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Radiation damage study of SensL (onsemi) J-Series SiPMs using 101.4 MeV protons

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GMOD detector on board EIRSAT-1

- EIRSAT-1 is a 2U CubeSat developed by UCD students as part of ESA’s *Fly Your Satellite!* (FYS) programme. To be launched in 2023.

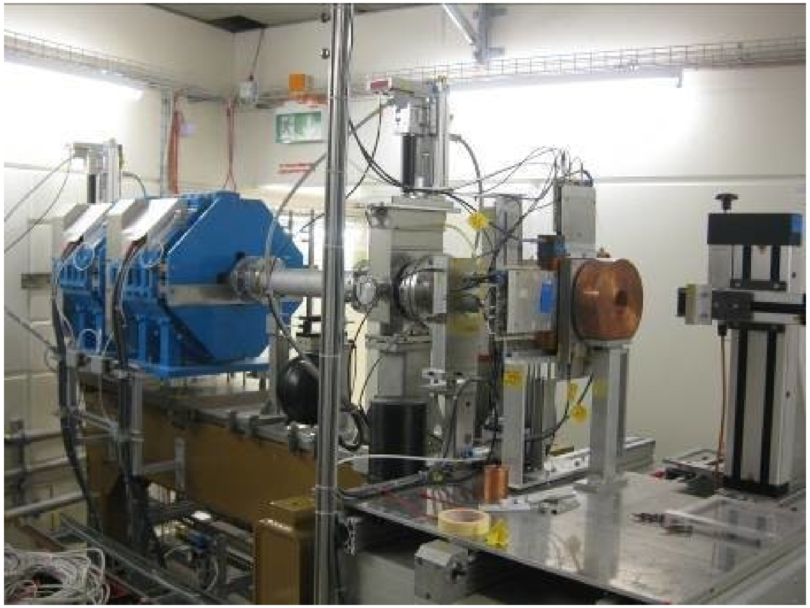
- Gamma-ray Module (GMOD) is a small ramma-ray burst detector on board EIRSAT-1:
  - 25 x 25 x 40 mm^3 $CeBr_3$ scintillator
  - custom-built 4 x 4 array of J-Series SiPMs (MicroFJ-60035-TSV: 6 mm, 35 um pixel size)
  - Low-power radiation tolerant SiPM readout ASIC by IDEAS (SIPHRA)

https://doi.org/10.1007/s10686-021-09779-9

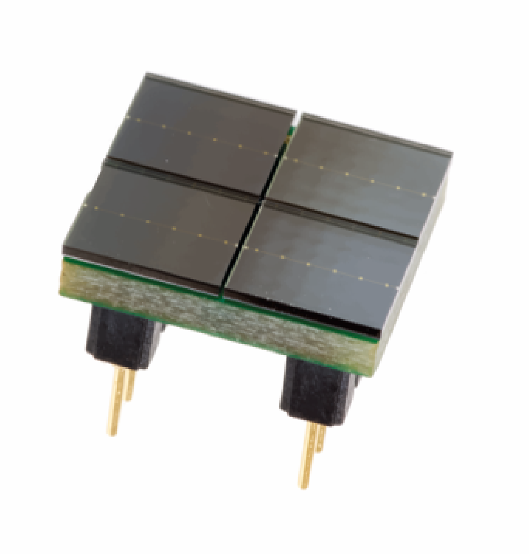
https://doi.org/10.1007/s10686-022-09842-z

Radiation test campaign

- This study was conducted within a radiation test campaign organised by the ESA Education Office in the framework of the FYS programme.
- Irradiation was performed at the Proton Irradiation Facility in the Paul Scherrer Institute (PSI), an ESA facility constructed specifically for testing spacecraft components.
- The main purpose of this study was to assess potential damage to J-series SiPMs from proton radiation in space and effects of the SiPM damage on the spectral performance of the GMOD detector.



Irradiated SiPMs



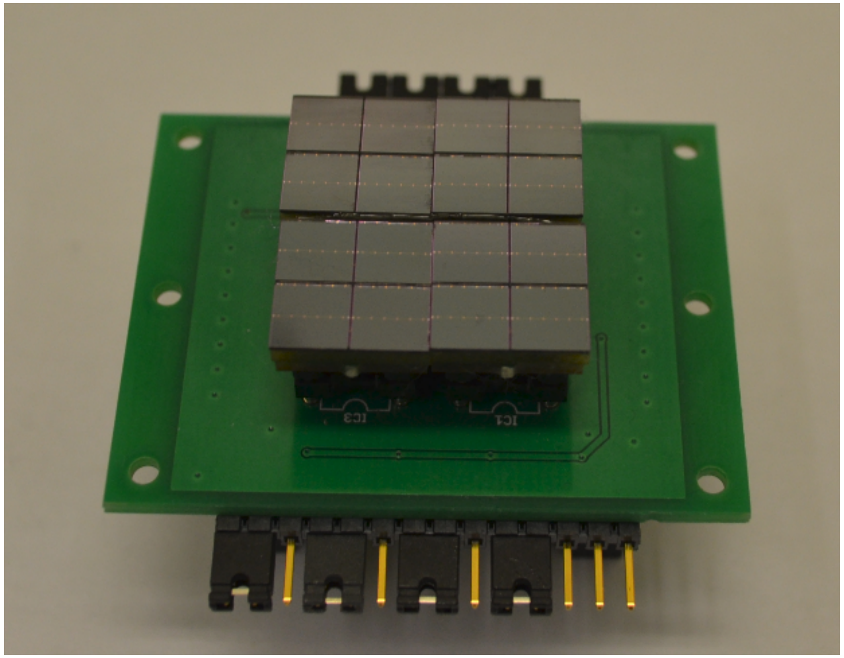
SensL ARRAYJ-60035-4P-PCB composed of four MicroFJ-60035-TSV

16 x MicroFJ-60035-TSV will be used in the GMOD

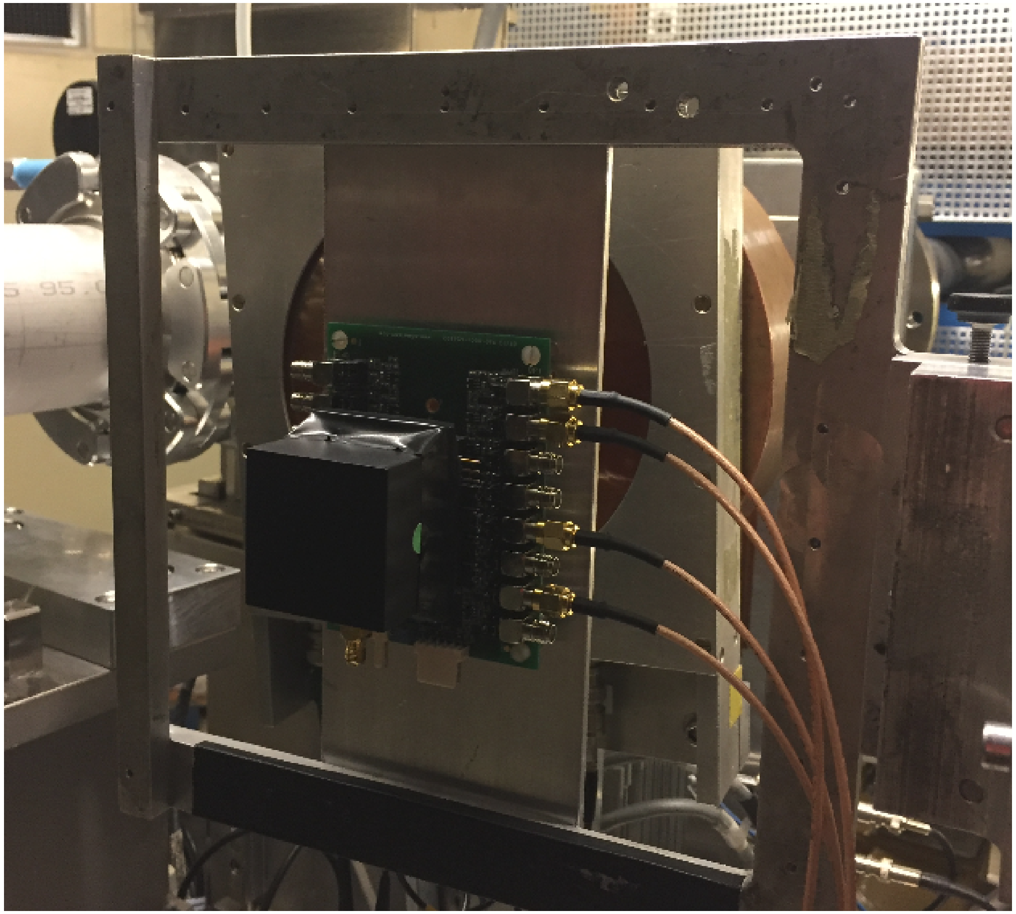
MicroFJ-60035-TSV parameters
(at an overvoltage of 3.65V):

Active area	6.07×6.07 mm^2
Microcell size	35 μm
No. of microcells	22292
Breakdown voltage $V_{\rm br}$ at 21°C	24.2 to 24.7 V
Temperature dependence of $V_{\rm br}$	21.5 mV/°C
Operating overvoltage $V_{\rm ov}$	1 to 6 V
Gain	4×10^6
PDE at 380 nm (peak emission of CeBr3)	37%
Capacitance	4140 pF
Microcell recharge time constant	50 ns
Crosstalk probability	13%

SiPM Set 1

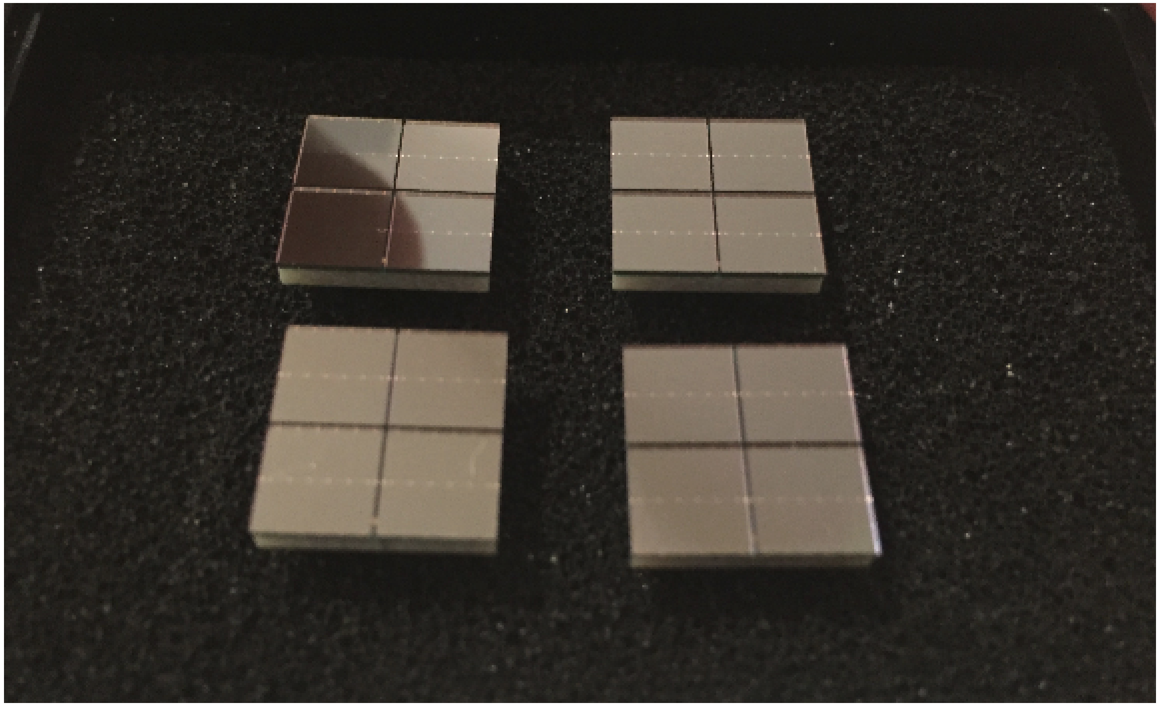


- Four 2x2 arrays were combined into one 16-SiPM array using an adaptor board.



