Simulation of HR GaAs:Cr Timepix3 detectors with Allpix2

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09.05.2022

Introduction

- High resistivity (HR) GaAs:Cr has become an interesting material for X- and gamma- ray imaging detectors.
- But, it can be also used for particle tracking:
  - higher electron mobility -> faster device;
  - higher stopping power -> more particle species can be separated in mixed radiation fields.
- The GaAs:Cr charge carrier transport properties were studied experimentally (by means of 125 MeV protons irradiation):
  - the parameters of Ruch model [1] for electrons drift velocity were founded for GaAs:Cr;
  - based on the simulation and testbeam data the mobility μ_h and lifetime τ_h of holes were estimated;
  - charge carrier space spread was measured as a function of interaction depth;
  - obtained parameters were used to simulate the GaAs:Cr-Timepix3 response to gammas of 10 – 60 keV.

Why do we need proper knowledge of transport properties of charge carriers?

- In pixel detectors the small pixel effect plays the significant role.
- The dependence of Charge Collection Efficiency (CCE) on interaction depth is almost flat, electrons give main contribution, but in close to pixel region the contribution of holes is significant -> for proper simulation of events which occur close to pixels it is important to know lifetime and mobility of both charge carriers – electrons e^- and holes h^+.
- Transport properties of electrons in HR GaAs:Cr were measured and recently reported multiple times [2, 3], but for holes such information was not found updated.

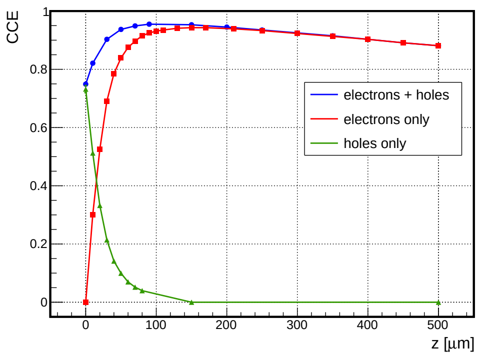


Figure: CCE versus interaction depth z for 500 μm thick GaAs:Cr-Timepix3 detector. z = 0 μm are pixels plane.

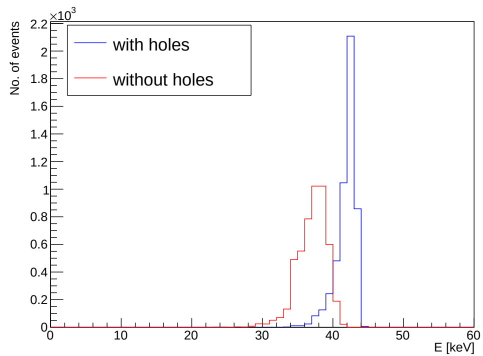


Figure: Simulated energy spectrum of 10 ke$^-$ charge placed at 50 μm from pixel.

Detector based on Timepix3 chip and HR GaAs:Cr sensor

Timepix3:

- Matrix of 256x256 pixels with pitch 55 μm.
- Simultaneous measurements of deposited energy (ToT) and time of interaction (ToA with binning of 1.5625 ns) in each pixel.
- Data driven readout.
- Maximum hit rate: 40 Mhits/cm^2/s.

High resistivity GaAs:Cr:

- Technology of chromium compensation is developed by Tomsk State University.
- $\rho \sim 10^9$ Ohm·cm.
- e$^-$ are main charge carriers: $\tau_e \in [10, 100]$ ns.
- Transport properties of h$^+$ are very pure.
- Sensor thickness 300/500 μm.

Figure: HR GaAs:Cr-Timepix3 detector with readout interface Katherine.

Measurements with charge particles at grazing angles

- Protons of 125 MeV and pions of 120 GeV/c at impact angles of **30 – 75** deg.
- Timepix3 chip operated in hole/electron collection mode.
- Electron collection mode: verify Ruch et al. electron drift velocity model.
- Hole collection mode: estimate lifetime and mobility of holes.

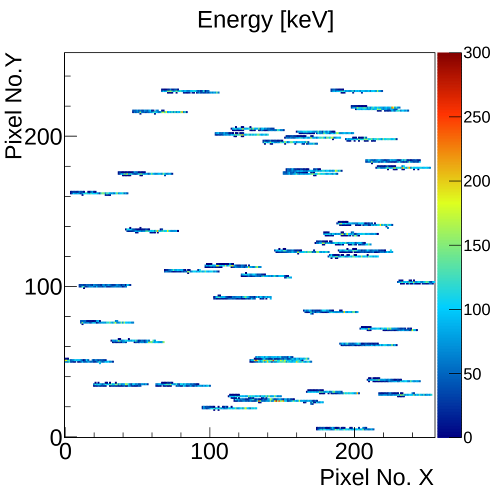


Figure: Typical protons tracks in electron collection mode at 75 deg.

