Development of Field-Shaping Electrode Configurations for High-Resolution Semiconductor Radiation Detectors for Nuclear Sciences, Forensics, and Safeguards

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Outline

- Goals & Objectives
- Approach
- Relevance to DOE-NP, others applications, and opportunities for training of new workforce
- State-of-the art implementations
- Challenges and limitations
- Status
  - Fabrication
  - Characterization
  - Readout
- Summary & Outlook

Goal and Objective

- **High-resolution semiconductor detectors are widely used in basic and applied research and many other fields, not the least recently in mapping and monitoring releases of radioactive materials from the Dai-ichi NPP**
- **Semiconductor detectors provide excellent energy resolution, efficiency, and –along with segmentation – ~mm position resolution in 3D**
- **Two recent developments illustrate the *potential* but also *limitation* in the implementation of advanced concepts, particularly related to the non-contact surfaces:**
  - **Segmentation of contact for position-sensitive detection, etc.**
  - **Point-contact geometries for low-noise applications, etc.**
- ***Limitations* due to imperfect electrical contact and non-contact surfaces**
- ***Goal* of this project is to better understand current and to develop improved processes and technologies to enhance performance and reliability in the operation of advanced semiconductor implementations**
  - **Evaluate experimentally and theoretically detector fabrication processes, electrical contacts, and surfaces resulting in better and more reliable performance of advanced contact configurations**

Uniqueness and Opportunities

- ***LBNL's Semiconductor Detector Laboratory*** **reflect many years of experience in fabricating semiconductor detectors such as Si, Ge, and CZT**
  - **E.g. Amorphous contact and passivation technologies, segmentation and readout schemes, point contact configuration, coplanar-grid CZTs to minimize impact of incomplete charge collection of holes, …**
  - **Established fabrication and characterization processes**
- **Opportunity now for revisiting earlier studies to improve:**
  - **Basic understanding in operation of detectors by including bulk and surface properties (e.g. electrical contacts and non-contact surfaces)**
  - **Understanding of fabrication processes and their impact on detector properties**
  - **Fabrication and operation of detectors**

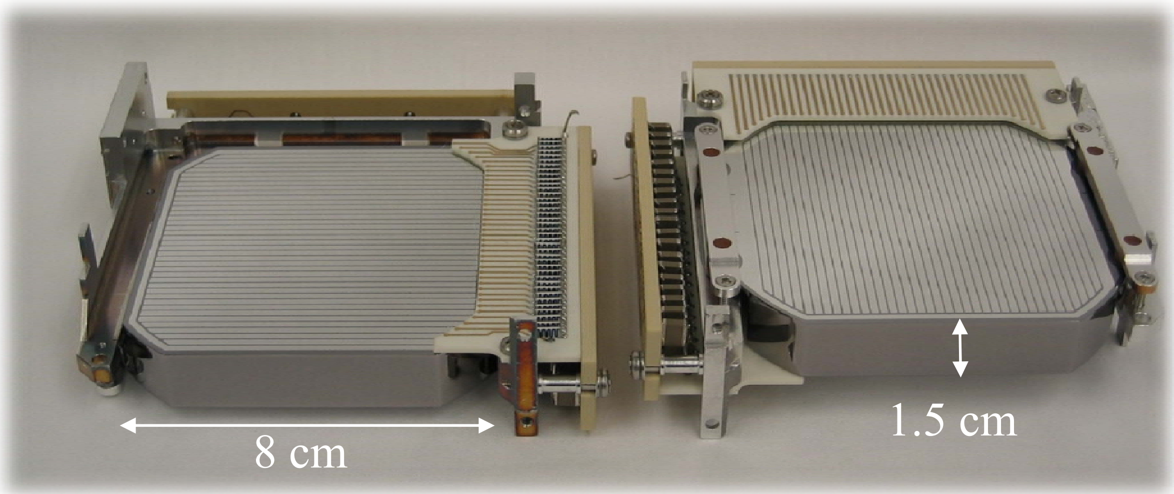
Approach – Basic Timeline

- Year 1
  - Initially, focus on HPGe detector technologies
  - Define and establish baseline in terms of detector fabrication, theory and modeling as well as characterization
  - Establish tools and processes to perform work
- Year 2
  - Perform systematic evaluation of detector and contact fabrication processes
  - Refine characterization and contact/ surface models
- Year 3
  - Apply improved concepts to segmented HPGe detectors and point contact detectors
  - Evaluate improved concepts for other semiconductor detectors

Relevance for Nuclear Physics, Applications and Training

- **Nuclear Physics**
  - Segmentation: Gamma-ray tracking/ imaging
  - Point contacts: Ultra-low noise/ threshold - Physics of weakly interacting particles (neutrinos, WIMPS, etc…)
- **Other Applications**
  - Monitoring/ response/ nuclear forensics – e.g. Fukushima (detection, identification, quantification, imaging)
  - Safeguards and Nonproliferation
  - Homeland security
  - Astrophysics
  - …
- **Training**
  - Coupling to UC Berkeley (Nuclear engineering/ physics) – Quinn Looker (PhD student), Micah Folsom, Anagha Iyengar
  - Junior researcher – Paul Barton, Anders Priest

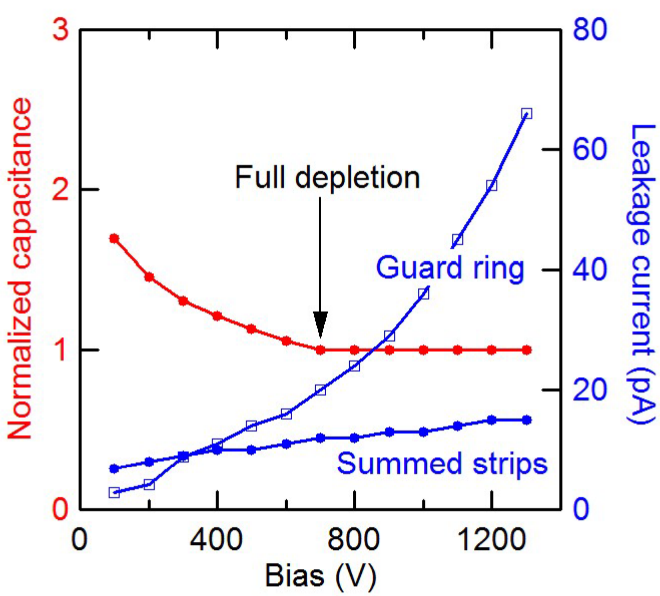
Examples of State-of-the Art - I
Orthogonal Strip Detectors

