Proton radiation damage in SiPM for gamma-ray spectroscopy

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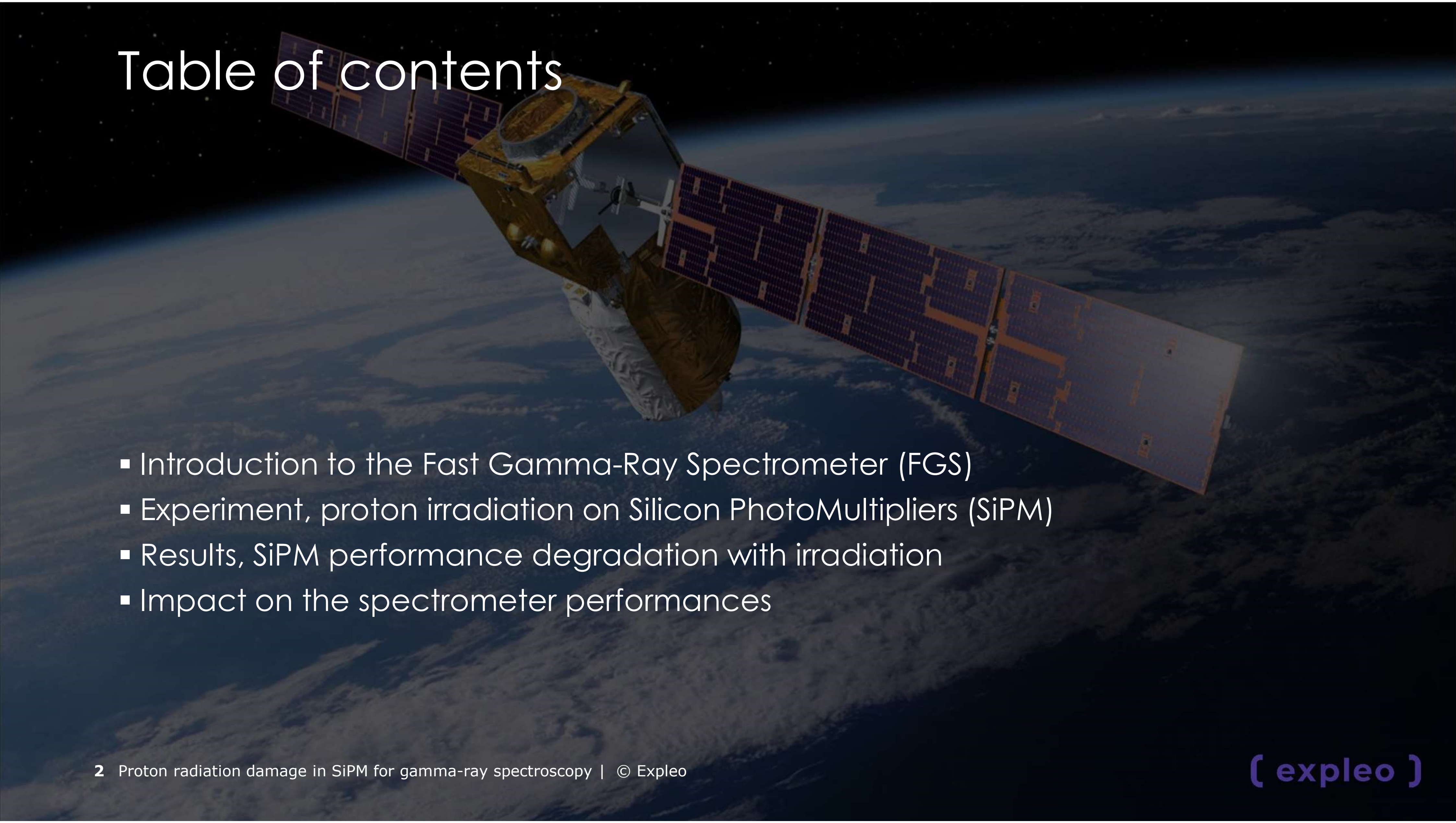