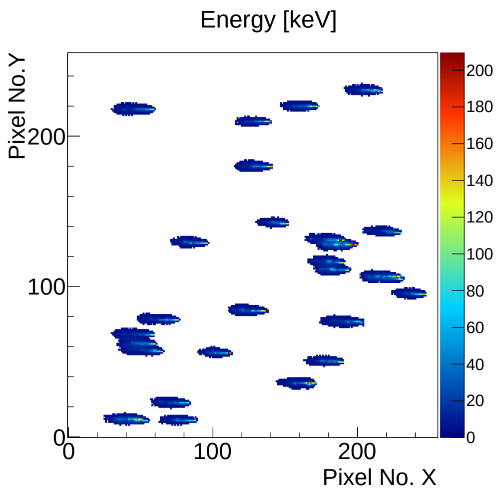
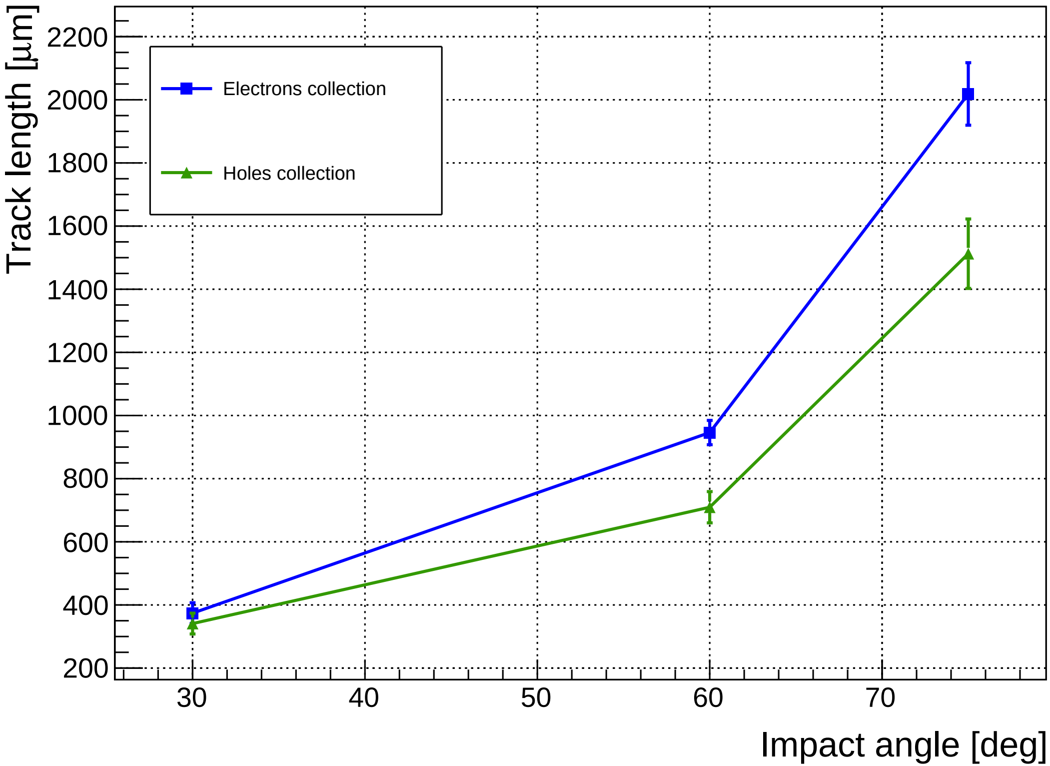


Figure: Typical protons tracks in hole collection mode at 75 deg.

Tracks length comparison in two collection modes

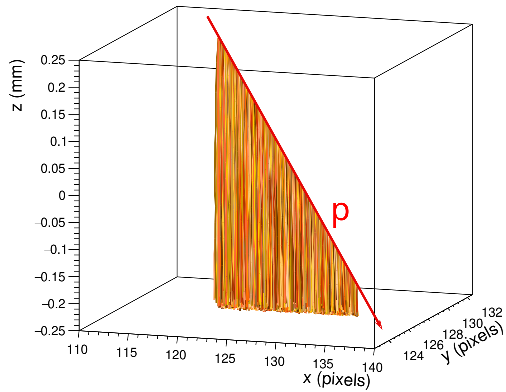
- Proton tracks in hole collection mode are shorter than in electron collection mode for all impact angles.



