R&D on a Scintillating Fiber Tracker with SiPM array readout for Application in Space

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Astroparticle physics and high energy astrophysics are in a “golden” era thanks to a series of very successful and long-running space and ground based experiments (eg. PAMELA, Fermi, AMS-02, H.E.S.S., Auger, IceCube, ...) – The multi-messenger/multi-wavelength/multi-platform approach is opening up new possibilities in observation and discovery – The hot topics are still: dark matter, comic ray origin, antimatter

The future of ground-based observation is very brilliant with approved new projects (CTA, LHASSO) and proposed projects (KM3NeT, IceCube Gen2, ...) 

Need complementary future space missions
– Direct cosmic ray detection: getting to the “knee” (HERD, ...)
– Close the gamma-ray “MeV” gap (PANGU/e-ASTROGAM, ...)
– Antimatter and DM search with antiparticles > TeV (ALADINO, ...)
The University of Geneva has long experience in silicon tracker detectors in Space (AMS-01, AMS-02, DAMPE).

New technologies to replace silicon detectors are under study:
- Our idea is to use scintillating fiber mats instead of silicon strip detectors.

DAMPE plane

AMS-02 plane

PoS(Vertex2014)028

PoS(ICRC2015)1192

Fiber mat

SiPM
The SciFi project for Space

- Six fiber layers in each mat
- 250 μm diameter, Kuraray SCSF-78M (LHCb)
- 2 lengths
- SiPM on each end of the fiber mat to measure particle with Z = 1 on one side and Z ≤ 20 on the other (two different gains)
- ∼ 9.8 cm width to match for 3 SiPM arrays

- SiPM multi-channel array from Hamamatsu S10943-3183(X)
  - 128 channels per array
  - 96 pixels per channel
  - Pixel size: 57.5 μm × 62.5 μm
  - Channel size: 230 μm × 1500 μm
From the project to reality (1)

Extremities polished at EPFL (Lausanne, CH) with diamond head

C. Perrina
**Printed Circuit Board**
The 128 channels of each SiPM array are split in 4 x 32 lines with flex cables going in opposite direction.

**Front-end electronics board**
2x VATA 64 HDR 16, to readout the 128 MPPC channels.

Four zero-insertion-force (ZIF) sockets to connect the MPPC board.
Fiber module prototypes

- Two fiber modules ready and tested during a test beam (May 15 - 19, 2017) at CERN with a hadron beam of 100 GeV/c.

- 4 millions events collected

- Data analysis just started
Signal distribution integrated over the 128 channels of a SiPM.

No clusterization performed.

First peak = no signal.

One peak corresponds to one photo-electron (p.e.).

From the signal distribution we can compute the signal for one pixel.
This kind of detector (fiber + SiPM) has never been used in Space.

- Needed space qualification tests
  - Thermal tests;
  - Vacuum tests;
  - Vibrations.

- Tests on
  - SiPMs;
  - SiPMs mounted on PCB;
  - fiber mats.
The $V_{BD}$ for each channel can be found by plotting (Inverse Logarithmic Derivative method):

$$\frac{1}{I} \times \frac{dI}{dV}$$

$V_{BD}$ is given by the V for which the linear fit crosses zero.
Flex 4 V_{BD} corrected for 25 °C
$V_{BD}$ vs. Temperature

Flex 4 Channel 129

\[
\begin{align*}
\text{Output current (nA)} & \\
10^{-3} & \quad 10^{-2} & \quad 10^{-1} & \quad 10^0 & \quad 10^1 & \quad 10^2
\end{align*}
\]

\[
\begin{align*}
\text{Reverse voltage (V)} & \\
52.5 & \quad 53.0 & \quad 53.5 & \quad 54.0 & \quad 54.5 & \quad 55.0 & \quad 55.5 & \quad 56.0 & \quad 56.5 & \quad 57.0
\end{align*}
\]

\[
\begin{align*}
0^\circ C & \quad 5^\circ C & \quad 10^\circ C & \quad 15^\circ C & \quad 20^\circ C & \quad 25^\circ C & \quad 30^\circ C & \quad 35^\circ C & \quad 40^\circ C
\end{align*}
\]

\[
\begin{align*}
\text{Breakdown voltage vs. Temperature at 6 step bw}
\end{align*}
\]

\[
\begin{align*}
\frac{dV_{BD}}{dT} = 52.8 \text{ mV/}^\circ C
\end{align*}
\]
Flex 4 after thermal cycles
$V_{BD}$ corrected for 25 °C

Thermal cycles
5 x (-30 °C -> +60 °C)
The discrepancy between $V_{BD}$ measured before thermal cycles and after is $< 0.16 \%$.
Readout improvement: SIPHRA chip

- SIPHRA = “Silicon Photomultiplier Readout ASIC”
- New ASIC from IDEAS for space applications
- The circuit has been designed under contract from the ESA with support from the Norwegian Space Center and the University of Geneva.

- **12-bits ADC included.**
- One line to readout and digitize one PT100 temperature sensor.
- One single power supply voltage: **3.3 V**.
- Various operation modes available.
  - It can provide in output only the channels with a signal higher than a programmed threshold (one for each channel).
  - Data reduction at ASIC level!
- 1 mW power consumption per channel.
- Test board for SIPHRA chip is being produced and tests will start in the next weeks.
Conclusions

Advantages

• Less fragile;
• Flexible geometry;
• No wire bonds;
• Single photon response;
• High detection efficiency;
• High gain at low bias voltage;
• Together with SIPHRA: simplified DAQ electronics;
  • No Op-amp needed, data reduction done at ASIC level;
  • Only 3.3 V power line needed (apart from bias line).

