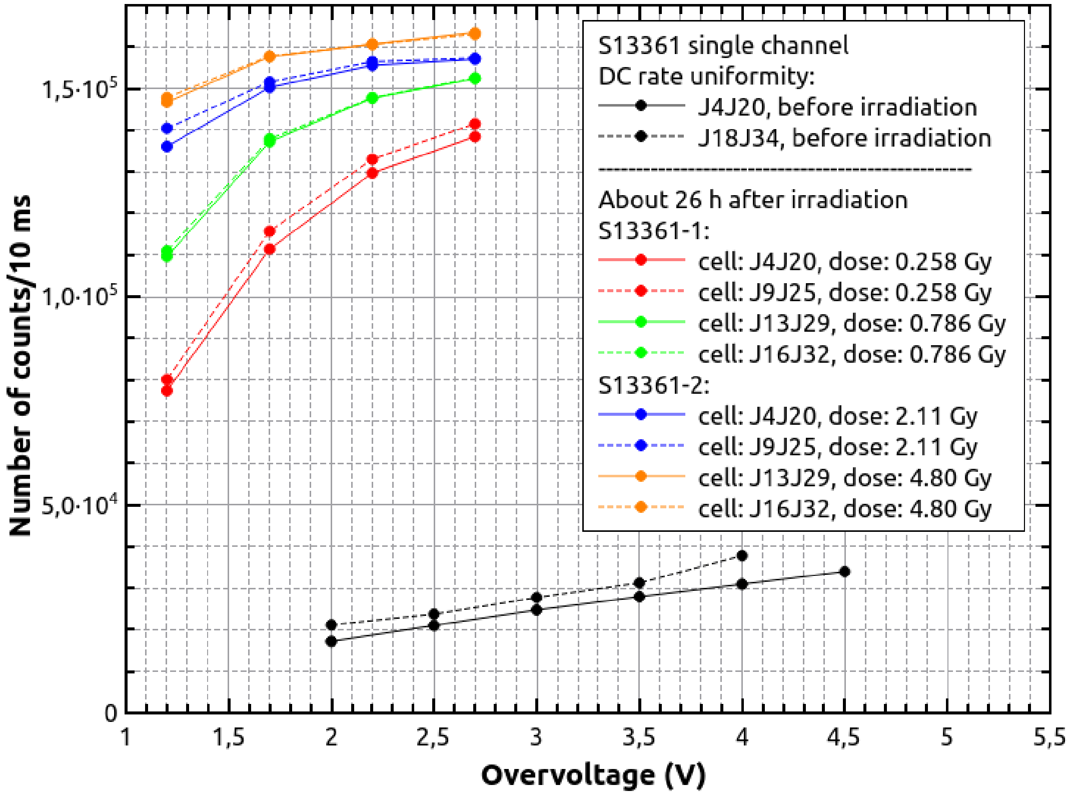


Fig. 17. The number of dark counts per 10 ms for two different channels before and 26 h after irradiated.

Experimental results: Dark Counts analysis

S13361

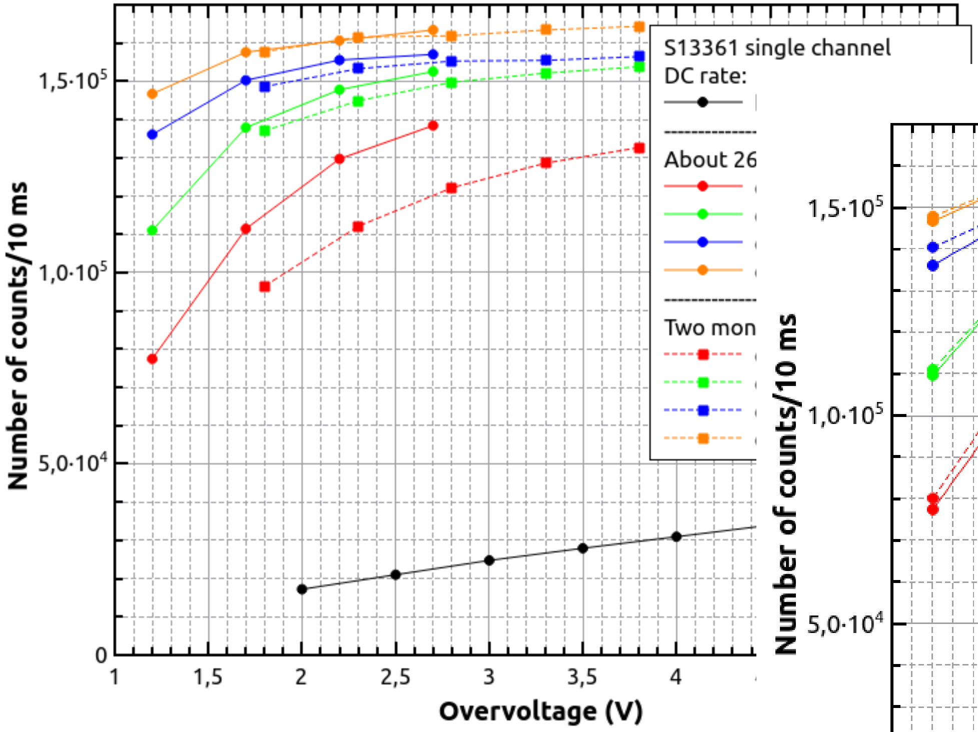


Fig. 16. The number of dark counts
interval time measured at room te
for S13361 before irradiation, 26
months after