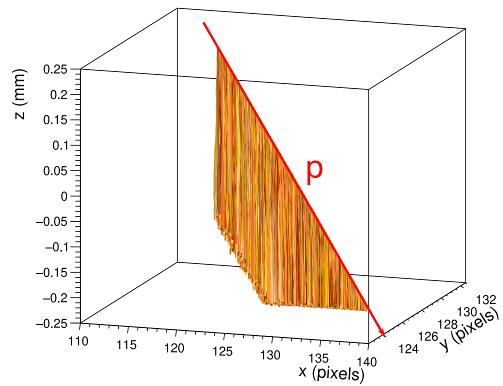
Simulation with Allpix^2 framework

- Several modules of Allpix^2 framework were modified in order to add:
  - GaAs as physical material;
  - drift velocity models and charge carrier lifetime.
- TransientPropagation module was used in order to obtain the evolution in time of induced charge on pixel electrodes according to Shokley-Ramo theorem.
- Constant electric field model was chosen as appropriate for GaAs:Cr [2].
- ToA information was calculated as time when induced on pixel charge crossed the threshold ($\neq$ drift time) + smeared according to $\sigma_{timewalk}$ [5].

Visualization of electrons drifted to pixels from 125 MeV proton track path.

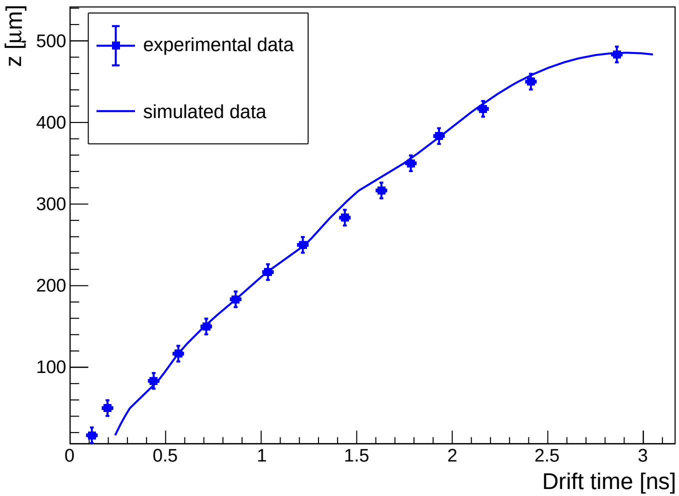


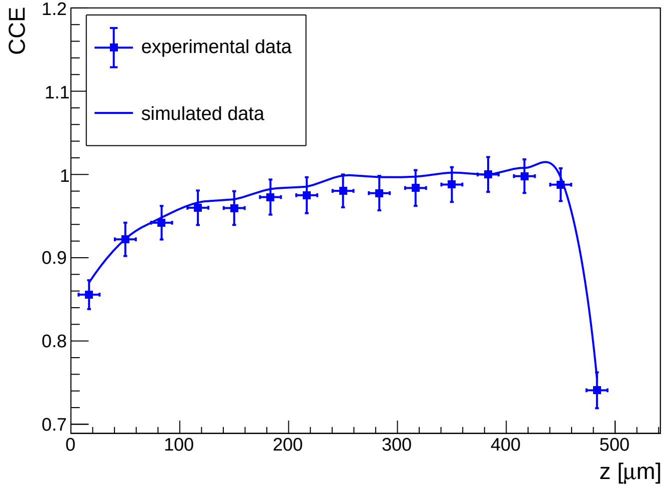
Visualization of holes drifted to pixels from 125 MeV proton track path.



Drift time(z) & CCE(z) in electron collection mode

- Z coordinate is calculated from geometry (incident angle is known)
- The best agreement between simulation and experimental data was found for $\mu_e = 3227$ cm^2/V/s and $\tau_e = 30$ ns.
- These values give typical many times reported value of $\mu_e \times \tau_e \sim 10^{-4}$ cm^2/V.
- Drift time is ∼3 ns for 500 μm thick detector with U_{bias}=-300 V, what is already good enough to fully utilize the time resolution of Timepix3.





Drift time(z) in hole collection mode

- Iterative simulation with different values of μ_h and τ_h with step on mobility of 10 cm^2/V/s and lifetime – 0.5 ns.
- The best agreement is achieved for $\mu_h = 320 \pm 10$ cm^2/V/s and $\tau_h = 4.5 \pm 0.5$ ns.