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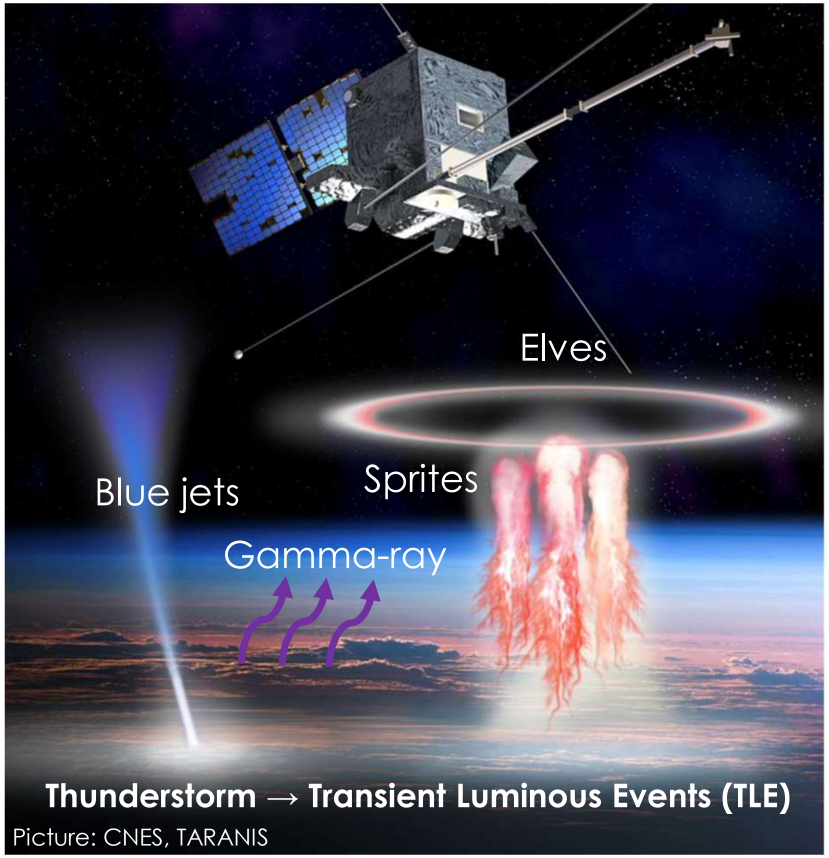
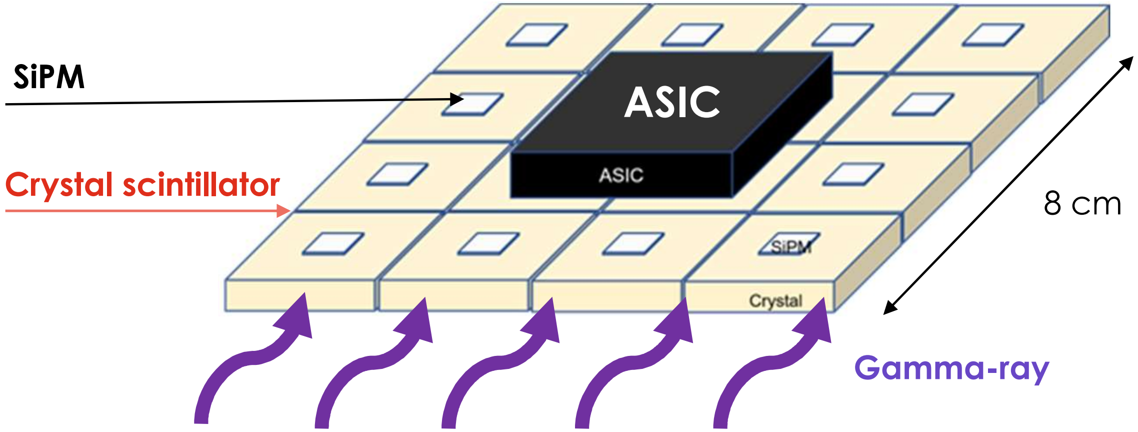
The Fast Gamma-ray Spectrometer (FGS)



CNES objective : prepare future spaceborne **Gamma-Ray spectrometers** for **Terrestrial Gamma Ray Flash (TGF)** detection with promising, versatile, and more integrated technologies, while enhancing the Technology Readiness Level of the building blocks.

