Pulse shape simulation for segmented germanium detectors

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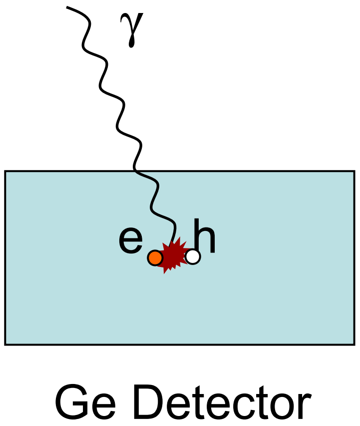
Germanium workshop, Beijing

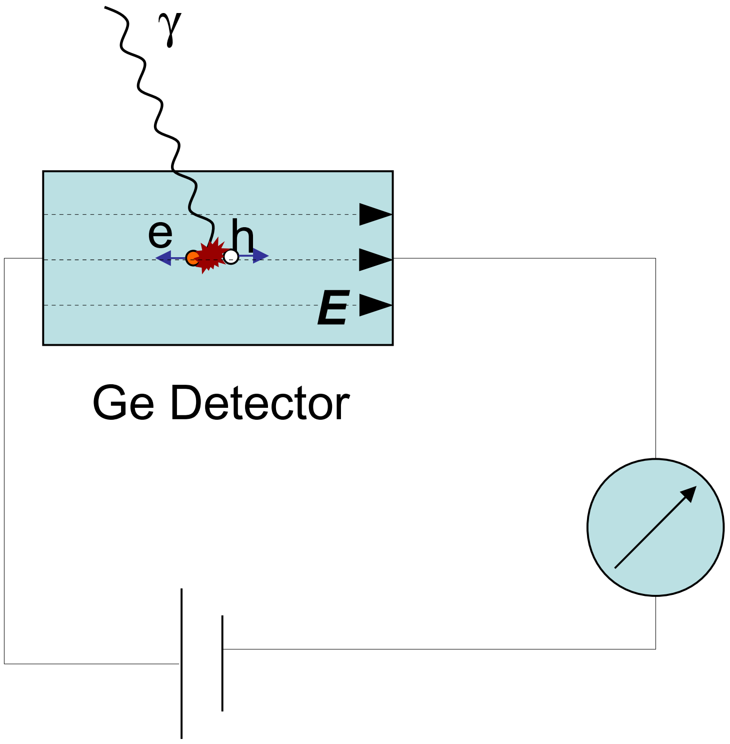
2011 March 26

What is pulse shape simulation ...

Internal or external radiation can create electron-hole pairs inside a germanium detector

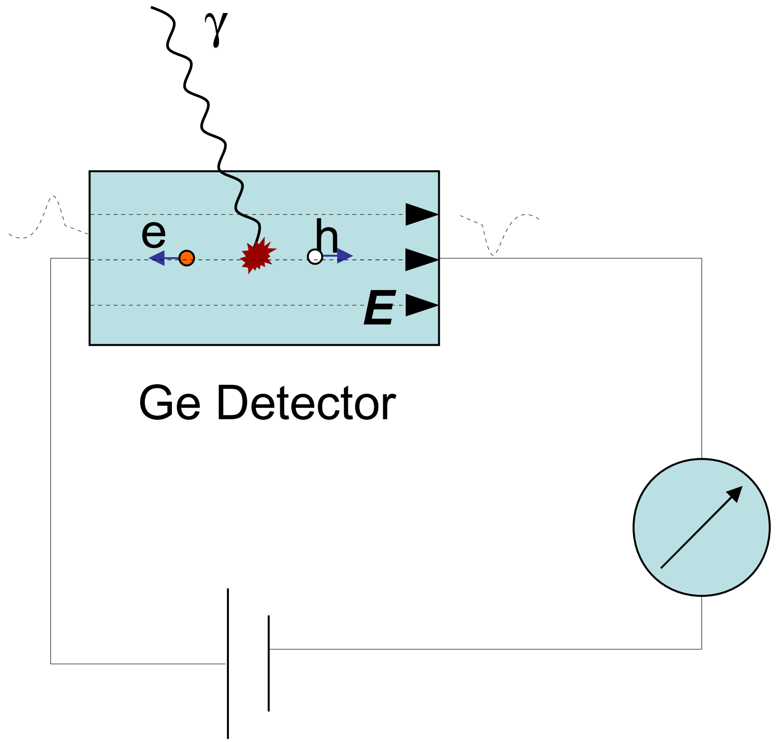


electron-hole pairs drift to electrodes if high voltage is applied to the detector



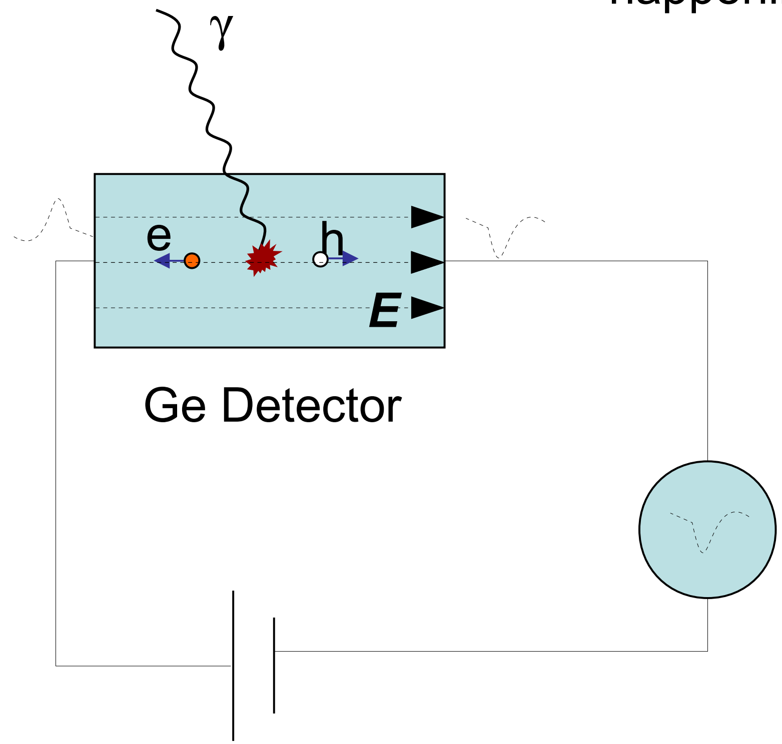
Ge Detector

Charges, Q(t), are induced on the electrodes when electron hole pairs drift away from each other

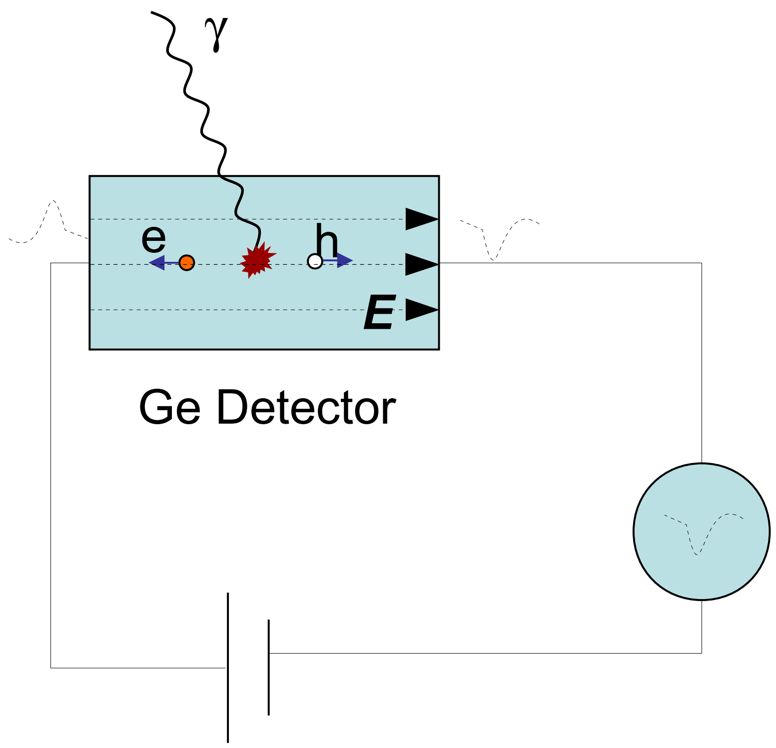


This change on the electrodes can be recorded by the electronics,

giving us hints on what's happening inside the detector



Modeling of electric signal formation process in germanium detector system in computer is called Pulse Shape Simulation (PSS in short)



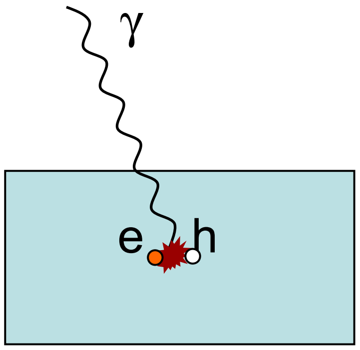
Why pulse shape simulation (PSS)

- Estimate PS Analysis (PSA) efficiency
  - Generate single or multi-site event samples
- Help on experiment design
  - Try different detector configurations
- Improve understanding of germanium detector
  - Study impurity distribution, for example
- Help analysis
  - Generate PS library for NN, for example

How to do it ...

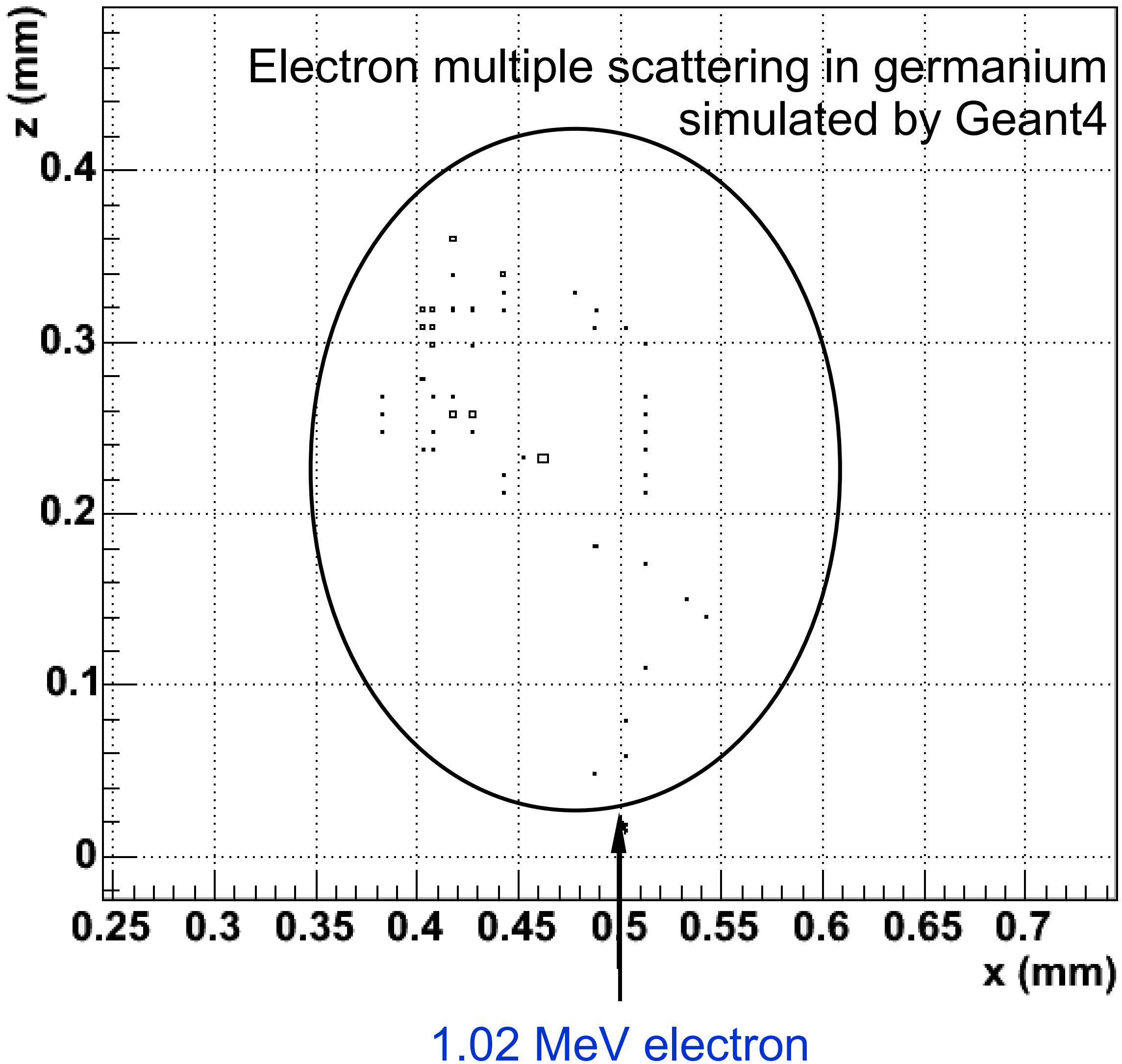
1. Simulate interactions using Geant4 (Prof. Yu's talk)

Internal or external radiation can create electron-hole pairs inside a germanium detector



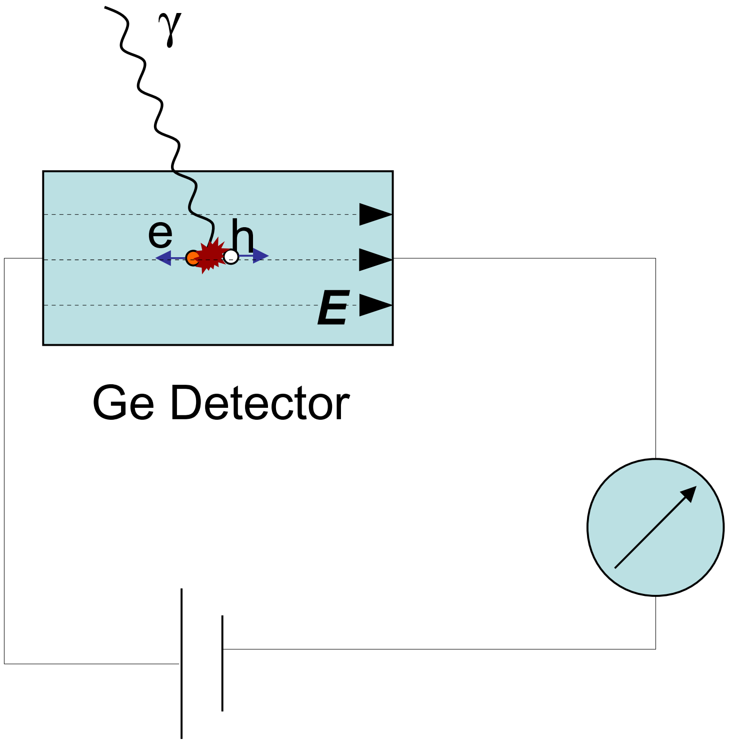
Ge Detector

Group hits based on position and time resolution to increase efficiency



2. Electric field calculation

electron-hole pairs drift to electrodes if high voltage is applied to the detector



Electric field calculation:

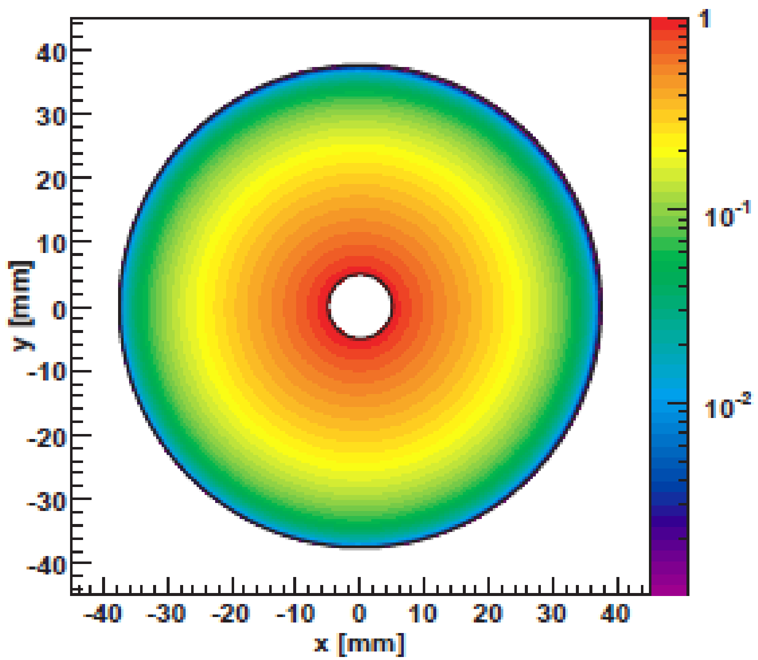
home made codes or commercial software (Prof. Li's talk)

Poisson's equation:

