GRETINA Signal Decomposition and Cross-talk

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GRETINA SWG Meeting

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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Outline

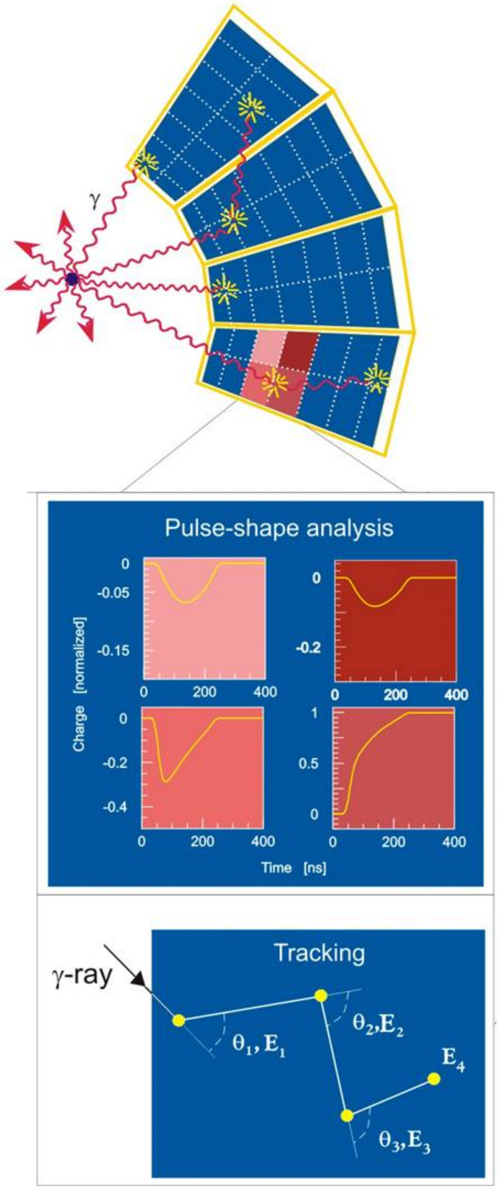
- Signal decomposition basics
  - Search algorithm
  - Basis signals
  - Parameters
- Preamp and cross-talk corrections
  - Origin of the effects
  - How we measure the parameters
- Signal calculation uncertainties
  - Impurity profile, geometry, charge carrier mobilities
  - Need some procedure for further optimization

Principles of gamma-ray tracking

3D position
sensitive
Ge detector

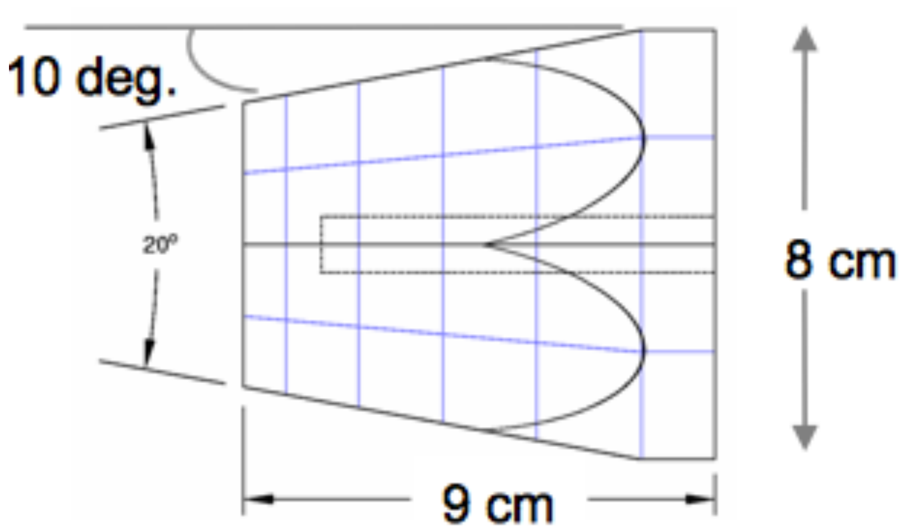
Resolve position
and energy of
interaction points

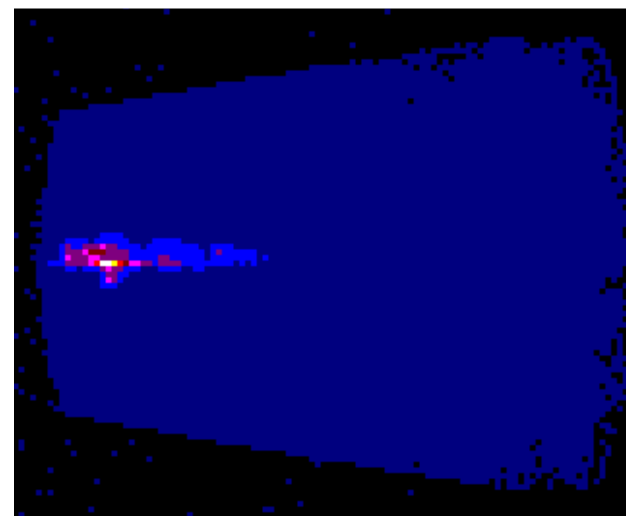
Determine
scattering
sequence



GRETINA Detectors

- Tapered irregular hexagons, 8 x 9 cm
- Closed-end coaxial crystals, n-type
- 36-fold segmentation (6 azimuthal, 6 longitudinal)
- 37 signals (including central contact)

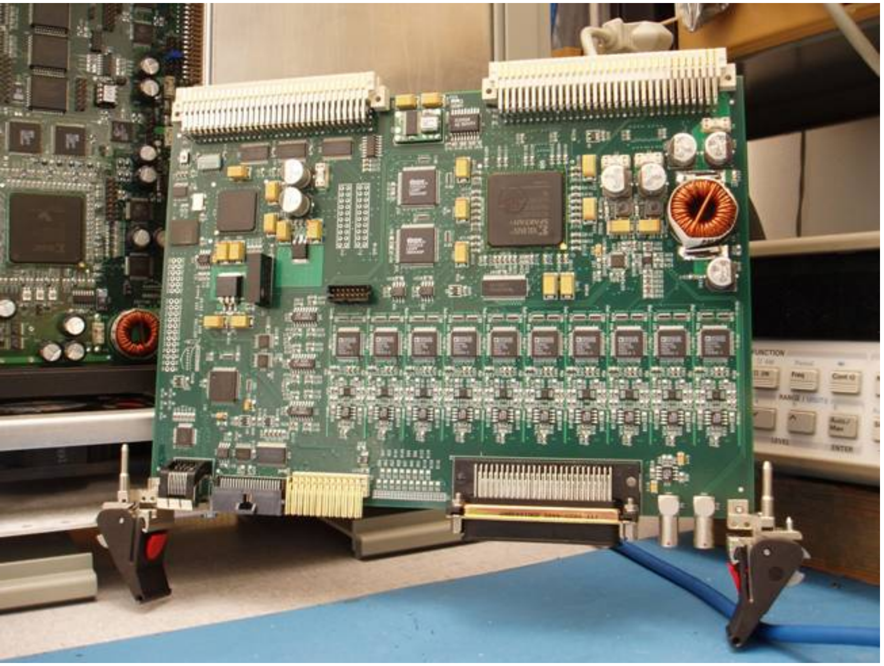




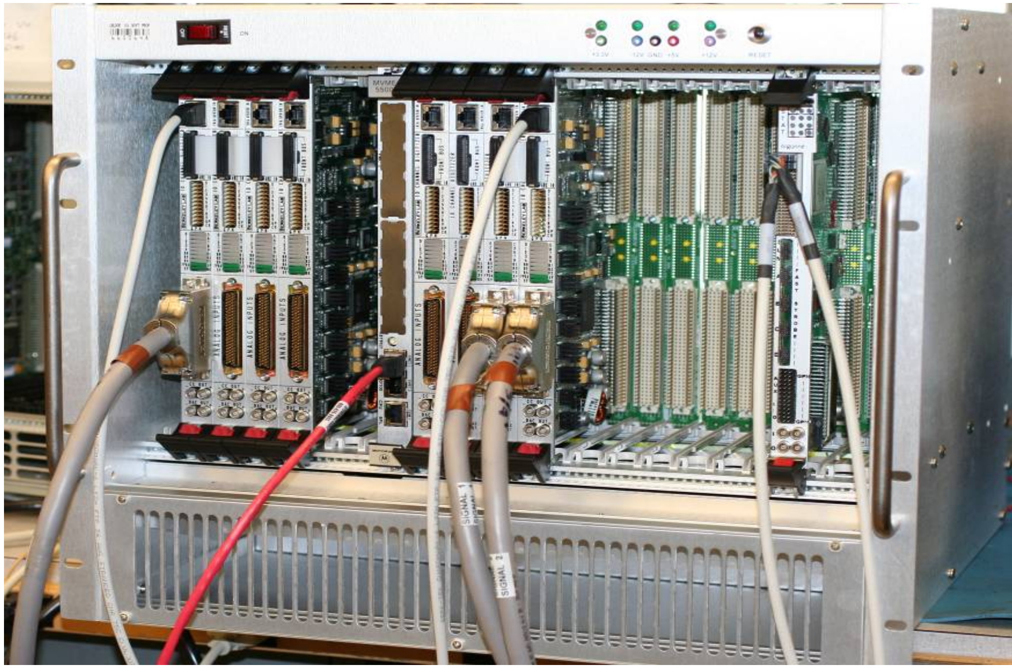
Electronics

Digitizer module (LBNL) and trigger module (ANL)

Digitizer module



Digitizer and trigger modules under test



Computing and Data Flow

63 nodes
2 cpu / node
4 core / cpu
30 TB storage

Data from GRETINA Detectors → *Segment events* (37 segments per detector)

Crystal Event Builder

Crystal events

Signal Decomposition

Interaction points (1-28 crystals)

