Le modelisation des Detecteurs de grand volume de Germanium Hyper Pure dans la communité de spectroscopie gamma haute resolution (AGATA)

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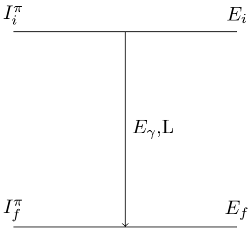
High-purity Germanium detectors in experimental nuclear physics

Gamma-ray spectroscopy excellent tool to study properties of excited states in nuclei



- Excitation energy from E_γ
- Spin from angular distributions and correlations
- Parity from photon polarisation

And in less direct ways

- Transition strengths
- Electromagnetic moments

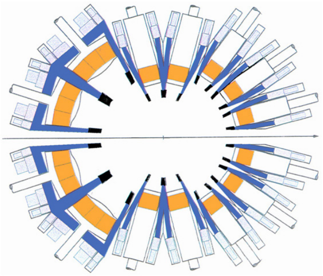
- $E_\gamma = E_i - E_f$
- $|I_i - I_f| < L < |I_i + I_f|$
- $\Delta\pi = -1^L$ for E
- $\Delta\pi = -1^{L+1}$ for M

Gamma-ray tracking - why pulse-shape analysis (PSA)?

What defines a good γ-ray spectrometer?

- Full-energy peak efficiency
- Peak-to-Total
- Energy resolution
- Isolated hit probability

Compton suppressed array 1



Gamma-ray tracking - why pulse-shape analysis (PSA)?

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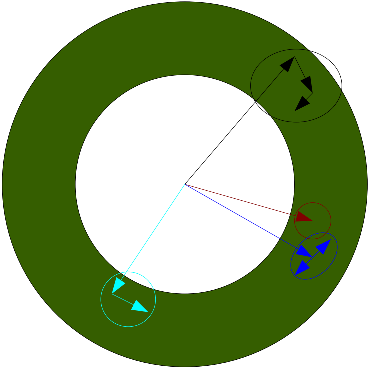
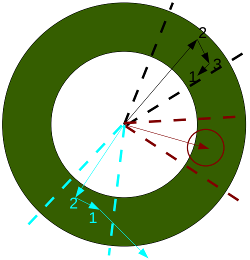
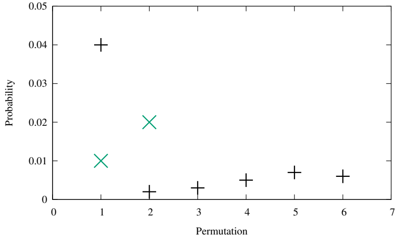
Replace with γ-ray tracking



Gamma-ray tracking - why pulse-shape analysis (PSA)?



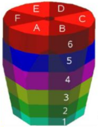


Start with all interaction points from γ rays.

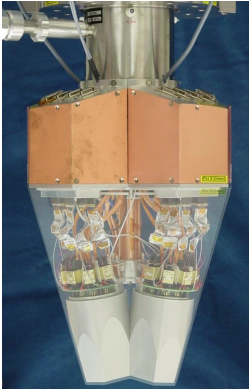
- Make clusters out of them
- For clusters N$\geq$1, find permutation with highest prob. If P$\geq$Some limit$\rightarrow$Good γ
- For single interactions, check P(photoelectric)
- Emission angle of γ ray
- Compton suppression

Gamma-ray tracking - why pulse-shape analysis (PSA)?

