CadTool - a end-to-end x-ray/gamma-ray solid state detector simulation framework

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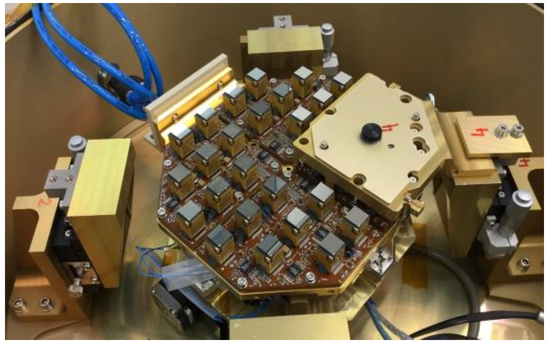
[3] CEA IRFU, Université Paris Saclay
[4] Kavli IPMU (WPI), UTIAS, The University of Tokyo

Context

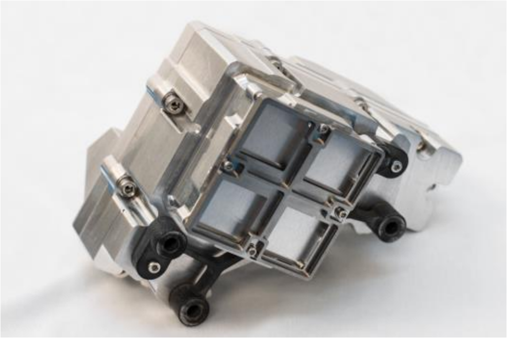
The need of a Simulation Tool

Present
2026

Solar Orbiter / STIX esa



PADRE Nanosat NASA



Future
2030's

esa **M8 Proposals**

SPARK
Solar Physics
~150 keV
CdTe 1 mm
250 µm x 250 µm

PHEMTO
High-Energy Astrophysics
~600 keV
Thick CZT (10 mm)
<300 µm Δxy (Laue Lenses imaging)

Simulation Tool helps with
1) Understanding detector effects
2) Evaluating detector configuration (pixel pattern)
3) Design new readout techniques
4) Modeling detector response (science)

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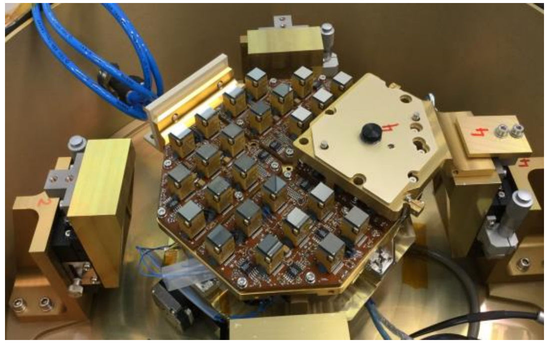

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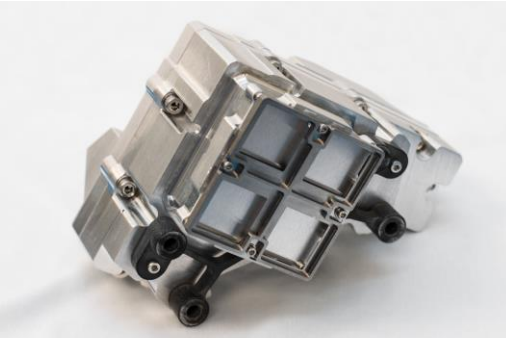

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PhD

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Outline

1. Simulation Tool Requirements
- Inputs
- Physics
- Outputs

2. Detector Physics
- Geometry and Fields
- Charge cloud dynamics
- Electrode induced charge

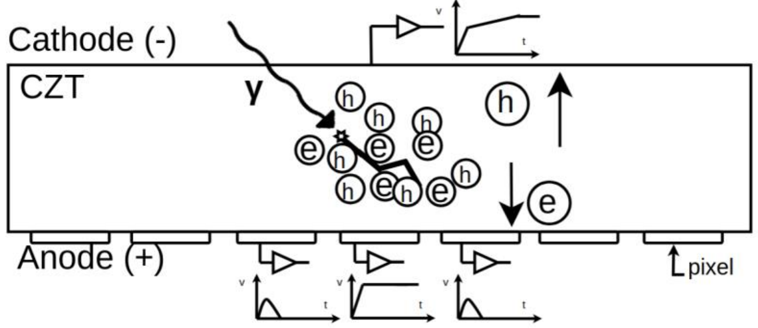
3. Events List Generator
- Monte-Carlo events
- Detector Spectra

4. Tool Validation
- Low Energy
- High Energy

5. Examples
- 3D
- Transient signals

Context

Simulation Tool Requirements



Inputs

Detector Parameters
Material, Pixel/Strip, Bias, Mobility, Lifetime, Fano

Enviroment Geometry
Box, Passive material, collimator, etc

Source Configuration
Geometry, Energy, Intensity

Electronics
ENC, ADC range, Threshold

Detector Physics

Electric Field and Potential

Weighting Potential

Charge Drift
- Trapping
- Diffusion
- Repulsion

Event list generation

Photon-matter interaction

Electrode charge induced

Front-end & Back-end electronics

Outputs

Transient Signals
- Charge profile
- Current profile

Data analysis
- images
- spectrum
- lightcurve
- response matrix

Context

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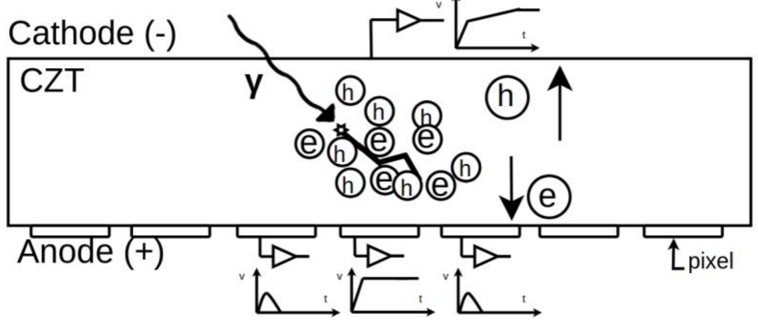

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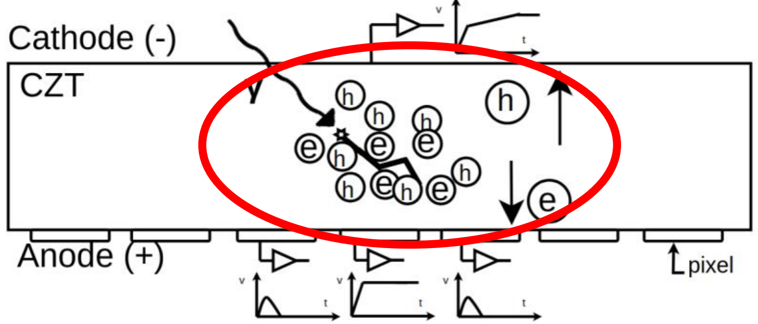

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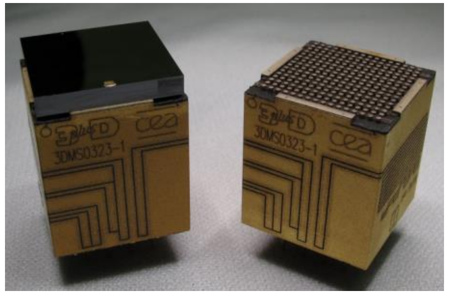
Cadtool

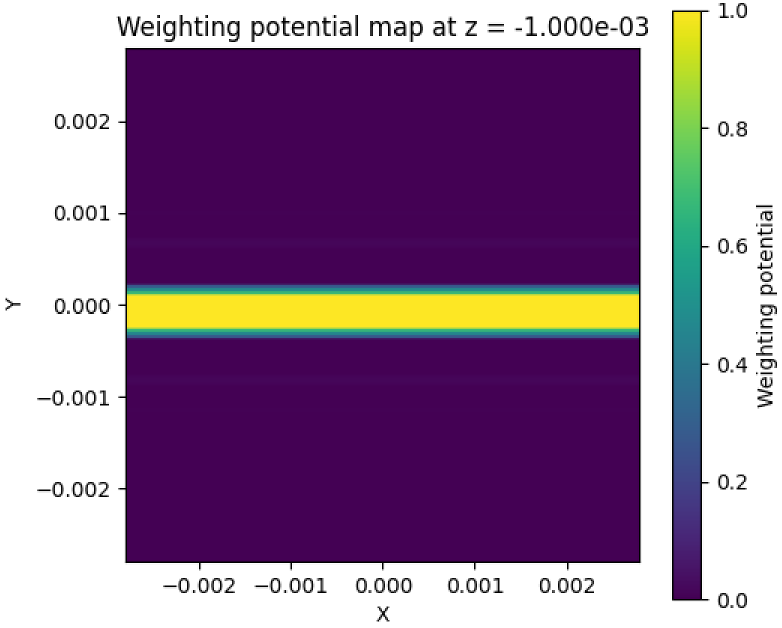
Geometry and Fields

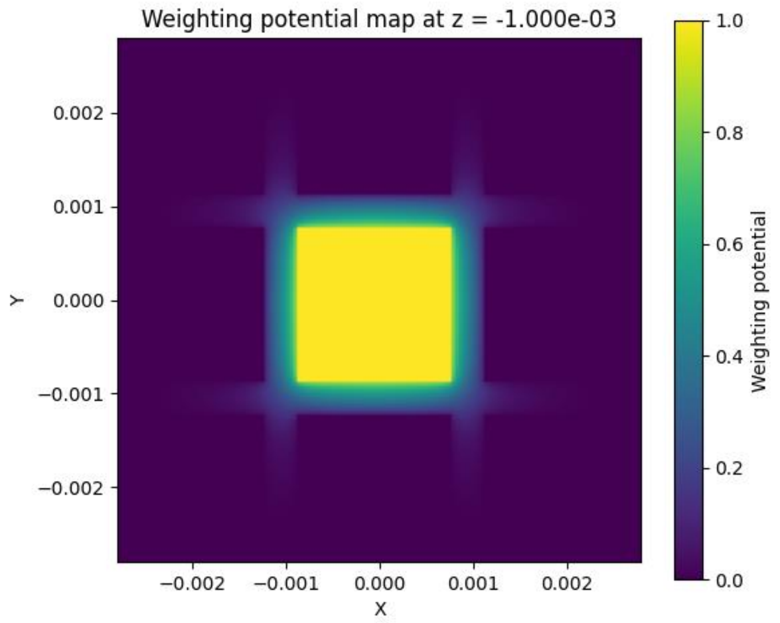
- *solidstatedetectors.jl* library
- Geometry definition: planar, pixel, strip

Caliste-O



2mm CdTe pixel 800µm





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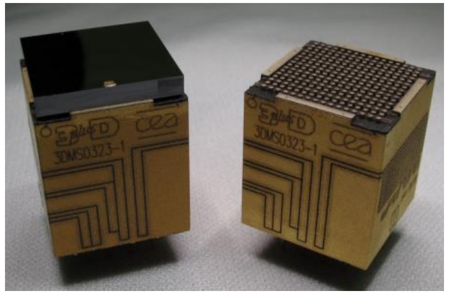

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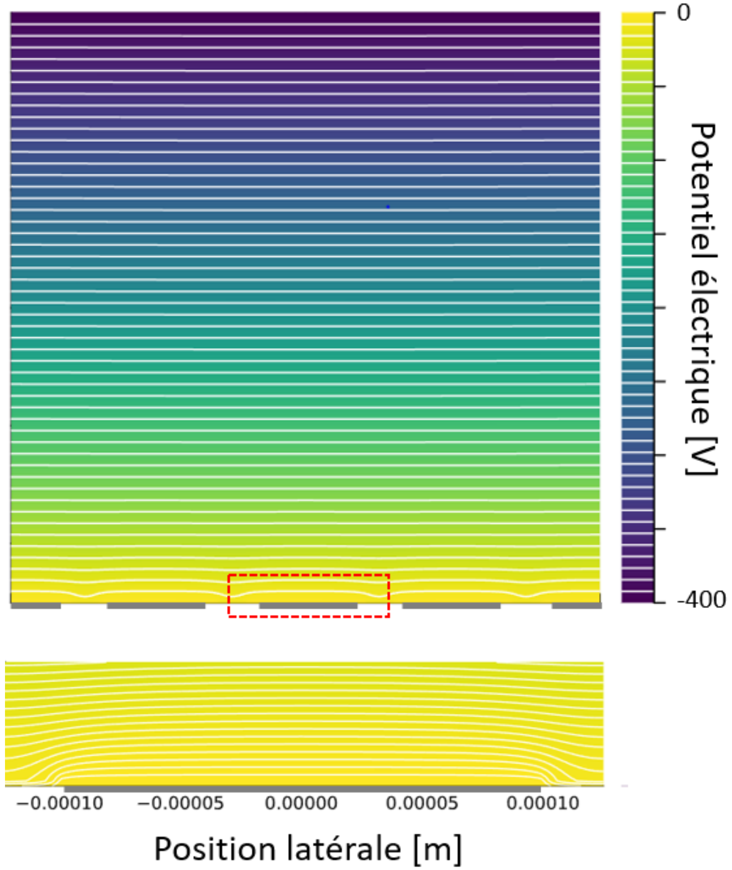
$$\vec{v_e} = -\mu_e \vec{E}$$
$$\vec{v_h} = \mu_h \vec{E}$$

Input for charge dynamics



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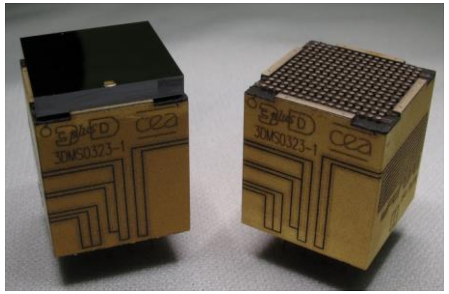

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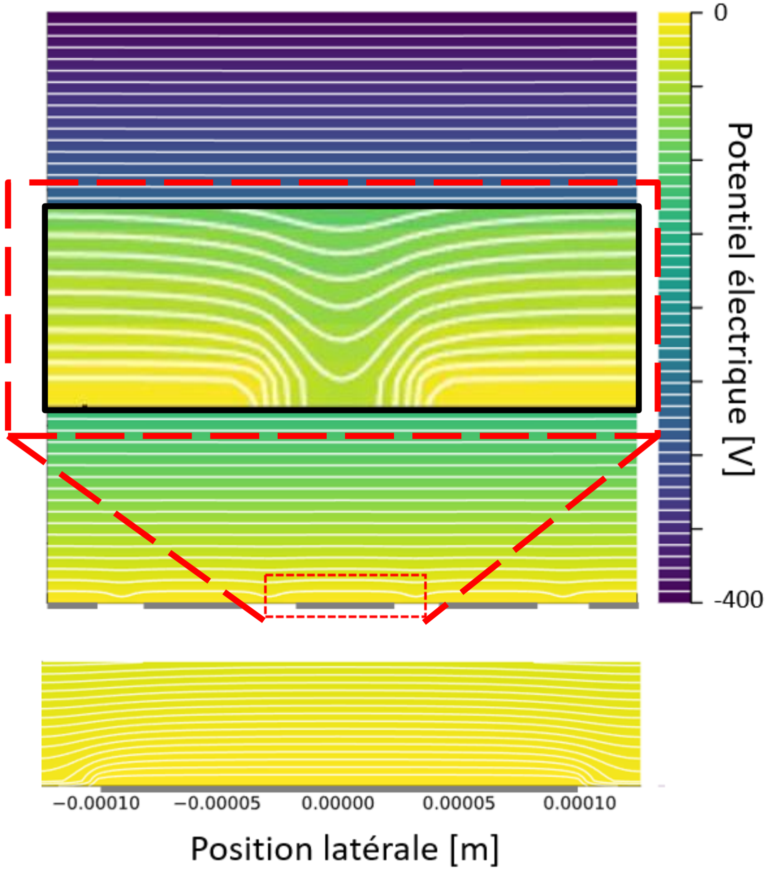