- The 16-SiPM array + 25 x 25 x 10 mm^3 CeBr3 scintillator crystal were irradiated with 101.4 MeV protons (from the SiPM side).
- After each exposure the detector was removed from the beam to perform characterisation measurements.

SiPM Set 2



Three bare 2x2 SiPM arrays were irradiated one by one with 101.4 MeV protons, each to a different fluence level.

One SiPM array was not irradiated and was used as a reference.

Irradiation levels

CeBr3 detector with **Set 1** SiPMs irradiated with 101.4 MeV protons
(reduced to 94 MeV by the PCBs in front of the SiPMs)

Exposure number	Duration (s)	Cumulative fluence (p/cm²)	Cumulative fluence (n_{eq}/cm²)	TID (rad)	Equiv. SiPM exposure for EIRSAT-1/GMOD*
1	40	1×10^8	1.3×10^8	9.8	4 months in ISS orbit
2	79	3×10^8	4.0×10^8	30	1 year in ISS orbit
3	339	9.3×10^9	1.2×10^{10}	910	6 years in 550km/40° orbit

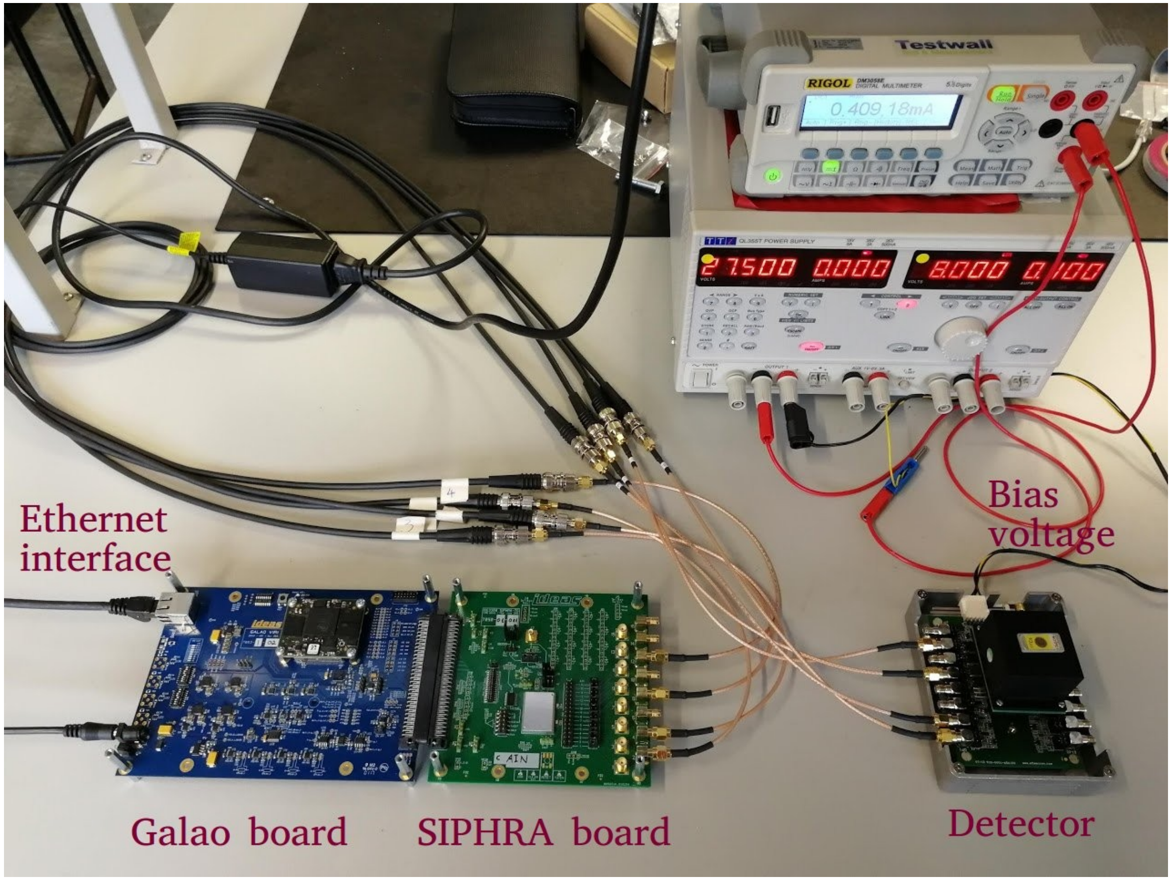
Bare SiPMs **(Set 2)** irradiated with 101.4 MeV protons

SiPM array	Duration (s)	Fluence (p/cm²)	Fluence (n_{eq}/cm²)	TID (rad)	Equiv. SiPM exposure for EIRSAT-1/GMOD*
1	0	0	0	0	0
2	35	1×10^8	1.3×10^8	9.8	4 months in ISS orbit
3	105	3×10^8	3.8×10^8	29	1 year in ISS orbit
4	347	1×10^9	1.3×10^9	98	3 years in ISS orbit

* SiPMs are protected by the CeBr crystal from one side and ~3 mm Al from the back

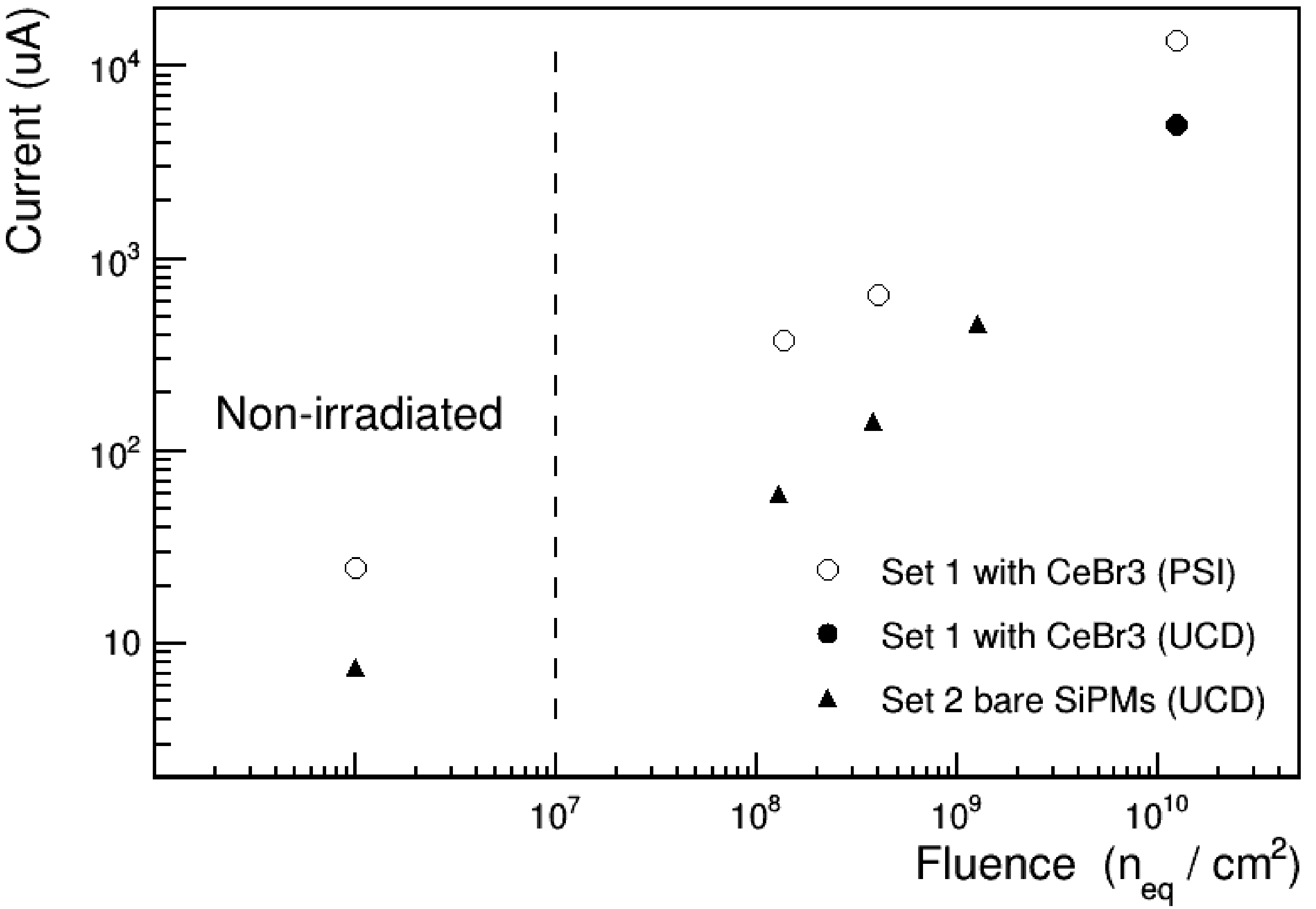
Measurement setup

- After each exposure the detector was removed from the beam and measurements were performed outside the shielded irradiation area.
- The detector was connected to the SIPHRA board using four 2.5 m long cables: four SIPHRA inputs were connected to four 2x2 arrays (different from the GMOD).
- Gamma-ray spectra of ^{137}Cs and ^{241}Am and total SiPM current were measured in PSI



- Bias voltage = 28.15 V (overvoltage of 3.65 V).
- Further measurements were performed in UCD 86-89 days after the irradiation.

