U.S. NAVAL RESEARCH LABORATORY

Radiation Damage of SiPMs in Space

(Radiation Damage Assessment of Commercial SiPMs)

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High Energy Space Environment Branch
Space Science Division

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NRL High Energy Space Environment Branch

NASA's **Gamma Ray** Observatory (GRO) satellite 1990's

NRL contributed the **oriented scintillation spectrometer experiment**, observed gamma-ray sources in the 0.1–10 MeV range.

NASA \ DoE 's **Fermi Telescope**

NRL led the team that designed and manufactured the calorimeters for the Large Area Telescope (LAT), a pair-conversion instrument which detects photons with energy from about 20 MeV to 300 GeV

Space Test Program

U.S Department of Defense (DoD) Space Test Program (STP)

- Provides space flight to the DoD's space science and technology community for experiments, new technologies and demonstrations.
- Mission: space qualify new technology for the DoD
- Available competitively to qualified and relevant investigations
- Service provided at no cost to the experimenter and includes
  - Spacecraft
  - Integration and testing (on spacecraft)
  - Launch
  - One year mission operations (e.g., spacecraft control, data transmissions)
- Experimenter covers the cost of
  - Development and construction of the instrument
  - Pre-ship environmental testing
  - Analysis of data.
- A typical STP flight will host numerous experiments.

STP-Sat6 (hosting the SIRI-2 instrument.)

SiPMs vs PMTs

SiPMs used as readouts for scintillation style X-ray or gamma ray detectors.

- **Ground and space-based applications.**

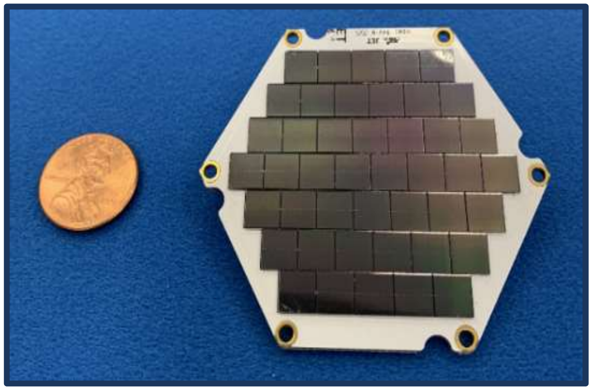
Benefits

- **Size** – Compact design saves space and allows for easier integration into more complex systems.
- **Weight** – Limited mass budgets on most spacecraft make SiPMs ideal.
- **Power** – Limited power budgets
- **Low Voltage** –
  - SiPMs close to the 28V (typical of the spacecraft bus)
  - PMTs typically hundreds of volts (700-1200V)