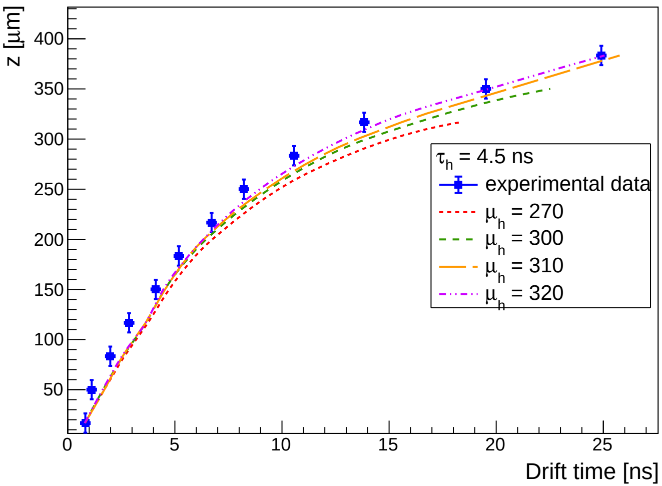


Figure: Fixed $\tau_h = 4.5$ ns, various mobilities.

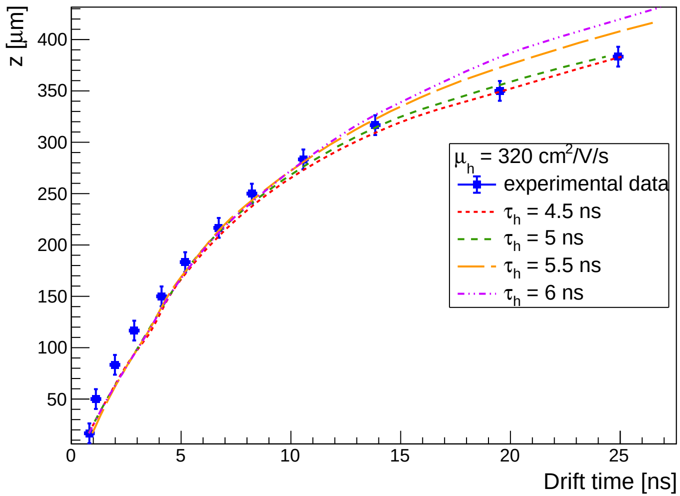


Figure: Fixed $\mu_h = 320$ cm^2/V/s, various lifetimes.

HR GaAs:Cr charge transport models

Electrons drift velocity dependence on electric field – from Ruch et al.:

- if E < E_0: $V^e_{drift} = \mu_e \cdot E$.
- if E ≥ E_0: $V^e_{drift} = \mu_e \cdot E/\sqrt{1 + (E - E_0)^2/E_c^2}$.
- For 300 μm thick detector: $E_0 = 3517$ V/cm, $E_c = 2004$ V/cm, $\mu_e = 4982$ cm^2/V/s.
- For 500 μm thick detector: $E_0 = 3100$ V/cm, $E_c = 1360$ V/cm, $\mu_e = 7600$ cm^2/V/s.
- $\tau_e = 30$ ns.

For holes:

- Simple approach: $V^h_{drift} = \mu_h \cdot E$ (will be checked with recent testbeam data).
- $\mu_h = 320$, $\tau_h = 4.5$ ns (for now checked only for 500 μm thick detector and one bias voltage)

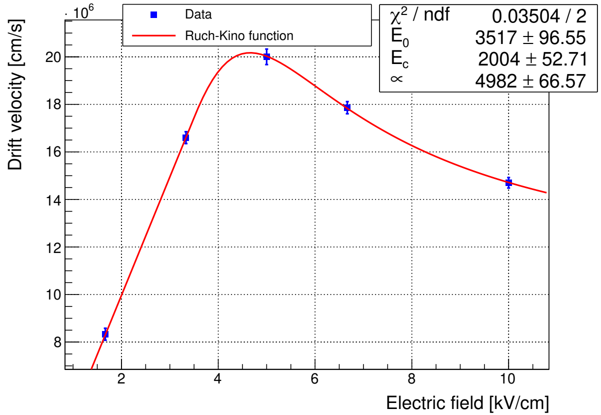
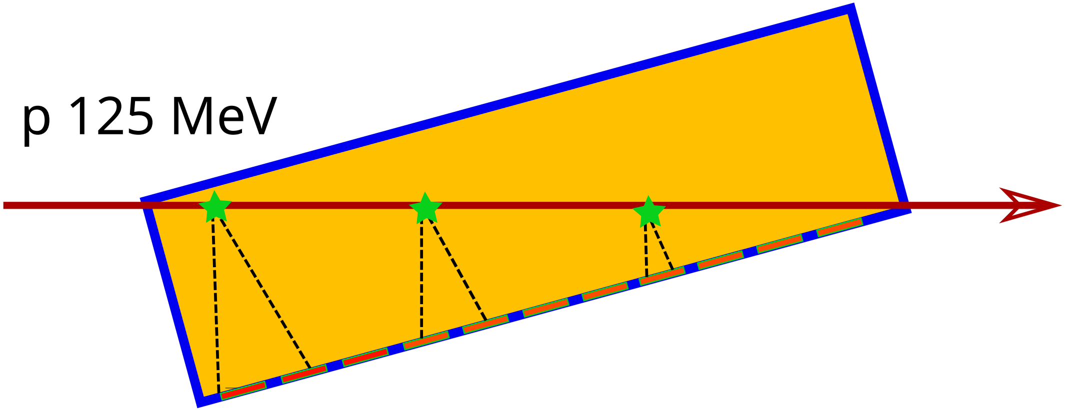


Figure: Dependence of electrons drift velocity on electric field.

