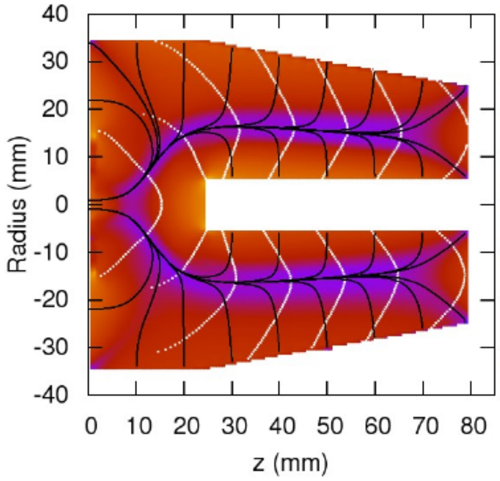
A Novel Inverted-Coaxial Point-Contact Detector



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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

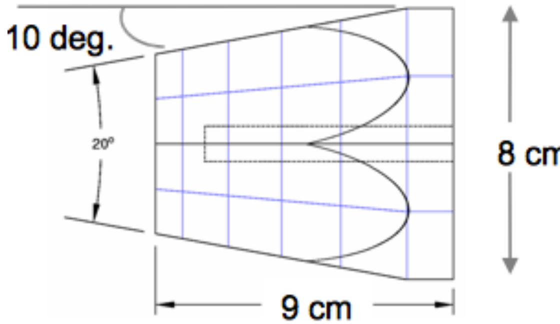
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

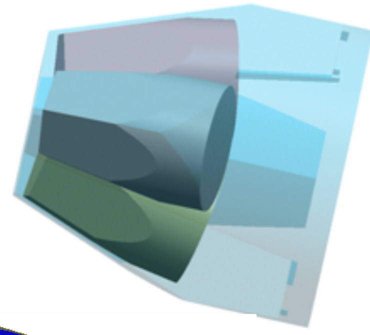
Outline

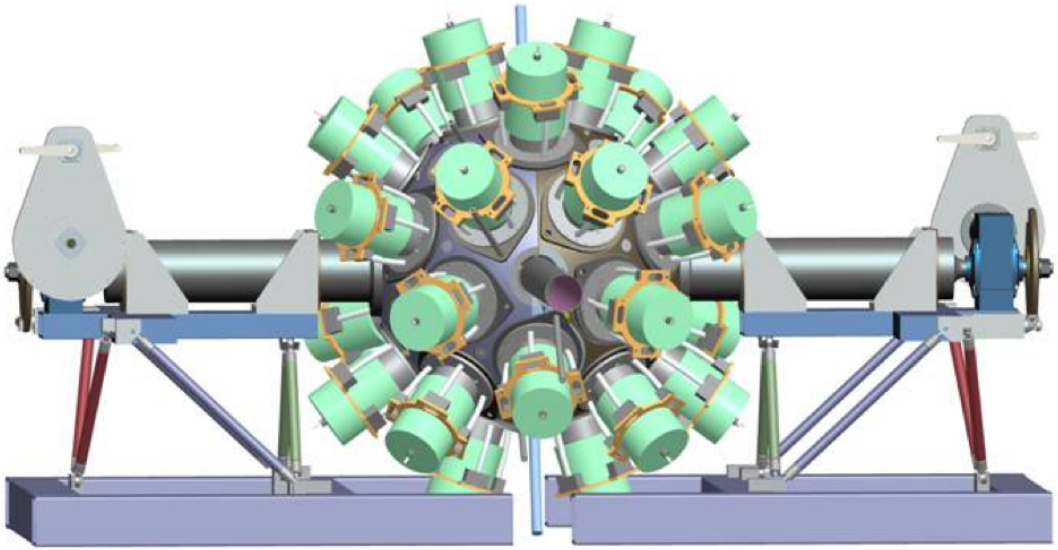
- Gamma-ray tracking; GRETINA and AGATA
  - Signal decomposition
  - Signal calculation and signal bases
  - Performance and results
  - Room for improvement
- Majorana and the advantages of point-contact detectors
- Novel “inverted-coaxial” point contact design
  - Unsegmented prototype (p-type)
  - Segmented prototype (n-type)
- First results for segmented detector
  - Signal calculation and validation
- Anticipated performance
- Summary

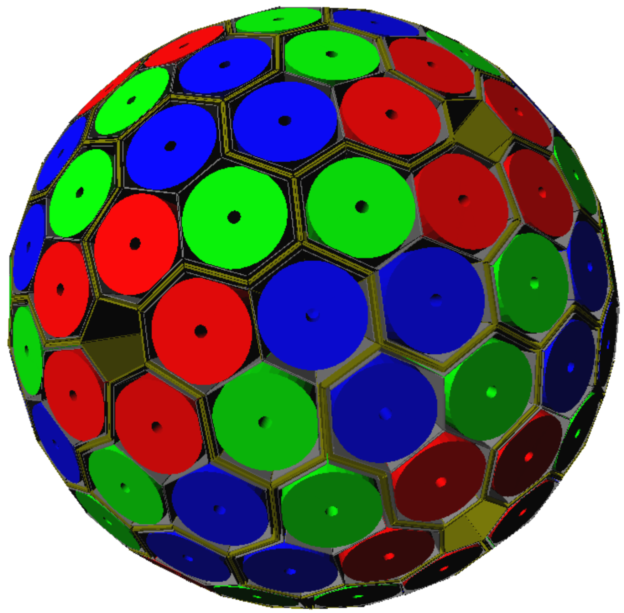
GRETA and AGATA

- Large, tapered, highly segmented crystals
- ~ 8x9 cm, 36 segments

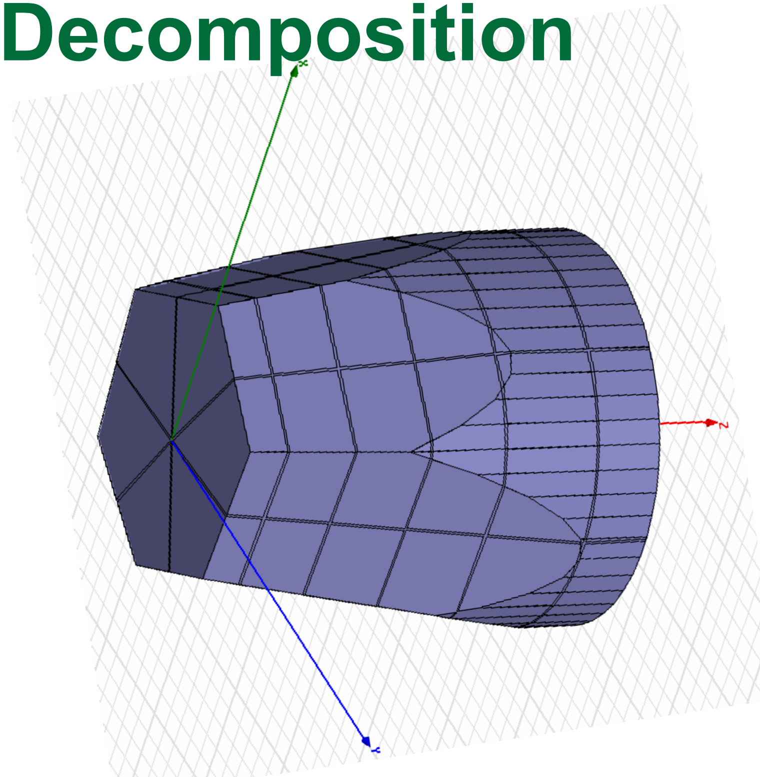




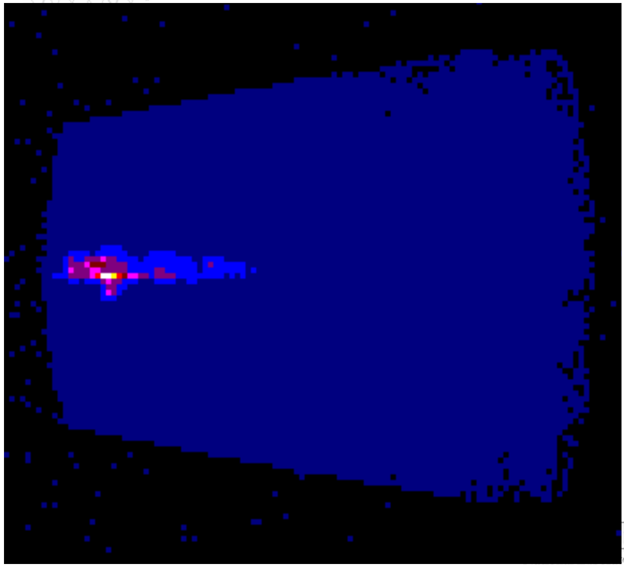




Gamma Tracking and Signal Decomposition



- Digital signal processing to determine the *number, positions,* and *energies* of gamma interactions in the crystal
  - Uses pre-calculated pulse shapes for ~ 10^5 positions throughout the crystal
  - Can have multiple interactions per hit segment
- *Position resolution* is crucial for energy resolution, efficiency, and peak-to-total ratio

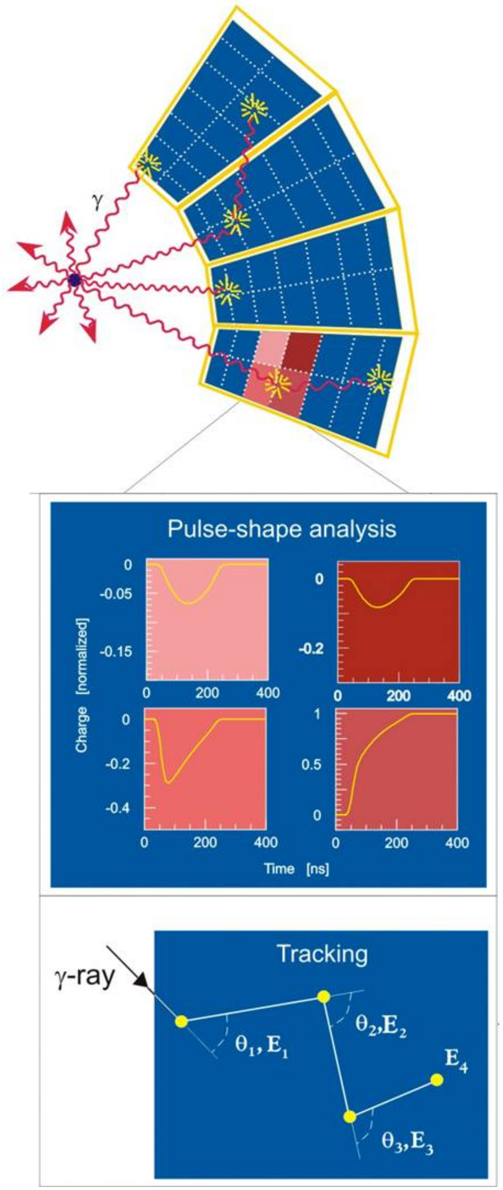


Principles of Gamma-ray Tracking

3D position sensitive Ge detector

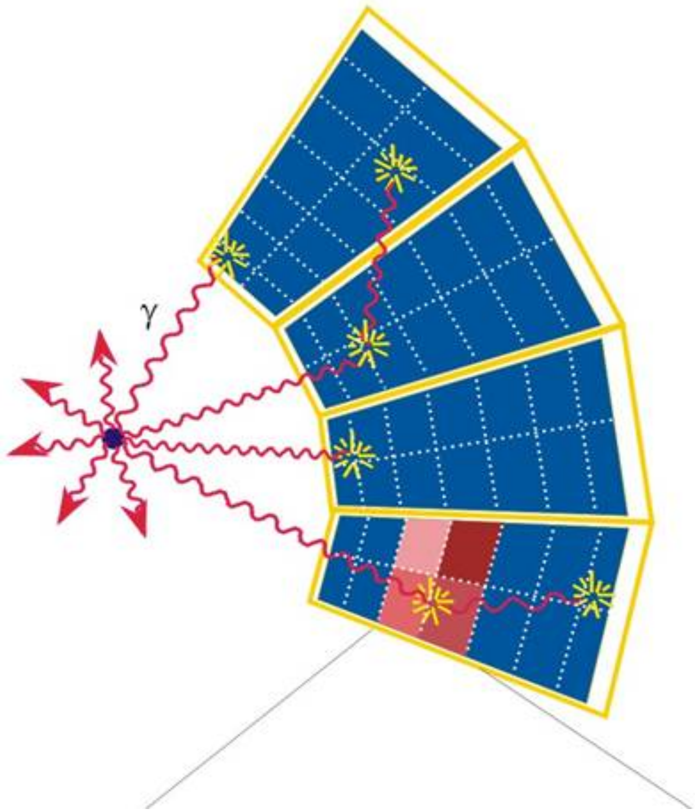
Resolve position and energy of interaction points

Determine scattering sequence

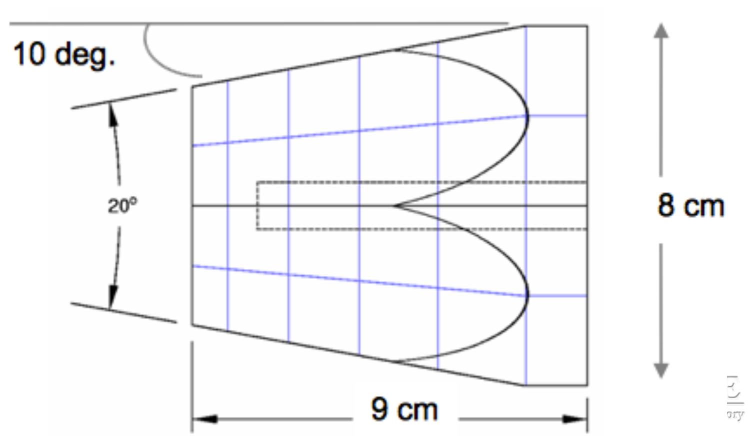


Principles of Gamma-ray Tracking

3D position
sensitive
Ge detector



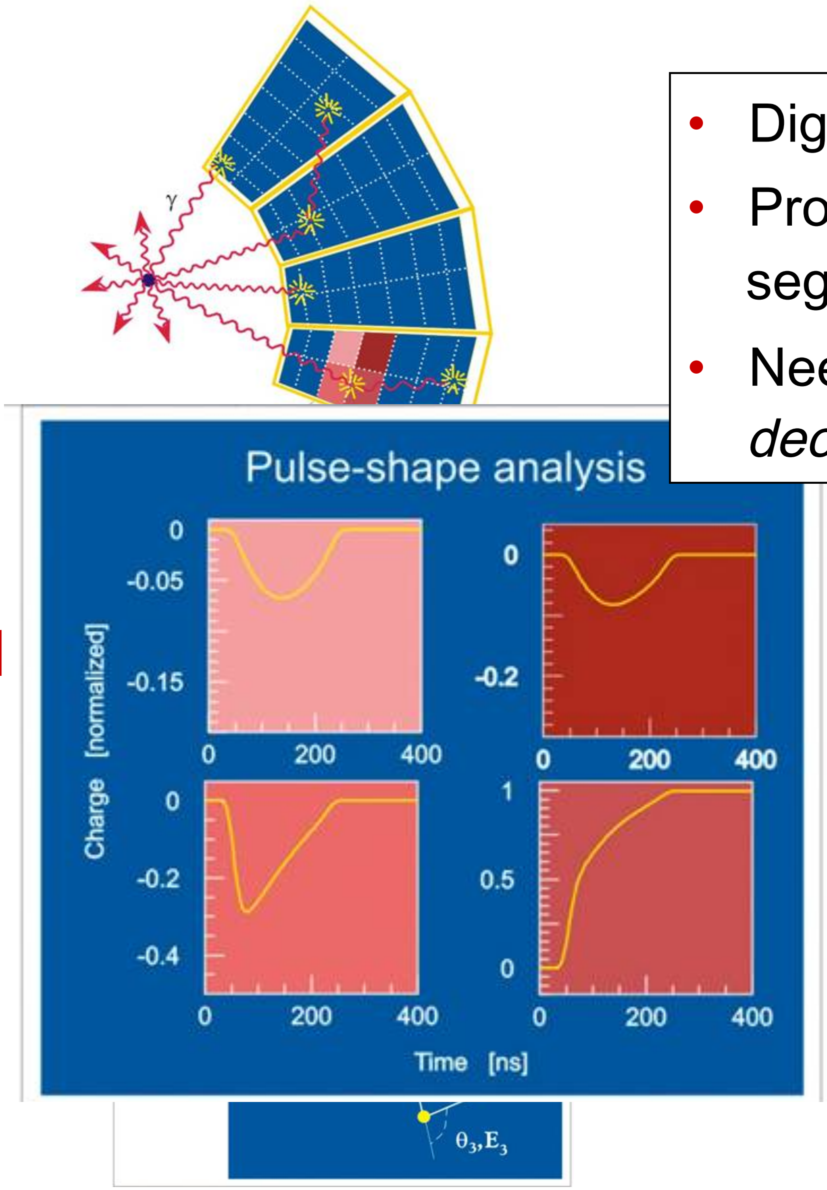
- Large n-type HPGe semi-coaxial detectors
- Outside surface electrically segmented into 36 separate contacts (6 azimuthal x 6 longitudinal)
- Get *sub-segment position resolution* with digital pulse processing



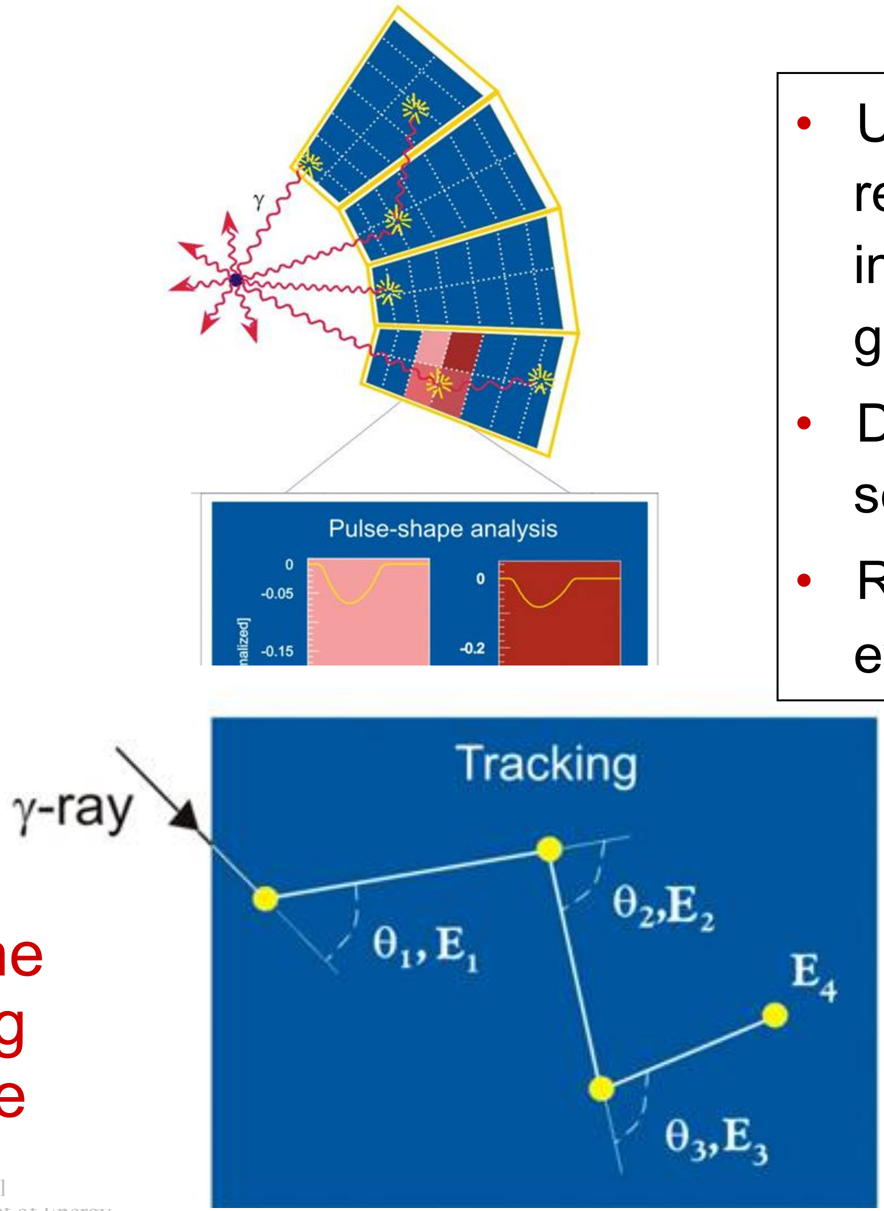
Principles of Gamma-ray Tracking

- Digital pulse processing
- Process all segments (hit segment and neighbours)
- Need a sophisticated *signal decomposition algorithm*