FGS under development by APC and LESIA integrates :

- **Silicon Photomultipliers (SiPM) detectors**;
- GaGG:Ce scintillators;
- rad-hard 16 channels ASIC designed by IDEAS.



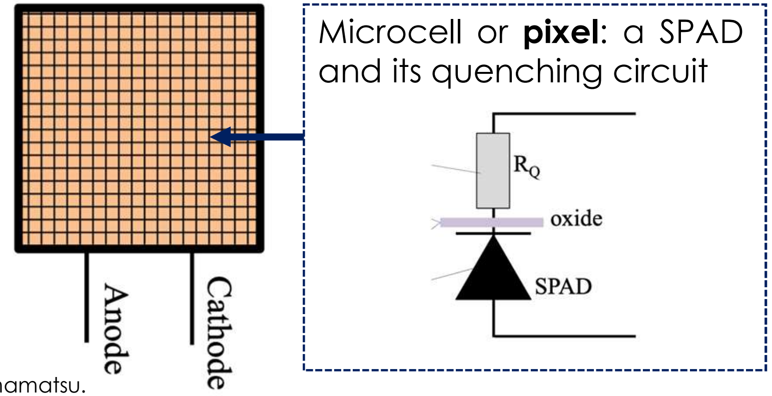
FGS detection module architecture featuring 1 ASIC with its 16 channels.

Gamma-ray spectrometer requirements	
Maximum incident flux	5 x 10^4 photons/cm²/s
Gamma photons dynamic range	20 keV – 20 MeV
Resolution	15% @ 511 keV

The Silicon Photomultipliers (SiPM)

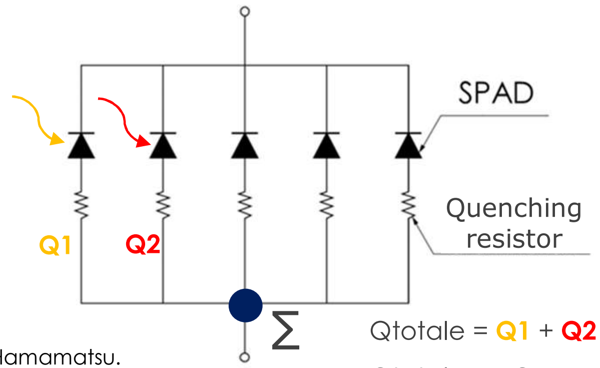
Detector composed of Single-Photon Avalanche Diodes (SPADs) implanted on a common substrate.

Simplified diagram of a SiPM :



Source : Hamamatsu.

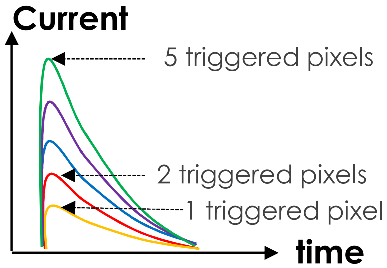
Simplified circuit diagram of a SiPM :



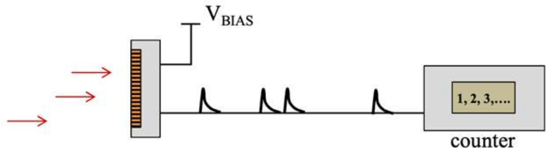
Source : Hamamatsu.

Qtotale = Q1 + Q2 = 2Q1

Qtotale = nQ1

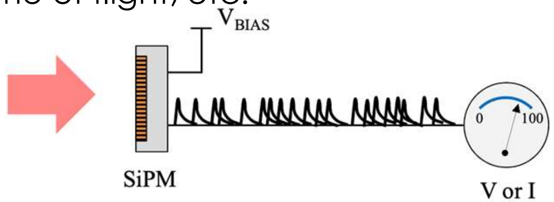


Summation of charges: output signal amplitude ~ number of triggered pixels (number of detected photons if efficiency = 1).



Source : Hamamatsu.

