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NUCLEAR SCIENCE DIVISION

# Novel Approaches to Radiation Detection

**Ren Cooper**

Lawrence Berkeley National Laboratory

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# Who Am I?

**B.Sc., M.Sc., Ph.D from The University of Liverpool**

- HPGe strip detectors for (medical) gamma-ray imaging

**Postdoc at Oak Ridge National Lab**

- HPGe detectors for $0\nu\beta\beta$ and gamma-ray tracking

**Staff Scientist/Sr. Scientist at Lawrence Berkeley National Lab**

- Radiation detection and imaging, data fusion, sensor networks
- Basic science, nonproliferation, biomedical imaging
- Head, Applied Nuclear Physics Program
- Deputy Director, Nuclear Science Division

# Lecture Topics

- **Lecture 1: Novel HPGe Detectors for Nuclear Physics**
  - Germanium detectors with applications in fundamental science

- **Lecture 2: Multimodal Sensing for Advanced Radiation Detection and Imaging in Real-World Applications**
  - Advanced concepts in radiation detection and imaging for nuclear safety and security

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# Novel HPGe Detectors for Nuclear Physics

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# Some Things I Want You To Consider

- Advanced detectors are essential tools for pushing nuclear science forward, including in real-world applications
- Key measurement quantities include the energy, time, and position of particle/photon interactions
- We need to find ways to extract this information from the signals produced by a detector
- Understanding the fundamentals of detector design and operation can help us find ways to measure new physics and advance applications

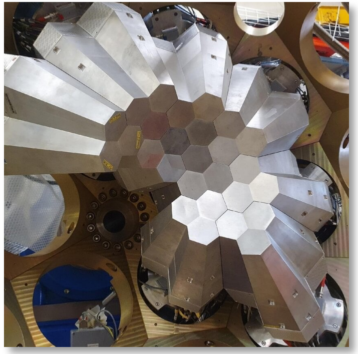
# The Plan

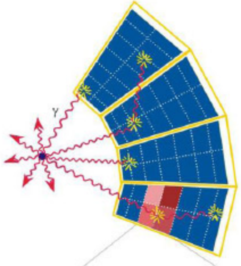
- Use a couple of science use cases to introduce some advanced HPGe detector technologies
- Use these technologies to expose some important concepts related to detector design and operation
- I will skip over a lot of technical details – please ask questions!

# Example 1

**Goal:** Measure the energy and position of gamma-ray interactions with high accuracy

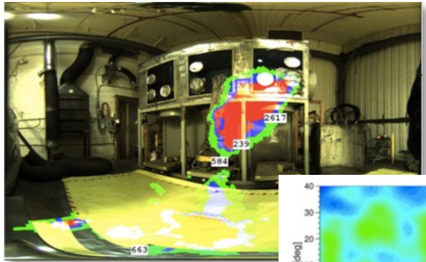
### Gamma-ray tracking/high-resolution gamma-ray spectroscopy

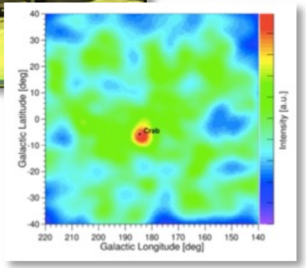


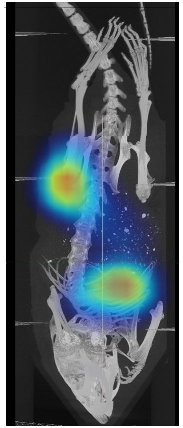



See H. Crawford lectures next week

### High-resolution gamma-ray imaging



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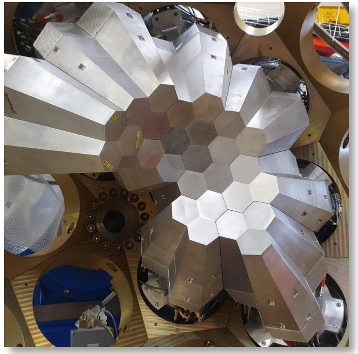
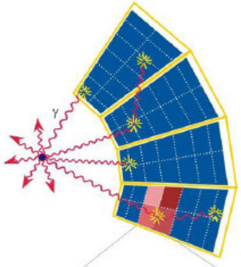
**Goal:** Measure the energy and position of gamma-ray interactions with high accuracy

**Gamma-ray tracking/high-resolution gamma-ray spectroscopy**





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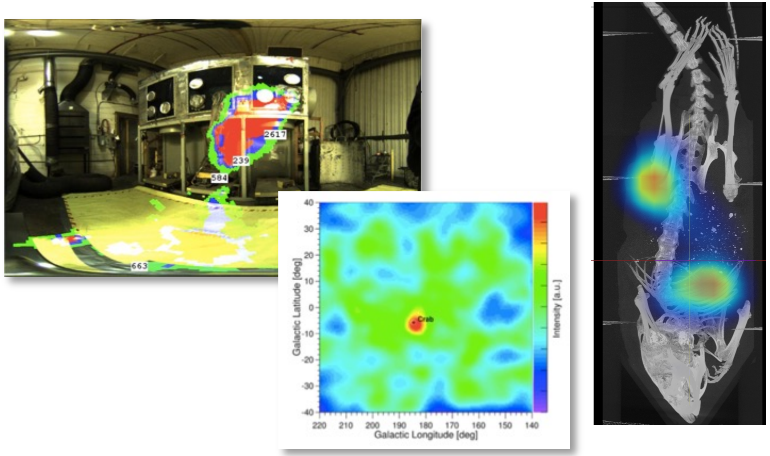
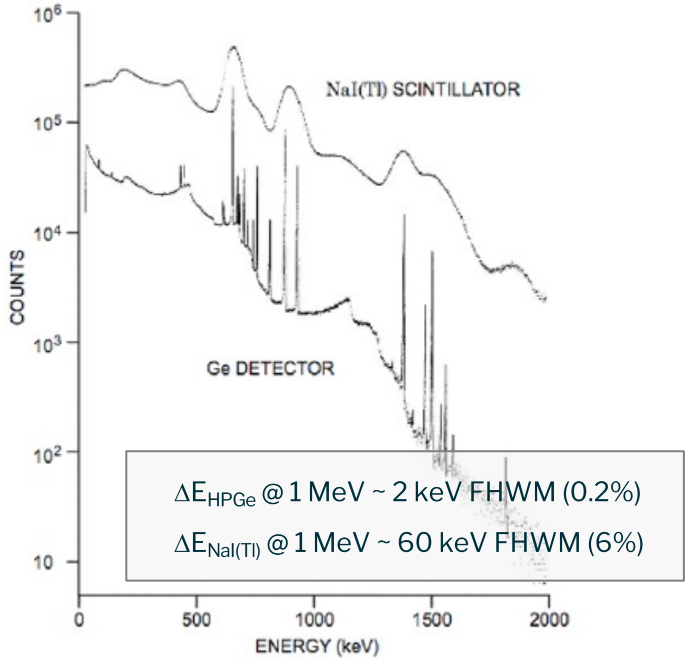
**High-resolution gamma-ray imaging**




**Solution: Position sensitive High Purity Germanium (HPGe) detectors**

# High Purity Germanium Detectors 101

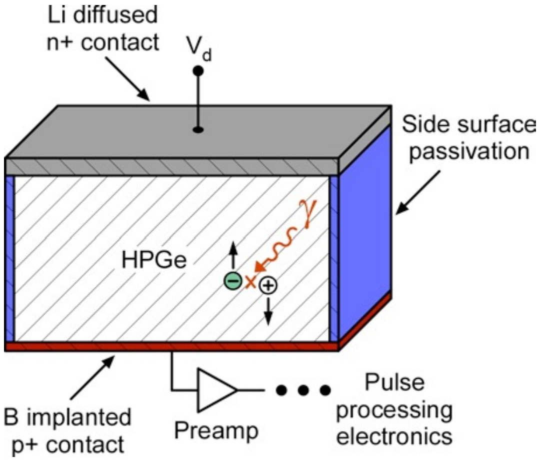
**Gold standard for high-resolution gamma-ray spectroscopy due to their superior energy resolution**



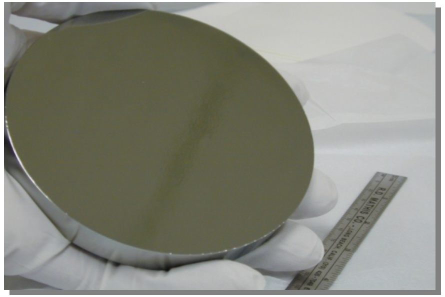

$\Delta E_{HPGe}$ @ 1 MeV ~ 2 keV FHWM (0.2%)

$\Delta E_{NaI(Tl)}$ @ 1 MeV ~ 60 keV FHWM (6%)

