High Resolution PET detector based on Continuous Crystal and SiPMs
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Introduction

- Physical base of detection

- Type of coincidence events
  - True \((T)\)
  - Scatter \((S)\)
  - Random \((R)\)

- Other degradation effects
  - Acolinearity, positron Range, Detector intrinsic resolution
  - Depth of Interaction (DOI) uncertainty
Introduction

Why Continuous Crystal and SiPM as photodetector?

- Sensitivity
  - Higher efficiency than pixellated at lower cost

- DOI (Depth of Interaction)
  - Some methods provide information of DOI
  - reduce parallax effects near the edges of FOV

- Spatial resolution
  - Accurate position determination methods
  - It is not easy (Work in progress)

- SiPM pixels small
**Scintillation Crystal**

**Properties**
- Material: LYSO (Ce)
- Continuous Crystal
- Thickness = 5, 10 mm
- White painted

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>BGO</th>
<th>LYSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>50.6</td>
<td>75</td>
<td>63</td>
</tr>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>3.67</td>
<td>7.13</td>
<td>7.1</td>
</tr>
<tr>
<td>$\tau$ (ns)</td>
<td>230</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>$L_m$(ph/MeV)</td>
<td>45000</td>
<td>8200</td>
<td>30000</td>
</tr>
</tbody>
</table>

- Continuous Crystals vs pixellated Crystals
  - Higher Efficiency
  - More difficult position determination

Quick decay
High luminosity
Materials

- Photodetector: Silicon Photomultiplier (SiPM)
  - Properties
    - High gain
    - Compactness
    - Insensitivity to magnetic fields
    - Fast response properties
  - Description of the SiPM matrix
    - 8x8 pixels (SiPMs)
    - Each pixel
      - size is 1.5 by 1.4 mm
      - 840 microcells (G.M. APD)
      - Signal $\alpha$ deposited energy
    - Readout on two sides

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Materials

- PET Detector (C. C. + SiPMs)
  - Printed Circuit Board (PCB)
    - Support
    - Bias
    - Connect pixels to channels of the readout electronic board
  - Scintillator Crystal
  - SiPMs matrix

- Bias

- 64 channels
Materials

- PET Tomograph prototype
  - 2 Head detectors
    - 6 steps, 30°/step
    - FOV (12x12x12 mm³)
  - Parameters
    - Coincidence Window: 25ns
    - Dead time: 80μs (due to the readout)

![Diagram of PET Tomograph prototype](image)

- Radioactive Source holder
- Methacrylate frame

- 45.8 mm
Characterization of the detectors

- Energy Resolution

\[ R(\%) = \frac{FWHM}{\text{centroide}} \times 100 \]

\[ R(\%) = (21.2 \pm 0.2)\% \]

Energy resolution: 21% FWHM at 511keV
Characterization of the detectors

Time Resolution

FWHM = (12.82 ± 0.22) ns

Timing resolution relatively poor
Trigger given by OR of all channels

Set up

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High Performance PET detector based on Continuous Crystal and SiPM
Charaterization of the detectors

- Tomographic Reconstruction of Real data
  - Two source (d=1mm)

  ![Sagittal](image1.png)  ![Transaxial](image2.png)

- Sub-millimeter point-source Resolution
Monte Carlo Simulations

- **GATE** (Geant4 Application for Emission Tomography)

  - GATE is a Monte Carlo simulation toolkit
    - Dedicated to Medical imaging and radiotherapy
    - Based on Geant4 libraries

  - Advantages
    - User-friendly scripted interface
    - Management of time dependent phenomena
      - Movements of volumes (rotation of head detector)
      - Acquisition time
      - Decay of radioactive source

  - Disadvantages
    - less flexible than GEANT4
Monte Carlo Simulations

- Simulation of the prototype
  - Detector head
    - LYSO crystal (12x12x5 mm$^3$)
    - Rotation (30°/step)
  - Source
    - 511keV gamma
    - Back-to-back
  - Electronic chain
    - Energy blurring (21%)
    - Time resolution (12.82ns)
    - Coincidence chain
      - Window (25 ns)
      - Dead time (80 us)
  - Acquisition time
    - Time step=1h
Monte Carlo Simulations