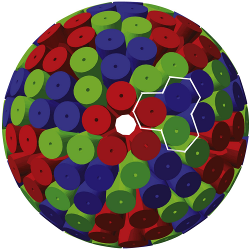
36 folded segmentation

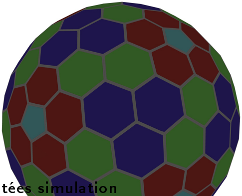


Put 3 by 3 in cryostats (~77° K)

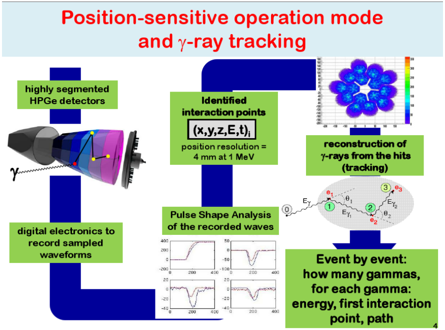


60 triple clusters (we have 17)





A few words on the PSA

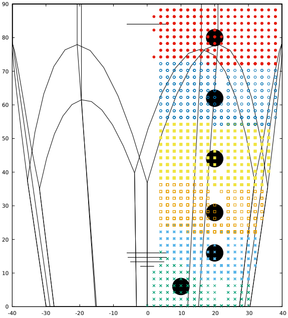


- Need $\Delta R < 5$ mm.
- Compares with calculated pulses
- Adaptive grid-search
- One interaction/ segment
- No error-estimate on the position

Information in pulse-shapes

"r from rise times. z and φ from transient signals". PSA is grid-search where the metric is $\sum |y_{exp} - y_{basis}|^{0.3}$

Is PSA for gamma-ray tracking a high-precision or low-precision endeavour?



- "Size of segments" ~20^3 mm
- We seek 5 mm/20 mm precision
- $\rightarrow$ ~ 60 voxels/segment

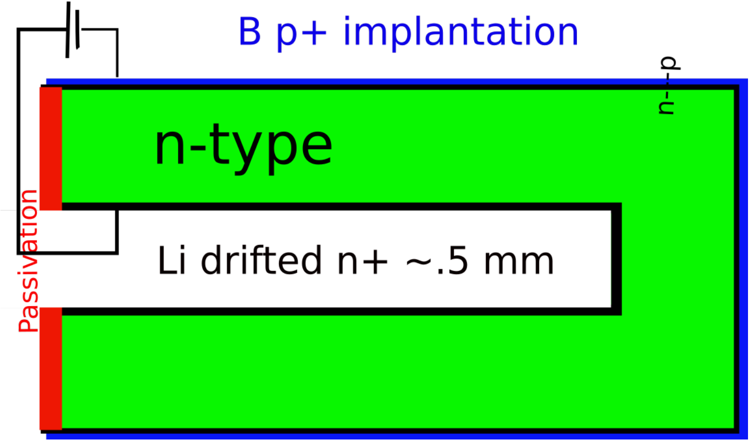
Need for high-precision modeling of detectors not for accuracy in PSA but for hit multiplicity and error estimates!

Important topics I will not touch

- Influence of electronics. We use cross talk+some integration+50 μs decay.
- We correct trapping from fast neutron damage in HPGe on event-by-event basis. See Bruyneel epj a 2013

A reminder

AGATA detectors n-type Ge diodes cooled to 77° K.



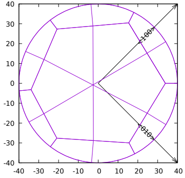
Unlike for planar geometries, electric field not parallel with a crystallographic axes.

Formulation of problem to solve

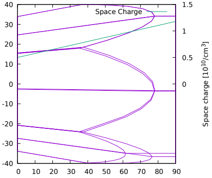
- Electric field from solution of Poisson equation $\nabla^2\varphi(\vec{r}) = -\frac{\rho(\vec{r})}{\epsilon_{Ge}}$
- Charge carrier transport in this field $d\vec{r}/dt = \vec{v}(\vec{E})$, $\vec{E} = -\nabla\varphi$
- Currents on electrodes from Shockley-Ramo theorem $\frac{dQ(t)}{dt} = e\left[N_h\ \vec{v}_h(\vec{r}_h)\cdot\vec{W}(\vec{r}_h) - N_e\ \vec{v}_e(\vec{r}_e)\cdot\vec{W}(\vec{r}_e)\right]$, $\vec{W}(\vec{r})$ the weighting field
- (Cross talk, Front-end electronics. . .)