J.Cl. Philippot (1970), DOI: 10.1109/TNS.1970.4325723

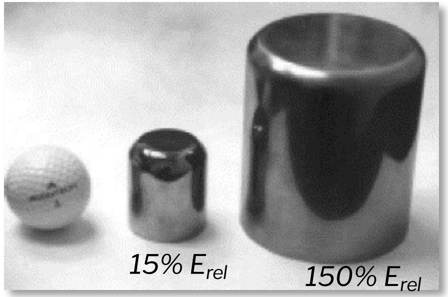



Planar



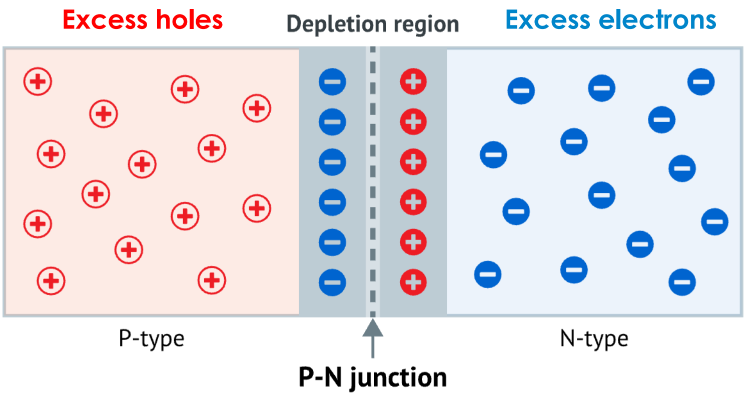
50-100 mm diameter
Up to 20 mm thick

Coaxial



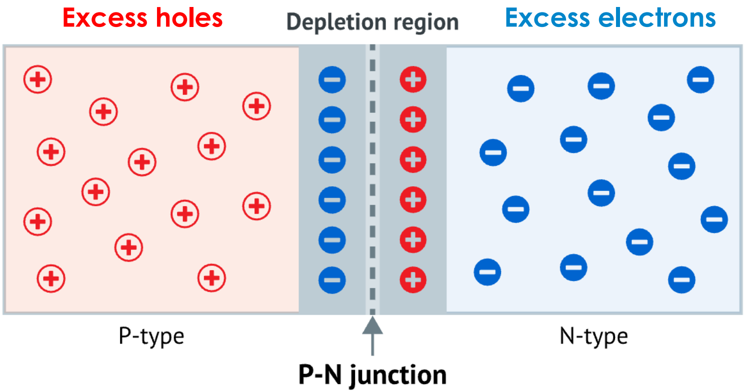

60-80 mm diameter
60 - 100 mm long

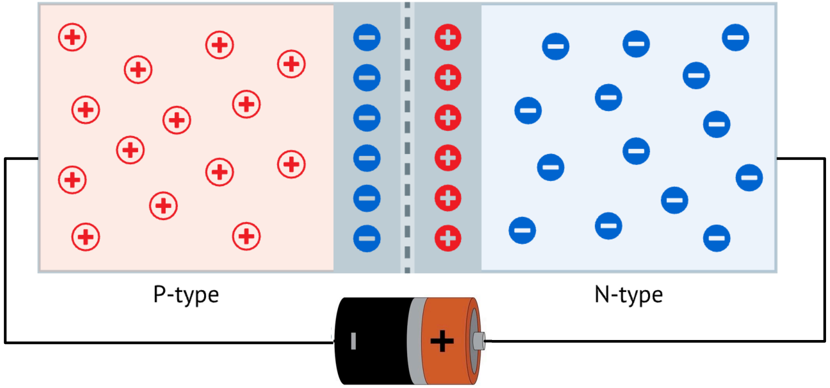
# A Reminder: P-N Junction, Depletion, Reverse Biasing




- Bring n-type and p-type material into contact to create a **p-n junction**
- Diffusion of mobile carriers begins
- Ionized atoms on ‘each side’ create an electric field that opposes further diffusion
- This establishes a **depletion region** free of mobile charge carriers

# A Reminder: P-N Junction, Depletion, Reverse Biasing



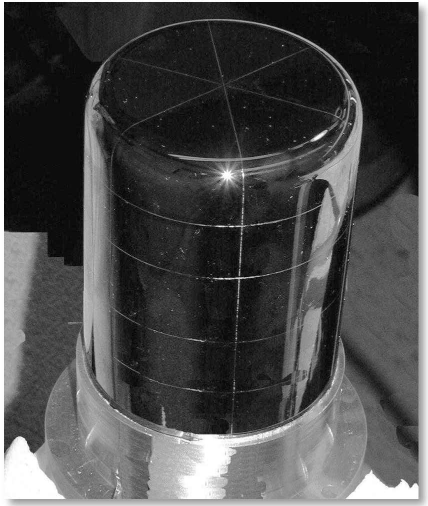

- Bring n-type and p-type material into contact to create a **p-n junction**
- Diffusion of mobile carriers begins
- Ionized atoms on 'each side' create an electric field that opposes further diffusion
- This establishes a **depletion region** free of mobile charge carriers
- Applying a **reverse bias** increases the size of the depletion region
- This is the active area of the detector - we can measure the free charges created via ionization following radiation interactions

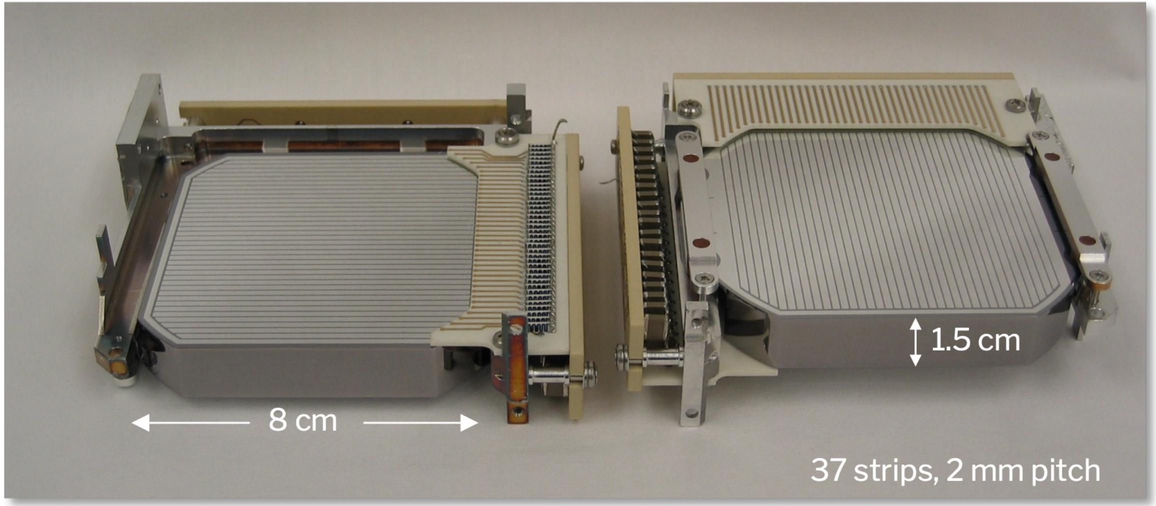
# Tutorial Questions

- What are the factors that influence the energy resolution in semiconductor and scintillation detectors?
- Why is the energy resolution of HPGe so much better than NaI?
- What factors affect the maximum active volume of a HPGe detector?

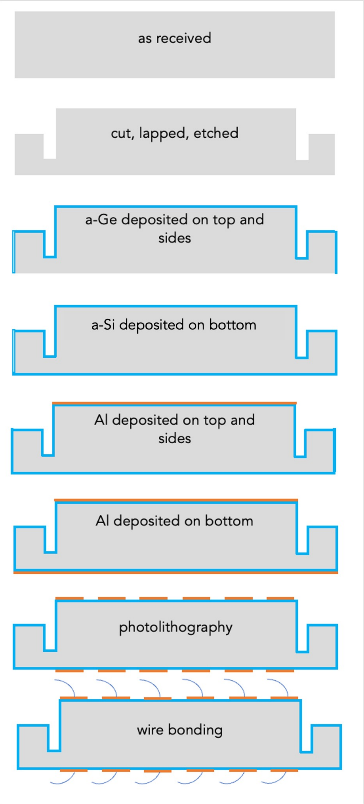
# Highly Segmented HPGe Detectors

- Electrically segment the outer contact of the detector and read each segment out individually
- Identifying which segment the charge was collected to provides position sensitivity





# Aside: Fabrication of HPGe Strip Detectors (@ LBNL)



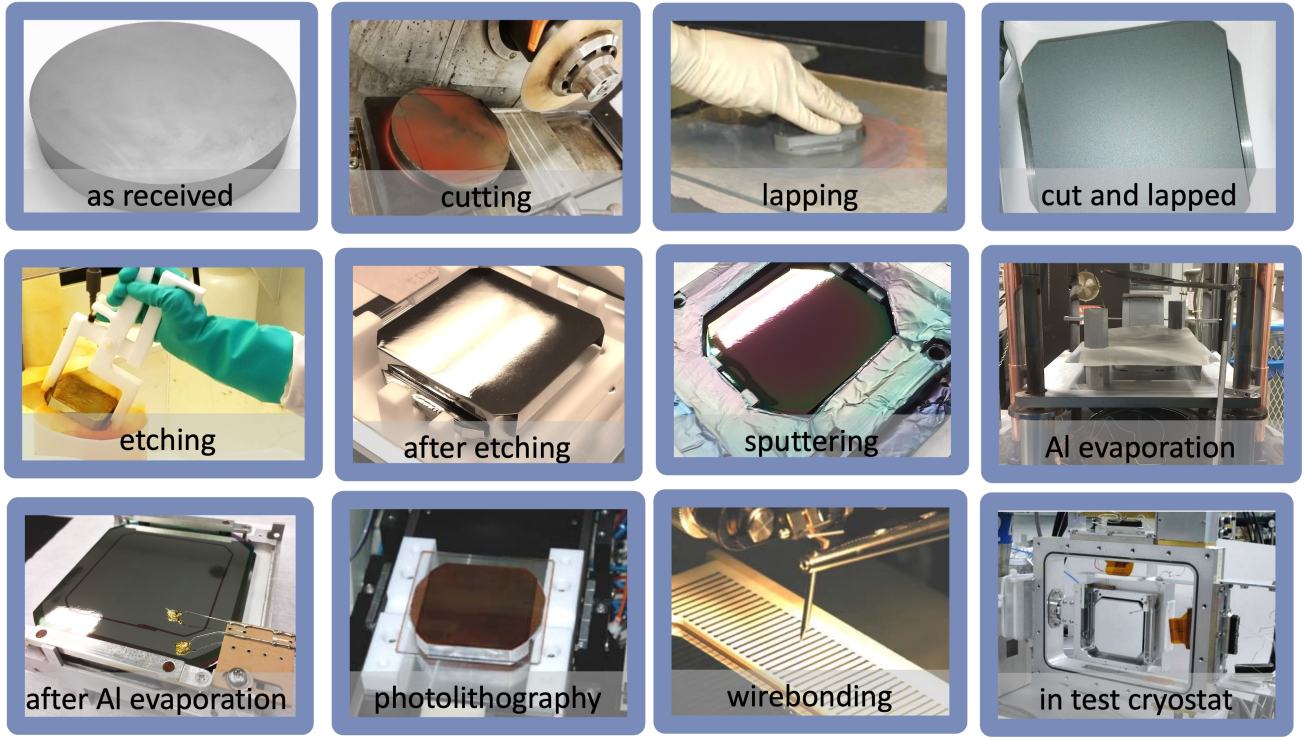





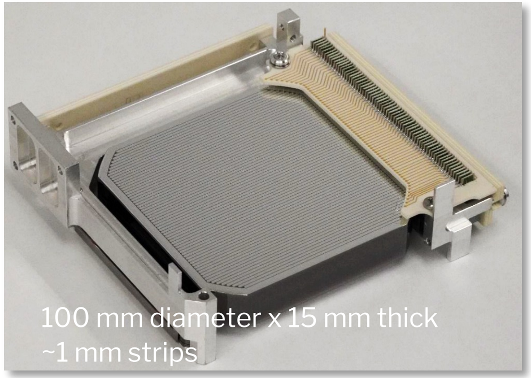

Image credit: Joanna Szornel, LBNL

More details: M. Amman (2018), arXiV:1809.03046

# Example Application: Gamma-Ray Astronomy

- High-resolution gamma-ray imaging system will be launched in 2027
- Science includes study of galaxy formation and distribution of galactic positrons