Resolve position and energy of interaction points



Principles of Gamma-ray Tracking

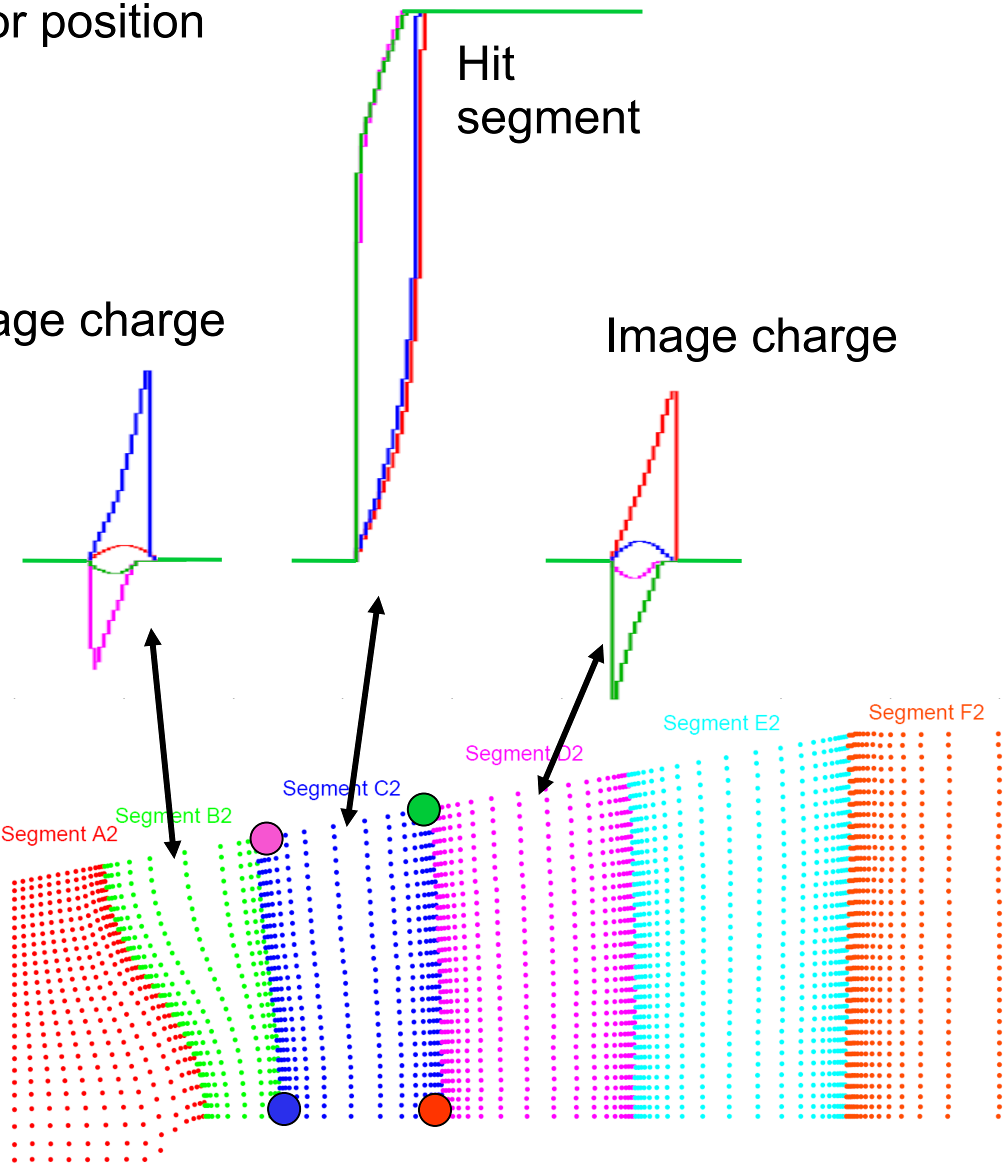


- Use Compton scattering relation to group the interactions from each gamma
- Determine scattering sequence
- Reject incomplete-energy events on basis of chi-square

Determine scattering sequence

Calculated Signals: Sensitivity to position

Signals are color-coded for position



Signals are nonlinear with respect to position; a necessary condition for extracting multiple interactions

Signal Calculation

- Requires:
  - 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

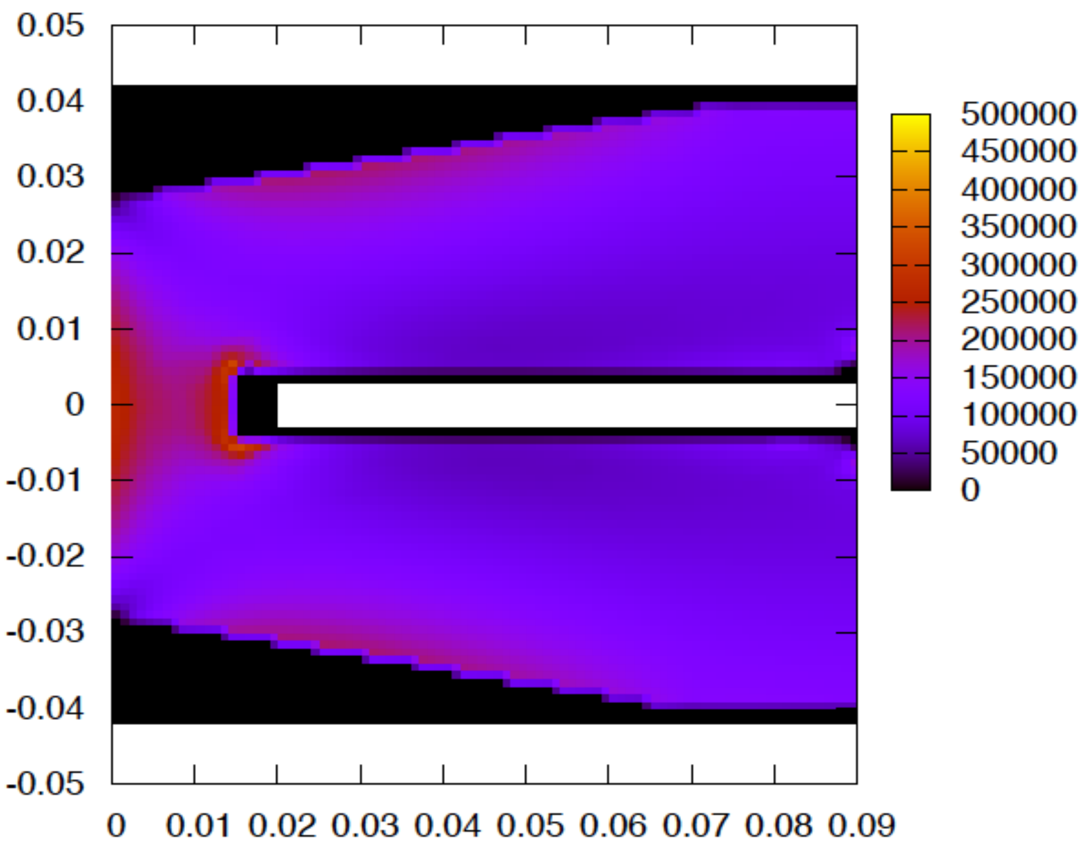
- Mobilities for electrons are well known, available in literature
- Mobilities for holes less well determined

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.

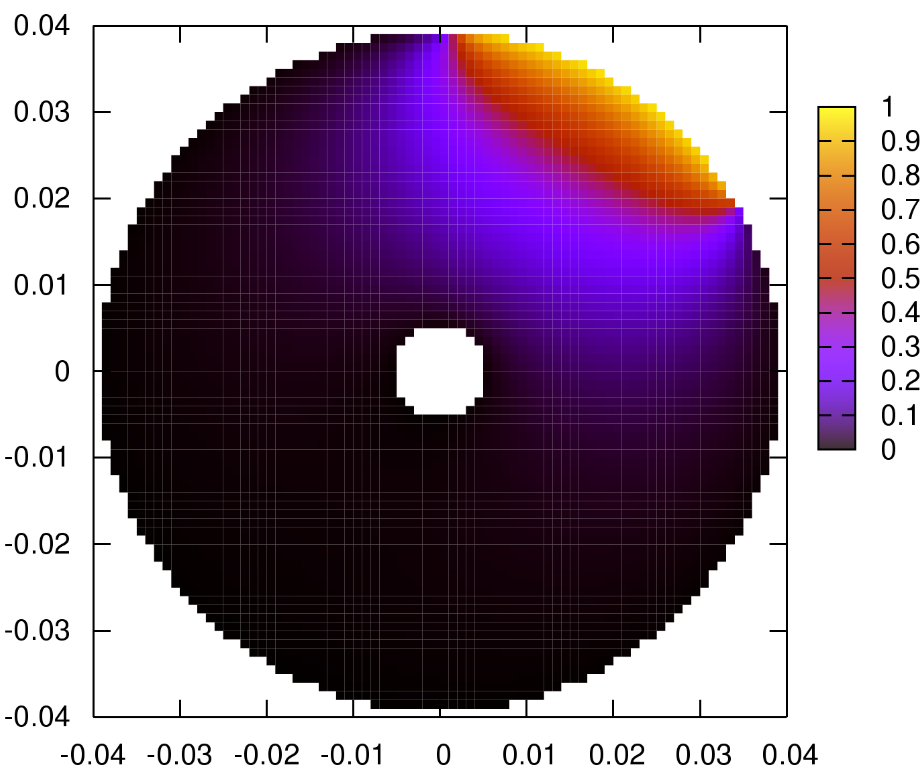
Electrons move to the center, holes to the outside.

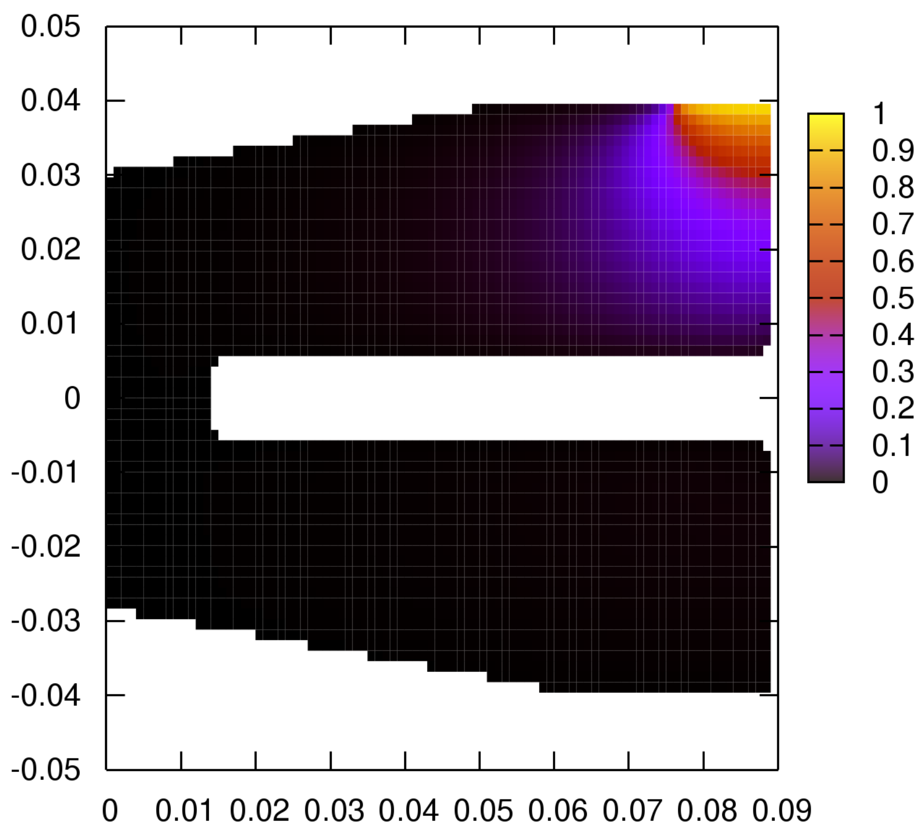


Signal Calculation: Weighting potentials

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

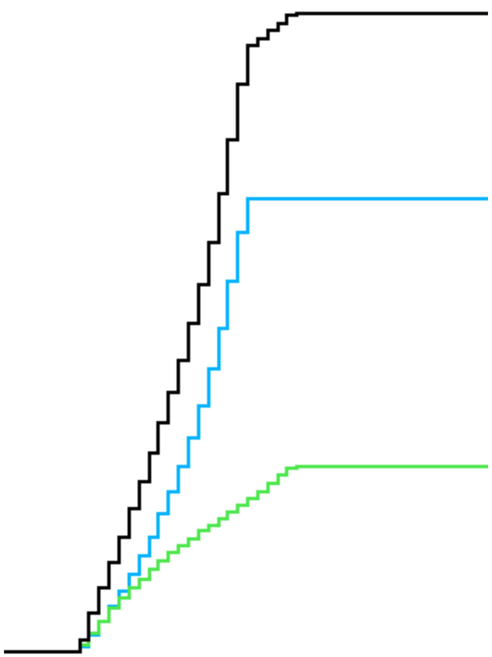
One of the rear segments:

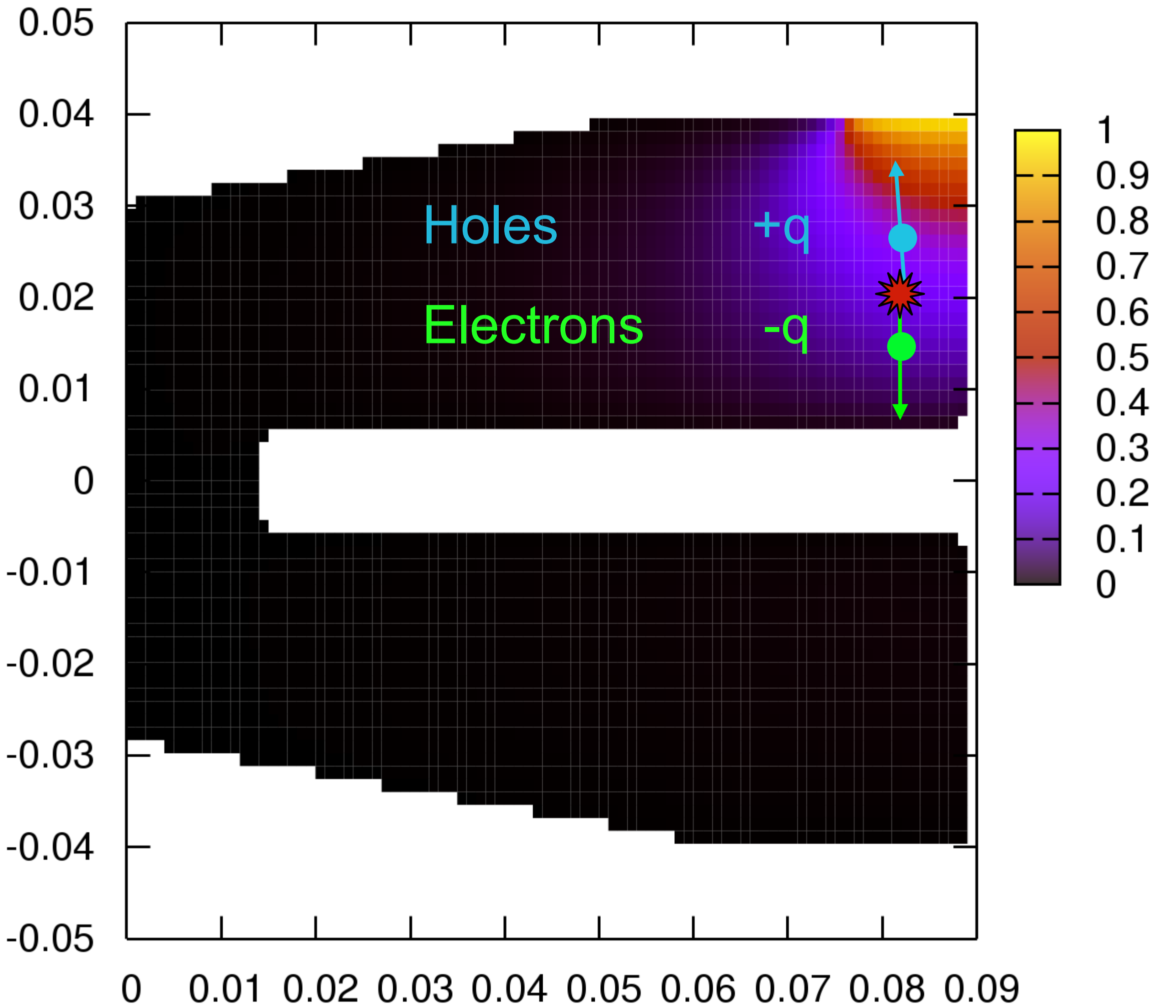




Signal Calculation

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





Signal Calculation

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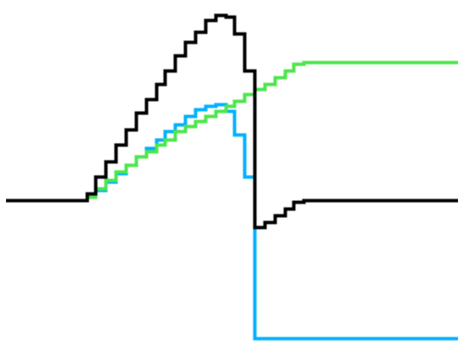
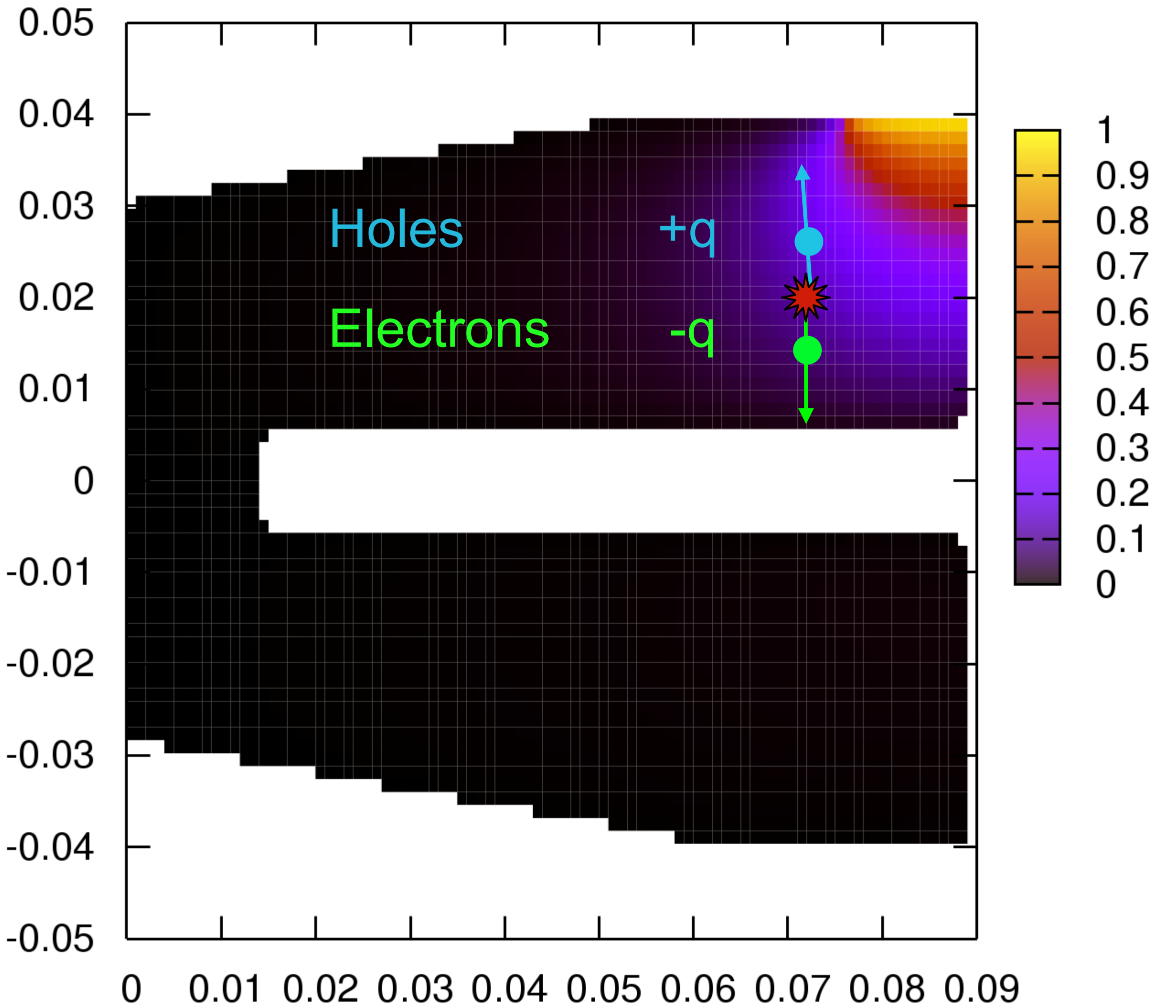
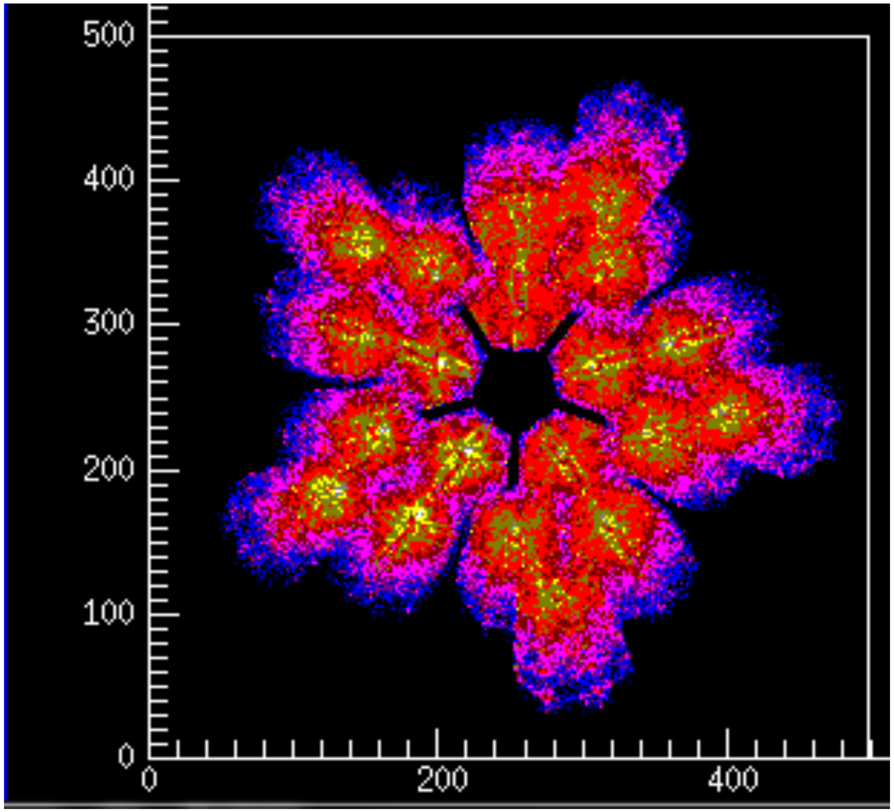
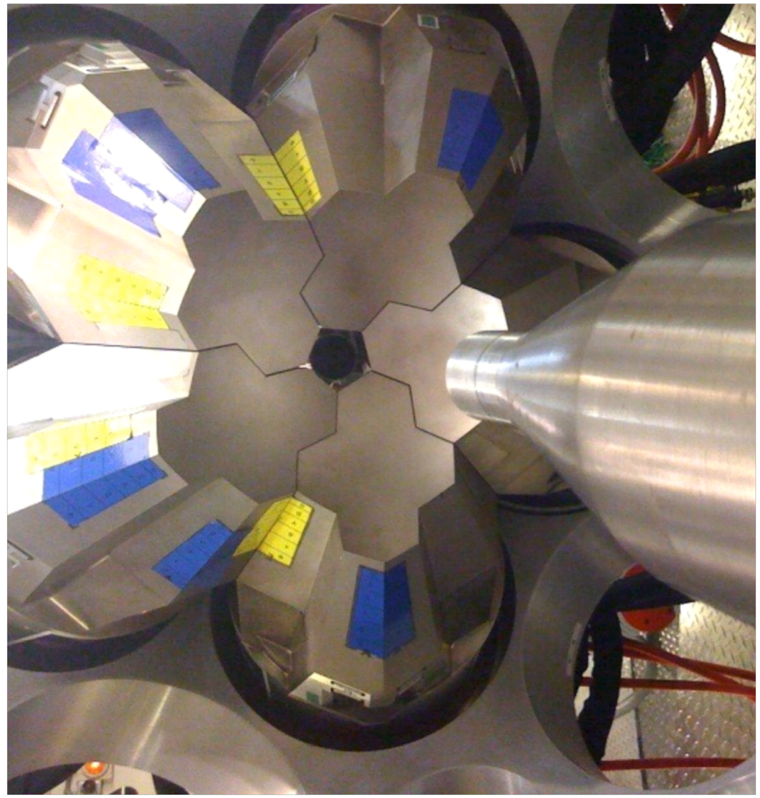