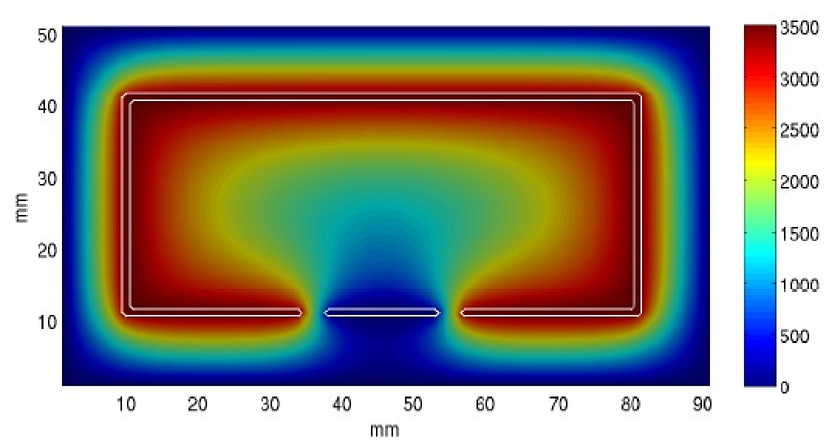
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon},$$

Space charge density from impurity

Calculation can be optimized if detector has symmetric configuration

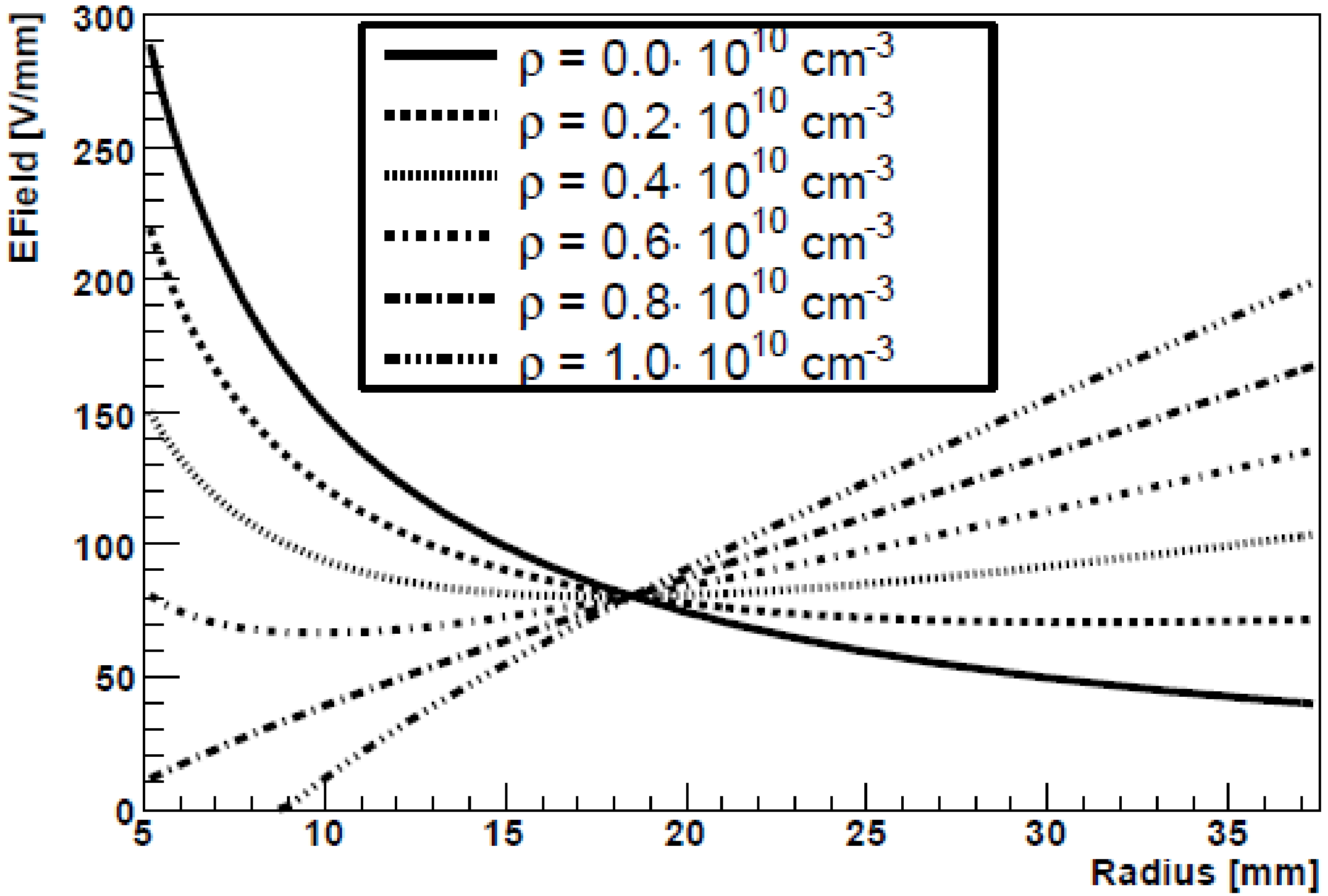


Electric potential of a true co-axial HPGe (XY cross section)



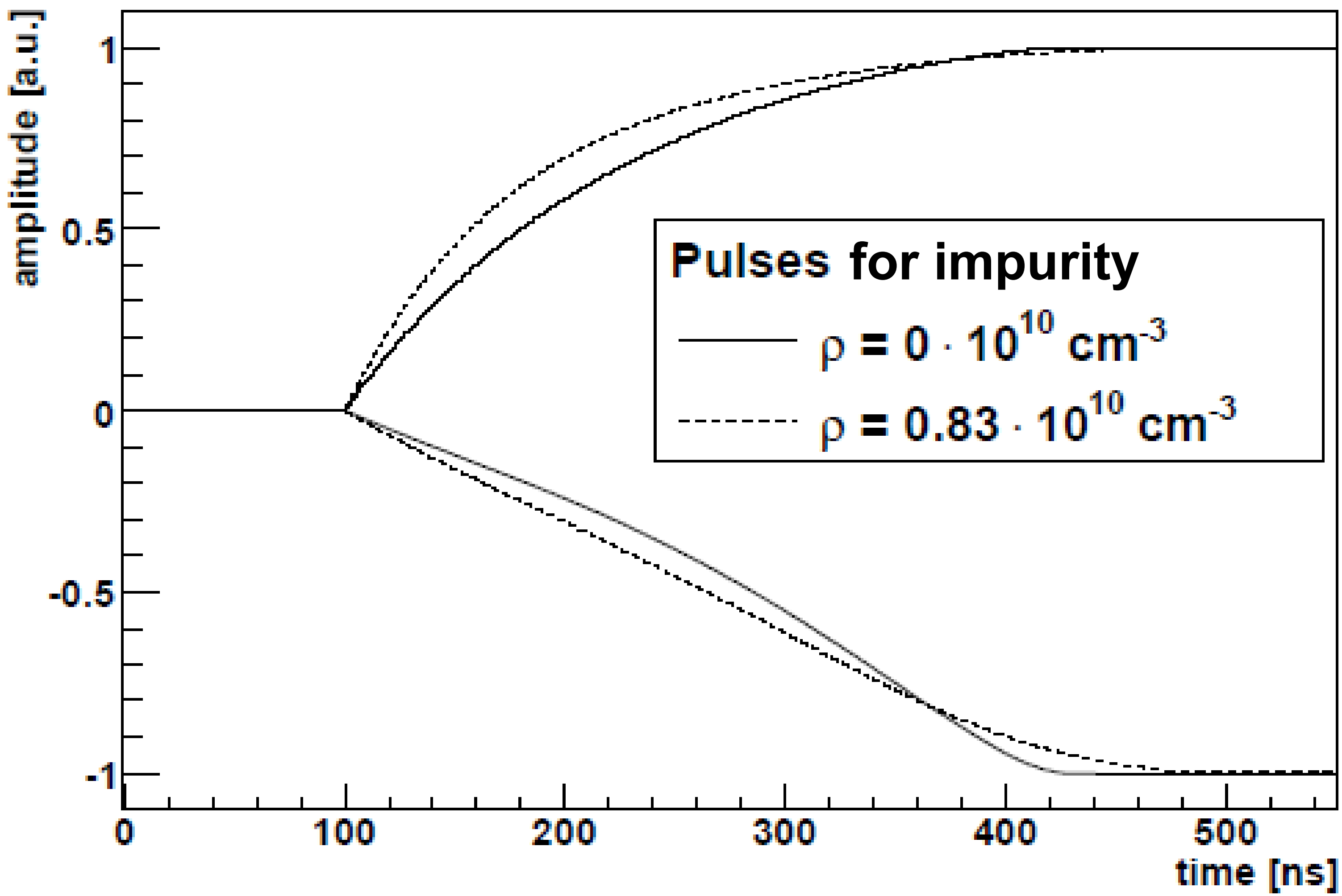
Electric potential of a BEGe (XZ cross section)

Effect of impurity on electric field inside a germanium detector



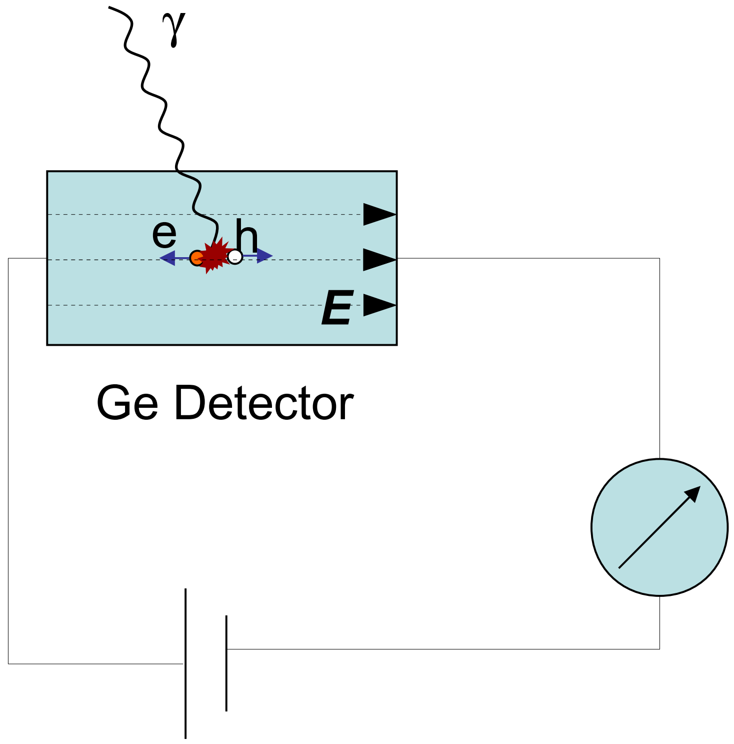
Change of the radial electric field strength as a function of the radius for different active bulk impurity densities ρ and fixed applied electric potential of 3000 V. For each calculation the impurity density was constant throughout the detector. At $\rho = 1.0 \cdot 10^{10}\,\mathrm{cm}^{-3}$ the detector is not fully depleted anymore.

Impurity → electric field → pulses



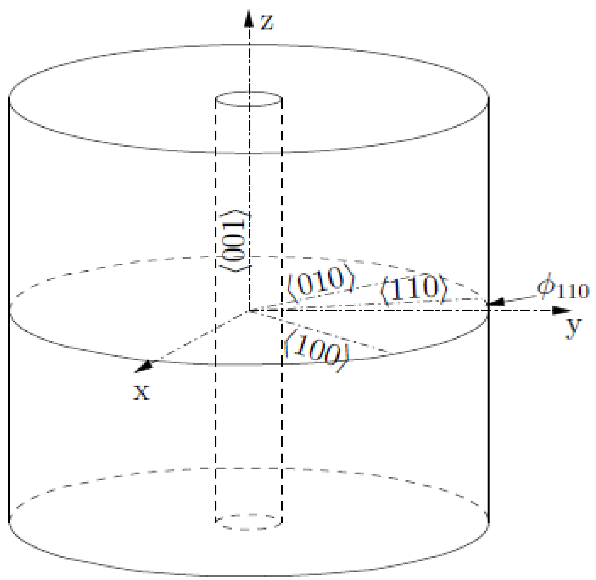
3. Drift of charge carriers

electron-hole pairs drift to electrodes if high voltage is applied to the detector

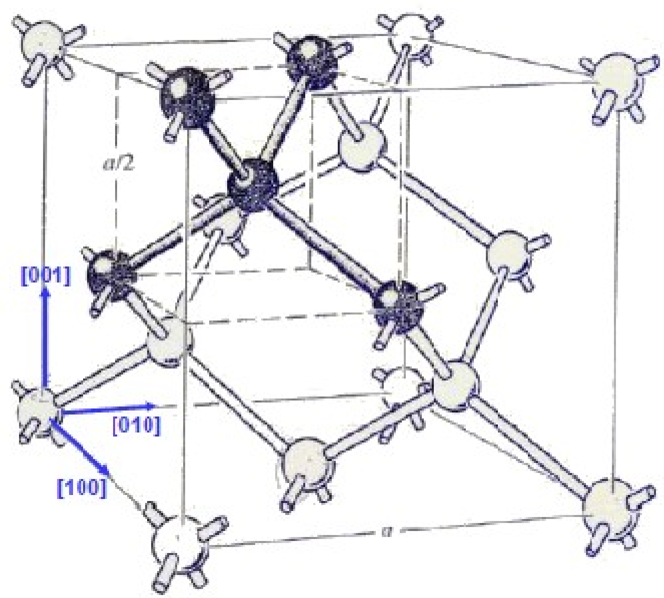


Germanium crystal structure and axes

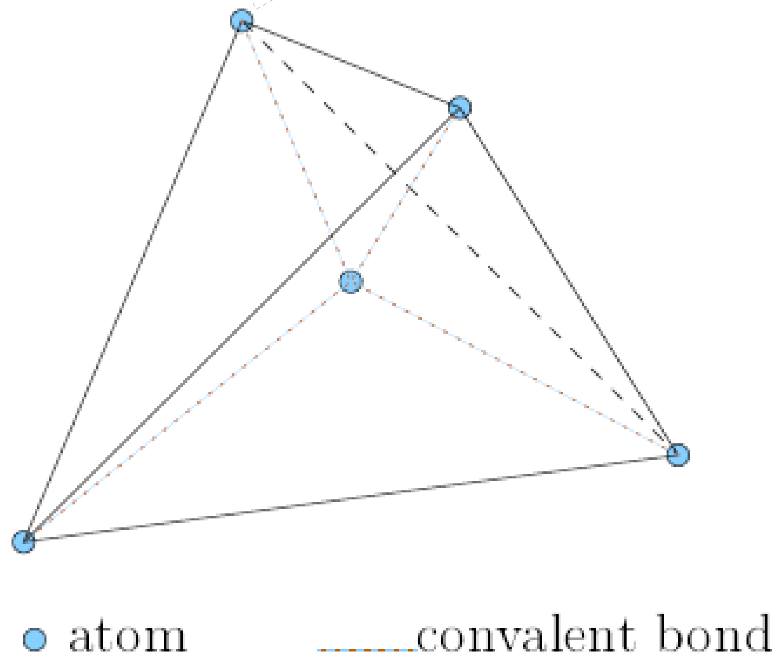
Crystal axes and detector coordinate system



Crystal axes (Miller index)



Crystal basic configuration



Drift velocity

Mobility (tensor)

Drift velocity (vector)

E field (vector)

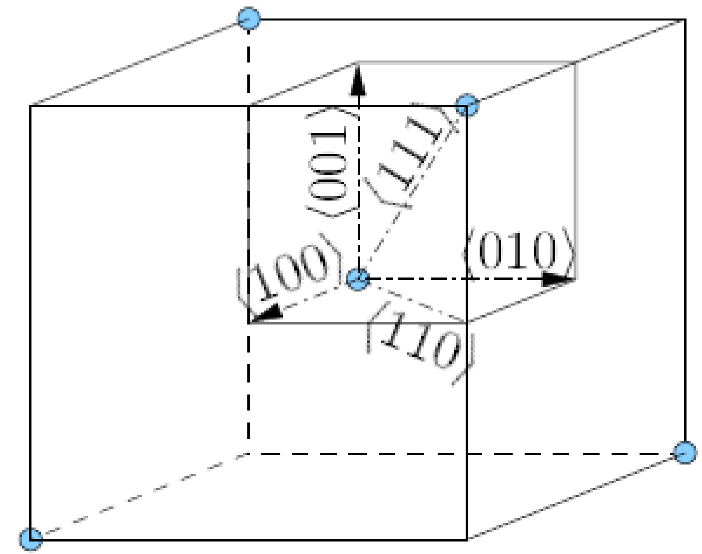
$$\mathbf{v}_{e/h}(\mathbf{r}) = \mu_{e/h}\mathbf{E}(\mathbf{r})$$

