AG GDR, Mi2b

Marseille, le 29.06.2026

Comparison of the simulated response of hybrid pixel detector with synchrotron beam tests

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Outline

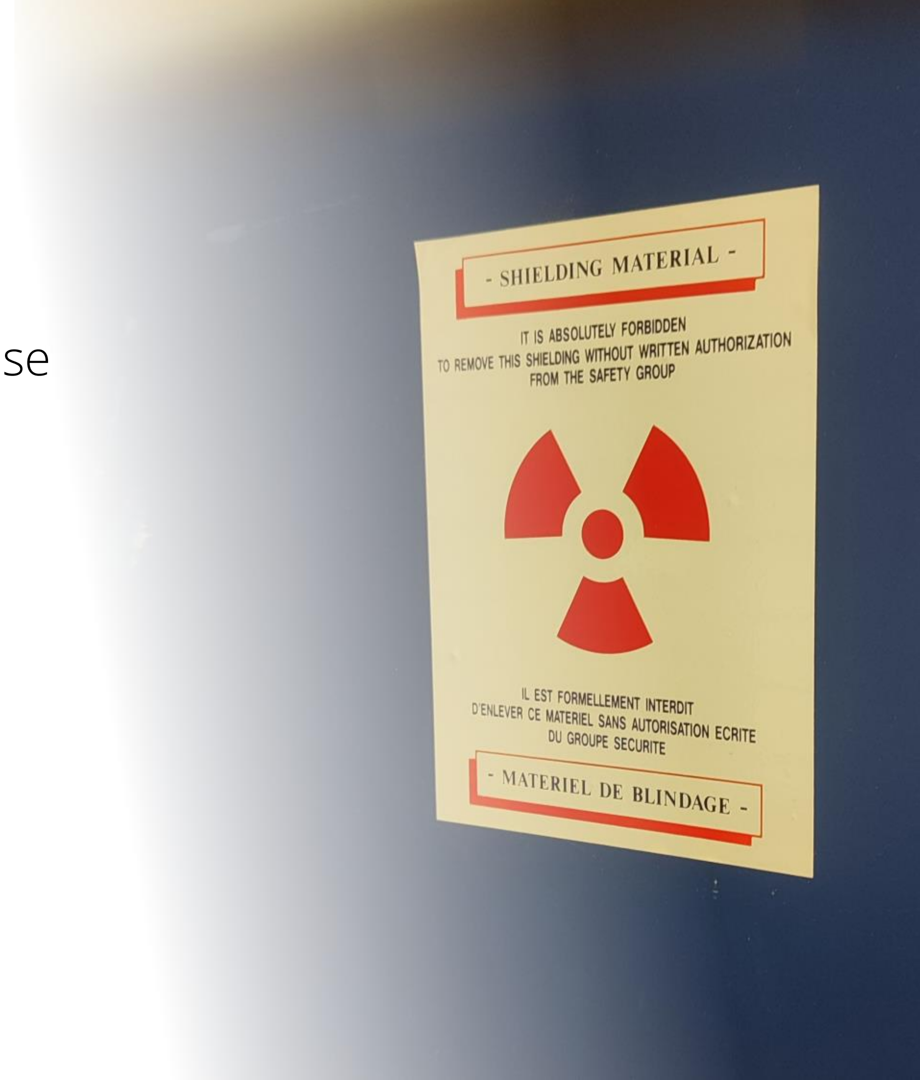
1 – Context and goals of the thesis

2 – Modelling hybrid pixel detectors response

3 – Simulation pipeline

4 – Validation cases

5 – Conclusion and prospect



1 - Context of the thesis

Global project in Detection Technology (DT) company:

→ Develop Photon Counting Detectors (PCD) and associated technology solutions
→ Build an X-ray chain simulator as an internal research and development tool for the company

Medical X-ray imaging
- Computed tomography
- Dental imaging
- Surgical imaging

Security X-ray imaging
- Baggage and parcel scan
- Cargo and vehicle scan
- People scan

Industrial X-ray imaging
- Food industry
- Recycling and sorting
- Mining industry

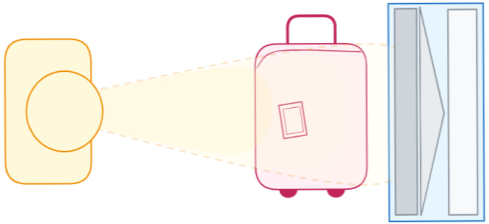
Thesis:

Simulation of hybrid pixel Photon Counting Spectral Detectors

→ **Detection Technology (DT)** leverage the simulation expertise of imXgam team **(CPPM)**

Motivation: why developing a simulation pipeline ?

→ Optimize detector design
→ Generate training datasets for Deep Learning methods
→ Develop correction algorithms
→ Enhance physical understanding of the detector response



2 – Modelling hybrid pixel detectors response

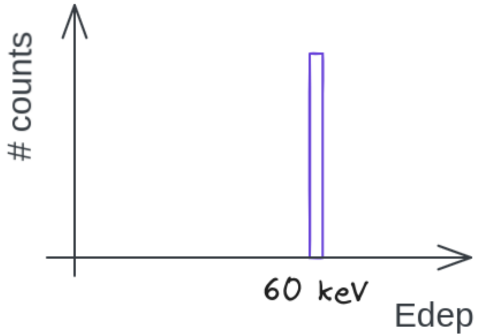
a. Ideal detector response

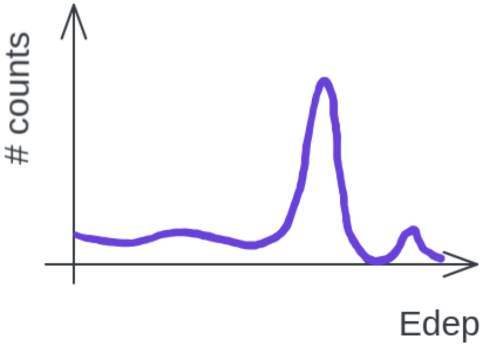
$$N_{charges} = \frac{E_{deposited}}{E_{e\text{-}/h}}$$

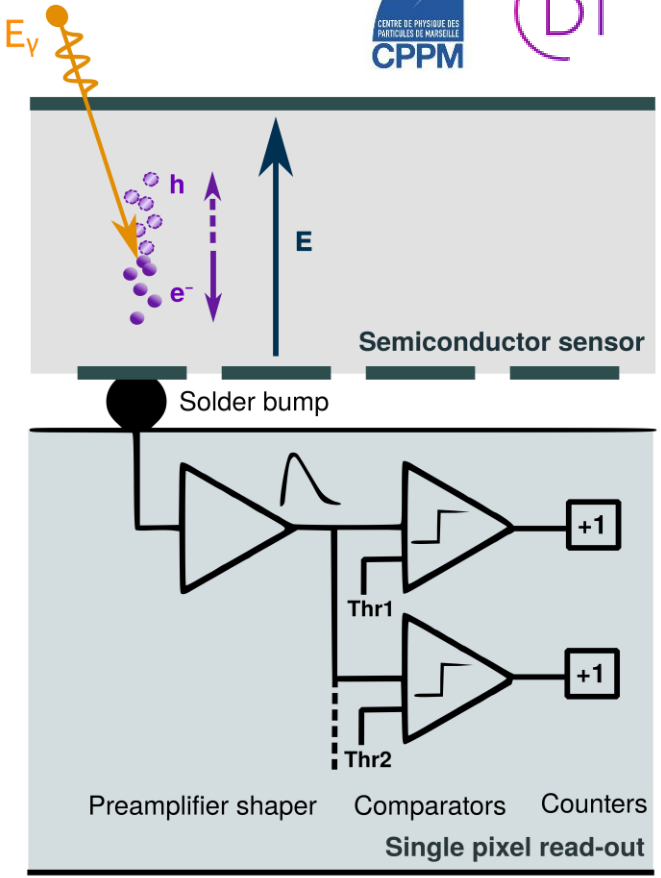
$N_{charges}$: Number of electron-hole pairs created
$E_{deposited}$: Energy deposited in the sensor
$E_{e/h}$: Electron-hole pair creation energy

Material		$E_{e/h}$
Cadmium Telluride	CdTe	4.43 eV
Cadmium-Zinc Telluride	CdZnTe	4.64 eV
Silicon	Si	3.64 eV
Germanium	Ge	2.97 eV
Gallium Arsenide	GaAs	4.2 eV