Distinguishable pulses: ability to count, measure the time intervals between events, time of flight, etc.



Source : Hamamatsu.

Ability to operate in analog mode, measuring either current or voltage.

Experiment

Objective:

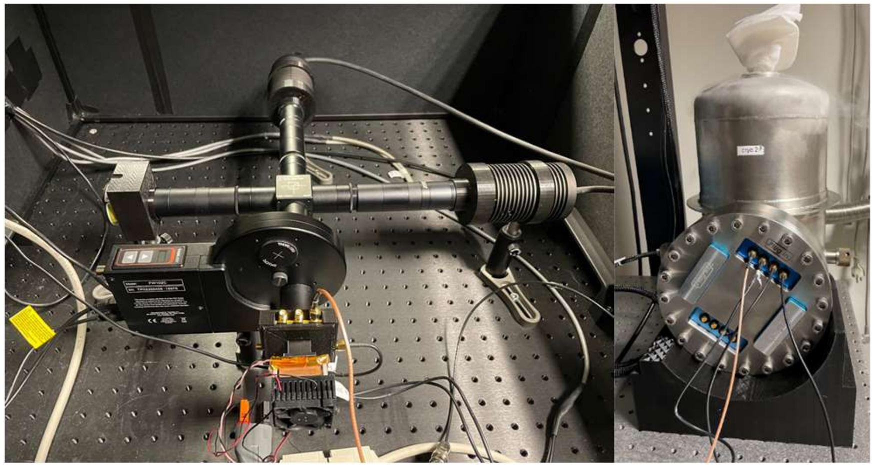
- **SiPM** end-of-life performance assessed through protons radiation campaign;
- evaluate the impact on the spectrometer **threshold energy** and **resolution**;
- select the best SiPM candidate and anticipate mitigating strategies such as low temperature regulation of the detectors;
- 3 references : **Advansid RGB4S-P**, **Onsemi FJ60035**, **Hamamatsu S13360-6050**.

Irradiation:

- **62 MeV proton irradiation** at Université Catholique de Louvin (UCL);
- 2 years mission duration at 700 km ⇒ **fluence : 4×10^9 p+/cm²** with 10 mm aluminum shielding;
- fluence applied: 1×10^9, : 4×10^9 and 8×10^9, with 1×10^7 p+/cm²/s flux.

SiPM test plan

	Initial	At UCL after protons	After ambiant temperature annealing
I(V) @ 22°C	X	X	X
I (V) @-20°C	X		X
Gain	X		X
Dark Count Rate DCR	X		
Photon Detection Efficiency PDE	X		X
Afterpulse	X		
Crosstalk	X		