Potential Issues

- Radiation susceptibility of SiPMs compared to traditional PMTs

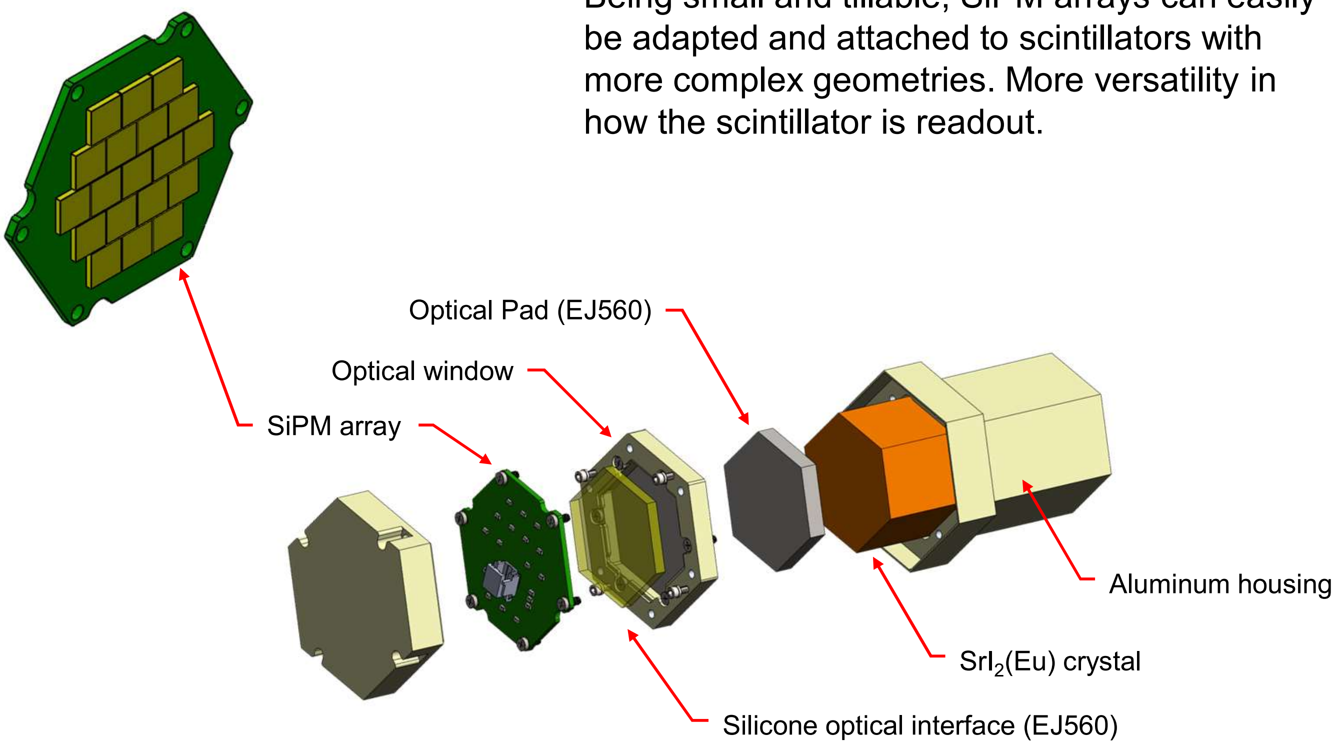
Traditional Photomultiplier Tubes



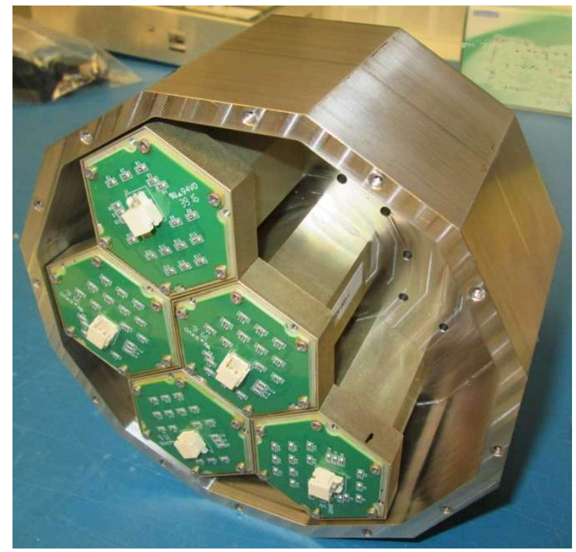
Tiled SiPM readout for a scintillation detectors.

SiPM Readout Configuration

Being small and tillable, SiPM arrays can easily be adapted and attached to scintillators with more complex geometries. More versatility in how the scintillator is readout.



Exploded View of SIRI-2 Detector shows a typical configuration.



SIRI-2 mission instrument

Optical pads handle mismatch in coefficient of thermal expansion

Space Qualifying New Materials and Electronics

Space Science Division at NRL is space qualifying new scintillator materials through instruments such as SIRI and GARI.

Objective: Demonstrate and characterize scintillator and SiPM technology for use as a component in larger space-based defense- or science-related missions.

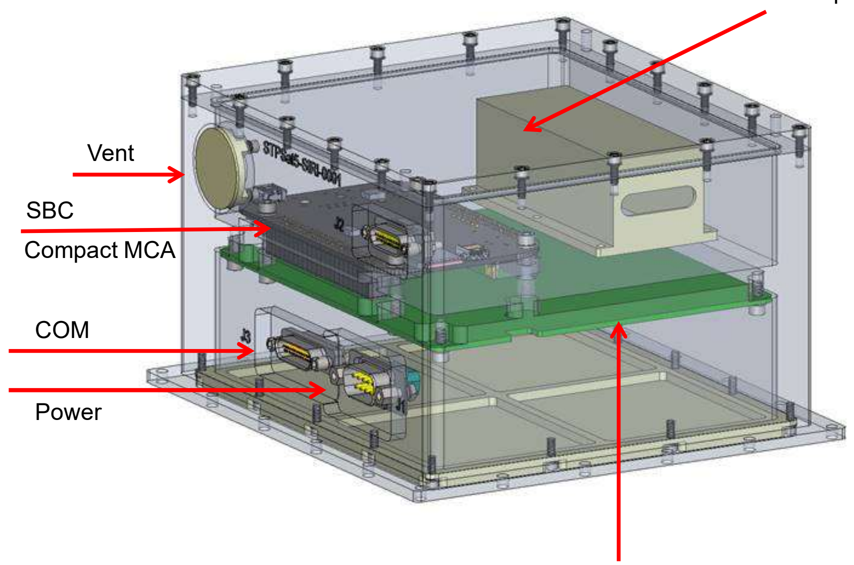
- SIRI-1 Launched on STP-Sat5 Dec 3 2018.(completed 1 year mission)
- GARI 1& 2 launch (Launched Dec of 2021 in operations on the ISS

SIRI-1 Specification

- Size: 8.9 cm (H) x 14 cm (D) x 15 cm (L), 1.620 kg, 6 W.

