Novel HPGe Detector Design for Gamma-ray Tracking and Imaging

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

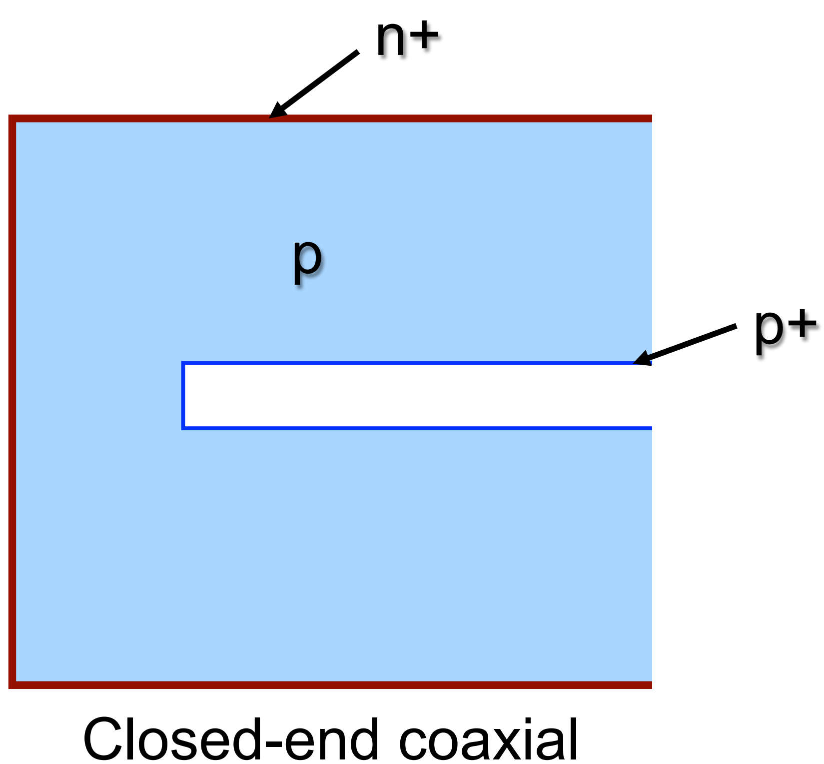
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

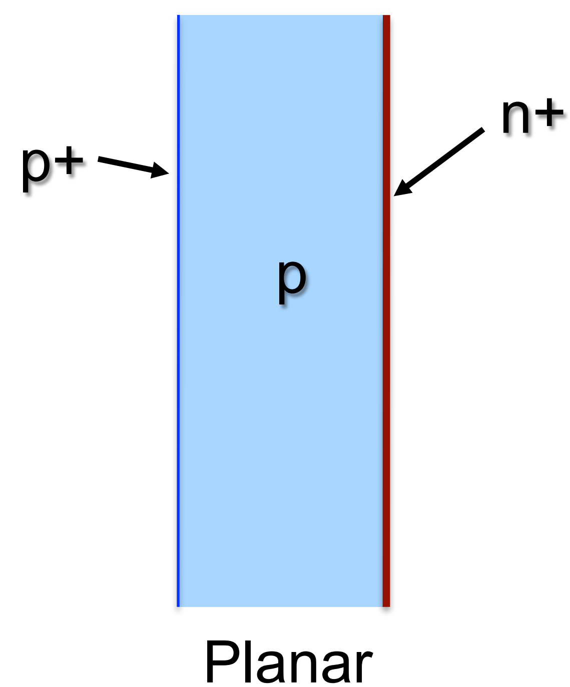
HPGe Detectors

- Ge(Li) detectors developed in the 1960's, HPGe developed in 1970's
  - Made from a single large crystal pulled from molten hyper-pure Ge
  - Operated as a large reverse-biased diode, usually ~3-5 kV bias
  - Operated at cryogenic temperatures to prevent thermal generation of electron-hole pairs
- Hyper-Pure Ge (HPGe) detectors are the "gold standard" for gamma-ray spectroscopy
- Unsurpassed energy resolution
- Indispensible to in-beam nuclear structure and decay studies for many decades

HPGe Detectors

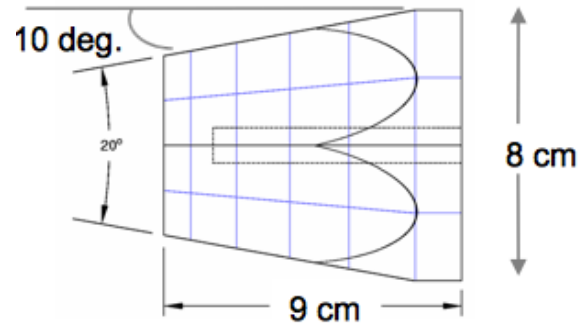
Historically, there have been two designs: Coaxial and Planar.

