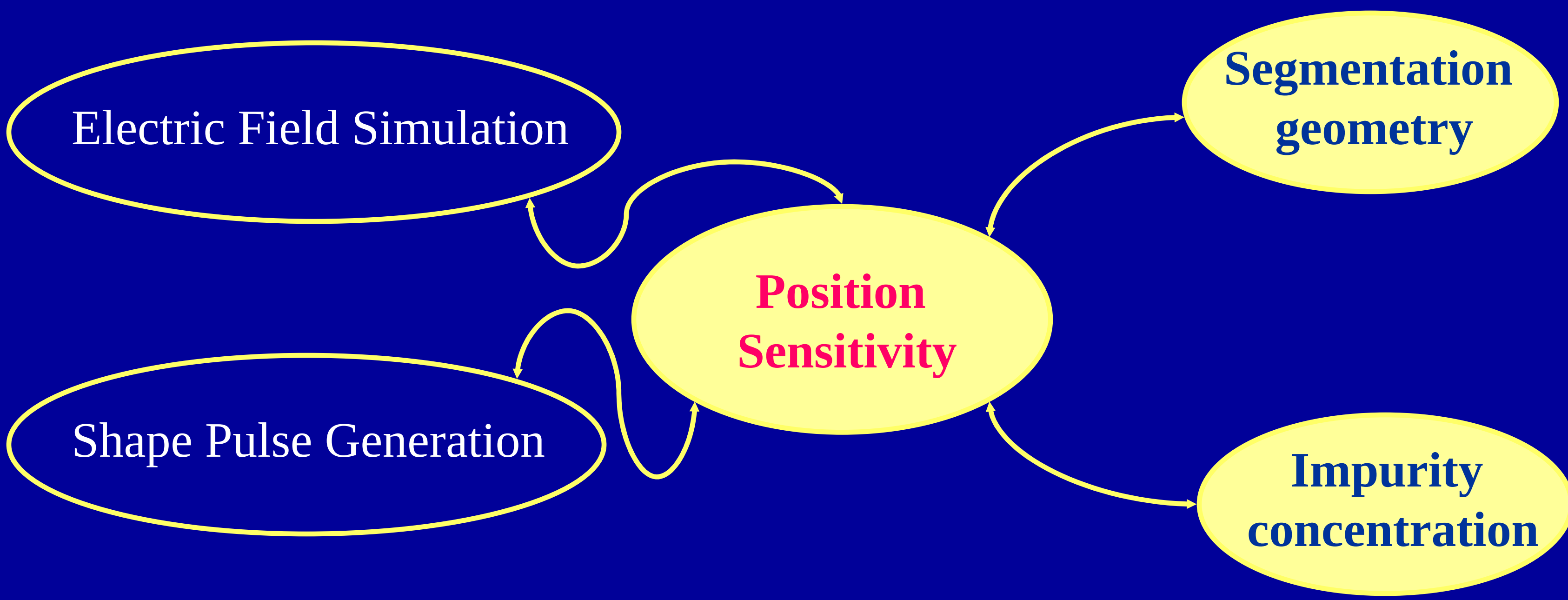
Segmentation Geometry and Optimization

GRETINA Detector Working Group Meeting
ORNL, March 19-20, 2004

Martina Descovich

Introduction

In order to study the performance of the detector in terms of position sensitivity and to optimize its geometry pulse shape simulations have to be carried out.



Principles of Signal Generation

For pulse shapes calculation, ELECTRIC FIELD and WEIGHTING POTENTIAL inside the detector have to be determined.

- An electric signal arises due to the motion of the e-h pairs towards the electrodes, under the influence of the electric field.
- The ELECTRIC FIELD is generated by the application of an external potential across the electrodes. It is given by Poisson's equation (1).
- The electric field determines the path of the charges carriers.
- At the electrodes, mirror charge is induced and a current flows. (2)
- The shape of the signal is determined by the WEIGHTING POTENTIAL experienced by the charge during its motion.
- The total induced charge corresponds to the energy deposited by the radiation.

1)

$$\nabla^2 \Phi(r) = \rho(r)/\varepsilon$$

$$E(r) = -\nabla \Phi(r)$$

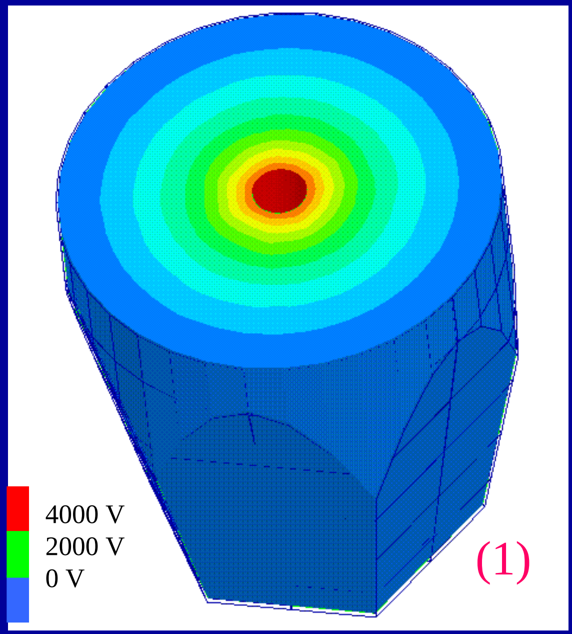
2)

