Radiation characterization for space missions

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Co-advisor: Felicia Barbato

2nd year activity report

16/10/2025

Overview

Radiation Hardness for the NUSES space mission:

- The NUSES space mission
- Simulation of the radiation environment
- Characterization of FBK NUV-HD-MT/RH SiPM
- TID test at ESTEC Co60 facility
- Proton test at PIF facility PSI, FBK/HAMAMATSU SiPM
- Comparison of the dose calculation strategy
- Industrial Period Activity
- Next short-term and long-term project activities

Astrodynamic simulations for the Crystal Eye and WINK missions:

- Earth/Moon occultation strategies for astronomical sources estimation
- Solar exposure estimation of the WINK payload on orbit

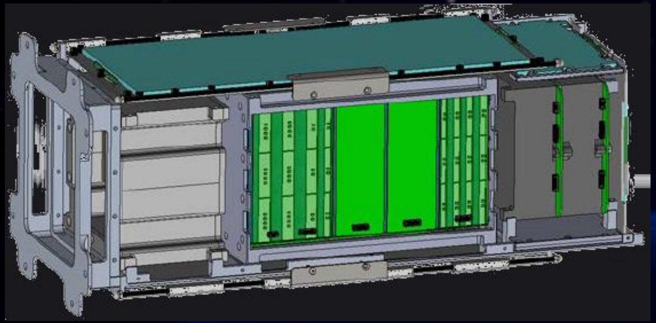
NUSES in a Nutshell

GRAN SASSO SCIENCE INSTITUTE

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

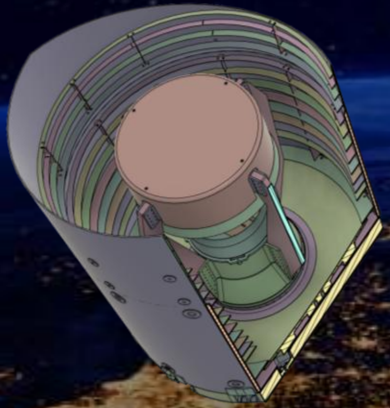
Mission Goals

Ziré



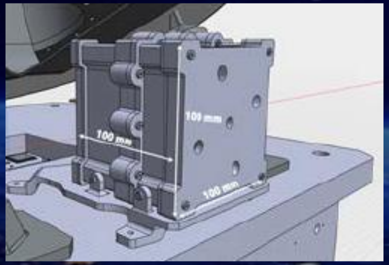
- To monitor the fluxes of low energy(< 300 MeV) **e,p, and low Z nuclei** of solar/galactic origin;
- To study the cosmic radiation variability (**Van Allen Belts**);
- To look for possible correlation with **seismic activity**;
- To study transient and steady **gamma sources**[0.1-30MeV];

Terzina



- To measure **UHE cosmic rays** and enable **neutrino astronomy** through space-based atmospheric Cherenkov light detection;

Low Energy Module (LEM)



- to detect low-energy fluxes of **e** in the 0.1–7-MeV range and **p** in the 3–50 MeV range

Gran Sasso Science Institute
Gran Sasso National Laboratory
University of L'Aquila
University of Geneva
University of Trento and INFN-TIFPA
University of Bari and INFN Bari
University of Turin and INFN Turin
University "Federico II" and INFN Napoli
University of Salento and INFN Lecce
University of Padua and INFN Padua
University of Chicago

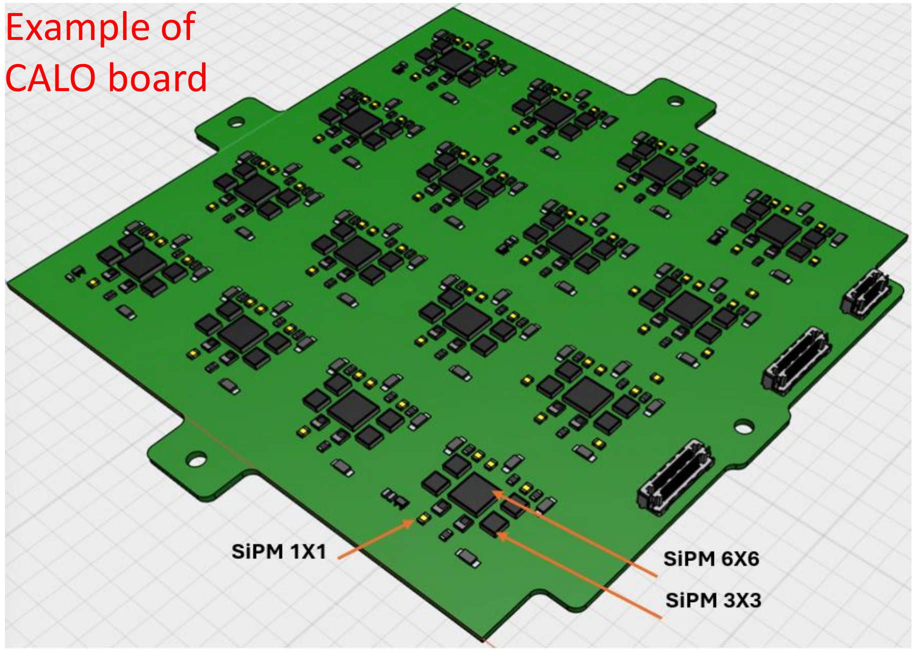
Technological Challenges

The crucial objectives of the mission are also to develop new observational techniques, to test **Silicon Photo Multiplier (SiPM)** and **related electronics/DAQ** for space missions.

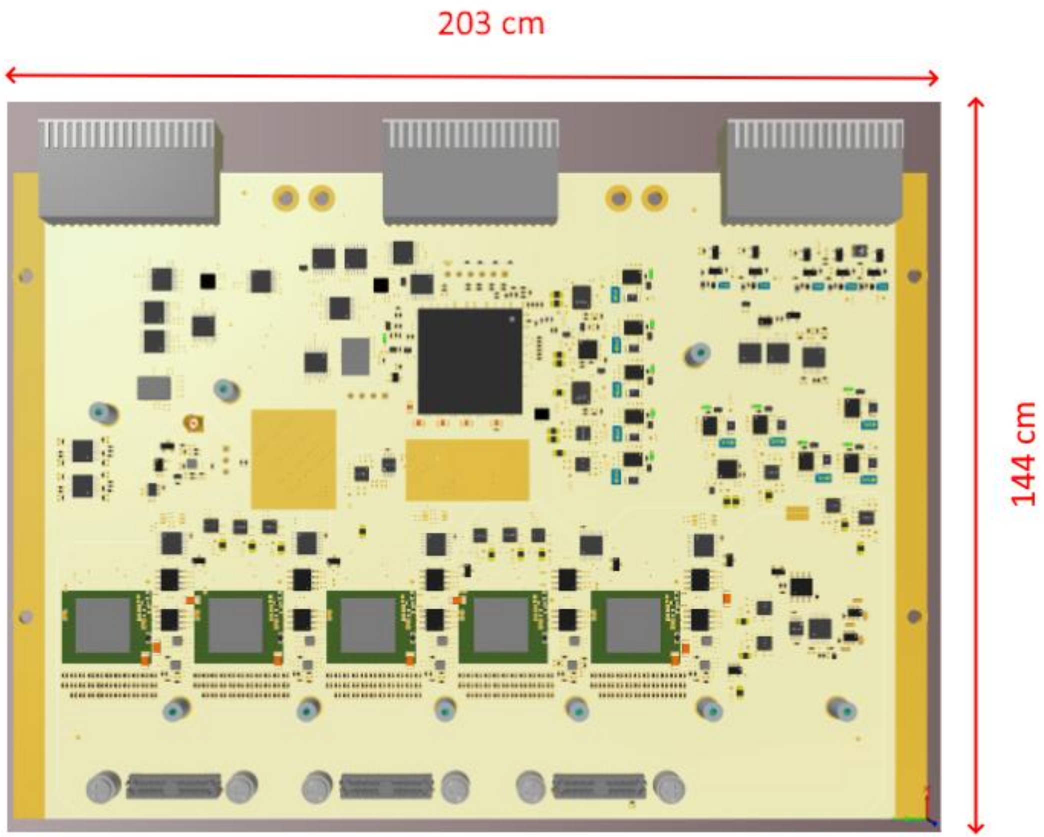
Critical tests are those related to radiation damage, in particular:

- Total Ionizing Dose
- Single Event Effect
- Total non-Ionizing Dose

Example of CALO board



Massive use of SiPMs (Silicon PhotoMultipliers, FBK) and MPPC (Multi-Pixel Photon Counters, Hamamatsu Photonics) in Space. Total surface covered by SiPMs = 11420 mm^2

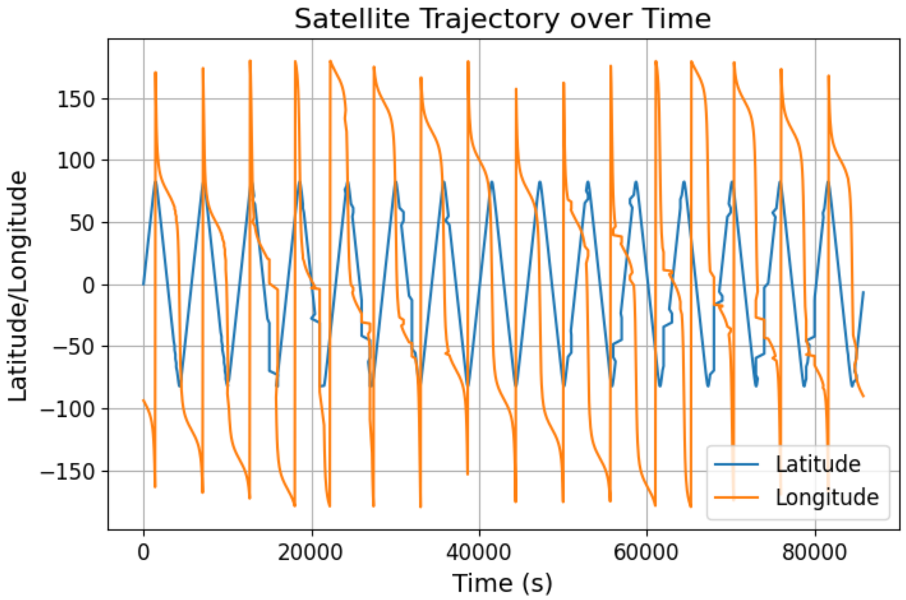


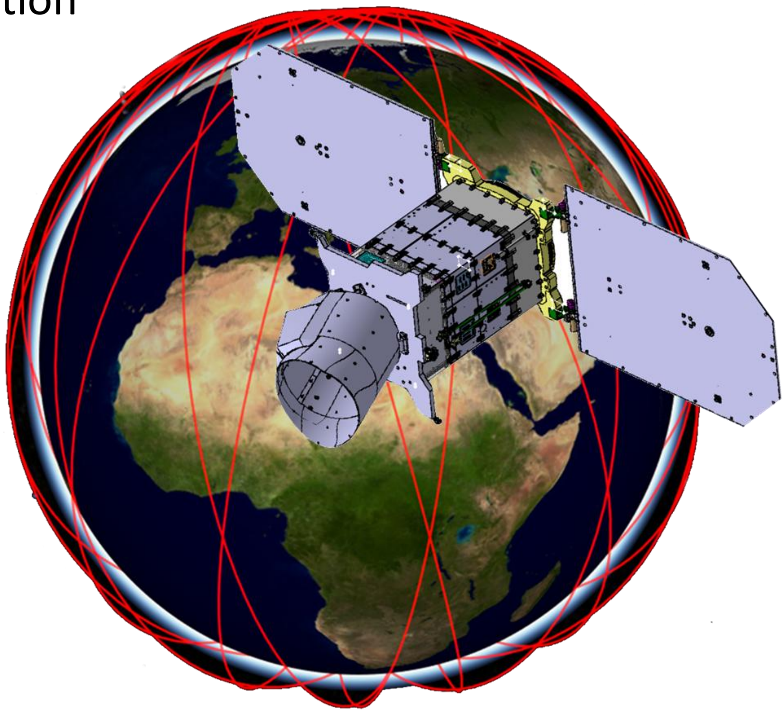
Electronics mostly based on the use of COTS

The NUSES orbit

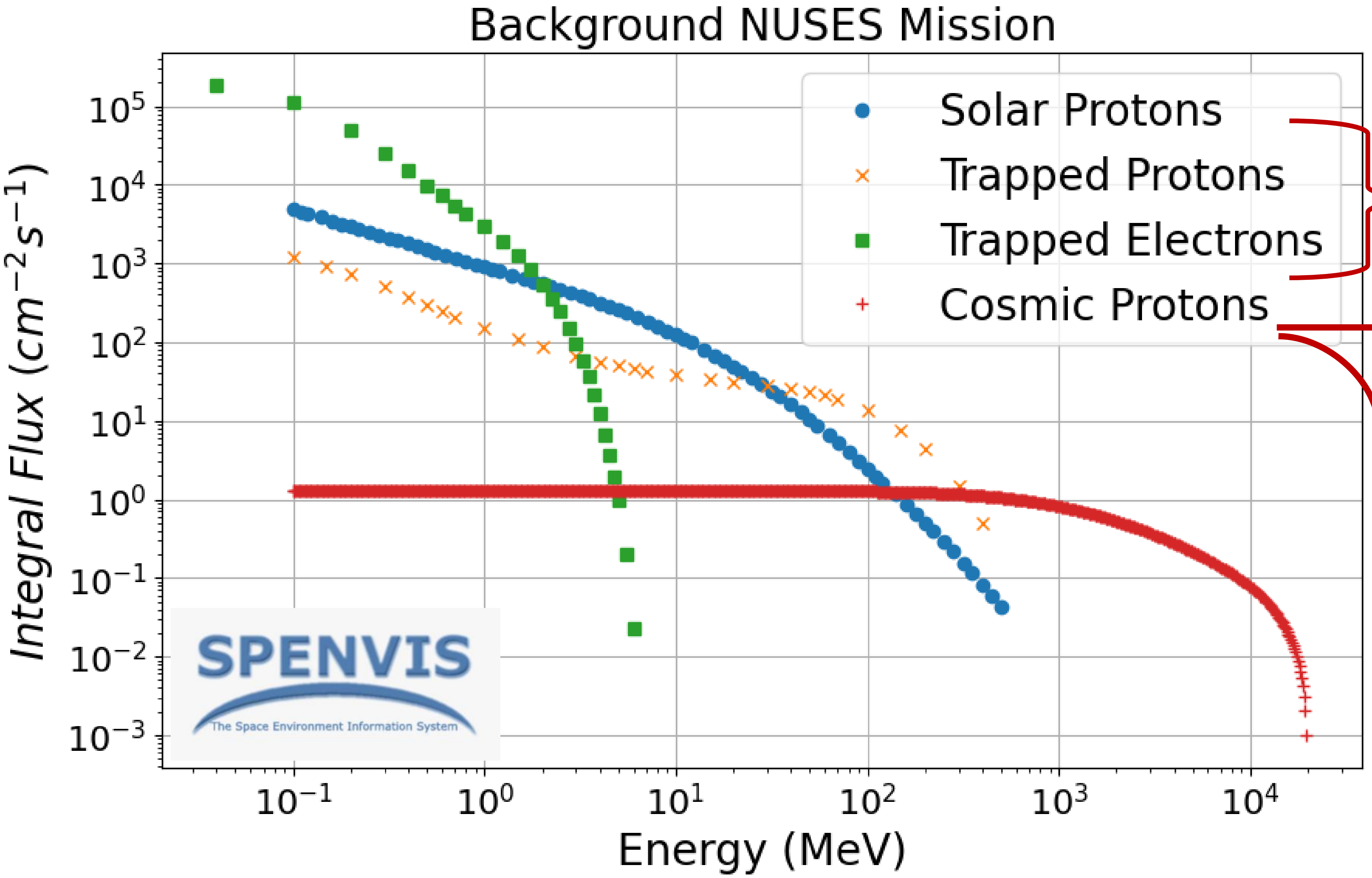
Mission Lifetime	3.25y
Mean Altitude	550 km, LEO
Semi-major axis	6913 km
Eccentricity	0
Inclination	97.7 deg, SunSync
LTAN	16:46
Pointing	< 0.1 deg

- Low Earth Orbit at high inclination, Sun-Sync orbit on the day-night border;
- The orbit has been tailored around the requirement for the optimal detection of the Cherenkov light;
- "Ballistic" mission (no propulsion for orbital elevation corrections);
- Expected launch window 2026



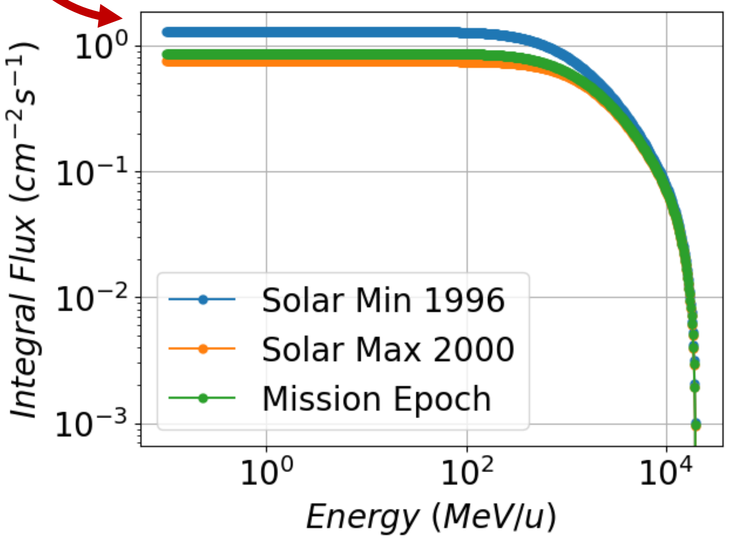


The NUSES background particles



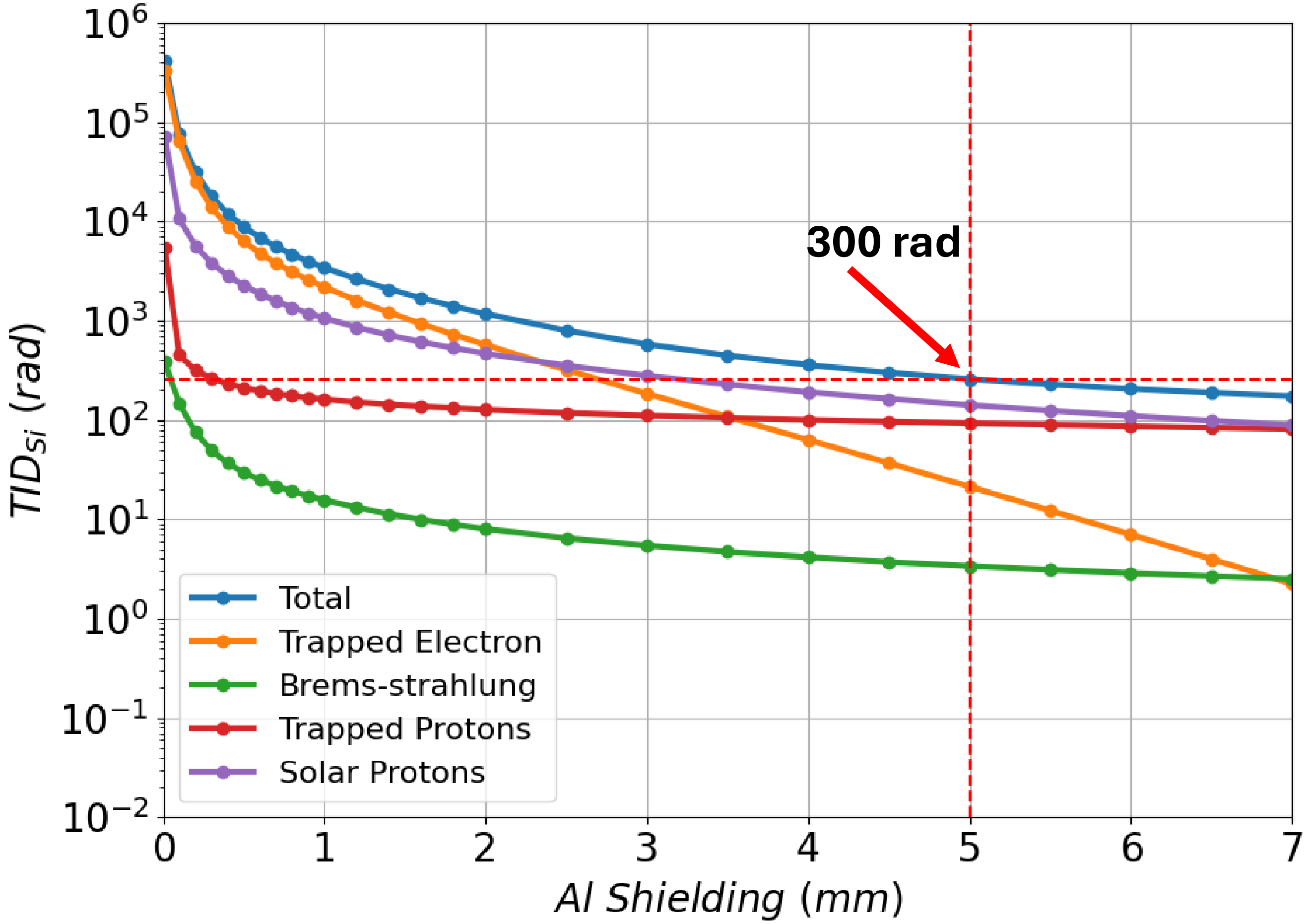
Used to analyze cumulative radiation damage

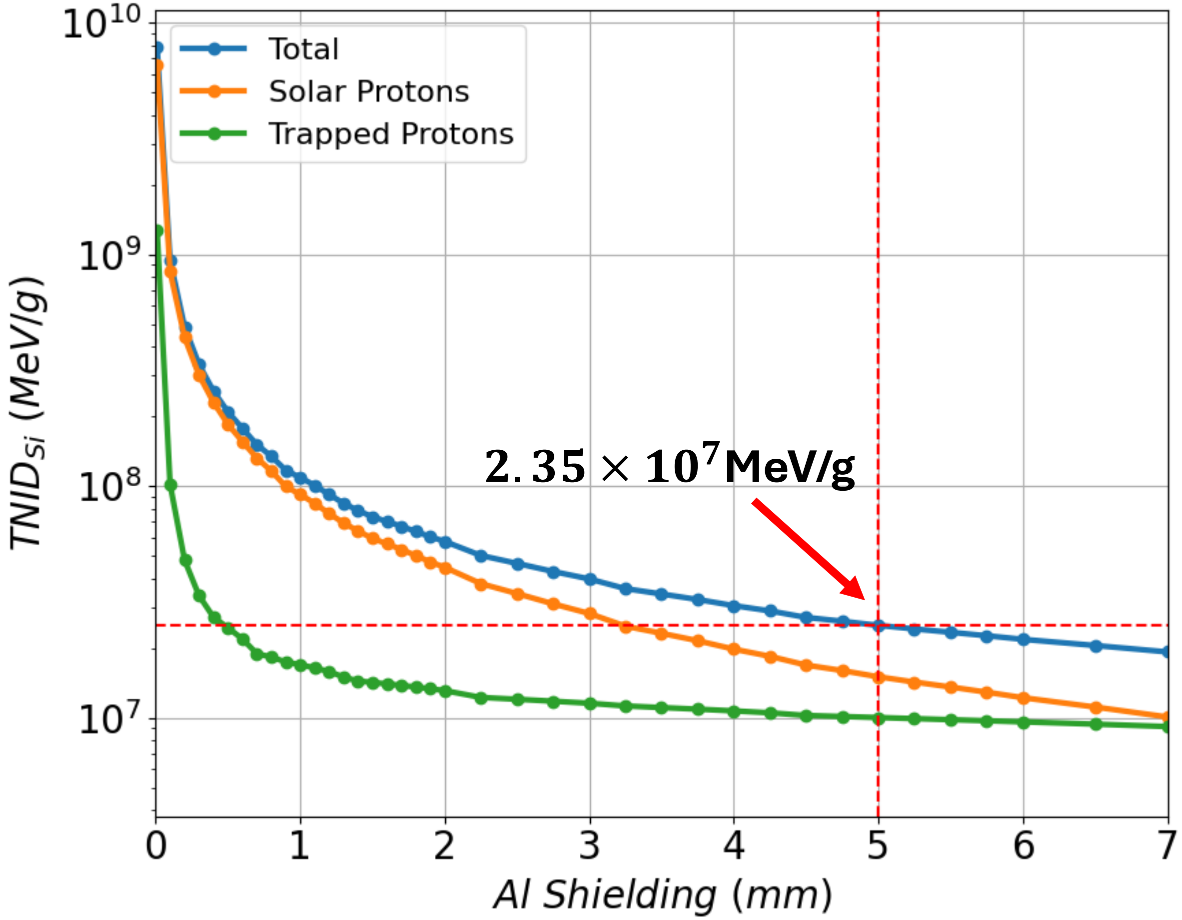
Used to analyze SEE damage. Reference is made to the solar minimum of May 1996 (worst case)



Total ionizing and non-ionizing dose for 3y mission

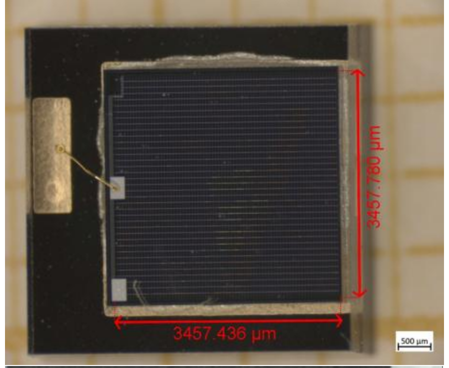
Material to simulate the shielding = pure Aluminum (Al)
Material to simulate the detector = Silicon (Si)

