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Radiation damage study of SensL J-Series SiPMs

Alexey Uliyanov[1], David Murphy[1], Joseph Mangan[1], Viyas Gupta[2], Wojciech Hajdas[3], Daithi de Faoite[1], Brian Shortt[2], Lorraine Hanlon[1], Sheila McBreen[1]

[1] *University College Dublin*
[2] *European Space Agency*
[3] *Paul Scherrer Institute*

1st June 2020 – GRB Nanosats meeting

GMOD detector on board EIRSAT-1

- EIRSAT-1 is a 2U CubeSat being developed by UCD students as part of ESA's *Fly Your Satellite!* (FYS) programme.

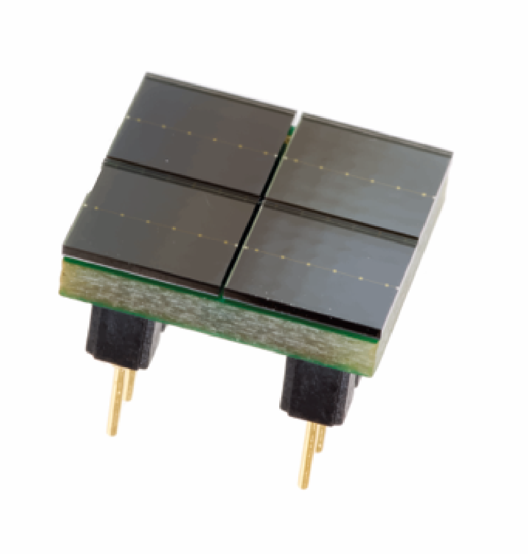
- Gamma-ray Module (GMOD) is a small GRB detector on board EIRSAT-1:
  - 25 x 25 x 40 mm^3 $CeBr_3$ scintillator
  - custom-built 4 x 4 array of J-Series SiPMs (MicroFJ-60035-TSV: 6 mm, 35 um pixel size)
  - SiPM readout ASIC by IDEAS (SIPHRA)

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 (PIF) in the Paul Scherrer Institute (PSI), a facility constructed specifically for testing spacecraft components.

Irradiated SiPMs



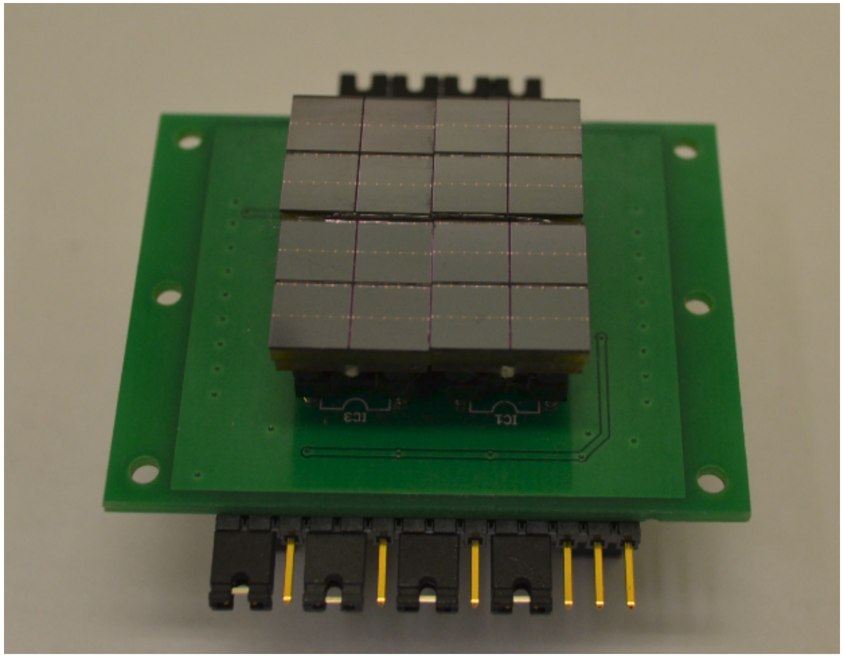
SensL ARRAYJ-60035-4P-PCB composed of four MicroFJ-60035-TSV

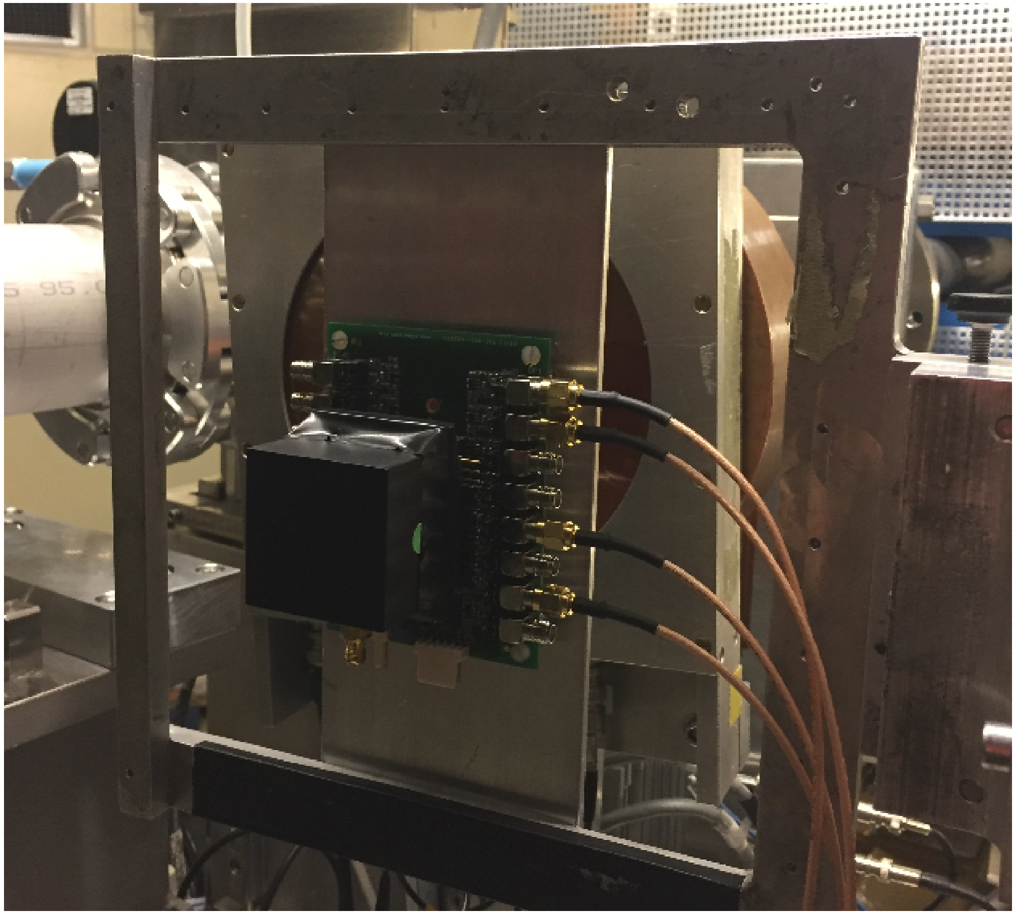
16 x MicroFJ-60035-TSV will be used in the GMOD