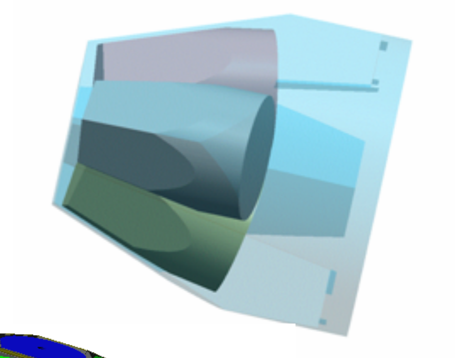


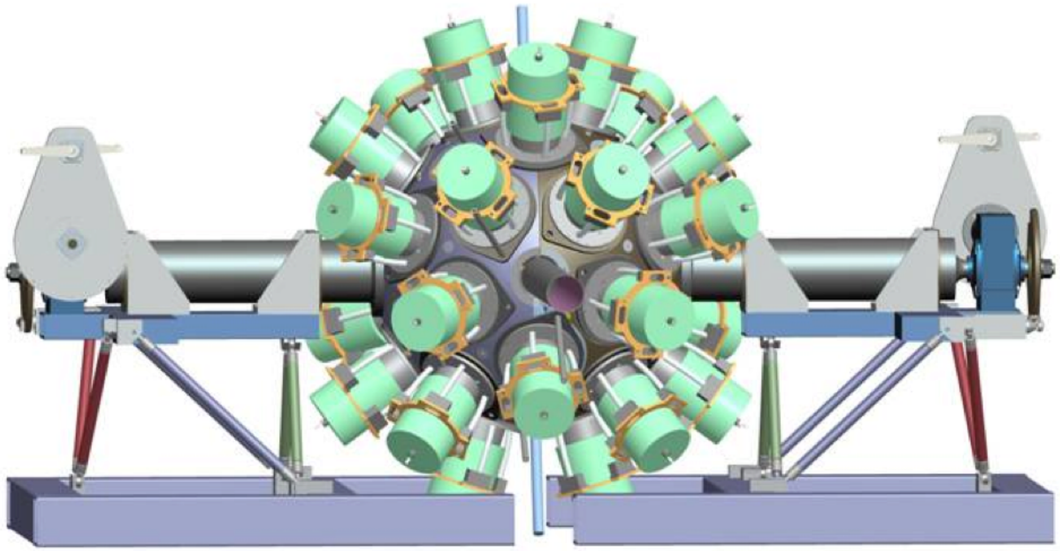


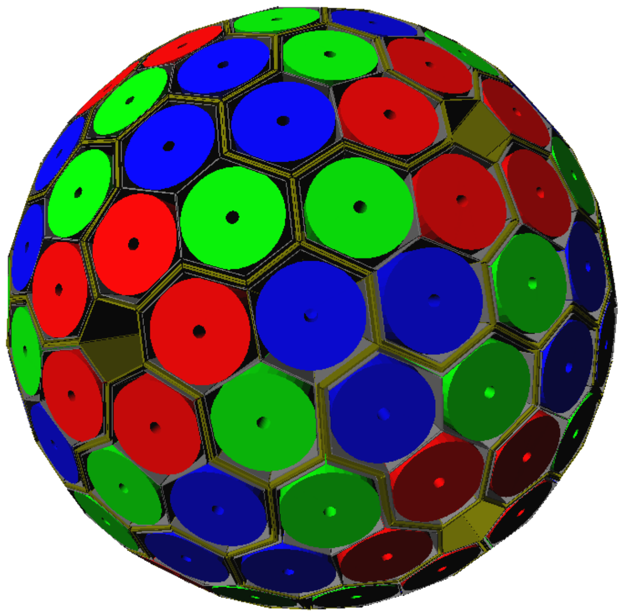
GRETA and AGATA

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

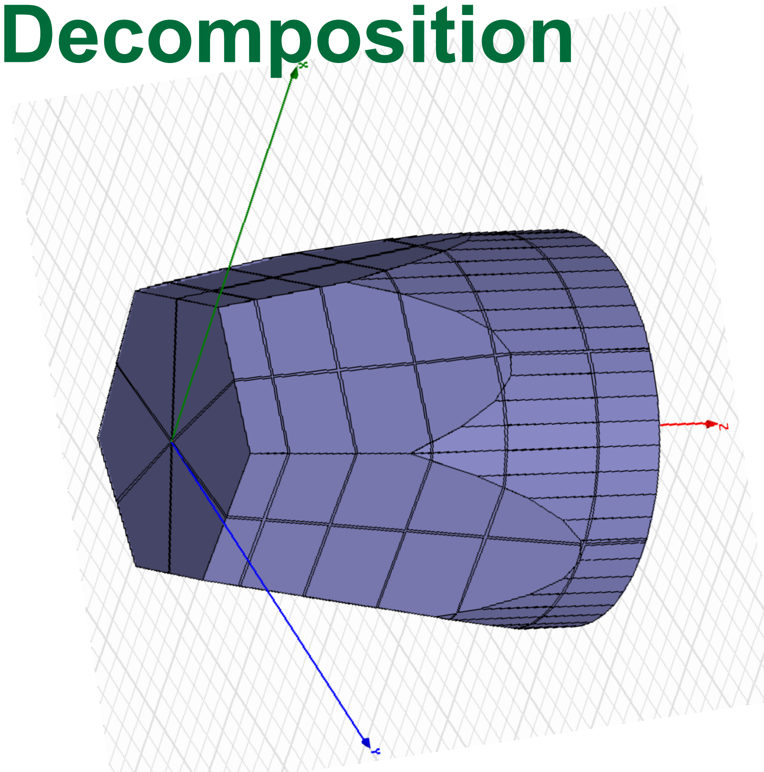


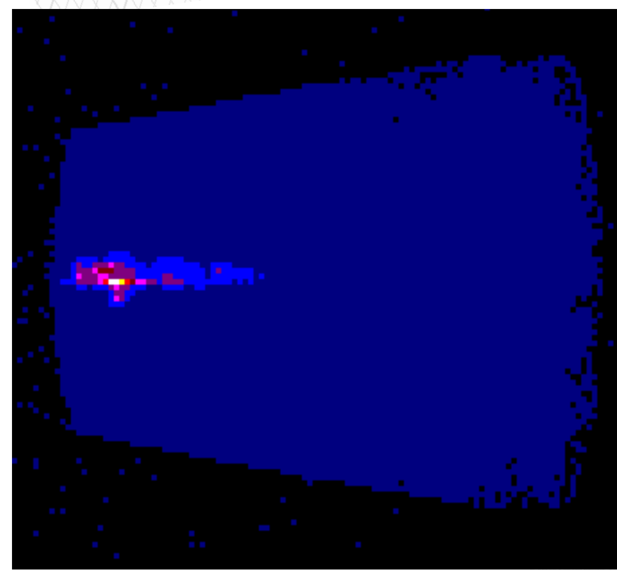






Gamma Tracking and Signal Decomposition



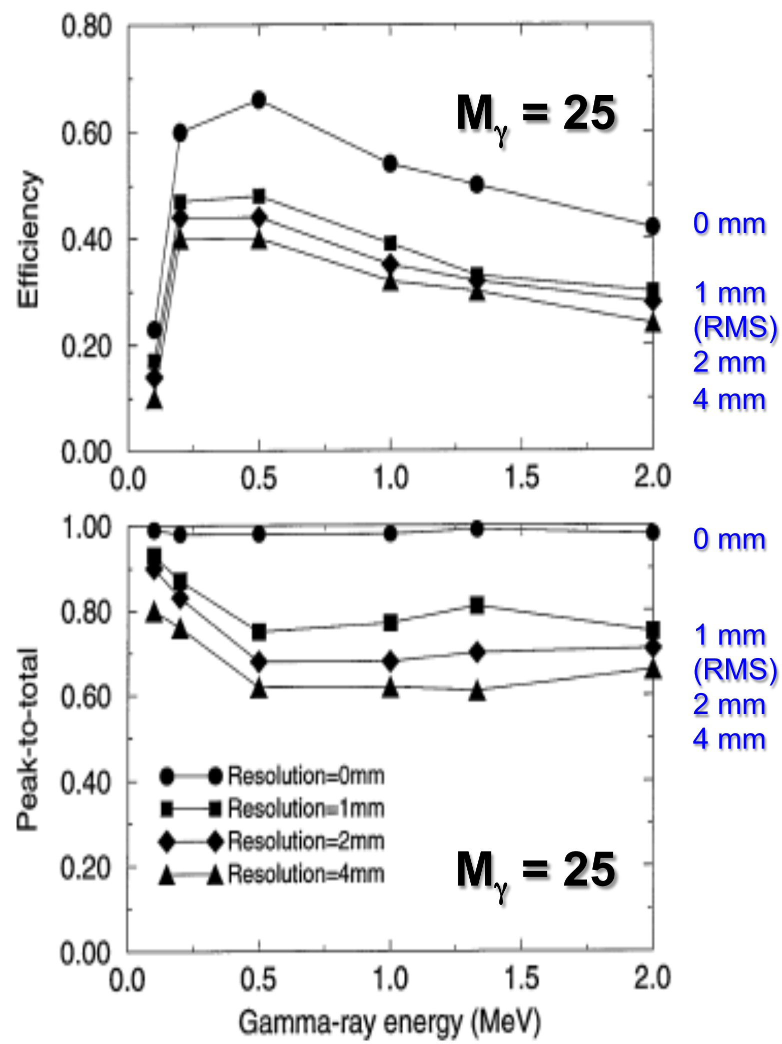


- Digital signal processing to determine the *number, positions,* and *energies* of gamma interactions in the crystal
  - Uses pre-calculated pulse shapes for ~ 10^5 positions throughout the crystal
  - Can have multiple interactions per hit segment
- *Position resolution* is crucial for energy resolution,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

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

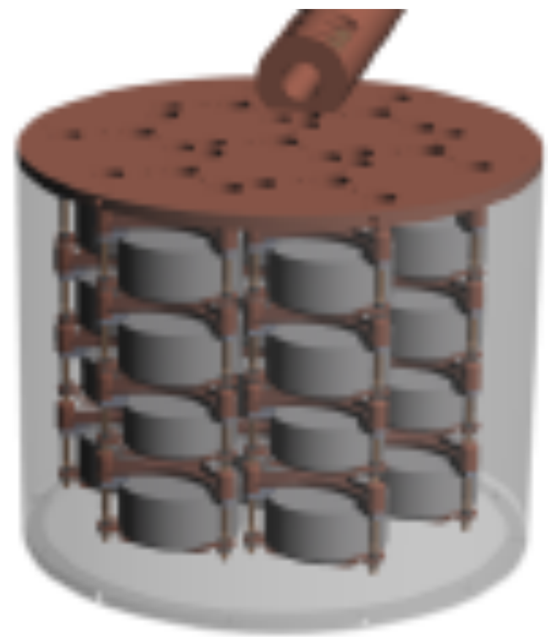
Science goals:

- 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



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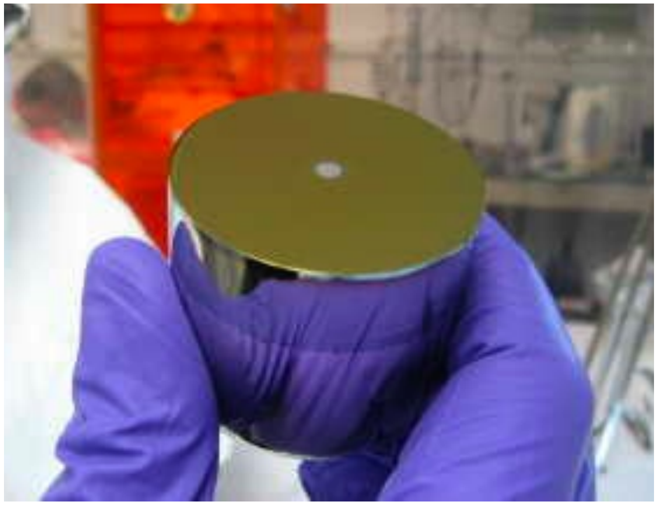
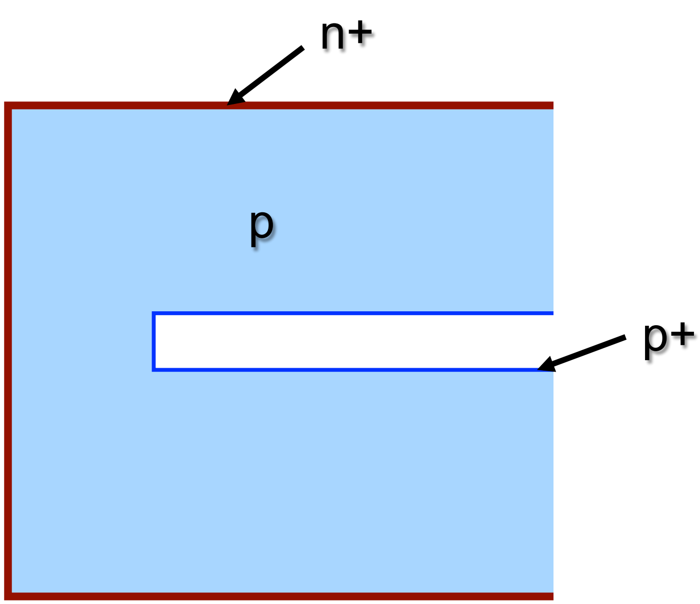
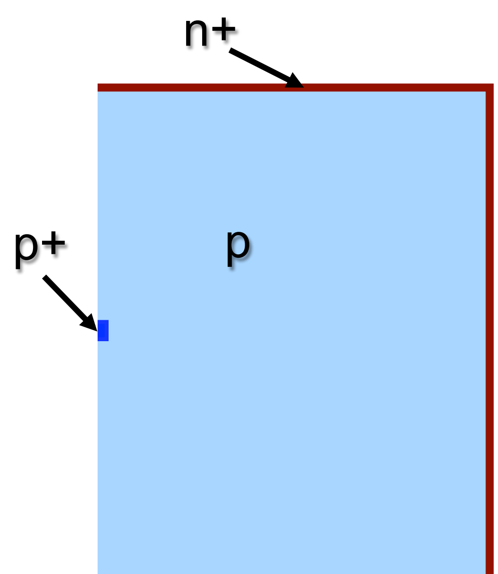
MAJORANA Choice: Point Contact Detectors





