Radiation damage study of silicon photomultipliers and the GIFTS project

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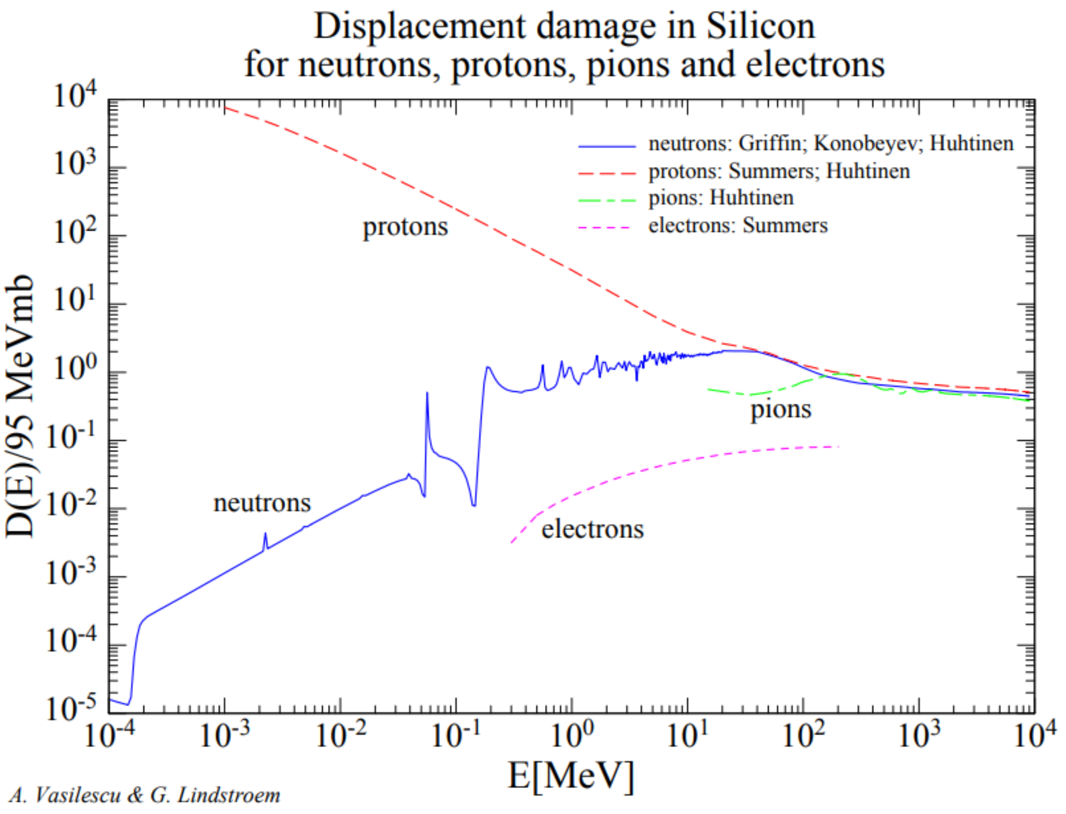
Displacement damage in SiPMs

- The dominant radiation damage mechanism for silicon photomultipliers in space environment is displacement of silicon atoms in the crystal lattice mainly caused by protons.
- These crystal deffects facilitate thermal generation of electron-hole pairs increasing the SiPM dark count rate, dark current and noise
- NIEL scaling hypothesis: displacement damage is proportional to the non-ionizing energy loss of the particle which depends on particle type and energy
- Non-ionizing dose is typically expressed as an equivalent fluence of 1 MeV neutrons



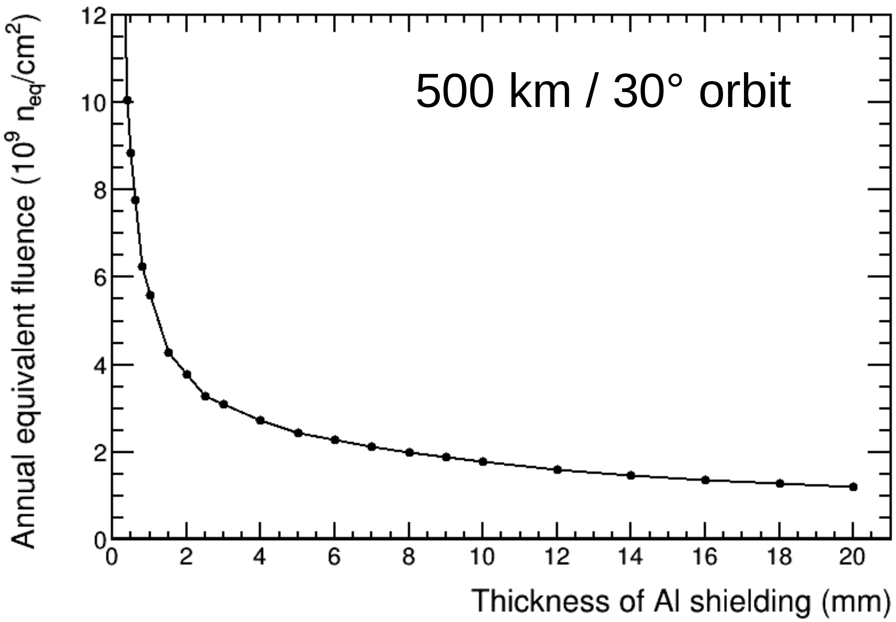
Annual proton fluence in LEO

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	5.3×10^7
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.

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SiPM radiation damage study

- The study was conducted within a radiation test campaign organised by the ESA Education Office in the framework of the Fly Your Satellite! programme.
- Irradiation was performed at the Proton Irradiation Facility (PIF) in the Paul Scherrer Institute (PSI), a facility constructed specifically for testing spacecraft components.

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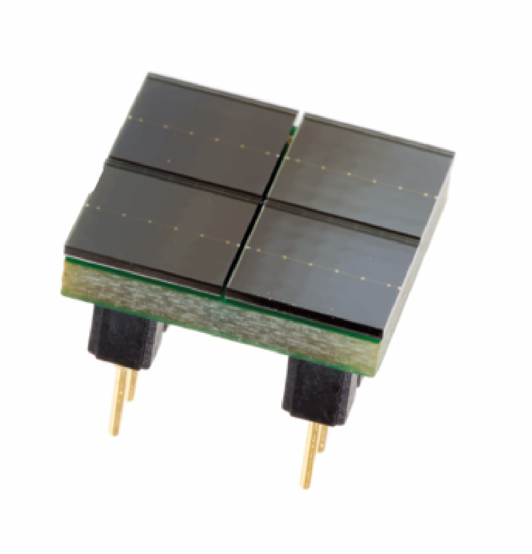
Irradiated SiPMs