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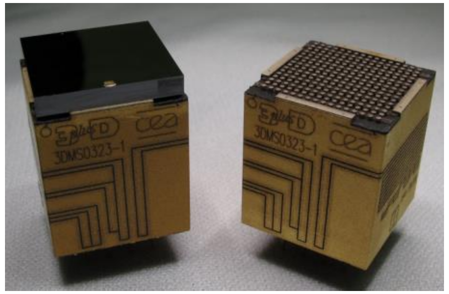

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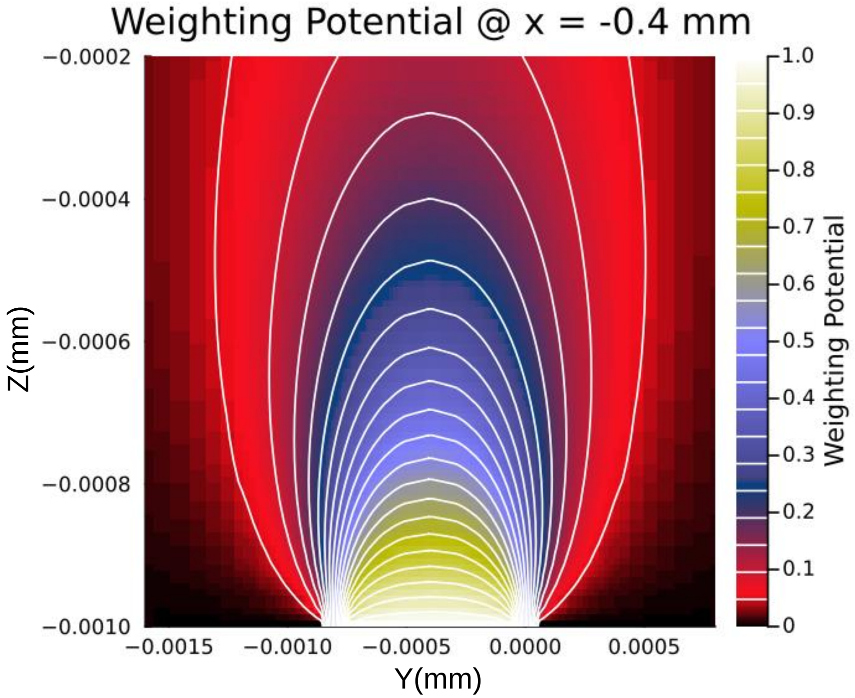

Shockley-Ramo Theorem

$$E_0 = -\nabla \phi_0(x)$$

$$Q = -q\phi_0(x)$$

Charge at electrode

Moving charge

Electrode Weighting Potentiel

Cadtool

Geometry and Fields

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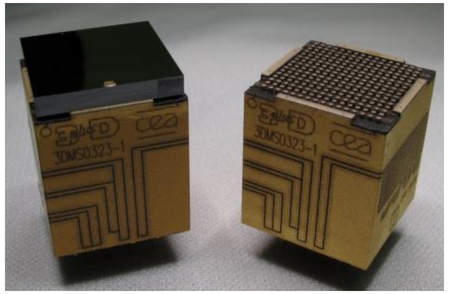
Caliste-O



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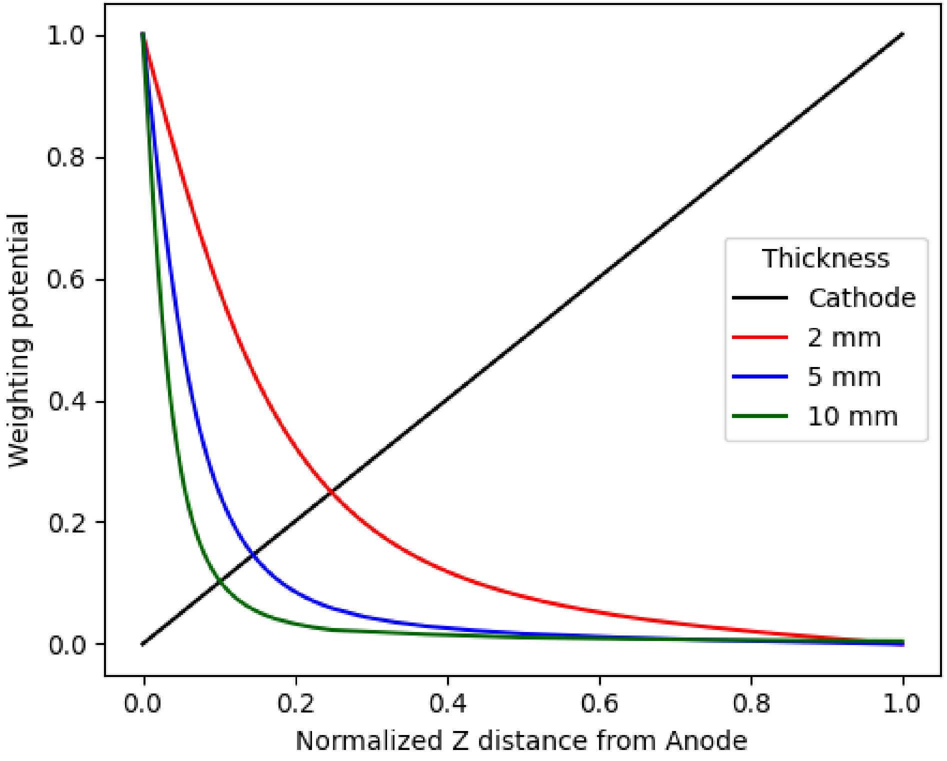
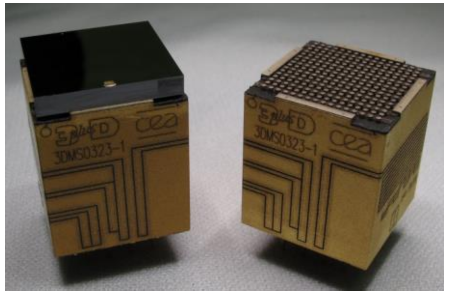


Cadtool

Charge Cloud Dynamics

- **Charge Drift Model:**
  - [Benoit & Hamel, 2009] diffusion and repulsion spherical model

Caliste-O



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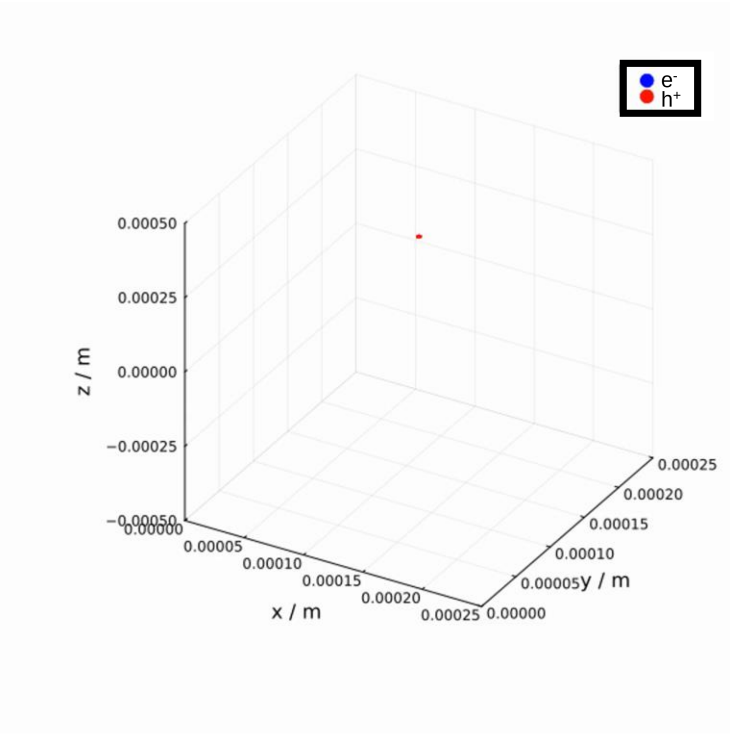
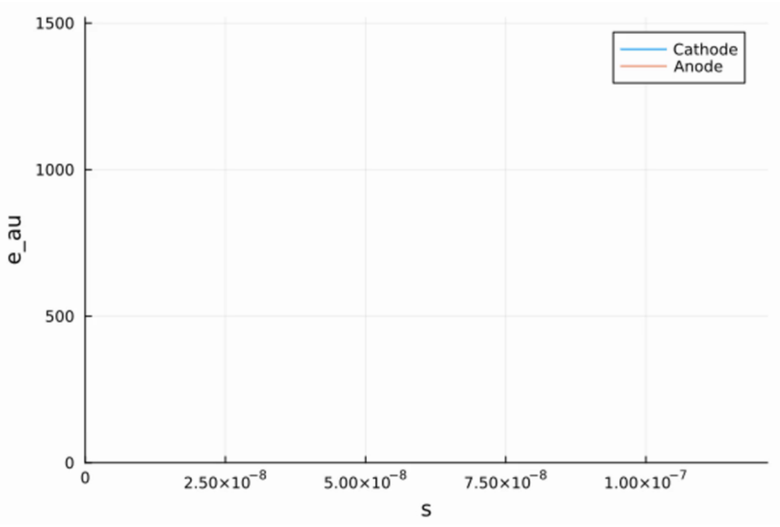
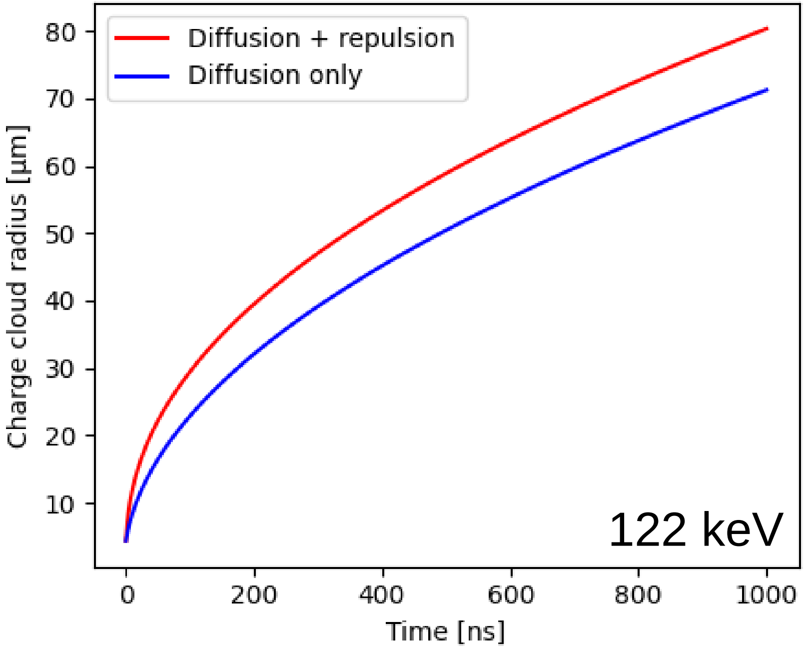


Induced charge on electrodes





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$\mu_e = 950\ cm^2V^{-1}s^{-1}$

$\mu_h = 73\ cm^2V^{-1}s^{-1}$

$T = 300\ K$

$\tau_e = 1.2 \times 10^{-6}\ s$

$\tau_h = 4.6 \times 10^{-6}\ s$

$\epsilon_{CdTe} = 4.42\ eV$

Cadtool

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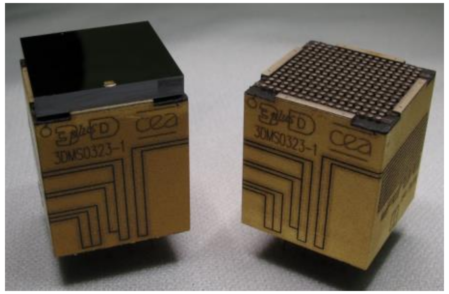

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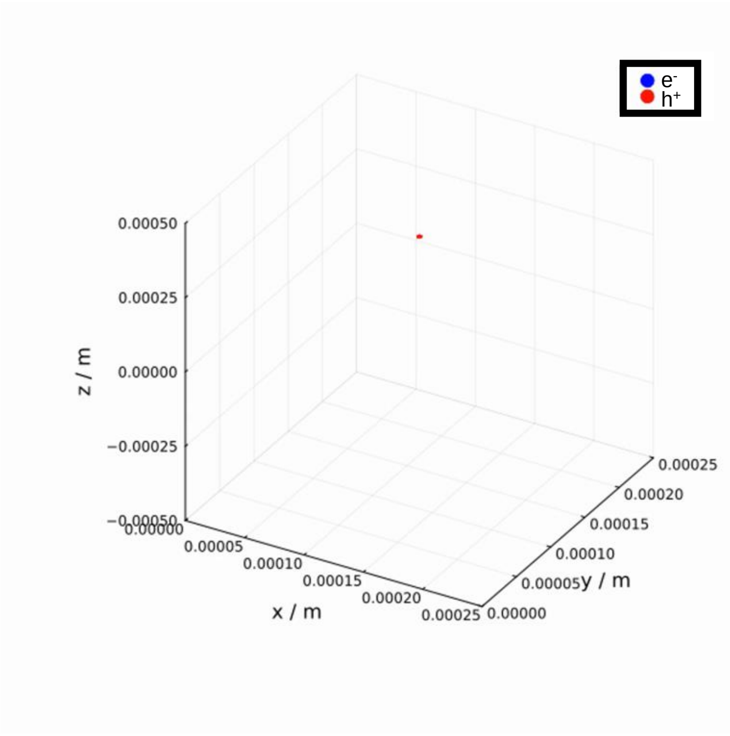