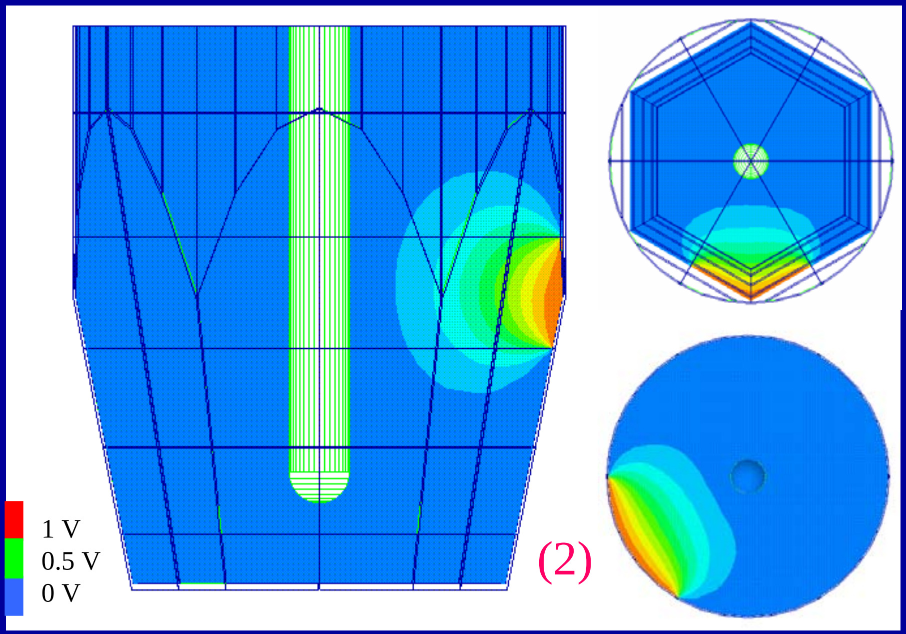
$$v(r) = -\mu\, E(r) \qquad \mu = e\,\tau/m^*$$

$$I(t) = q\, E_w(r(t))\, v(r(t)) \qquad \textit{(Ramo Theorem)}$$

$$Q = \int I(t)\, dt = q[\Phi_w(x_1) - \Phi_w(x_2)]$$

Calculated Potential





- Operating potential (1) and weighting potential (2) inside the detector.
- The weighting potential is a mathematical concept, useful for pulse shape calculations in segmented detector (Ramo's Theorem).
- It is calculated by applying 1 V on the segment collecting the charge while grounding all the others, with zero impurity concentration (Laplace Equation).
- It measures the electrostatic coupling between the moving charge and the sensing contact.

Work Outline

Electric Field simulations

- Electric Field and weighting potential for each segment have been calculated using Maxwell 3D.
- Maxwell 3D is a commercial software package, which uses the Finite Element Analysis to solve 3D electromagnetic problems.
- Electric field and potential are calculated on a grid of **1 mm**.
- The program enables an accurate geometry definition, including irregular shapes, rounded corners, partial tapering and bulletized inner contact .

Pulse Shape Calculations

- Pulse shapes have been calculated using an existing code (genps1.cc by Greg Schmidt, Kai Vetter, Austin Khun)
- Genps1 calculates, for a given gamma-ray interaction, the drift path of the charge carriers and the charge induced on each segment at a finite time interval of **1 ns**.
- Effect of anisotropy of the drift velocity (magnitude) is included for the electrons but MORE WORK needs to be done for the holes.
- MORE WORK is also required to include effects of the anisotropy in the direction of the drift velocity (Paul Luke-tomorrow).
- The charge signal is then convoluted with the preamplifier response (read out electronics).

Pulse Shape Calculation: Limits

❖ Intrinsic sources of uncertainty, which limit the achievable position resolution are:

• Finite range of the primary electron in the crystal (< 1 mm) and finite size of the e-h distribution.
• Broadening of the distribution of the charge carriers traveling towards the electrodes (< 0.1 mm)
•Uncertainty in the energy-angle relation of the Compton formula due to the momentum distribution of photo-electrons. It is assumed that the binding energy and the initial momentum of the photo-electron are zero. The uncertainty arising from the Compton profile is of ~1 mm.

❖ Additional effects which can be included in the model are:

• Anisotropy in the direction and magnitude of the drift velocity.
• Variations in the impurity concentration
• In the model, passivated back face and surfaces between segments are considered perfect surfaces (Neumann boundary conditions).

As a consequence, experimental position resolution is limited to ~1 mm.

The Triple Crystal Module

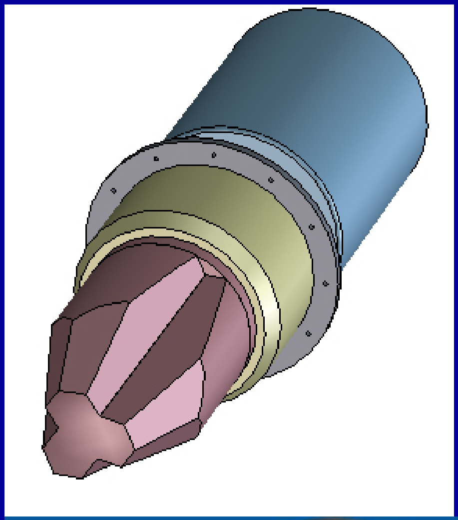
The 3-crystal module consists of 3 encapsulated Ge detectors, each with 36 segments, placed in a single cryostat.

