Large Area SiPM Pixels for SPECT: from high energy astrophysics to medical imaging

Daniel Guberman\textsuperscript{1}, R. Paoletti, A. Rugliancich, C. Wunderlich and A. Passeri

\textsuperscript{1}Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa
daniel.guberman@pi.infn.it

ANIMMA 2021, Prague
25 June 2021
Single Photon Emission Computed Tomography (SPECT):

- A single-gamma-ray tracer is injected to the patient
- One or more gamma-ray sensitive cameras equipped with a collimator rotate around him
- Several planar images are taken to build a 3D functional image

Flyckt & Marmonier (2002)  
GE Healthcare  
VisualSnow (2014)
The bulky gamma camera

Typical camera for full-body SPECT:

- **50 x 40 cm² area NaI(Tl) scintillator**
- **~50-100 Photomultiplier tubes (PMTs) of ~2-3” diameter**
- **A lead collimator**
- **~1-3 cm thick layer of lead shielding the whole volume**

→ A SPECT camera is a heavy (a few hundred kg) and bulky system

→ A large fraction of the volume is occupied by the PMTs
SiPMs in full-body SPECT?

Silicon Photomultipliers (SiPMs) are natural candidates to replace PMTs

- **SiPMs** are compact photodetectors:
  - Reduce camera volume
  - Reduce amount of lead needed for the shielding
  - **Reduce weight** and **size** of a camera

Main obstacle: No large-area SiPMs

- SiPM typical size $< 6 \times 6 \text{ mm}^2$ (capacitance increases with SiPM area)
  - $\sim 4000$ channels needed to equip a full-body SPECT camera
Solutions in gamma-ray astrophysics

Same problem in Very-High-Energy Astrophysics:

- Typical **pixel diameter** in large telescopes \( \sim 25 \text{ mm} \)
- \( \sim 1000 \) **channels** per telescope
- Moving towards **more telescopes** and **larger cameras**
- Several developments aiming to build Large-Area SiPM pixels

→ **Can we apply one of these solutions in SPECT?**
A LASiP is built by summing the individual currents of several SiPMs into a single output:

- **Less readout channels** without a dramatic increase in capacitance
- **Solution** already tested in high-energy astrophysics
- **Sum** can be performed with passive components or using a dedicated ASIC...

![Diagram of LASiP](image1)

![LASiP example](image2)

*Fink et al. (2016)*

*A. Gonzalez*

*MAGIC coll.*

*Rando et al. (2015)*
The MUSIC ASIC\(^1\)

**Multipurpose ASIC for SiPM readout** developed at ICCUB (Barcelona)

- **Preamplifier, shaper and summation** in a single chip
- Has many other functionalities (e.g. SiPM bias adjustment)
- Can sum up to 8 SiPMs

LASiP Prototype

- It uses a **matrix** of 16 SiPMs of 6 x 6 mm$^2$ (FBK NUV-HD) and an **eMUSIC MiniBoard** (plug-and-play board from SCIENTIFICA SRL)
- **8 SiPMs** are summed by the **MUSIC** (the remaining 8 are not used)
- Pixel is a 2 x 2 cm$^2$ square with a **dead corner (~2.2 cm$^2$ active area)**
Proof-of-concept micro camera

- 4 LASiP prototypes coupled to a \(40 \times 40 \times 8 \text{ mm}^3\) NaI(Tl) crystal (OST Photonics)
- Custom-made holder compatible with 2 different collimators
- Took images using \(^{99m}\text{Tc} (140 \text{ keV})\) and \(^{241}\text{Am} (60 \text{ keV})\) gamma-ray sources
Monte Carlo simulations

We simulated the **micro-camera** response to gamma-rays with **Geant4**:  

- **Scintillation photons** are tracked until they reach the LASiPs, they escape or are absorbed
- **Electronic and SiPM noise** was injected in the simulations...
SiPM noise

- **Optical crosstalk probability.** Probability that a triggered cell generates a trigger in a neighboring cell.

- **Dark counts.** A cell that undergoes an spontaneous trigger. Randomly distributed in time, their rate increases linearly with the area.