S13361

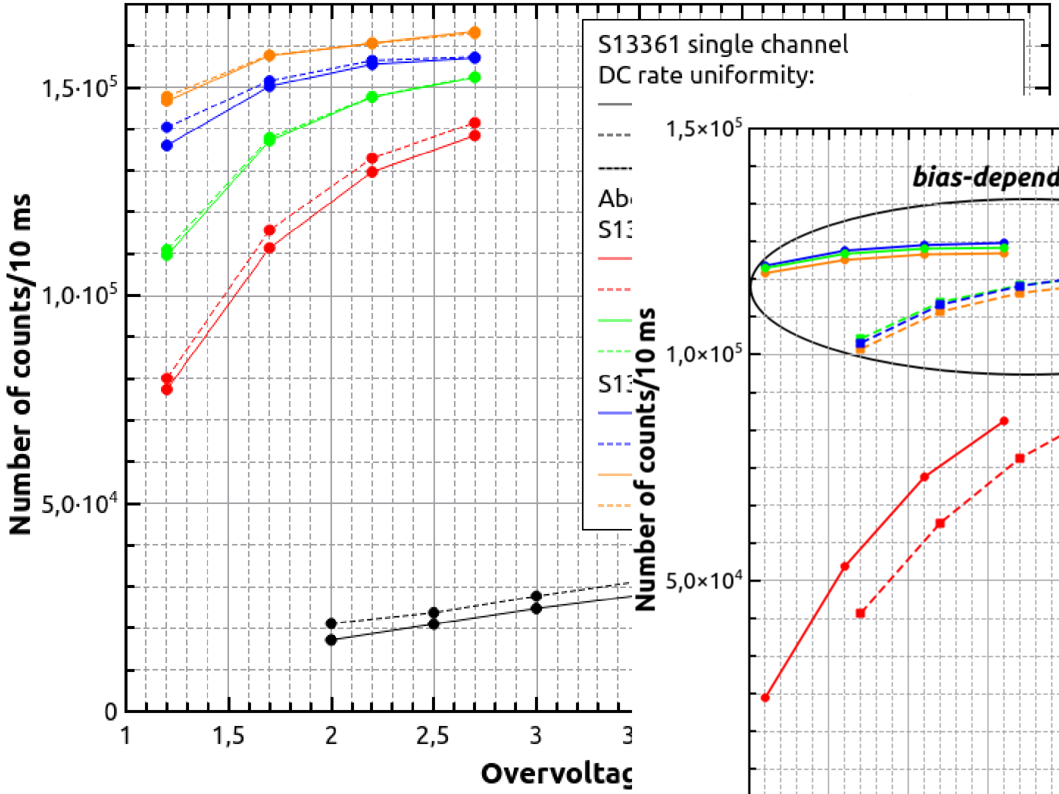


Fig. 17. The number of darl
for two different channel
after irradiated.