$$\boxed{\text{Signal} \propto E_\gamma}$$

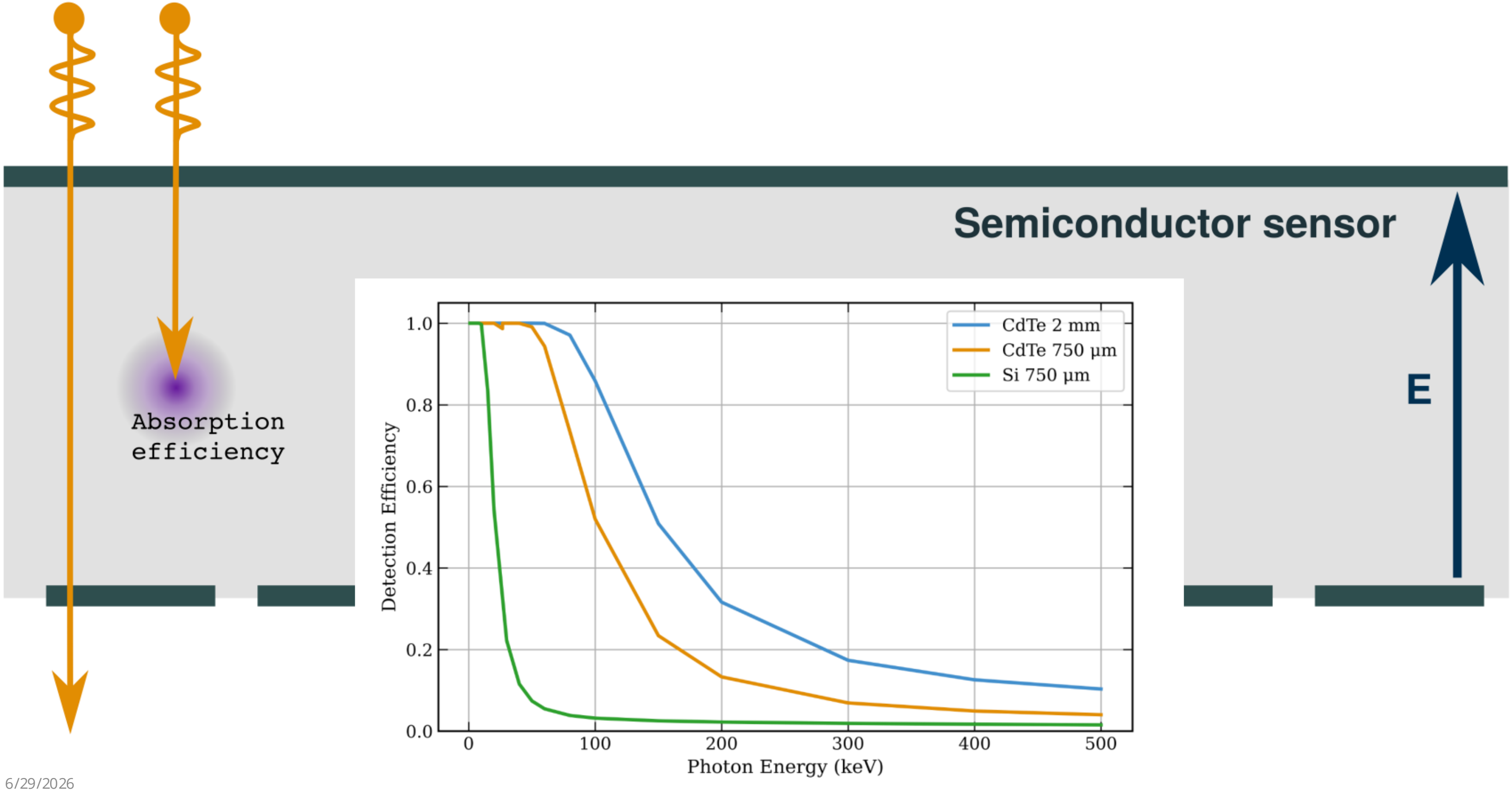






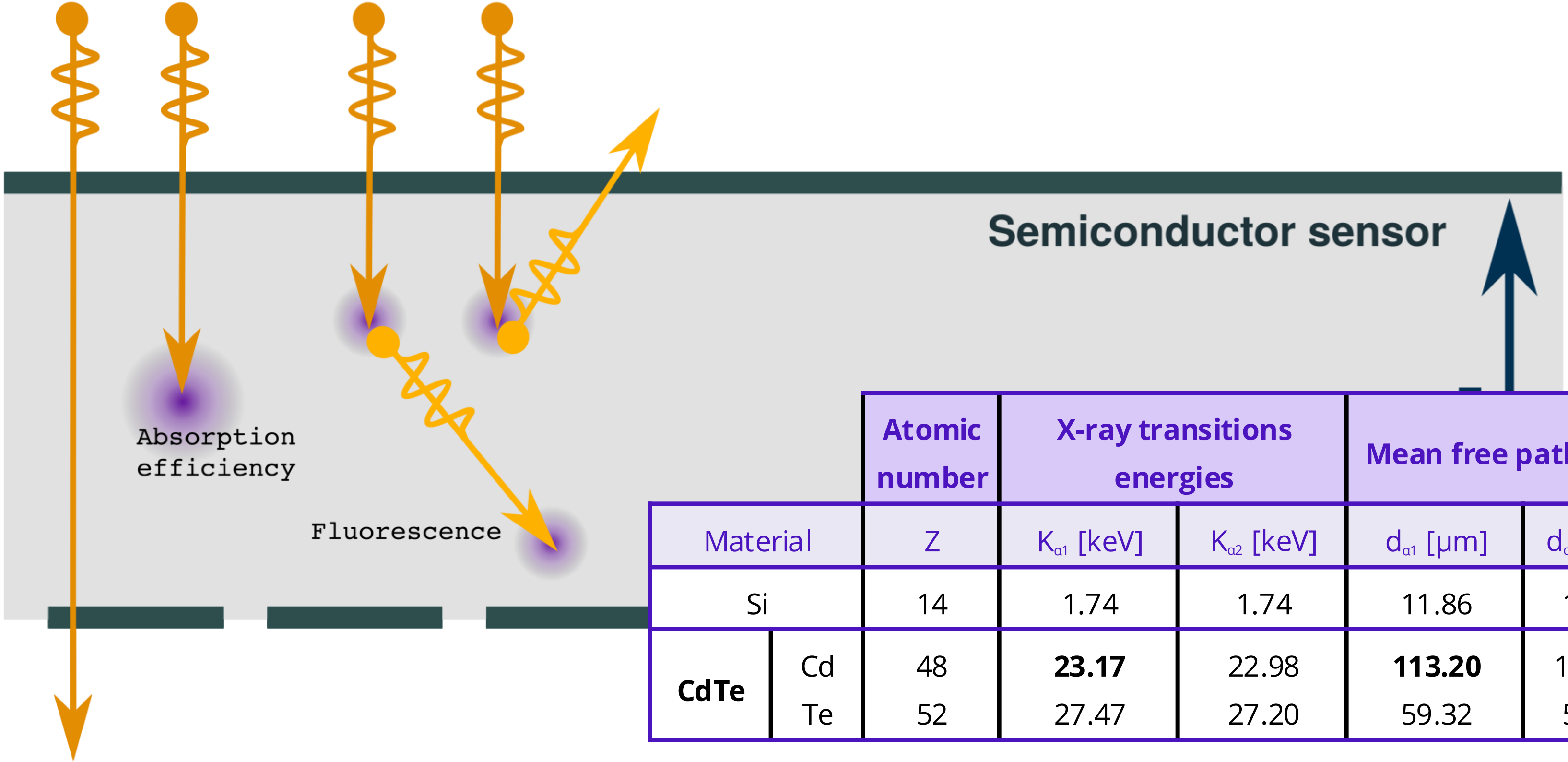
2 – Modelling hybrid pixel detectors response

b. Physical limitations of real detectors



2 – Modelling hybrid pixel detectors response

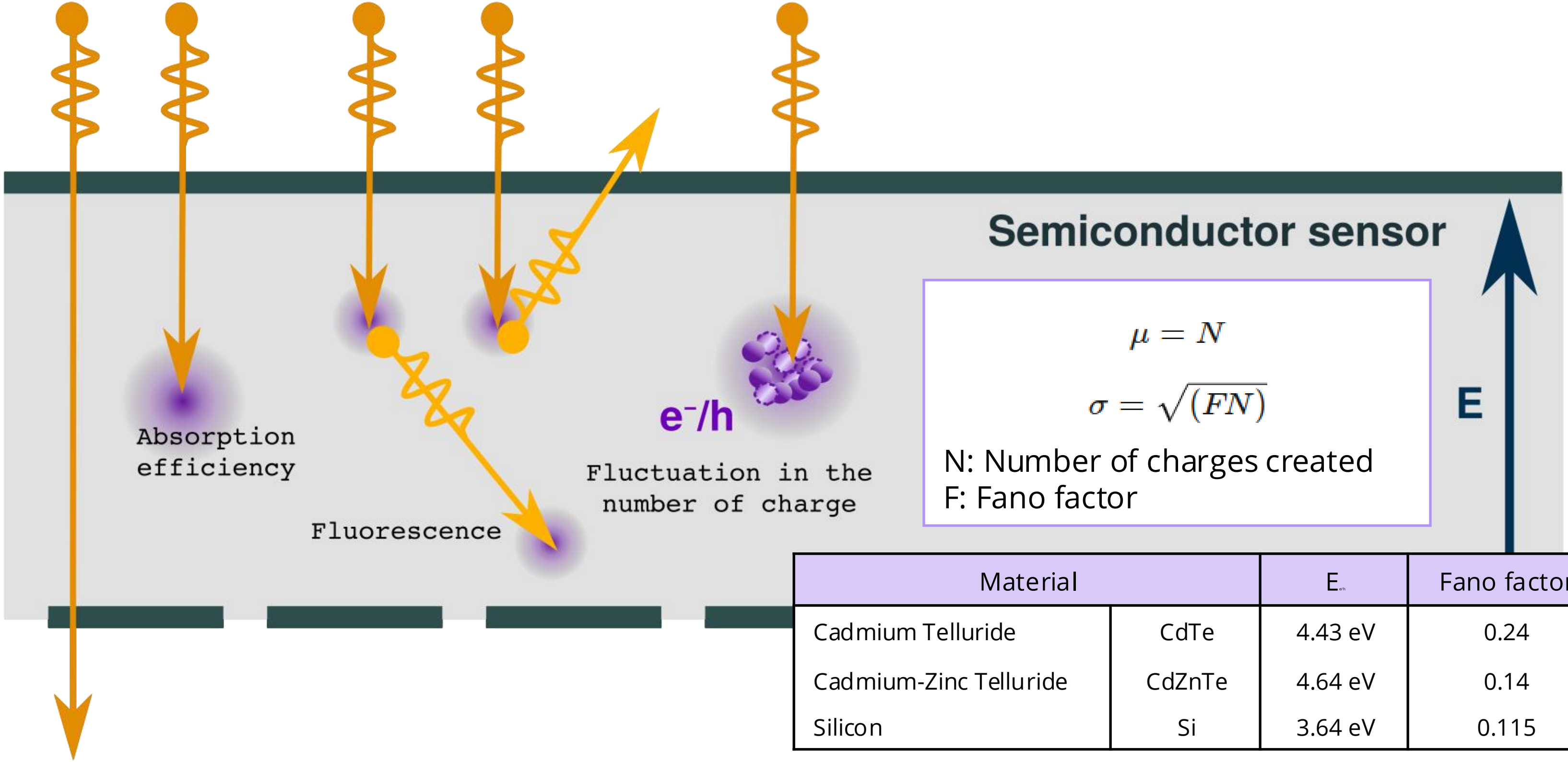
b. Physical limitations of real detectors



		Atomic number	X-ray transitions energies		Mean free path (1/μ)	
Material		Z	$K_{\alpha1}$ [keV]	$K_{\alpha2}$ [keV]	$d_{\alpha1}$ [μm]	$d_{\alpha2}$ [μm]
Si		14	1.74	1.74	11.86	11.86
CdTe	Cd	48	**23.17**	22.98	**113.20**	110.75
	Te	52	27.47	27.20	59.32	57.85

2 – Modelling hybrid pixel detectors response

b. Physical limitations of real detectors



$$\mu = N$$

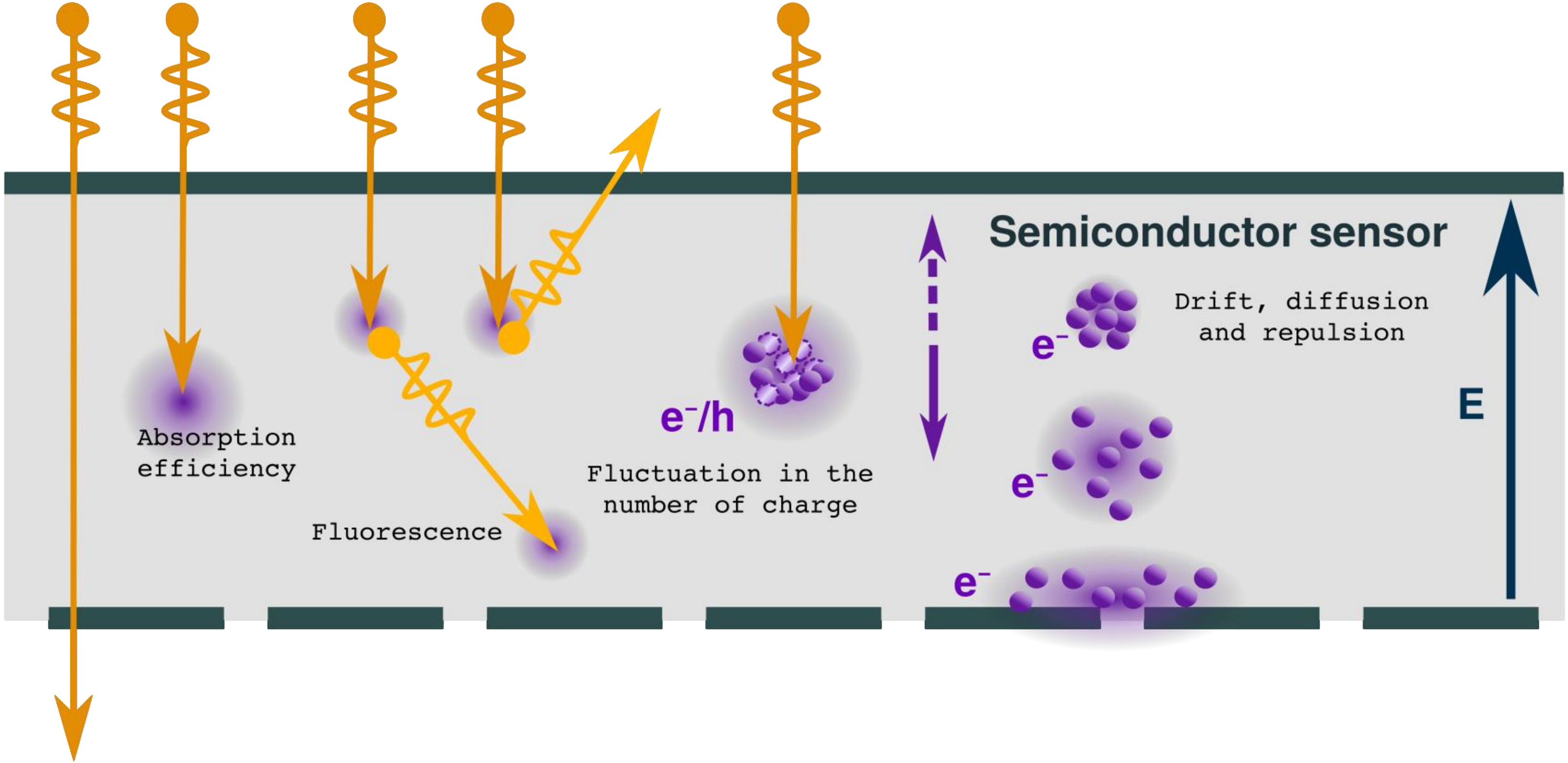
$$\sigma = \sqrt{(FN)}$$

N: Number of charges created
F: Fano factor

Material		$E_{e/h}$	Fano factor
Cadmium Telluride	CdTe	4.43 eV	0.24
Cadmium-Zinc Telluride	CdZnTe	4.64 eV	0.14
Silicon	Si	3.64 eV	0.115

