Quantitative measurement and analysis of in-orbit radiation damage of SiPMs in GRID-02 CubeSat detector

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on behalf of the **GRID** collaboration

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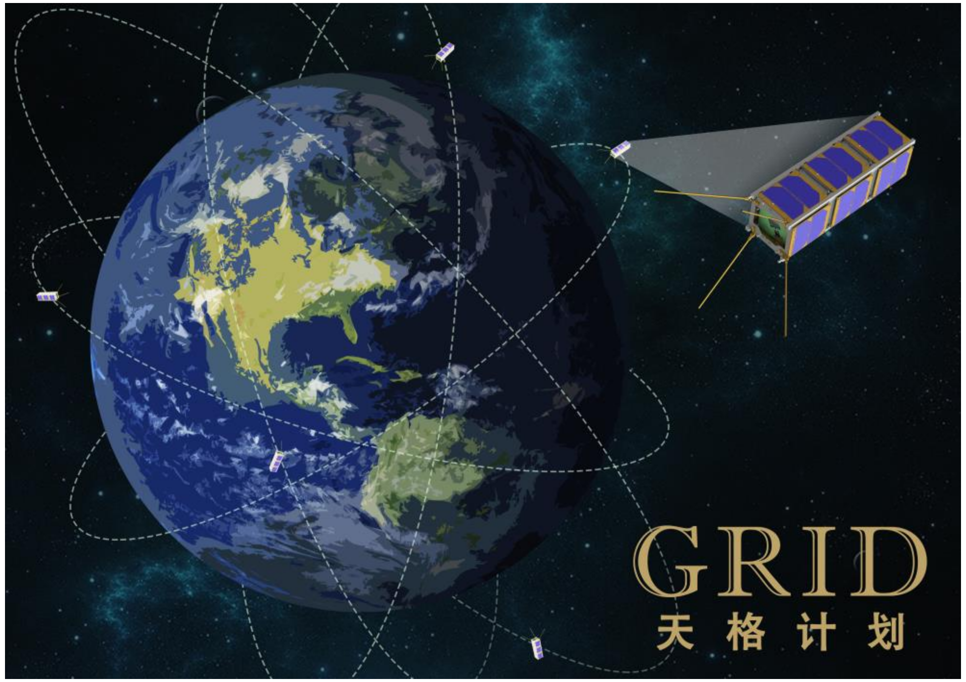
SiPM Radiation: Quantifying Light for Nuclear, Space and Medical Instruments under Harsh Radiation Conditions

25–29 Apr 2022 CERN

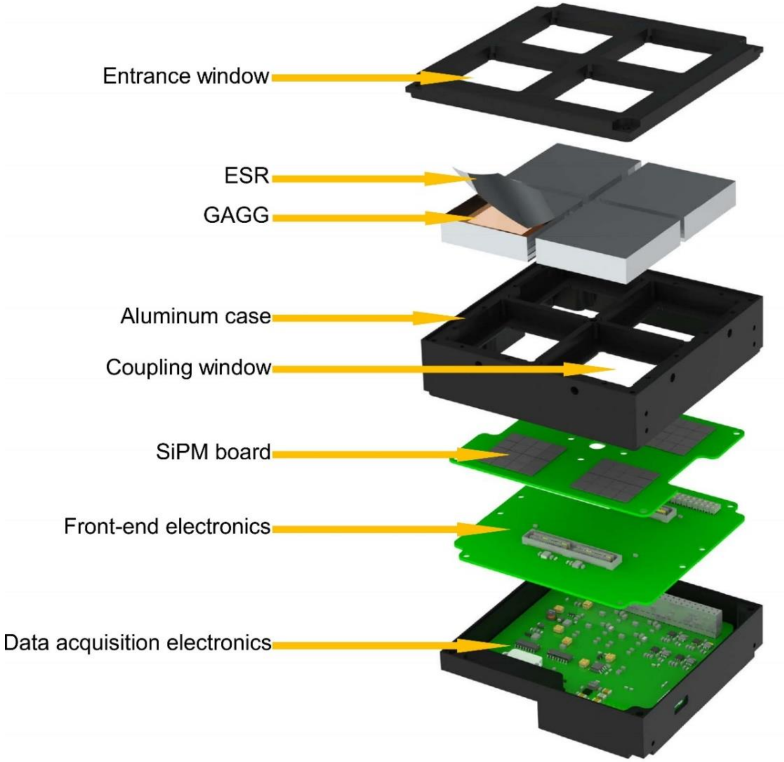
The GRID Project and Detector



Gamma Ray Integrated Detectors (GRID) concept: [1]

- 10 ~ 24 CubeSats scattered in low Earth orbits
- Compact gamma-ray detectors

3D model of the GRID detector [2]



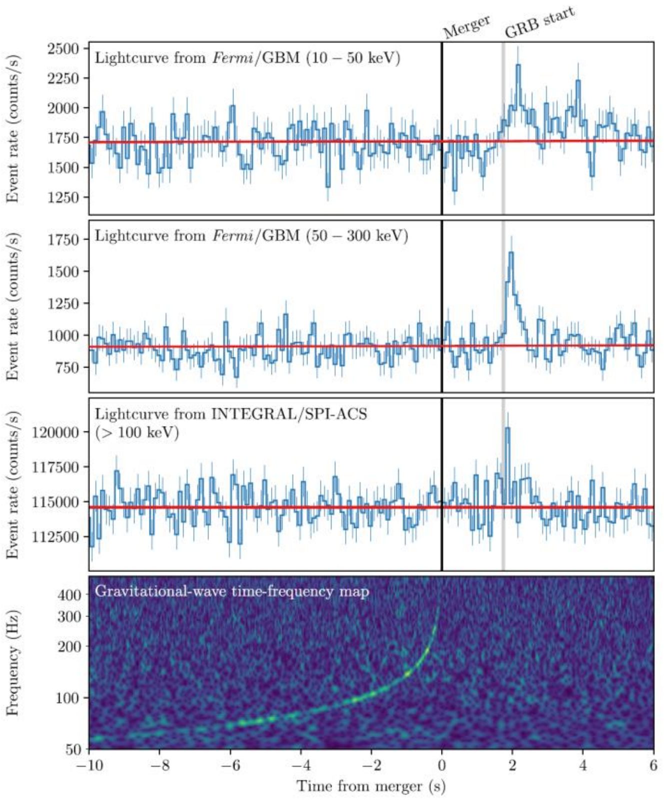
Specifications of GRID-02

Size	< 0.5U (9.4×9.4×5 cm^3)
Weight	~ 780 g
Power consumption	Typ. 2 W Max. 2.8 W
Geometric area	~ 58 cm^2
Field of view	2π
Energy range	Lower threshold < 15 keV Upper threshold ~ 2 MeV
Dead time	~ 20 us
Background count rate	Norm. ~ 2000 cps SAA > 8000 cps
Telemetry	~ 1 GB/day

[1] Wen, J., Long, X., Zheng, X. *et al.* GRID: a student project to monitor the transient gamma-ray sky in the multi-messenger astronomy era. *Exp Astron* **48,** 77–95 (2019)
[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Scientific Goals

Joint, multi-messenger detection of GW170817 and GRB 170817A [3]



Detection of GRBs associated with future NS-NS mergers

- ✓ Confirmation of the EM counterparts
- ✓ Constrain the jet physics (structured vs. cocoon breakout)
- ✓ Possible improvement in position accuracy

Other gamma-ray transients

- ➢ Soft gamma-ray repeaters (SGRs)
- ➢ Magnetars
- ➢ Terrestrial gamma-ray flashes (TGFs)
- ➢ Terrestrial electron beams (TEBs)
- ➢ Solar flares
- ➢ Other high-energy transients

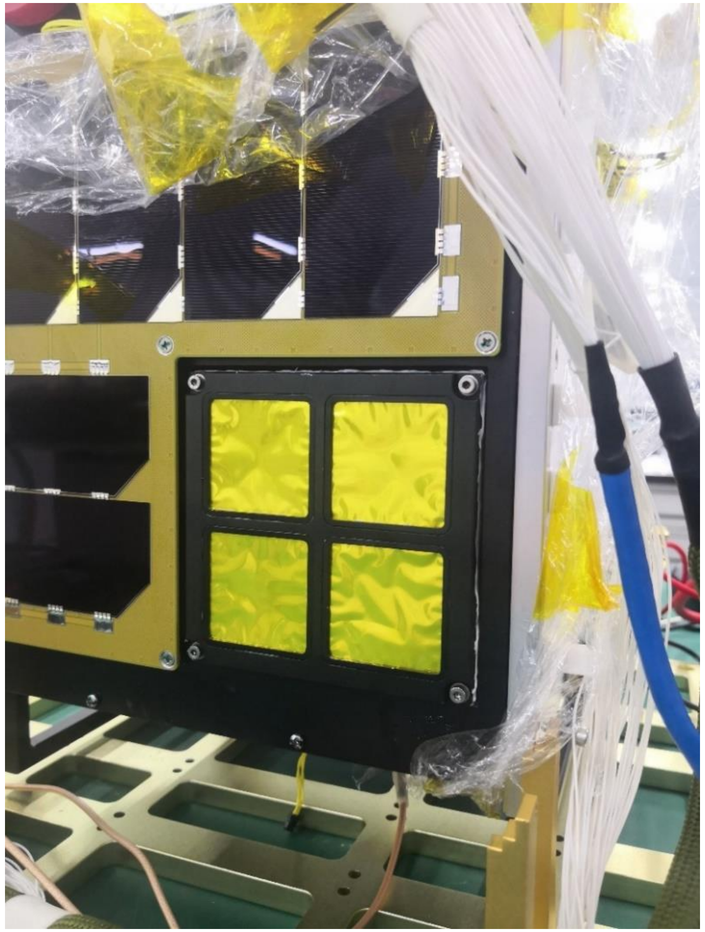
GRID: collect the first dozen GRBs associated with NS-NS mergers