P-type Coaxial

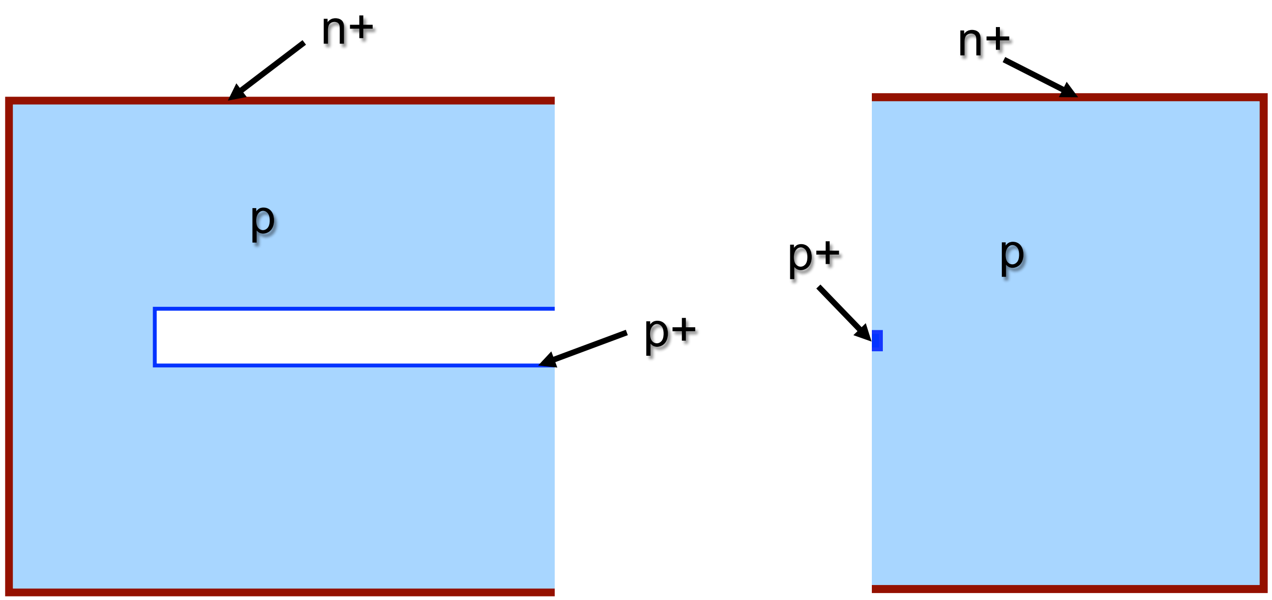


P-type Point Contact

MAJORANA Choice: Point Contact Detectors

P-type Point-Contact (PPC) detectors

- P. Luke et al., IEEE Trans. Nucl. Sci. 36, 926 (1989) (n-type)
- No deep hole; small point-like central contact
- Excellent PSA sensitivity for discrimination between single-site and multi-site events
- Low capacitance (~ 1 pF) gives superb resolution at low energies
- *Length is limited*; shorter than standard coaxial detector



