# Three-Dimensional Position-Sensitive Germanium Detectors

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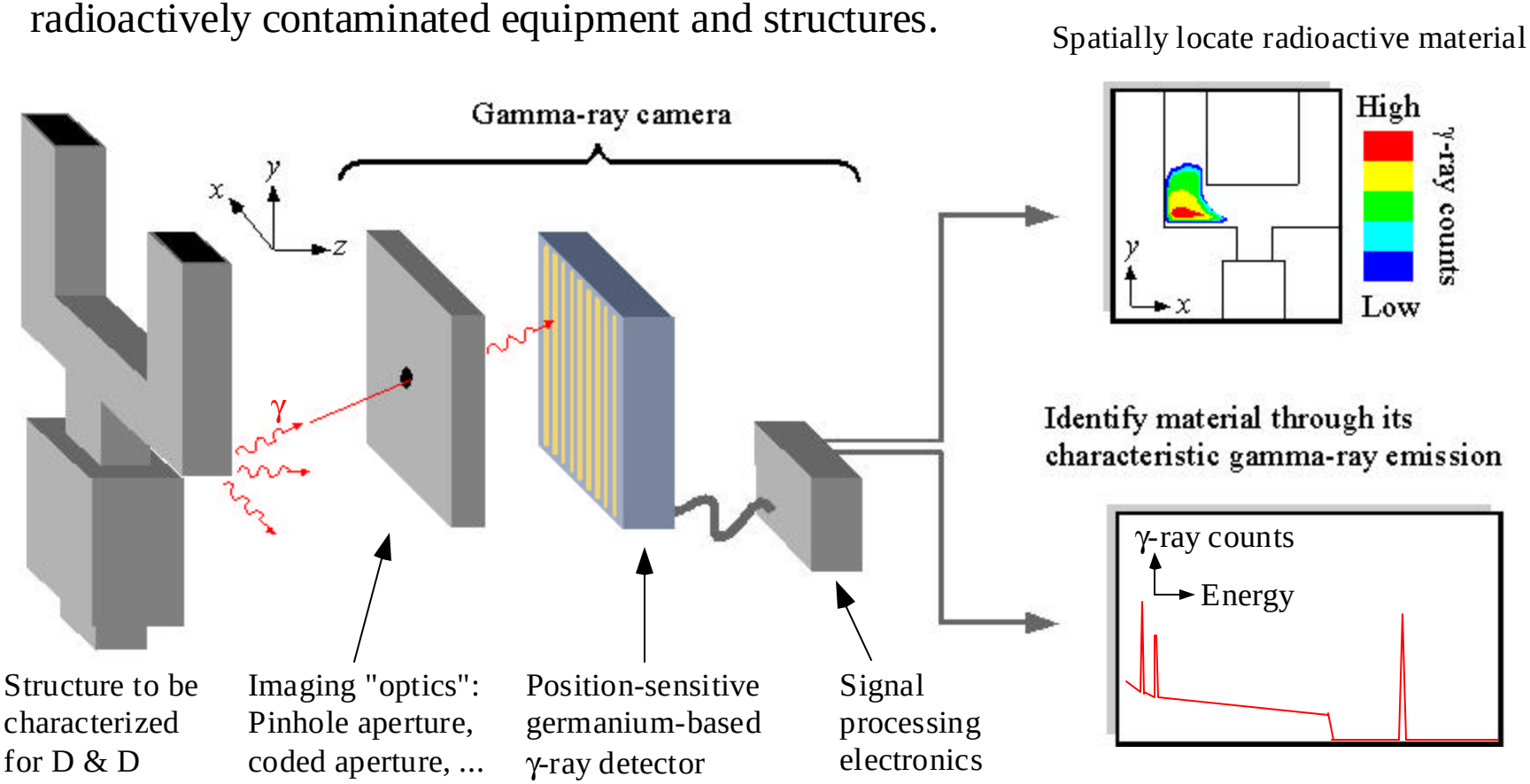
# Abstract

Gamma-ray spectroscopy and imaging with germanium (Ge) based detectors are potentially powerful techniques for the quick and accurate in-situ identification, spatial mapping, and quantification of radioactive contaminants. However, the image resolution obtained with a Ge detector can be limited by the accuracy to which the gamma-ray interaction events are spatially detected within the detector itself. Our primary objective is to develop the technologies necessary to produce Ge gamma-ray detectors with enhanced accuracy in locating gamma-ray interaction events thereby resulting in improved image resolution. Our approach is to locate the gamma-ray interaction events within the detector in all three dimensions rather than just two. Additionally, we are basing the detectors on simple LBNL-developed fabrication technologies and are working to develop the simplest possible detector geometries and signal-readout electrode structures in order to reduce the system complexity and difficulties in fabrication. The technologies developed as a result of this research will form the basis for the design and construction of future high-performance gamma-ray imaging systems. These instruments will greatly facilitate DOE's radioactive materials characterization process.