S14161

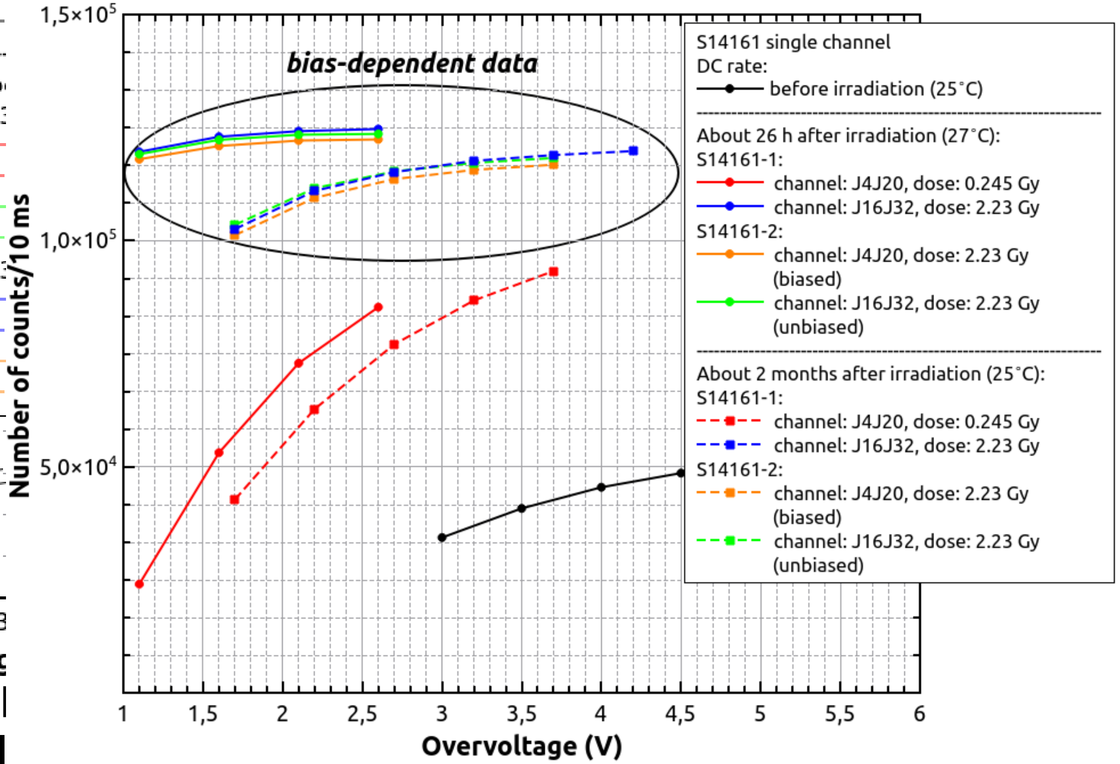
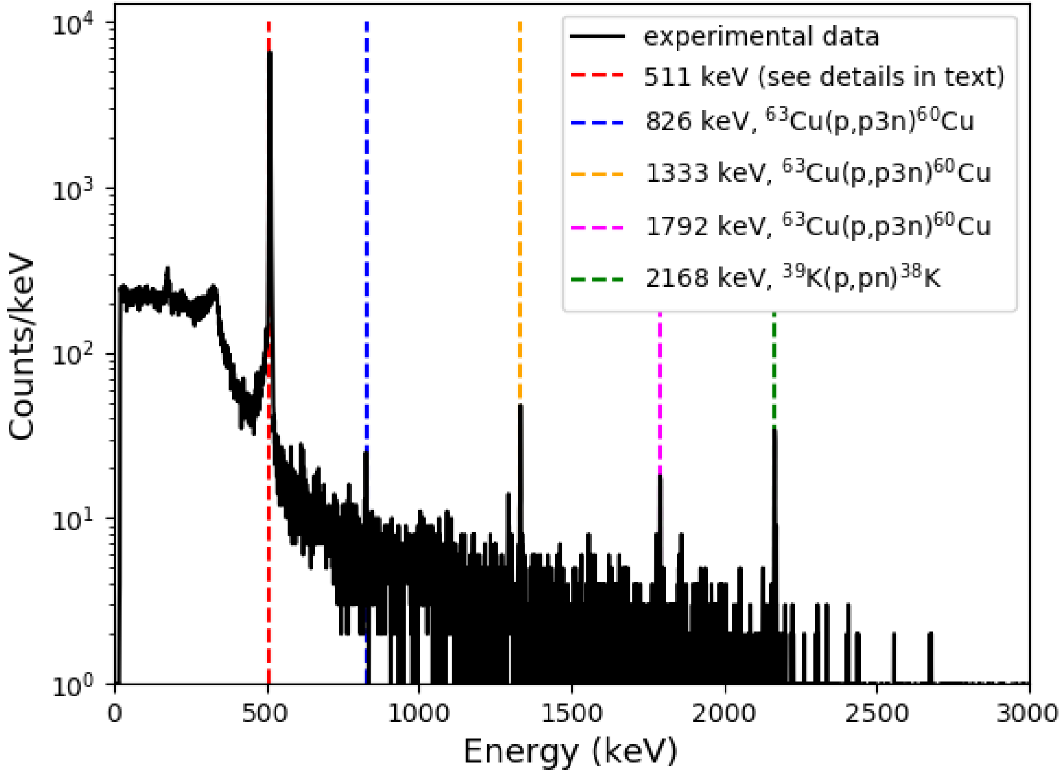


Fig. 18. The number of dark counts per 10 ms interval time measured for S14161 before irradiation, 26 h and 2 months after at room temperature.

Experimental results: activation analysis

- Gamma-ray energy spectra measured with HPGe detector.
- Time after proton irradiation: ~10 min.
- The series of measurements: 100 s each file.