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



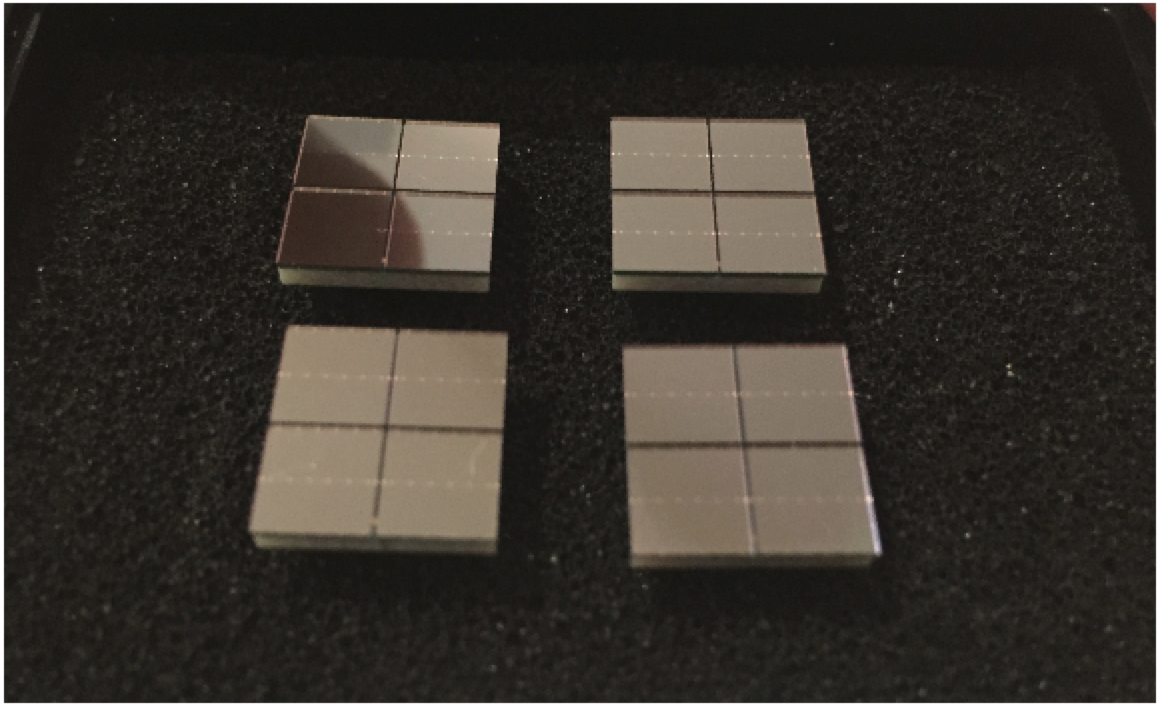


- Four 2x2 arrays were combined into one 16-SiPM array using an adaptor board.

- 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).

- The SiPMs were unbiased during the irradiation.

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)

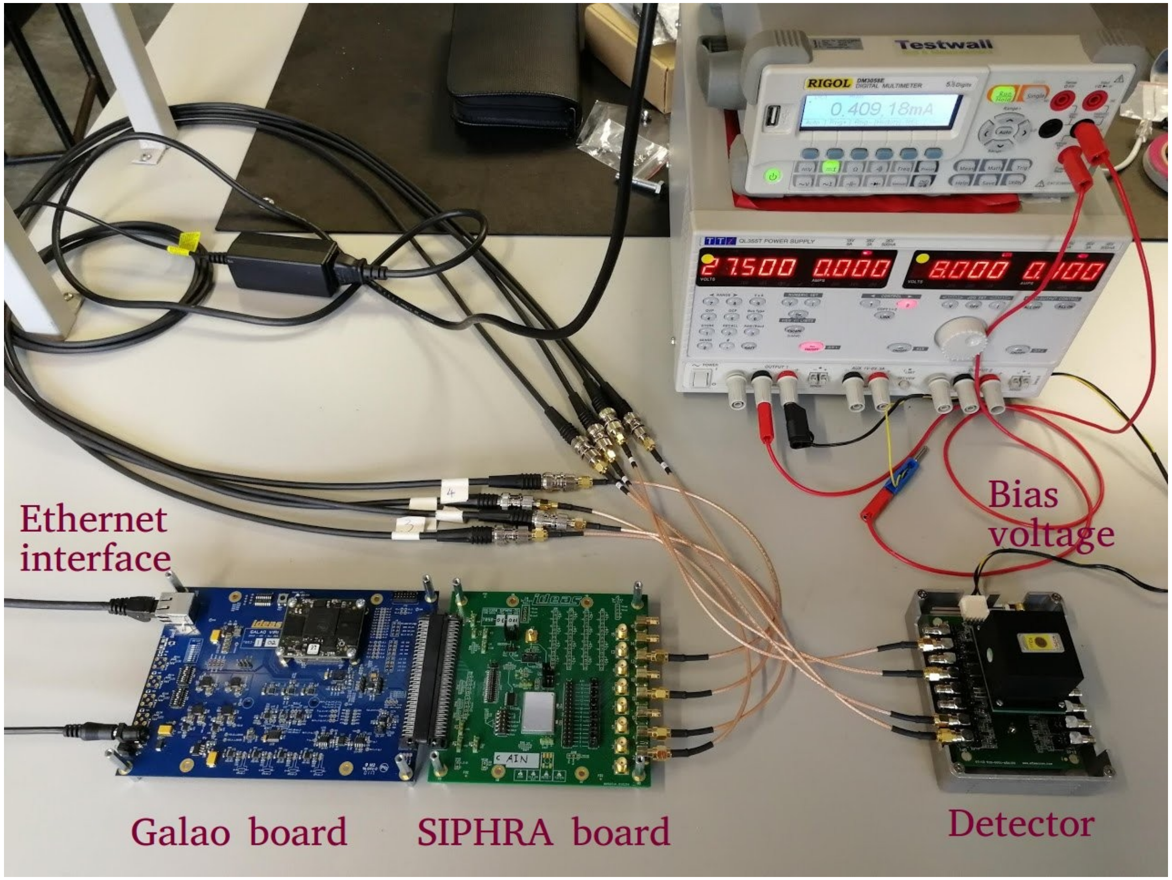
Exposure number	**Flux ($p/cm^2/s$)**	**Duration (s)**	**Cumulative fluence** (p/cm^2)	(n_{eq}/cm^2)	**Equiv. SiPM exposure for EIRSAT-1/GMOD**
1	2.56×10^6	40	1×10^8	1.3×10^8	4 months in ISS orbit
2	2.54×10^4	79	3×10^8	4.0×10^8	1 year in ISS orbit
3	2.66×10^7	339	9.3×10^9	1.2×10^{10}	6 years in 550km/40° orbit

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

SiPM array	**Flux ($p/cm^2/s$)**	**Duration (s)**	**Fluence** (p/cm^2)	(n_{eq}/cm^2)	**Equiv. SiPM exposure for EIRSAT-1/GMOD**
1	0	0	0	0	0
2	2.89×10^6	35	1×10^8	1.3×10^8	4 months in ISS orbit
3	2.87×10^6	105	3×10^8	3.8×10^8	1 year in ISS orbit
4	2.89×10^6	347	1×10^9	1.3×10^9	3 years in ISS orbit