Signal Decomposition

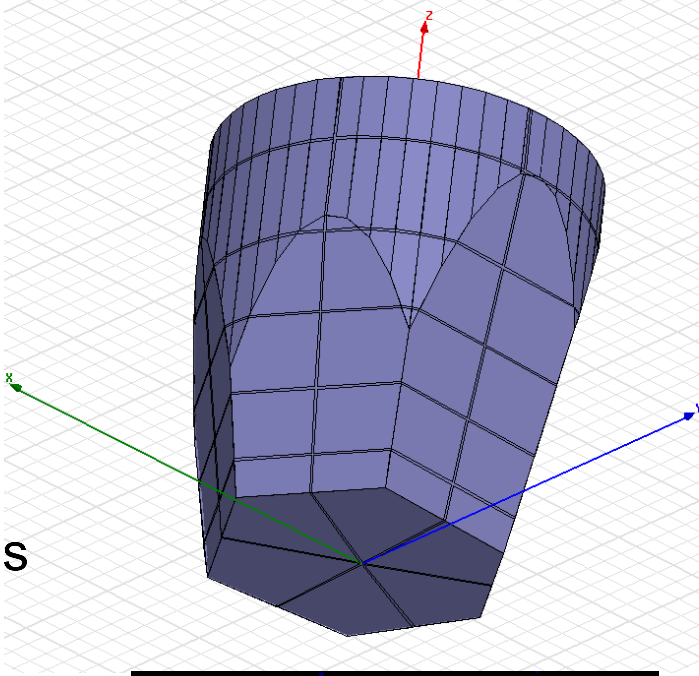
Position of interaction points determined by signal decomposition



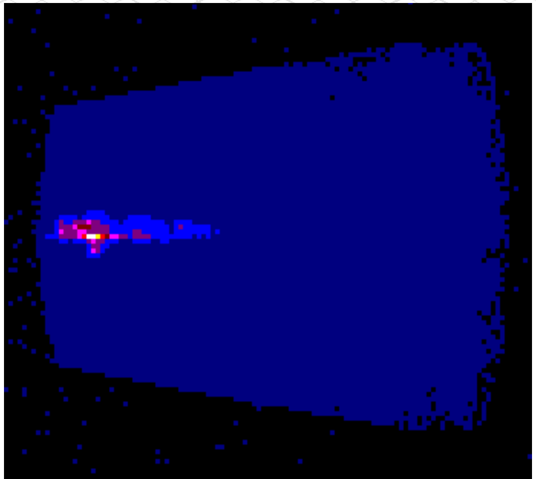


Signal Decomposition – at the heart of gamma tracking

ORNL lead the development of the GRETINA signal decomposition algorithm / codes.



- Determine, in near-real-time, the *number, positions,* and *energies* of gamma interactions in the crystal
- These interactions are required as input for gamma tracking
- Uses data from both hit segments and image charges from neighbors
- Uses a set of pre-calculated basis pulse shapes
- Must allow for one, two, or three interactions per hit segment; but number of interactions in a given hit segment is not easy to determine
- *Position resolution* is crucial; dominates energy resolution, efficiency, and peak-to-total ratio
- *Speed* is also crucial; determines triggered count-rate capability of array



Signal Decomposition Algorithm

Hybrid Algorithm

- *Adaptive Grid Search with Linear Least-Squares (for energies)*
- *Non-linear Least-Squares (a.k.a. SQP)*

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

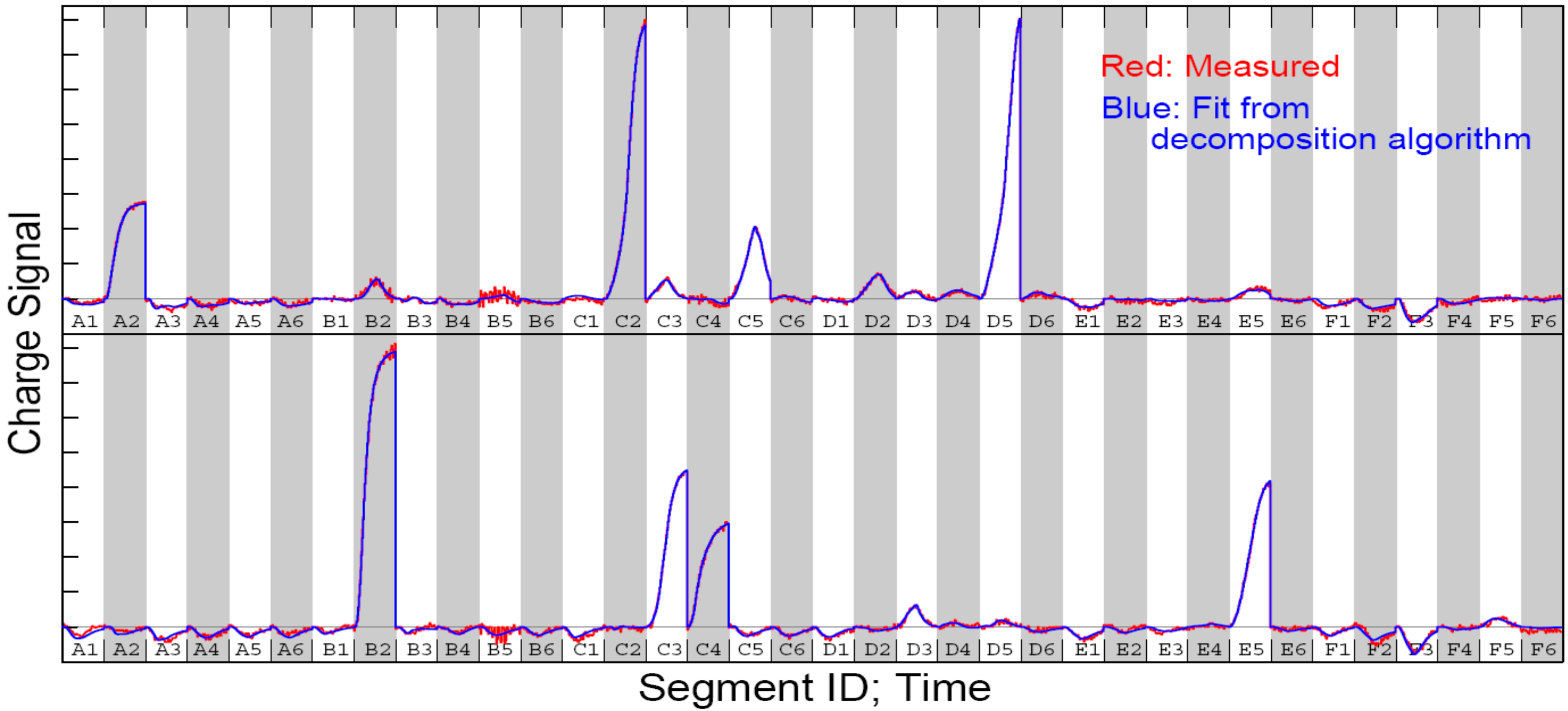
✓ A challenging but tractable problem

- Precision is limited by fidelity of the signal basis used

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!

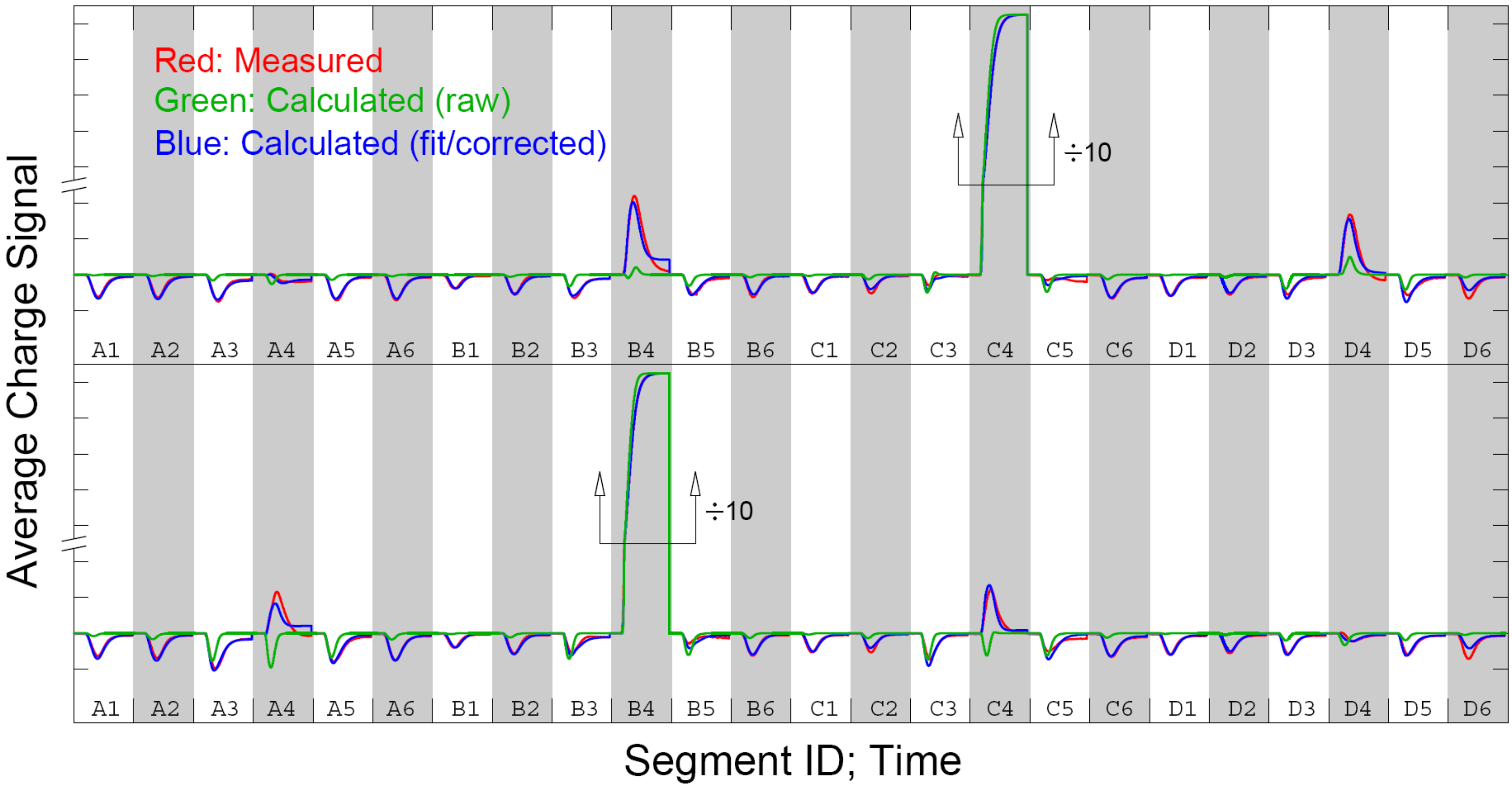


Decomposition Basis (Signal Library)

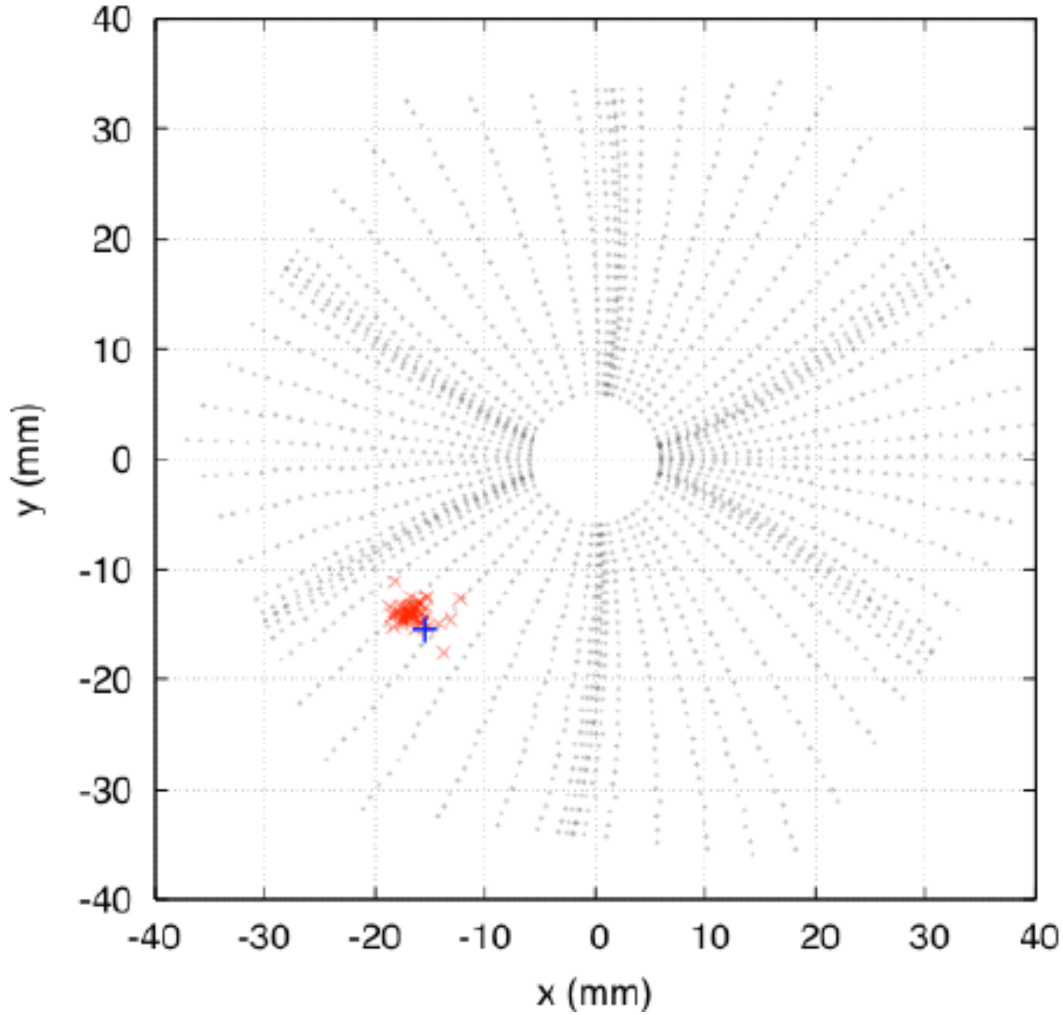
- Pre-*calculated* on an irregular non-Cartesian grid
- Excellent signal fidelity is required, so must carefully include effects of
  - Integral cross-talk
  - Differential cross-talk
  - Preamplifier rise-time / impulse response
- Poor fidelity results in
  - Too many fitted interactions
  - Incorrect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

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”



Scanning-table coincidence-data test



Evaluated positions (red)
Collimator position (blue)

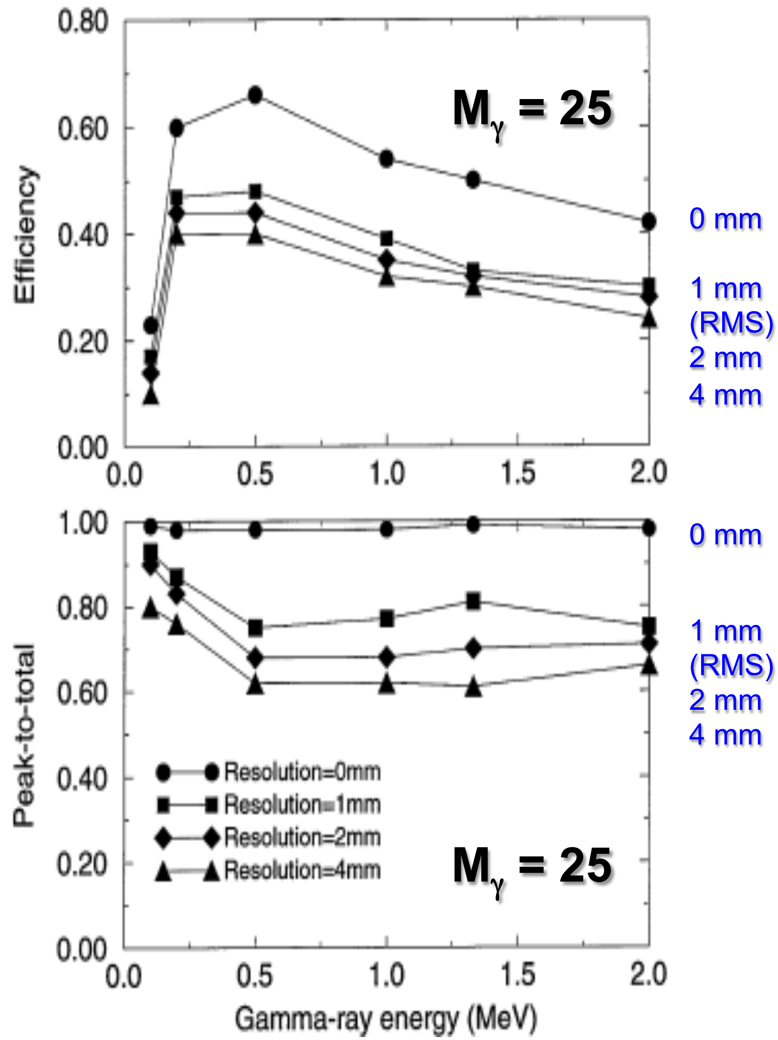
66 events

Position resolution:
σ_x = 1.2 mm; σ_y = 0.9 mm

Could We Improve the GRETA Resolution?

