Study and development of silicon photomultipliers for space within the JEM-EUSO Program

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Past, present and future experiments with SiPMs

Observation of Fluorescence and Cherekov emissions for UHECR and neutrino detection

- EUSO-SPB1 /2017
- Mini-EUSO /2019
- EUSO-SPB2 /2023
- EUSO-SPB3 /2026
- POEMMA /2030+
Focal surfaces in the JEM-EUSO experiments

The photo-detection modules of the JEM-EUSO fluorescence telescopes are made of MAPMTs

- In the first missions, SiPMs were used in ancillary detectors;
- In the last years, with EUSO-SPB2, SiPMs started to be used as sensors of the main focal surface (Cherenkov telescope)
Silicon Photomultipliers

**Advantages**
- High gain \(10^5-10^6\)
- Low Voltage (<100 V)
- Excellent photon-counting capability
- Excellent time resolution
- Robust against damage from strong light emissions (can be used with moon-light)
- Insensitive to magnetic fields
- Compact size

**Disadvantages**
- Temperature dependency: thermal background proportional to the area (high noise for T>30° C)
- Radiation sensitivity

SiPM models from HAMAMATSU multi-pixel photon counter (MPPC)
Experiments and R&D with SiPMs within JEM-EUSO

• Program of R&D funded by ASI in the framework of the EUSO-SPB2 project to rise the technical readiness level of SiPMs in space, by means of the development of ancillary cameras with SiPMs
  • The low voltage and low power consumption, the robustness and the compactness make SiPMs good candidates for space-based missions

• In the next slides, the past, present and future experiments of the JEM-EUSO Program hosting SiPMs are described, including the R&D activity
**EUSO-Super Pressure Balloon (EUSO-SPB1)**

**Mission:**
25 April - 7 May 2017

**Characteristics:**
- Fluorescence telescope with MAPMTs
- 1 additional fluorescence camera with SiPMs (SiECA)
- Optics: 2 Fresnel lenses

**Goals:**
- Detect UHECRs for the first time from high altitude
- Test the detector at high altitude
- Measurement of the UV background of the atmosphere from above
SiECA on EUSO-SPB1 (1)
Silicon photomultiplier Elementary Cell Add-on

- Developed at the Karlsruhe Institute of Technology (KIT), Germany
- Designed as an ancillary device to be easily attached to existing fluorescence telescope of EUSO-SPB1, utilizing the same optics

SiECA with 2x2 SiPM array, 8x8 pixels each

SiECA camera next to the photo-detection module made of MAPMTs
SiECA on EUSO-SPB1 (2)

Simulation of a proton event of energy $1.1 \times 10^{19}$ eV going through the field of view of the detector with a zenith angle 22.3°. No background is added to the plot [PoS(ICRC2017)442]

Full camera test in the lab with nonuniform light source. Response is average photons detected per 2.5 mus [PoS(ICRC2017)442]
Mini-EUSO onboard the ISS

Mission:
October 2019 – now

Characteristics:
• Fluorescence telescope with MAPMTs
• 2x UV-light sensors
• 1 SiPM single pixel
• 1 SiPM array 8x8 pixels
• Optics: 2 Fresnel lenses

Goals:
• Map the night-time Earth emissions in the near-UV range
• Study of atmospheric phenomena (TLEs, ELVES)
• Meteors
• Search for Extensive Air Showers (EAS) with energies above $10^{21}$ eV
• Search for SQM and interstellar meteors
Sensors on the Focal Surface of Mini-EUSO

Main Focal Surface MAPMTs
R11265-M64 (2304 pixels)

SiPM Array
• MPPC C14047-3050EA-08
• 8x8 channels
• Read independently (Multiplexer, no FPGA) (used in day/night transition)

SiPM C13365 single pixel

2 UV-light sensors (photodiodes)
• S1226-5BQ log 190-1000 nm
• ML8511 linear 280-400 nm (used for day/night transition)
EUSO-Super Pressure Balloon 2 (EUSO-SPB2)

Mission:
13 - 14 May 2023

Characteristics:
• 1 fluorescence telescope with MAPMTs
• 1 Cherenkov telescope with SiPMs
• Optics: Schmidt mirrors

Goals:
• Measurements of background for upward going neutrinos
• Observation of tau neutrinos with $E>10^{16}$ eV below the limb
• Observation of UHECRs through:
  • Cherenkov emission just below the limb
  • Fluorescence light at nadir

Talk by Lawrence Wiencke
Cherenkov Camera of EUSO-SPB2

- Developed at Georgia Tech, USA
- 8x4 SiPM arrays
- 4x4 pixels/SiPM array (pixel 6.4 mm x 6.4 mm)
- Overall field of view of 12.8° x 6.4° (H x V)
- Effective aperture area 0.78 m²
- Wide spectral response 200-1000 nm
  (peak efficiency of 50% at 450 nm)