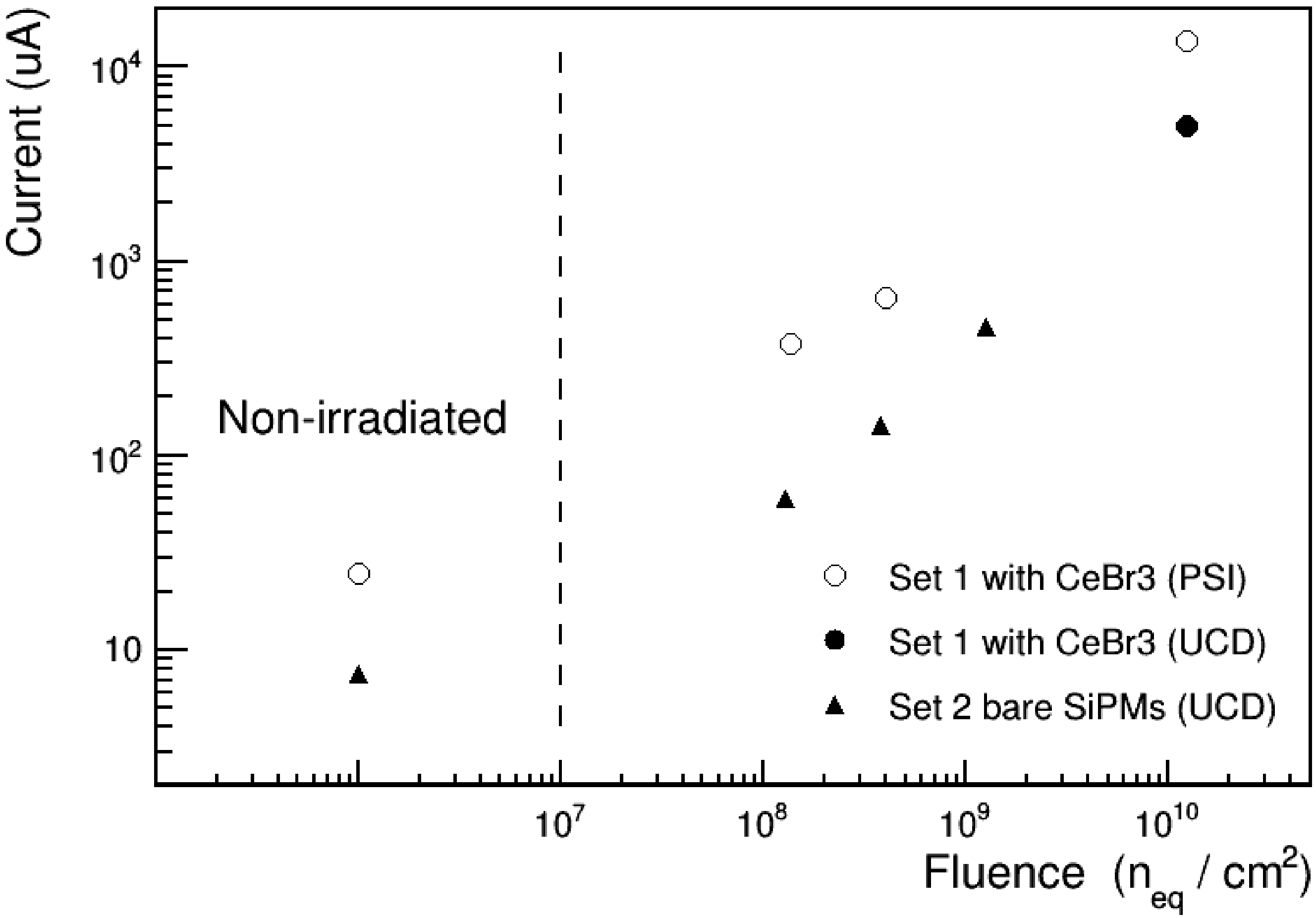
Measurement setup

- 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)

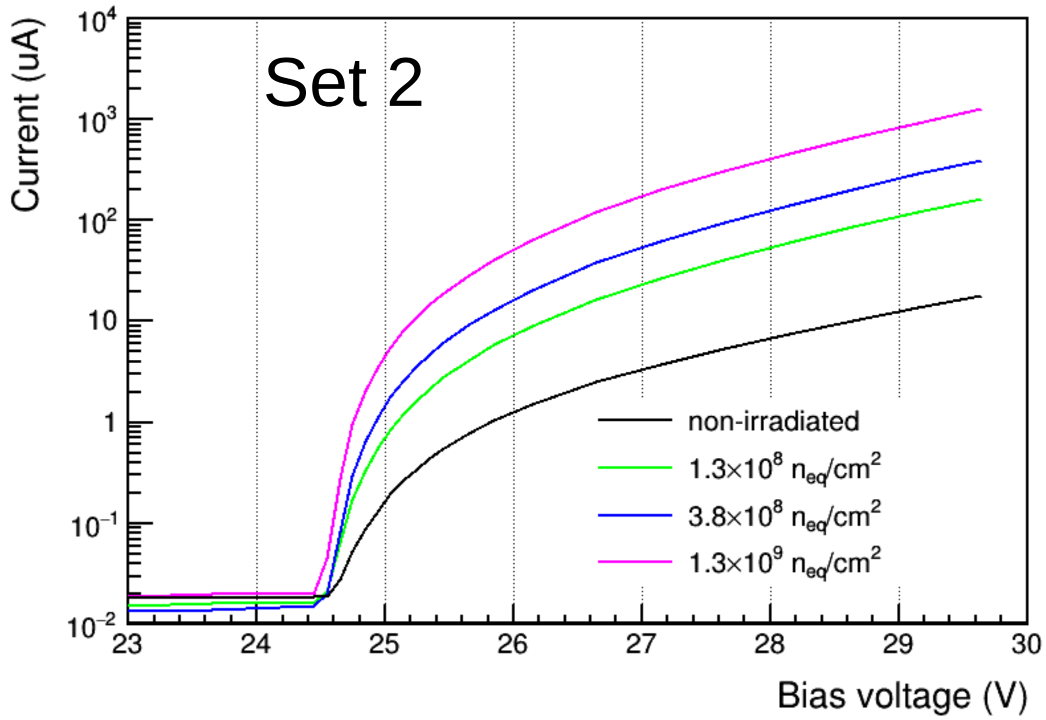


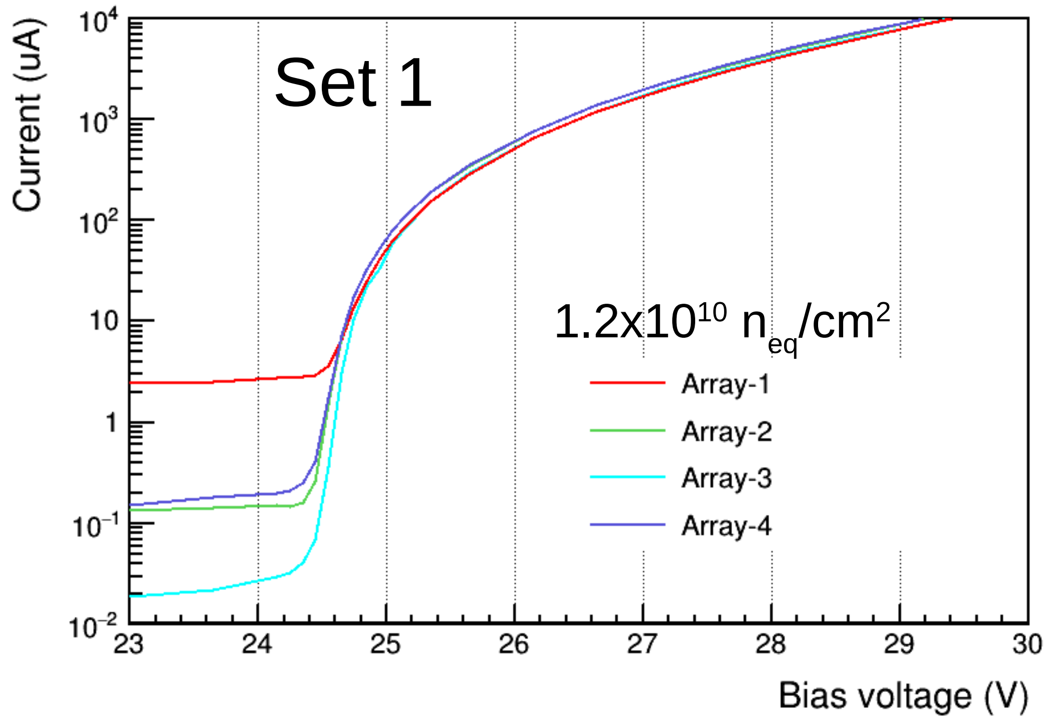
- PSI: 10-20 min after exposure, T = 24^{o}C.
- UCD: 86-89 days after exposure, T = 21^{o}C.
- Self-heating after 1.2x10^{10} n_{eq}/cm^2 (current increasing from 5 to 10 mA in 2 hours in UCD measurements, adapter PCB temperature increasing from 21^{o}C to 36^{o}C)

In UCD measurements the current reduced by a factor of 3 which indicates partial recovery from radiation damage (but also due to the 3 ^{o}C lower temperature).

Set 1 vs Set 2 difference for the non-irradiated SiPMs may be related to the age of the Set 1 SiPMs or possible damage they received in earlier studies.