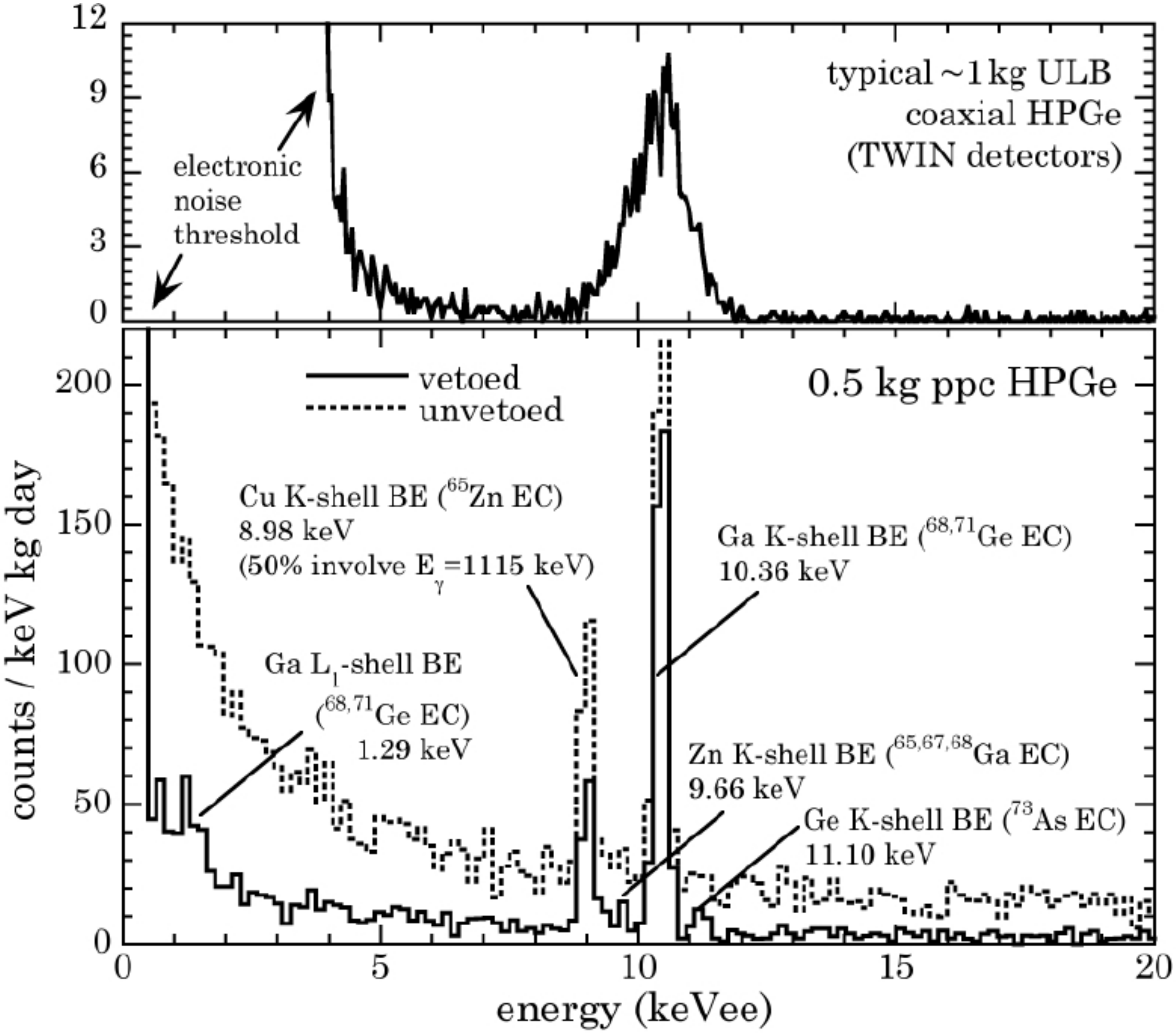
P-type Coaxial   P-type Point Contact

PPC Low-Energy Resolution

Juan Collar, University of Chicago

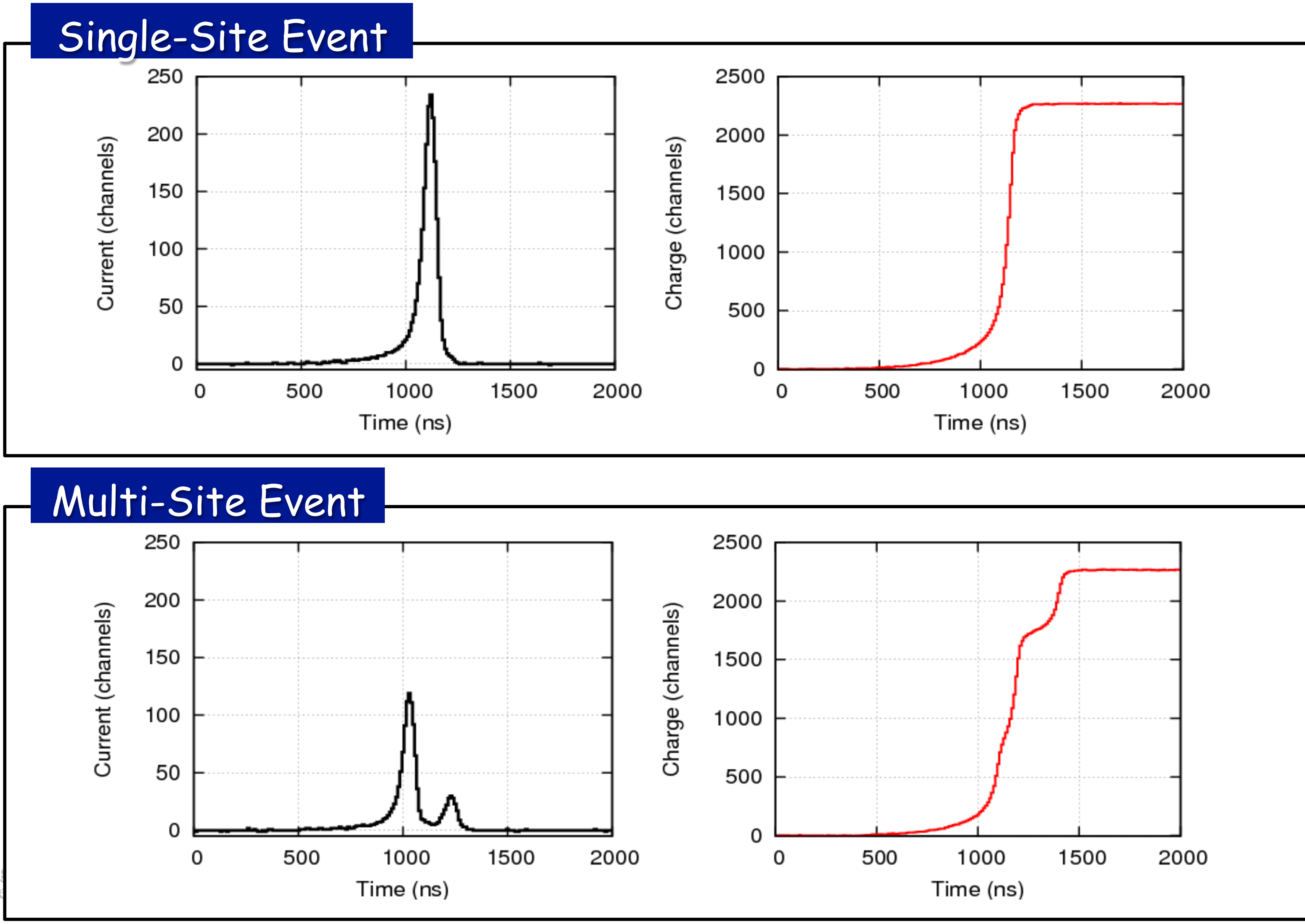
Threshold ~ 400 eV

High gain, pulse-reset preamp



Pulse-Shape Response

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

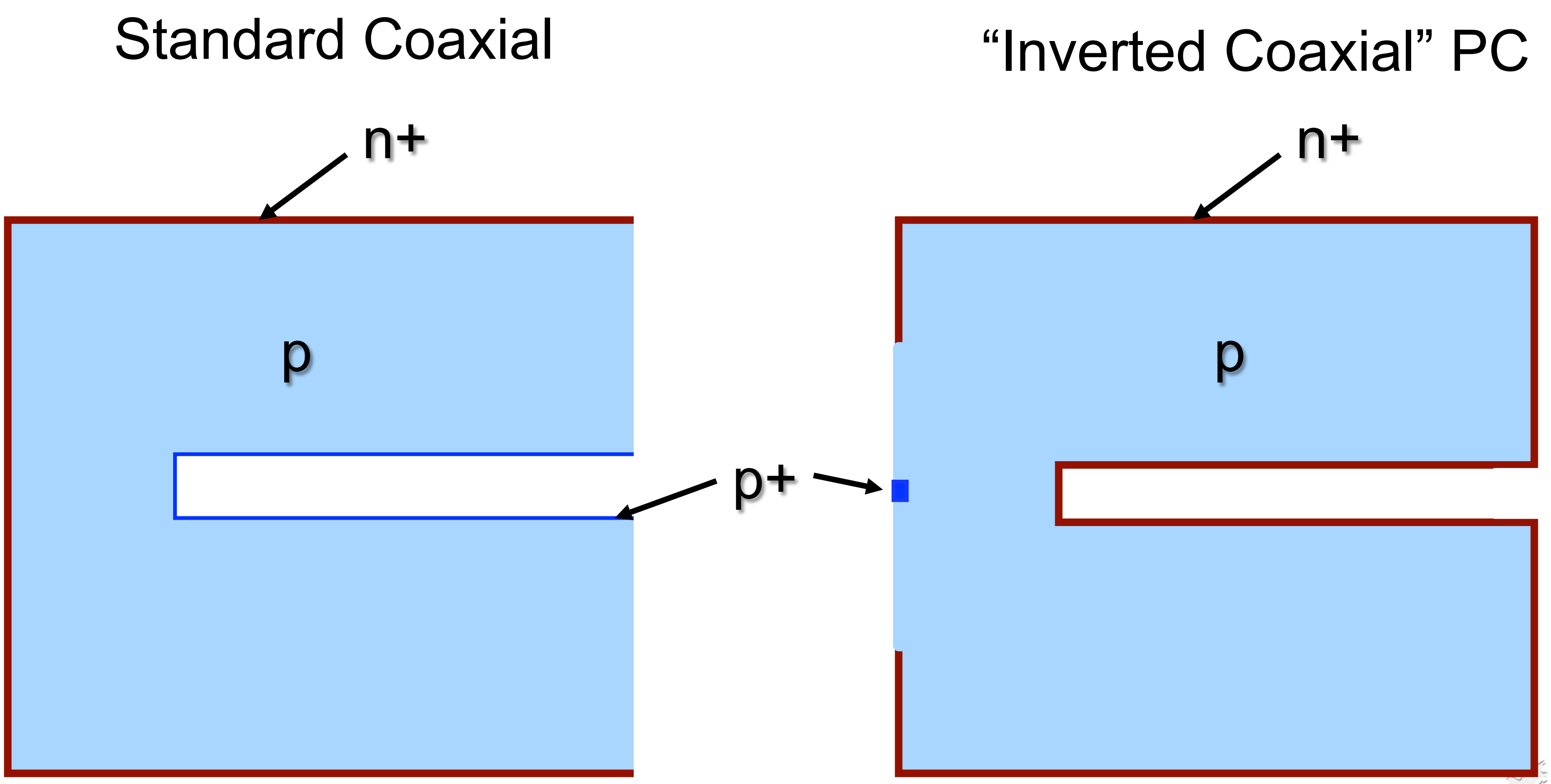


Novel Design: Large Point Contact Detectors

Normal point-contact detectors are limited in size

- Long crystals result in an undepleted region in the middle of the detector

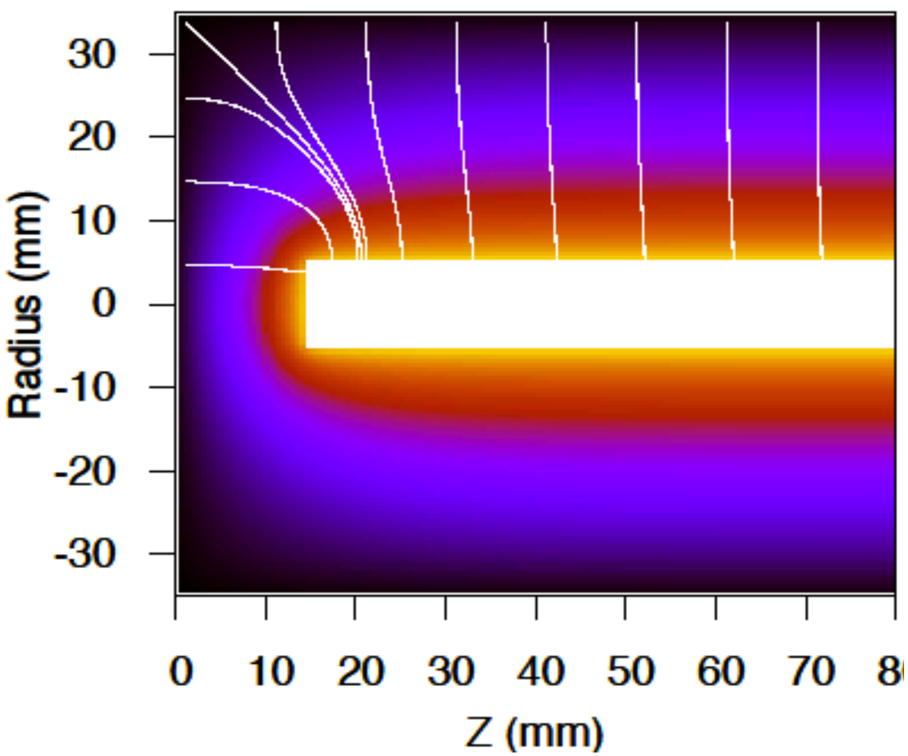
