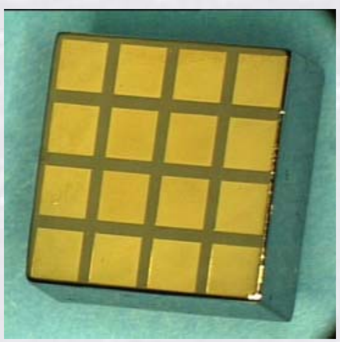
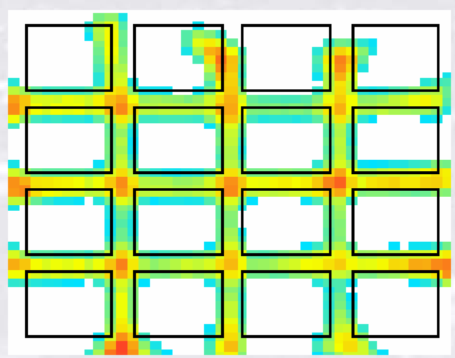
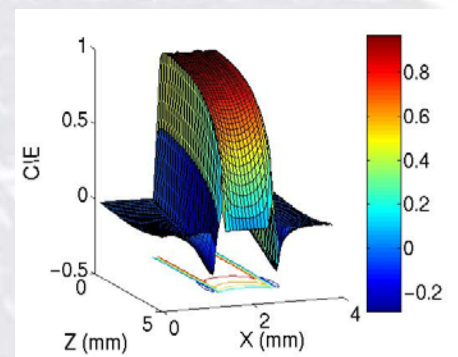
Charge Sharing on Monolithic CdZnTe Gamma Ray Detectors: A Simulation Study







E. Gros d’Aillon, L. Verger, J. Tabary, A. Glière

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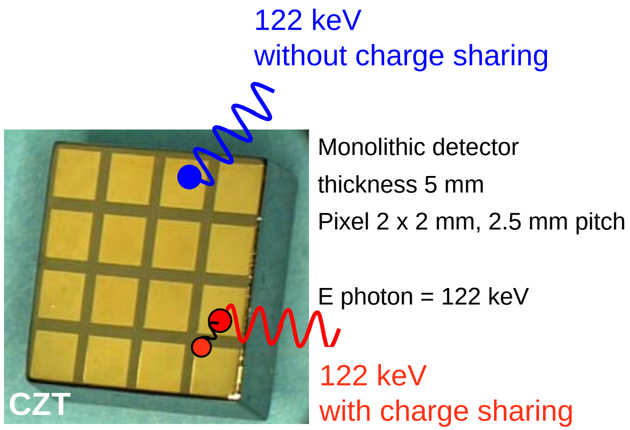
Context and outline

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

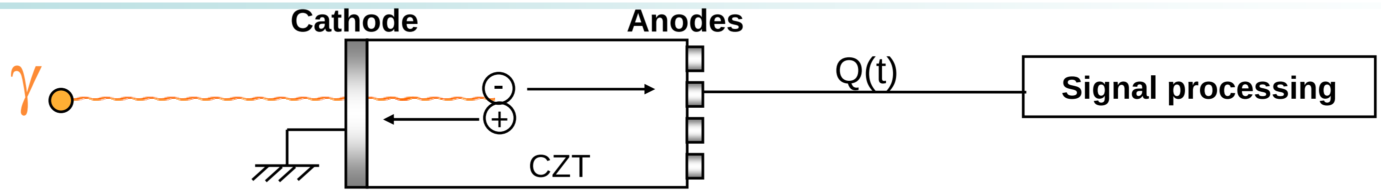
- Typical energy 122 keV (^{57}Co medical energy)
- Typical **pitch** 2.5 mm (between 0.2 to 3 mm)
- Typical thickness 5 mm



Outline

- Ulysse : 3D simulator of CZT gamma ray spectrometer
- γ ray matter interaction → size of the the **deposited cloud**
- Physic phenomena in **detectors** → measured charge sharing
- First **comparison with experimentation**

Ulysse



γ or X emission → Interaction : position and energy deposition

Electrons/holes creation

Electrons/holes migration

Monte Carlo interaction simulation

Charge induction simulation

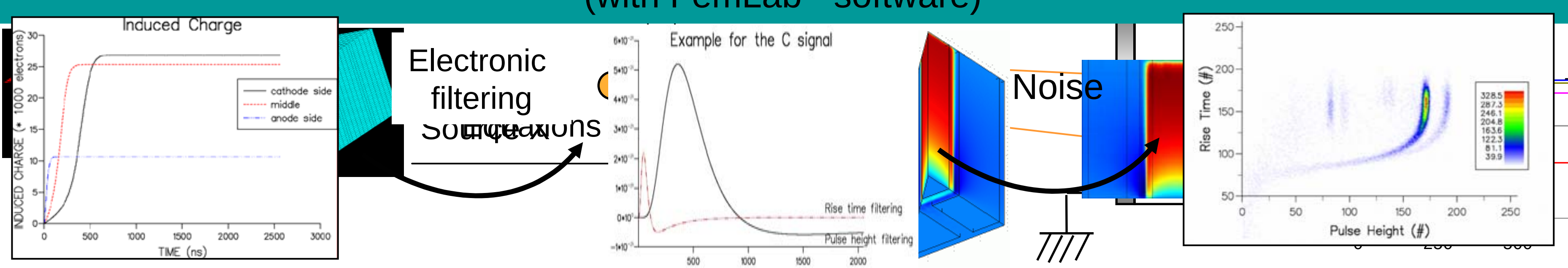
Transient induced charge Q(t)

Filtering and electronic noise modeling

Pulse time and rise time computing

Electronic simulation

Signal processing module developed in Fortran and integrated in Ulysse :
(with FemLab® software)



3D Grid

mapping of the charge

Biparametric spectrum

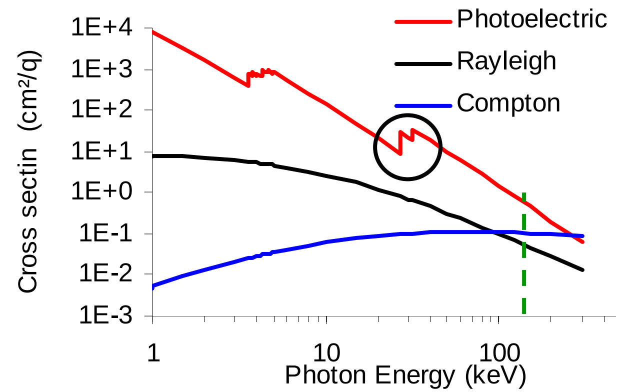
J. Sempau, E. Acosta, J. Baro, J.M. Fernandez-Varea and F.Salvat, "An algorithm for Monte Carlo simulation of the coupled electron-photon transport", NIM. B, 132, 377, 1997

