A SiPM based camera for the Terzina telescope on board the NUSES space mission

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(on behalf of NUSES collaboration)

Outline:
- The NUSES mission
- Intro.
- The Terzina telescope
- SiPM intro.
- Simulation of the instrument
- Radiation hardness
- Annealing
The NUSES Collaboration

60+ persons from many institutions.
Large expertise (and synergies) from space missions/R&D:
AMS, DAMPE, eASTROGAM, FERMI, GAPS, HERD, LIMADOU,
PAMELA, POEMMA, SPB2, ....

GSSI is leading the mission

Current list of the Italian groups:
- Gran Sasso Science Institute
- INFN – Laboratori Nazionali del Gran Sasso
- Università dell’Aquila
- Università di Roma “Tor Vergata” and INFN-Roma2
- Università di Torino and INFN Torino
- Università di Trento and INFN-TIFPA
- Università di Bari and INFN
- Università di Padova and INFN
- Università “Federico II” and INFN Napoli
- Università del Salento and INFN

University of Geneva +
University of Chicago +
Possible interests from:
- other US institutions
- Spain
-......
The NUSES mission: two payloads

Terzina
Pathfinder for future missions devoted to **UHE cosmic rays and neutrino astronomy** through space-based atmospheric **Cerenkov light** detection.

See talks from:
R. Aloisio and L. Burmistrov

Zirè
Measure the fluxes of **low energy (<250 MeV) CR**, mainly electrons and protons, to study cosmic rays, Van Allen belts, space weather and the magnetosphere-ionosphere-litosphere couplings (MILC) in case of seismic / volcanic activities.

Detect **0.1-10 MeV photons** for the study of transient (GRB, e.m. follow up of GW events, SN emission lines,...) and steady gamma sources.

See talks from:
Ivan De Mitri
Riccardo Nicolaidis

New technologies and approaches
Development of new observational techniques, testing new sensors (e.g. **SiPM**) and related electronics/DAQ for space missions. New solutions for the satellite platform.

Poster by: Pillera (zirè-FTK)

See talks from:
Andrea Di Salvo
The NUSES mission composed of two payloads.

Two main components:

- **ZIRE**
  - Telescope
  - 60 x 60 x 50 cm³
  - TERZINA weight < 30 kg
  - Monitors the fluxes of low energy cosmic rays (< 250 MeV), Electrons and protons to study Van Allen radiation belts, Space weather and the magnetosphere-ionosphere-litosphere couplings
  - And much more ….

- **TERZINA**
  - Demonstrator of Cherenkov light detection produced by Extensive Air Showers
  - First measurement of showers with Cherenkov light from space (E>100PeV)
  - Proves the technology for detecting Earth skimming muon and tau neutrinos
  - Measure the background conditions
  - Further Development of SiPM technology for space
Camera vs POEMMA

TERZINA Telescope
primary mirror daim.: 0.4m

POEMMA Telescope
primary mirror daim.: 4m

SiPM part
(Detection of Cherenkov light)

TERZINA SiPM photo detection plane

~ 12 x 6 cm²

John F. Krizmanic
arxiv:2008.04984v2
### SiPM vs ma-PMT (PMT)

<table>
<thead>
<tr>
<th>Feature</th>
<th>SiPM</th>
<th>PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation voltage</td>
<td>&lt;100 V</td>
<td>~1000 V</td>
</tr>
<tr>
<td>Currents</td>
<td>~1 μA</td>
<td>~100 μA</td>
</tr>
<tr>
<td>Power per cm²</td>
<td>~0.1 mW</td>
<td>~0.1 W</td>
</tr>
<tr>
<td>Weight per cm² of sensitive area</td>
<td>~10 g</td>
<td>~100 g</td>
</tr>
<tr>
<td>Total integrated charge</td>
<td>infinite</td>
<td>200 Q</td>
</tr>
<tr>
<td>Time resolution</td>
<td>&lt;100 ps</td>
<td>&lt; 1 ns</td>
</tr>
<tr>
<td>Special resolution</td>
<td>~1 mm</td>
<td>~10 mm</td>
</tr>
<tr>
<td>Photo detection efficiency @ 400 nm</td>
<td>&gt; 50 %</td>
<td>&lt; 50 %</td>
</tr>
<tr>
<td>Variation with temperature</td>
<td>very sensitive</td>
<td>low</td>
</tr>
<tr>
<td>Need of pre-amplifier/PMT gain</td>
<td>0.1 mV</td>
<td>5 mV</td>
</tr>
<tr>
<td>Radiation resistance</td>
<td>low</td>
<td>good</td>
</tr>
</tbody>
</table>

### Single photon response PMT vs SiPM

- **Prompt cross-talk within one channel**
  - SiPM
  - PMT

- Change sharing between anodes.

- Large variation of the response defined by secondary emission.
SiPM all the cells are connected in parallel

Prompt cross talk.

After pulsing

Delayed crosstalk imposed in other pixels is not simulated.