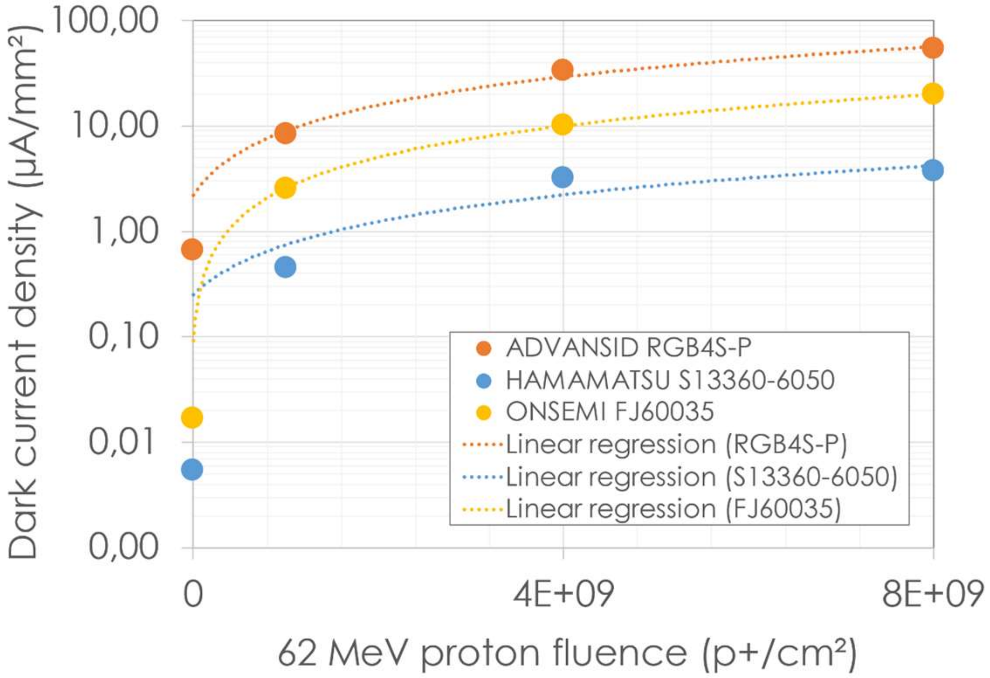


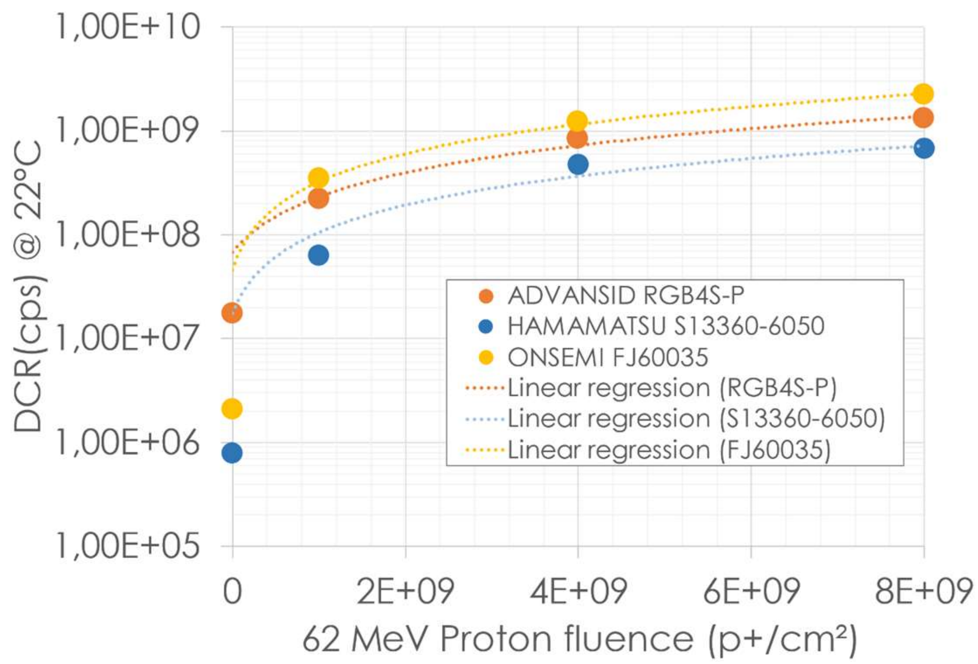
SiPM testbench at CNES.

Irradiation facility at UCL.

Results

- No significant change in measured gain and PDE after irradiation.