To overcome this, have developed a new “Inverted Coaxial” design



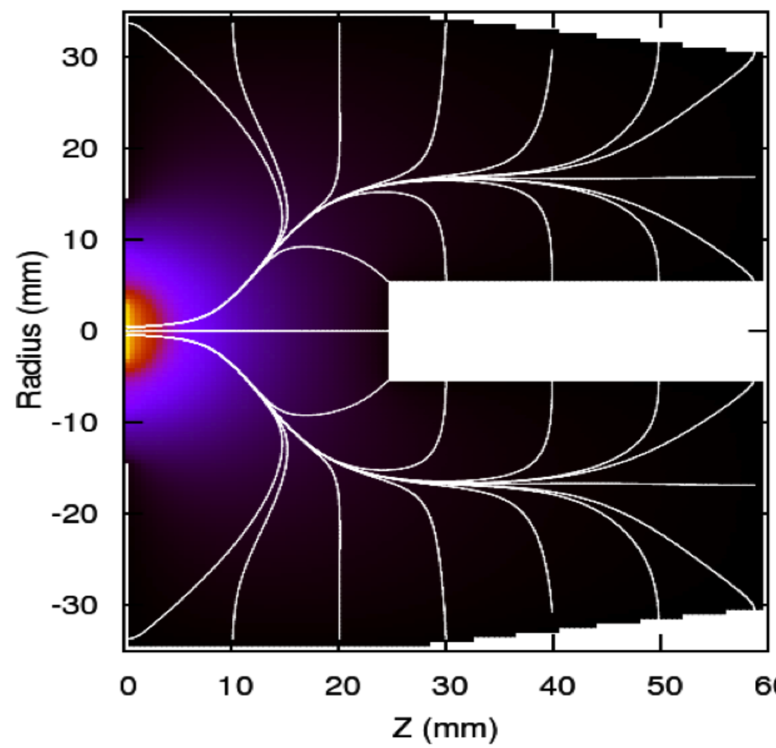
“Inverted Coaxial” Detector

- 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

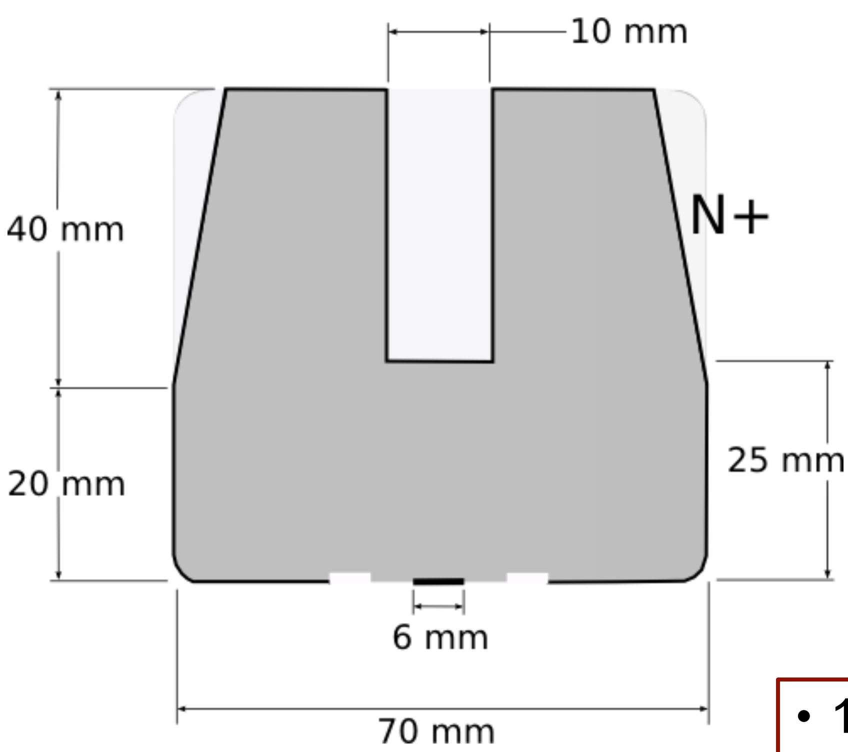


Inverted Coaxial



Unsegmented Prototype

- 70 mm x 60 mm tapered cylindrical detector
- Purchased with ARRA funds from DOE ONP



Prototype has excellent resolution and efficiency

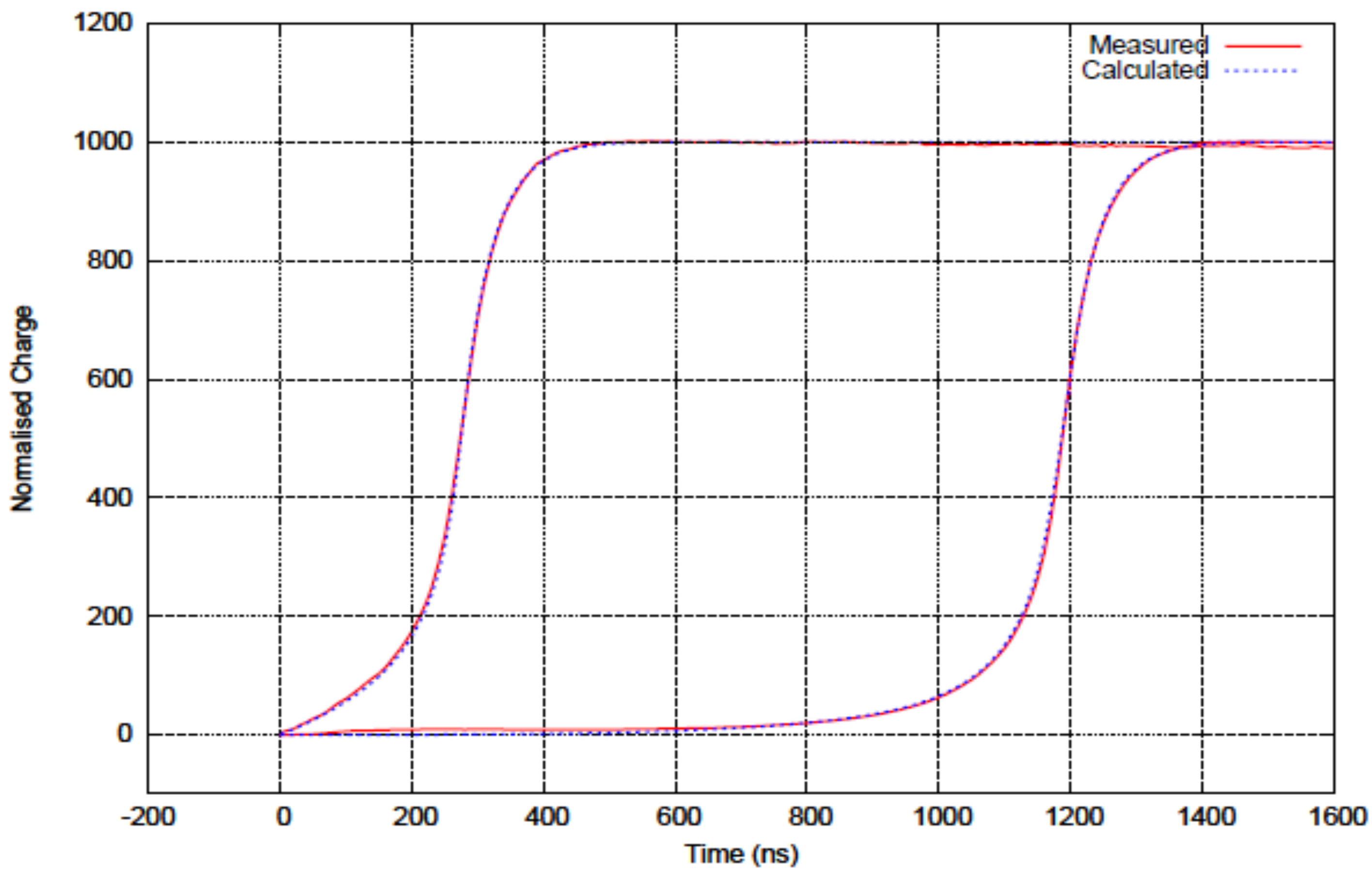
Depletion Voltage	(+) 2600 V
Operating Bias	(+) 3500 V
Leakage Current	<10.0 pA
Capacitance	~ 1 pF