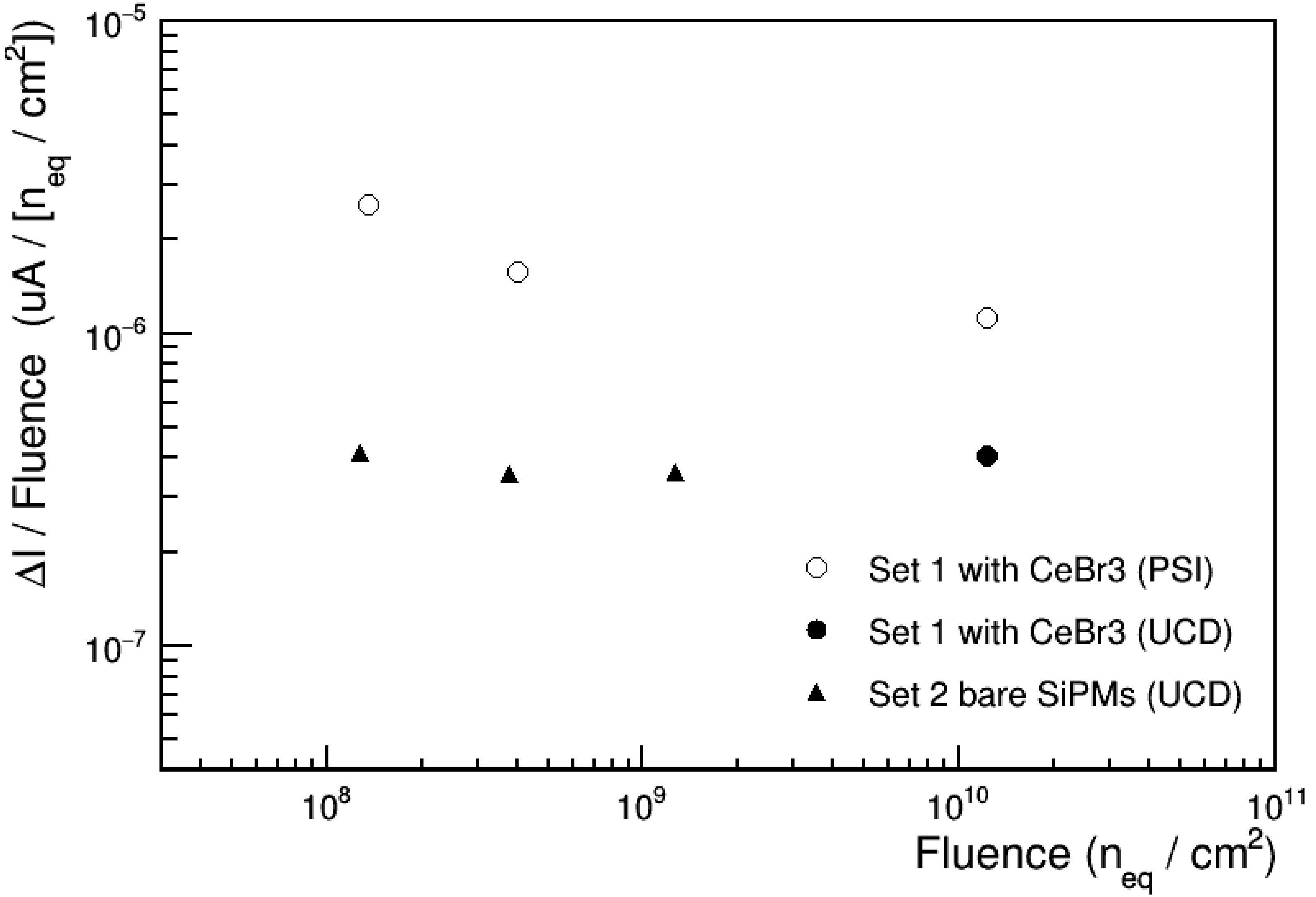
Current drawn by a 2x2 array (1.47 cm^2)



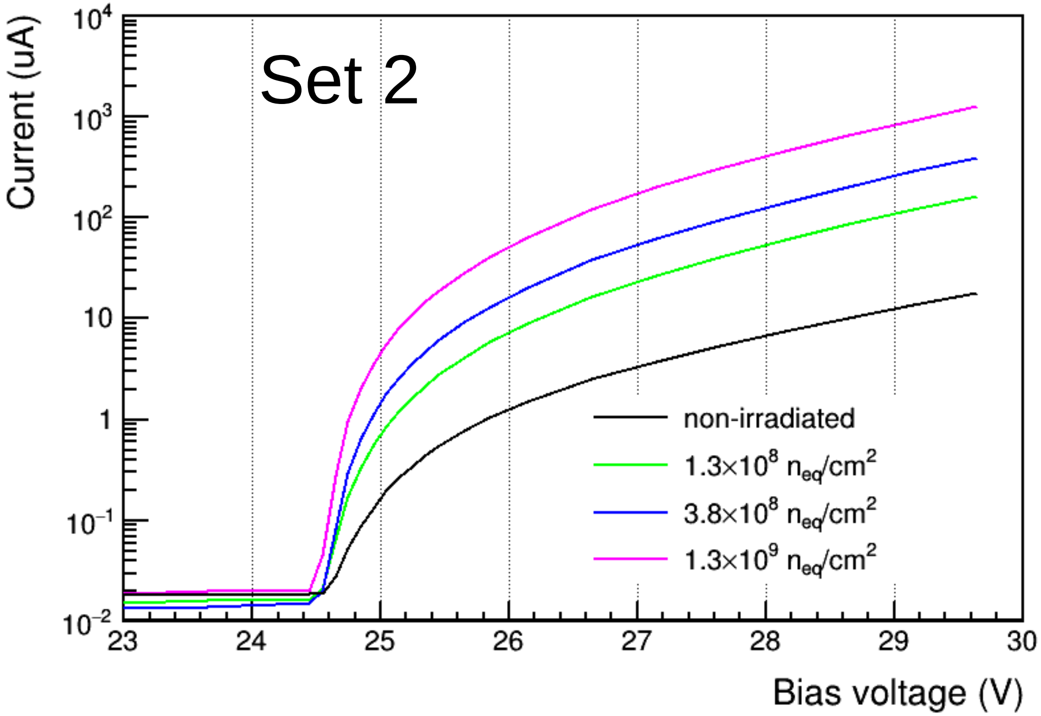
- PSI: 10-20 min after exposure, T = 24^{o}C.
- UCD: 86-89 days after exposure, T = 21^{o}C.
- Self-heating after 1.2x10^{10} n_{eq}/cm^2 (current increasing from 5 to 10 mA in 2 hours in UCD measurements, adapter PCB temperature increasing from 21^{o}C to 36^{o}C)

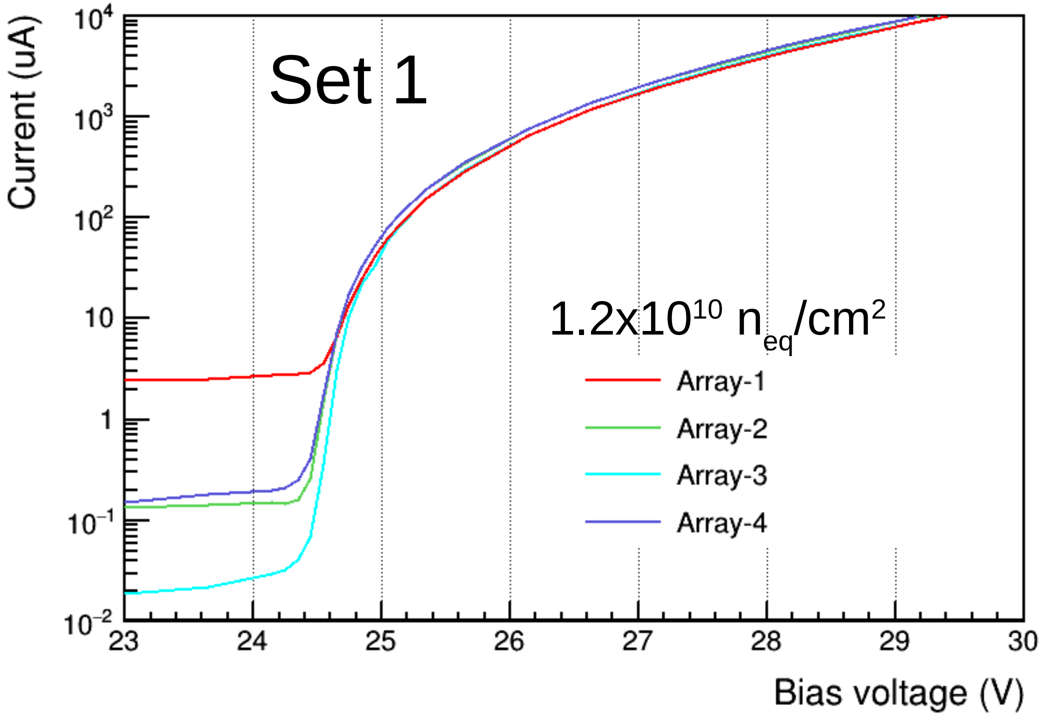
In UCD measurements the current reduced by a factor of 3 which indicates partial recovery from radiation damage (but also affected the lower temperature).