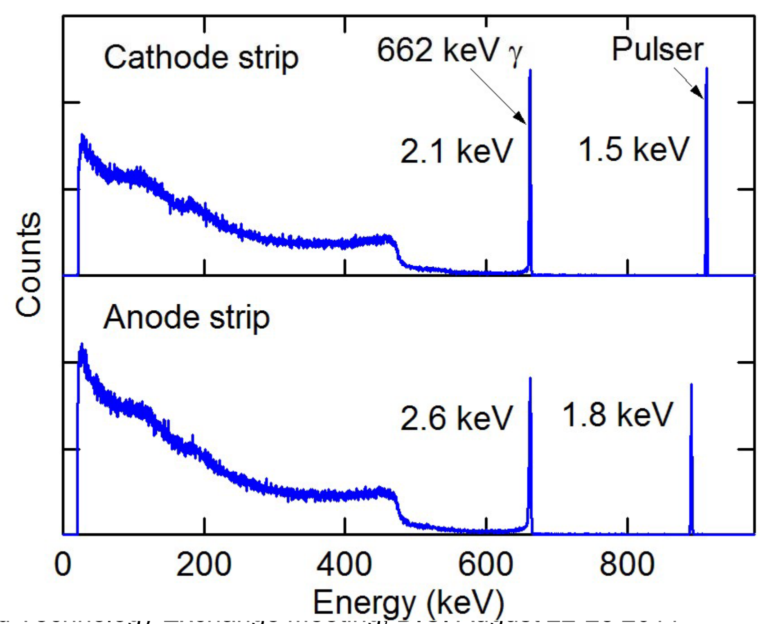


Developed for gamma astronomy, NCT
S. Boggs, et al., SSL UCB

37 strips each side, 2 mm strip pitch

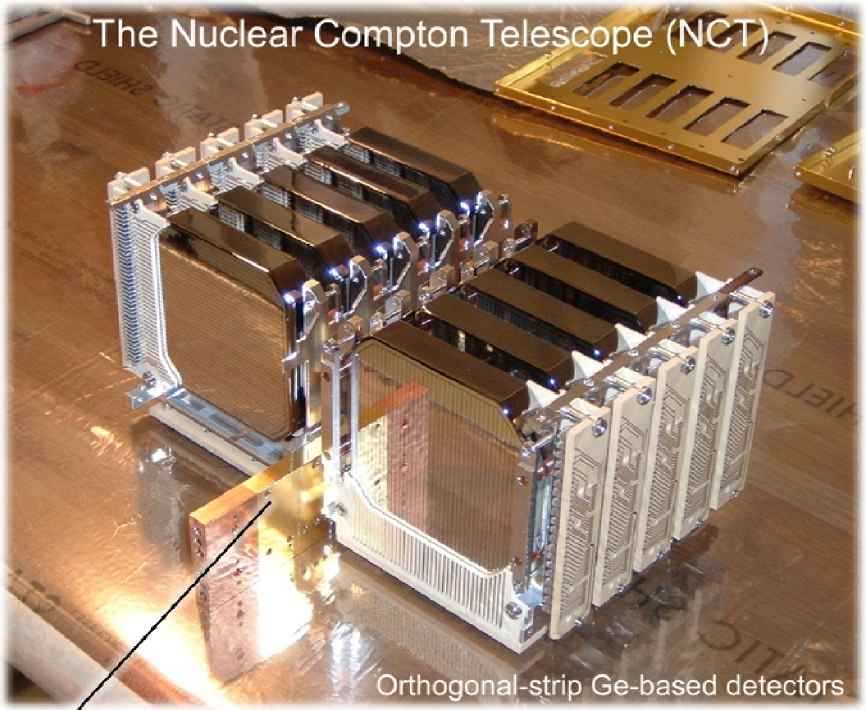
a-Ge/HPGe/a-Si
< 1pA / strip @ 82 K

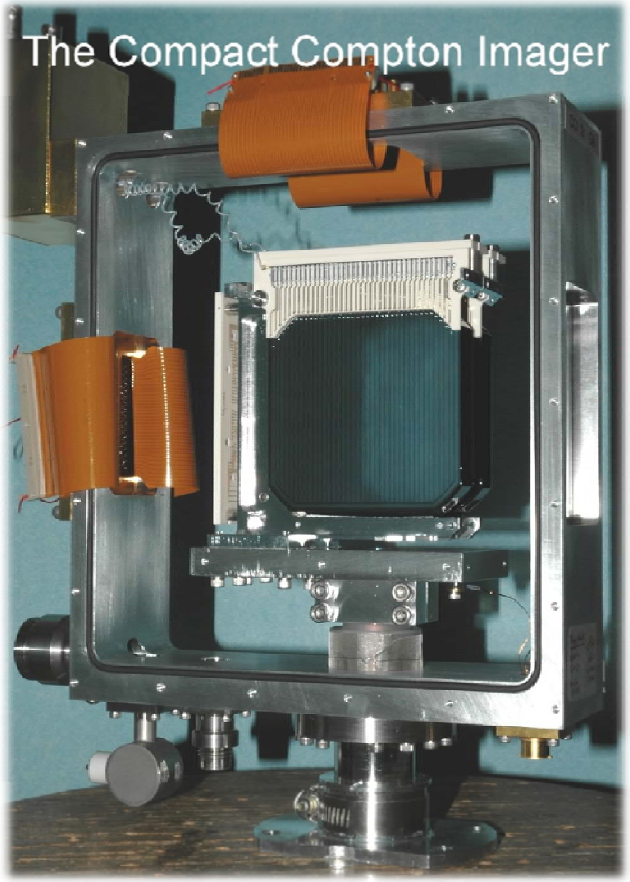




Cs-137 spectra
1200 V
2 μs shaping

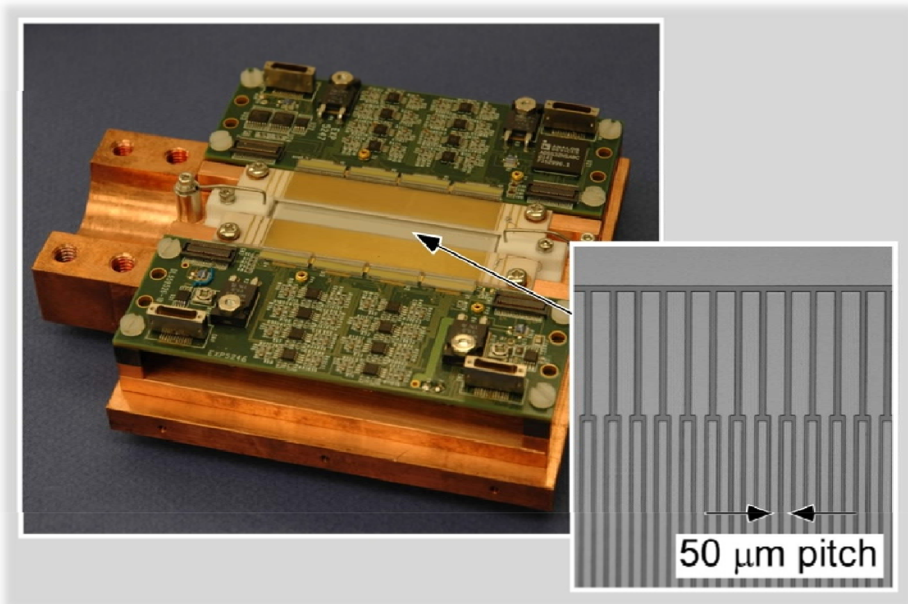
Examples of State-of-the Art - II
Orthogonal Strip Detector Instruments

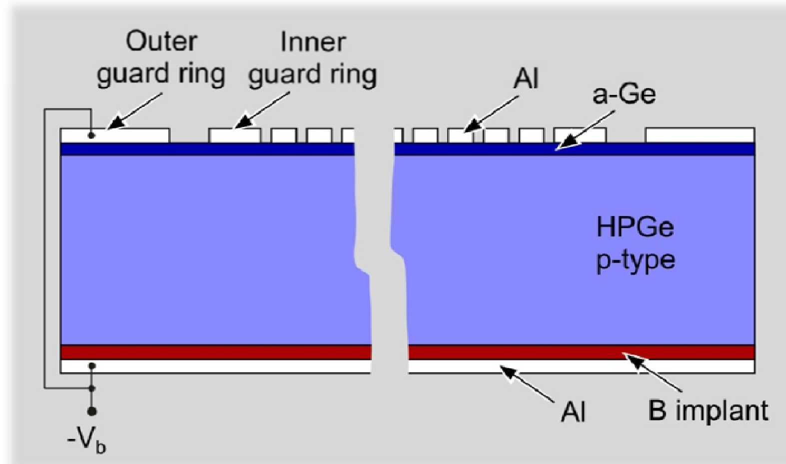




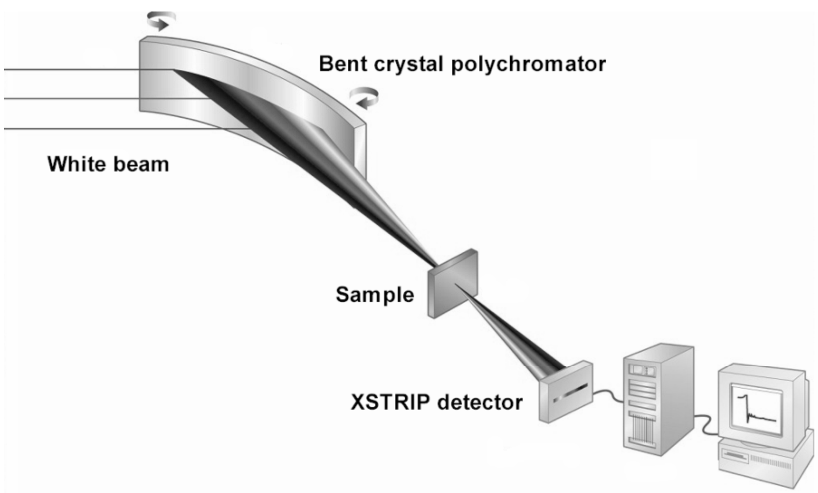
S. Boggs, et al.
UCB Space Sciences Laboratory
Gamma-ray astronomy