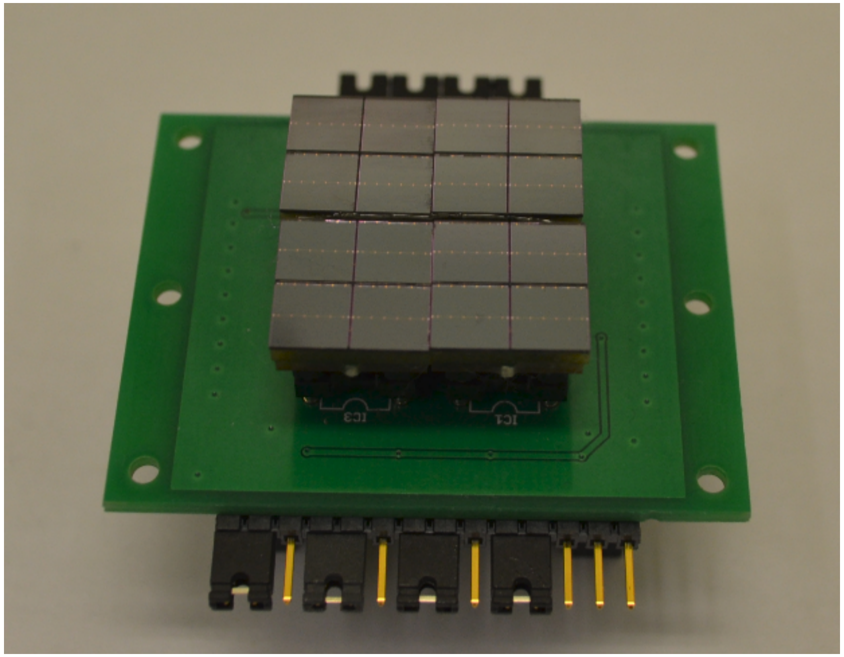
SensL / ON Semiconductor ARRAYJ-60035-4P-PCB composed of four MicroFJ-60035-TSV

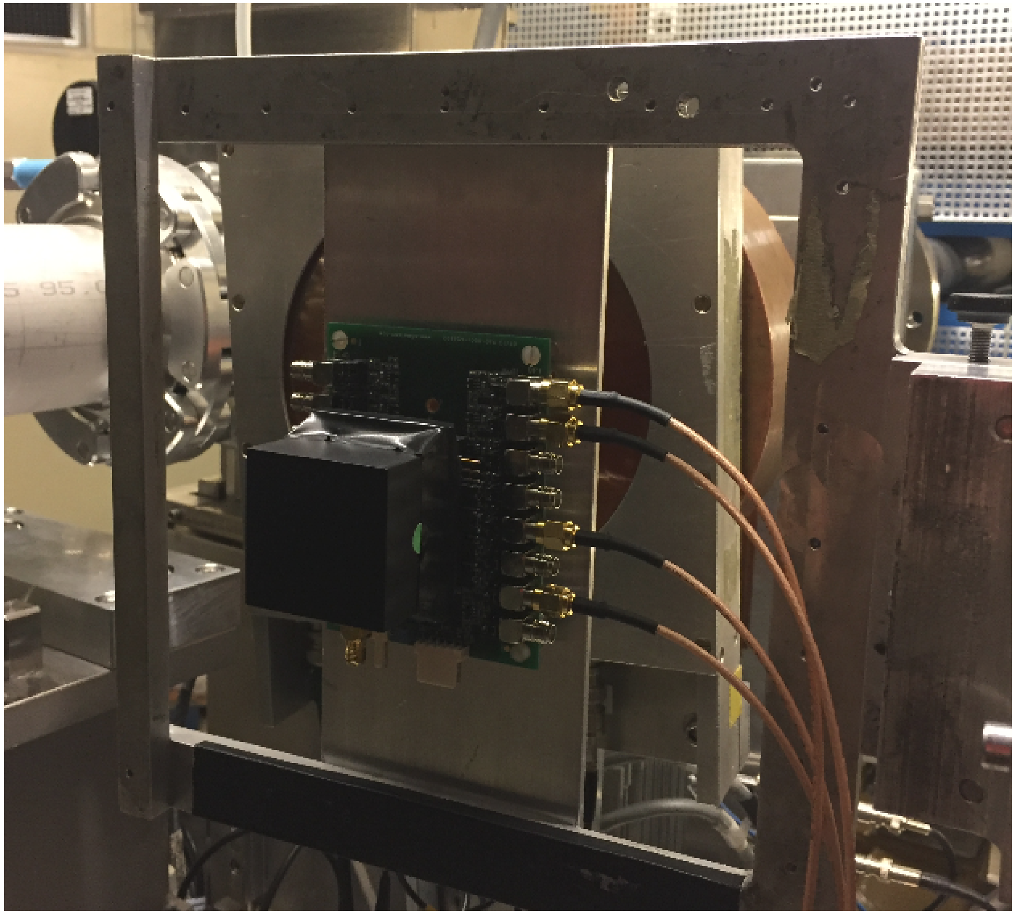
16 x MicroFJ-60035-TSV will be used in the GMOD CeBr3 detector on board EIRSAT-1

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

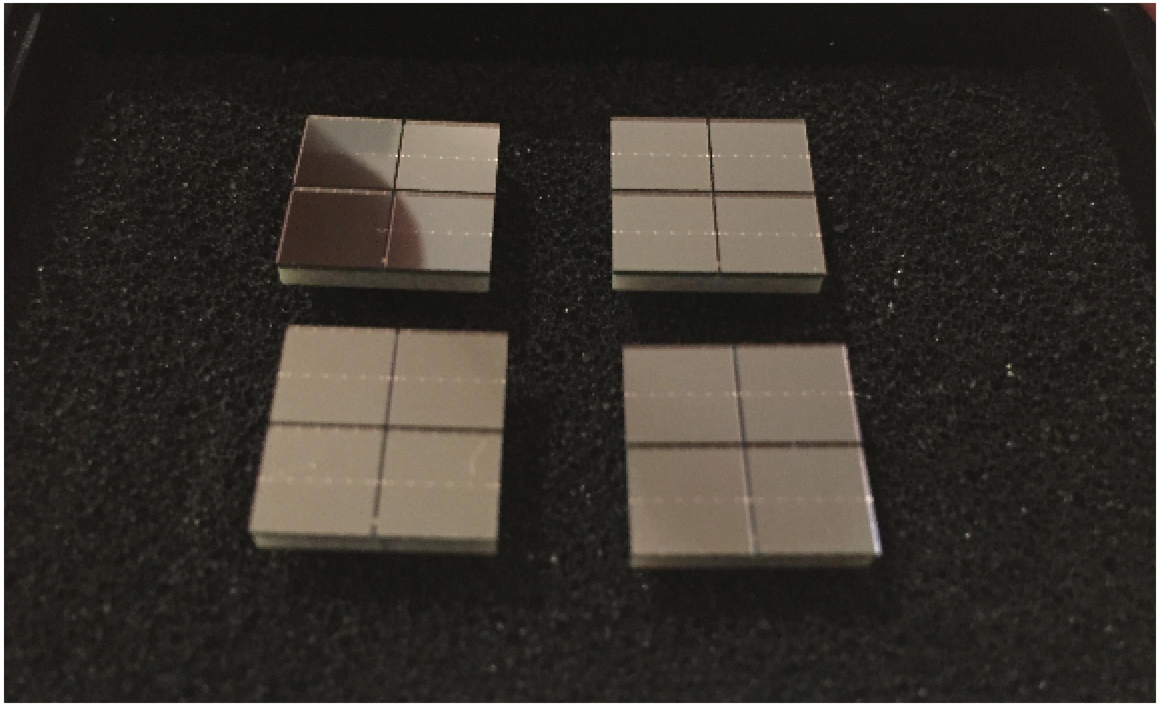




- Four 2x2 arrays were combined into one 16-SiPM array using an adaptor board.

