Charge Sharing on Monolithic CdZnTe Gamma Ray Detectors: A Simulation Study

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Context and outline

Factor degrading performances of monolithic CdZnTe detectors (tailing)

- Interaction depth dependence of induced signal
  Affecting energy resolution
- **Charge sharing** between adjacent pixels
  Affecting energy resolution or efficiency

CdTe / CdZnTe Gamma Ray pixelated detectors

- Typical energy 122 keV (\(^{57}\)Co medical energy)
- Typical **pitch** 2.5 mm (between 0.2 to 3 mm)
- Typical thickness 5 mm

Outline

- **Ulysse** : 3D simulator of CZT gamma ray spectrometrer
- \(\gamma\) ray matter interaction → size of the the **deposited cloud**
- Physic phenomena in **detectors** → measured charge sharing
- First **comparison with experimentation**
Signal processing module developed in Fortran and integrated in Ulysse:
(with FemLab® software)

Monte Carlo interaction simulation

- \( \gamma \) or X emission
- Interaction: position and energy deposition
- Electrons/holes creation
- Electrons/holes migration
- Charge induction simulation
- Transient induced charge \( Q(t) \)
- Filtering and electronic noise modeling
- Pulse time and rise time computing
- Electronic simulation

3D Grid

- Mapping of the charge Biparametric spectrum
- Induced Charge
- Electronic filtering
- Noise

At 122 keV
- **Photoelectric**: 82%
  - Non radiative (Auger electrons)
  - Radiative X: Te 27 - 31 keV; Cd 23 - 26 keV; Zn 8 - 10 keV
- **Compton scattering**: 11%
- **Rayleigh scattering**: 7%

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### Nb secondary photon

<table>
<thead>
<tr>
<th>Nb secondary photon</th>
<th>Ratio</th>
<th>Mean distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Auger)</td>
<td>25 %</td>
<td>0 µm</td>
</tr>
<tr>
<td>1 fluorescence</td>
<td>45 %</td>
<td>75 µm</td>
</tr>
<tr>
<td>2 fluorescence</td>
<td>25 %</td>
<td>111 µm</td>
</tr>
<tr>
<td>&gt; 2 fluorescences</td>
<td>5 %</td>
<td>118 µm</td>
</tr>
</tbody>
</table>

**Mean distance X photons**: 75 %, 90 µm
**Mean distance (all)**: 100 %, 67 µm
Electron cloud size at its creation

Monte Carlo simulation

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Photoelectrons mean distance: 10 µm

\( \gamma \) photon (122 keV)

Distribution of events in function of size (photoelectric effect)

Ratio of events which size is inferior to the distance in abscise

For photoelectric effect
- 50% of events: size inferior to 36 µm
- 80% of events: size inferior to 120 µm
- 90% of events: size inferior to 190 µm

Monte Carlo simulation:
1. Interaction
2. Interaction + induction
3. Comparison with experimentation
Monte Carlo study: the deposit cloud

Monte Carlo simulation

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

pixel 1 pixel 2

E photon = 122 keV
Threshold = 15 keV
Perfect electric field or jointed anode

The distance to which charge sharing occurred is 500 µm.
Charge sharing is important for 80 µm (FWHM).
Results Generalization …

• for other photon energy:
  - cross section ratio depends on energy: photoelectric ratio: 140keV 78%; 122keV 83%; 60keV 95%
  - X fluorescence occurred until 32 keV (Kedge)

• for other threshold:
  - low effect as long as threshold < Kedge

• for other pitch (irradiation on the full detector surface):
  - shared events ratio increases up to 75% (Auger)
  - then reach a plateau until 10 µm (photoelectron)

2.5 mm pitch, 122 keV: 5.3% of events are shared, (60 keV: 3% of events are shared)
Electron cloud diffusion in the detector

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

(planar projection) \[ \sigma_D = \sqrt{\frac{4DL^2}{\mu V}} \]

\[ D_{CdTe} = 0.0026 \, \text{m}^2/\text{s} \]
\[ \mu = 0.1 \, \text{m}^2/\text{V/S} \]
\[ L = 5 \, \text{mm} \]
\[ V = 400 \, \text{V} \]

Fluorescence: some photons
\ne \neq \neq\neq \neq Diffusion: all electrons clouds

\[ \sigma = 190 \, \mu\text{m} \, \text{FWHM} \, (80 \, \mu\text{m} \, \text{rms}) \]

Nuclear medicine: \( E = 140 \, \text{keV} \), CdTe thickness = 5 mm, \( V = 300 - 1000 \, \text{V} \) \( \Rightarrow \sigma_D = 120 - 220 \, \mu\text{m} \, \text{FWHM} \)
Simulation of the detector: CIE computation

Computation of the Induced Charge on each electrode

- **Applied potential charge transport**
  \[ \nabla \sigma \nabla \varphi = 0 \]

- **Weighting potential charge induction**
  \[ \nabla \varepsilon \nabla \psi = 0 \]

**Charge Induction Efficiency**

Ratio measured charge on deposited charge

\[ CIE = \frac{Q}{Q_0} = \int_t \int_\Omega \int_\Omega q \mu_n n \nabla \varphi \nabla \psi \ d\Omega \ dt \]

The CIE map contains the whole information to model the detector (i.e. signals induced by an interaction in any point in the detector)

- **Detector simulation**
- **Bias 400 V**
- **Electron life time 3 µs**
- **Electron mobility 1000 cm²/V/s**
- **τ** 1 - 5 µs electron lifetime
- **σ** $10^{-9}$ Ω⁻¹ cm⁻¹ conductivity
- **ε_r** 11 permittivity
- **µ_n** 0.1 m² V⁻¹ s⁻¹ electron mobility
- **G** cm⁻³ s⁻¹ electron generation

approximations: conductivity and trapping are homogeneous in the bulk
The Charge Induction Efficiency