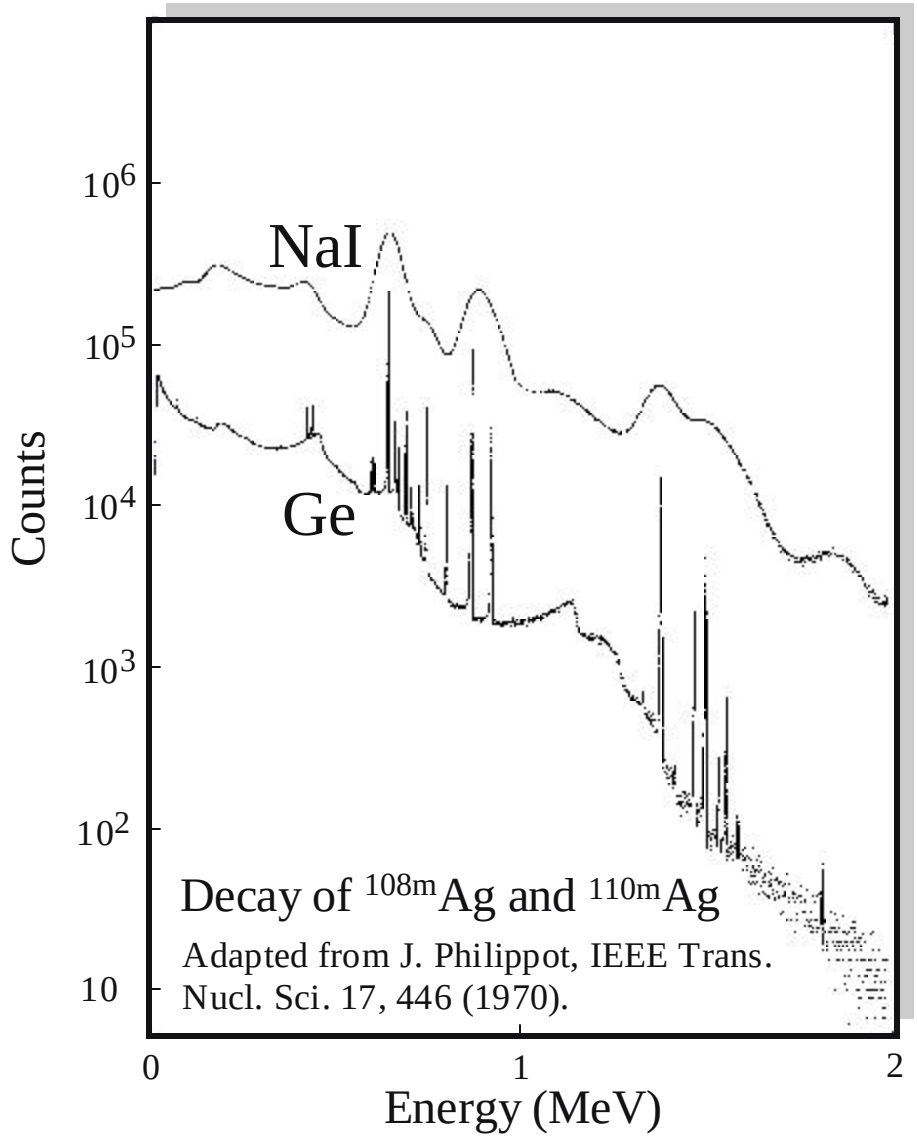
# Background - γ-Ray Camera and Ge Detectors

Need: quick and accurate characterization of radioactively contaminated equipment and structures.




Basic concept: in-situ isotopic identification, spatial mapping, and quantification of radioactive contaminants based on the detection of the characteristic gamma rays passively emitted by the contaminants.