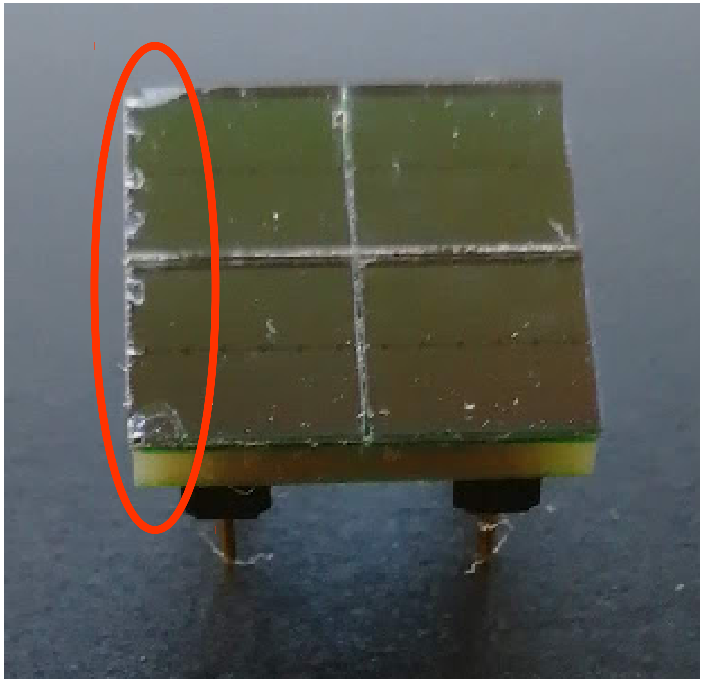
Current-voltage curves of 2x2 SiPM arrays, 3 months after irradiation, T=21°C

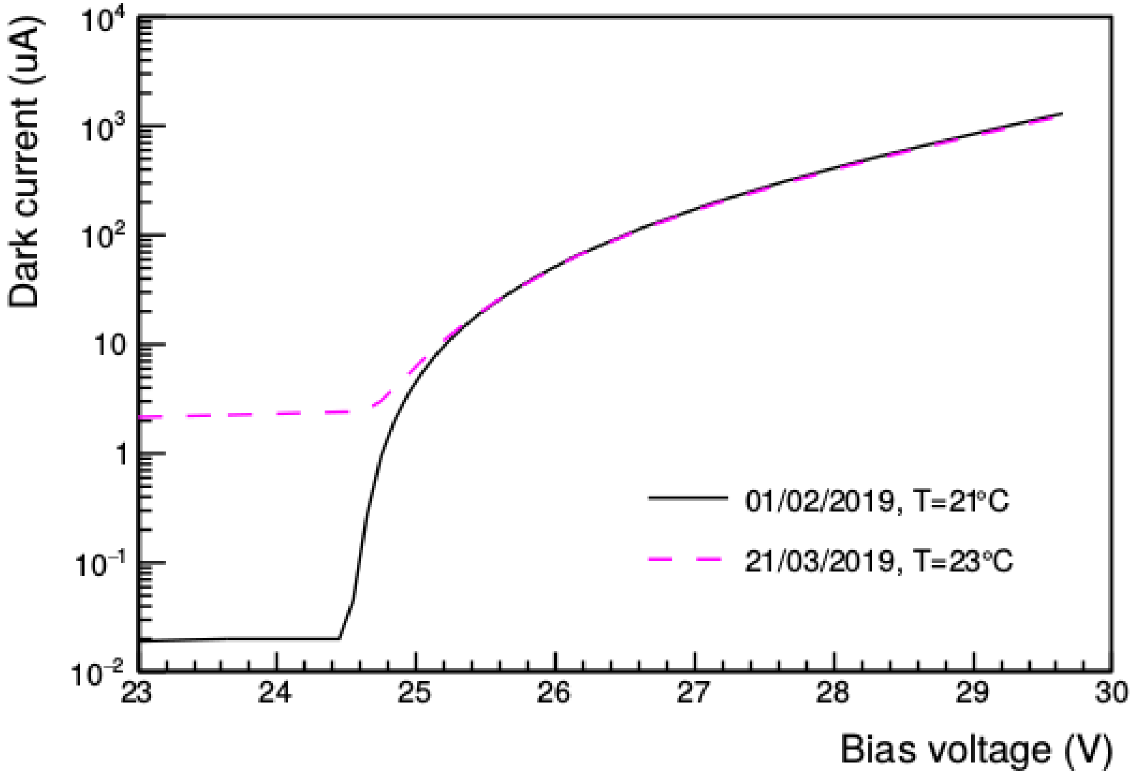




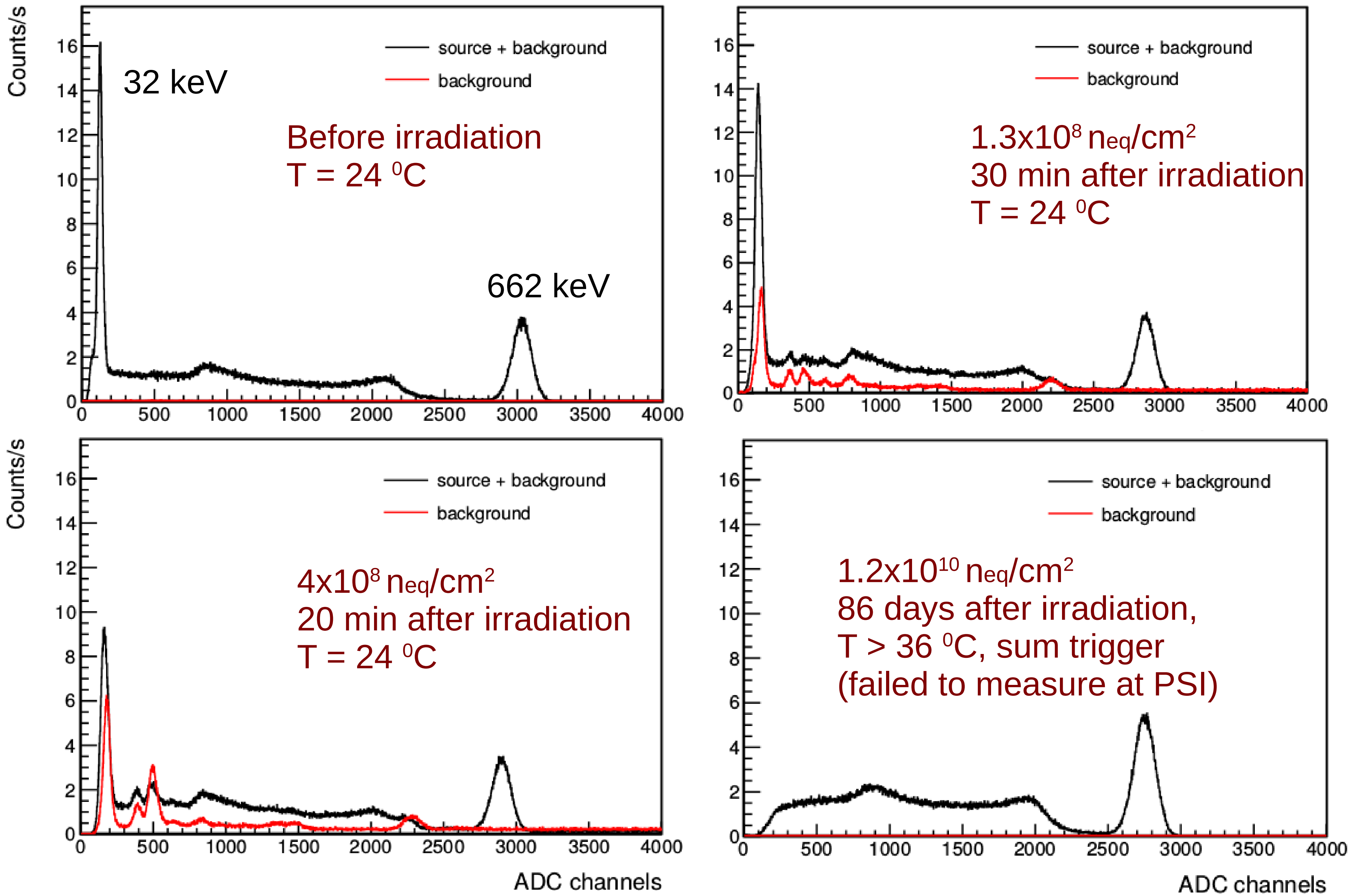
- Includes 10-15 nA leakage current through the adaptor PCB.
- V_{br} = 24.5 ± 0.1 V for all SiPMs.
- Large leakage current below V_{br} for some SiPMs in Set 1 (mechanical damage?)