Data from Auxiliary Detectors → **Global Event Builder**

Global Events

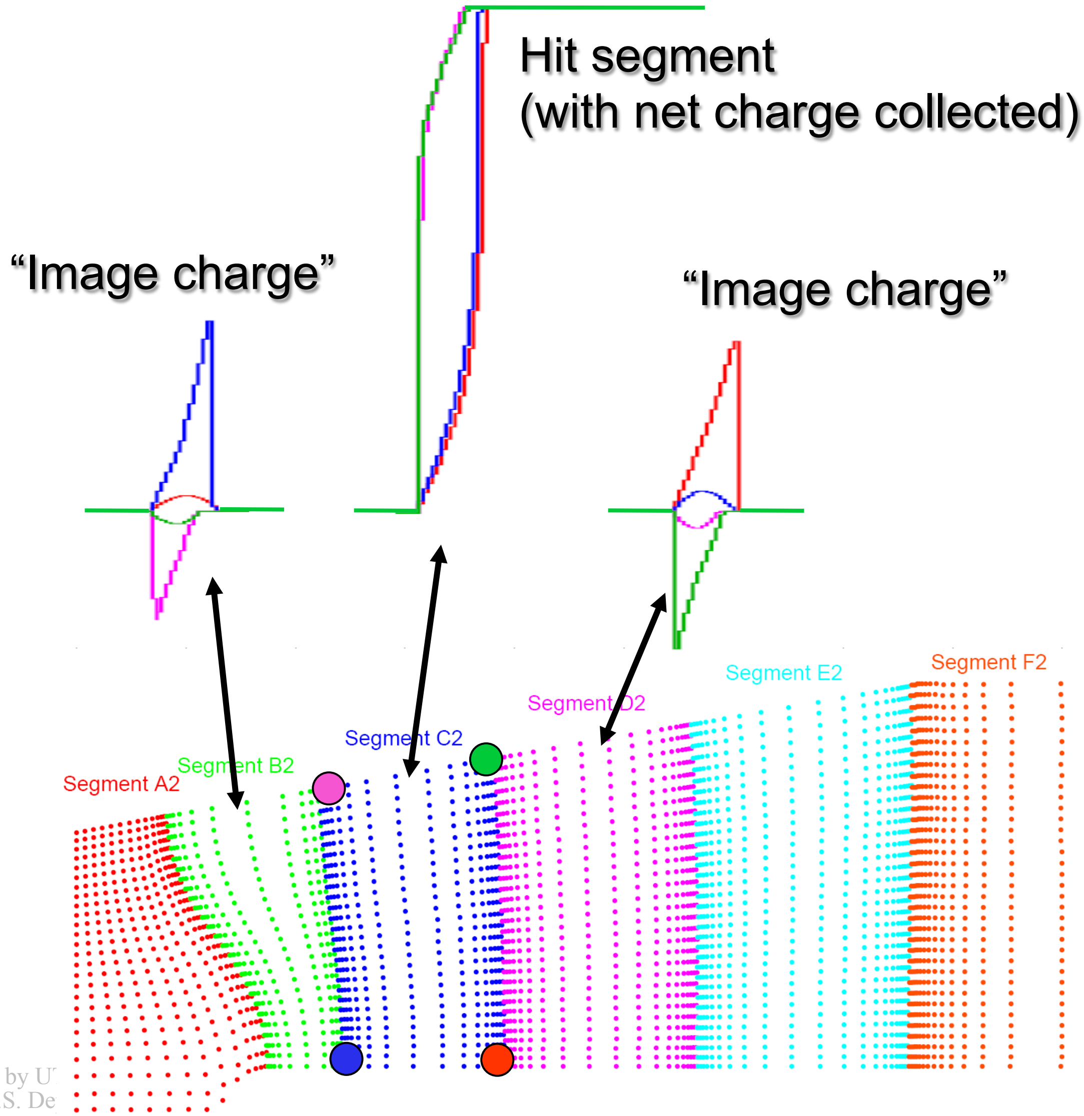
Tracking

Analysis & Archiving

Requirement: Processing 20,000 γ /s

Calculated Signals: Sensitivity to Position

Signals are color-coded for position



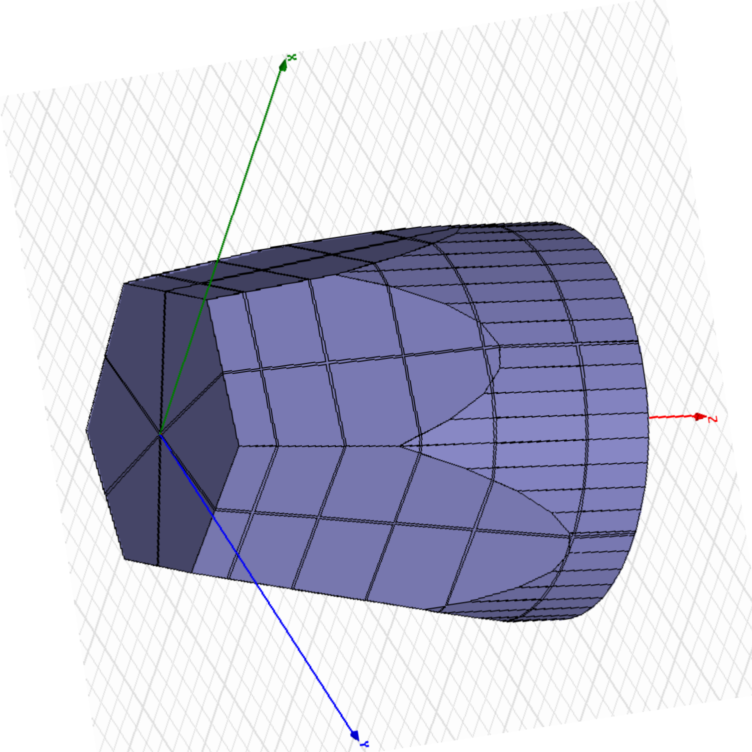
Signals are nonlinear with respect to position.

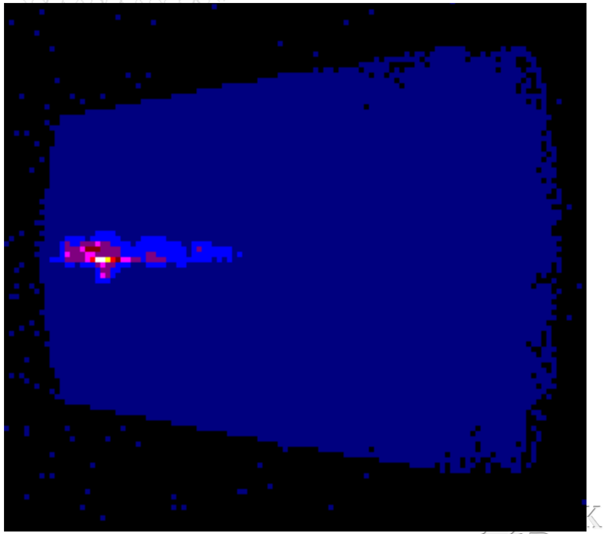
This is a good thing; it is a necessary condition for extracting multiple interactions

Signal Decomposition

At the heart of gamma-ray tracking

- Digital signal processing to determine, in near-real-time, the *number, positions,* and *energies* of gamma interactions in the crystal. Also fits t_0 *(time-zero)* for the event.
- Uses data from both hit segments and image charges from neighbors
- Uses a set of pre-calculated pulse shapes for $\sim 10^5$ positions throughout the crystal
- Allows for multiple interactions per hit segment
- *Position resolution* is crucial for energy resolution, efficiency, and peak-to-total ratio
- *Speed* is also crucial; determines rate capability
- A very hard problem…





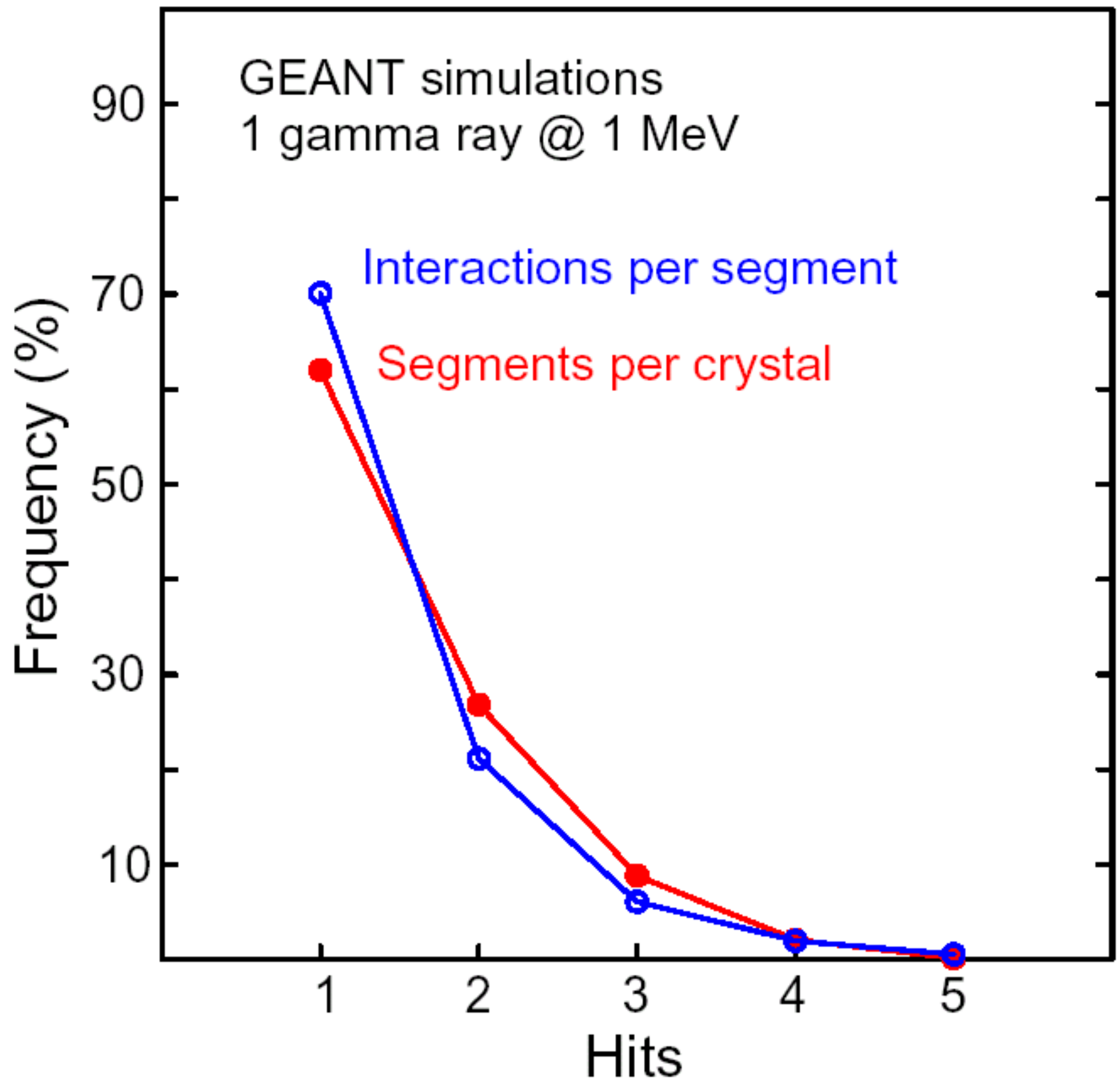
Signal Decomposition: Interaction Multiplicity

GEANT simulations;
1 MeV gamma into GRETA

Most gammas hit one or two crystals

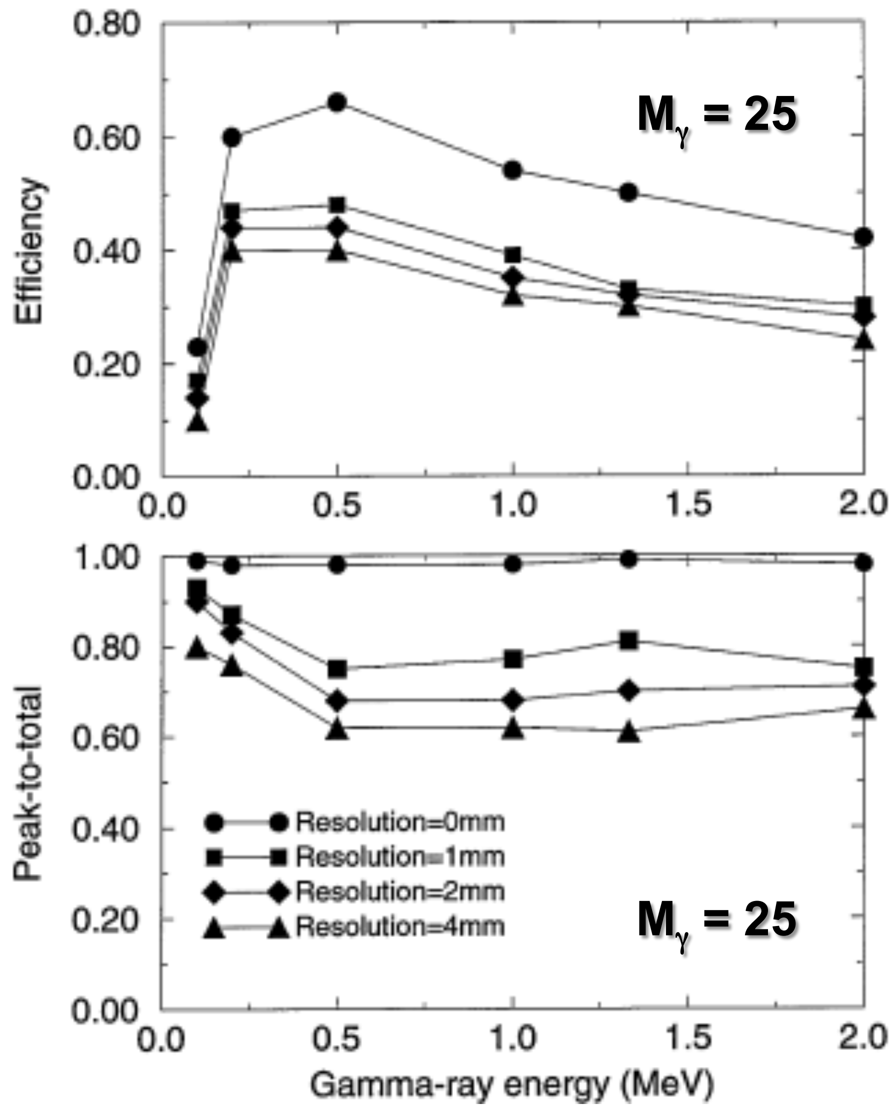
Most hit crystals have one or two hit segments

Most hit segments have one or two interactions



Position Resolution and Tracking Efficiency

Efficiency and P/T of GRETA depends on position resolution and gamma-ray multiplicity



0 mm

1 mm (RMS)
2 mm
4 mm

0 mm

1 mm (RMS)
2 mm
4 mm

Signal Decomposition – Why is it Hard?

Very large parameter space to search

Average segment ~ 6000 mm^3, so for ~ 1 mm position sensitivity

- two interactions in one segment: ~ 2 x 10^6 possible positions
- two interactions in each of two segments: ~ 4 x 10^{12} positions
- two interactions in each of three segments: ~ 8 x 10^{18} positions

PLUS energy sharing, time-zero, …

Underconstrained fits, especially with > 1 interaction/segment

For one segment, the signals provide only

~ 9 x 40 = 360 nontrivial numbers

Strongly-varying, nonlinear sensitivity

$\delta\chi^2/\delta(\theta z)$ is much larger near segment boundaries

For n interactions, CPU time goes as

Adaptive Grid Search : ~ $O(300^n)$

Singular Value Decomp : ~ $O(n)$

Nonlinear Least-Squares : ~ $O(n + \delta n^2)$

Signal Decomposition Algorithm

Hybrid Algorithm

- *Adaptive Grid Search with Linear Least-Squares (for energies)*
- *Non-linear Least-Squares (a.k.a. SQP)*
- *Have also explored Singular Value Decomposition*

Status:

✓ Can handle *any number* of hit detector segments, each with *one or two interactions* (*three interactions* for single hit segment in the crystal)

✓ Uses optimized, irregular grid for the basis signals

✓ Incorporates fitting of signal start time t_0

✓ Calculated signals are accurately corrected for preamplifier response and for two types of cross talk

✓ CPU time meets requirements for processing 20,000 gammas/s

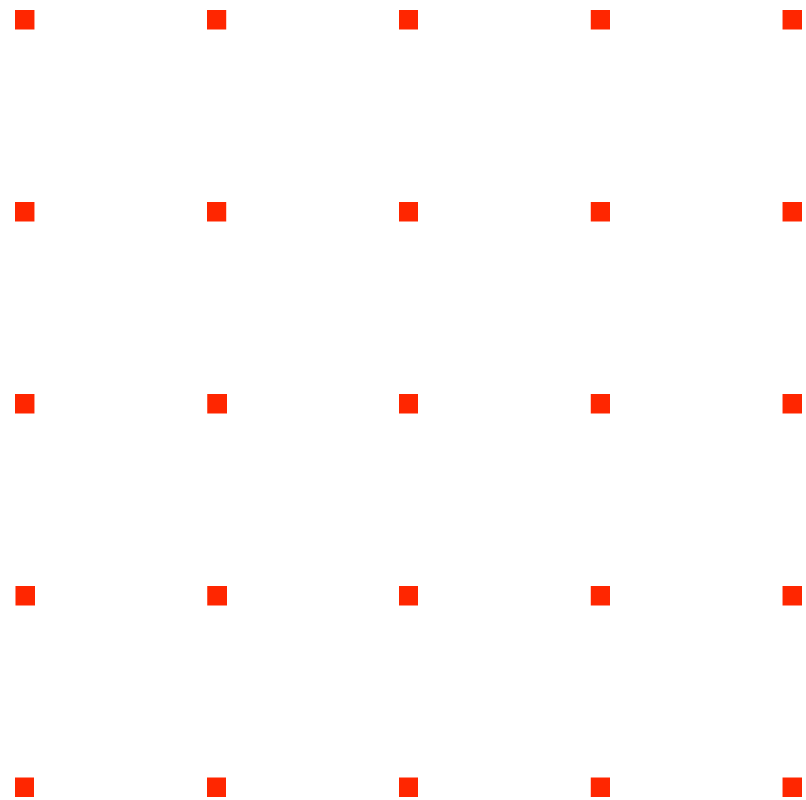
Some work still to be done, but we have demonstrated that the problem of signal decomposition for GRETINA is solved.