The focal surface of the Cherenkov telescope of EUSO-SPB2 made of 32 4x4 channels SiPMs S14521-6050AN-04 [PoS(ICRC2021)1191]
Ancillary cameras for EUSO-SPB2

• In Italy, ASI-INFN agreement to develop and test different SiPMs, to select a few candidates to fly on EUSO-SPB2 to assess their performance with the aim of using SiPMs in space
• The main activities are the design of the ASIC board for Cherenkov cameras (Turin), the characterization of SiPMs (Catania), and implementation of SiPMs on the detectors (Rome)
• Since the schedule did not allow for the integration with EUSO-SPB2, the systems have been developed as standalone elements

• Fluorescence detector
  with (BG3) UV-filter working on different timescales (from ns to above)

• Cherenkov detector

• Gamma ray detector
  atmospheric events: in particular Terrestrial Gamma Flashers (TGF)

• Charged particle detector
  (with some Z capability)
Gamma-ray detector

Cesium iodide crystal (Scionix) + SiPM readout

Thorium

Cesium137 from Fukushima soil (660 keV line)
Installation of the gamma-ray detector at the EUSO-TA site

Mission:
October 2015 – 2016
Upgrade is foreseen

Characteristics:
• Fluorescence telescope with MAPMTs
• Optics: 2 Fresnel lenses

Goals:
• Test the overall design of the detectors of the JEM-EUSO program on ground
• Detect cosmic ray events
• Detect meteors, stars
• Environment used to test the other experiments before launch (EUSO-SPB1, EUSO-SPB2)
Gamma-ray/charged particles detector

Cesium iodide crystal (CsI(Tl) - Scionix) + multi-SiPM readout
+ Anti-coincidence between inner and outer part
→ discrimination gamma-ray/charged particle
SiPM array board for the multi-pixel Cherenkov detector

- The multi-pixel Cherenkov detector moves in the direction of testing the full characteristics of the ASIC board developed in Turin (talk by Andrea di Salvo)
- AiT SiPM array module with discrete amplification electronics and power supply
- Preamplifier
Future: EUSO-SBP3

- Fluorescence + Cherenkov camera
  - Fluorescence: CR showers (nadir+inclined) + High-altitude CRs showers (tilted)
  - Cherenkov: CRs + neutrinos (tilted)
- Tiltable from 0° to 90°

- Optics: same (maybe larger) design than EUSO-SPB2 + bifocal optics only for CT to be studied
- Auxiliary devices: IR, Radio, gamma-ray, X-ray, SQM
- Goal: 2026
Future: POEMMA (1)

Cherenkov tel. with SiPMs (300-900 nm, ~ns)
Top of the focal surface that images the limb of the Earth

Fluorescence tel. with MAPMTs (300-400 nm, ~10 ns)
~90% of the focal surface

Talk by John Krizmanic
Future: POEMMA (2)

- Two Schmidt telescopes with variable separation (300-25 km)
- Altitude: 525 km
- Instrument Mass: 1547 kg
- Primary Mirror: 4 meter → FOV: 45 deg
- Hybrid focal surface (MAPMTs + SiPM): 1.6 m
• Several experiments of the JEM-EUSO program hosted and host SiPMs:
  • EUSO-SPB1 with the fluorescence camera SiECA
  • Mini-EUSO with single or multi-pixel cameras to evaluate day/night transition
  • EUSO-SPB2 with the focal surface of the Cherenkov detector

• In Italy, ASI and INFN allowed the design of the ASIC board for Cherenkov cameras (Turin), the characterization of SiPMs (Catania), and implementation of SiPMs on the detectors (Rome).

• The experience acquired will be essential in view of EUSO-SPB3 and also on another experiment based on Cubesats for solar physics under development in Rome (SEE-SuncubW onE).