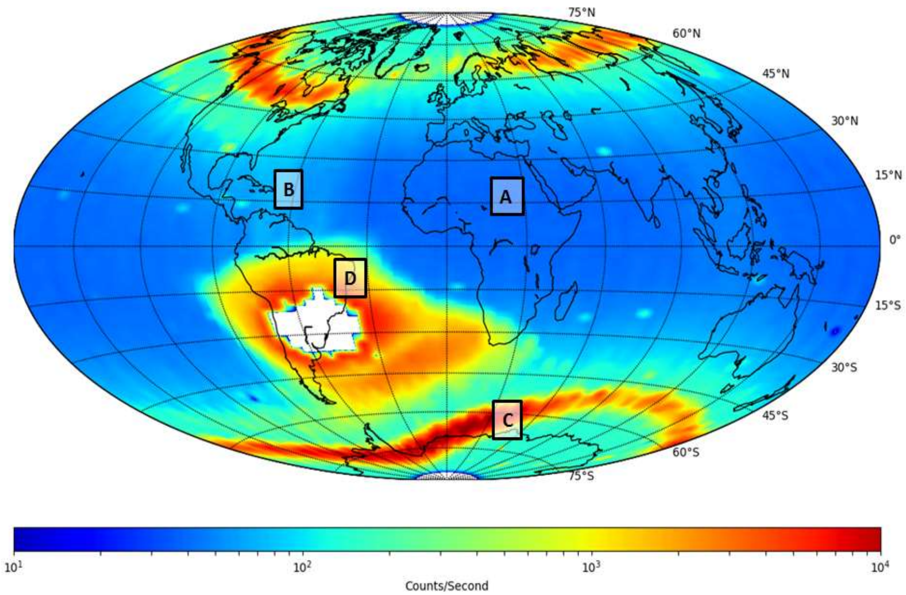
Detector Specifications for SIRI-1

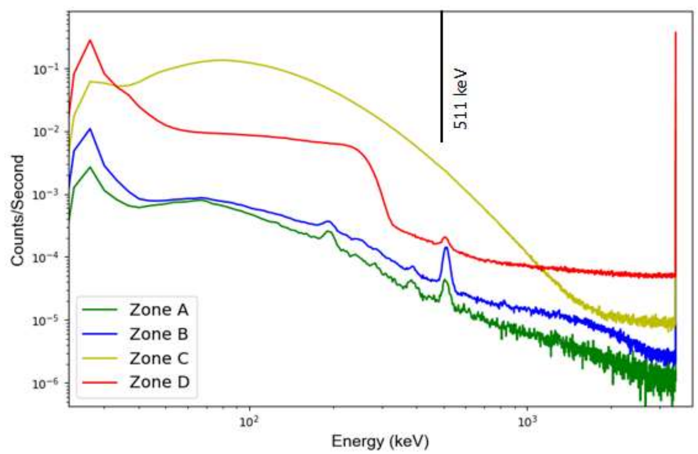
- Single SrI_2(Eu)
  - 17 x 17 x 40 mm^3
  - 4% resolution at 662 keV
  - Density: 4.55 g/cm^3
- 2 x 2 array of 6-mm SensL J-series SiPMs



SIRI-1 instrument to space qualify SrI and SiPM technology

Radiation Background in Space

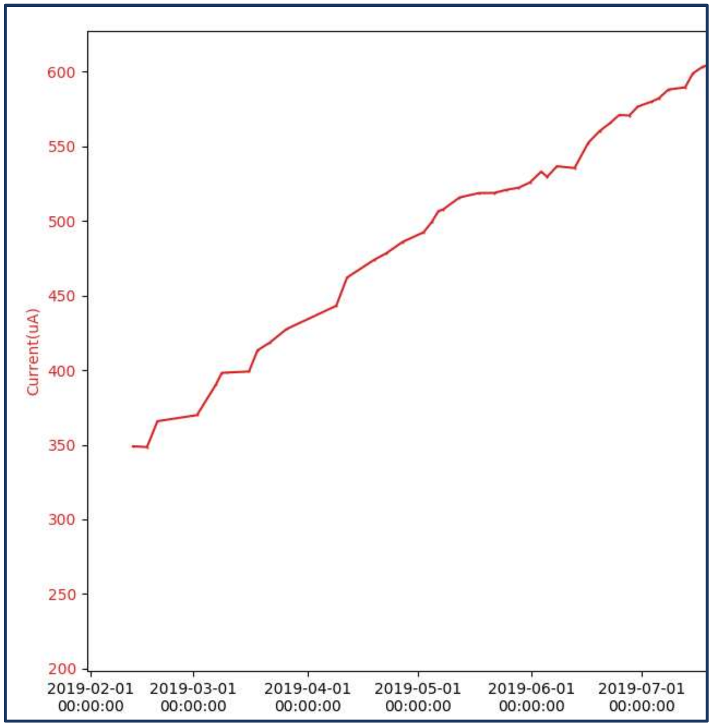




Gross gamma-ray count rate showing the elevated background as the instrument transitions through the various trapped particle regions. The four zones A, B, C and D were used generate the spectra shown in plot above right. No data is indicated by the white areas of the plot. (Measurements made with the SIRI-1 instrument in LEO in a sun synchronous orbit).