✓ A challenging but tractable problem

Signal Decomposition: AGS

Adaptive Grid Search algorithm:

• Start on a course grid, to roughly localize the interactions

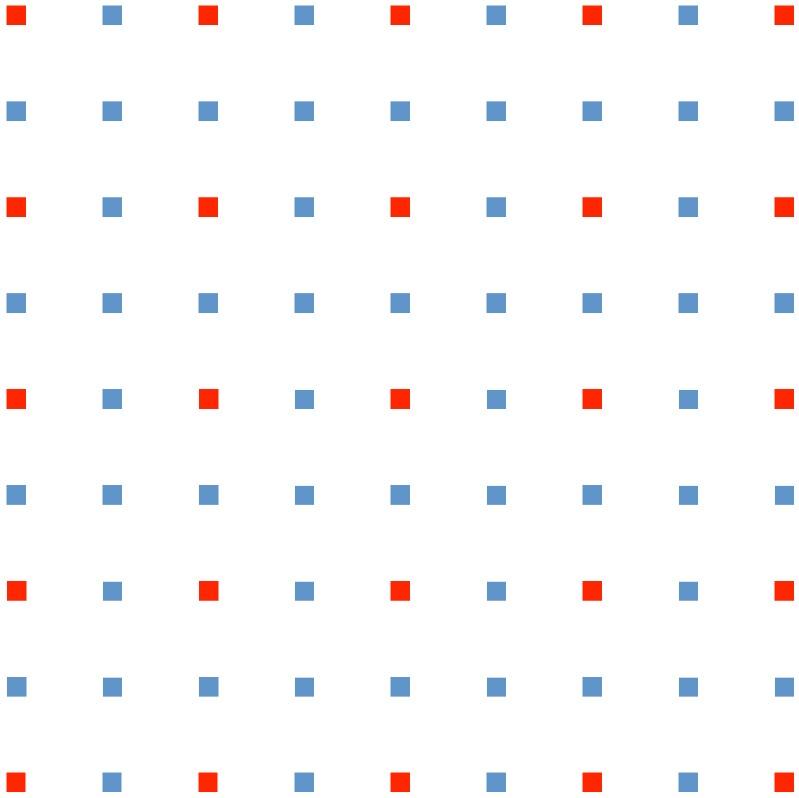


Signal Decomposition: AGS

Adaptive Grid Search algorithm:

• Start on a course grid, to roughly localize the interactions

• Then refine the grid close to the identified interaction points.



Signal Decomposition: AGS

Adaptive Grid Search algorithm:

- Gives starting values for constrained least-squares / SQP
- 2 interactions per hit segment
  - SQP allows up to 3 interations for single-hit events
- Grid search in position only; energy fractions are L-S fitted
- For two interactions in one segment, have $N(N-1)/2 < 1.8 \times 10^5$ pairs of points for grid search
- This takes < 3 ms/cpu to run through
- Reproduces positions of simulated events to ~ ½ mm

Adaptive grid search fitting

Linear Least-Squares

For two interactions of energies e_i, e_j at locations i and j, the calculated signal is $C_{kt} = (e_i s_{ikt} + e_2 s_{jkt})$ where k is the segment and t the time step. s_{ikt} is the basis signal calculated at point i.

If the observed signal is O_{kt}

$$\chi^2 = \sum_{kt} \frac{(O_{kt} - C_{kt})^2}{\sigma_{kt}^2} = \frac{\sum_{kt}(O_{kt} - e_i s_{ikt} - e_j s_{jkt})^2}{\sigma^2} \qquad (1)$$

where $\sigma_{kt} = \sigma$ is the uncertainty (noise) in O_{kt}, assumed independent of k, t.

We want a minimum in χ^2, *i.e.*

$$\frac{\partial \chi^2}{\partial e_i} = \frac{\partial \chi^2}{\partial e_i} = 0 \qquad (2)$$

$$\frac{\partial \chi^2}{\partial e_i} = \frac{2\sum_{kt}(O_{kt} s_{ikt} - e_i s_{ikt}^2 - e_j s_{ikt} s_{jkt})}{\sigma^2} = 0 \qquad (3)$$

Adaptive grid search fitting

Thus we get two equations in two unknowns:

$$\sum_{kt} O_{kt} s_{ikt} - e_i \sum_{kt} s_{ikt}^2 - e_j \sum_{kt} s_{ikt} s_{jkt} = 0 \tag{4}$$

$$\sum_{kt} O_{kt} s_{jkt} - e_j \sum_{kt} s_{jkt}^2 - e_i \sum_{kt} s_{ikt} s_{jkt} = 0 \tag{5}$$

We can *precalculate*

$$\sum_{kt} s_{ikt}^2$$

and

$$\sum_{kt} s_{ikt} s_{jkt}$$

once for all events, and

$$\sum_{kt} O_{kt} s_{jkt}$$

once per event.

Adaptive grid search fitting

Energies e_i and e_j are constrained, such that $0.1(e_i+e_j) < e_i < 0.9(e_i+e_j)$

Once the best pair of positions (lowest χ^2) is found, then all neighbor pairs are examined on the finer grid. This is 26x26 = 676 pairs. If any of them are better, the procedure is repeated.

For this later procedure, the summed signal-products cannot be precalculated.

Finally, nonlinear least-squares (SQP) is used to interpolate off the grid and determine t_0. This improves the fit at least 50% of the time.

Events with multiple hit segments

The problem: Combinatorics

CPU time for the AGS goes as ~ 300^n where n is the number of interactions. If we allowed 2 interactions in more than one segment, the algorithm would be much too slow.

Also, dot-products of the basis signals are precalculated for all pairs on the coarse grid within one segment, but if we tried to take pairs in different segments, the precalculated sums would exceed the available memory.

So we limit the AGS to finding best pairs in one segment at a time.

So how do we process events where more than one segment is hit?

Events with multiple hit segments

The solution: Sequential principal component analysis

1. Order the hit segments in order of energy, highest energy first
2. Use SQP to do a first rough fit, with one interaction per segment
   - Assume initial positions in center of each segment
3. Subtract the fitted signals resulting from all segments except for the first one
   - Now have approximate signal resulting from segment 1 alone
4. Run AGS on this signal for segment 1 to determine best pair of interactions
5. Re-run SQP on the full signal, now with these two interactions in segment 1, plus one interaction in all the others
6. Repeat this procedure for all the other hit segments in turn
   - Each step potentially adds one more interaction to the fitted set
   - Check that the addition of an interaction actually reduces the χ^2

Singular Value Decomposition

Mean χ^2 and time per event, SVD+SQP rel. to AGS+SQP, as development proceeded:

Version	Mean chi-squared	Time per event
1	1.27	1.23
2	1.051	1.14
3	0.987	3.45
4	1.0	2.6
5	0.994	1.2
6	1.025	0.76

- Main issue is how to time-align measured and basis signals, i.e. determine t_0.
- If have non-zero time offset, then get position error and wrong number of interactions.
- t_0 can be fit in SQP, but only determined in SVD by expensive trial-and-error.

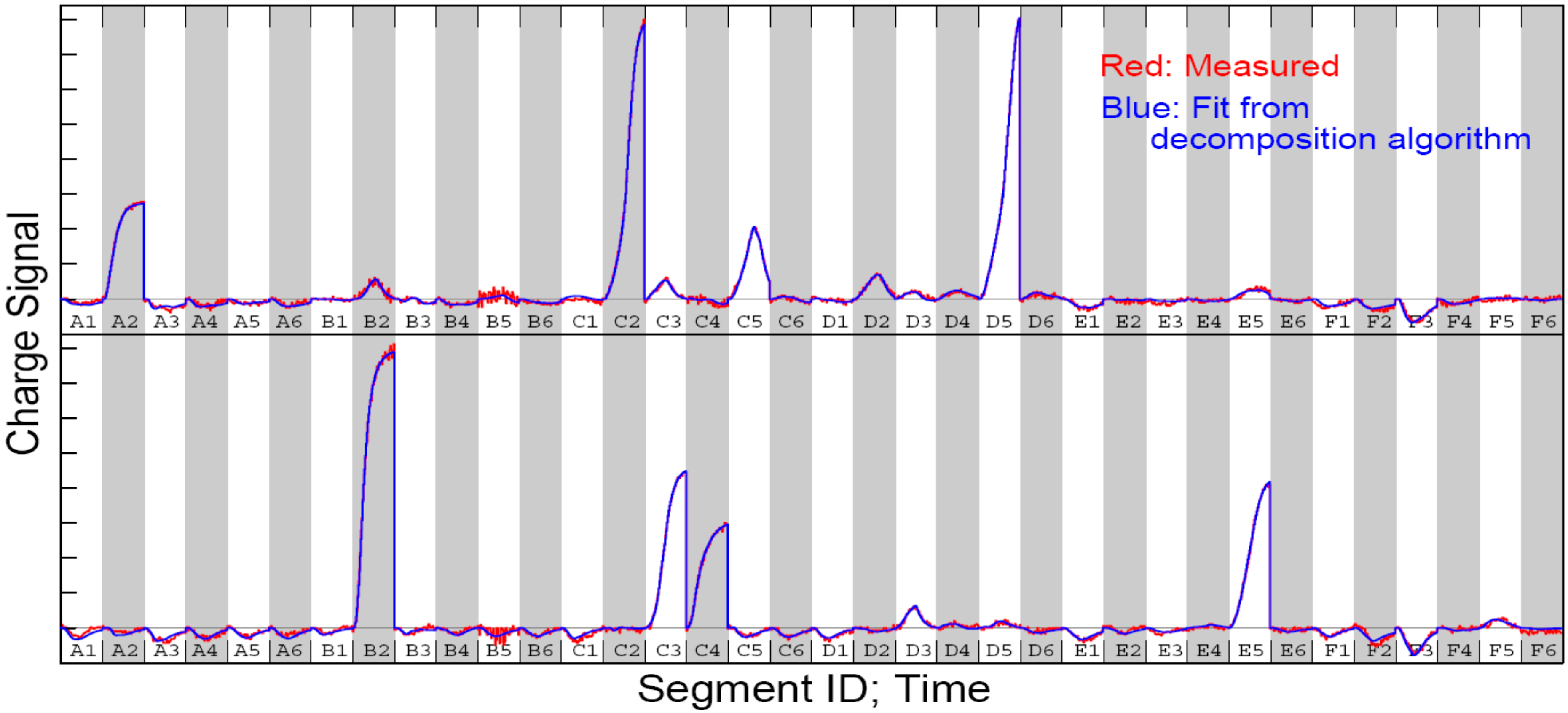
Bottom line:

- Performance of SVD is quite similar to AGS
- Can include SVD in the toolbox, but it does add complexity and RAM requirements