F. Mathy, A. Glière, E. Gros d'Aillon, P. Masse, M. Picone, J. Tabary, L. Verger, "A three-dimensional model of CdZnTe gamma-ray spectrometer and its experimental validation", IEEE TNS, 51, 5, 2004

γ ray matter interactions

At 122 keV

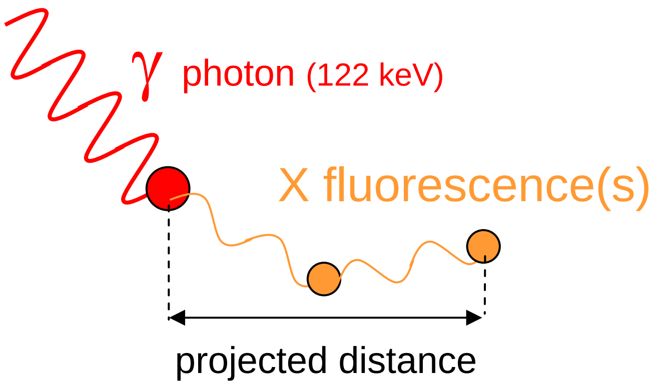
- Photoelectric : 82 %
    - Non radiative (Auger electrons)
    - Radiative X : Te 27 - 31 keV ; Cd 23 - 26 keV
      Zn 8 - 10 keV
- Compton scattering : 11%
- Rayleigh scattering : 7%



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

Nb secondary photon	Ratio	Mean distance
0 (Auger)	25 %	0 µm
1 fluorescence	45 %	75 µm
2 fluorescences	25 %	111 µm
> 2 fluorescences	5 %	118 µm
Mean distance X photons	75 %	**90 µm**
Mean distance (all)	100 %	**67 µm**

Monte Carlo simulation : PENELOPE

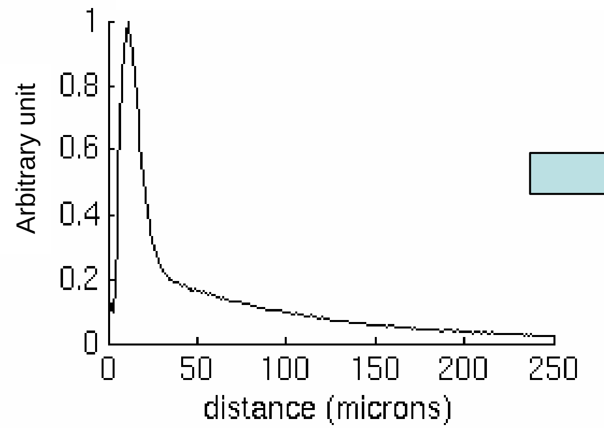


Electron cloud size at its creation

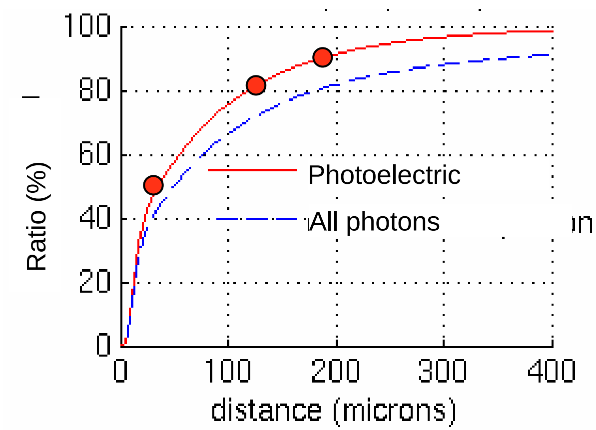
Monte Carlo simulation

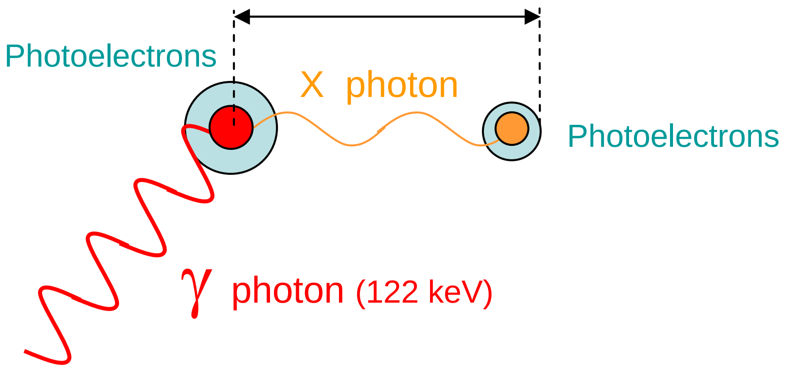
1. Interaction
2. Interaction + induction
3. Comparison with experimentation

Distribution of events in function of size (photoelectric effect)