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

Calculated and Measured Signals

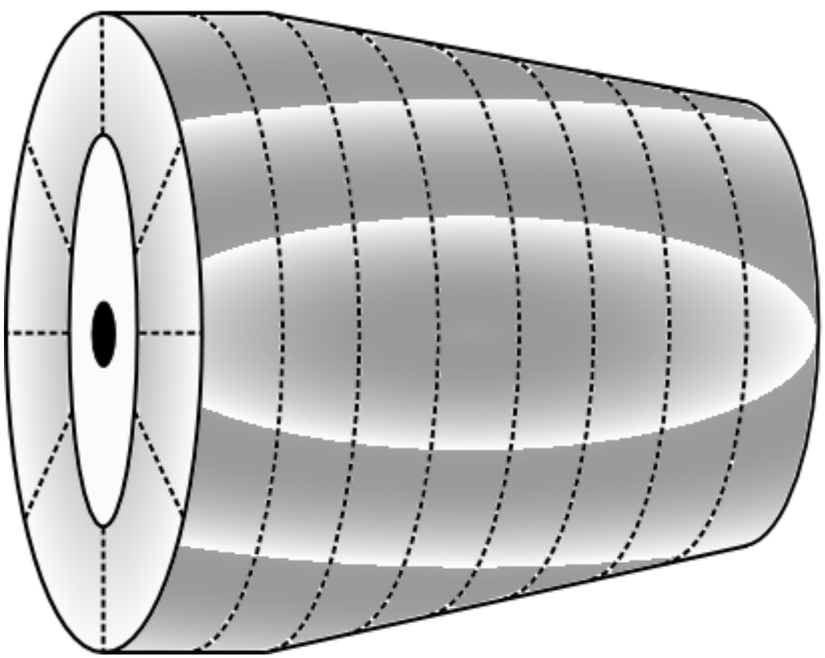
Excellent agreement with both *time* and *shape* of signals from different locations

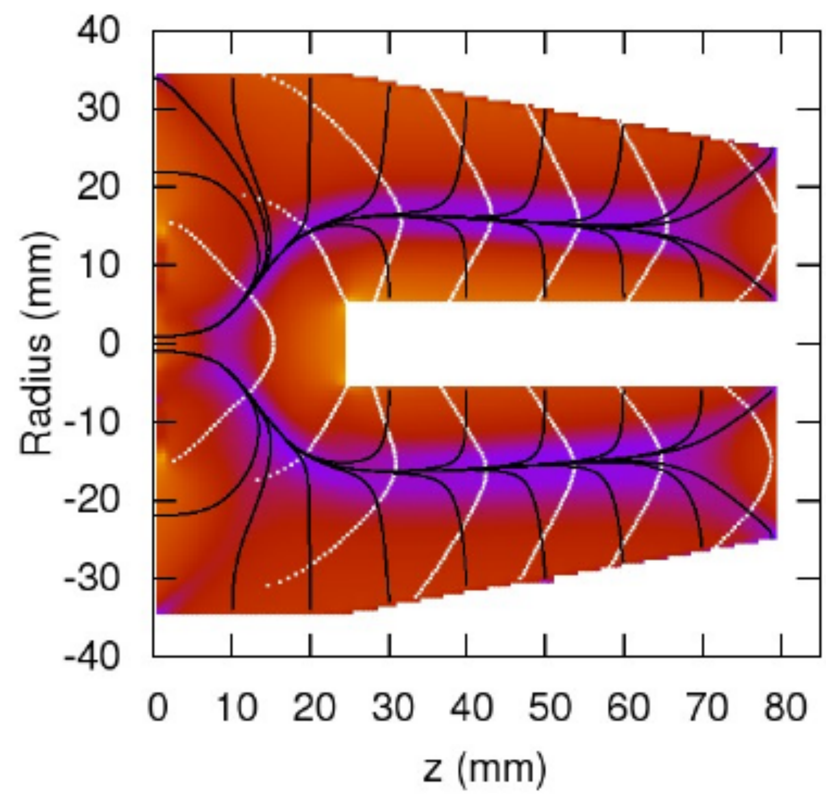
- Confident that we really understand these detectors and can model them properly



Segmented Design

- Segmentation allows a good determination of drift time and position
- Longitudinal ring-style segments and pie-slice azimuthal segments separate the longitudinal and azimuthal directions
  - Similar to X and Y in a DSSD





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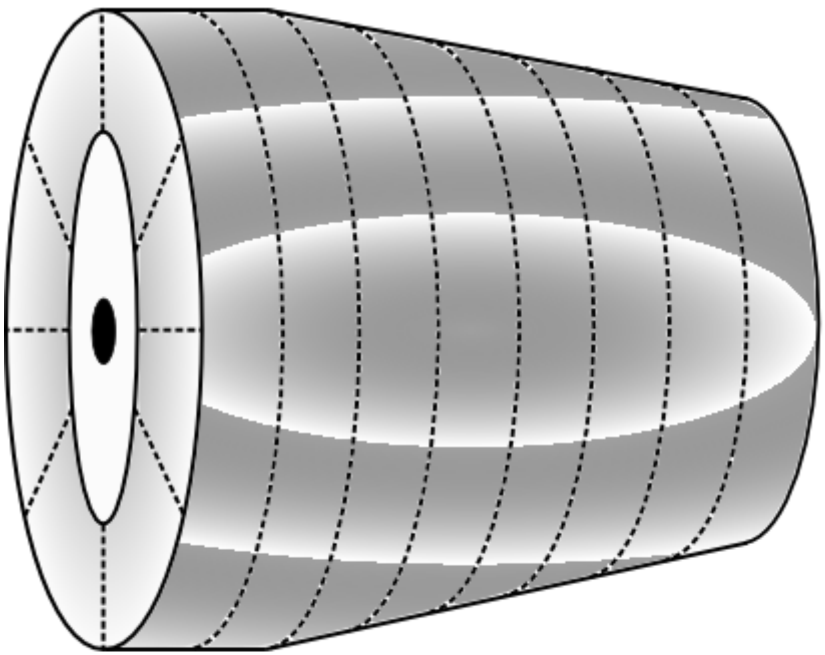


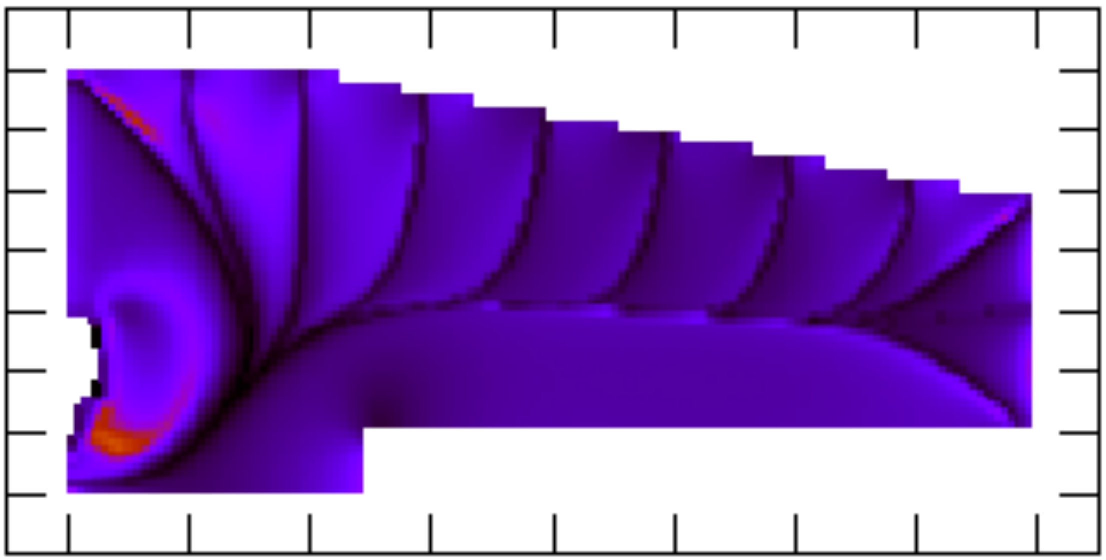
- Prototype ordered from Canberra (Lingolsheim)
- 19 segments; 20 signals
- 7 cm diameter, 8 cm long
- n-type