In simulation we include as well:
Gain variation, electronic noise, pre-amplifier, ADC.
Single p.e. avalanche tree

Trial parameters for generator testing:

Probability of the cross talk is set to 0.2
Probability of the after-pulse is set to 0.15
And after pulse decay time 15 ns.

Recurrent process

Single p.e.

Cross Talk

After pulse

Crosstalk

Initial p.e.

After pulse

Clearly saturated due to cell recovery time

Final result waveform.
Experimental setup

Hamamatsu 2021 (Vbias -54 V)

Read cathode
SiPM characterization: $V_{\text{break down}} (V_{\text{bd}})$

Break down voltage – defines when SiPM start to detect light. It is a function of a temperature.

- **Breakdown Voltage**
  - Defines when SiPM starts to detect light.
  - A function of temperature.

- **Forward Biasing**
  - Measure the quenching resistor.

**Diagram Details**

- **IV – characterization connection**
- **Keithley – picoammeter**
- **Ground (floating)**
- **Keithley LOW (Rear) (banana)**
- **Keithley HI (Rear) (banana)**
- **Keithley HI (Rear) (tree-ax.)**
- **Central pin**
- **Internal ground**

**Graphs**

- **Linear Regime**
- **Geiger Regime**

**V_{bd} calculated with:**
- Second log derivative

**NuV-HD MT without resin 25 um cell size, 1x1mm^2**

**IV data**

- Forward biasing.
SiPM characterization: IV curves for different mu-cell sizes.

Temperature coefficient is 33mV/°C

Cell size

Current at same V

V_{bd} as a function temperature

~32.6 V (20°C)
~31.2 V (-20°C)
SiPM characterization: response on very large number of photons from laser (~10 ps).

- **“Forward” (positive)**
- **Reverse (negative)**

Rise time of the signal is 200 ps !!!

Very good timing (the record I have measured :-))
SiPM characterization: decay time of the slow component. Preamplifier optimization.

Normalized single p.e. shape after amplification.

Laser vs Laser + int. sphere

Zoom
SiPM characterization: DCR (dark current rate), (CT) optical cross-talk, PDE (photo detection eff.)
Irradiation facility with horizontal beam line (AIC-144 cyclotron)

https://web.infn.it/EURO-LABS/

EXPERIMENTAL SETUP

Acknowledgments: IFJ-PAN and Jan Swakon (responsible for proton irradiation campaign).

Energy: 0-58 MeV;
Dose rate: 0.001 - 1 Gy/s (measured in water);
Single scattering;
Beam field size: ≤ 40 mm;
Field homogeneity ≥ 5%;
Min flux of protons: 5e5 p/cm²·s (50MeV);
Typical flux: 10e8 - 10e9 p/cm²·s;
Irradiation in SOBP available;
Sample positioning precision (> 0.1 mm);
It is not possible to deposit high doses (>1 kGy);

Resin samples

https://www.ifj.edu.pl/
IV measurements after each irradiation step
Results after irradiation test

We observe linear increase of the DCR with irradiation dose.

Standard characterization of the SiPM is impossible after irradiation.

The PDE measurements can be done only with large number of photons, as a consequence large systematical are expected for this measurements.

30 % of the expected dose are coming from protons.

We “simulate” 10 years on the orbit (planned mission duration is 3 years).

No optical degradation of the resin samples have been observed.

No change of the quenching resistor has been observed.

No change of the $V_{bd}$ behavior as a function of temperature measured.

<table>
<thead>
<tr>
<th>Current multiplication per Gy</th>
<th>wo resin</th>
<th>resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 μm</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>30 μm</td>
<td>475</td>
<td>173</td>
</tr>
<tr>
<td>35 μm</td>
<td>252</td>
<td>183</td>
</tr>
<tr>
<td>50 μm</td>
<td>235</td>
<td>246</td>
</tr>
</tbody>
</table>
Annealing at 40 °C

- The irradiated samples are stored at -20 °C to avoid room temperature annealing.
- We use the climatic chamber for temperature control.
- Measurements IV measurements were done every 2-5 hours (excluding nights).
How much light do we produce in the photo sensor window

Amplitude 237 mV @ $10^6$ amplification

Beam parameters: 5.6 GeV/c, 15 x 10 mm$^2$, ~ 2 kHz (single electrons)
Bare SiPM or SiPM with thin window?

Thickness of the protective window 400 – 40 μm

Can we make it thinner? 10 μm?

Can we completely remove it?

Perpendicular track at maximum will produce 4 p.e. equivalent signal

If the bare surface is not planar very thin resin can form micro-lenses need to have additional R&D.

This effect can be vanished by removing the window :-} ...
Conclusions

- SiPM are promising photo sensors to be used for space base experiments.
- We present full chain of different activities for Terzina telescope on board the NUSES space mission.
- We present the parametric simulation of the SiPM used in the full simulation chain.
- We characterize SiPM with different mu-cell sizes with and without resin.
- The radiation test with 50 MeV protons up to 30 Gy integrated dose (corresponds to 10 years on the orbit).
- SiPM annealing at 40 °C has been studied.
Backup