Current-to-fluence ratio for 2x2 arrays



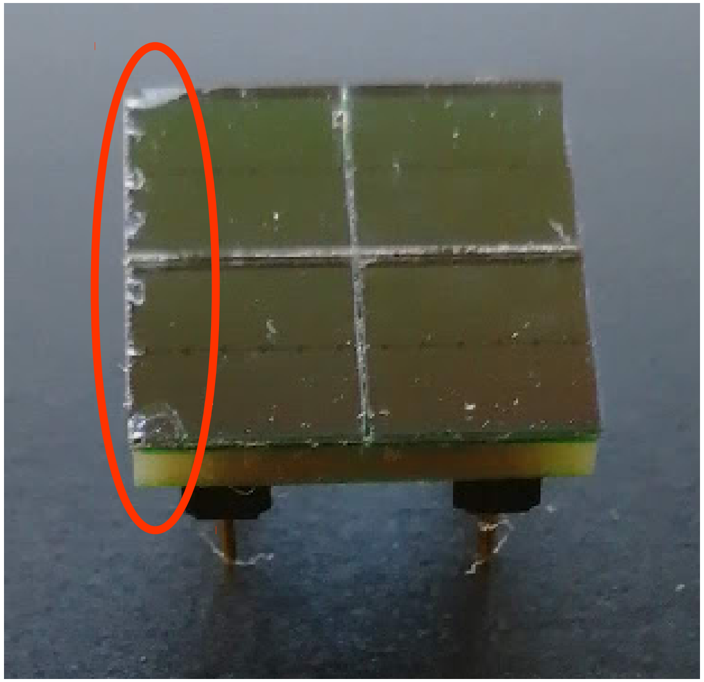
Current-voltage curves of 2x2 SiPM arrays, 3 months after irradiation, T=21^{o}C

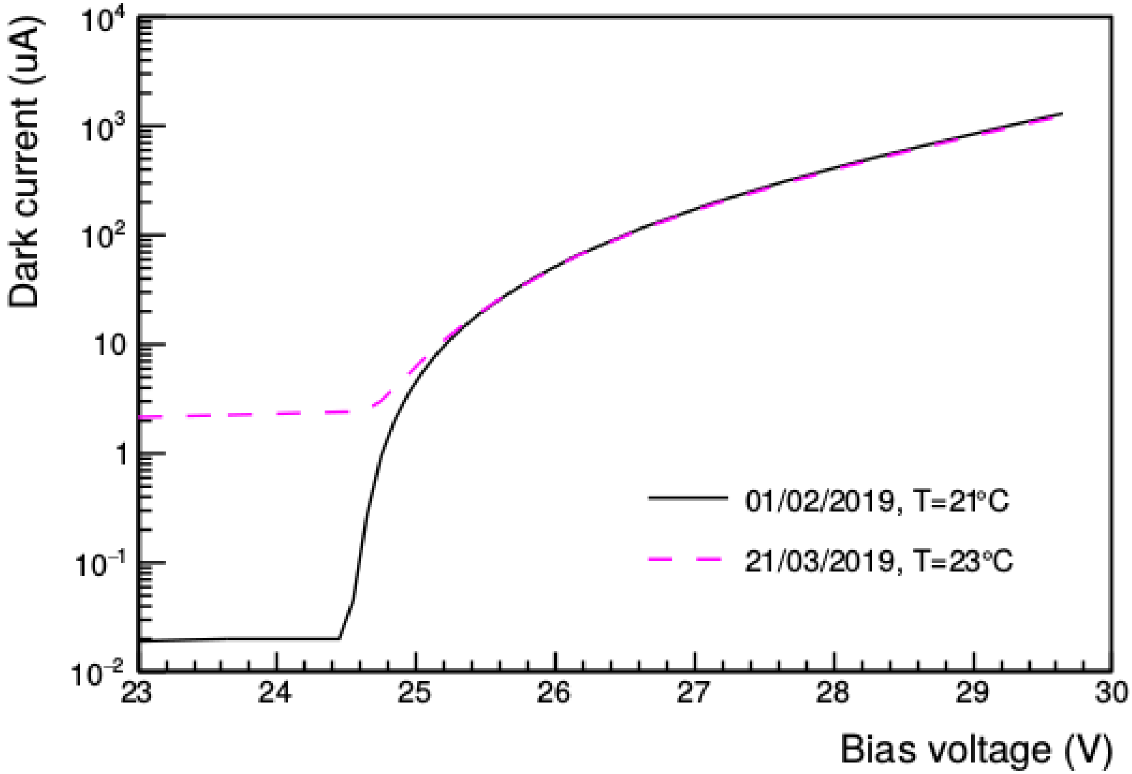




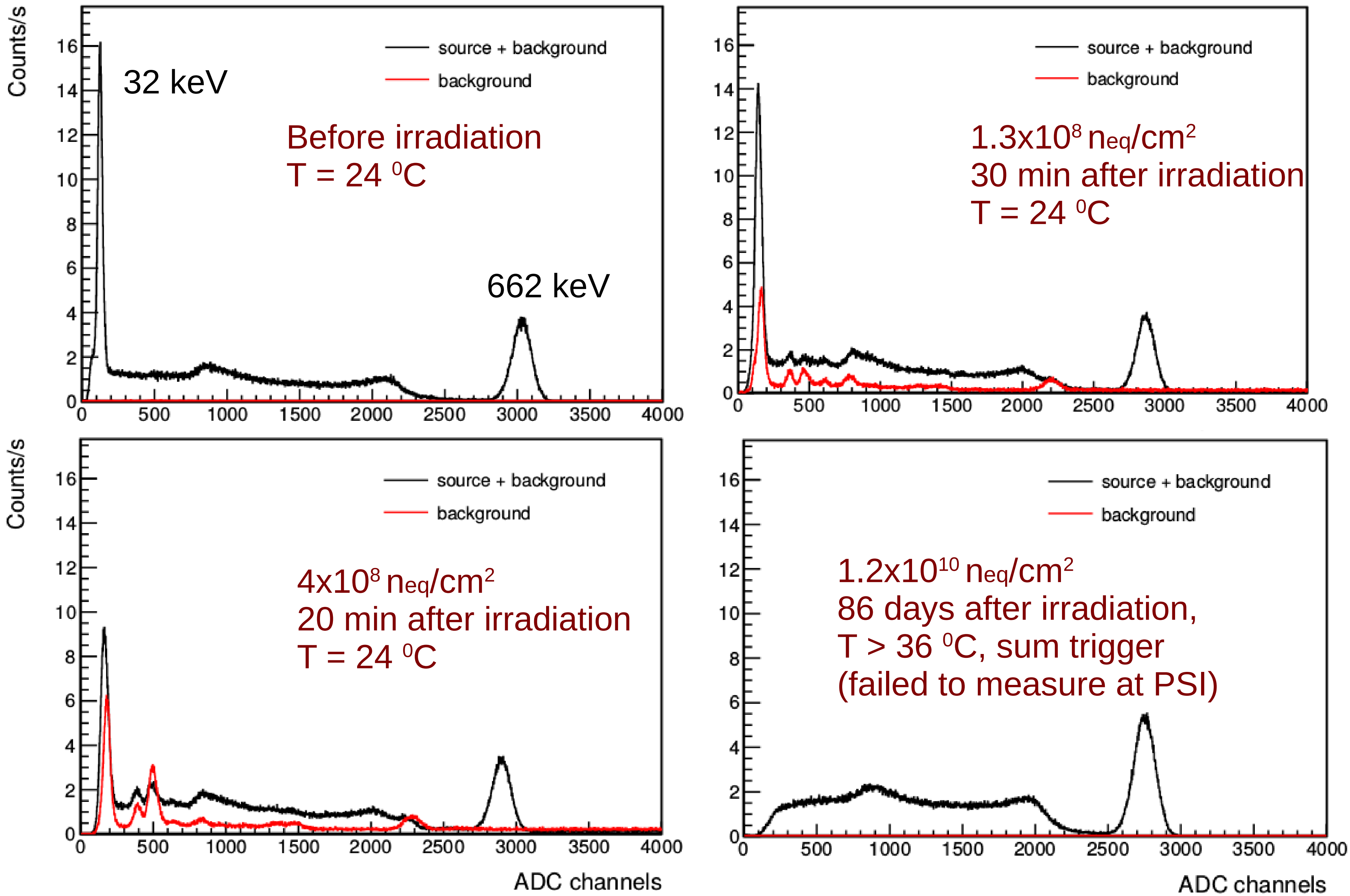
- Includes 10-15 nA leakage current through the adaptor PCB.
- V_{br} = 24.5 ± 0.1 V for all SiPMs.
- Large leakage current below V_{br} for some SiPMs in Set 1 (mechanical damage?)