Ingredients for pulse-shape simulations

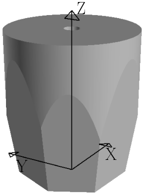
Lattice orientation



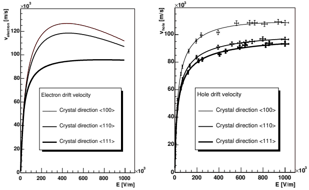
Space Charge distribution



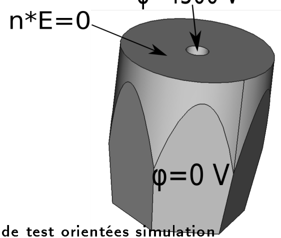
Geometry



Charge carrier mobilities



Boundary conditions



What is known/given from the manufacturer

- Weight and dimensions of crystal (~2.4 kg)
- Segmentation (but without inter-segment spacing)
- Impurity concentrations
- C vs V curve
- Crystal Lattice orientation
- Energy resolution all segments and core

What we measure/verify

- Energy resolution
- Cross talk
- (C vs V)
- (Crystal Lattice orientation) EPJ. A52, 70 (2016)
- (Impurity concentration profile) NIM A 640 176-184

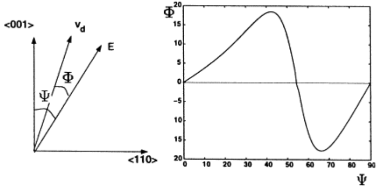
Approximations we do

- Transport of point charges
- Zero segment boundary widths
- No leakage currents
- Simple boundary condition on passivated surface
- Li contact ~ 0.5 mm everywhere
- Precision in geometry description (we are not given all information) and finite resolution in PDE solvers.
- No temperature or impurity dependence on charge-carrier velocities

Anisotropy of "hot" charge carriers

Short(!) introduction

- Charge carrier velocity not parallel to E-field (except at symmetry axes i.e. <100>, <110>, <111>)
- Important for Large Volume HPGe (~ 3 mm "error")

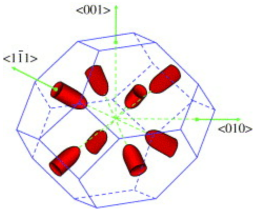


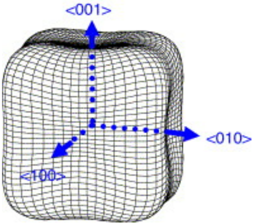
Mihailescu et al.

Anisotropy of "hot" charge carriers

Models used for AGATA

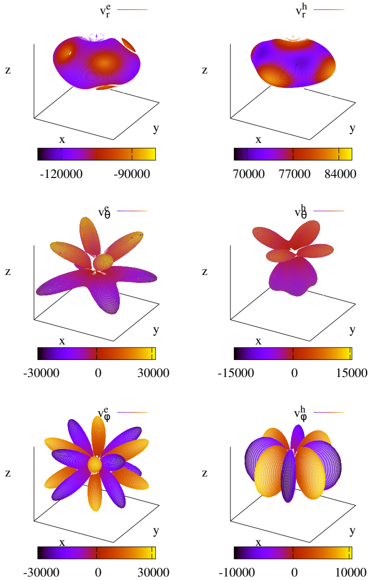
- Electrons - Nathan. Anisotropic effective mass+population changes in conduction valleys oriented differently to E-field.
- Holes - "Streaming motion" by Bruyneel et al or simpler by Ljungvall. Anisotropy from effective mass in conduction band.





Figures from Bruyneel et al..

Anisotropy of "hot" charge carriers



The electric field

Poisson equation - typical strategies for PDE's used

Finite difference method

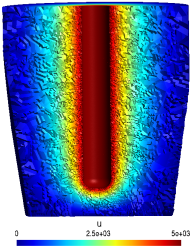
- "Easy" to implement
- Used in the community for ion traps etc.
- Codes: MGS, JASS, ADL

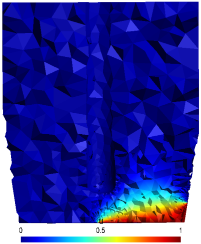
Finite element method

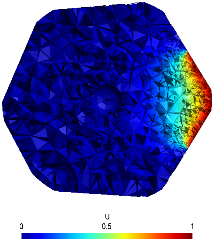
- Easy to be precise in geometry description.
- Grid adapted to complexity of solution.
- Codes: "MARS", AGATAGeFEM

Space charge from measurements or manufacturer.