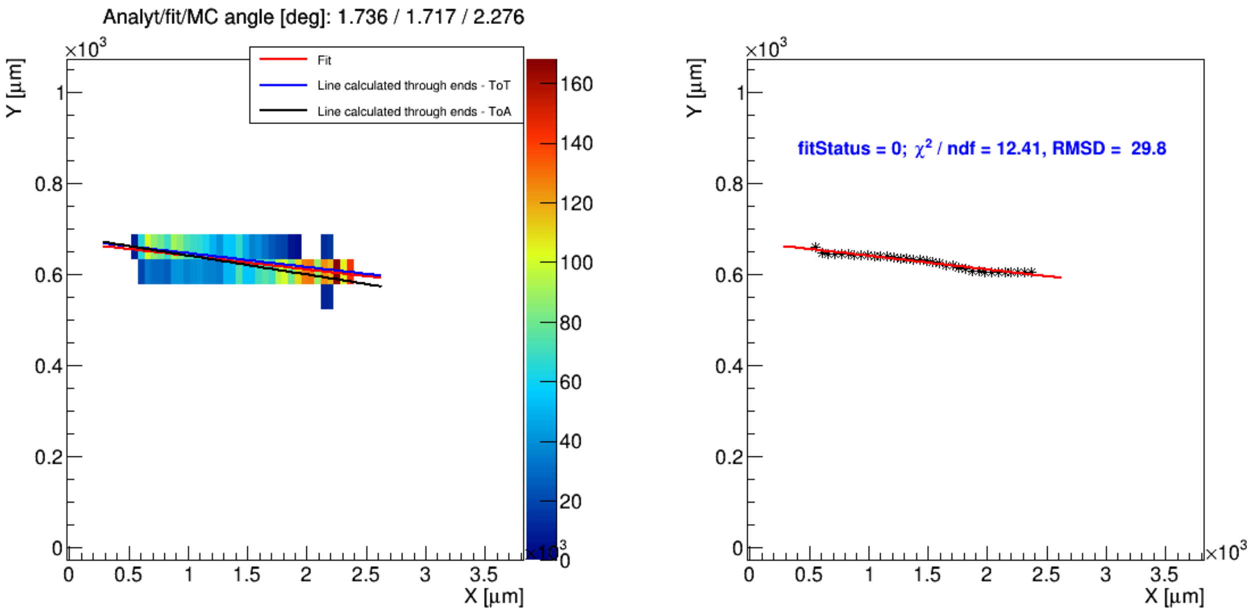
Charge carrier space spread – charge sharing

- Main influencing factors: initial charge cloud size, diffusion, repulsion, weighting field, capacitive coupling.
- All these contributions can be measured simultaneously with energetic protons impacted to the detector at grazing angle.



Methodology: charge cloud σ dependence on depth

- Protons of 125 MeV at 75 deg. to the detector normal.
- Select only clusters at small angle (1-2 deg.) to rows.
- Fit by line to obtain sub-pixel position of the track -> extract sub-pixel $y_{subpixel}$ position for each x position of track.
- Calculate depth z coordinate of the track from geometry.
- Fit by Gaus + Landau the energy spectrum for each (z, Δy = y - $y_{subpixel}$) position.
- Create pixel "sensitivity map" MPV(Δy) for each depth position, fit by function below and extract σ.



Pixel sensitivity maps for different depths

- Fit MPV(Δy) dependence for each depth bin by function [6]:

$$MPV(\Delta y) = MPV_0 * (1 + Erf(\frac{27.5 - y}{\sqrt{2}\sigma}))$$

- Flatter top – lower charge sharing.