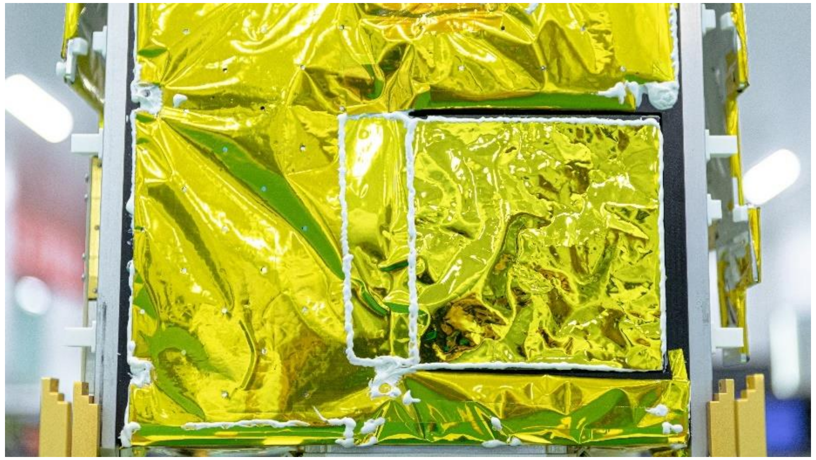
[3] B. P. Abbott *et al* 2017 *ApJL* **848** L13

History of GRID since 2016

- The GRID concept was first proposed in October of 2016 by a group of undergraduate students, inspired by discussions with several professors.
- The first and second detector (GRID-01 & GRID-02) have been launched in 2018 and 2020 respectively.
- 25 universities and institutes in China have joined the GRID collaboration.

GRID-02 Overview

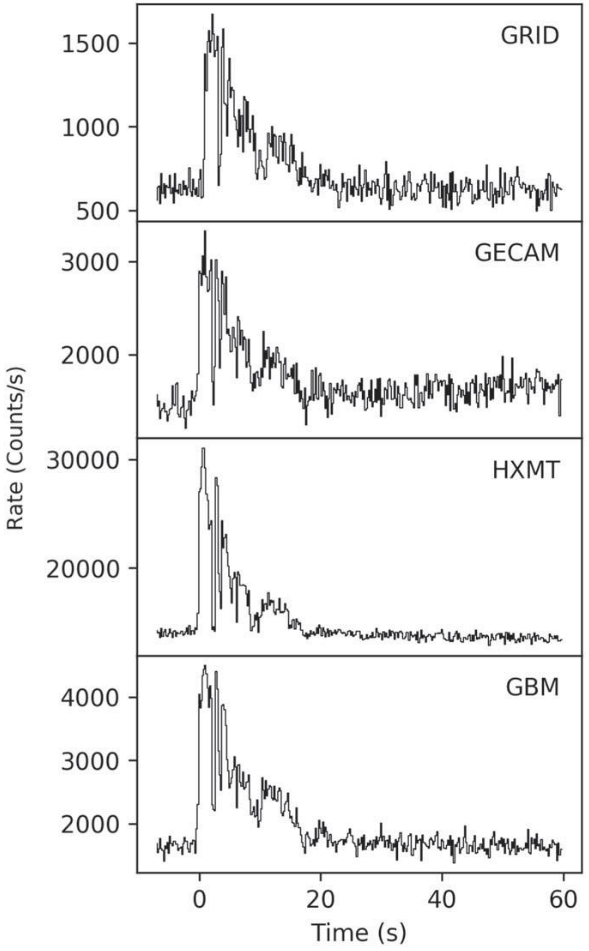




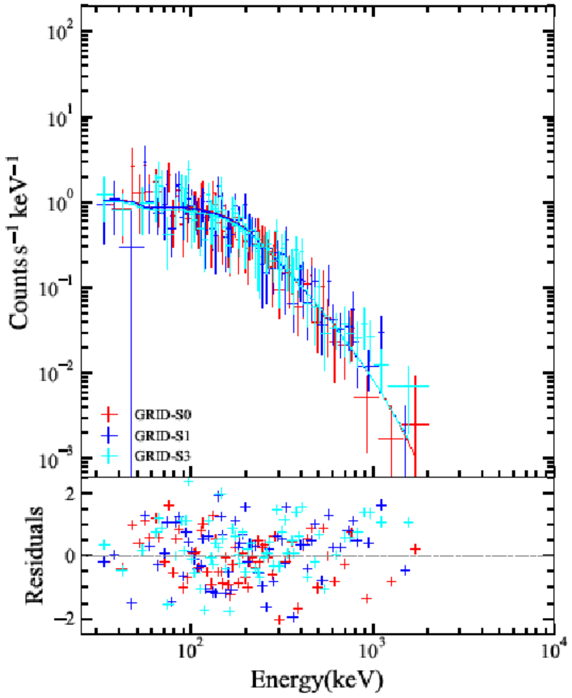
Spacetrack catalog number	46838
Orbit	464 x 474 km, 97.3°
Launch Date (UTC)	2020.11.06, 03:19
Launch site	Taiyuan Space Launch Center
Launch vehicle	Long March 6

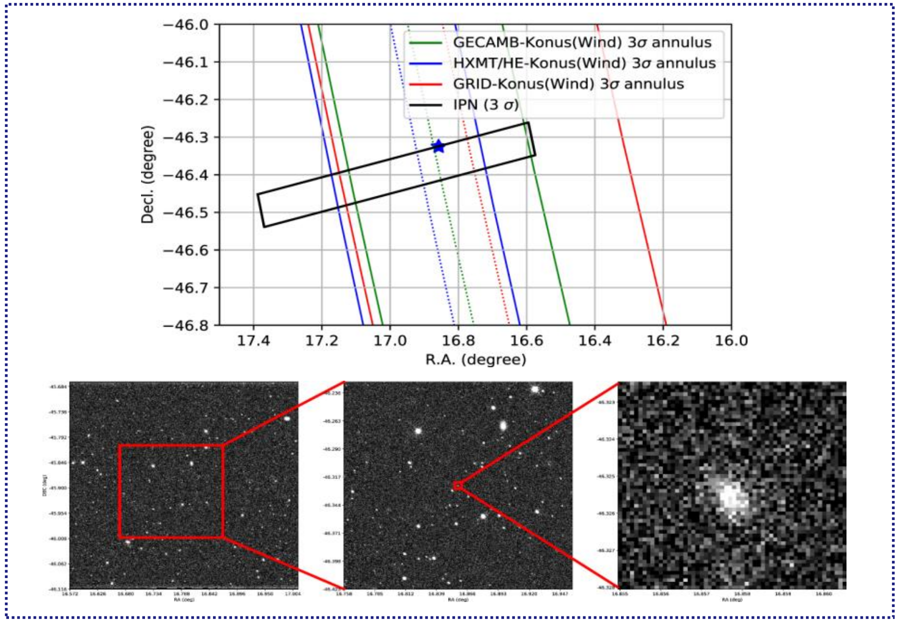
Data from https://www.heavens-above.com/

GRB 210121A: GRID-02 Detection



Light curves of the four missions [4]





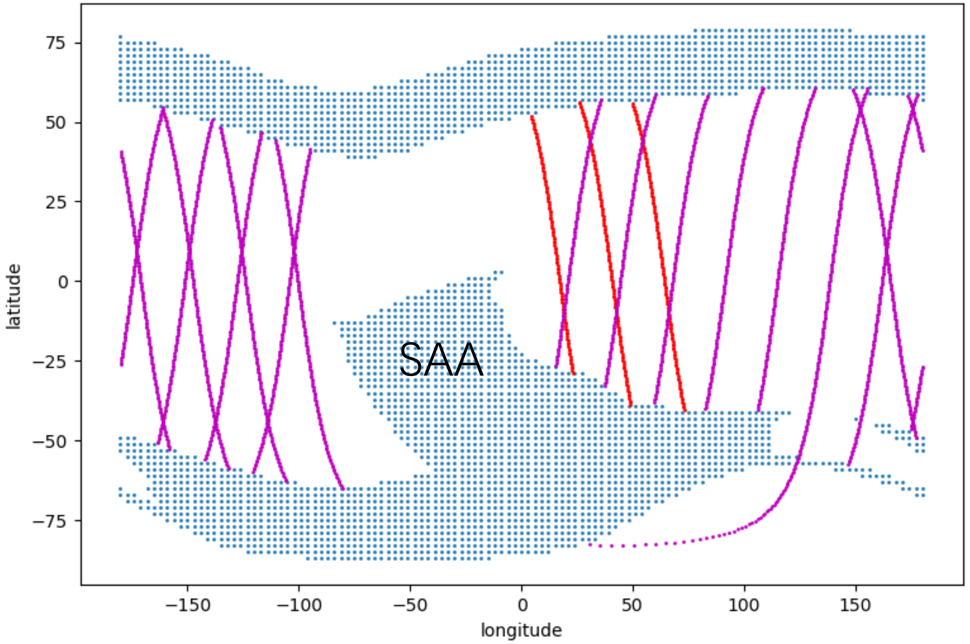
The joint localization of GRB 210121A [4]