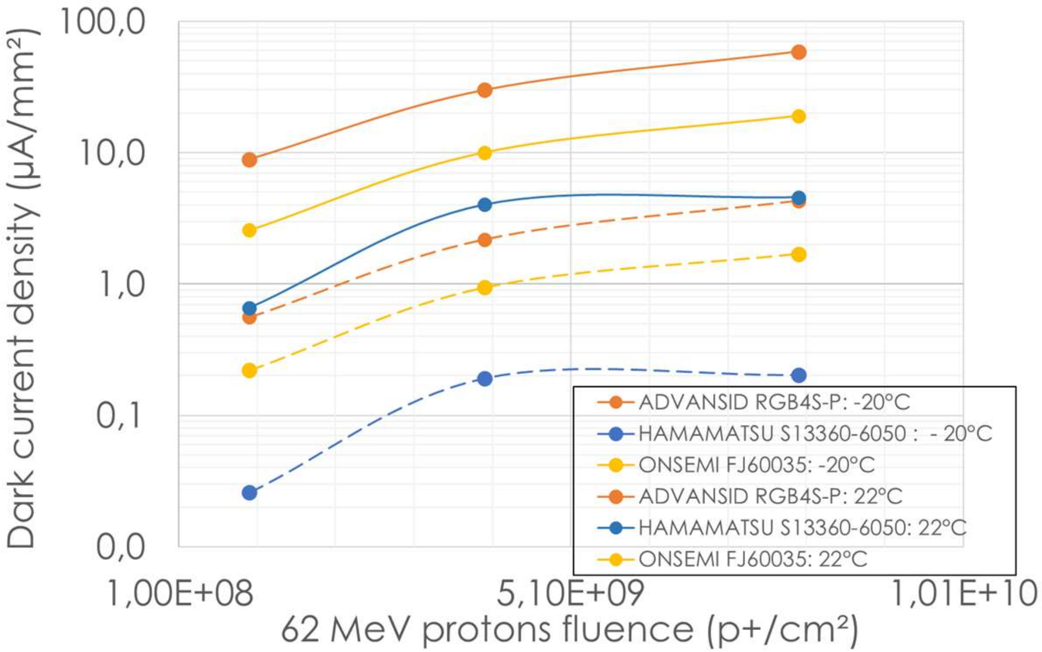
Approximation of the **Dark Count Rate**, $DCR = \frac{I_{dark}}{q \times G \times ECF}$

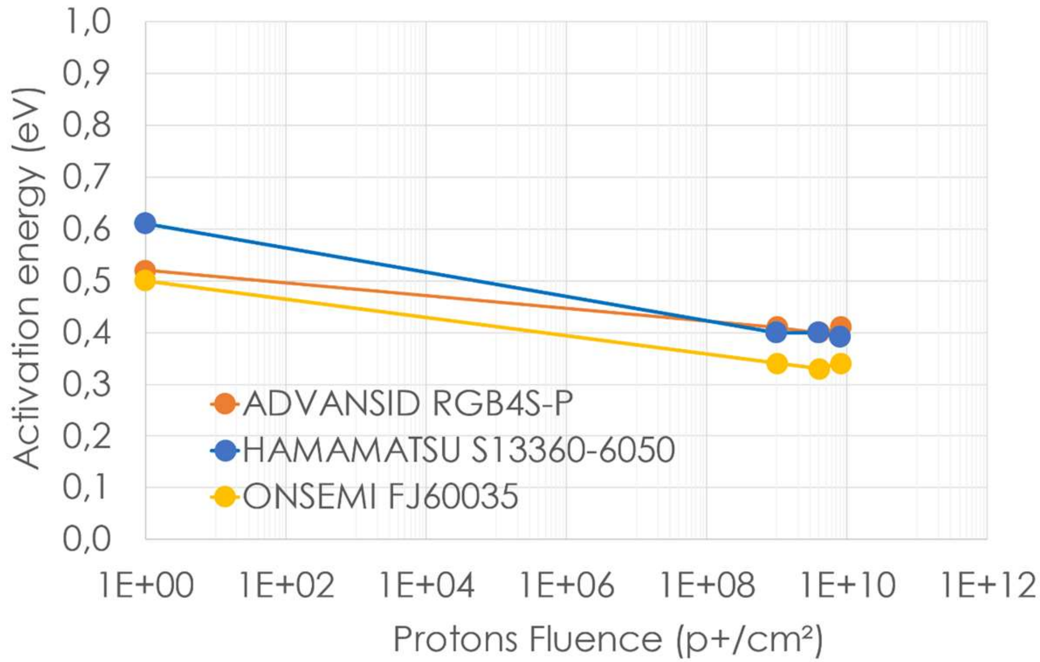
I_{dark}: dark current; q: elementary charges; G: gain; ECF: excess charge factor.

- Excess Charge Factor is not degraded by proton radiation, as reported by [1] and [2] for our range of fluences.