- After signal decomposition, the position resolution from GRETINA detectors is 1-2 mm RMS (2.5 – 5 mm FWHM)
- Better position resolution would improve efficiency and P/T ratio
- Double-sided strip Ge detectors can provide resolution as good as ~ 0.1 mm, but are limited to at most 20mm thickness

Can we build large detectors with better position resolution?



MAJORANA $0\nu2\beta$ Decay Search

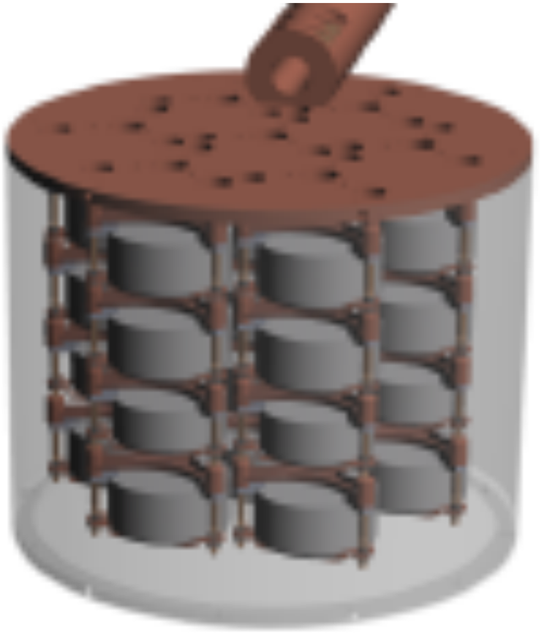
Science goals:

- Determine the nature of the neutrino : Majorana or Dirac particle?
- Test the fundamental symmetry of lepton number conservation
- Probe the absolute neutrino mass scale

Some of the many challenges:

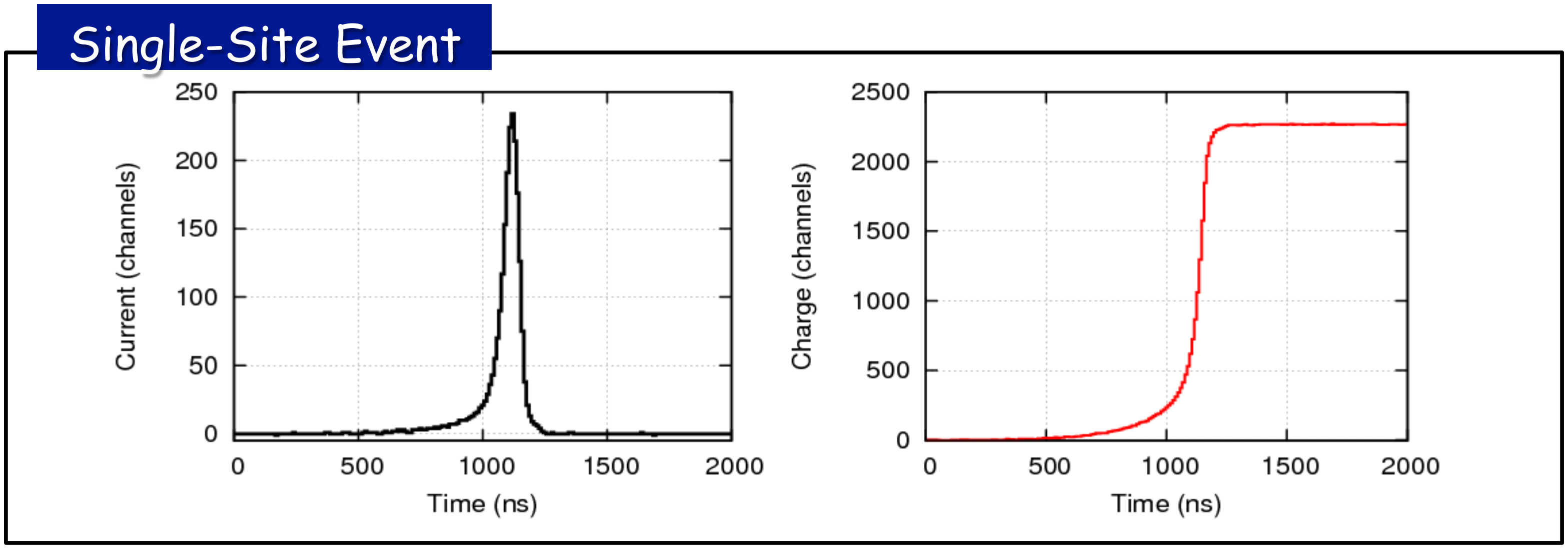
- Enriched ^{76}Ge detectors; requires large quantity of enriched material
- Background goal of 1 count/ton/year in a 4-keV window at 2.04 MeV (!)

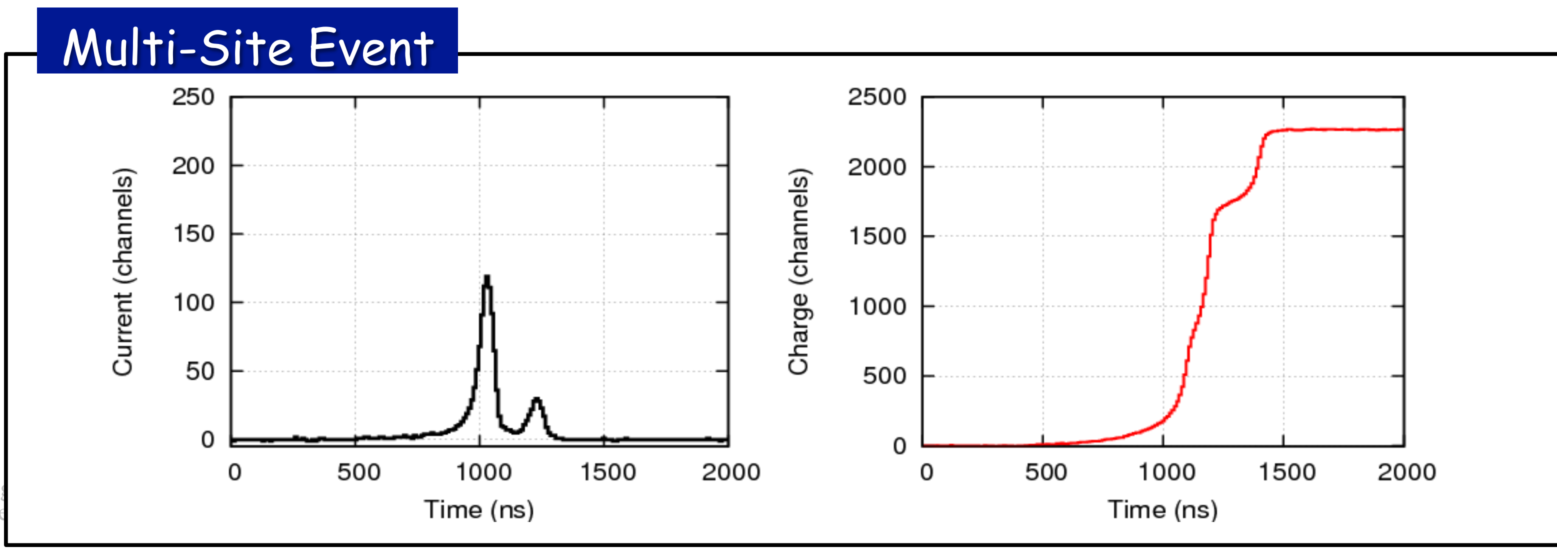
  $\Rightarrow$ Extreme radio-purity requirements for all materials



Pulse-Shape Response

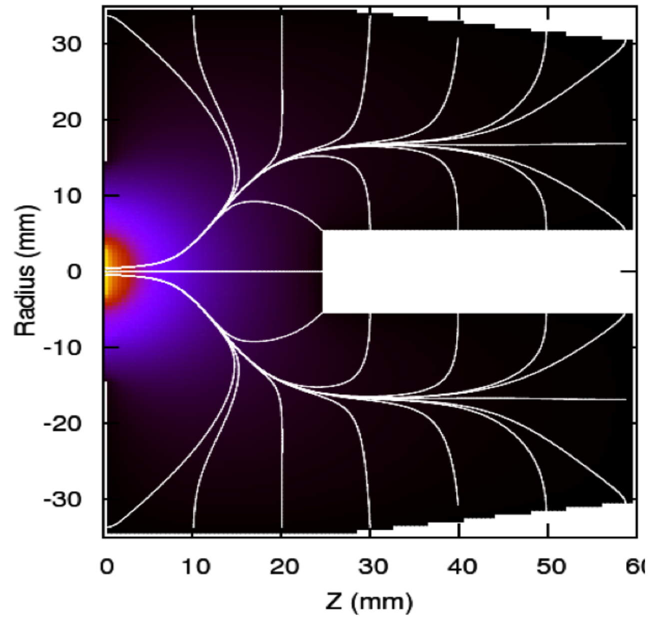
PPC detectors are ideal for discrimination between single-site and multi-site events (or determining the number of interactions)





A Novel HPGe Gamma-ray Detector Design

- "Inverted Coaxial Point-Contact" detector
- Can be bigger and much longer than a normal PC detector
- Drift of charges is radically different from a normal coaxial detector; "Ge Drift Detector"
- Long drift times, up to ~2 μs
- Drift time helps determine position of interactions



- Segmentation provides precise position information on number and locations of interactions
- Theoretical resolution is a factor of 3 - 4 better than GRETINA

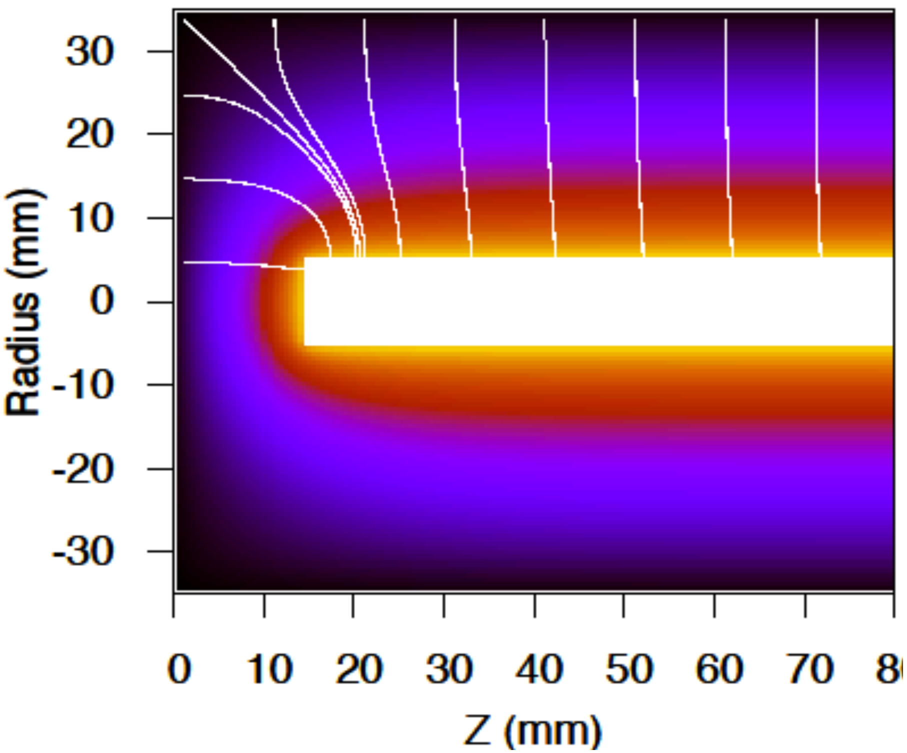
R.J. Cooper et al., NIM A 665 (2012) 25

- Can use exactly the same crystal shape, and make a drop-in replacement for GRETINA detectors. Expect much improved gamma-ray tracking performance.

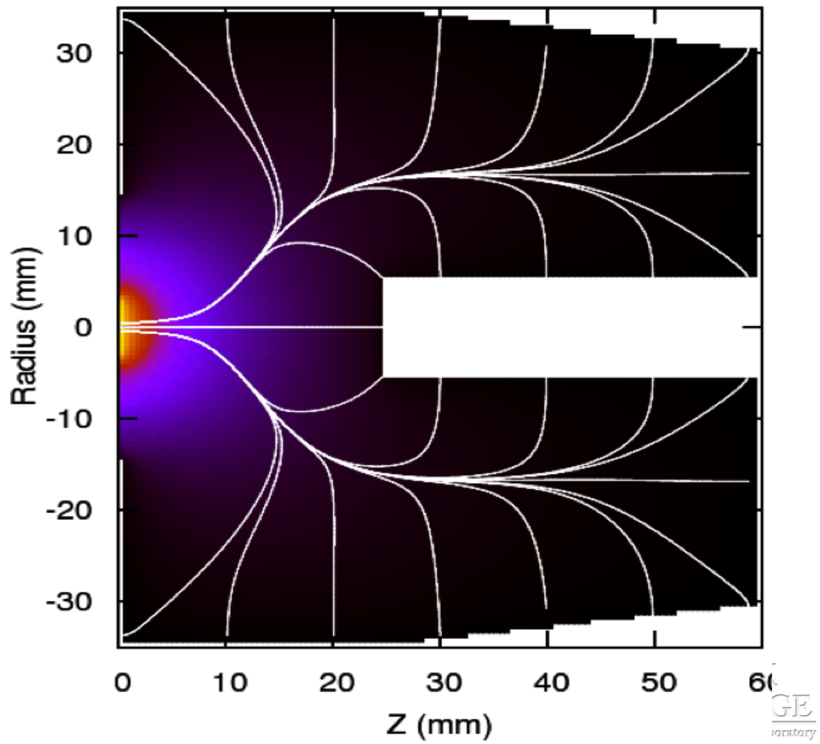
"Inverted Coaxial" Detector

- Drift of charges is radically different from a normal coaxial detector
- Long drift times, up to ~ 2 μs
- Signal time determines drift distance and therefore position
- Very low noise

Closed-end Coaxial

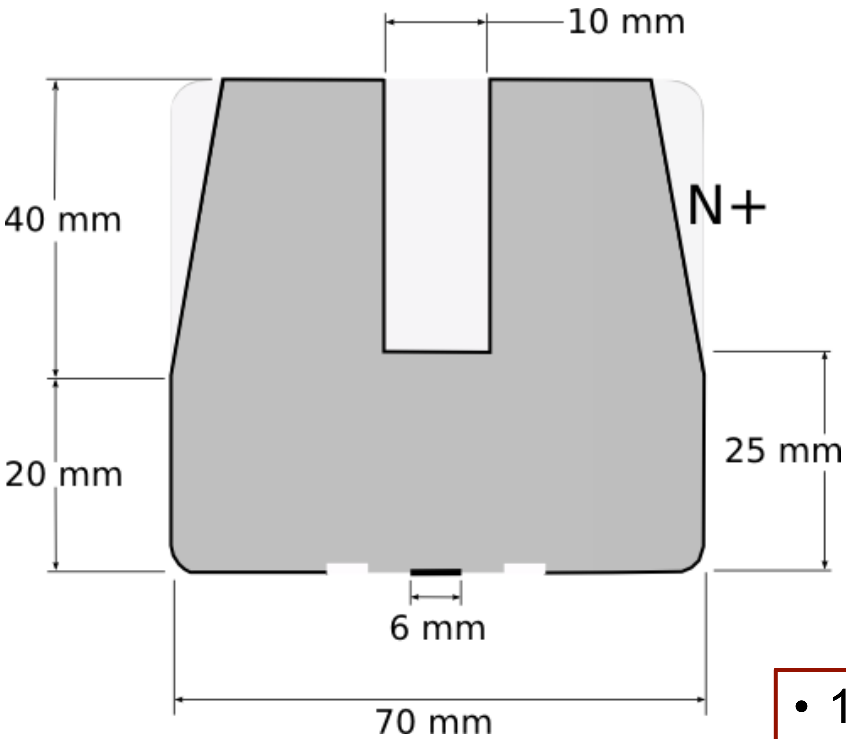


Inverted Coaxial



Unsegmented Prototype

- 70 mm x 60 mm tapered cylindrical detector
- Purchased with ARRA funds from DOE ONP
- Produced by Canberra Meriden (CT, USA)

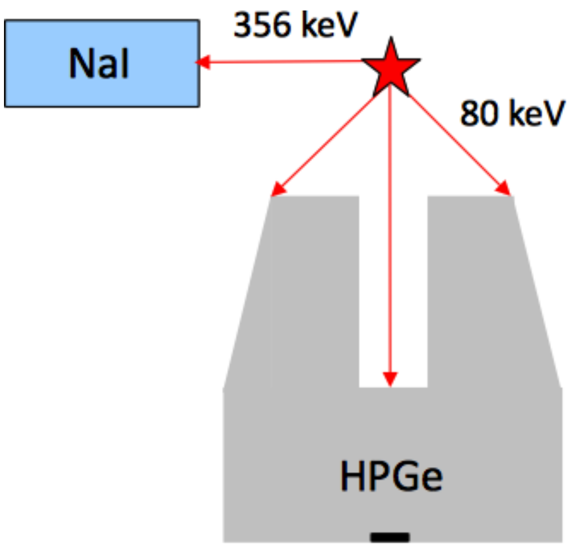


Prototype has excellent resolution and efficiency

Depletion Voltage	(+) 2600 V
Operating Bias	(+) 3500 V
Leakage Current	<10.0 pA
Capacitance	~ 1 pF

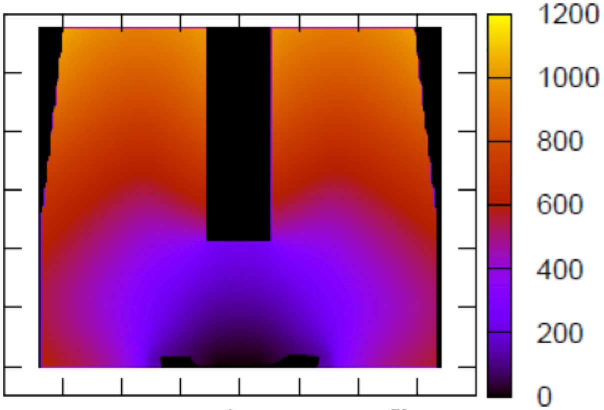
- 1.80 keV FWHM at 1332 keV (6μs shaping)
- 320 eV FWHM noise (6μs shaping)
- 44% relative efficiency

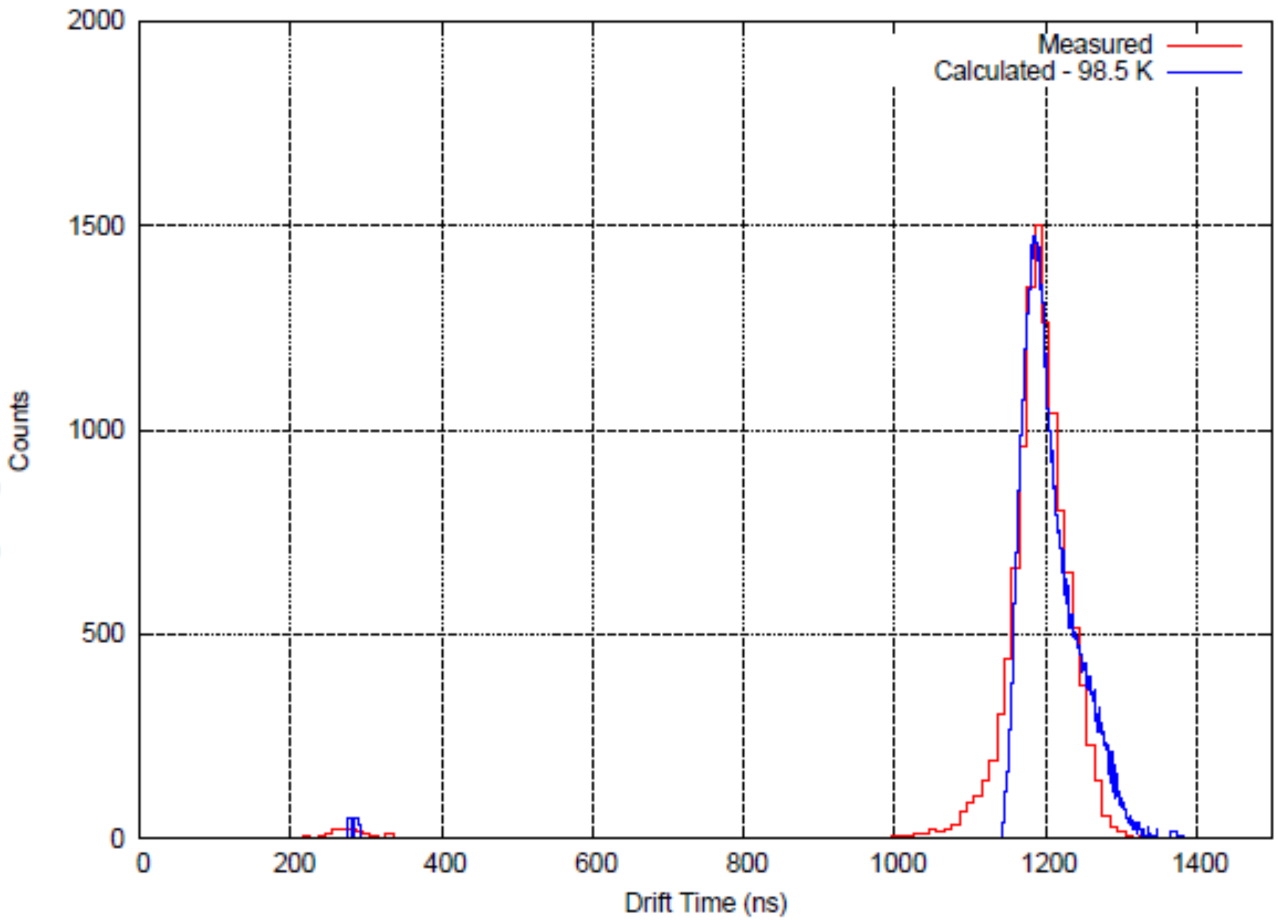
Measured Drift Times



Compare with calculated distribution of drift times

- Good agreement with measured data
- Remaining discrepancies are due to bulletization