- 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).

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)

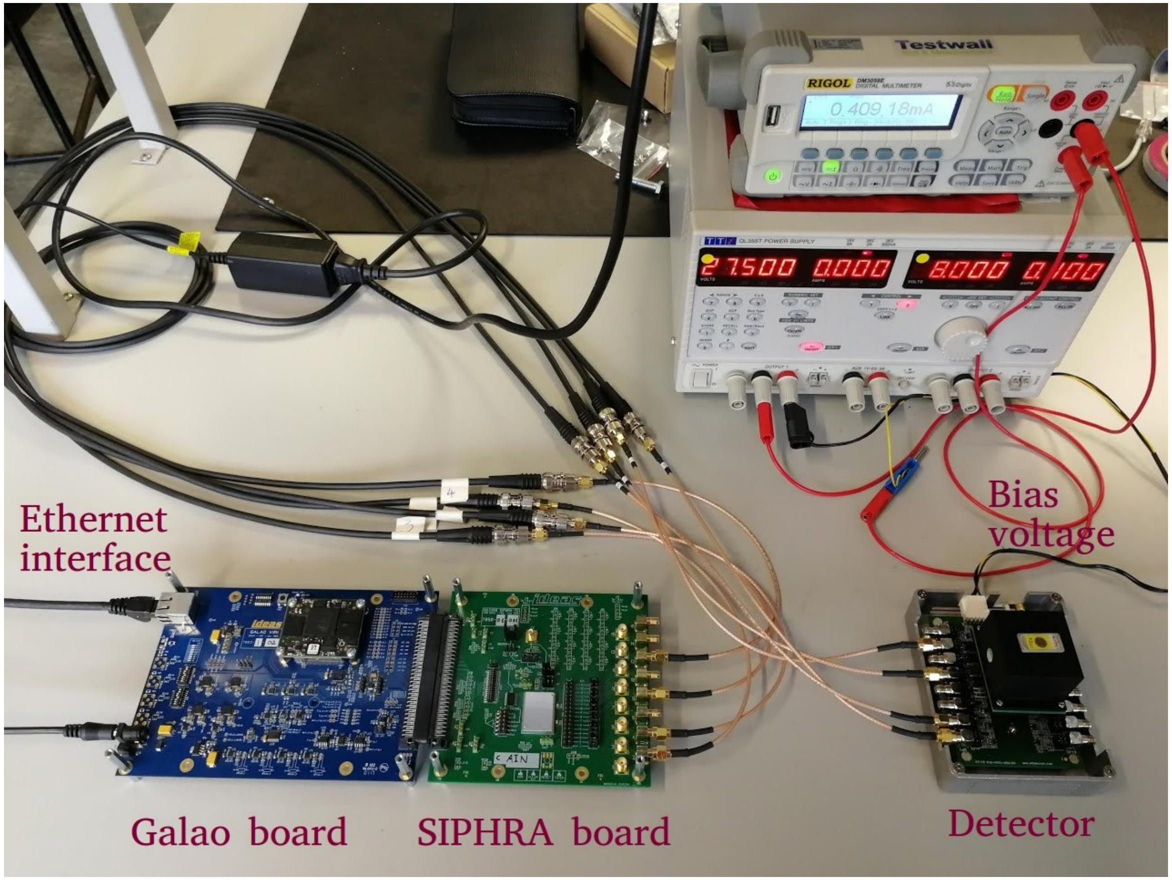
Exposure number	Flux ($p/cm^2/s$)	Duration (s)	Cumulative fluence (p/cm^2)	(n_{eq}/cm^2)	Equiv. SiPM exposure for EIRSAT-1/GMOD
1	2.56×10^6	40	1×10^8	1.3×10^8	4 months in ISS orbit
2	2.54×10^4	79	3×10^8	4.0×10^8	1 year in ISS orbit
3	2.66×10^7	339	9.3×10^9	1.2×10^{10}	6 years in 550km/40° orbit

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

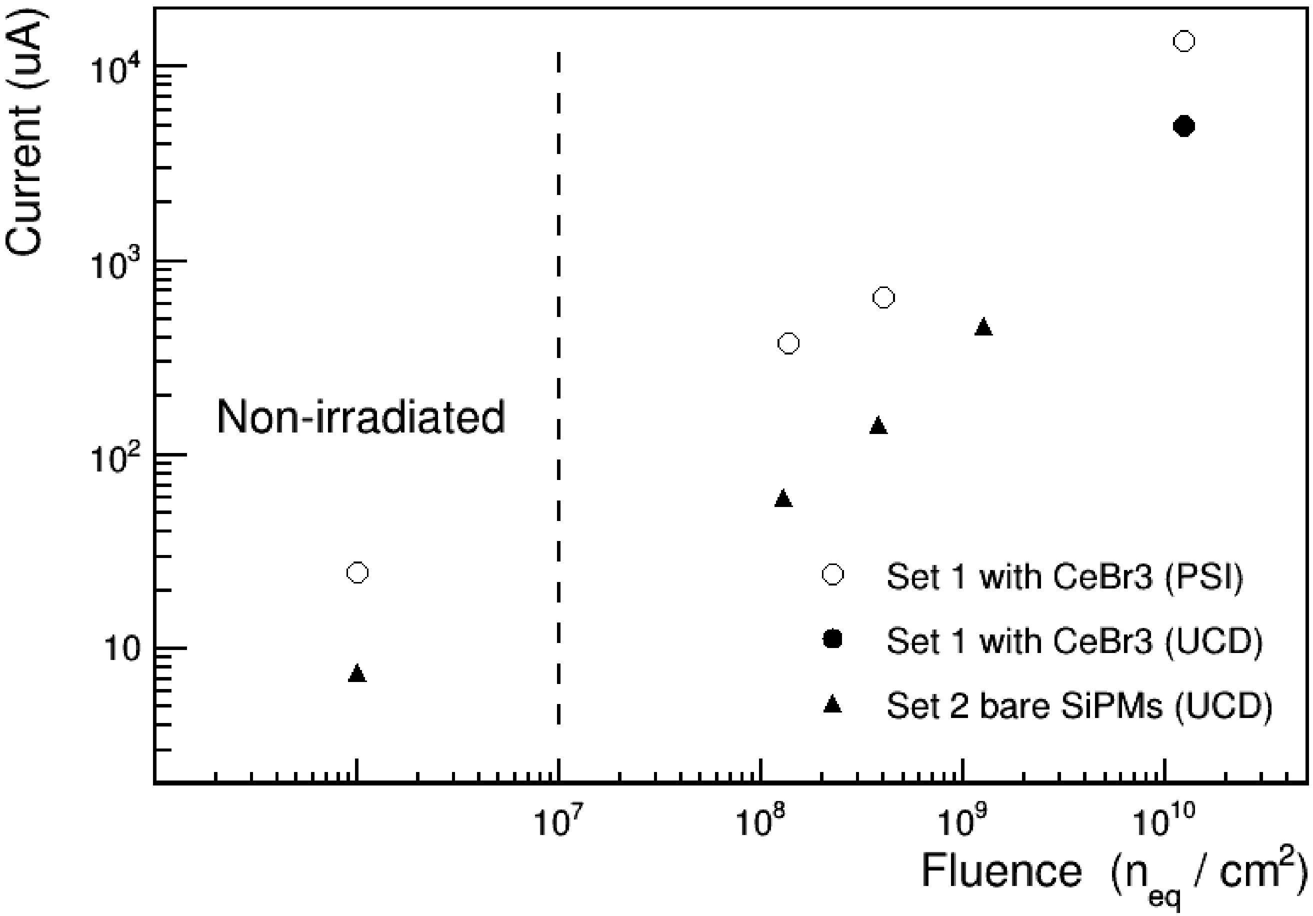
Measurement setup

- 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)