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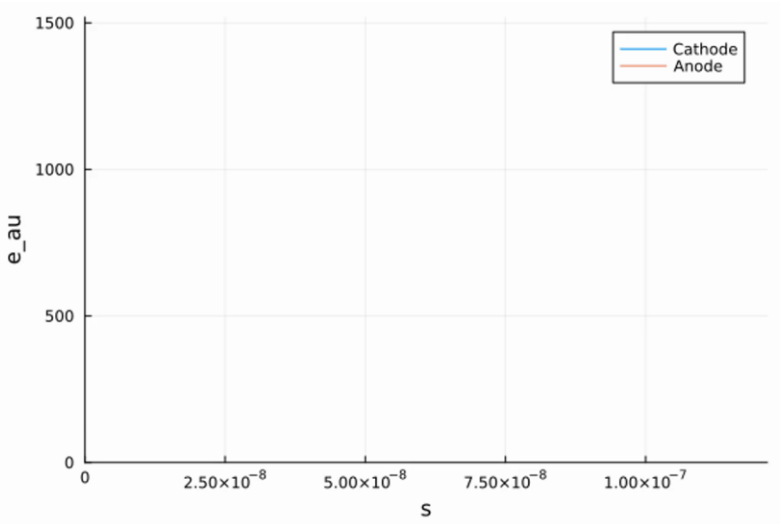

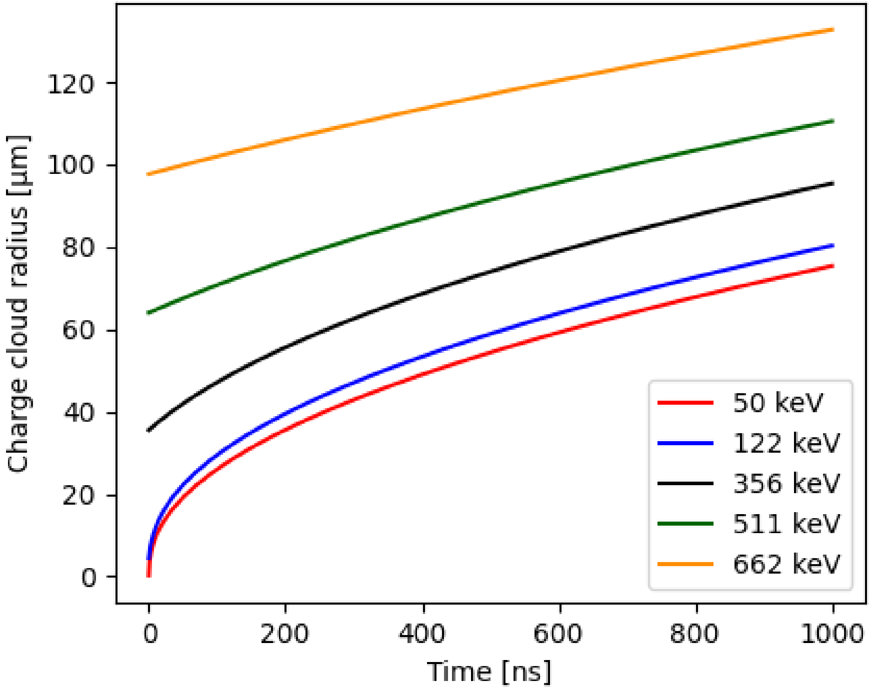

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Cadtool

Charge Cloud Dynamics

- **Charge Drift Model:**
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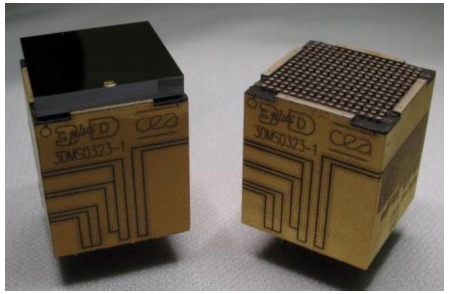
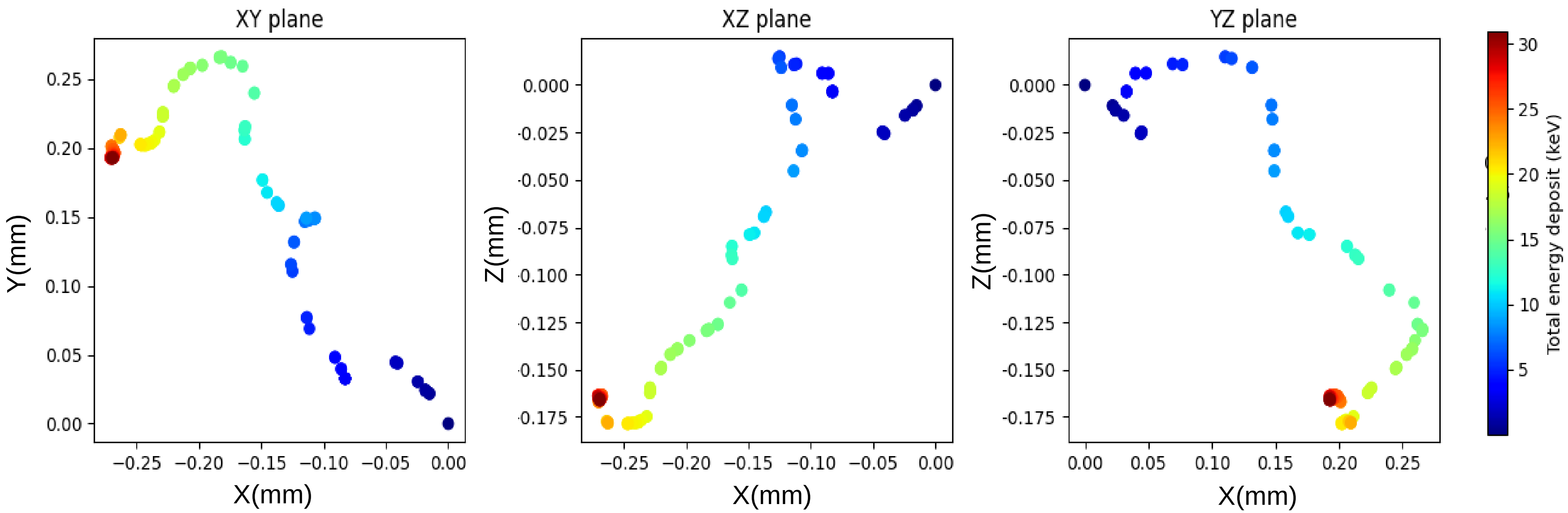
- **Initial Radius:**
  - GATE photoelectron path simulation

Caliste-O



2mm CdTe pixel 800µm

700 keV



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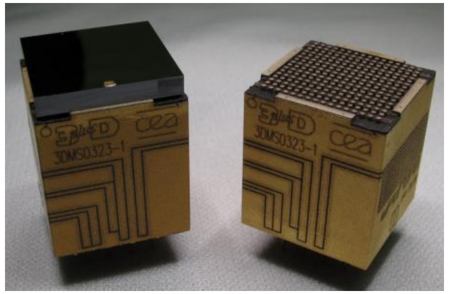
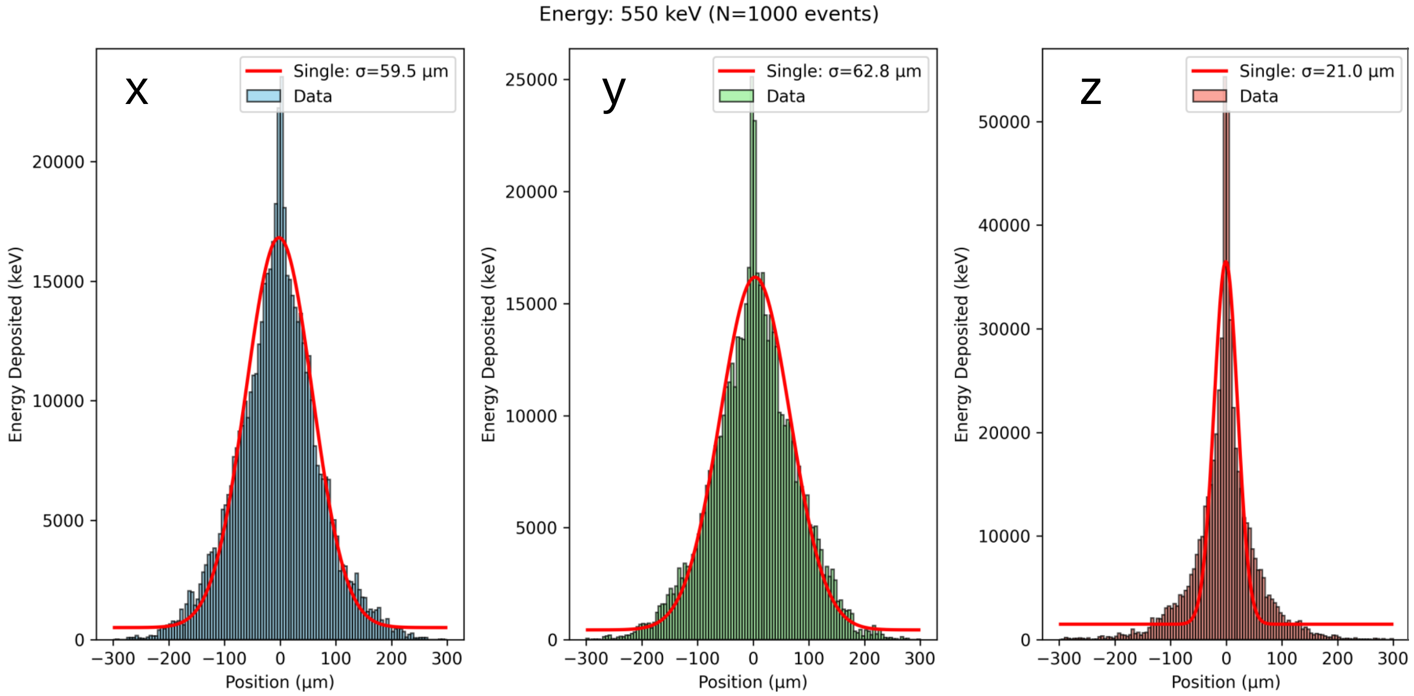


2mm CdTe pixel 800µm

$$D_0 = FWHM = 2.35\sigma$$

$$R_0 = \frac{avrg(FWHM_{xyz})}{2}$$



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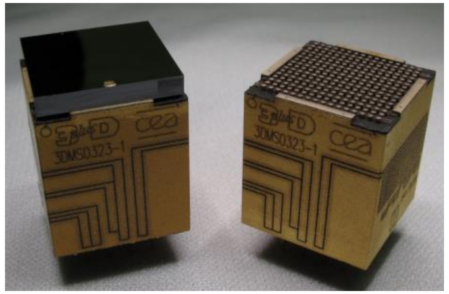
- **Trapping:**
  - 0-1 random probability by time-step

$$N_e(t) = N_0 e^{\left(\frac{-t}{\tau_e}\right)}$$

$$N_h(t) = N_0 e^{\left(\frac{-t}{\tau_h}\right)}$$

Caliste-O



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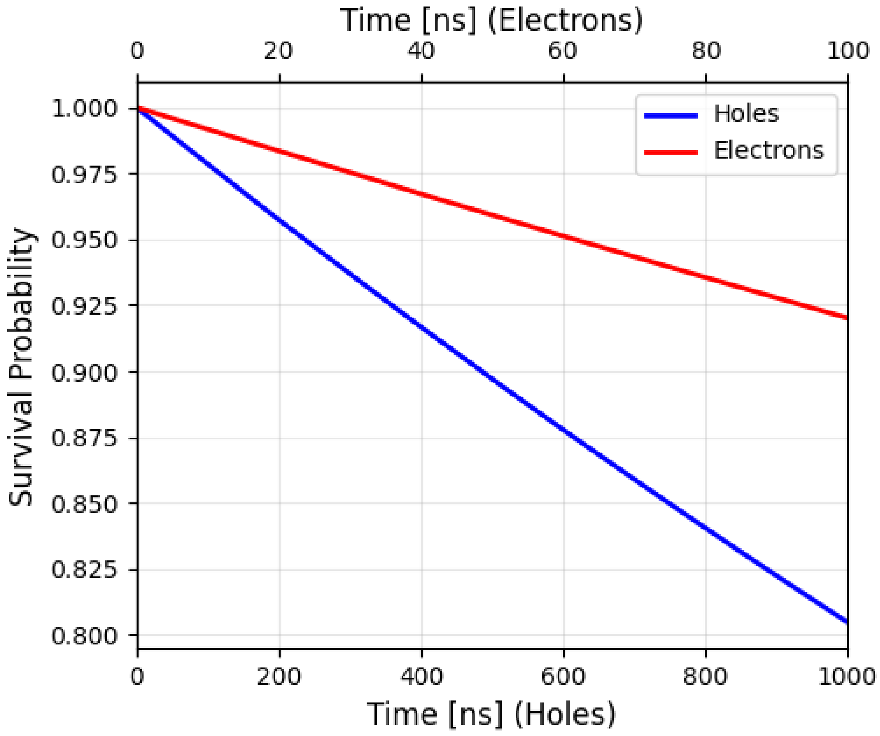

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Sanity Check : Hecht relations

$$\frac{Q}{Q_{theory}} = \frac{V_0}{D^2}\left(\mu_e\tau_e\left(1-e^{-\frac{t_e}{\tau_e}}\right)+\mu_h\tau_h\left(1-e^{-\frac{t_h}{\tau_h}}\right)\right)$$

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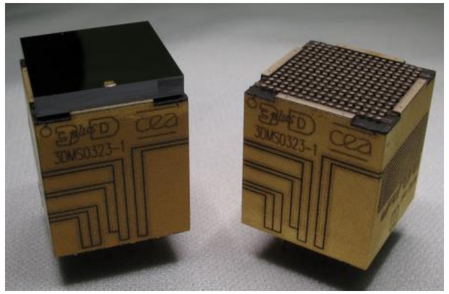

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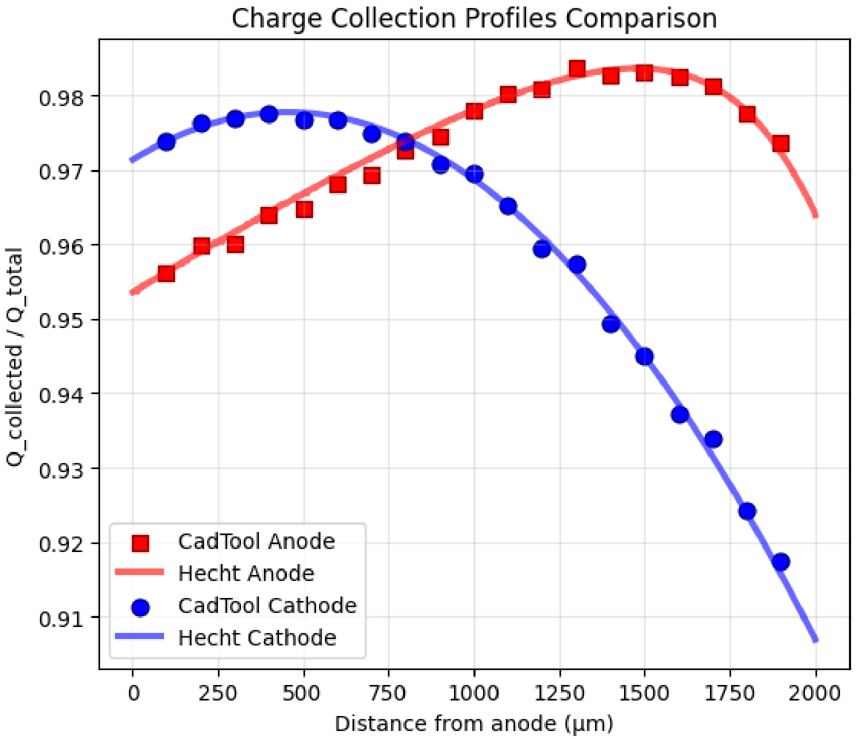