COSI




https://cosi.ssl.berkeley.edu/

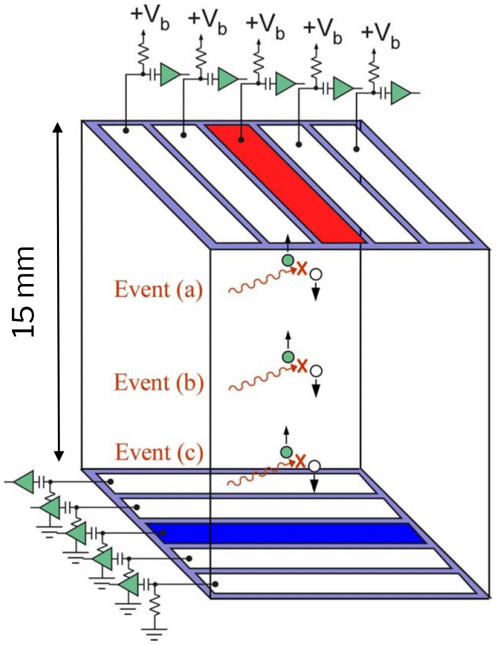
# 3D Position Sensing

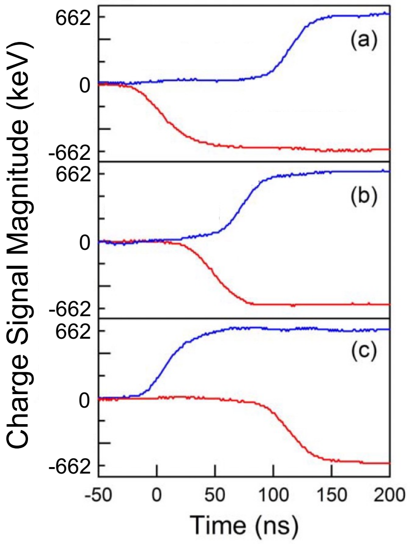
- The segmentation of the detector provides some amount of position resolution
  - Several $mm^3$ to several $cm^3$ depending on the design

- We can further refine this by analyzing the charge vs. time signals recorded at each contact
  - $\sim mm^3$

# 3D Position Sensing

**The shape of the (charge) signals measured on the electrodes depends on the 3D position of the gamma-ray interaction**



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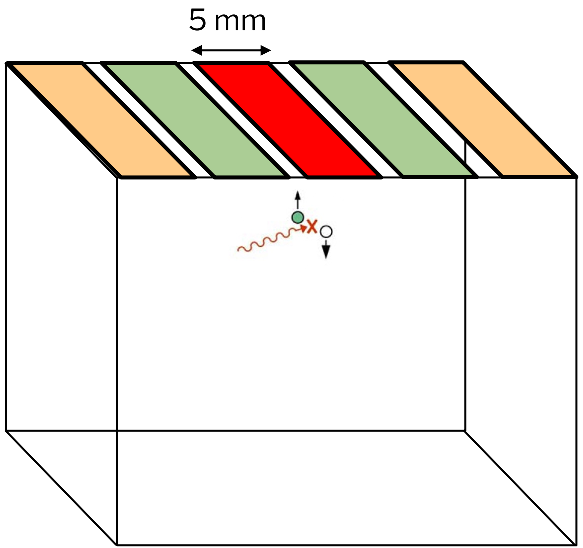



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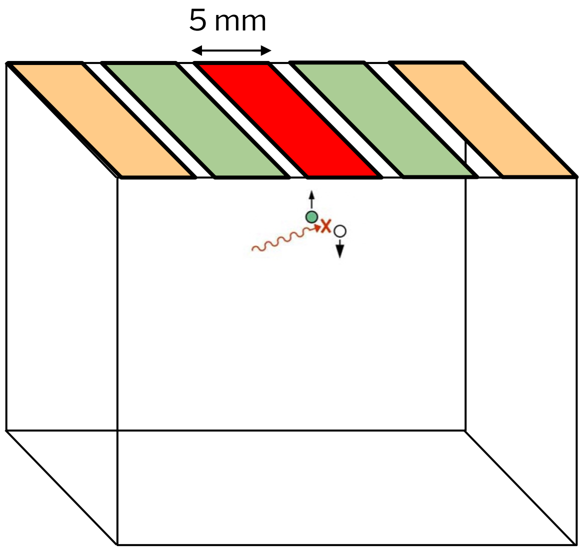


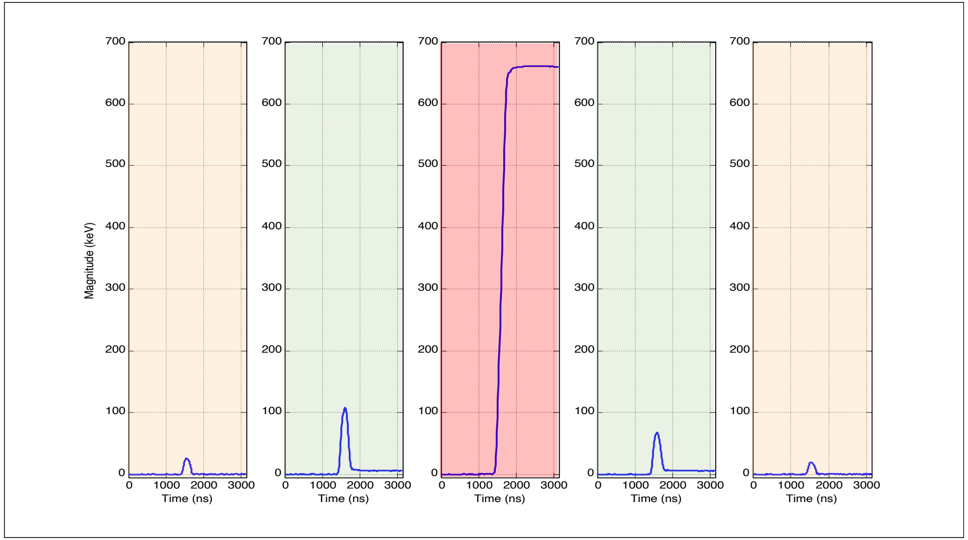


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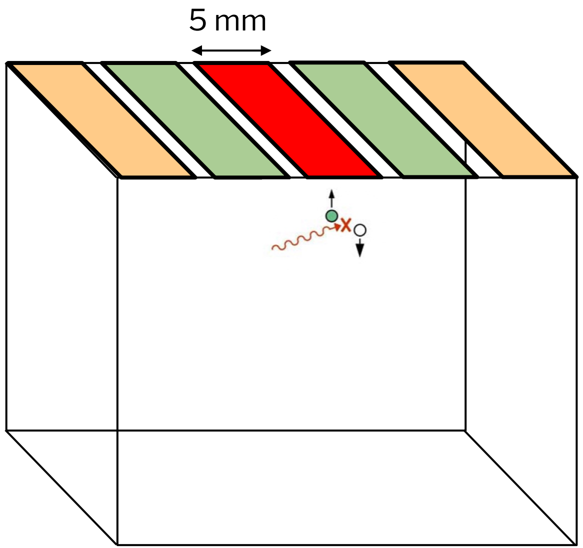


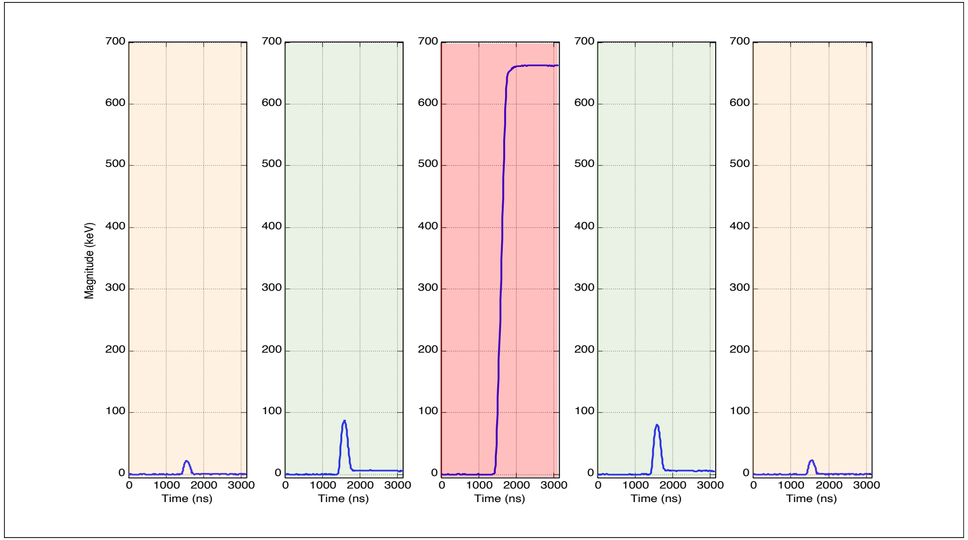


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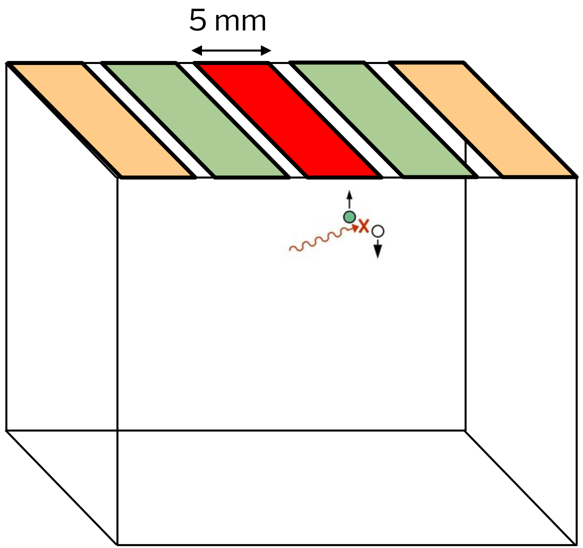