Degenerate along <111> & <100>

$$v = \frac{\mu_0 E}{[1 + (\frac{E}{E_0})^\beta]^{1/\beta}} - \mu_n E.$$

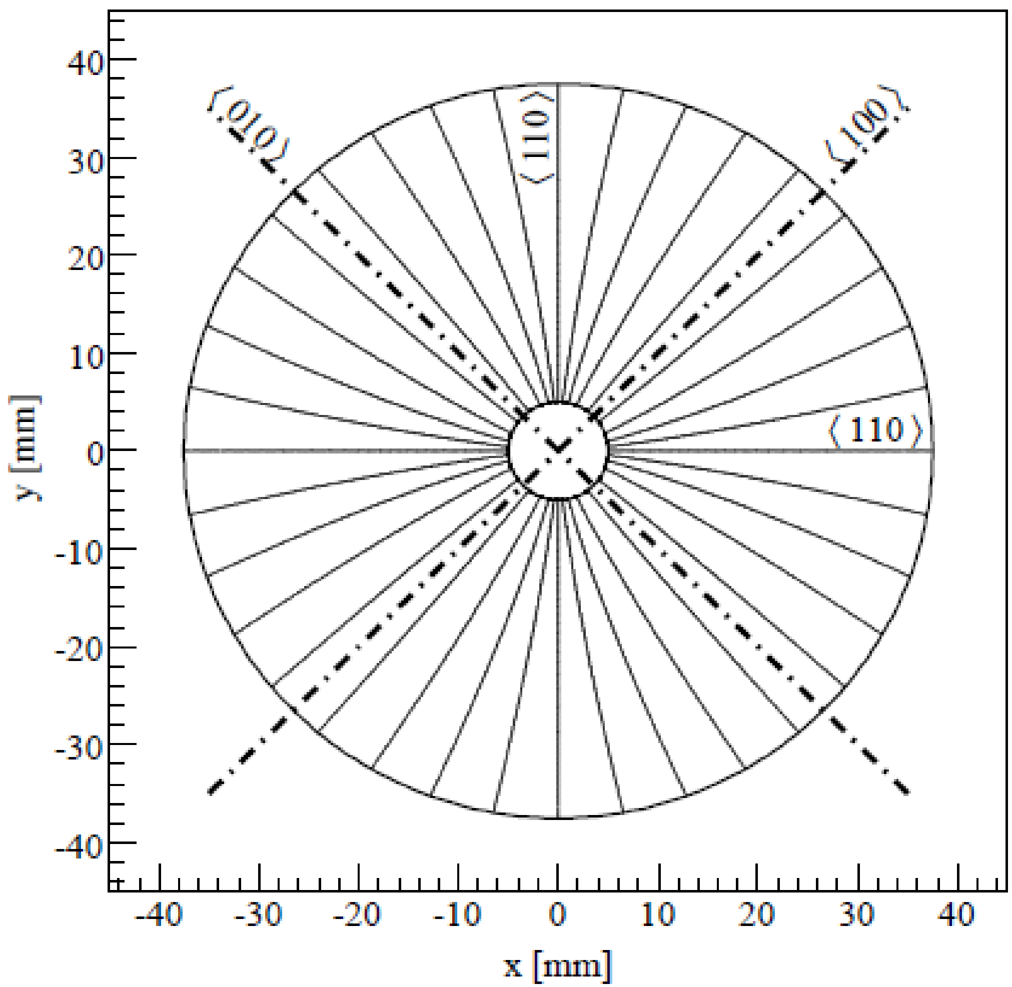
Mobility (just a number)

Parameters can be measured

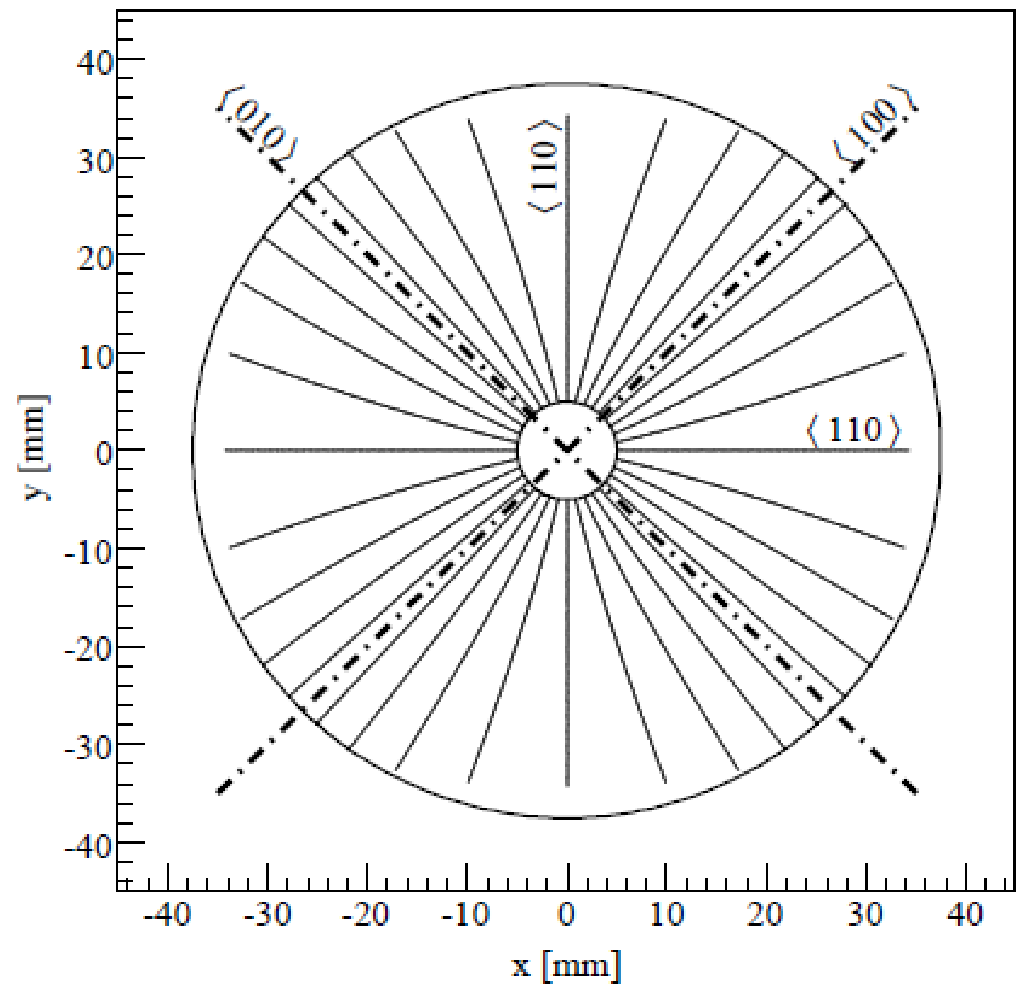


Effect of crystal structure on drift trajectories

Holes drift inward from outer surface

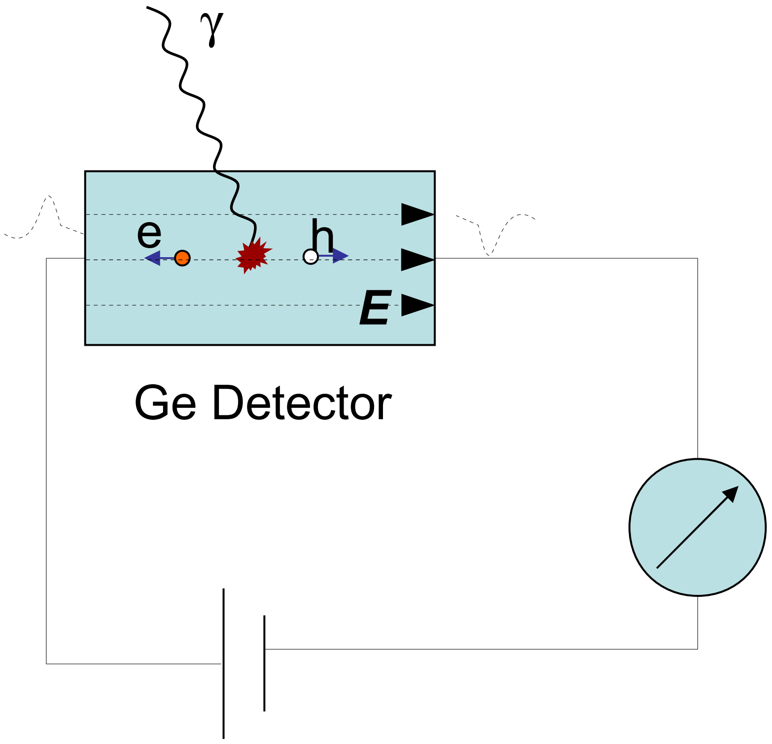


Electrons drift outward from inner surface

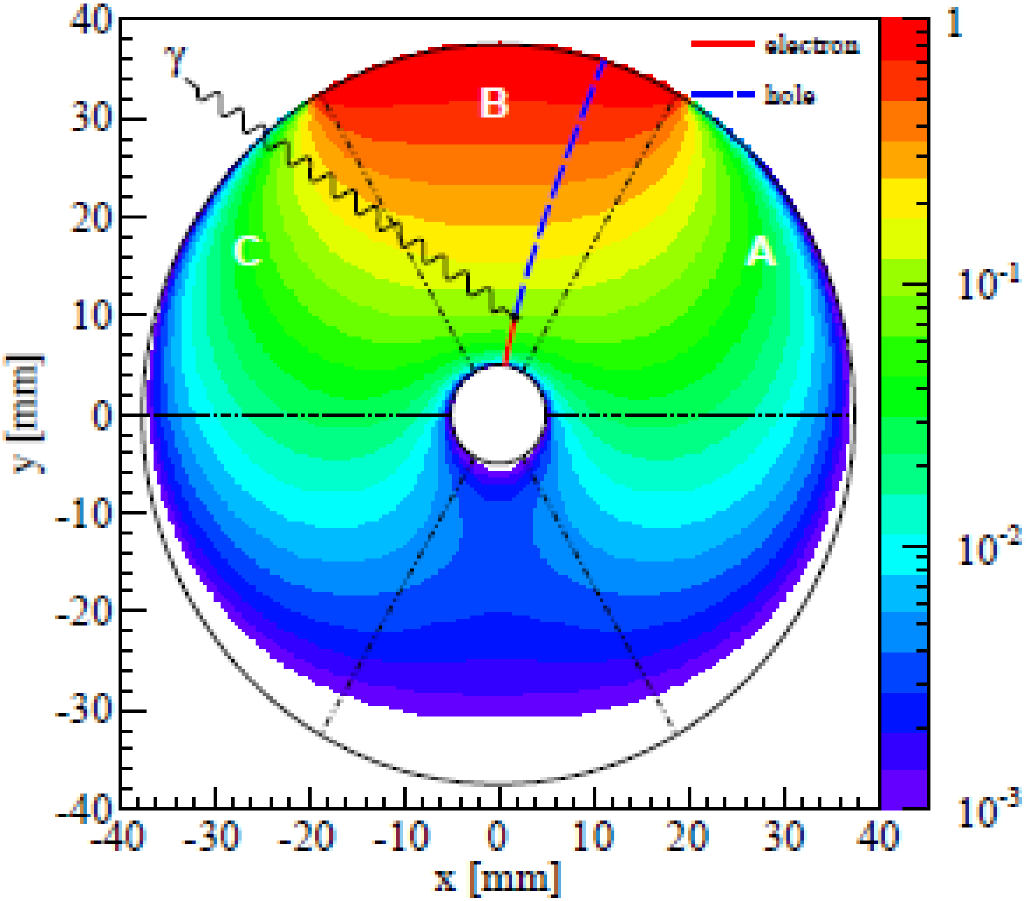


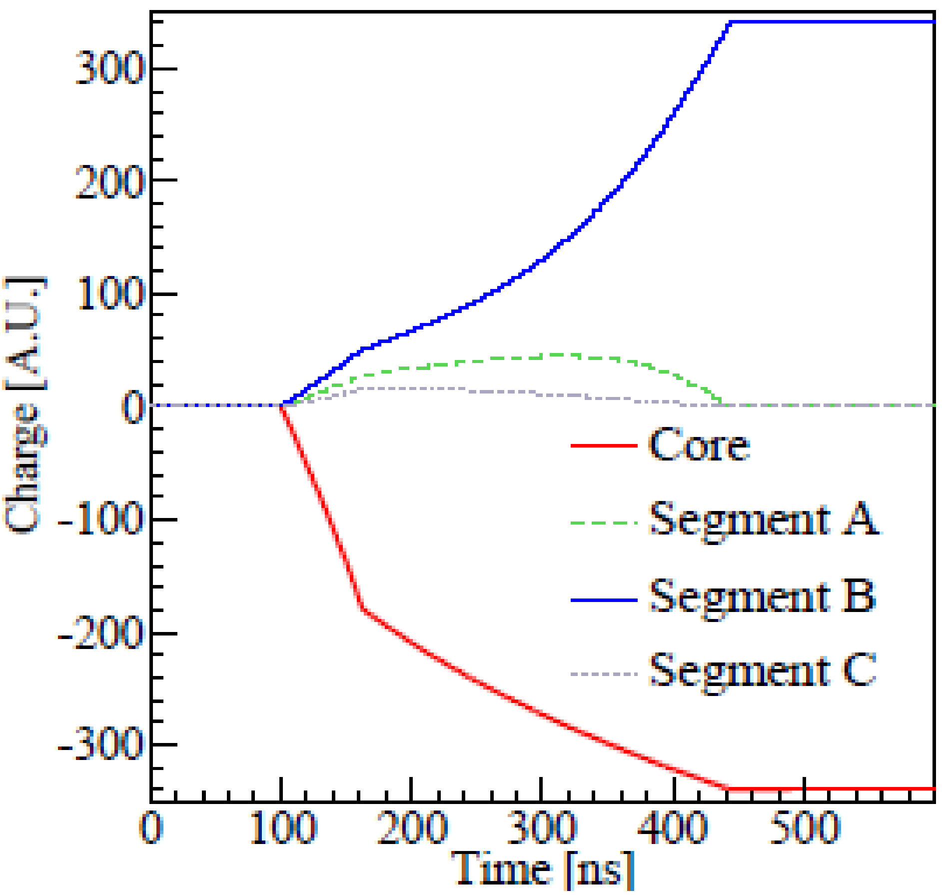
4. Charges induced on electrodes

Charges, Q(t), are induced on the electrodes



Induced charge is proportional to the Weighting Potential seen by charge carriers along their trajectories (Ramo's theory)