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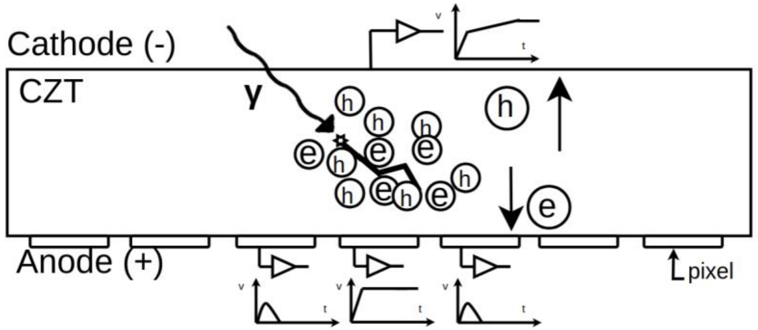
Simulation Tool



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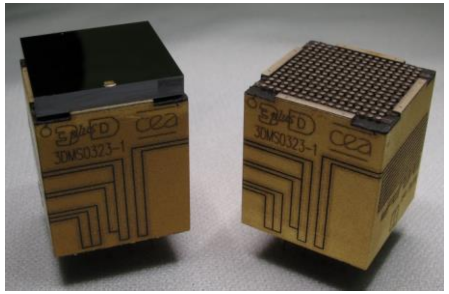
Charge Induced Efficiency

- **Charge Induced Efficiency (CIE):**
  - Create 3D mesh of section of detector
  - Drift charges for each point

$$CIE_{xyz} = \frac{Q_{collected}}{Q_{initial}}$$

Caliste-O



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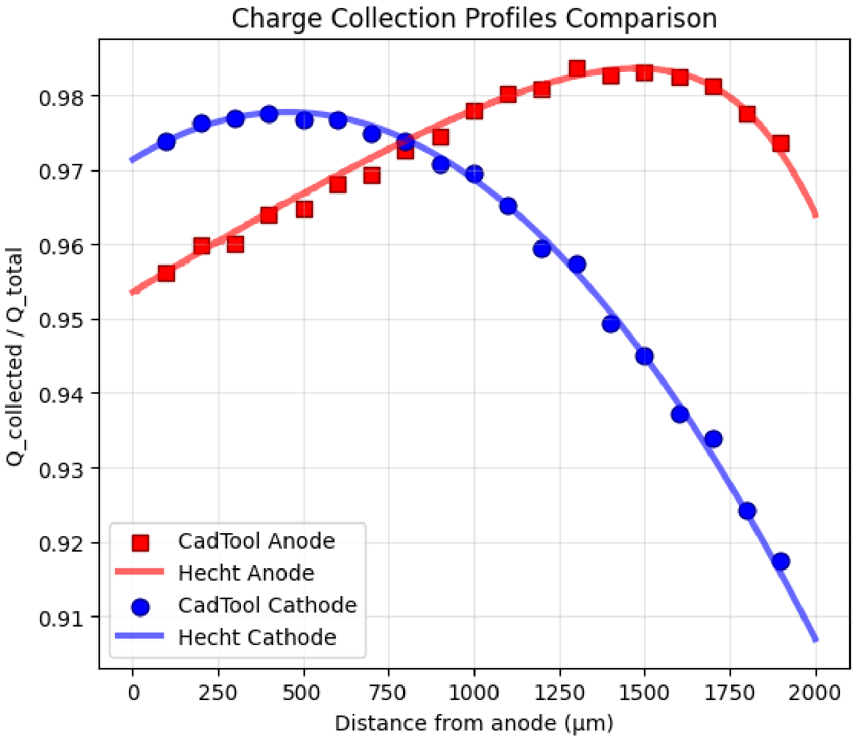

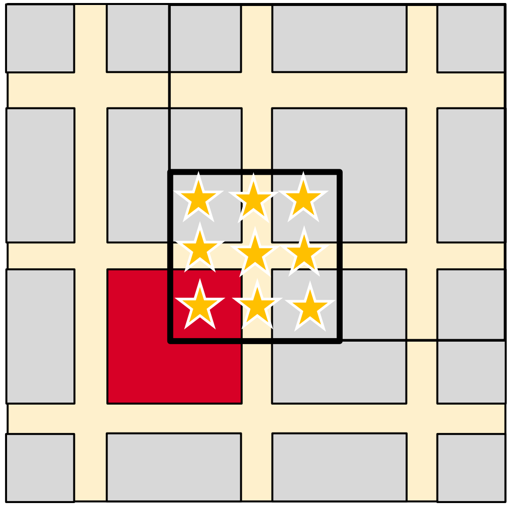

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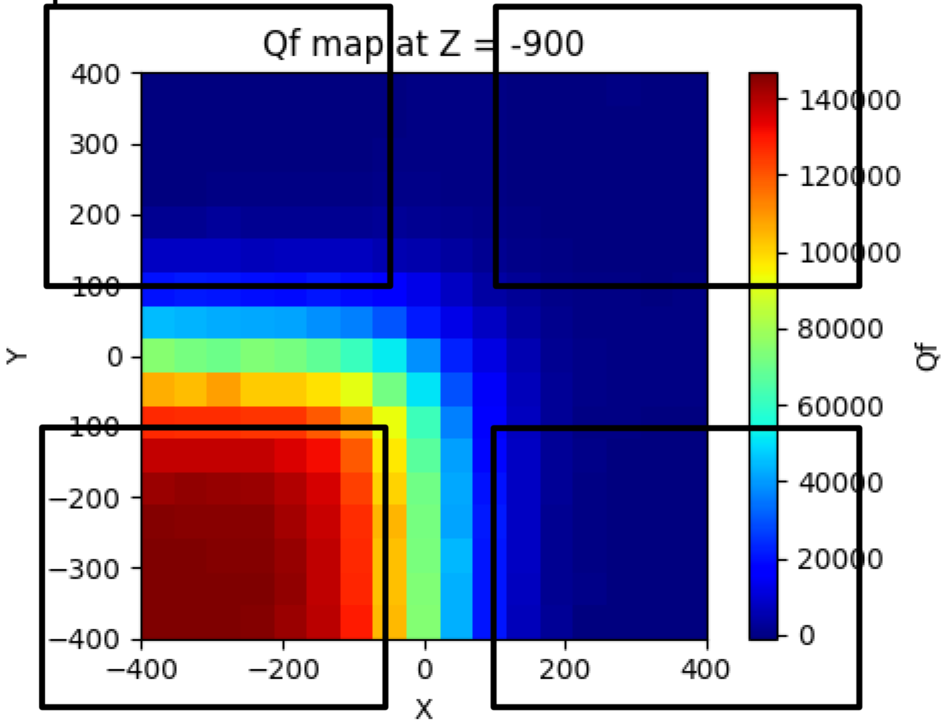

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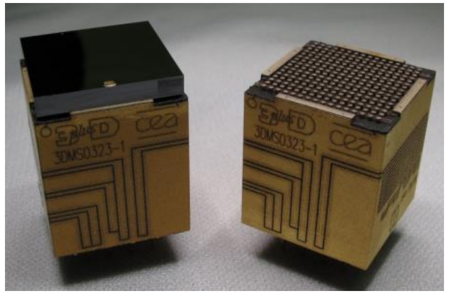

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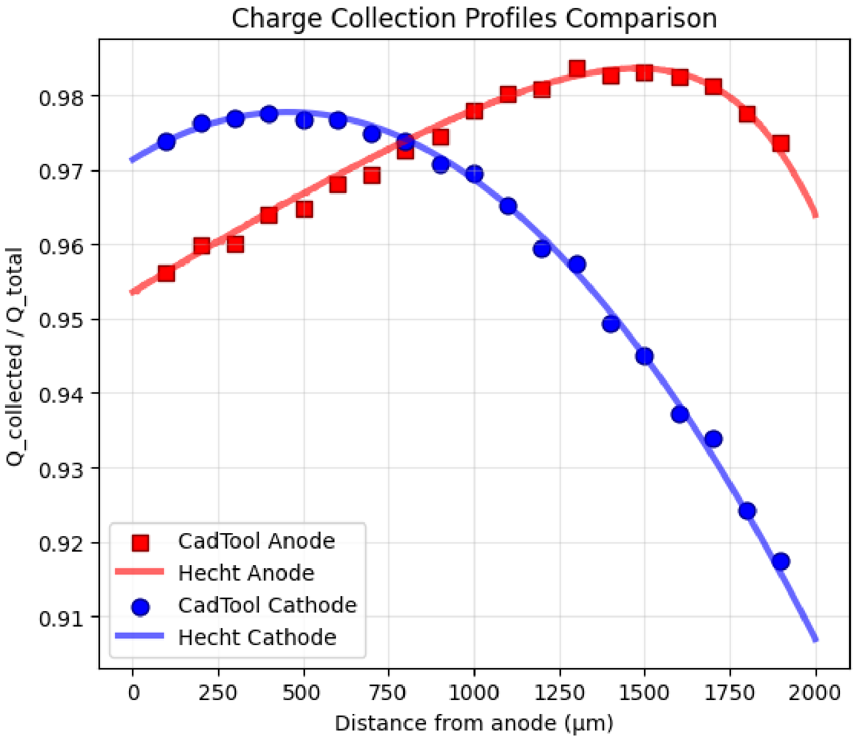

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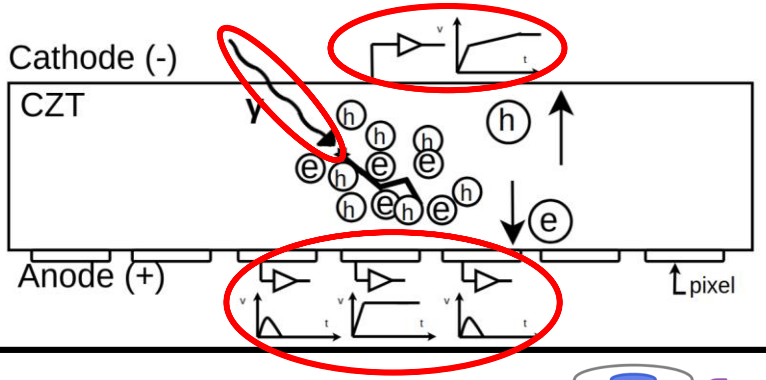

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opengatecollaboration.org

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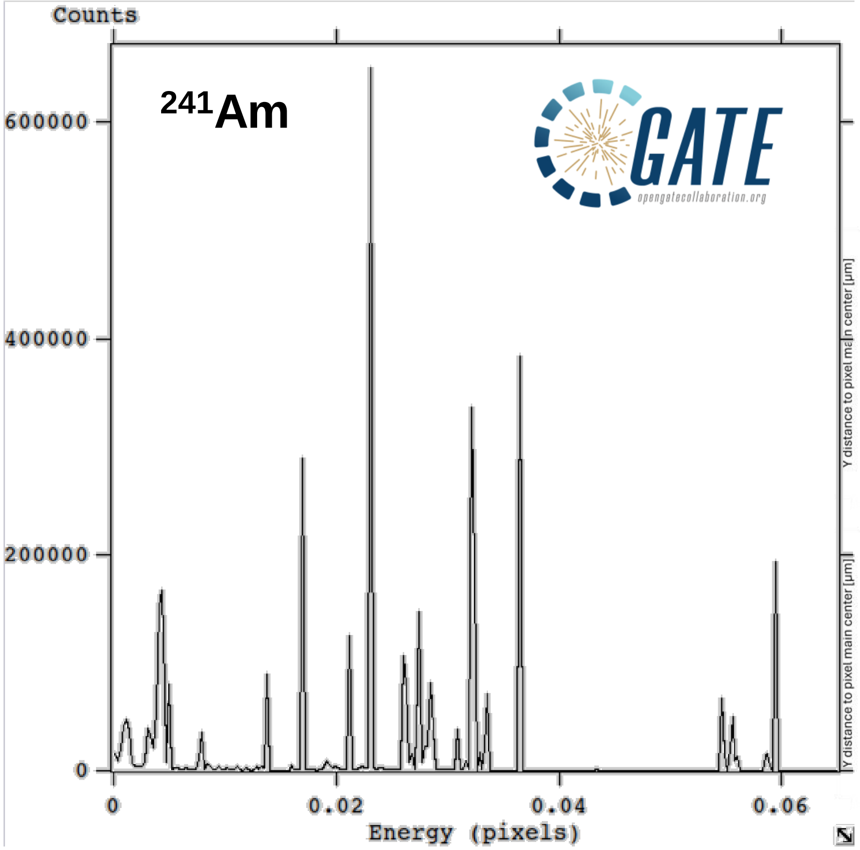
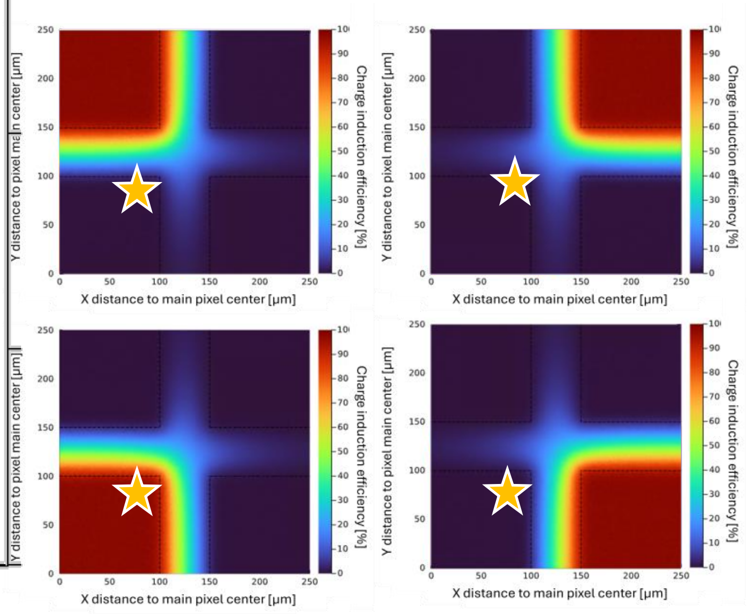
Cadtool