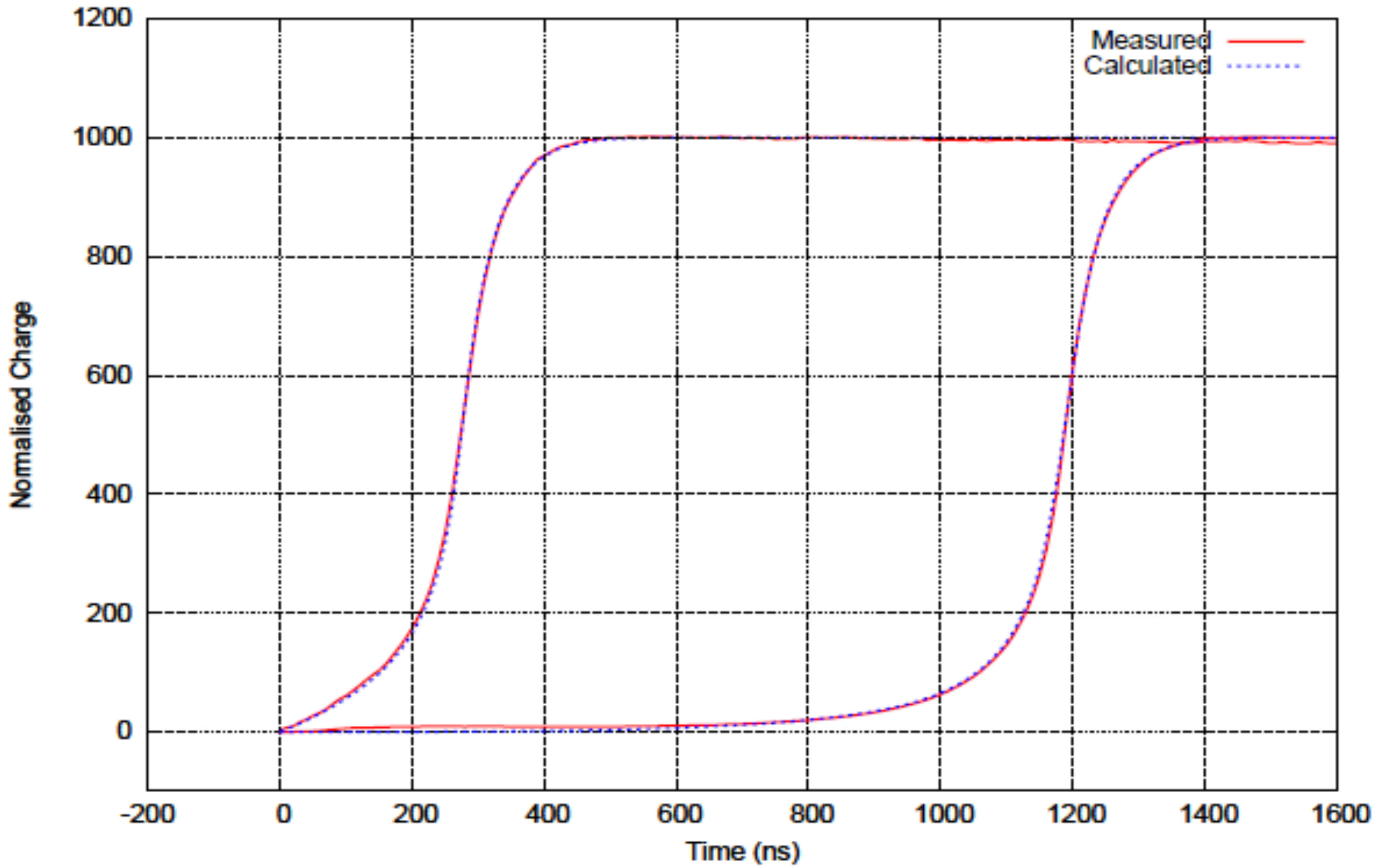




Calculated and Measured Signals

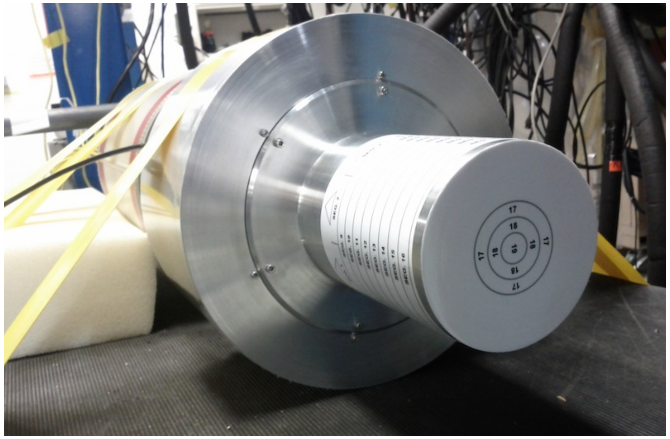
Excellent agreement with both *time* and *shape* of signals from different locations

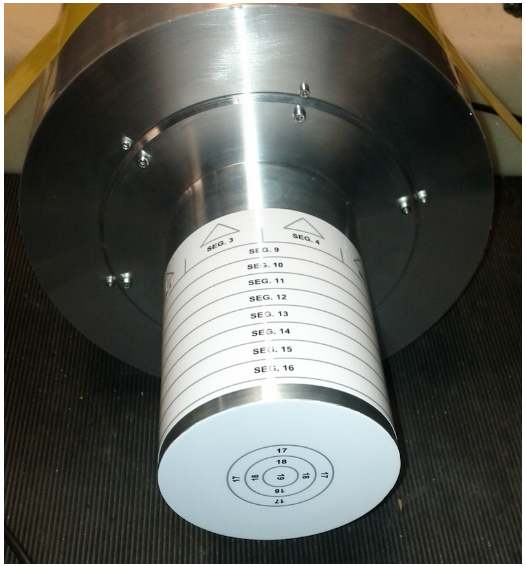
- Confident that we really understand these detectors and can model them properly



Segmented Prototype

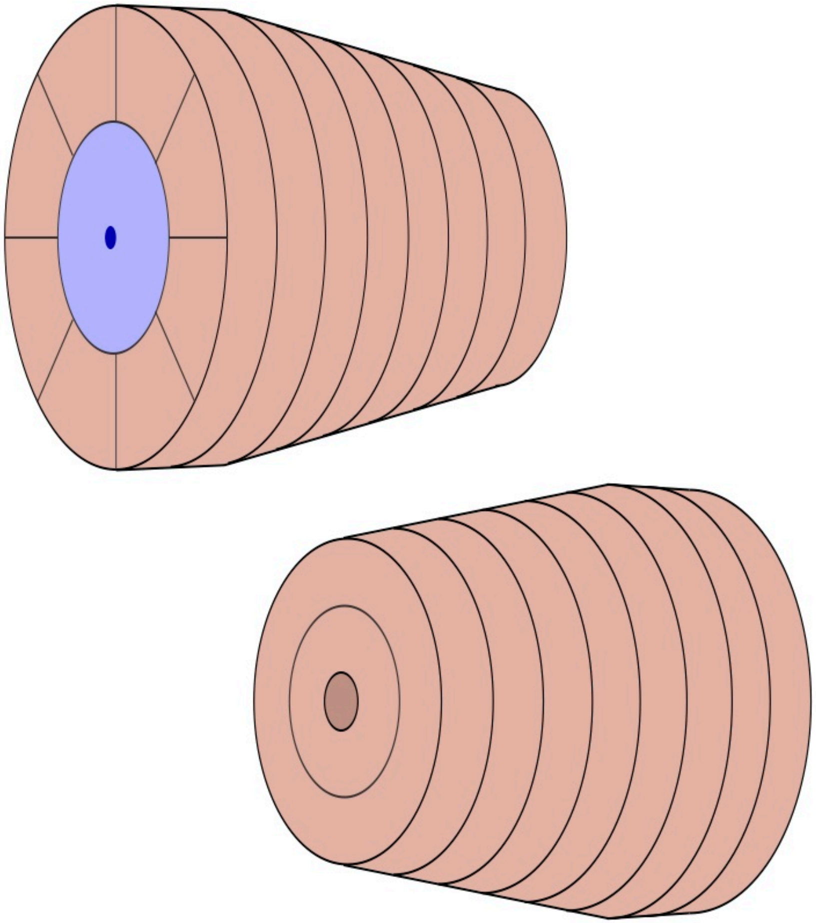
- A segmented prototype has recently been produced by Canberra France
- 7 cm diameter, 8 cm long, 10-degree taper over 6 cm of length
- N-type crystal (chosen by manufacturer for segmentation reasons)
- Mounted in a scanning table, currently being characterized
- Preliminary results are very encouraging; measured signals are almost exactly as simulated
- Will develop signal decomposition code, and measure position resolution

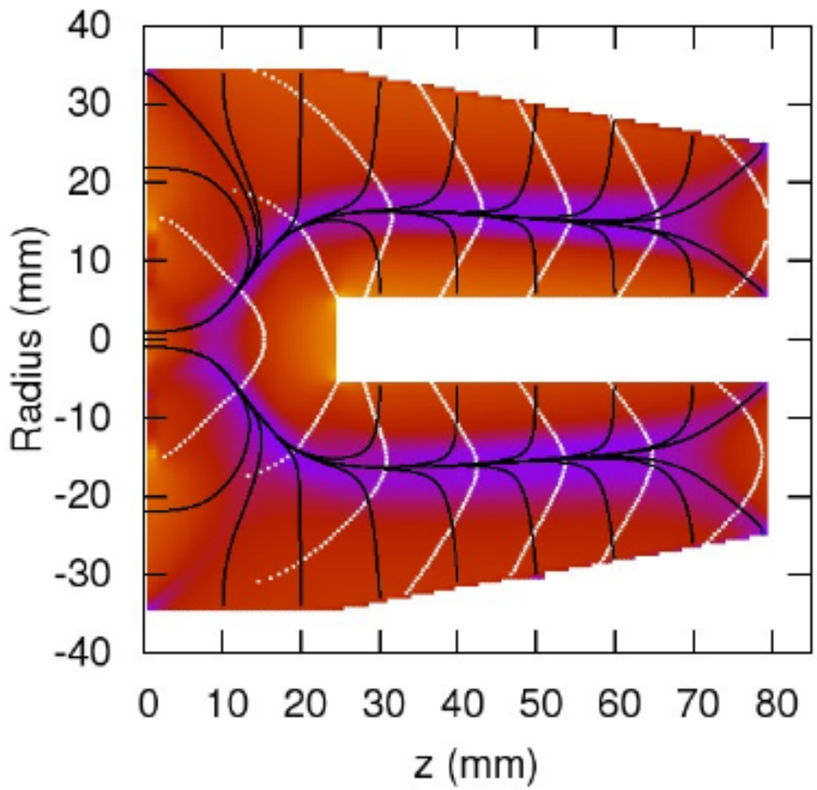




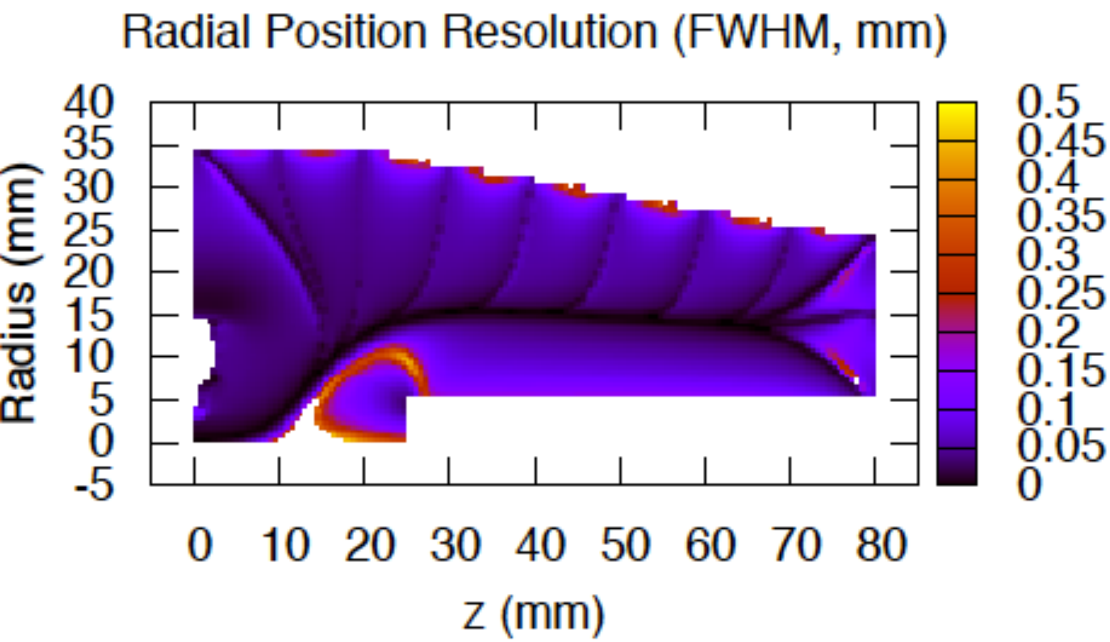
Segmentation Design

- Total of 19 segments, 20 signals
- Longitudinal ring-style segments and pie-slice azimuthal segments separate the longitudinal and azimuthal directions
  – Similar to X and Y in a DSSD

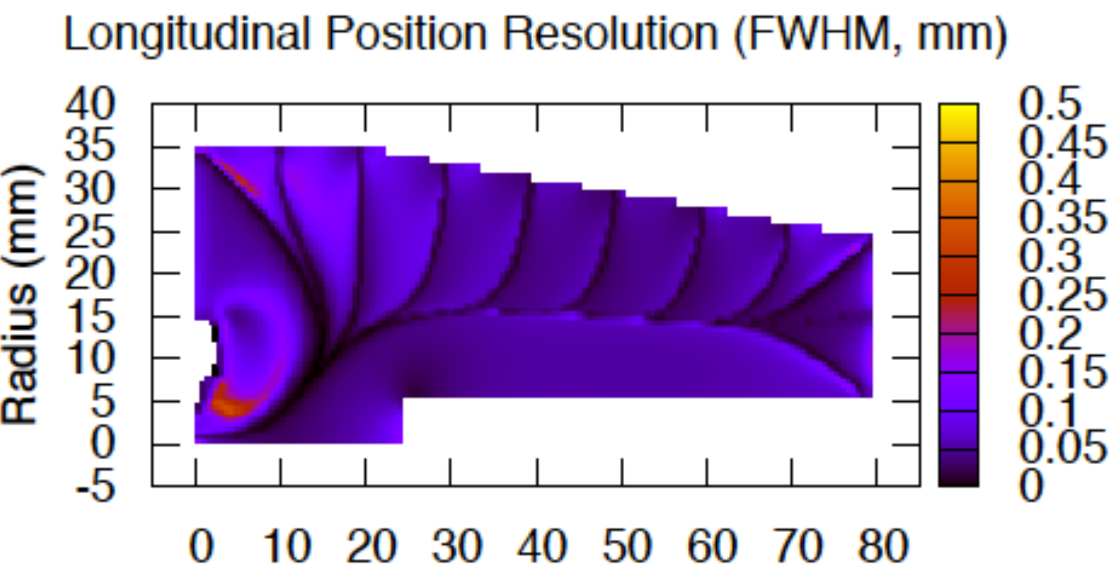


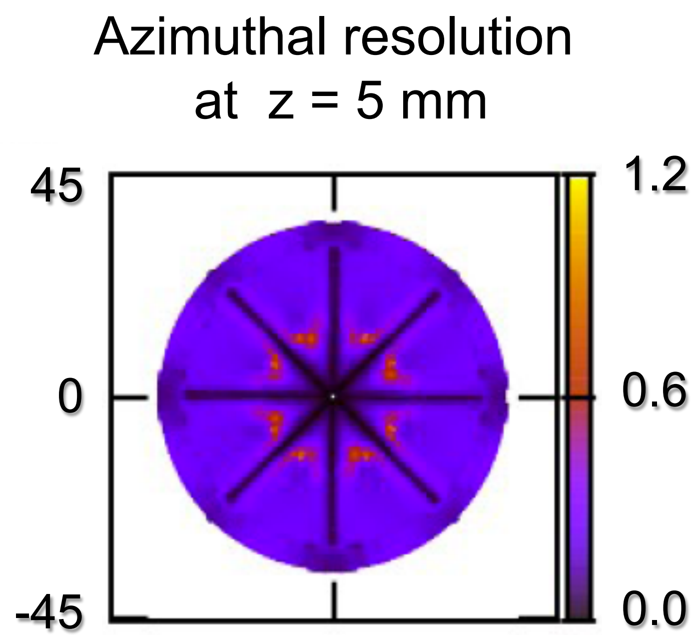


Calculate Excellent Position Sensitivity



Best-case theoretical FWHM
for E ~ 300 keV,
preamp rise time ~ 70 ns
Point charges, no diffusion



