Pulse Shape Analysis
With the AGATA DEMONSTRATOR

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Ingredients of Gamma-Ray Tracking

1. Highly segmented HPGe detectors

2. Digital electronics to record and process segment signals

3. Identified interaction points \((x,y,z,E,t)_i\)

4. Reconstruction of tracks evaluating permutations of interaction points

Pulse Shape Analysis to decompose recorded waves

Reconstructed gamma-rays
PSA with the AGATA demonstrator

• How to simulate detector responses
• PSA methods used for AGATA
• First PSA results
• Optimisation:
  – Crystal orientation measurements
  – Response function of electronics
  – Derivative crosstalk analysis
  – CV measurements for doping profile
How to simulate detectors

Requirements:
- Weighting potentials
- Electrical field ↔ space charge
- Anisotropic Mobility
- Response of electronics

Solution to Laplace equation

Weighting potential for this segment

10 … 90%
1 … 9%
0.1 … 0.9%

B. Bruyneel NIMA 569 (2006) 764-773
B. Bruyneel NIMA 569 (2006) 774-789
Mobilities: Intro

- Monocrystalline Ge
- Periodic potential

\[ \Psi_{n,k}(\vec{r}), \varepsilon_{n,k} \]

- Wave vector \( \vec{k} \) in first Brillouin zone
- Band index \( n \)

\[ \vec{\nu}_{n,k} = \frac{1}{\hbar} \nabla_{\vec{k}} \varepsilon_{n}(\vec{k}) \]

- Longitudinal anisotropy
- Tangential anisotropy

\[ |\nu_r| \text{ angle dependent} \]

Crystal symmetry: [100], [110], [111]
Electron and Hole Mobility in Ge

Electrons
- L. Mihailescu et al. NIMA 447 (2000) 350
- Distributed over 4 ellipsoidal valleys
- Each valley is MB distributed, T(E)
- Intervalley scattering \( \nu(E) \) defines valley population
- \( \nu_{100}(E) \) and \( \nu_{111}(E) \) defines all.

Holes
- B. Bruyneel et al. NIMA 569 (2006) 764-773
- Only “warped” heavy hole band is important
- “Streaming motion” → drifted MB distribution:
- \( \nu_{100}(E) \) and \( \nu_{111}(E) \) defines all.

Band Gap

\[ \alpha k = \frac{2\pi}{\text{Band Gap}} \]
Electrons and holes have different longitudinal and tangential velocity anisotropy components.

- Electrons $v_r$ mainly slower near [111],
- Holes $v_r$ mainly faster near [100]
- Tangential components 0 along symmetry axes and largest near same directions of largest $v_r$ differences
Pulse Shape Analysis Concept

Result of Grid Search algorithm

Calculating PS data base or library:
- Weighting potentials
- Electrical field ↔ space charge
- Anisotropic Mobility
- Response of electronics

z = 46 mm
The classical PSA scheme consists of 3 components:

• Figure of Merit (FOM) e.g. \( \sum_{i \in \text{ROI}} |\text{event1}_i - \text{event2}_i|^n \) (n=0.3)

• Search Routine: optimization of FOM over library
  - Adaptive Grid Search (A. Venturelli, INFN Padova)
  - Particle Swarm Optimization (M. Schlarb, TU Munich)

• Decomposition strategy for multiple interactions:
  - assuming maximum 1 hit per segment
  - segments influenced by multiple hits excluded
PSA Codes within AGATA

Other PSA schemes
• Matrix method (A. Olariu, P. Desesuelles, CSNSM Orsay)

\[ \text{[library]} \cdot \text{[x]} = \text{[event]} \]

Partial PSA information
• Recursive Substraction algorithm (Fabio Crespi, INFN Milan)
  Gets radial coordinates & # interactions (~ steepest slope)
AGATA online

1st experiment with AGATA (18/02/10)

- < 5mm resolution deduced from Doppler shift correction (D. Bazzacco)
- psa online at rates > 5kHz per crystal
Optimisation: Crystal orientation

- 400kBq Am source +
- Lead Collimator: \( \Phi 1.5\text{mm} \times 1\text{cm} \)
- Front Scan at \( \Phi 4.7\text{cm} \): 300 cts/s

- Fitfunction Risetime(\(\theta\)) =

\[
A.[1+R_4\cos(\theta-\theta_4)].[1+R_2\cos(\theta-\theta_2)]
\]

![Graph showing Risetime vs \(\theta\)](image)
The reaction: $^{56}\text{Fe}$ at 220 MeV $\rightarrow ^{197}\text{Au}$ recoils with $\beta \sim 8\%$ $E_\gamma = 847$ keV ($^{56}\text{Fe}$)

The detectors: $\gamma$ detection with ATC1 in coincidence with DANTE for scattered ions