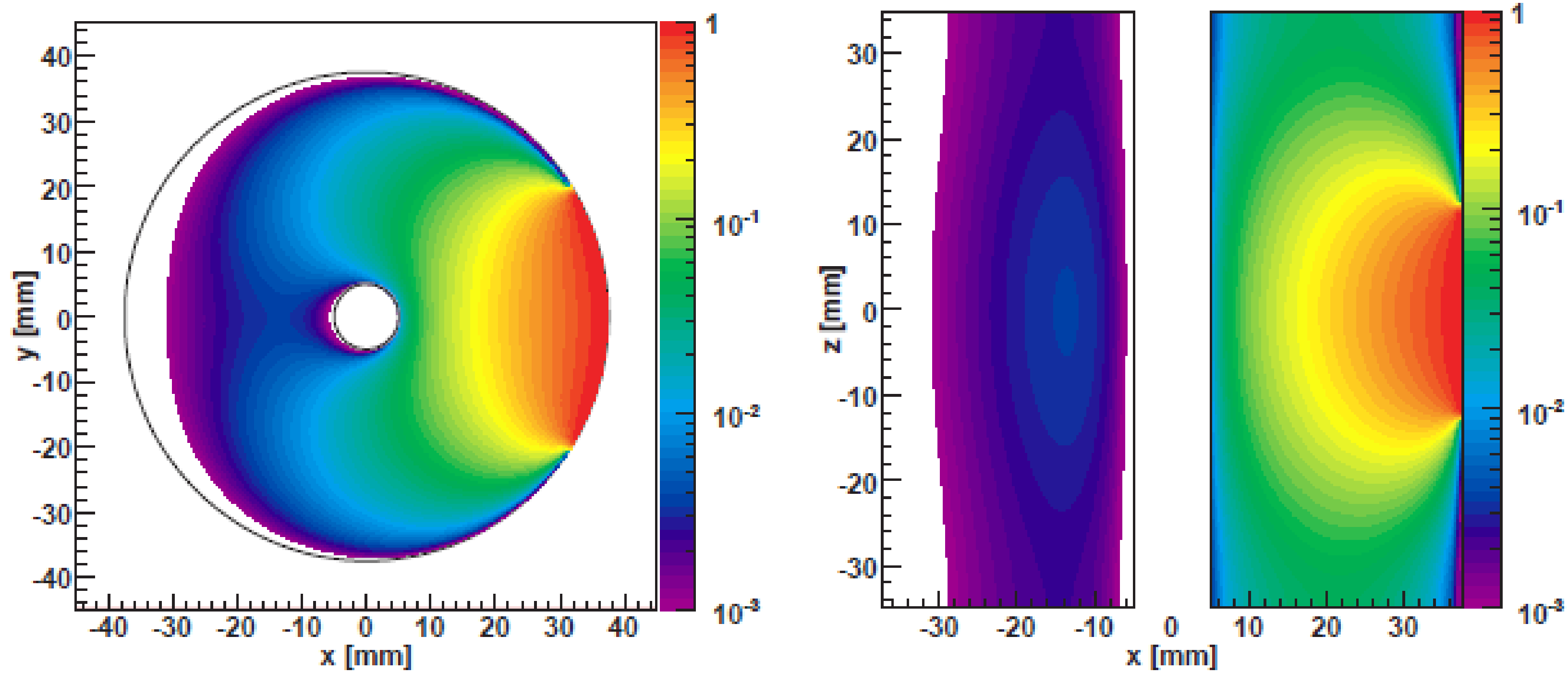




Weighting potential calculated for one segment

Not affected
By impurity

$$\nabla^2 \varphi(\mathbf{r}) = 0$$

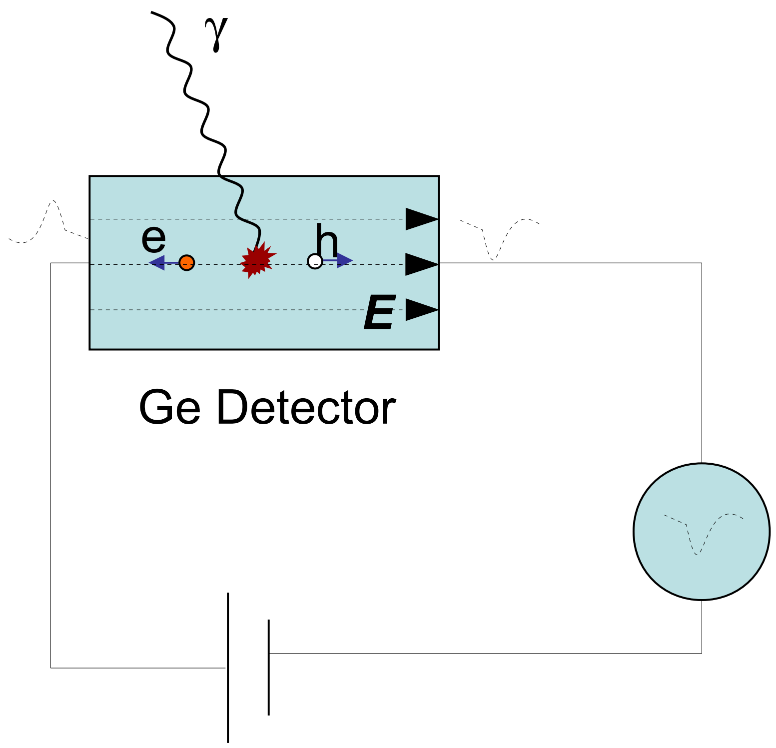


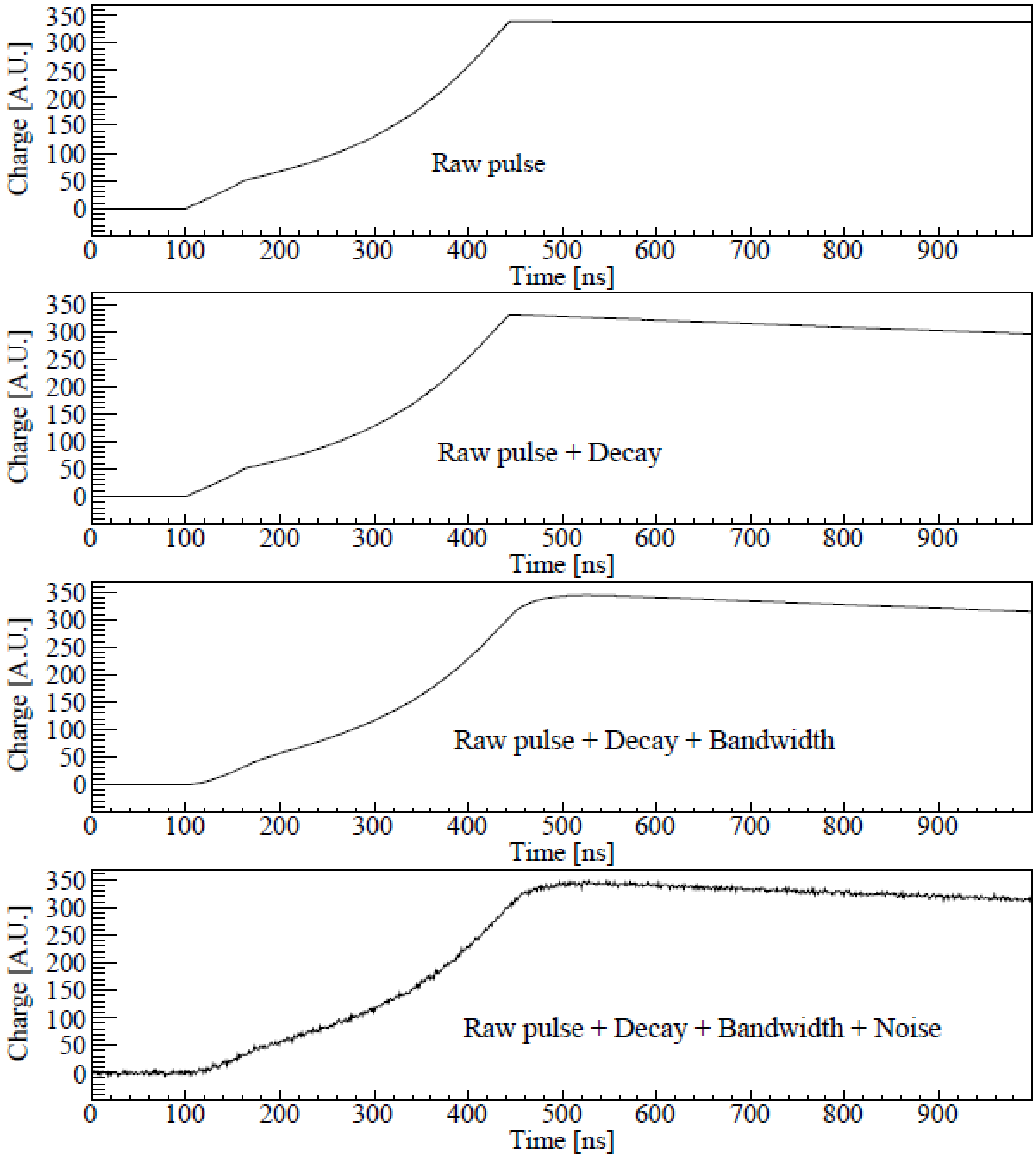
(a) (b)

Weighting potential of a central segment electrode of a true coaxial 18-fold segmented germanium detector in (a) horizontal cross section (z=0) and in (b) vertical cross section (y=0). The weighting potential equals unity on the considered electrode and zero on all other electrodes.

5. Fold in electronic effects

This change on the electrodes can be recorded by the electronics, which is normally not perfect...



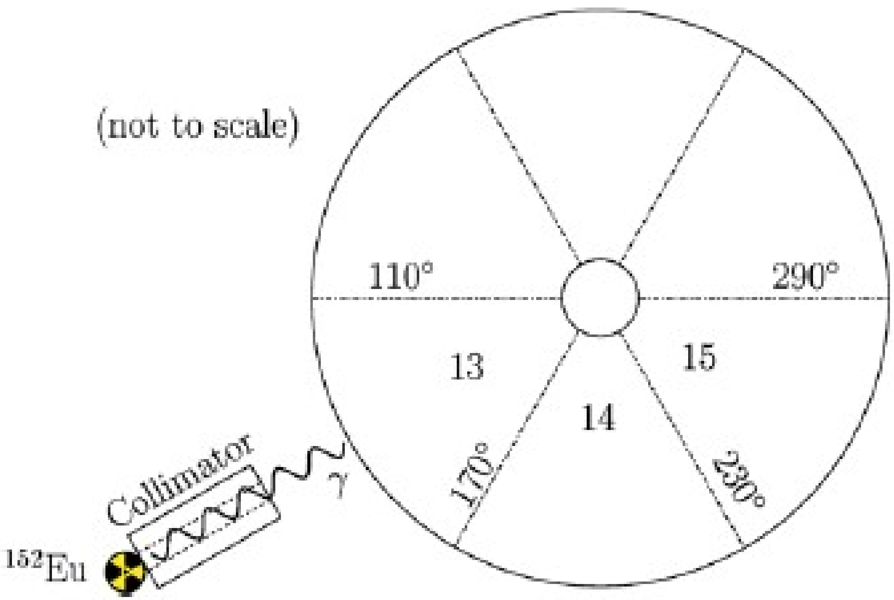


Charge [A.U.]
Time [ns]
Raw pulse
Raw pulse + Decay
Raw pulse + Decay + Bandwidth
Raw pulse + Decay + Bandwidth + Noise

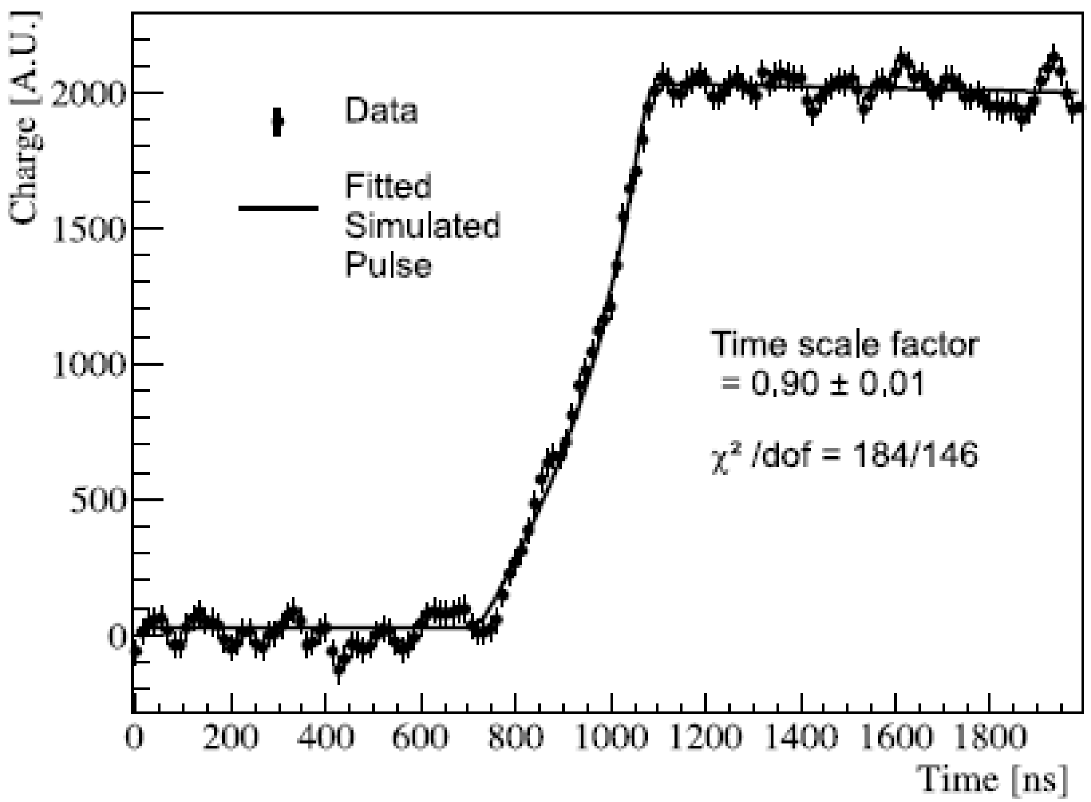
Can PSS be trusted ...

Compare simulation to data

Scanning the outer surface of a segmented HPGe detector with a collimated gamma source



Core pulse from surface scanning data (electrons drift inward from outside)



Let's put it into real use!

(an example in detector design)

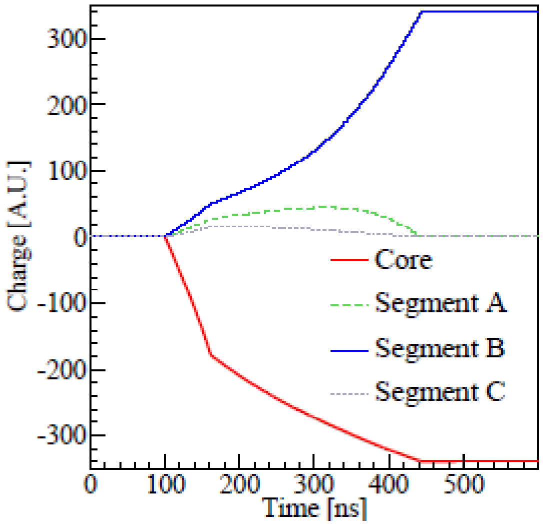
Advantage & disadvantage of segmented HPGe detectors

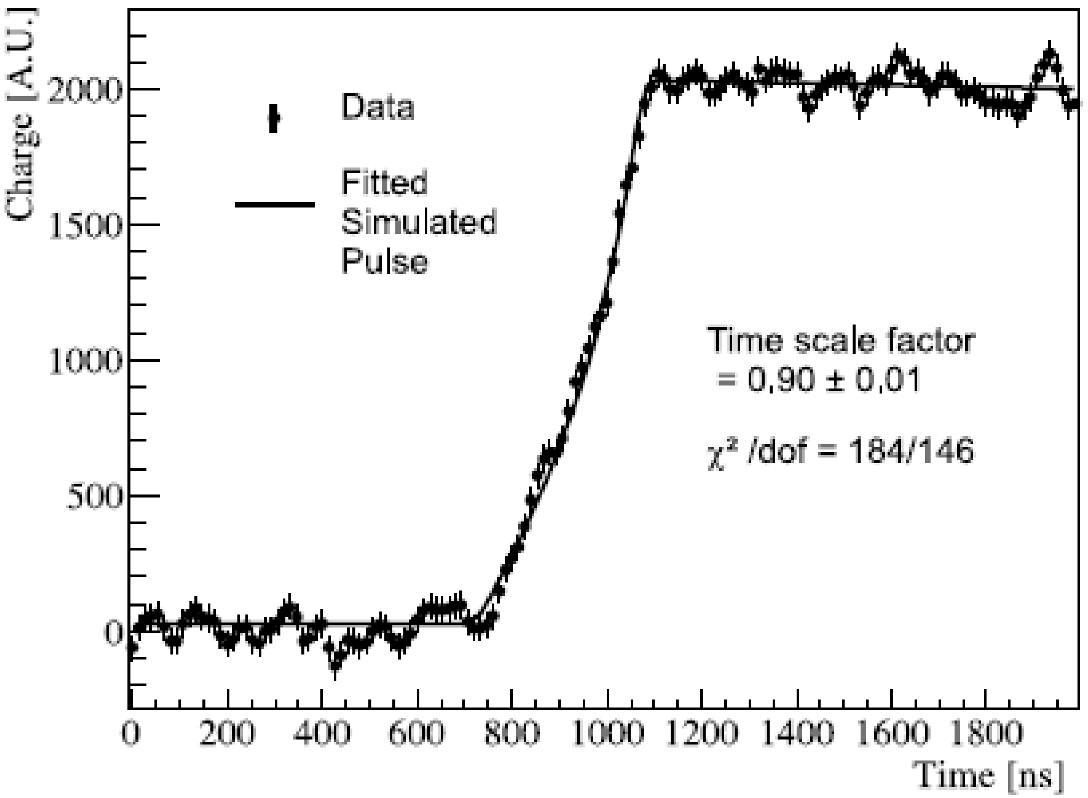
Disadvantages:

- Big capacity → noisy
- Short drift length → Short rise time
- Segmentation → more material

Advantages:

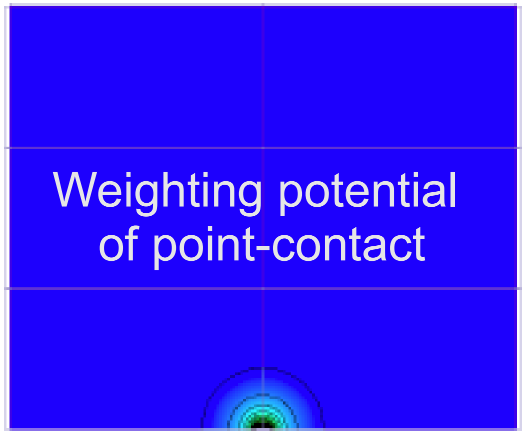
- More information is available from segment pulses





Advantage & disadvantage of PPC or BEGe

Excellent in distinguishing single-site and multi-site events (Dusan's talk)