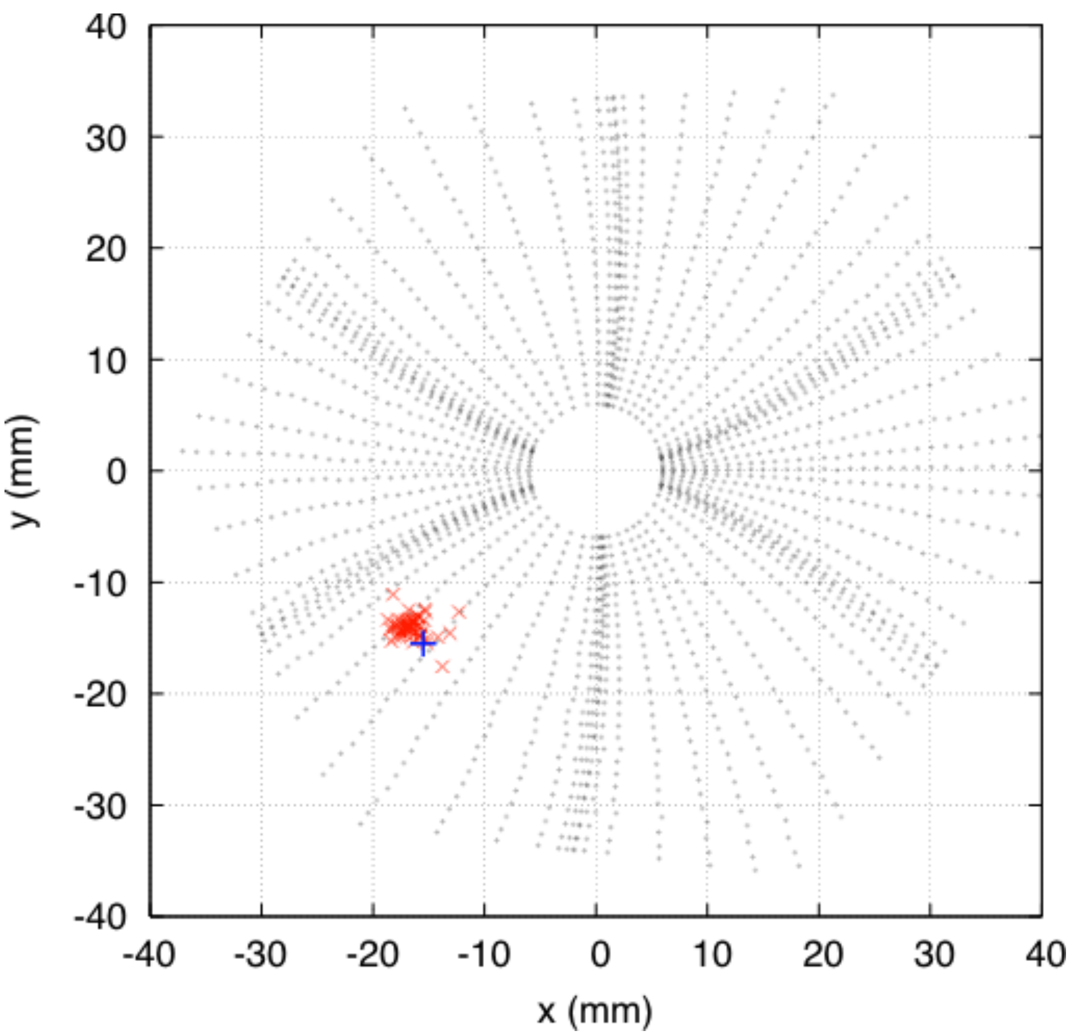
Decomposition Algorithm: Fits

- Red: Two typical multi-segment events measured in prototype triplet cluster
  - concatenated signals from 36 segments, 500ns time range
- Blue: Fits from decomposition algorithm (linear combination of basis signals)
  - includes differential cross talk from capacitive coupling between channels

Requires excellent fidelity in basis signals!



Coincidence scan - Q1 detector

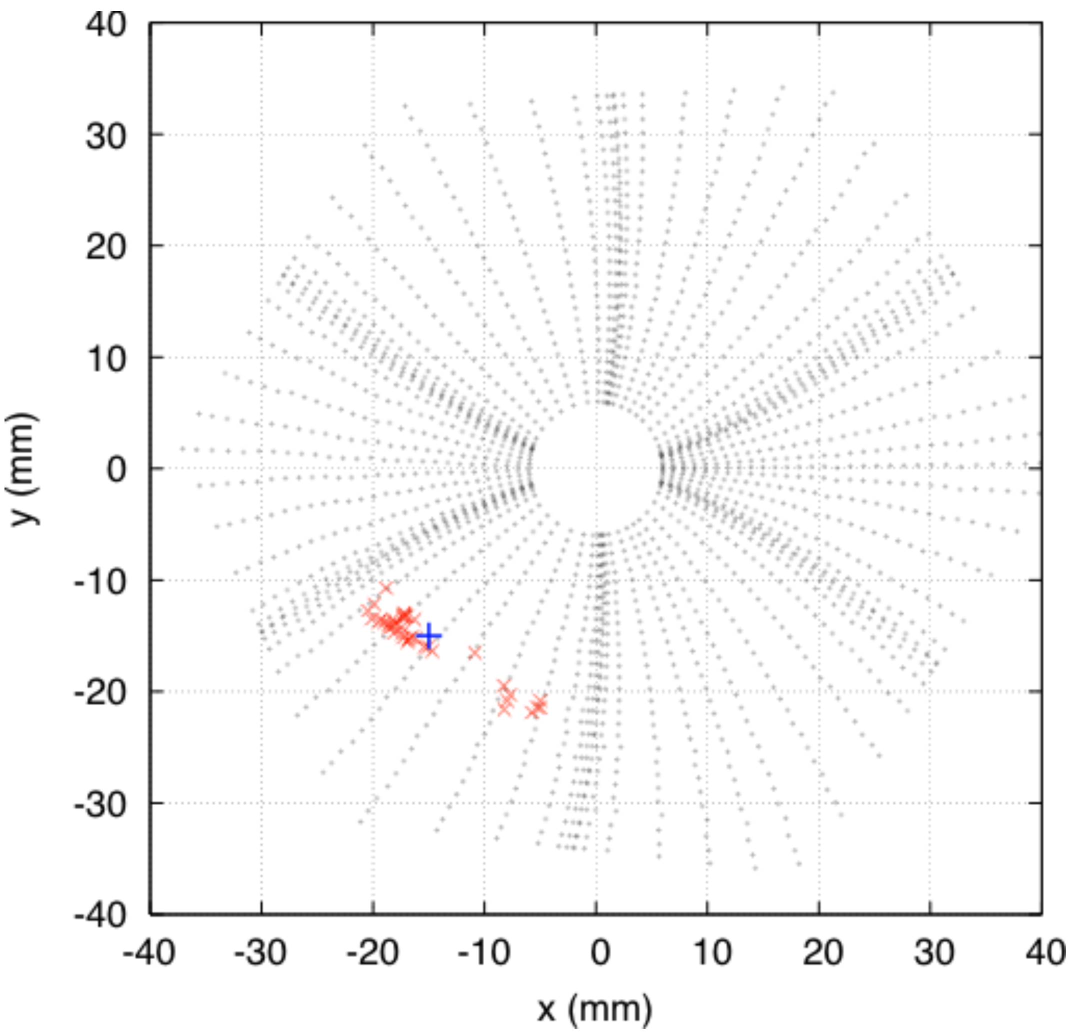


66 events

σ_x = 1.2 mm

σ_y = 0.9 mm

Bifurcation



- Seen in some locations in pencil and coincidence data
- Subset of events at wrong azimuthal position

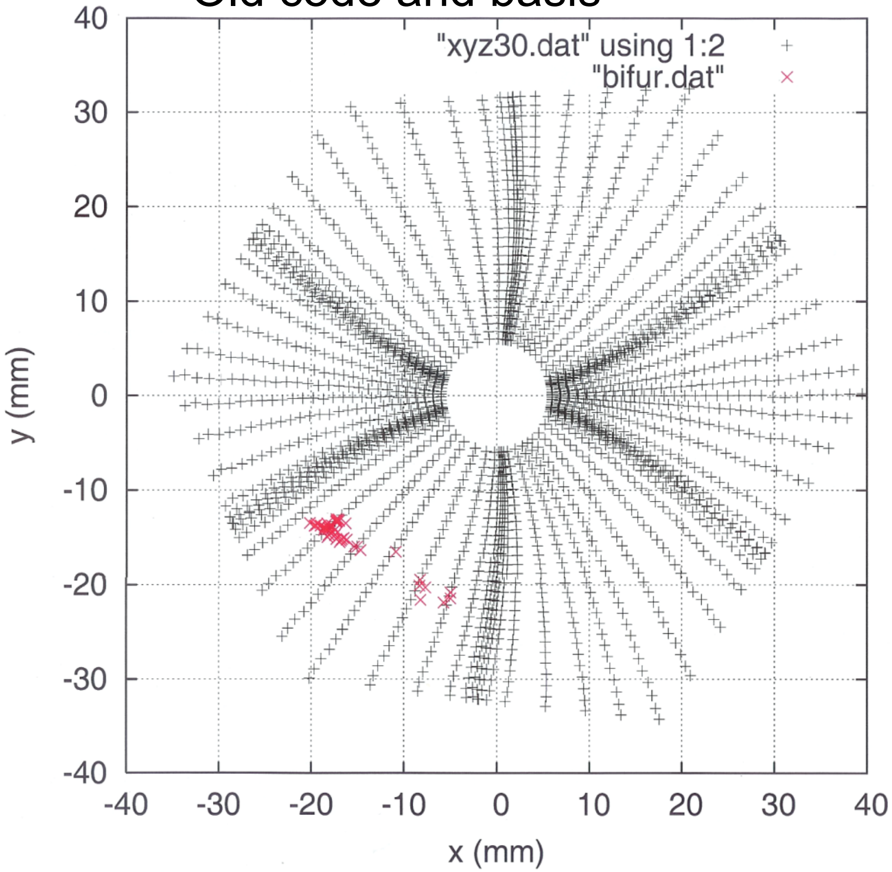
Signals are consistent with correct position but decomposition fit is incorrect.

Bifurcation: Solved

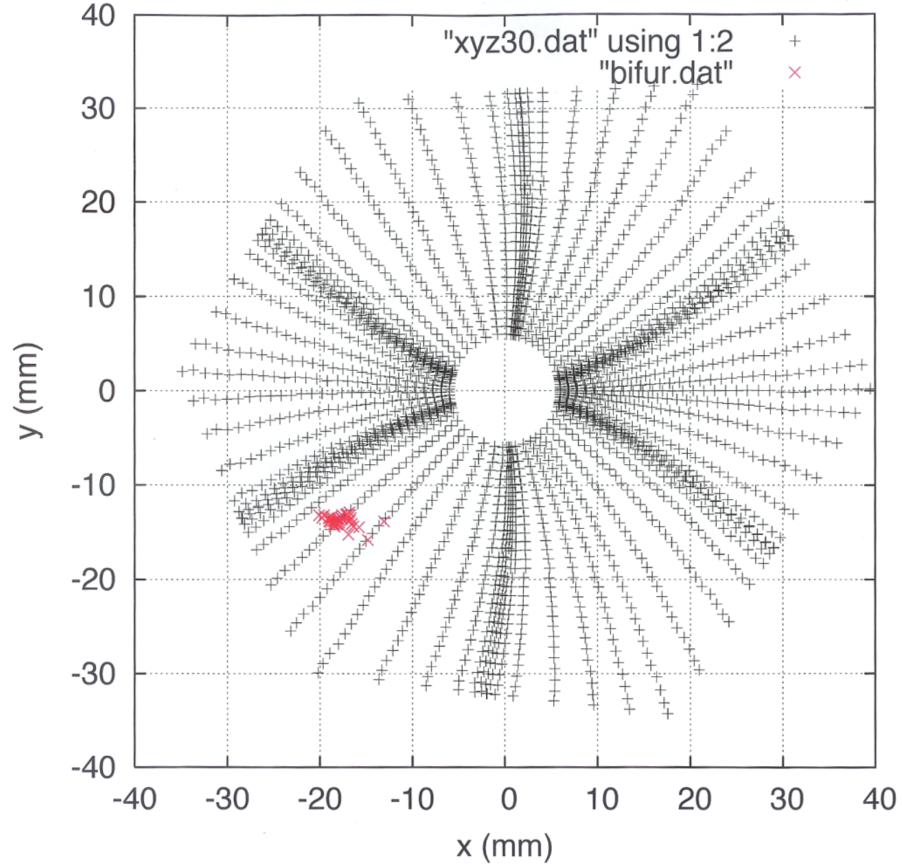
Improved determination of number of interactions, and charge mobilities / preamp rise-times used for basis

We can make things worse… or better.