Event List Generation

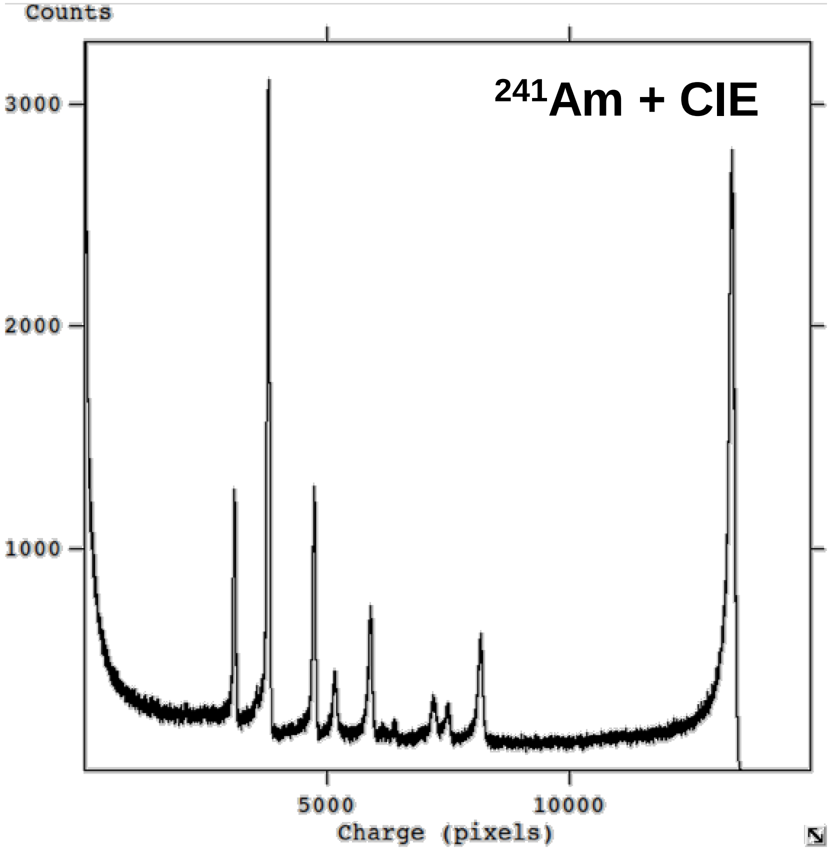
Source Configuration



Symmetric CIEs



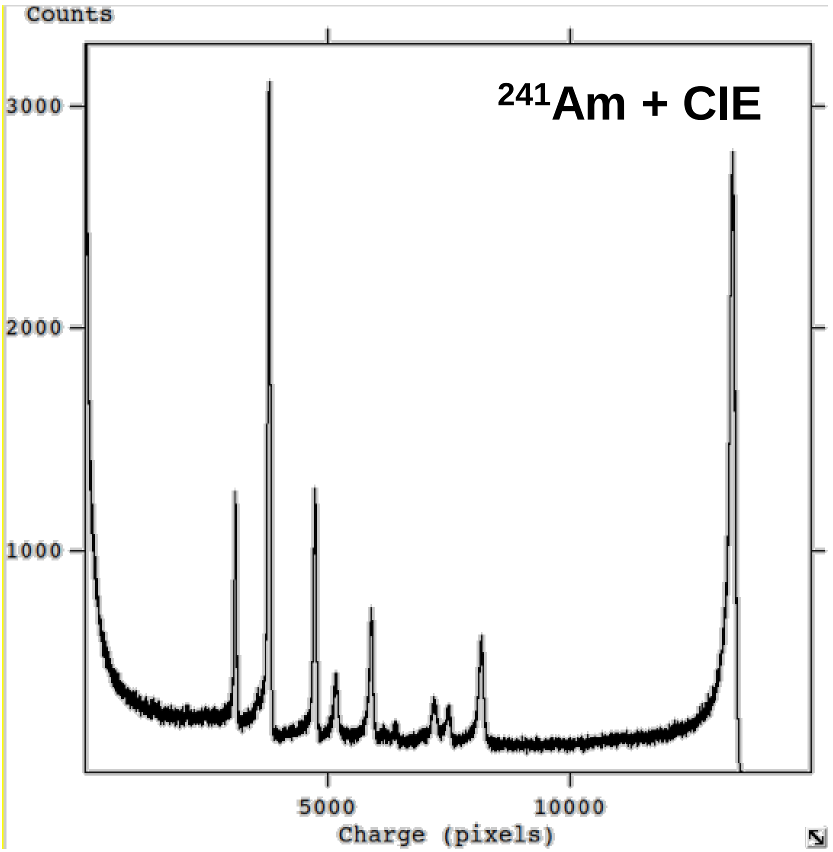
4 Multiplicity limit



Cadtool

Event List Generation

Output a readout list
1 Time
2 List of electrode index
3 List of PHA (in ADU)



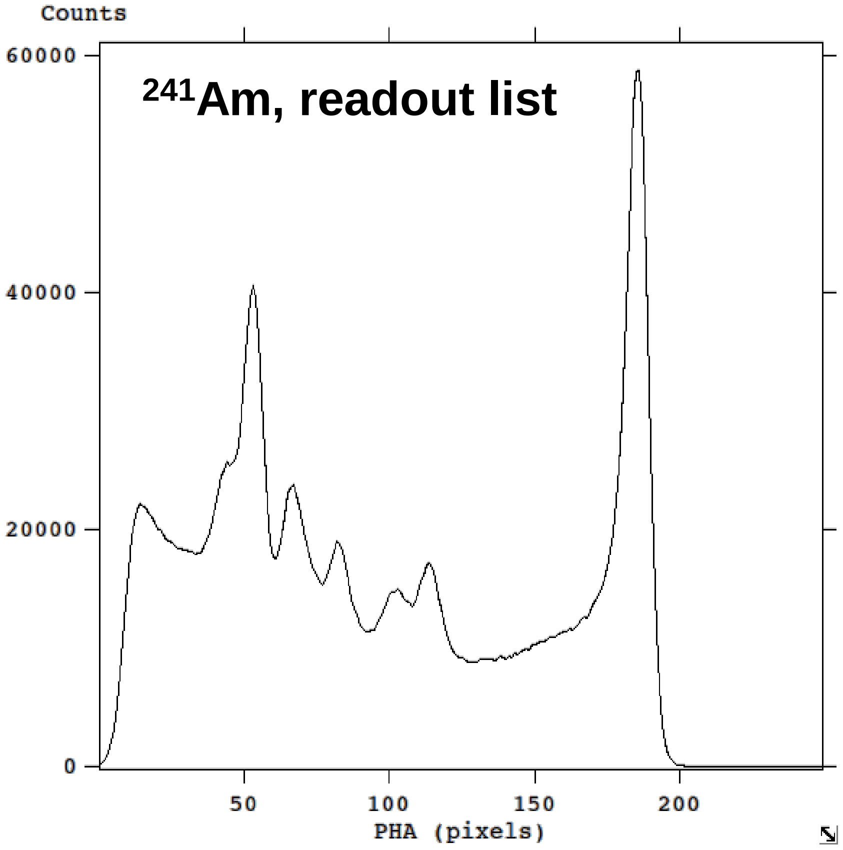
Electronic readout

Modular Configuration

Our use case

Front-end characteristics:
ADC, Threshold, filter
ENC, timing, deadtime

Back-end characteristics:
File format



Cadtool

Simulation Tool Requirements

CadTool

Inputs

Detector Parameters
Material, Pixel/Strip, Bias, Mobility, Lifetime, Fano

Enviroment Geometry
Box, Passive material, collimator, etc

Source Configuration
Geometry, Energy, Intensity

Electronics
ENC, ADC range, Threshold

Detector Physics

Solid State Detectors

Electric Field and Potential

Weighting Potential

Charge Drift
- Trapping
- Diffusion
- Repulsion

Event list generation

Photon-matter interaction

GATE
opengatecollaboration.org

Electrode charge induced

Front-end & Back-end electronics

Outputs

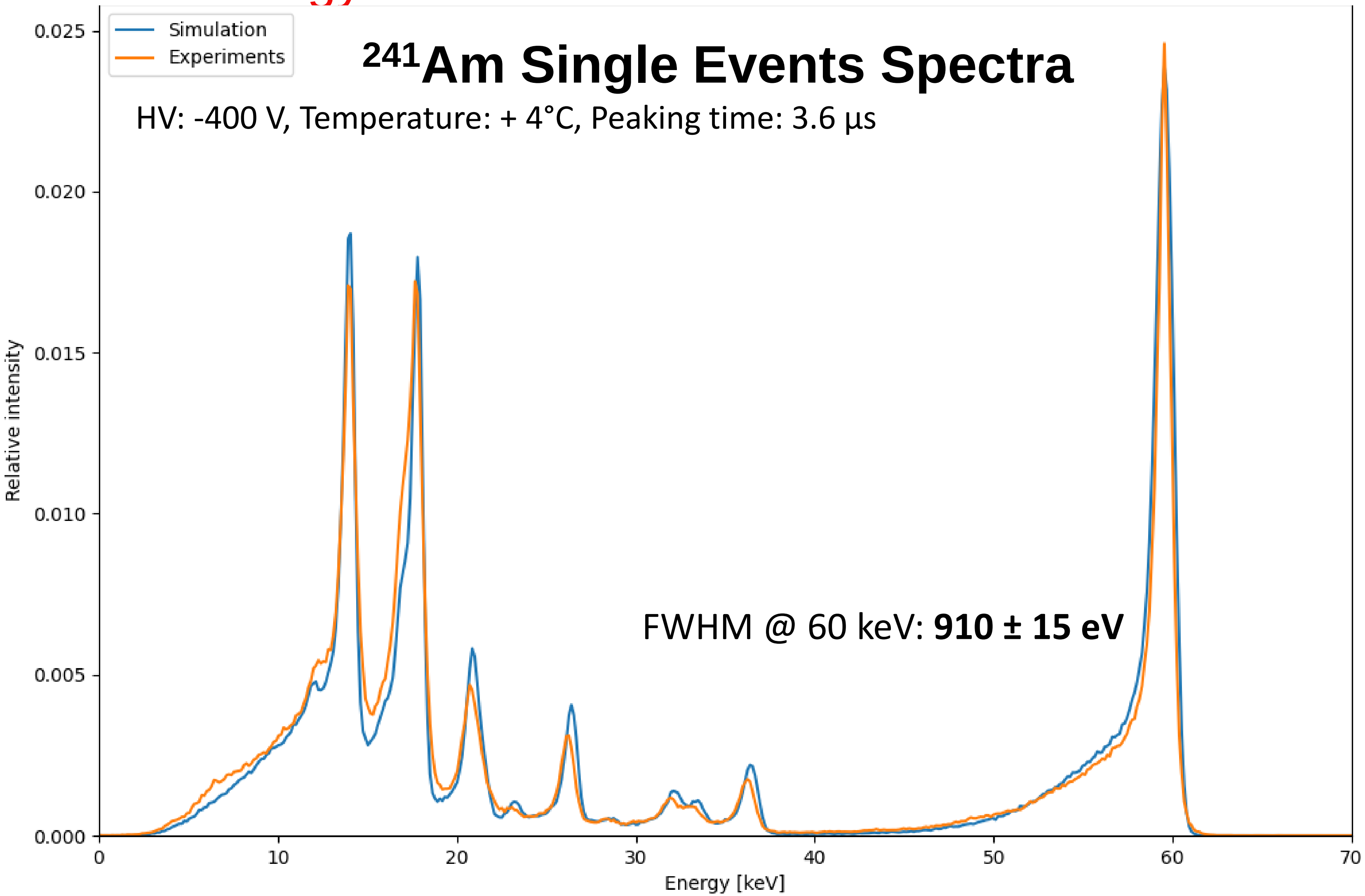
Transient Signals
- Charge profile
- Current profile

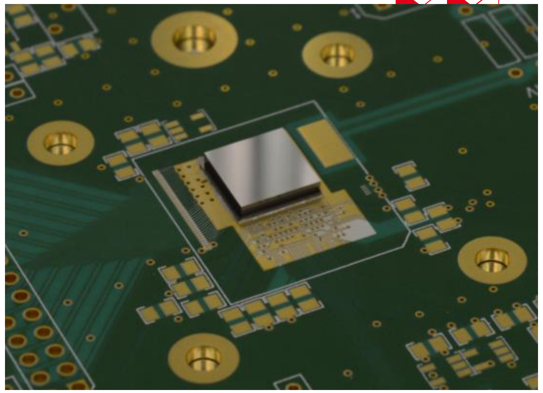
[redacted]alysis
[redacted]es
- s[redacted]um
[redacted]rve
[redacted] matrix

Cadtool

Low Energy Validation

< 100 keV



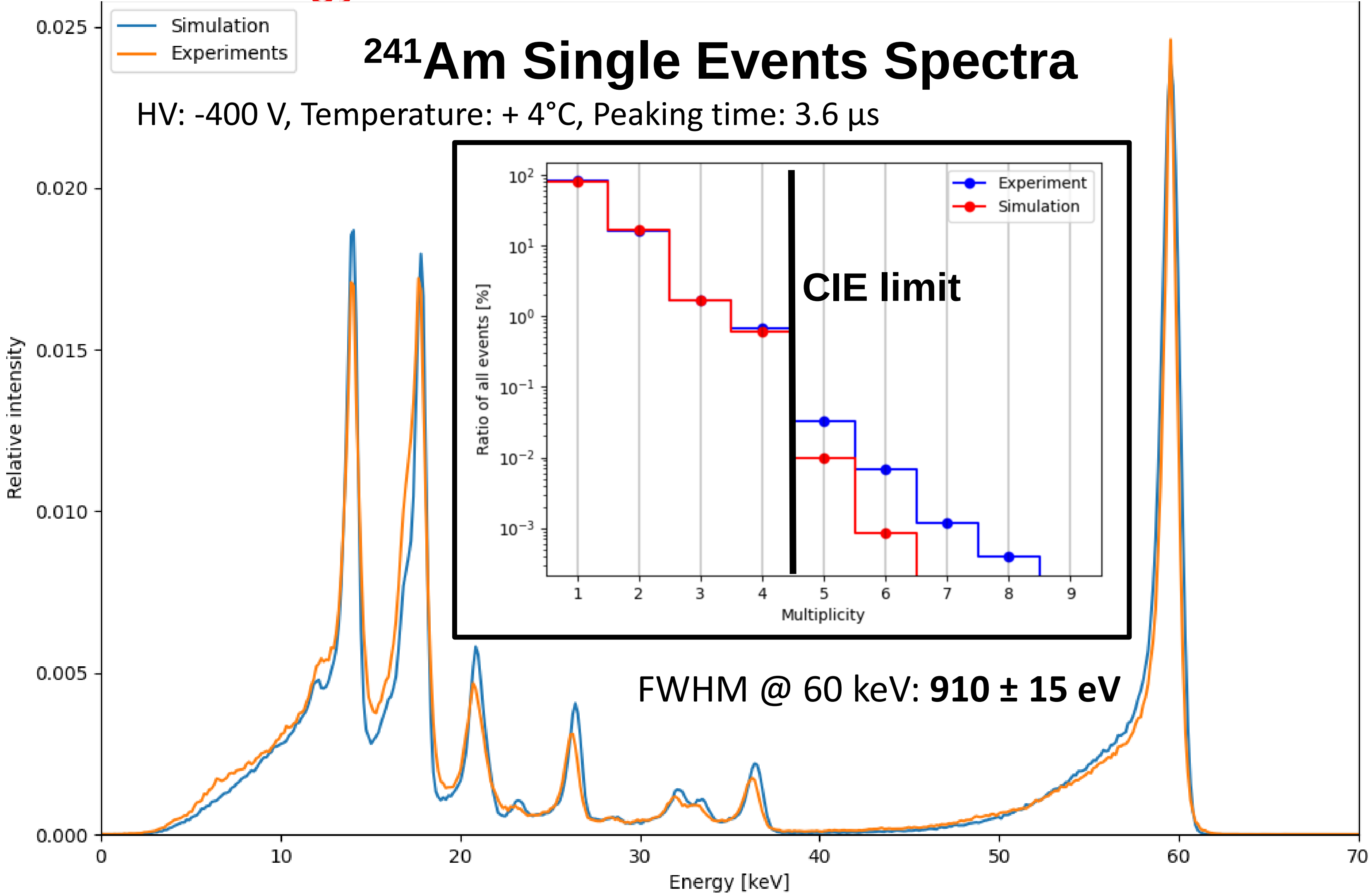


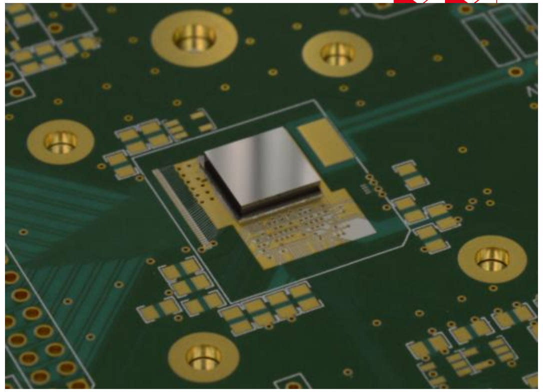
Mini-CdTe on Chip (MC^2)-1K
32 x 32 pixels,
8 x 8 mm^2 sensitive area
1 mm-thick
Schottky-diode type CdTe
250 µm pixel pitch