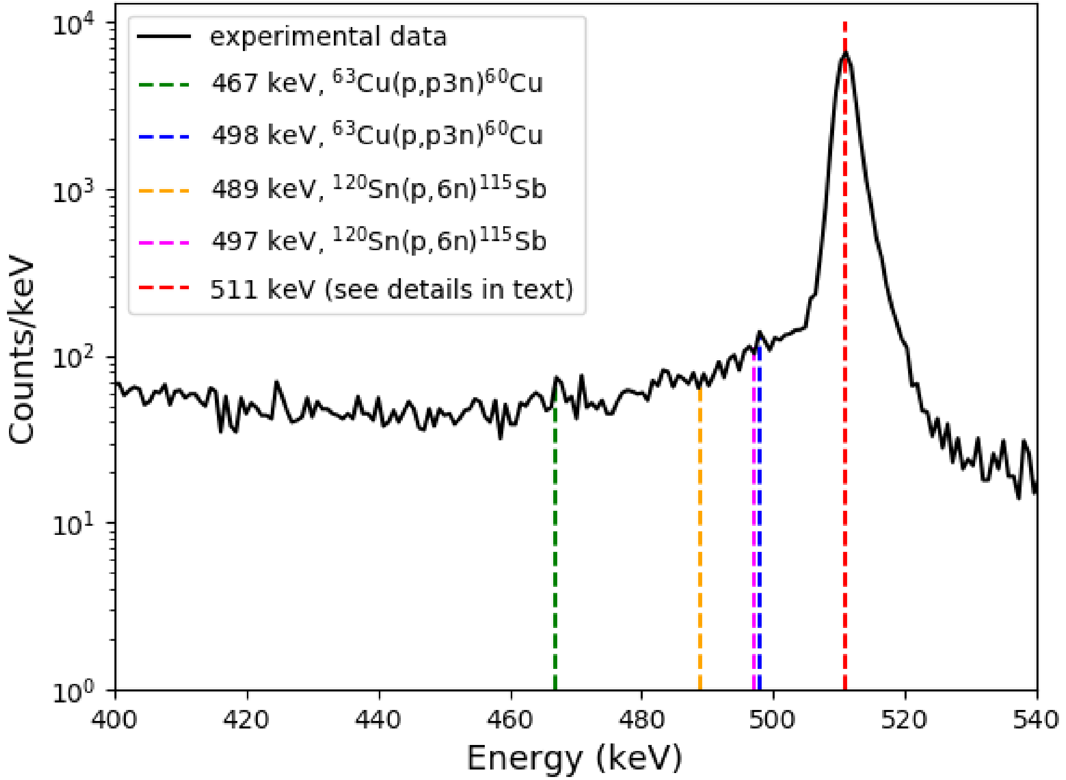


Fig. 19. The example of gamma-ray energy spectrum measured with HPGe detector after SiPM proton irradiation. Black line shows experimental data. Dashed colour lines show identified peaks.

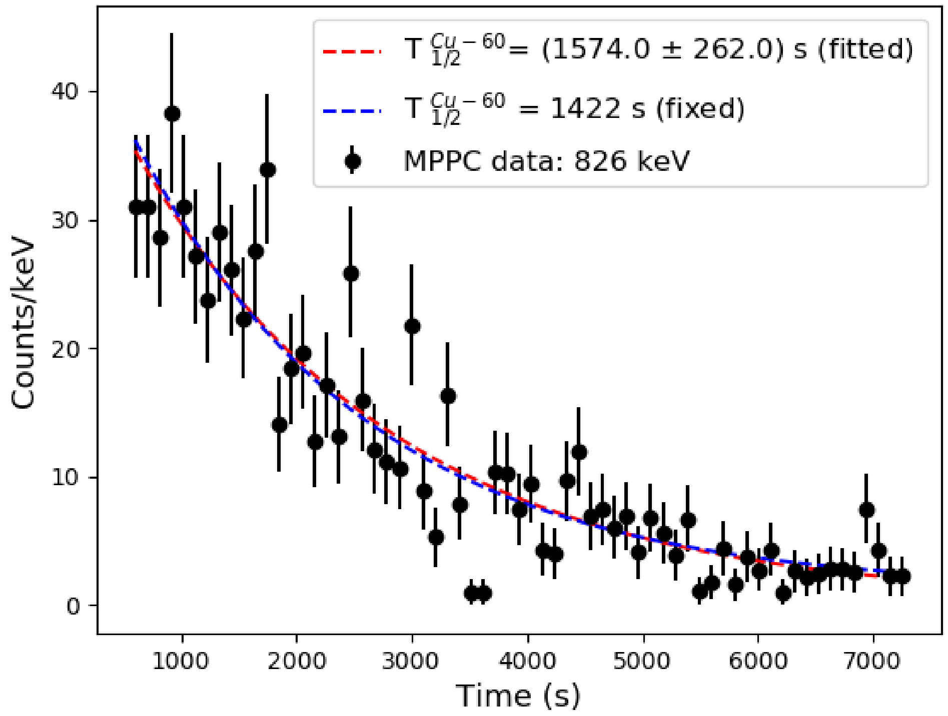
Experimental results: activation analysis

- What components of the SiPM array and PCB plate are important? Candidates are: carbon, silicon, oxygen, cupper… something more?
- The TALYS software was used to simulate the nuclear reactions from 58 MeV protons.
- The tables of possible decay channels with total cross-sections were generated (based on the highest cross-section criterion).
- The absence of silicon and oxygen may be surprising. However, for silicon, the decay time is in the range of a few seconds. For oxygen, the most prominent decay channel has a decay time of 122 s.

Mother nuclei	Abundance (%)	Daughter nuclei	Reaction type	Total cross section (mb)	$T_{1/2}$ (s)	Dominant energies (keV)
Sn-120	32.6	Sb-115	(p,6n)	223.6	1926	511
Cu-63	69.0	Cu-60	(p,p3n)	27.8	1422	511, 826, 1333, 1792
Cu-63	69.0	Cu-61	(p,p2n)	92.8	12010	511
Cu-63	69.0	Cu-62	(p,pn)	167	580	511
Cu-65	31.0	Cu-64	(p,pn)	167	45724	511
Cu-65	31.0	Cu-62	(p,p3n)	117	580	511
C-12	99.0	C-11	(p,pn)	167	1222	511
K-39	93.0	K-38	(p,pn)	67.3	459	511, 2168

Tab. 3. Dominant reactions of 58 MeV protons on SiPM(+PCB) based elements calculated using TALYS.