Accidental mechanical damage to Array-4 from Set 2

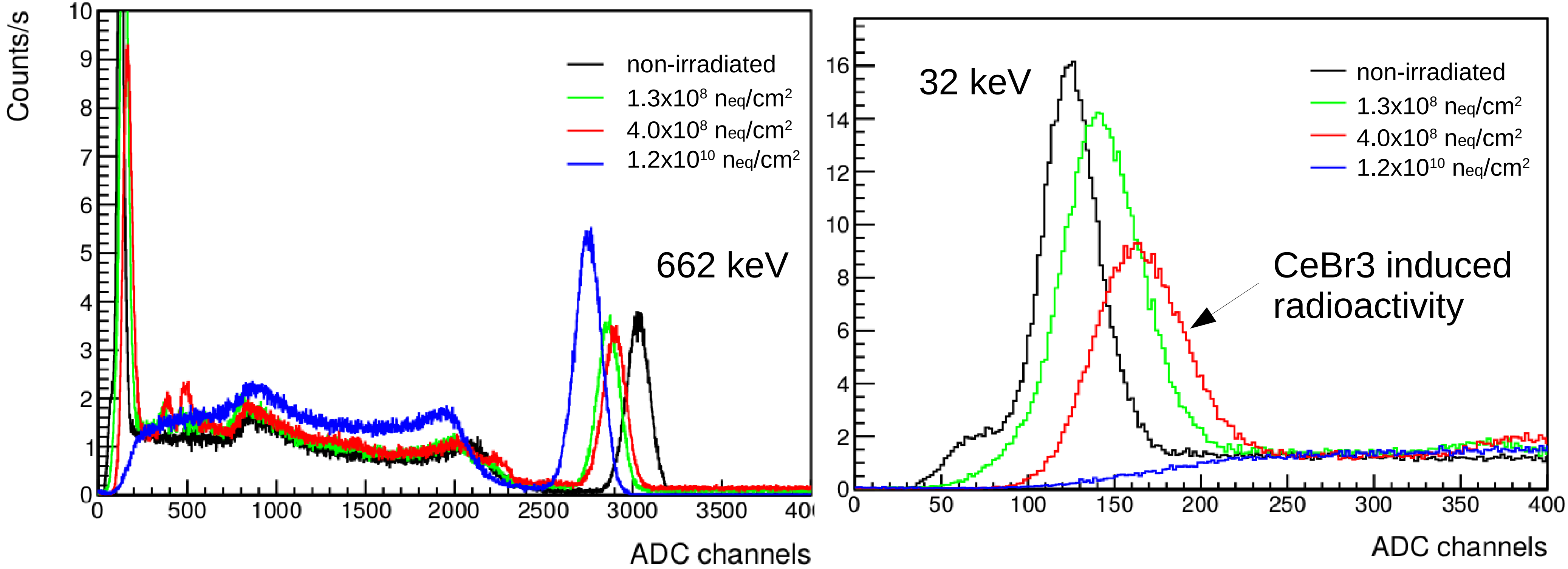




CeBr3 + 16 SiPMs (Set 1): ^{137}Cs spectra

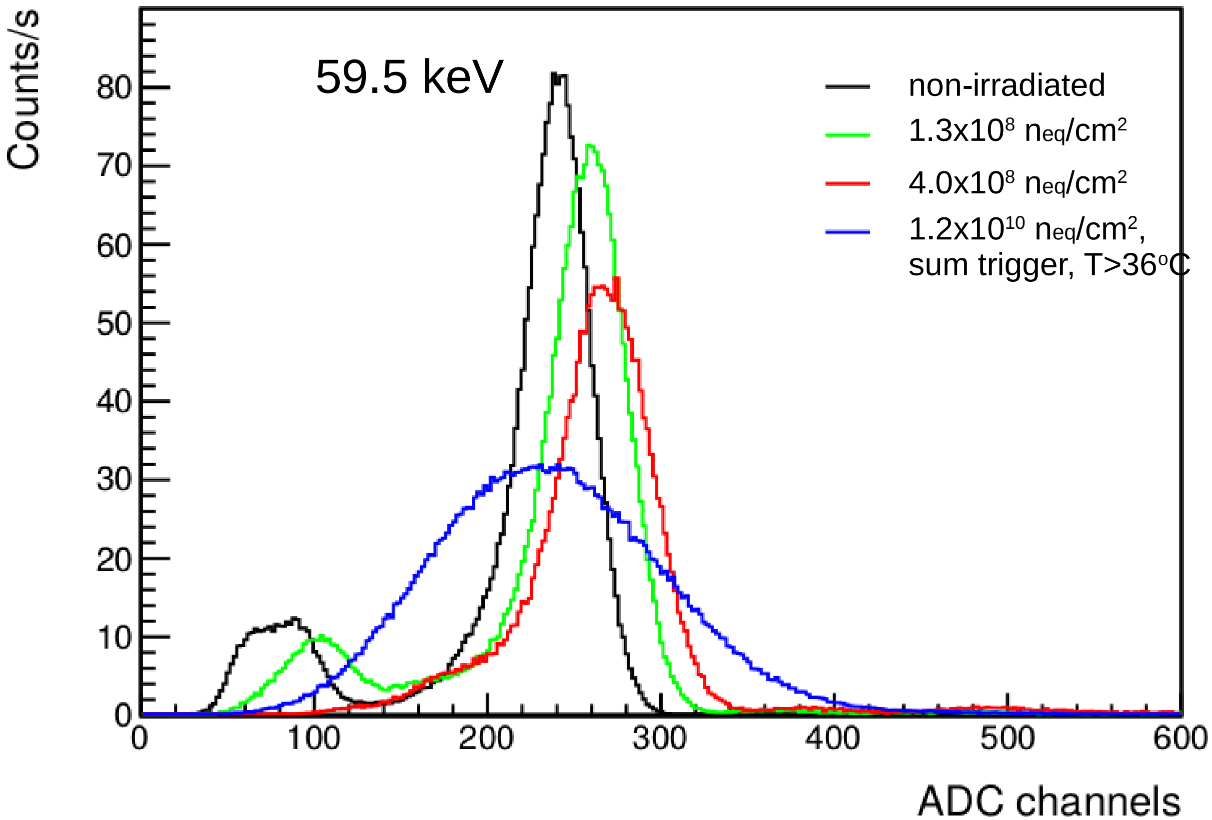


Comparison of ^{137}Cs spectra



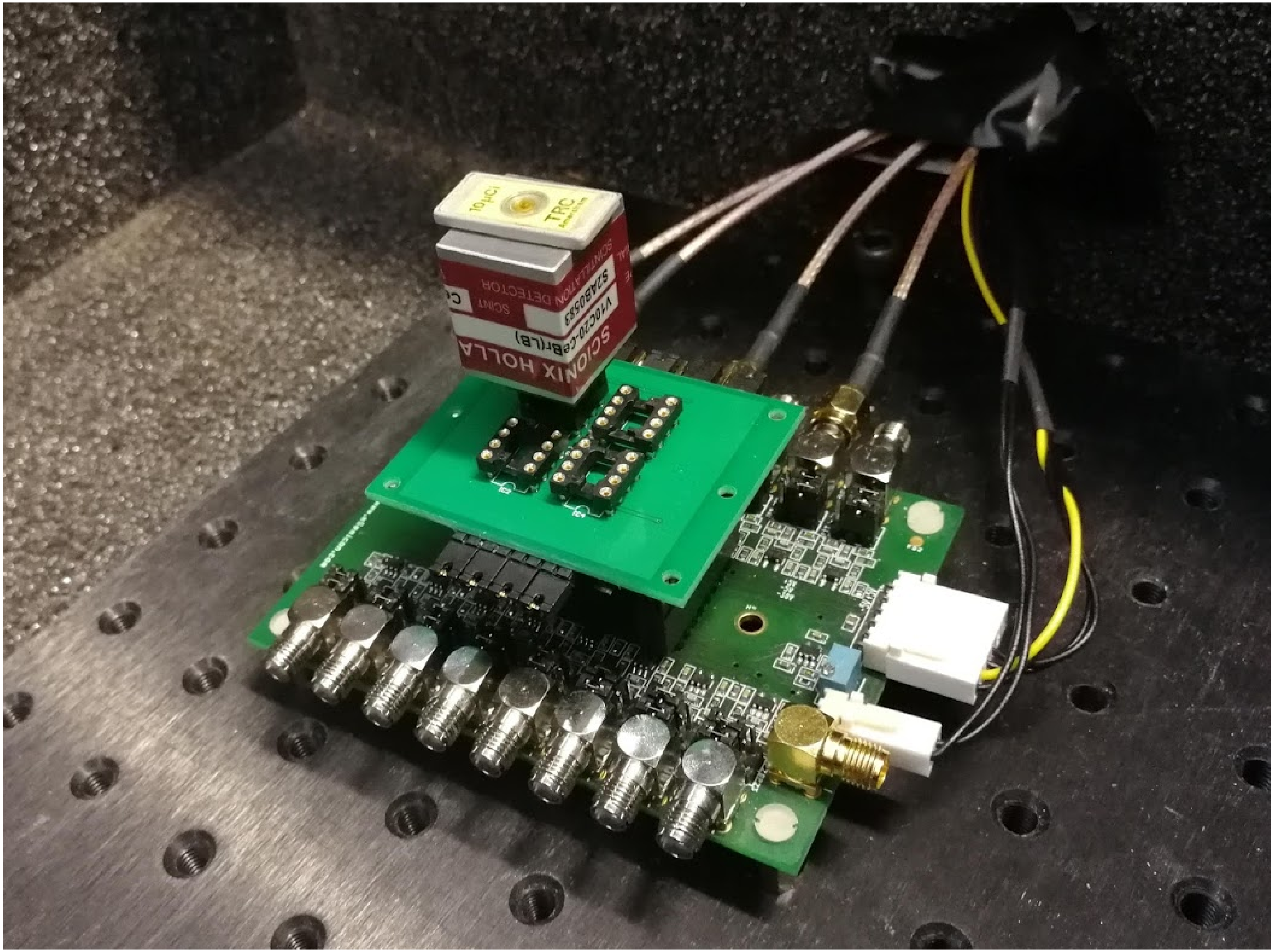
- 9% spread in the position of the 662 keV peak is not fully understood (temperature, trigger conditions, radiation damage?)
- The low energy cut-off is defined by the trigger threshold, which was increased after each exposure to prevent noise triggers. The detector efficiency at 32 keV is already reduced after $3x10^8$. The 32 keV peak is contaminated by induced scintillator radioactivity.

Comparison of ^{241}Am spectra

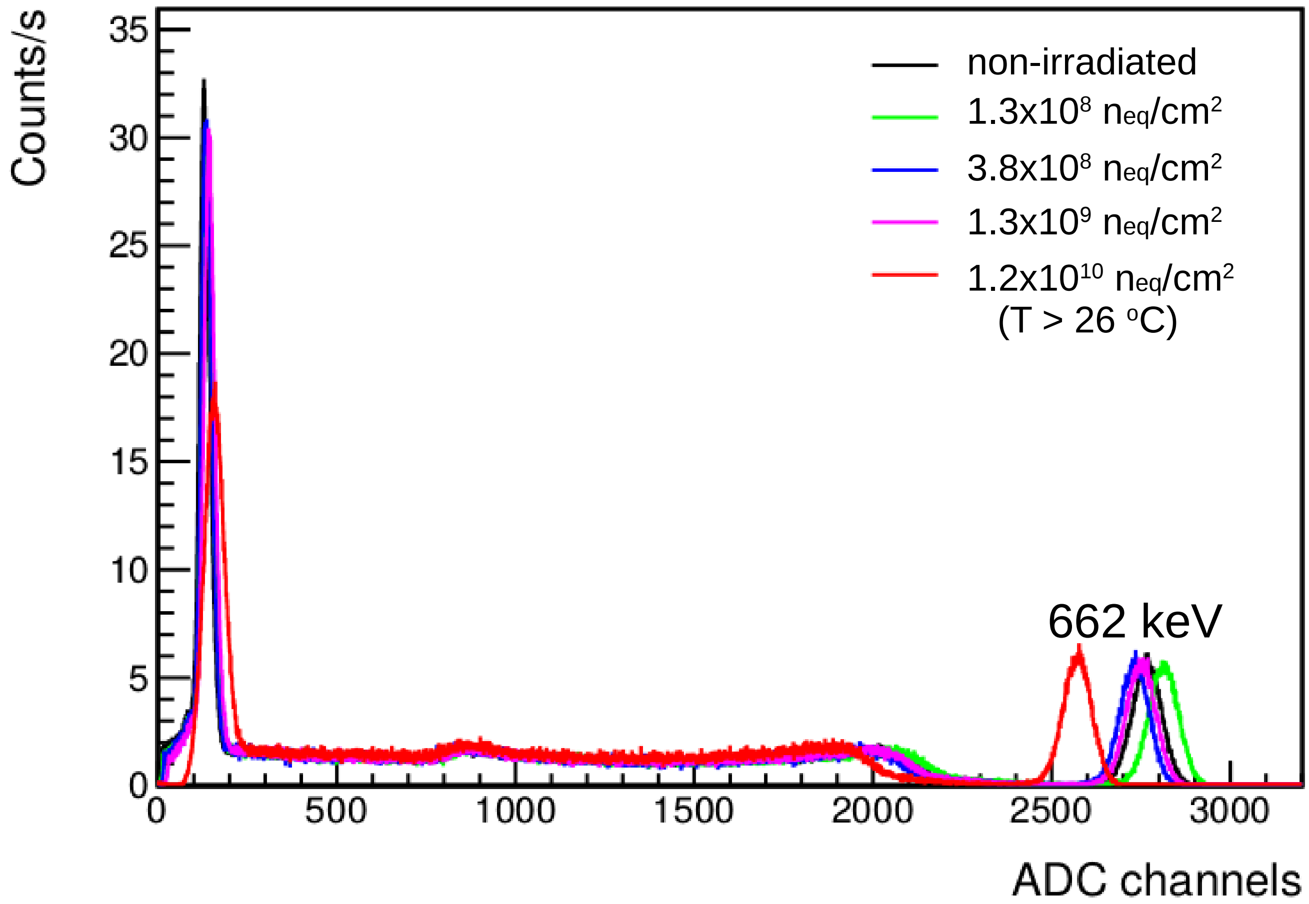


- The 59.5 keV peak moves up by 12% after $3x10^8$ cm^{-2} (time-walk effect in the trigger?). The peak moves down after $9.3x10^9$ cm^{-2} (due to summing channel trigger?)
- The peak width increases from 18% to 22% ($3x10^8$ cm^{-2}) to 64% ($9.3x10^9$ cm^{-2}) due to the increased SiPM noise.
- No significant change in 59.5 keV detection efficiency after $4x10^8$ cm^{-2}