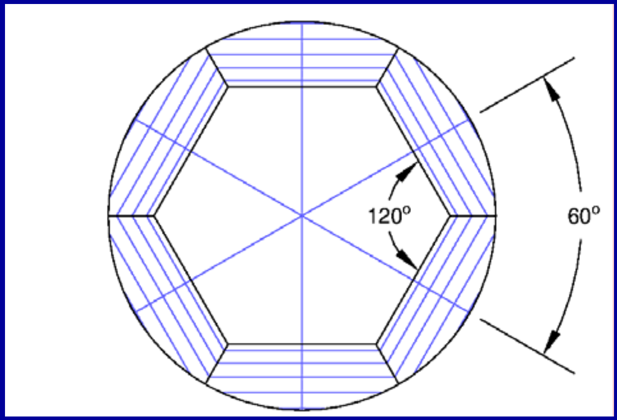
- Regular hexagons
- 6 vertical ring
- 6 sector for each ring
- 8 cm diameter
- 9 cm length
- Partially tapered
- 10 degree taper angle

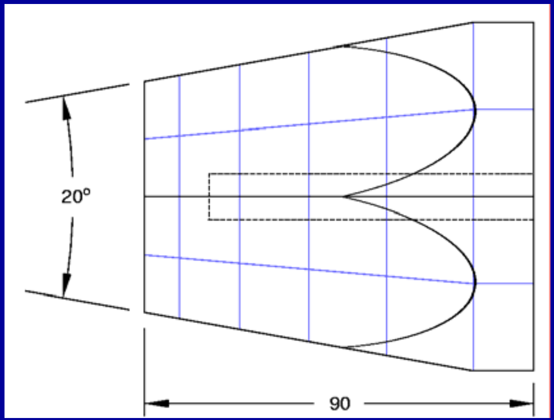
Non equal vertical segmentation spacing:

- ring 1: 0.8 cm (now 1.0 cm)
- ring 2: 1.4 cm (now 1.2 cm)
- ring 3: 1.6 cm
- ring 4: 1.8 cm
- ring 5: 2.0 cm
- ring 6: 1.4 cm

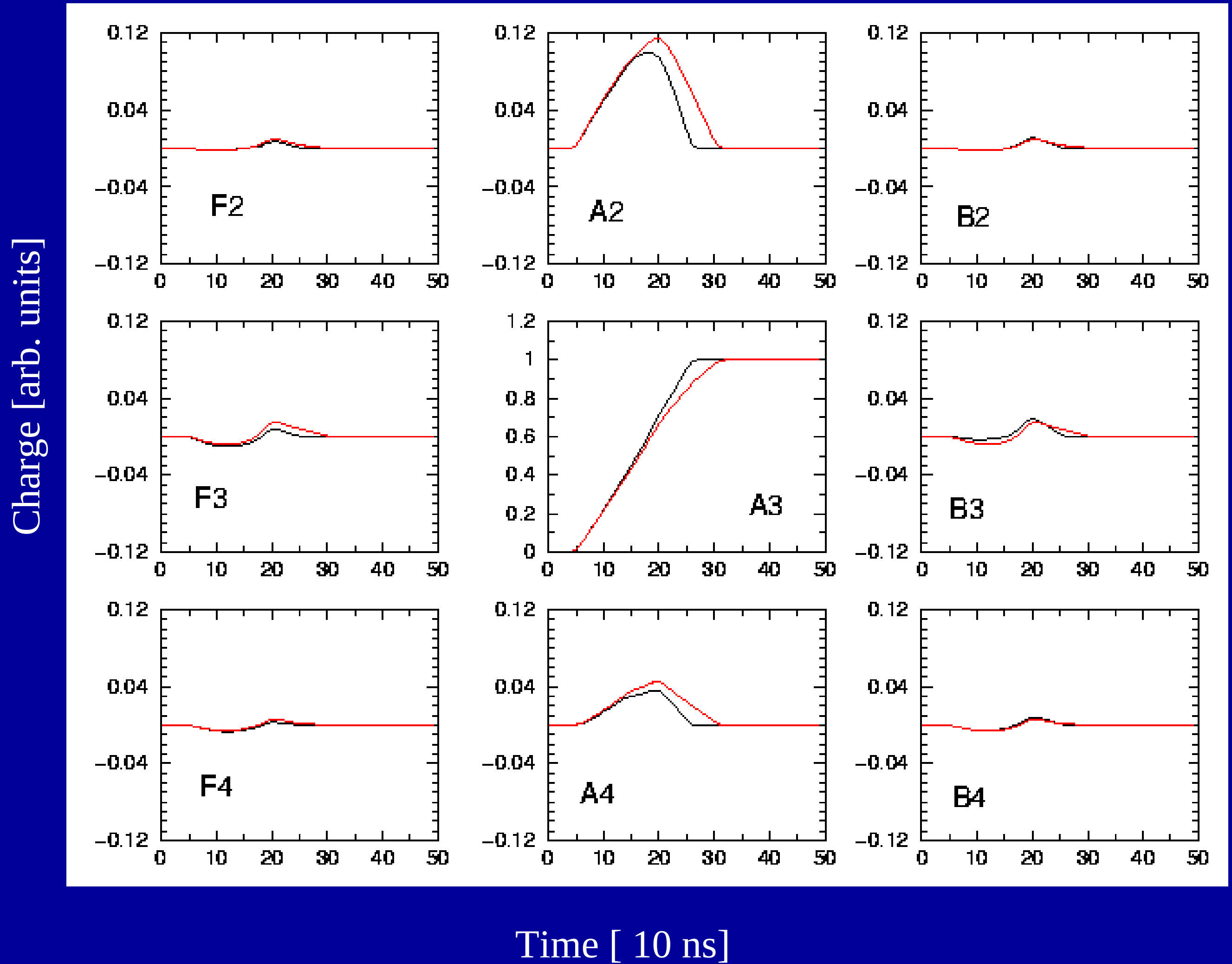
- no rounded corners
- 10 mm inner contact
- 100 μm segmentation