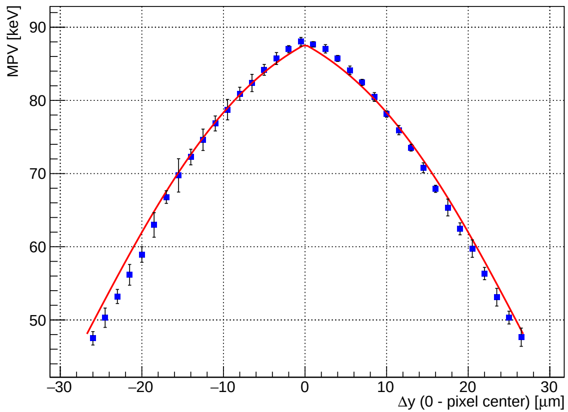


Figure: Interaction close to the common electrode: $\sigma = \sim 16\ \mu$m.

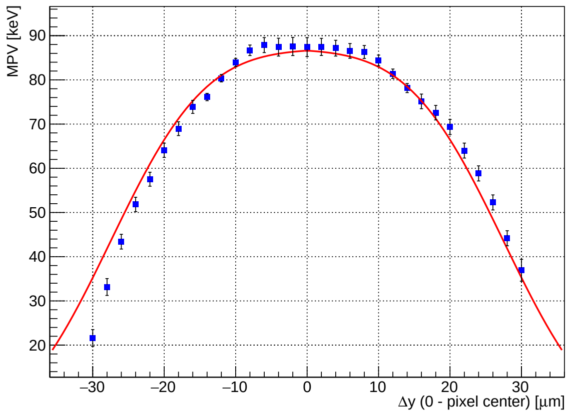
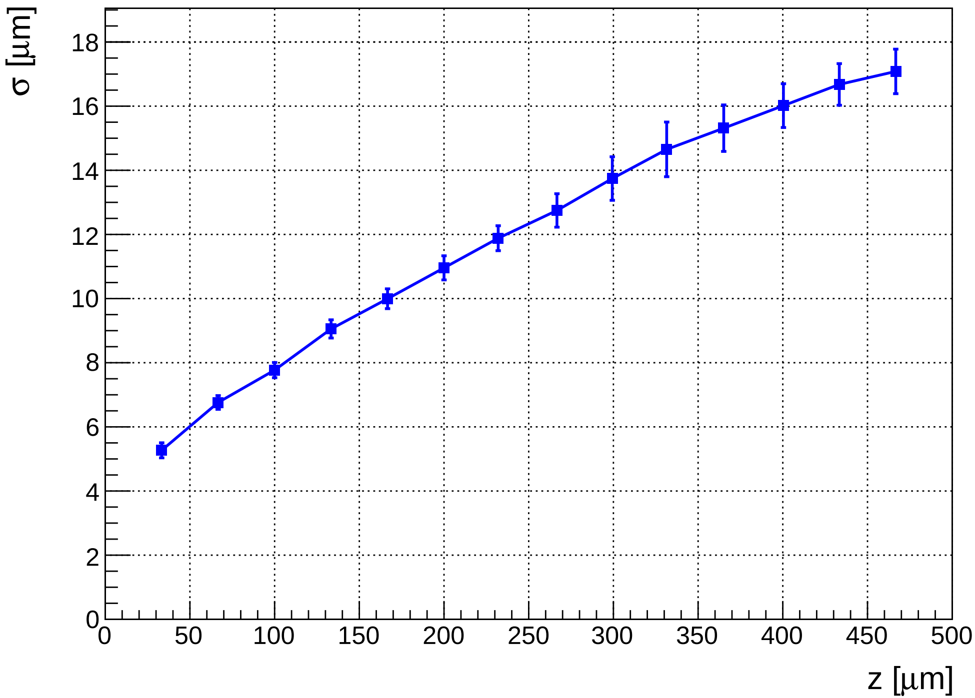


Figure: Interaction in the middle of the sensor: $\sigma = \sim 5\ \mu$m.

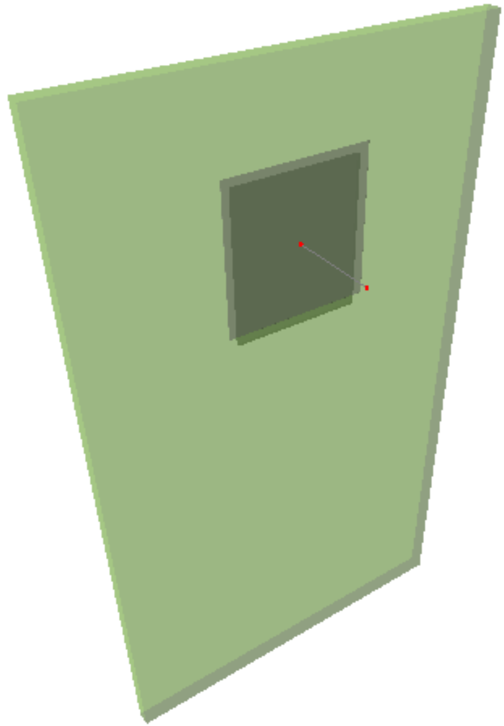
Preliminary results

- The obtained dependence can be used for quick detector response simulation.
- More experimental data is needed to obtain dependence σ (z, U_{bias}): bias voltage scan.