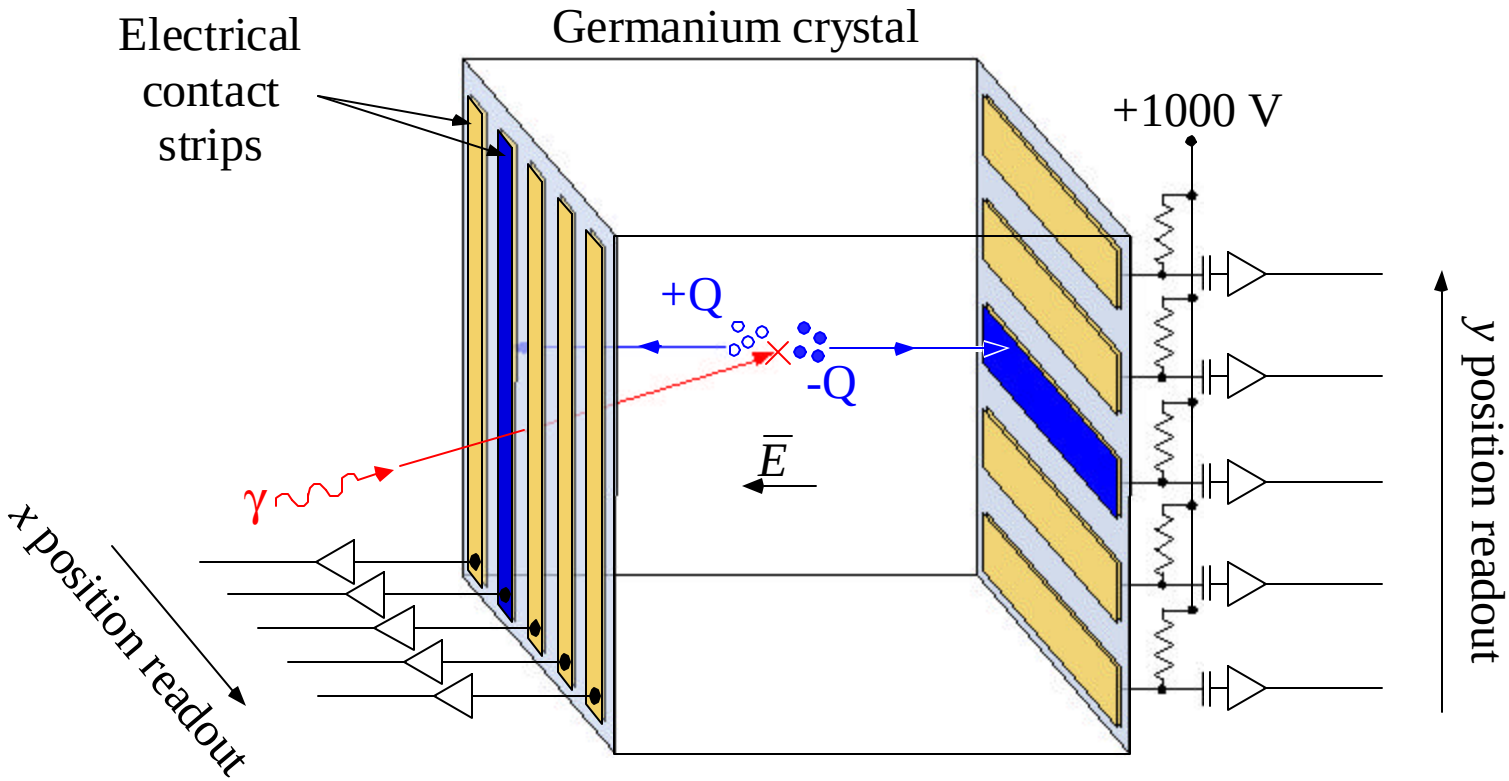
# Background - Why Ge?




Gamma-ray imaging is commonly done today with scintillator-based detectors. These detectors however have poor energy resolution. This comparison of a gamma-ray spectrum acquired with a NaI scintillator-based spectrometer to that acquired with a Ge-based spectrometer illustrates the superior spectroscopic performance of Ge detectors over that of the competing scintillator technologies. This superior performance leads to better specificity and sensitivity with the Ge detector technology.

A typical Ge detector energy resolution is about 2 keV at 1.17 MeV.

# Background - Detector Physics




The function of the detector in a gamma-ray camera is to accurately measure both the energy and location of each gamma ray that interacts within the detector. One way to accomplish this with a Ge-based detector is illustrated here. When a gamma ray interacts in the Ge detector, free electrons and holes are generated. This charge is collected (under the influence of an applied bias) to electrical contact strips that have been fabricated onto two opposing detector surfaces. For imaging purposes, the *x-y* position of the gamma-ray interaction is determined based on the position of the contact strips that collect the gamma-ray generated charge. For spectroscopy purposes, the energy of the gamma ray is determined from the amount of collected charge, Q, which is proportional to the gamma-ray energy.

# Research Focus - Detector Development

## Needs addressed by research

Key to the success of gamma-ray cameras based on Ge detectors is the development of a detector fabrication process that is simple and reproducible and that produces detectors with the following properties:

- Fine electrical contact segmentation
- Low noise and leakage current
- Long-term stability and insensitivity to environmental conditions

Also critical are needs related to detector design and signal readout:

- Accurate measurement of energy and position
- Reduced complexity

## Research objectives

We are further developing the LBNL Ge detector fabrication processes to meet the needs of the gamma-ray imaging application.

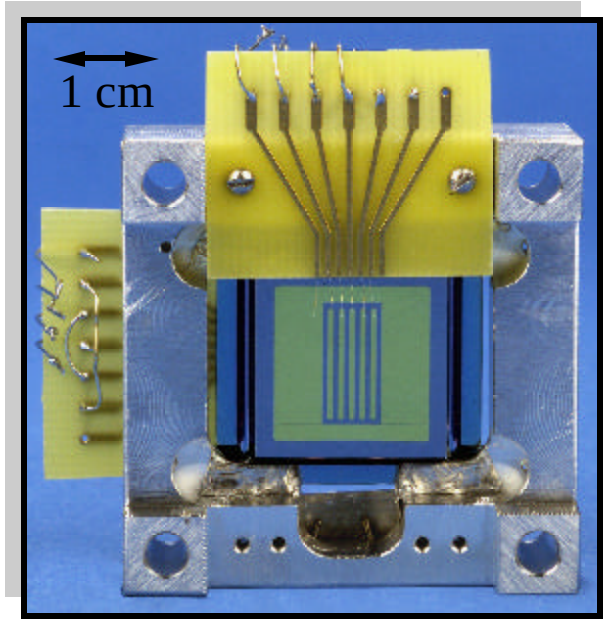
We are also developing techniques to more accurately measure the gamma-ray interaction location without degrading energy resolution. Specifically:

- Position measurement in 3 dimensions ($x$,$y$,$z$) rather than only 2.
- Interpolation to improve $x$-$y$ resolution.
- Interstrip biasing and fabrication process optimization to prevent energy resolution and efficiency degradation.