Accidental mechanical damage to Array-4 from Set 2

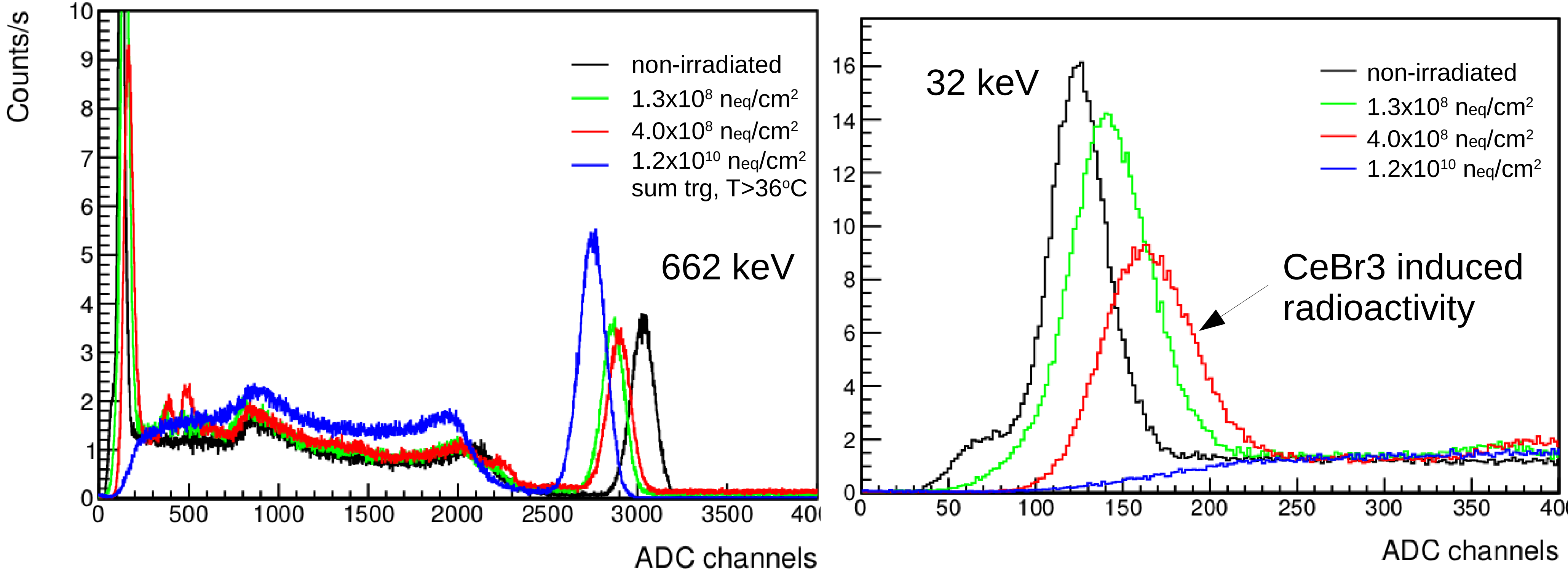




CeBr3 + 16 SiPMs (Set 1): ^{137}Cs spectra



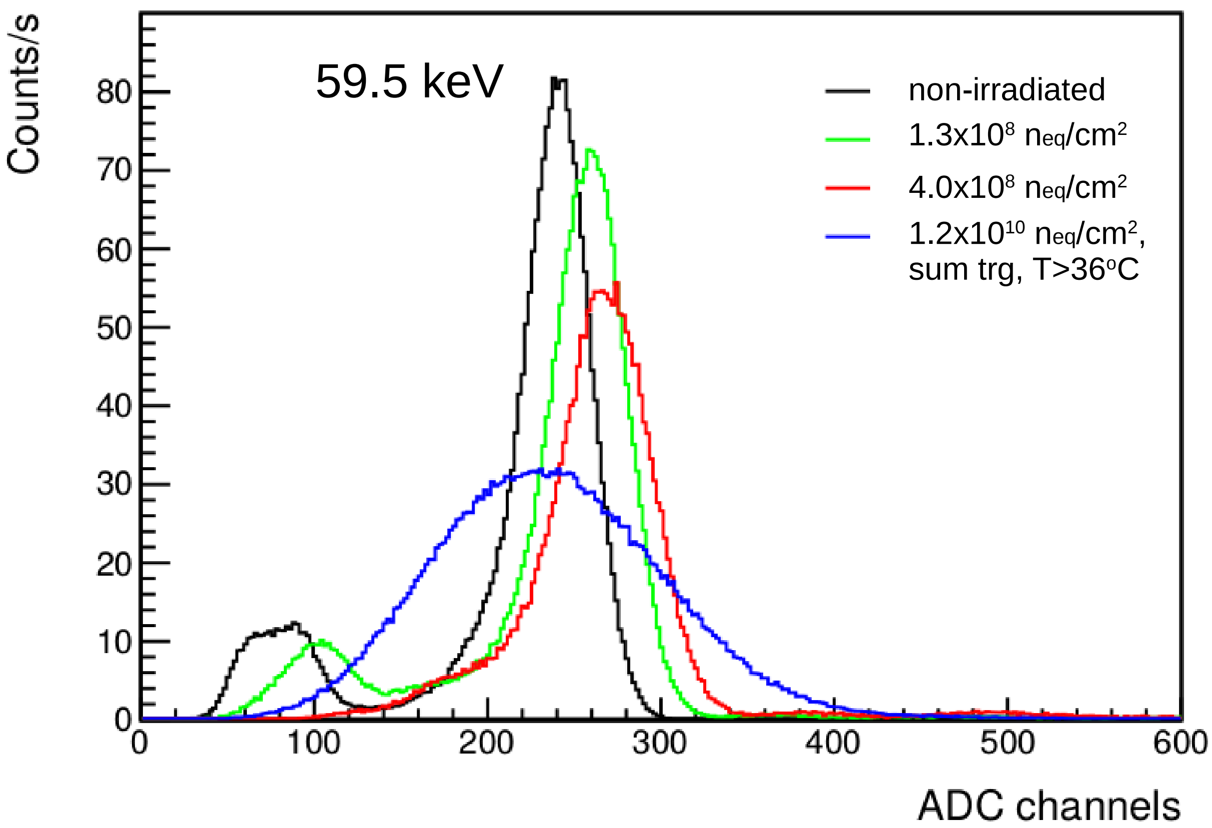
Comparison of ^{137}Cs spectra



- 9% spread in the positions of the 662 keV peak is not fully understood (effects of temperature, trigger threshold, radiation damage)

- The low energy cut-off is defined by the trigger threshold which was increased after each exposure to suppress noise events. The 32 keV line was completely suppressed by the trigger threshold after 1.2×10^{10} n_{eq}/cm^2.