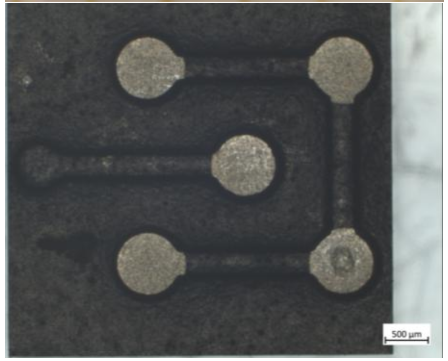


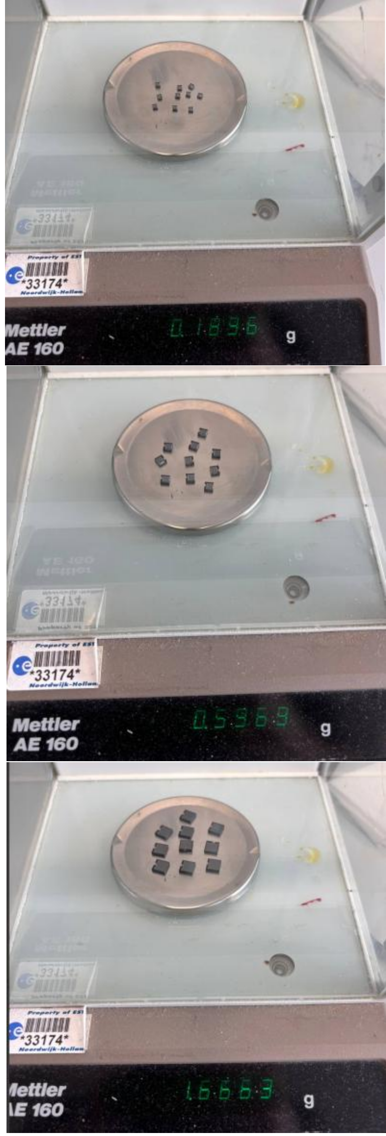


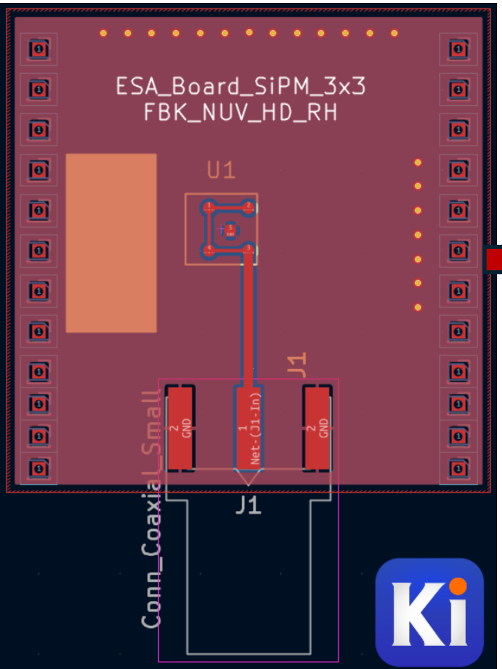
Visual analysis of the NUV-HD SiPMs

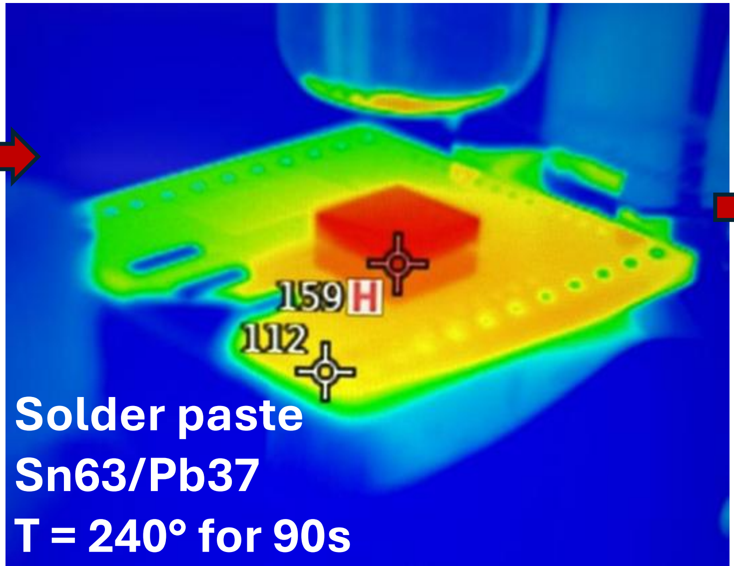
- MPPC, Multi-Pixel Photon Counters, Hamamatsu Photonics
  - S14160-6050HS 6X6 mm^2, microcell dimension 50 µm;
  - S14160-3050HS 3x3 mm^2, microcell dimension 50 µm;
  - S14160-1315PS 1X1 mm^2, microcell dimension 15 µm;
- NUV-HD, Fondazione Bruno Kessler
  - NUV-HD-MT 6X6 mm^2, microcell dimension 40 µm;
  - NUV-HD-RH 3x3 mm^2, microcell dimension 40 µm;
  - NUV-HD-RH 1X1 mm^2, microcell dimension 15 µm;

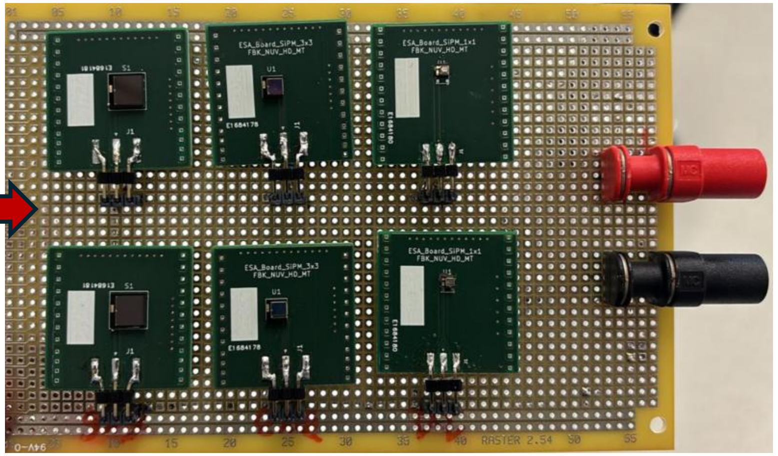






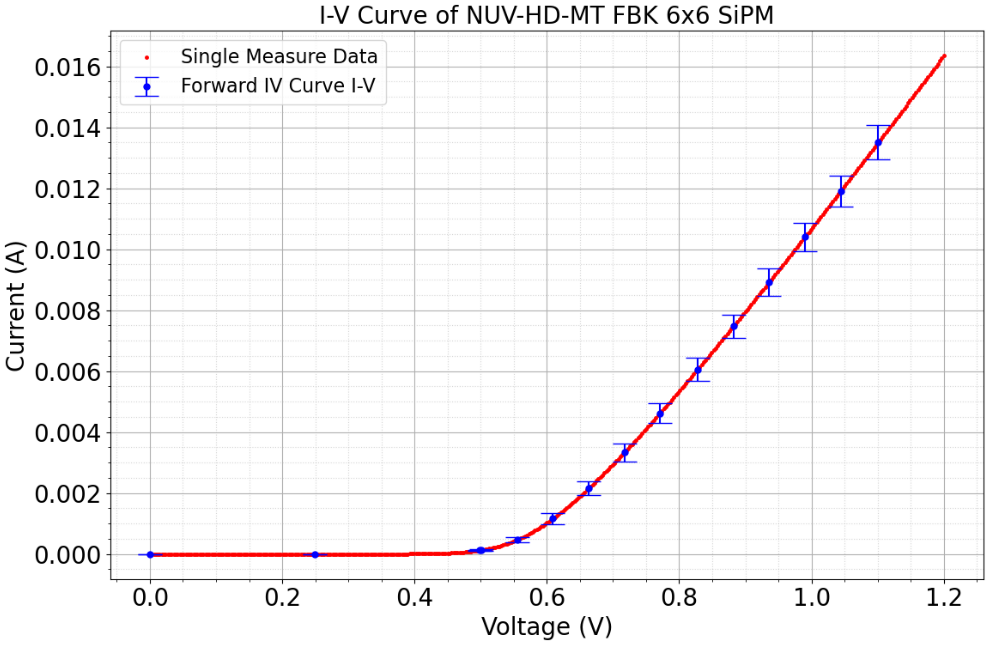


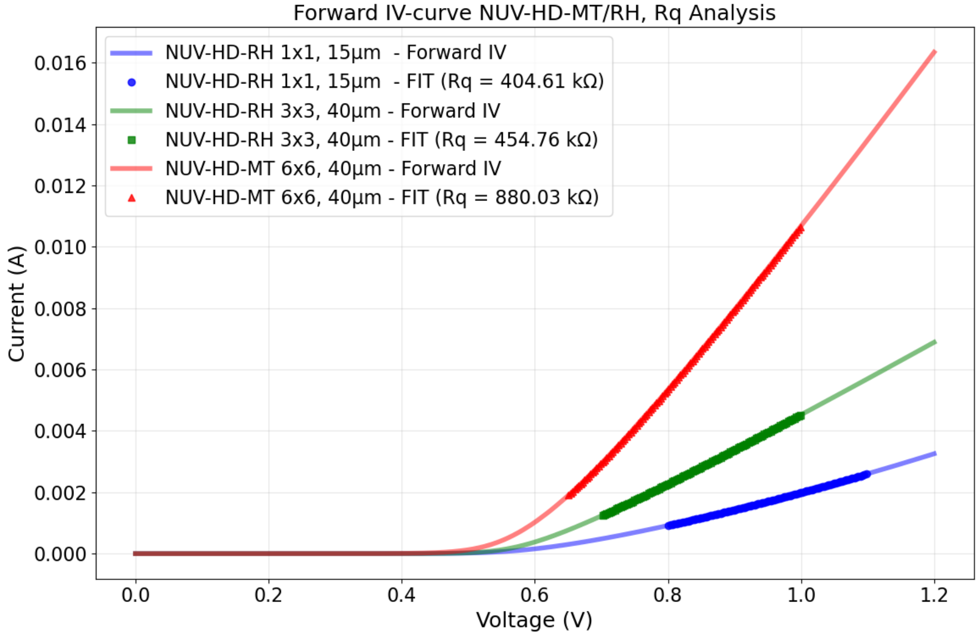




Characterization analysis: Forward Analysis results

$$* V_{bias} = \eta V_T \left[\ln\left(\frac{I}{I_s} + 1 \right) \right] + I \frac{R_s + R_q}{N_{\mu cell}} \Rightarrow for \ \frac{I}{N_{\mu cell}} > 5\mu A \ \Rightarrow \ V_{bias} \sim I \frac{R_s + R_q}{N_{\mu cell}}$$





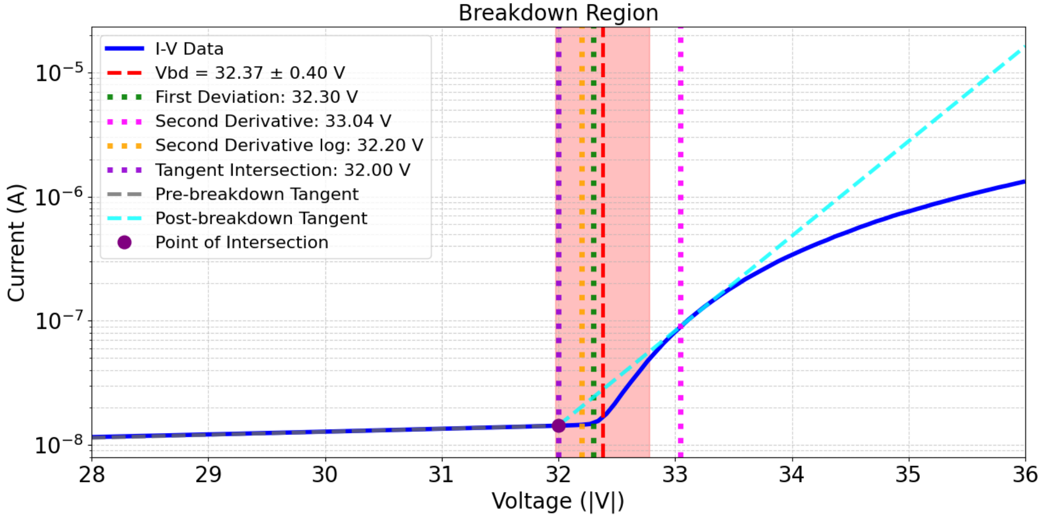
**A. Nagai, C. Alispach, A. Barbano, V. Coco, D. della Volpe, M. Heller et al., Characterization of a large area silicon photomultiplier*

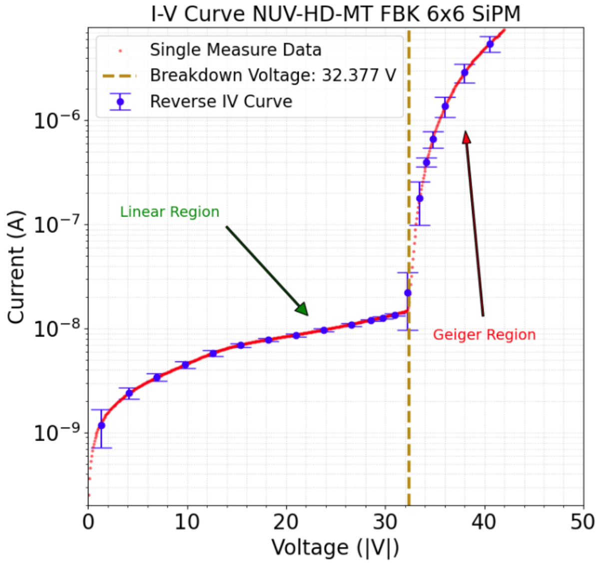
Characterization analysis: Reverse analysis results

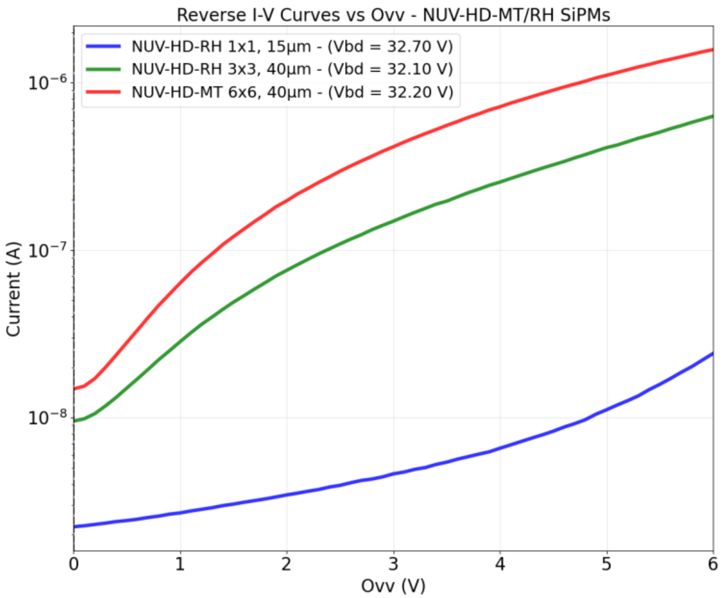
*Multiple models evaluated; one provided the best Vbd estimation :

Second logarithmic derivative: $\frac{d^2 lnI(V)}{dV^2} = \frac{d}{dV}\left(\frac{dlnI(V)}{dV}\right)$

F. Nagy, et al., A model based DC analysis of SiPM breakdown voltages, Nuclear Instruments and Methods in Physics Research Section

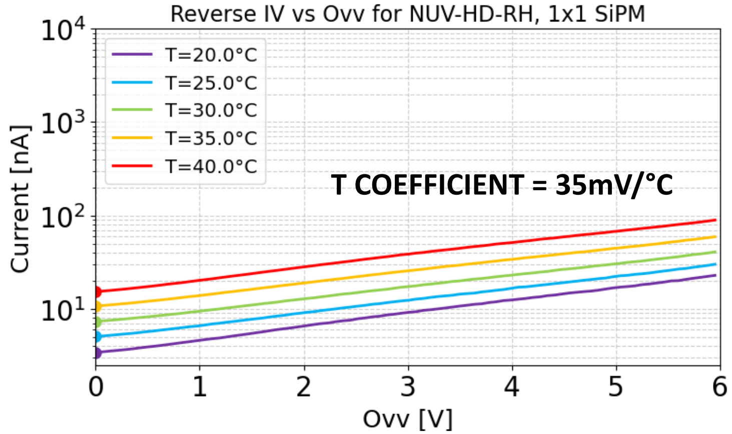


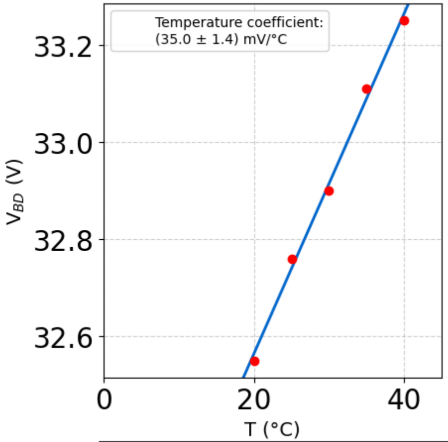


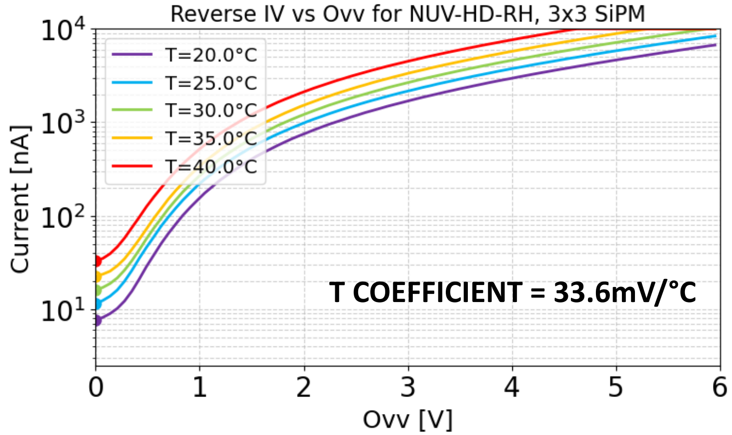


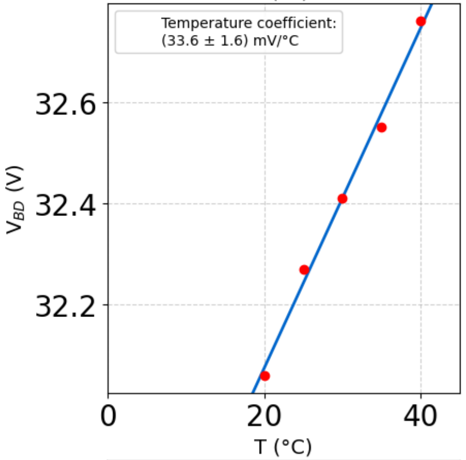
	NUV-HD-RH 1X1	NUV-HD-RH 3X3	NUV-HD-MT 6X6
Number of analyzed files	12	12	12
Mean Break Down Voltage	32.32 V	32.11 V	32.4 V
First Derivative	32.00 V	32.10 V	32.30 V
Second Derivative	32.87 V	33.18 V	33.04 V
Second log Derivative	32.7 V	32.10 V	32.20 V
Tangent Intersection	32.51 V	31.04 V	32.00 V

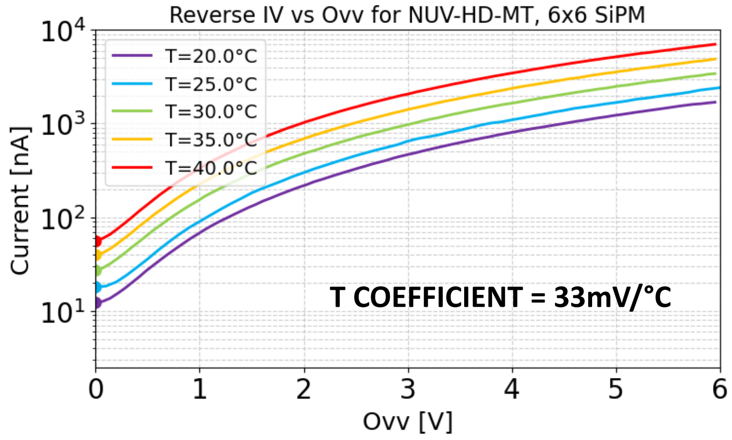
Vbd calculation in function of the temperature variation

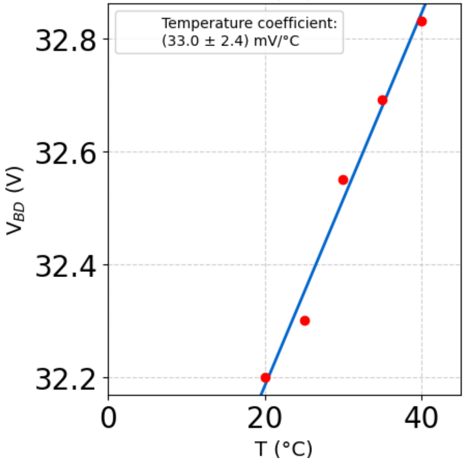


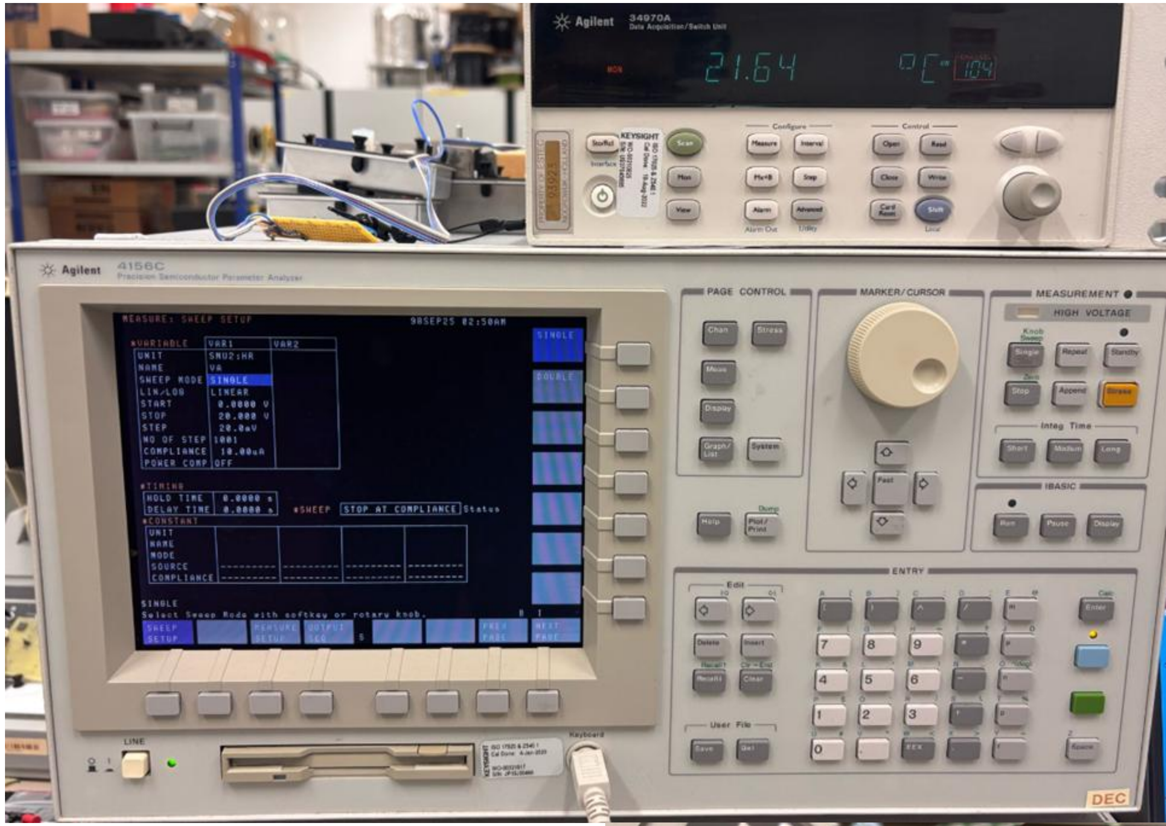




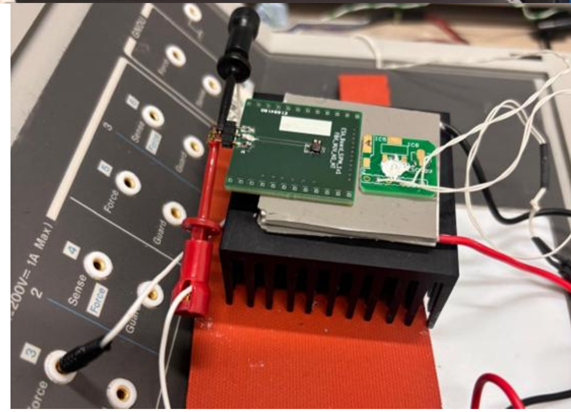








Peltier and PT100 temperature controller



$$V_{BD} = a \cdot T + b$$

Where:

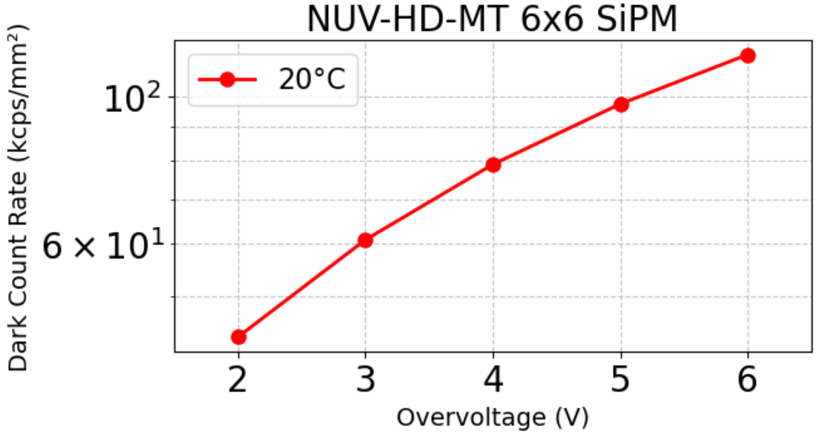
V_{BD} = Break down Voltage [V]

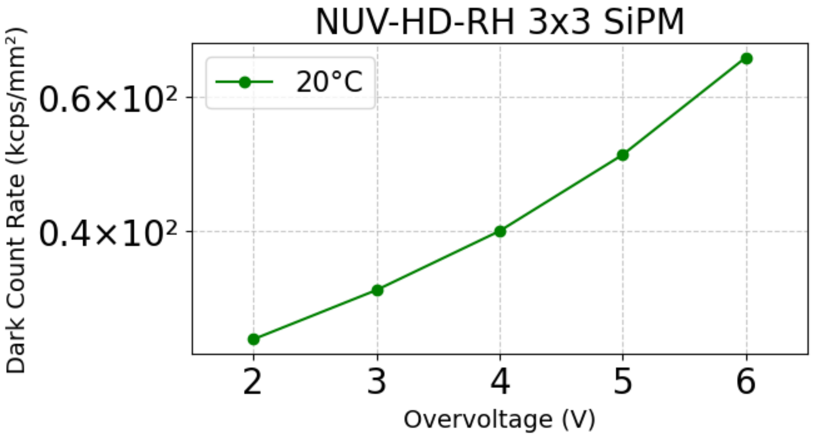
a = Slope [V/°C]

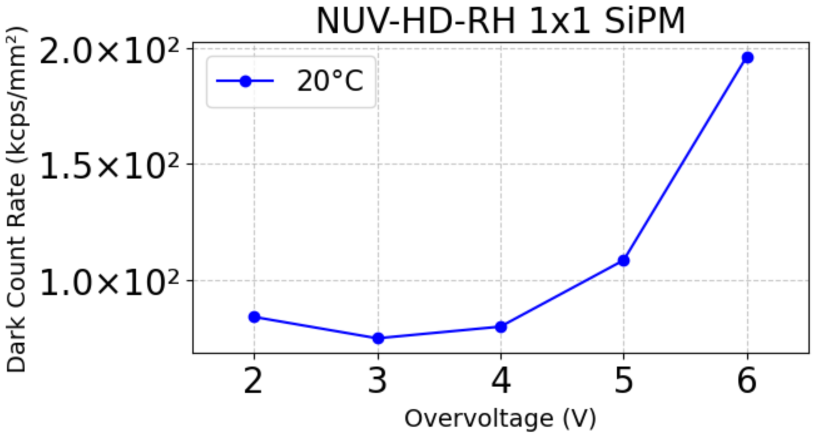
b = Intecept [theoretical V_{BD}]

T = Temperature [°C]