Detector simulation

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Comparaison between FemLab and Flux Expert computation

CIE decrease from maximum to negative value is not abrupt
Distance => 500 µm due to diffusion

Independent on numerical parameters

Electron cloud (190 µm FWHM due to diffusion)
Induction mechanism and electron cloud diffusion

Monte Carlo + Detector

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

• counts on pixel 1
• counts on pixel 2
• counts shared

According to Interaction position

Bias 400 V
Electron life time 3 µs
Electron mobility 1000 cm²/V/s

E photon = 122 keV
Threshold = 15 keV

Monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

Charge sharing: 210 µm FWHM
Recall: diffusion = 190 µm FWHM

Diffusion enlarge charge sharing area from 80 µm to 210 µm FWHM
Monte Carlo and detector study

Ratio of shared events according to deposited position

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Monté Carlo + Detector

Pixel 1
Pixel 2

Bias 400 V
Electron life time 3 µs
Electron mobility 1000 cm²/V/s

E photon = 122 keV
Threshold = 15 keV

Monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

In this situation, the main effect on charge sharing is electron cloud diffusion
Monte Carlo study: the deposit cloud

Ratio of shared events according to deposited position

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Pixel 1
Pixel 2

Monte Carlo simulation

E photon = 122 keV
Threshold = 15 keV
Monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

The charge sharing distance occurred in 500 µm.
Charge sharing is important for 80 µm (FWHM).
Results Generalization

- **for other detector geometry:**
  - gap: no effect on charge sharing (if it is insulating)
  - thickness and bias: little effect on diffusion
  - pitch and thickness $\rightarrow$ pixel effect

- **for other pitch** (irradiation on the full detector surface):
  - charge sharing increases drastically for pitch < 1 mm

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

![Graph showing the ratio of events shared vs. pitch.](image)

- 2.5 mm pitch
  - 122 keV: 13% of event measured as shared (deposit 5.2%)
  - 60 keV: 8% of events are shared (deposit 3%)
Simulation with a 500 µm collimator

Monté Carlo +
Detector +
collimator

1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Bias 400 V
Electron life time 3 µs
Electron mobility 1000 cm²/V/s

E photon = 122 keV
Threshold = 15 keV

Monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

Collimator Pb 500 µm

Charge sharing FWHM: 570 µm to compare to 210 µm with a straight source
Collimator width will hide other effects
Experimentation with a 500 µm collimator

HPBM CZT monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch
Bias 400 V
E photon = 122 keV
Threshold = 15 keV
Collimator Pb 500 µm

On the full area 10 % of events are shared
Recall: in simulation 13 % of event measured as shared
**Conclusion**

**Monte Carlo Study only: the deposit cloud**

- **Gamma ray – matter interaction**
  - Photoelectric effect: 82%:
    - Mean distance of fluorescence (75%) \(90 \, \mu m\)
    - Mean distance (all) \(67 \, \mu m\)
  - Photoelectron range \(10 \, \mu m\)

- **Fluorescence**
  - For photoelectric effect considering photoelectron range:
    - 50% of events: size inferior to 36 \(\mu m\)
    - 80% of events: size inferior to 120 \(\mu m\)
    - 90% of events: size inferior to 190 \(\mu m\)
  - For all events, charge sharing FWHM \(80 \, \mu m\) (→ 500 \(\mu m\))

- **Pixilated detector**
  - For a 2.5 mm pitch detector
    - At 122 keV: 5.3% of events are shared
    - At 60 keV: 3% of events are shared

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**Monte Carlo + Induction in the Detector**

- Diffusion enlarge charge sharing to \(210 \, \mu m\) FWHM

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- **Pixilated detector**
  - For a 2.5 mm pitch detector
    - At 122 keV: 13% of event as shared (10% experimentally)
    - At 60 keV: 8% of events are shared

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**Notes**

- \(E_{\text{photon}} = 122\,\text{keV}\)
- Threshold = 15\,\text{keV}
- Monolithic detector thickness 5 mm
- Pixel 2 x 2 mm, 2.5 mm pitch
- Bias 400 V
- Electron life time 3 \(\mu s\)
- Mobility 1000 \(\text{cm}^2/\text{V}/\text{s}\)
thank you for your attention
Diffusion, thickness and bias

Diffusion is independent of thickness and bias because bias is chosen to collect charge (mean free path >> thickness).
But bias must not be too high to limit noise.

\[ \sigma_D = \sqrt{\frac{4DL^2}{\mu V}} \]

Mean free path >> thickness

\[ \frac{\mu \tau V}{L} \gg L \rightarrow \frac{\mu \tau V}{L} \approx \alpha L \rightarrow V \approx \alpha L^2 / \mu \tau \]

Diffusion

\[ \sigma_D^2 = 4D \tau / \alpha \]
At 122 keV

MVB CZT monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

Bias 700 V

E photon = 122 keV
Threshold = 15 keV

Collimator Pb 500 µm / 3 mm

Counts

Energy (#)

0.5 mm R = 1.90 %
3 mm R = 1.90 %

0.5 mm R = 1.35 %
Pulser R = 1.35 %

3 mm collimator R = 3% ± 0.7 %
0.5 mm collimator R = 2.46% ± 0.64 %
Treatments

Scatter plot pixel 1 versus pixel 2

Distinction between charge sharing and charge loss

Bad measured
Pulse height

Maximal depth line

Iso-energy line
Good measured pulse height

Cathode Amplitude

Anodes Sum