Old code and basis



New code and basis

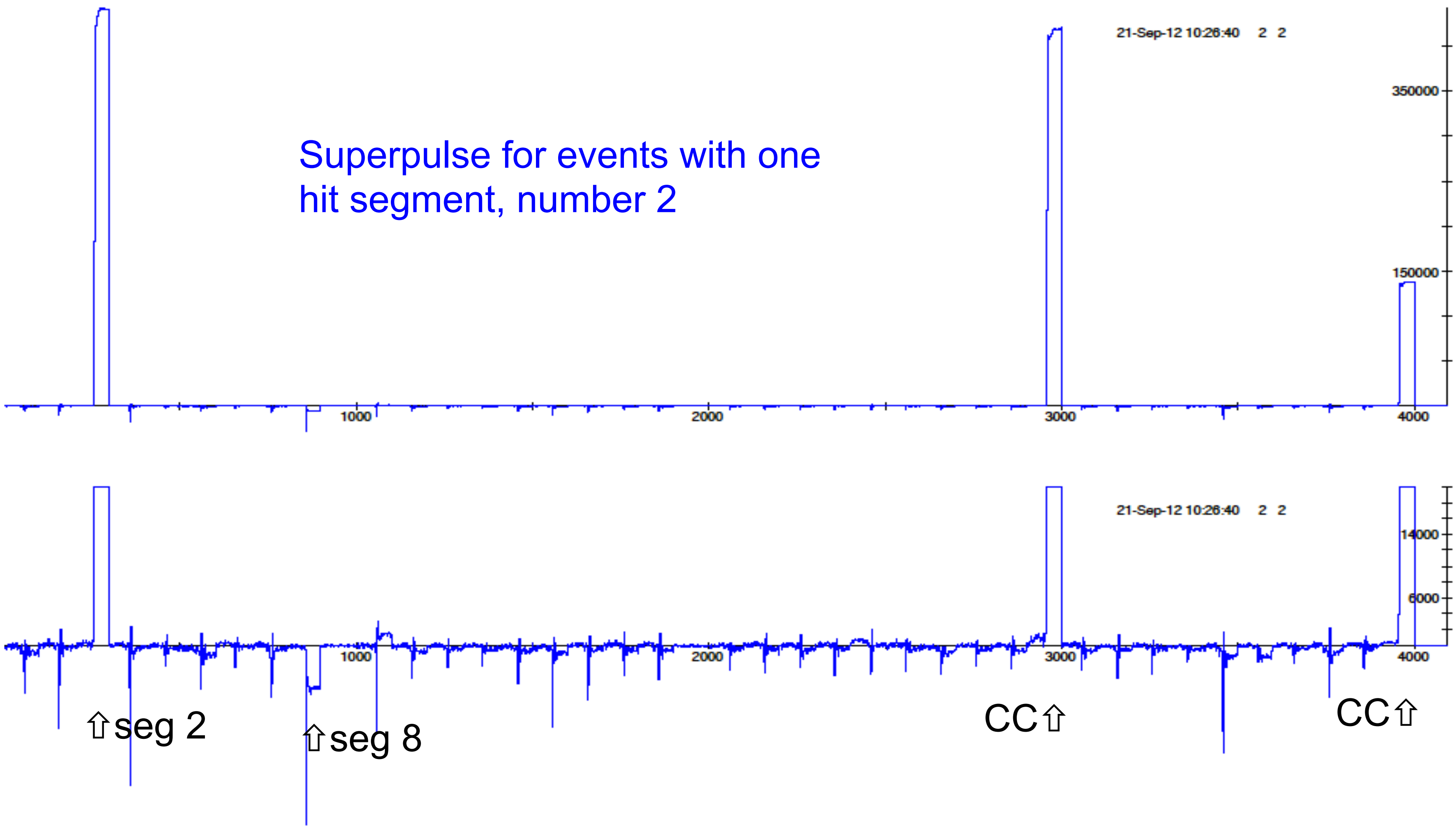


Decomposition Basis (Signal Library)

- Pre-*calculated* on an irregular non-Cartesian grid
- Excellent signal fidelity is required, so must carefully include effects of
  - Integral cross-talk
  - Differential cross-talk
  - Preamplifier rise-time / impulse response
- Poor fidelity results in
  - Too many fitted interactions
  - Incorrect positions and energies
- *Differential cross-talk* signals look like image charges, so they strongly affect position determination

Cross-talk

- Two types
  - Integral cross-talk; affects sum of segment energies



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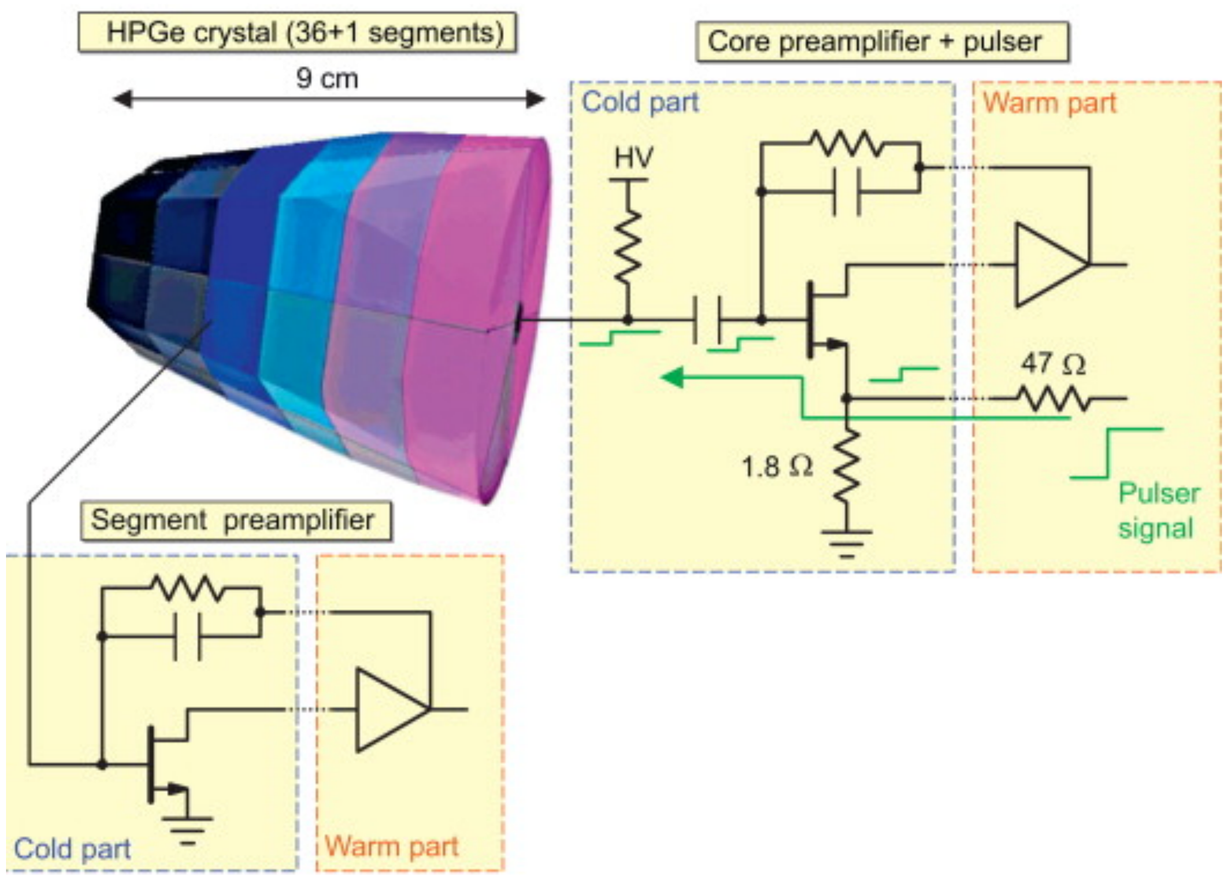

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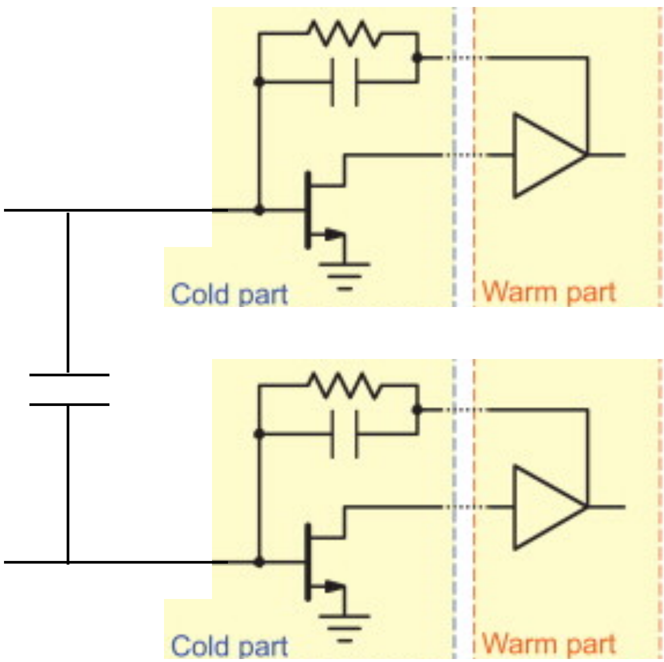


- Capacitive coupling between segments / preamp inputs leads to coupling derivative of one signal to the input of another
- Real detector capacitance as well as stray capacitance from wiring
- Symmetric between pairs of channels

Generating a Realistic Basis

- Fit set of 36 "Superpulses" with ~ 800 parameters defining cross-talk and preamplifier response
- Use fitted parameters to correct basis signals

simulation

- calculate fields, weighting potentials
- generate grid, calculate uncorrected signals
- simulate ^{60}Co interaction points, generate simulated superpulses (net = 1)

measurements, fits

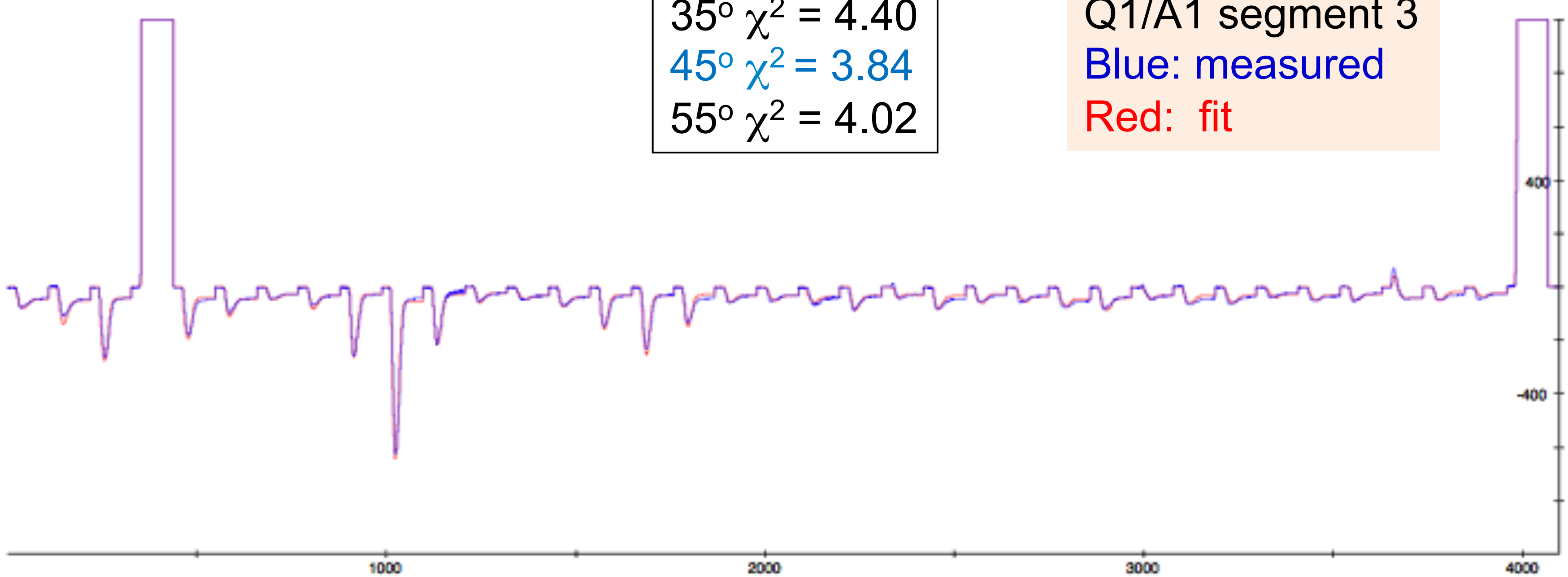
- collect ^{60}Co data consistent with simulation
- generate experimental superpulses
- fit cross-talk, relative delays and shaping times
- apply corrections to each signal in simulated basis

Generating a Realistic Basis

- Fit set of 36 “Superpulses” with ~ 800 parameters defining cross-talk and preamplifier response
- Use fitted parameters to correct basis signals
  - Algorithm accurately reproduces ^{60}Co data
  - Sensitive to crystal orientation
  - Orientation misidentified by Canberra-Eurisys