Verification of M. C. simulation of the prototype

- Superposition of the energy spectrum and the time resolution

\[ R_{\text{simulated}} = (21.15 \pm 0.12)\% \]
\[ R_{\text{experimental}} = (21.2 \pm 0.2)\% \]
\[ \text{FWHM}_{\text{simulated}} = (12.82\pm0.03)\text{ns} \]
\[ \text{FWHM}_{\text{experimental}} = (12.82 \pm 0.22)\text{ns} \]
High Performance PET detector based on Continuous Crystal and SiPM

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Monte Carlo Simulations

Verification of M. C. simulation of the prototype

- Reconstruction

Pixel size 0.5mm
- $D_{\text{source}} = 1\text{mm}$
- $\Delta E = (360-660) \text{ keV}$

FWHM$_{\text{tot}} = (1.0696 \pm 0.0008) \text{ mm}$

FWHM$_{\text{transversal}} = (0.6176 \pm 0.0005) \text{ mm}$

FWHM$_{\text{coronal}} = (0.734 \pm 0.004) \text{ mm}$

19% FWHM larger off centre source
Monte Carlo Simulations

Random study in Continuous and Pixelated Crystals

- Simulations with different type of crystals

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**Continuous**

LET=400 keV

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**Pixelated**

LET=400 keV

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Two detector heads in coincidence

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Random estimation methods

- Single Rate (SR) method
  \[ R^{SR} = 2 \tau S_1 S_2, \]
  \( \tau = \text{coincidence window, } S = \text{singles rate in detector i} \)

- Delayed Coincidence Window (DW) method
  - Second coincidence window in parallel, shifted in time
  - Time offset = 800ns \( \tau = 25 \text{ns} \)
Monte Carlo Simulations

Both methods overestimate random rate
DW better than SR
SR worse applied to C.C.

Objective: Improve SR method
working on a theoretical model to understand
Simulation of the detector with optical photons

- More Realistic simulation of detector performance
  
  - Physical processes
    
    - Interaction of annihilation photons within the crystal
    - Scintillation process
    - Transport of scintillation photons through the crystal
    - Reflection of scintillation photons at boundaries
    - Optical absorption of the photons in Silicon SiPM
Simulation of the detector with optical photons

- Geometry for 5mm crystal thickness

![Diagram of detector geometry]

- Air
- LYSO(Ce)
- Meltmount
- Epoxy coating
- SiPM matrix
- Pixel (Silicon)
- 5 mm
- 12 mm
- d
- 0.05 mm
- 0.24 mm
- 0.4 mm
Simulation of the detector with optical photons

- M. C. simulations with optical photons
  - Unified model to modelate reflection of photons between to dielectric media
  - Type of Surfaces employed
    - dielectric-dielectric
    - dielectric-metal (pixel-SiPM)
  - Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm$^3$)</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.29</td>
<td>1.00028</td>
</tr>
<tr>
<td>LYSO(Ce)</td>
<td>7.10</td>
<td>1.82</td>
</tr>
<tr>
<td>Meltmount</td>
<td>1.036</td>
<td>1.704</td>
</tr>
<tr>
<td>Epoxy</td>
<td>1.0</td>
<td>1.67</td>
</tr>
</tbody>
</table>
Simulation of the detector with optical photons

- Position determination measurements for the validation M.C
- Set up

Detector in coincidence with a 1mm x 1mm x 10mm crystal coupled to 1 MPPC
High Performance PET detector based on Continuous Crystal and SiPM

Simulation of the detector with optical photons

- Flood map of the detector
- 8 Dead pixels in the detector
Simulation of the detector with optical photons

Monte Carlo simulations vs Real data \textit{WS\_5mm}

- Point1 (-1.4,0.8) mm, Point3 (-3.75,3-75) mm
- Red lines (Real data), Black lines (simulation) (in progress)
Simulation of the detector with optical photons

- Monte Carlo simulations vs Real data

**Real Data**
- Sub-millimeter resolution
- (0.7 mm FWHM)

Simulation
Simulation of the detector with optical photons

- Monte Carlo simulations vs Real data   WS_10mm

- Point1 (-1.4,0.8) mm
- Red lines (Real data)
  Black lines (simulation)

(in progress)
Conclusions and Future work

Conclusion

- Fully functioning of C.C./ SiPM detector
  - DOI estimation (in progress)
  - Sub-millimeter point-source spatial resolution

Future work

- Optimize simulation parameters
- Improve DOI estimation
- Development of a full ring prototype
¡¡Thank you for your attention!!