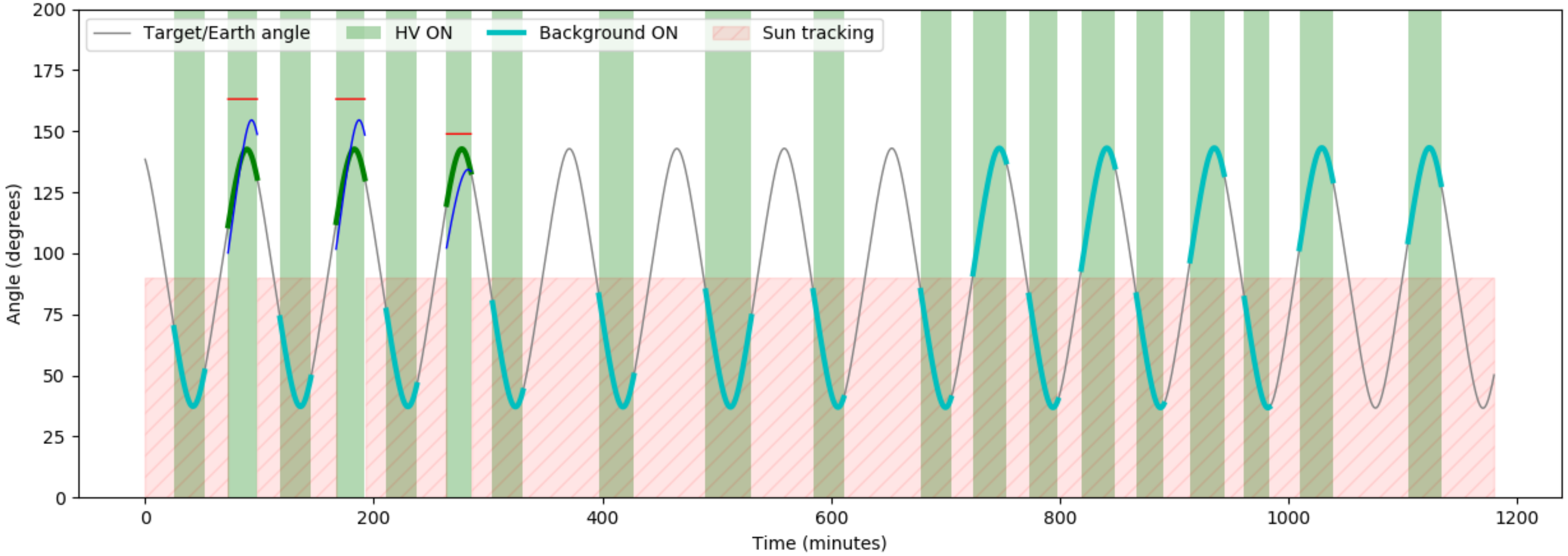
[4] Xiangyu Ivy Wang *et al*, GRB 210121A: A Typical Fireball Burst Detected by Two Small Missions, 2021 *ApJ* **922** 237

Daily Observation Phase

GRID 天格计划

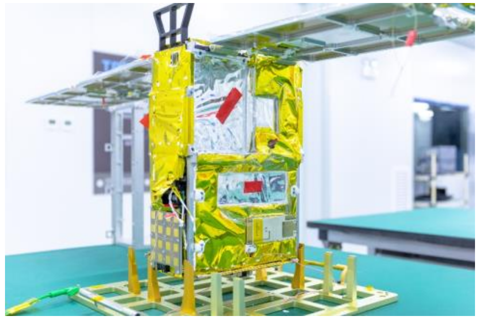
- Undergraduate students on duty make observation plan every day
- 10 ~ 20 observations per day, 20 ~ 40 minutes each (depends on other payloads and CubeSat platform)
- Shutdown in South Atlantic Anomaly (SAA) and high-latitude region
- ✓ Targeting observation: point to Crab (Inertial pointing mode)
- ✓ Non-targeting observation: random orientation (Inertial or magnetic sun tracking mode)

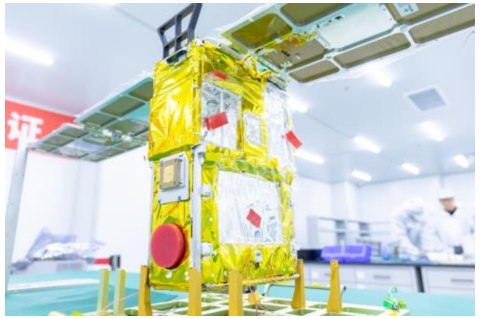




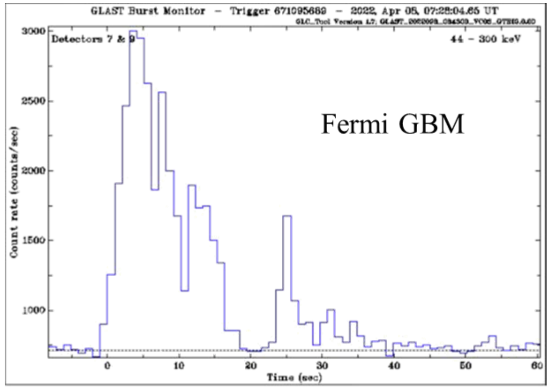
Example observation plan during Nov. 29 2020 17:00 ~ Nov. 30 2020 12:30 (UTC)

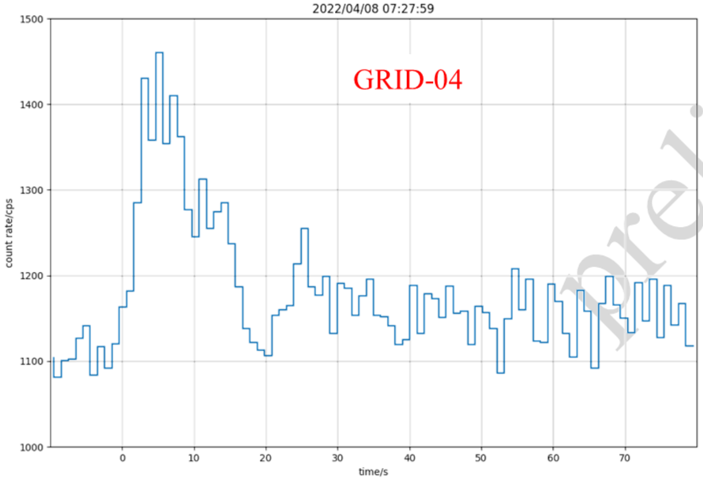
Preliminary Results from GRID-03b & GRID-04



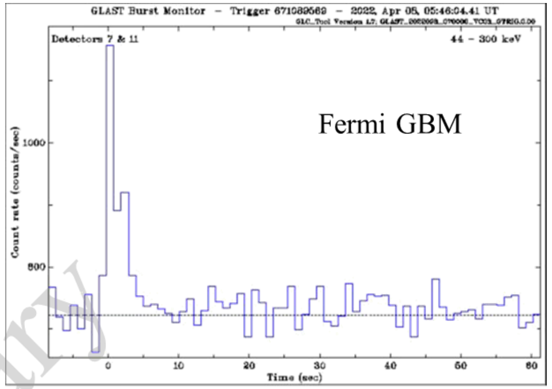


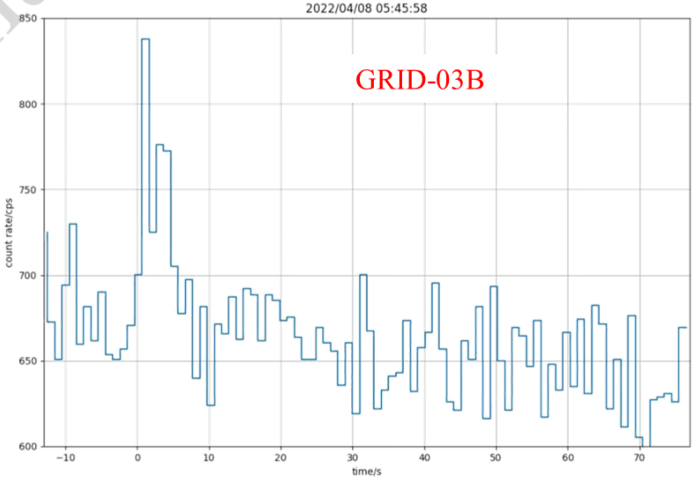
GRID-03B & GRID-04
Catalog number: 51830
Launched 02/27/2022