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





photoelectrons mean distance : 10 µm

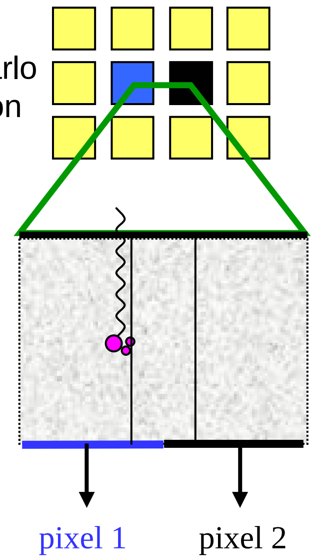
For photoelectric effect

50 % of events : size inferior to **36 µm**

80 % of events : size inferior to **120 µm**

90 % of events : size inferior to **190 µm**

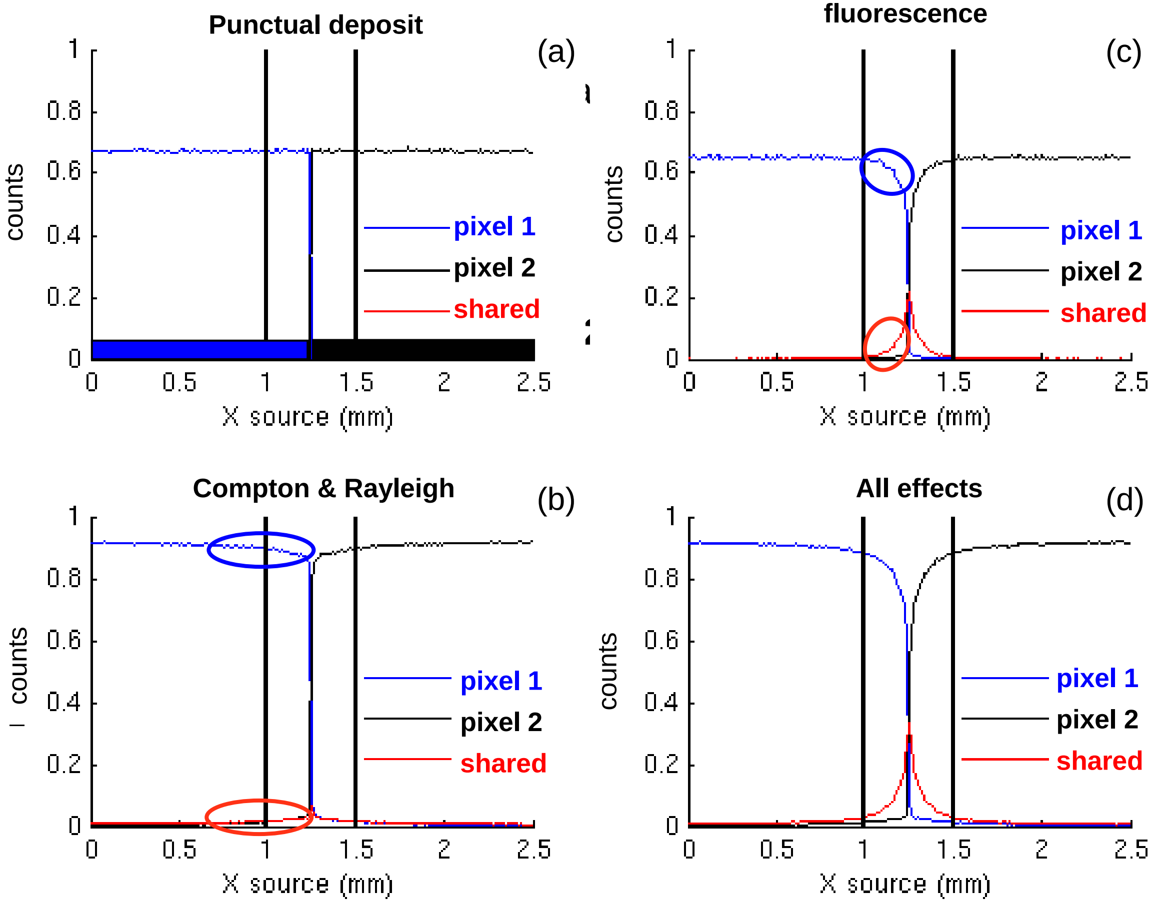
Monte Carlo study: the deposit cloud



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

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

Ratio of shared events according to deposited position

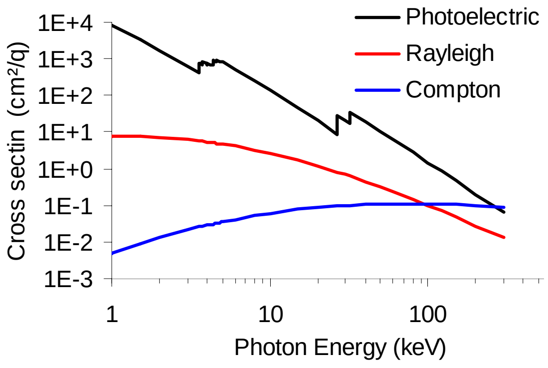


The distance to which charge sharing occurred is **500 µm**.

Charge sharing is important for **80 µm** (FWHM).

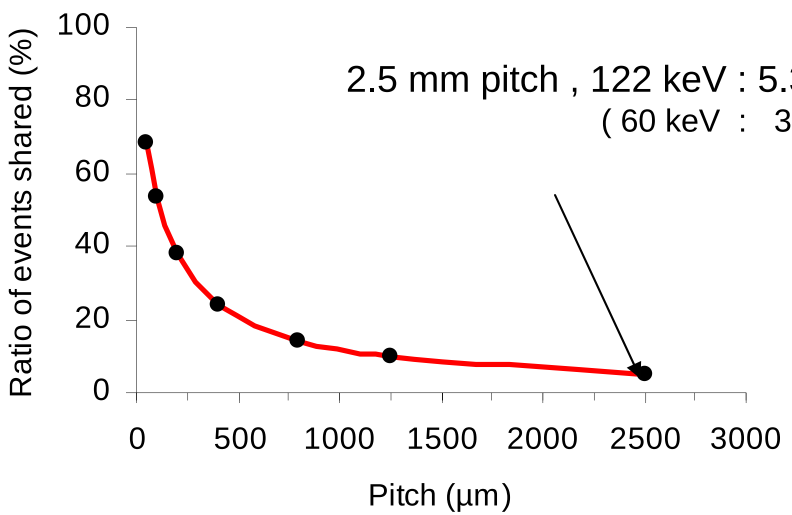
Results Generalization …

- **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)

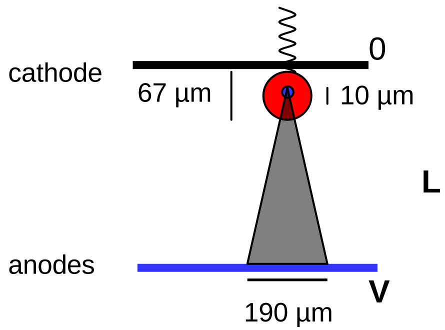


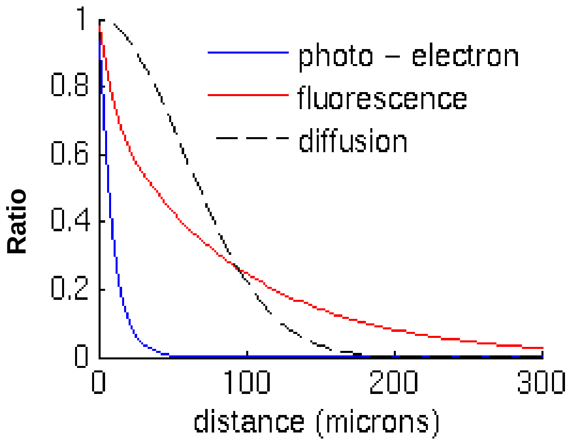
Electron cloud diffusion in the detector

1. Interaction

2. Interaction + induction

3. Comparison with experimentation





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

Fluorescence : some photons

≠ Diffusion : all electrons clouds

D_{CdTe} = 0.0026 m²/s	diffusion constant	$D = k_B T \mu / e$
µ = 0.1 m²/V/S	electron mobility	
L = 5 mm	detector **thickness**	
V = 400 V	applied **bias**	

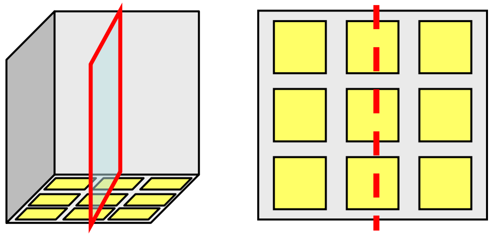
σ = 190 µm FWHM (80 µm rms)