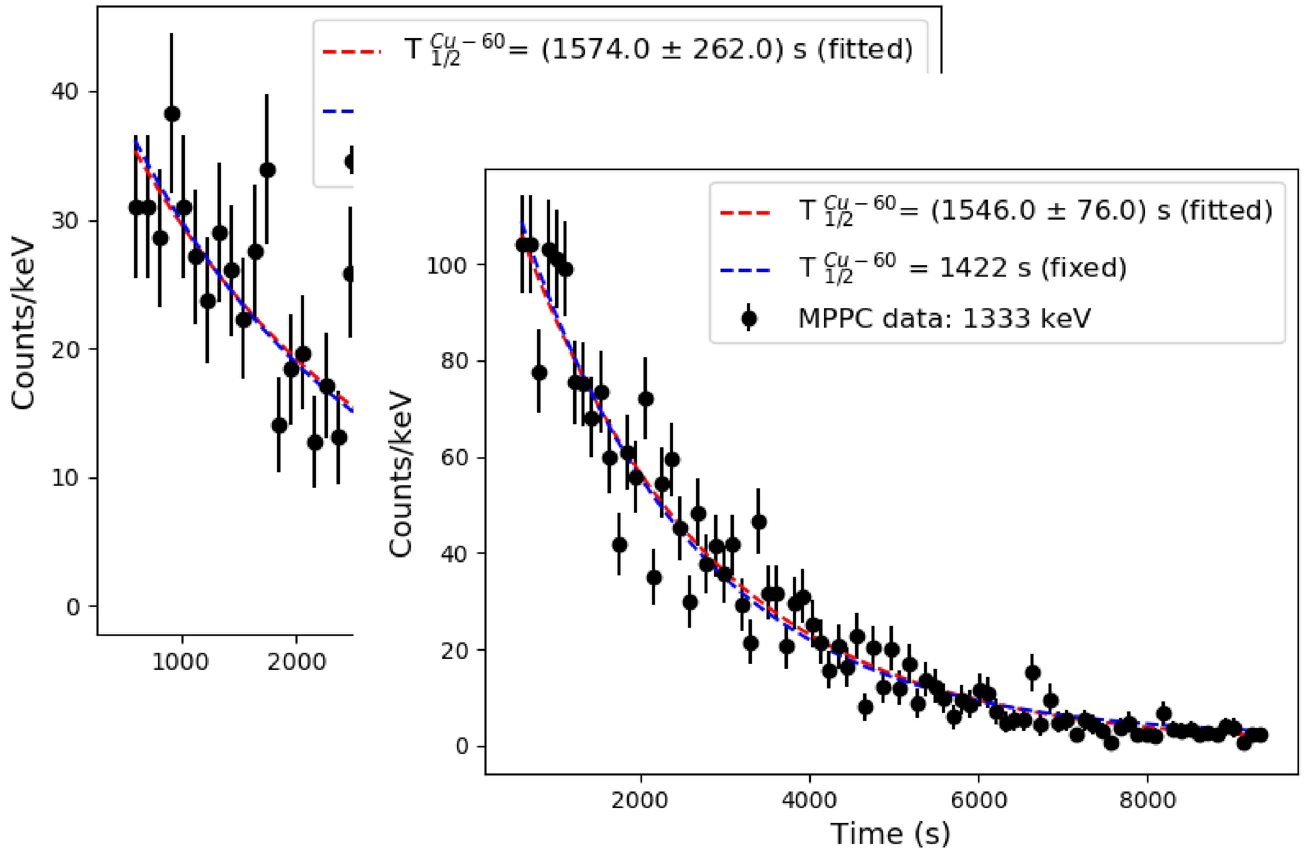
Experimental results: activation analysis



Decay time distributions.

Fig. 20. Decay time distributions measured for 58 MeV proton irradiated SiPM. Red dashed lines correspond to fitting procedure, where amplitudes and decay times were set as a free parameters. Blue dashed lines describe the cases with fixed decay times

Experimental results: activation analysis



Decay time distributions.

Fig. 20. Decay time distributions measured for 58 MeV proton irradiated SiPM. Red dashed lines correspond to fitting procedure, where amplitudes and decay times were set as a free parameters. Blue dashed lines describe the cases with fixed decay times

Experimental results: activation analysis

Decay time distributions.