 Managed by UT-Battelle
for the U.S. Department of Energy

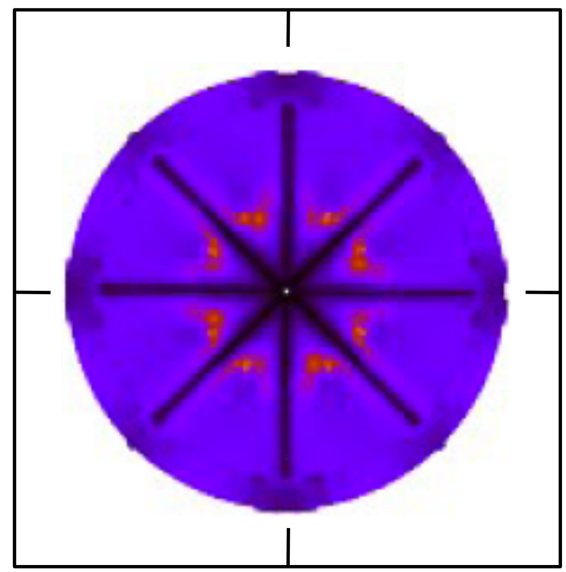
Excellent Position Sensitivity

Theoretical resolution is roughly a factor of 3 - 4 better than GRETINA

Calculated longitudinal position resolution



Azimuthal resolution



R.J. Cooper, D.C. Radford, et al., NIMA 665 (2012) 25

Larger diameter detectors?

- Diameter of coaxial detectors is presently limited to ~8-10 cm
  - Mostly from depletion voltage requirements
  - To deplete the crystal at a reasonable voltage, larger diameters require much higher purity of the Ge
- In this new design, the crystal depletes from both the inside and outside simultaneously, so larger diameters should be possible

Disadvantages

- Unsegmented version has poor timing resolution
  - Drift time of 1-2 μs; no signal until charges are close to contact
  - So good timing requires at least modest segmentation to generate earlier signals
- N-type version should have significant charge trapping
  - To get good energy resolution, will need to do position-dependent trapping correction
  - Should be easy and accurate, but not yet tested
  - Requires segmentation and digital signal processing
  - P-type version has better resolution but is prone to neutron damage
- Probably somewhat poorer count rate capability than coax

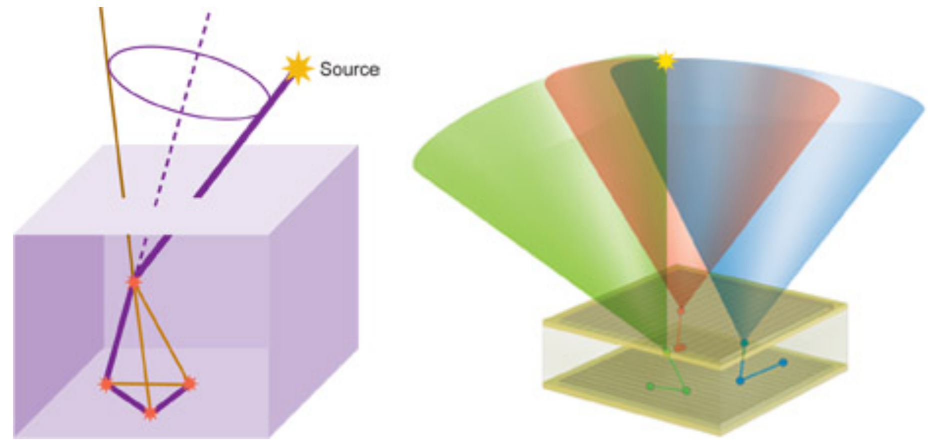
Implications for GRETA

- Geometry identical to existing detectors; drop-in replacement
- Fewer signals per crystal (~20 instead of 37)
- Better position sensitivity
- Better determination of *number* of interactions
- Questions:
  - Production yield?
  - Cost?
  - Reliability?
  - Larger-diameter detectors?
  - Count rate capability?
  - Need to demonstrate measured position resolution

Other Applications?

The excellent position resolution and large size of these detectors could make them ideal for some important *Compton imaging* applications:

- Medical imaging, e.g. SPECT
  (Single-photon emission computed tomography)
- Gamma-ray astronomy
- Homeland security



In gamma-ray astronomy, the number of signals determines the number of feed-throughs, which is limited by the energy budget. Good position resolution from fewer contacts per unit volume would have a significant impact.

Other Applications?

- Dark Matter detection
- Coherent neutrino-nucleus scattering
  - Both of these require very low energy threshold and relatively large mass

- Canberra are developing a version as a radio-assay well detector.

Summary

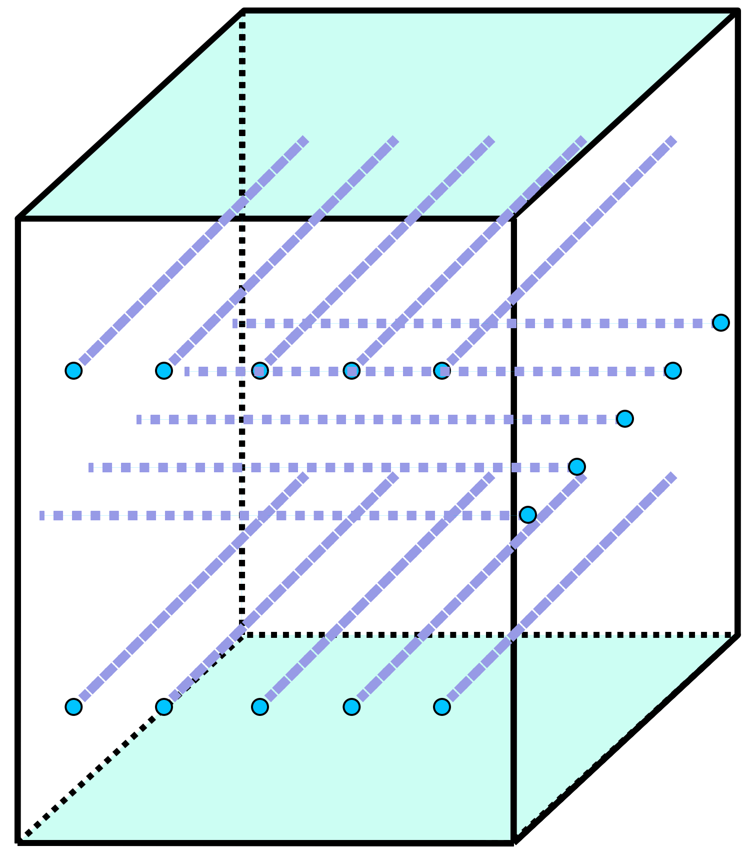
- ✓ Efforts on GRETINA, AGATA, and MAJORANA have developed many tools for understanding and modeling Ge detectors and their signals
- ✓ These tools can now be used to develop new concepts for Ge detectors
- ✓ New point-contact detector geometries are being explored for making efficient, high-resolution position-sensitive gamma detectors
  - Use long drift times to improve position determination
  - Hope to achieve a factor of ~ 2-4 better *position* sensitivity than GRETINA, with fewer signals
  - Better determination of the *number* of interactions
  - Better efficiency, P/T, and E-resolution in gamma-tracking arrays
  - Can use same tapered-hexagonal geometry as GRETA and AGATA
- ✓ Unsegmented p-type prototype works extremely well
- ✓ Prototype n-type detector with 19 segments is on order
- ✓ These detectors could also be used for Compton imaging, with important applications in medical imaging, γ-ray astronomy, homeland security, etc.

Backup Slides

“Solid-State Wire Chamber”

Even more far-out ...

Drill holes ~ 1mm diameter through the crystal, then drift Li into the material to make wire-like electrodes.
Place planes of “wires” in alternating directions.