Gamma-ray measurements using a small CeBr3 and 4-SiPM arrays (UCD, 134 days after the irradiation)



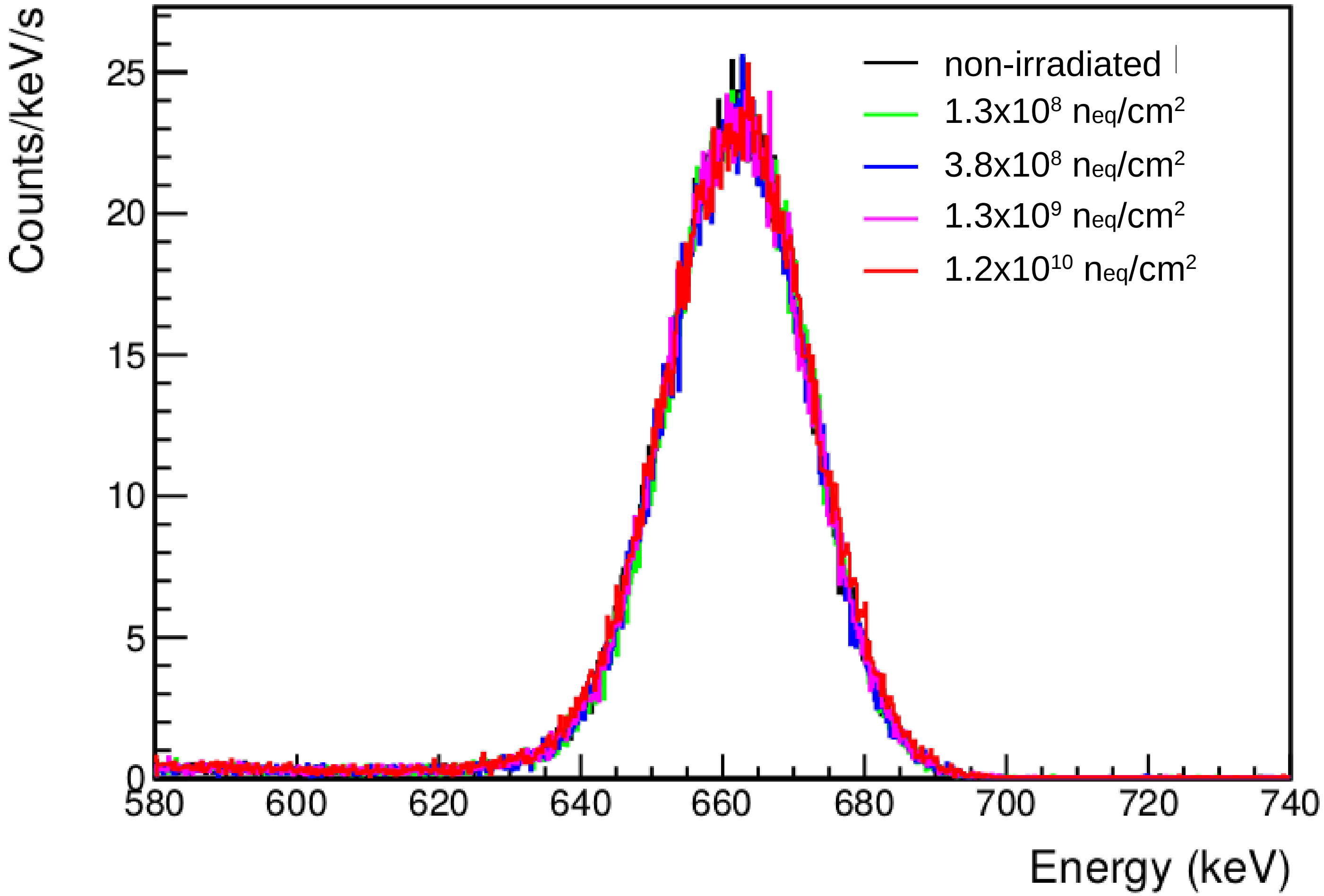
Comparison of ^{137}Cs spectra (4 SiPMs)



A small spread in the detector response should be expected, as the SiPM properties can vary from sample to sample and the crystal coupling is not always ideal.

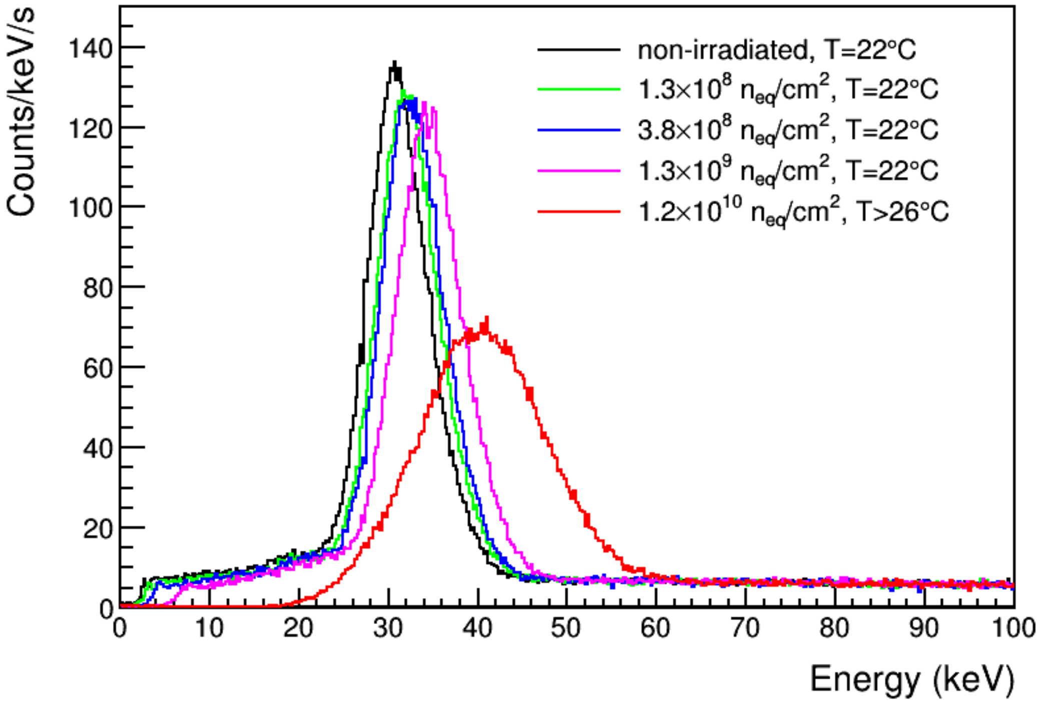
Better cooling in this configuration: the single channel trigger was used for all SiPM arrays including one irradiated to $1.2 \times 10^{10}\ n_{eq}/cm^2$.