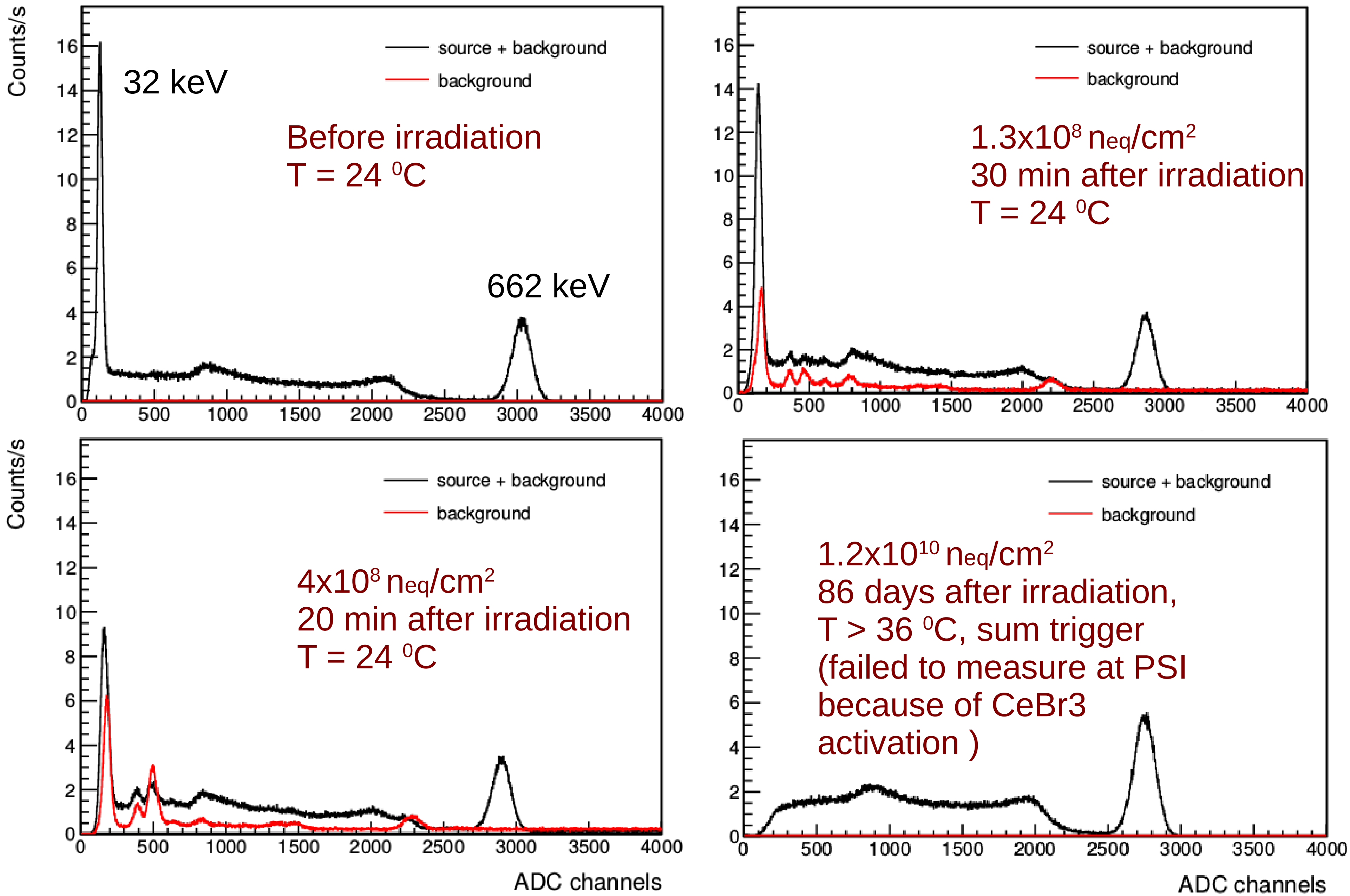


- PSI: 10-20 min after exposure, T = 24^{o}C.
- UCD: 86-89 days after exposure, T = 21^{o}C.
- Self-heating after 1.2×10^{10} n_{eq}/cm^2 (current increasing from 5 to 10 mA in 2 hours in UCD measurements, PCB temperature increasing from 21^{o}C to 36^{o}C)

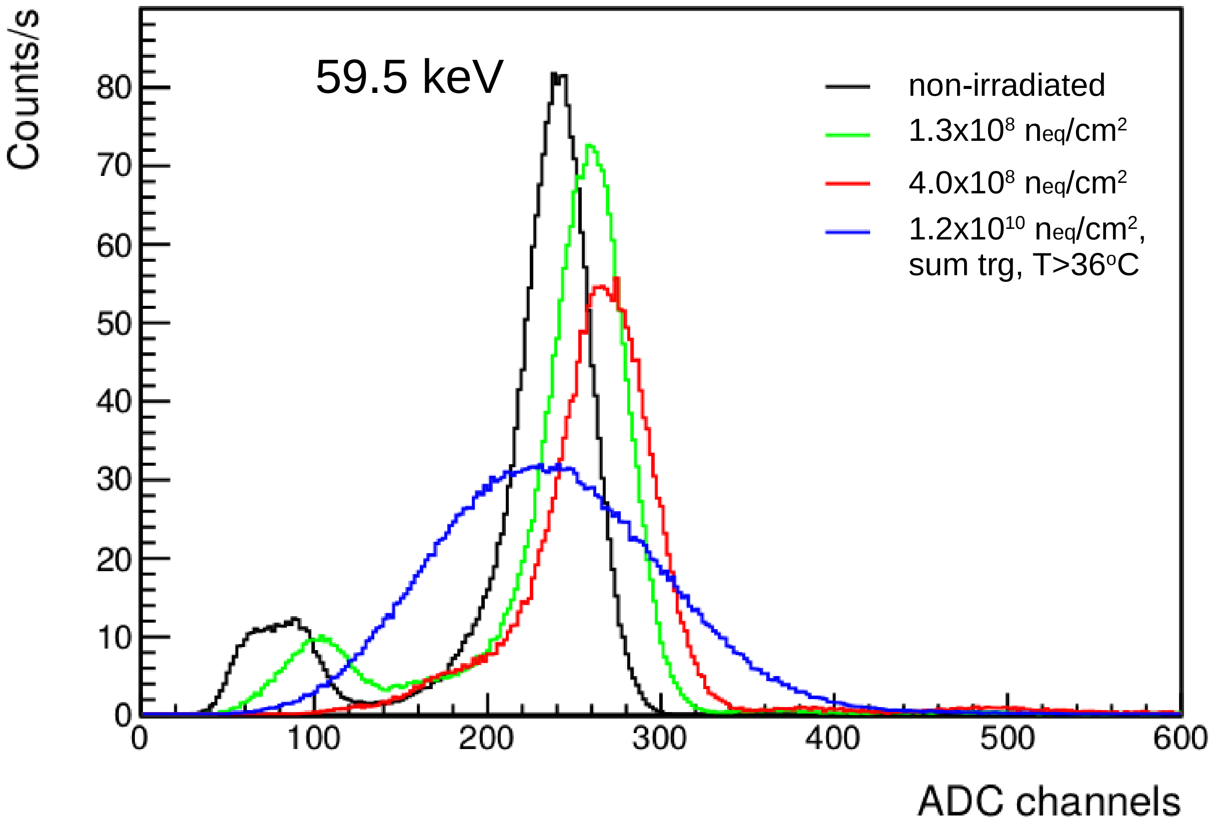
In UCD measurements the current reduced by a factor of 3 which indicates partial recovery from radiation damage (but also due to the 3 ^{o}C lower temperature).