Nuclear medicine : E= 140 keV , CdTe thickness = 5 mm, V = 300 – 1000 V ➔ σ_D= 120 – 220 µm FWHM

Simulation of the detector: CIE computation

Computation of the **Induced Charge** on each electrode

Detector simulation



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

τ	1 - 5 µs	electron lifetime
σ	$10^{-9}\ \Omega^{-1}cm^{-1}$	conductivity
ε_r	11	permittivity
μ_n	0.1 $m^2V^{-1}s^{-1}$	electron mobility
G	$cm^{-3}s^{-1}$	electron generation

approximations: conductivity and trapping are homogeneous in the bulk

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

Applied potential
charge transport

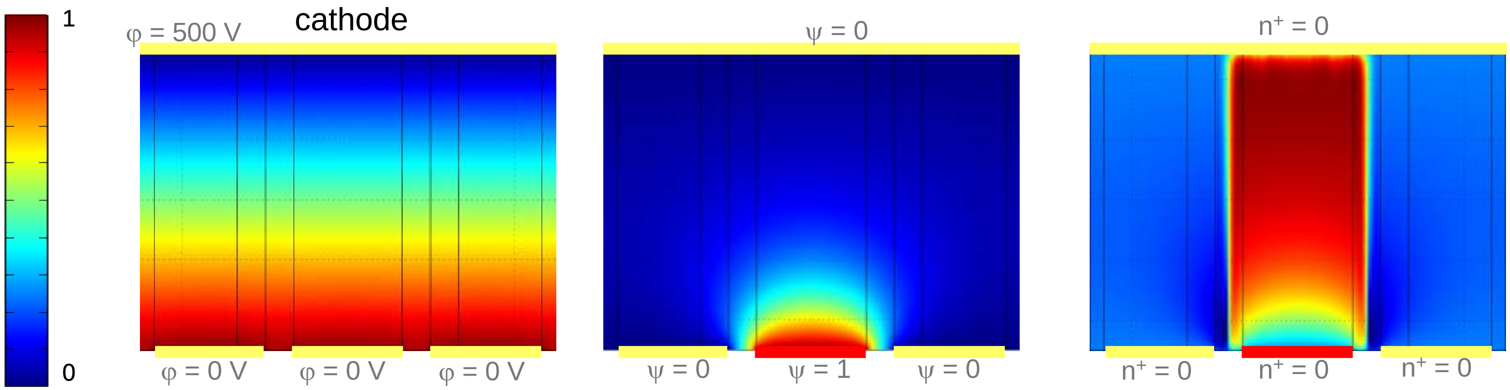
$$\vec{\nabla}\sigma\vec{\nabla}\varphi = 0$$

Weighting potential
charge induction

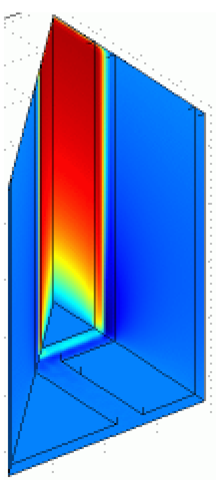
$$\vec{\nabla}\varepsilon\vec{\nabla}\psi = 0$$

Charge Induction Efficiency
Ratio measured charge on deposited charge

$$CIE = Q \big/ Q_0 = \int_t \left(\iiint_\Omega q\mu_n n\vec{\nabla}\varphi\,\vec{\nabla}\psi\, d\Omega \right) dt$$



anodes
studied anode
studied anode



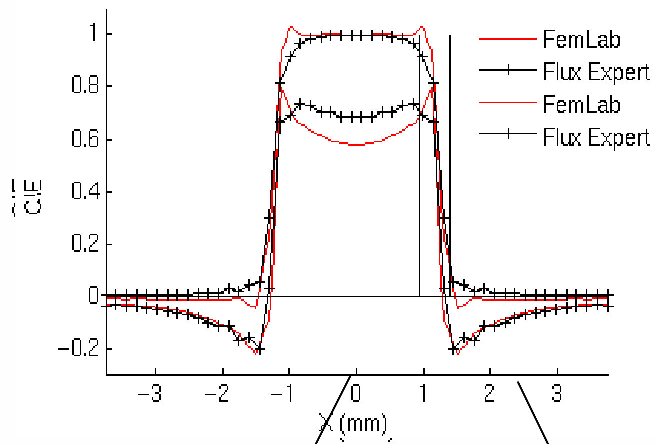
The CIE map contains the whole information to model the detector
(i.e. signals induced by an interaction in any point in the detector)

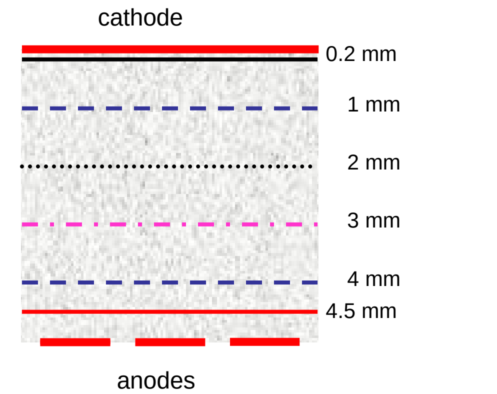
The Charge Induction Efficiency

Detector simulation

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

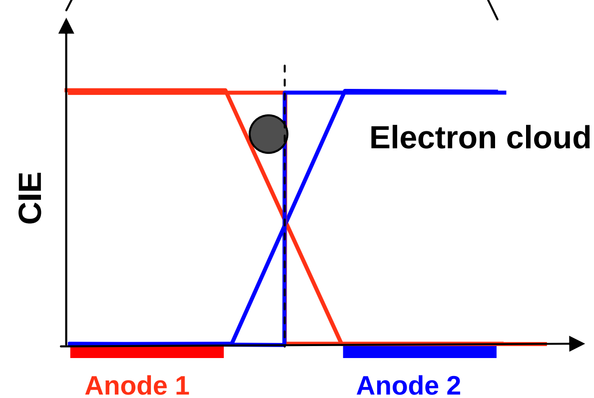
Comparaison between FemLab and Flux Expert computation





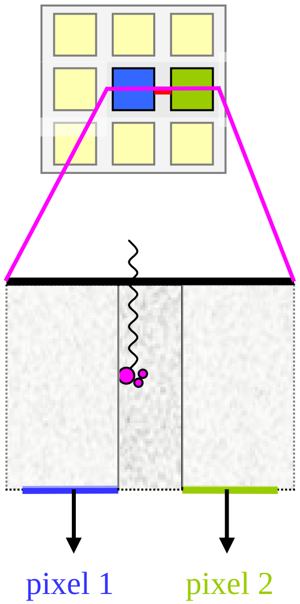
CIE decrease from maximum to negative value is not abrupt
Distance => 500 µm due to **diffusion**