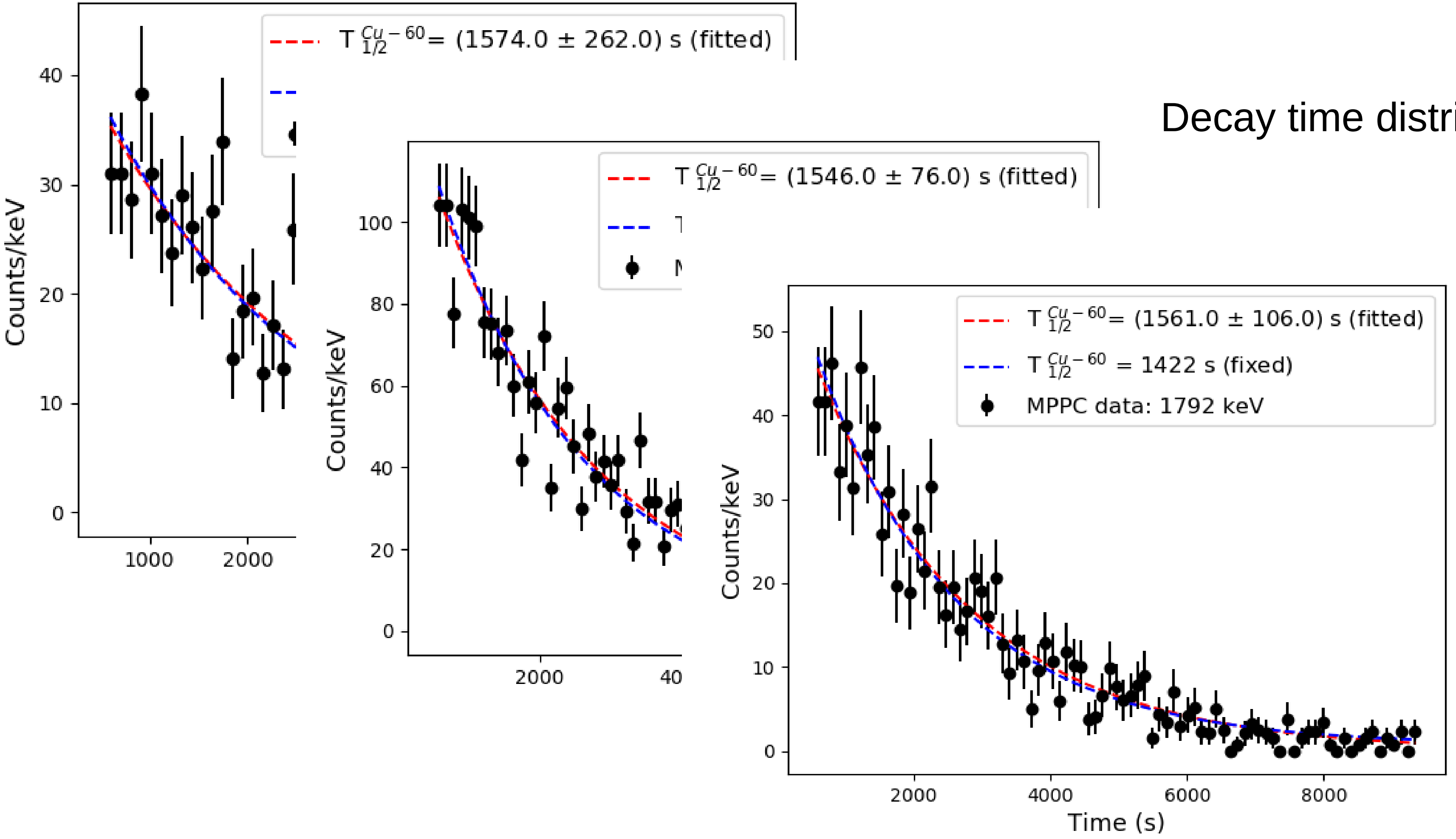
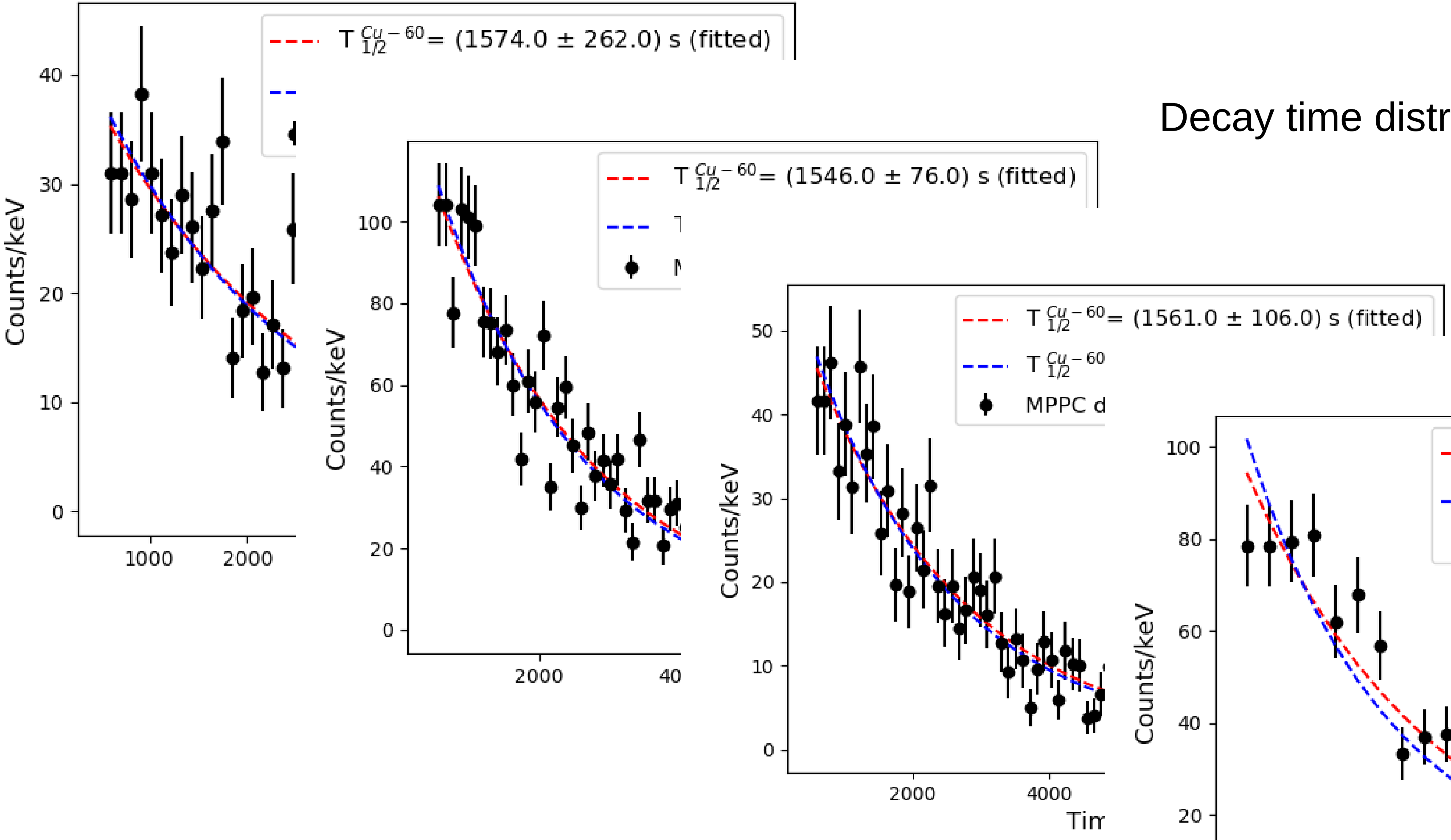