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 including a 5-hour baloon flight.

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

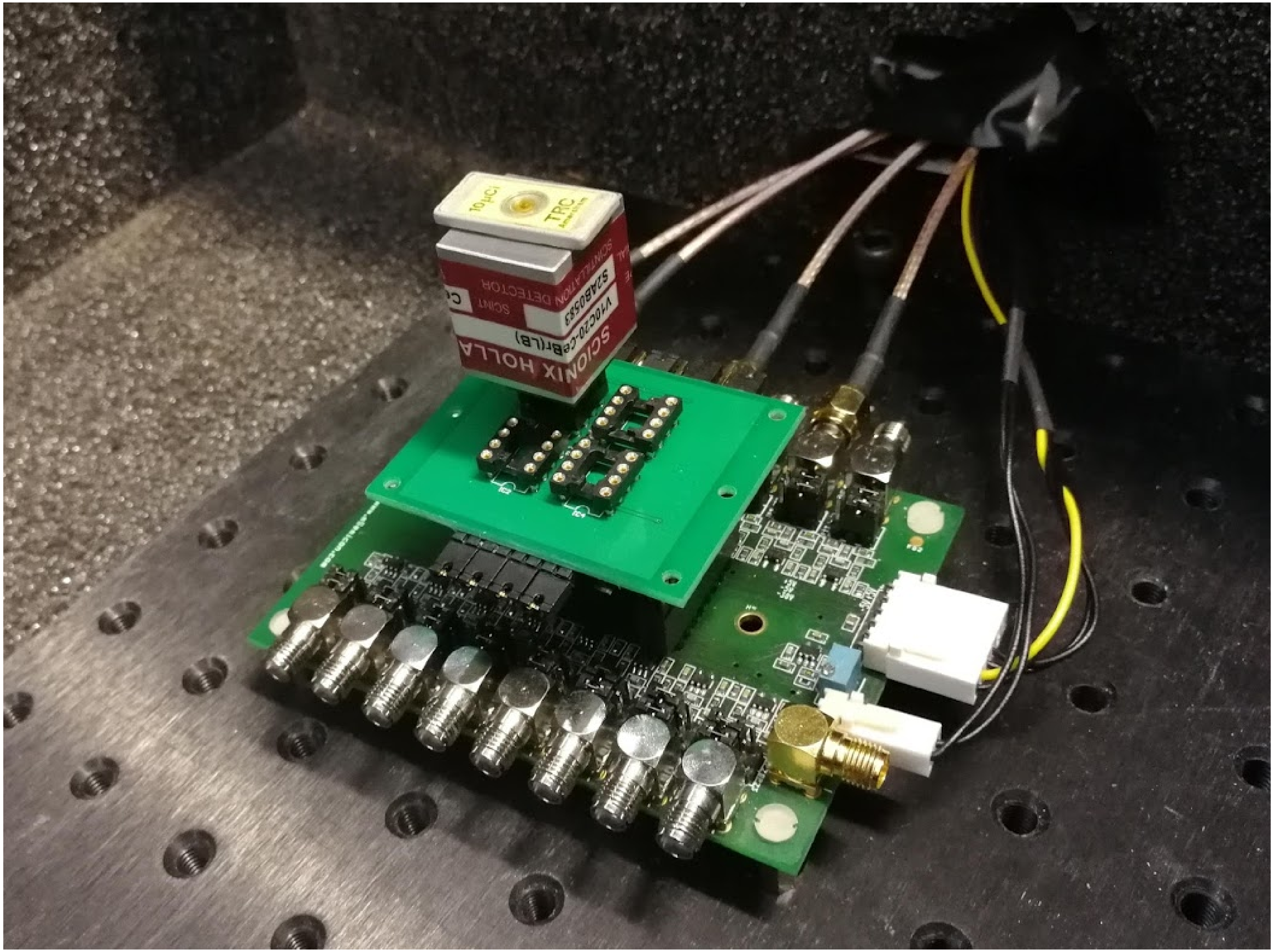


^{241}Am spectra



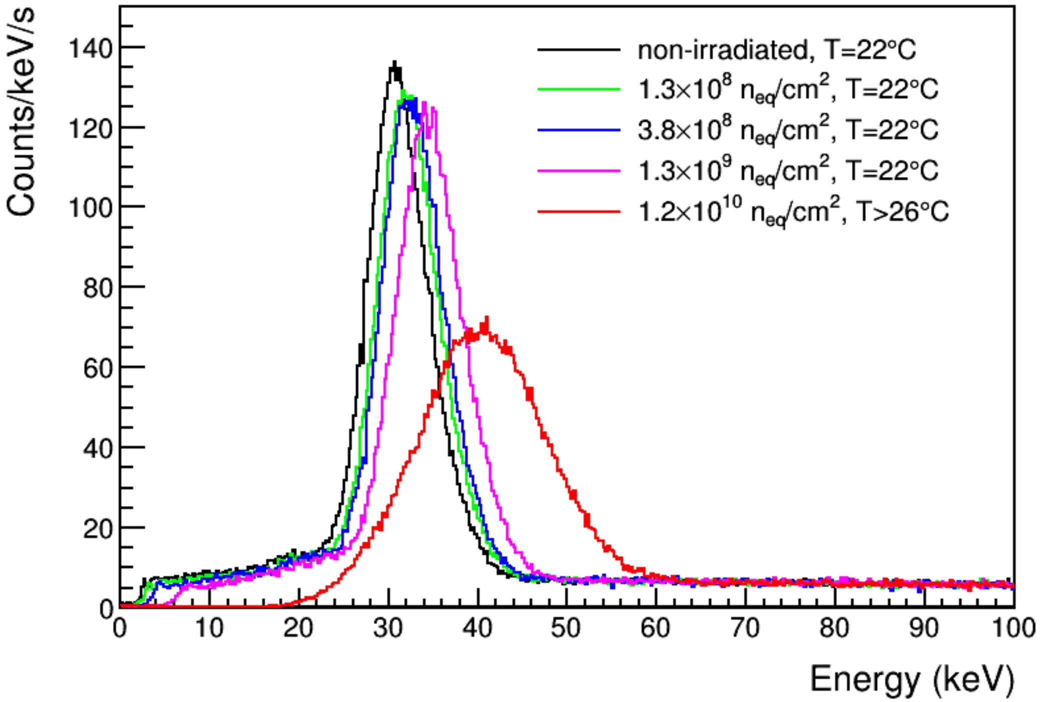
- Trigger threshold is increased after each exposure to prevent triggering from the SiPM dark noise
- 26 keV gamma rays are no longer detected after $4x10^8$ n_{eq}/cm^2
- 59.5 keV gamma rays are still detected after $1.2x10^{10}$ n_{eq}/cm^2 and 86-day recoovery period but the line width is affected by the noise.
- Line positions are affected by the trigger threshold (SIPHRA effect)