Examples of State-of-the Art – III
Fine-Pitched Strip Detectors





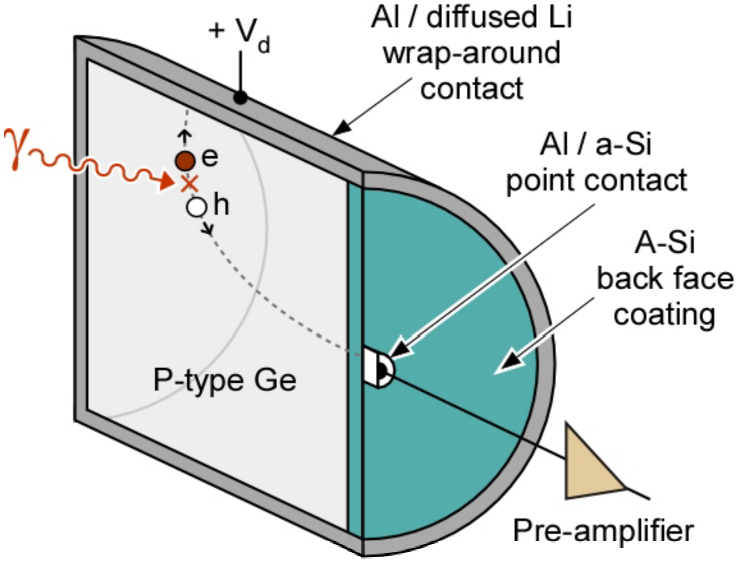
1024 strips, 50 μm pitch, 5 mm length
1 mm thick detector
~ 30 pA / strip @ V_b = 55 V, T >100 K

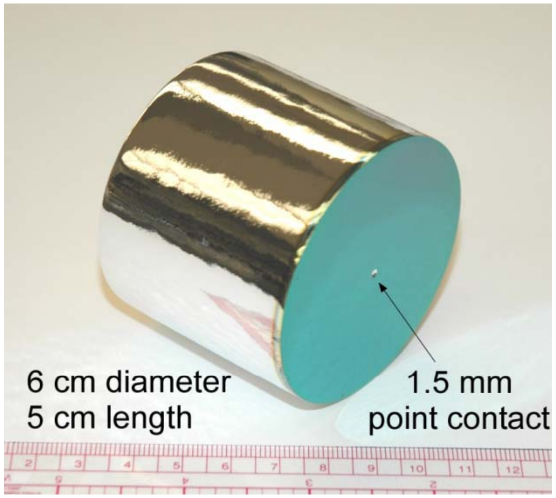


Developed for time-resolved x-ray absorption spectroscopy
J. Headspith, et al., Daresbury Lab

Examples of State-of-the Art – IV
Point Contact Detector - Concept

Detector cross-section





Fabricated for Majorana test system

N-type shaped field point-contact detector

P.N. Luke, F.S. Goulding, N.W. Madden, R.H. Pehl, IEEE TNS 36, 926 (1989).