Cadtool

Low Energy Validation

< 100 keV





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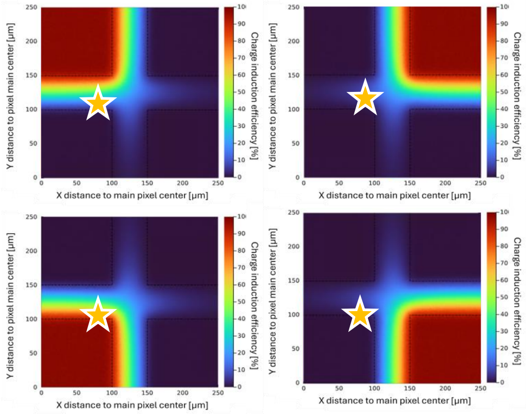
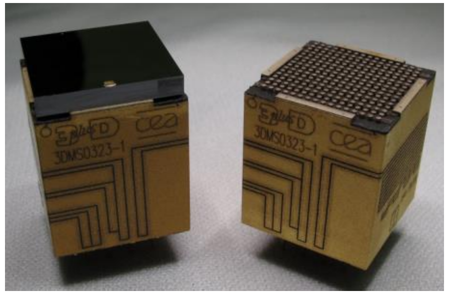


Cadtool

High Energy Validation

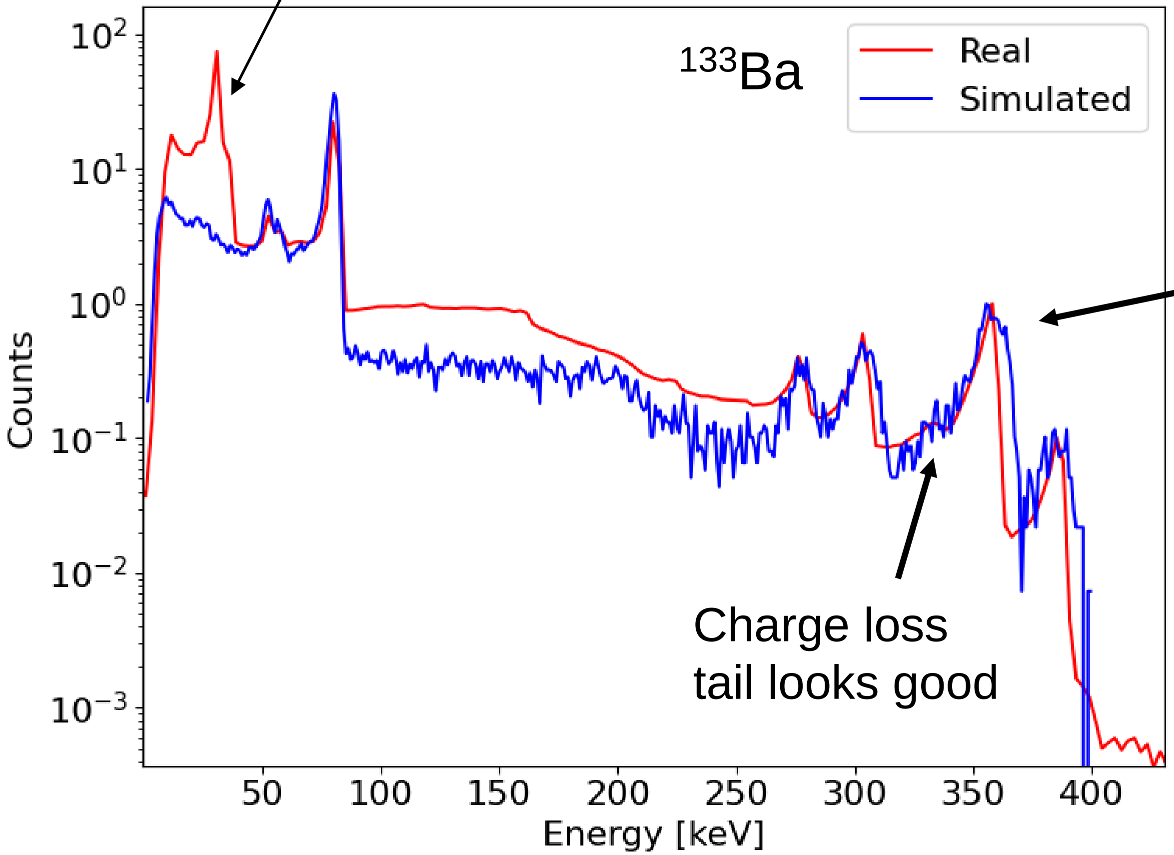
< 1 MeV

Caliste-O



2mm CdTe pixel 800µm

Didn't put Cs daughter fluorescence on Simulation source



Charge loss tail looks good

ENC badly modeled / Bad calibration (user problem)

$E = 300\ Vmm^{-1}$ $\quad$ $T = 300\ K$ $\quad$ $\epsilon_{CdTe} = 4.42\ eV$

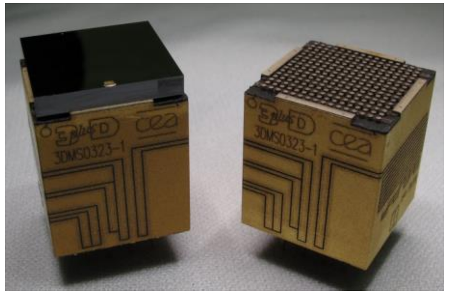
$\mu_e = 950\ cm^2V^{-1}s^{-1}$ $\quad$ $\tau_e = 1.2 \times 10^{-6}\ s$

$\mu_h = 73\ cm^2V^{-1}s^{-1}$ $\quad$ $\tau_h = 4.6 \times 10^{-6}\ s$

Cadtool

High Energy Validation

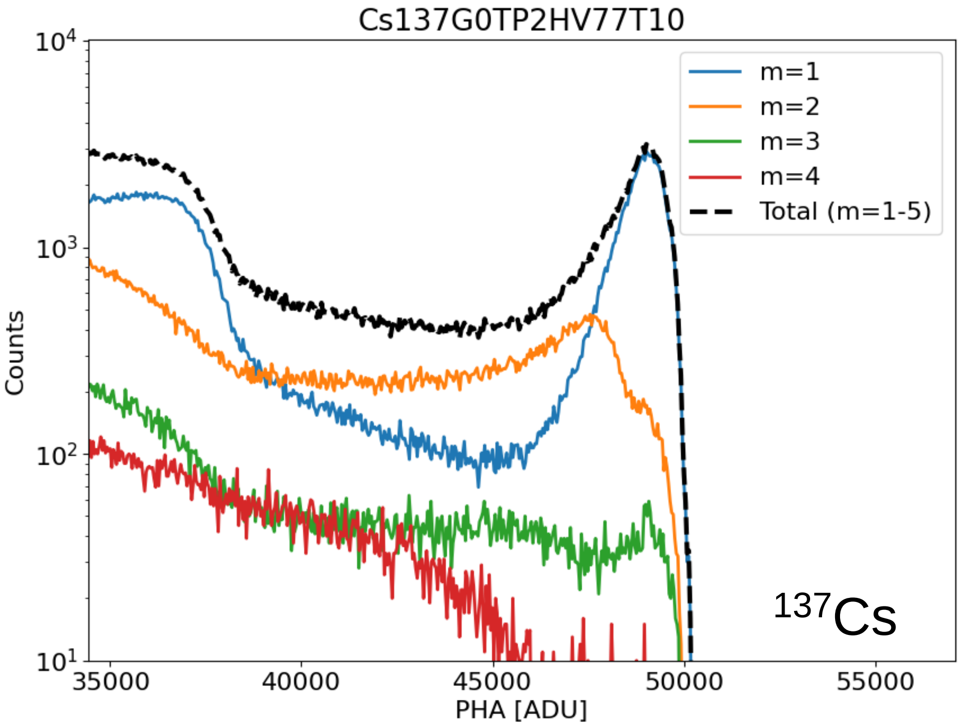
Caliste-O



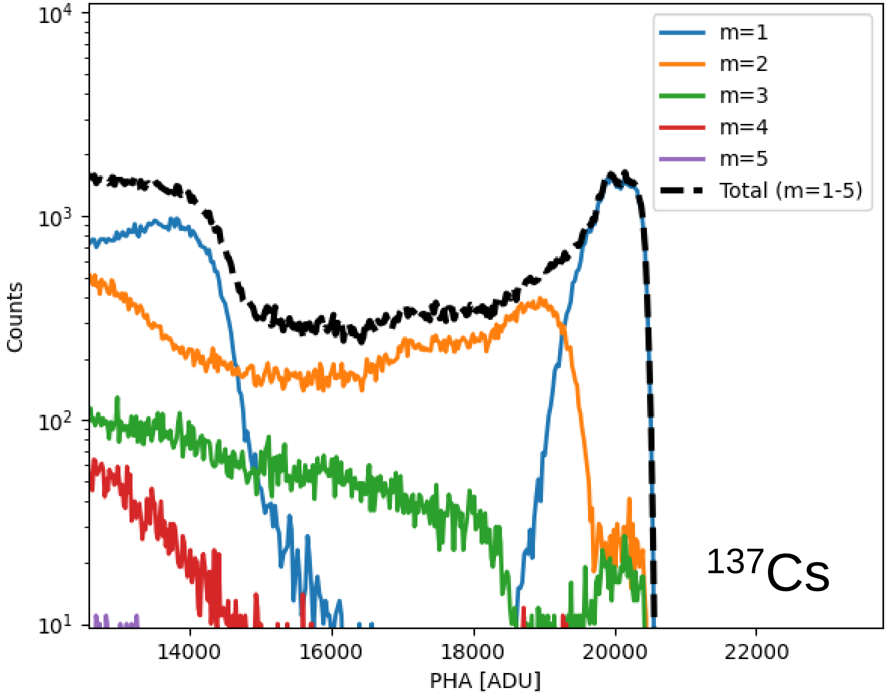
2mm CdTe pixel 800µm

Work in progress

Real Caliste-O data



Simulated Caliste-O data



Cadtool

Simulation Tool Requirements

CadTool

Examples

Inputs

Detector Parameters
Material, Pixel/Strip, Bias, Mobility, Lifetime, Fano

Enviroment Geometry
Box, Passive material, collimator, etc

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Electrode charge induced

Front-end & Back-end electronics

Outputs

Transient Signals
- Charge profile
- Current profile

Data analysis
- images
- spectrum
- lightcurve
- response matrix

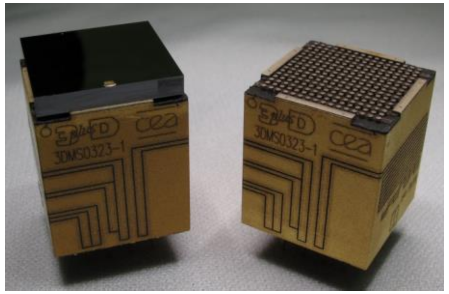
Cadtool

Possible use case, 3D compensation

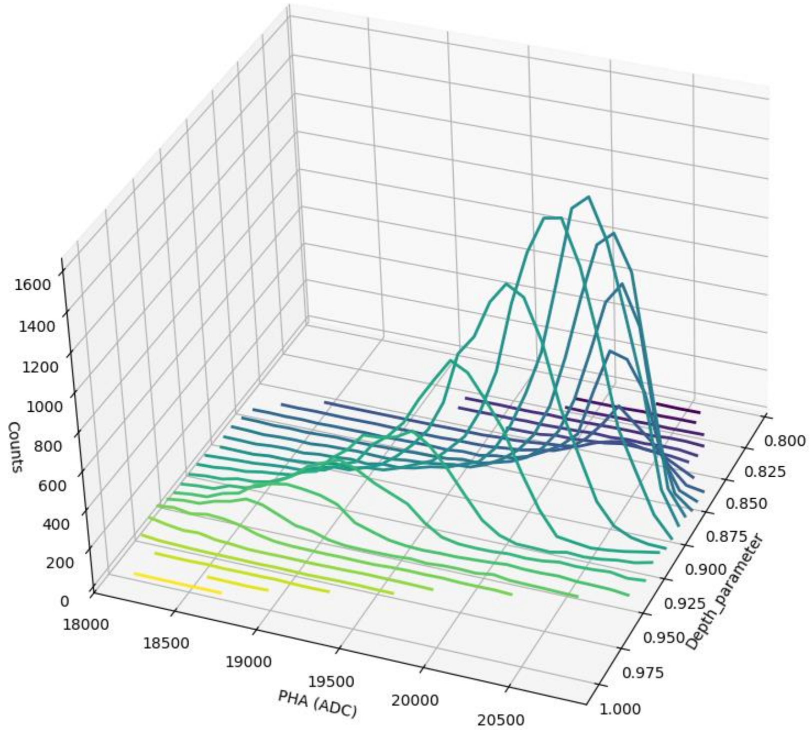
$$doi = \frac{Q_{cathode}}{Q_{anode}} \propto D$$

