Caratterizzazione e installazione di filtri ottici per la SiPM camera del progetto EUSO-SPB

Tesi di laurea in fisica, 5/12/2016

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My Erasmus collaboration

From the 25th of April to the 25th of June in Karlsruhe

My closer tutors

The whole Cosmic rays group

The KIT North Campus

Karlsruhe

06/12/2016

Optical Filters for SIECA
Extreme energy cosmic rays

Cosmic rays are nuclei of various elements traveling in the space at relativistic speed.

They interact with atmosphere and generate a shower of photons and particles that we can detect in different ways.

We need to integrate on a big area or on a long time in order to get a good statistic.

Flux for $E > 5 \cdot 10^{19}$ eV: 1 event/km²/century

The Extreme Universe Space Observatory is a program with the main goal of observing very high energy cosmic rays ($E > 5 \cdot 10^{19}$ eV). The main object of the project will be to build a space telescope pointing to the Earth atmosphere.
Observation principle

Cosmic rays interaction with the atmosphere generates a shower of particles.

The instruments will detect fluorescence and Cerenkov photons from the interaction between the shower and the atmosphere in a very big area ($r \sim 250 \ km$)
Pathfinders

EUSO TA
On ground calibration facility in USA (running since 2013)

EUSO Balloon
The first flying prototype of EUSO launched in 2014

MINI-EUSO
Smaller version of the EUSO PDM will fly on the ISS in 2017

EUSO-SPB
Spring 2017
EUSO-SPB

EUSO-SPB has the objective of detect extreme high energy cosmic ray from the upper atmosphere, using a Super Pressure Balloon provided by Nasa which can fly at ~30/40km.

First 2 flight of the NASA SPB

This fly with be a lower altitude than the ISS, but still it should be able to detect come events in an area on ground with a side of ~6/8 km
EUSO-SPB structure

- Fresnel lens L3 fixed/tight
- Fresnel lens L1 adjustable
- Radiator
- Evacuation holes
- Baffle & "deceleration cylinder"
- PDM
- IR Camera
- Electronics (DP) on "dry shelf"

Optical Filters for SIECA

06/12/2016
On the EUSO-SPB there will be an array of new Silicon Photomultiplier (SiPM) beside the standard photomultiplier tubes (MAPts) in order to test the actual possibilities of this technology.

SiPMs pros:
- More durables
- Slower ageing
- More lightweight
- More sensible
- No high voltage required

Cons:
- Bigger dark noise
- Big noise temperature dependence

My work was focused on testing and assembling the optical filters for this camera.
Schott BG3 filters

Hamamatsu MPPC S12642 epoxy and S13361 silicone - sketch

BG3 filter transmittance (1mm)
Microscope analysis of the filters

The nanotechnology department helped me with a visual analysis of the filters' surfaces. They are resulted nearly perfects for our propose. There aren't big scratches or holes, or, at least, they are several orders of magnitude smaller than a dust particle. We use a 5x objective microscope with a 2560x1920 resolution CCD.

This filter is the one with most imperfections, because it's the one that has been handled more. As shown in the pictures, is the only filter which shows a dig (left picture), probably caused by a hit. The right picture shows the dirtiest part of the filter, which is still quite clean.
Each channel of our SiPM will be a square with a 3,2mm side, so we can consider the filters’ surface nearly optically perfect.
Filter transmittance properties

As next step I concentrate on the filters’ transmittance properties, using different light sources and a photodiode (OphirPD39) for the power detection.

It was important to study the filter transmittance in the peaks’ wavelength, but I can’t use single LEDs for the measure with the SiPM because they light output was too low for the SiPMs’ experimental system.
Experimental apparatus

The dark chamber I used for my measures, part of SPOCK (Single PhOton Calibration stand at KIT)
Single LED results
Multiple LED results

![Graph showing the transmittance of single LEDs with red and green lines representing average filter and Schott data, respectively. The x-axis represents wavelength in nm ranging from 320 to 440, and the y-axis represents transmittance ranging from 0.5 to 1.0.](image-url)
Design of mechanical devices

Gluing stand

Filter holder
Gluing process

Glue: Epotex 301-2:
Pros:
• very good UV transparency (94%-99% transmittency)
• easy to handle
• low temperature curing

Cons:
• Silicone and epoxy can have bad behaviour together
• very low viscosity
SiPM measurement

SiPM board
Filter
Photodiode

Light source
SiPM
Amplifier

LDD Cern-NP N4168
-2 to -24 V
Photon shielding

SiPM measurement

Pulser HP8082A
Gate generator

Fan-in/fan-out
LeCroy LRS 428F

QADC CAEN v965
VME-USB2.0 Bridge CAEN v1718

0 fotoelectrons (Pedestal peak)
1 fotoelectron
2 fotoelectrons
3 fotoelectrons

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Optical Filters for SIECA
First measure result