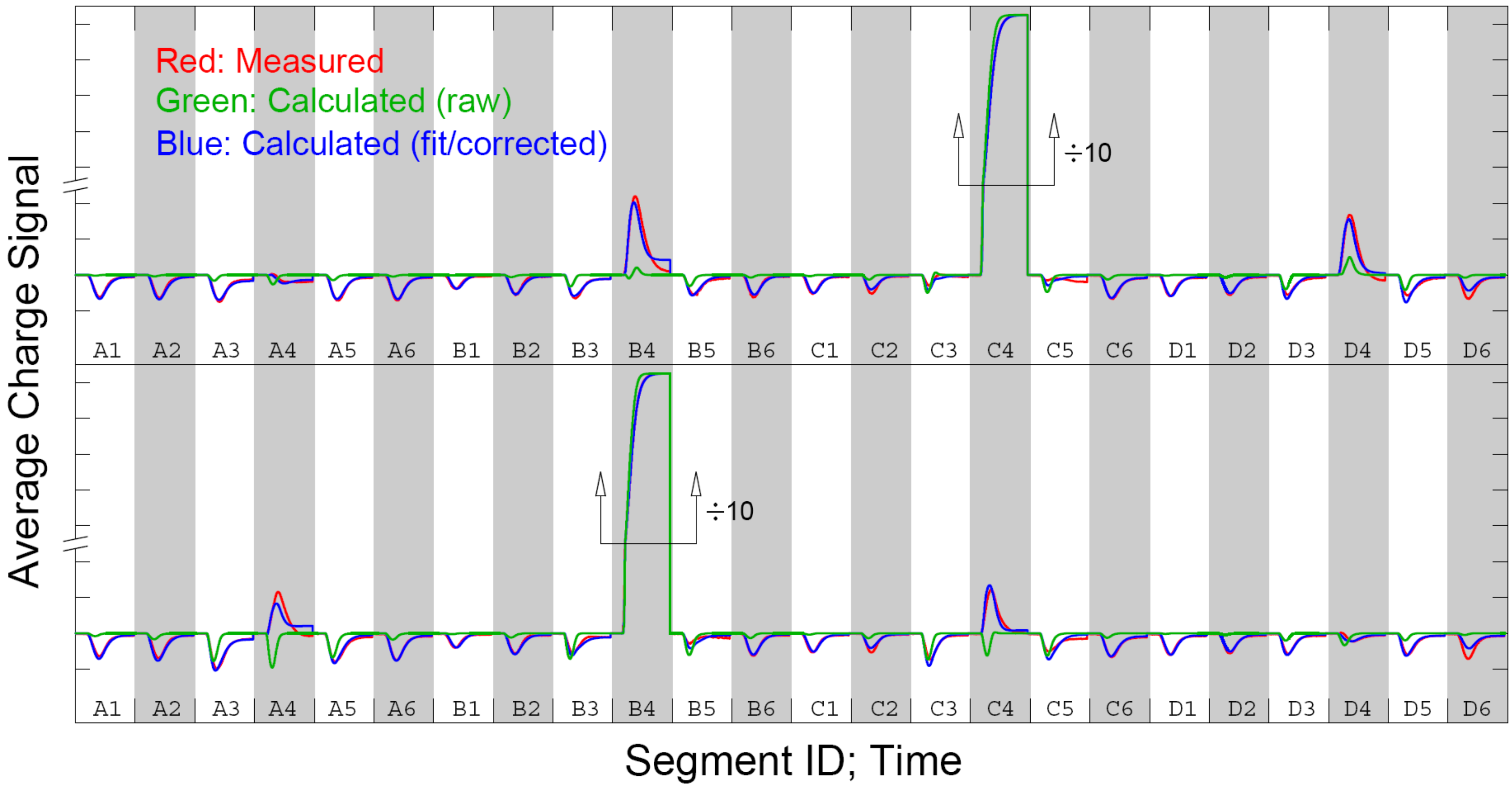
35° χ^2 = 4.40
45° χ^2 = 3.84
55° χ^2 = 4.02

Q1/A1 segment 3
Blue: measured
Red: fit



Fitting cross-talk and rise-time parameters

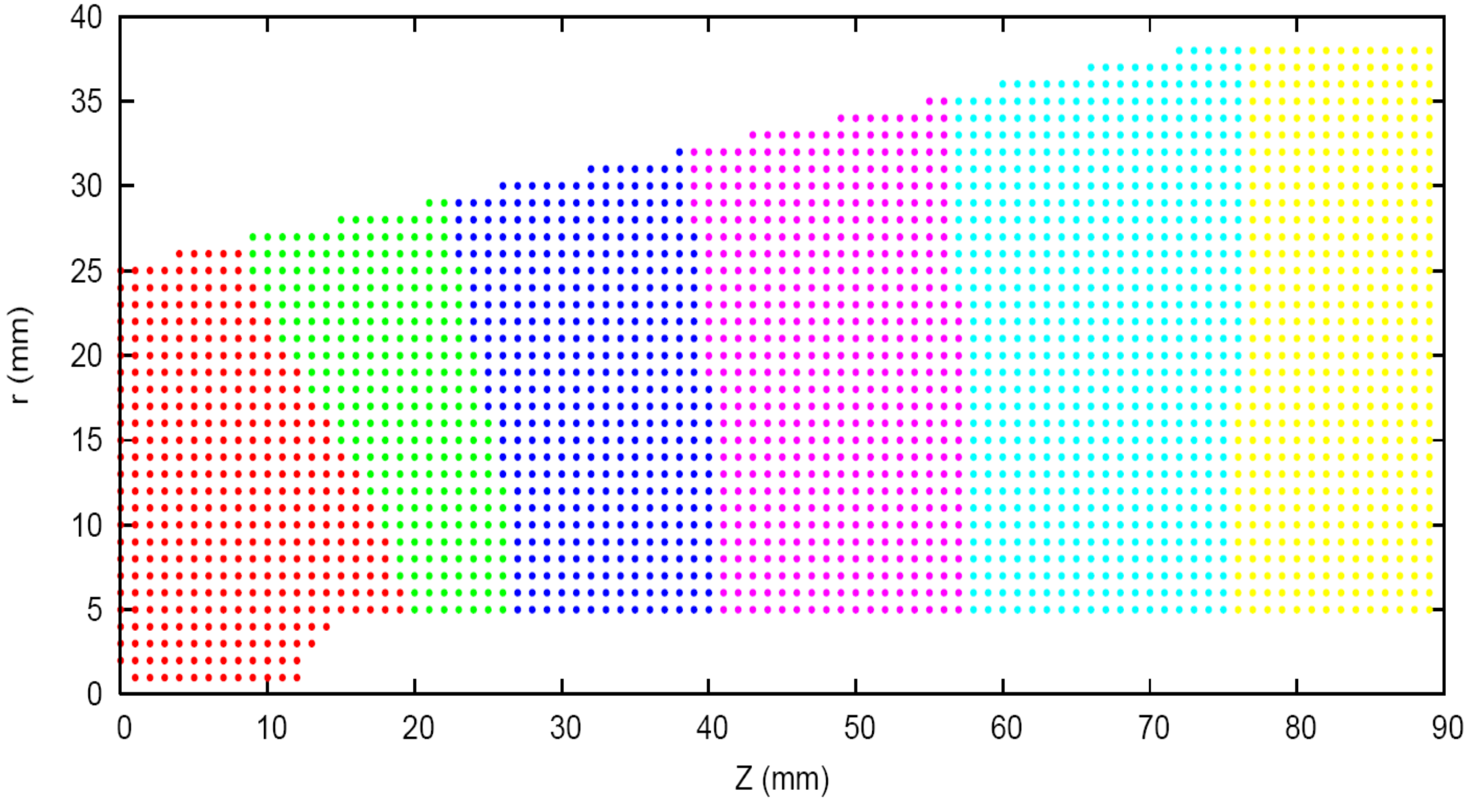
- 36 “superpulses” : averaged signals from many single-segment events (red)
- Monte-Carlo simulations used to generate corresponding calculated signals (green)
- 996 parameters fitted (integral and differential cross-talk, delays, rise times) (blue)
- Calculated response can then be applied to decomposition “basis signals”



Optimized Quasi-Cylindrical Grid for basis signals

- The old Signal Decomposition algorithm for GRETINA used a Cartesian grid, 1 mm spacing in all three directions.

Different colors show active regions
for the different segments



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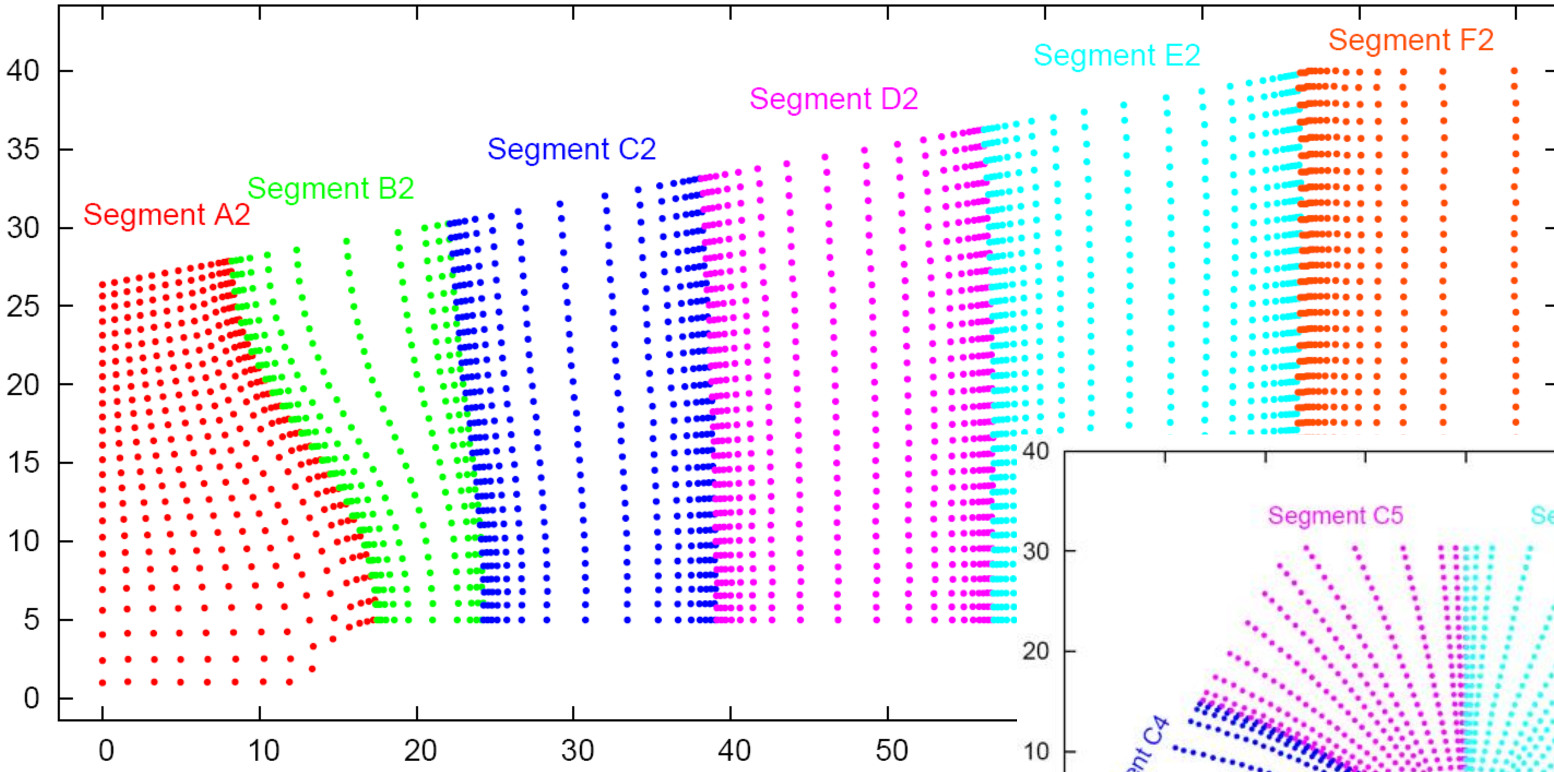
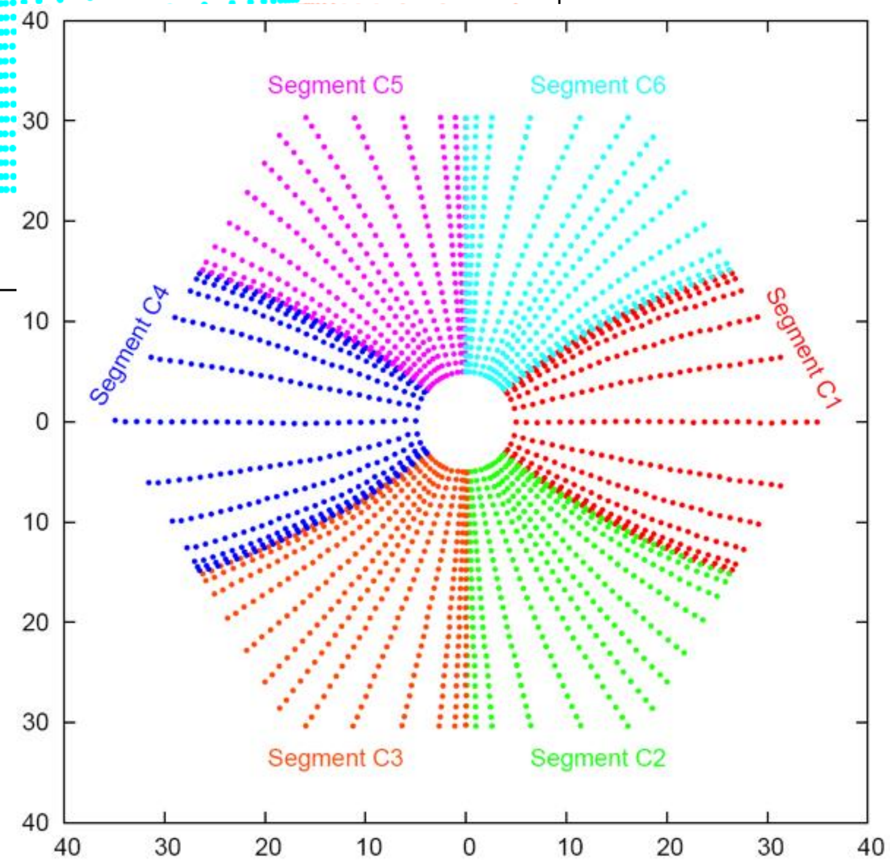




- Spacing arranged such that χ^2 between neighbors is approximately uniform - inversely proportional to sensitivity
- Optimizes RAM usage and greatly simplifies programming of constraints etc.