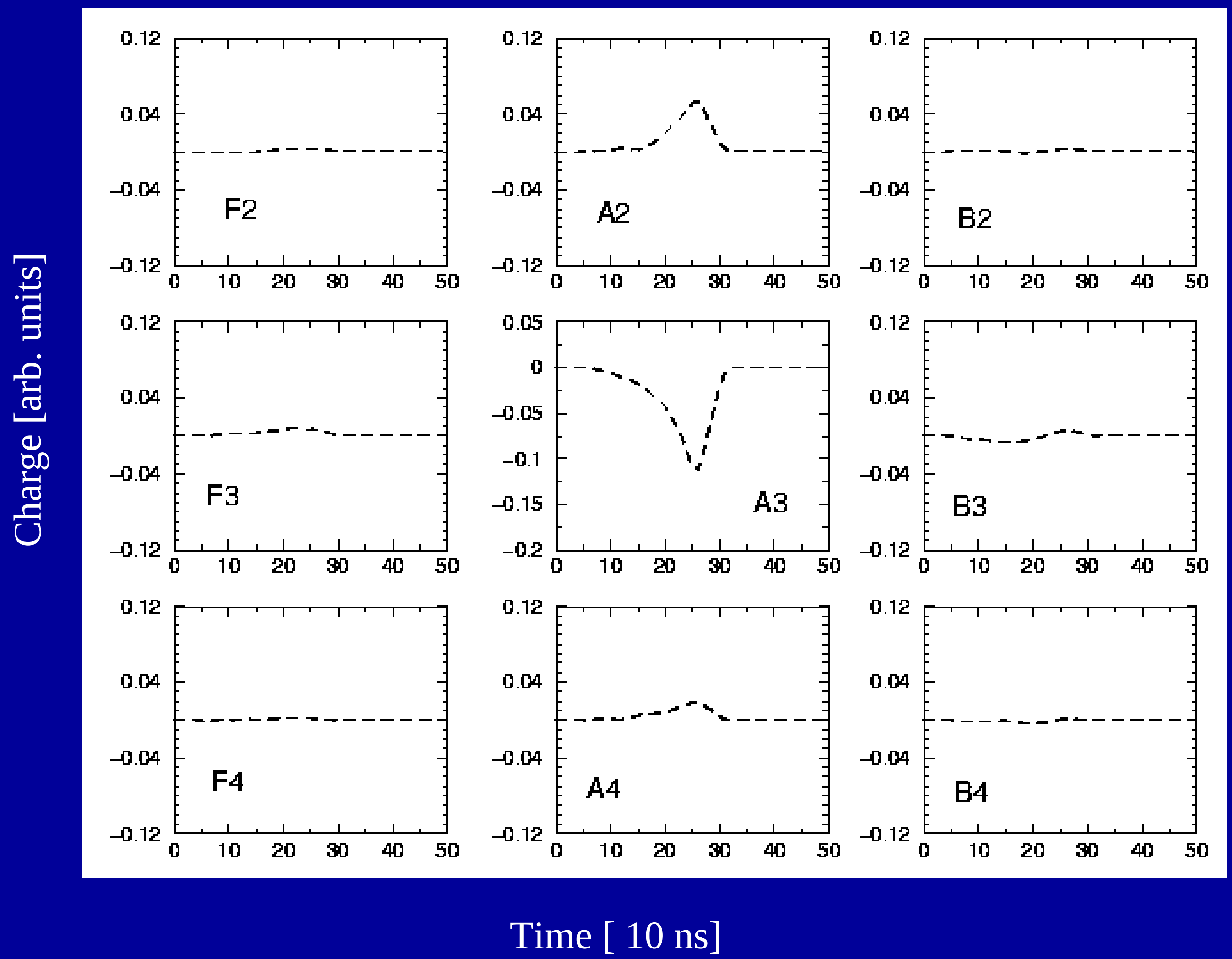
Calculated Pulse Shapes



Pulse shapes corresponding to interactions in segment A3, 2mm apart

P1 = (20, 0, 30)
P2 = (20, 2, 30)