The SiPM for the first test was not working before the gluing, after the gluing those are the results for 423 nm light:

<table>
<thead>
<tr>
<th></th>
<th>Channel 1</th>
<th>Channel 44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitted photons (pulse)</td>
<td>3.06±0.06</td>
<td>3.06±0.06</td>
</tr>
<tr>
<td>Detected photons (pulse)</td>
<td>0.89±0.03</td>
<td>0.91±0.03</td>
</tr>
<tr>
<td>PDE (photon detection efficiency)</td>
<td>29.0% ± 1.2%</td>
<td>29.5% ± 1.2%</td>
</tr>
</tbody>
</table>
Photo detection efficiency calculation

\[ PDE = \frac{N_r}{N} \]

\[ N = \frac{P \cdot R \cdot \lambda}{h \cdot c \cdot f} \]

With:
- \( N \): Number of incoming photons
- \( P \): Optical power of one pulse
- \( R \): Collimation Ratio
- \( \lambda \): Wavelength if LED light
- \( h \): Planck constant
- \( c \): Speed of light
- \( f \): Pulse frequency

\[ N_r = \ln \left( \frac{N_{Dark}}{N_{TOT}} \right) - \ln \left( \frac{N_{Light}}{N_{TOT}} \right) \]

With:
- \( N_r \): Number of detected photons
- \( N_{Dark} \): Pedestal peak area with no light
- \( N_{TOT} \): Number of pulses
- \( N_{Light} \): Pedestal peak area with light

Error sources (numeric values for channel 1)

<table>
<thead>
<tr>
<th>Channel 1</th>
<th>Incoming photons</th>
<th>Detected photons</th>
<th>PDE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.06 ± 0.06</td>
<td>0.89 ± 0.03</td>
<td>29.0% ± 1.2%</td>
</tr>
</tbody>
</table>

- 0.058 from collimation error
- 0.01 from wavelengths’ error
- Mostly from pedestal area error (Gauss) and QADC non-linearity
- Other minor error sources
Gluing problems and defects

Analysed channels

First gluing attempt

Bubbles (C4)

Damage (A4)

Clean (H8)
## Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>PDE</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4</td>
<td>27.8 ±1.6%</td>
<td>under the dig</td>
</tr>
<tr>
<td>C2</td>
<td>26.3 ±1.6%</td>
<td>bubbles</td>
</tr>
<tr>
<td>C4</td>
<td>26.0 ±1.6%</td>
<td>bubbles</td>
</tr>
<tr>
<td>C5</td>
<td>27.1 ±1.6%</td>
<td>crack</td>
</tr>
<tr>
<td>E2</td>
<td>27.4 ±1.6%</td>
<td>clear</td>
</tr>
<tr>
<td>E4</td>
<td>27.2 ±1.6%</td>
<td>clear</td>
</tr>
<tr>
<td>H8</td>
<td>27.0 ±1.6%</td>
<td>clear</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Without filter</th>
<th>With filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>371</td>
<td>20,7±0,8%</td>
<td>20,0±1,0%</td>
</tr>
<tr>
<td>394</td>
<td>38,5±1,2%</td>
<td>36,4±1,5%</td>
</tr>
<tr>
<td>420</td>
<td>41,6±1,4%</td>
<td>27,4 ±1,0%</td>
</tr>
</tbody>
</table>
Final gluing

Degassing process

New gluing stand

SiECA Assembled
SiECA simulation-the ESAF software

ESAF (EUSO SIMULATION AND ANALYSIS FRAMEWORK)

SIMU (events’ simulation)
- Shower
- Atmosphere
- Detector

RECO (shower reconstruction)
Not used in my work

Simulation parameters
- Energy: $6.3 \cdot 10^{17} < E < 1.6 \cdot 10^{19}$ eV
- Clouds: Clear, low (2km top) and middle (5km top) clouds
- Clouds optical depth: 5
- Detector’s height: 38km
- PDE (MAPTs): 10%
- PDE (SiPMs): 13.3%
- Generated events: 10000
Event example

Event with no background

Energy: $1.10 \cdot 10^{19}$ eV
Zenit angle: 22.31°

Event with background

*GTU=Gate Time Unit= 2,5μs
Triggered spectra calculation

Trigger performances evaluated in term of events collected in a spectrum

\[ \Delta N(E) = \frac{d\phi(E)}{dE} \cdot \Delta(E) \cdot \Psi(E) \]

- **\( \Delta N(E) \):** Number of events per energy bin
- **\( \frac{d\phi(E)}{dE} \):** Differential flux (Auger Flux – ICRC 2013)
- **\( \Delta(E) \):** Energy range
- **\( \Psi(E) \):** Detector exposure

\[ \Psi(E) = \varepsilon(E) \cdot A_{fov} \cdot \pi \cdot t \cdot DC \]