GRB 220408B

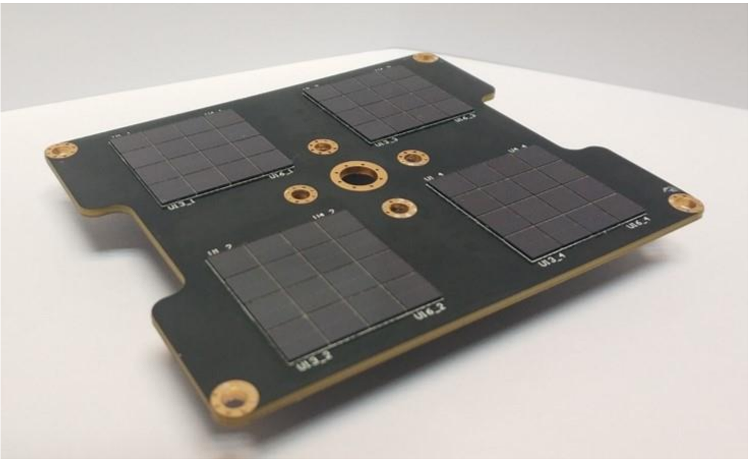




GRB 220408A

preliminary

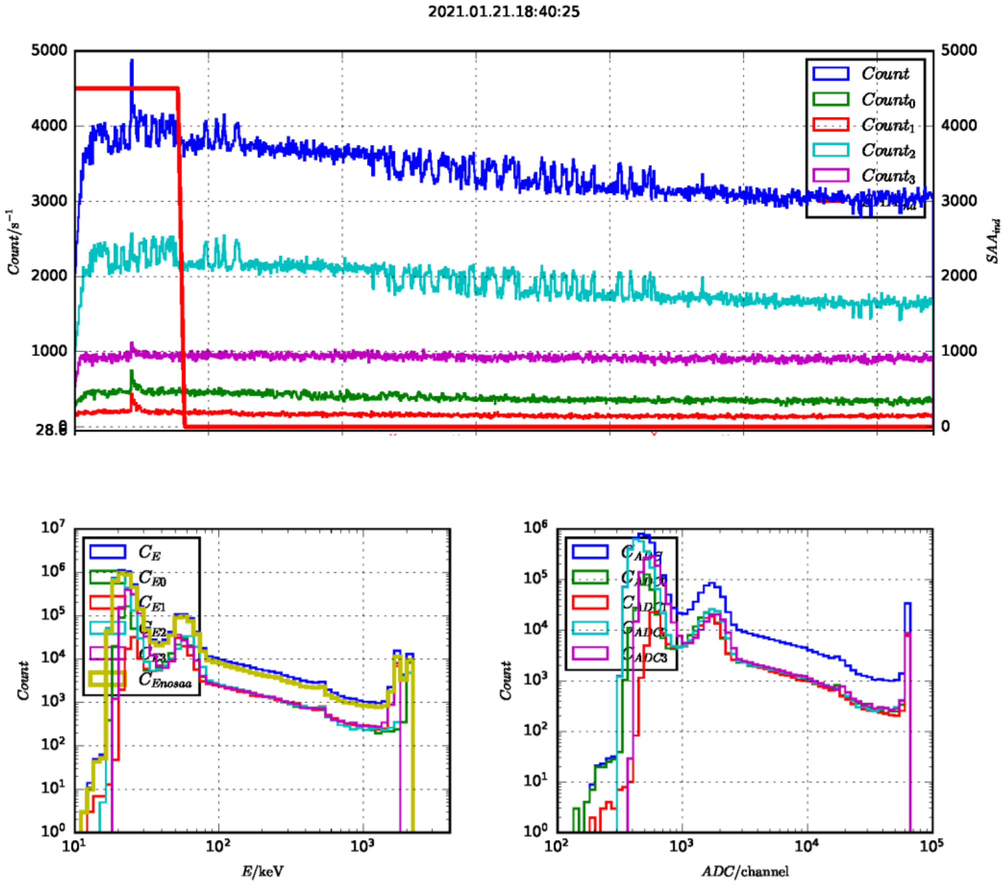
Silicon Photomultipliers

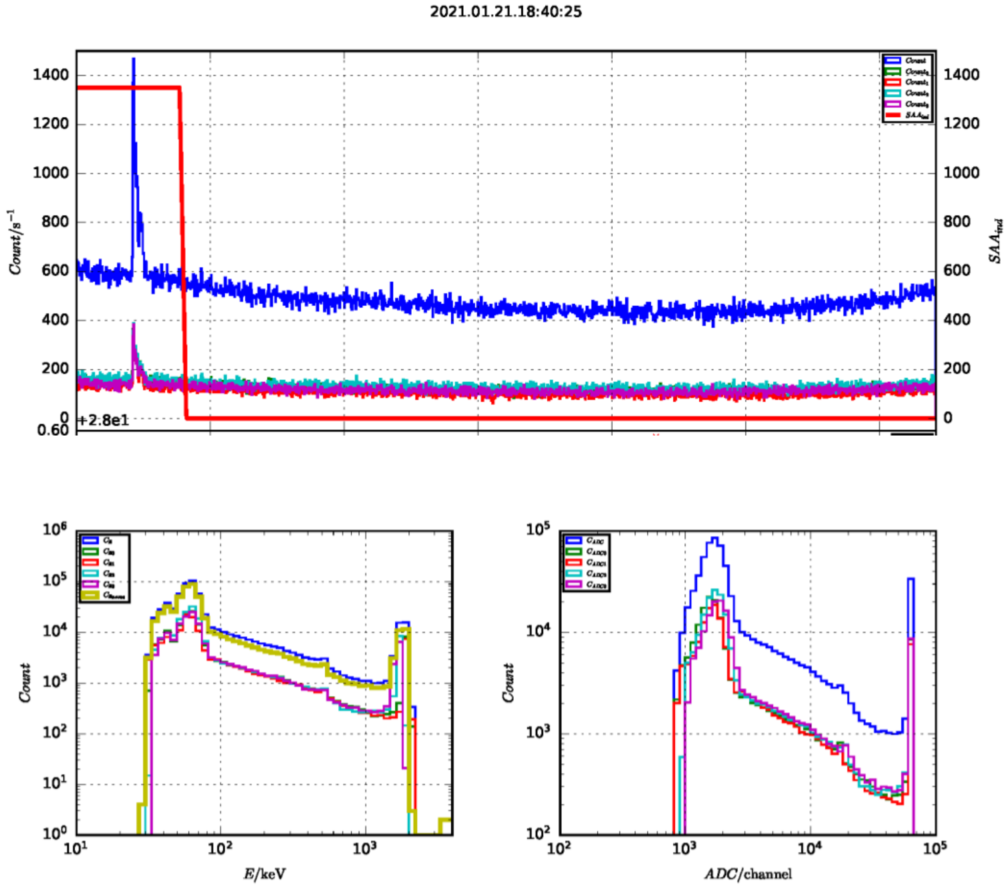


SensL MicroFJ-60035-TSV SiPM chip (top)
and the GRID SiPM array board (bottom)

Performance parameters specified by manufacturer	
Breakdown Voltage (V_{BD})	24.2 ~ 24.7 V
V_{BD} Temperature Coefficient	21.5 mV/℃
Overvoltage (V_{OV})	1 ~ 6 V
Operating Voltage	25.2 ~ 30.7 V
Dark Count Rate	50 kHz/mm^2 @+2.5 V V_{OV} 150 kHz/mm^2 @+6.0 V V_{OV}
Dark Current (Typ.)	0.9 μA @+2.5 V V_{OV} 7.5 μA @+6.0 V V_{OV}

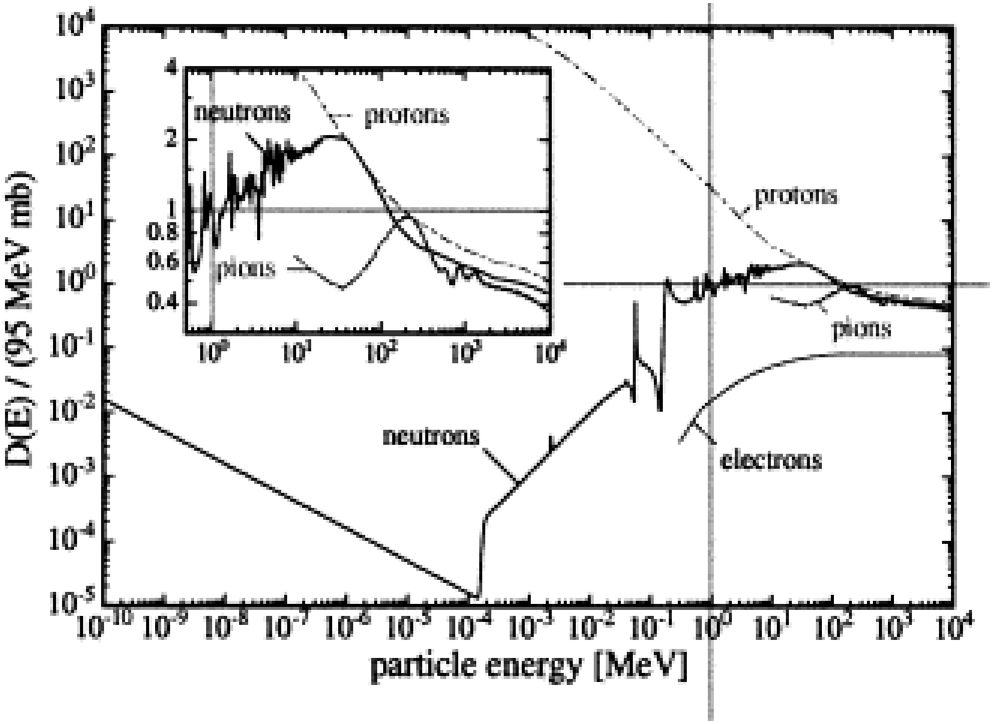
GRB 210121A: GRID-02 Detection



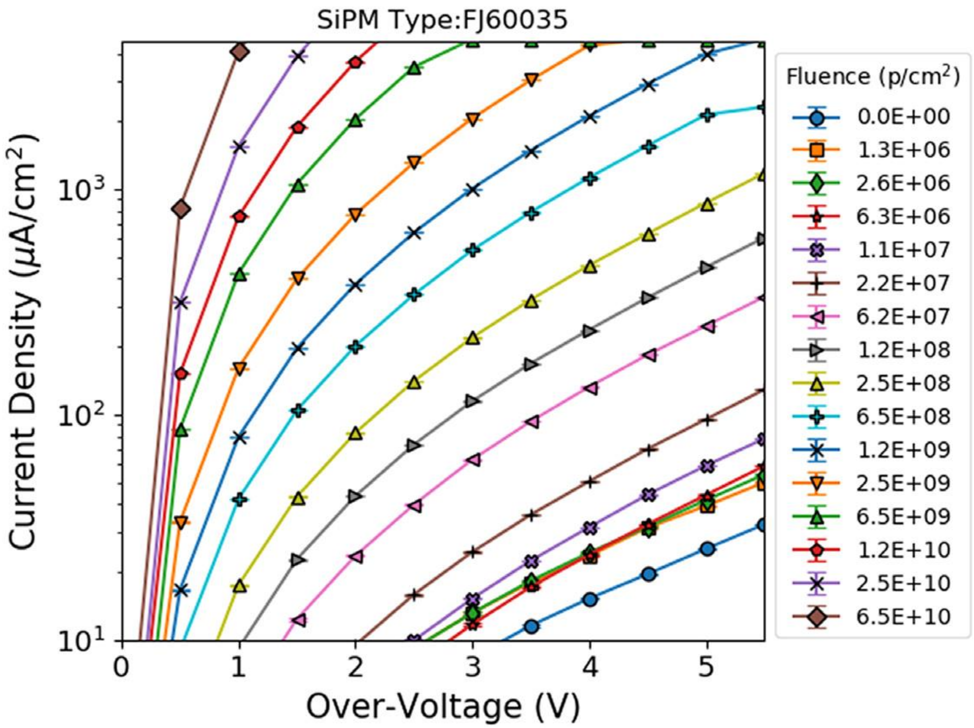


6σ cut-off
dark count noise

Radiation Damage of SiPMs



Non-ionizing energy loss (NIEL) for different particles in Si [5]