Strontium Iodided Radiation Instrument (SIRI-1) On-orbit Results

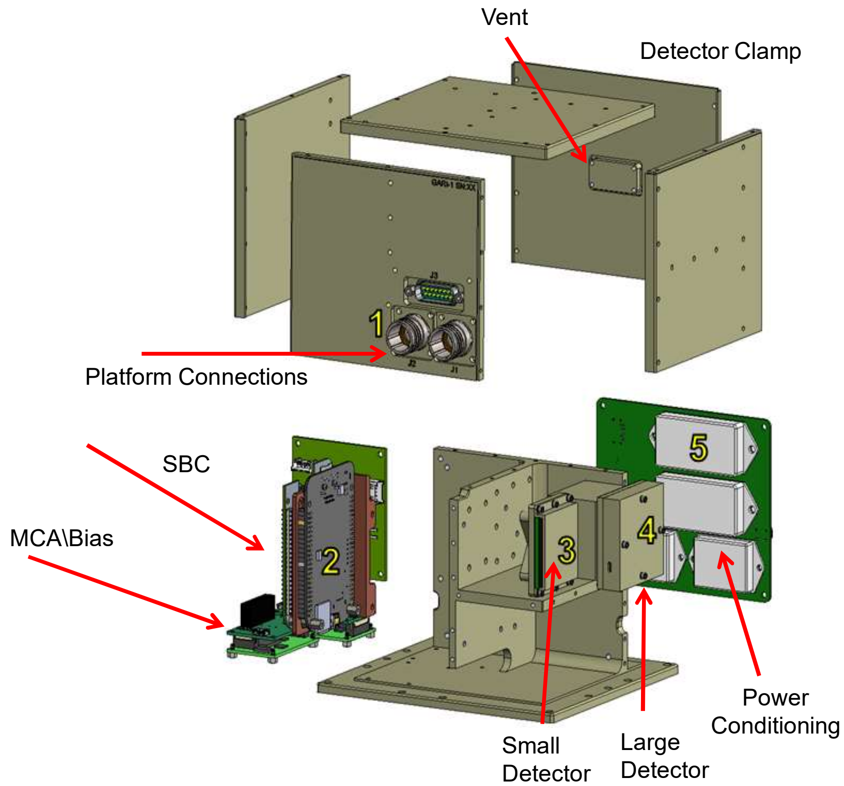
- SIRI-1 observed an 44uA/month increase in the SiPM current.
- Estimated annual proton dose was roughly 90 rads (Si). (1.2E+9 1MeV Neut. Eq.)
- Tiling many SiPMs together to form a single large readout can lead to power supply issues.
- Small PCB mounted power supplies are limited in what the can produce.
- Detector energy resolution degraded somewhat.
- Observed an increase of ~0.1% per month increase in FWHM energy resolution. (determined by fitting the 511 keV line)



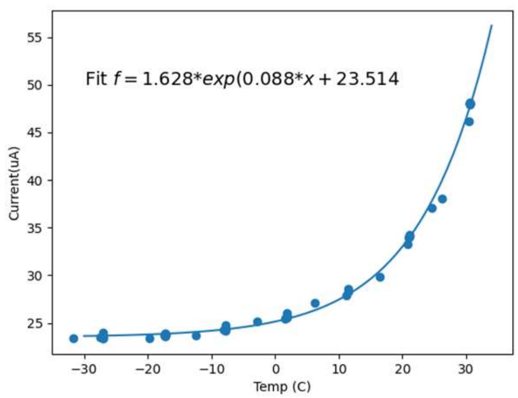
Linear increase in current over several months. Total current from 4 J-series 60035 SensL SiPMs.

GAGG Radiation Instrument (GARI)

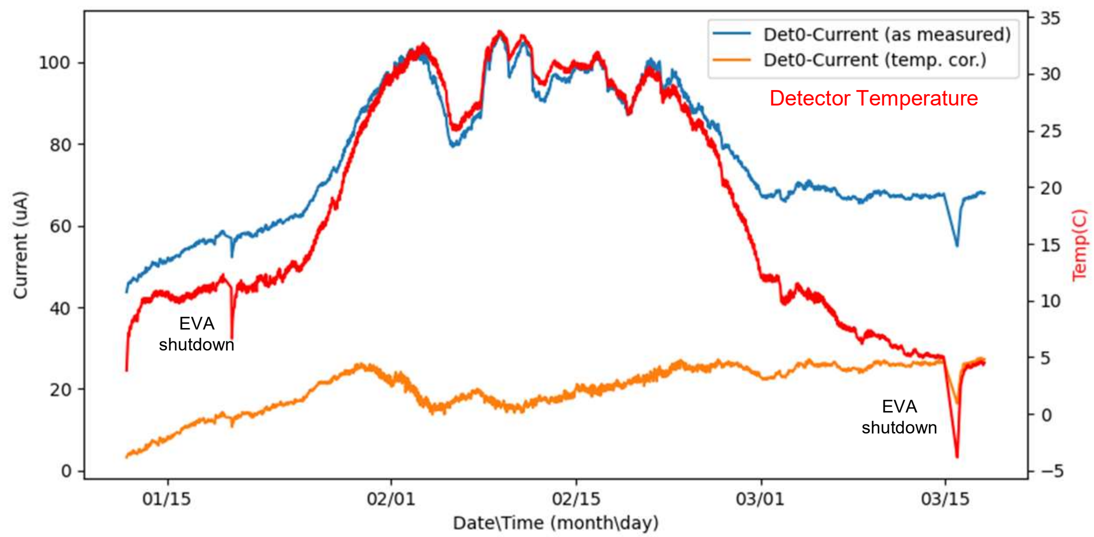
- GARI-1a and GAR-1b two identical instruments on the ISS.
- GARI-1a is one of five experiments on STP-H7.
- STP-H7 is currently attached to the European Space Agency (ESA's) Columbus module
- GARI-1b on STP-H8 is current attached to the Japan's JEM module.
- GARI (size-weight-power) SWAP
  - 2 detectors
    - (3x3x3) cm^3
    - (0.2 x 3.5 x 3.5) cm^3
  - Size 11.4cm (H) x 14.5 cm (D) x 15.7 cm (L)
  - Mass of 2.8 kg
  - Power 1.5 W
  - Resolution 5.5% @ 662keV
  - 45 keV threshold
- Primary Components
  - Enclosure
  - Detector GAGG-HR – C&A Corporation (Japan)
  - Single Board Computer (SBC) – Beaglebone Black (BBB)
  - Multichannel Analyzer (MCA) – modified BridgePort Emorpho
  - Detector Bias Supply – AiT HV80
  - Printed Circuit Board (PCB) - NRL Custom, power conditioning, temperature sensors, RS-232 -> RS-422, pre-amp, HV controls, and connectors