• All the effort is done to obtain stable and reliable detectors in view of space-based experiments, like POEMMA.
Backup slides
# MAPMTs vs SiPMs

<table>
<thead>
<tr>
<th></th>
<th>(MA)PMTs</th>
<th>SiPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength range</strong></td>
<td>300-800 nm</td>
<td>300-1000 nm</td>
</tr>
<tr>
<td><strong>Internal Gain</strong></td>
<td>$10^5$-$10^7$</td>
<td>$10^5$-$10^7$</td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
<td>$\leq 1100$ V</td>
<td>$\leq 100$ V</td>
</tr>
<tr>
<td><strong>Single Photon Counting Capability</strong></td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Time Resolution</strong></td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Power Consumption</strong></td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>Low at $\leq 800$ nm</td>
<td>Noisier than PMTs at $\leq 800$ nm</td>
</tr>
<tr>
<td></td>
<td>Increases with voltage and wavelength</td>
<td>Comparable over whole range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increases with temperature (high at $T&gt;30^\circ$C)</td>
</tr>
<tr>
<td><strong>Sensitivity to Magnetic Fields</strong></td>
<td>Sensitive</td>
<td>Insensitive</td>
</tr>
<tr>
<td><strong>Sensitivity to Radiation</strong></td>
<td>Less sensitive to radiation than SiPMs</td>
<td>Sensitive</td>
</tr>
<tr>
<td><strong>Robustness</strong></td>
<td>More sensitive to intense light than SiPMs</td>
<td>Robust, can work under Moon light conditions</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Larger than SiPMs</td>
<td>Compact</td>
</tr>
</tbody>
</table>
POEMMA

Observation Modes

PRIMARY UHECR OBSERVATION MODES
UHECR stereo & no neutrino observation

PRIMARY NEUTRINO & SECONDARY UHECR OBSERVATION MODES

“HYBRID” OBSERVATION MODE
2x neutrino monocular & UHECR stereo

UHECR observation in stereo
(Fluorescence)

Above Limb observation
Earth skimming neutrinos
SAT 1 & SAT2
(Cherenkov)

UHECR observation in stereo
(Fluorescence)

(Upper) Limb observation
Earth skimming neutrinos
SAT 1
(Cherenkov)
POEMMA designed to observe cosmic rays with $E > 10^{18}$ eV

Statistics of such events higher from space than on ground

Significant increase in exposure (~10 x ground arrays, ~100 x fluorescence detectors)

Good energy, angular, and shower maximum resolutions, to guarantee the discovery of UHECR sources
POEMMA designed to observe neutrinos with $E > 10^{16}$ eV through Cherenkov signal of tau decays.

- The UHE neutrinos are expected to be born as $\nu_\mu$ or $\nu_e$. Due to vacuum oscillations, however, the astrophysical and cosmogenic neutrino flux at the Earth is expected to be almost equally distributed among the three neutrino flavours $\nu_\mu$, $\nu_e$, $\nu_\tau$.

- Some experiments search for $\nu_\tau$ (ANITA, IceCube-Gen2, MAGIC...)

$\rightarrow$ POEMMA will join the research!
Experience from EUSO-Super Pressure Balloon (EUSO-SPB)

Goals:
- Detect UHECRs for the first time from high altitude
- Test the detector at high altitude
- Measurement of the UV background of the atmosphere from above

Mission start:
25 Aprile 2017 from New Zealand

Mission end:
7 Maggio 2017 Pacific Ocean
Radiation environment @ EUSO-TA

• 24/6/2022
EUSO-SPB1 altitude with SiECA operation periods indicated in green circles. Descents indicate night cold cycles, rising with heat from the sun. [W. Painter PhD Thesis]
Scionix CsI scintillation detector with SiPM readout

<table>
<thead>
<tr>
<th>Description</th>
<th>CsI(Ti) scintillation detector with SiPM readout and built-in preamplifier / bias generator and temperature sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillation material</td>
<td>CsI(Ti), 25.4 x 25.4 mm</td>
</tr>
<tr>
<td>Drawing number</td>
<td>VS-1426</td>
</tr>
<tr>
<td>Maximum detector diameter</td>
<td>30 mm, 83 mm high</td>
</tr>
<tr>
<td>Crystal read out</td>
<td>SENSIL: ArrayJ-80035-4P</td>
</tr>
<tr>
<td>Electronics</td>
<td>Trans impedance amplifier and bias generator, temperature sensor</td>
</tr>
<tr>
<td>Power supply Voltage</td>
<td>5.2 - 16 V (5 mA @ 5.2 V)</td>
</tr>
<tr>
<td>SiPM Bias Voltage</td>
<td>27.5 V</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>DS18B20</td>
</tr>
</tbody>
</table>
| Electrical connections | Flying leads  
Brown = + 5.2-16 V  
Yellow = Signal  
Braid = Common ground  
White = DG (DS18B20)  
Green = Vout (DS18B20) |

**PERFORMANCE**

| Output impedance | 50 Ω |
| Pulse rise time | 1.3 μs (50 Ω) |
| Pulse fall time (1/e) | 2.8 μs (50 Ω) |
| Energy resolutions (662 keV) | < 8% FWHM |
| Noise level | < 15 keV |
| Gain | Approx. -0.3 V / MeV (1 MD) |
References