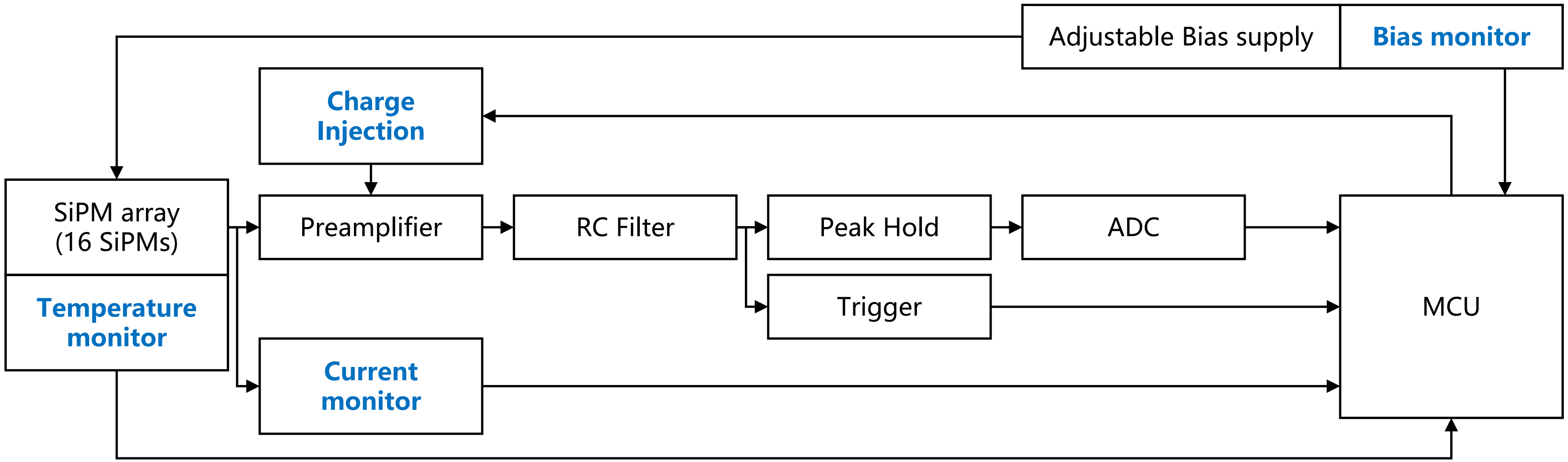
IV Curve for SensL MicroFJ-60035-TSV for the list proton fluence [6]

Proton —NIEL→ Bulk damage (defects) —Thermal excitation→ Dark current increase

[5] G. Lindström, Radiation damage in silicon detectors. *Nucl. Instrum. Methods Phys. Res. Sect. A.* **512**, 30–43 (2003)

[6] Mitchell, L. et al., Radiation damage assessment of SensL SiPMs. *Nucl. Instrum. Methods Phys. Res. Sect. A.* **988**, 164798 (2021)

In-orbit Characterization Setup and Methods



Block diagram of the front-end electronics and characterization circuits of one channel in GRID detector. Details about GRID instrument design can be found in [2].

Housekeeping data:

- Timestamp
- Bias voltage
- Current
- Temperature

Scientific observation: ~20k seconds (5 ~ 6 hours) per day

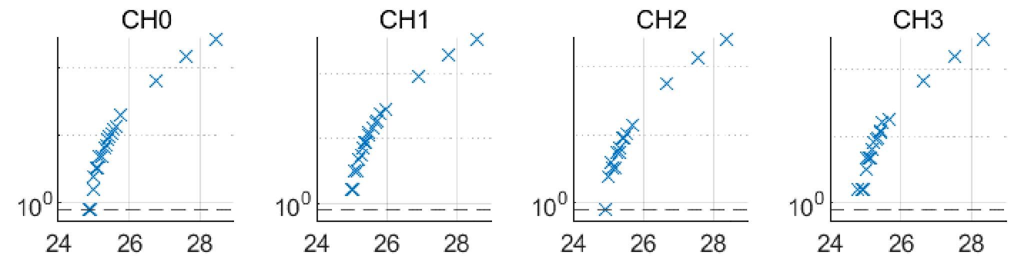
- Housekeeping data recorded to analyze SiPM dark current

Daily characterization experiments:

- I-V measurement at different bias voltage
- Charge injection test without and with bias voltage

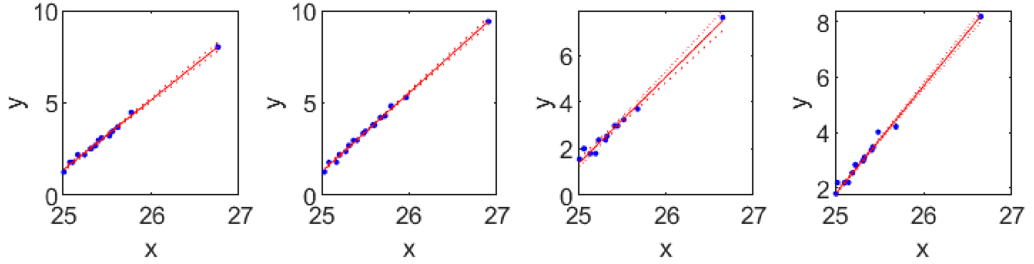
[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Breakdown Voltage Determination

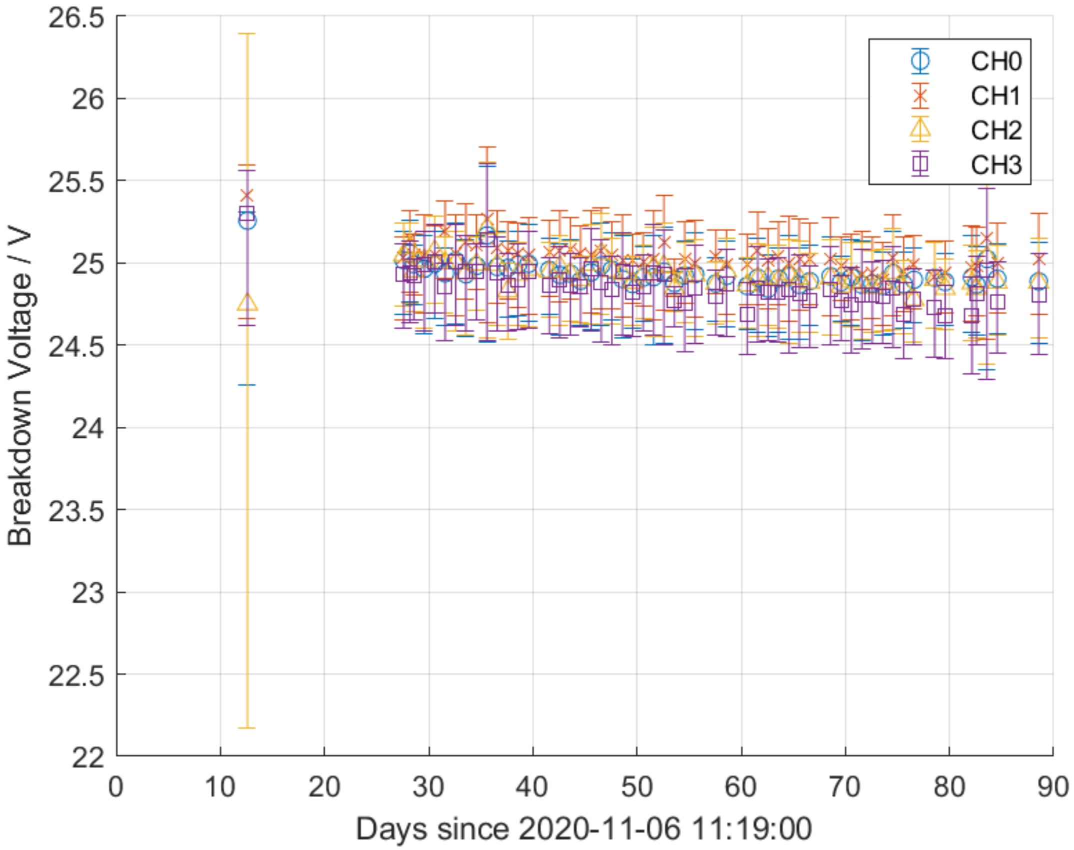


↑ I vs. V

↓ Fit of $\sqrt{I} = k \times (V - V_{\mathrm{BD}})$



An example result of the daily I-V measurement at different bias voltages



V_{BD} corrected to 21℃ with the 21.5 mV/℃ temperature coefficient specified in datasheet

Dependence of Dark Current

- Dark current is dominated by dark count

$$
\begin{aligned}
I_{\text{dark}} &= DCR \cdot (Gain \cdot e) \cdot ECF \\
&= DCR \cdot C_{\text{pix}} \cdot (V_{\text{bias}} - V_{\text{BD}}) \cdot ECF \\
&\propto DCR(T) \cdot \left(V_{\text{bias}} - V_{\text{BD}}(T)\right)
\end{aligned}
$$