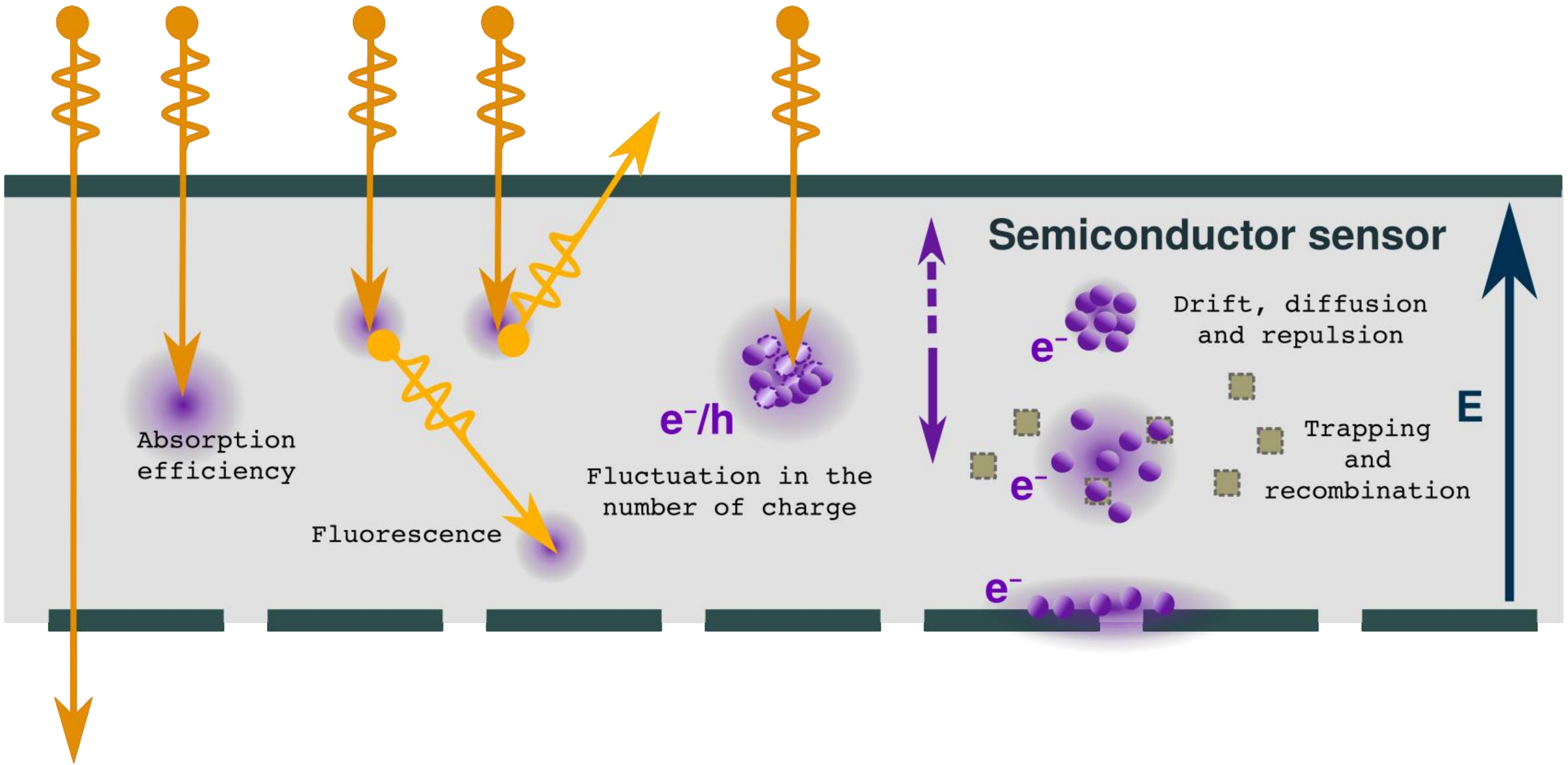
2 – Modelling hybrid pixel detectors response

b. Physical limitations of real detectors



2 – Modelling hybrid pixel detectors response

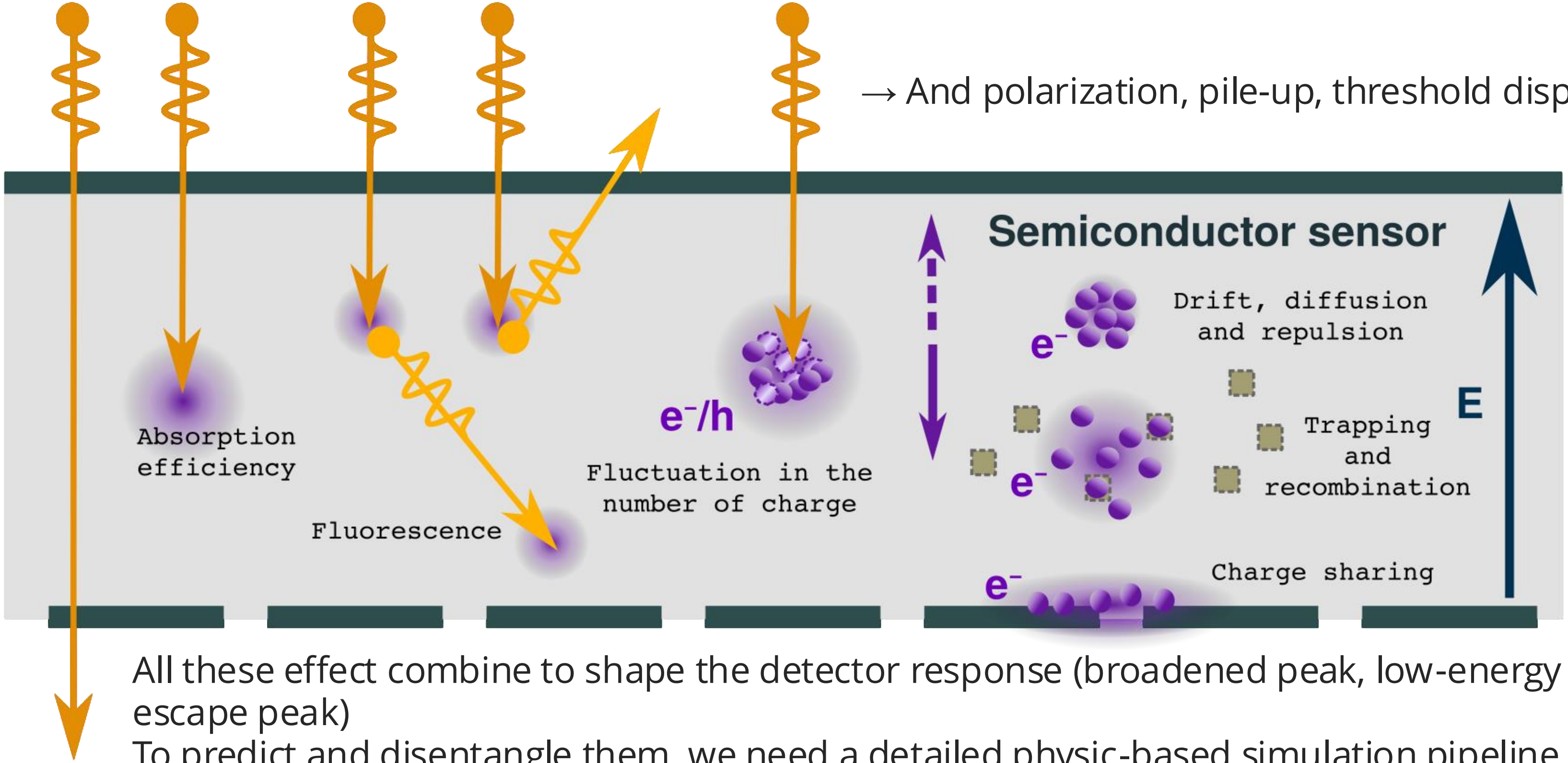
b. Physical limitations of real detectors



2 – Modelling hybrid pixel detectors response

b. Physical limitations of real detectors

→ And polarization, pile-up, threshold dispersion…



All these effect combine to shape the detector response (broadened peak, low-energy tail, escape peak)
To predict and disentangle them, we need a detailed physic-based simulation pipeline