Spectra calibrated using the 662 keV line

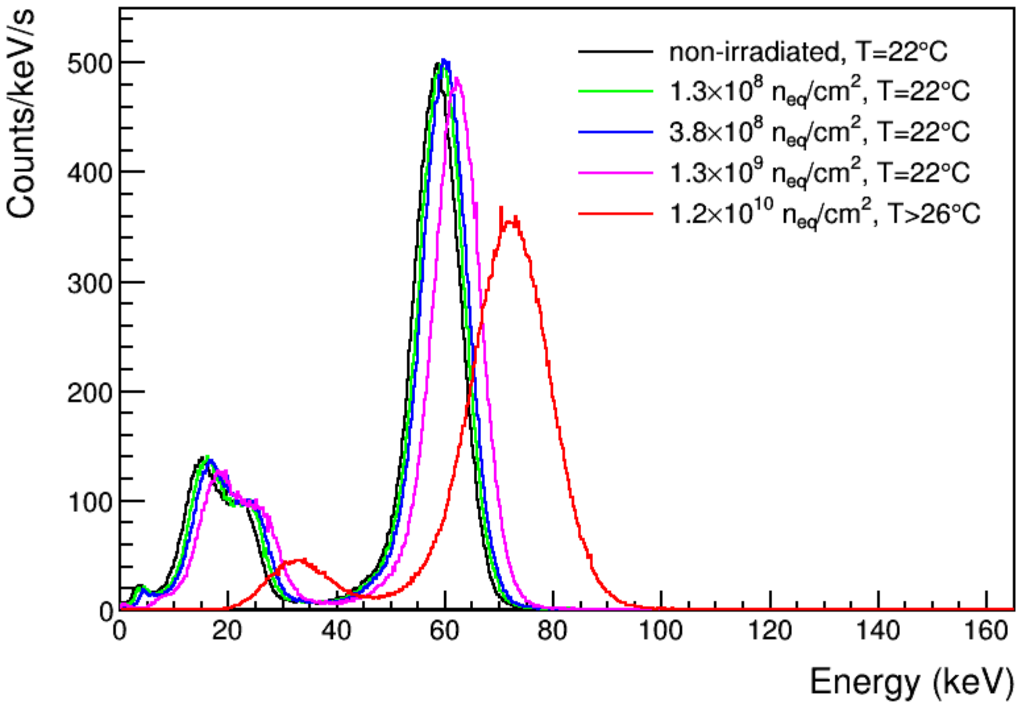


Calibrated spectra

32 keV from ^{137}Cs



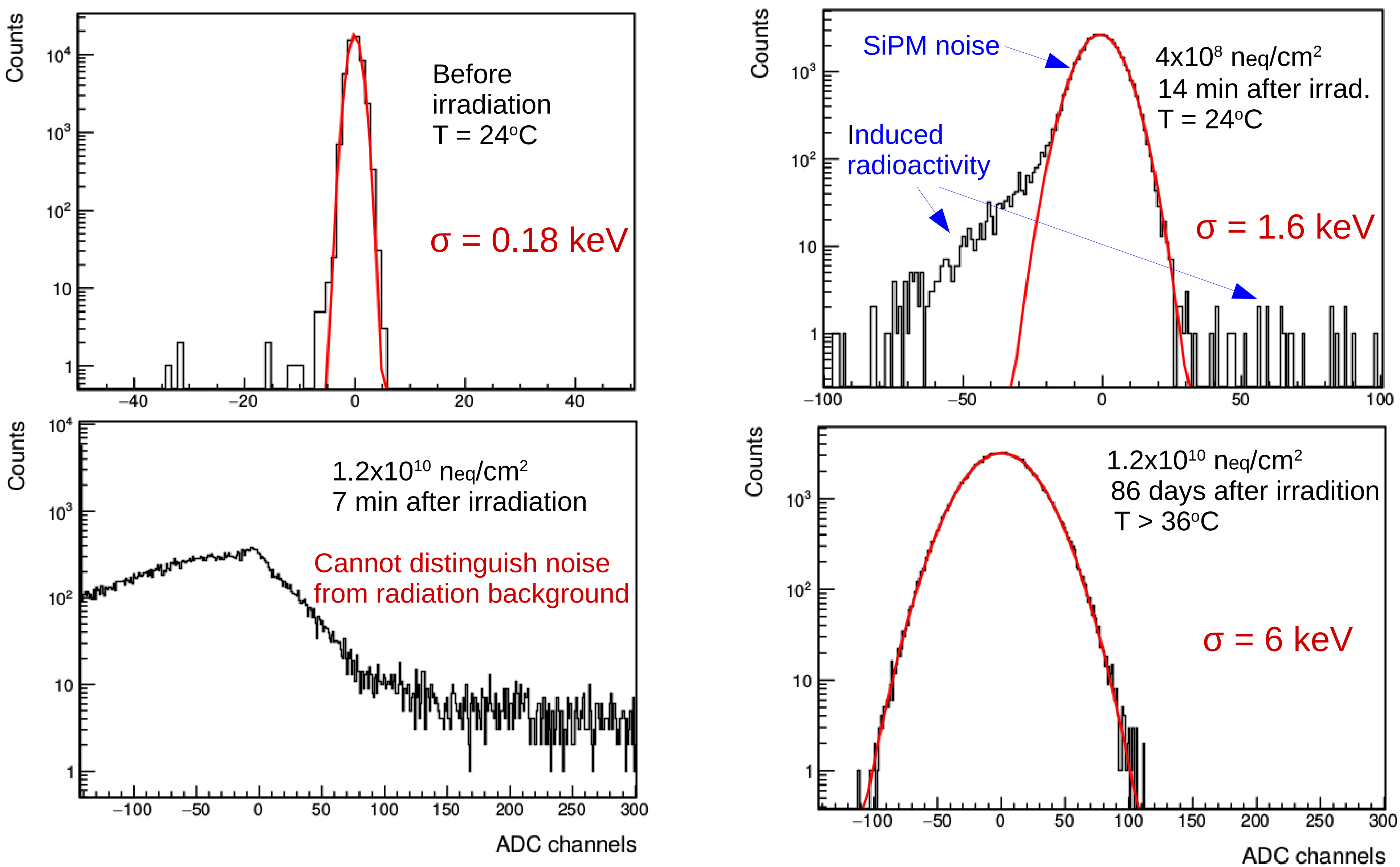
59.5 keV from ^{241}Am



32 keV X-rays are still efficiently detected after 1.2×10^{10} neq/cm^2.

As the fluence increases, the peaks systematically shift upward and the detector non-linearity becomes larger (readout effect)

Noise of a 2x2 SiPM array (+CeBr3)

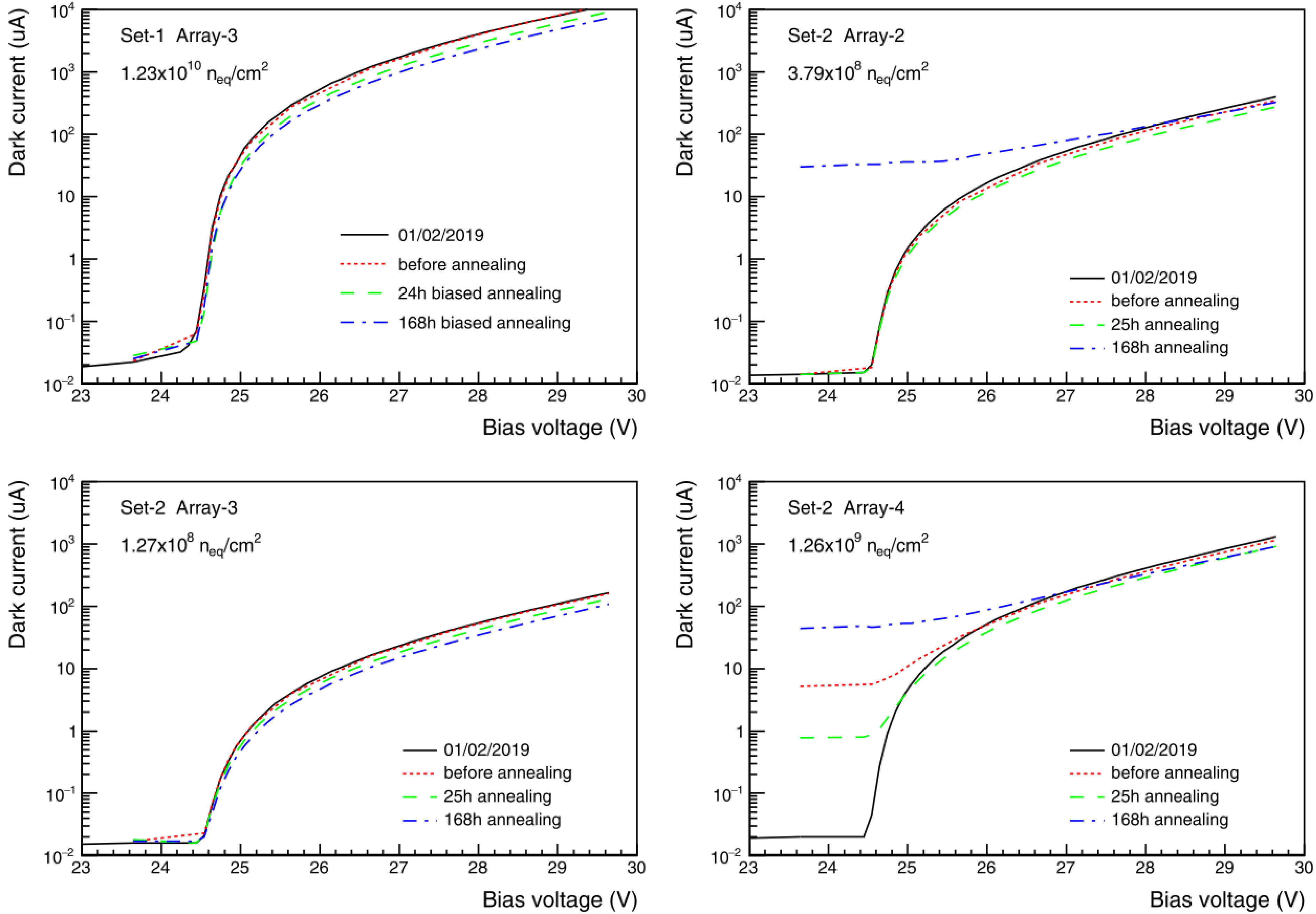


SiPM noise summary

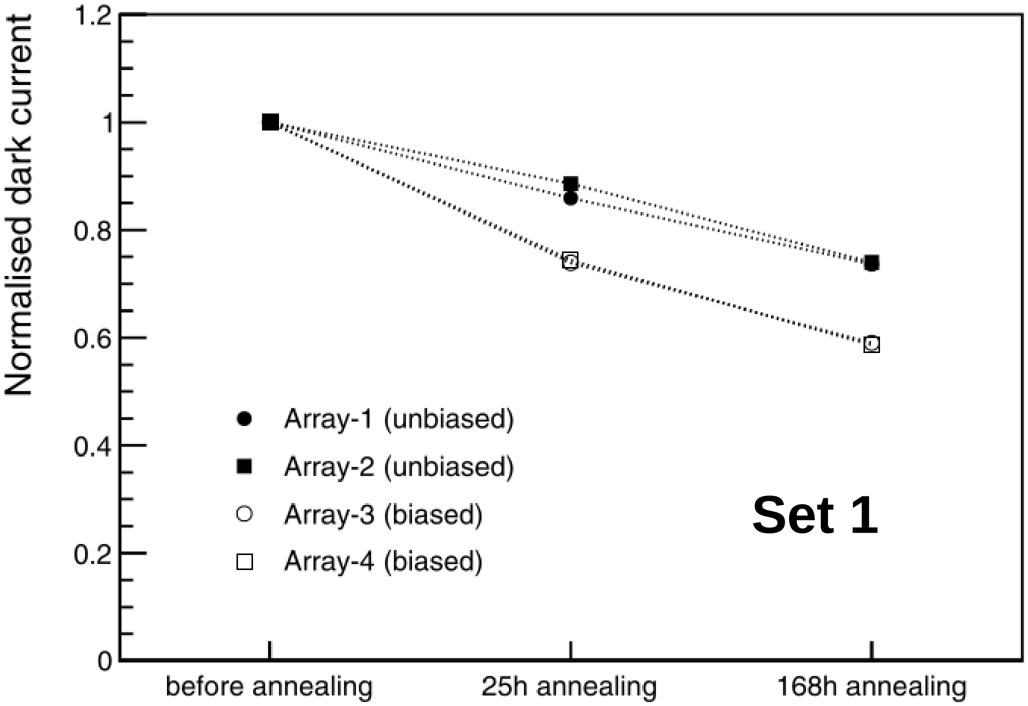
SiPM set	Fluence (n_{eq}/cm^2)	Time after irradiation	Temp (^0C)	σ_{noise} (keV)	
				4 SiPMs	16 SiPMs
1	0	-	24	0.18	0.40
1	1.3×10^8	28 min	24	1.09	2.3
1	4.0×10^8	14 min	24	1.6	3.6
1	1.2×10^{10}	86 days	>36	6.0	13.1
2	0	-	20	0.17	-
2	1.3×10^8	89 days	20	0.47	-
2	3.8×10^8	89 days	20	0.74	-
2	1.3×10^9	89 days	20	1.24	-