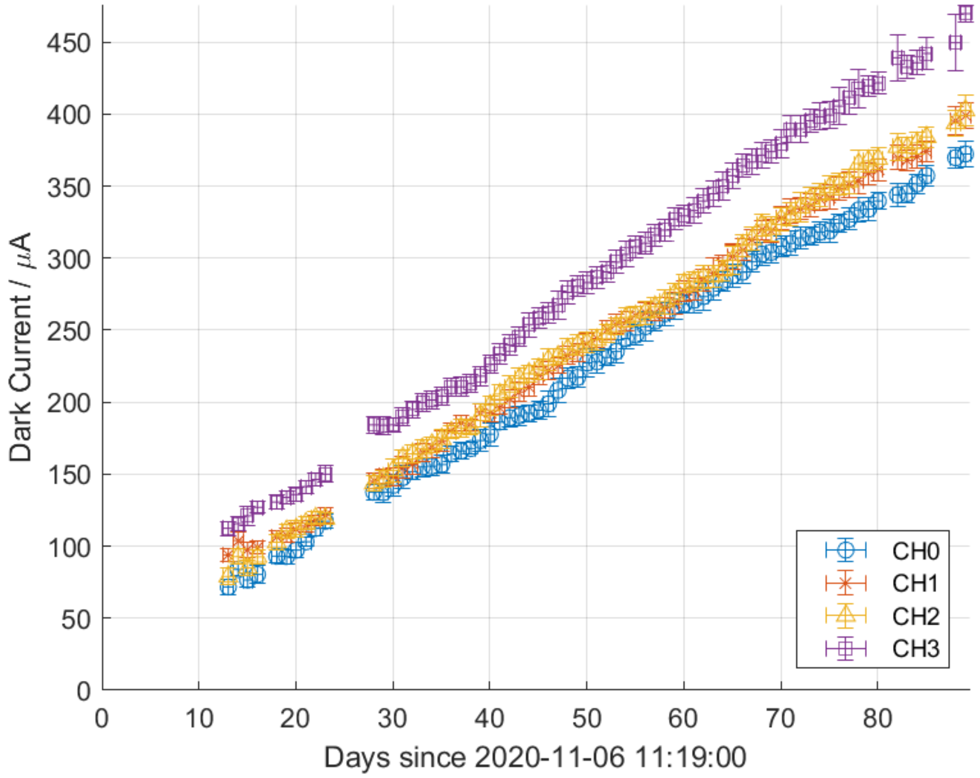
- V_{bias} keeps 28.5 V

- FE-SRH model [7] indicates the temperature dependence of dark count rate:

$$DCR \propto \left(1 + 2\sqrt{3\pi}\frac{F_{\text{eff}}}{(kT)^{3/2}} \mathrm{e}^{\left(\frac{F_{\text{eff}}}{(kT)^{3/2}}\right)^2}\right) T^2 \mathrm{e}^{-\frac{E_{\text{a}}}{kT}}$$

[7] G. A. M. Hurkx et al., A new analytical diode model including tunneling and avalanche breakdown. *IEEE Transactions on Electron Devices*, vol. 39, no. 9, pp. 2090-2098 (1992)

Dark Current Increase



Dark current increasing rate:

GRID-02: ~ 93/96/98/110 μA / (year · chip) @5 ℃ & 28.5 V

~ 50 μA / (year · chip) @-20 ℃ & 28.5 V

SIRI-1: ~ 132 μA / (year · chip) @28.5 V, temp. not mentioned (22 ℃?) [4]

Dark current corrected to 5℃, a typical temperature of GRID-02. The current values are the sum of 16 SiPMs in the same channel.

Dark Current Prediction

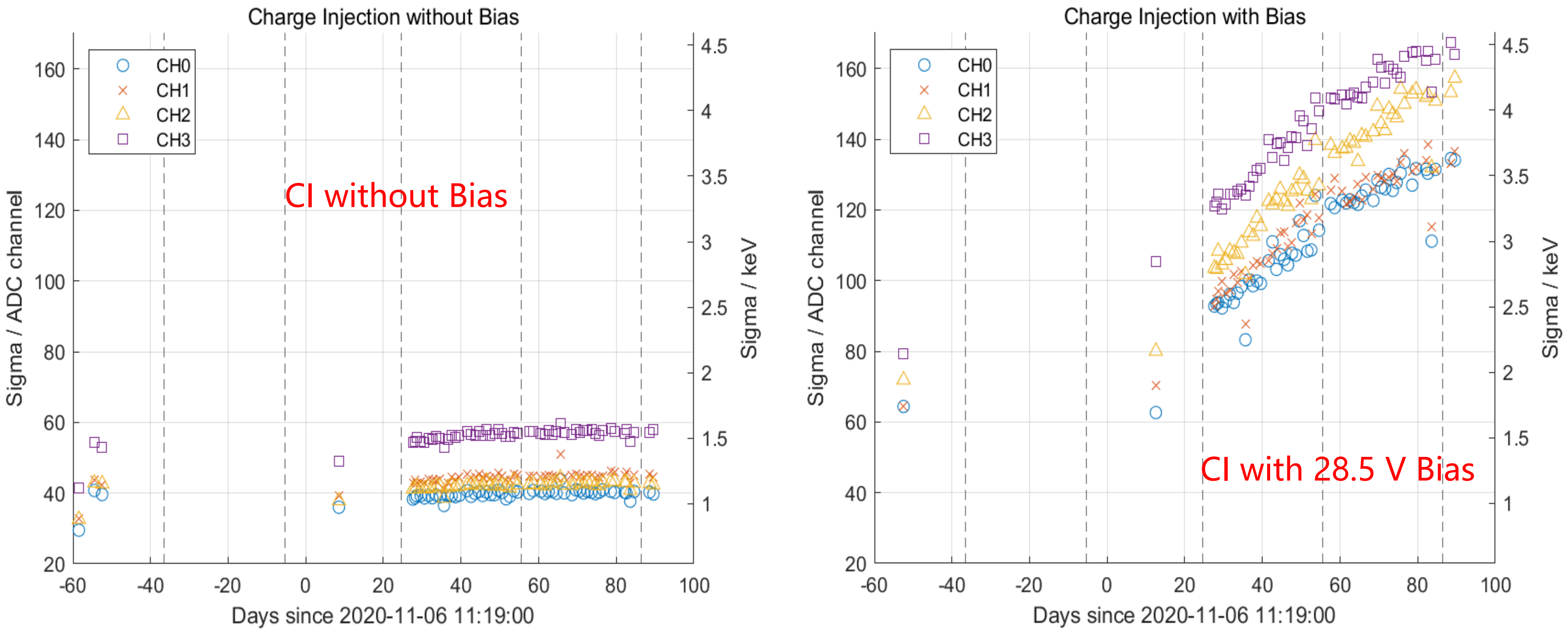
- Linear relationship between I_{dark} and radiation damage (dose or particle fluences) is found [4,5]
- Assuming:
  - Linear relationship between radiation damage and Time
  - F_{eff} independent of radiation damage

$$I_{\text{dark}} = (A \cdot Time + B) \cdot \left(1 + 2\sqrt{3\pi}\frac{F_{\text{eff}}}{(kT)^{3/2}} \mathrm{e}^{\left(\frac{F_{\text{eff}}}{(kT)^{3/2}}\right)^2}\right) T^2 \mathrm{e}^{-\frac{E_a}{kT}} \cdot \left(V_{\text{bias}} - V_{\text{BD}}(T)\right)$$

- An approximate empirical equation around room temperature is

$$I_{\text{dark}}(\mu\text{A}) = 16 \cdot (0.26 \cdot Time(\text{Days}) + 1.96) \cdot e^{0.03428 \cdot (T - 273.15 - 5)}$$

Noise Assessment Through Charge Injection



CI peak width (sigma) vs. time (days)

- Overall noise includes dark count noise and electronics noise

$$\sigma_{\text{total}}^2 = \sigma_{\text{dark current}}^2 + \sigma_{\text{electronics}}^2$$

Noise Contributions Analysis

- Overall noise includes dark count noise and electronics noise

$$\sigma^2_{\text{total}} = \sigma^2_{\text{dark current}} + \sigma^2_{\text{electronics}}$$

- Campbell’ s theorem gives

$$\sigma^2_{\text{dark current}} = DCR \cdot (Gain \cdot e)^2 \cdot \int h^2(t)\,\mathrm{d}t$$

$$\propto I_{\text{dark}} \cdot (V_{\text{bias}} - V_{\text{BD}})$$

Noise Assessment Through Charge Injection

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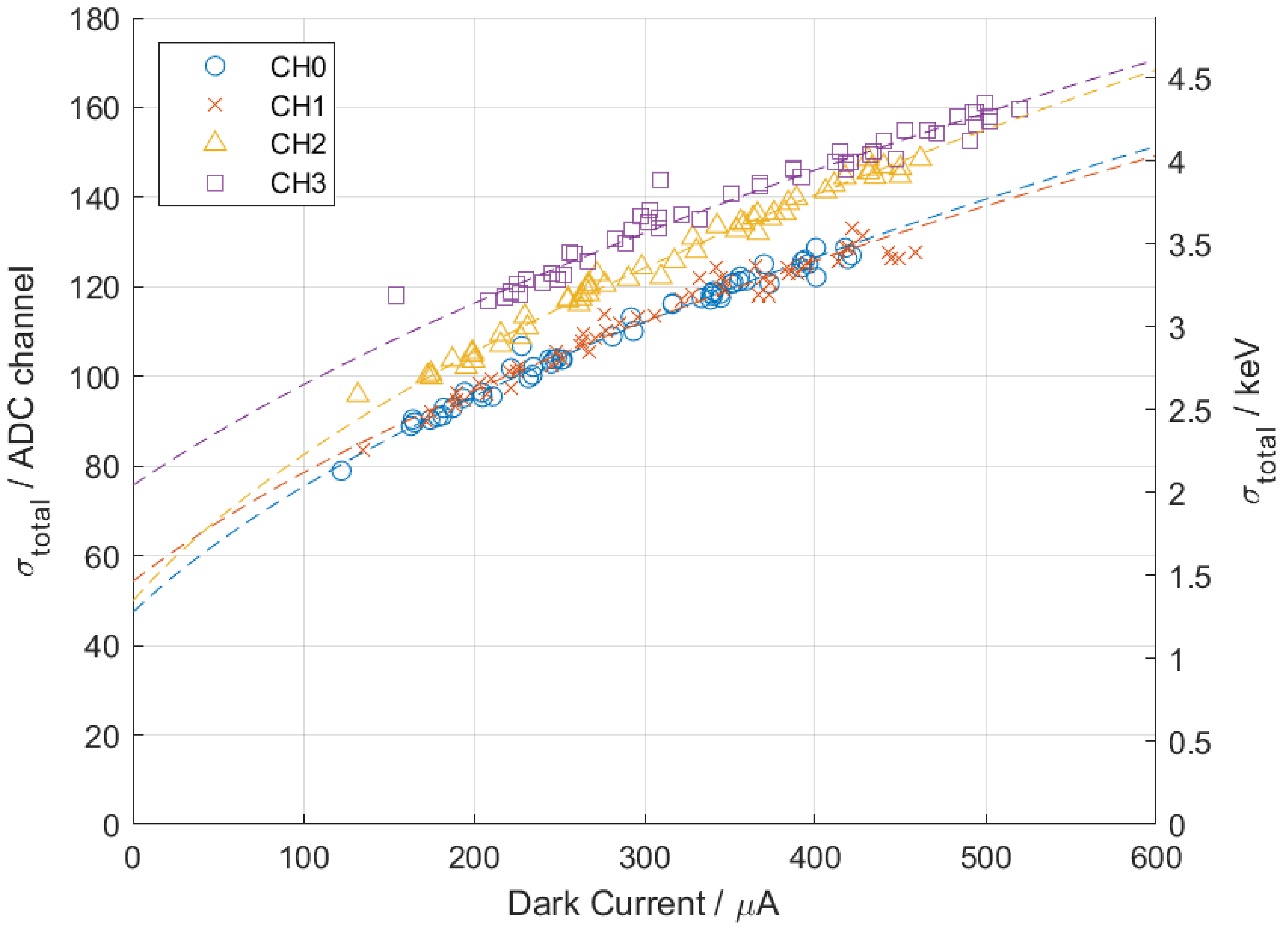
$$\sigma^2_{\text{dark current}} = DCR \cdot (Gain \cdot e)^2 \cdot \int h^2(t)\,\mathrm{d}t$$

$$\propto I_{\text{dark}} \cdot (V_{\text{bias}} - V_{\text{BD}})$$

GRID-02 energy-channel calibration result [8]



Noise (sigma) increasing rate: ~ 7.5 keV/year

[8] H. Gao, et al., GRID Collaboration, On-ground calibrations of the GRID-02 gamma-ray detector, Exp Astron. (2021).