GARI-1 Early On-orbit Results



Detector SiPM current fitted from TVAC measurements made prior to launch. The amplitude and offset were tweaked a bit for finding the corrected current to the right.

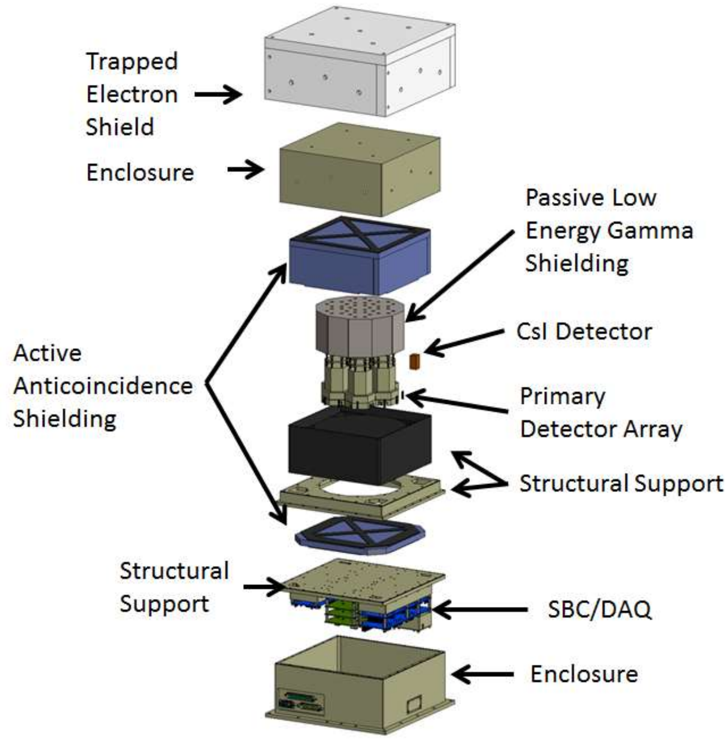


- Large temperature fluctuation due to beta angle (angle between the sun and the orbital plane) changes with slow procession of the ISS around the earth.
- Smaller temperature changes due to activity on the ISS, ISS geometry, or power levels changing in other instruments on the pallet.
- Current in GARI-1a detector appears to be increasing at roughly 10 uA every couple of month. (16 J-series 60035 SensL SiPMs)
- Significantly less increase in current observed, compared SIRI
  - More benign orbit compared to SIRI,
  - Heavily shielded by the ISS (from one side).
- Observed increase in offset and amplitude of the fit function.

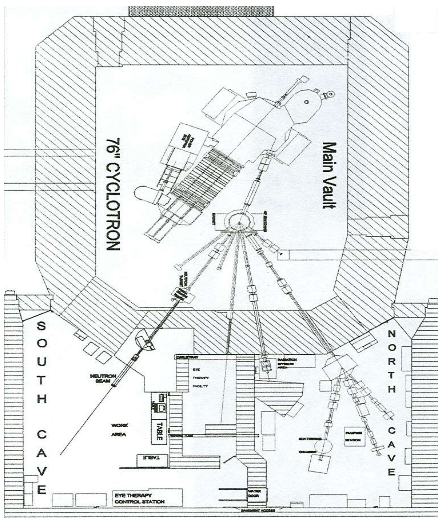
SIRI-2 Demonstrator

Launched in Dec of 2021 into GEO and is currently in operation on STPSat-6.

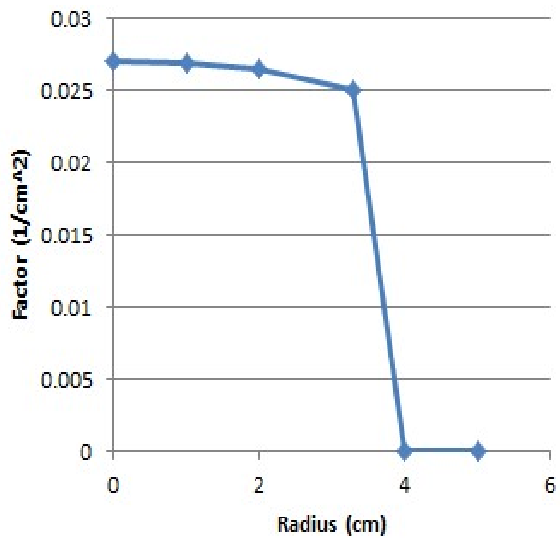
- Objective: Measure energetic gamma-rays from solar flares.
- Primary detectors
  - Seven $SrI_2(Eu)$
    - Hexagonal close-pack design
    - 38.1 mm diameter (19.05 mm per side) x 38.1 mm length
  - SiPM readouts
    - 19 6-mm SensL J-series SiPMs in hexagonal array on PCB
- Active shield
  - Six plastic detectors for approx. 4π coverage
  - Anticoincidence rejects high energy cosmic-ray protons that pass through the detector and shielding.
- Passive shield
  - Reduce low photons during solar events (prevent “swamping” of system)
  - Reduce Bremsstrahlung produced by electrons interacting with enclosure.
- Single CsI detector (external to passive shield)
  - External to passive gamma shield
  - Measure low-energy hard x-ray component of solar flare