- **Single photoelectron resolution.** Variations in the charge generated by a single photon. Depends on the number of SiPMs that are being summed...
Single-phe resolution vs summed SiPMs
Image Reconstruction

- $^{99m}$Tc capillary (0.5 mm diameter, 140 keV)
- LEUHR Collimator
- 2cm src-collimator distance
- Reconstruction algorithm: centroid (Anger logic) + linearity and uniformity corrections
Micro-camera performance

- We were able to reconstruct simple images (capillary and point-like sources)
- We measured an energy resolution of \(~11\%\) and an intrinsic spatial resolution of \(~2\ mm\)
- Good agreement between data and Monte Carlo simulations (MC)
- Simulations:
  - Dead corners significantly degrade the performance
  - Low impact of SiPM optical crosstalk on Energy resolution (<5%)
  - Moderate impact of Dark Count Rate at room temperature, gets worse at higher rates

Image reconstruction of a $^{241}\text{Am}$ point-like source using an 0.5 mm x 2 cm collimator.
Towards a large LASiP-SPECT camera (I)

• ~ 500 channels needed to equip a full-body SPECT camera if using LASiPs of ~2 x 2 cm²
  → Larger LASiPs (e.g. ~ 4 x 4 cm²) desirable to reduce the number of readout channels to ~100
  → A 32-SiPM LASiP is under development (sums the output of 4 MUSICs)

• In larger LASiPs we can also play with pixel geometry
Towards a large LASiP-SPECT camera (II)

Scintillation light produced in a single event will be distributed over many more SiPMs...

... and with more SiPMs the impact of dark counts will be higher

→ Trigger settings (Nr of LASiPs used to collect the charge, integration time) should be optimized. This optimization will depend on:

- LASiP size, geometry and distribution inside the camera
- SiPM PDE vs DCR

**Top:** Distribution of the mean charge collected by 4636 SiPMs of 6×6 mm² filling a camera of 500x400x9 mm³ for a collimated gamma-ray beam of 140 keV. **Bottom:** Percentage of the total charge collected as a function of the number of SiPMs employed for the trigger. In red the expected number of integrated dark counts (DCR =0.13 MHz/mm²) for an integration time of 0.6 μs.
Conclusions

LASiPs could be an alternative to build low-cost, compact, large gamma cameras, providing that:

- Pixel size and geometry are optimized
- Trigger settings are optimized
- Impact of DCR is mitigated

We provided two key ingredients for such optimization:

- We proved that LASiPs can be used to reconstruct simple images with a comparable performance to standard SPECT systems.
- We validated MC simulations that can be extended to simulate a larger camera with larger LASiPs

Extended version of the results and methods in:

doi:10.1016/j.ejmp.2021.01.066
Backup
Image Reconstruction

Simple centroid method + corrections (uniformity, linearity)

- Simple and fast: useful for the proof-of-concept and comparing experiment and simulations

- Worse spatial resolution compared to more elaborated techniques
Simulation results

<table>
<thead>
<tr>
<th>Nr</th>
<th>XT [%]</th>
<th>$\sigma_0$ [m.c.u]</th>
<th>$\sigma_1$ [m.c.u]</th>
<th>U.N. [m.c.u.]</th>
<th>$\epsilon$ (LASiP) [%]</th>
<th>$\epsilon$ (36 SiPMs) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.7</td>
<td>9.1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.1</td>
<td>9.4</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.2</td>
<td>9.5</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.5</td>
<td>9.9</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>10.3</td>
<td>9.6</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>10</td>
<td>1</td>
<td>-</td>
<td>10.7</td>
<td>9.9</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>1</td>
<td>5</td>
<td>-</td>
<td>10.7</td>
<td>9.9</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>1</td>
<td>10</td>
<td>-</td>
<td>11.3</td>
<td>10.8</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10.7</td>
<td>10.0</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>11.5</td>
<td>10.8</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>16.7</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Table 1: Simulations performed with Geant4. $d_1$ and $d_2$ are the distance between disk and side and bottom mirrors, respectively, $R$ is the reflectivity of the mirrors and $\Delta$ is the thickness of the coupling. The trapping efficiency $\epsilon$ is computed por quantum yields $Y$ of 100 and 84%.
Micro-camera performance

• We were able to reconstruct simple images (capillary and point-like sources)

• We measured an energy resolution of ~11.5% and an intrinsic spatial resolution of ~2 mm

• Good agreement between data and Monte Carlo simulations (MC)

Charge spectrum of $^{99m}$Tc sources obtained with a micro-camera for a flood-field irradiation (left) and a 0.5 mm capillary at a distance of 2 cm from a LEUHR resolution collimator (right)
Simulations: LASiP impact in the performance

- LASiP **dead corners** significantly **degrade the performance**

- **Low impact** of SiPM optical crosstalk on Energy resolution (< 5 %)

- **Moderate impact** of Dark Count Rate at room temperature, degrades faster at higher rates (x 2 increase in DCR can worsen Energy resolution by 10-15%)

Simulated charge spectrum of a flood-field irradiation with $^{99m}$Tc for LASiPs with (top) and without (bottom) dead corners.