# Research Status

Detector fabrication process development:

- Wire bonding process developed.
- Amorphous-semiconductor electrical contacts appropriate for strip detector fabrication developed.
- Small test detectors fabricated.

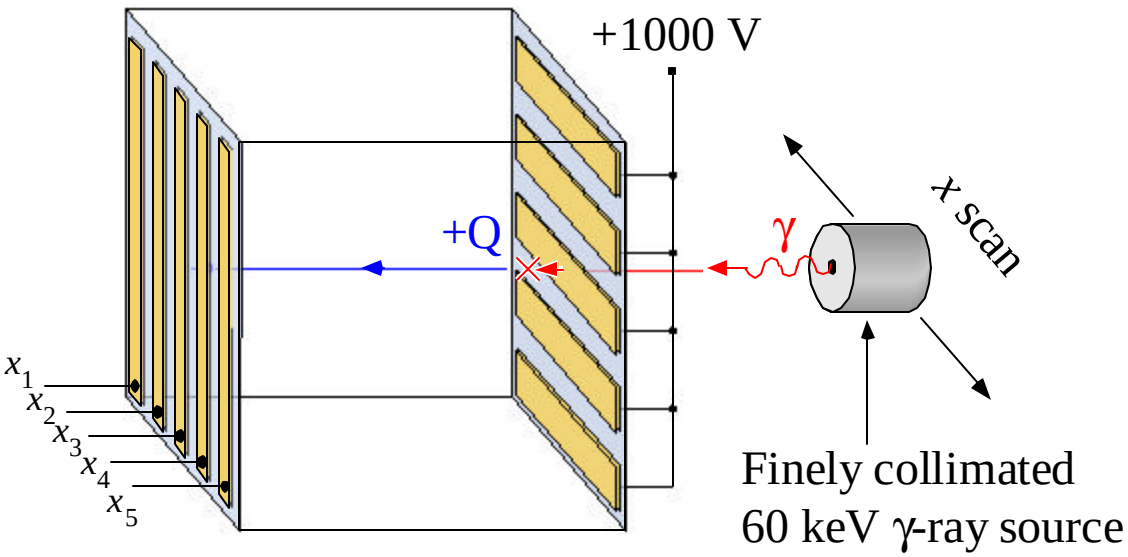


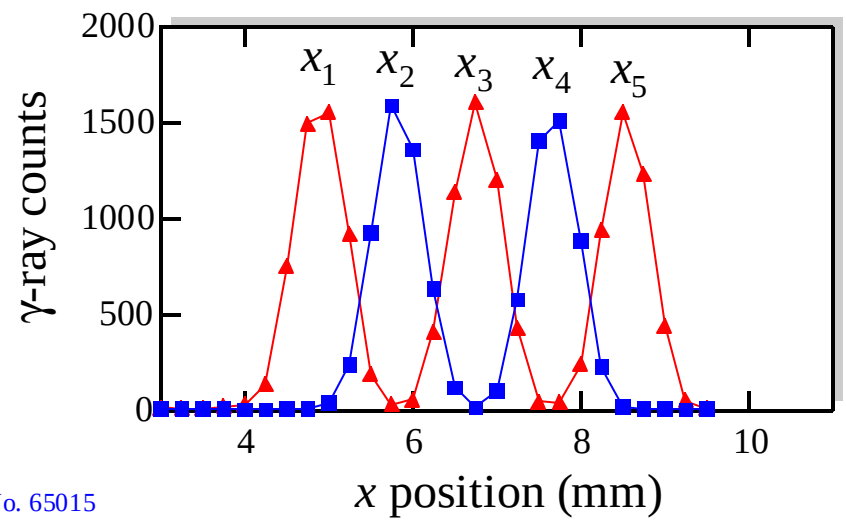

Detector design and signal readout development:

- Modeled and experimentally demonstrated position sensing in 3 dimensions.
- Improved efficiency and energy resolution through interstrip biasing and through optimization of the amorphous-semiconductor contact layer.