Some examples for electric fields and weighting fields (with AGATAGeFEM)



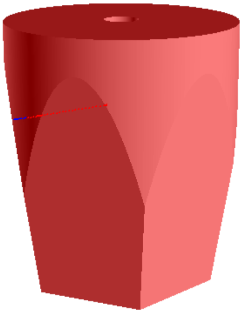




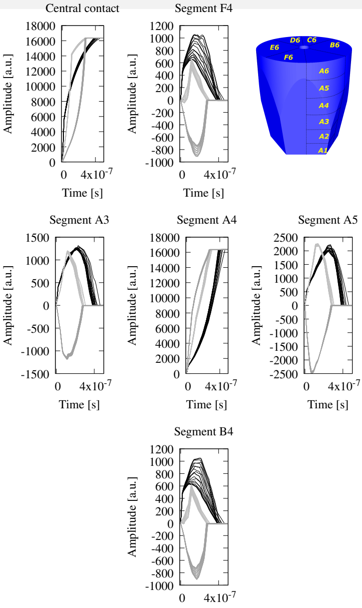
Charge transport

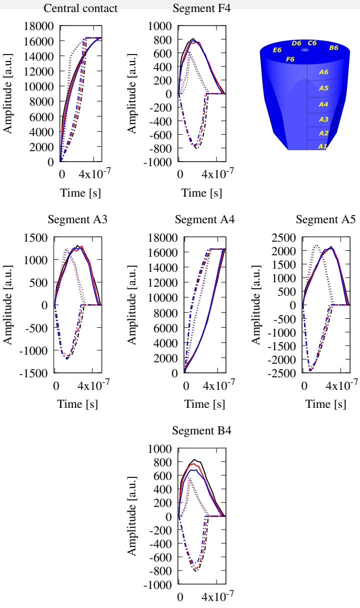
This is not complicated.

- This problem is typically solved using existing time dependant ODE solvers using different versions of Runge-Kutta
- Specifically AGATAGeFEM uses a Runge-Kutta-Prince-Dormand



Examples of pulses shapes





Are our simulations good?

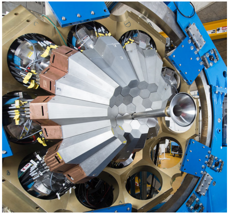
- Compare with experimental pulses from known positions (see more of this later).
- It is the end results that interests us (the most), so we check after γ-ray tracking

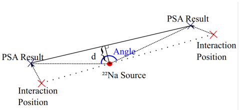
Results from source data

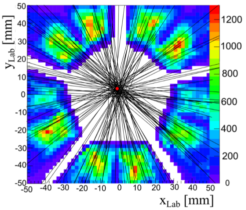
^{22}Na emits two 511 keV back-to-back (Lewandowski et al.)

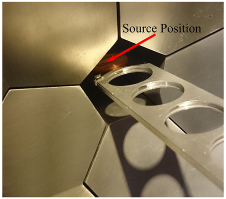
AGATA at GANIL

d $\Longrightarrow$ position resolution $\Longrightarrow$ correct signals





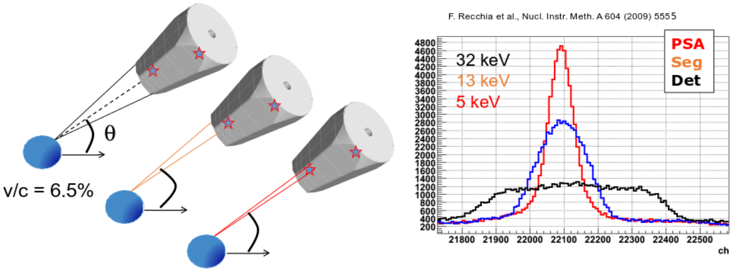




Conclusion is that we have $\Delta R < 5$mm FWHM, i.e. within specs.