P-type version

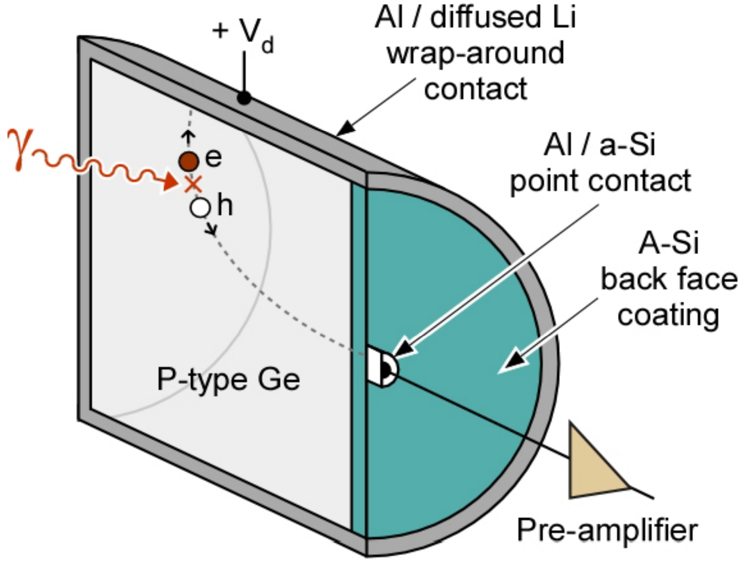
P.S. Barbeau, J.I. Collar, O. Tench, J. Cos. Astr. Phys. 9, 1 (2007).

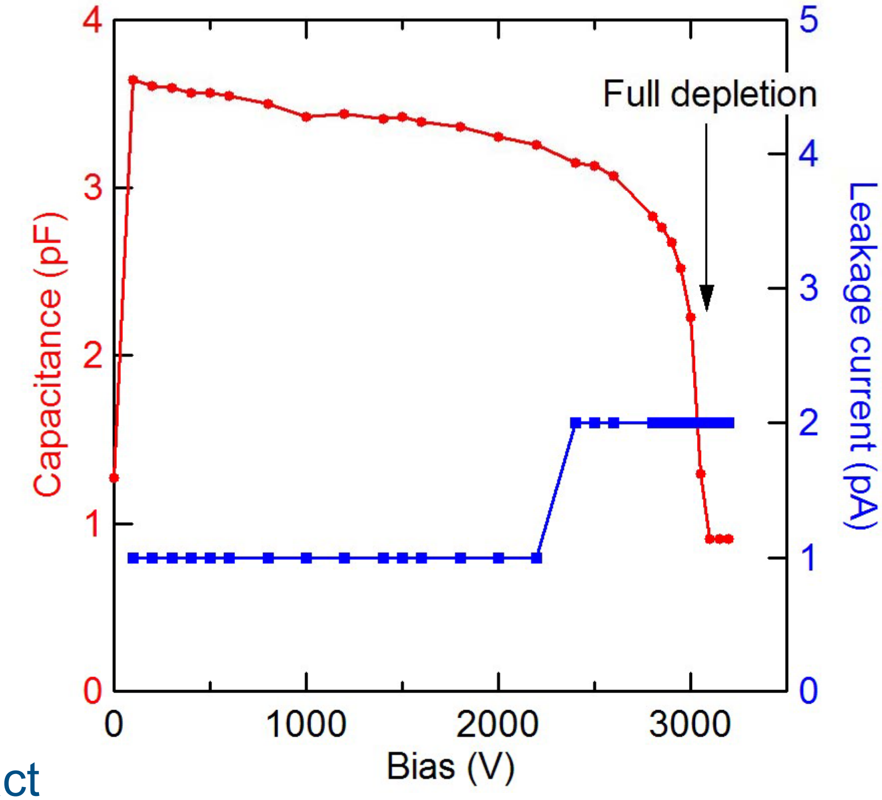
Benefits

- Large detector volume (~140 cm^3, 0.75 kg)
 → high efficiency
- Low capacitance (~1 pF)
 → extremely low electronic noise
 → extremely low energy threshold
- Interaction site number discrimination
 → event rejection (e.g., Majorana experiment, neutrinoless double-beta decay in ^{76}Ge)

Examples of State-of-the Art – V
Point Contact Detector – LBNL Fabrication

Detector cross-section





Amorphous Si:

- Effective electron blocking point contact
  - ➢Low electron injection at contact
- Back surface passivation
  - ➢Low surface leakage
  - ➢Excellent spectroscopic performance
  - ➢Stability with time, cycling, or environment appears to be a problem

Full depletion values:

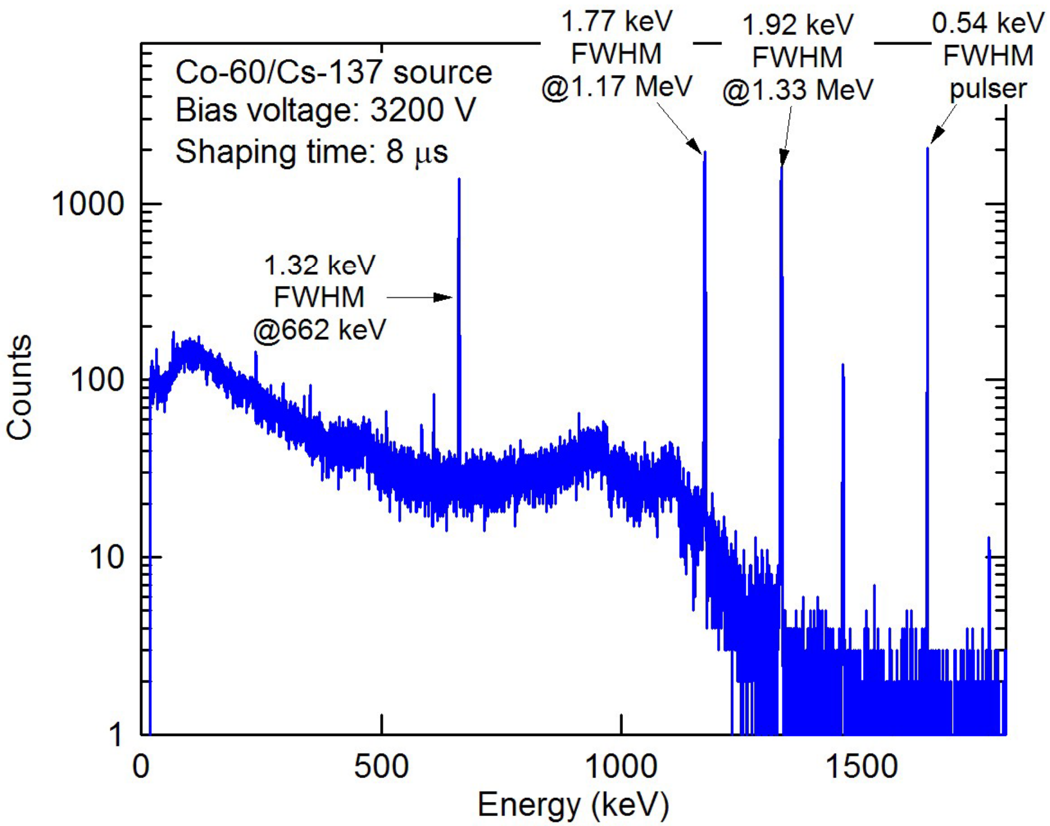
V_d = 3100 V

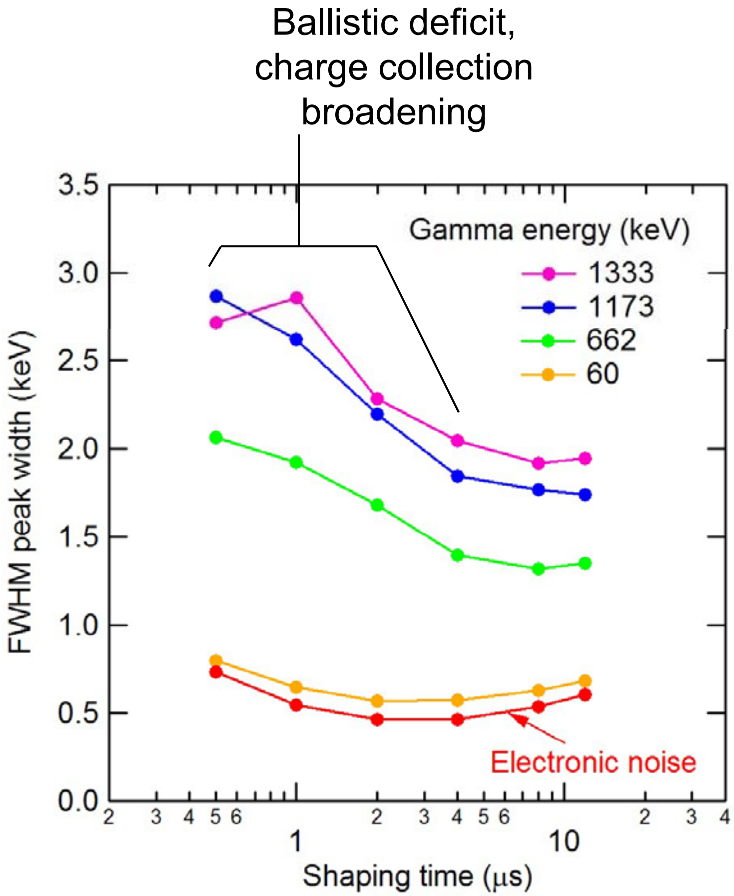
C_d = 0.9 pF

I_d ~ 2 pA

Examples of State-of-the Art – VI
Point Contact Detector – LBNL Fabrication

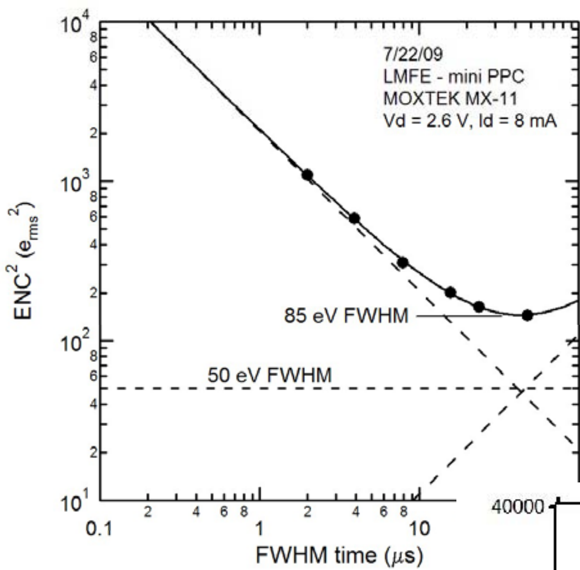
Spectroscopic performance

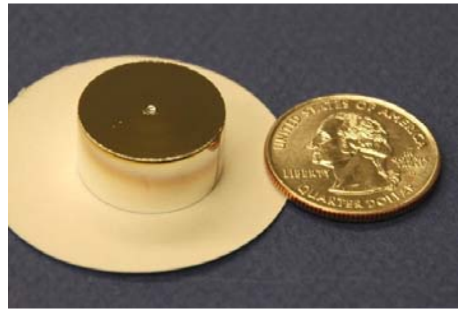




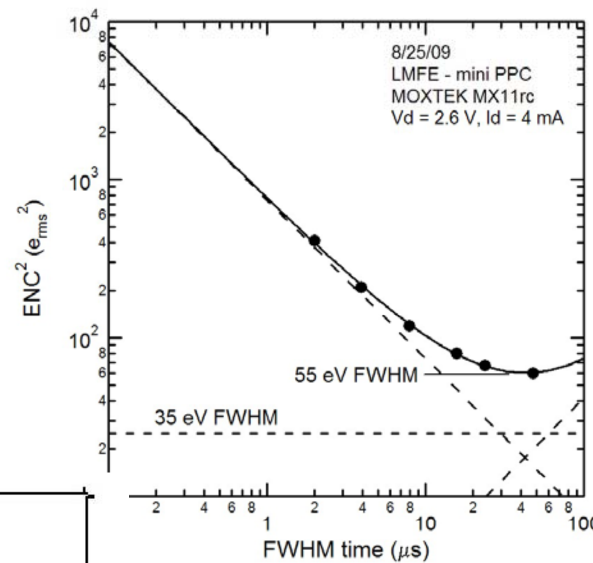
Examples of State-of-the Art – VII
Point Contact Detector – Mini-PPC