Independent on numerical parameters



Induction mechanism and electron cloud diffusion

Monte Carlo
+
Detector

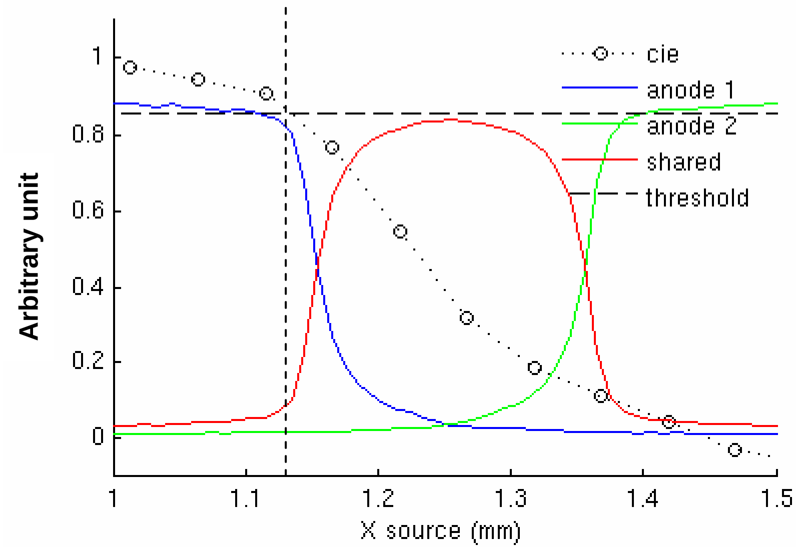


1. Interaction
2. Interaction + induction
3. Comparison with experimentation

- counts on pixel 1
- counts on pixel 2
- counts shared

According to Interaction position

Induced charge : Monte Carlo + detector



charge sharing : 210 µm FWHM
recall : diffusion = 190 µm FWHM

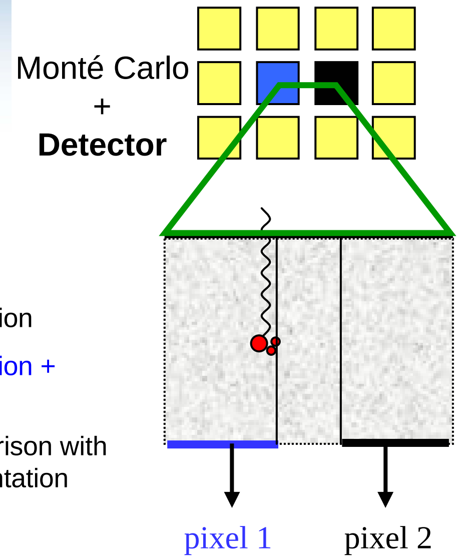
Bias 400 V
Electron life time 3 µs
Electron mobility 1000 cm²/V/s

E photon = 122 keV
Threshold = 15 keV

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

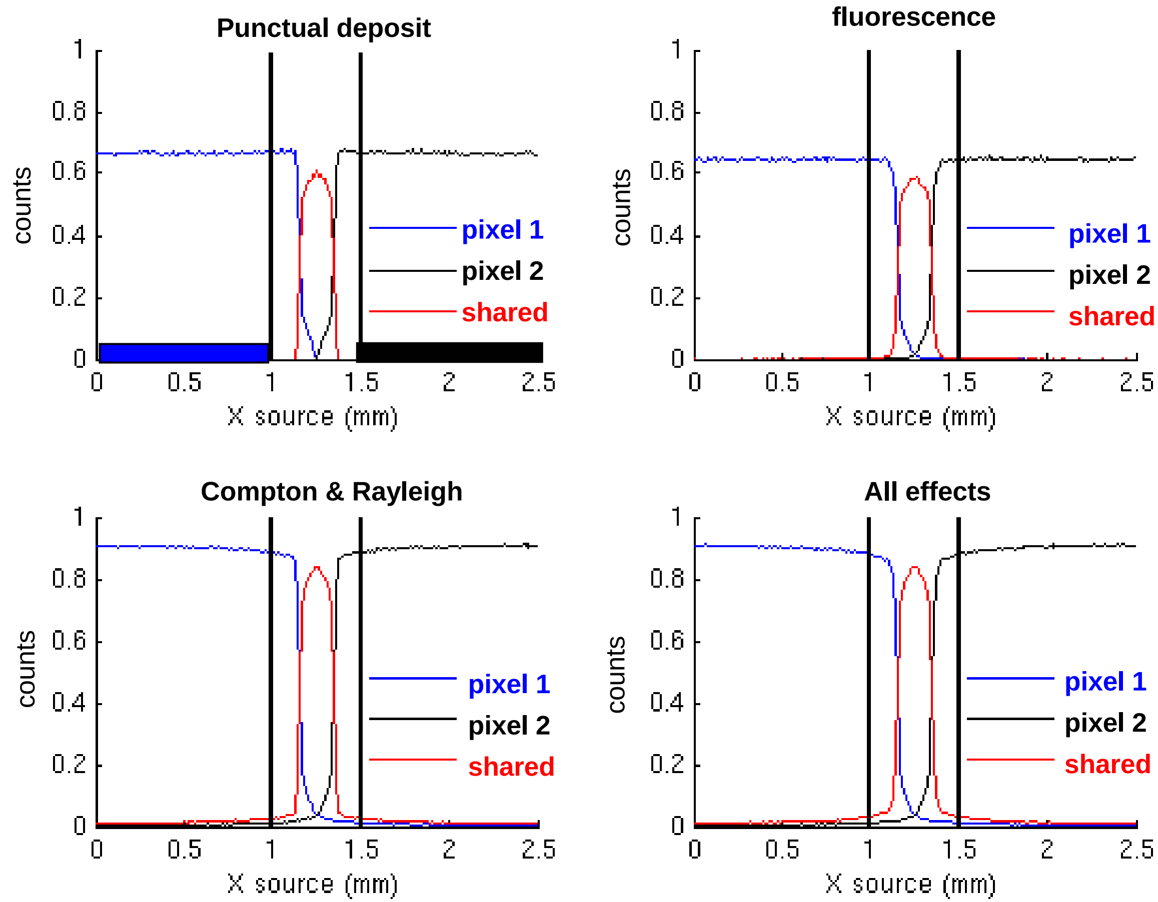
Diffusion enlarge charge sharing area from 80 µm to 210 µm FWHM