Disadvantages

- Low Technology Readiness Level (TRL);
- Effects of dark count;
- Dependence of SiPMs on temperature.
Future

- More complete diagnostic tool will be introduced
  - Calibration with LEDs;
  - Calibration with radioactive sources;

- Space qualification tests to increase the TRL
  - Thermal tests;
  - Vacuum tests;
  - Vibrations.

- Tests on
  - SiPMs;
  - SiPMs mounted on PCB;
  - Fiber mats;
  - Complete modules;
  - Planes made of more modules.

Work in progress!
Thank you!!
Principle of operation

Basic operation
- Each pixel operates separately in Geiger-mode
- Each pixel outputs a same amplitude pulse
- Pulse generated by multiple pixels are output while superimposed onto each other (detected at the same time)
- No position information
MPPC Technology Overview

What is an MPPC?
- Multi-Pixel Photon Counter
  a new type of photon-counting device
  made up of multiple APD pixels
  operated in Geiger mode

Features
- Small size / light weight
- Room temperature operation
- Low bias operation : ~70V
- High gain: $10^5$ to $10^6$
- Excellent timing resolution
- Insensitive to magnetic fields
- Simple readout circuit operation
Geiger-mode operation of SiPMs

Geiger-mode operation

APD
Quenching resistor

Output current [A]

Reverse Voltage [V]

Vop: Operating voltage
VBR: Breakdown voltage

Geiger mode region

Vov: Over voltage
Vov = Vop - VBR

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Product outline
- MPPC
- Effective photosensitive area 0.23×1.5mm, 128ch. Array (64ch/chip × 2chip)
- Surface mounted package with 2 holes

![Image of SiPM array]

### Table: Parameters and Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Rating</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective active area / channel</td>
<td>--</td>
<td>230(X) × 1500(Y)</td>
<td>μm</td>
</tr>
<tr>
<td>GAP between channels (on chip)</td>
<td>--</td>
<td>20</td>
<td>μm</td>
</tr>
<tr>
<td>GAP between channels (between chip)</td>
<td>--</td>
<td>250 ± 50</td>
<td>μm</td>
</tr>
<tr>
<td>Number of channels</td>
<td>--</td>
<td>128 (64 × 2chip)</td>
<td>ch</td>
</tr>
<tr>
<td>Number of pixels / channel</td>
<td>--</td>
<td>4(X) × 24(Y)</td>
<td>--</td>
</tr>
<tr>
<td>Pixel size</td>
<td>--</td>
<td>57.5(X) × 62.5(Y)</td>
<td>μm</td>
</tr>
</tbody>
</table>
### Properties of our SiPM array

<table>
<thead>
<tr>
<th>Property</th>
<th>ID</th>
<th>VR=Vop</th>
<th>40</th>
<th>VBR+2.5</th>
<th>65</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage</td>
<td>VBR</td>
<td>--</td>
<td>40</td>
<td>--</td>
<td>65</td>
<td>V</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>Vop</td>
<td>--</td>
<td>VBR+2.5</td>
<td>--</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vop variation between channels</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.4</td>
<td>1.0</td>
<td>V</td>
</tr>
<tr>
<td>Dark current / channel</td>
<td>ID</td>
<td>VR=Vop</td>
<td>--</td>
<td>20</td>
<td>100</td>
<td>nA</td>
</tr>
<tr>
<td>Cross talk</td>
<td>--</td>
<td>VR=Vop</td>
<td>--</td>
<td>8</td>
<td>15</td>
<td>%</td>
</tr>
<tr>
<td>Terminal capacitance / channel</td>
<td>Ct</td>
<td>VR=Vop 100kHz</td>
<td>--</td>
<td>12</td>
<td>--</td>
<td>pF</td>
</tr>
<tr>
<td>Gain</td>
<td>M</td>
<td>VR=Vop</td>
<td>--</td>
<td>2×10⁶</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Quenching resistance</td>
<td>Rq</td>
<td>120</td>
<td>160</td>
<td>240</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient of operating voltage</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>60</td>
<td>--</td>
<td>mV/C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectral response range</th>
<th>λ</th>
<th>VR=Vop</th>
<th>320 to 900</th>
<th>nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td>VR=Vop</td>
<td>--</td>
<td>450</td>
</tr>
<tr>
<td>Photon detection efficiency at λp *1</td>
<td>PDE</td>
<td>VR=Vop</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>
Layout of our SiPM array

top = odd channels

bottom = even channels
Flex 4 before thermal cycles

$V_{BD}$ NON corrected by temperature
Flex 4 after thermal cycles

\[ V_{BD} \] NON corrected by temperature

![Graph showing output current vs. reverse voltage and breakdown voltage vs. channel id at 4 step bw.](image)
• Altera Cyclone V FPGA.
• FEE board analogue signal digitization.
• Communication/data transfer via an USB3 port.
• DAQ architecture developed by the DPNC electronics group.
• Common digital interface and related control software, to be used by different experiments.