Signal calculation

- Requires knowledge of
  - Electric field
  - Weighting potential (WP) for each electrode
  - Electron and hole mobilities **v**(**E**) along each crystal axis

- Field and WPs are calculated with a “relaxation code”
  - Use space charge density (net impurity concentration) provided by detector manufacturer
  - Can adjust/normalize concentration profile to match measured *depletion voltage*

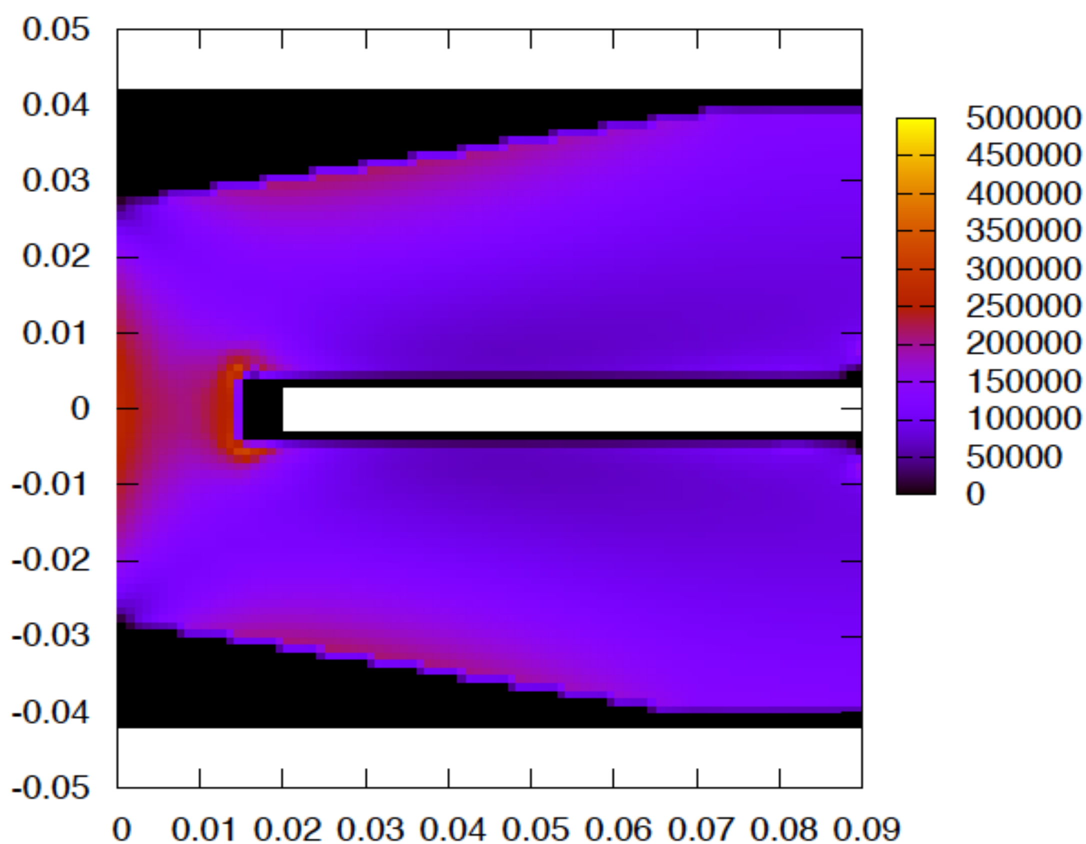
- Mobilities for electrons are well known, available in literature
- Mobilities for holes less well determined

Signal calculation: Electric field

The gamma-ray interaction creates electron-hole pairs inside the Ge diode; requires 3 eV per e-h pair.

The signals are generated as these charges move in the field inside the detector and are eventually collected on electrodes.

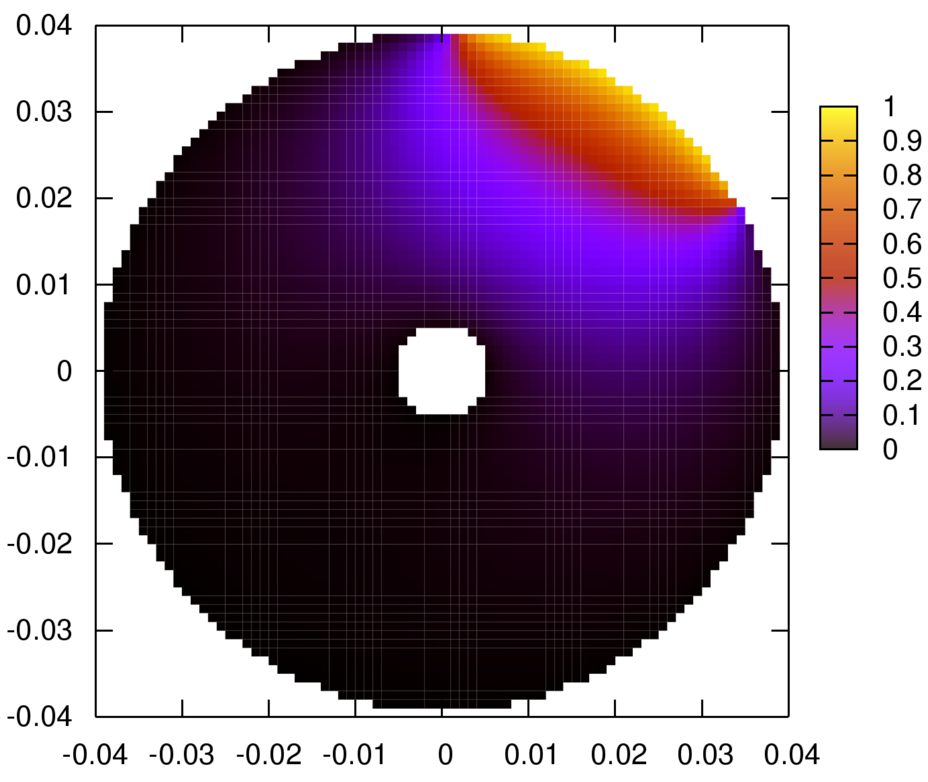
Electrons move to the center, holes to the outside.

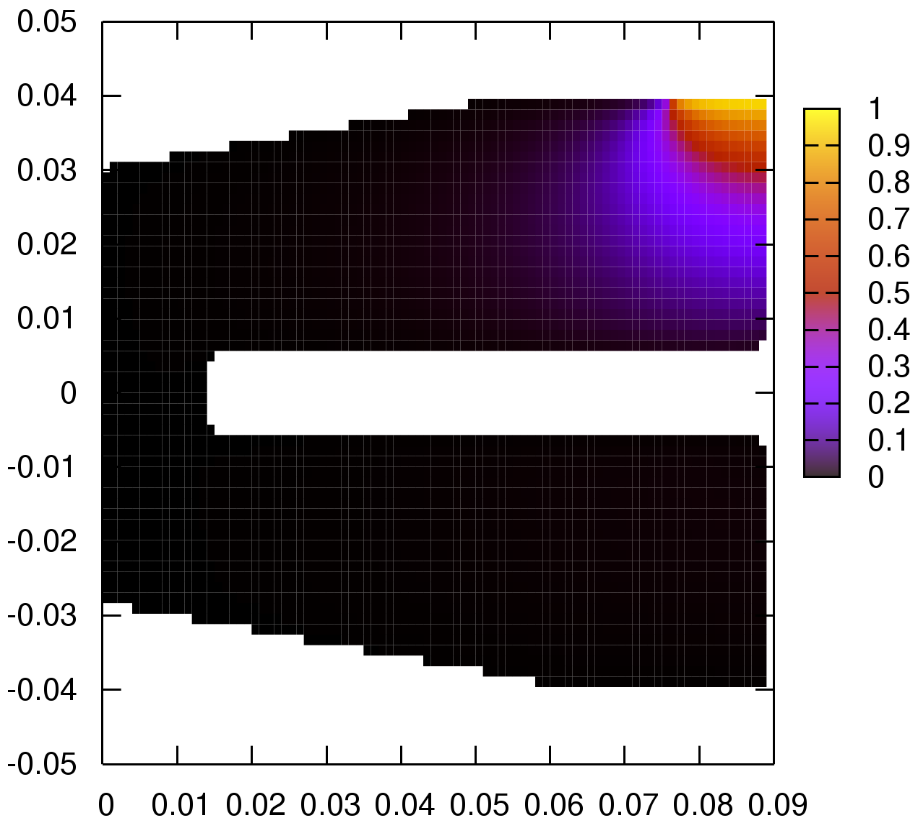


Signal calculation: Weighting potentials

The signals are generated as the charges move into or out of the *weighting potentials.*

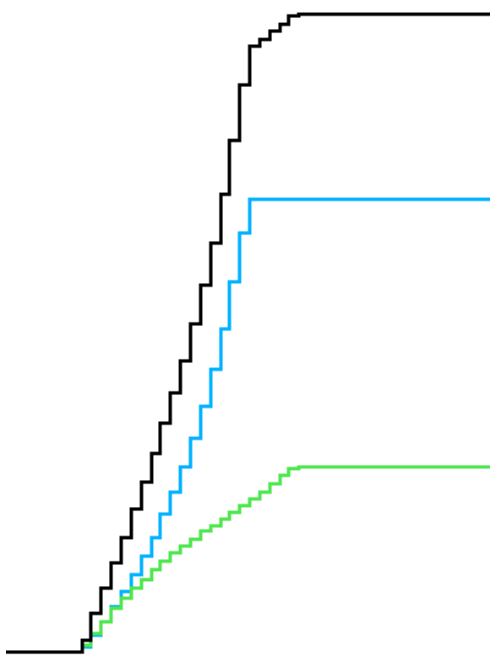
One of the rear segments:

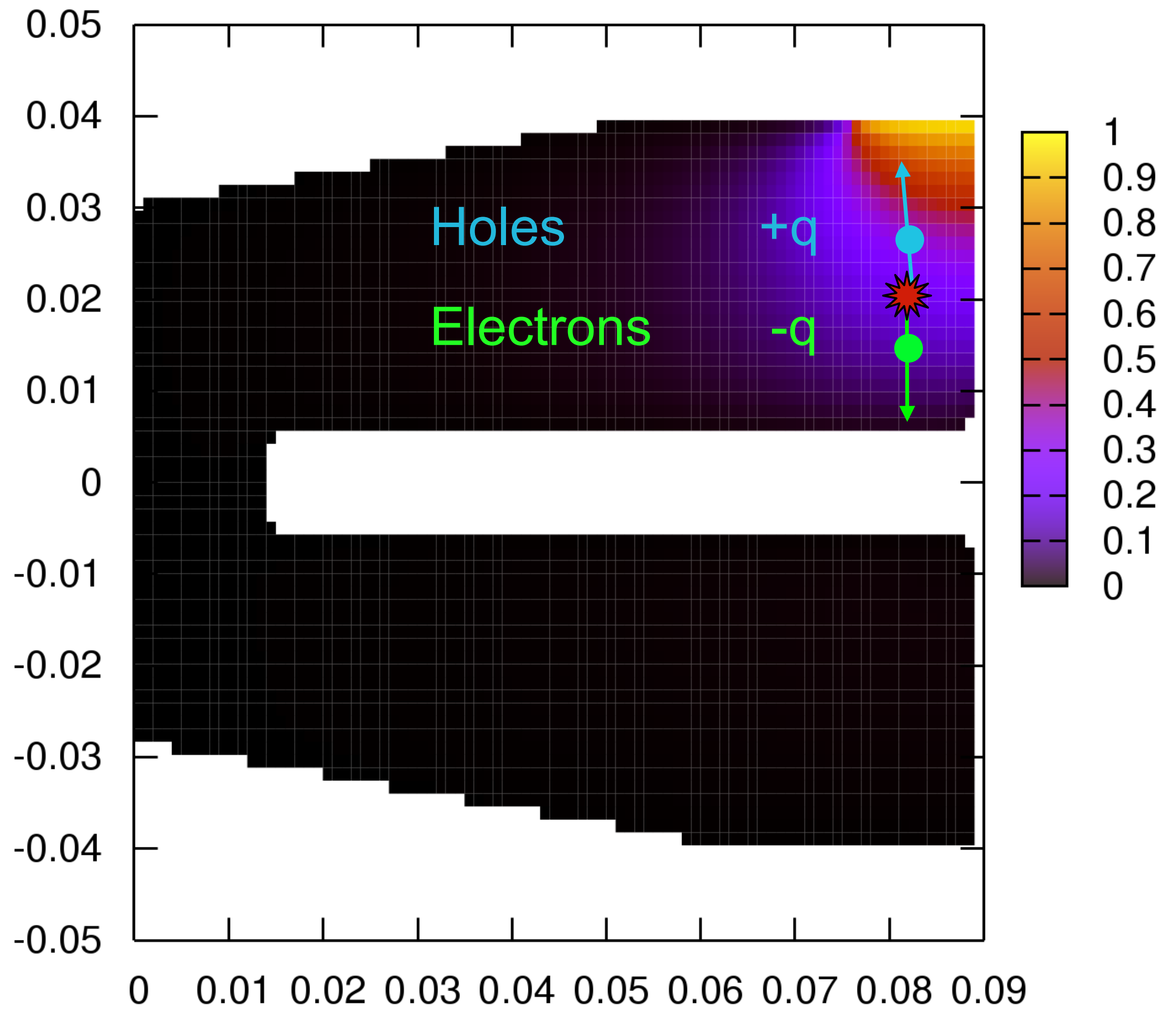




Signal calculation

$$\text{Signal}(t) = (+q)[W(\mathbf{r}_h(t))-W(\mathbf{r}_0)] + (-q)[W(\mathbf{r}_e(t))-W(\mathbf{r}_0)]$$