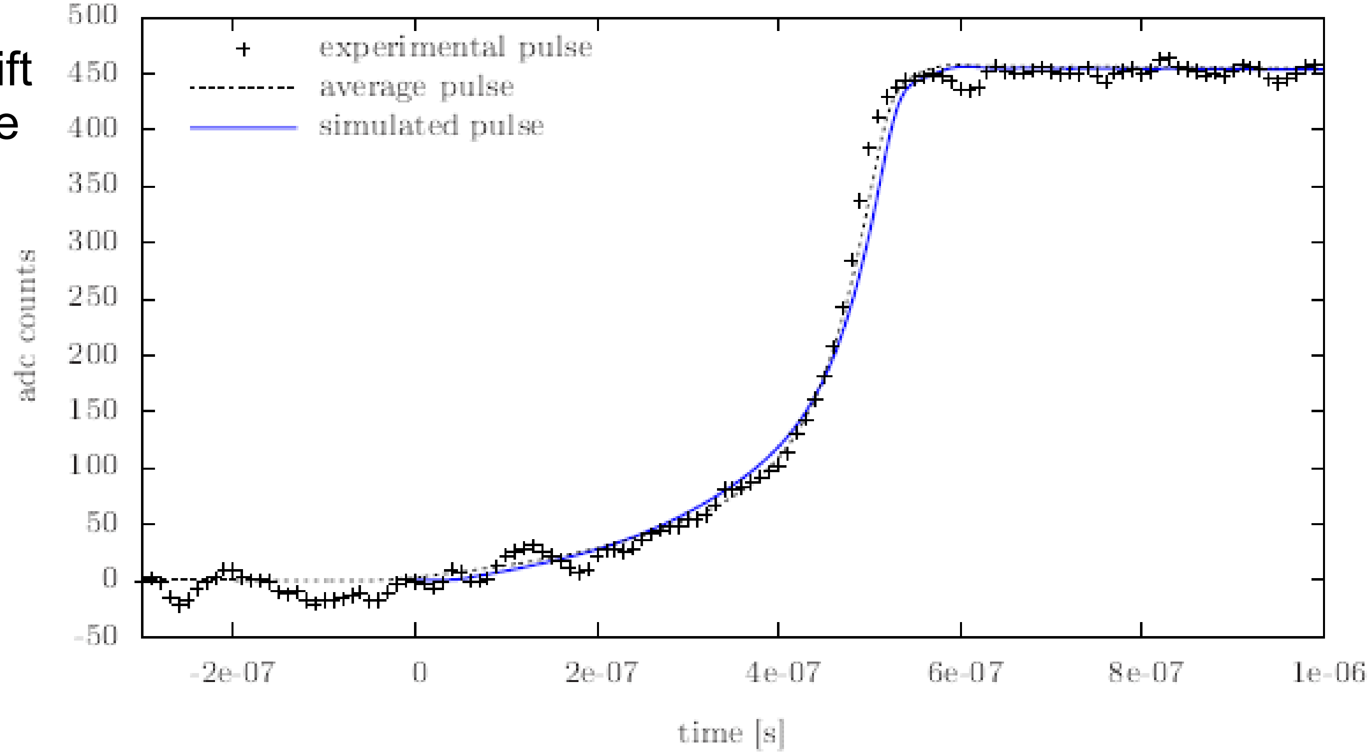


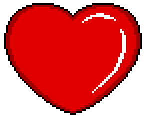
Advantages:

- Low capacity → Low noise
- Low field in bulk → long drift
- Singleton WP → shape rise at the end

Disadvantages:

- Less information

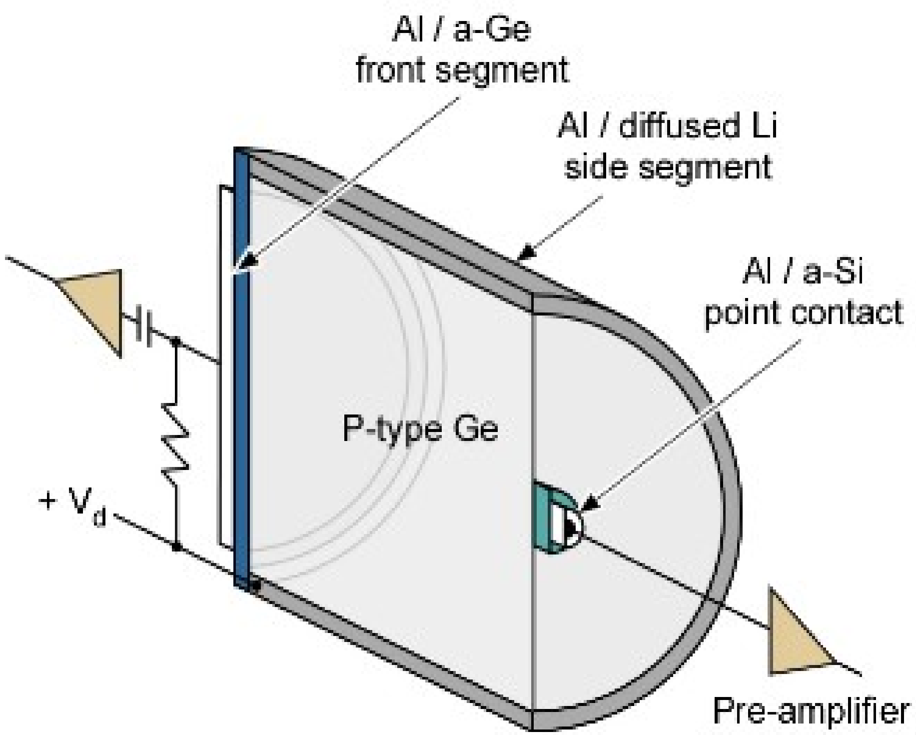


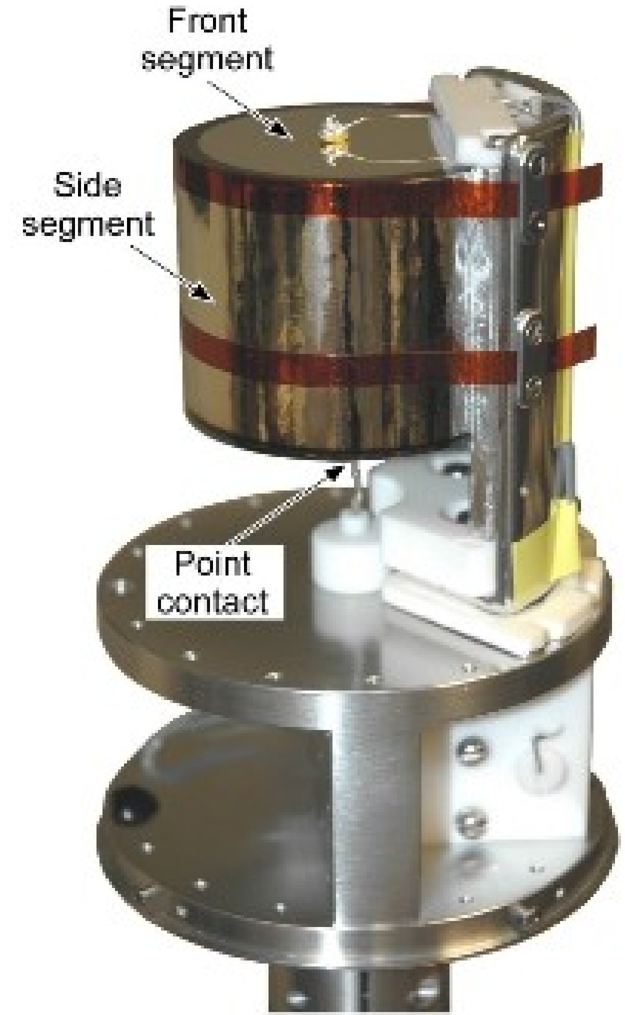
Segmented HPGe  Point-contact or BEGe

LBNL fabricated segmented PPC (SPPC)

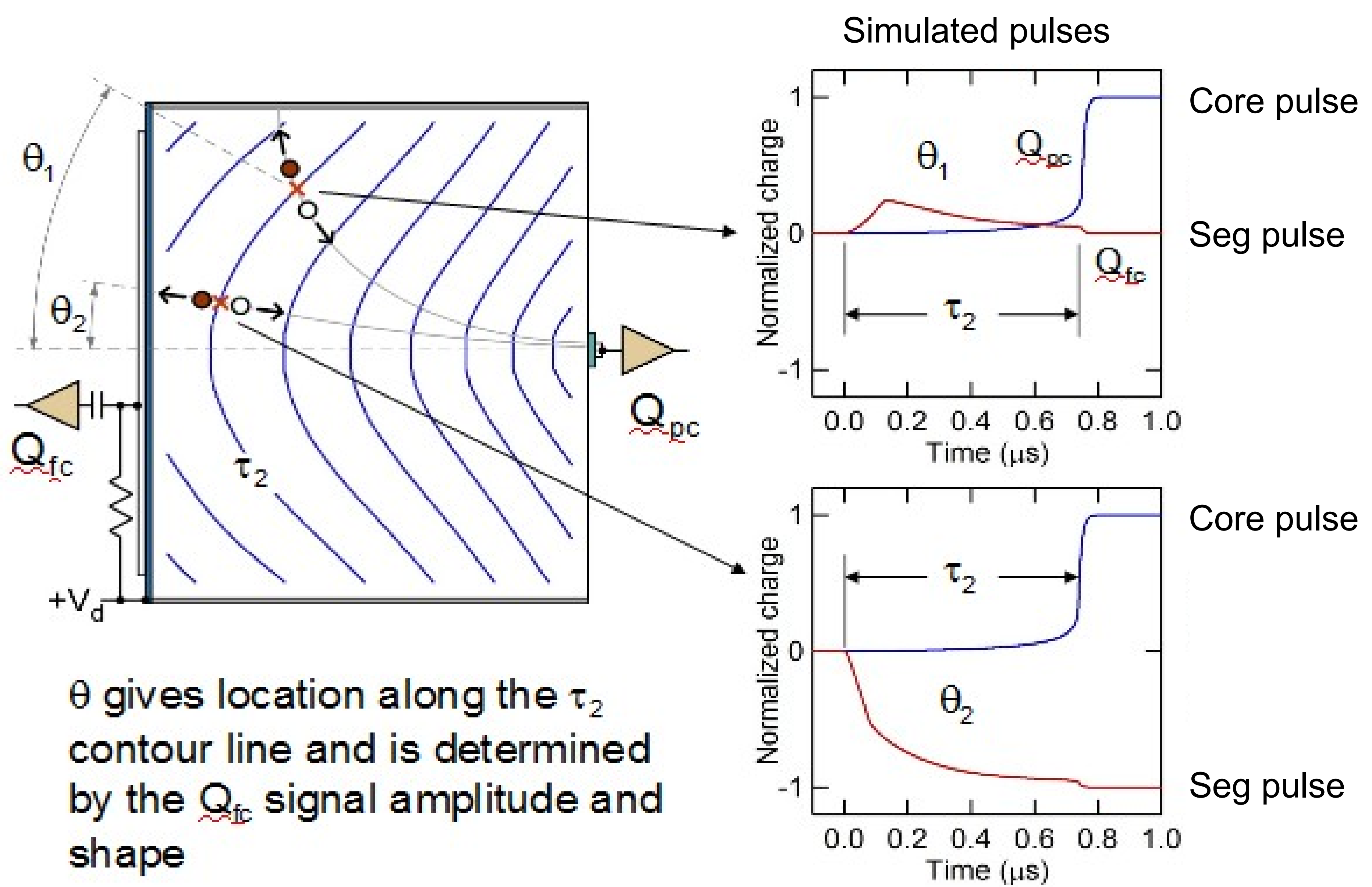
Simplest segmentation:

- two segments
- readout one



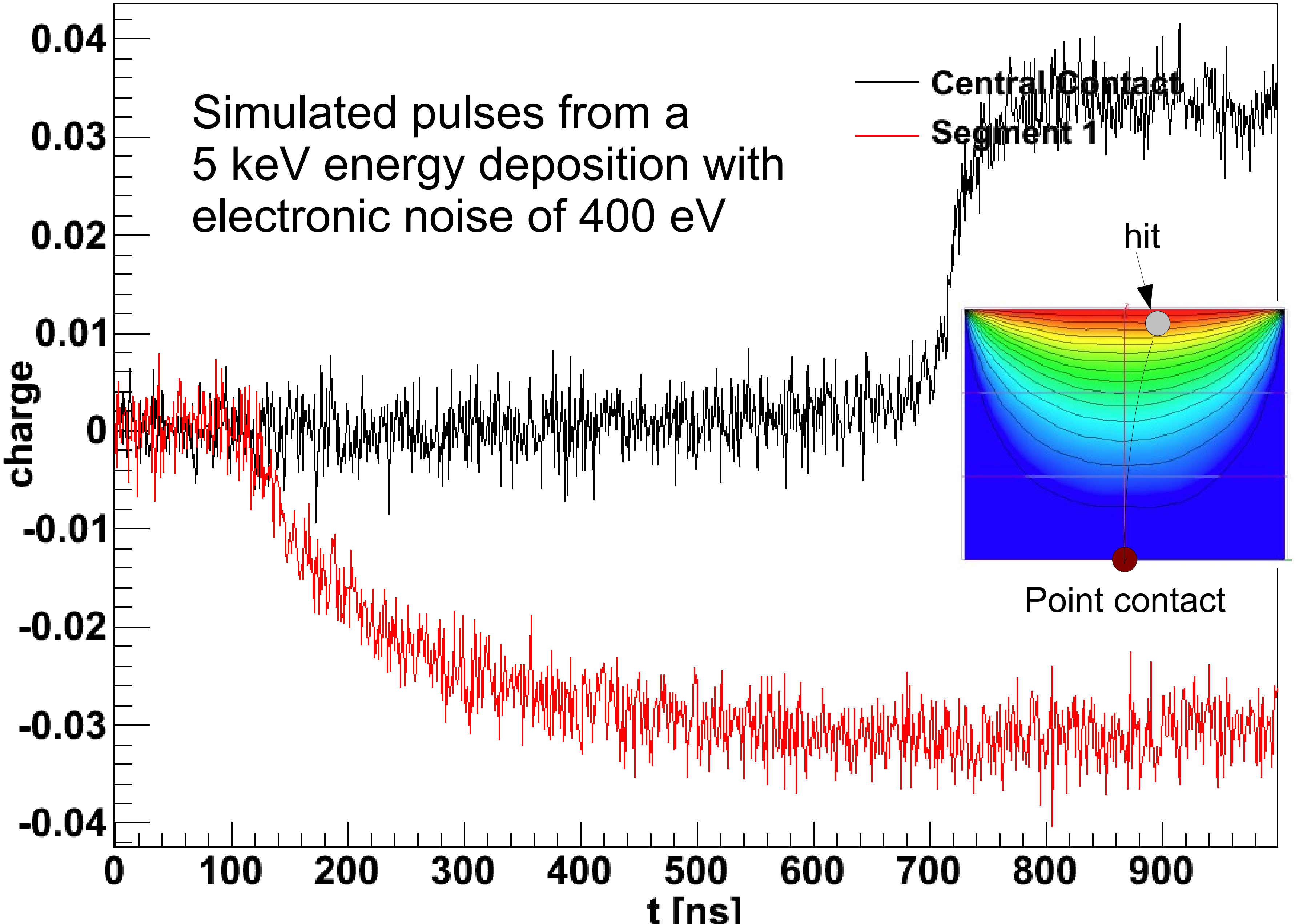


Even one single segment gives much more information



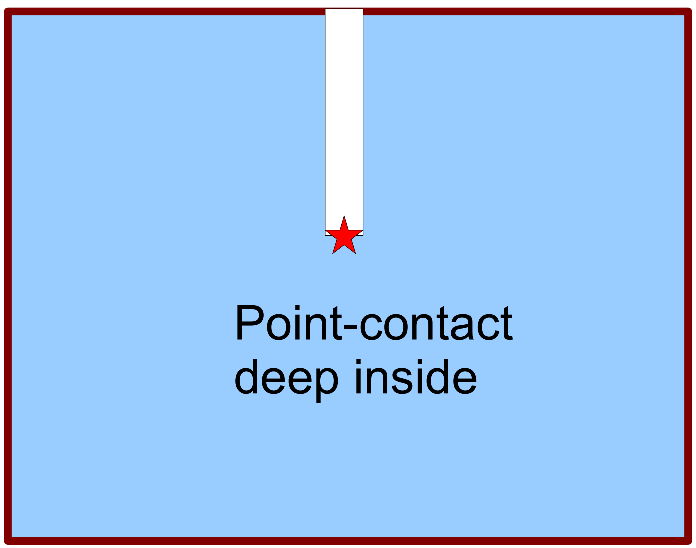
θ gives location along the τ_2 contour line and is determined by the Q_{fc} signal amplitude and shape

Determine time zero using segment pulse

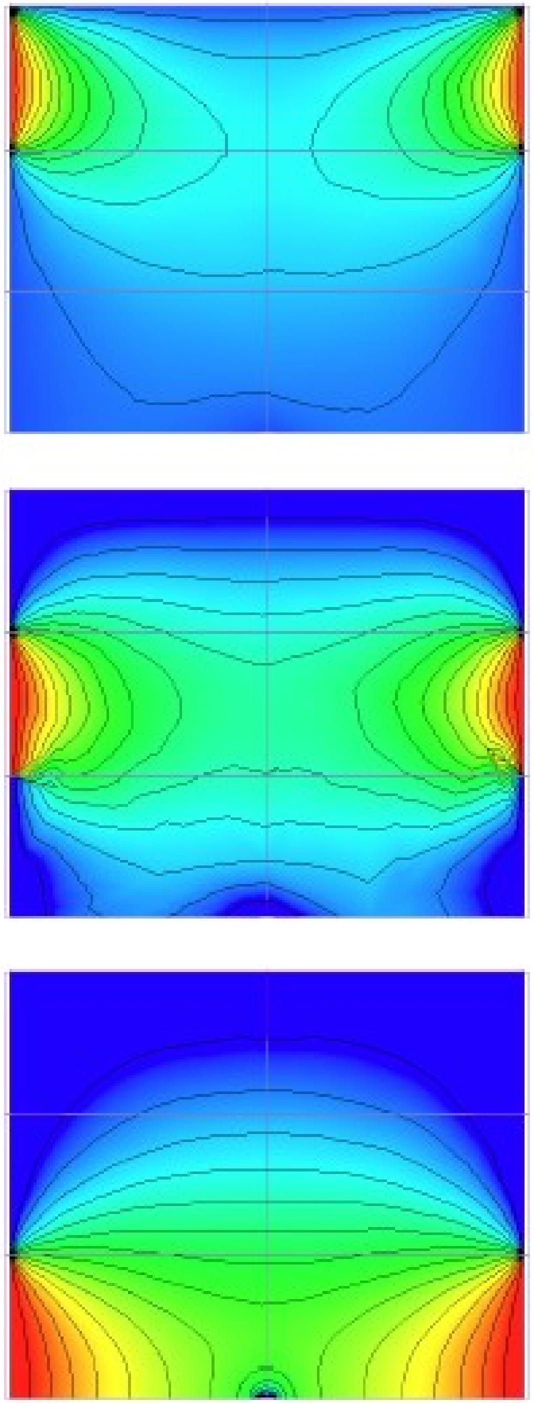


More examples

Equipped with PSS tools we can easily investigate different configurations in a quick and efficient way!