Experimental Testing of SiPM

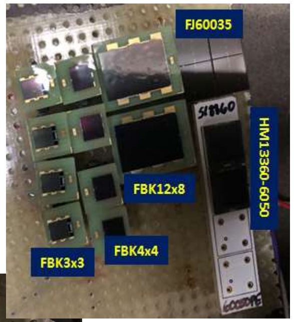


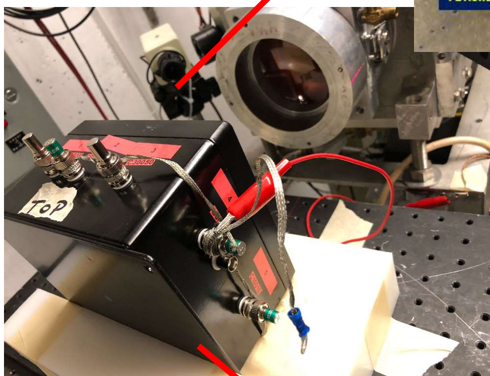
UC Davis Accelerator Facility

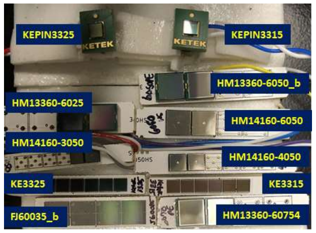


Beam Distribution In MeV

Two light tight boxes aligned in front of the beam port were used to irradiate the samples.



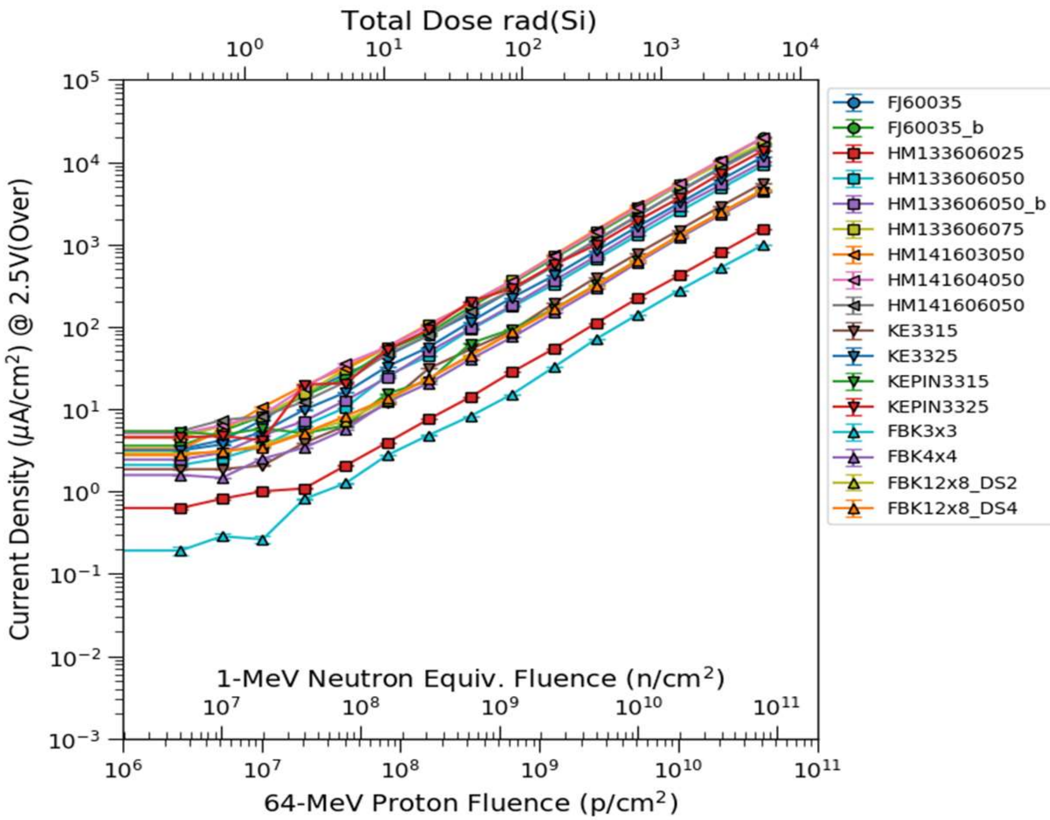




- 64 MeV Proton Beam at UC Davis was used to irradiate SiPM targets.
- Irradiated a variety of SensL, Hamamatsu, KETEK and FBK SiPMs.
- Samples were irradiated to fluences of up to 4.1E+10 protons/cm^2
- Currents were measured incrementally with Keithley High Voltage Source Measure Unit (K237)