Simulation of the response to gammas

- Obtained charge transport parameters were applied in the simulation of the detector response to γ-s.
- Standard geometrical model of the Timepix detector in Allpix^2 was used.
- It includes PCB, bump-bonds, chip and sensor covered by Al.
- Surrounding safety box was not taken into account (scattering).
- Experimental dataset: ^{241}Am source with 59.6 keV γ-line was placed in front of the detector + several X-ray fluorescence lines were used.



Simulated/measured energy spectra

- GP - GenericPropagation [no Shokley-Ramo theorem, artificial charge smearing]
- TP - TransientPropagation [Shokley-Ramo theorem, proper simulation of Timepix3 electronics]
- Relative energy resolution $\sigma/E \sim 6$ % @ 60 keV.

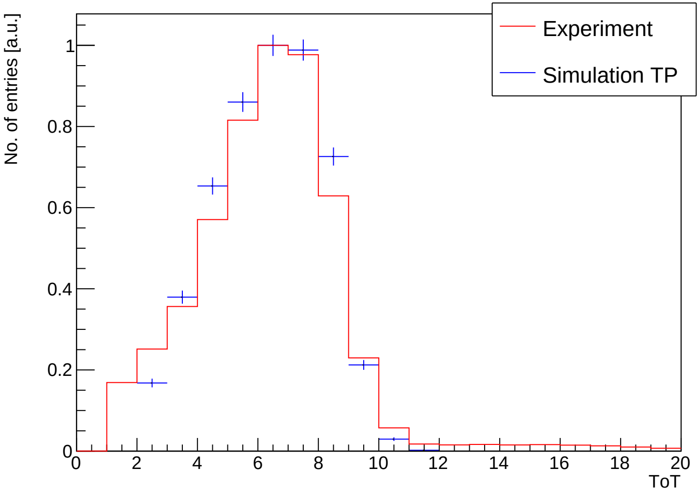


Figure: 8 keV photons spectra.

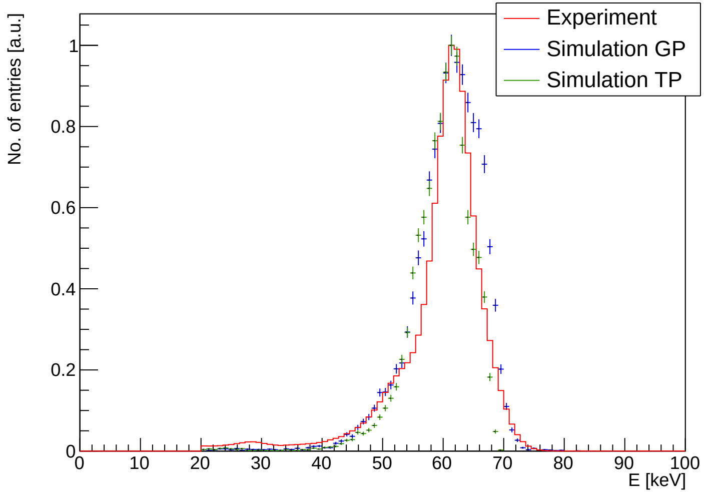


Figure: of ^{241}Am source spectra.

Simulated spectra of 10÷60 keV gammas

- The energy resolution of simulated spectra is very close to experimental ones, especially in case of Transient current simulation.

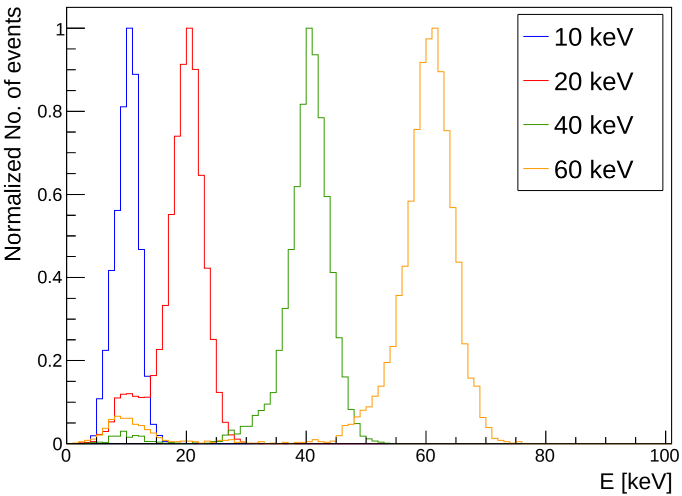


Figure: Simulated spectra.