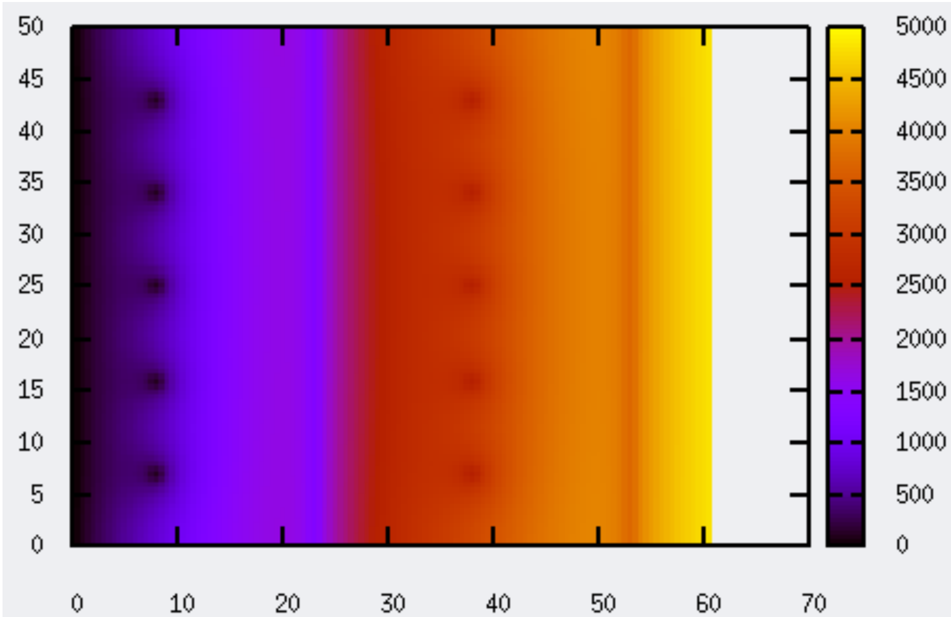


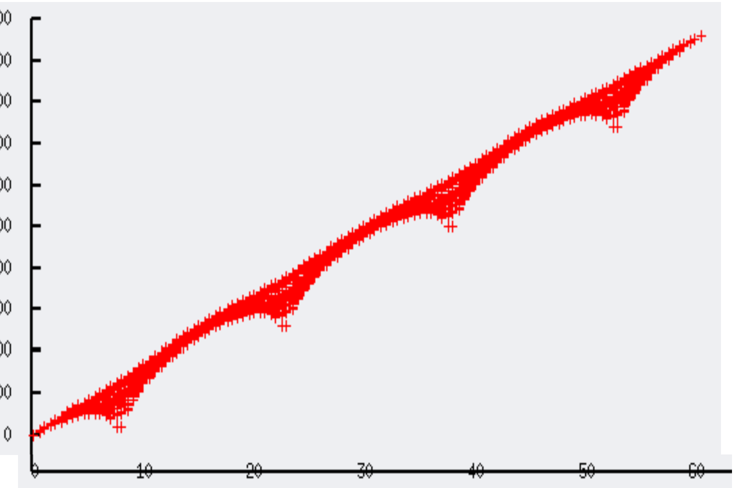
Allows depletion of very thick planar detectors, and provides excellent position resolution.

But can it be made?

Solid-State Wire Chamber - Field calculations

V





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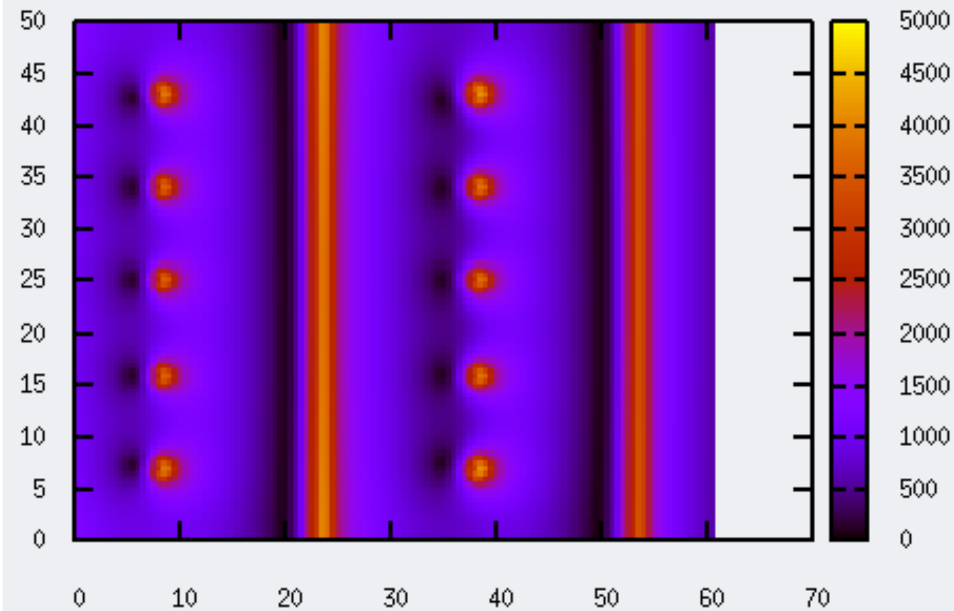
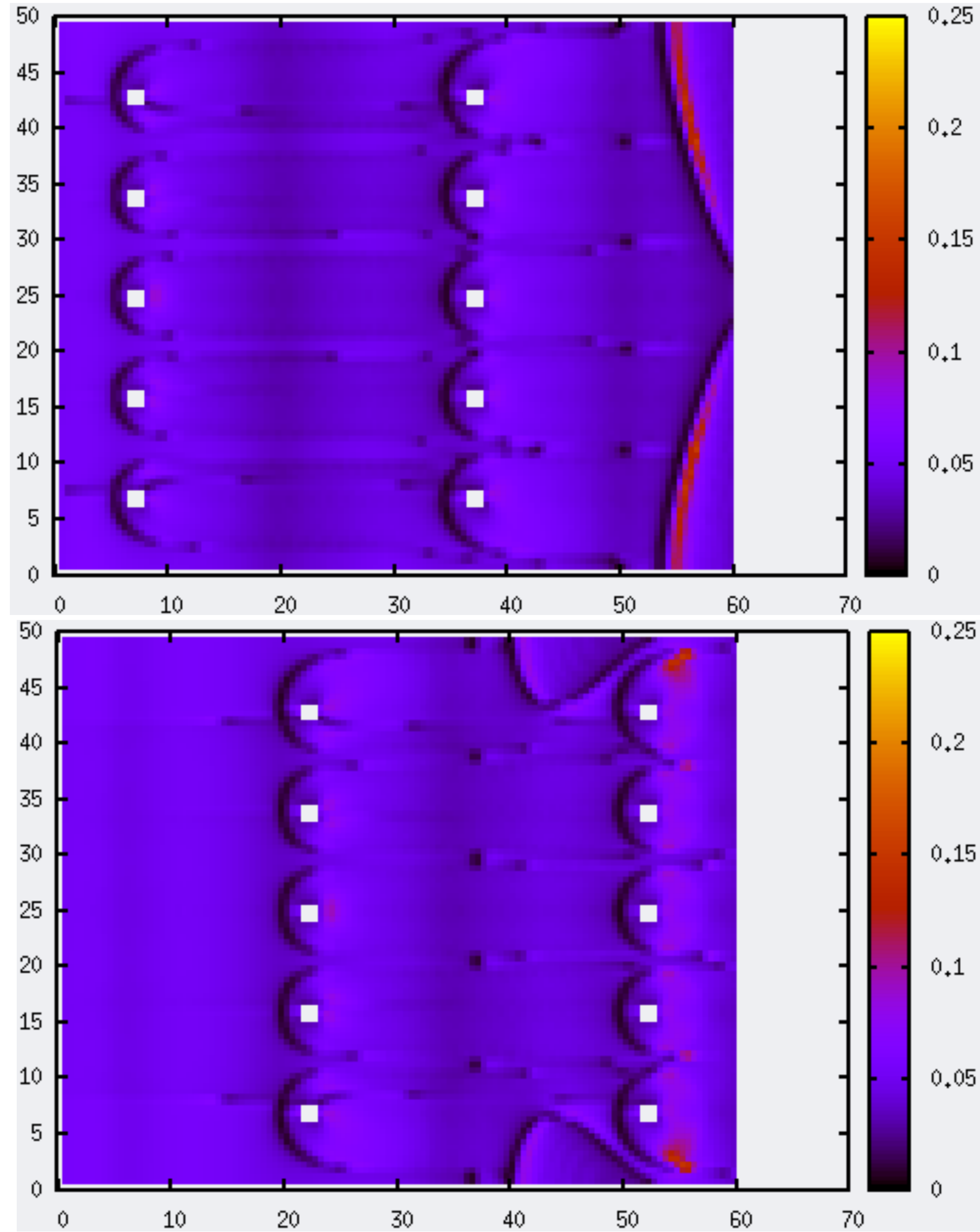


Solid-State Wire Chamber - Position resolution

Z-resolution (FWHM, mm)
in X-Z and Y-Z planes:



Position resolution is
comparable to a DSSD.

Solid-State Wire Chamber

Could we get 10x10x8 cm^3 detectors with FWHM < 0.5 mm everywhere?