[1]P. Bohn, et al., "Radiation Damage Studies of Silicon Photomultipliers," *Nucl. Instrum. Methods Phys. Res., A*, pp. 722-736, 2009.
[2] E. Garutti and Y. Musienko, "Radiation damage of SiPMs," *Nuclear Instruments and Methods in Physics Research Section A*, pp. 69-84, 2019.

Results





Activation energy from the comparison of measurements from -20°C to + 22°C.

Observation:

- Increase of current after irradiation reduced by lowering the temperature.
- However, the decrease in activation energy with increasing proton fluence ⇒ the cooling efficiency also decreases.

Impact on the spectrometer performance

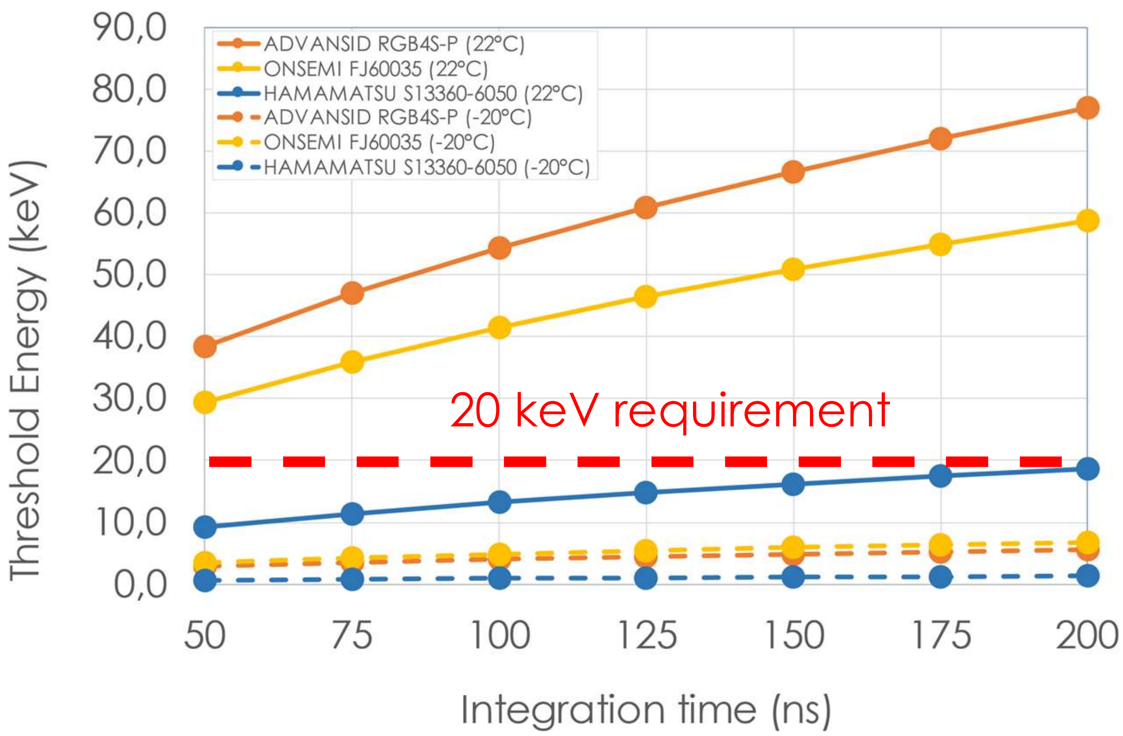
Energy threshold:

$$E_{thres\_SiPM} = \frac{5\times\sqrt{ENF\times DCR\times T_{int}}}{K_{lin}}$$

- One Gamma-Ray photon with energy **Eγ** gives rise to ***Npe*** photoelectrons over the decay time of the scintillator;
- K_{lin} : theoretical slope of the $N_{pe}(E\gamma)$ curve in the linear region;
- ENF : Excess Noise Factor;
- T_{int} : integration time.

Observation:

- DCR increases with radiations ⟹ increase in energy threshold.
- SiPM **HAMAMATSU 13360-6050** : only candidate to comply with the **20 keV threshold requirement at end-of-life for operating temperature at + 22°C**.
- SiPMs RGB4S-P and FJ60035 require cooling.