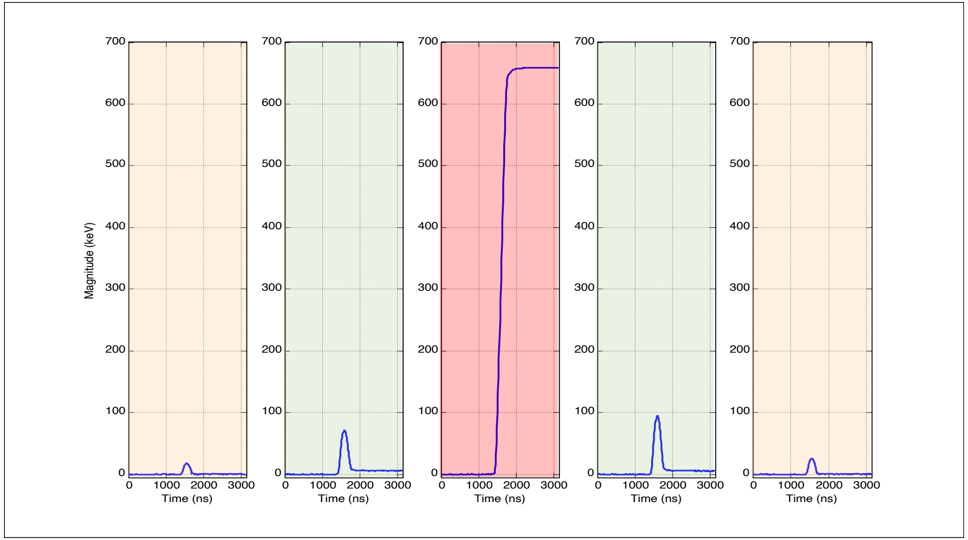


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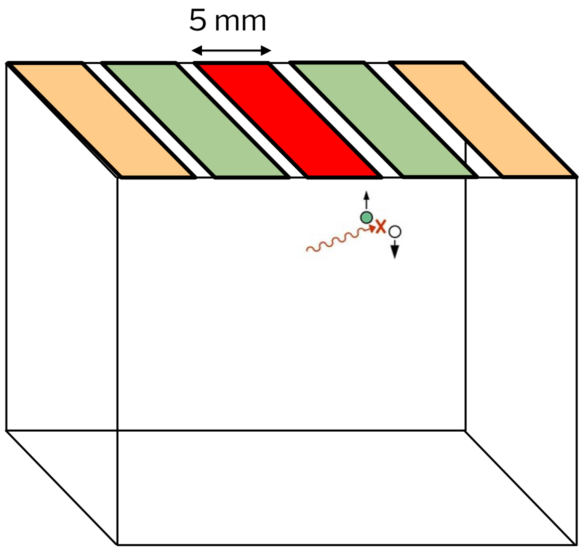


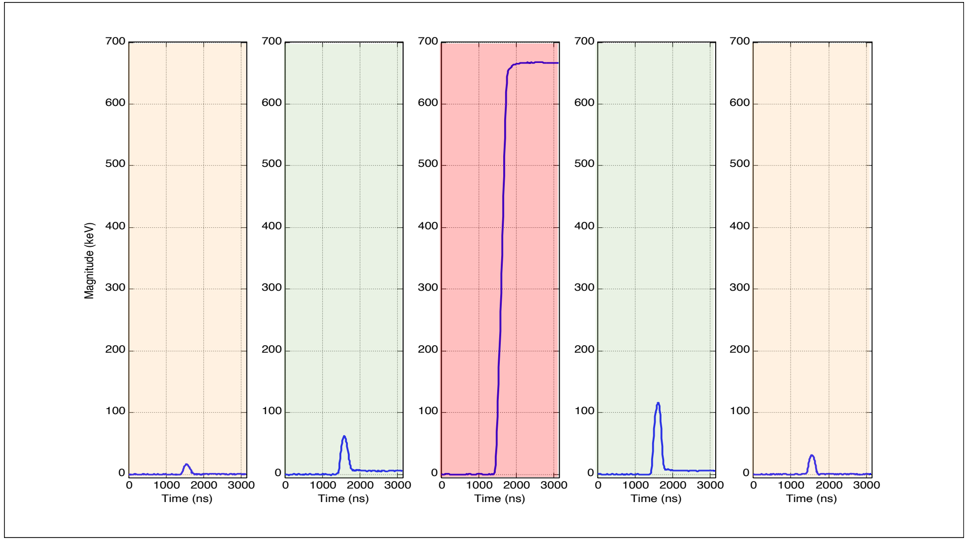


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# Signal Induction

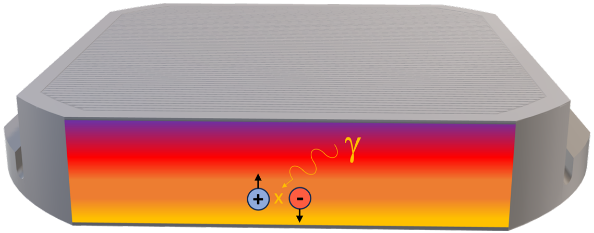
- **Radiation interaction produces electron-hole pairs**

# Signal Induction

- Radiation interaction produces electron-hole pairs
- **Charge cloud drifts to the electrodes under the influence of the applied electric field**

Poisson's equation

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

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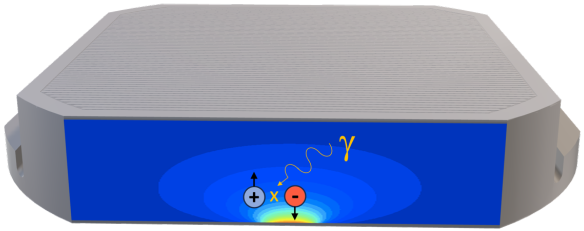
# Signal Induction

- Radiation interaction produces electron-hole pairs
- Charge cloud drifts to the electrodes under the influence of the applied electric field
- **As charges drift through the changing weighting potential, they induce a signal on the electrodes**

Laplace's equation

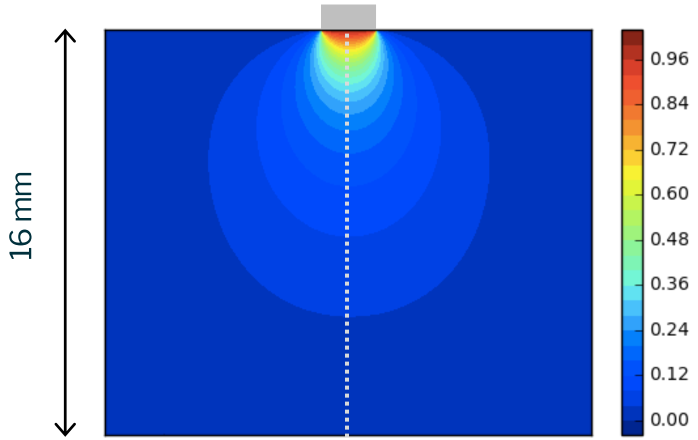
$$\nabla^2 V = 0$$



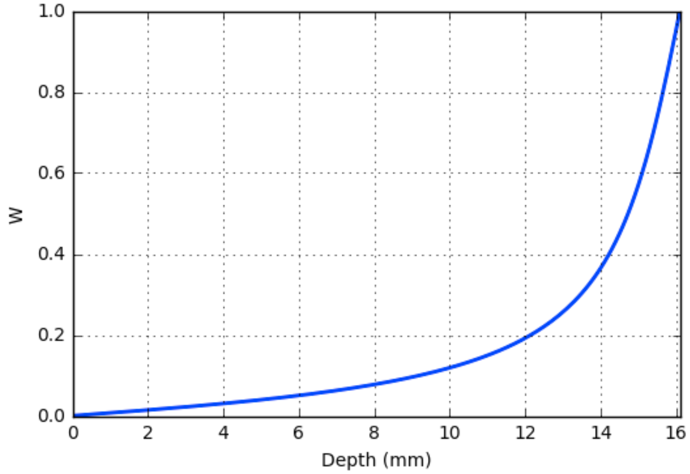
# Wait, What Potential?

**The weighting potential describes the position dependent electrostatic coupling between a charge carrier and an electrode**

Weighting Potential of a single strip




Slice through the Weighting Potential



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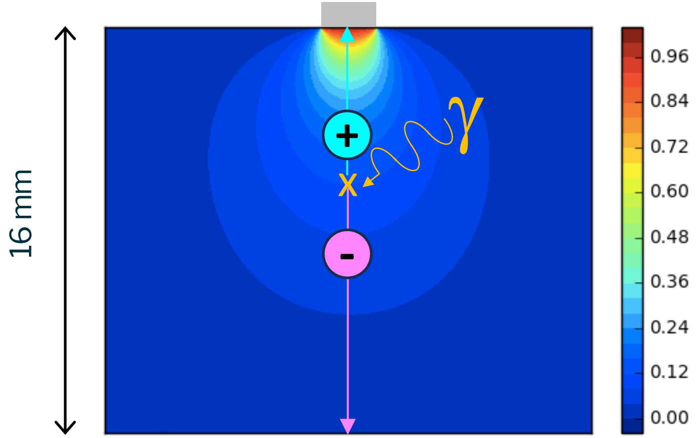


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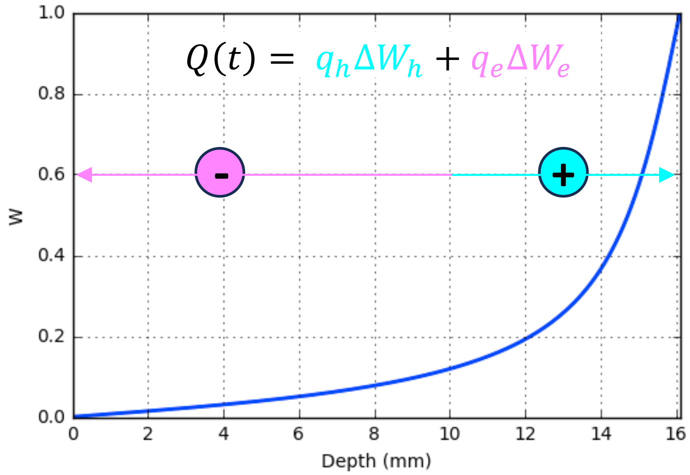