3 - Simulation pipeline

a. Global diagram

Ignores Shockley-Ramo signal induction, polarization, pile-up

Configuration

- Detector geometry
- X-ray source properties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          "z": -1.00
        }
      },
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      "z": 0.5
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      "y": 1
    }
```


JSON

X-ray interactions

Geant4: Tracking of particles in the sensor, their position and energy loss

GEANT4 A SIMULATION TOOLKIT

Carrier generation and fluctuation

Number of charges created and lifetime calculation

$$\mu = N$$

$$\sigma = \sqrt{(FN)}$$

N: Number of charges
F: Fano factor

Charge carriers dynamics

New positions of charges after drift, diffusion and repulsion

Charge carriers collection

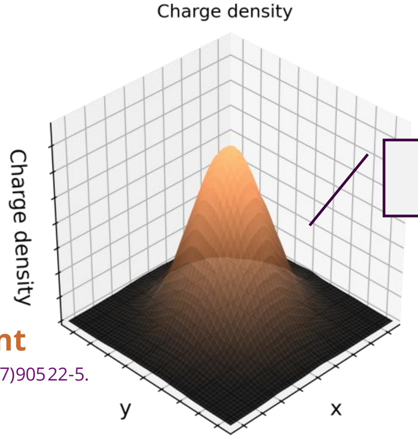
Electronic noise added to the pixel collected charge spectrum reconstruction

$$E_{dep,pix} = N_{charges,pix} \cdot E_{e/h}$$

Output

- Energy spectrum from the simulated detector
- Counts in each of several predefined energy bins

$$\frac{\partial \rho}{\partial t} = \underbrace{D\nabla^2\rho}_{\text{Diffusion}} - \underbrace{\mu\nabla.(\rho\boldsymbol{E})}_{\text{Electrostatic repulsion}}$$



$\sigma(t_{drift})$

$$t_{drift}(z) = \frac{1}{\mu k}\ln\left(\frac{E(z)}{E_0}\right)$$

The 2 models studied :

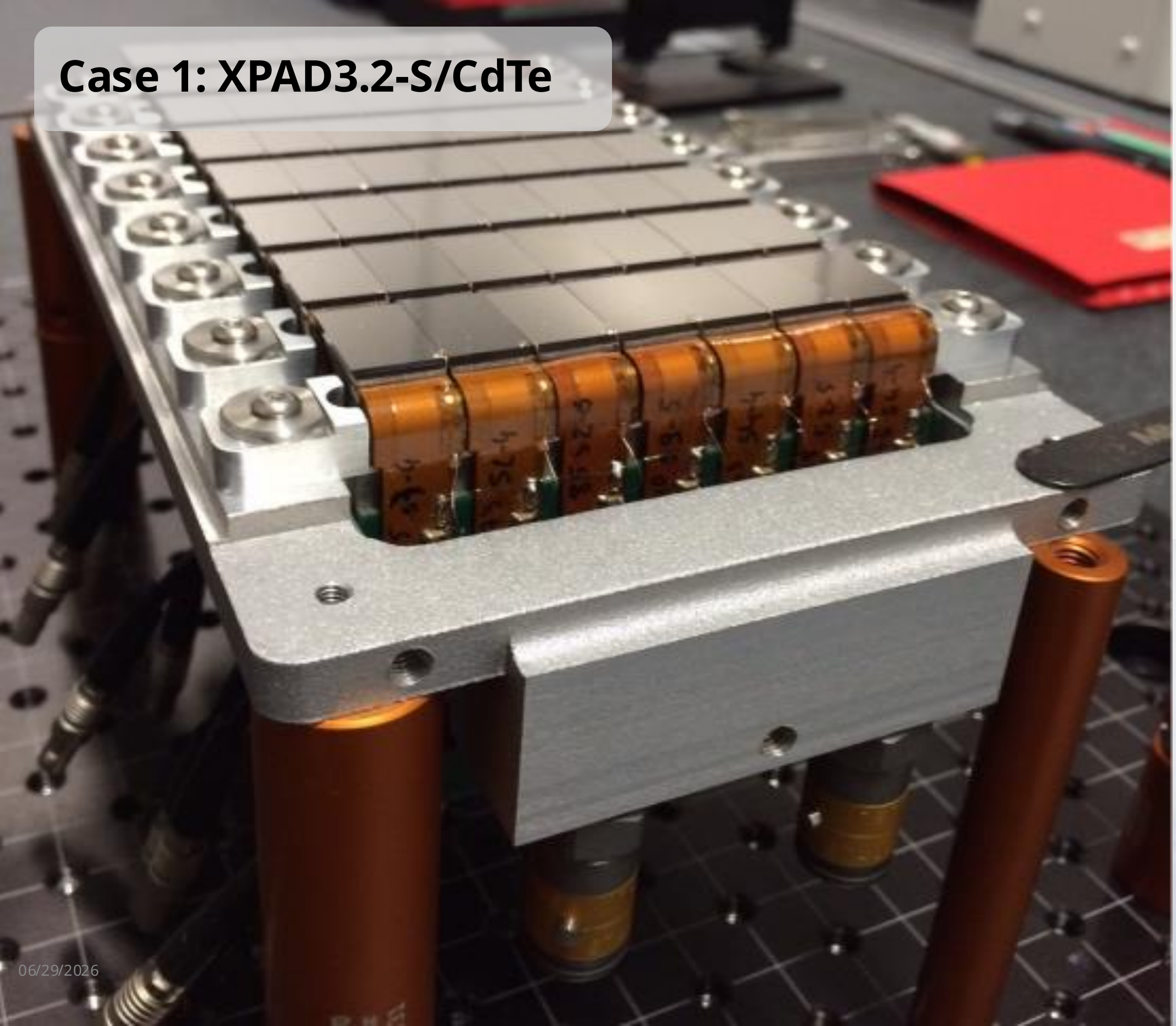
- Repulsion and diffusion are **independent**

E. Gatti et al., NIMA, 253 (1987) 393-399, DOI: 10.1016/0168-9002(87)90522-5.

- Repulsion and diffusion are **dependent**

M.Benoit et al., NIMA, 606 (2009) 508-516, DOI: 10.1016/j.nima.2009.04.019.

Case 1: XPAD3.2-S/CdTe



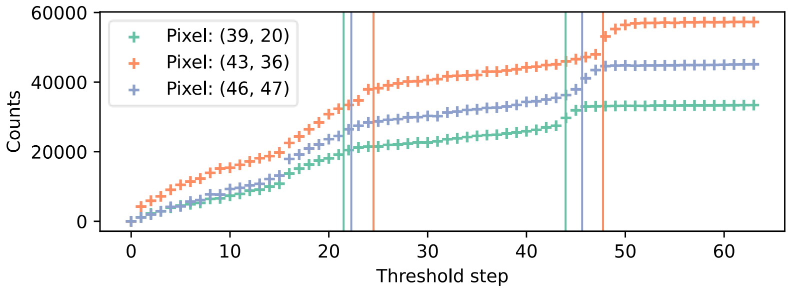
CPPM: XPAD3.2-S/CdTe

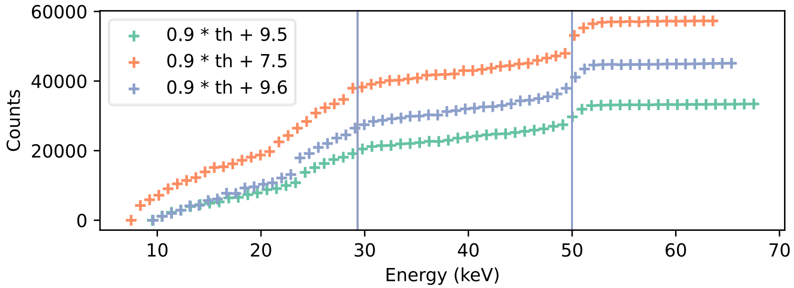
- 2D Matrix
- 130 µm pitch
- 750 µm CdTe
- 1 threshold

4 - Validation case 1: XPAD3.2-S/CdTe

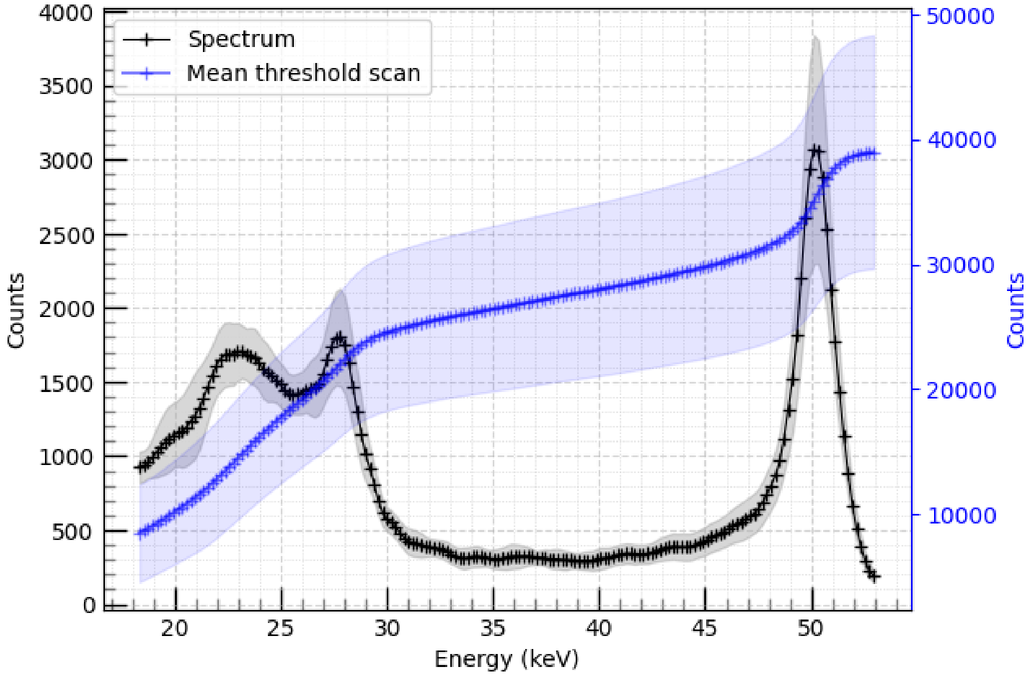
a. SOLEIL acquisitions

- Synchrotron acquisition with XPAD3.2-S/CdTe
- Threshold scan
- Flat field 52 keV beam





- A sample of 500 pixels reliable pixels
- Calibration performed using two different spectral point
  - Full energy peak
  - Cd K-escape energy

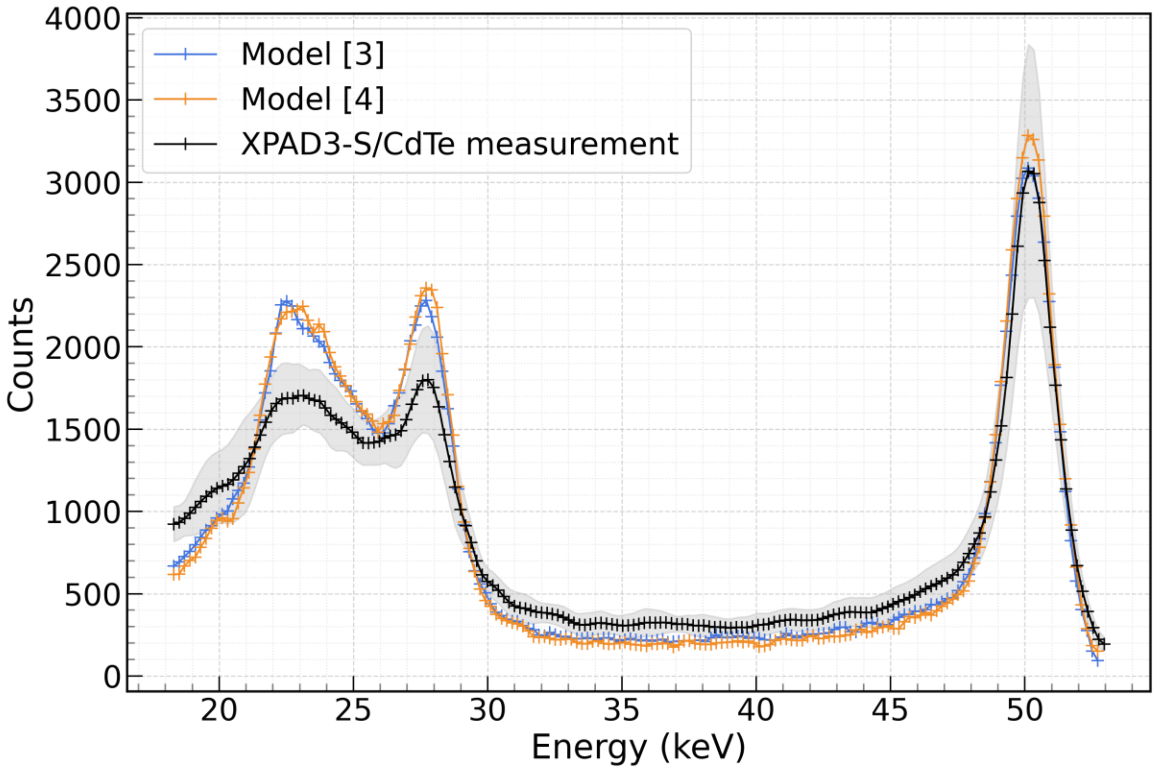


4 - Validation case 1: XPAD3.2-S/CdTe

b. Simulation vs Measurements

Source of discrepancies:

- Higher noise than expected (close to 170 e^- RMS)