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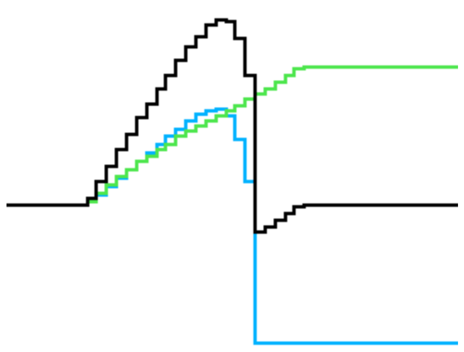
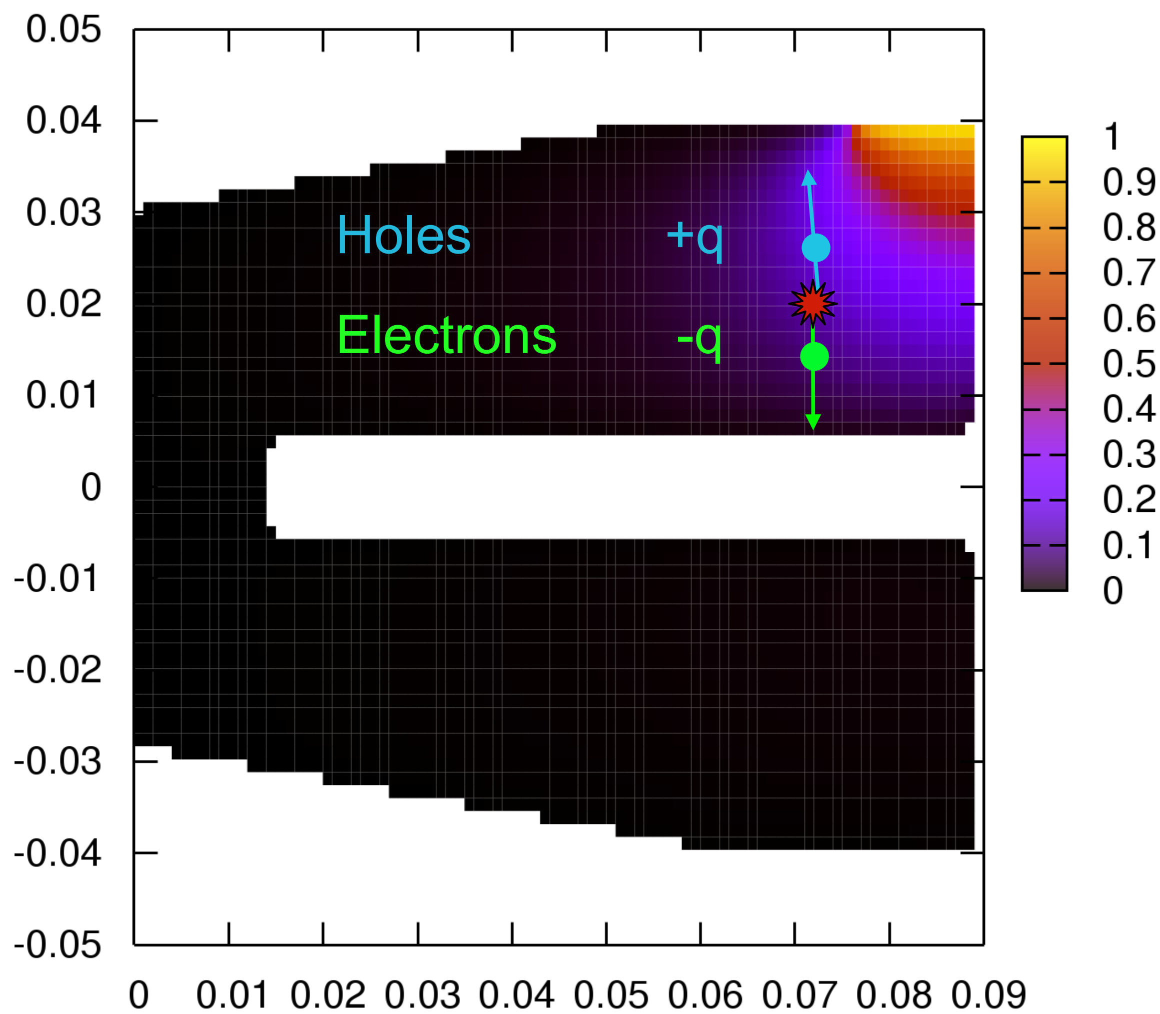
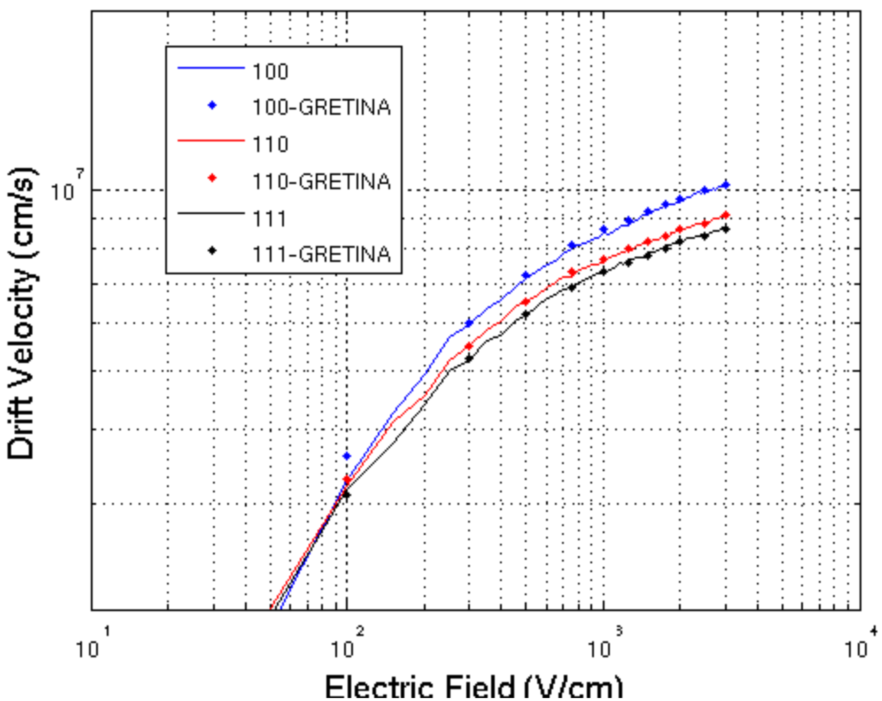
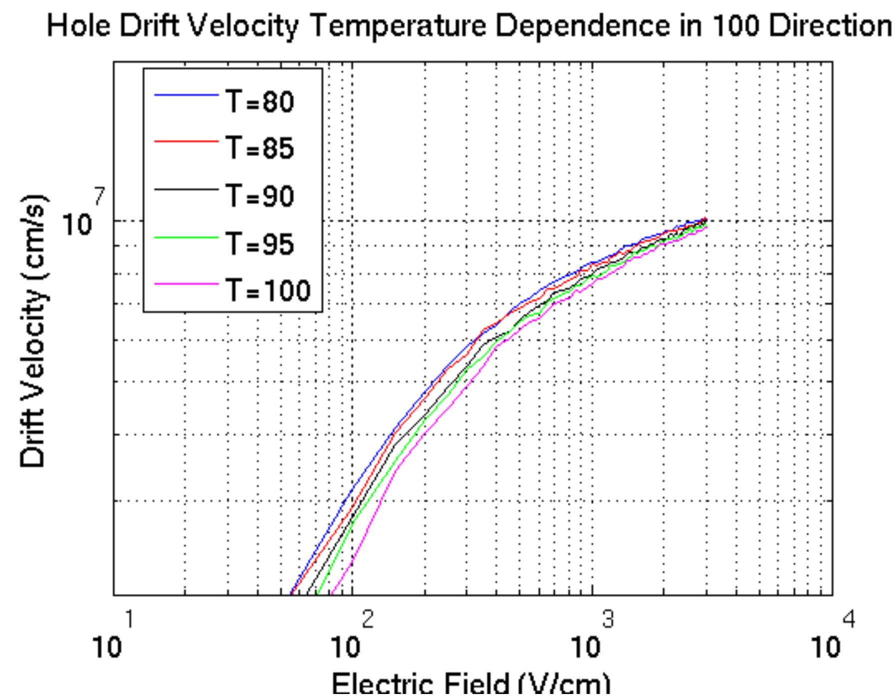




Hole drift mobilities; Tech-X SBIR

- Monte-Carlo calculations of hole drift velocity as a function of field, crystal orientation, and temperature
- Comparing with data from GRETINA and DSSDs
- Also starting to examine diffusion of holes and electrons





Field / Signal calculation: Uncertainties

- Net impurity concentration, ρ
  - Profile is assumed linear; this is a poor approximation
  - No radial dependence included
  - Uses detector manufacturer measurement, which are quite uncertain
  - Sometimes use calculated/measured depletion voltage to adjust ρ
  - AGATA had some detectors with impurity concentration reversed in z
- Relaxation boundary conditions at the back of the crystal
  - Assumes reflective symmetry, results in field parallel to Ge surface
- Possible variances in detector geometry
  - Size and axial offset of central contact, segment boundaries, bulletization, crystal axis rotation, …
- Some evidence that hole mobilities are incorrect by ~ 10%
  - Could try optimizing by scaling hole mobility and evaluating χ^2
- Also need to verify temperature dependence, n-damage dependence

Field / Signal calculation: Uncertainties

- There is room for significant improvement in determining and correcting for these possible effects
- Requires dedicated, long-term effort

Summary

- Signal decomposition algorithm itself is in good shape
  - Almost always gives same results as exhaustive search
  - Nonlinear grid gave a big boost in performance
  - Little room for real improvement, but some parameters could be optimized

- Cross-talk fit/correction also works well but has room for incremental improvements
  - Not all crystals have been exhaustively studied

- Field / signal calculation has the largest shortcomings
  - Requires dedicated, long-term effort for improvement

Acknowledgements

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Augusto Machiavelli

Stefanos Paschalis

Heather Crawford

Chris Campbell

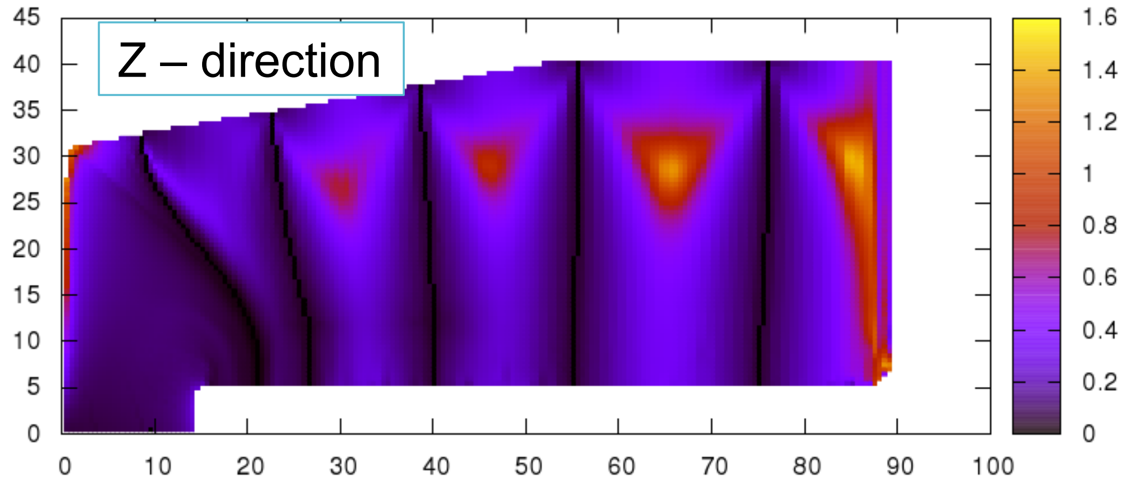
ORNL / UTK

Karin Lagergren: Signal calculation code; Optimized basis grid

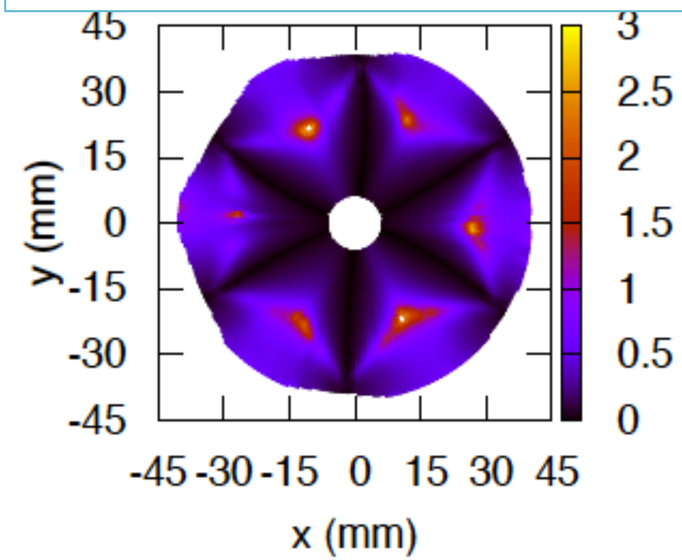
Calculated position sensitivity

Theoretical FWHM, in mm

Signal/noise = 100, preamp rise time = 70 - 90 ns



Azimuthal direction; z = 65 mm



Radial direction; z = 65 mm