Fig. 20. Decay time distributions measured for 58 MeV proton irradiated SiPM. Red dashed lines correspond to fitting procedure, where amplitudes and decay times were set as a free parameters. Blue dashed lines describe the cases with fixed decay times

Experimental results: activation analysis

Decay time distributions.



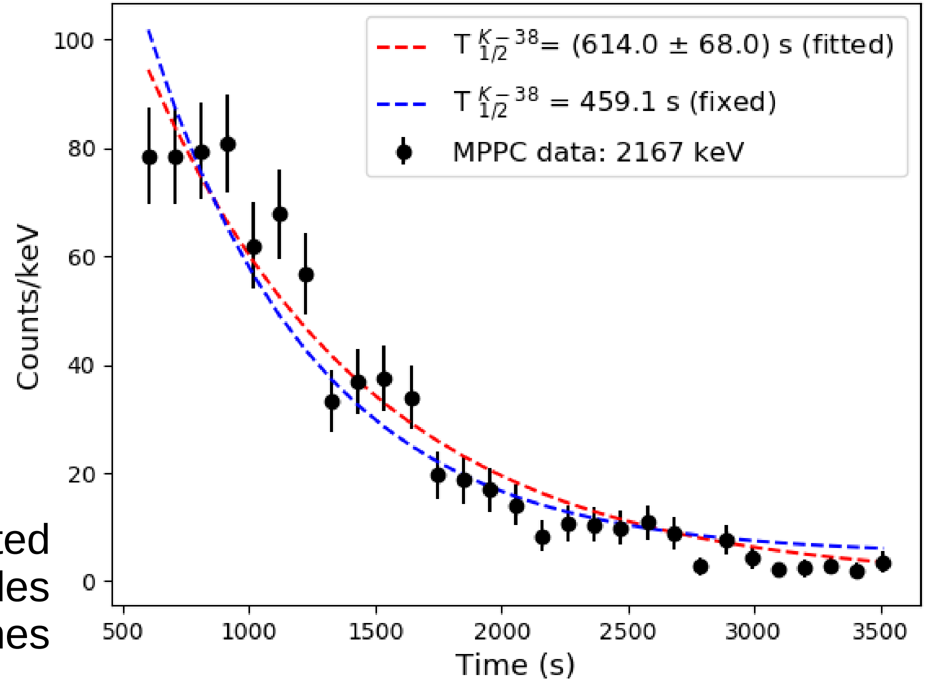
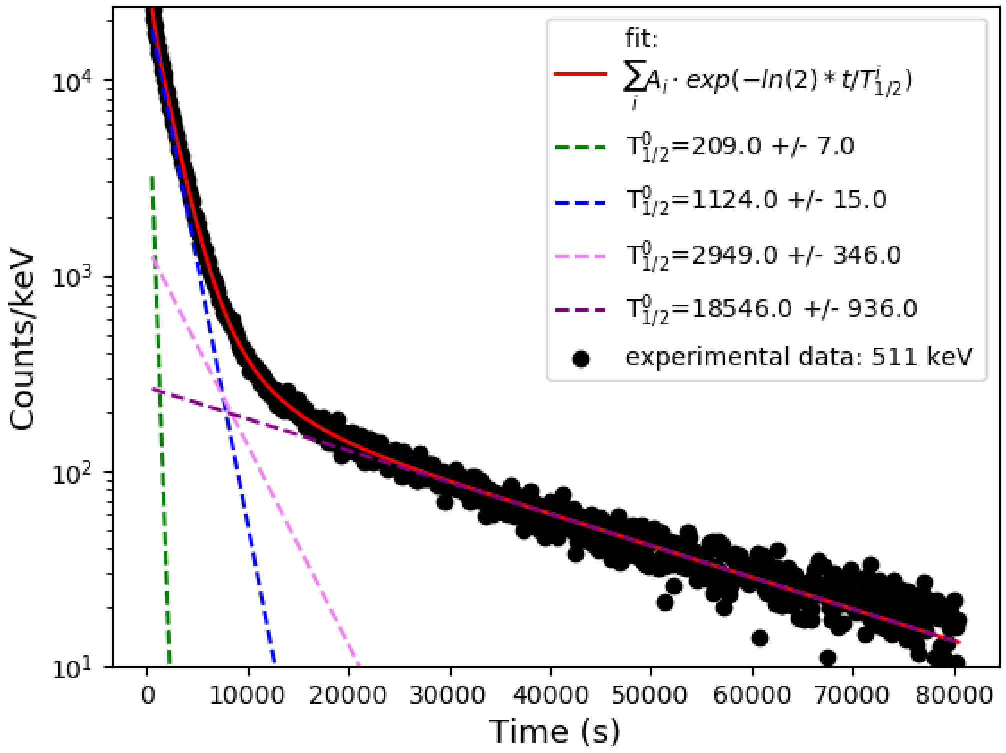