- Non-uniform distribution of the threshold steps
- Missing mechanisms from the simulation



[3]: Repulsion and diffusion independents

[4]: Coupled repulsion and diffusion

Case 2: DT demonstrator

DT: prototype

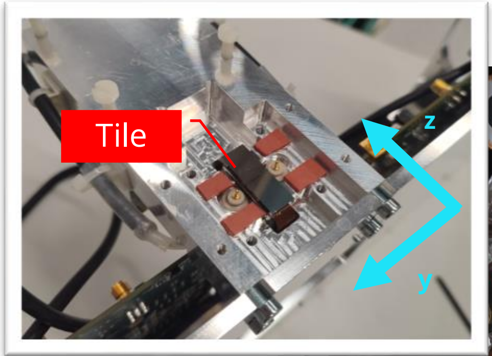
- 2D Matrix
- 2x 24x36 pixels
- 350 µm pixel pitch
- 2 mm thickness CdTe / CZT
- 6 thresholds

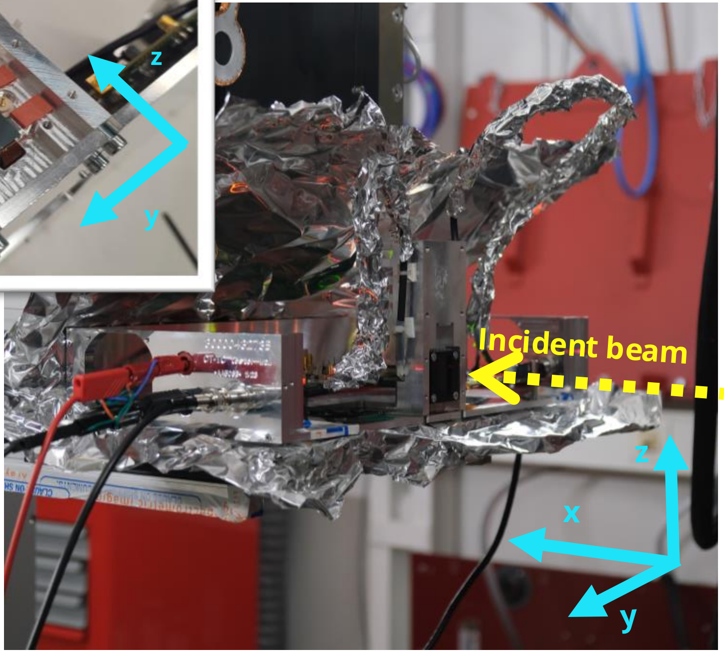
4 - Validation case 2: DT demonstrator

a. ESRF ID11 experimental set-up

Beamtime (5 days allocated):
Characterize the prototype developed by DT and acquired experimental data to validate and refine detector simulation

Y. Boursier et al. (2026), "2D-CdZnTe detector prototype characterization for simulation validation," Experimental report, Proposal MI-1525, Beamline ID11, ESRF, DOI: 10.15151/ESRF-ES-2266935027



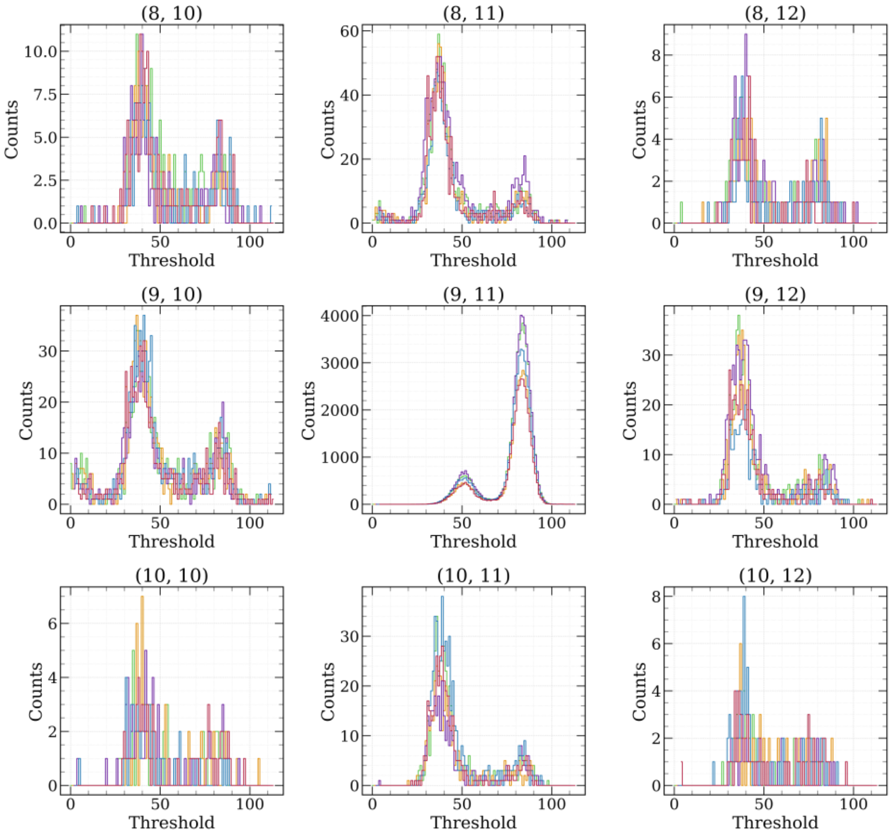


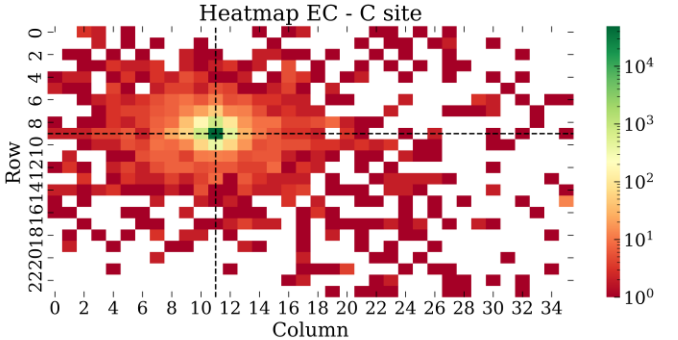
ESRF
The European Synchrotron

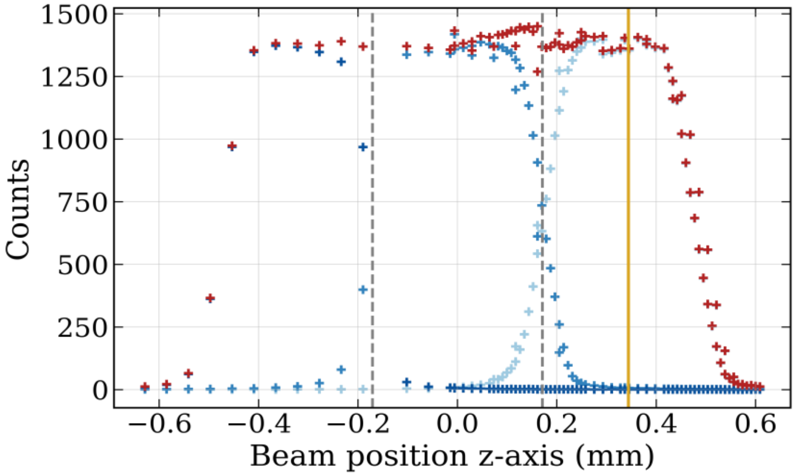
4 - Validation case 2: DT demonstrator

b. Spot scans and spectral measurements

- Heatmap of the matrix
- Counts recorded for 3 adjacent pixels vs beam position beam position
- Spectra of the target pixel and its neighbour





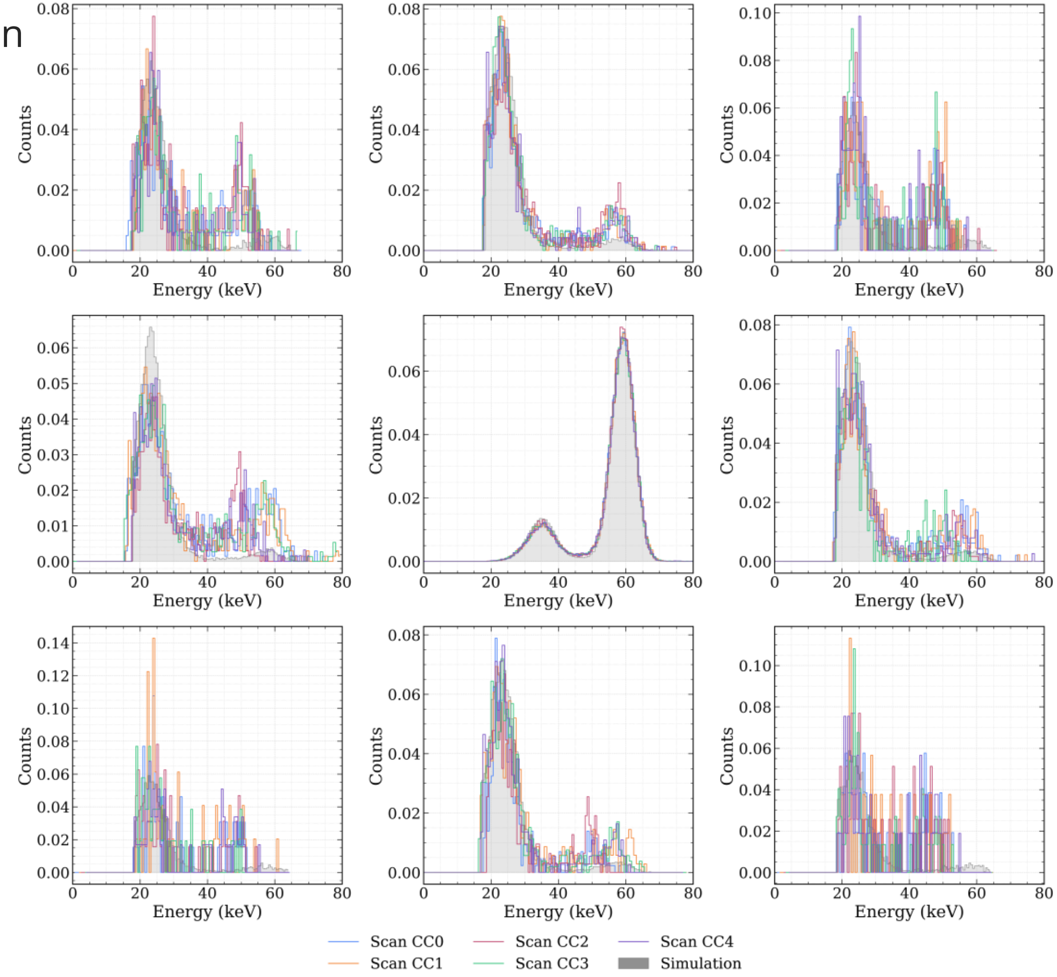


4 - Validation case 2: DT demonstrator

c. Spectral measurements vs simulation

• Good agreement between simulated and measured spectra.

• Accurate reproduction of the full-energy and fluorescence peaks.

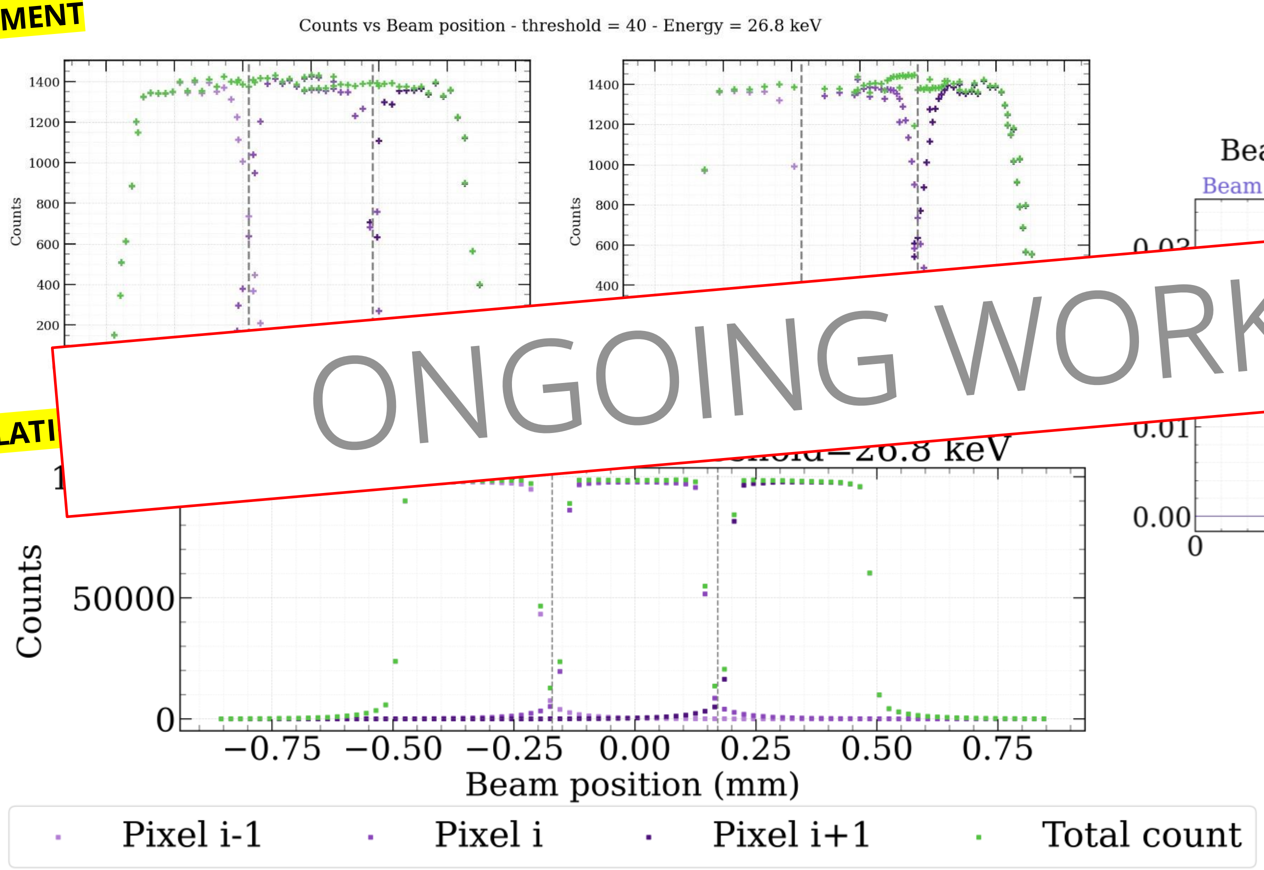


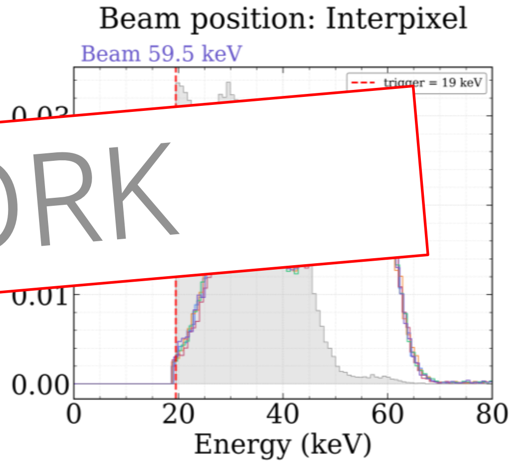
4 - Validation case 2: DT demonstrator

d. Spot scans measurements vs simulation

MESUREMENT

SIMULATI





5 - Conclusion

Goals of the study:

- Simulation of high Z semiconductor pixel detectors response
- Focus on the simulation of fluorescence escape and charge sharing

Method:

- Simulation integrates charge carriers' generation and dynamics
- Study of 2 charge transport models, essential to reproduce accurately charge sharing
- Processing of XPAD3.2-S/CdTe measurement performed in synchrotron
- Measurement campaign spot beam performed with DT CdTe/CZT based prototype in Dec. 2025

Results:

- Good agreement
- Behavior at this interpixel needs to be refined – ongoing work

Prospects:

- Integration of signal induction on electrodes
- Comparison with other simulation tools
- Continue measurements analysis to refine the model

AG GDR, Mi2b

Marseille, le 29.06.2026