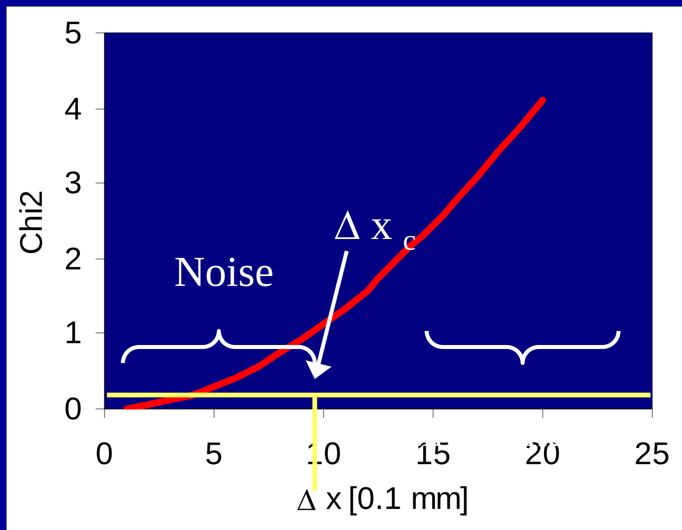
Calculated Pulse Shapes



Difference in pulse shapes corresponding to interactions in segment A3, 2mm apart

P1 = (20, 0, 30)
P2 = (20, 2, 30)

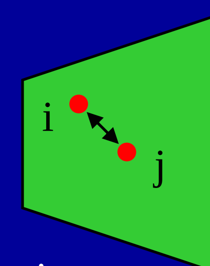
Position Sensitivity



Pulse shape varies as a function of the gamma-ray interaction location.
Position sensitivity is the minimum distance at which difference in pulse shapes become distinguishable over the noise.
It depends on the segmentation geometry, the segments size, the location within each segment and the direction.
An interaction at position *i* is distinguishable from one at *j* if the overall difference in signal shapes is greater than that caused by the random fluctuation (noise).

The quantity χ^2 is defined as:

$$\chi_{ij}^2 = \sum_{m=1}^{9}\sum_{t=t_0}^{50} \frac{[q_i(m,t)-q_j(m,t)]^2}{2\sigma^2}$$

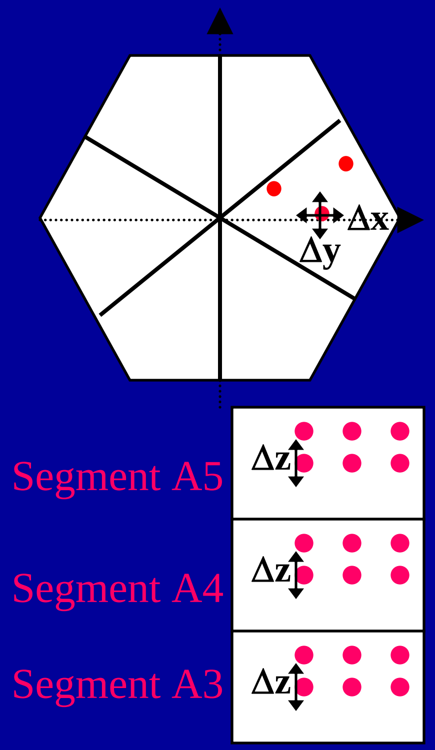


The noise level is assumed to be constant (σ = 5 keV).

If χ^2 =1, the difference between the pulse shapes is equal to the total noise contribution.
If χ^2 =1, the pulse shapes are distinguishable.

Position Sensitivity Results (1)

- ❖ χ^2 was calculated at 0.1 mm step along the x-, y- and z- direction, for 6 starting positions.
- ❖ A3, A4 and A5 are representative segments.
- ❖ For each segment the average value is considered.
- ❖ The z-planes are at a relative distance of:
  8 mm, 14 mm, 16 mm, 18 mm, 20 mm, 14 mm.



<u>Segment A3:</u>
$\Delta x = 0.05$ mm
$\Delta y = 0.06$ mm
$\Delta z = 0.10$ mm

➢ $\Delta_{tot} = 0.07$ mm

<u>Segment A4:</u>
$\Delta x = 0.04$ mm
$\Delta y = 0.06$ mm
$\Delta z = 0.10$ mm

➢ $\Delta_{tot} = 0.07$ mm

<u>Segment A5:</u>
$\Delta x = 0.05$ mm
$\Delta y = 0.10$ mm
$\Delta z = 0.09$ mm

➢ $\Delta_{tot} = 0.08$ mm

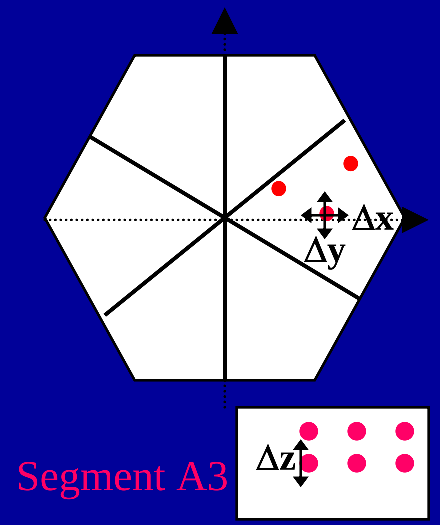
❖ The average position sensitivity is: $\Delta = 0.07$ mm

Position Sensitivity Results (2)

❖ The calculations were repeated using a different z-segmentation.
The z-planes are at a relative distance of:
10 mm, 12 mm, 18 mm, 18 mm, 18 mm, 14 mm.

❖ χ^2 was calculated at 0.1 mm step along the x-, y- and z- direction, for 6 starting positions.

❖ A3 is considered as representative segments.