Comparison of ^{241}Am spectra

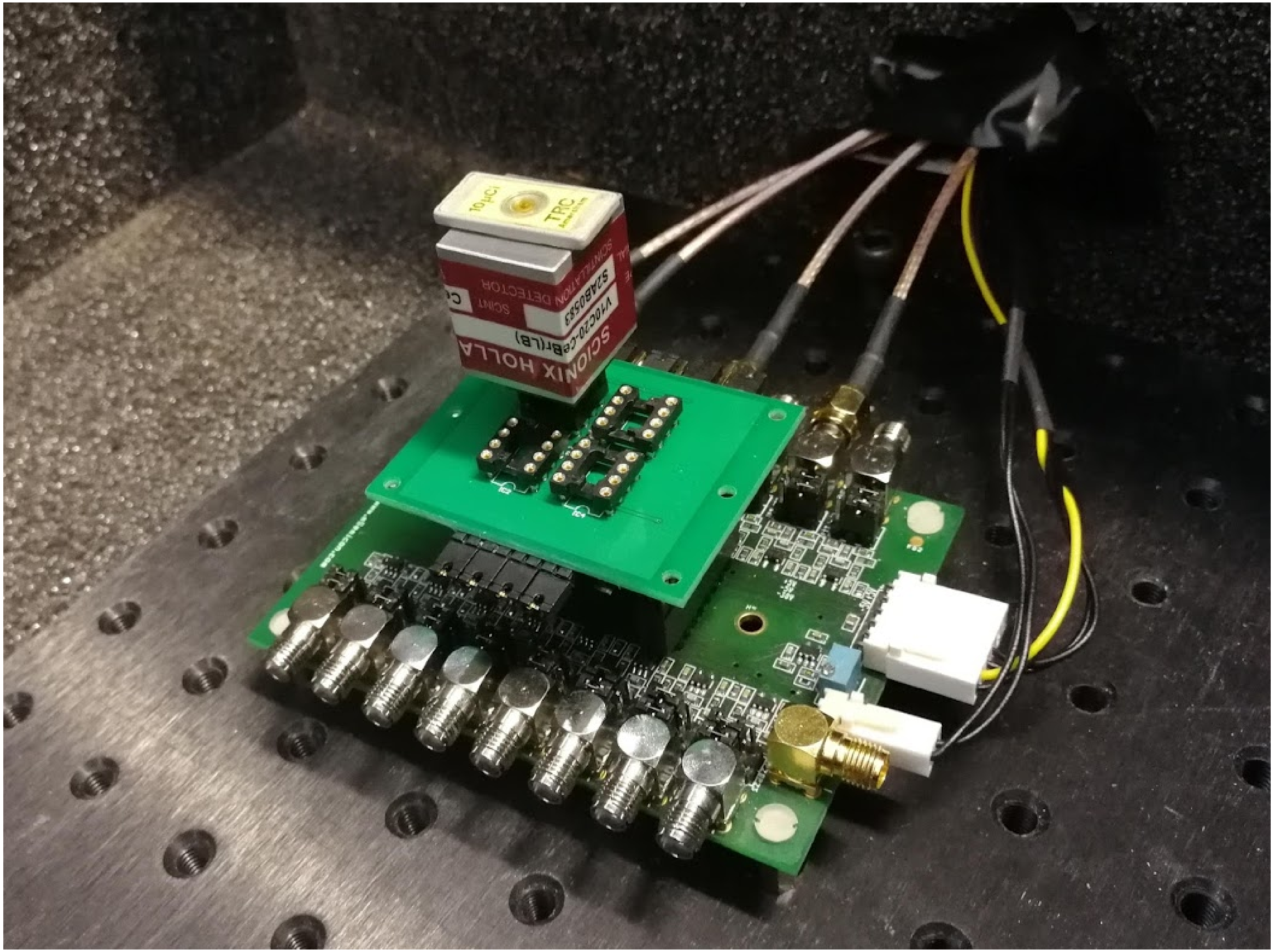


SIPHRA samples the SiPM signal after a fixed delay following the trigger signal. Depending on the trigger threshold the signal may be measured before or past the peak of the pulse, which makes the measured signal sensitive to the trigger threshold.

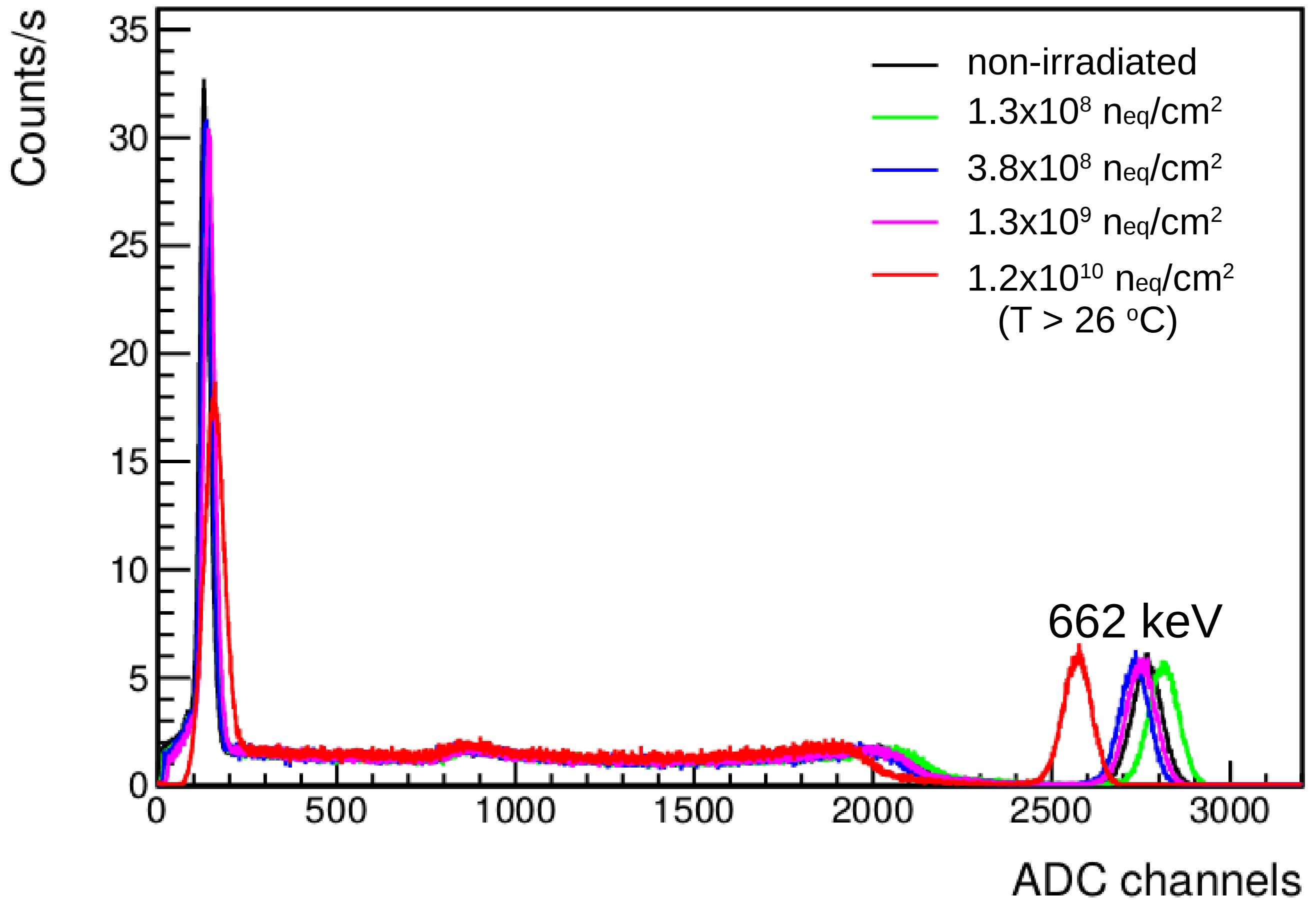
The 59.5 keV peak is shifted up by 12% after $4x10^8$ n_{eq}/cm^2 due to a higher trigger threshold and delayed signal sampling.

The peak is shifted down after $1.2x10^{10}$ n_{eq}/cm^2 due to triggering in the sum channel.