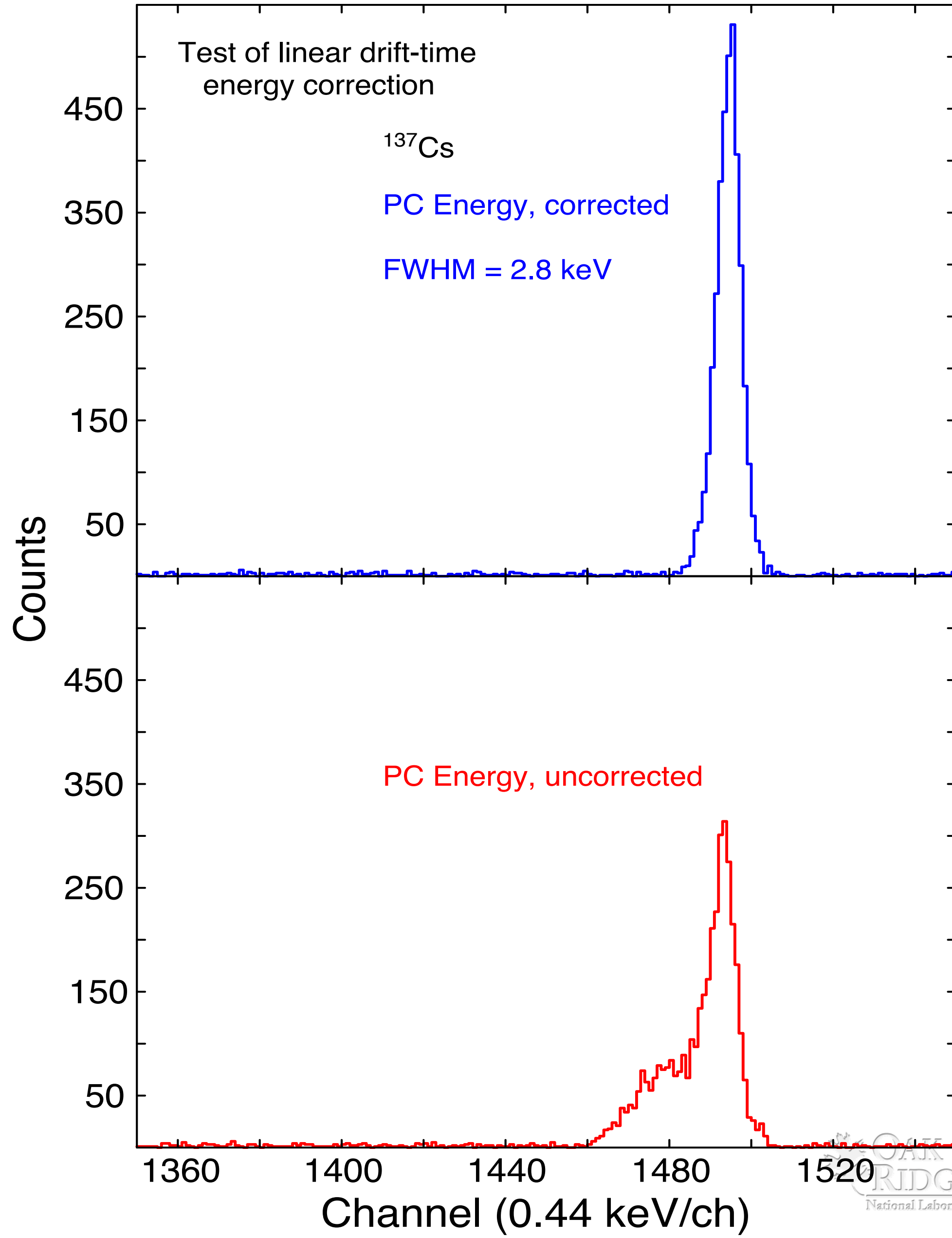


Segmented Prototype: Signals

- Twenty signals (PC plus 19 segments); 4μs each

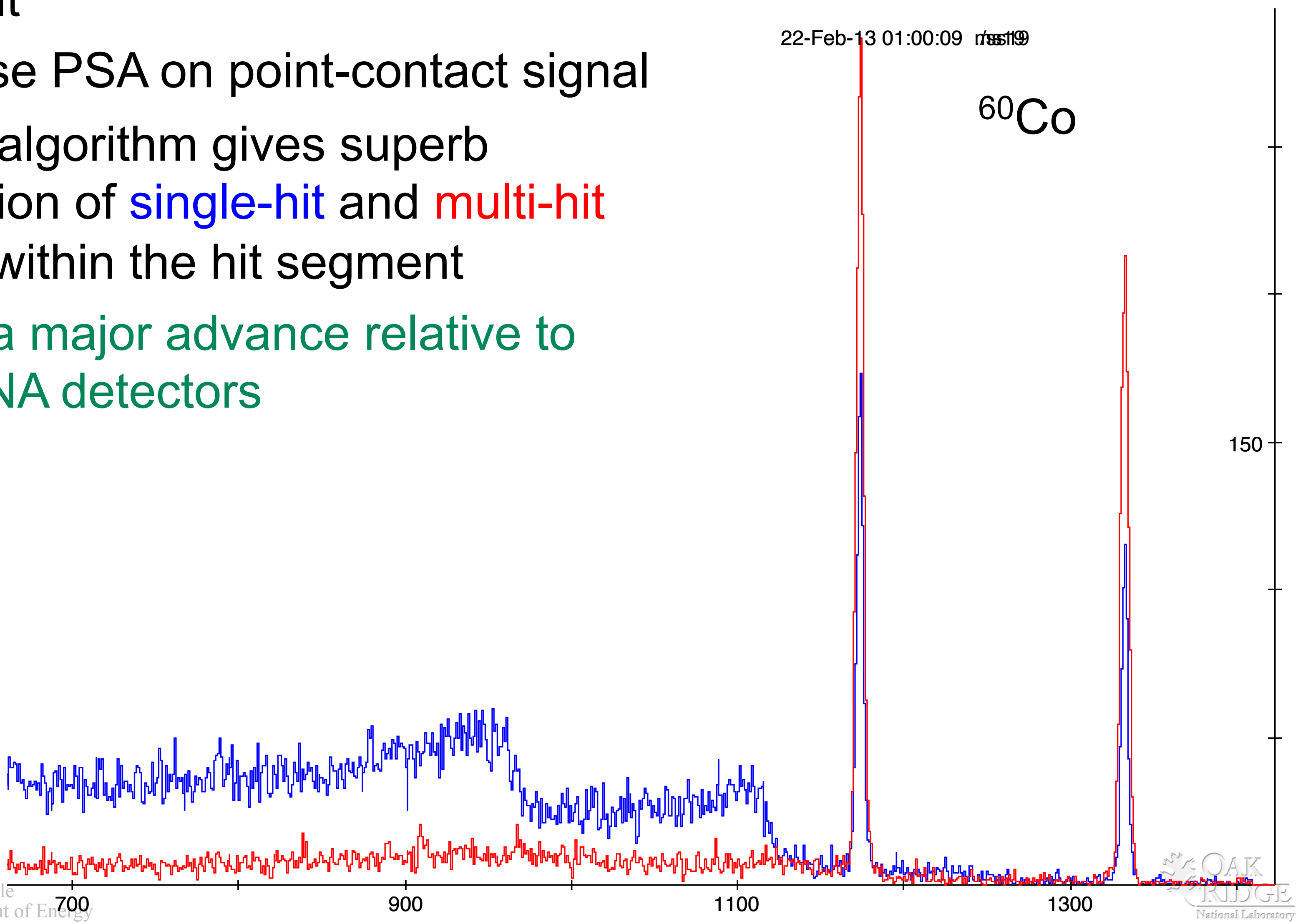
Charge-Trapping Correction

- Detector is n-type Ge, with long drift times
- Trapping of electrons, which are collected at the PC
- Long drift time results in significant trapping; ~ 15 keV at 1.33 MeV
- But can do an excellent correction using a factor that is *linear in drift time*
- Time is measured using 20% of segment signal to 80% of point-contact signal



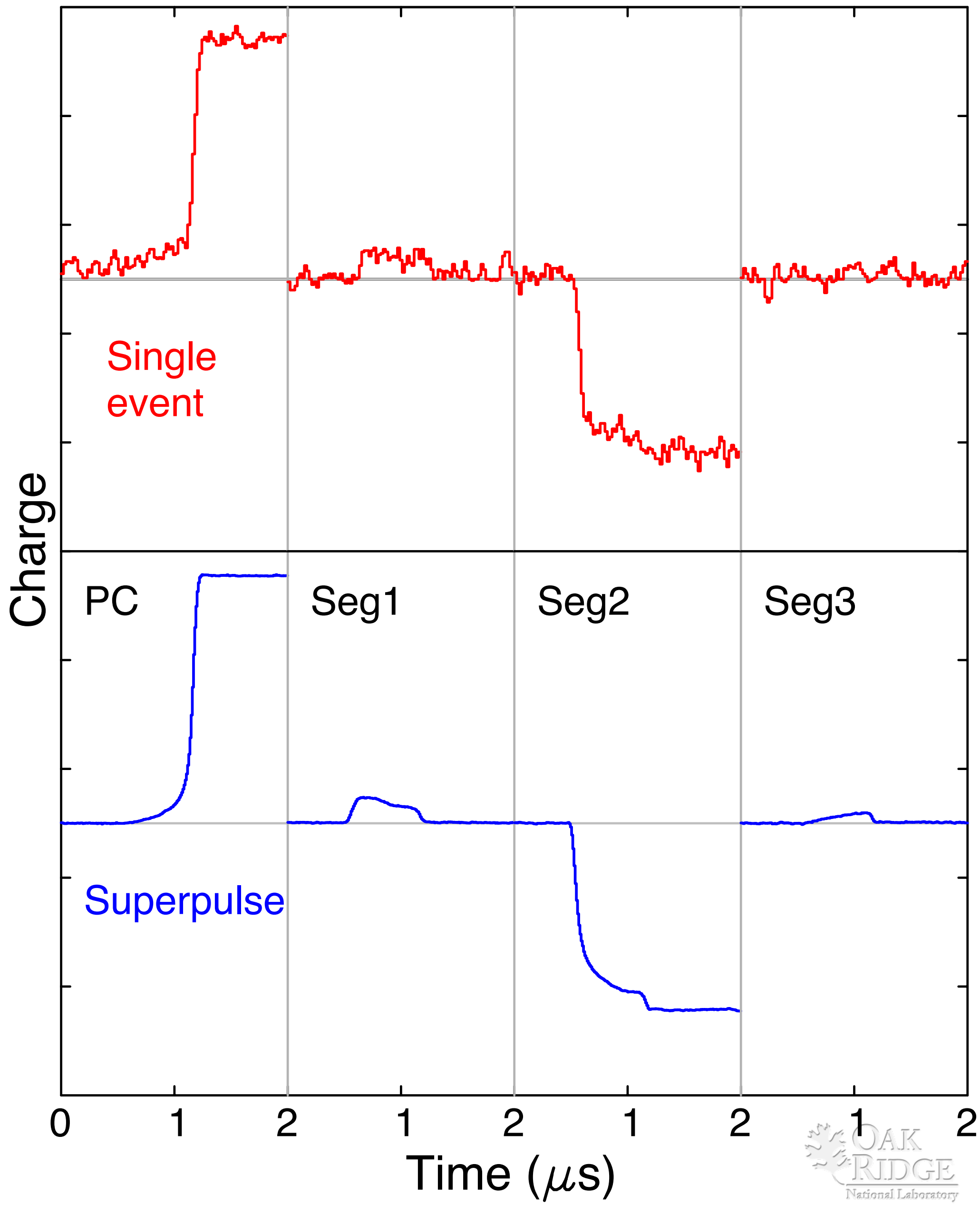
Point-Contact PSA

- Select events with only in a single hit segment
- Then use PSA on point-contact signal
- Simple algorithm gives superb separation of single-hit and multi-hit events within the hit segment
- This is a major advance relative to GRETINA detectors



Am "SuperPulses"

- Finely collimated Am source, directed at known location on the detector surface
- Select events with 60 keV in a single hit segment
- Use PSA (A/E) to select only single-site events
- Time-align each event using the PC signal (60% time)
- Take average signal to reduce noise to negligible level



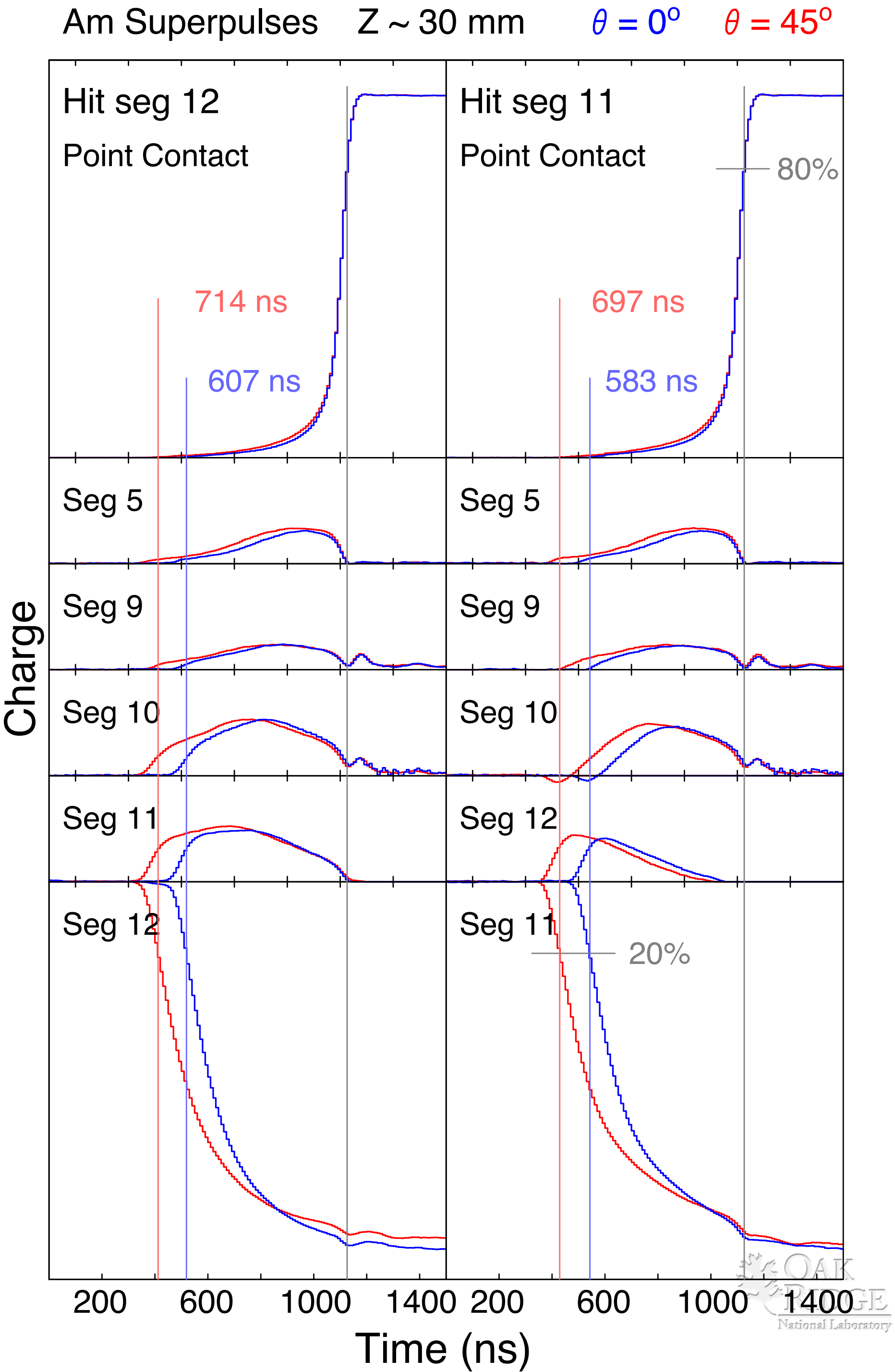
Extracting Drift Times

from SuperPulses

- Time from 20% of segment signal to 80% of point-contact signal
- Collimated spot overlaps the boundary between segments 11 and 12

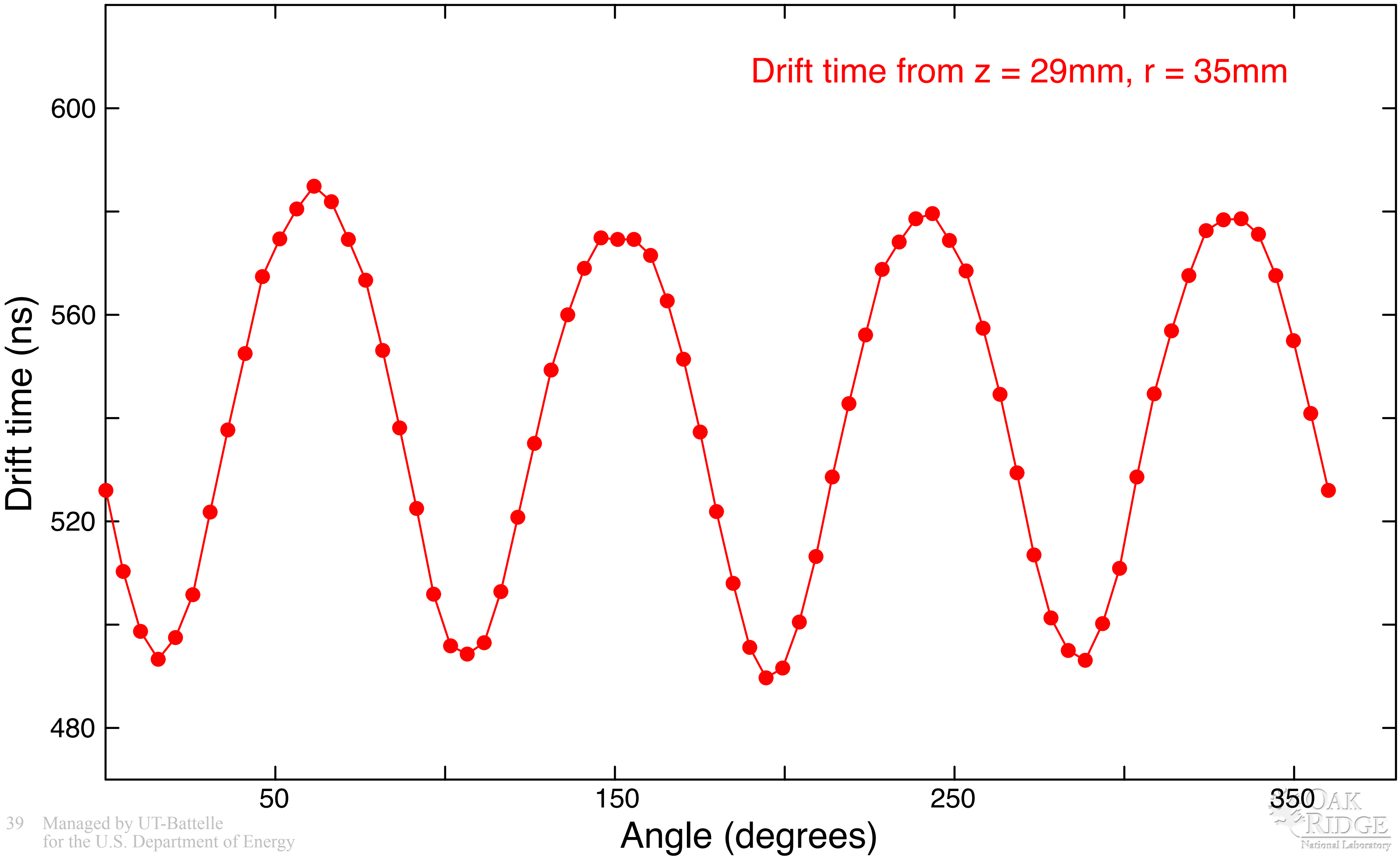
Blue: On crystal axis

Red: At 45 degrees to axis



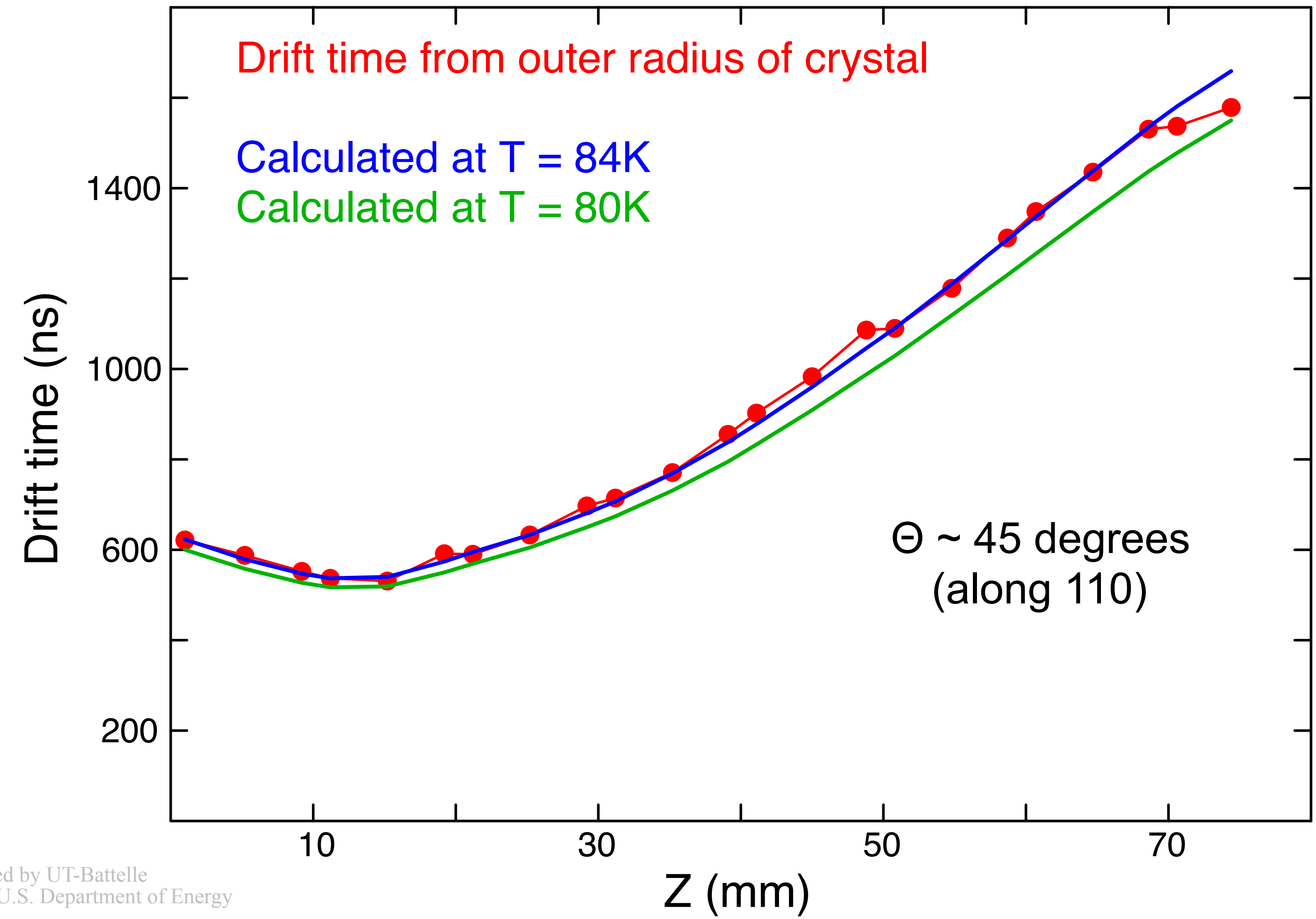
Azimuthal Scan

Data are reproducible to within 1 ns. Note variation in max, min.