Characterization analysis: DCR vs Ovv and Temperature Dependence



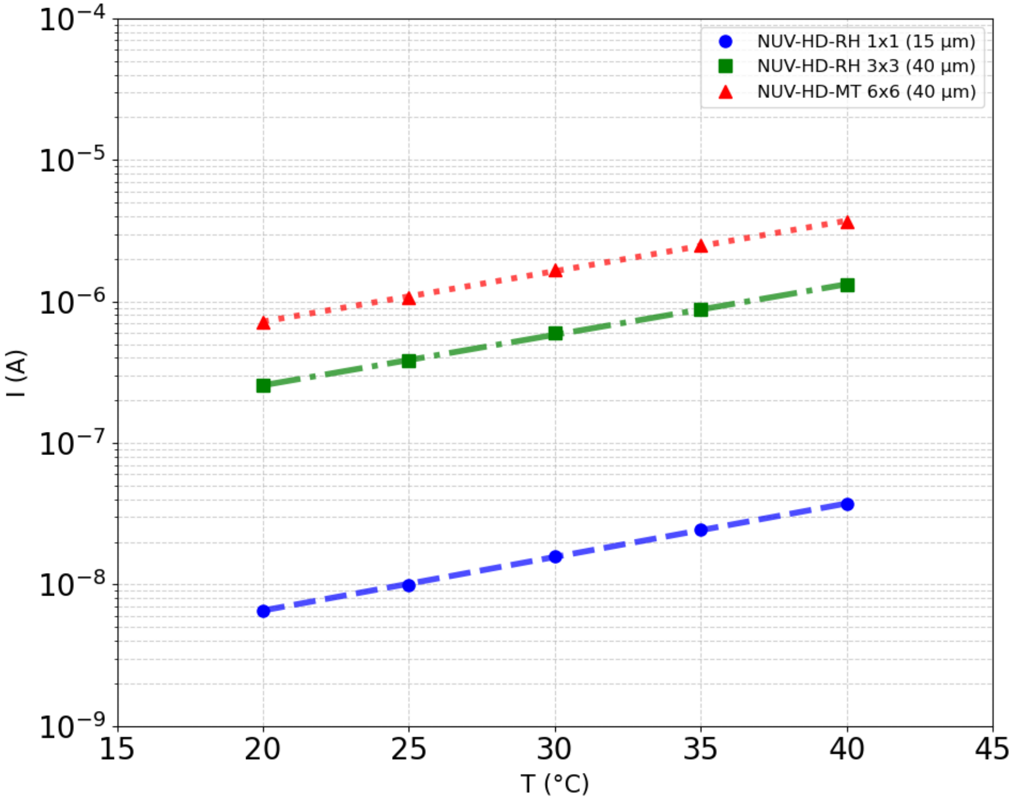




$$dcr = \frac{I_{dark}}{q * Gain}$$

Values are scaled with the active area of the SiPMs

$$ActiveArea = A_{SiPM} * ff \qquad DCR = \frac{dcr}{ActiveArea}$$



Thermal behaviour at 5 Ovv:

$$*I(T) = I_0 \cdot e^{\lambda T}$$

λ = Temperature coefficient

Temperature correction:

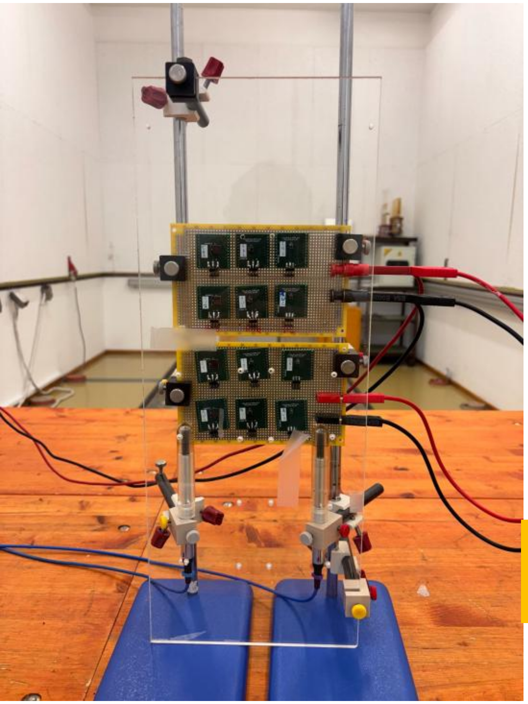
$$T_{I_2} = \frac{\ln(2)}{\lambda}$$

Current Doubling:

- **1x1, 8°C**
- **3x3, 9°C**
- **6x6, 9°C**

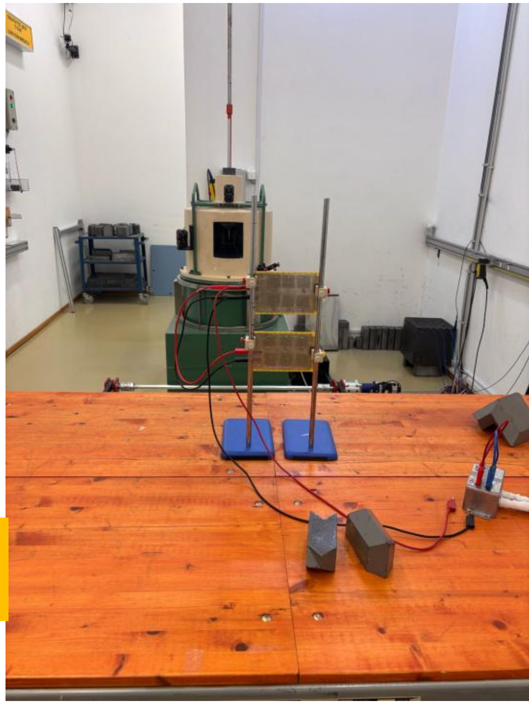
**L. Burmistrov et al., Performance and radiation damage mitigation strategy for silicon photomultipliers on LEO space mission*

NUV-HD-RH/MT SiPMs ESA/ESTEC 1st TID Test

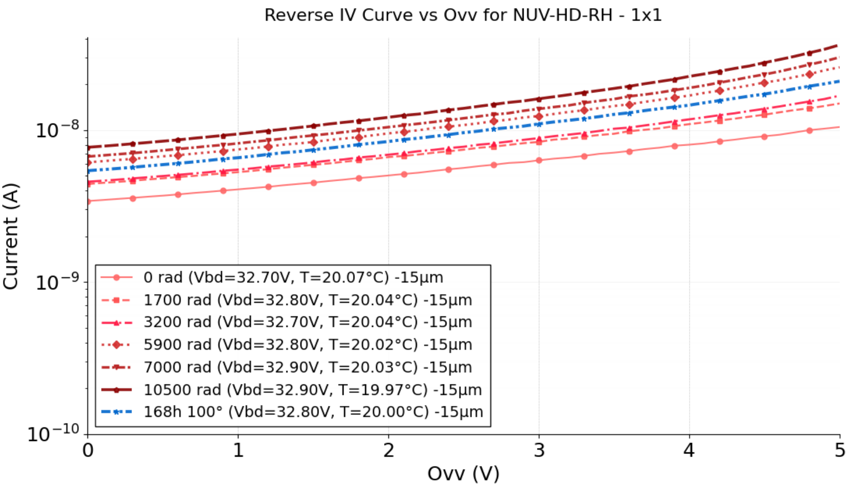


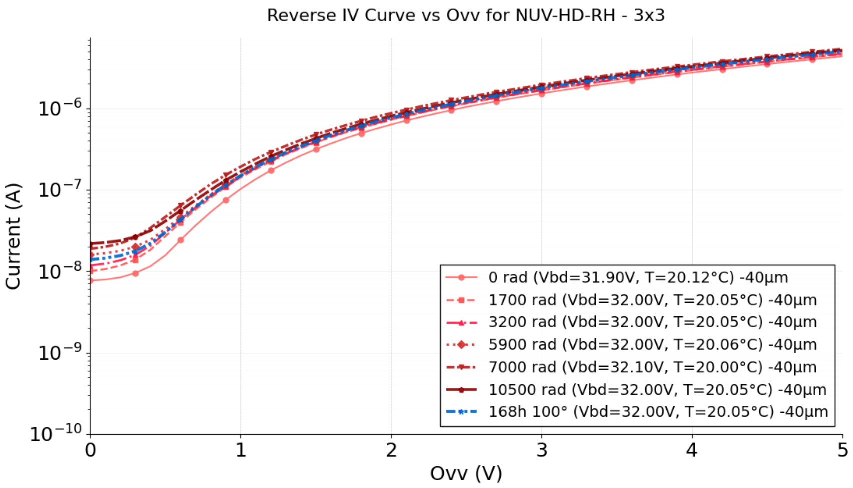
- TID test with the Co60 source in the ESTEC radiation lab.
- 12 components in total; 4 per size; 2 boards: 6 devices each → 3 biased 20V - 3 unbiased
- Test started on the 12/05/2025 at 10:32
- Test finished on the 19/05/2025 at 12:46
- One day of Annealing at room temperature + one week at 100°

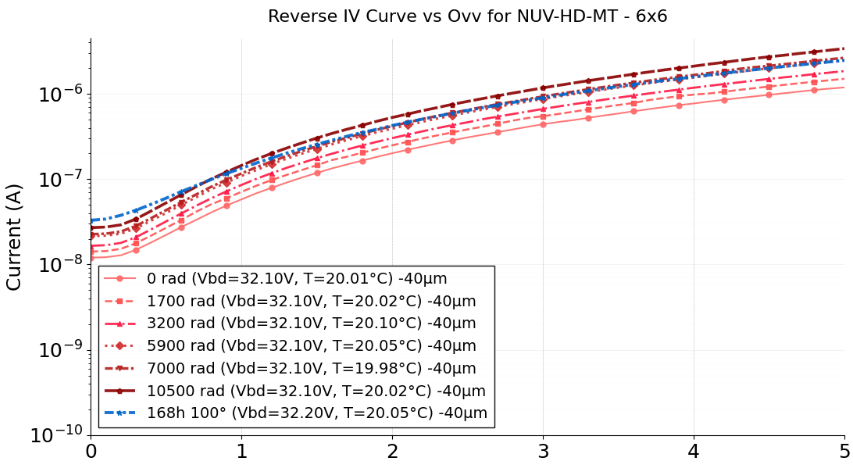
* Total dose and dose rate are expressed as Gy and Gy/h in <WATER >.



DATA REFERRING TO BIAS BOARD-1 COMPONENTS







FBK/HAMAMATSU SiPMs PSI/PIF PROTON Test

SiPM board FBK 4x 6x6 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board FBK 4x 3x3 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board FBK 4x 3x3 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board Hamamatsu -> 3 device/dimension Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

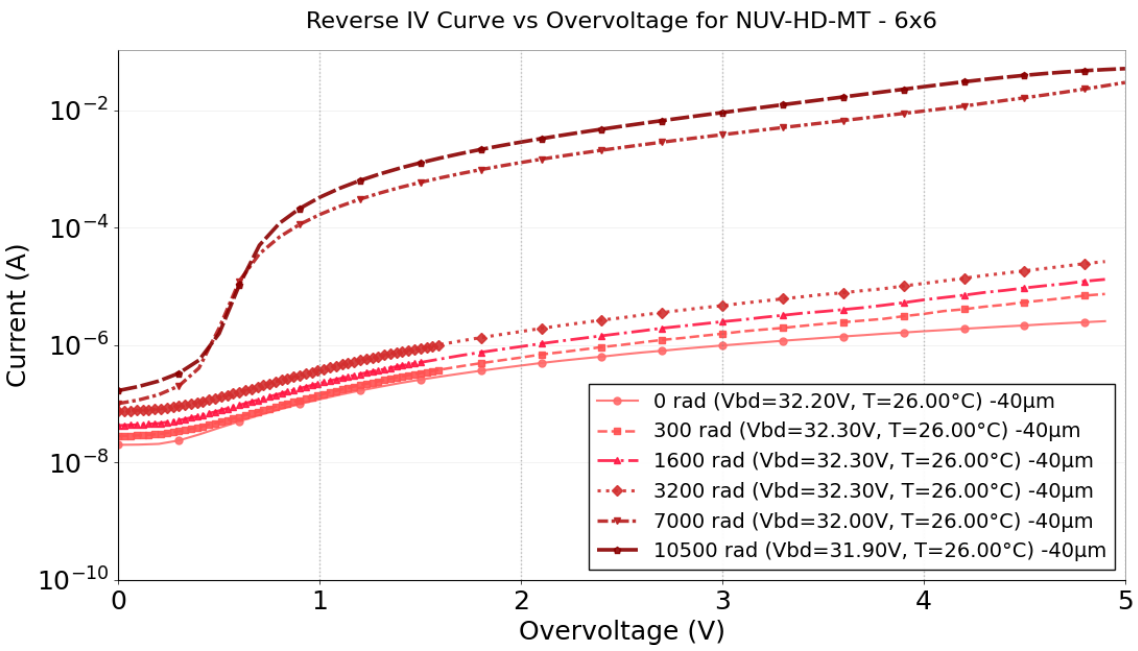
SiPM board Hamamatsu -> 3 device/dimension Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

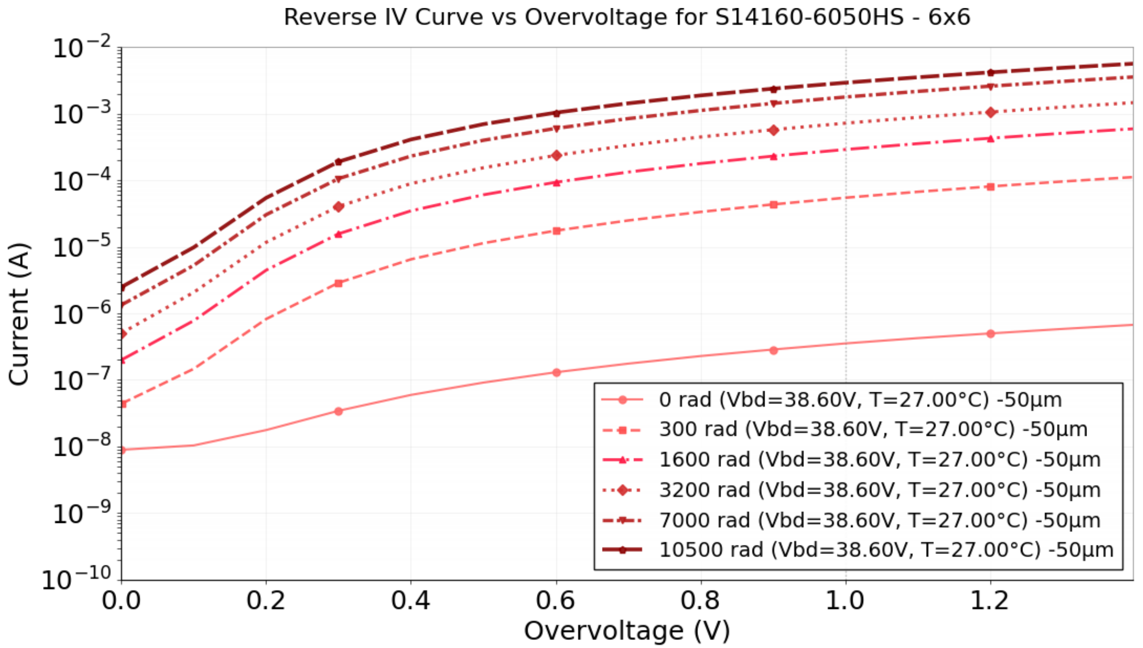
$$TNID = F \cdot NIEL = \left[\frac{MeV}{g}\right], NIEL_{Si}, for\ a\ beam\ of$$

$$p^{+}\ 100MeV, = 2.97x10^{-3}\ \frac{(MeV \cdot cm^2)}{g}$$

SPENVIS simulated value with 5mm of Al shielding = 2.35x10^7 $\left[\frac{MeV}{g}\right]$ ~ a Fluence of 8.03x10^9 ~ IonizingDose of 7.5 Gy

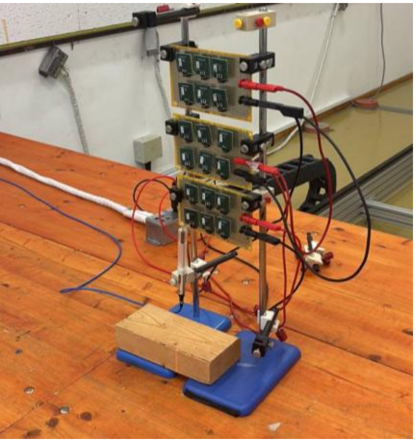
FLUENCE $\left[\frac{p}{cm^2}\right]$	TNID $\left[\frac{MeV}{g}\right]$
3.21×10^9	9.55×10^6
1.71×10^10	5.09x10^7
3.43×10^10	1.02x10^8
7.49×10^10	2.23x10^8
1.12×10^11	3.33x10^8

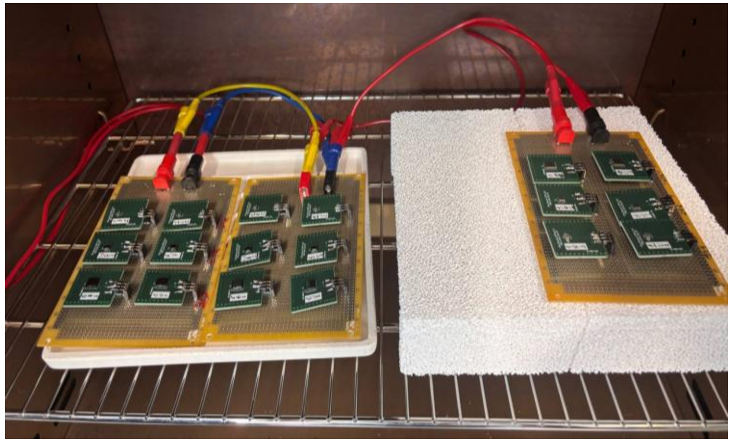




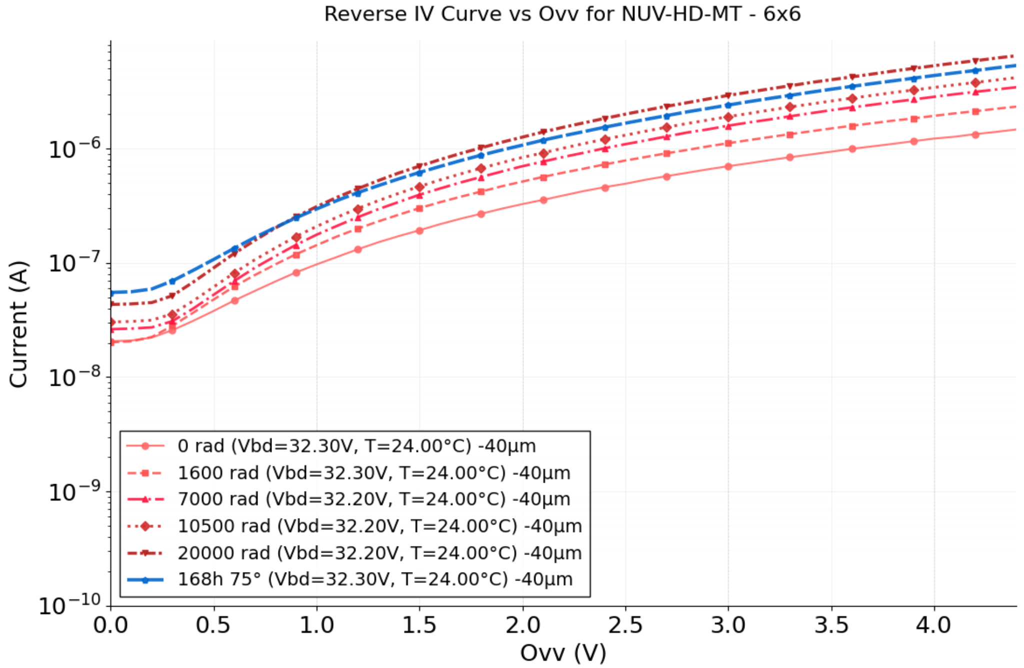
FBK/HAMAMATSU SiPMs ESA/ESTEC 2nd TID Test

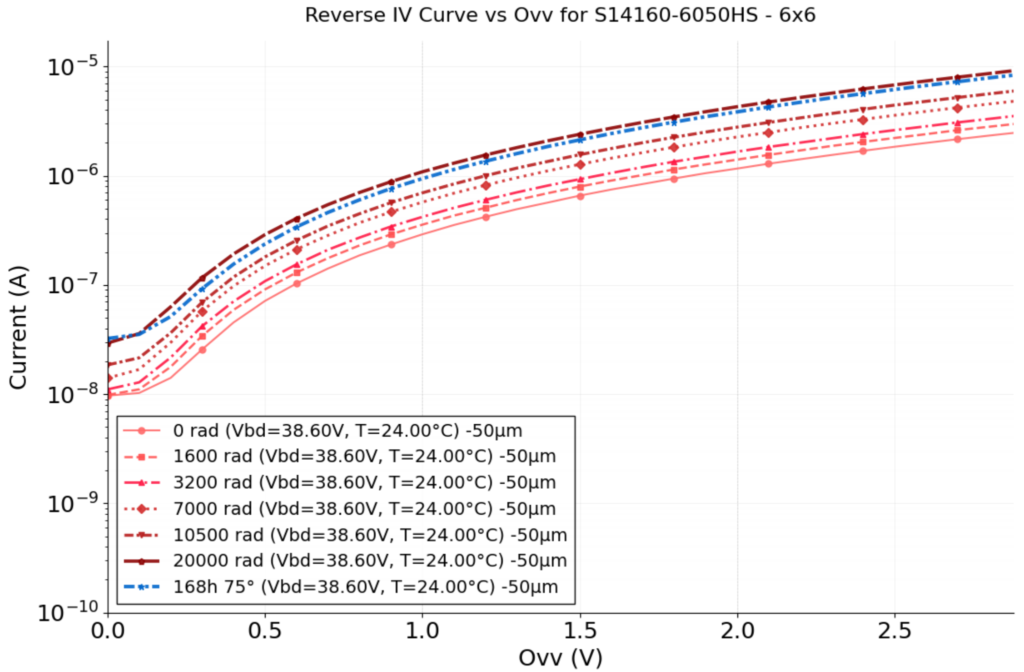
- TID test with the Co60 source in the ESTEC radiation lab.
- 12 FBK components in total; 4 per size; 2 boards: 6 devices each → 3 biased 20V - 3 unbiased
- 6 HAM components in total; 2 per size; 1 boards: 3 devices each → 3 biased 20V - 3 unbiased
- Test started on the 22/07/2025 at 10:30
- Test finished on the 05/08/2025 at 13:15
- One day of Annealing at room temperature + one week at 75°



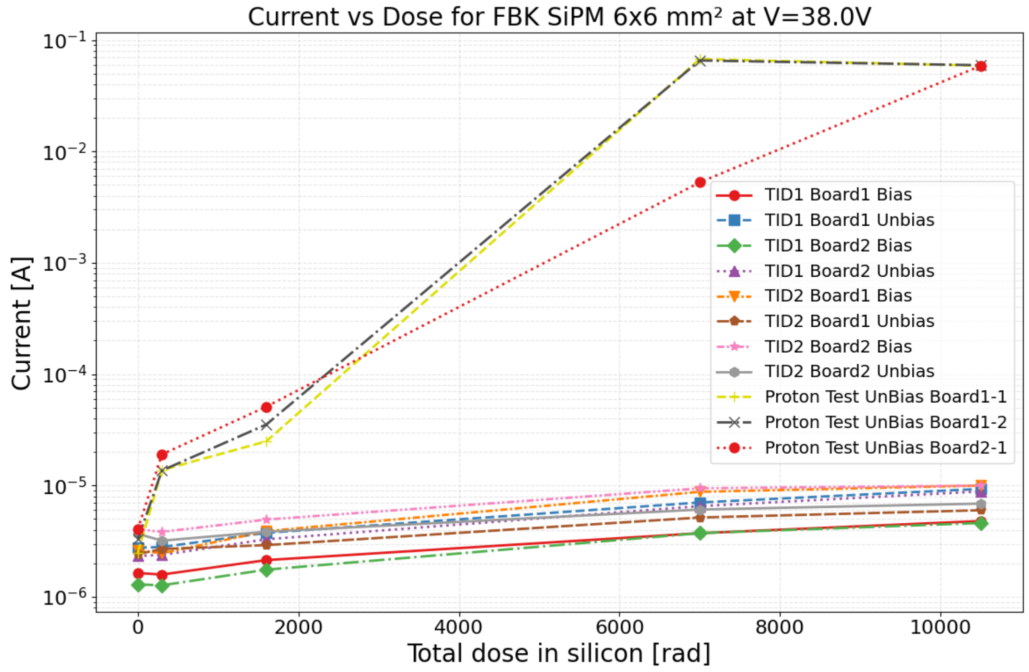


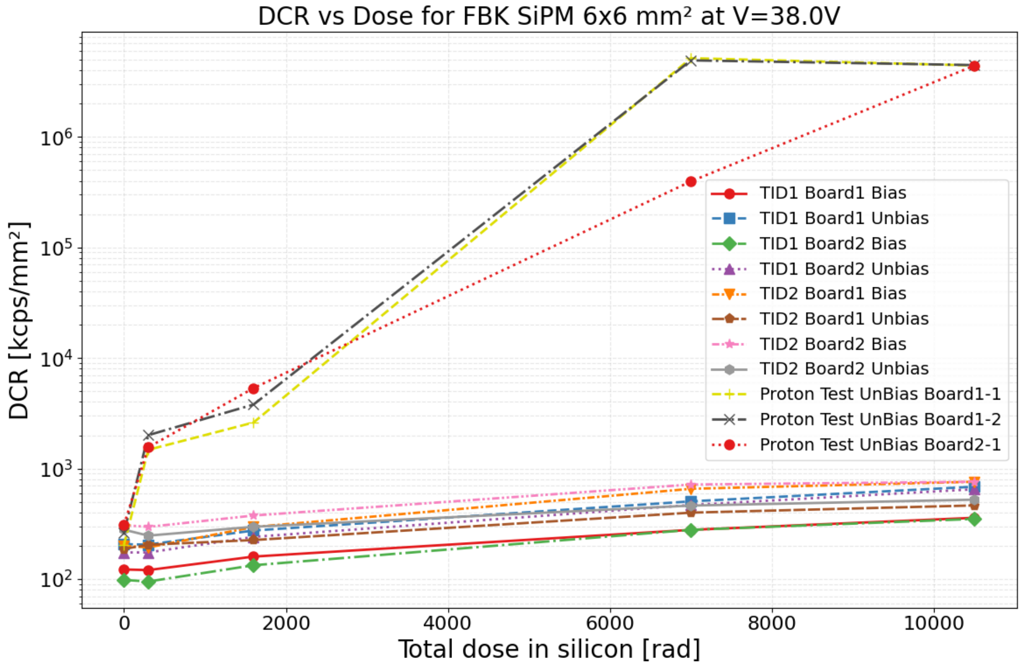
DATA REFERRING TO BIAS BOARD-1 COMPONENTS