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

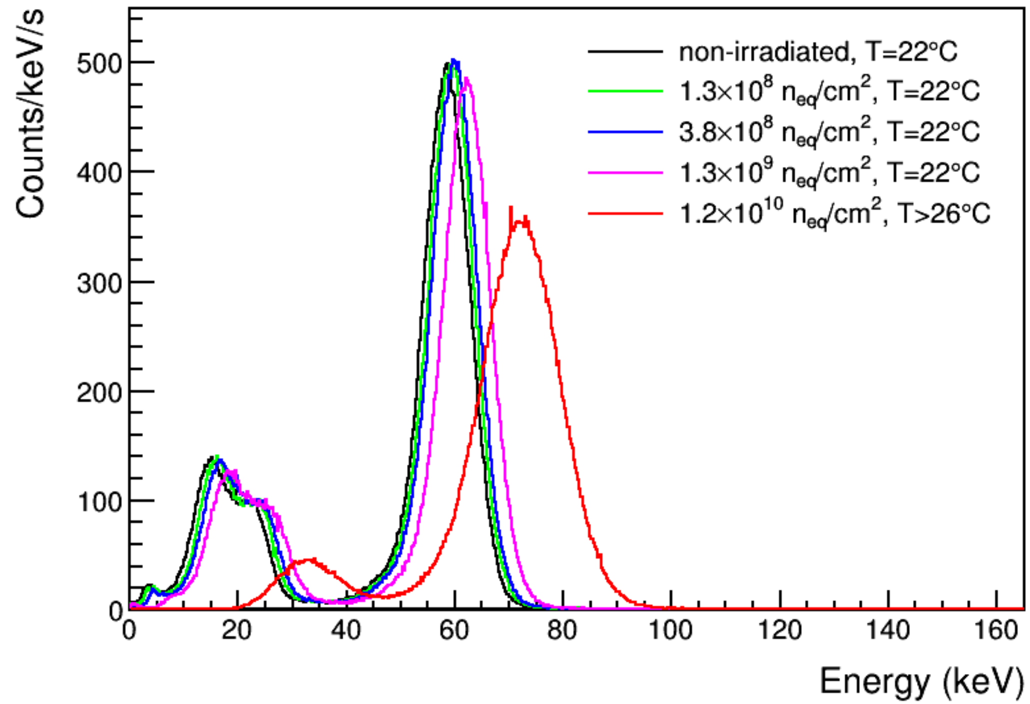


Spectra with 4-SiPM array

32 keV from ^{137}Cs

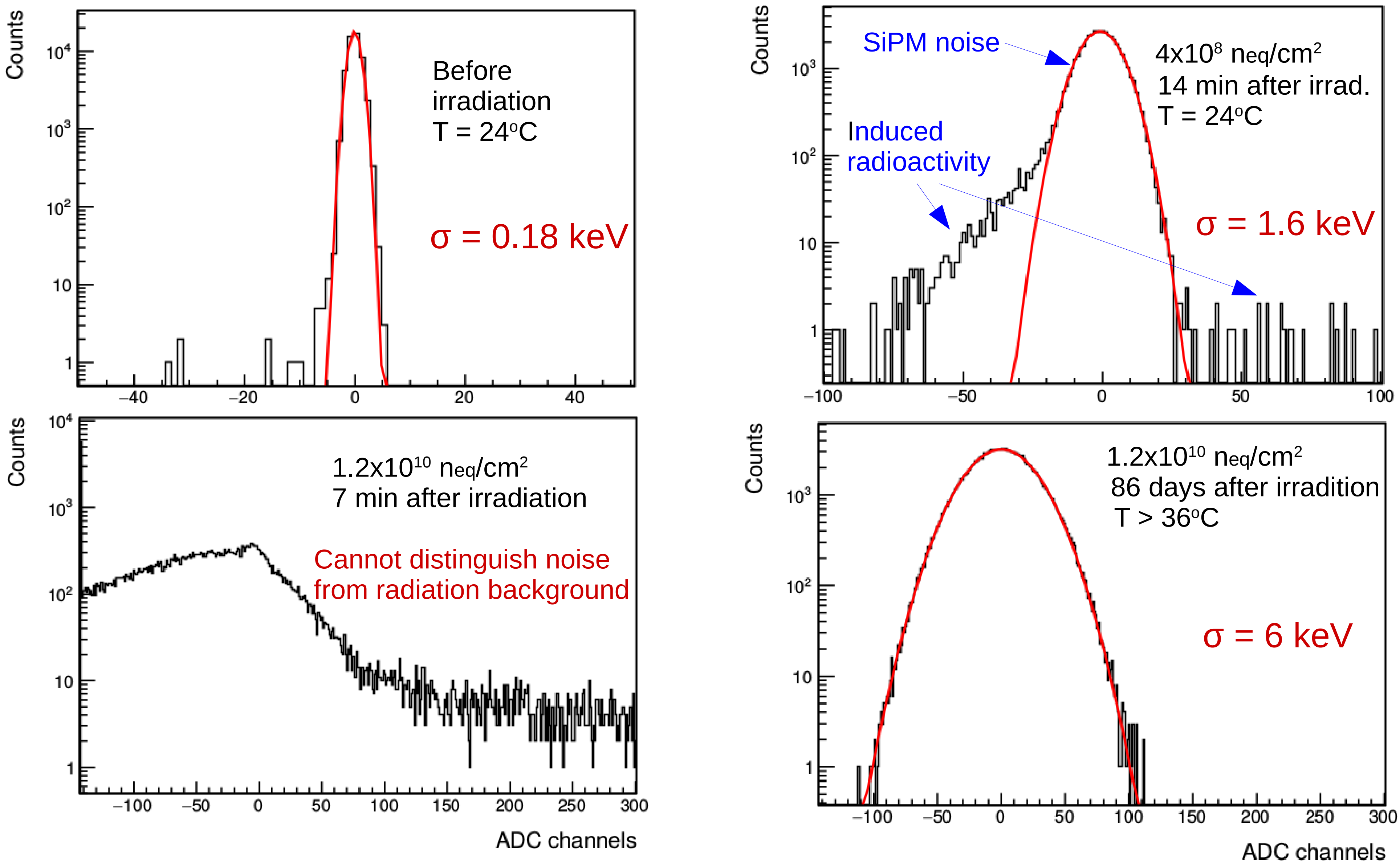


59.5 keV from ^{241}Am



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

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.