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



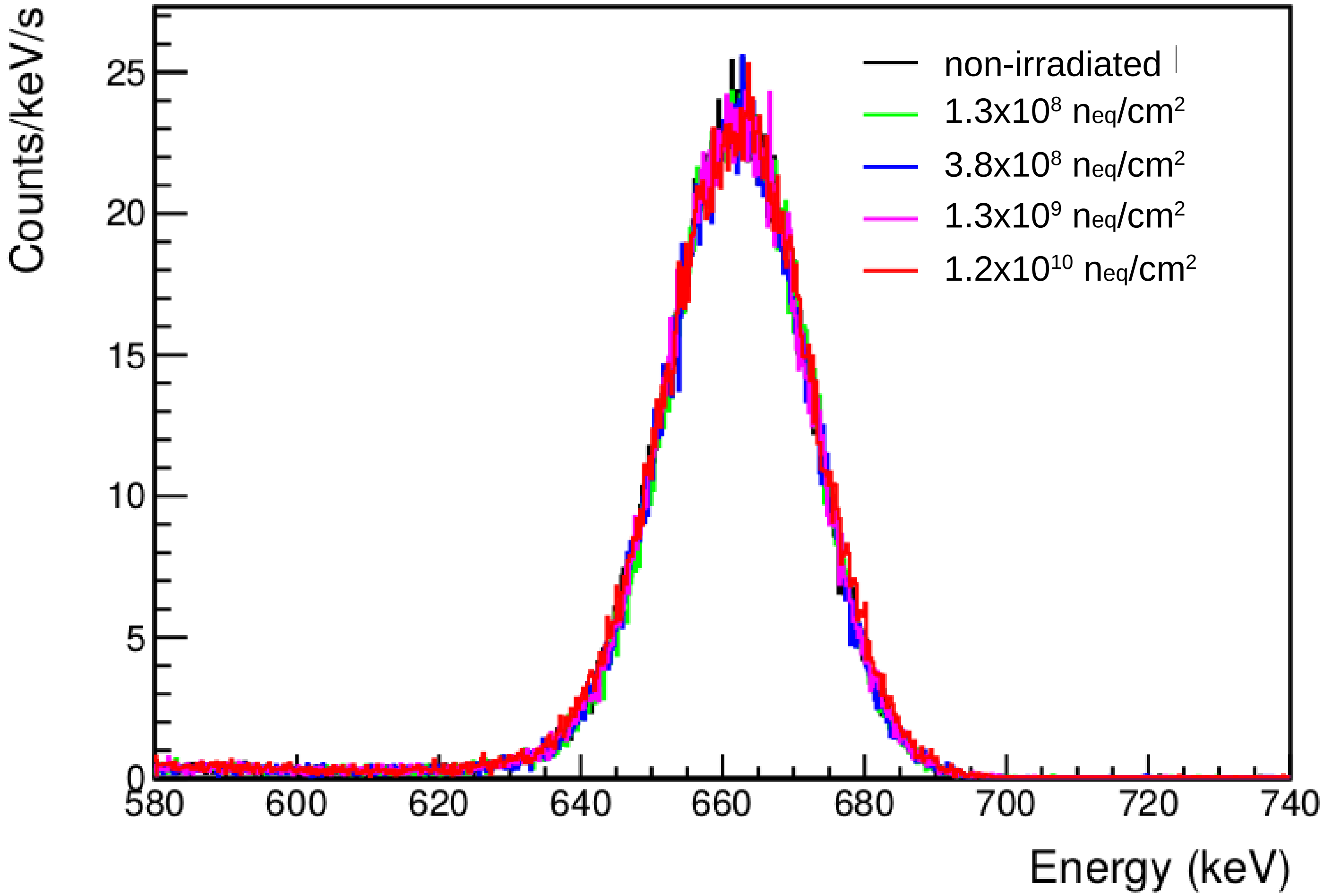
Comparison of ^{137}Cs spectra (4 SiPMs)



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.

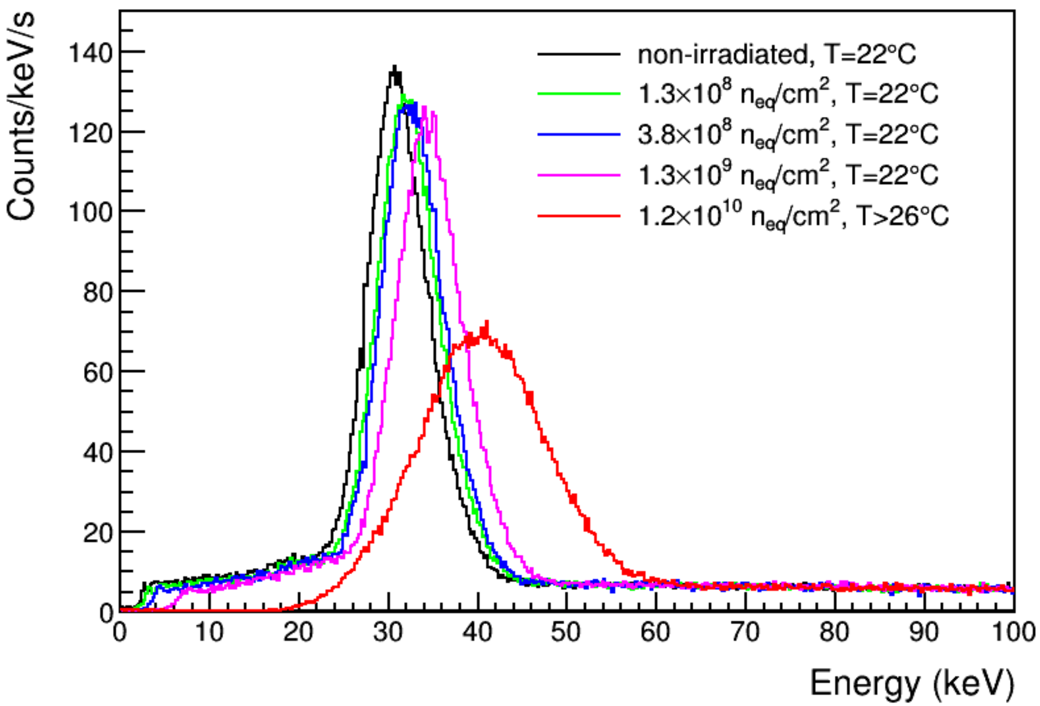
Better cooling in this configuration: the single channel trigger was used for all SiPM arrays including the 2x2 array irradiated to 1.2×10^{10} n_{eq}/cm^2.