Results from in-beam data

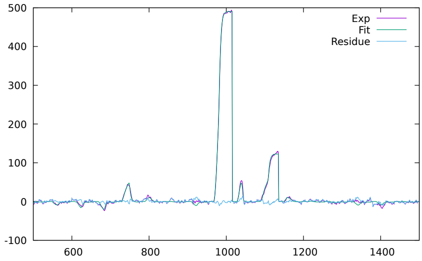
Doppler Correction after the reaction ^{48}Ti(d,p)^{49}Ti

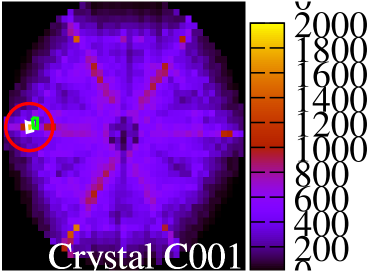


ΔR<5 mm FWHM

Are we happy with this?

- We have achieved, on average, the needed position resolution.
- We see artifacts in the interaction position distributions. Question if this is signal treatment or PSA basis. . .





So the answer is yes and no.

Counting the interactions and event-by-event error estimate

The next goals are to be able to disentangle two interactions in the same segment. . .

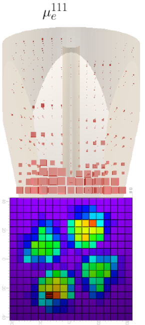
- This might be possible with a "perfect" base of signals: A χ^2 could be used to discriminate between over-fitted one interaction or two interactions.

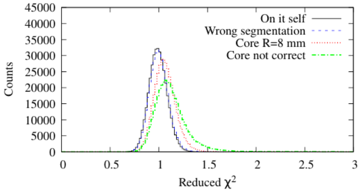
. . . and be able to do error estimates on event-by-event basis.

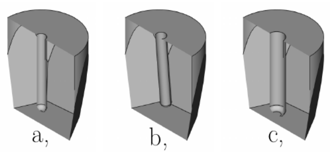
- Present metric not χ^2. Other ideas under investigation such as boot strapping (see Siciliano et al.)

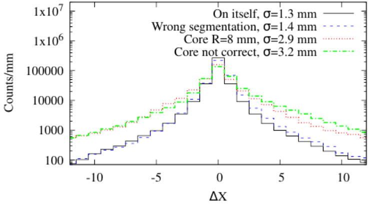
If we achieve this γ-ray tracking will work even better

Find the most important parameters

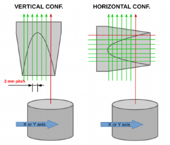


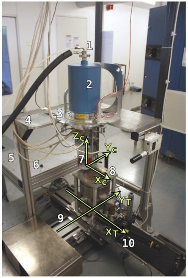


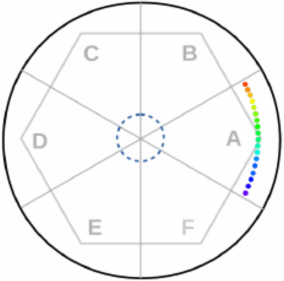


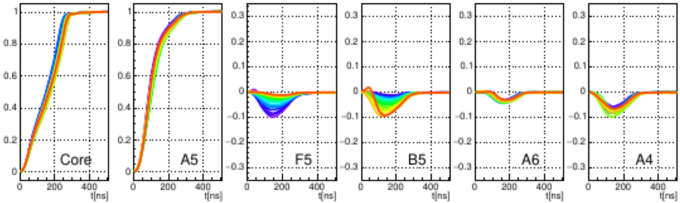


Use data from scanning tables, fit parameters









PhD thesis of B. De Canditiis, IPHC