<u>Segment A3:</u>
$\Delta x = 0.05$ mm
$\Delta y = 0.07$ mm
$\Delta z = 0.19$ mm

$\Delta_{tot} = 0.09$ mm

❖ The largest variation in position sensitivity is along the z-direction:
At position (20, 0, 37) → $\Delta z = 0.038$ mm (close to the z-segment boundary)
At position (20, 0, 30) → $\Delta z = 0.255$ mm (in the middle of the segment)

❖ These preliminary results show that the position sensitivity is not affected by small variations (2 mm) in the z-segmentation.

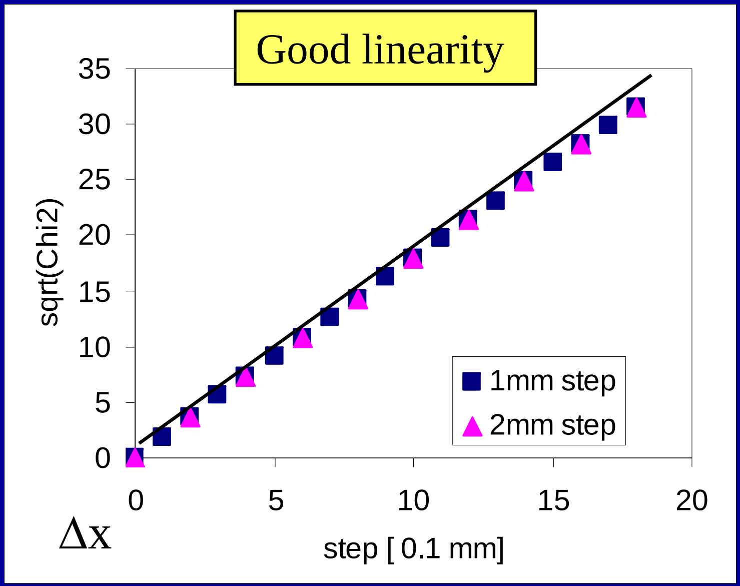
Grid step

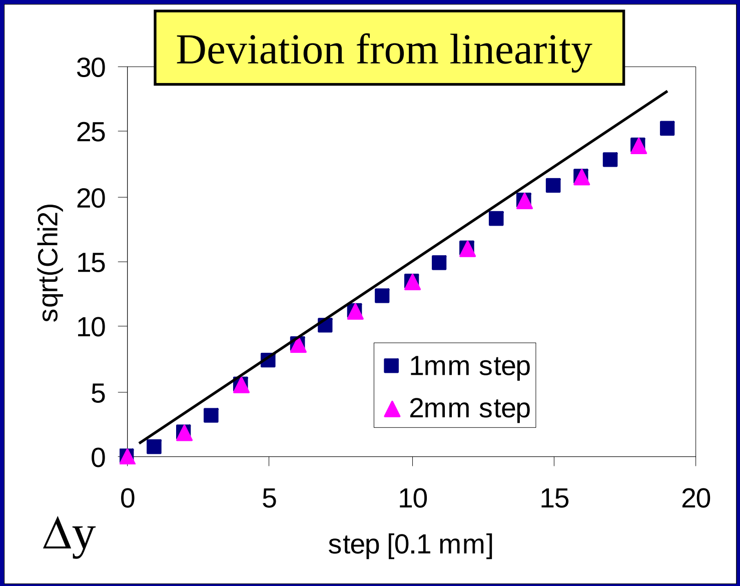
❖ Is 1 mm grid step sufficient?

• Position sensitivity finer than the grid step can be recovered if χ is LINEAR in Δ.
• In ~25% of the cases the curve deviates from linearity and the reason is still not clear.

Assuming linearity to calculate position sensitivity between grid point, results in an error of ~0.03 mm which, in average, is less then the measured position sensitivity.

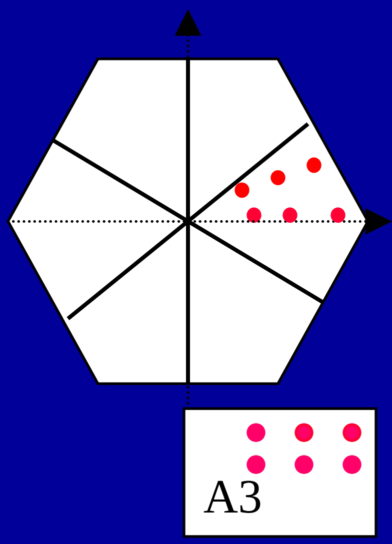
❖ More tests need to be done





Impurity Concentration

❖ Is the capability of reconstructing the interaction position affected by the impurity concentration used in the model?



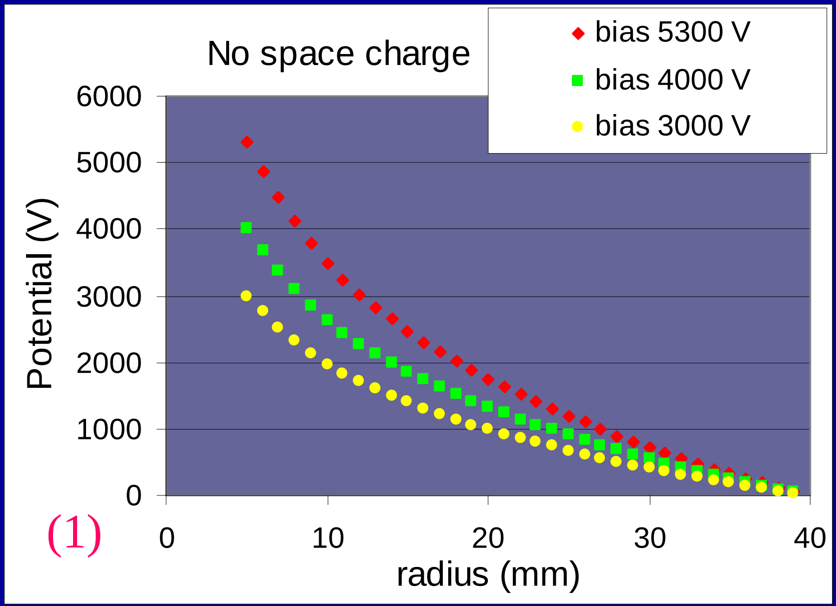
From the manufacturer we know that:
Crystal 1: $\rho = (0.76 - 1.2) \times 10^{10}$ atoms/cm^3
Crystal 2: $\rho = (0.45 - 1.5) \times 10^{10}$ atoms/cm^3
Crystal 1: $\rho = (0.83 - 1.8) \times 10^{10}$ atoms/cm^3