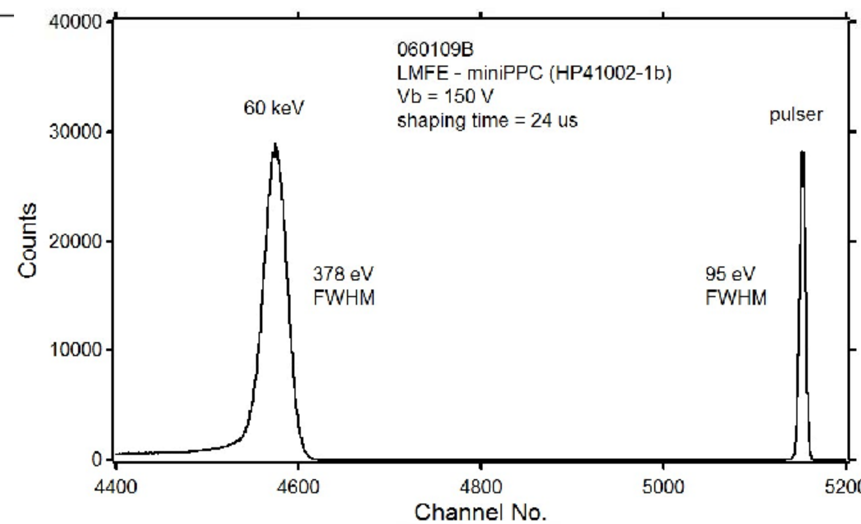
LMFE + Mini-PPC detector





Optimized LMFE w/o detector



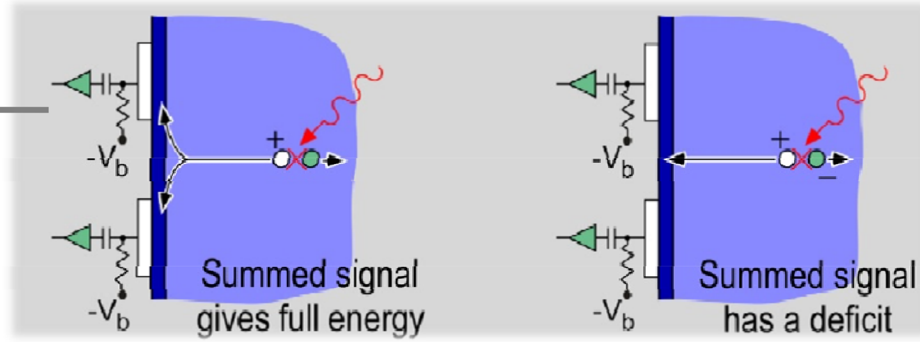


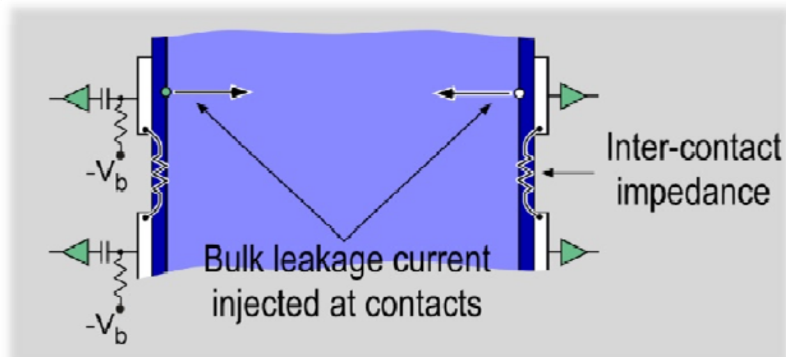
Results by Paul Luke @ LBNL

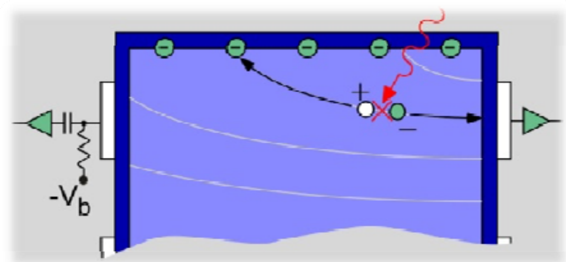
- ≤ 50 eV noise (≤ 100 eV threshold) with 1 kg Ge detectors ?

Status – Challenges and Limitations
All is not perfect: Strip detectors

Detector characteristics	Primary performance measures affected
Inter-contact charge collection	Intrinsic resolution (pulse-height deficits) Efficiency (event loss) Sensitivity (background event increase)
Bulk leakage	Electronic noise (shot noise)
Inter-contact impedance	Electronic noise (thermal noise)
Surface channels	Efficiency (event loss) Sensitivity (background event increase)
Stability with temperature and vacuum cycling	Degraded performance
Immunity to high voltage breakdown	Yield, lifetime, reliability