Experimental setup:

On-line event rate: 250 Hz of coincidences
Statistics: 150 Mevents for 2 Tbyte of saved traces
Influence of crystal orientation

FWHM of Doppler corrected 847keV peak by varying lattice orientation in basis (stopped peak 2.7 keV)

~20%

~10%

Main improvement from 1st ring

Front view of T_{10-90} simulations

Angles with respect to x-axis
Optimisation: Electronics & Response

- Preamps 30-35ns rise time
- Core - built in progr. pulser ~ 60ns
  - bypass for fast 1ns pulser
- Segment pulser input (non-standard)

In core

Rectangular wave
1ns rise time

In seg

HPGe crystal (36+1 segments)

Core preamplifier + pulser

- Responses
- Capacities
- Time – alignment
  - ...
Response function

Raw data (10 ns/sample)
Averaged data (2 ns/sample)
Avg. $T_{10-90} = 43$ ns

Derivative of Averaged data

...Averaging = Convolution...
Optimisation: Origin of Crosstalk

Proportional Xtalk (50µs decay) → Energy

Differential Xtalk (only during risetime) → PSA

Pure Xtalk signal:

With $Z_{\text{in}} = 1/sA C_{\text{fb}} + (1/sC_{\text{ac}}) + R_{\text{cold}}$

$X\text{talk} \sim Z_{\text{in}} / Z_{01}$

$\sim C_{01}/A C_{\text{fb}} + (C_{01}/C_{\text{ac}}) + s \cdot R_{\text{cold}} C_{01}$

= Proportional + Differential Xtalk

!!! Proportional and Differential Xtalk are related !!!
For any 1406keV single event in the detector:

Baseline Shift in A1 (keV)

Additional contributions from seg. to seg. capacities!

Segment labeling:
- Sectors: A...F
- Rings: 1...6
How to measure derivative Xtalk?

Energy deposition in segment A

<table>
<thead>
<tr>
<th>Event A</th>
<th>Seg A</th>
<th>Seg B</th>
<th>Seg X=A,B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

Energy deposition in segment B

Residue A-B

![Graph](image)

Source position at segmentation line

- Seg A
- Seg B
- Seg X

Xtalk components

- ![Graph](image)
- ![Graph](image)
- ![Graph](image)

Derivative vs Proportional Xtalk

![Graph showing the relationship between Integral of Derivative Xtalk (in % ns) and Proportional Xtalk (in per mille).]
Impact of Xtalk – First results

ATC1-R
Same data,
Same analysis
BEFORE…

and
AFTER
implementation of crosstalk correction
The impact of the field strength

Graph: Core $T_{10-90}$ for position (0,0,0) for different detectors
(values from full energy gates on six front segments)

Coordinate (0,0,0)

Table: Impurity concentration and bias voltage (source Canberra)

<table>
<thead>
<tr>
<th>Detector</th>
<th>1R</th>
<th>1G</th>
<th>1B</th>
<th>2R</th>
<th>2G</th>
<th>2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias voltage [V]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>4500</td>
<td>4500</td>
<td>4000</td>
</tr>
<tr>
<td>Imp. Front [$10^{10}$cm$^{-3}$]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>1.22</td>
<td>0.54</td>
<td>0.48</td>
<td>1.12</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Depletion of a HPGe detector

A: Bare HPGe germanium crystal symmetric AGATA detector

B: Geometry in simulation
   The HV contact is colored yellow

C-G: Undepleted volume as function of HV.

(assumption: $10^{10}$ impurities / cm$^3$)
Impurity from C-V measurements

How it works (e.g. cylindrical geometry):

- \( C(V) \) gives depletion boundary \( R_1 \):

\[
C = \frac{2\pi \epsilon H}{\ln \frac{R_2}{R_1}}
\]

- \( C(V), \frac{dC}{dV} \) give impurity concentration at \( R_1 \)

\[
N_D(R_1) = -\frac{C^3 e^{\frac{4\pi \epsilon H}{C}}}{4\epsilon\pi^2 H^2 eR_2^2 \frac{dC}{dV}}
\]
Results with the cylindrical approximation

Impurity concentration \([10^{10} \text{ cm}^{-3}]\)

Values from Canberra: 0.5 till 1.8

Impurity concentration in coaxial part (Last 4 rings)

- ~0.5
- ~0.6
- ~0.8

inner radius [m]
First in-beam- and source measurements show position resolution of ~ 5 mm

Value is in line with the design assumptions of the AGATA spectrometer, feasibility of $\gamma$-ray tracking is confirmed

PSA is based on calculated pulse shape libraries

Optimisation and tests with data sets from first experiments
  - crystal properties
  - response functions
  - cross talk
  - impurity concentration

Compare with pulse shape data from scanned detectors