Pulse shapes are calculates for various impurity concentration values:
from no charge up to $\rho = 1.4 \times 10^{10}$ atoms/cm^3.
The reference impurity concentration is $\rho = 1 \times 10^{10}$ atoms/cm^3 .
The effective position resolution is of the order of 1 mm →
χ^2 is normalized so that $\chi^2 = 1$ corresponds to 1 mm position sensitivity.

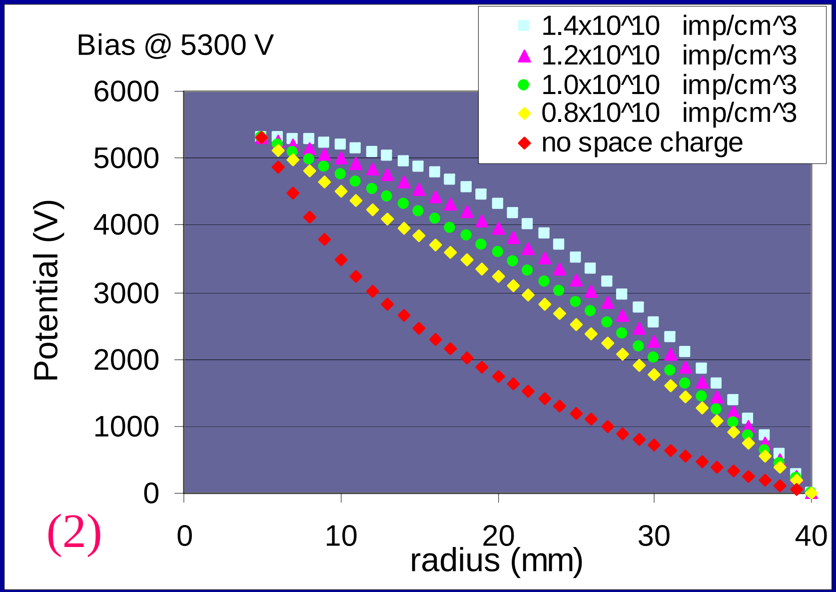
A3 is considered as representative segments.
χ^2 is calculated for 12 points and the average value is taken.

Calculated Potential

❖ Why the shape of the pulse is affected by the concentration of impurity?



(1)



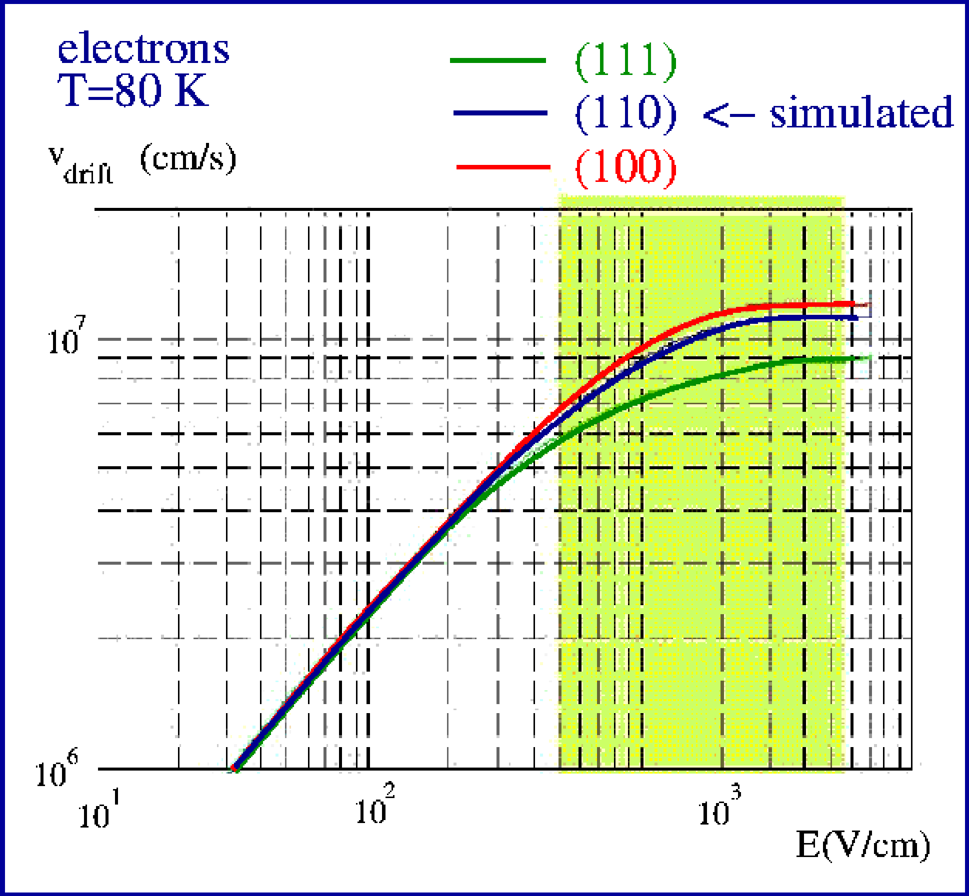
(2)

Electric potential in the detector as a function of the radial distance from the centre:

(1) Electrostatic potential for different bias on the centre contact.