# Research Results - 3-D Position-Sensing

Conventional *x*-*y* position measurement (*x* as an example):

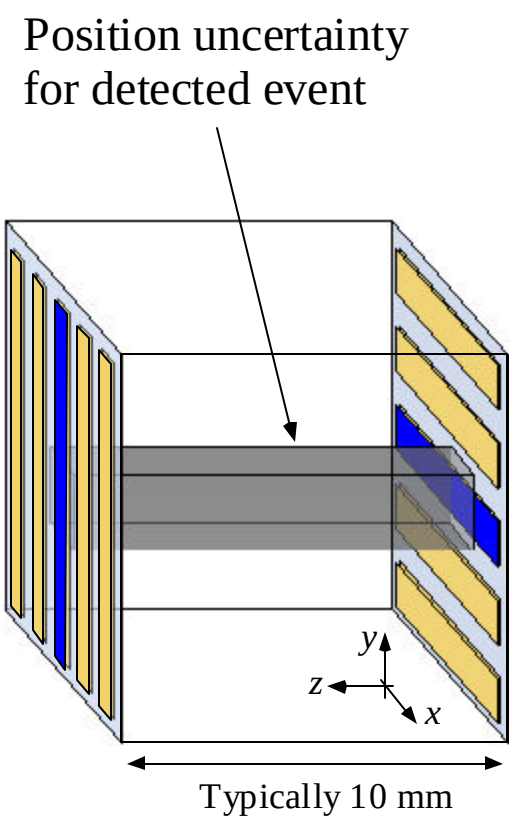



In the graph to the left is shown a plot of integrated gamma-ray counts within the photopeak as a function of the position of a collimated gamma-ray source as measured with one of our small prototype Ge detectors. As the source is scanned and the hole collection moves from from one *x* strip to the next, the gamma-ray counts from the strips fall or rise as expected thereby demonstrating good *x* position sensitivity. Likewise, the *y* strips behave similarly for the measurement of the gamma-ray location in the *y* direction. Consequently, the location of each gamma-ray interaction event can be determined in 2 dimensions.

# Research Results - 3-D Position-Sensing

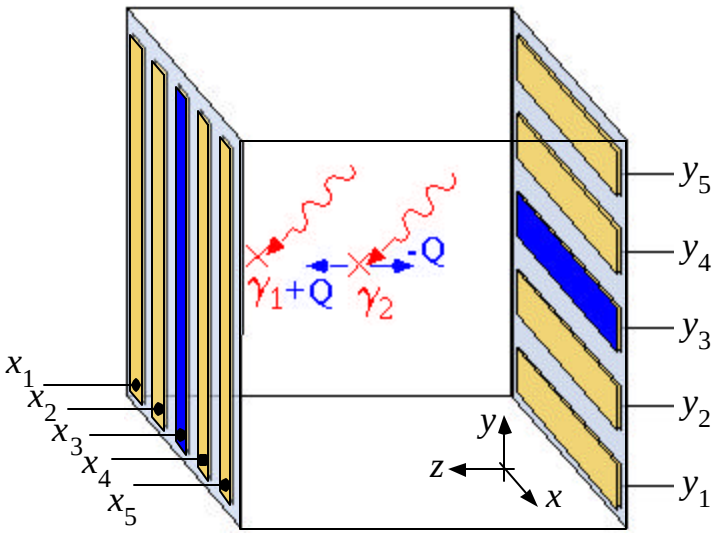
Problem: depth-of-interaction variation (*z* position) - parallax image broadening

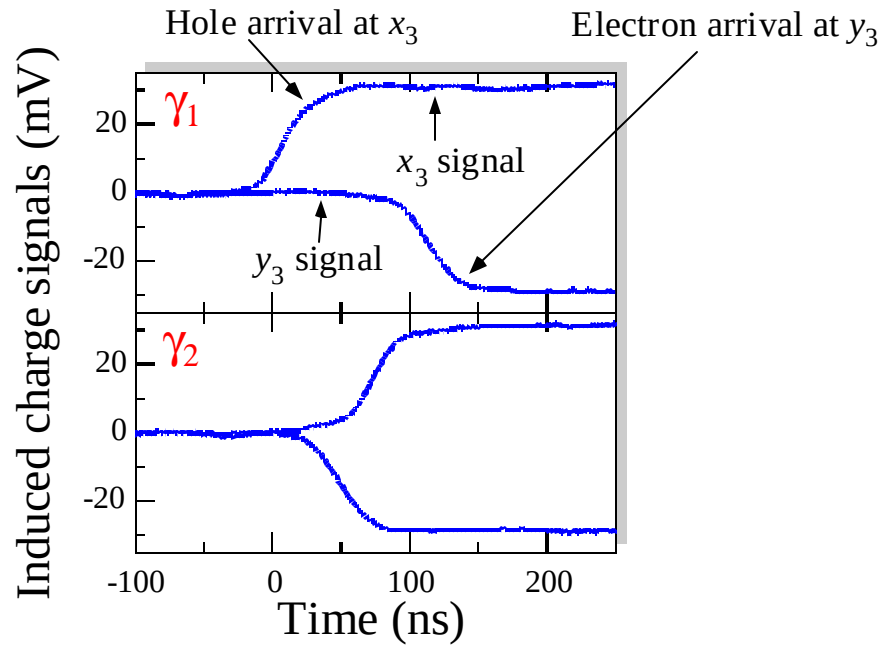



The deeply penetrating nature of gamma rays allows for the in-situ identification of radioactive contaminants through intervening materials. However, this also necessitates thick detectors in order to stop the gamma rays. The random nature of the gamma-ray interaction leads to a variation in the depth (*z* position) at which the gamma rays interact. If the gamma-ray interaction locations are determined only in the *x* and *y* directions, as is conventionally done, a large uncertainty exists in the *z* locations. The result of this uncertainty is a loss of spatial resolution (parallax image broadening).