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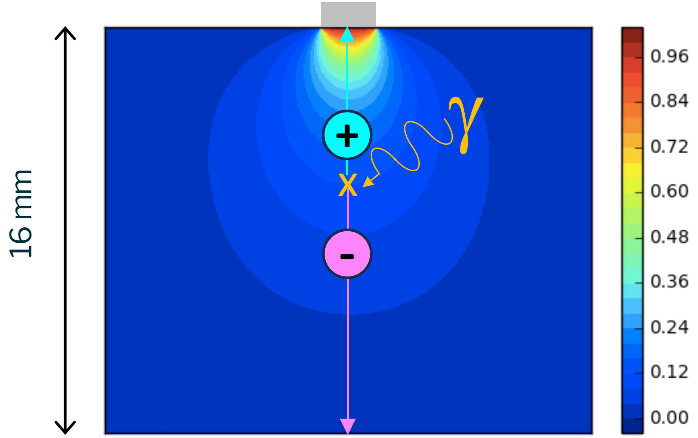
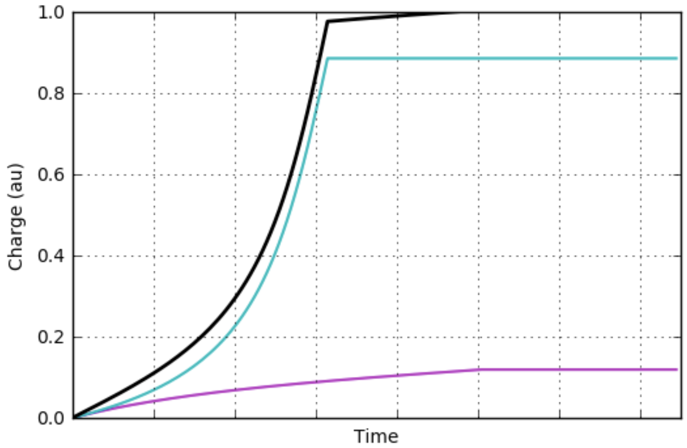



Signal



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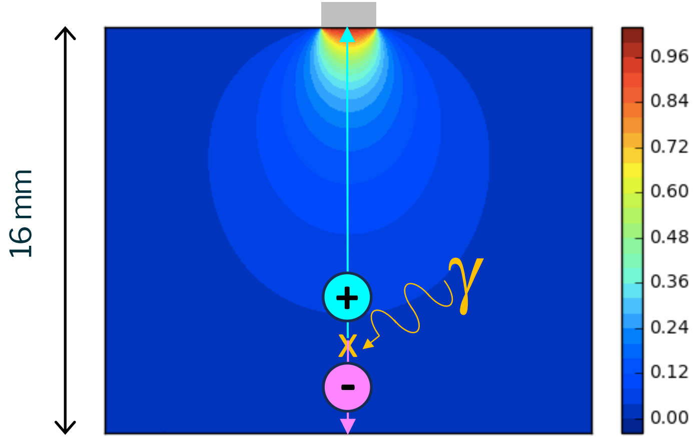


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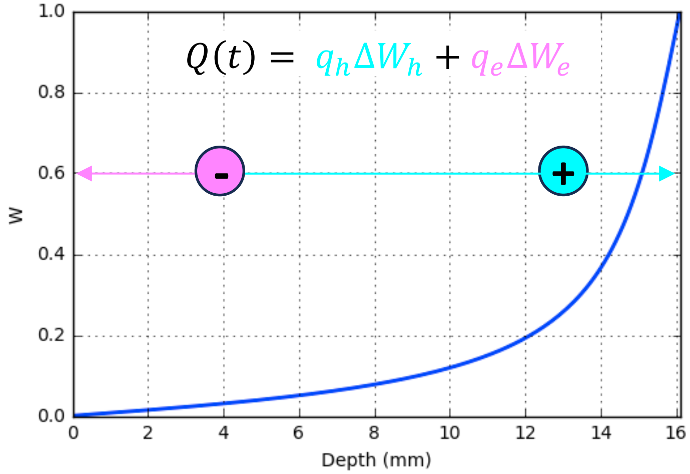

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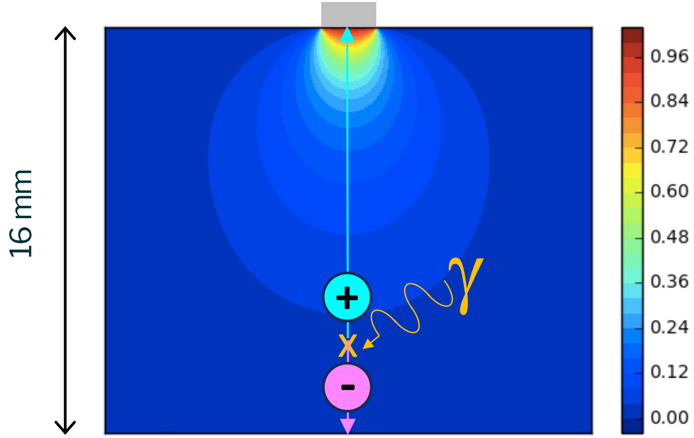


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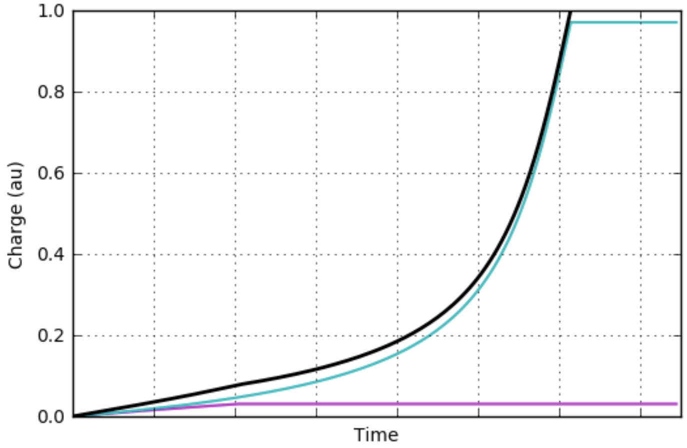


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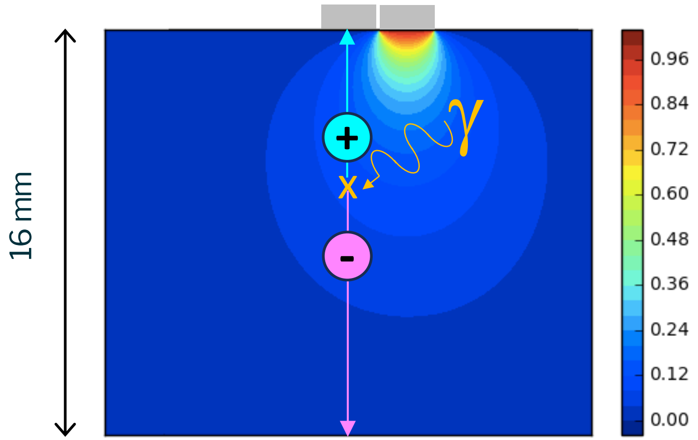
**The Weighting Potential of the neighbouring strip(s) extends into the 'hit' strip to give rise to image charges**

Weighting Potential of a neigbour strip

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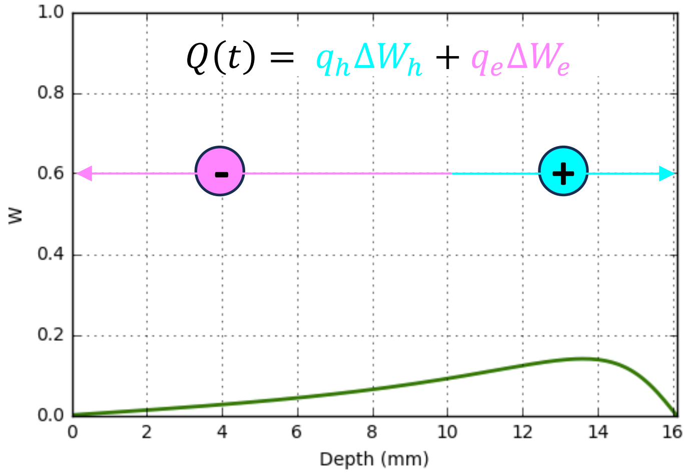

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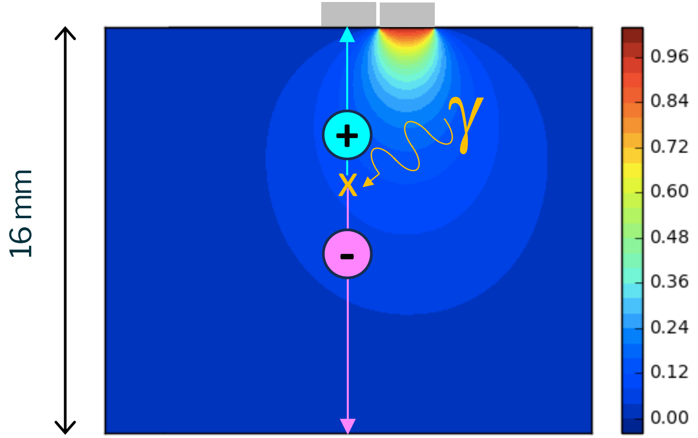
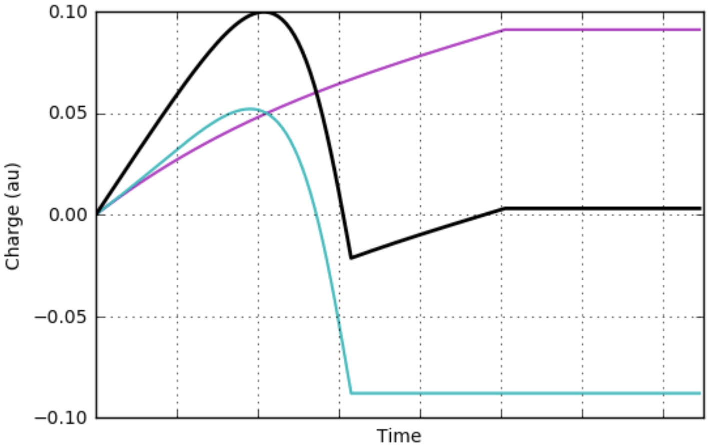



Signal



# Signal Induction

- Radiation interaction produces electron-hole pairs
- Charge cloud drifts to the electrodes under the influence of the applied electric field
- As charges drift through the changing weighting potential, they induce a signal on the electrodes
- **The signal shape is dependent on the position of the interaction**
  - Assuming there is a varying weighting potential (i.e., a weighting field)!

# Signal Induction – Shockley-Ramo Theorem

## Currents to Conductors Induced by a Moving Point Charge

W. SHOCKLEY
*Bell Telephone Laboratories, Inc., New York, N. Y.*
(Received May 14, 1938)

General expressions are derived for the currents which flow in the external circuit connecting a system of conductors when a point charge is moving among the conductors. The results are applied to obtain explicit expressions for several cases of practical interest.