Irradiation Results

- **Objective:** Given a particular brand\model what is the expected annual current increase from on-orbit radiation damage.
- We were not looking to compare performance between various brand\models
- Other Factors go into our choice of SiPM:
  - Gain
  - Response to emission of scintillator
  - Temperature Effects
  - PSD performance
- Paper: Radiation damage assessment of SiPMs (under review in NIMA)



Compiled Results

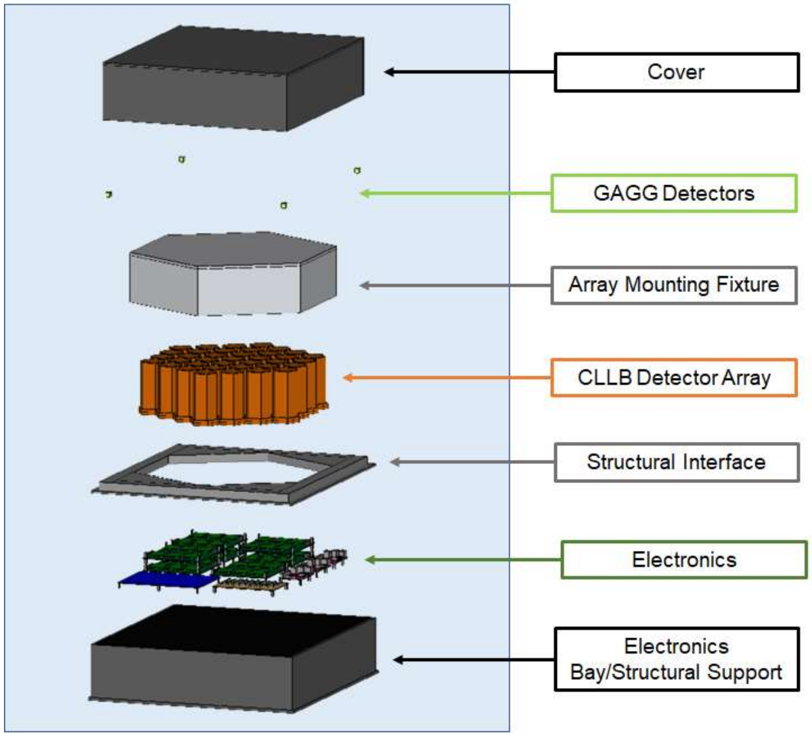
Hamamatsu 13360-6050 (HM133606050)