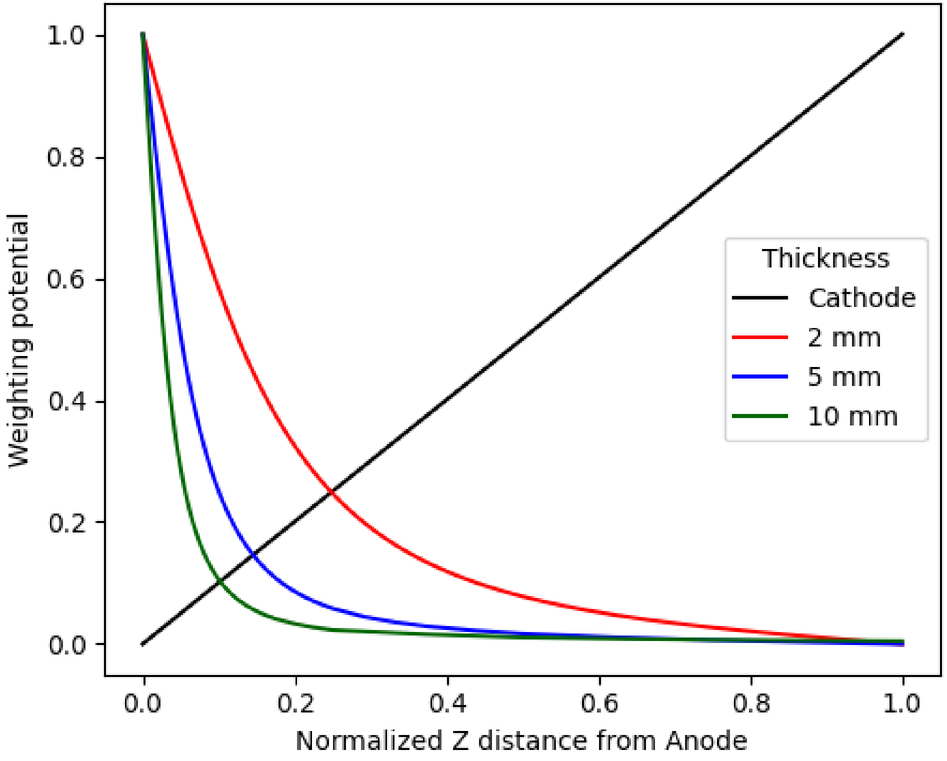
Specially when there is small pixel effect

Caliste-O



2mm CdTe pixel 800µm





Cadtool

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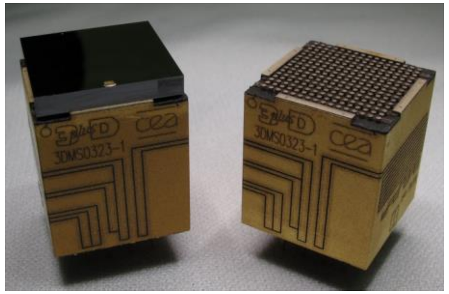
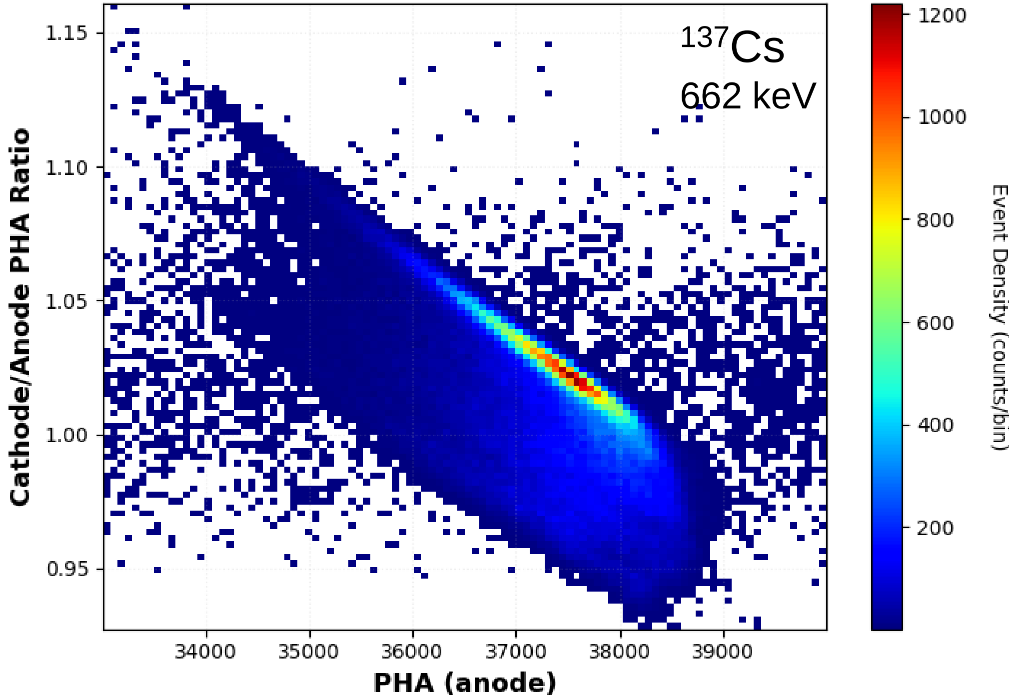


2mm CdTe pixel 800µm

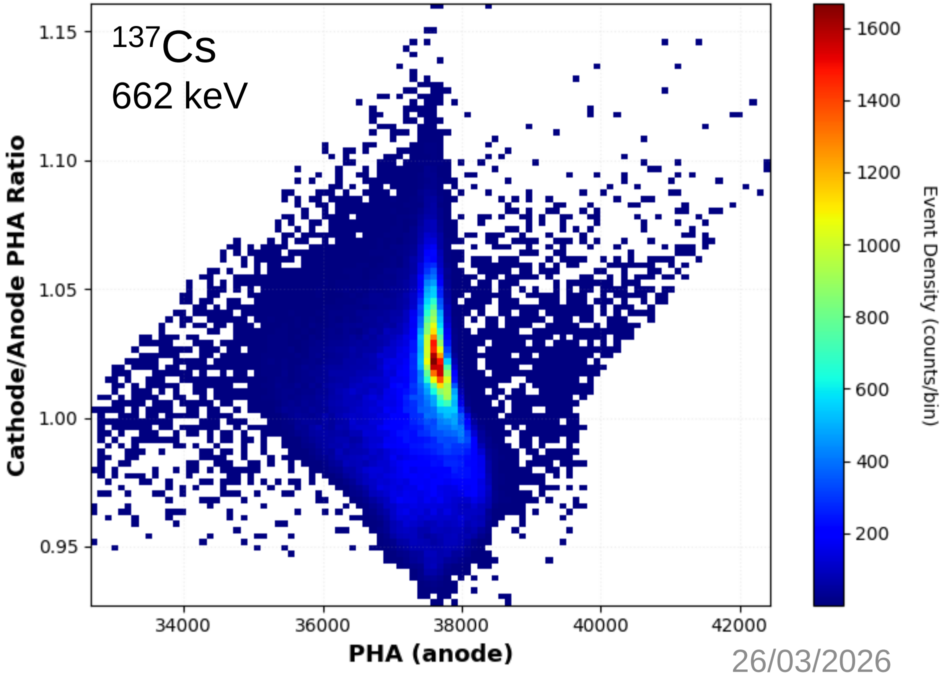
Pre-Correction

Simulation data



After Correction

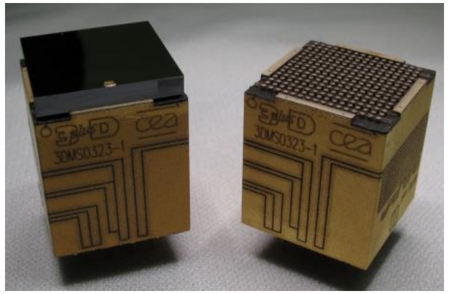
Simulation data



Cadtool

Possible use case, 3D compensation

Caliste-O



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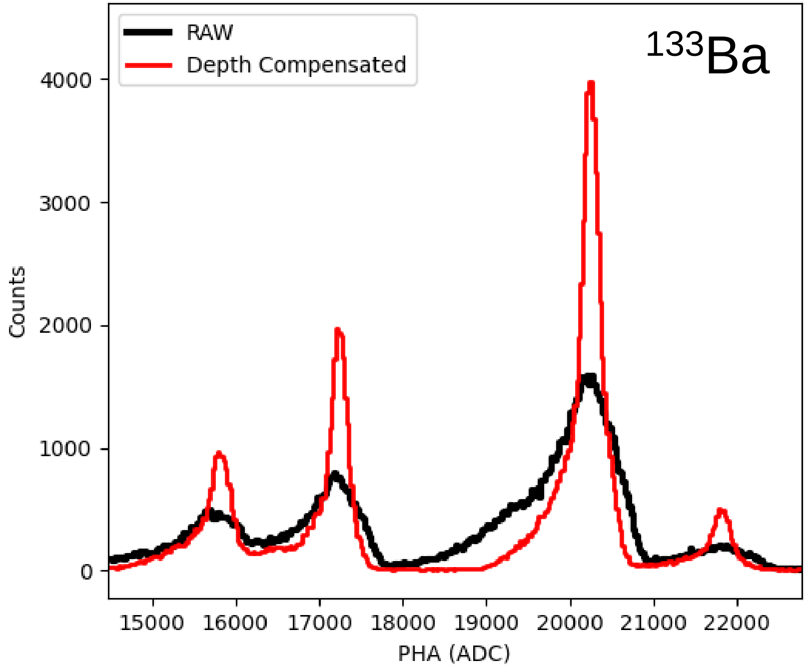
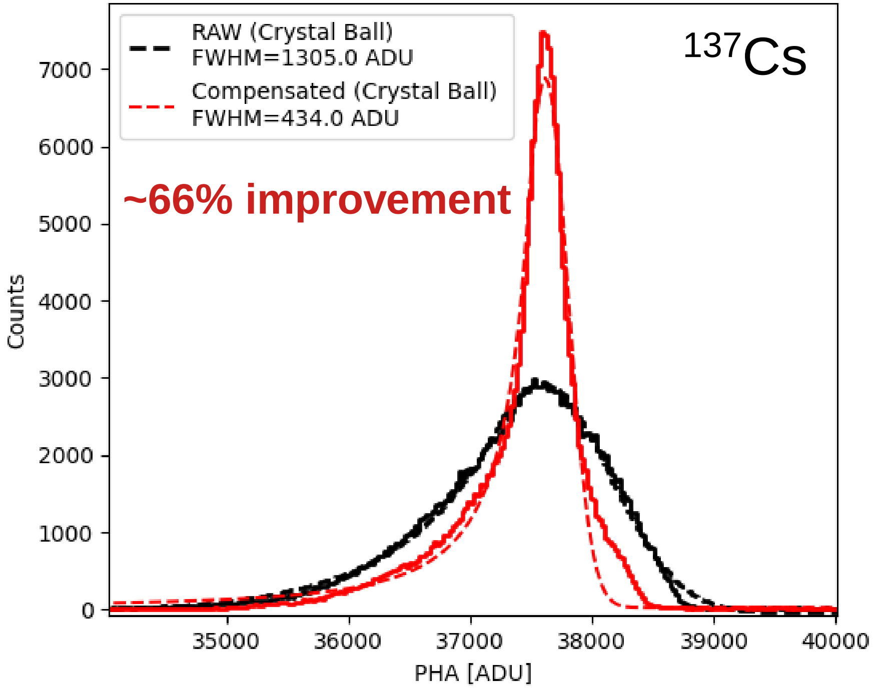


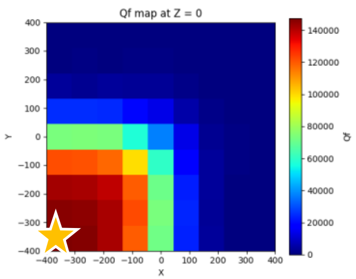
How much can we improve spectral response with cathode readout?

Simulation data



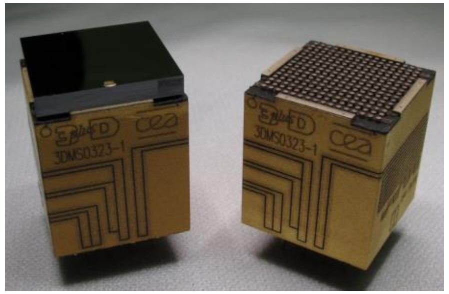
Cadtool

Transient Curves



Input for electronics simulator
Cadence, SPICE

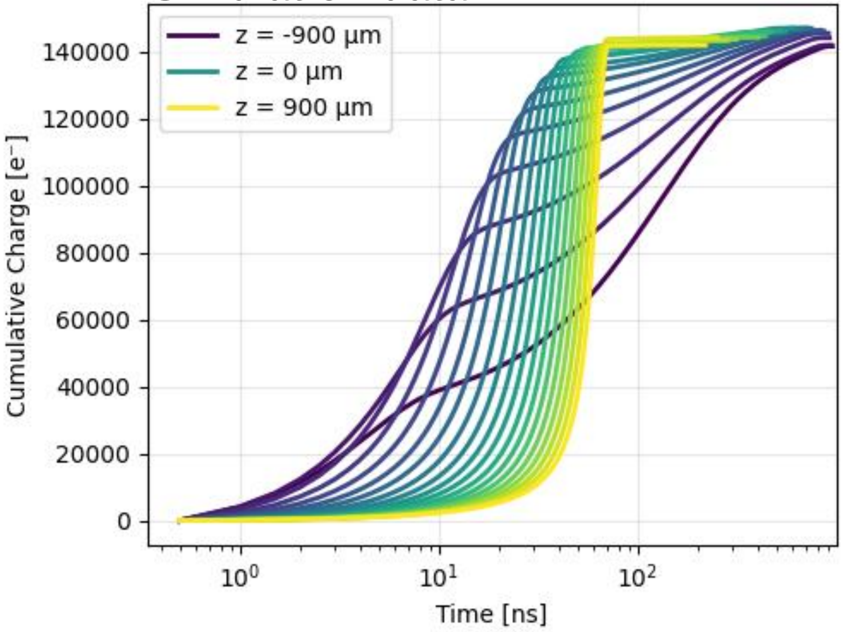
Caliste-O



2mm CdTe pixel 800µm

Main Pixel Charge Curve

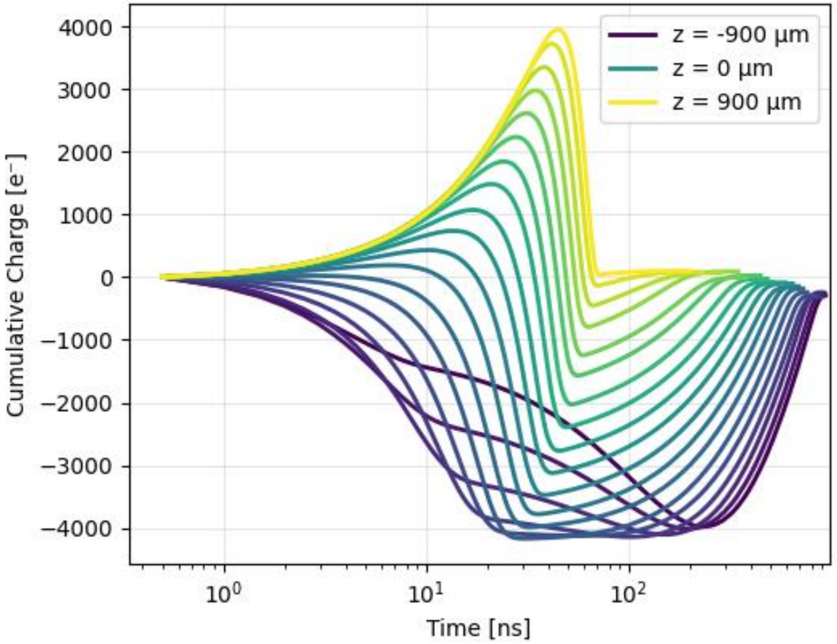
Simulation data



Can we use side neighbor Max/Min for 3D?