More segments for PPC



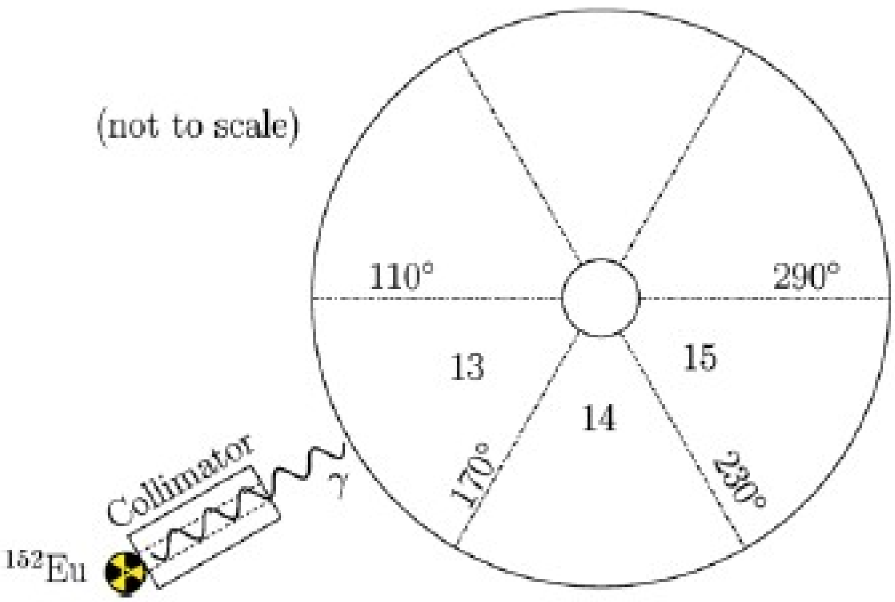
I am sure you have better ideas

Thank you!

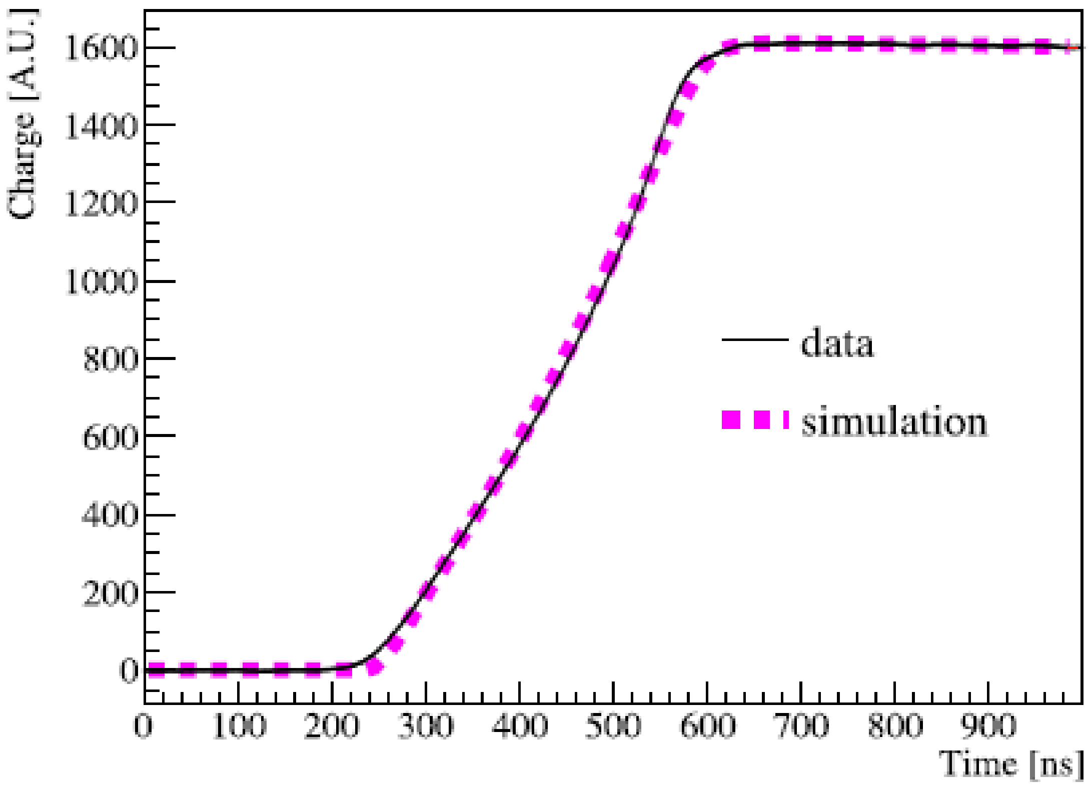
backup

Average out noise

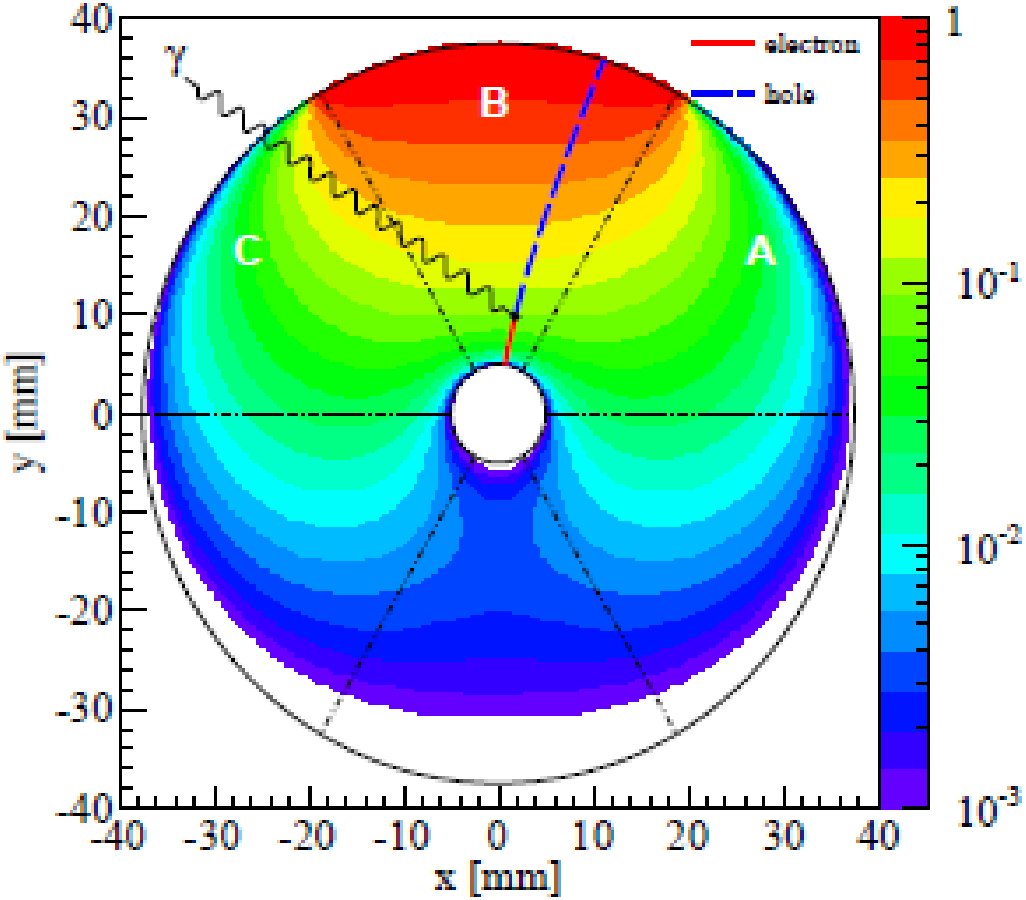
Scanning the outer surface of a segmented HPGe detector with a collimated gamma source

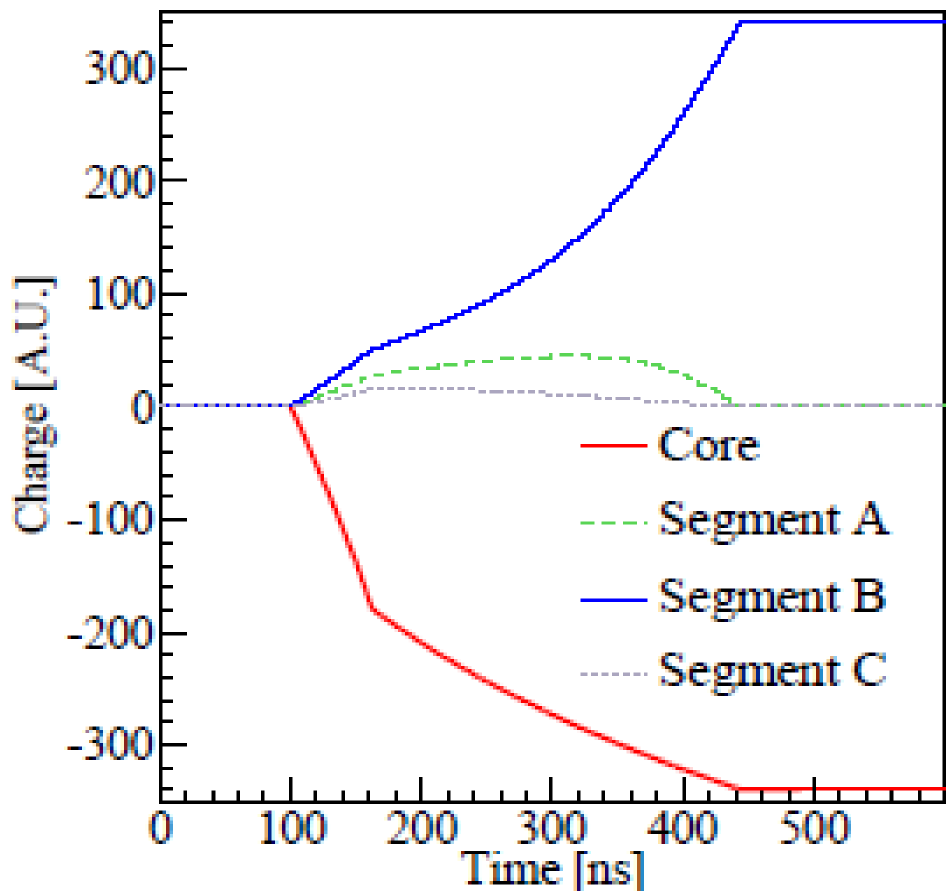


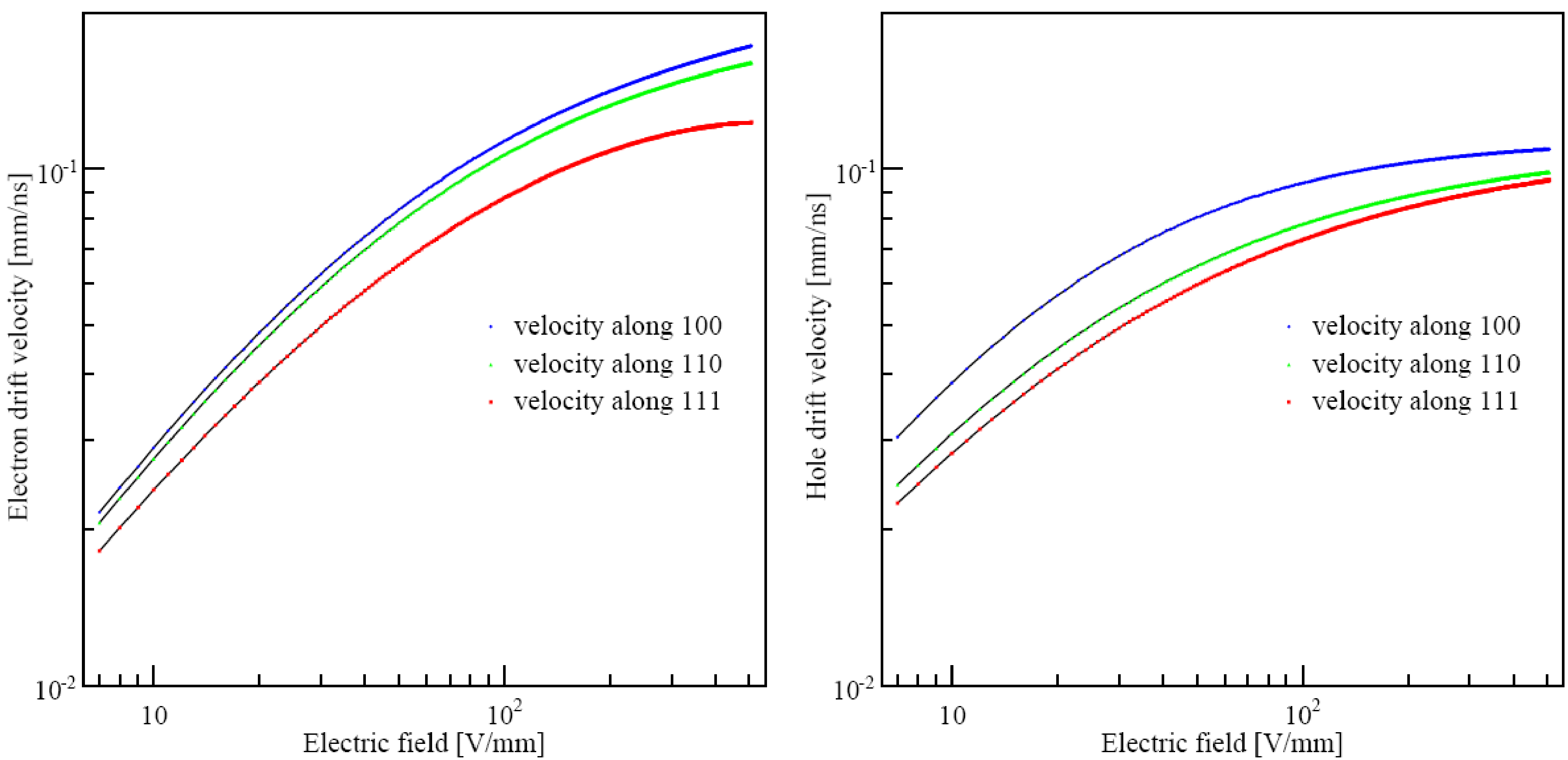
Averaged core pulses from data and simulation



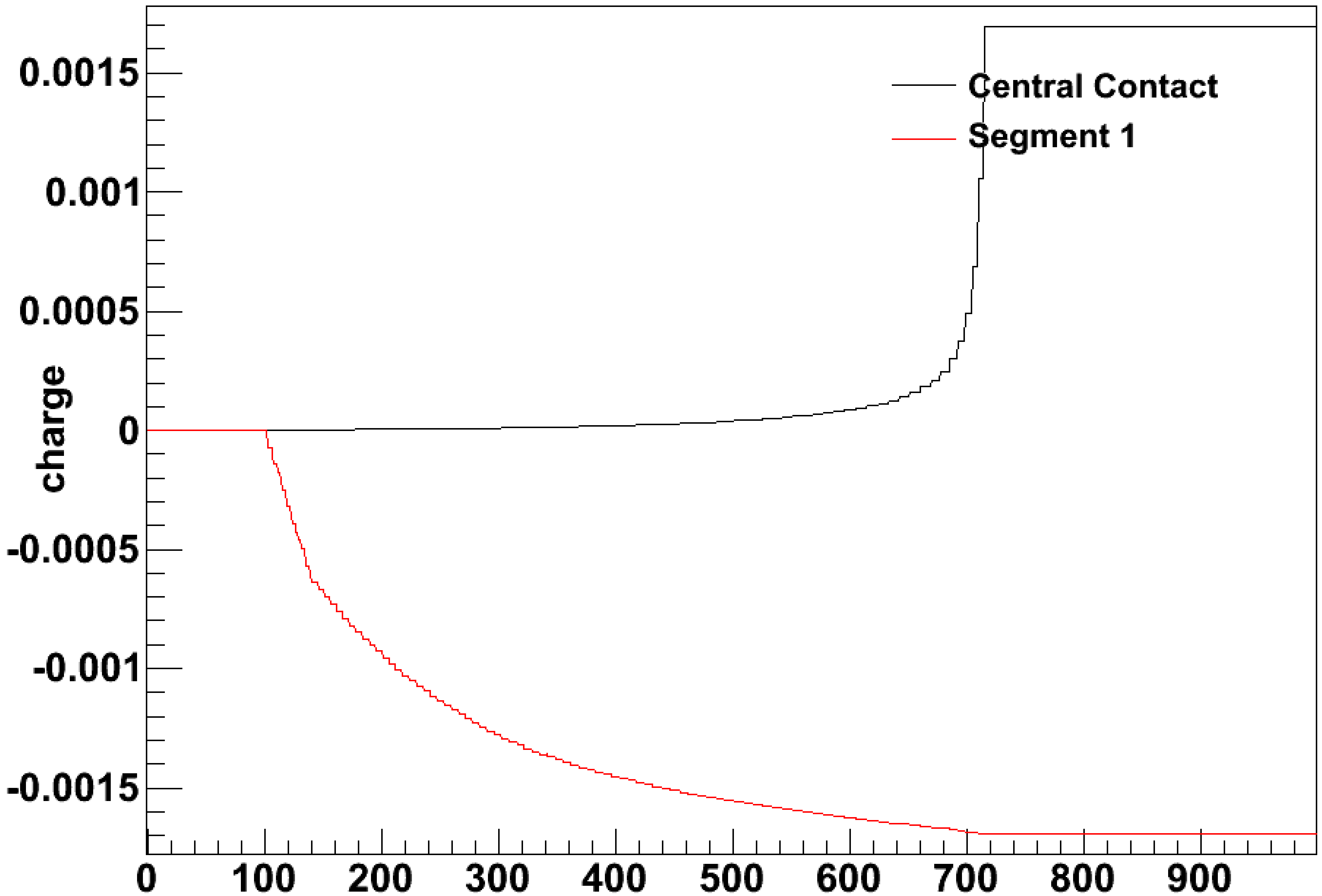
Segment pulses give more information about the interaction