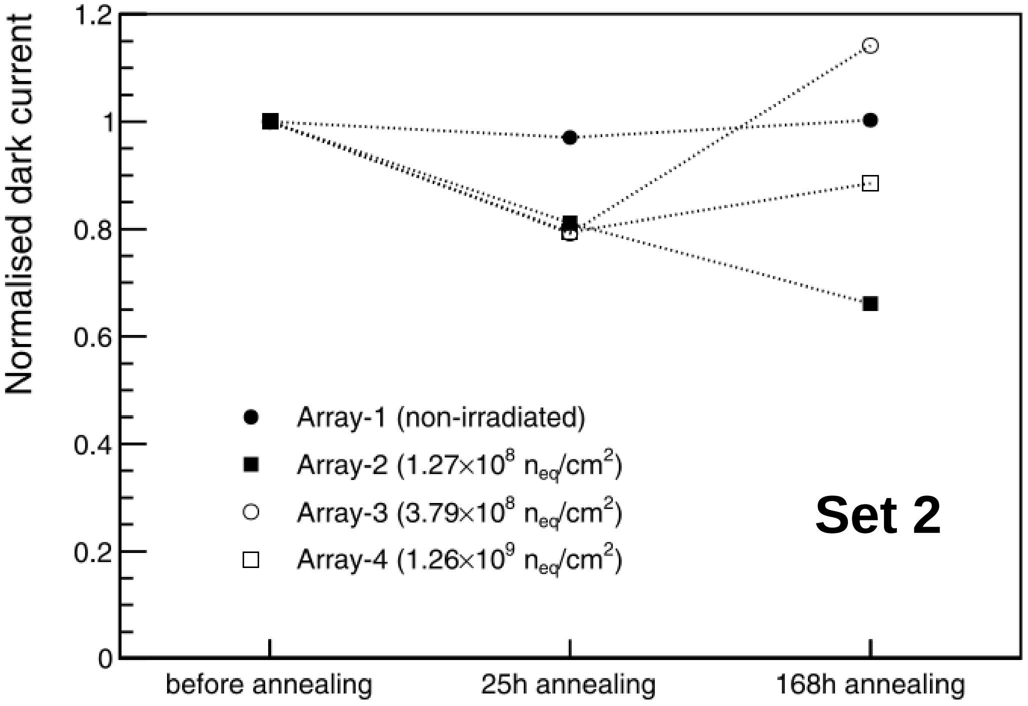
The noise of 16 SiPMs was larger by a factor of 2 than the noise of 4 SiPMs.

Annealing at 79ºC



Annealing at 79°C

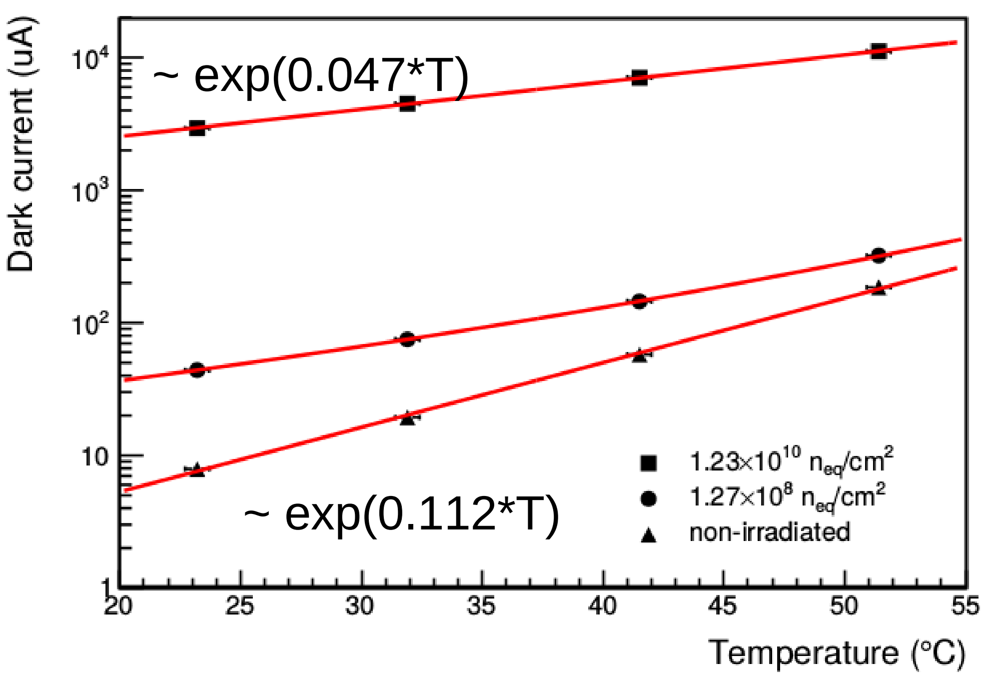


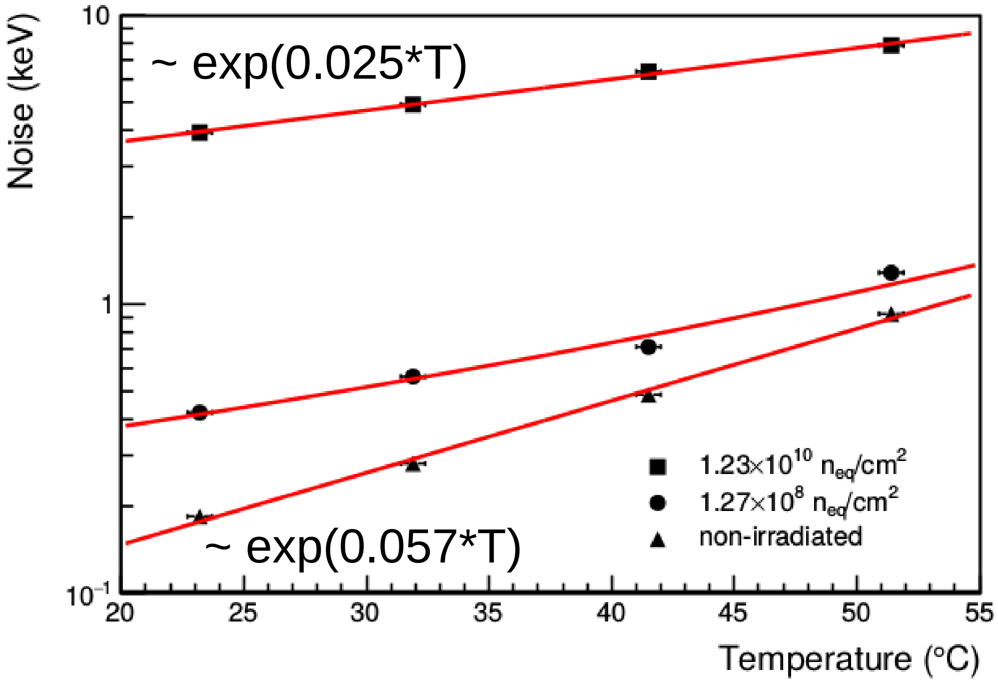


- Additional recovery at high temperature, partcularly for biased SiPMs
- Some SiPMs appeared to be damaged and showed high leakage (non-amplified) current
- No further change in 3 years after the annealing

Temperature effect at a constant overvoltage of 3.65 V

2x2 SiPM array 5 months after irradiation and after 168-hour annealing at 79 °C





Conclusions

- Large SiPM current after proton irradiation in space may pose problems for long running/high altitude missions in terms of thermal control and power consumption: 3.4 mA/cm^2 or 100 mW/cm^2 at 3.65 V overvoltage and room temperature after 6 years in a 550 km/40º orbit (1.2 x 10^{10} n_{eq}/cm^2, taking into account partial recovery from radiation damage).
- The SiPM current can be reduced by using a lower overvoltage, cooling and shielding.
- Increased SiPM noise can be a problem for detection of low energy gamma rays, particularly for detectors using low light yield or slow scintillators (about 40 keV with CeBr3 and 16 SiPMs after 6 years in a 550 km/40º orbit).
- No significant problem for the GMOD/EIRSAT-1 (1 year in ISS orbit) :
  - 40 uA per SiPM channel -> OK for SIPHRA;
  - 20 mW total power for 16 SiPMs;
  - σ_{noise} = 2 keV for 16 SiPMs;
  - Trigger threshold will need to be adjusted depending on the SiPM noise.
- Irradiation rate effect? NIEL scaling for 1-500 MeV protons?

Backup slides

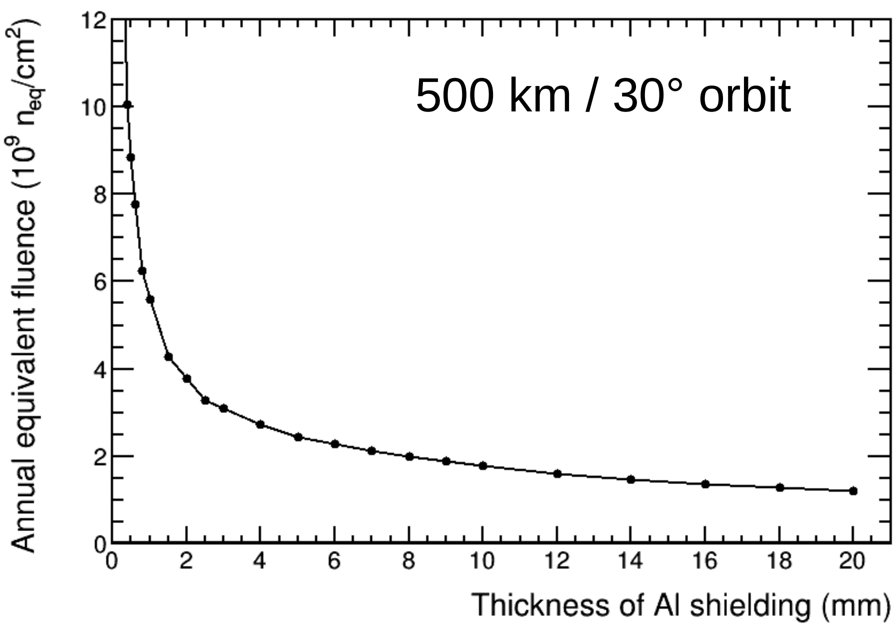
Annual proton fluence in LEO

In typical low Earth orbits, displacement damage is mainly done by trapped protons during SAA passages.

Annual fluence estimates using the AP9 model in SPENVIS

(3 mm aluminium shielding around SiPMs)

Orbit inclination	Annual equiv. fluence (n_{eq}/cm^2)		
	400 km	500 km	600 km
5°	1.4×10^7	9.8×10^7	5.3×10^8
30°	9.6×10^8	3.1×10^9	7.6×10^9
50°	6.8×10^8	2.0×10^9	4.6×10^9
98°(*)	4.2×10^8	1.3×10^9	3.0×10^9



* Solar proton events will make an additional contribution for polar orbits and in some cases may significantly increase the annual fluence.

SIPHRA shaper and T&H