Fig. 20. Decay time distributions measured for 58 MeV proton irradiated SiPM. Red dashed lines correspond to fitting procedure, where amplitudes and decay times were set as a free parameters. Blue dashed lines describe the cases with fixed decay times

Experimental results: activation analysis

511 keV case...

$$y = \sum_{i}^{N} A_i \cdot exp\left(-\frac{t \cdot ln(2)}{T^i_{1/2}}\right)$$



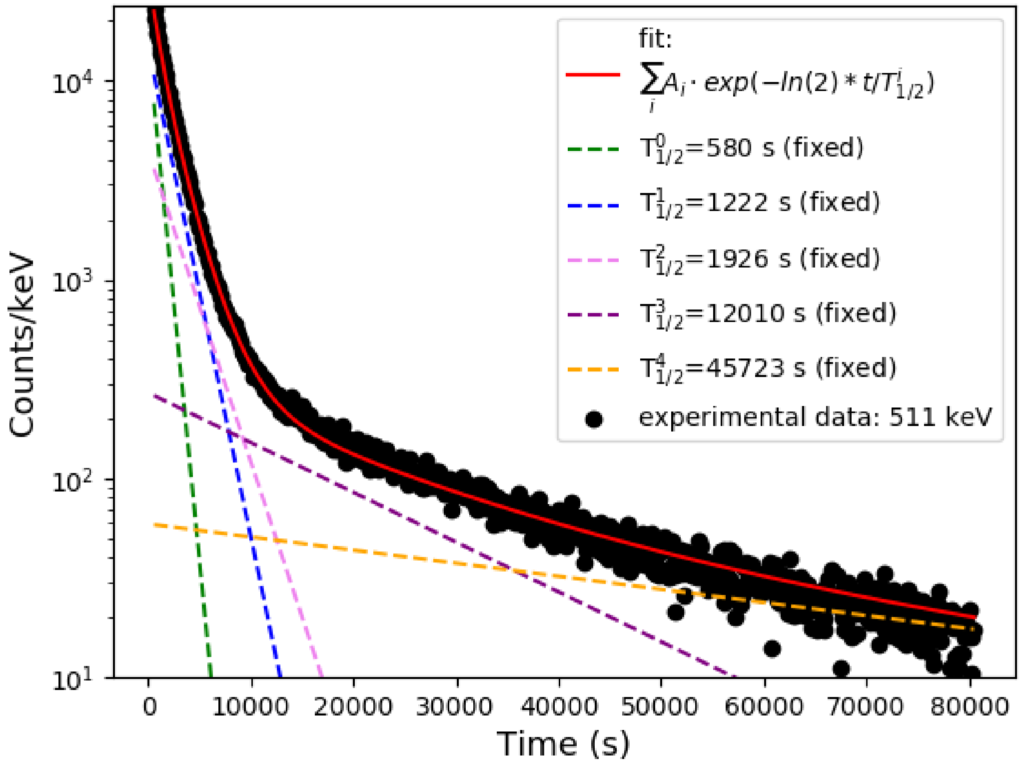


Fig. 21. Decay time distribution of 511 keV line measured for 58 MeV proton irradiated SiPM. Red lines show the results of fitting procedure for left - N=4 (8 free parameters) and right - N=5 (5 free parameters - only amplitudes). Dashed lines show each component contribution.

Summary and outlook

- After an exposure of 4.96 Gy, it was found that the S13361 SiPM array is still operational.
- The most prominent effects after proton irradiation are the increase in dark current and dark counts, mostly by cross-talk events.
- The maximum DC amplitudes for V_{ov} =2.8 V increased from about 110 mV (the last p.e. peak at 25°C, before irradiation) to about 350 mV (left edge of DC spectrum, 27°C, 4.96 Gy), showing the necessity of a well-thought threshold determination.
- Annealing processes were observed for DC spectra taken after 2 hours, 26 hours and 2 months (see also Nicolas De Angelis talk).
- The results show a dominant contribution of the 511 keV line in the energy spectrum measured with the HPGe detector.
- In conclusion, due to the shielding in the ’Full Instrument + CSS’ scenario, we do not expect POLAR-2 to greatly suffer from a rapidly degrading SiPM through background radiation.

POLAR-2 collaboration:

University of Geneva:
Xin Wu, Merlin Kole, Nicolas Produit, Jerome Stauffer, Nicolas de Angelis, Franck Cadoux, Johannes Hulsman, Hancheng Li

NCBJ, Poland:
Agnieszka Pollo, Dominik Rybka, Slawomir Mianowski, Adam Zadrozny

MPE, Germany:
Jochen Greiner, J. Michael Burgess

IHEP, China:
Shuang-Nan Zhang, Jianchao Sun, Bobing Wu

Special thanks for prof. Jan Swakoń, IFJ group and Zuzanna Mianowska from NCBJ!

Thank you for your attention

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