Electron drift velocity [mm/ns]
10^{-1}
10^{-2}
velocity along 100
velocity along 110
velocity along 111
10
10^2
Electric field [V/mm]
Hole drift velocity [mm/ns]
10^{-1}
10^{-2}
velocity along 100
velocity along 110
velocity along 111
10
10^2
Electric field [V/mm]



Central Contact
Segment 1
charge
0.0015
0.001
0.0005
0
-0.0005
-0.001
-0.0015
0
100
200
300
400
500
600
700
800
900

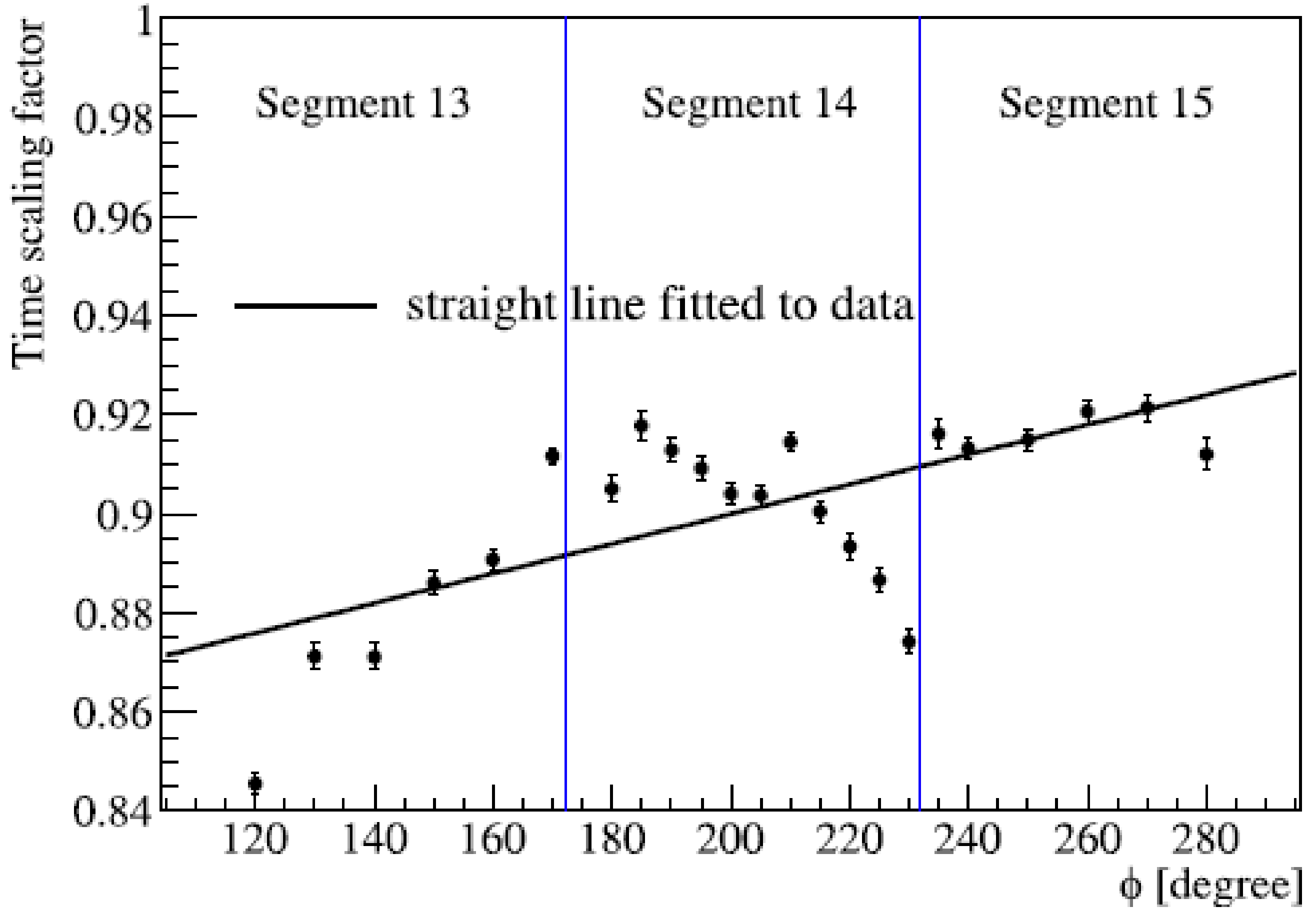


Fig. 16 Mean time scaling-factors, points, as extracted for each ϕ. The uncertainties were taken from the Gaussian fits. The result of a straight line fit to the points is given as a *solid line*

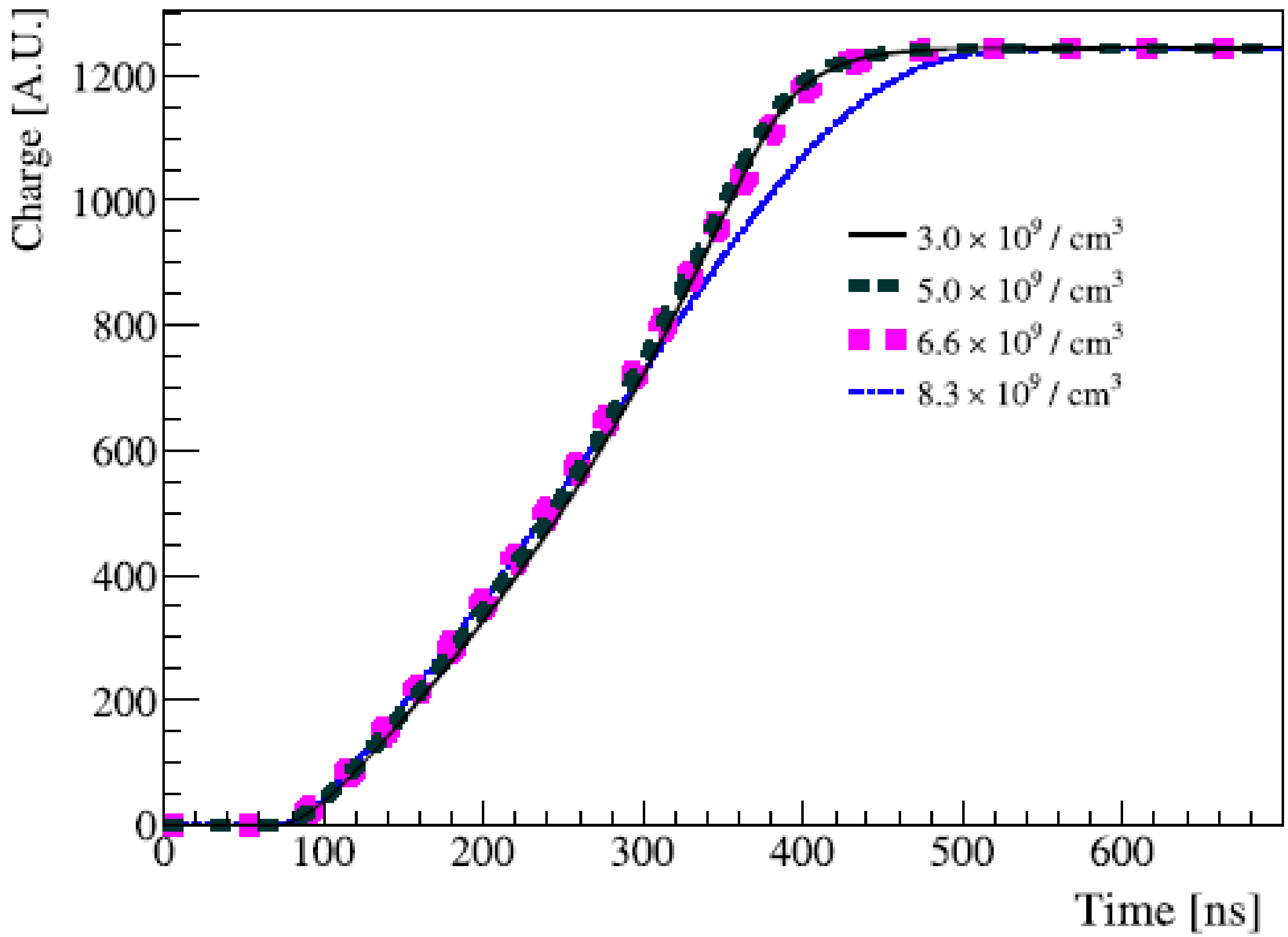


Fig. 11 Simulated core pulses for different impurities, ρ_{imp}

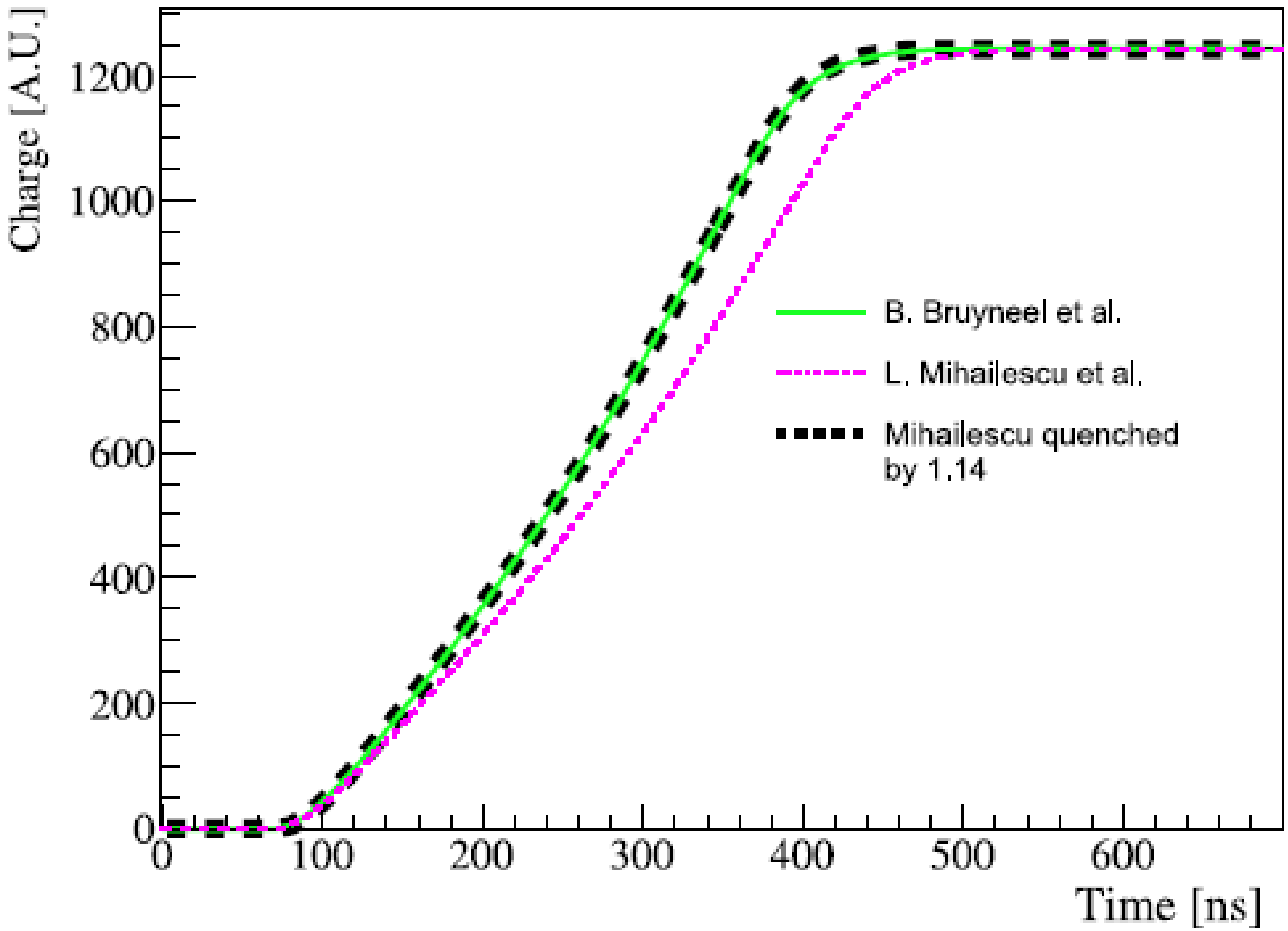
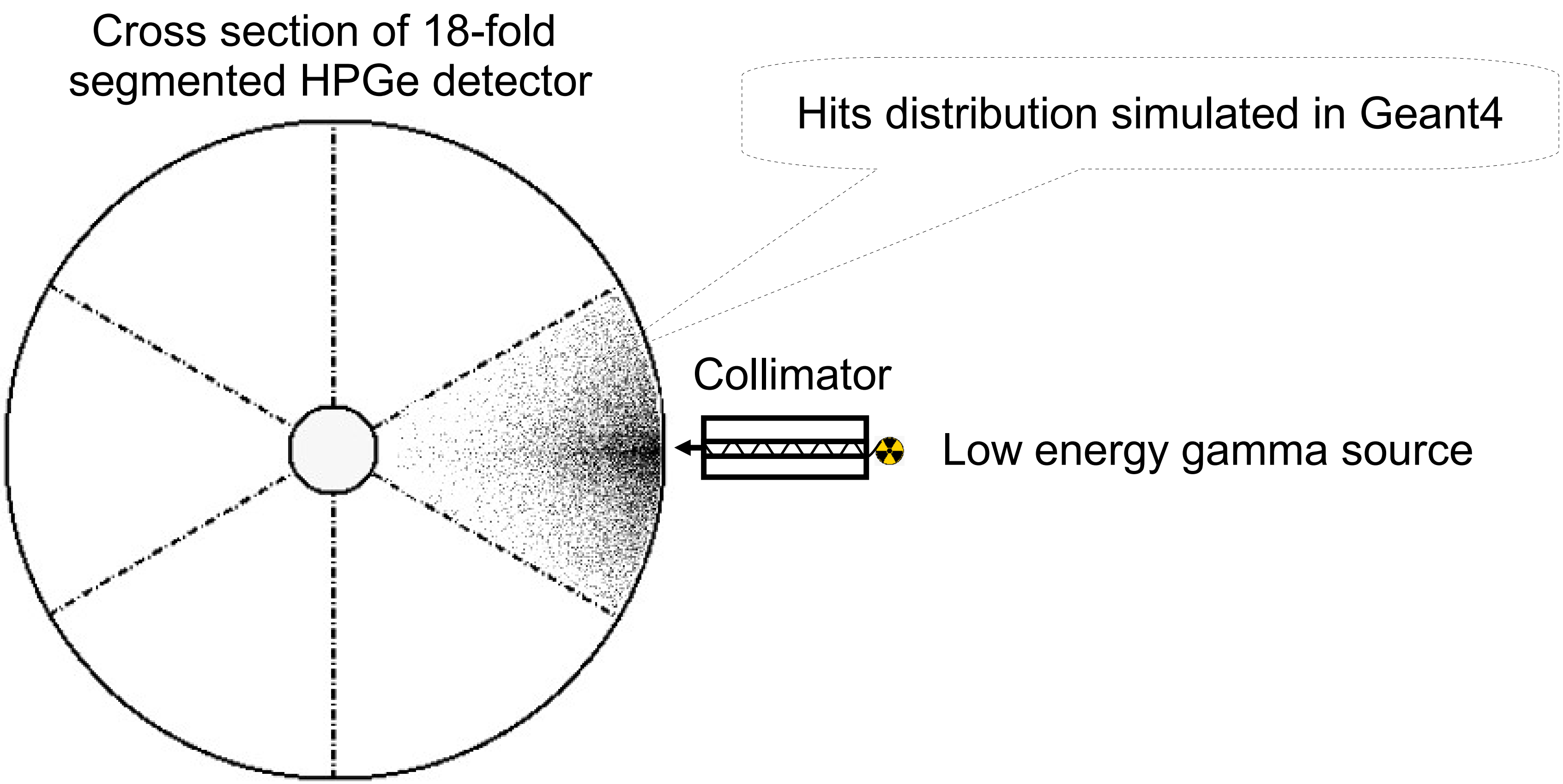