Fluence (p/cm^2)	0.0E+0	2.6E+6	5.2E+6	1.0E+7	2.0E+7	4.0E+7	8.0E+7	1.6E+8	3.2E+8	6.4E+8	1.3E+9	2.6E+9	5.1E+9	1.0E+10	2.0E+10	4.1E+10
Total Dose (rad(Si))	0.0E+0	3.5E-1	6.9E-1	1.4E+0	2.7E+0	5.4E+0	1.1E+1	2.1E+1	4.3E+1	8.5E+1	1.7E+2	3.4E+2	6.8E+2	1.4E+3	2.7E+3	5.4E+3
NIEL Dose (MeV/g)	0.0E+0	1.6E-4	3.2E-4	6.3E-4	1.3E-3	2.5E-3	5.0E-3	1.0E-2	2.0E-2	4.0E-2	8.0E-2	1.6E-1	3.2E-1	6.4E-1	1.3E+0	2.5E+0
1-MeV Neut. Eq. (n/cm^2)	0.0E+0	5.1E+6	1.0E+7	2.0E+7	3.9E+7	7.9E+7	1.6E+8	3.1E+8	6.2E+8	1.2E+9	2.5E+9	5.0E+9	1.0E+10	2.0E+10	4.0E+10	8.0E+10
Overvoltage(V) Vb=51.5	Current Density (uA/cm^2)															
0.5	0.11 ±0.03	0.06 ±0.03	0.21 ±0.03	0.14 ±0.03	0.43 ±0.03	0.51 ±0.03	1.04 ±0.03	1.73 ±0.03	3.61 ±0.03	6.98 ±0.03	12.53 ±0.03	24.94 ±0.03	49.03 ±0.03	94.61 ±0.03	181.29 ±0.03	359.61 ±0.03
1	0.27 ±0.03	0.29 ±0.03	0.59 ±0.03	0.61 ±0.03	1.2 ±0.03	1.86 ±0.03	4.33 ±0.03	7.35 ±0.03	15.18 ±0.03	28.79 ±0.03	53.38 ±0.03	108.3 ±0.03	211.93 ±0.03	394.33 ±0.26	751.39 ±0.26	1433.41 ±0.26
1.5	0.53 ±0.03	0.83 ±0.03	1.09 ±0.03	1.38 ±0.03	2.42 ±0.03	3.82 ±0.03	9.61 ±0.03	16.43 ±0.03	33.8 ±0.03	64.16 ±0.03	119.26 ±0.03	243.53 ±0.03	463.25 ±0.26	898.42 ±0.26	1706.19 ±0.26	3223.12 ±0.26
2	0.85 ±0.03	1.33 ±0.03	1.75 ±0.03	2.31 ±0.03	4.06 ±0.03	6.72 ±0.03	16.8 ±0.03	28.84 ±0.03	58.93 ±0.03	112.39 ±0.03	211.0 ±0.03	421.02 ±0.26	827.36 ±0.26	1602.59 ±0.26	3050.38 ±0.26	5699.32 ±2.63
2.5	1.28 ±0.03	2.1 ±0.03	2.52 ±0.03	3.56 ±0.03	6.29 ±0.03	10.48 ±0.03	25.63 ±0.03	44.31 ±0.03	92.65 ±0.03	174.65 ±0.03	330.29 ±0.03	658.63 ±0.26	1300.3 ±0.26	2521.77 ±0.26	4836.71 ±2.63	9133.26 ±2.63
3	1.81 ±0.03	2.89 ±0.03	3.42 ±0.03	5.1 ±0.03	8.89 ±0.03	15.18 ±0.03	36.48 ±0.03	64.88 ±0.03	133.37 ±0.03	252.01 ±0.03	468.69 ±0.26	954.8 ±0.26	1889.56 ±0.26	3680.71 ±0.26	7153.9 ±2.63	>10000
3.5	2.42 ±0.03	3.74 ±0.03	4.59 ±0.03	7.17 ±0.03	12.1 ±0.03	20.59 ±0.03	50.23 ±0.03	89.33 ±0.03	182.38 ±0.03	348.78 ±0.03	647.07 ±0.26	1327.21 ±0.26	2623.95 ±0.26	5205.71 ±2.63	>10000	>10000
4	3.08 ±0.03	5.04 ±0.03	5.95 ±0.03	9.45 ±0.03	15.95 ±0.03	26.93 ±0.03	65.77 ±0.03	116.61 ±0.03	240.77 ±0.03	456.64 ±0.26	861.82 ±0.26	1765.2 ±0.26	3518.09 ±0.26	7029.28 ±2.63	>10000	>10000
4.5	3.9 ±0.03	6.29 ±0.03	7.27 ±0.03	12.34 ±0.03	20.69 ±0.03	34.55 ±0.03	84.11 ±0.03	150.74 ±0.03	309.78 ±0.03	589.26 ±0.26	1117.42 ±0.26	2292.87 ±0.26	4649.77 ±2.63	9296.92 ±2.63	>10000	>10000
5	4.75 ±0.03	7.91 ±0.03	9.05 ±0.03	15.55 ±0.03	26.22 ±0.03	43.75 ±0.03	106.54 ±0.03	190.61 ±0.03	387.76 ±0.26	748.39 ±0.26	1419.93 ±0.26	2938.06 ±0.26	5979.73 ±2.63	>10000	>10000	>10000
5.5	5.84 ±0.03	9.87 ±0.03	11.17 ±0.03	19.64 ±0.03	32.74 ±0.03	54.87 ±0.03	132.24 ±0.03	239.66 ±0.03	484.27 ±0.26	932.62 ±0.26	1785.02 ±0.26	3688.25 ±0.26	7613.74 ±2.63	>10000	>10000	>10000
6	7.06 ±0.03	11.62 ±0.03	13.08 ±0.03	24.73 ±0.03	39.91 ±0.03	67.32 ±0.03	165.03 ±0.03	295.66 ±0.03	595.2 ±0.26	1163.66 ±0.26	2213.33 ±0.26	4652.4 ±2.63	9585.21 ±2.63	>10000	>10000	>10000
6.5	8.44 ±0.03	14.3 ±0.03	16.37 ±0.03	30.3 ±0.03	47.6 ±0.03	82.09 ±0.03	203.34 ±0.03	363.18 ±0.03	731.61 ±0.26	1420.72 ±0.26	2739.83 ±0.26	5784.91 ±2.63	>10000	>10000	>10000	>10000
7	10.06 ±0.03	16.88 ±0.03	19.74 ±0.03	36.72 ±0.03	58.88 ±0.03	97.87 ±0.03	249.99 ±0.03	440.13 ±0.26	889.26 ±0.26	1746.06 ±0.26	3350.79 ±0.26	7140.77 ±2.63	>10000	>10000	>10000	>10000
7.5	12.34 ±0.03	20.69 ±0.03	23.64 ±0.03	44.89 ±0.03	70.92 ±0.03	118.97 ±0.03	299.22 ±0.03	531.91 ±0.26	1080.59 ±0.26	2134.27 ±0.26	4119.74 ±2.63	8821.7 ±2.63	>10000	>10000	>10000	>10000

Values for the tested SiPMs were compiled into look up tables for quick estimation of current for a given NIEL dose.

Future Missions and Related Work

- Space based measurements of SiPM have shown significant current issues for on-orbit operations.
- The SiPMs we tested can all be used in space.
- Radiation susceptibility issue needs to be managed to ensure mission suitability.
- Future NRL mission using SiPMs include:
  - SIRI-3: a Solar Gamma Ray Spectrometer
    - focused on studying energetic gamma ray emission during solar flares.
  - NERDI: Anthony Hutcheson (PI)
    - (looking for space qualify TLYC)
  - Glowbug -Richard Woolf (PI) and NASA's Starburst
    - Two instruments for detection and localization GRBs



Solar Gamma Ray Mission (SIRI-3)
LEO, launch late 2025