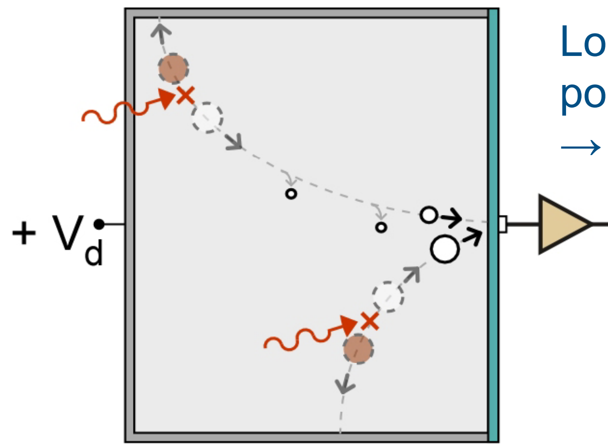




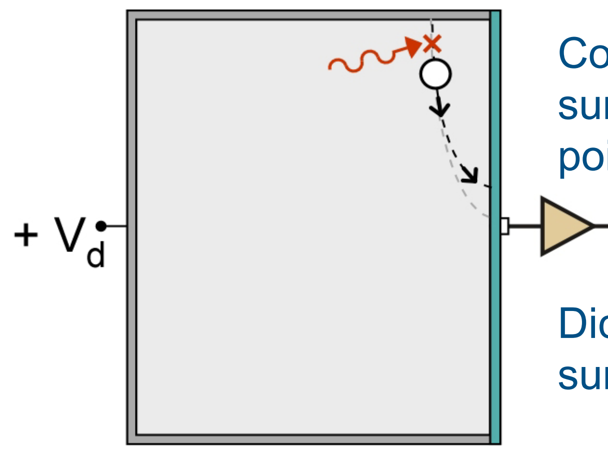
Status – Challenges and Limitations
Same issues impact other geometries

Challenges

- Charge collection
  - Charge trapping
  - Collection to back surface
- Leakage current
  - Contact injection
  - Back surface conduction

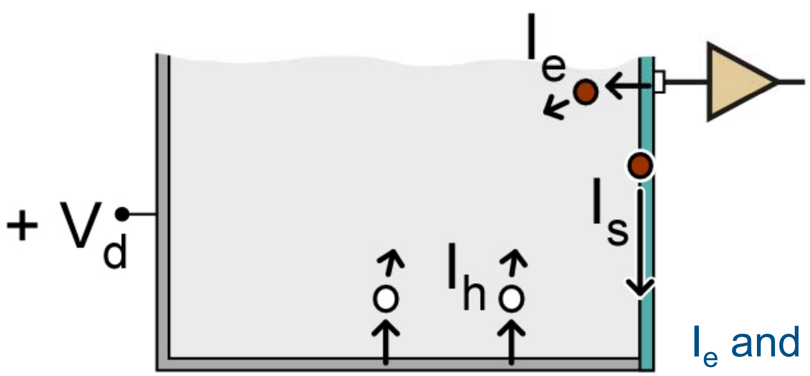


Long drift lengths, possible low fields → charge trapping



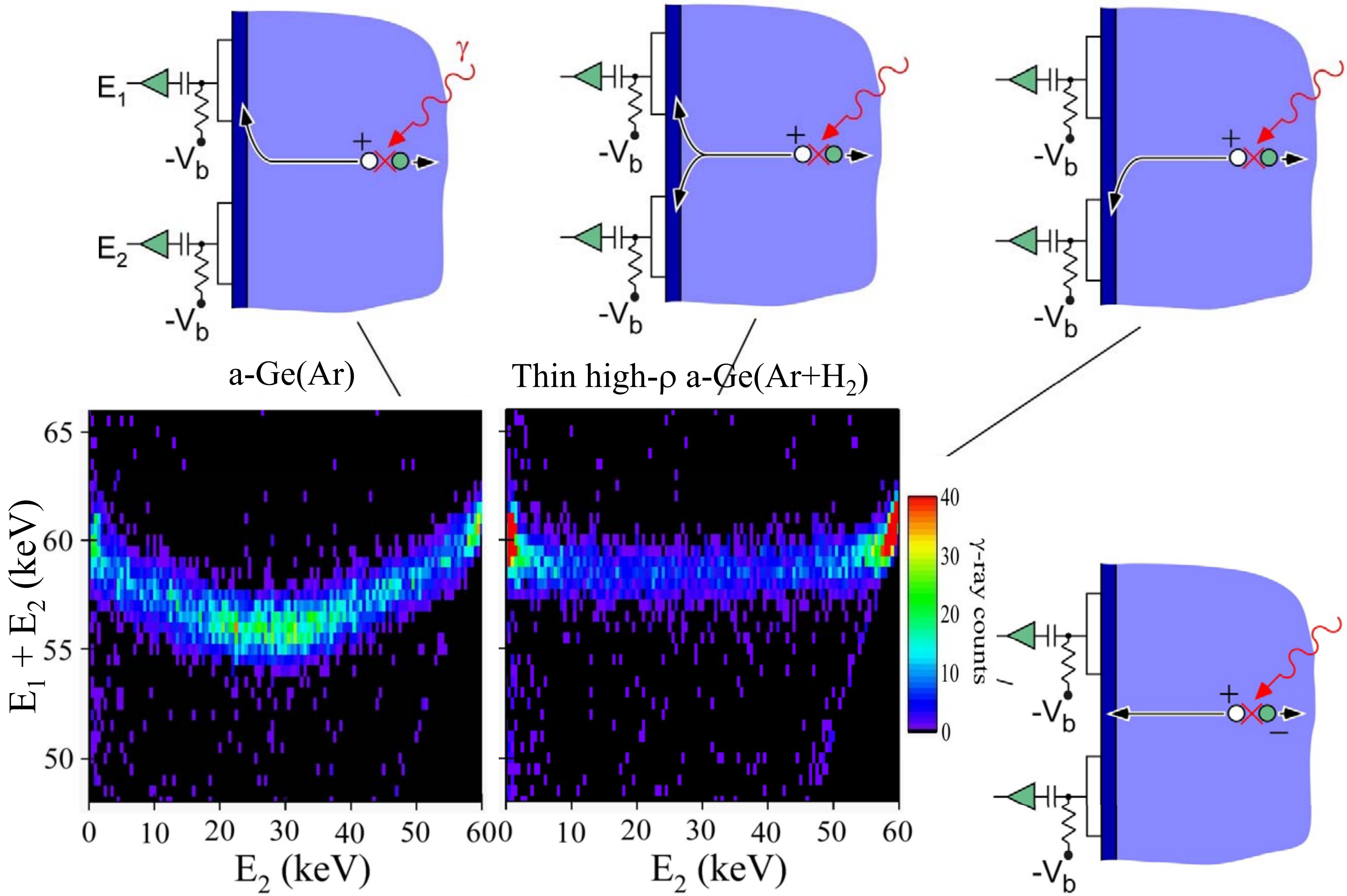
Collection to back surface rather than point contact