IN the earlier days of vacuum tube technique when the radiofrequencies in use were relatively low compared to those attained at present, it was acceptable to regard the transit of an electron across a vacuum tube as an instantaneous burst of current. At present, however, the time of transit of the electron is of comparable duration with the periods of alternating circuits and it is consequently of interest to know the instantaneous value of the current induced by the moving charge over its entire time of transit.

Before discussing what effect the moving charge has, we must introduce certain conventions as to what part of the total field is to be attributed to the charge and what part to other causes. It proves most convenient to consider that all of the conductors are grounded and to examine the currents to them through the external circuit due to the motion of the charge. If the voltages on the conductors are varying, however, charges will be induced and currents will flow as dictated by the coefficients of capacity. In keeping with the superposition principle,[1] the net current is found by adding the currents induced by the moving charge (or each moving charge if there are several) and the currents due to changing voltages.

We are thus led to consider the charges and currents induced on a system of grounded stationary conductors by the motion of a point charge. If we have a system of grounded conductors, perhaps as illustrated in Fig. 1, numbered 1, 2, $\cdots$ $n$, say, then the charge $q_1$ induced on conductor 1 due to a unit point charge in the space is calculated as follows: Let conductor 1 be at unit potential and the others be grounded and let the space between the conductors be free of charge. The electrostatic potential produced by this situation has the value $V_1(r)$ at the arbitrary point $r$ of space. Then, in terms of this potential distribution, the charge, $q_1$, induced on 1 by a unit charge at $r$ is

$$q_1 = -V_1(r). \quad (1)$$

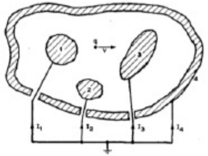


FIG. 1. Schematic representation of conductors and currents.

[1] Jeans, *Mathematical Theory of Electricity and Magnetism*, fourth edition, p. 90.



## Currents Induced by Electron Motion*

SIMON RAMO†, ASSOCIATE MEMBER, I.R.E.

*Summary—A method is given for computing the instantaneous current induced in neighboring conductors by a given specified motion of electrons. The method is based on the repeated use of a simple equation giving the current due to a single electron's movement and is believed to be simpler than methods previously described.*

### INTRODUCTION

IN designing vacuum tubes in which electron transit-time is relatively long, it becomes necessary to discard the low-frequency concept that the instantaneous current taken by any electrode is proportional to the number of electrons received by it per second. Negative grids, it is known, may carry current even though they collect no electrons and current may be noted in the circuit of a collector during the time the electron is still approaching the collector. A proper concept of current to an electrode must consider the instantaneous change of electrostatic flux lines which end on the electrode and the methods given in the literature for computing induced current due to electron flow are based on this concept.

A method of computing the induced current for a specified electron motion is here explained which is believed to be more direct and simpler than methods previously described. In the more difficult cases, in which flux plots or other tedious field-determination methods must be used, only one field plot is needed by the present method while the usual methods require a large number.

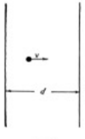



Fig. 1

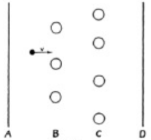



Fig. 2

### METHOD OF COMPUTATION

The method is based on the following equation, whose derivation is given later:

$$i = E_v ev \quad (1)$$

where $i$ is the instantaneous current received by the given electrode due to a single electron's motion, $e$ is the charge on the electron, $v$ is its instantaneous velocity, and $E_v$ is the component in the direction $v$ of that electric field which would exist at the electron's instantaneous position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded. The equation involves the usual assumptions that induced currents due to magnetic effects are negligible and that the electrostatic field propagates instantaneously.

### SIMPLE EXAMPLE

A simple example is offered in the computation of the instantaneous current due to an electron's motion between two infinite plates (Fig. 1). (The result is a starting point for the analysis of a diode, for example, when the transit-time is long.)

From (1) we obtain immediately

$$i = evE_v = \frac{ev}{d} \cdot$$

In the literature[1] it is stated that this same result is deduced from image theory. This involves the setting up of an infinite series of image charges on each side of the plates for a given position of the electron and a consideration of the total flux crossing one of the planes due to the series of charges, a method which is lengthy and requires no little familiarity with methods of handling infinite series.

### THE GENERAL CASE

Consider a number of electrodes, $A$, $B$, $C$, $D$, in the presence of a moving electron (Fig. 2) whose path and instantaneous velocity are known. A tedious way to find the current induced in, say, electrode

* Decimal classification: R138. Original manuscript received by the Institute, September 16, 1938.
† General Engineering Laboratory, General Electric Company, Schenectady, N. Y.

[1] D. O. North, "Analysis of the effects of space charge on grid impedance," PROC. I.R.E., vol. 24, pp. 108–158; February, (1936).



**W. Schockley, J. Appl. Phy. 9 635 (1938)**

**S. Ramo, Proc. IRE 27 (1939) 584**

# Signal Induction – Shockley-Ramo Theorem Revisited

*Ann. Rev. Nucl. Part. Sci. 1988. 38: 217–77*


LOW-NOISE TECHNIQUES IN DETECTORS

*Veljko Radeka*

Brookhaven National Laboratory, Upton, New York 11973

Some more recent discussions of the Schockley-Ramo theorem

N·H
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Nuclear Instruments and Methods in Physics Research A 463 (2001) 250–267

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Review of the Shockley–Ramo theorem and its application in semiconductor gamma-ray detectors

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Received 10 July 2000; received in revised form 7 November 2000; accepted 14 November 2000

BERKELEY LAB



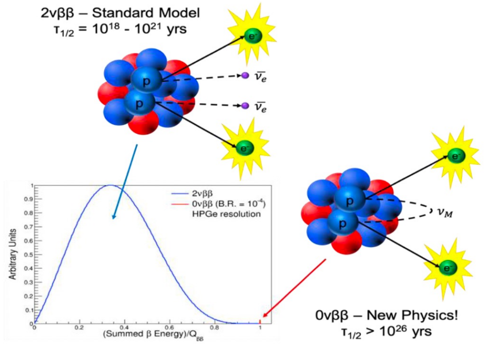
NUCLEAR SCIENCE DIVISION

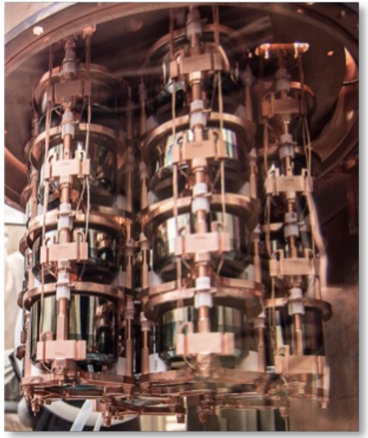
# Example 2

**Goal:** Single-channel HPGe detector* with excellent energy resolution and the ability to distinguish single-site from multi-site interaction events

## Neutrinoless Double Beta Decay Search

*[76]Ge is a candidate isotope for 0νββ decay



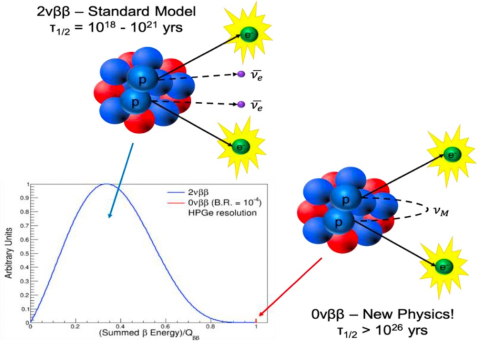



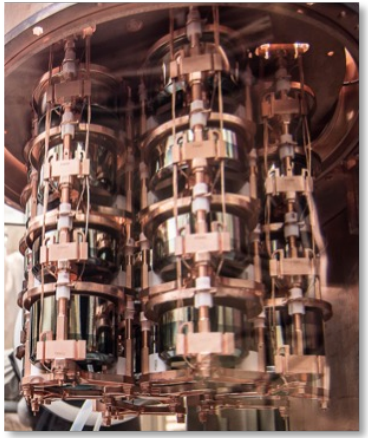
# Example 2

**Goal:** Single-channel HPGe detector* with excellent energy resolution and the ability to distinguish single-site from multi-site interaction events

**Neutrinoless Double Beta Decay Search**

*$^{76}$Ge is a candidate isotope for $0\nu\beta\beta$ decay

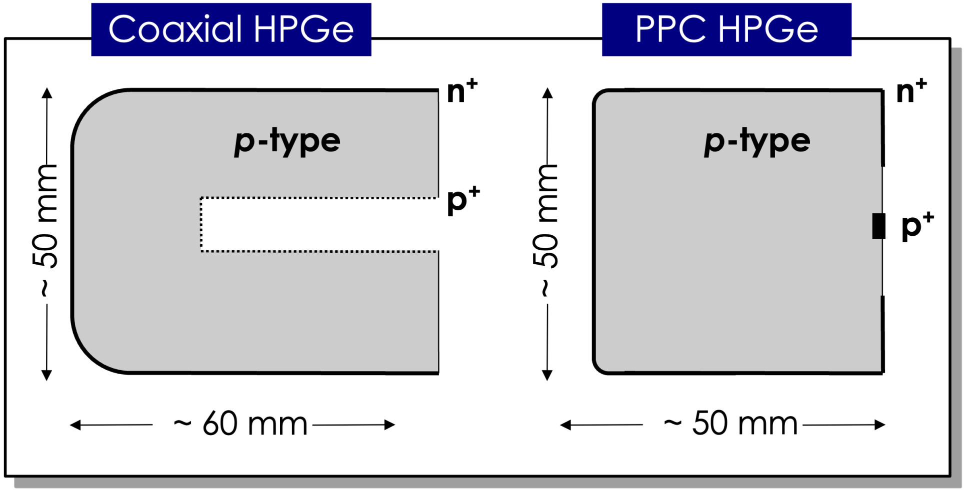


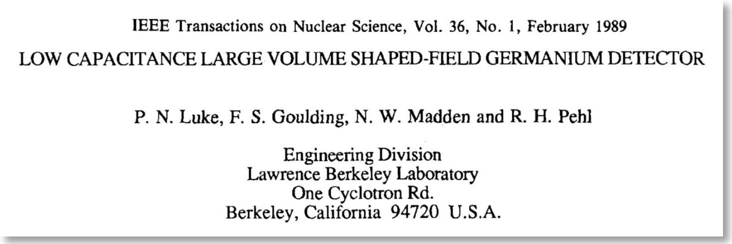



**Solution: Point contact HPGe detectors**

# Point Contact HPGe Detectors

- Large-volume, low-noise HPGe detectors
  - Signal read from point contact
  - Point contact → low capacitance → low noise