Monte Carlo and detector study



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

Ratio of shared events according to deposited position



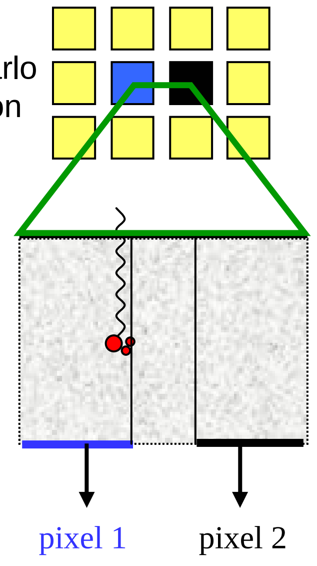
Bias 400 V
Electron life time 3 µs
Electron mobility 1000 cm²/V/s

E photon = 122 keV
Threshold = 15 keV

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

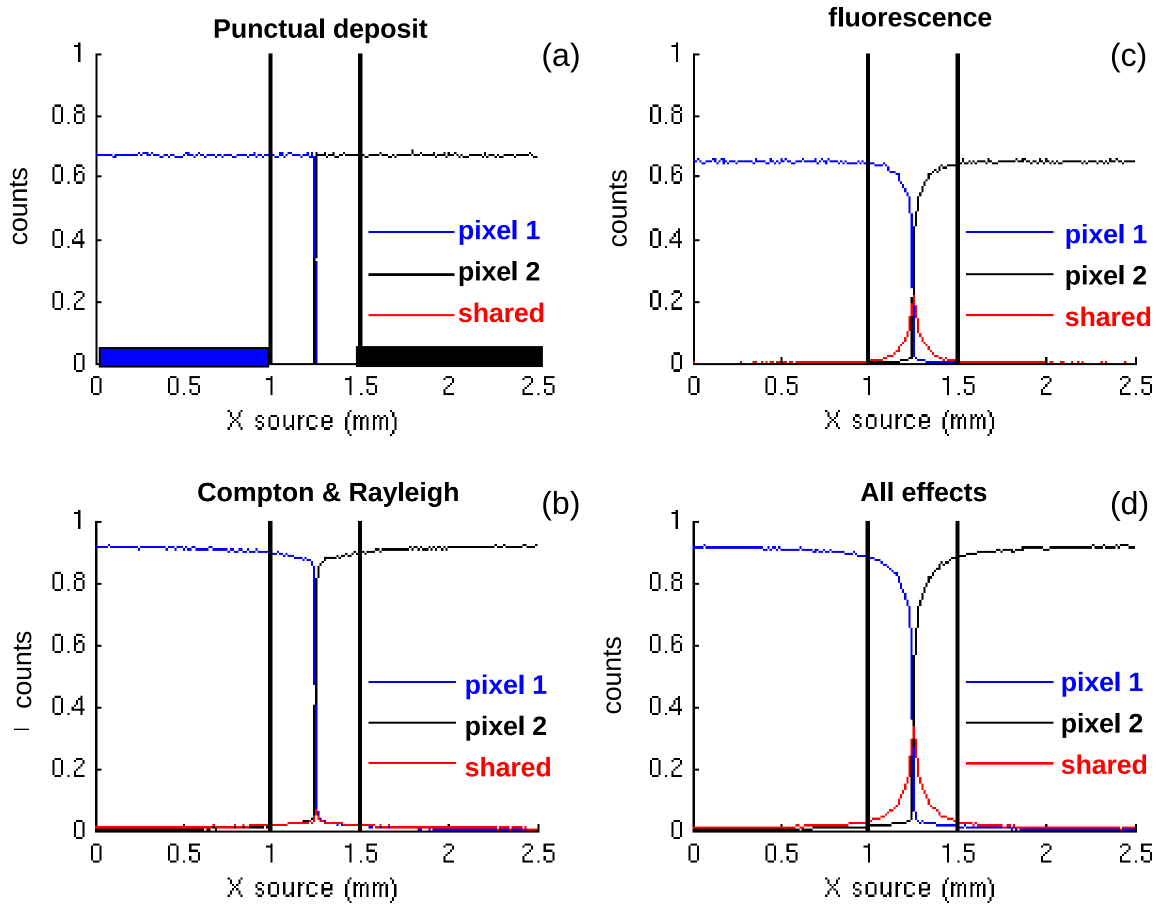
In this situation, the main effect on charge sharing is electron cloud **diffusion**

Monte Carlo study: the deposit cloud



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

Ratio of shared events according to deposited position



E photon = 122 keV
Threshold = 15 keV

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

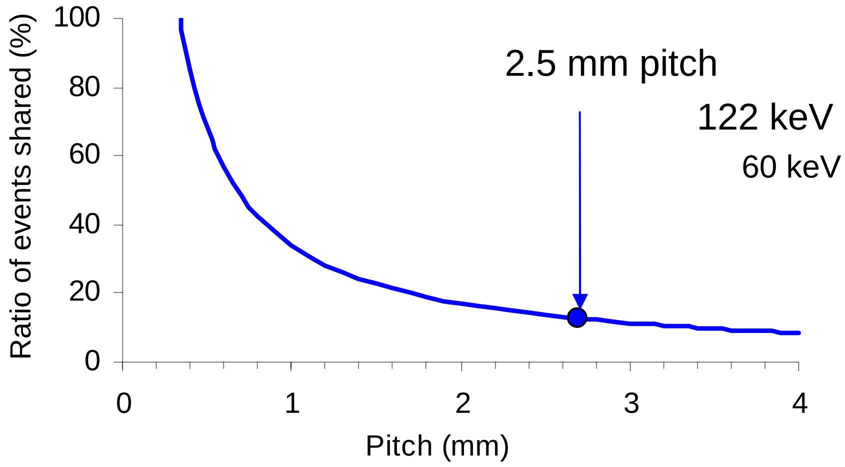
The charge sharing distance occurred in **500 µm**.

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 → pixel effect

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

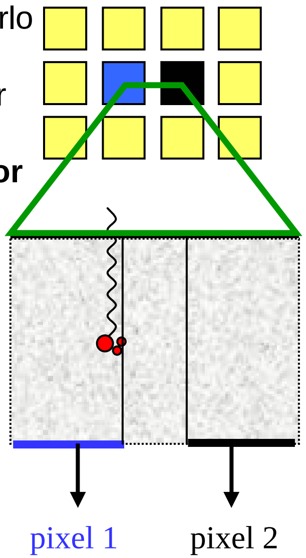


122 keV : 13 % of event measured as shared (deposit 5.2%)