Detection Technology

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

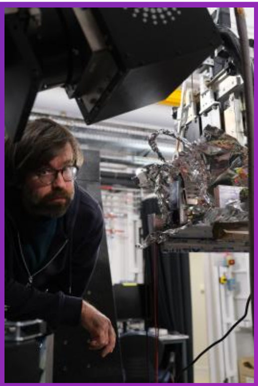
Thank you for your attention

Questions ?

Acknowledgement:

→ We acknowledge the European Synchrotron Radiation Facility (ESRF) for the provision of synchrotron radiation facilities under proposal ID MI-1525 and on beamline ID11. We thank Loic Jegou and the beamline staff for assistance and support during the beamtime.

→ We thank G. Gey, M.Plainemaison, T.Pierson, A. Winkler and M. Matikkala from Detection Technology for their support during data acquisition and experimental preparation.


X-ray interactions → Carrier generation and recombination → Charge carriers dynamics → Charge carriers collection

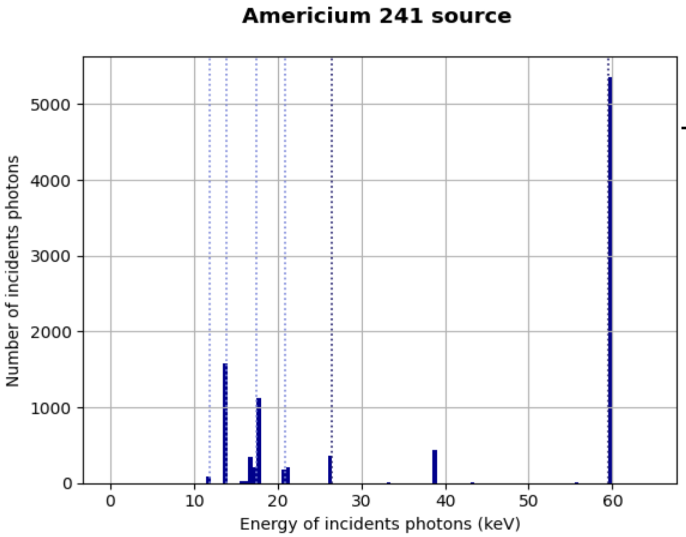
3 - Simulation pipeline

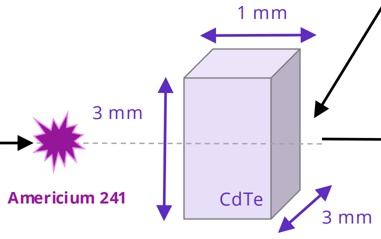
b. X-ray interactions with Geant4

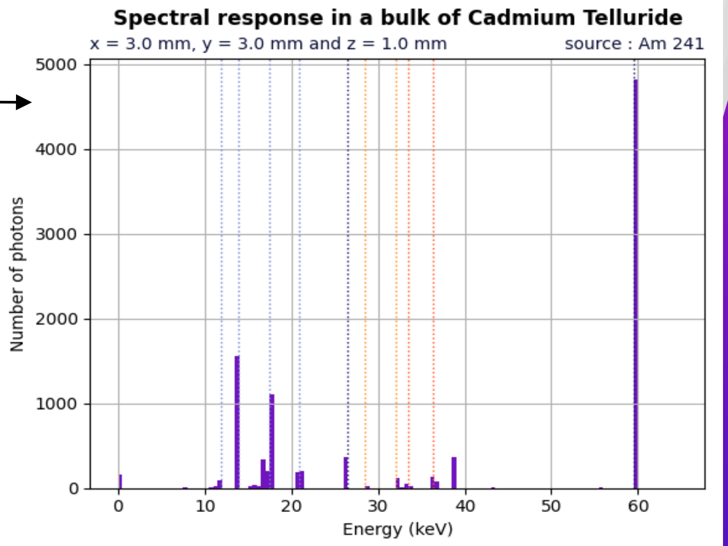
- Tracking of particles in the sensor, their position and energy loss
- Photoelectric effect, Compton scattering
- CdTe : fluorescence escape photon

Amptek : XR-100T-CdTe

- Mono-pixel detector
- CdTe
- 3 mm pitch
- 1 mm thickness



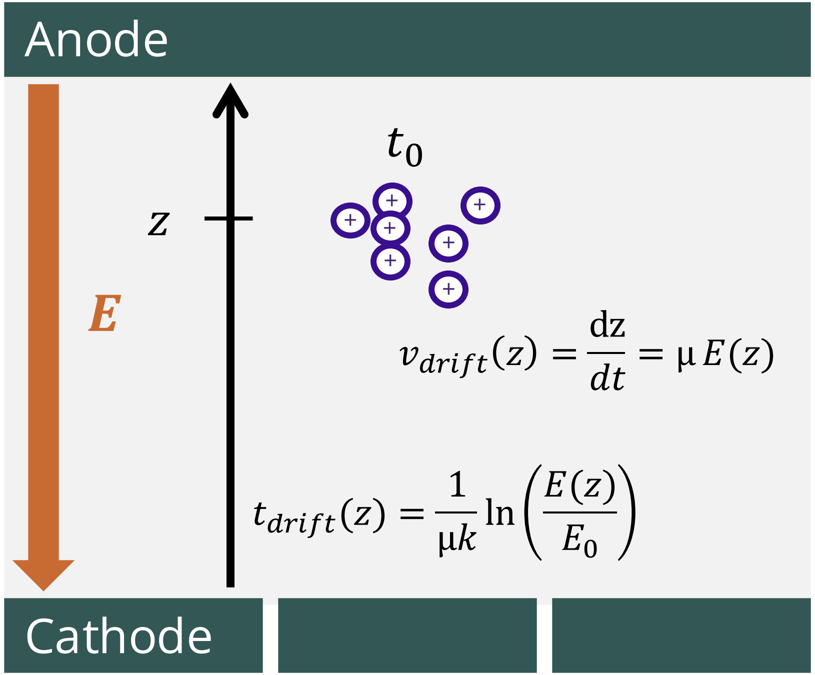




3 - Simulation pipeline

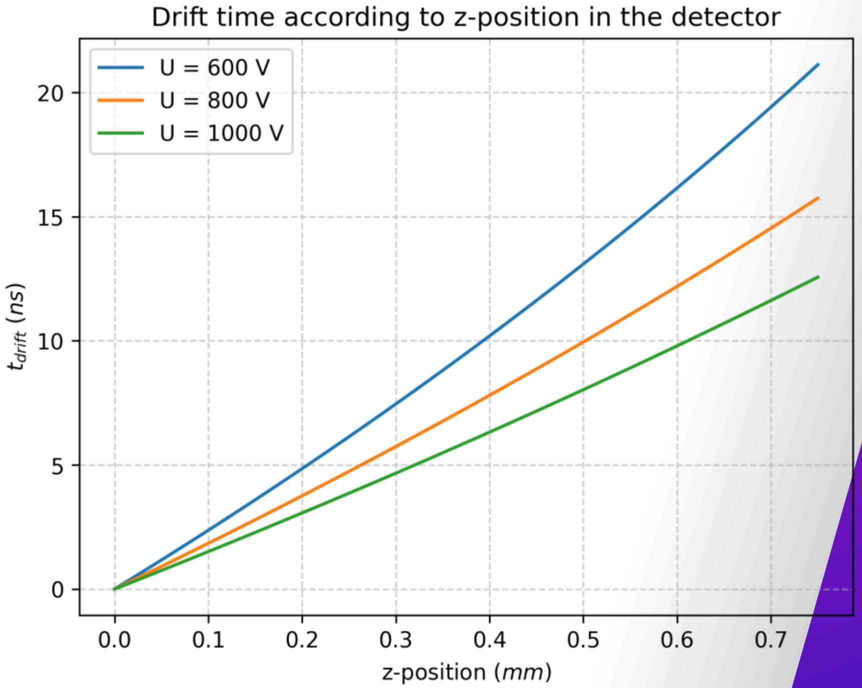
c. Charge carriers dynamics

- Charges drift toward the electrodes under the influence of electric field
- Drift time is deduced from the position of the interaction z and a linear electric field



$$v_{drift}(z) = \frac{dz}{dt} = \mu E(z)$$

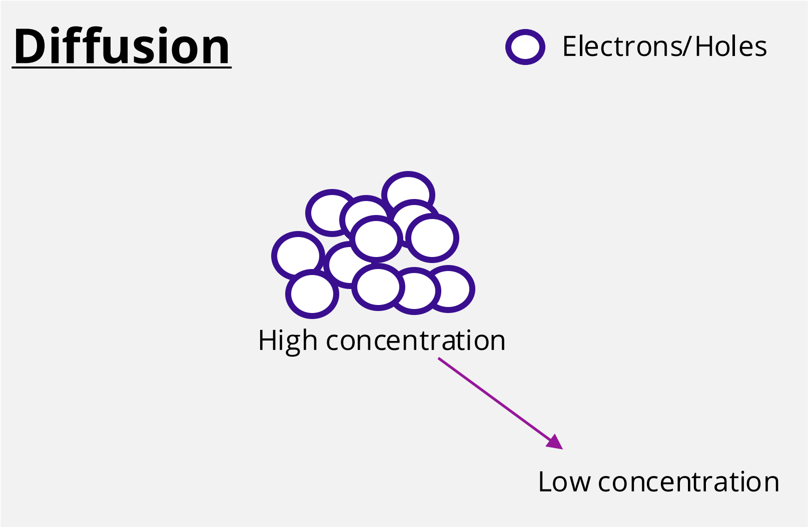
$$t_{drift}(z) = \frac{1}{\mu k} \ln\left(\frac{E(z)}{E_0}\right)$$



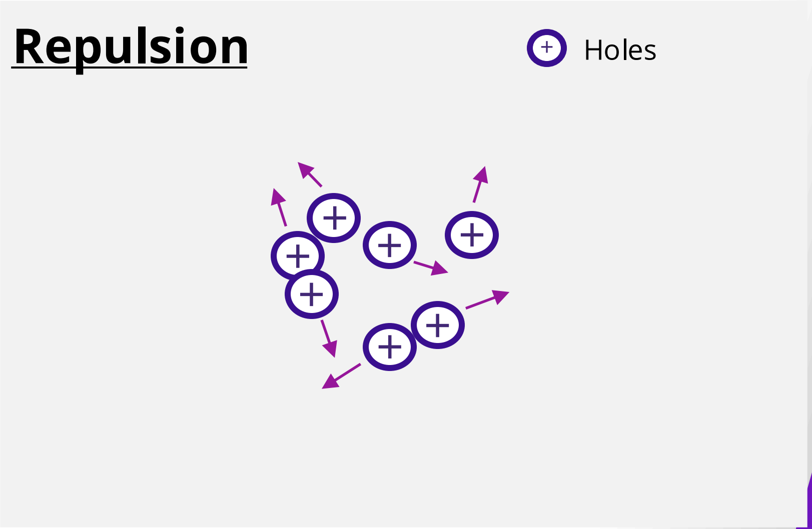
2. Simulation framework
c. Charge carrier dynamics

X-ray interactions → Carrier generation and recombination → Charge carriers dynamics → Charge carriers collection

- Diffusion and repulsion cause a spontaneous spread of charge carriers



An inhomogeneous distribution induce a spontaneous Brownian motion



Charges of same sign repel each other due to electrostatic forces

3 - Simulation framework

c. Charge carriers dynamics

- Diffusion and repulsion cause a spontaneous spread of charge carriers

Charge continuity equation

- Describes the concentration of charge carrier evolution with respect to space and time
- Neglecting generation and recombination at t > 0:

$$\frac{\partial \rho}{\partial t} = \underbrace{D\nabla^2\rho}_{\text{Diffusion}} - \underbrace{\mu\nabla.(\rho\boldsymbol{E})}_{\text{Electrostatic repulsion}}$$

ρ: Density of charges
D: Diffusion coefficient
μ: Mobility of charge carriers
$\boldsymbol{E}$: Electric field induced by charge carriers

Equation solving

- Complex + time consuming in simulation: approximation of the solution using models

- The 2 models studied :
  - Repulsion and diffusion are **independent**

    E. Gatti et al., NIMA, 253 (1987) 393-399, DOI: 10.1016/0168-9002(87)90522-5.
  - Repulsion and diffusion are **dependent**

    M.Benoit et al., NIMA, 606 (2009) 508-516, DOI: 10.1016/j.nima.2009.04.019.

2. Simulation framework

c. Charge carriers dynamics

X-ray interactions → Carrier generation and recombination → Charge carriers dynamics → Charge carriers collection

Model 1: Decoupling repulsion and diffusion

$$\frac{\partial \rho}{\partial t} = \underbrace{D\nabla^2\rho}_{\text{Diffusion}} - \underbrace{\mu\nabla.(\rho\boldsymbol{E})}_{\text{Electrostatic repulsion}}$$

Diffusion-only equation:

$$\frac{\partial \rho}{\partial t} = D\nabla^2\rho$$

Repulsion-only equation:

$$\frac{\partial \rho}{\partial t} = -\mu\nabla.(\rho\boldsymbol{E})$$

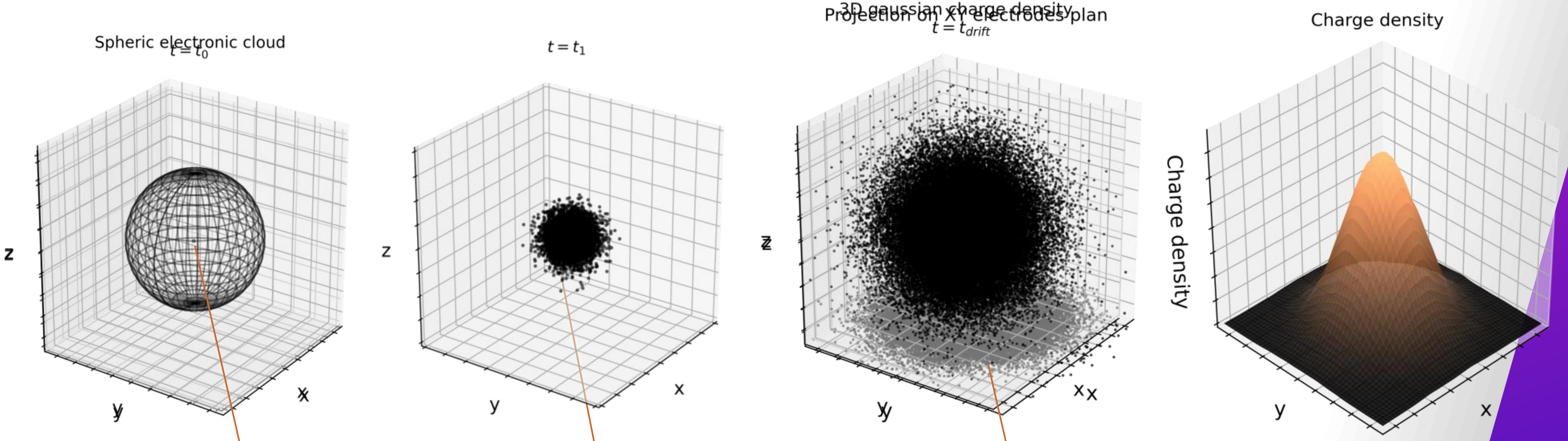
2. Simulation framework

c. Charge carriers dynamics

X-ray interactions → Carrier generation and recombination → **Charge carriers dynamics** → Charge carriers collection

Model 1: Decoupling repulsion and diffusion

- Diffusion-only equation: $\frac{\partial \rho}{\partial t} = D\nabla^2 \rho$
- For a spherical symmetry, the **diffusion** cause the electronic cloud to extend with $\boldsymbol{\sigma}(\mathbf{t}) \propto \sqrt{\mathbf{t}}$



At t = 0, charges are concentered in a point

Charges density follows 3D gaussian distribution

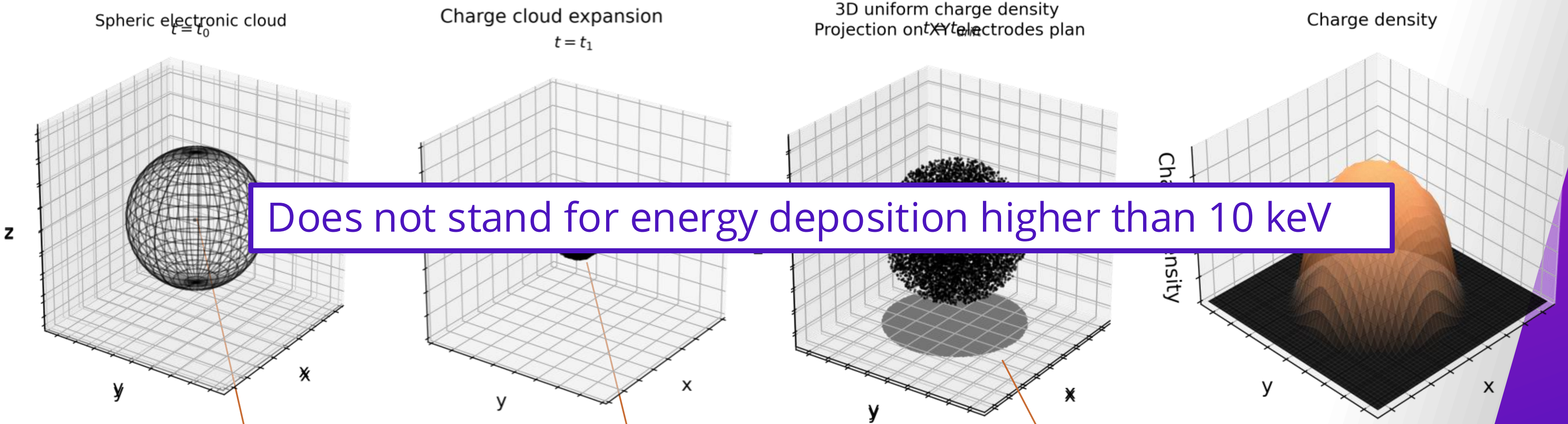
$\boldsymbol{\sigma_{diff}(t_{drift}) = \sqrt{2Dt_{drift}}}$

2. Simulation framework

c. Charge carriers dynamics

Model 1: Decoupling repulsion and diffusion

- Repulsion-only equation: $\frac{\partial \rho}{\partial t} = -\mu \nabla . (\rho \boldsymbol{E})$
- For a **spherical** symmetry, the **repulsion** cause the electronic cloud to extend and $\boldsymbol{r}(\boldsymbol{t}) \propto \sqrt[3]{\boldsymbol{t}}$



Does not stand for energy deposition higher than 10 keV

At t = t_0, charges are concentered in a point

Charges density follows a uniform distribution