Spectra calibrated using the 662 keV line

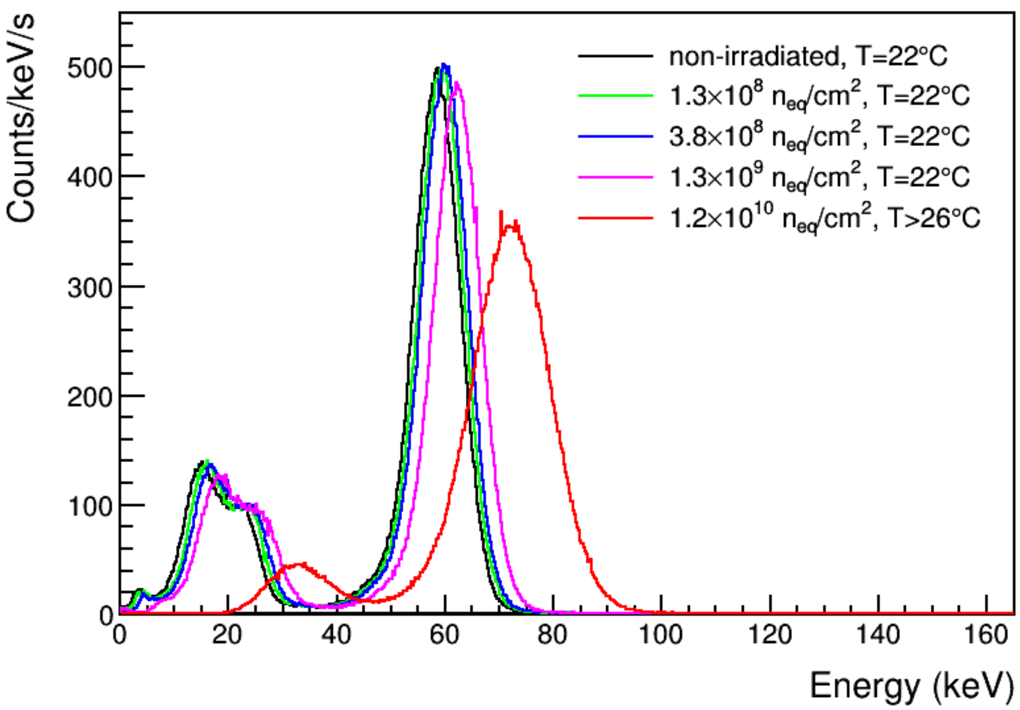


Calibrated spectra

32 keV from ^{137}Cs



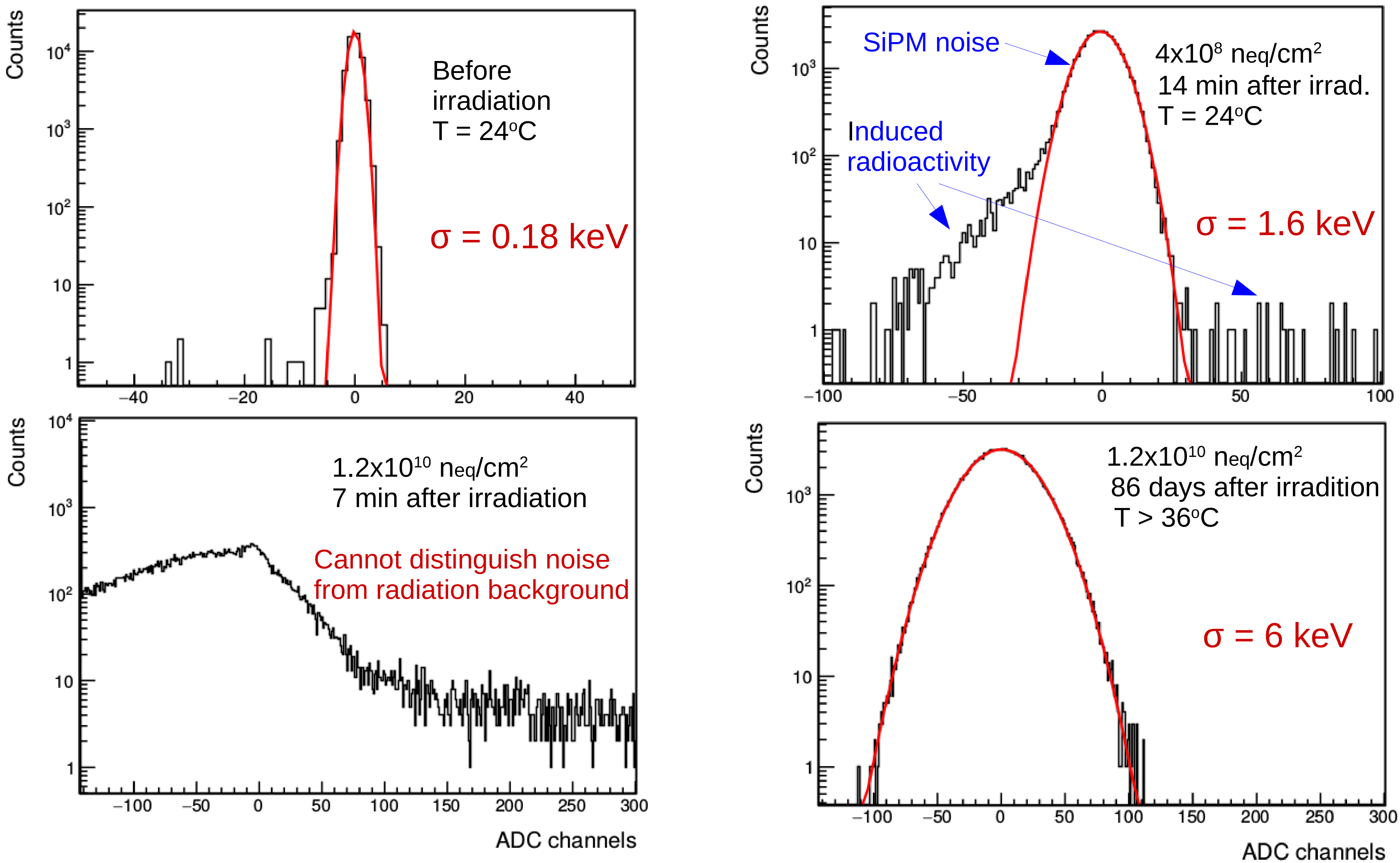
59.5 keV from ^{241}Am



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

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

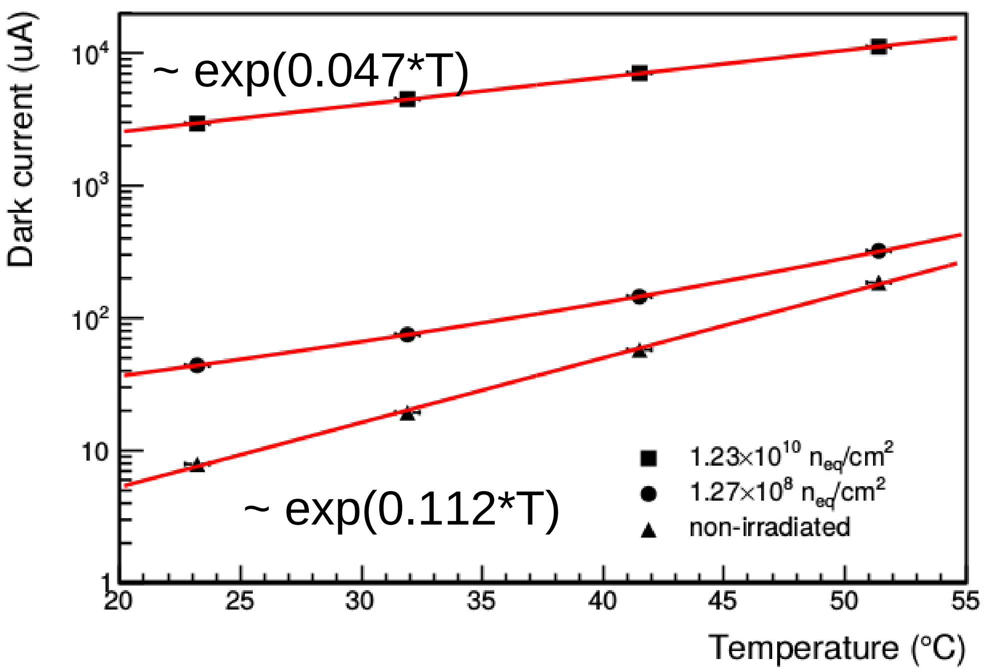
Noise of a 2x2 SiPM array (+CeBr3)

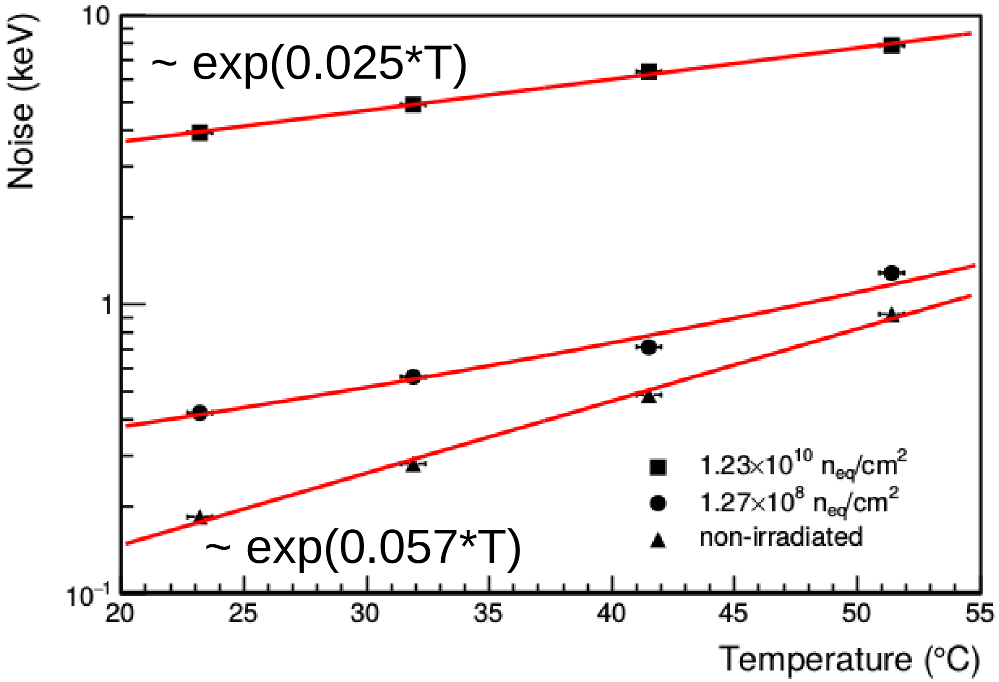


The noise of 16 SiPMs was larger approximately by a factor of 2 than the noise of 4 SiPMs.

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





For irradiated SiPMs the effect of temperature on the dark current and noise is much weaker

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/40^o 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/40^o 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;
  - The detector energy scale may be affected in a non-linear way but precise detector calibration is not crucial for GRB detection.