# Research Results - 3-D Position-Sensing

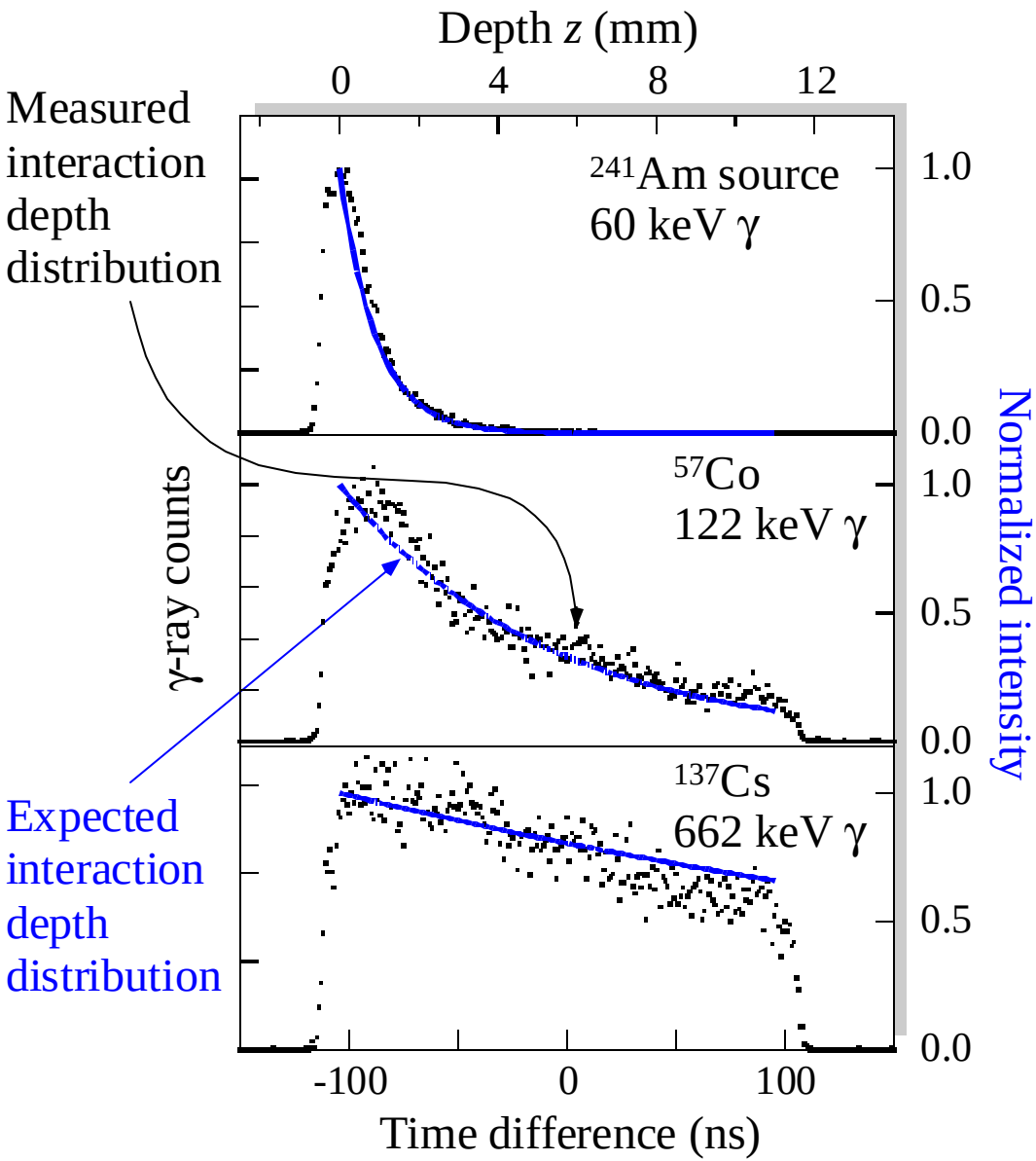
Solution: newly-developed depth-of-interaction ($z$) measurement




In addition to the $x$ and $y$ position measurement for each gamma-ray interaction event, the depth of each interaction can be determined based on the time difference between the hole arrival at an $x$ strip and the electron arrival at a $y$ strip. The plots on the right show induced charge signals measured from the $x_3$ and $y_3$ strips of one of our prototype detectors. Each pulse pair results from the collection of the charge generated by a 122 keV gamma ray. For the $\gamma_1$ event, the hole pulse occurs well before the electron pulse thereby indicating that the event took place at a depth near the $x_3$ strip. In contrast, for the $\gamma_2$ event, the pulses occur at nearly the same time as is expected for an event that occurred near the center of the detector.