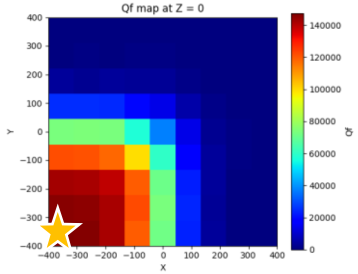
Side Neighbour Curve

Simulation data



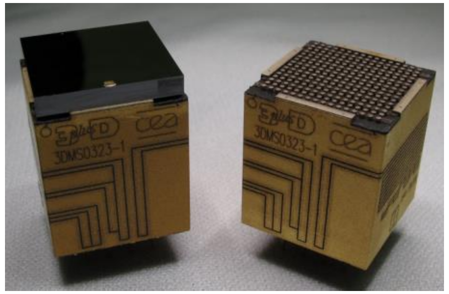
Cadtool

Transient Curves



Input for electronics simulator Cadence, SPICE

Caliste-O



2mm CdTe pixel 800µm

Main Pixel Charge Curve

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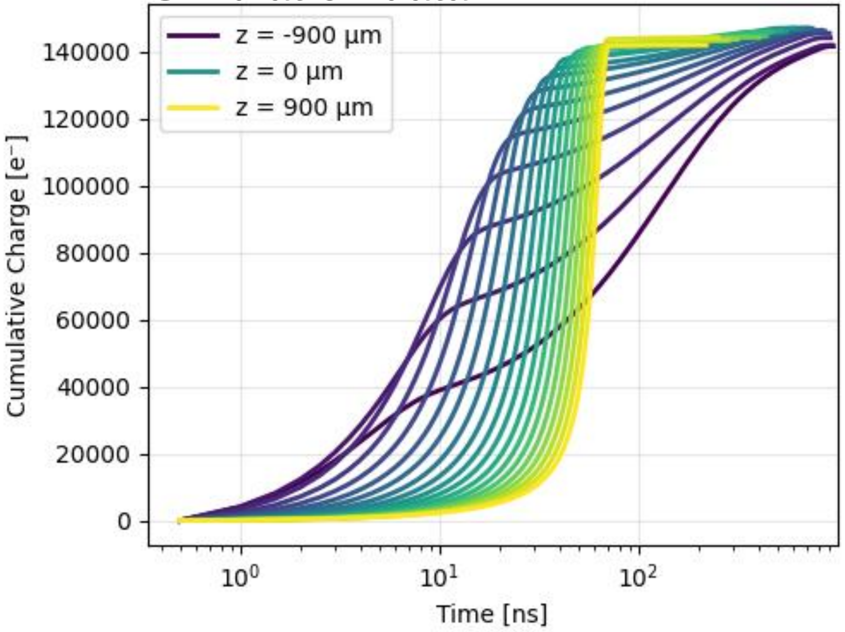
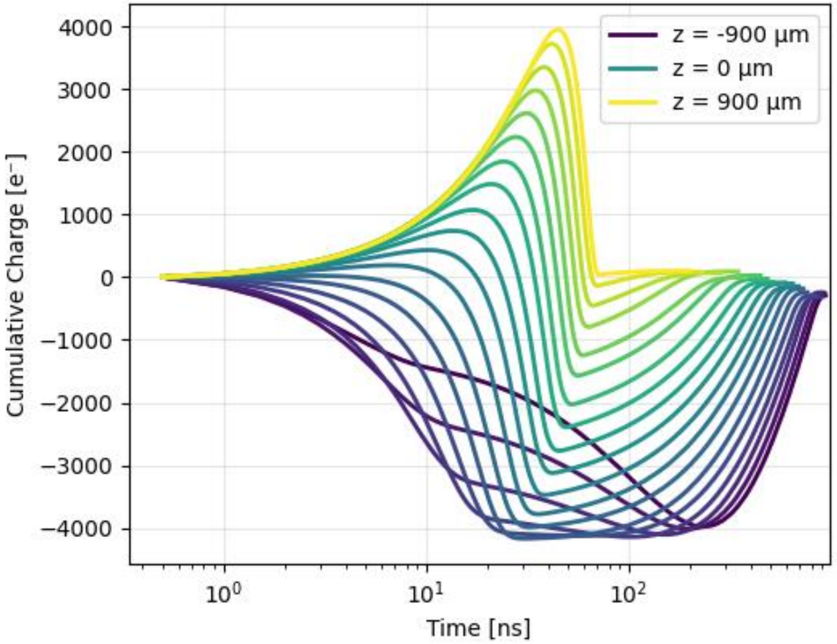


Can we use side neighbour Max/Min for 3D?

Which gives best performance, <u>cathode</u> or <u>side neighbour</u>?

Side Neighbour Curve

Simulation data



Future Work

Development

Larger CIE area

Implement Elipsoidal Charge Cloud

Validation

High Energy multiplicity with Caliste-O CdTe (ongoing)

Cathode side spectra with readout on Caliste-O (ongoing)

Validate charge cloud model ESRF (LIP Coimbra - Timepix3) and SPRING8 data (IPMU Tokyo - Strip)

Transient curves with real 5mm CZT integrated with TIA – anode and cathode

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<u>Larger CIE area</u>

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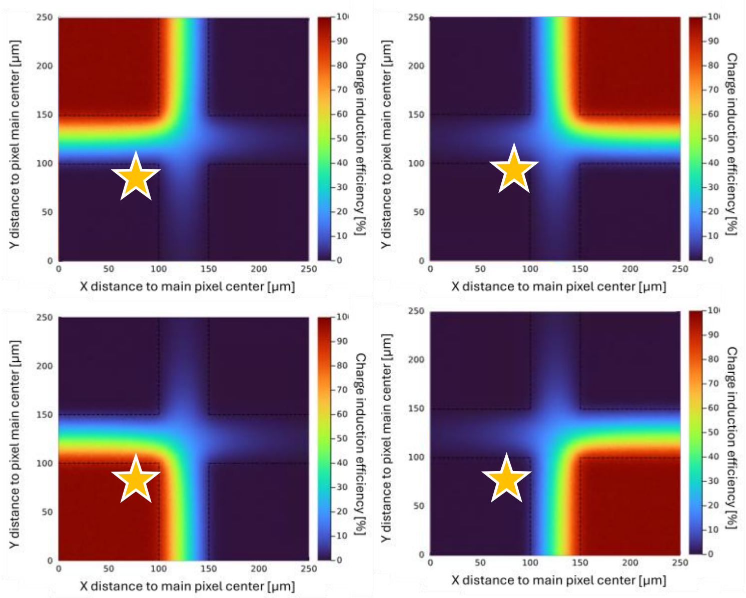

4 Multiplicity limit

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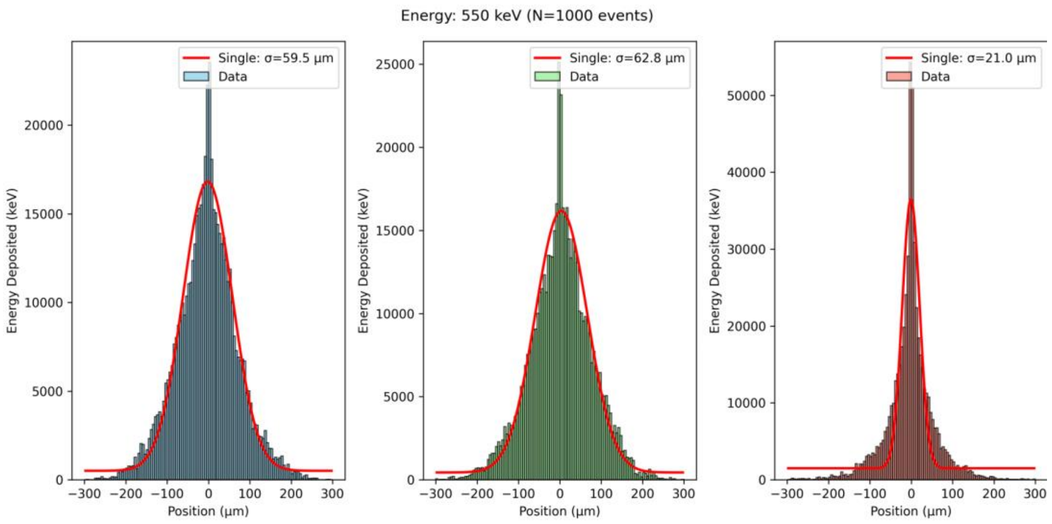

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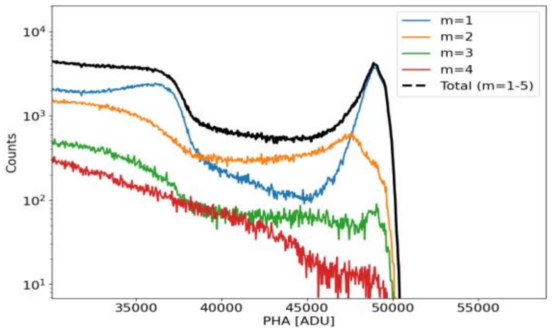
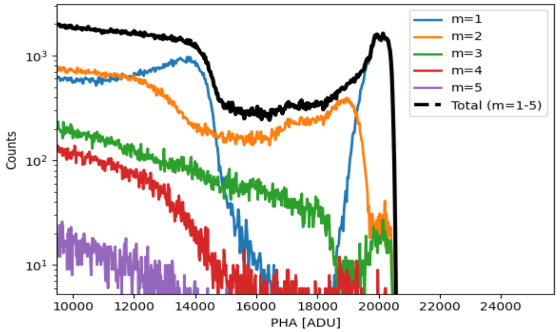
Real Caliste-O data



Simulated Caliste-O data



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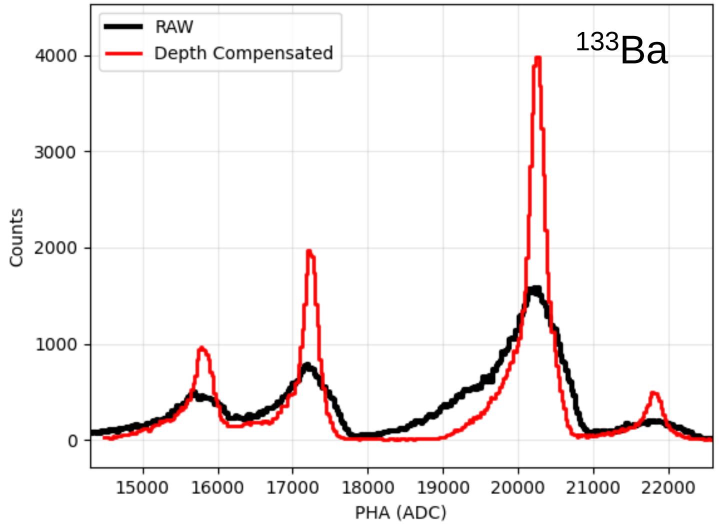

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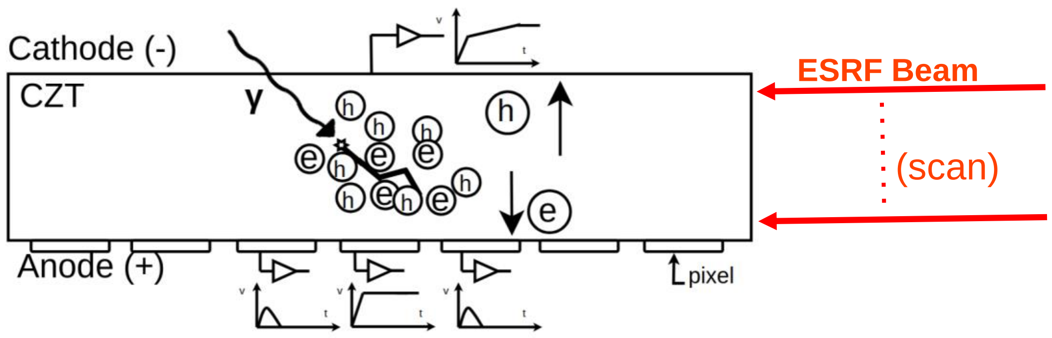

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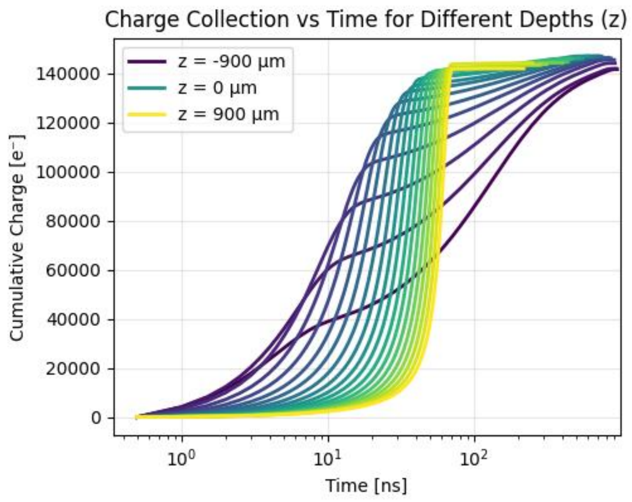

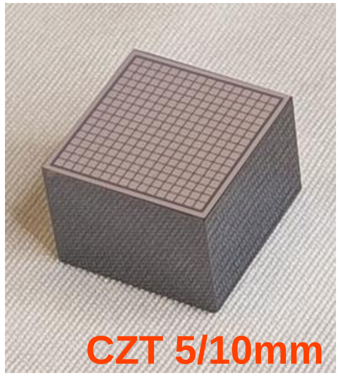

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<u>Transient curves with real 5mm CZT integrated with TIA – anode and cathode</u>

Future use of CadTool

My PhD

Thick CZT (10mm)
Cathode readout
3D sensing
Subpixel with transient signals

Detector Community

Public Release
3Q 2026
https://github.com/hallaire/CadTool

CadTool - a end-to-end x-ray/gamma-ray solid state detector simulation framework

J.F. Sousa[1], A. Meuris[2], D. Baudin[3], H. Allaire[2, 4], O. Limousin[2], R. Le Breton[3]

[1] Université Paris-Saclay, CEA IRFU, AIM
[2] Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM
[3] CEA IRFU, Université Paris Saclay
[4] Kavli IPMU (WPI), UTIAS, The University of Tokyo

references

Benoit, M., & Hamel, L. A. (2009). Simulation of charge collection processes in semiconductor CdZnTe γ-ray detectors. Nuclear Instruments & Methods in Physics Research. Section A, Accelerators, Spectrometers, Detectors and Associated Equipment, 606(3), 508–516. doi:10.1016/j.nima.2009.04.019

I. Abt et al., 'Simulation of semiconductor detectors in 3D with SolidStateDetectors.jl', J. Instrum., vol. 16, no. 08, p. P08007, Aug. 2021.

H. Allaire, PhD thesis, Université de Paris, 2023