Conclusions from the radiation study

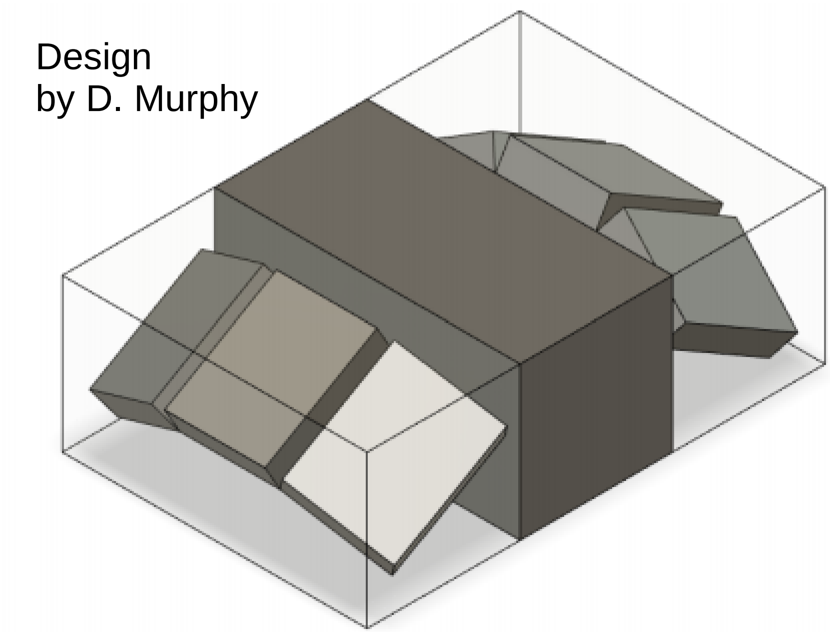
- No big change in the average detector response. The observed changes are limited to ~10% and are likely to have been caused by changes in experimental conditions, such as temperature and trigger threshold, rather than by radiation damage.
- Large SiPM current after proton irradiation in space may pose 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, SiPM cooling or shielding from proton radiation.
- Increased SiPM noise can be a problem for detection of low energy gamma rays:
  - A trigger threshold of about 40 keV would be required for CeBr3 with 16 SiPMs (5.9cm^2) after 6 years in a 550 km/40^o orbit to suppress “noise events”
  - Larger trigger thresholds are needed for low light yield or very slow scintillators, or for larger SiPM arrays coupled to one scintillator crystal.
- No significant problem for the GMOD/EIRSAT-1 (1 year in ISS orbit):
  - 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

GIFTS

Gamma-ray Investigation of the Full Transient Sky

- PI: Sheila McBreen
- Objectives:
  - Design a GBM-like instrument for a 6U CubeSat capable of GRB localisation
  - Build and test at least one detector module comprising a scintillator crystal, an SiPM array and readout electronics
  - Simulate the performance of a single/multiple instruments
- Long-term goal:
  - Build the complete instrument and launch it as part of a network of GRB detecting satellites – requires additional funding

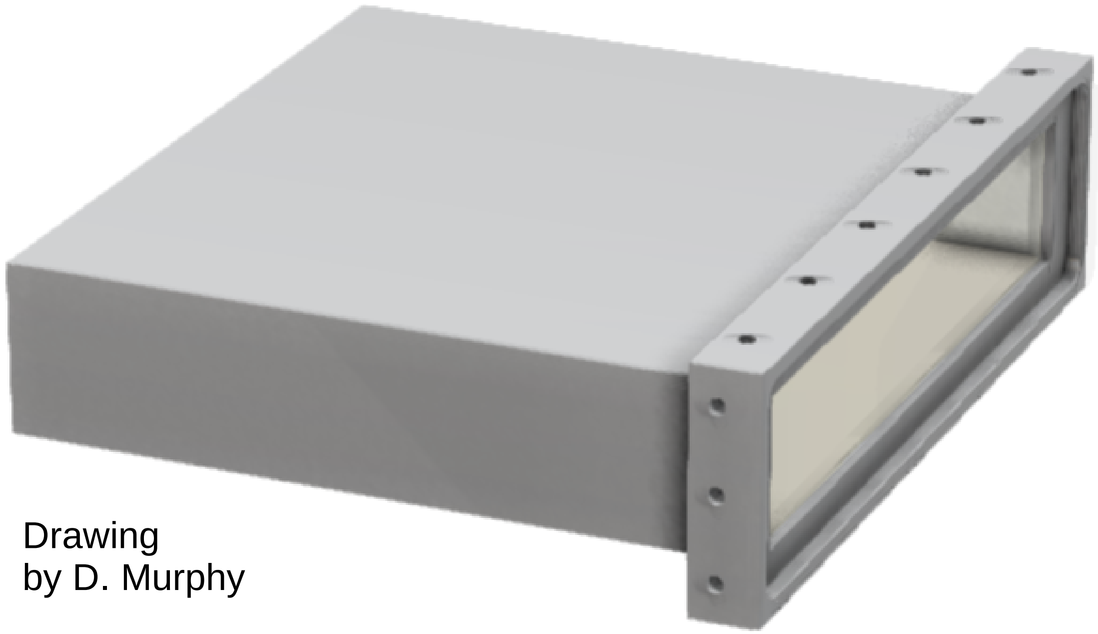
GIFTS conceptual design



- Six CeBr3 detectors inclined at different angles
- 70 x 70 x 13 mm scintillator size
- SensL SiPM readout
- The satellite stack is placed in the middle to minimise the obstruction of the field of view of the instrument

- Gamma-ray bursts are localised by comparing the count rates in the 6 detectors (similar to BATSE and GBM)
- Some source locations below the satellite may give similar count ratios to locations above the satellite. Such source locations are difficult/impossible to distinguish. Adding 2 mm thick lead shielding to the bottom and sides of the two middle detectors helps to distinguish sources above the satellite from sources below the satellite.