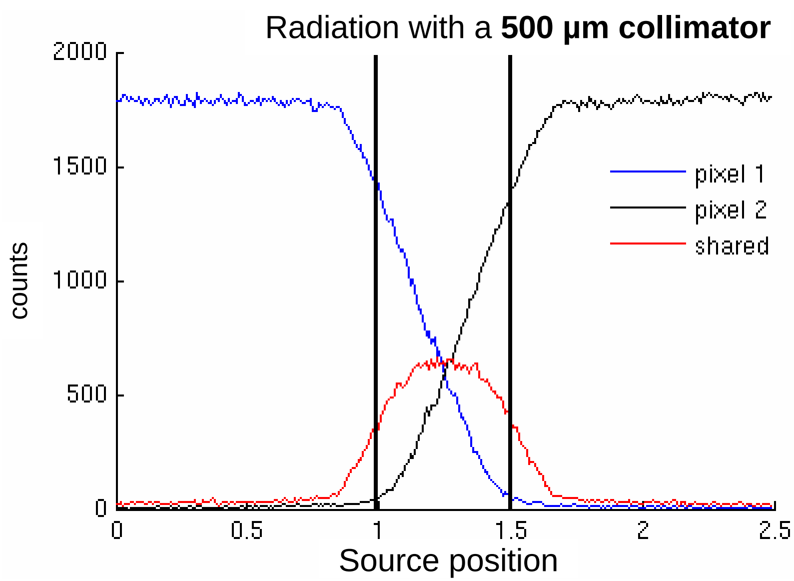
60 keV 8 % of events are shared (deposit 3%)

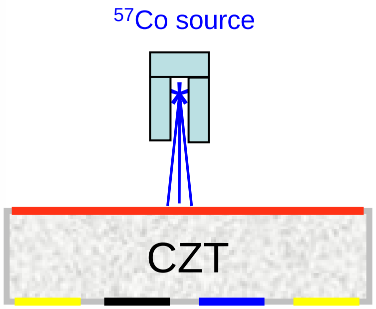
Simulation with a 500 µm collimator

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

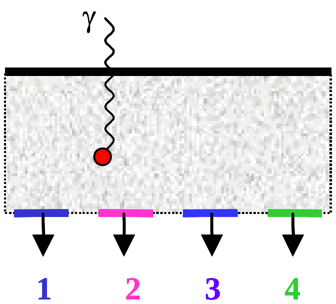
Monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

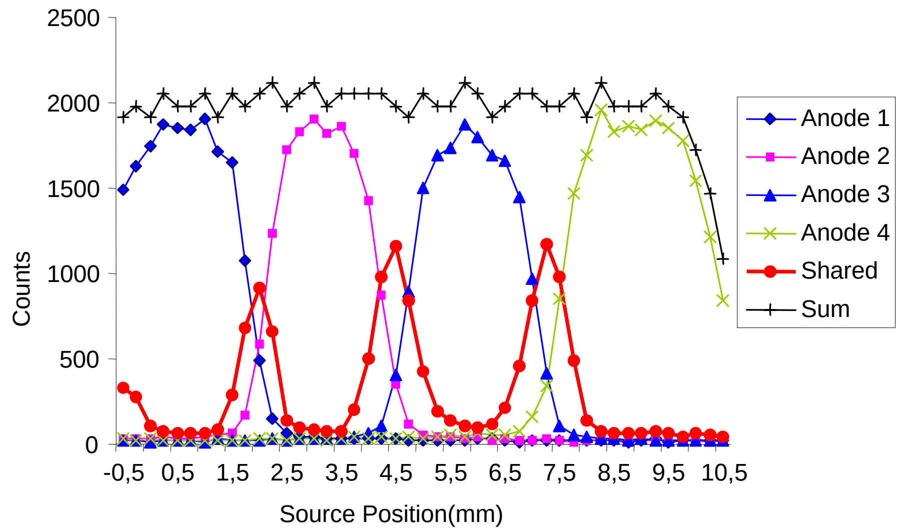
Collimator Pb 500 µm

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

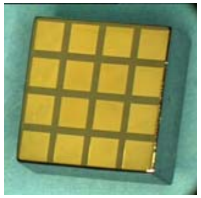




1. Interaction

2. Interaction + induction

3. Comparison with experimentation



Events sharing FWHM : 500 – 800 µm

Simulation : charge sharing FWHM = 570 µm

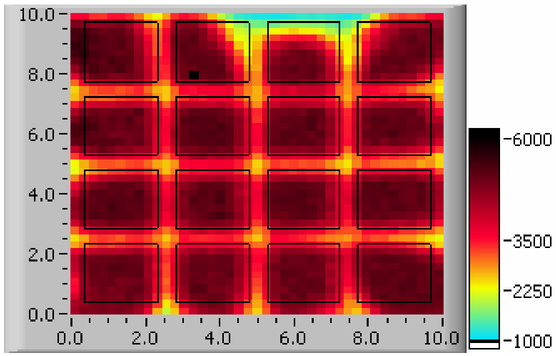
HPBM CZT monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

Bias 400 V

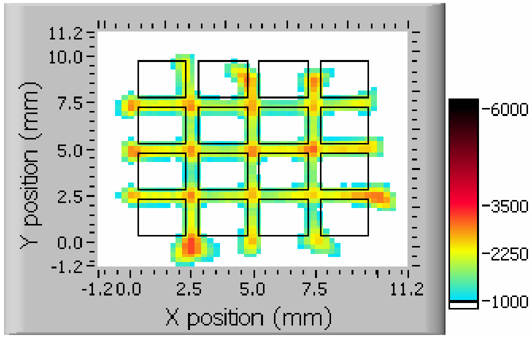
E photon = 122 keV
Threshold = 15 keV

Collimator Pb 500 µm

Events measured by one single anode



Events measured by more than one anode



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 µm**

Mean distance (all) **67 µm**

Photoelectron range **10 µm**

• Fluorescence

For photoelectric effect considering photoelectron range

50 % of events : size inferior to 36 µm

80 % of events : size inferior to 120 µm

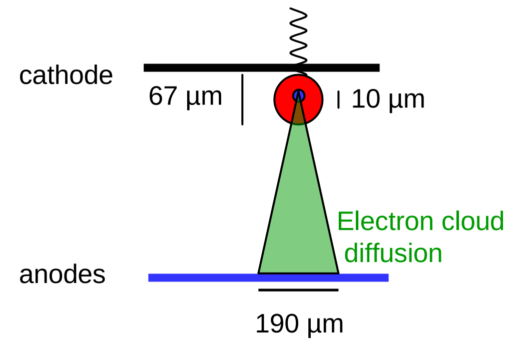
90 % of events : size inferior to 190 µm

For all events, **charge sharing** FWHM **80 µm** (→500 µm)

• 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



E photon = 122 keV
Threshold = 15 keV

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

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

Monte Carlo + Induction in the Detector

• Diffusion enlarge **charge sharing** to **210 µm** FWHM

• 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

thank you for your attention

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Diffusion, thickness and bias