# Research Results - 3-D Position-Sensing




These plots are time spectra acquired with one of our prototype Ge detectors and illustrate depth-of-interaction sensing. The time difference corresponds to the depth of the gamma-ray interaction. For comparison the expected exponential decay in the intensity of the gamma rays with depth (solid lines) is superimposed on top of the measured spectra (dots). The lower energy gamma rays are more strongly absorbed and therefore show a more shallow penetration depth.



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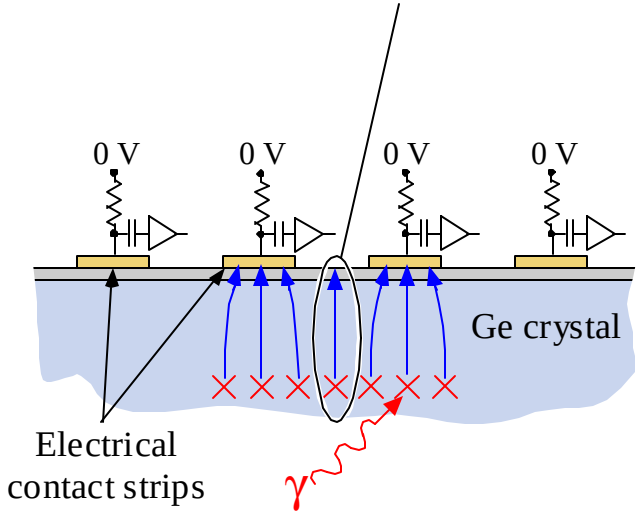
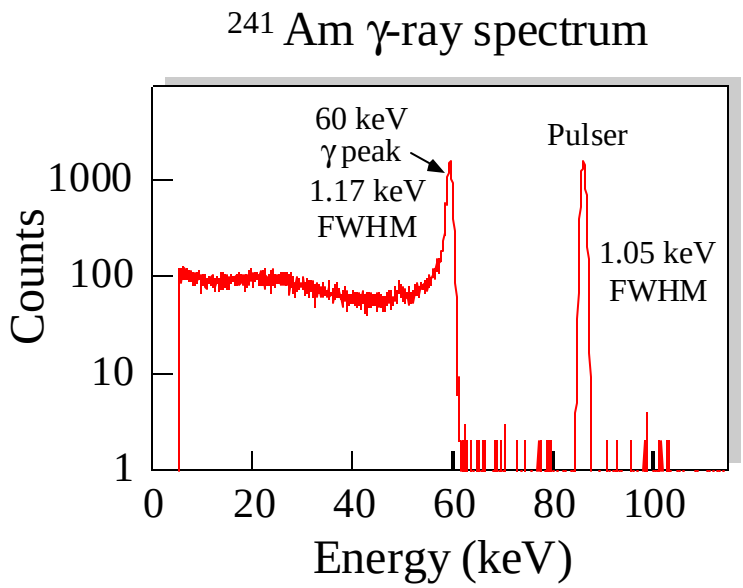
# Research Results - Interstrip Biasing

Problem: incomplete charge collection between strips

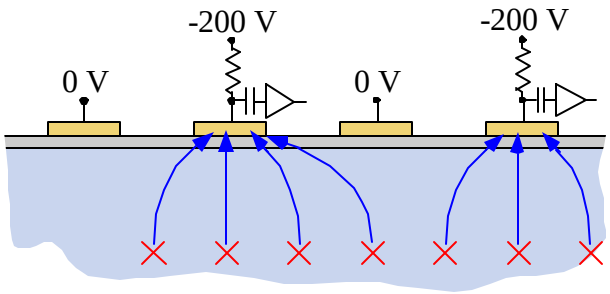


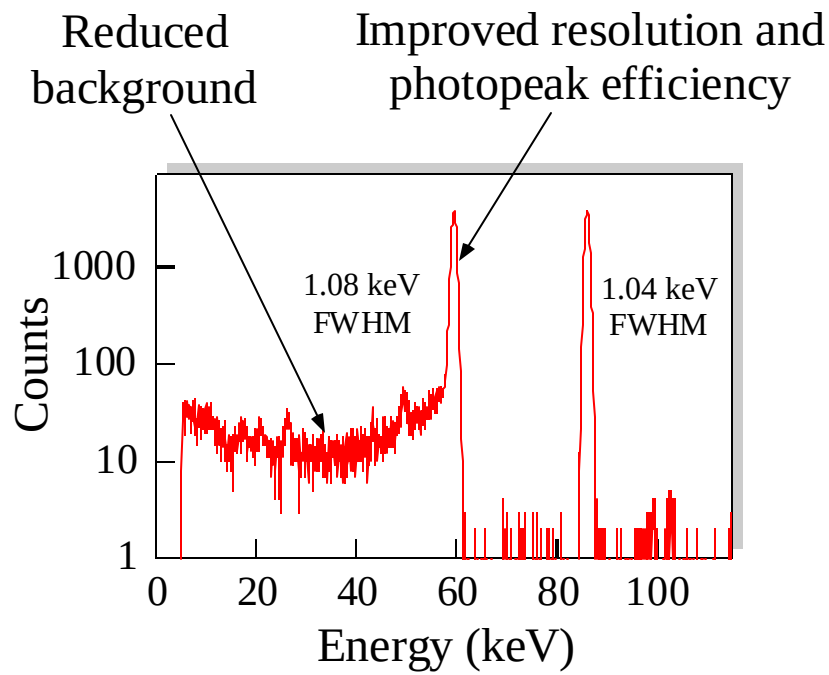




The weak electric field between adjacent strips allows the charge from some gamma-ray interaction events to be collected to the detector surface between strips rather than to the strips themselves. This incomplete charge collection degrades the detector performance by producing a loss of both energy resolution and photopeak efficiency.