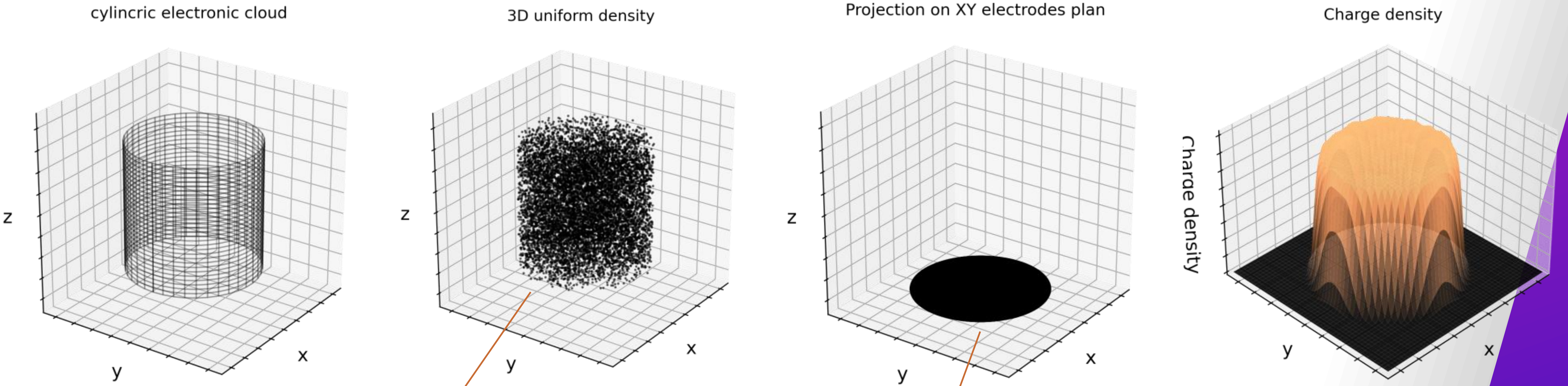
$$\boldsymbol{r}(\boldsymbol{t_{drift}}) = \sqrt[3]{\frac{3\mu N q_e t_{drift}}{4\pi\varepsilon_0\varepsilon_r}}$$

2. Simulation framework

c. Charge carriers dynamics

Model 1: Decoupling repulsion and diffusion

- For a **cylindric** symmetry, the **repulsion** cause the electronic cloud to extend and $\boldsymbol{r(t)} \propto \sqrt[2]{\boldsymbol{t}}$



Charges density follows a uniform distribution

$$r(t_{drift}) = \sqrt{q_e \frac{S_{LOSS}\mu_0 t_{drift}}{E_{eh}\pi\varepsilon}}$$

2. Simulation framework

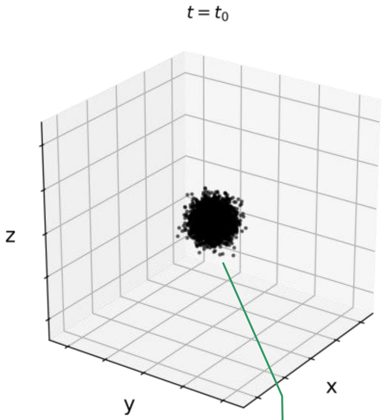
c. Charge carriers dynamics

X-ray interactions → Carrier generation and recombination → **Charge carriers dynamics** → Charge carriers collection

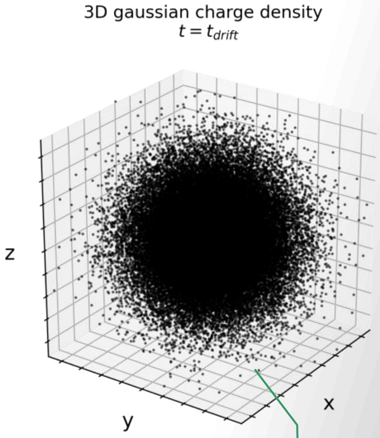
Model 2: Coupling repulsion and diffusion

$$\frac{\partial \rho}{\partial t} = \underbrace{D\nabla^2 \rho}_{\text{Diffusion}} - \underbrace{\mu \nabla . (\rho \boldsymbol{E})}_{\text{Electrostatic repulsion}}$$

$$\frac{d\sigma^2(t)}{dt} = \underbrace{2\left(D + \frac{\mu N q_e}{24\pi^{3/2}\epsilon_0 \epsilon_r \sigma(t)}\right)}_{D_{eff}} = 2D_{eff}$$



At t = t0, charges are distributed



Charges density follows 3D gaussian distribution

4 - Validation case 1: XPAD3.2-S/CdTe

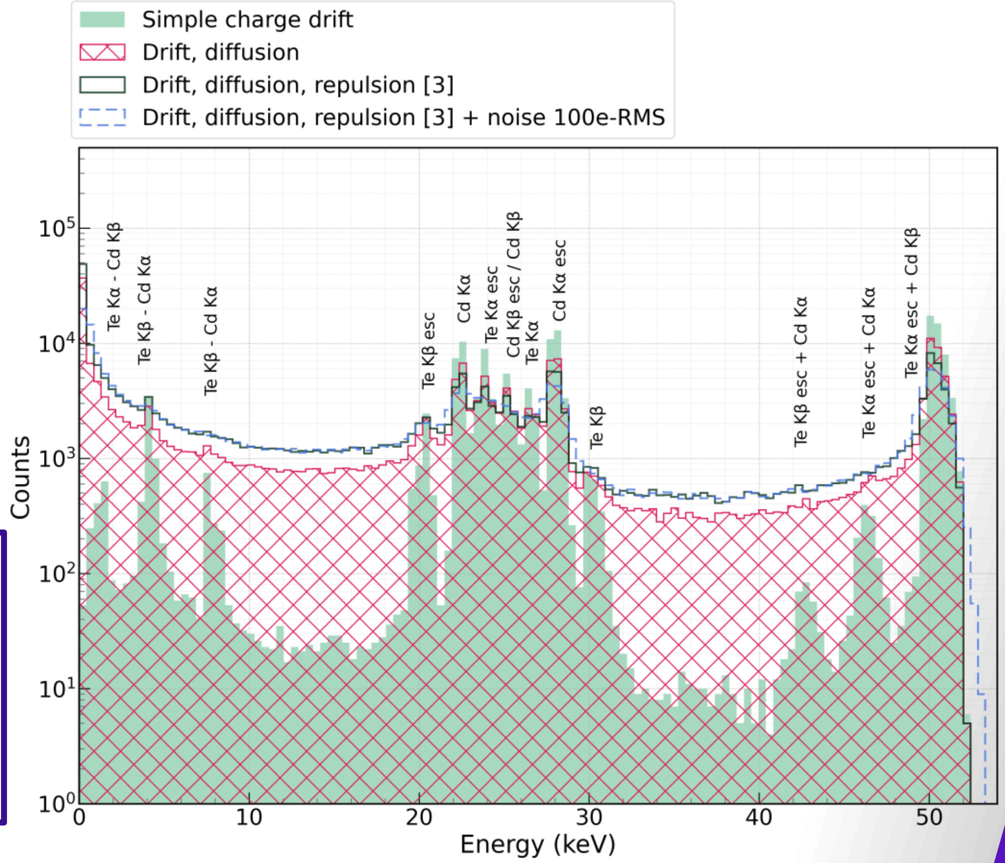
b. Simulation

- Electronic noise approximated by a convolution with a gaussian

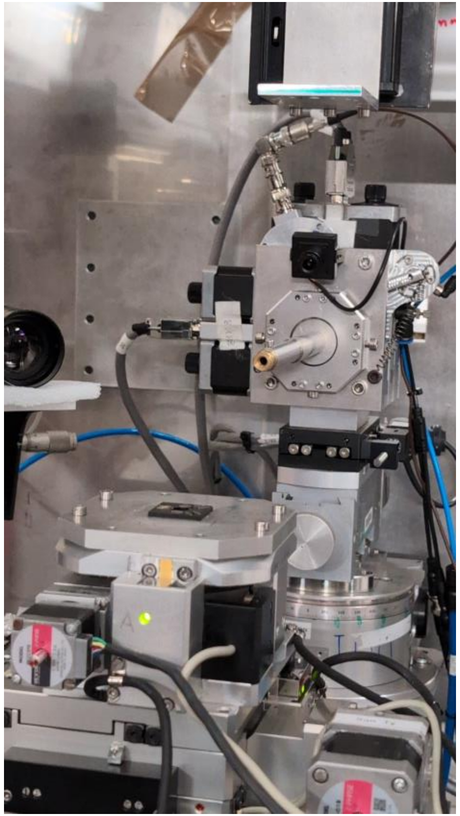
<u>**Simulation parameters**</u>

$E_{e\text{-h}}^{CdTe}\ (eV)$	4.43
h mobility $(cm^2/(Vs))$	100
h lifetime (μs)	2
Fano factor	0.24
Incident beam energy $(\mathrm{ke}V)$	52

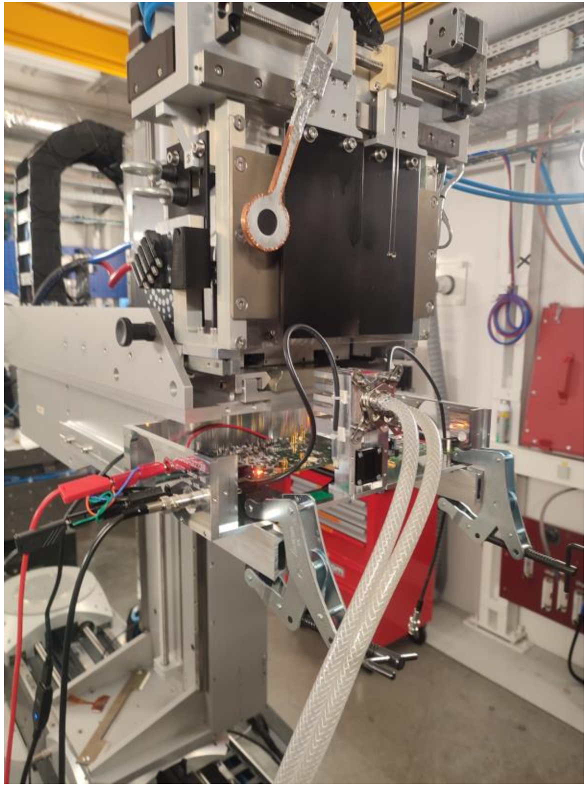
- Fluorescence escape peaks are visible on the spectrum
- The full energy peak is shifted due to an incomplete collection of charges
- Activation of diffusion and repulsion increase the size of the electronic cloud and so the charge sharing

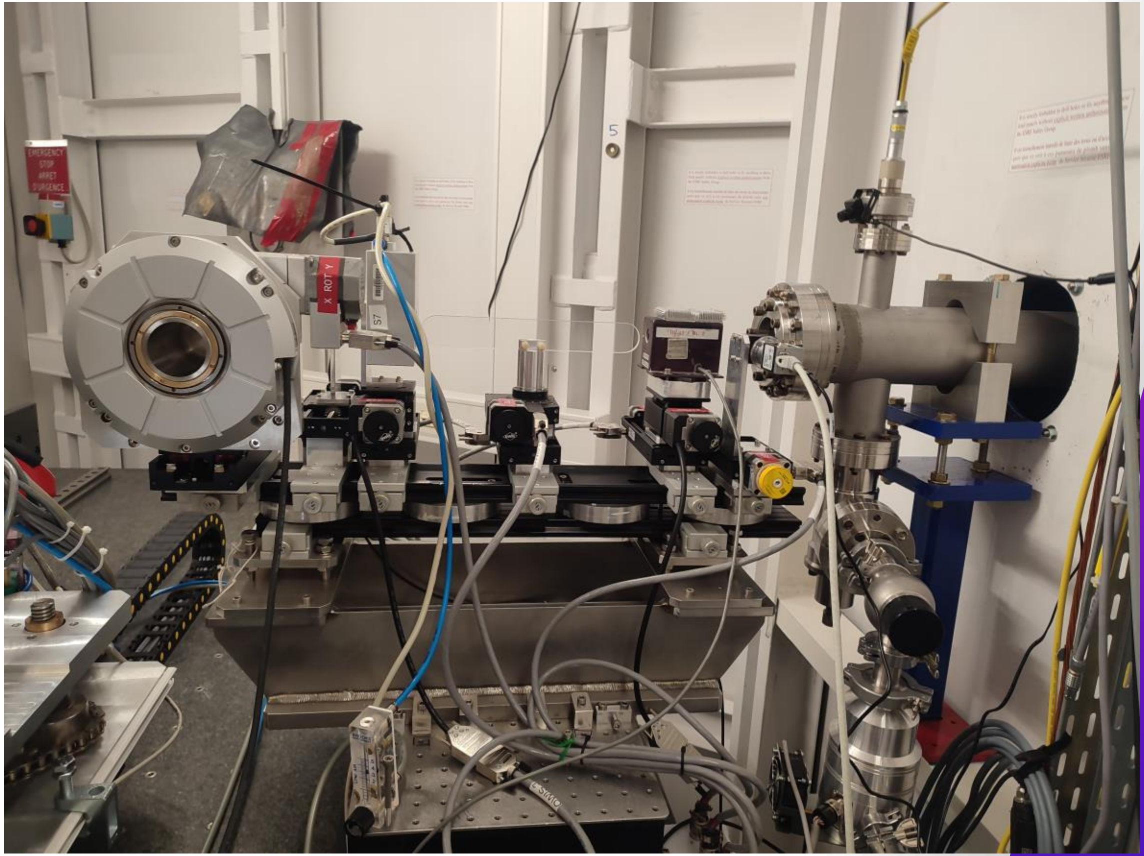


ESRF set-up additional pictures



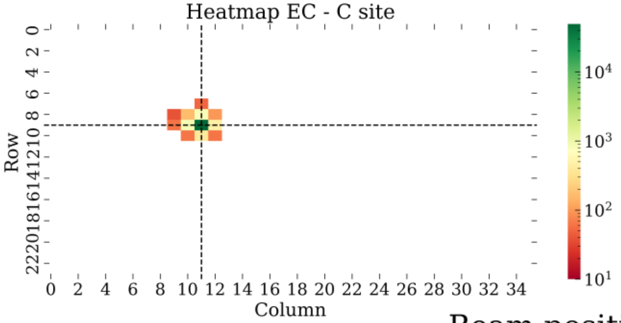
ESRF set-up additional pictures



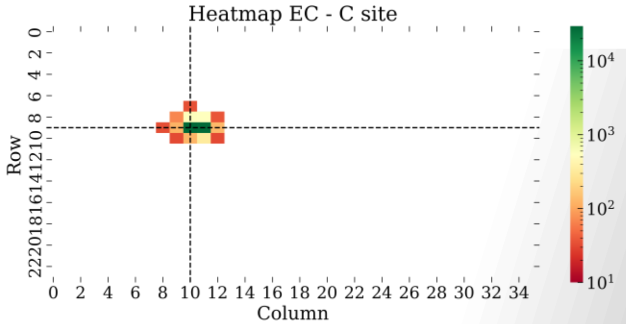


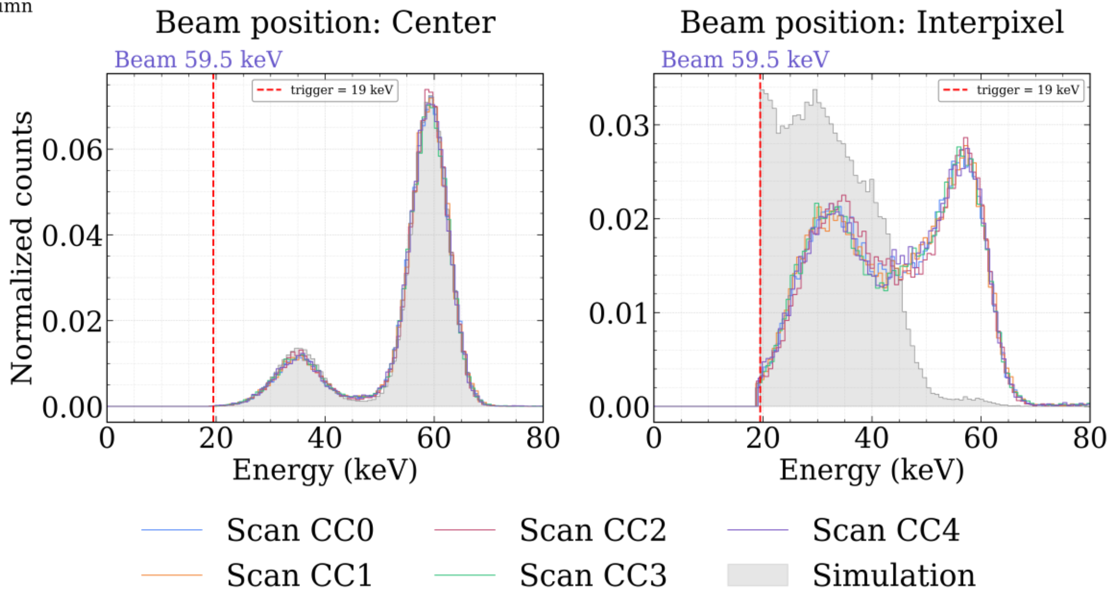
4 - Validation case 2: DT demonstrator

b. Spectral Detector Response - Simulation vs Measurements



Selection pixels with counts > 30





Back-up. sigma vs energy: thresholds

- Réponse spectrale d'un pixel pour un faisceau de 59.5 keV (droite) à et 79.5 keV (gauche)