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

Diffusion $\sigma_D = \sqrt{\dfrac{4DL^2}{\mu V}}$

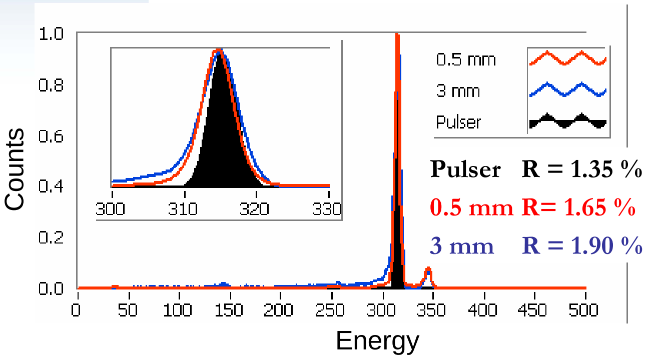
mean free path >> thickness $\mu\tau V / L >> L \Rightarrow \mu\tau V / L \approx \alpha L \Rightarrow V \approx \alpha L^2 / \mu\tau$

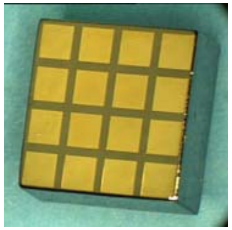
Diffusion

$$\sigma_D{}^2 = 4D\tau / \alpha$$

Spectroscopy

Good pixel





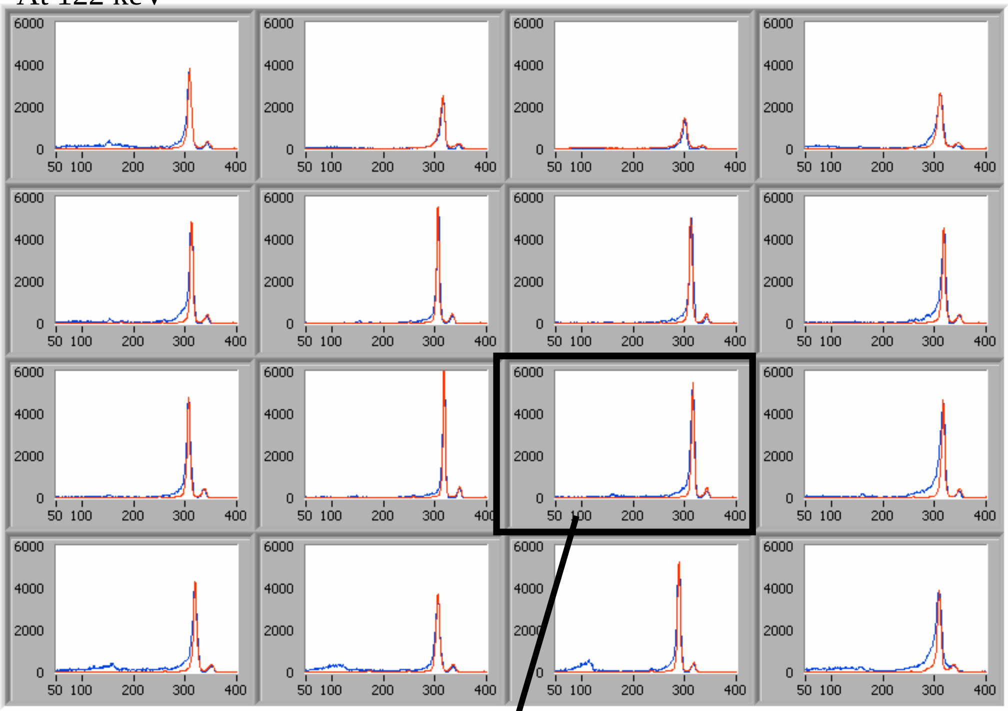
MVB CZT monolithic detector
thickness 5 mm
Pixel 2 x 2 mm, 2.5 mm pitch

Bias 700 V

E photon = 122 keV
Threshold = 15 keV

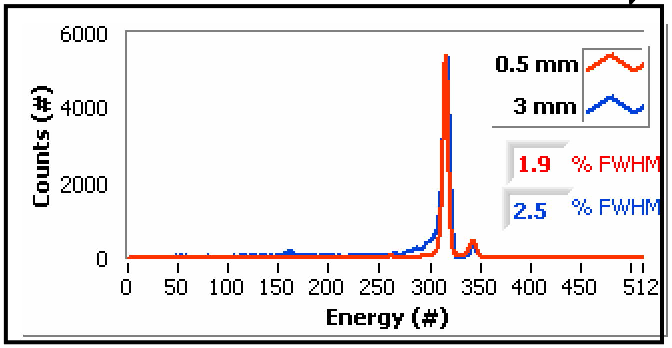
Collimator Pb 500 µm / 3mm

At 122 keV



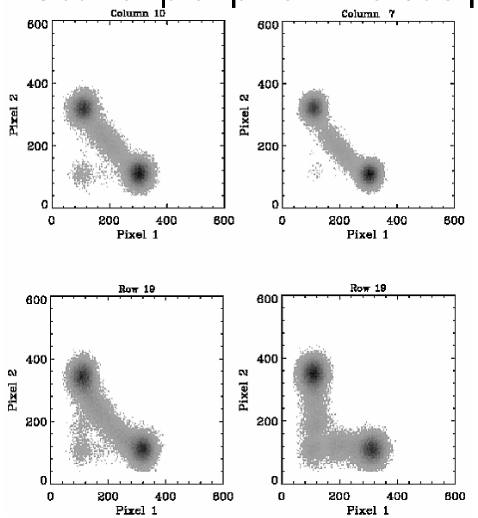
3 mm collimator R = 3% ± 0.7 %

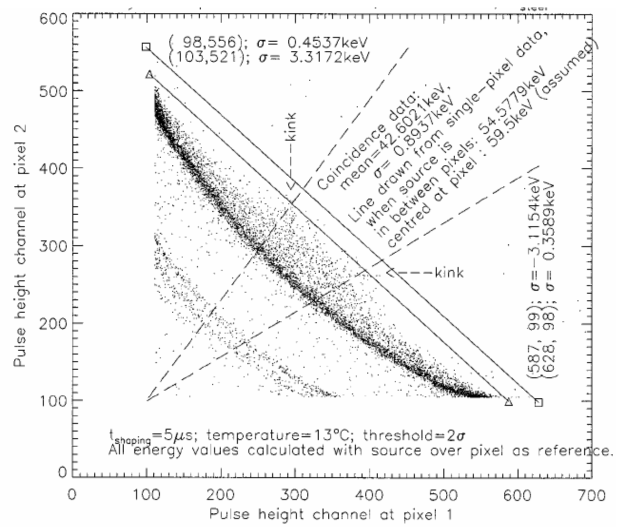
0.5 mm collimator R = 2.46% ± 0.64 %



Treatments

Scatter plot pixel 1 versus pixel 2





Distinction between charge sharing and charge loss