IEEE Transactions on Nuclear Science, Vol. 36, No. 1, February 1989

LOW CAPACITANCE LARGE VOLUME SHAPED-FIELD GERMANIUM DETECTOR

P. N. Luke, F. S. Goulding, N. W. Madden and R. H. Pehl

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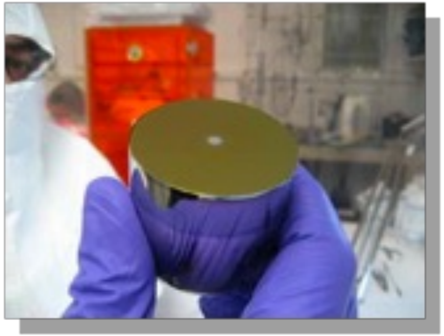
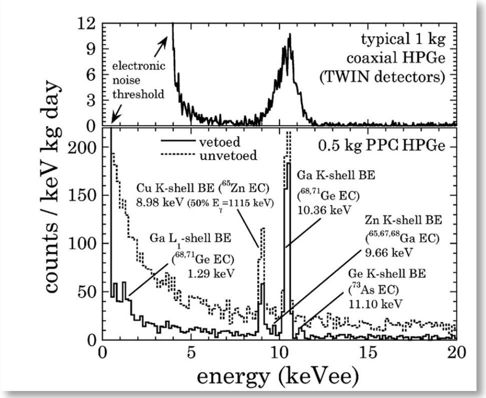


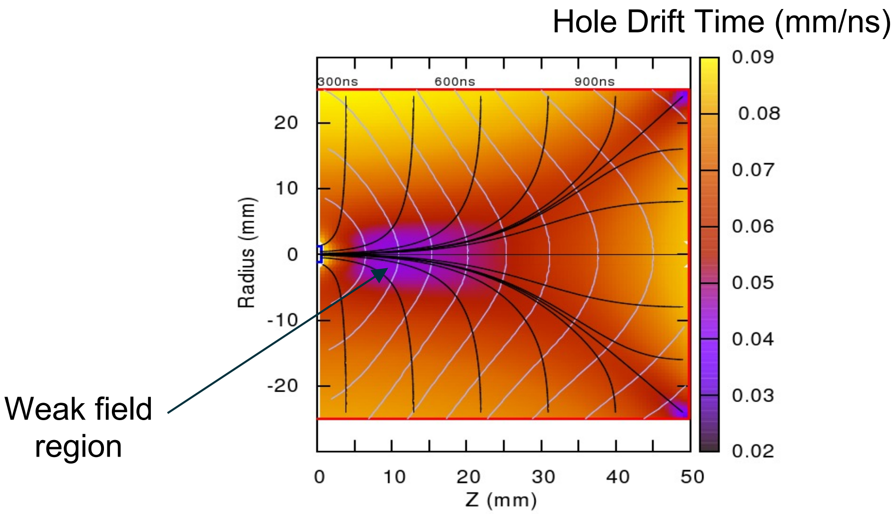


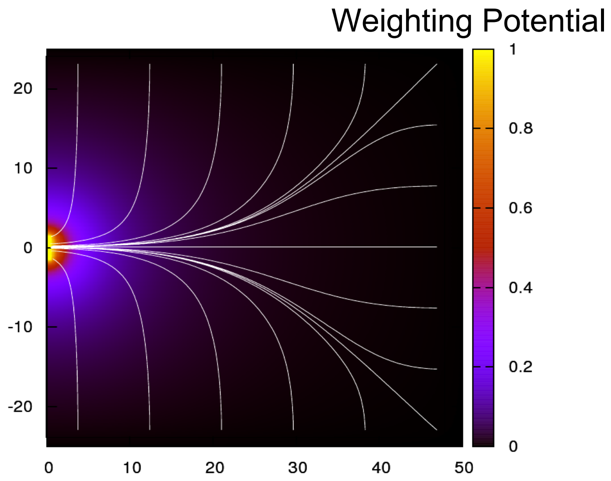



C.E. Aalseth et al, (2008), DOI: 10.1103/PhysRevLett.101.251301

# Point Contact HPGe Detectors

- Point contact geometry results in interesting charge collection and signal induction properties
  - Long charge drift times and highly localized weighting potential



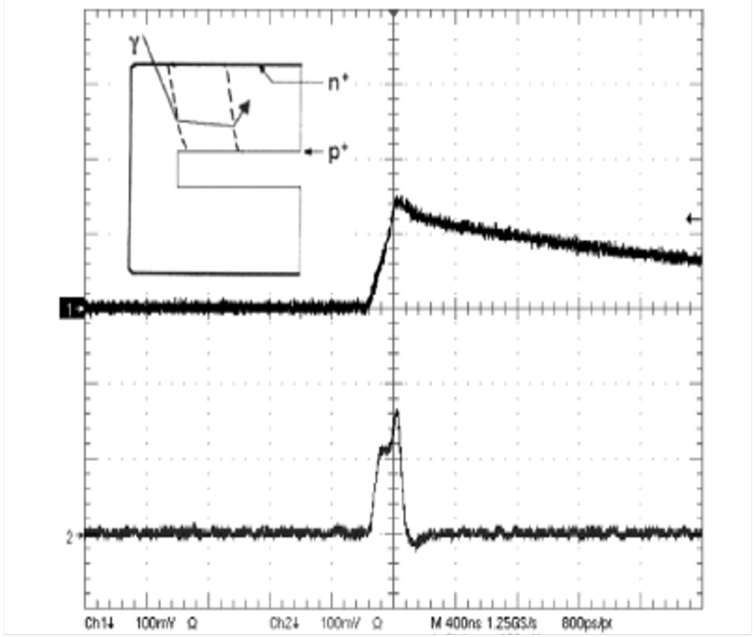




- Significant signal induced only when charge is in close proximity to the point contact
- **Large, sharp pulse induced for each interaction**

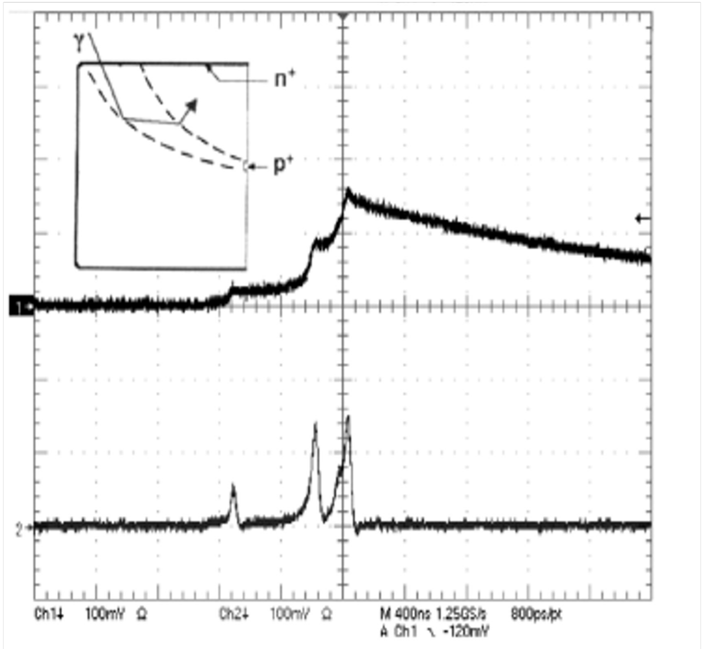
# Point Contact HPGe Detectors

- Powerful discrimination between single and multi-site events

**Coaxial HPGe**




**Point Contact HPGe**






P. Barbeau et al., (2007) DOI: 10.1088/1475-7516/2007/09/009

# Point Contact HPGe Detectors: Bigger is Better!

- Radioactive background is the limiting factor in rare event searches like $0\nu\beta\beta$ experiments

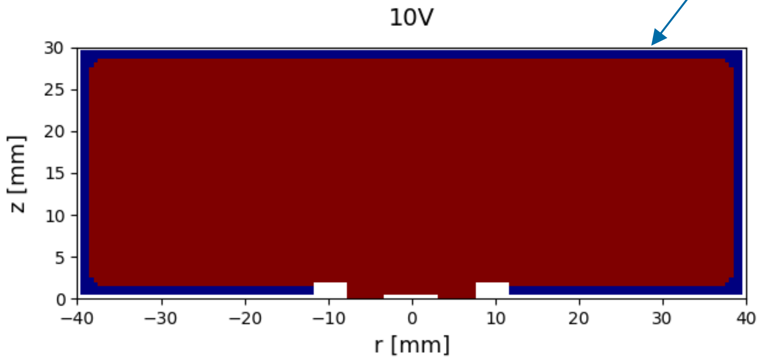
- Using bigger detectors would increase the total ‘target’ mass and reduce the number of detector holders, cables, front end electronics, …

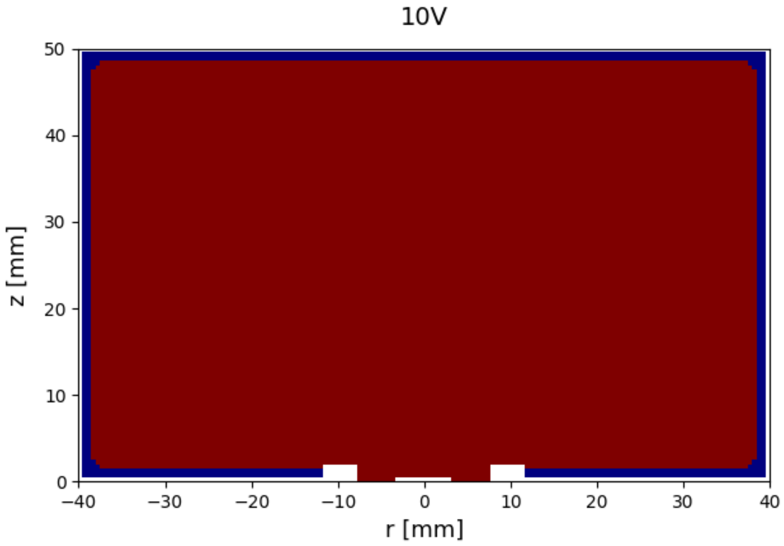
- Okay, so let’s just make bigger detectors….