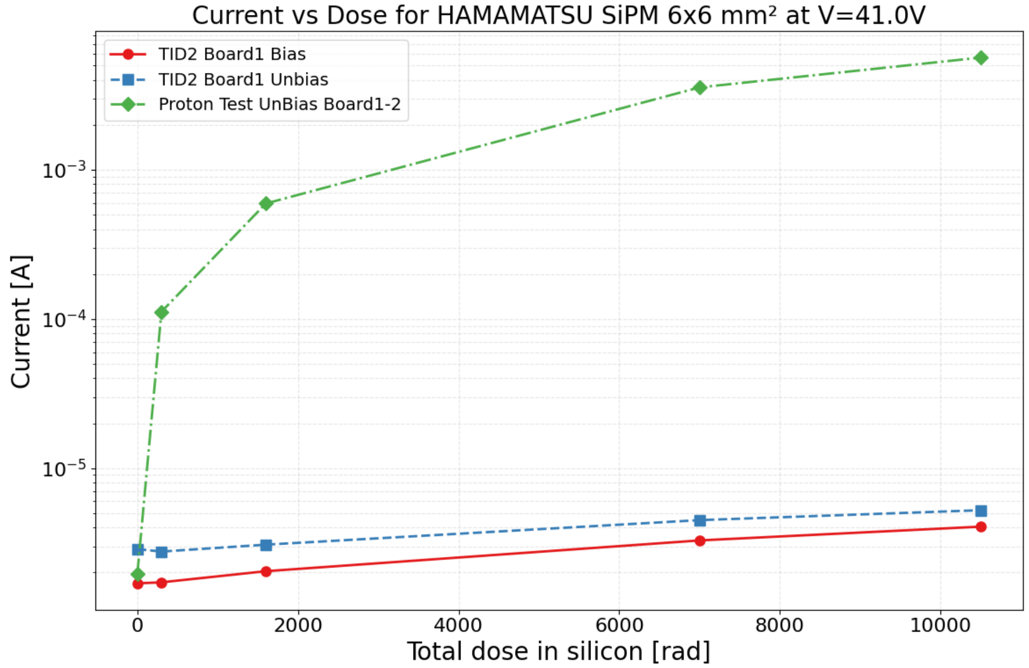


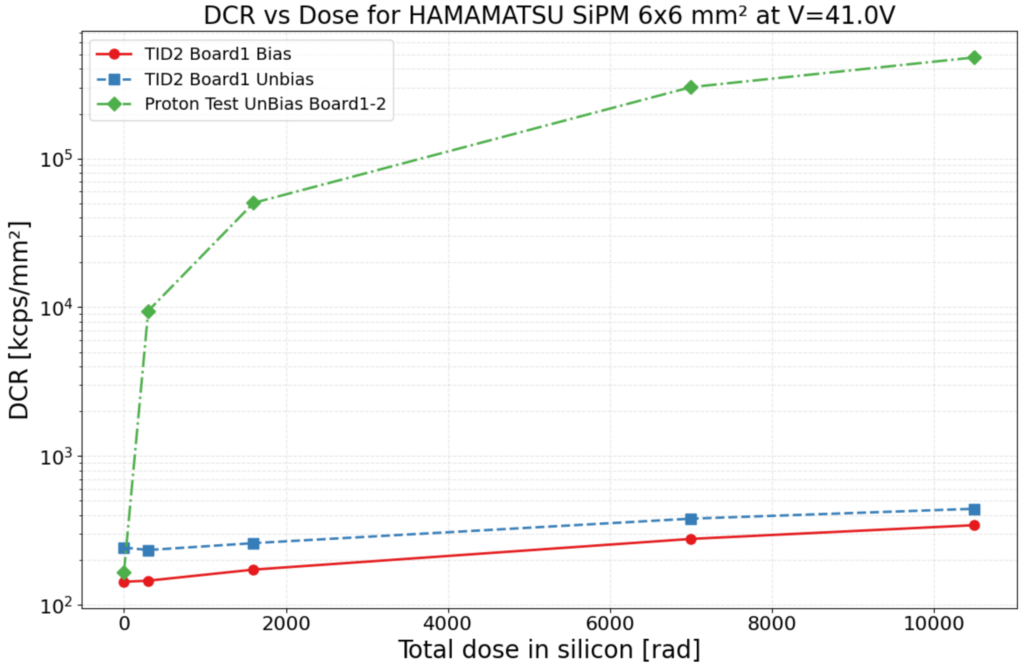


Comparison of the trend of the Current/DCR as function of the dose:







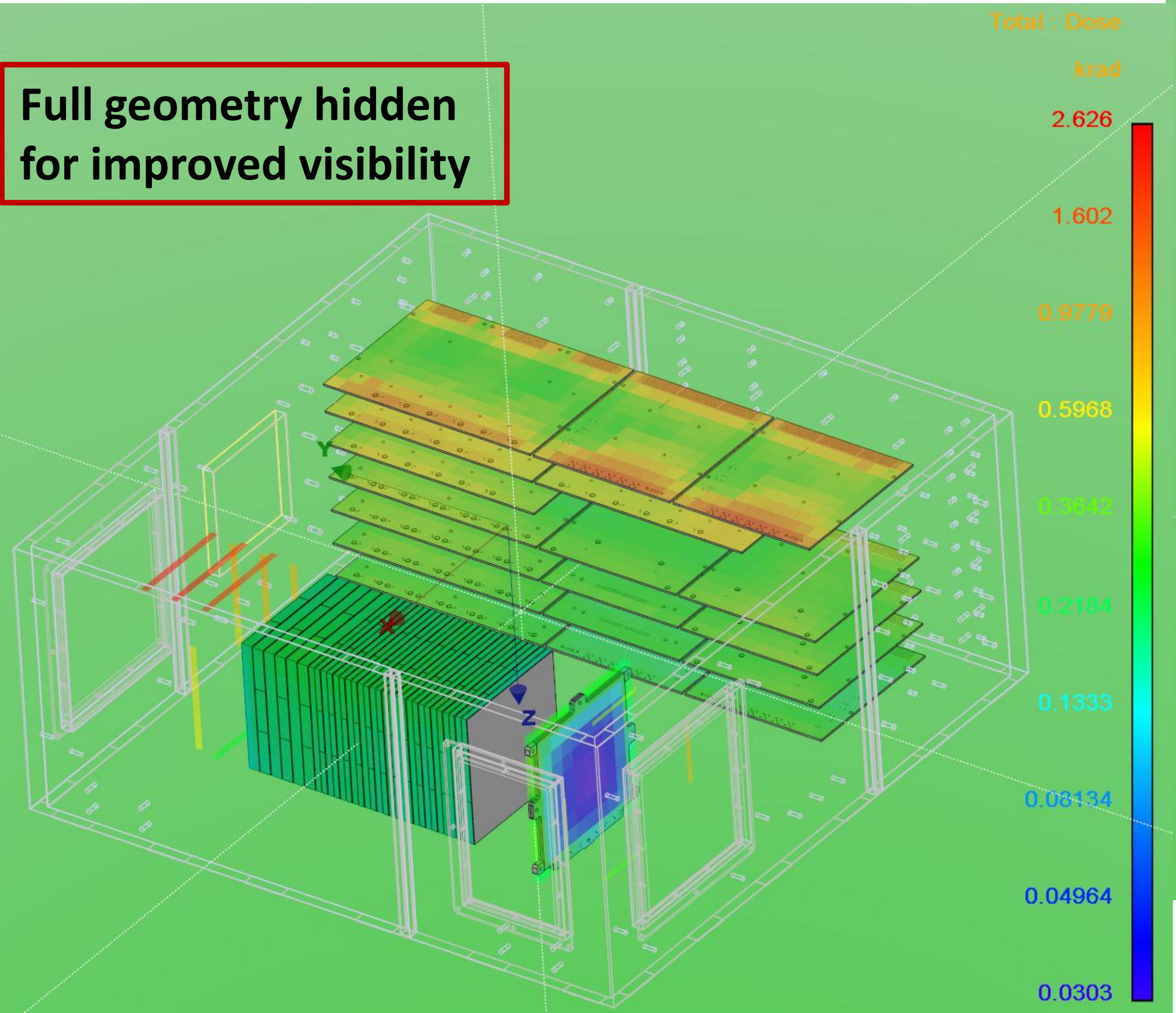


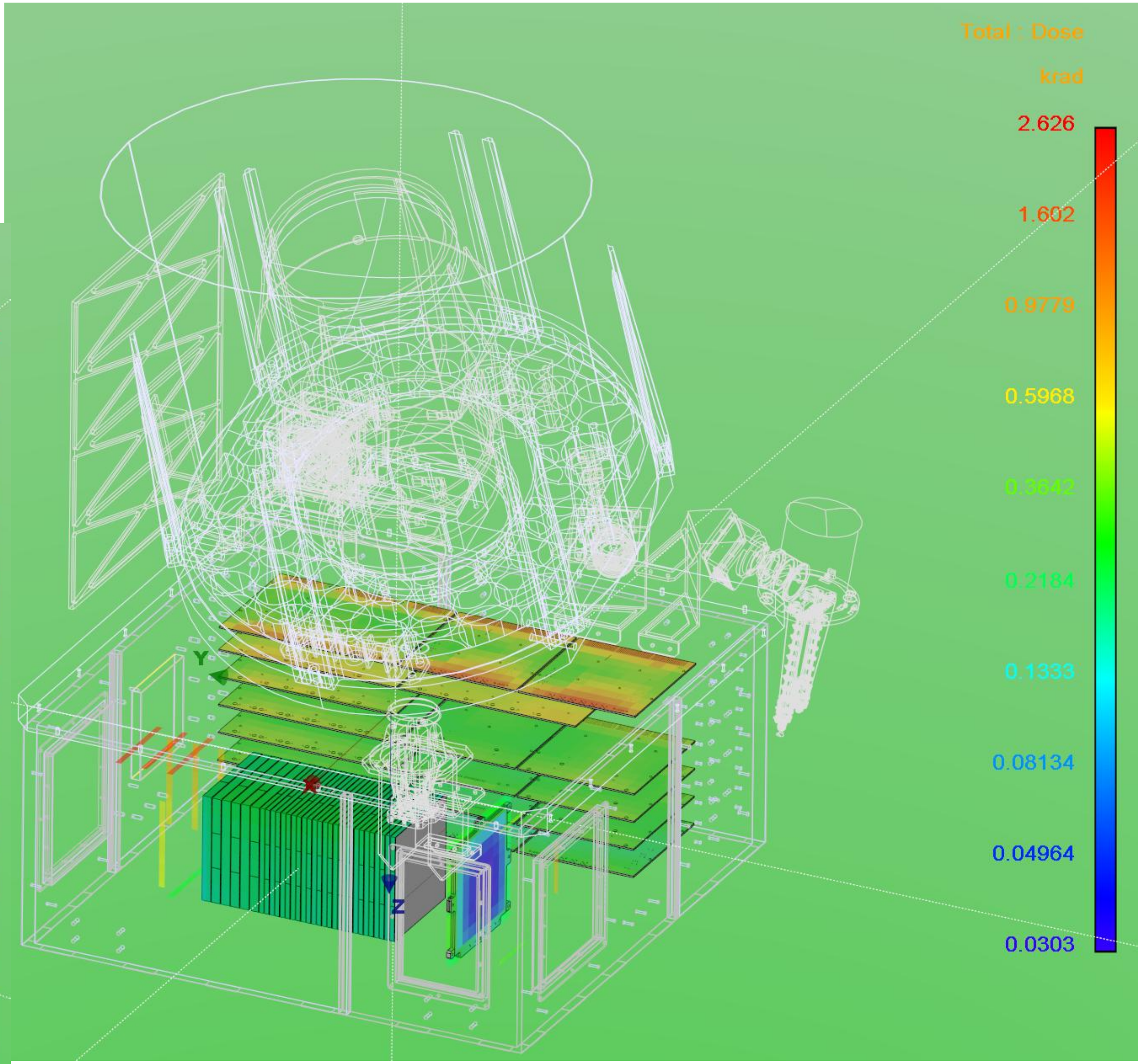
FASTRAD Total Dose Calculation:

FASTRAD SIMULATION

Full 3D geometry, real material definition
Total Dose calculation

Full geometry hidden for improved visibility





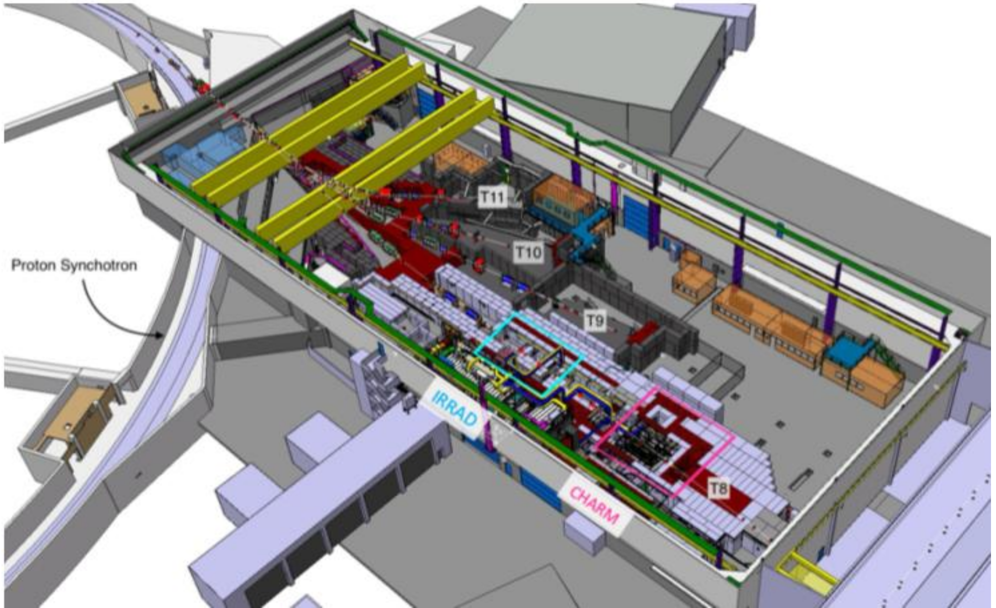
Industrial Period Activity, TASI SEE Board Level Testing

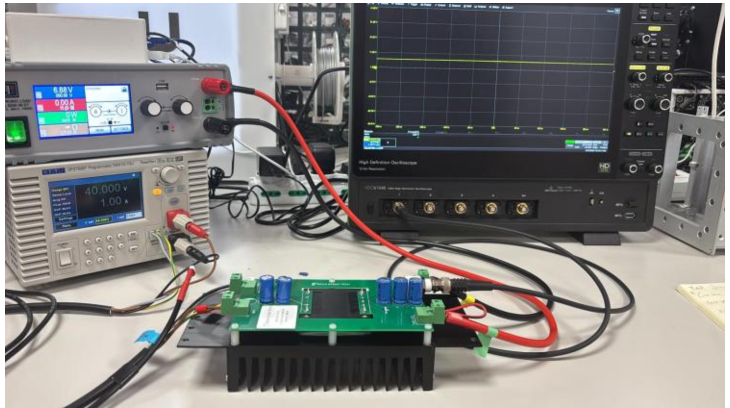
Device under trade-off for testing are DC/DC converters.

The first choice for this application are commercial DC/DC converters available in TAS:

- All DC/DC are Si based
- Standard brick dimension
- 6 part number selected available with high voltage input:
  - 34V / 75V Vin, 28V Vout, 1.8 A and 21.5 A.
  - 34V / 75V Vin, 3.3V Vout, 30 A.
  - 48V Vin, 24V Vout, 350 W.
  - 24V Vin, 100W.
  - 24V Vin, 400W.

Heavy Ions Test beam planned from 20 – 25/11/2025





HEARTS

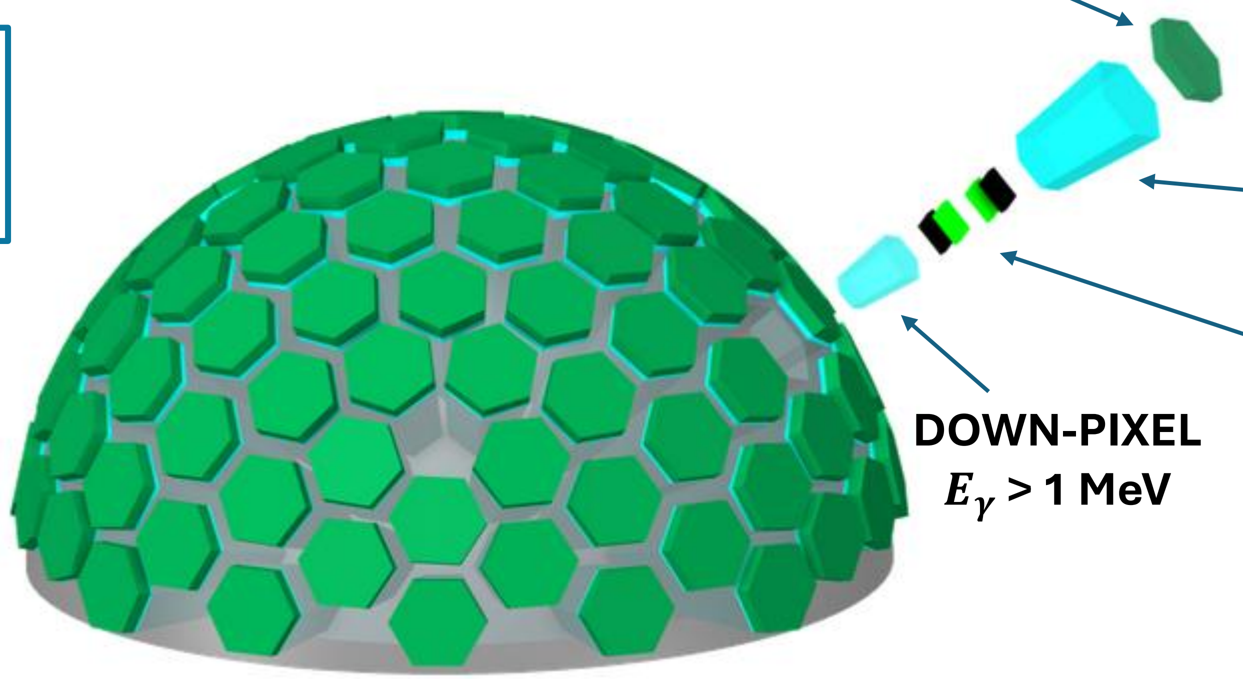
ThalesAlenia Space
a Thales / Leonardo company

The Crystal Eye detector:

BORN TO BE:
- Free-flyer
- Onboard of space stations
- GBM module of larger satellites

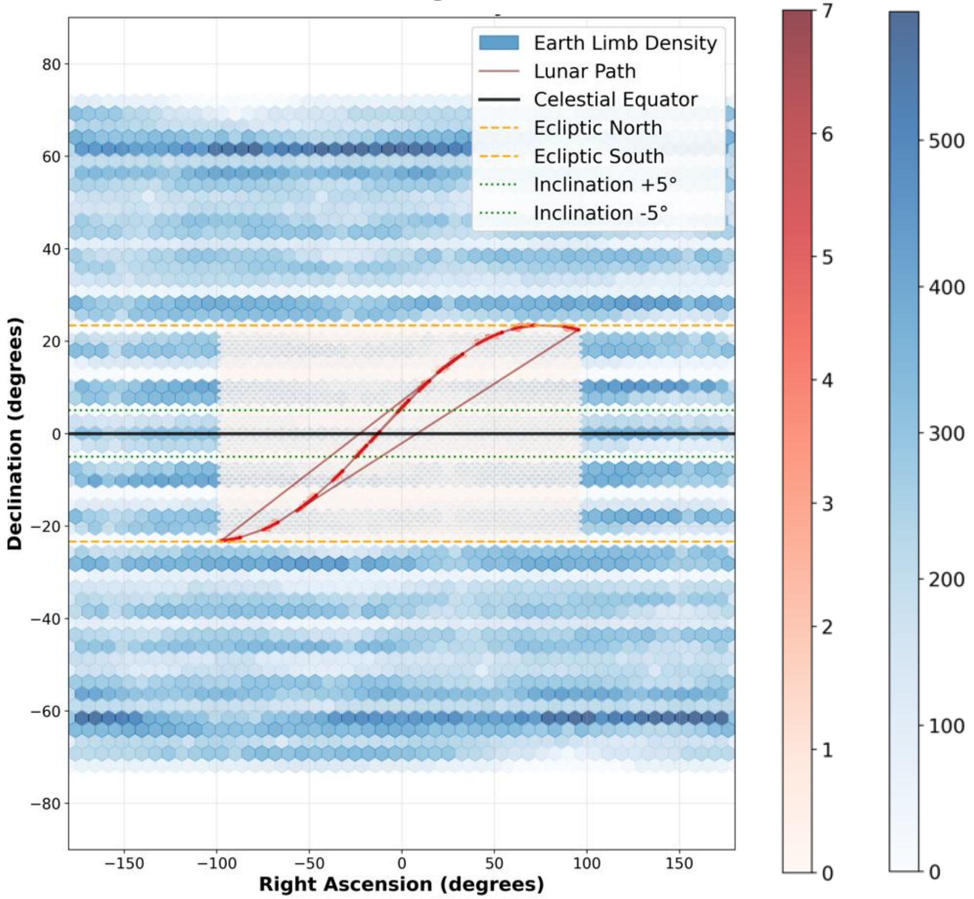
- LEO orbit, with altitude of 550 km, eccentricity of 0° and inclination of 5°/20°
- Expected time of the mission 3Y, start date 2030

SMART CONFIGURATION
- Wide FOV: > 2π sr
- Full sky coverage
- Compactness
- Symmetry
- Thermal protection of the SiPMs

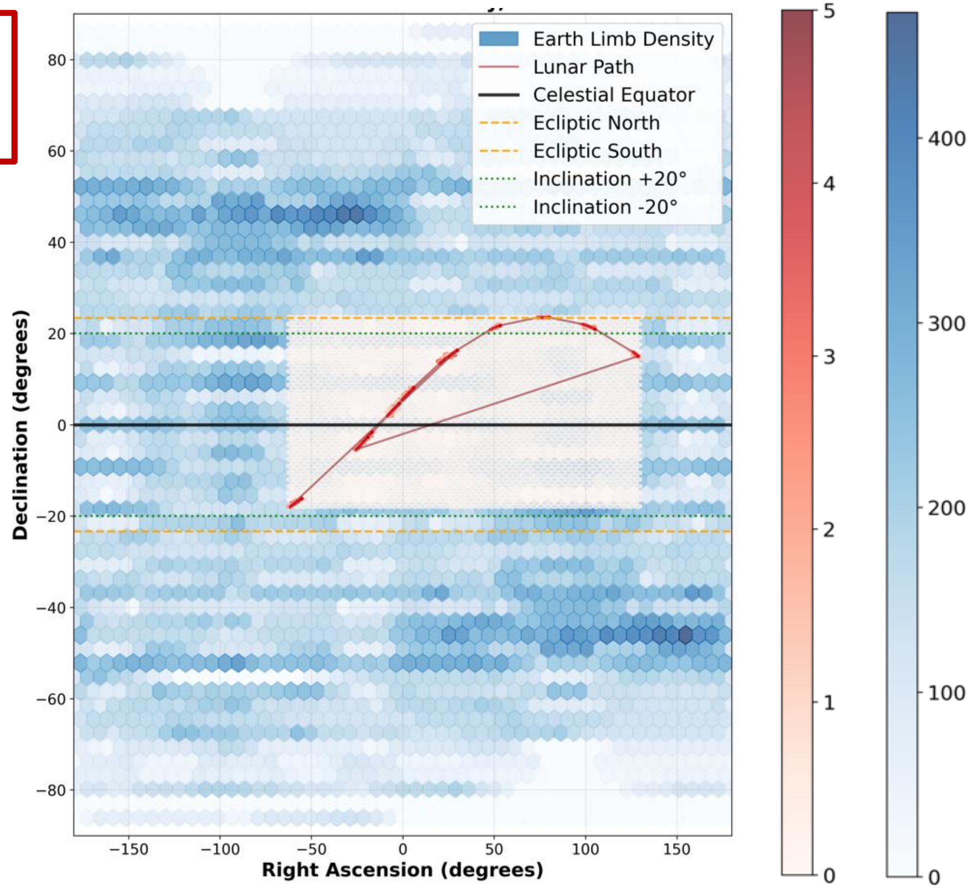


The Crystal Eye (CE) detector is a space-borne all-sky monitor designed to locate and explore electromagnetic (EM) spectra of extreme astrophysical phenomena in the energy range of about 10 keV to 30 MeV

Crystal Eye Earth/Moon occultations analysis:



Earth/Moon Limb density



- **Condition for the Earth Occultations:**

The earth's limb must be perpendicular to the direction of movement, Angle = 90° ± 15°

- **Condition for the Moon Occultations:**

The moon's limbr must be perpendicular to the direction of movement of the satellite, Angle = 90° ± 20°

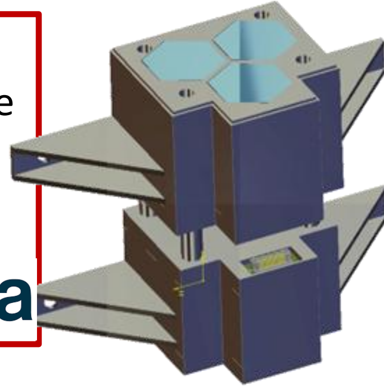
*The verification of occultations is calculated using an algorithm that counts the passages of Rise and Setting of the limbs through preferred conditions.

Harmon et al. (2002), The Burst and Transient Source Experiment Earth Occultation Technique

N. EARTH OCC. 5°	N. MOON OCC. 5°	N. EARTH OCC. 20°	N. MOON OCC. 20°
691	138	1589	85

WINK Sun Point estimation, Part 1:

- Prototype of the Crystal Eye mission headed by the GSSI
- The WINK detector is planned to be installed on board the ESA Space Rider spacecraft
- LEO orbit, with altitude of 411 km, eccentricity of 0° and inclination of 5°
- Expected time of the mission 2 months

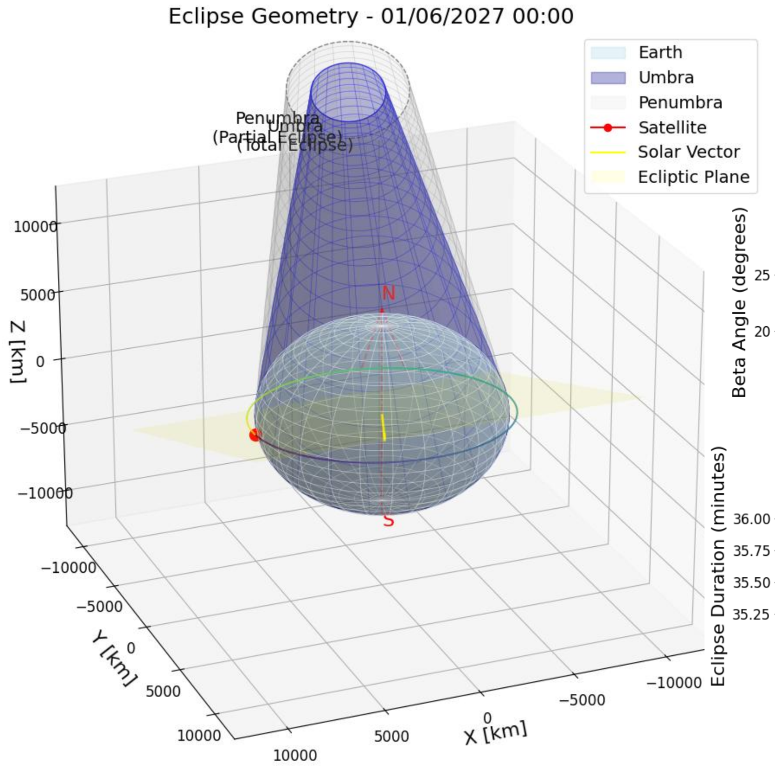


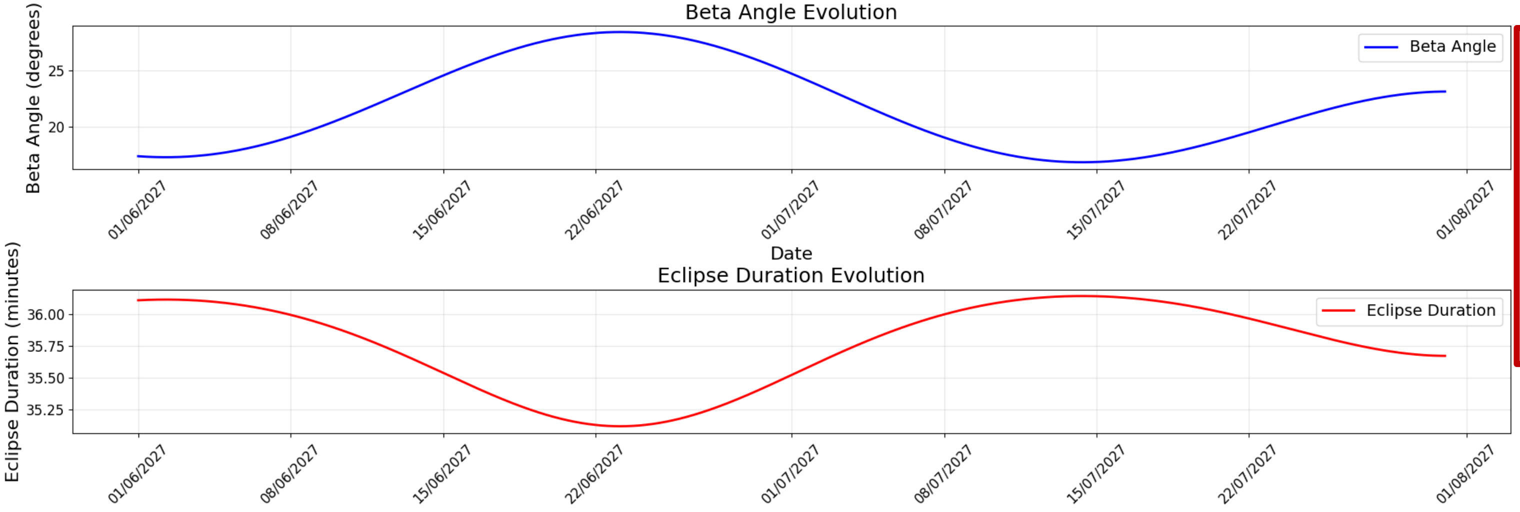
*To perform the analysis correctly, it is necessary to:

- Know the position of the Sun, calculate the solar vector
- Define the correct position of the satellite

- NASA JPL DE405/DE406 Ephemerides
- $i_s(t) = [\cos(\lambda_{true}), \cos(\epsilon) \times \sin(\lambda_{true}), \sin(\epsilon) \times \sin(\lambda_{true})]$

1. $ECI \rightarrow Ecliptic: R_x(\epsilon), \epsilon = 23.44°$
2. $ECI \rightarrow Orbital: R_z(\Omega) \cdot R_x(i)$
3. $Orbital \rightarrow Body\ Fixed: R_z\left(\nu + \frac{\pi}{2}\right)$
4. $R_{total} = R_1 \cdot R_2 \cdot R_3$





β is defined as the angle between the solar vector and its projection into the orbital plane

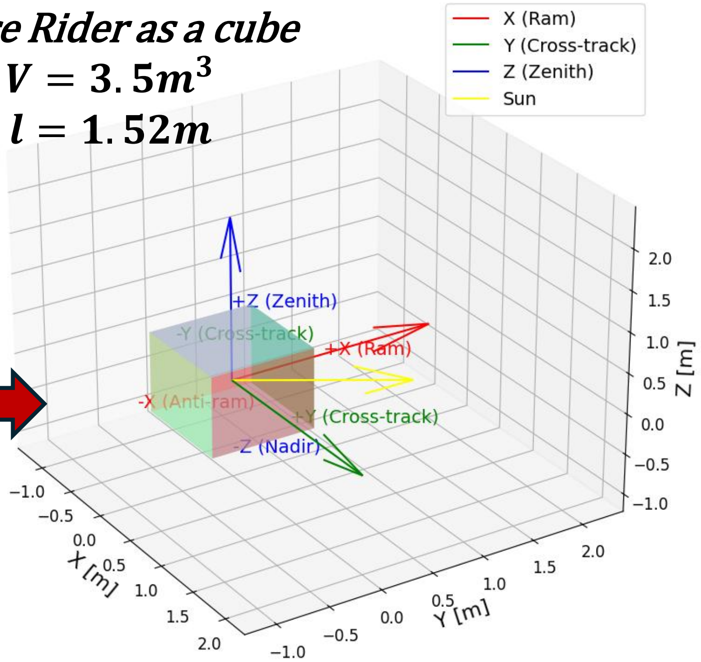
David A. Vallado, Fundamentals of Astrodynamics and Applications

*****Sumanth R M, Computation of Eclipse Time for Low-Earth Orbiting Small Satellites***

Space Rider as a cube

$V = 3.5m^3$

$l = 1.52m$



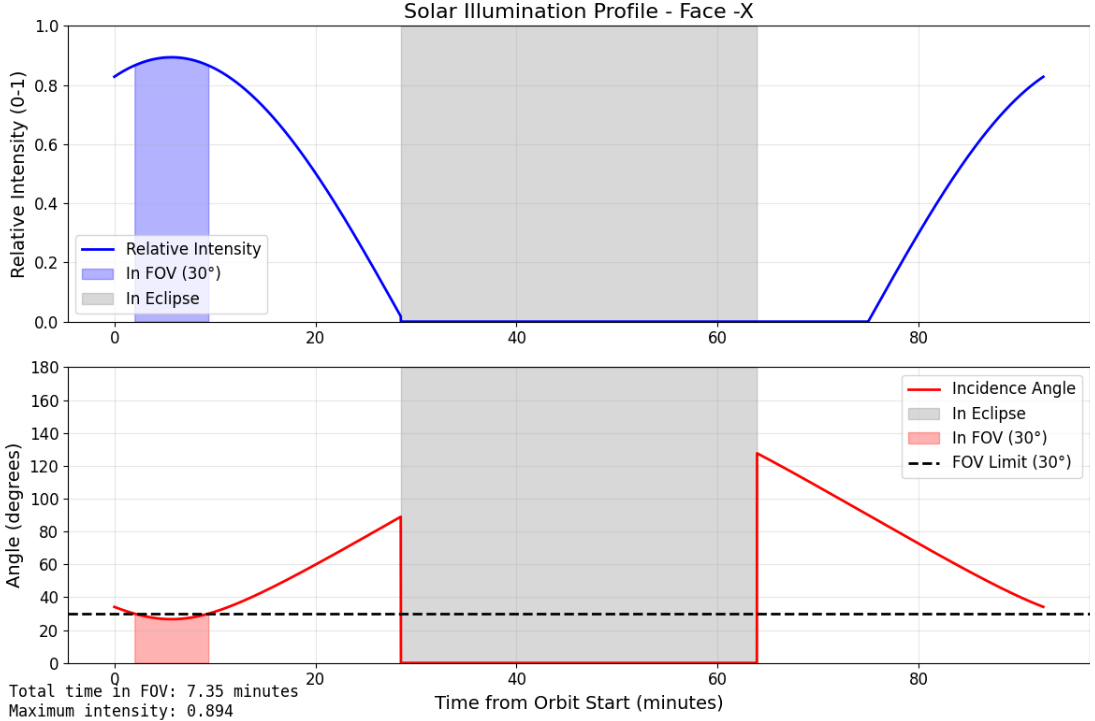
The reference system is the Body-Fixed system, each face has its normal vector.

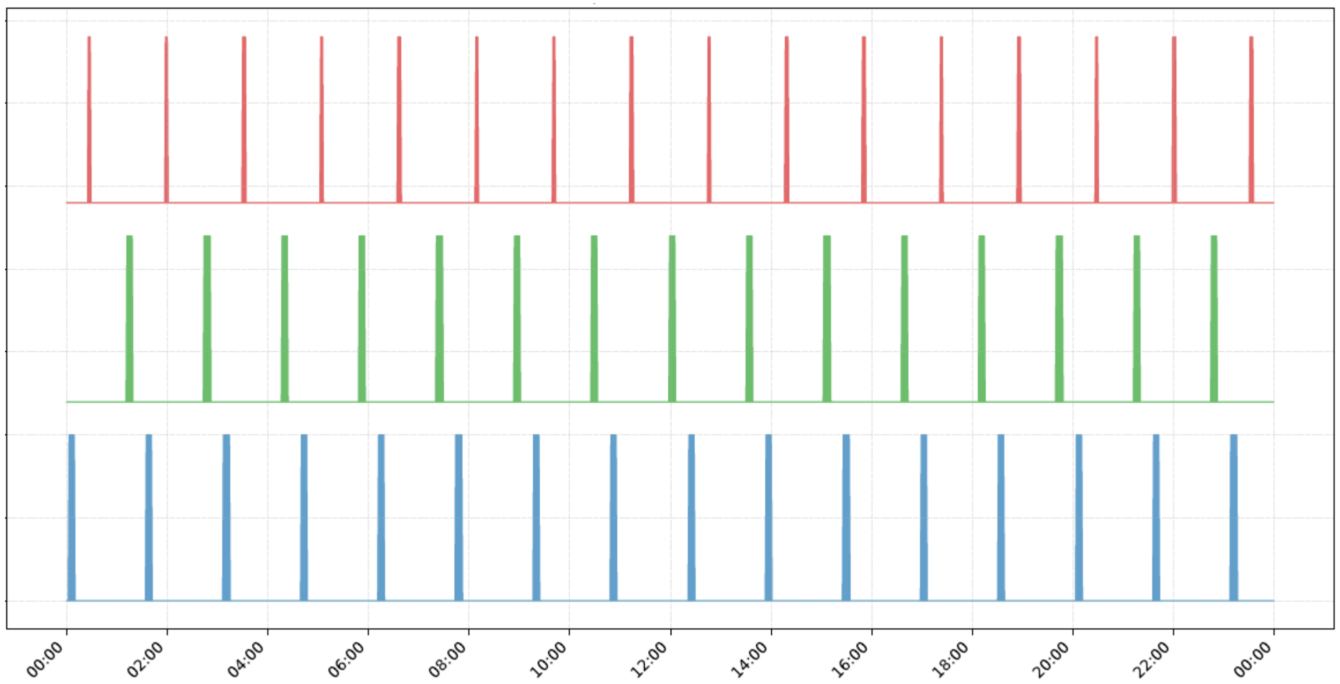
- The X-axis is aligned with the direction of flight (+X Ram, -X Anti-Ram)
- The Z-axis points towards space (+Z) and towards Earth (-Z)
- The Y-axis completes the right-handed system

With a FoV of 30°, for how long will the detector it be exposed to sunlight?

-Z in FoV
+Z in FoV
-X in FoV

Total exposure Time: 4h 41m





Conclusions and final remarks, 1…

- ➢ Simulation of the radiation environment ✓
- ➢ Complete mechanical model definition and radiation shielding simulation of TID and TNID damage ✓
- ➢ Characterization of FK NUV-HD-MT/RH SiPM ✓
- ➢ TID test at ESTEC Co60 facility ✓
- ➢ Proton test at PIF facility PSI, FBK/HAMAMATSU SiPM ✓
- ➢ Comparison of the dose calculation strategy ✓
- ➢ Astrodynamic simulations for the WINK and Crystal Eye missions ✓
- ➢ Next short-term and long-term project activities

- During both TID test, FBK's NUV-HD-MT/RH technology proves to be remarkably resistant to ionizing radiation damage at dose levels higher than those expected for the mission;
- MPPC Hamamatsu devices showed great resistance to ionizing radiation damage (TID) without significant increases in current consumption, even at dose levels much higher than those expected for the mission.
- Proton tests conducted on both technologies show a significant increment in the current/DCR levels to devices even at low doses, demonstrating the danger of heavy particles on optoelectronic devices;
- The comparison of the total dose calculated using different tools shows great consistency with the preliminary analysis, which differed from the standard;

Conclusions and final remarks, 2…

- Simulation of the radiation environment ✓
- Complete mechanical model definition and radiation shielding simulation of TID and TNID damage ✓
- Characterization of FK NUV-HD-MT/RH SiPM ✓
- TID test at ESTEC Co60 facility ✓
- Proton test at PIF facility PSI, FBK/HAMAMATSU SiPM ✓
- Comparison of the dose calculation strategy ✓
- Astrodynamic simulations for the WINK and Crystal Eye missions ✓
- Next short-term and long-term project activities

- Future activities will include conducting further functional tests on irradiated devices at the GranSasso laboratories. By analyzing the proton test data, it will be possible to accurately distinguish between the effects of ionizing and non-ionizing damage, thereby highlighting the dose values at which ionizing and non-ionizing damage caused by protons become significant.
- The analyses of the orbital data from WINK and CE are very satisfactory and demonstrate the feasibility of the required operations. Future activities will include the astronomical sources.
- Complete the industrial activity in TASI
- Properly prepare all data for writing a paper.

Workshops and conferences

- ASAPP conference Perugia 19-23/06/2023;
- Ensuring Electronic Reliability Against CERN's Radiation Environment, seminar Napoli 01/12/2023;
- NEW TRENDS AND CHALLENGES IN OPTIMIZATION THEORY APPLIED TO SPACE ENGINEERING conference L'Aquila 13-15/12/2023;
- SST – PhD National Days – 06-08/06/2024 – L'Aquila;
- RADSHIELD ESA/ESTEC 12-15/06/2024 – TALK;
- Società Italiana di Fisica SIF – 09-13/09/2024 -Bologna – TALK;
- Conference in Memory of Veniamin Sergeyevich Berezinsky – 01-03/10/2024 – L'Aquila;
- International Astronautic Congress IAC – 13-18/10/2024 – Milano;
- Young Professional Event (YPE) ESA-ESTEC – 2-3/06/2025 – Noordwijk - POSTER;
- SPACEMON ESA-ESTEC – 11-13/06/2025 – Noordwijk - TALK;
- Società Italiana di Fisica SIF – 22-26/09/2025 -Palermo – TALK;

Collaboration meetings

- Talks during working group meetings of HERD 09/11/2023
- Talks during working group meetings of NUSES 26/01/2024
- Talks during NUSES collaboration meeting 16-18/12/2024 – L'Aquila

Schools

- 6th HEP C++ course and hands-on training - Essential, virtual, 6-10 mar. 2023
- GEANT4 beginners course "First steps with Geant4 2024", virtual, 15-19 apr. 2024
- 13th international IDPASC school and workshop, Palermo, 17-27 sept. 2024

Other activities

- Working in Bari to test the mechanic structure of the HERD PSD, 12-16 apr. 2023
- Working in Bari to test the mechanic structure of the HERD PSD+ Zirettino prototype, 03-07 jul. 2023
- Test beam at CERN PS for the Zirettino prototype, 3-10 sept. 2023
- Test beam at CERN SPS for the Zirettino prototype, 24-31 oct. 2023
- Test beam at INFN-LNF for the Zirettino prototype, 19-26 feb. 2024
- Test beam at PIF Zurich for the GST DC/DC converter test, 12-17 may.2024
- Test beam at PIF Zurich for the NUSES SiPM test, 04-07 July .2025

Scientific publications

Conference Papers:

- PoS ICRC2023 (2023) 1538
- IWASI (2023) pp. 184-189, doi: 10.1109/IWASI58316.2023.10164305
- PoS ICRC2023 (2023) 140, doi: 10.22323/1.444.0140
- PoS ICRC2023 (2023) 112, doi: 10.22323/1.444.0112
- NIM-A 1068 (2024) 169794
- NIM-A 1069 (2024) 169888
- NIM-A 1068 (2024) 169706, doi:10.1016/j.nima.2024.169706
- PoS TAUP2023 (2024) 121, doi:10.22323/1.441.0121
- PoS ICRC2025 (2025) 235, doi:10.22323/1.501.0235
- PoS ICRC2025 (2025) 071, doi:10.22323/1.501.0071
- PoS ICRC2025 (2025) 418, doi:10.22323/1.501.0418
- PoS ICRC2025 (2025) 1346 doi:10.22323/1.501.1346
- PoS ICRC2025 (2025) 857, doi:10.22323/1.501.0857

Journal Papers:

- NIM-A 1069 (2024) 169888, doi:10.1016/j.nima.2024.169888
- J. Phys.: Conf. Ser. 3053 (2025) 012034, doi:10.1088/1742-6596/3053/1/012034
- JINST 20 (2025) C07014, doi:10.1088/1748-0221/20/07/C07014
- JCAP 07 (2025) 073, doi:10.1088/1475-7516/2025/07/073
- Astropart. Phys. 174 (2025) 103171, doi:10.1016/j.astropartphys.2025.103171
- Adv. Space Res. (2025), doi:10.1016/j.asr.2025.08.072

BACKUP

NUSES Mission: Mass Budget

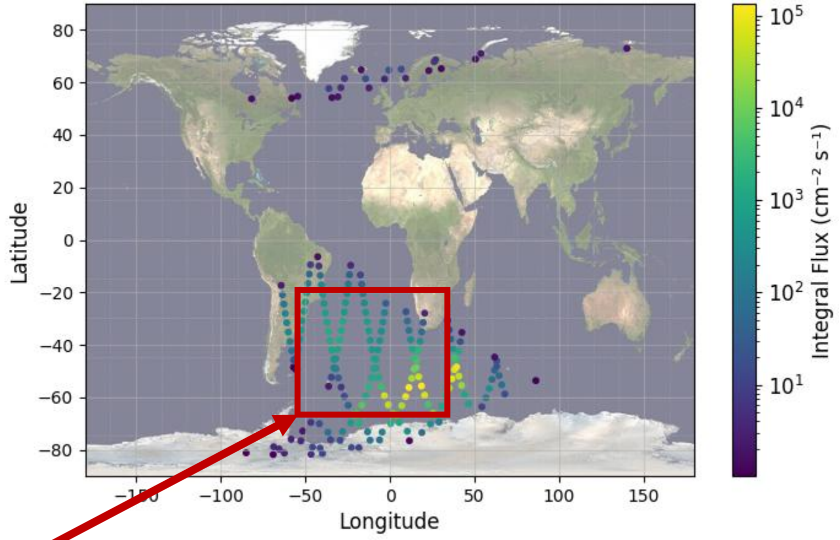
GRAN SASSO SCIENCE INSTITUTE

Device in P/L	Weight [kg]	S/C Location	
Ziré Instrument	23.3 (cont. 5%)	Tray	Ziré P/L
Electronics Unit (EU)	22.8 (5%)	Tray	
LEM	2.1 (5%)	Top Panel	
Terzina (Optical Telescope Assembly, OTA)	28.9 (10%)	Top Panel	Terzina P/L
Terzina (Focal Plane Assembly, FPA)	2.5 (10%)	Top Panel	
Thermal Control Assembly (TCA)	9.4 (10%)	Top Panel	
Harness	1.2* (10%)	Distributed	

Total: 90.2 kg

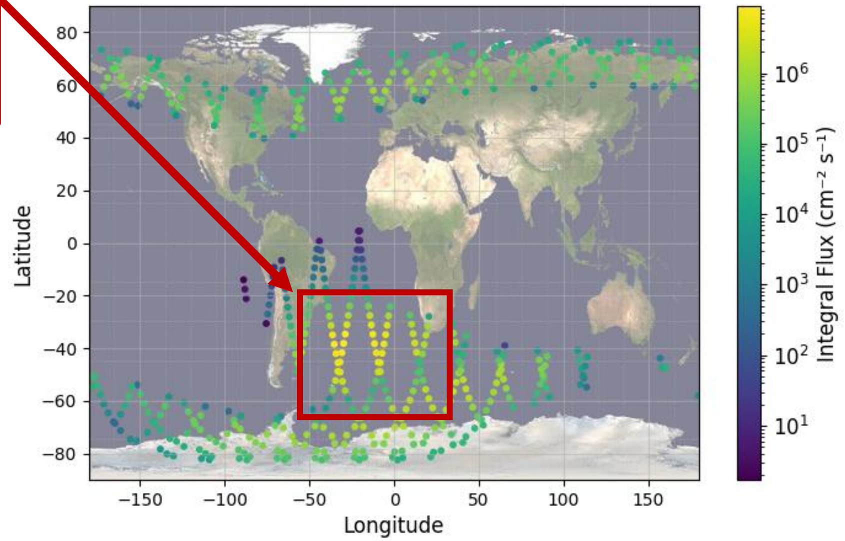
Geographical distribution of trapped particles

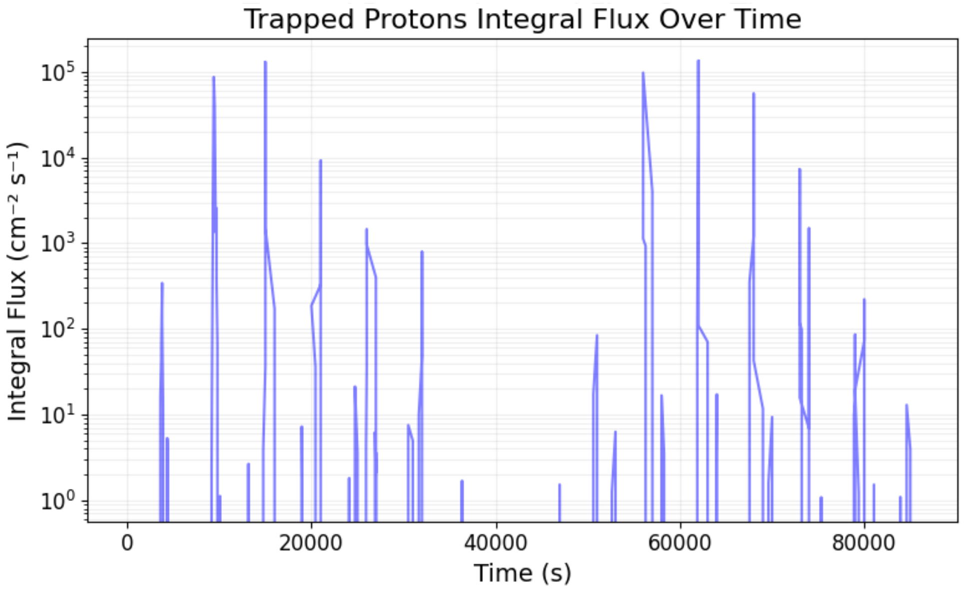
Protons Distribution along the Orbit

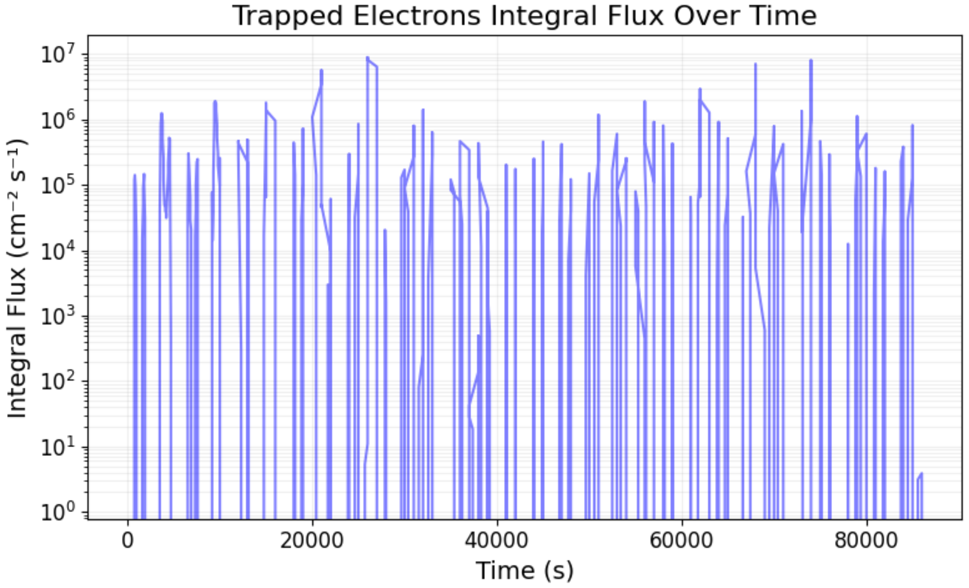


South Atlantic Anomaly (SAA)

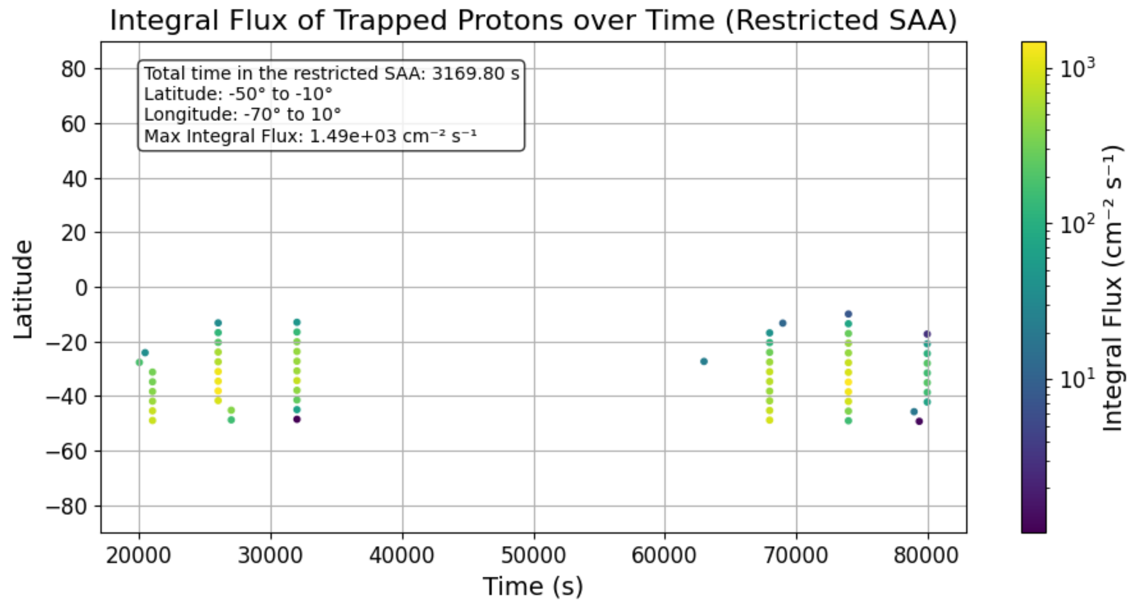
Electrons Distribution along the Orbit

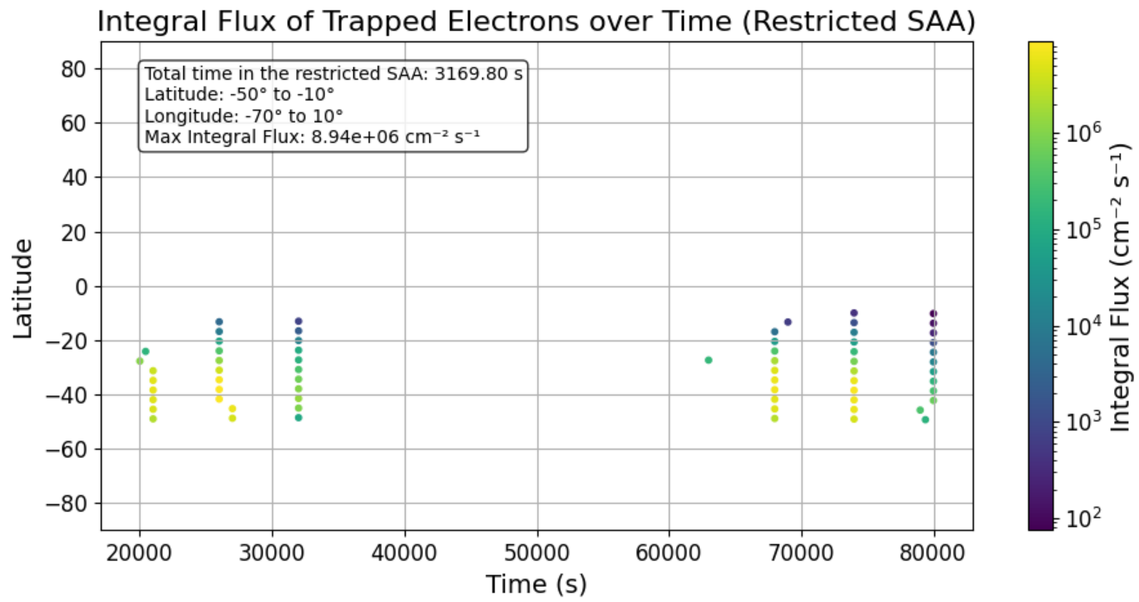






South Atlantic Anomaly (SAA) time definition



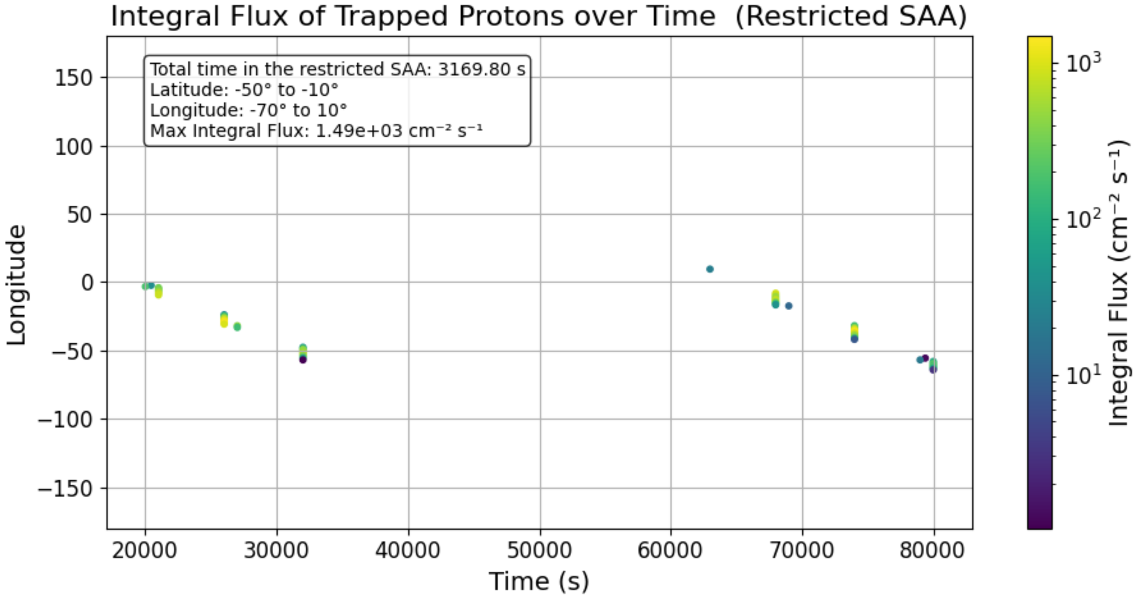


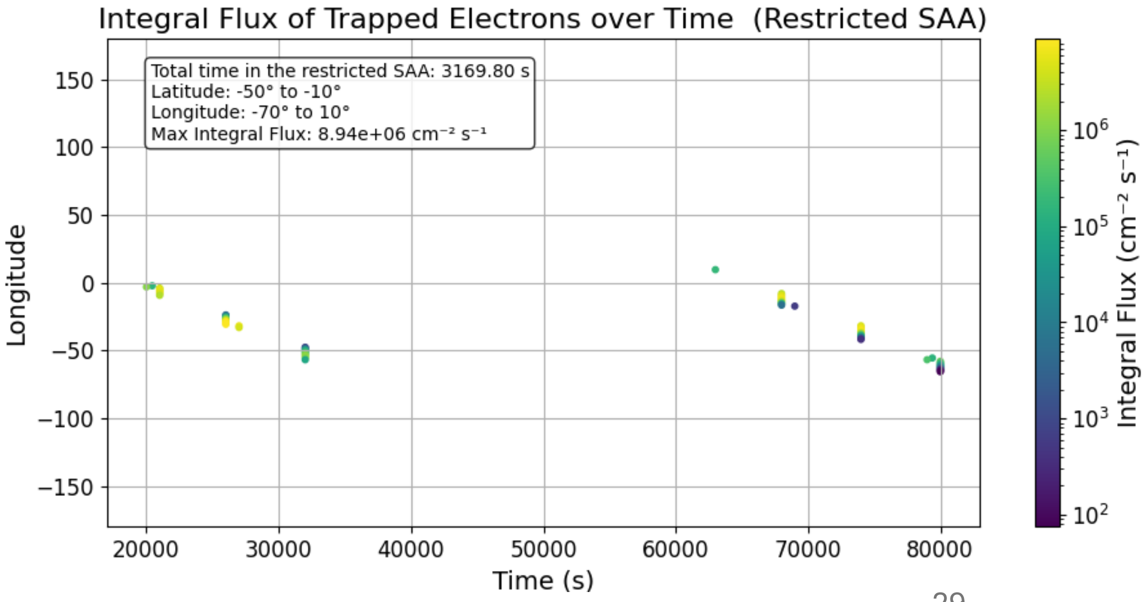
Expected Operative Time:

1360m/d

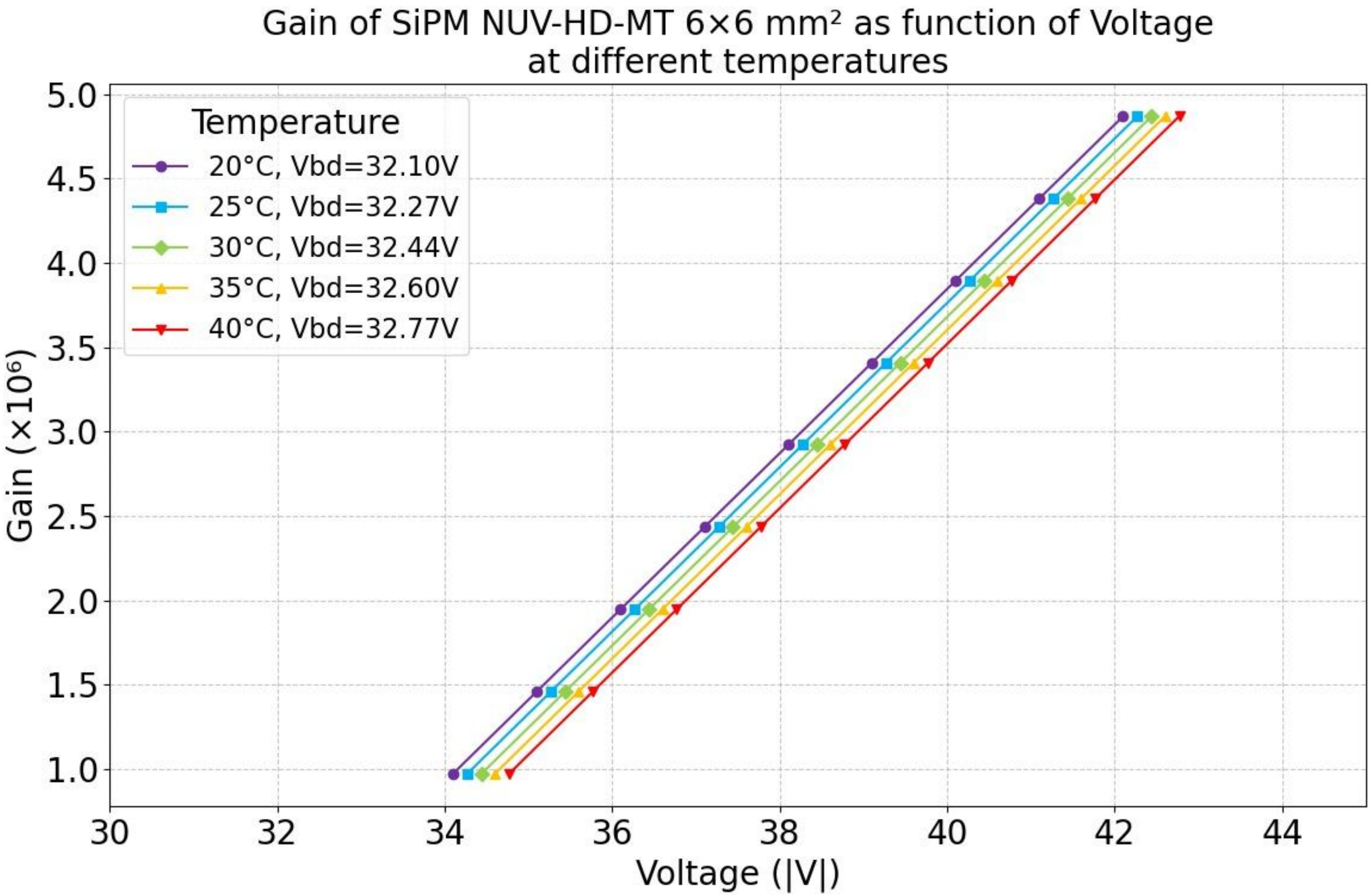
Expected Duty Cycle:

94.4%





Characterization analysis: Gain vs Ov for a 6x6 SiPM



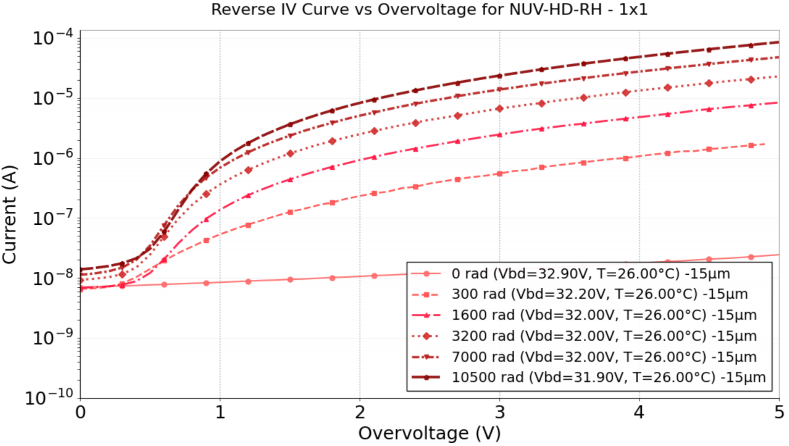
$$G(V_{OV}) = \frac{(C_q + C_\mu)}{q} V_{OV}$$

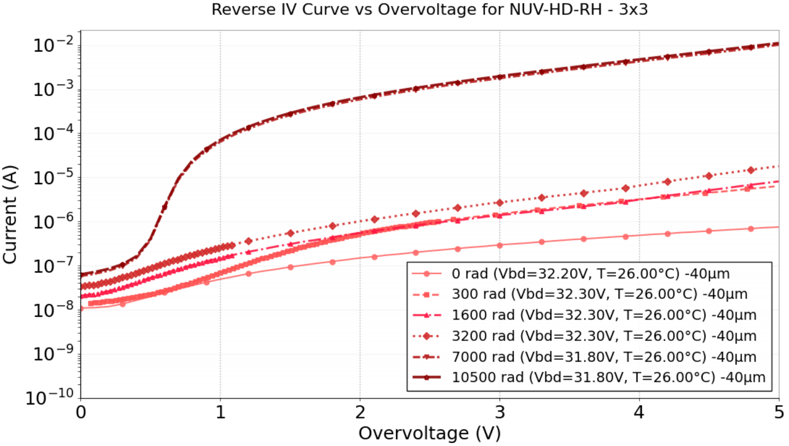
Where:

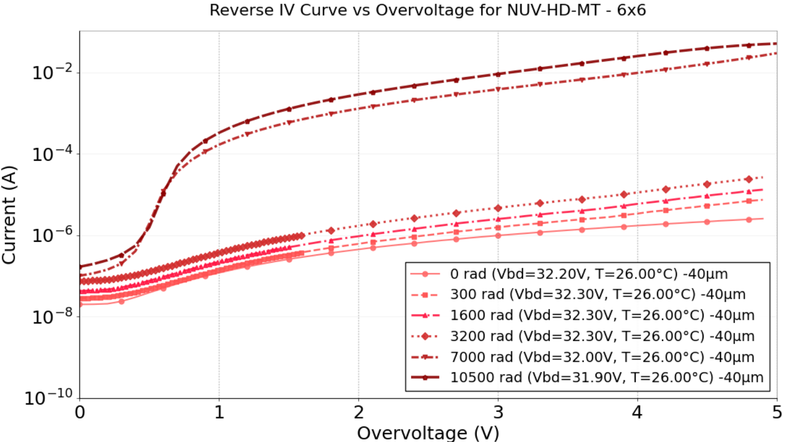
- $C_q = \frac{\tau_{rec}}{R_q}$,is the parasitic capacitance
- $C_\mu = \frac{(\epsilon_0 * \epsilon_r * A * FF)}{d}$, is the microcell capacitance
- q is the elementary charge
- $V_{OV} = V_{bias} - V_{BD}$, is the OverVoltage

	$(c_q + c_\mu)$
1x1	**40 e-15 F**
3x3	**220 e-15 F**
6x6	**78 e-15 F**

FBK/HAMAMATSU SiPMs PSI/PIF PROTON Test







SiPM board FBK 4x 6x6 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board FBK 4x 3x3 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board FBK 4x 3x3 Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

SiPM board Hamamatsu -> 3 device/dimension Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

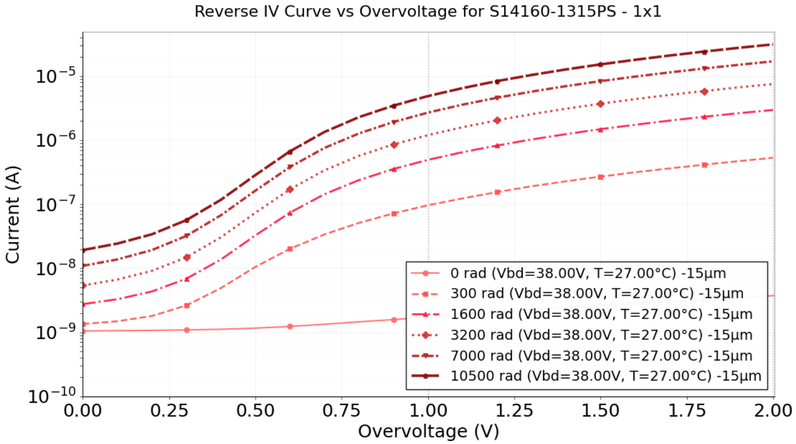
SiPM board Hamamatsu -> 3 device/dimension Unbias	Measurements	Dose in Si [Gy]	Fluence [p./cm^2]	Energy, MeV	Stopping power [MeVcm^2/g]	Flux avearge [p./(cm^2*s)]	Irradiation time [s]
	1	3	3.21E+09	100	5.838	2.00E+08	1.61E+01
	2	16	1.71E+10	100	5.838	2.00E+08	8.55E+01
	3	32	3.43E+10	100	5.838	2.00E+08	1.72E+02
	4	70	7.49E+10	100	5.838	2.00E+08	3.75E+02
	5	105	1.12E+11	100	5.838	2.00E+08	5.60E+02

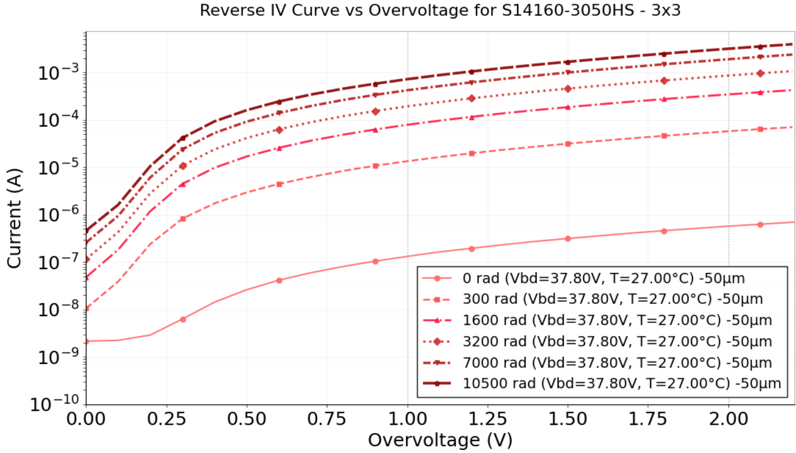
$$TNID = F \cdot NIEL = \left[\frac{MeV}{g}\right], NIEL_{Si}, for\ a\ beam\ of$$

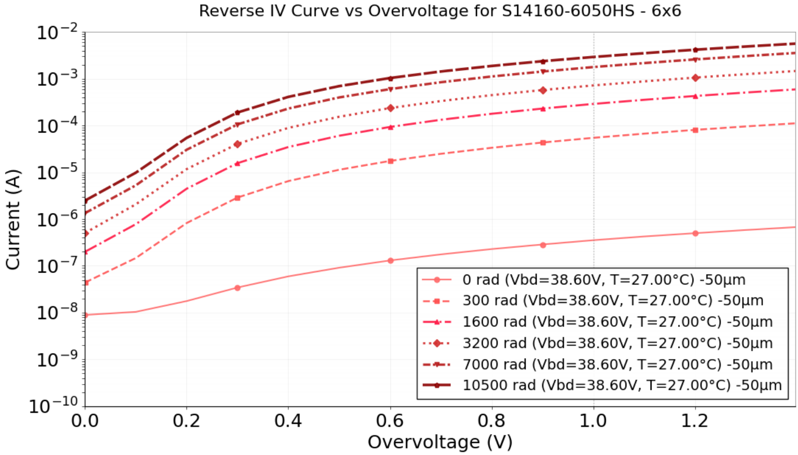
$$p^{+}\ 100MeV, = 2.97x10^{-3}\ \frac{(MeV \cdot cm^2)}{g}$$

SPENVIS simulated value with 5mm of Al shielding = 2.35x10^7 $\left[\frac{MeV}{g}\right]$ ~ a Fluence of 8.03x10^9 ~ IonizingDose of 7.5 Gy

FLUENCE $\left[\frac{p}{cm^2}\right]$	TNID $\left[\frac{MeV}{g}\right]$
3.21×10^9	9.55×10^6
1.71×10^10	5.09x10^7
3.43×10^10	1.02x10^8
7.49×10^10	2.23x10^8
1.12×10^11	3.33x10^8

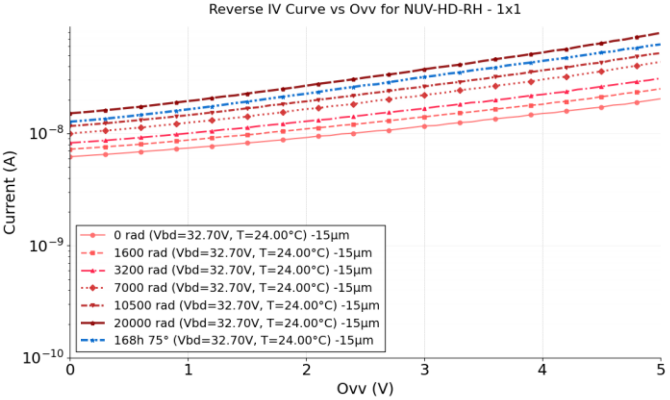


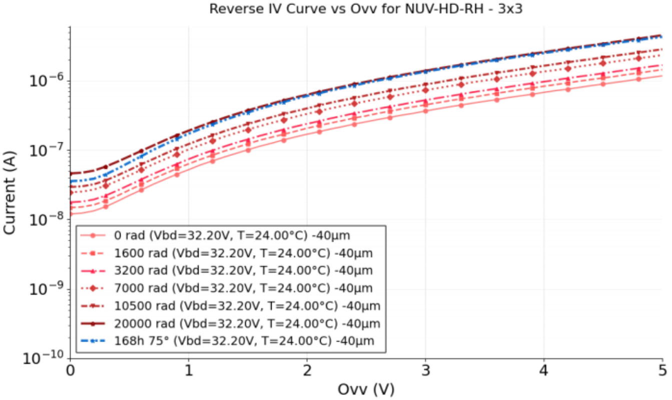


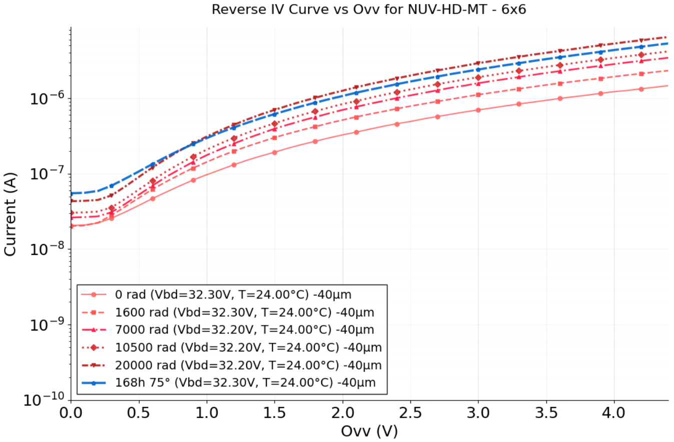


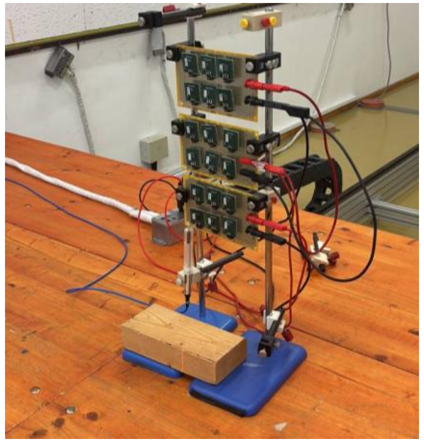
FBK/HAMAMATSU SiPMs ESA/ESTEC 2nd TID Test

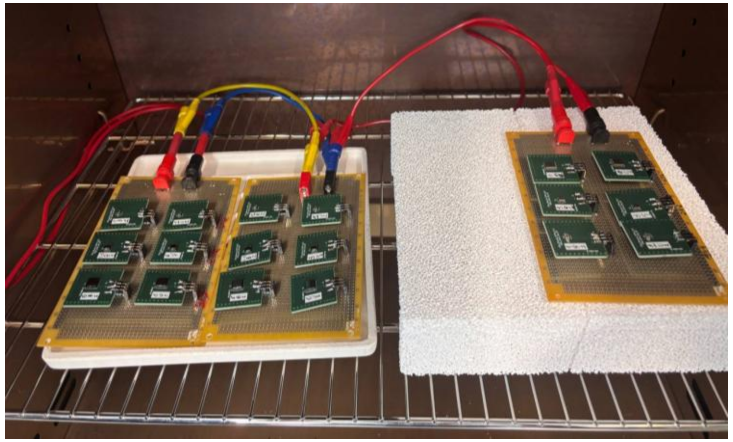
- TID test with the Co60 source in the ESTEC radiation lab.
- 12 FBK components in total; 4 per size; 2 boards: 6 devices each - 3 biased 20V - 3 unbiased
- 6 HAM components in total; 2 per size; 1 boards: 3 devices each - 3 biased 20V - 3 unbiased
- Test started on the 22/07/2025 at 10:30
- Test finished on the 05/08/2025 at 13:15
- One day of Annealing at room temperature + one week at 75°



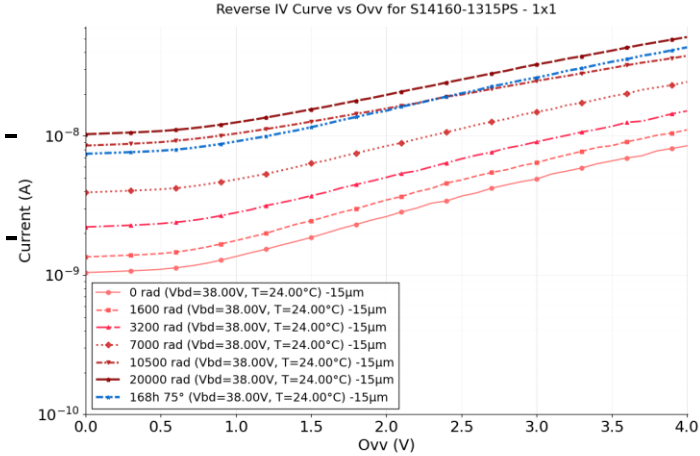


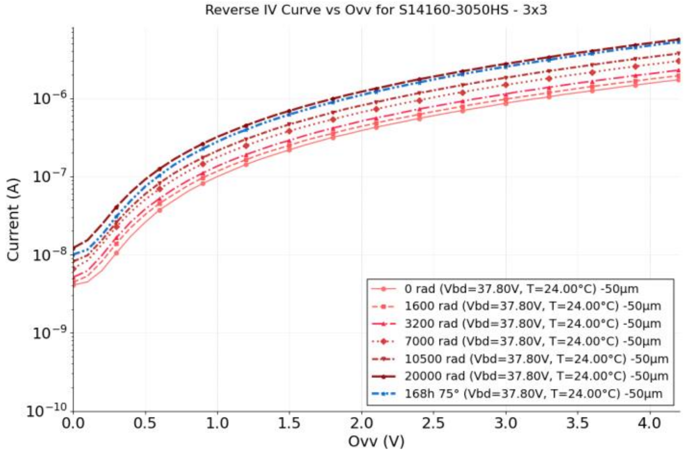


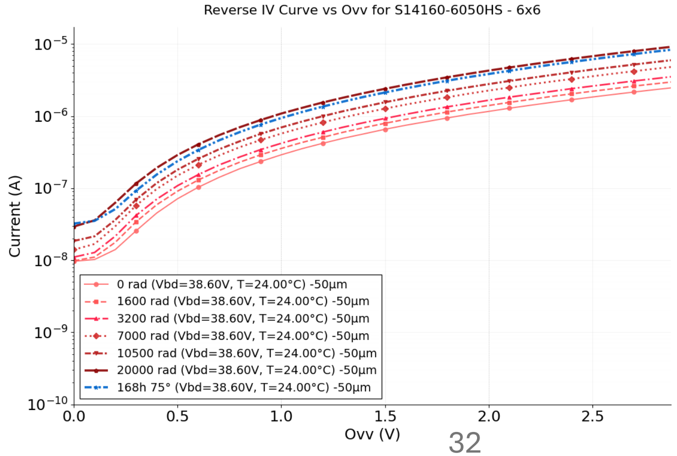




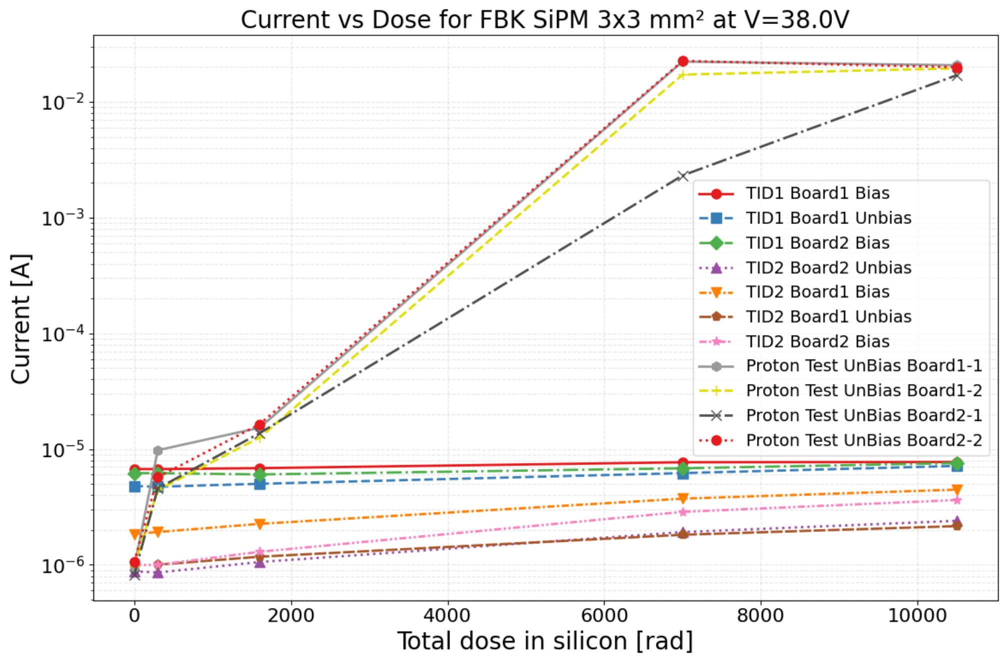
DATA REFERRING TO BIAS BOARD-1 COMPONENTS