Detector module design



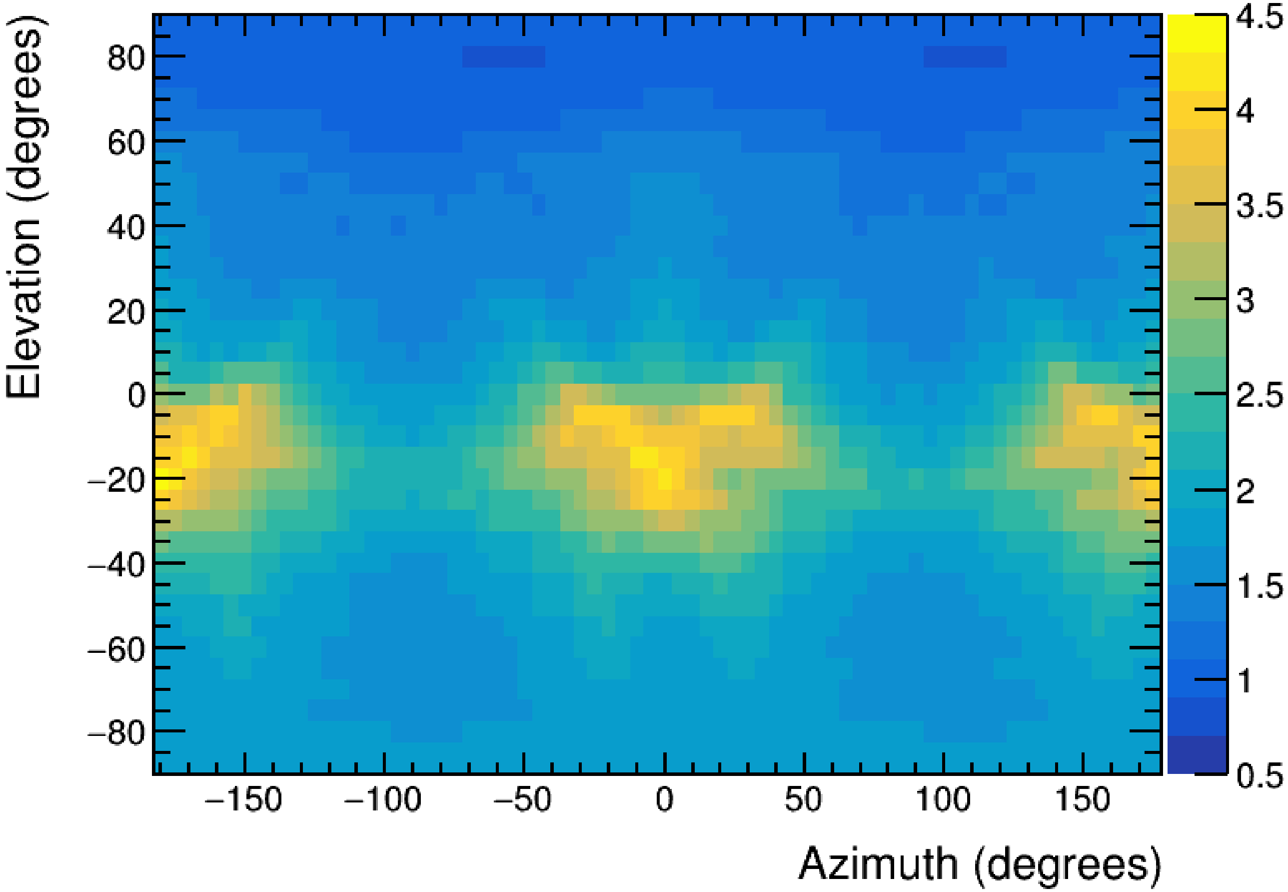
Drawing
by D. Murphy

- 3x12 SiPM array coupled to a side of the $CeBr_3$ crystal to reduce the number of SiPMs by a factor of 4 and thereby reduce the noise of the detector by a factor of 2

- The light output from the crystal may be reduced in this configuration – need to check that experimentally

Expected GRB sensitivity

Minimum 50-300 keV flux detectable in 1 s (ph/cm2/s)



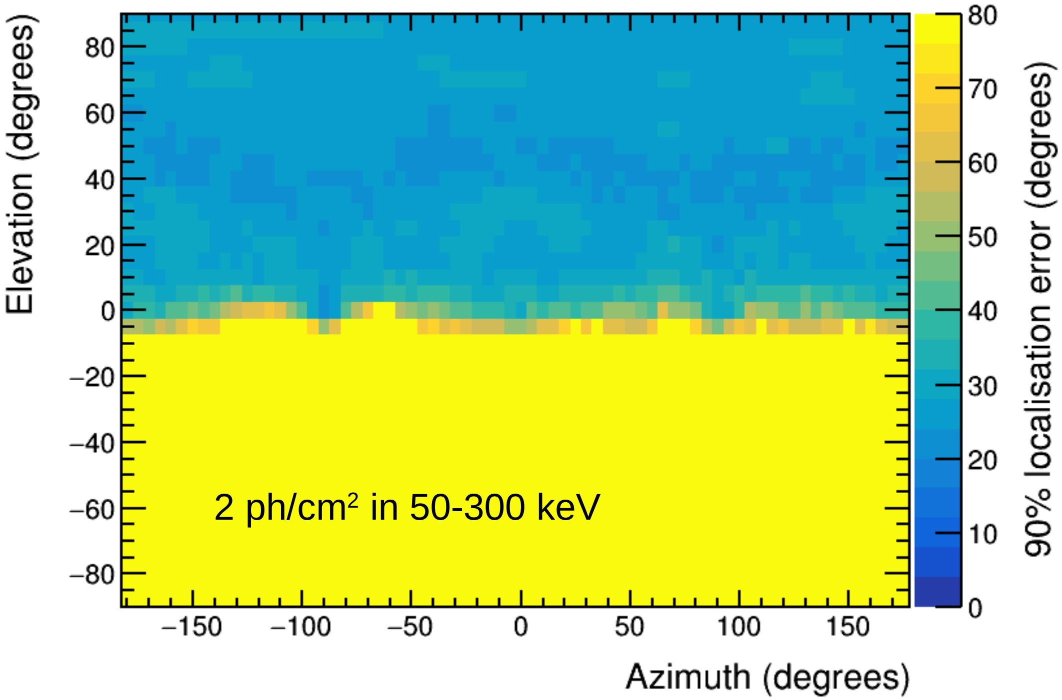
Detection threshold:
4.5σ excess rate in two detectors

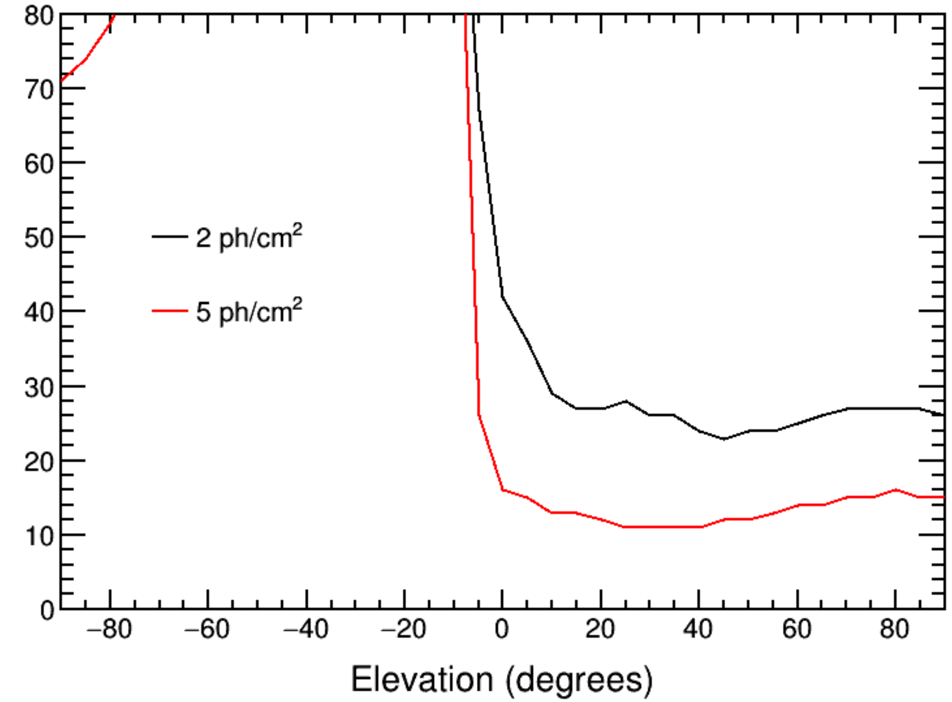
The flux detectable in 1 s:
1-2 ph/cm2/s in 50-300 keV depending on source location

Two “blind” spots just below horizon where the minimum detectable flux increases to 4 ph/cm2/s (source is facing the sides of the detectors)

Localisation performance

90% localisation error for a 1 second GRB





Above the satellite, the localisation error < 30° for 90% of the GRBs near the detection threshold (2 ph/cm^2) and the localisation improves for brighter bursts.

No or poor localisation for GRBs below the satellite.