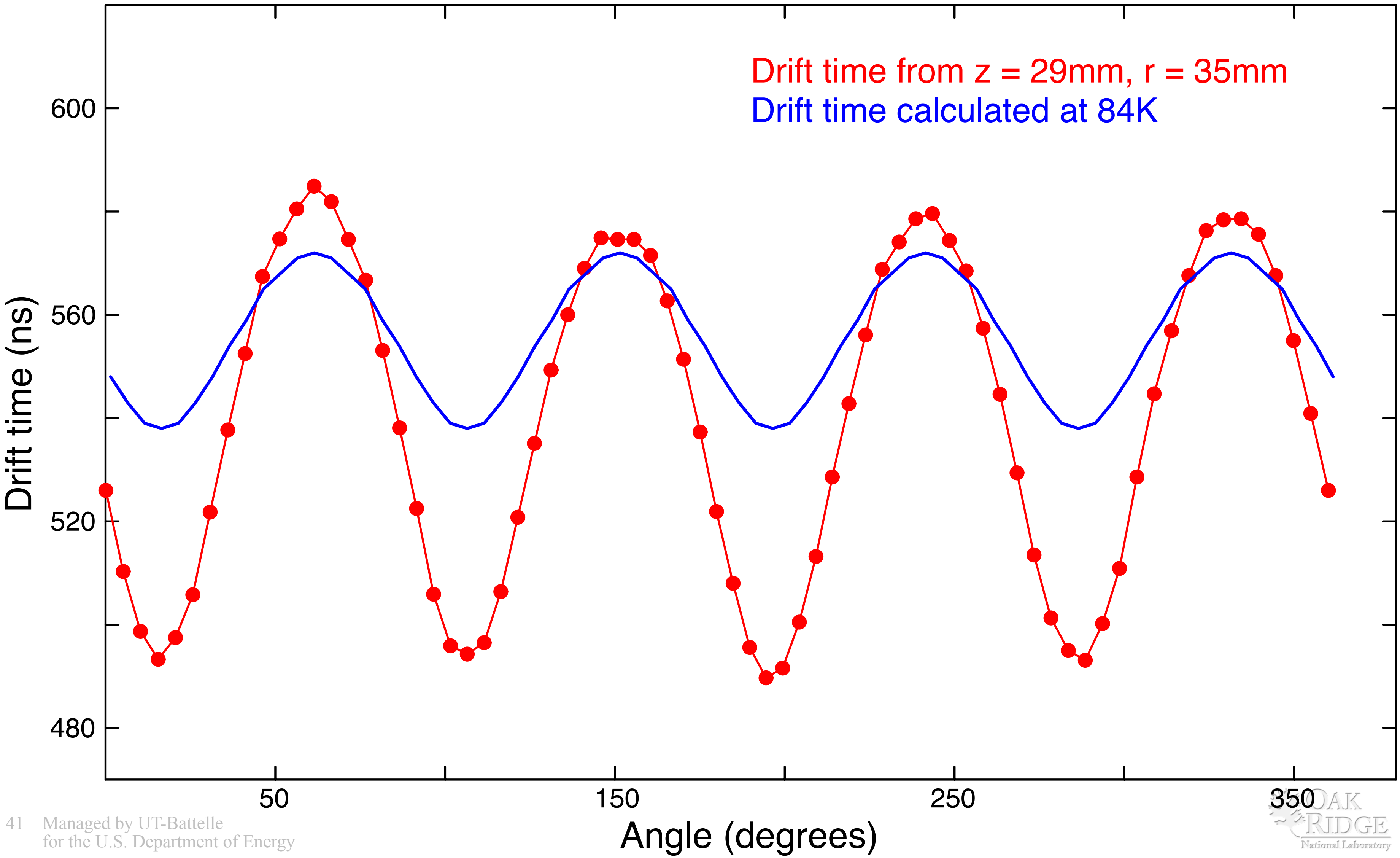
Longitudinal Scan

- Superpulse allows excellent determination of drift times
- Best-fit temperature depends on assumed impurity concentration gradient



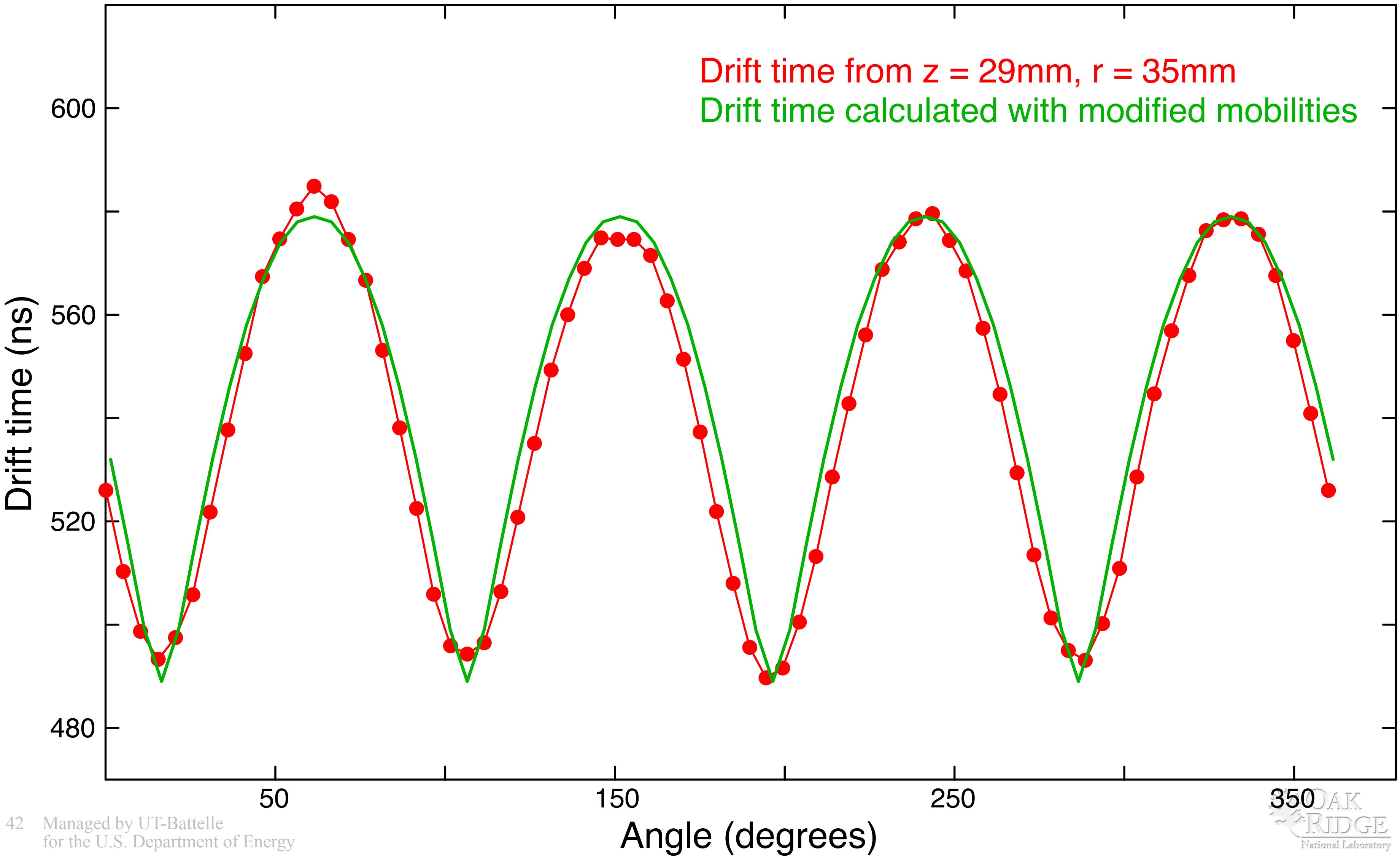
Azimuthal Scan – Measured and Calculated

Calculated drift times give far too small a variation with angle



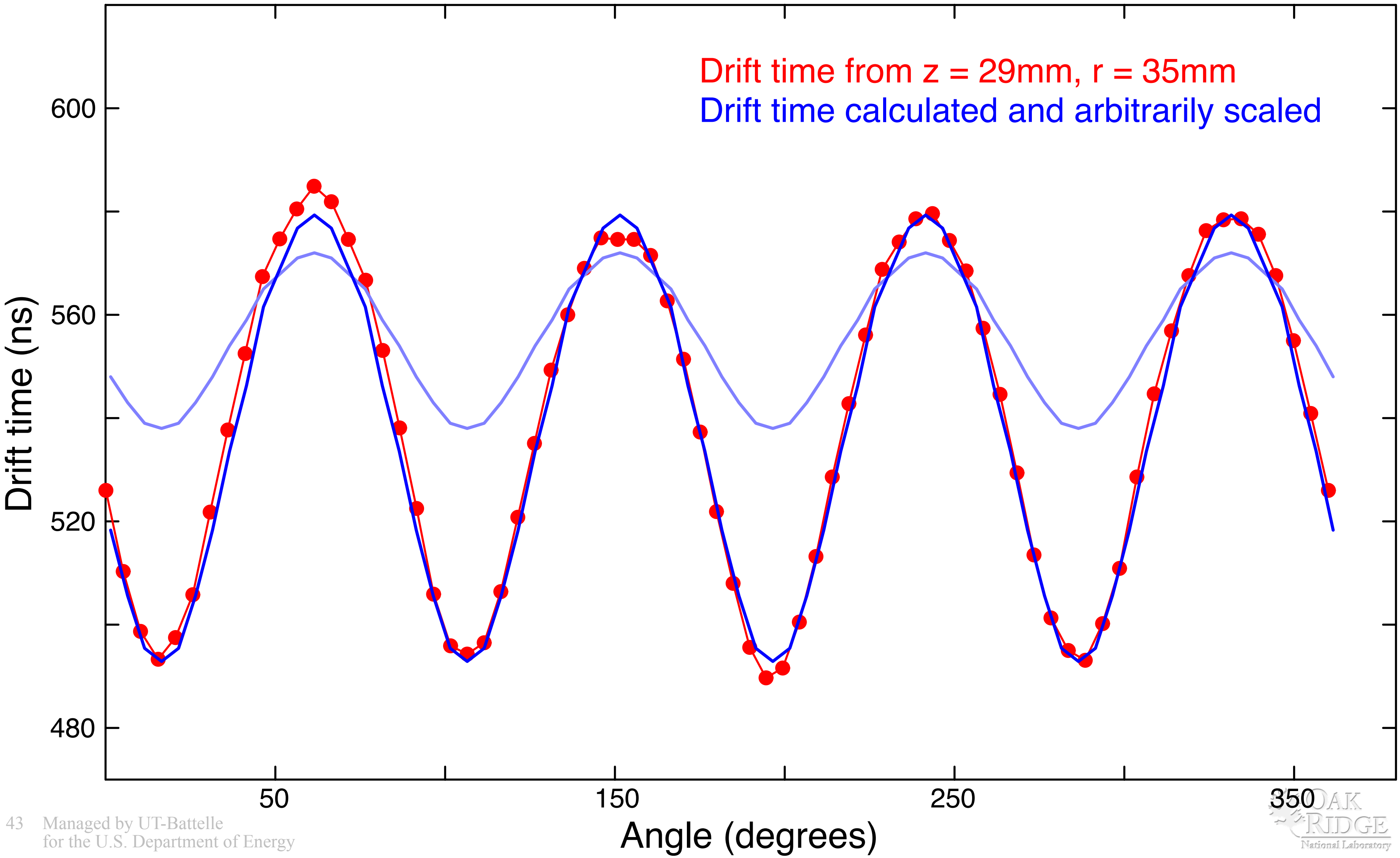
Azimuthal Scan with Modified Mobilities

Fudging the mobilities gives the wrong *shape* of the angular variation



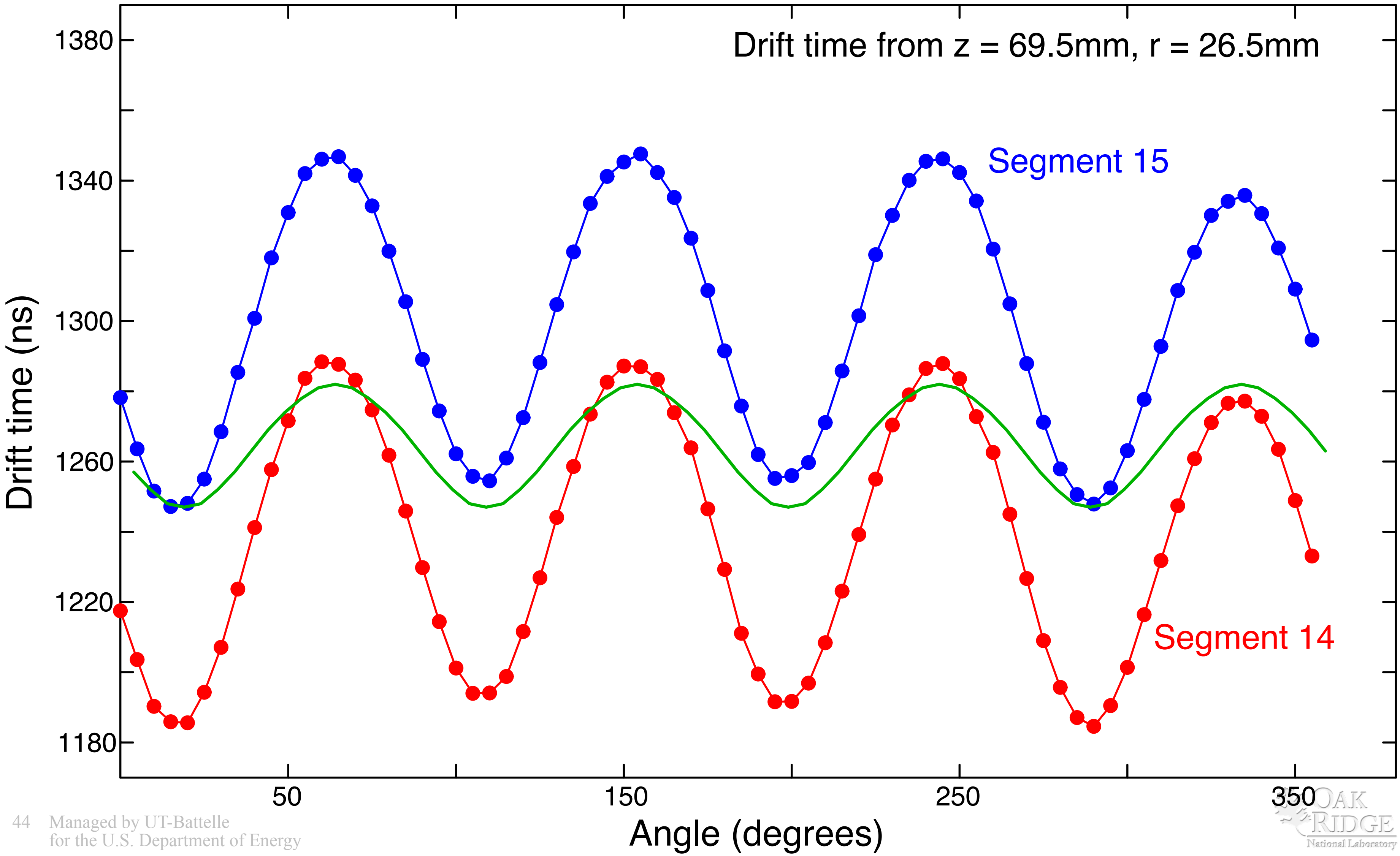
Azimuthal Scan – Measured and Calculated