Contribution of DCR to the Energy threshold at end-of –life for 8 10^9 p+/cm² 62 MeV proton radiation.

Impact on the spectrometer performance

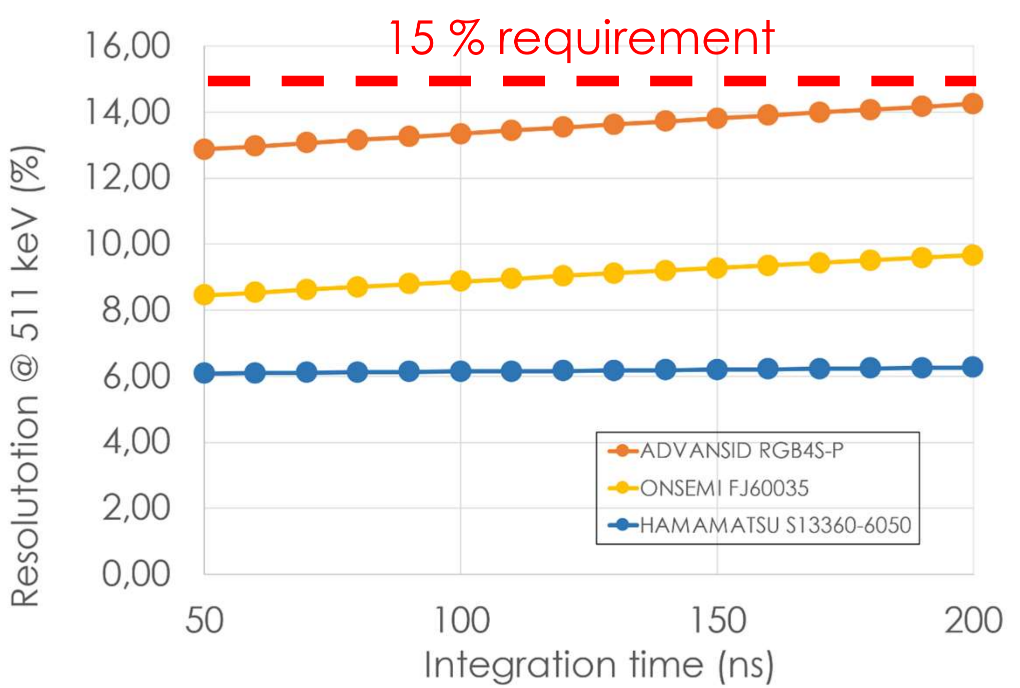
Resolution:

$$Resol_{511\ keV\_SiPM} = \frac{FWHM_{511keV}}{511}$$
$$= 2 \times \sqrt{2 \times ln2} \times \frac{\sqrt{ENF \times (DCR \times T_{int} + N_{pe})}}{N_{pe}}$$

- One Gamma-Ray photon with energy **Eγ** gives rise to ***Npe*** photoelectrons over the decay time of the scintillator;
- ENF : Excess Noise Factor;
- T_{int} : integration time.

Observation:

- DCR increases with radiations ⟹ enlargement of the energy resolution;
- Energy resolution at 511 keV is practically not affected by the DCR degradation with radiation. **The best result is obtained for SiPM HAMAMATSU S13360-6050.**



Resolution at 511 keV at 22°C end-of-life for 8 x10⁹ p+/cm², 62 MeV proton radiation.

Conclusion

Objective:

- The FGS instrument contains SiPM detectors; 3 references have been selected and need to be characterized to assess their radiation tolerance;
- For a satellite at an altitude of around 700 km for a 2 years mission duration, the main source of radiation that can damage the SiPMs is protons around 62 MeV with a fluence of 4×10^9 p+/cm² .

Main results:

- Characterizations show a degradation of dark current and DCR but no significant impacts on gain and PDE;
- DCR increases with radiations ⟹ increase in energy threshold and small enlargement of the energy resolution of the FGS spectrometer ;
- Only the **Hamamatsu S13360-6050** meets the specifications without the need to reduce the detector temperature.

Thank you for your attention!

(expleo)

Think bold, act reliable*

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* Osons l'audace, créons la confiance