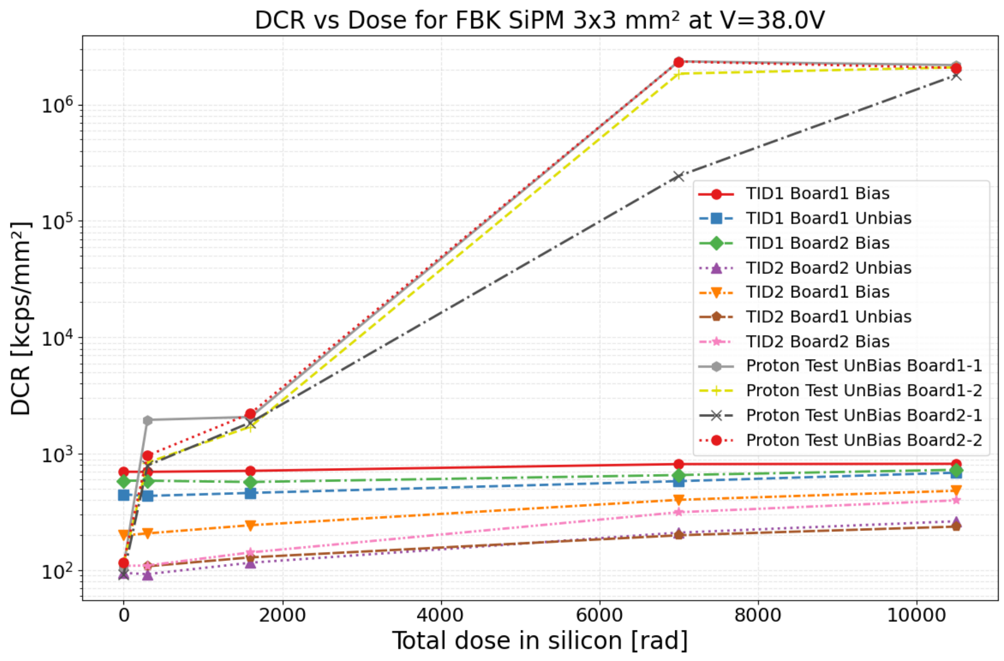


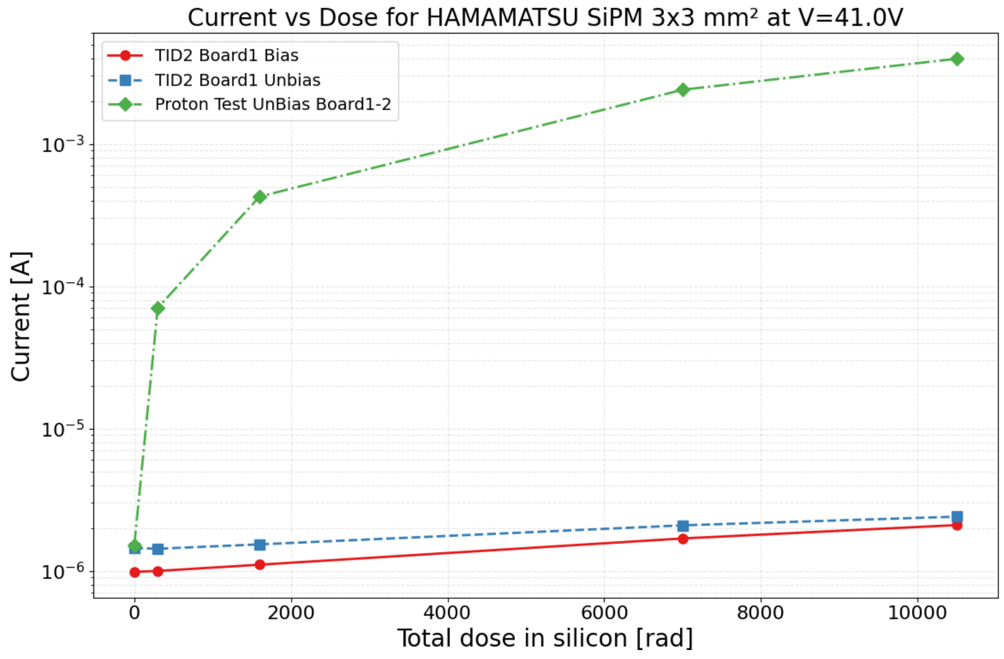


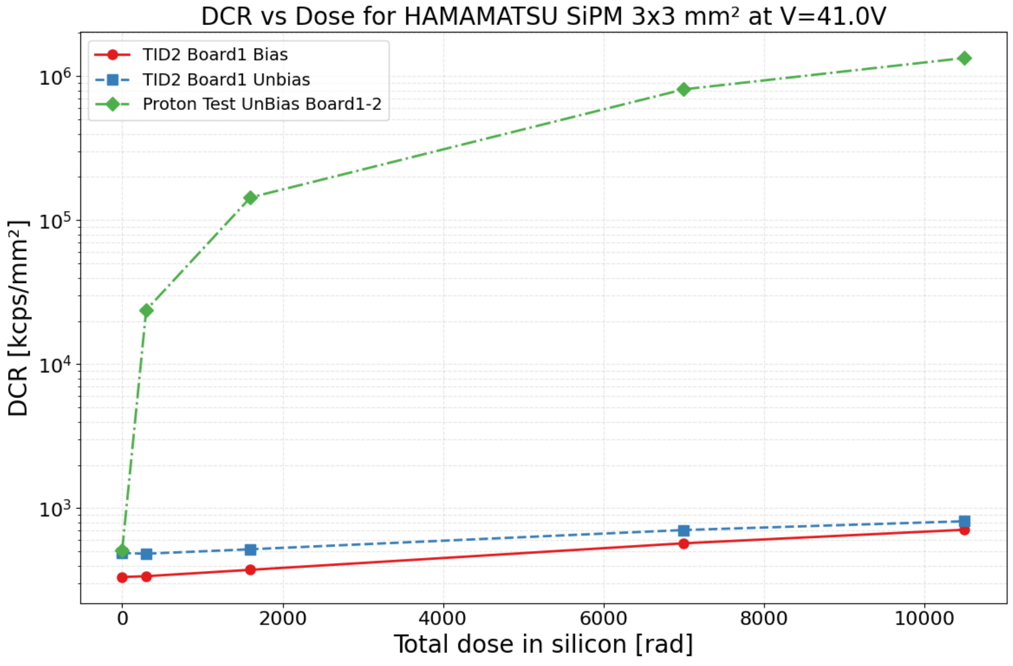


Comparison of the trend of the Current/DCR as function of the dose:

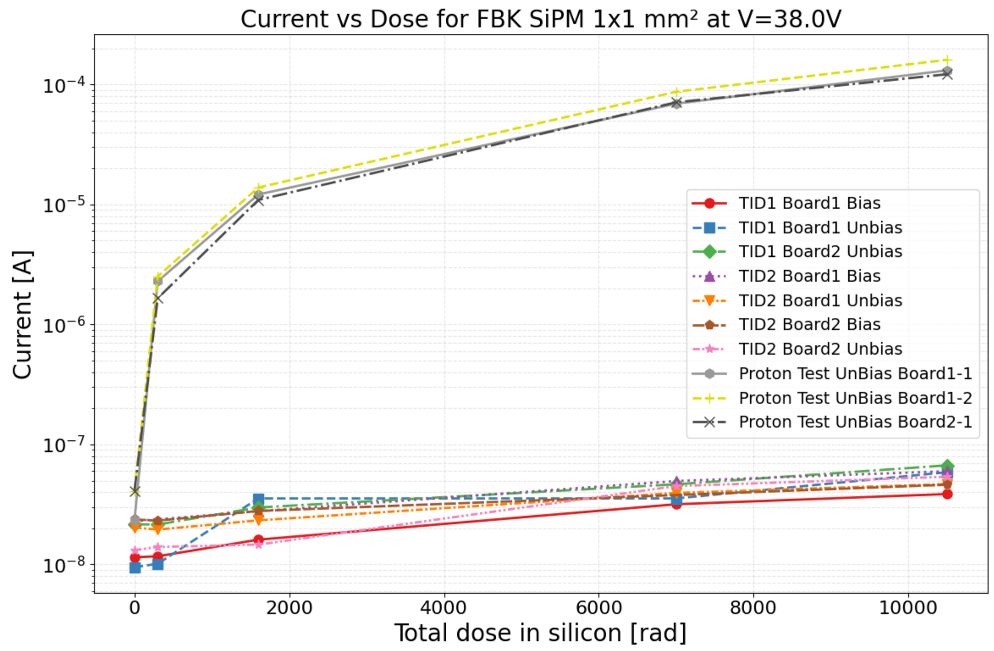


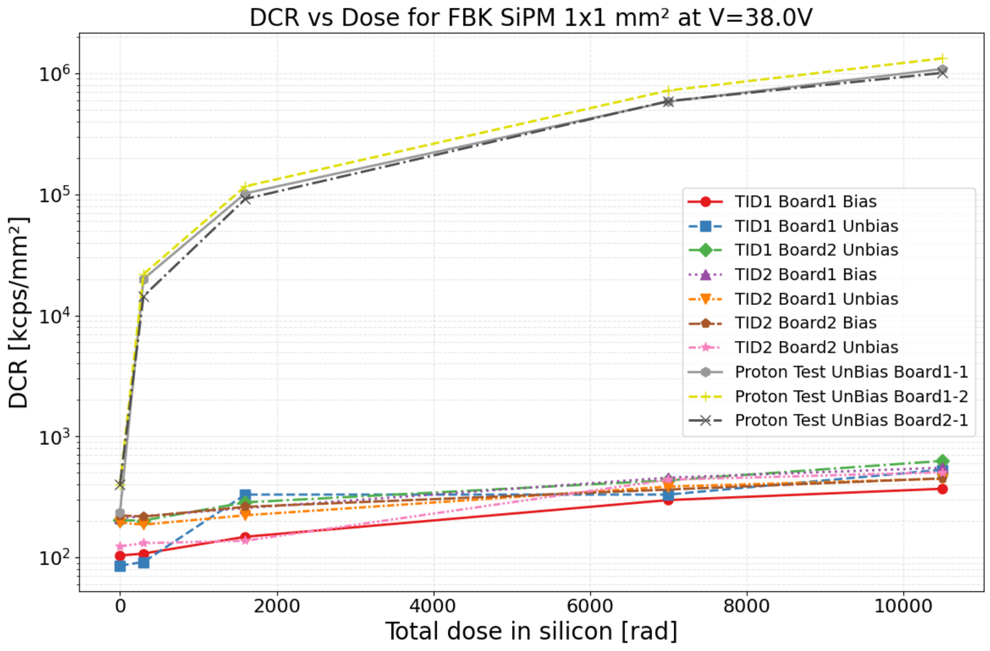


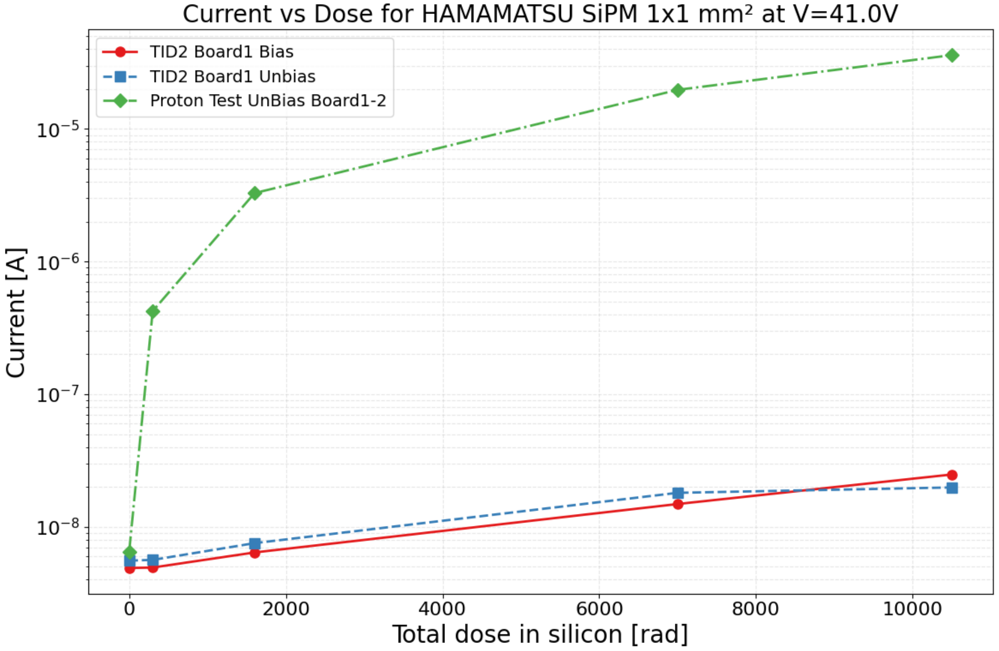


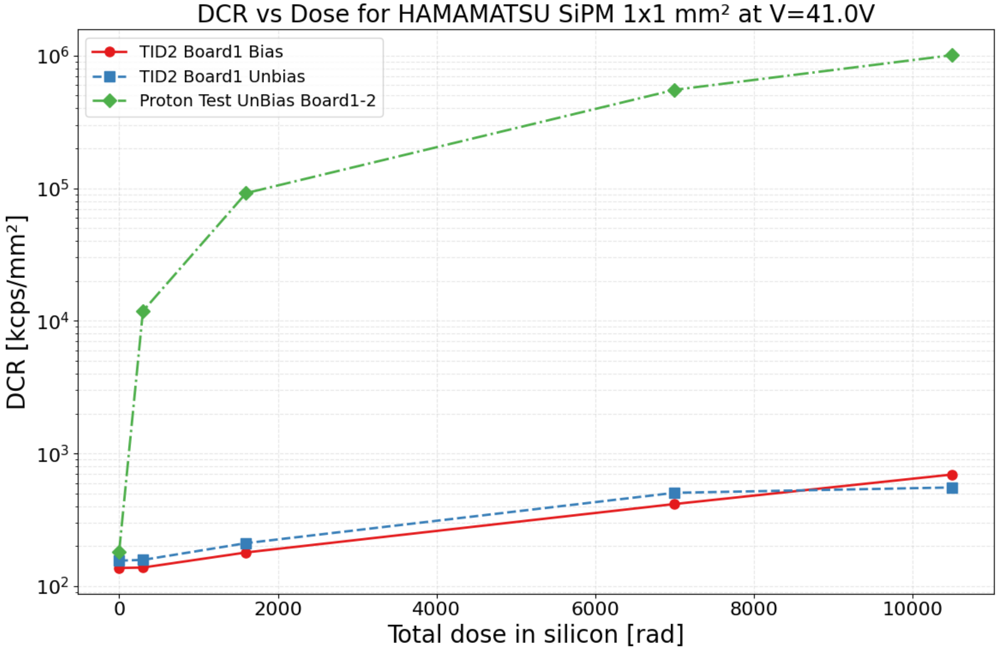


Comparison of the trend of the Current/DCR as function of the dose:





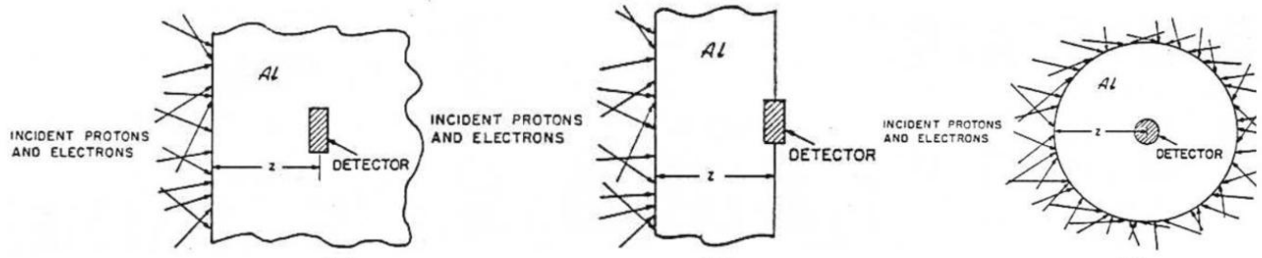




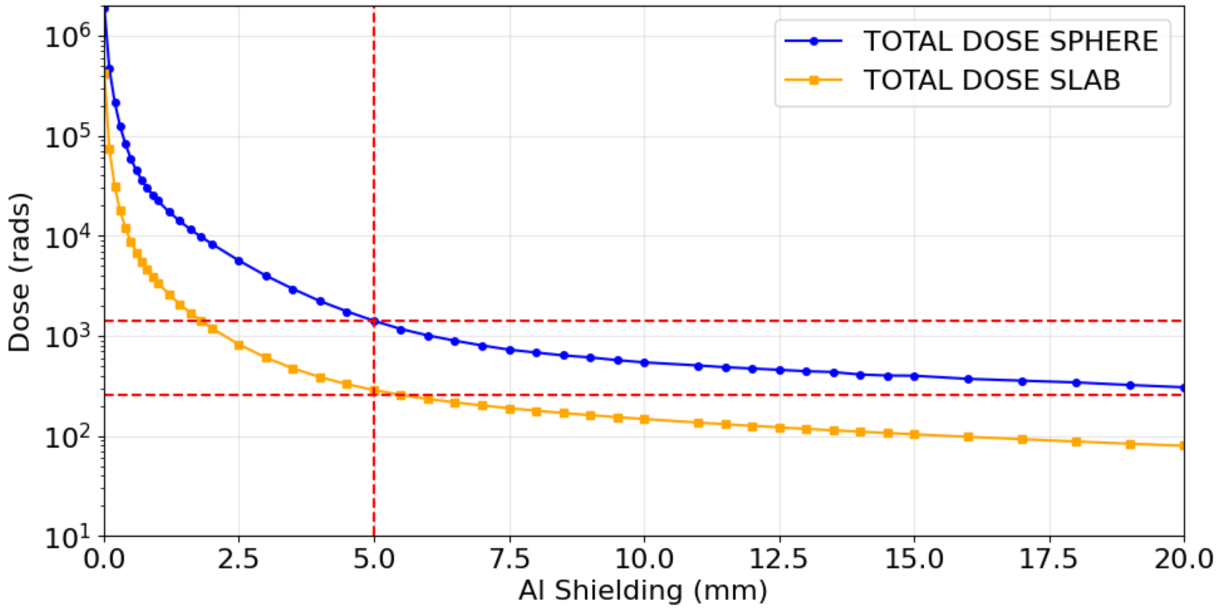
SPENVIS Total Dose Calculation:

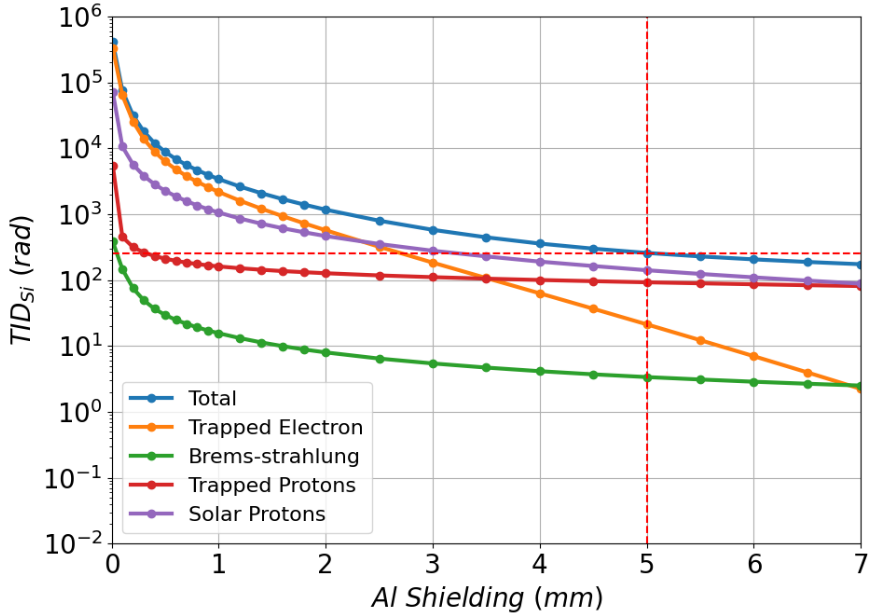
SHIELDOSE-2 Version 2.10

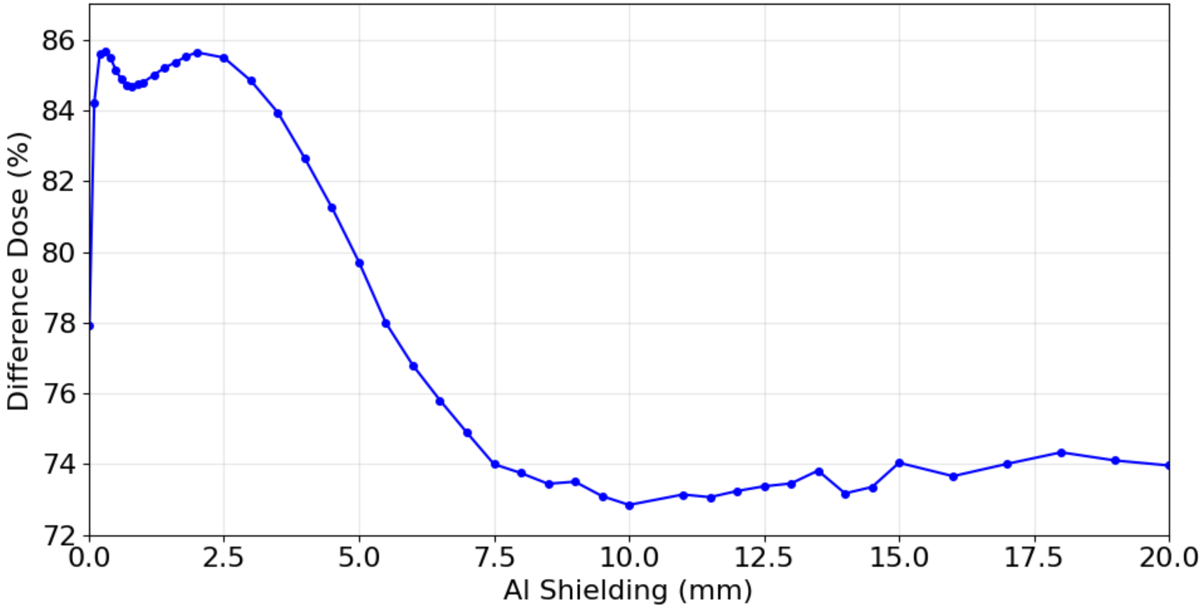
Target material: Si
Shield configuration: Transmission surface of finite Al slab shields
Proton results without nuclear attenuation



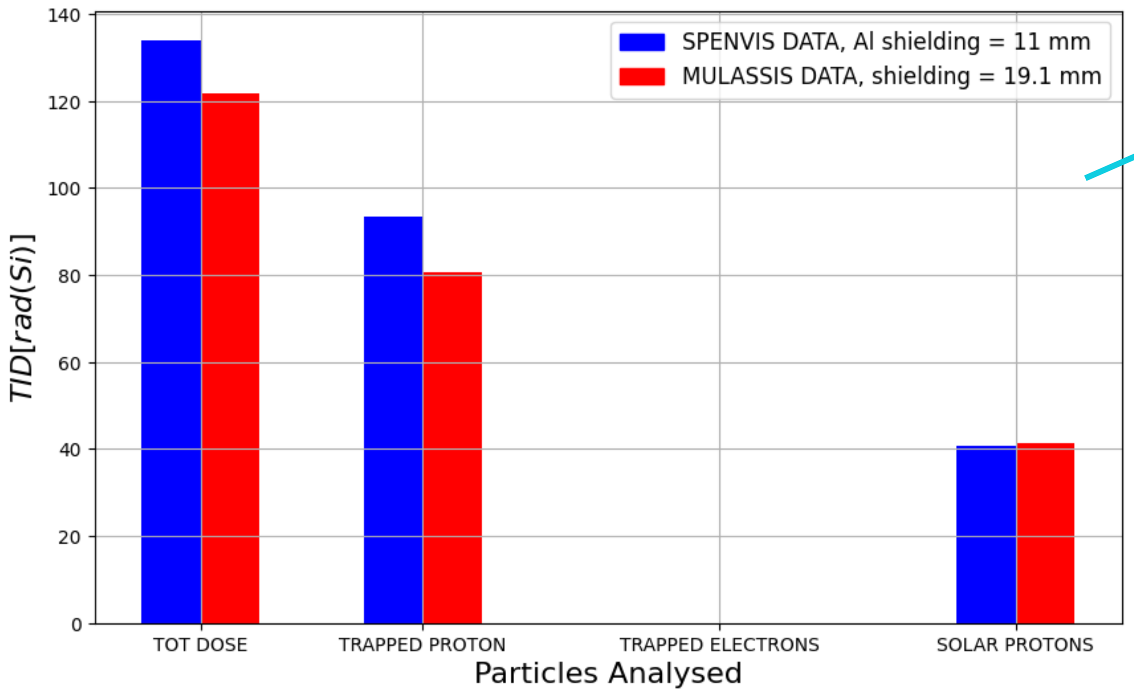
(a) (b) (c)







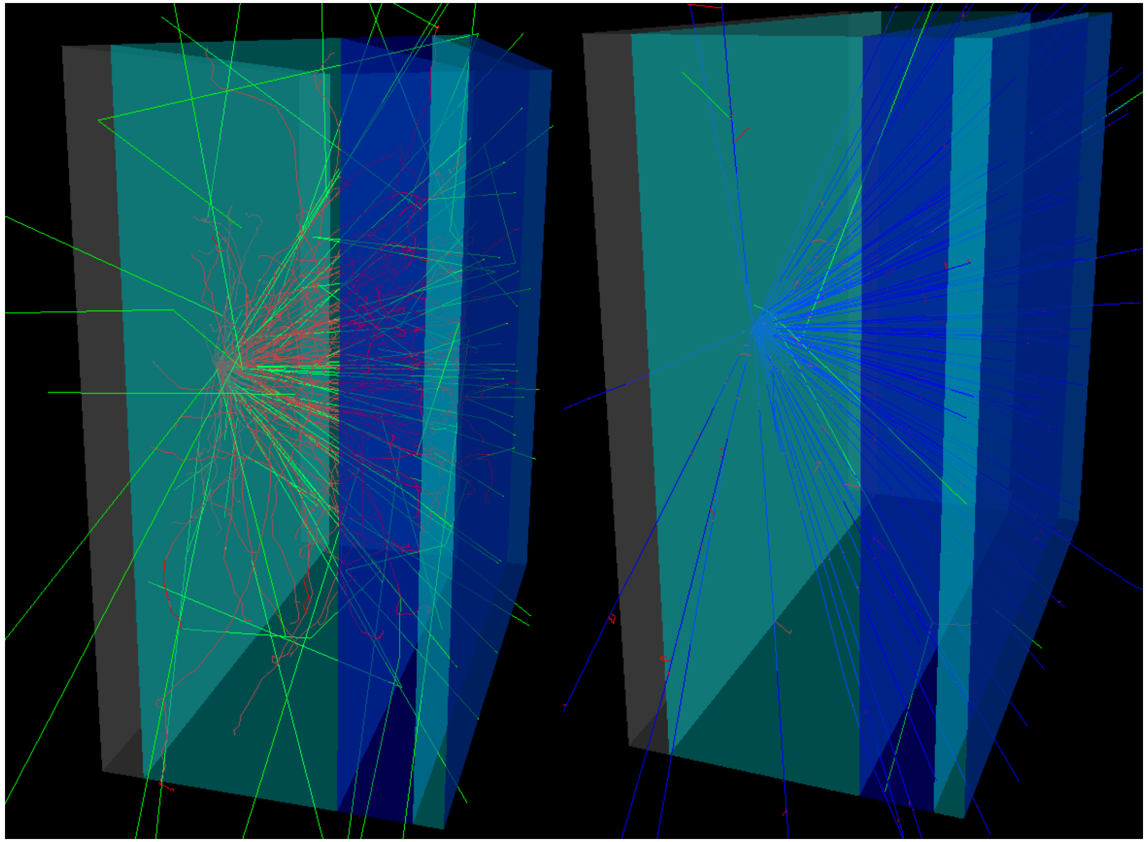
MULASSIS Total Dose Calculation:

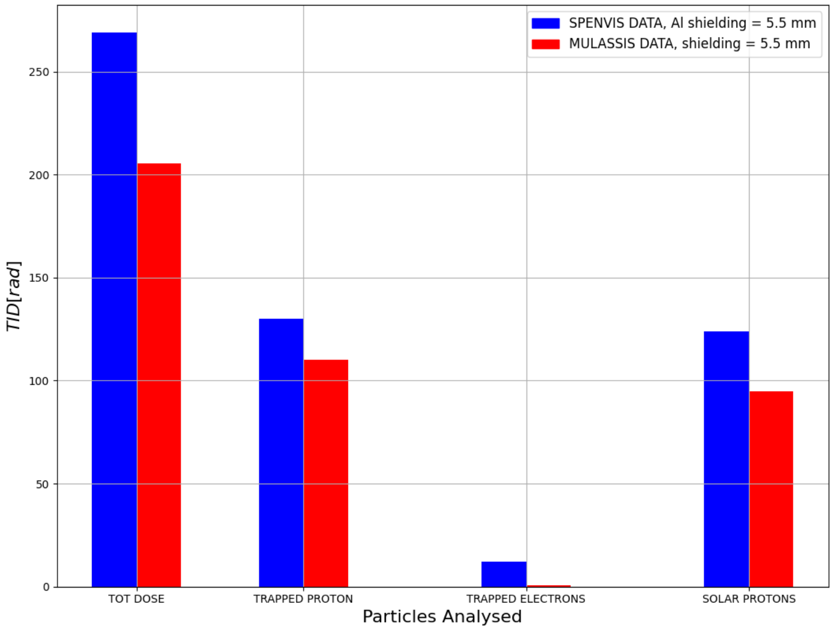


Dose units = rad

Layer	Thickness	Material	Density	Dose	Error
1	2.5 mm	G4_Al	2.699 g/cm3	5.9612e+02	3.2638e+01
2	1.1 cm	G4_PLASTIC_SC_V	1.032 g/cm3	1.6251e+02	3.0783e-01
3	4 mm	G4_Si	2.33 g/cm3	9.4033e+01	2.1974e-01
4	1.6 mm	G4_PLASTIC_SC_V	1.032 g/cm3	1.0539e+02	3.1655e-01
5	10 um	G4_Si	2.33 g/cm3	8.0564e+01	3.2143e-01

Trapped e^- *Trapped* p^+

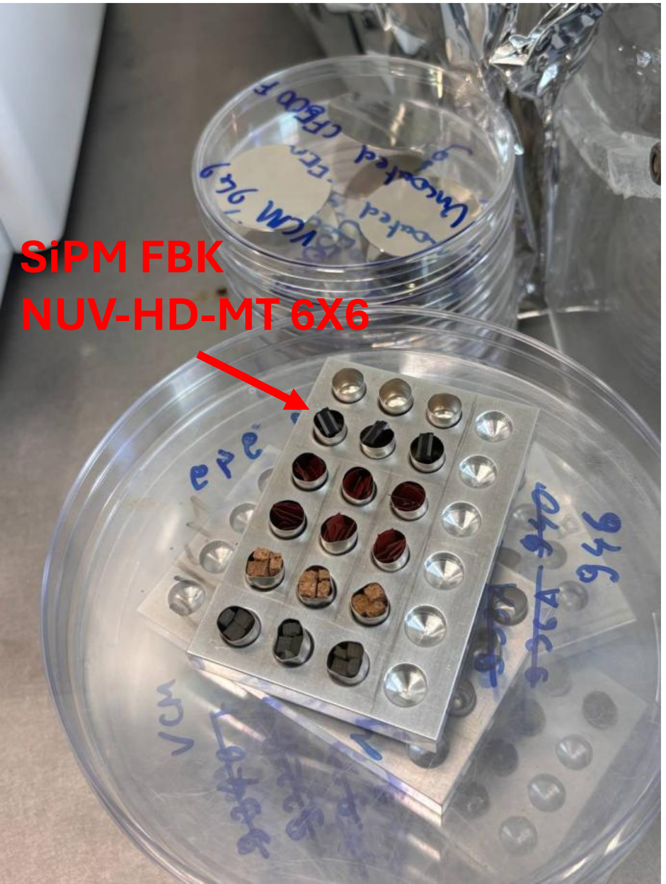




6X6 FBK SiPMs Out-Gassing analysis:

Test start: 28/07/2025
Test end: 01/08/2025
ECSS-Q-ST-70-02C Required:

- TML ≤ 1.0 %
- CVCM ≤ 0.1 %
- WVR ≤ 0.1 %



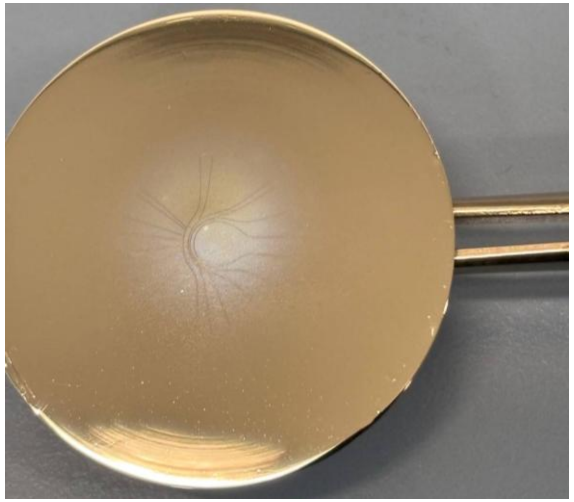
1. Preparation of the sample:
Sample weighing

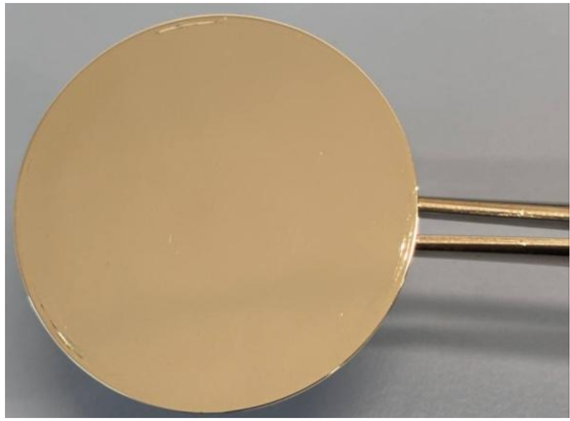
2. Environmental conditioning:
$T = 22 \pm 3°C , 55 \pm 5\% \, RH, 24h$

3. Preparation of the collection plates:
Cleaning, weighing, T-controlled
$T = 25 \pm 2°C$

4. Out-Gassing test:
$24h, p = 1 \cdot 10^{-3} Pa$
T $sample = 125 \pm 2°C$
T collector= $25 \pm 2°C$

5. Final measurements





Calculation of the solar vector, 1

To calculate the direction of the Sun as seen from Earth, the following must be taken into account:

- The position of the Sun varies throughout the year (apparent motion).
- The Earth's orbit is not perfectly circular.
- The Earth's axis is tilted by 23.44°.
- Solar ephemerides must be used, considering that a calculation is being predicted for 2027.

M = 357.5291092 + 35999.05034 * T

Solar Mean Anomaly (M) The mean solar anomaly represents the angle that the Sun would have travelled if it moved at a constant speed (mean motion) along its orbit. It is as if we were simplifying the motion of the Sun by assuming a perfectly circular orbit.

λM = 280.460 + 36000.771 * T

Mean Longitude of the Sun, is the angle measured along the ecliptic between the vernal point and the mean position of the Sun. 280.460° is the longitude at J2000.0 - 36000.771° is the variation over a century.
We are plotting the position of the Sun along the ecliptic, but still assuming uniform motion.

C = 1.914666471 * sin(M) + 0.019994643 * sin(2M)

Equation of the center corrects the difference between the true position of the Sun and the position it would have if viewed from a circular orbit

λtrue = λM + C, real position along the ecliptic

NASA JPL DE405/DE406 Ephemerides

Calculation of the solar vector, 2

Different refererence sistems are involved:

1. ECI
2. Ecliptic System, rotation of 23,44° wrt the ECI
3. Orbital System, is the reference of the orbital plane of the satellite
4. Body-Fixed System, is the system attached to the satellite

Ecliptic System:

- Origin: Center of the Earth
- Plane X-Y: Plane of the Earth orbit around the Sun
- Axis Z: Perpendicular to the ecliptic plane

Orbital System:

- Origin: Center of the Earth
- Plane X-Y: Plane of the satellite orbit
- Axis Z: Normal to the orbital plane

Body-Fixed System:

- Origin: Center of the satellite
- Axis X: Direction of the motion (ram)
- Axis Y: Zenith
- Axis Z: completes the right-handed system

The sequence of transformations used to study the variability of the solar vector is:

1. ECI → Ecliptic, used for 3D visualisation
2. ECI → Orbital
3. Orbital → Body-Fixed, so that exposure calculations can be performed

Calculation of the solar vector, 3

ECI → Ecliptic:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\epsilon) & -\sin(\epsilon) \\ 0 & \sin(\epsilon) & \cos(\epsilon) \end{bmatrix}$$

ε is the obliquity of the ecliplit (23.44°). This is a rotation around the X axis

Trasformazione ECI → Orbitale:

$$\begin{bmatrix} \cos(\Omega) & -\sin(\Omega) & 0 \\ \sin(\Omega) & \cos(\Omega) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Ω is the RAAN. This is a rotation around the Z axis.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(i) & -\sin(i) \\ 0 & \sin(i) & \cos(i) \end{bmatrix}$$

i is the inclination. This is a rotation around the X axis.

These two matrices must be multiplied to obtain the vector in the Orbital reference.
It must be taken into account that the RAAN is not constant but precedes in time due to the crushing at the poles, an effect of J2.0, and this is taken into account by implementing the formula for variation of the RAAN, dRAAN_dt, through Vallado's formulas.

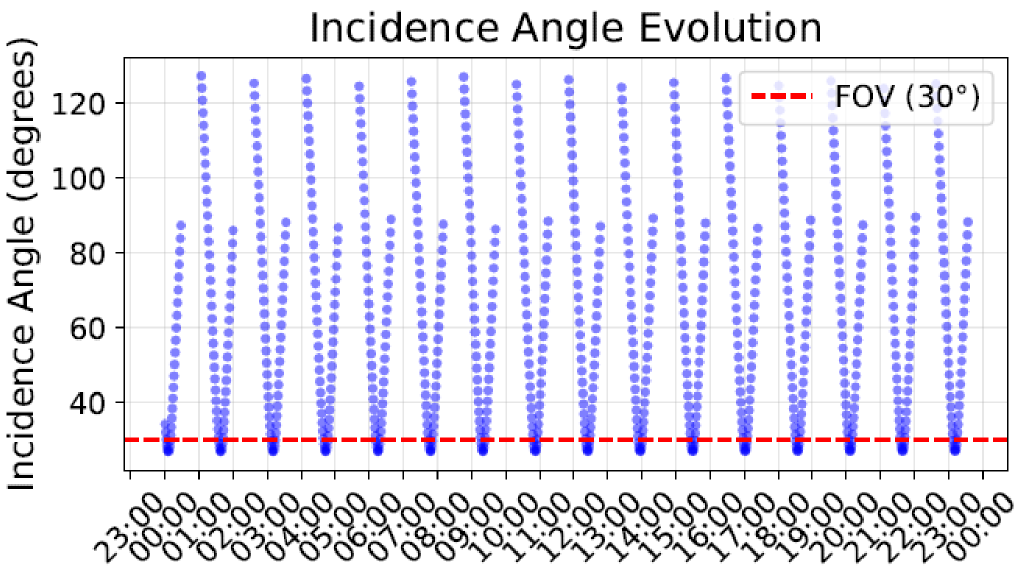
Trasformazione Orbitale→ Body-Fixed:

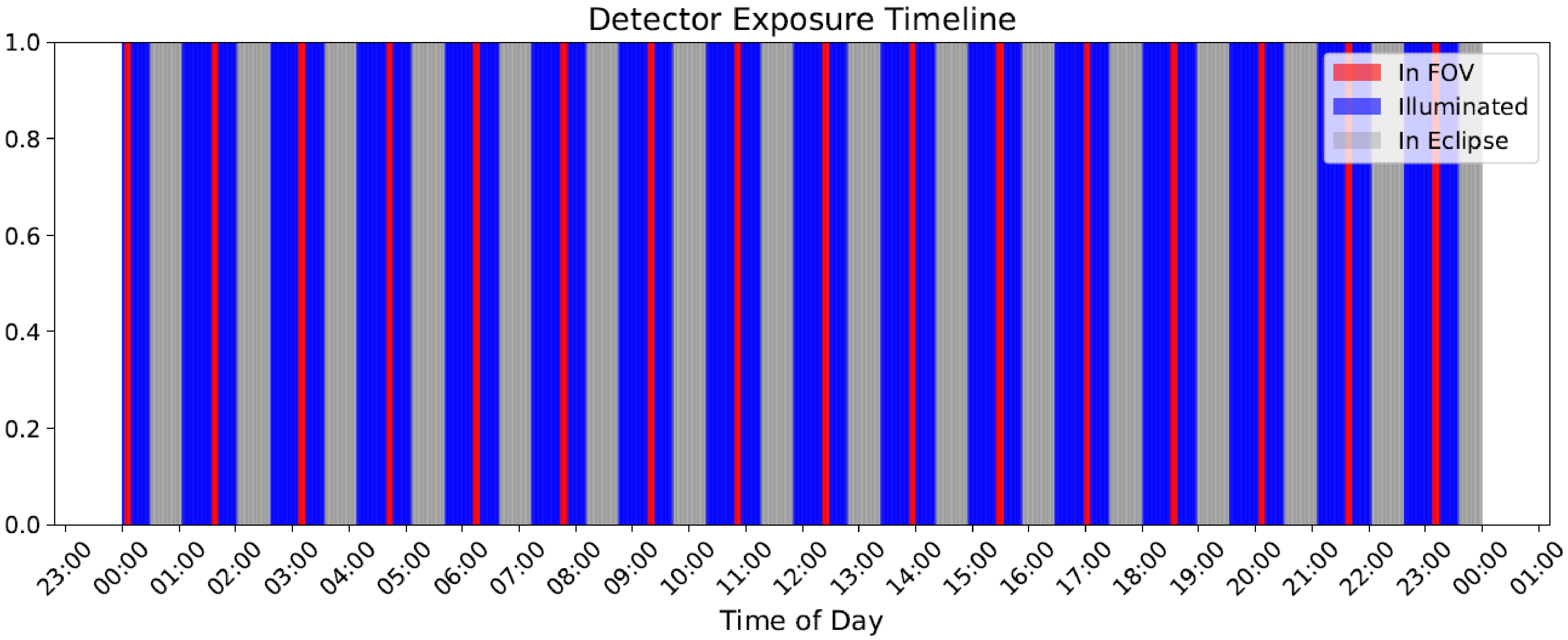
$$\begin{bmatrix} \cos(\nu + \frac{\pi}{2}) & -\sin(\nu + \frac{\pi}{2}) & 0 \\ \sin(\nu + \frac{\pi}{2}) & \cos(\nu + \frac{\pi}{2}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

v is the true anomaly. This is a rotation around the Z axis.

Detector Exposure Analysis - Face -x
First day of mission: 01/06/2027

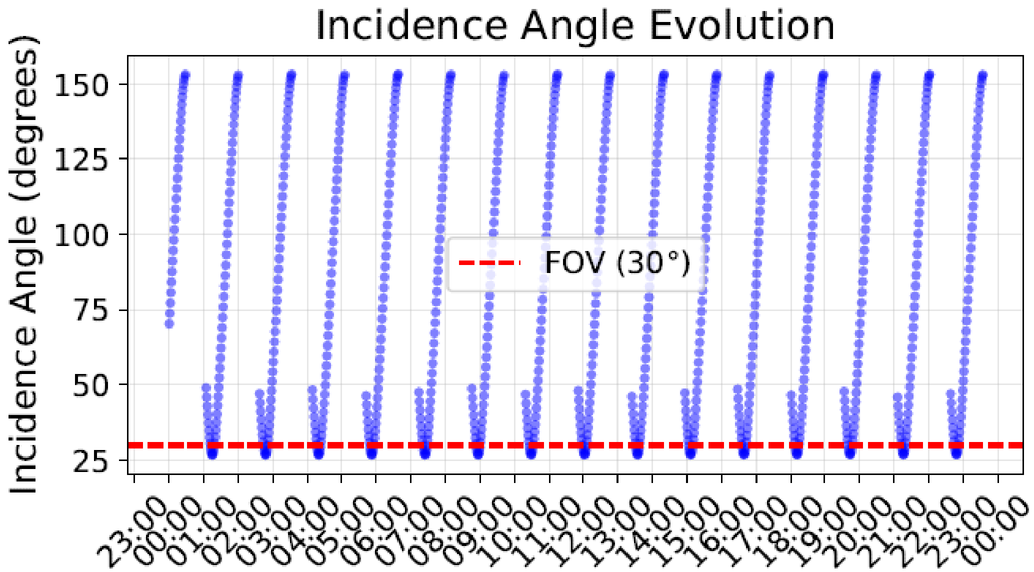
Daily statistics:
- Total exposure time: 1.9 hours
- Percentage of day: 8.1%
- Number of FOV passes: 16
- Detector FOV: 30°

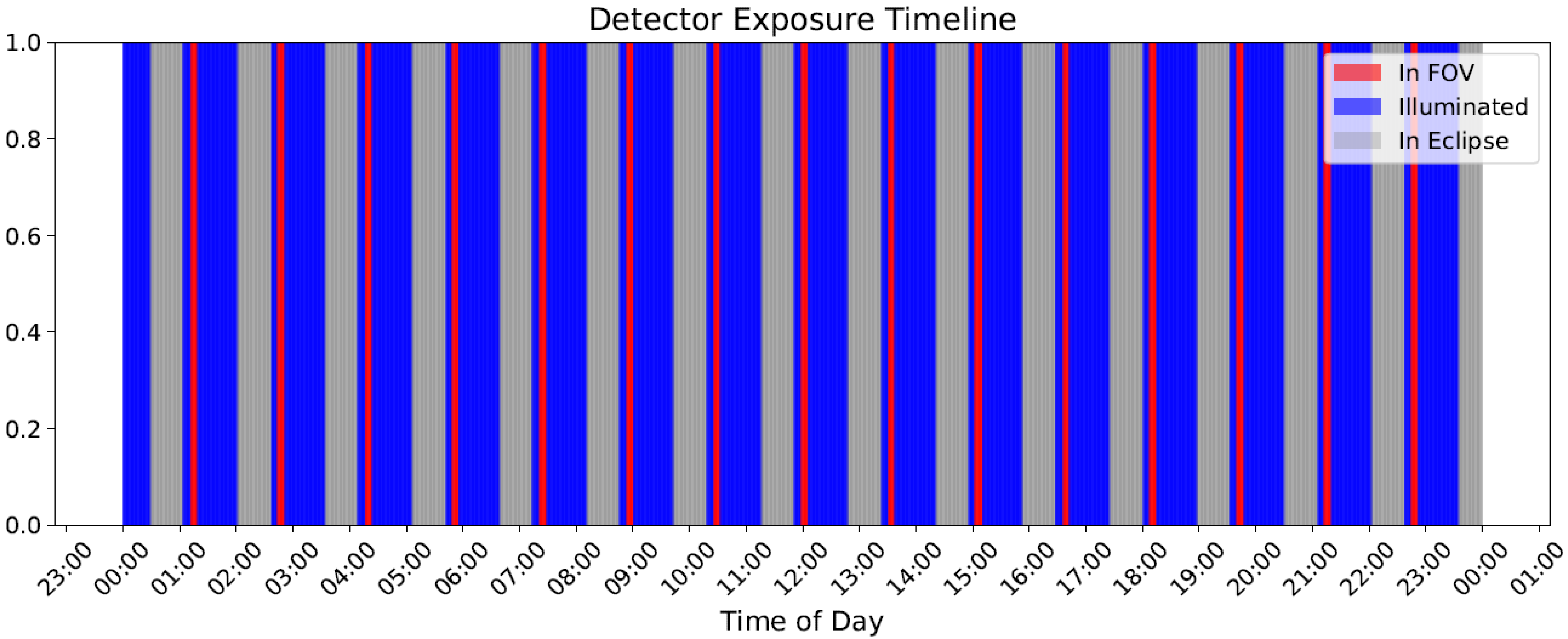




Detector Exposure Analysis - Face +z
First day of mission: 01/06/2027

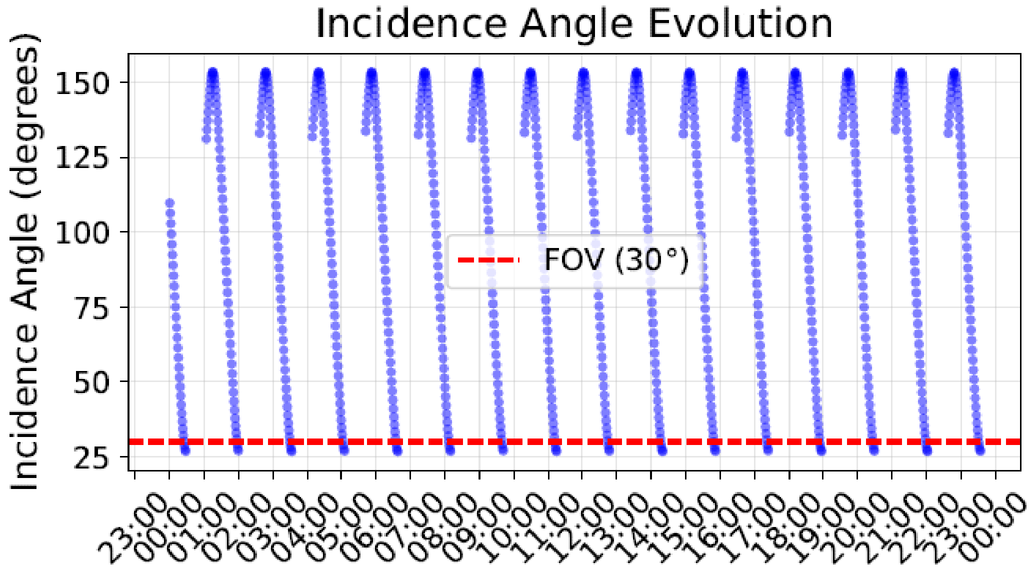
Daily statistics:
- Total exposure time: 1.8 hours
- Percentage of day: 7.6%
- Number of FOV passes: 15
- Detector FOV: 30°

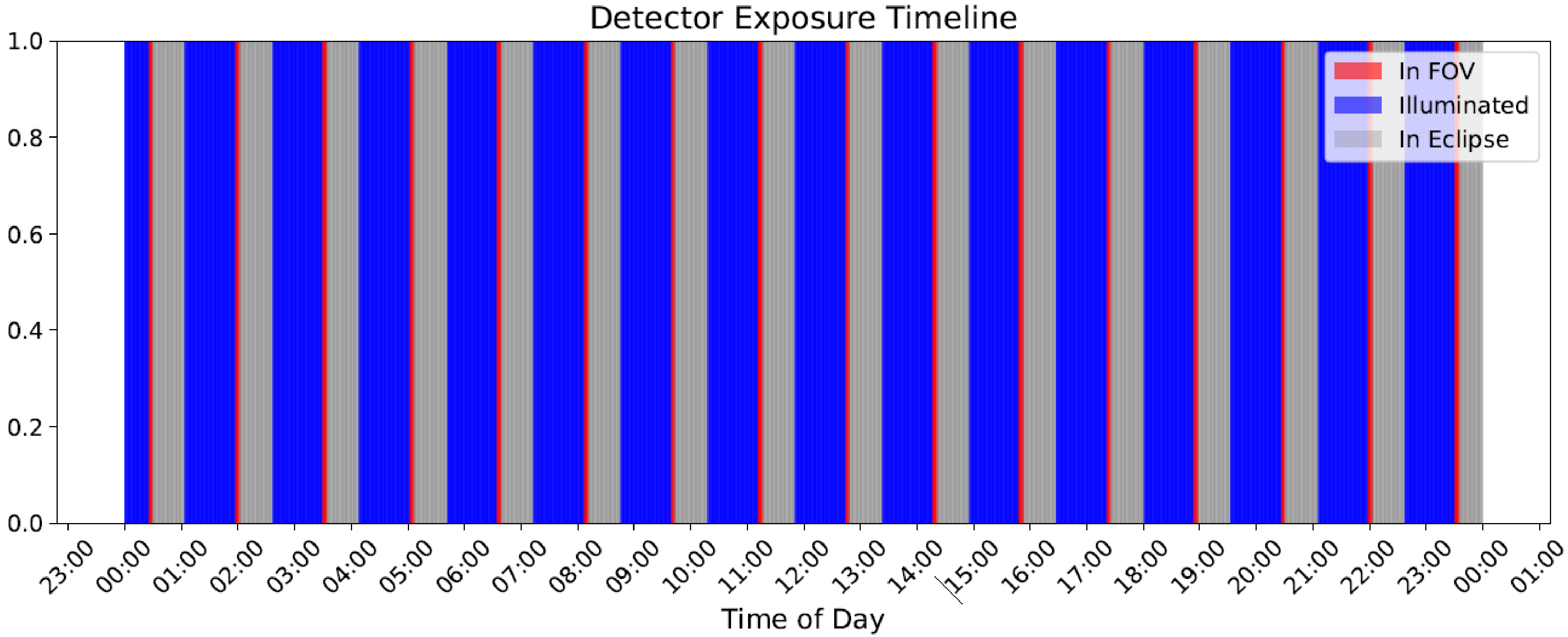




Detector Exposure Analysis - Face -z
First day of mission: 01/06/2027

Daily statistics:
- Total exposure time: 0.9 hours
- Percentage of day: 3.9%
- Number of FOV passes: 16
- Detector FOV: 30°





GEOMETRY OF THE EARTH OCCULTATION

The Earth's limb is defined mathematically as the apparent contour of the Earth as seen from an orbiting satellite, representing the boundary between the Earth and space. For a satellite in position $\vec{r}_{sat}$ (from the center of the earth to satellite) the earth's limb consists of the set of all directions $\hat{n}$ which satisfy this condition: $\hat{n} \cdot \frac{\vec{r}_{sat}}{|\vec{r}_{sat}|} = \cos(\alpha_{Earth})$.
With α_{Earth} angle subtended by the earth's limbo as seen from the satellite and calculated as:

$$\boldsymbol{\alpha_{Earth}} = \boldsymbol{arcsin}\left(\frac{\boldsymbol{R_{Earth}}}{\vec{r}_{sat}}\right) \sim \boldsymbol{\alpha_{Earth}} = \mathbf{arcsin}\left(\frac{\mathbf{R}_{\boldsymbol{Earth}}}{\boldsymbol{R_{Earth}} + \boldsymbol{h}}\right)$$

It represents half of the total angle subtended by the Earth as seen from the satellite. It measures the apparent angular size of the Earth's radius. It is the angle between the line from the satellite to the center of the Earth and the line tangent to the Earth's surface. Approximately 67°.
It is used to calculate the occultation dimension.

Harmon et al. (2002),
"The Burst and Transient Source Experiment Earth Occultation Technique"

GEOMETRY OF THE MOON OCCULTATION

The lunar limb, analogous to the Earth's limb, is defined mathematically as the apparent contour of the Moon as seen from the satellite. The major differences are due to the variable position of the Moon with respect to the Earth and the satellite.

Given a satellite with position $\vec{r}_{sat}$ $and\ the\ Moon\ in\ position\ \vec{r}_{Luna}$ the lunar limb consists of the set of all directions $\hat{n}$ that satisfy this condition: $\hat{n} \cdot \frac{\vec{r}_{Moon} - \vec{r}_{sat}}{|\vec{r}_{Moon} - \vec{r}_{sat}|} = \cos(\alpha_{Moon})$

With α_{Moon} angle subtended by the Moon's limb as seen from the satellite and calculated as:

$$\boldsymbol{\alpha_{Moon} = arcsin\left(\frac{R_{Moon}}{|\vec{r}_{Moon} - \vec{r}_{sat}|}\right) = \mathbf{arcsin}\left(\frac{\mathrm{R}_{Moon}}{384400km}\right)}$$

With R_{Moon} = 1737.4km ed α_{Moon} ~ 0.26°

Unlike Earth, whose position relative to the satellite is fixed in the satellite's orbital reference system, the Moon's position varies over time. The JPL ephemeris was used to calculate its position.
The angle subtended by the Moon as seen from the satellite is much smaller than that subtended by Earth due to the much greater distance..