# Research Results - Interstrip Biasing

Solution #1: interstrip biasing

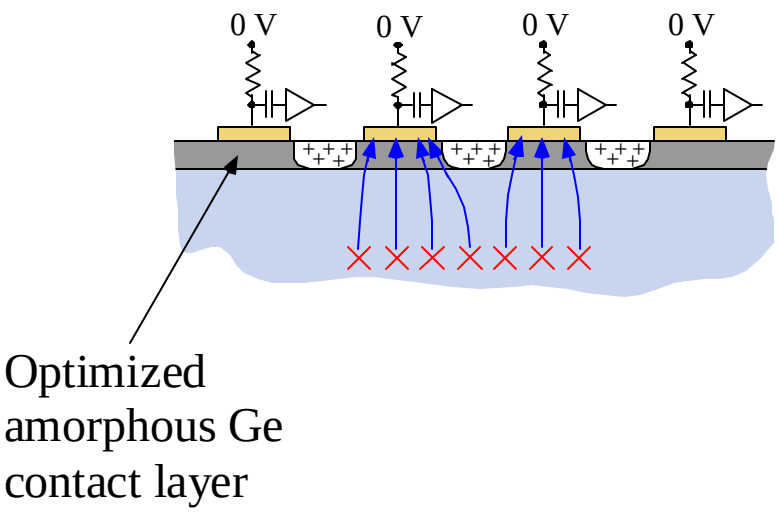


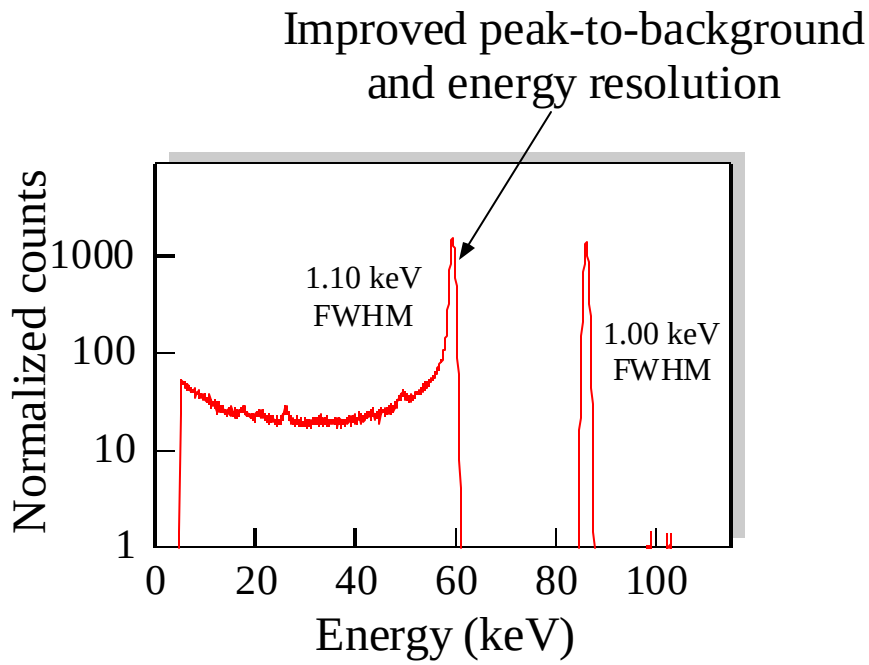




One method to overcome the incomplete charge collection problem is to introduce a potential difference between adjacent strips. This can be accomplished by using only every other strip for signal readout. The remaining strips would then be interconnected to act as field-shaping strips. Through the application of an appropriate bias between the field strips and the sensing strips, the weak lateral electric field at the detector surface can be eliminated, thereby enabling complete charge collection to the sensing strips. Using this technique, the improved $^{241}$Am gamma-ray spectrum shown above was obtained.

# Research Results - Contact Optimization

Solution #2: contact optimization




We have also investigated the influence that the amorphous-semiconductor contact layer has on the charge collection. We have found that the incomplete charge collection problem can be substantially reduced through the appropriate selection of the contact layer properties. This improvement is most likely a result of accumulated charge in the contact layer between strips that inhibits charge collection to the interstrip surfaces. The improved $^{241}$Am gamma-ray spectrum shown above was obtained with a more optimized amorphous-semiconductor contact layer.

# Project Direction and R&D Transition Strategy

- Continued refinements in fabrication processes
- Continued development of improved detector designs and detection techniques
- Application of developed fabrication processes, detector designs, and detection techniques to large-area detectors
- Mechanical structure, electronics, and software development
- Systems integration