(2) Electrostatic potential for different impurity concentration inside the crystal.
For an impurity concentration of 1.4 x 10^{10} atoms/cm^3, the depletion voltage is 5300 V

Drift Velocity



Field dependence of the electron drift velocity in Ge at a temperature of 80 K [AGATA proposal (2001)].

❖ Why the drift velocity changes as a function of the impurity concentration?

• At saturation, the drift velocity and (therefore the pulse shape) do not depend on the electric field value.

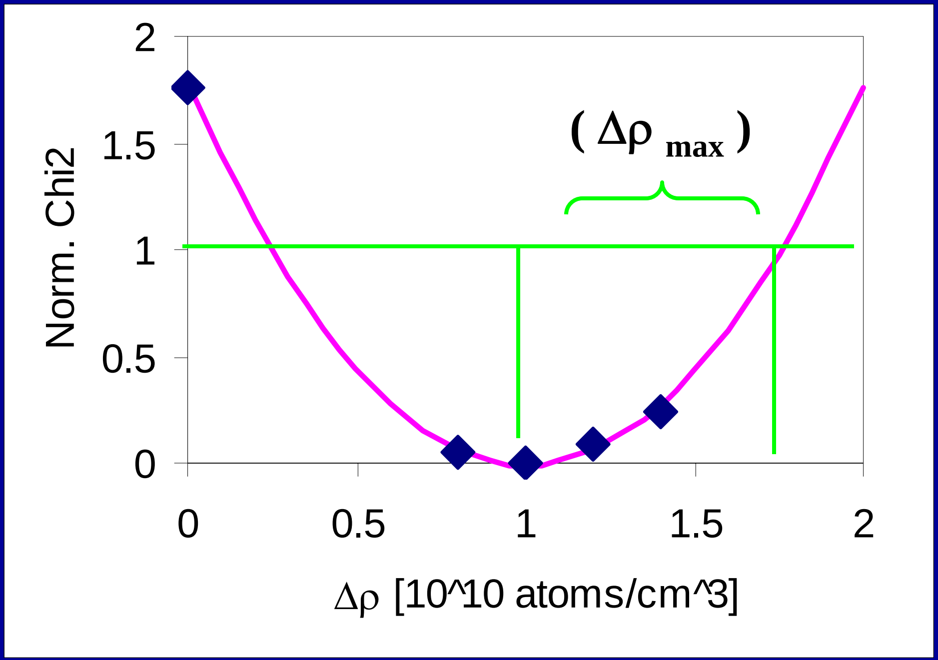
• In the detector there are regions where the drif velocity is not saturated.

From the simulation it results that the minumum and the maximun value of the electric field magnitude in the coaxial part of the detector are:

E_{min} = 6 x 10^2 V/cm

E_{max} = 5 x 10^3 V/cm

Impurity Concentration Results



- Impurity concentration values range from no charge up to $\rho = 1.4 \times 10^{10}$ atoms/cm^3.
- This range cover the impurity concentration measured in the triple crystal module.
- In the calculation, the reference concentration is

$\rho = 1 \times 10^{10}$ atoms/cm^3 .

$(\Delta\rho_{max}) = 0.75 \times 10^{10}$ atoms/cm^3

❖ If the difference between the impurity concentration entered in the model and the real value is less than $\Delta\rho_{max}$, our capability of reconstructing the interaction position with 1 mm position resolution, will not be affected.

BERKELEY LAB

Conclusions

- The position resolution is limited to ~1 mm by intrinsic sources of uncertainties but NOT by the capability of germanium detectors.

- A variation in the z-segmentation geometry of a few mm does not seem to affect the position sensitivity. To see a considerable improvement in the position sensitivity, a variation of ~cm should be made, which is not possible.
….open to discussion…

- A 1 mm grid seems to be sufficient for position reconstruction, but more accurate tests need to be performed…. open to discussion…

- The uncertainty in the impurity concentration does not affect the capability of reconstructing the position of the interaction.

- Effect that needs to be included in the model are: (work needed!!!)
  - Anisotropy in the direction of the drift velocity for both electrons and holes
  - Anisotropy in the magnitude of the drift velocity for holes

- Code genps1 needs to be written in a better form.

Acknowledgements

I-Yang Lee, Paul Fallon, Austin Kuhn, Augusto Macchiavelli, Mario Cromaz, Marie-Agnes Deleplanque, Frank Stephens, Dick Diamond, Rod Clark, David Ward, Elena Rodriguez-Vieitez, Hassan Mahmud
Lawrence Berkeley National Laboratory

David Radford
Oak Ridge National Laboratory

Kai Vetter
L Livermore National Laboratory