Methods of Improve SNR

- Dominant noise for radiation damaged SiPM:

$$\sigma^2_{\text{dark current}} = DCR \cdot (Gain \cdot e)^2 \cdot \int h^2(t)\,\mathrm{d}t$$

① Lower temperature, lower DCR
- DCR reduced by half for 16℃ decrease at room temperature
- Difficult for CubeSats ?

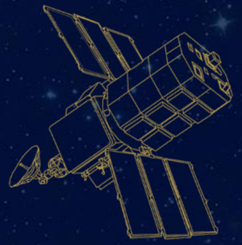
② Lower bias voltage, lower DCR
- Trade off: Gain & PDE decrease as well
- Care must be taken to find the optimum value

③ Lower readout time constant
- Limited by scintillation decay time

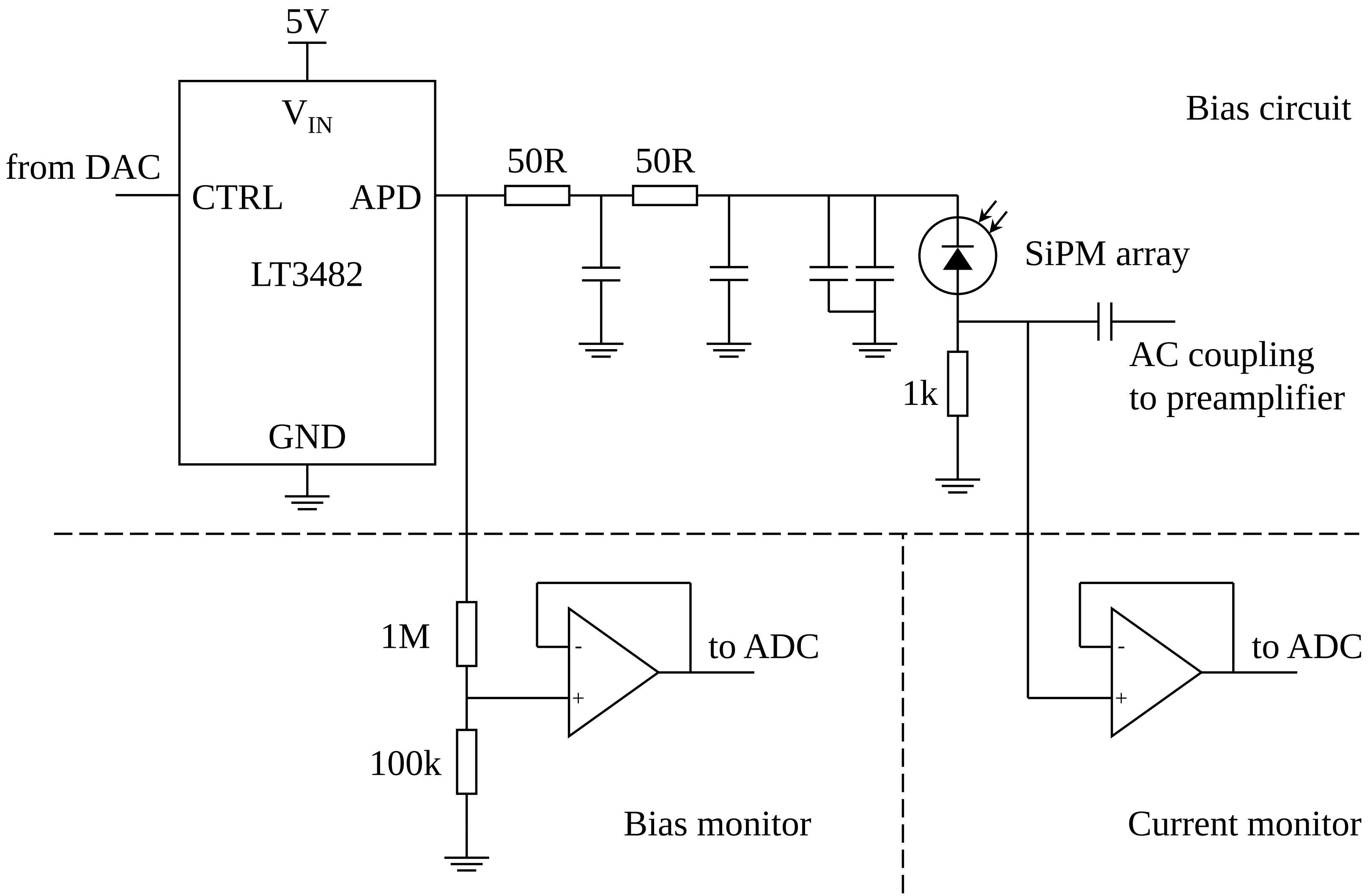
Conclusion

- GRID is a CubeSat detector designed with SiPM characterization setups.
- The characterization results of SiPM in GRID-02 are essentially in agreement with previous results.
- GRID-02 observes an increase in dark current of ~ 100 μA / (year · chip) at 5 ℃ and 28.5 V bias voltage for MicroFJ-60035-TSV SiPM.
- An approximate empirical equation around room temperature is given for estimate dark current.
- The noise level (sigma) increasing rate of GRID-02 is ~ 7.5 keV / year.
- CubeSat is a good platform for research on the performance degradation and lifetime evaluation of SiPM.

Thank you !