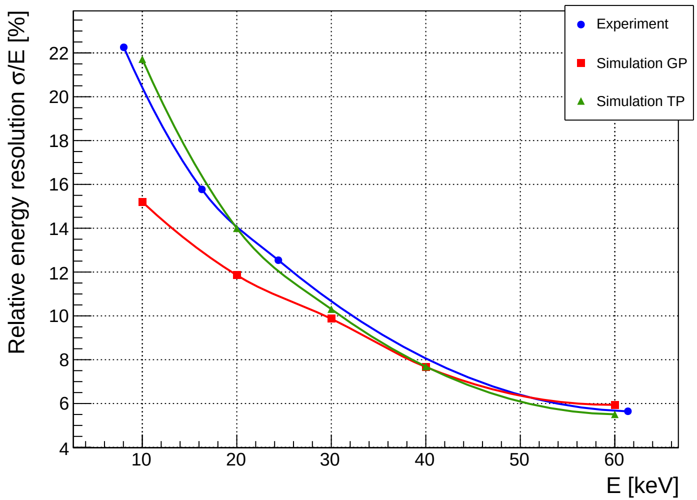


Figure: Relative energy resolution versus energy.

How to exploit this GaAs:Cr implementation in Allpix^2 v.2.3?

Timepix3-GaAs model file derived from Timepix model

- Other materials available: Si, GaAs, Ge, CdTe, CZT, Diamond, SiC

```
type = "hybrid"
number_of_pixels = 256 256
pixel_size = 55um 55um

sensor_thickness = 500um
sensor_excess = 1mm
sensor_material = "GaAs"

bump_sphere_radius = 9.0um
bump_cylinder_radius = 7.0um
bump_height = 20.0um
chip_thickness = 300um
chip_excess_left = 15um
chip_excess_right = 15um
chip_excess_bottom = 2040um

[support]
thickness = 1.76mm
size = 47mm 79mm
offset = 0 -22.25mm
```

ElectricField module for GaAs:Cr

- Constant electric field typically is enough

```
[ElectricFieldReader]
model = "constant"
bias_voltage = -350V
```

Propagation module for GaAs:Cr

- One can specify Ruch-Kino mobility model or constant values for mobility of electrons or holes
- Similarly the TransientPropagation module can be configured

```
[GenericPropagation]
temperature = 315K
mobility_model = "ruch_kino"
#mobility_model = "constant"
#mobility_electron = 3200cm*cm/V/s
#mobility_hole = 320cm*cm/V/s
recombination_model = "constant"
lifetime_electron = 30ns
lifetime_hole = 4.5ns
charge_per_step = 25
integration_time = 20ns
propagate_electrons = true
propagate_holes = false
```

Digitizer module for GaAs:Cr

- For basic simulation Default Digitizer module can used

```
[DefaultDigitizer]
electronics_noise = 70e
threshold = 1000e
threshold_smearing = 35e
qdc_smearing = 300e
```

Conclusions

- Timepix3 is a useful tool for sensors charge transport study.
- Charge transport models for HR GaAs:Cr were verified with experimental data and the reasonable agreement was demonstrated.
- Mobility and lifetime of holes in HR GaAs:Cr were estimated using the simulation and experimental data.
- The spread of charge cloud was measured in dependence on interaction depth.
- GaAs:Cr support was implemented in Allpix^2

Thank you very much for your attention!

We thank M. Sitarz and C. Søndergaard from Danish Center of Particle Therapy for the support. This work has been done using the INSPIRE Research Infrastructures and is part of a project that has received funding from the European Union's Horizon2020 research and innovation programme under grant agreement No 730983.

Links

1. J. G. Ruch and G. S. Kino. Transport Properties of GaAs. Phys. Rev. 174, 921 https://doi.org/10.1103/PhysRev.174.921
2. A.V. Tyazhev et al. GaAs radiation imaging detectors with an active layer thickness up to 1 mm. NIM A 509 (2003) 34–39
3. T. Billoud et al., Homogeneity study of a GaAs:Cr pixelated sensor by means of X-rays, 2018 JINST 13 P04002.
4. B. Bergmann et al., Detector response and performance of a 500 um thick GaAs attached to Timepix3 in relativistic particle beams, 2020 JINST 15 C03013
5. P. Smolyanskiy et al., Tracking and separation of relativistic ions using Timepix3 with a 300 um thick silicon sensor, 2021 JINST 16 P01022
6. E. J. Schioppa et al., Study of Charge Diffusion in a Silicon Detector Using an Energy Sensitive Pixel Readout Chip, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 5, OCTOBER 2015

Weighting potential for central and non-central pixels