- **\( \varepsilon(E) \):** Detector efficiency
- **\( A_{fov} \):** Detector field of view area
- **\( \pi \):** Solid angle
- **\( t \):** Triggering time
- **\( DC \):** Duty cycle

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Triggered events

Total number \((N_i)\) of triggered events in 118h

<table>
<thead>
<tr>
<th></th>
<th>Main camera trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear sky</td>
<td>5,7 ±0,6</td>
</tr>
<tr>
<td>Low clouds</td>
<td>16,8 ±0,6</td>
</tr>
<tr>
<td>Middle clouds</td>
<td>13,6 ±0,2</td>
</tr>
</tbody>
</table>

Cloud fractions \((f_i)\) in previous flights*

<table>
<thead>
<tr>
<th>Flight 1</th>
<th>Clear sky</th>
<th>Low clouds</th>
<th>Middle clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td>23%</td>
<td>37%</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Flight 2</td>
<td>40%</td>
<td>25%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Total number of triggered events in realistic conditions

\[
W = \frac{\sum_i f_i N_i}{\sum_i f_i}
\]

<table>
<thead>
<tr>
<th></th>
<th>Main camera trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted sum flight 1((W))</td>
<td>12,1 ±0,4</td>
</tr>
<tr>
<td>Weighted sum flight 2((W))</td>
<td>13,0 ±0,5</td>
</tr>
</tbody>
</table>

*From A. Veneziani Thesis
Different thresholds

SiECA doesn’t have any trigger (it will use the main trigger for the data acquisition), so we decide to use different arbitrary thresholds.

<table>
<thead>
<tr>
<th></th>
<th>Events flight 1</th>
<th>Events flight 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main trigger</td>
<td>$12.1 \pm 0.4$</td>
<td>$13.0 \pm 0.5$</td>
</tr>
<tr>
<td>5 counts/pixel in 1 GTU</td>
<td>$1.0 \pm 0.3$</td>
<td>$1.0 \pm 0.3$</td>
</tr>
<tr>
<td>8 counts/pixel in 1 gtu</td>
<td>$0.4 \pm 0.2$</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>20% of total signal</td>
<td>$1.2 \pm 0.2$</td>
<td>$1.1 \pm 0.2$</td>
</tr>
<tr>
<td>40% of total signal</td>
<td>$0.4 \pm 0.1$</td>
<td>$0.4 \pm 0.1$</td>
</tr>
</tbody>
</table>

Simulation parameters:
- Energy: $9.46 \cdot 10^{18}$ eV
- Zenit angle: $61^\circ$
- Low clouds
Conclusions

The optical filters are now mounted on SiECA and we know how they should perform.

Between 370 and 423 nm the filter transmittance is between 90% and 60% and the assembled SiPM’s PDE is between 20% and 36%.

The simulations show that the camera will likely detect at least 1 event during the flight. We should be able to test on the SiMPTs’ functionalities for cosmic rays detection.

The NASA website of the mission

Euso-SPB during the hang test at the NASA CS-BS (Palestine-Texas)
Grazie per l’attenzione

Thanks to:
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- William Painter (KIT)
- Thomas Huber (KIT)
- Max Renschler (KIT)
- Francesca Bisconti (KIT)
Geometrical analysis

For have a check on the simulated result I did a simple geometrical analysis of the asset. We can simulate the showers like segments casually generated in an area bigger than the FOV of both the camera. Then I took the ratio between the "events" which pass trough the main camera and the "events" which pass trough both SiECA and the main detector.
## Filter transmission

<table>
<thead>
<tr>
<th>Wavelengths (nm)</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>311 ± 4</td>
<td>88.0% ± 0.5%</td>
</tr>
<tr>
<td>319 ± 5</td>
<td>89% ± 1%</td>
</tr>
<tr>
<td>332 ± 5</td>
<td>89% ± 1%</td>
</tr>
<tr>
<td>337 ± 5</td>
<td>90.3% ± 0.2%</td>
</tr>
<tr>
<td>361 ± 13</td>
<td>89.8% ± 0.1%</td>
</tr>
<tr>
<td>373 ± 6</td>
<td>87.5% ± 0.1%</td>
</tr>
<tr>
<td>379 ± 7</td>
<td>87.8% ± 0.4%</td>
</tr>
<tr>
<td>395 ± 7</td>
<td>83.2% ± 0.5%</td>
</tr>
<tr>
<td>402 ± 8</td>
<td>79.7% ± 0.5%</td>
</tr>
<tr>
<td>423 ± 8</td>
<td>62% ± 1%</td>
</tr>
</tbody>
</table>
Detected spectrum

Main detector: 4.9 ± 0.6
SiECA threshold 5: 0.8 ± 0.3