# Point Contact HPGe Detectors: Bigger is Better!

- But when we make the detectors bigger, they won't fully deplete!

p-n junction




**Depleted volume**

**Non-depleted volume**



Calculation/Animation: David Radford, ORNL

# Q: How Can We Make the Detector Deplete?

**Hint:** Increase the strength of the electric field in the weak-field region

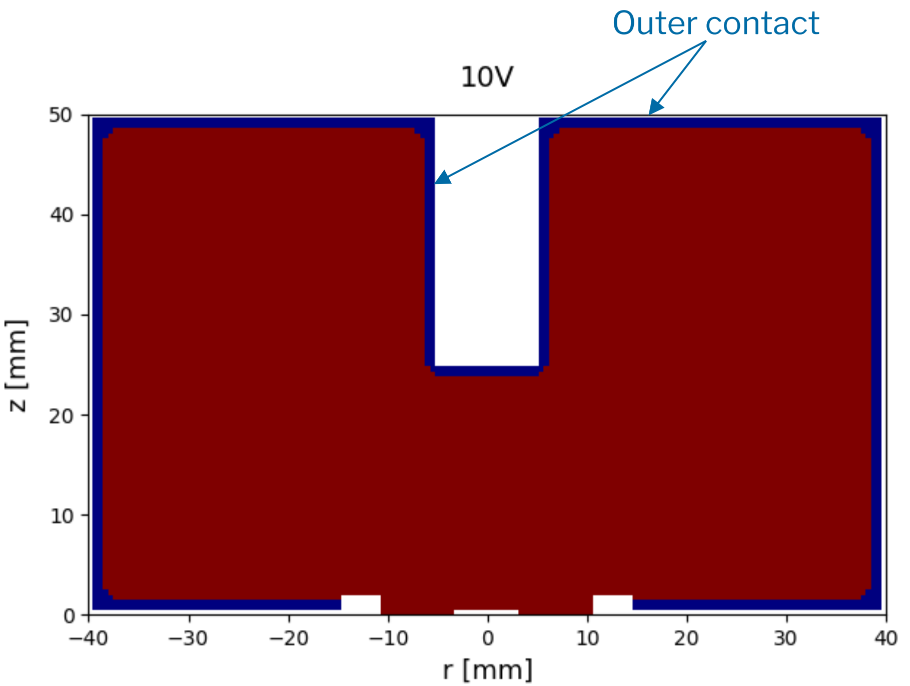
# Q: How Can We Make the Detector Deplete?

**Hint:** Increase the strength of the electric field in the weak-field region

**A**: Add a bore hole!

(removes <1% of mass)

This is called an Inverted Coaxial Point Contact Detector (ICPC)

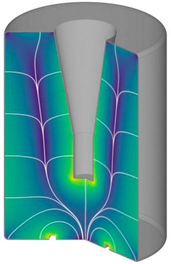



ICPC: R.J. Cooper et al., (2012) DOI: 10.1016/J.NIMA.2011.10.008

Calculation/Animation: David Radford, ORNL

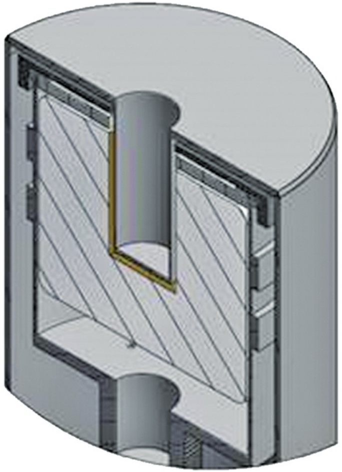
# Inverted Coaxial Point Contact Detectors

- Inverted Coaxial Point Contact (ICPC) detectors - large volume HPGe point contact detectors



LEGEND

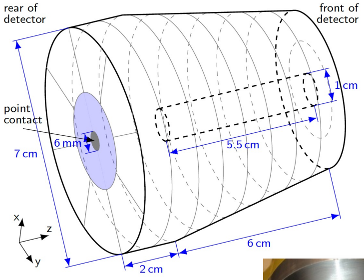

MIRION TECHNOLOGIES



SAGe Well Detector

**Segmented ICPC(s)**

Potential for 2-5x better position resolution than AGATA/GRETA




# Summary

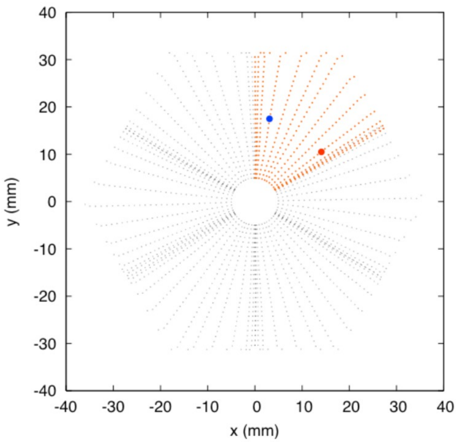
- Advanced detectors are essential tools for pushing nuclear science forward, including in real-world applications
- The energy resolution of HPGe detectors makes them the primary detector type for high resolution gamma-ray spectroscopy
- The signal shape encodes a wealth of important information which can be exploited
- Understanding the fundamentals of detector design and operation can help us find ways to measure new physics and advance applications

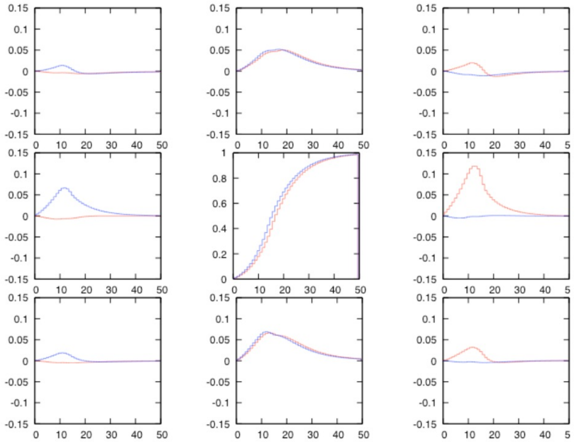
Photo Credit: Mark Bandstra, ANP

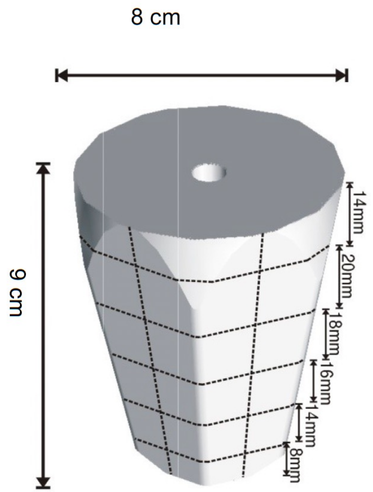
# Supplemental Material

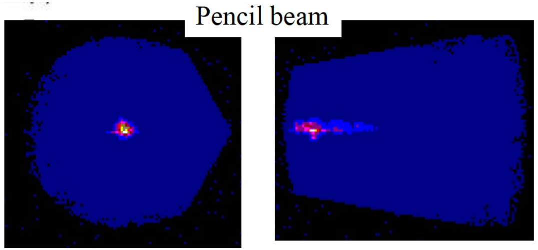
# Example: GRETA

**3D position extracted by fitting measured signals to ‘basis’ of simulated signals from known positions**



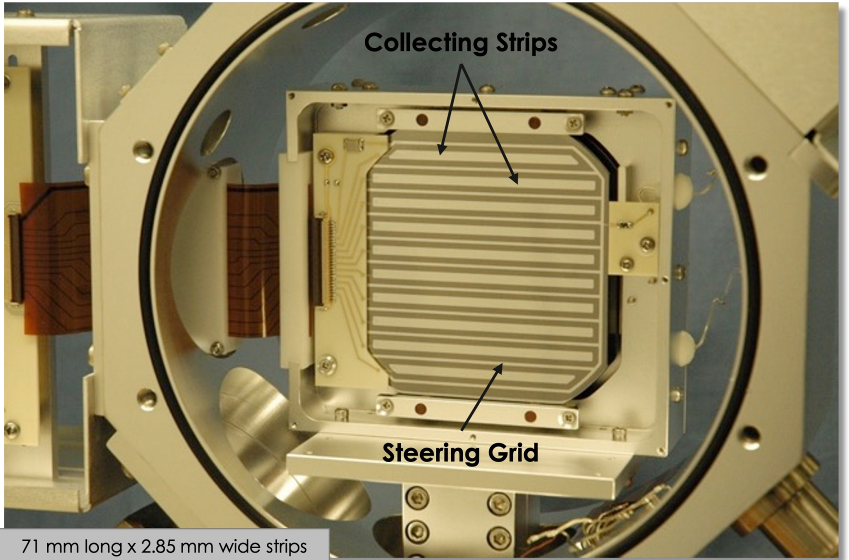



Position resolution better then 2mm (rms)!

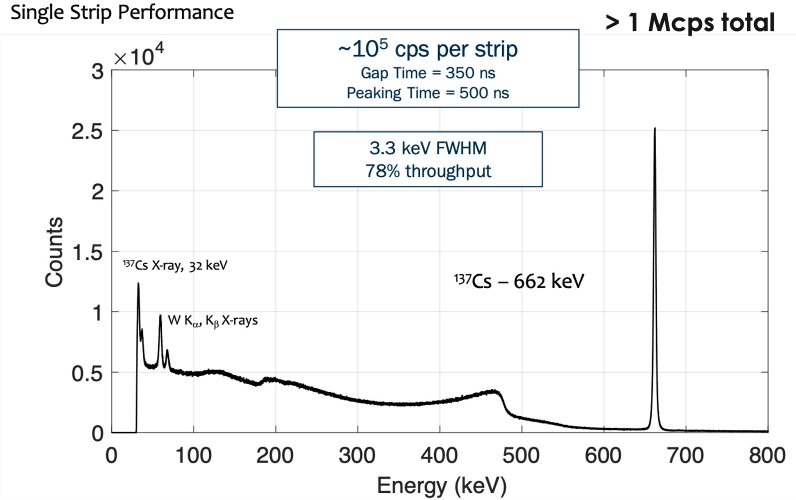
- Position extraction enables gamma-ray tracking
  → doppler broadening correction

# Ultra-High Count Rate HPGe Detectors




- 71 mm long x 2.85 mm wide strips
- 4.75 mm separation
- 0.95 mm wide steering grid

**> 1 Mcps total**




R.J. Cooper *et al.*, NIM A (2015), DOI: 10.1016/j.nima.2015.05.053
R.J. Cooper *et al.*, NIM A (2018), DOI: 10.1016/j.nima.2017.12.053