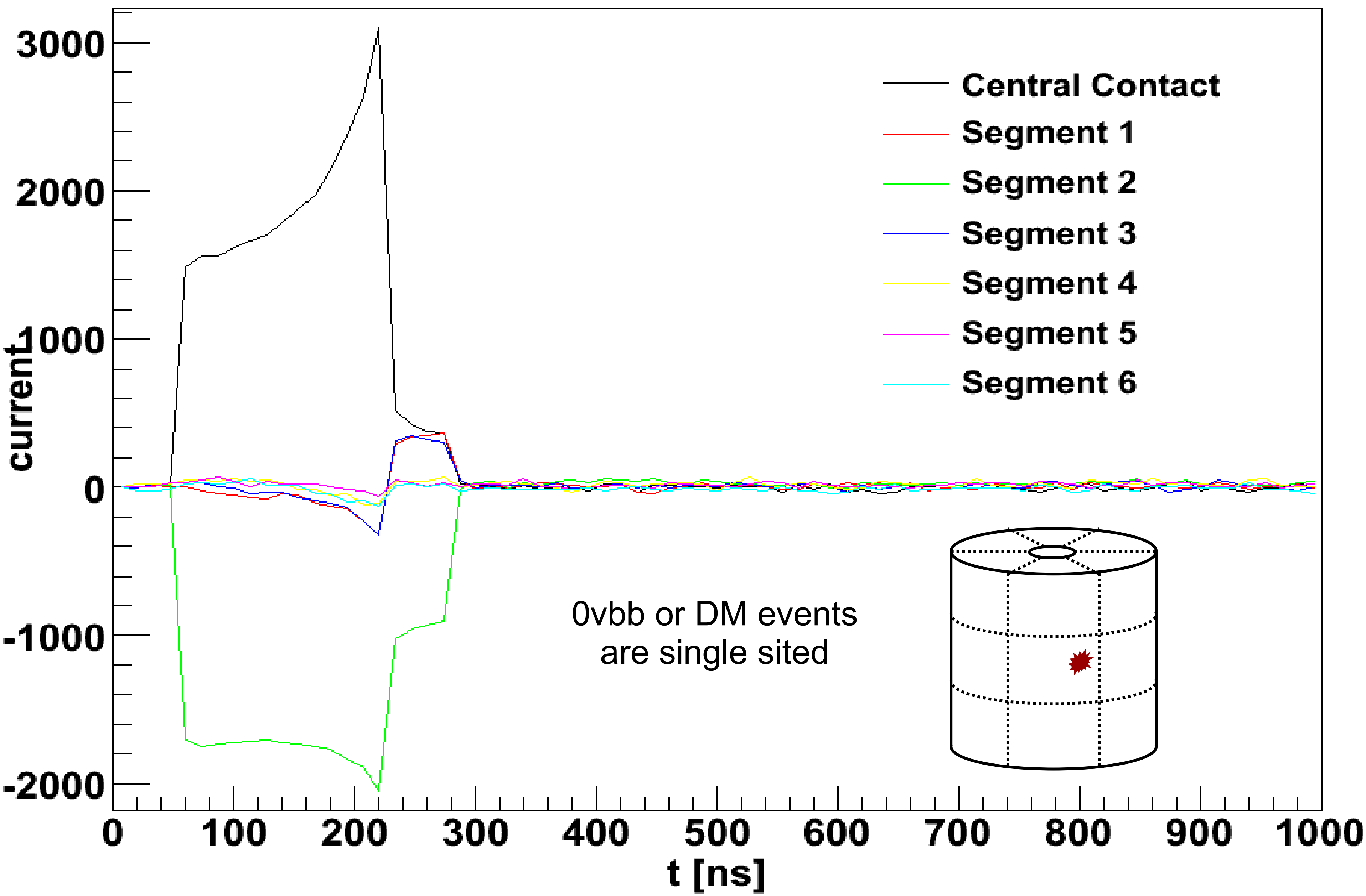
Fig. 10 Simulated core pulses for two different sets of input parameters for the electron mobility. The result of a time scaling of the longer pulse is also shown

Accurate Geant4 simulation gives a good start

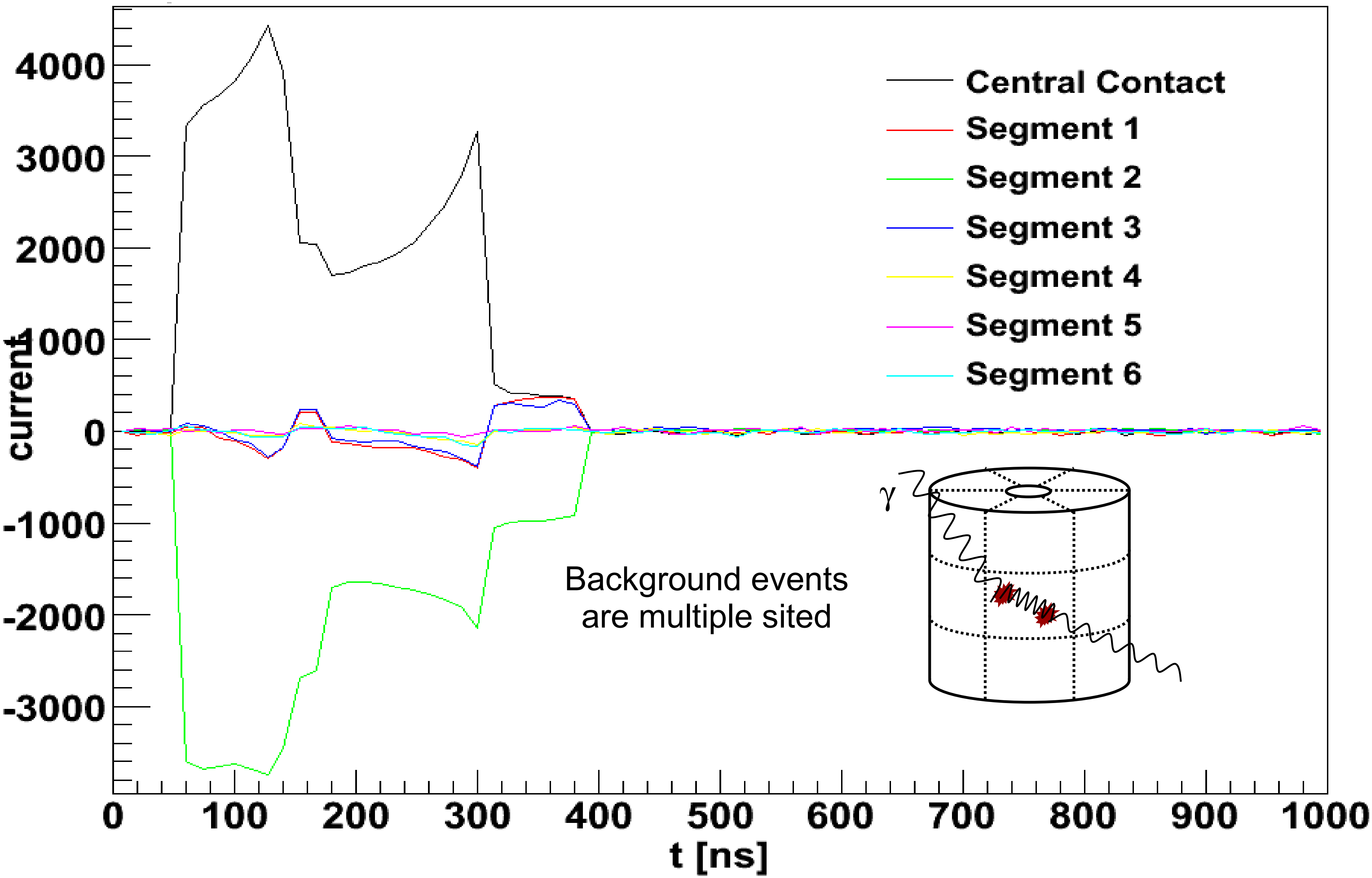


Why pulse shape simulation is needed ...

Pulses from a single-site event

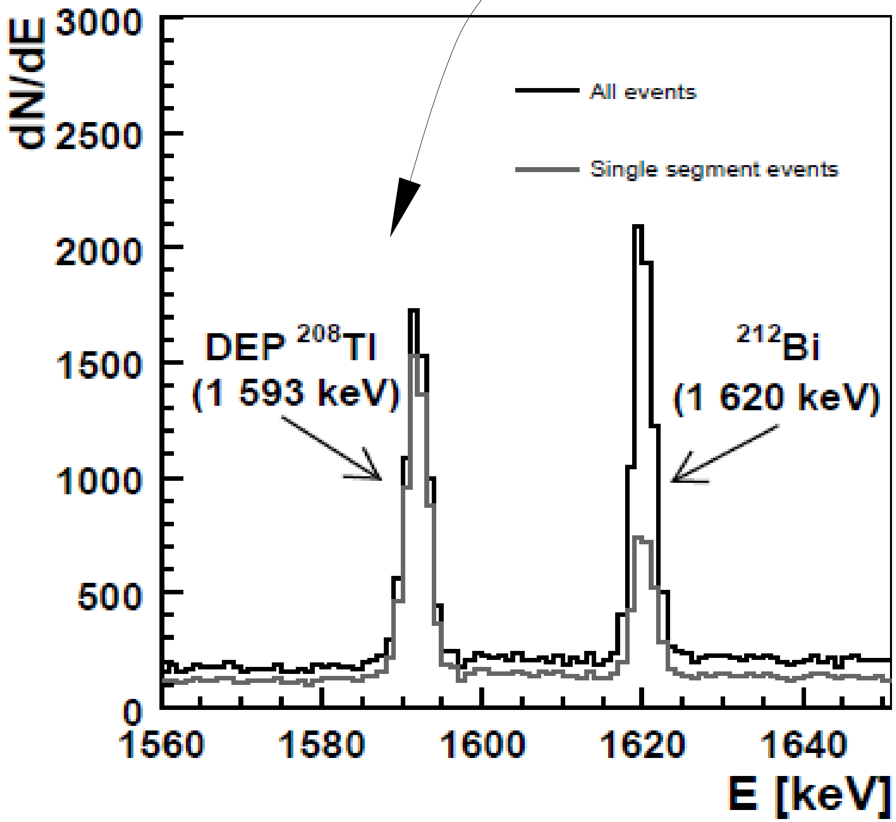


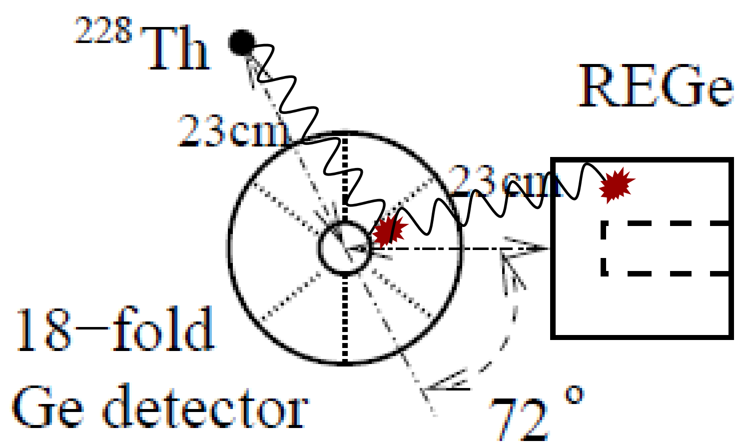
Pulses from a multiple-site event



How to get single-site event samples

Efficiency of PSA on 0vbb signal is estimated based on single-site event samples taken from

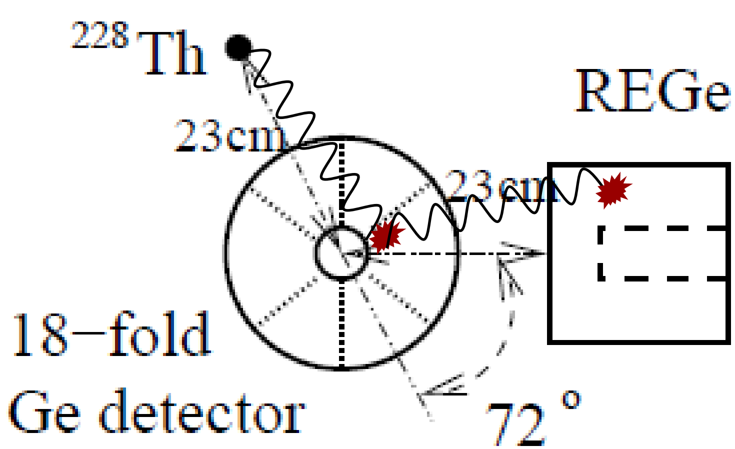


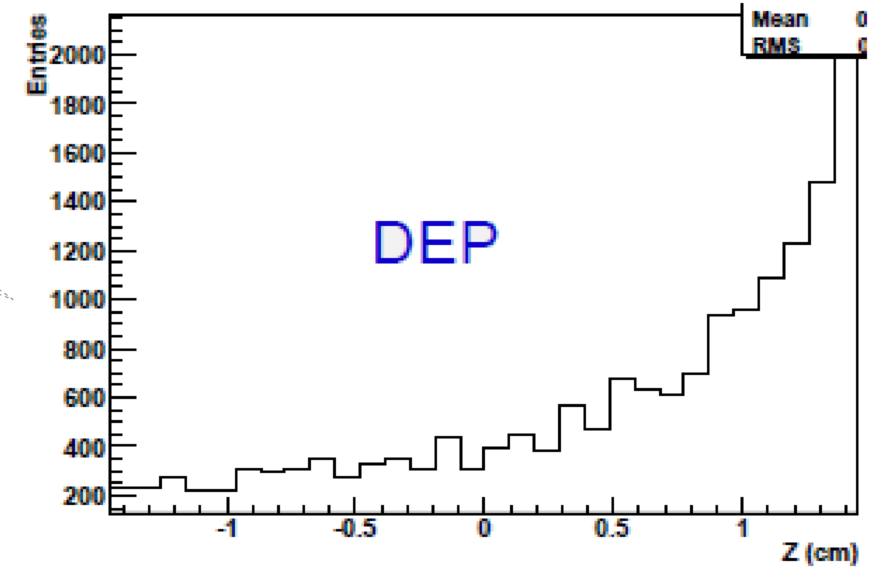


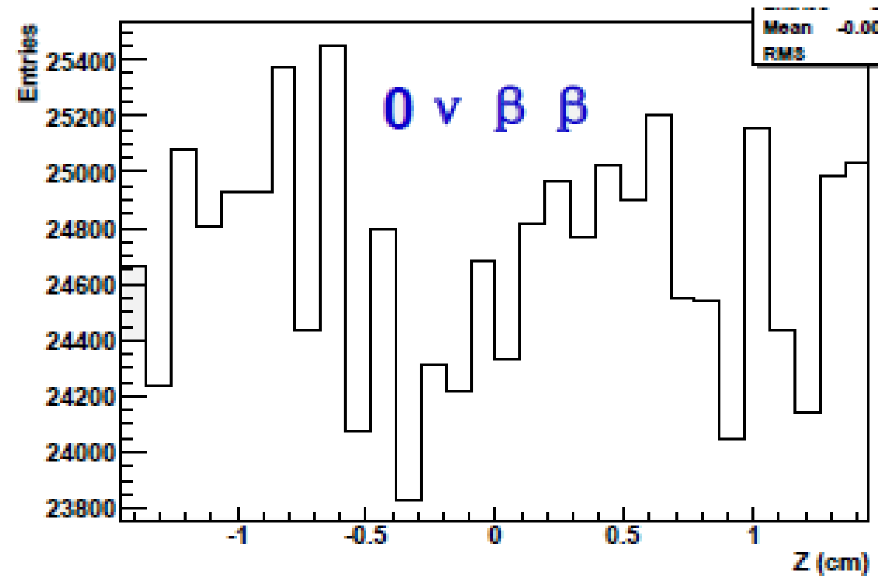
Single Compton scattering events

Single-site event data samples are not perfect

DEP samples suffer from different energy and spacial distribution



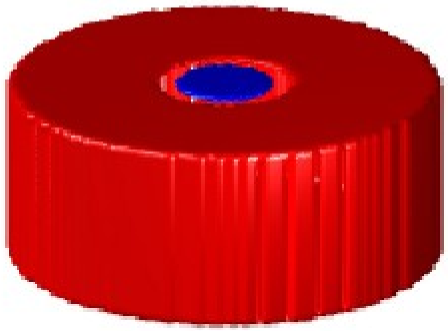




Single Compton scattering samples suffer from low event rate

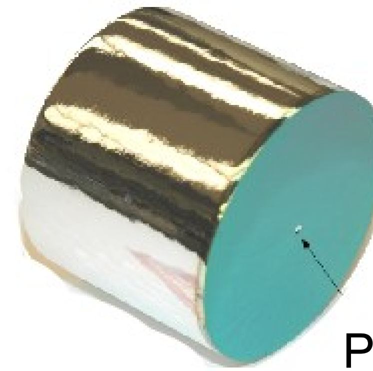
Why pulse shape simulation (PSS)

- Estimate PS Analysis (PSA) efficiency



BEGe

Segmented HPGe



PPC