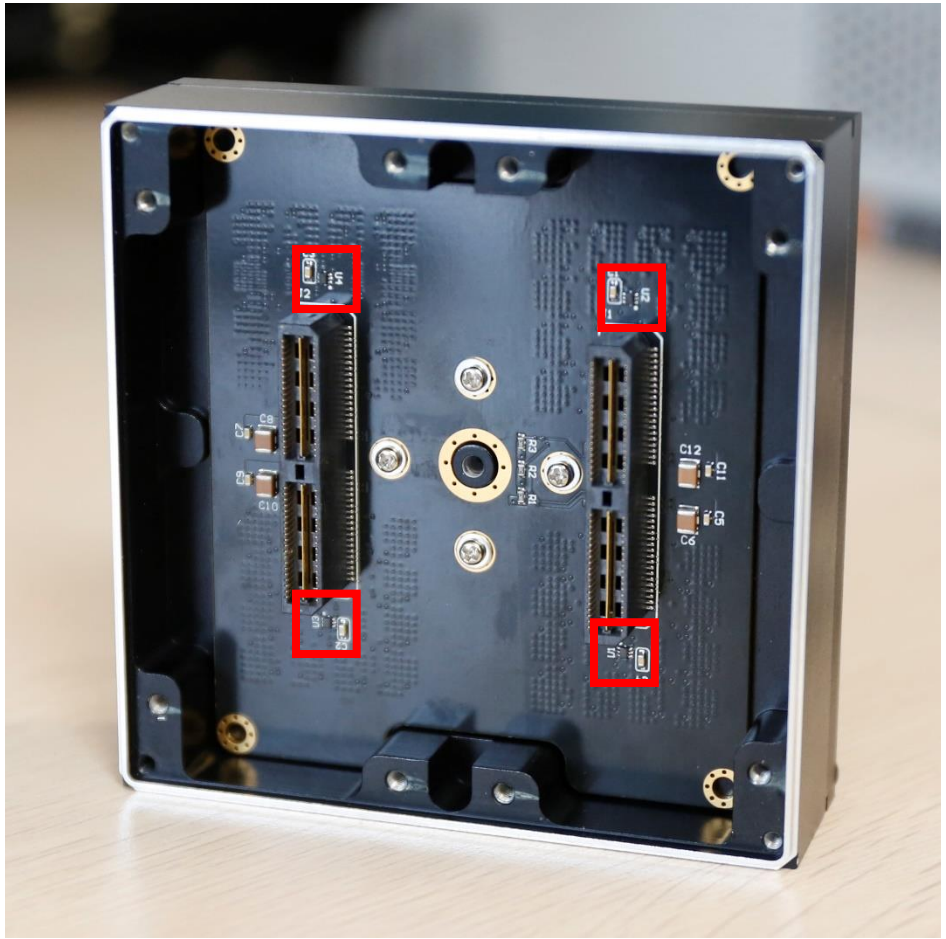
Backup: I-V Measurement Setup

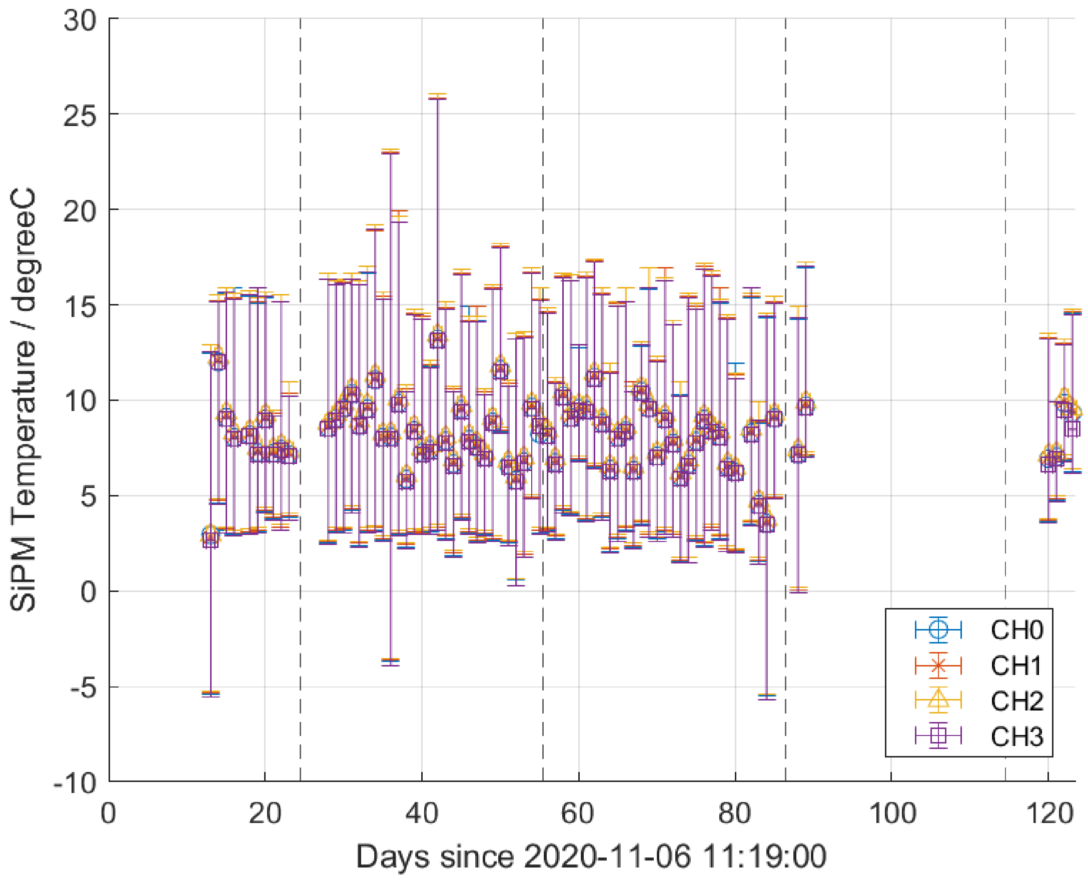


Schematic layout of the bias voltage monitor and current monitor in GRID detector. More details about GRID instrument design can be found in [1].

[1] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Backup: the Digital Temperature Sensor TMP112





The sensors are placed on the opposite side of SiPM chip on the printed circuit board (PCB) right below the SiPM arrays to get better heat conduction.

Backup: Fit of I_{dark} vs. Temperature

$$I_{gen} \propto T^2 e^{-\frac{E_a}{kT}}$$

$$I_{gen+tat} \propto (1+\Gamma)T^2 e^{-\frac{E_a}{kT}}$$

$$\Gamma \approx \frac{F_{eff}}{(kT)^{\frac{3}{2}}} e^{\left(\frac{F_{eff}}{(kT)^{\frac{3}{2}}}\right)^2}$$

$$E_a = 0.605\ \text{eV}$$

E. Garutti and Y. Musienko 2019

• Recombination via traps $R_{trap}(x)$. This term, which contains not only the conventional Shockley–Read–Hall mechanism but also tunneling via traps [1]–[4], is given by

$$R_{trap}(x) = (1 + \Gamma(x))R_{SRH}(x). \quad (4)$$

The function Γ, which accounts for the effects of tunneling on both the density of captured carriers by a trap and the emission rate of carriers from a trap, is given by

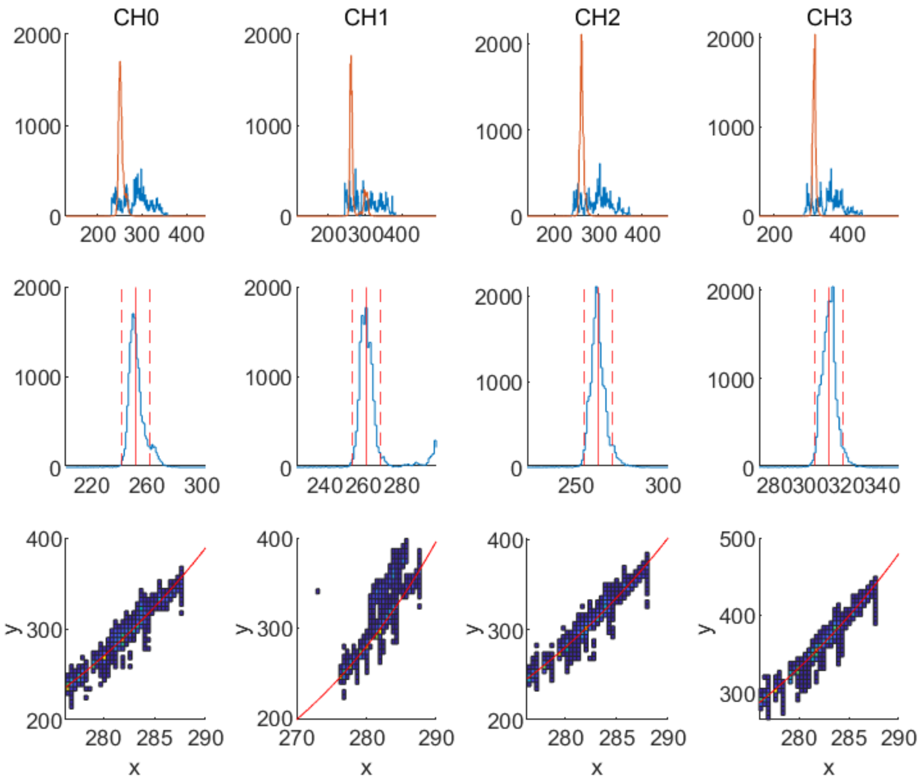
$$\Gamma = 2\sqrt{3\pi}\,\frac{|F|}{F_\Gamma}\exp\,(F/F_\Gamma)^2 \quad (5)$$

with

$$F_\Gamma = \frac{\sqrt{24m^*(kT)^3}}{q\hbar} \quad (6)$$

where F is the local electric field and m^* ($m^* = 0.25m_0$ [8]) is the effective mass of the carriers. A derivation of (5) is given in [8]. This expression is valid for $F < F_\Gamma(\Delta E/3kT)^{1/2}$, where ΔE is related to the trap level and under reverse bias conditions equal to $E_g/2$ for midgap states [8]. For stronger electric fields (i.e., stronger than

Hurkx et al. 1992



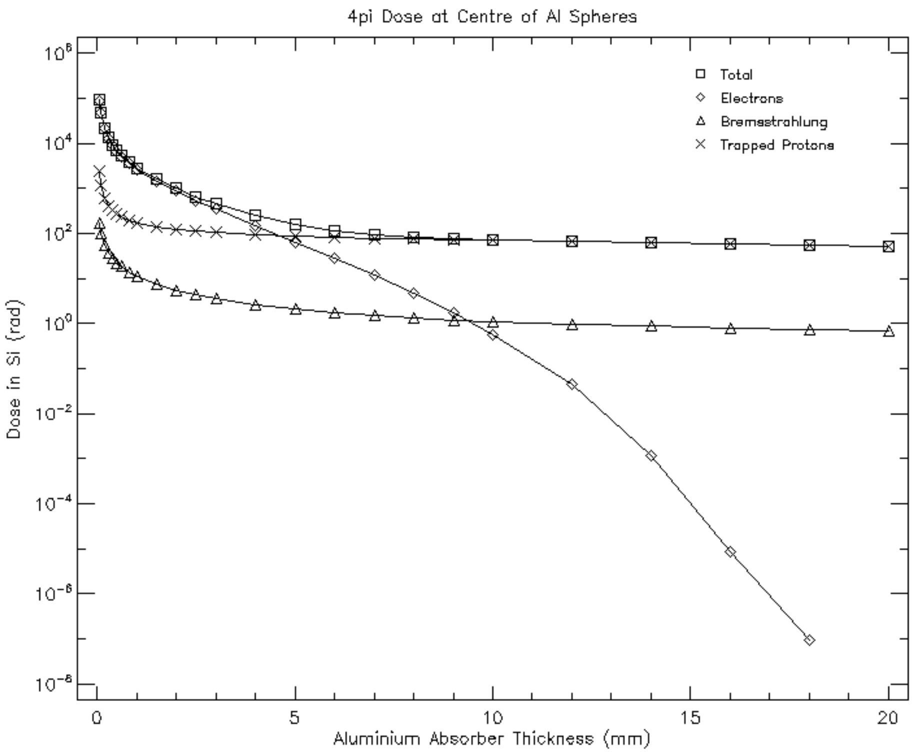
A * (9.9242-0.0215*x) * (1 + 2 * sqrt(3 * pi) * C / x^(3/2) * exp(C^2 / x^3)) * x^2 * exp(-7011.195459526643/x)

Gain

FE

SRH

Preliminary Dose Estimation



Annual dose in Si as a function of Al shielding thickness for GRID-02 given by SHIELDOSE-2 from SPENVIS
Trapped radiation model: AP-8 & AE-8, solar minimum

Dose asymptotically approaches 50 rad/year
The empirical formula becomes:

$$I_{\text{dark}}(\mu\text{A}) = 16 \cdot (1.9 \cdot Dose(\text{rad}) + 1.96) \cdot e^{0.03428\cdot(T-273.15-5)}$$

For SIRI-1, the dose is ~100 rad/year [4]
The expected I_{dark} at 22 ℃ is ~330 μA (annealing not considered)