The standard calculation gives the correct shape but wrong amplitude



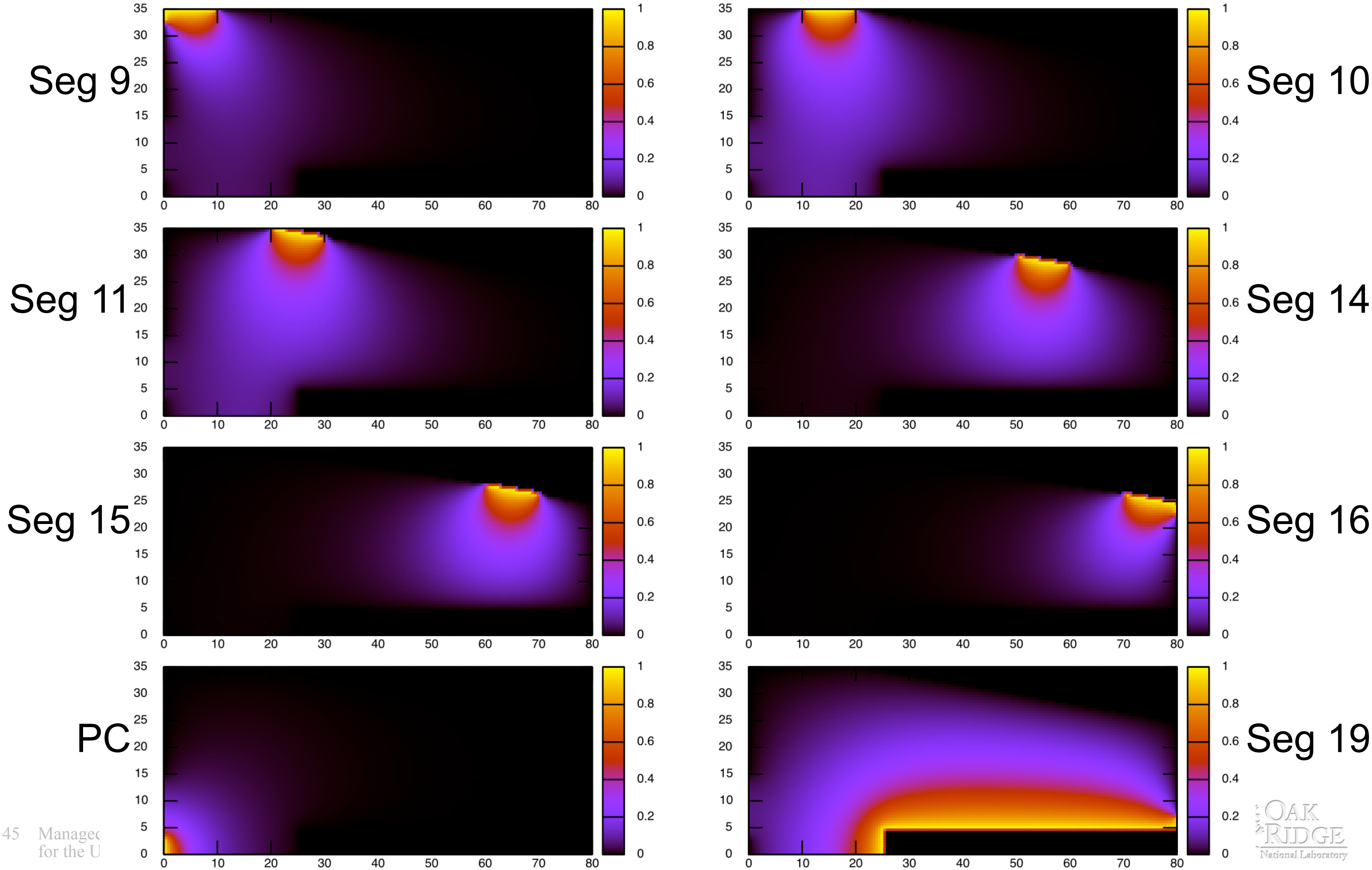
Azimuthal Scan at a different Z

Can easily determine crystal axes to better than one degree



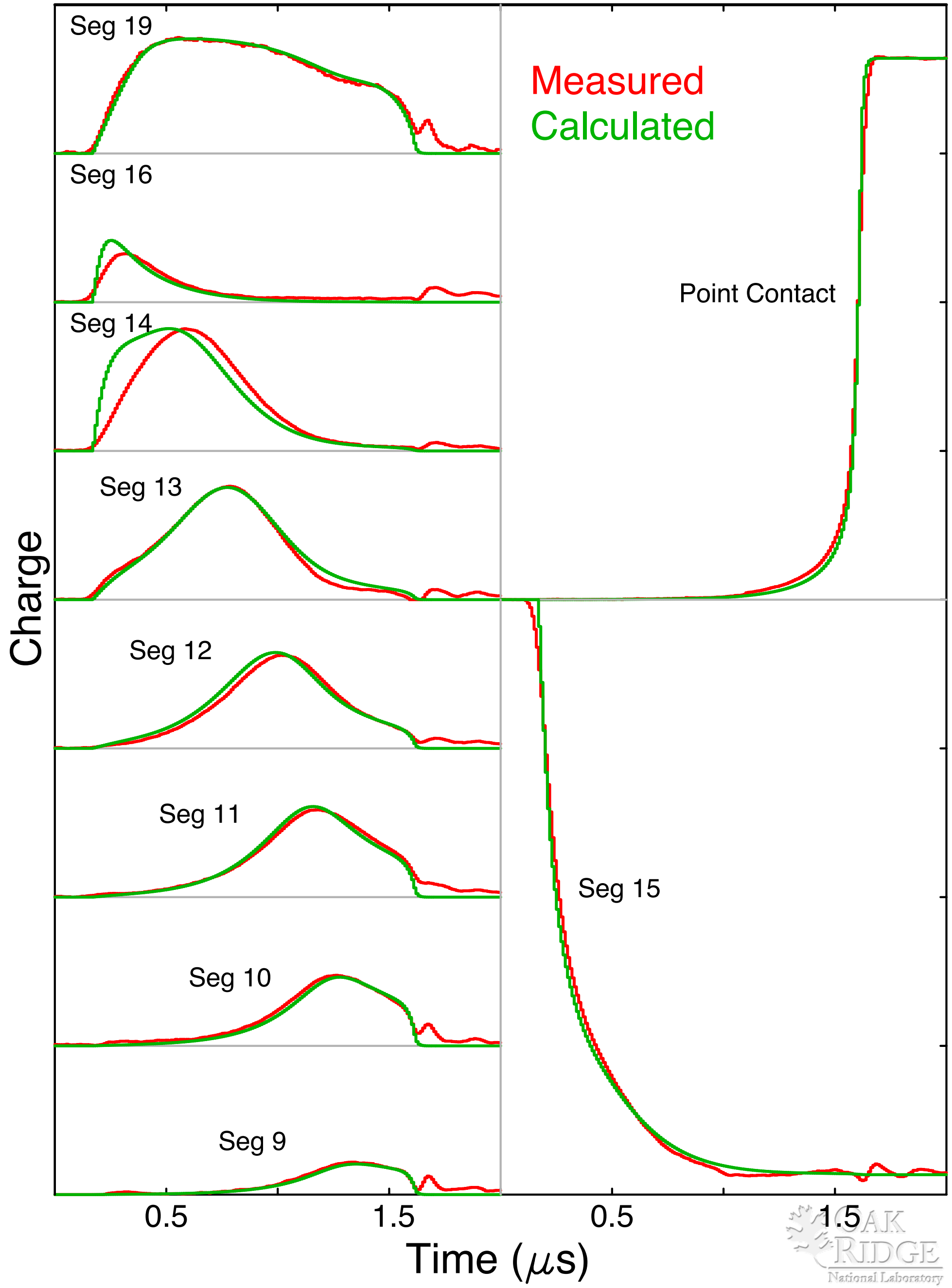
Segment Signal Calculations

Weighting Potentials



Calculated Signals

- Results of first test
- Simulation parameters not yet optimized
  - Impurity profile; temp.
  - Preamp response
- Next steps:
  - Add cross-talk
  - Add finite size of charge cloud
- Longer term:
  - Local variations in impurity concentration?
  - Signal decomposition
  - Measure position resolution



Pros and Cons for Gamma-ray Tracking

- Signals are more constrained; reliable, precise basis calculations
- Much better *number* and positions of interactions
- Will give better efficiency and P/T
- Excellent low-energy resolution
  - Low threshold; like having 4π LEPs detectors in front of the array
- Fewer segments; no problem using cold FETs
- May be able to use p-type detectors for in-beam (needs testing)
- Ideal device for RIB physics

- Costs uncertain, but likely be similar to GRETINA modules

- Long drift times probably means lower count-rate capability
- Fewer segments; may not be as good for summing seg energies?
  - Segment energies will also not be as low-noise as PC (capacitance)
  - But can optimize segment sizes for count rates

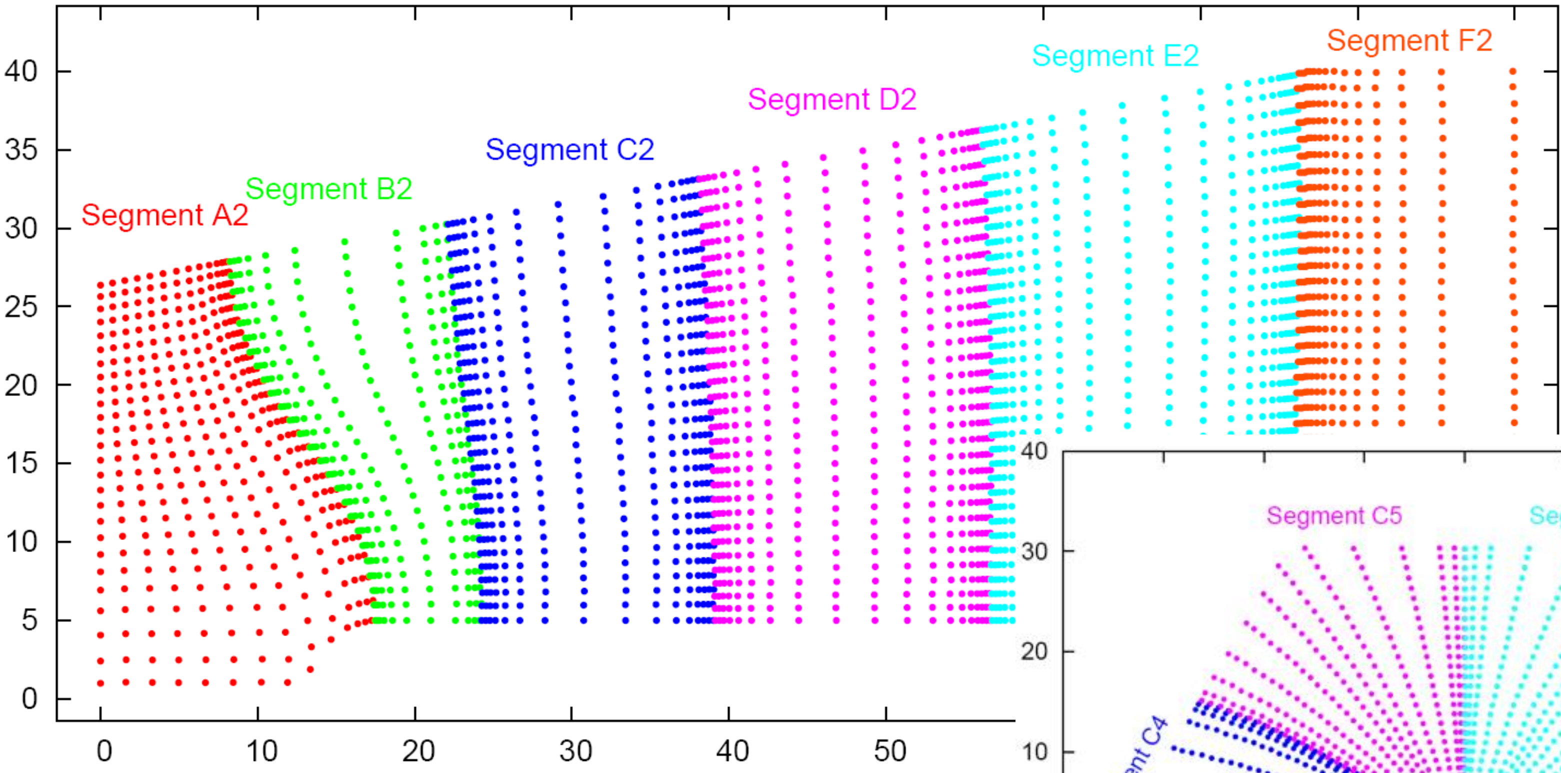
Summary

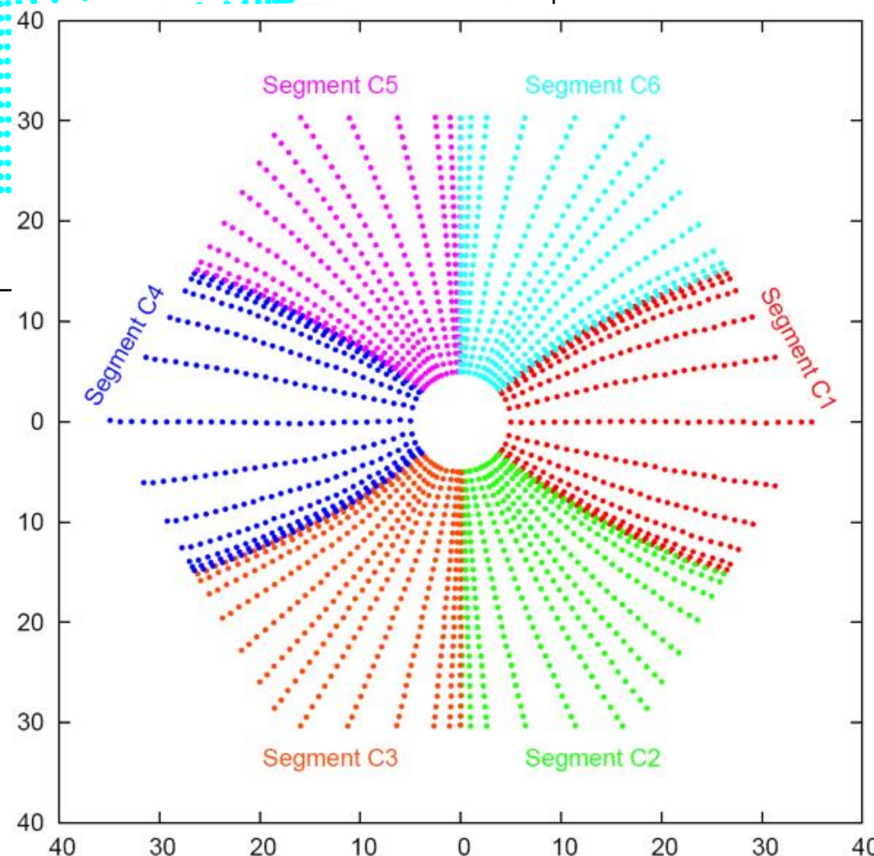
- Novel inverted-coax design; behaves like a Ge drift detector
- Results of initial characterization of segmented prototype are extremely promising
  - Signals are almost exactly as calculated
  - Excellent opportunity for detailed validation of signal simulations
  - Azimuthal variations appear to be much larger than simulations; this is not yet understood
  - Expected to have ~ 3-4 times better position resolution than GRETINA / AGATA (at least in r and z)
  - ~20 signals instead of 37
- Next steps will be to add cross-talk and individual preamp response to each segment channel

Summary Continued

- Schedule calls for signal decomposition algorithm and position sensitivity measurements to be developed by Oct 2013.
- Segmented version not required for low-background rare-event searches
  - Adds more background than it removes
- I wish to thank Canberra France for making such a beautiful detector

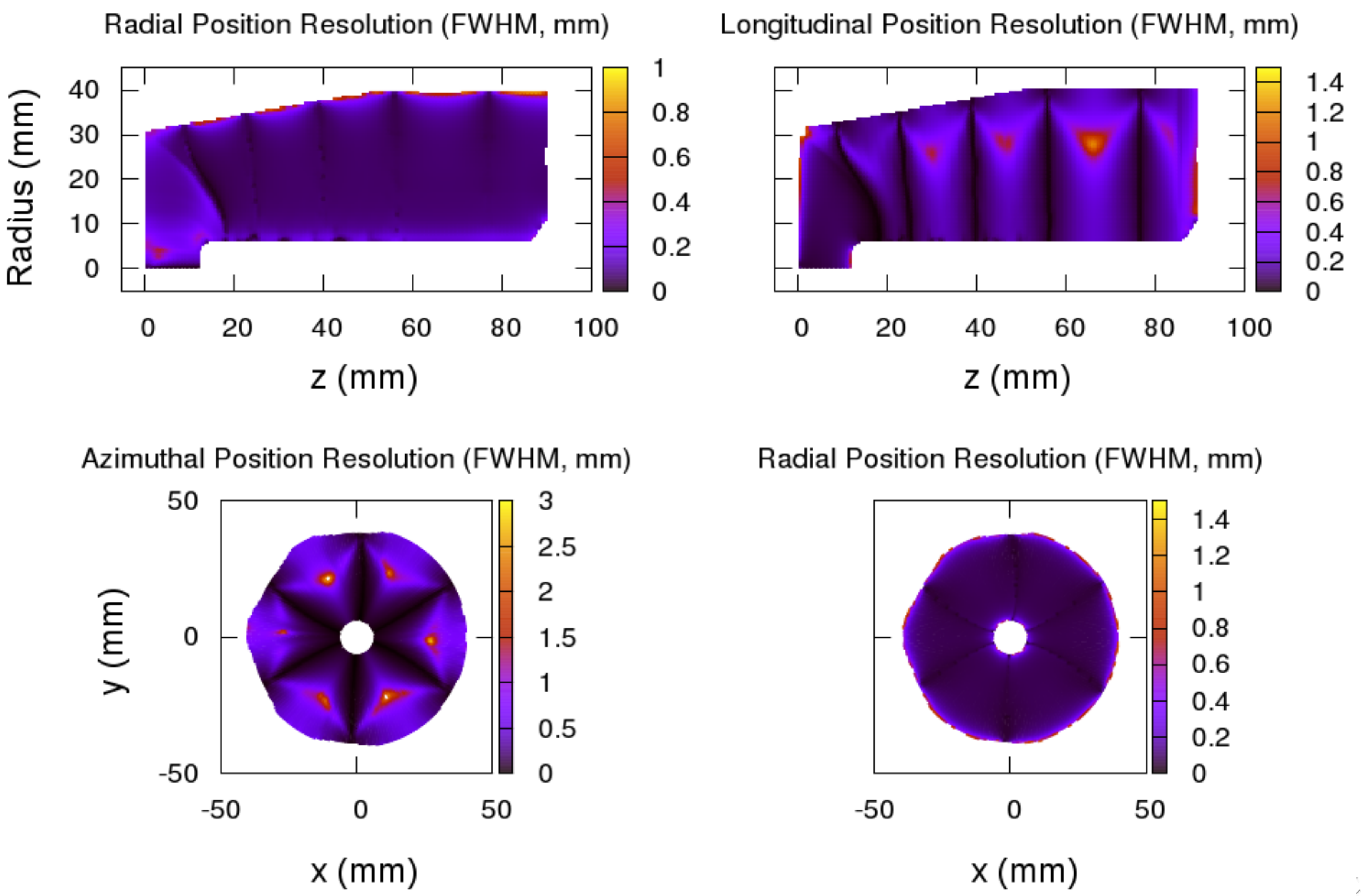
Optimized Quasi-Cylindrical Grid for basis signals





- 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.

Equivalent Calculations for GRETINA sensitivity



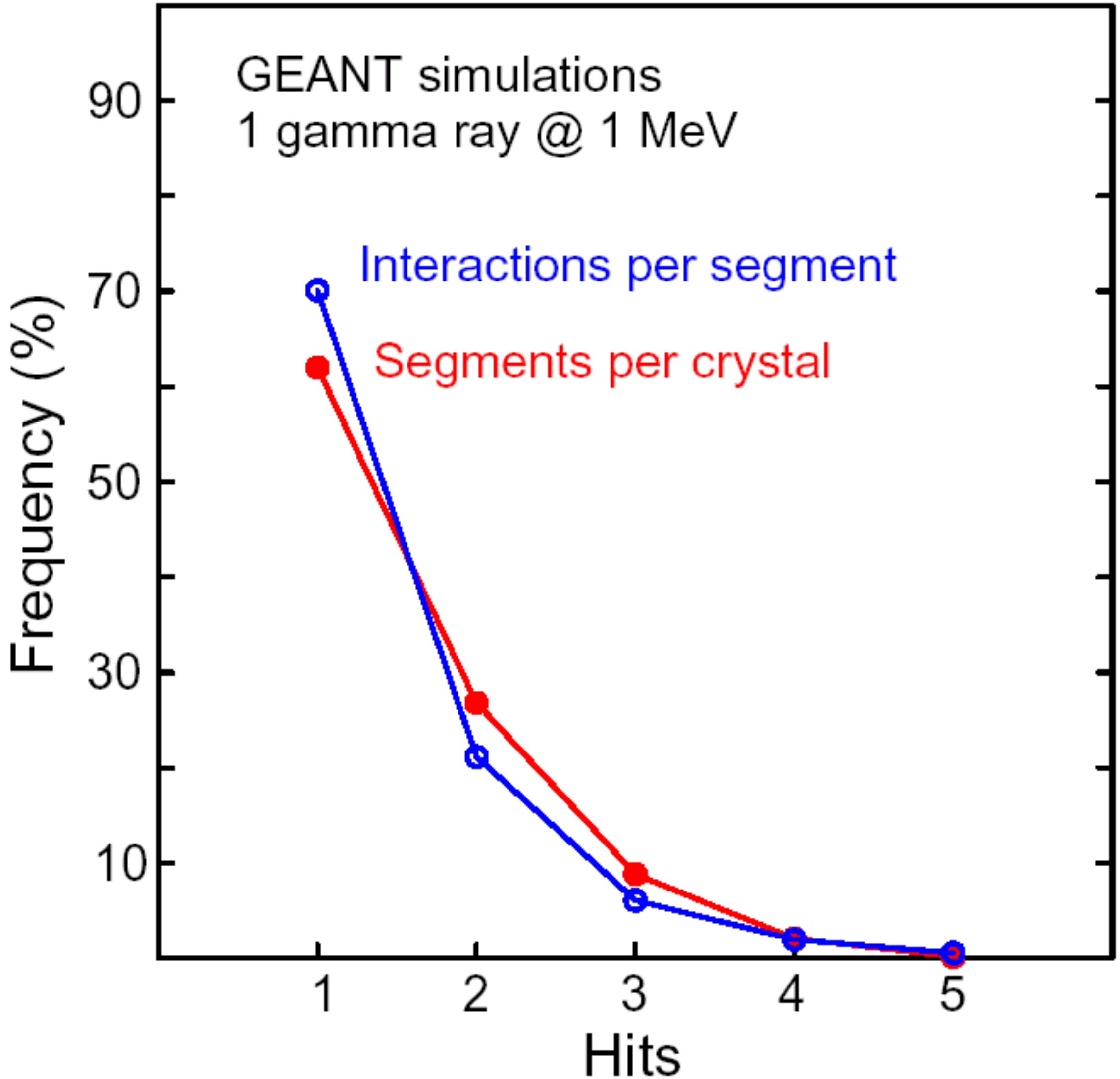
Signal Decomposition: Interaction Multiplicity

GEANT simulations;
1 MeV gamma into GRETA

Most gammas hit one or two crystals

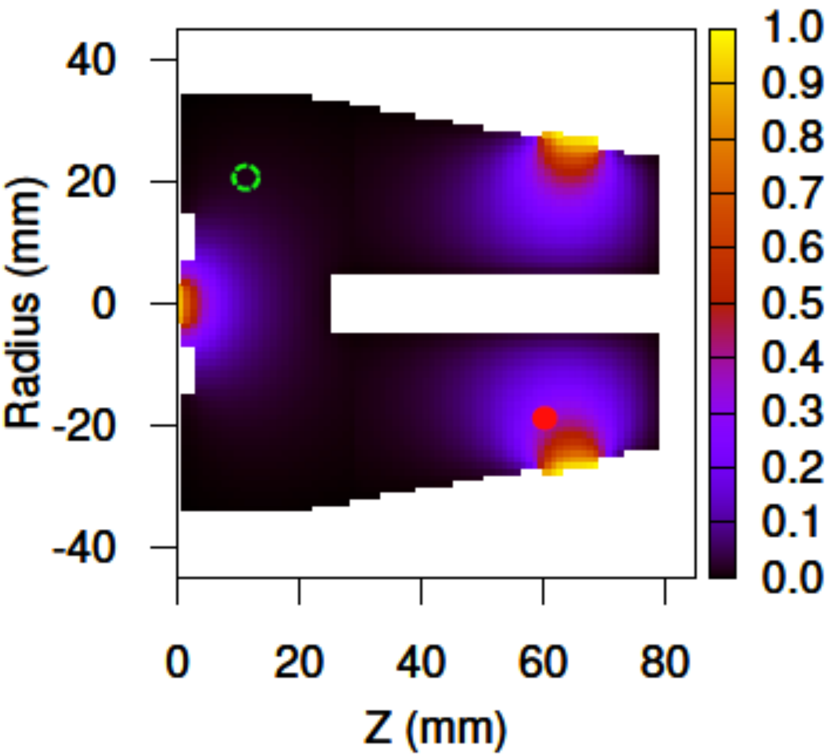
Most hit crystals have one or two hit segments

Most hit segments have one or two interactions



Calculated Signals

Weighting Potentials



Signals from two different points