Dictated by back surface processing

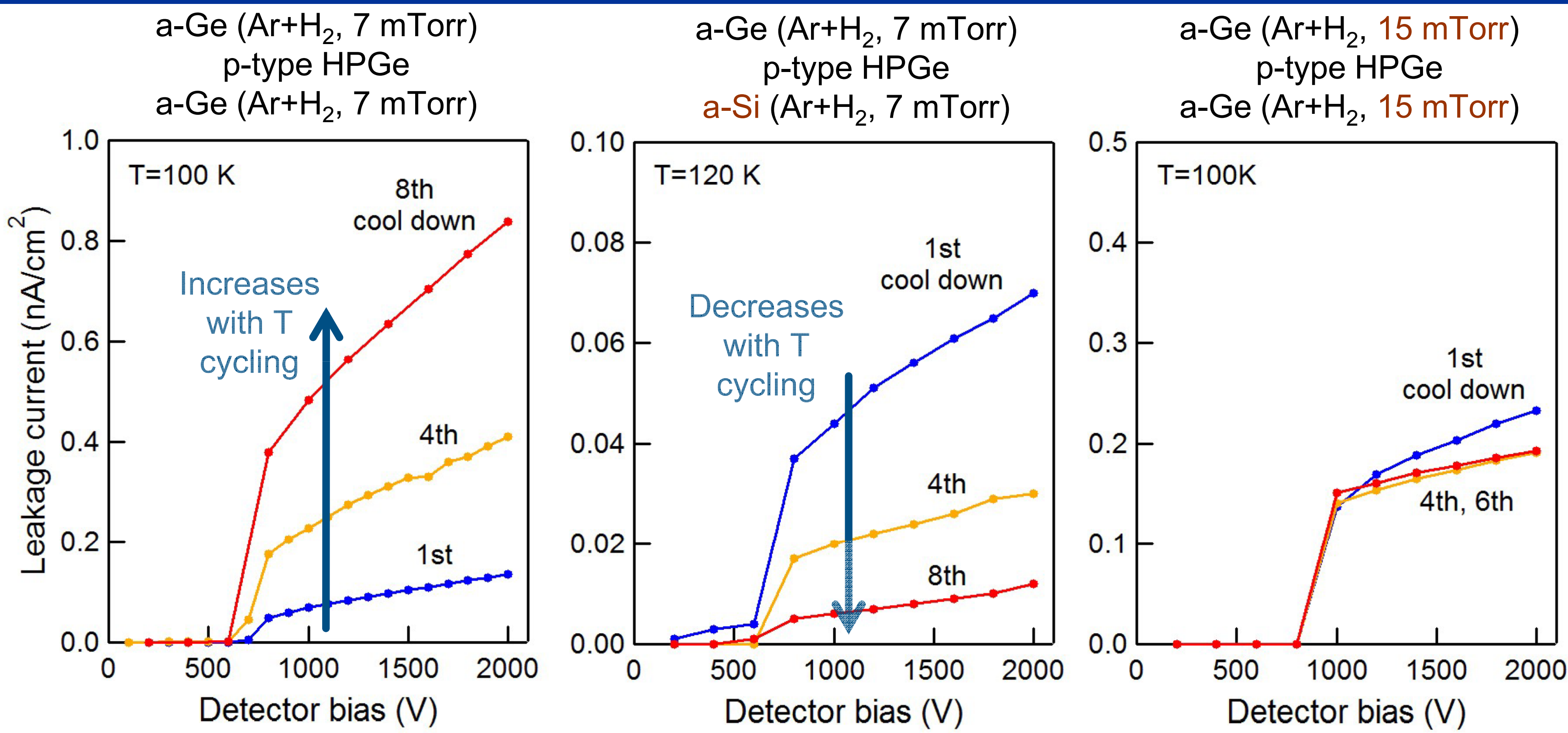


I_e and I_s of particular concern

Status – Challenges and Limitations
Charge sharing and associated charge loss



Status – Challenges and Limitations
Temperature cycling stability …



Electron injection at a-Ge contact increases with T cycling

Electron injection at a-Si contact decreases with T cycling

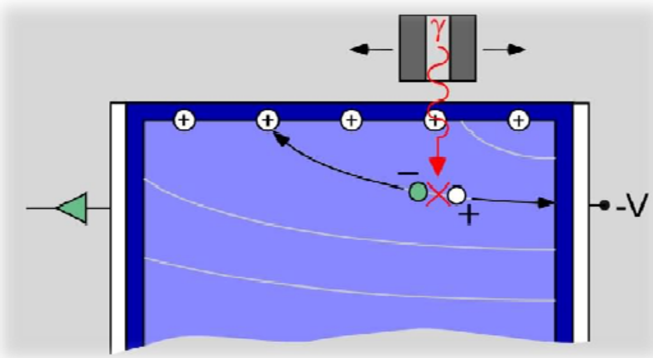
Process reproducibility and robustness?

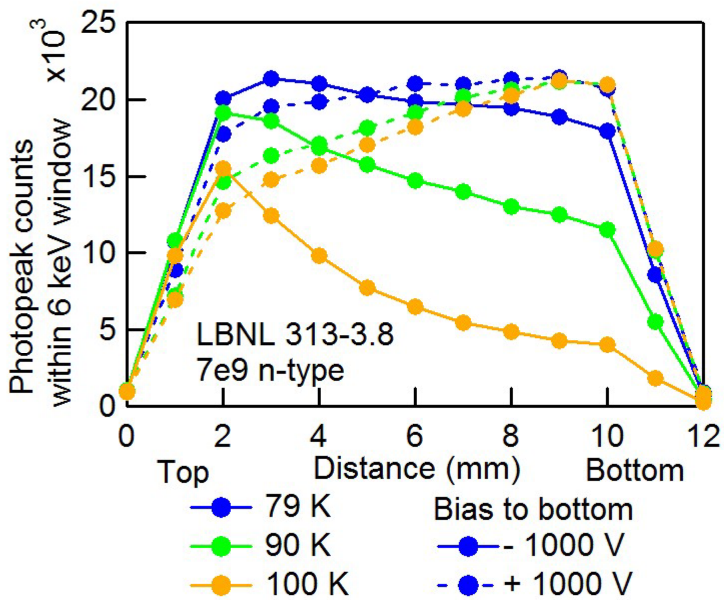
Possibly impacted by many process parameters: pre-deposition treatment, gas mixture, pressure, temperature, thickness, target impurities, …

Physical mechanism?

Status – Challenges and Limitations
And more … E.g. Surface Channels

Low E γ side scanning





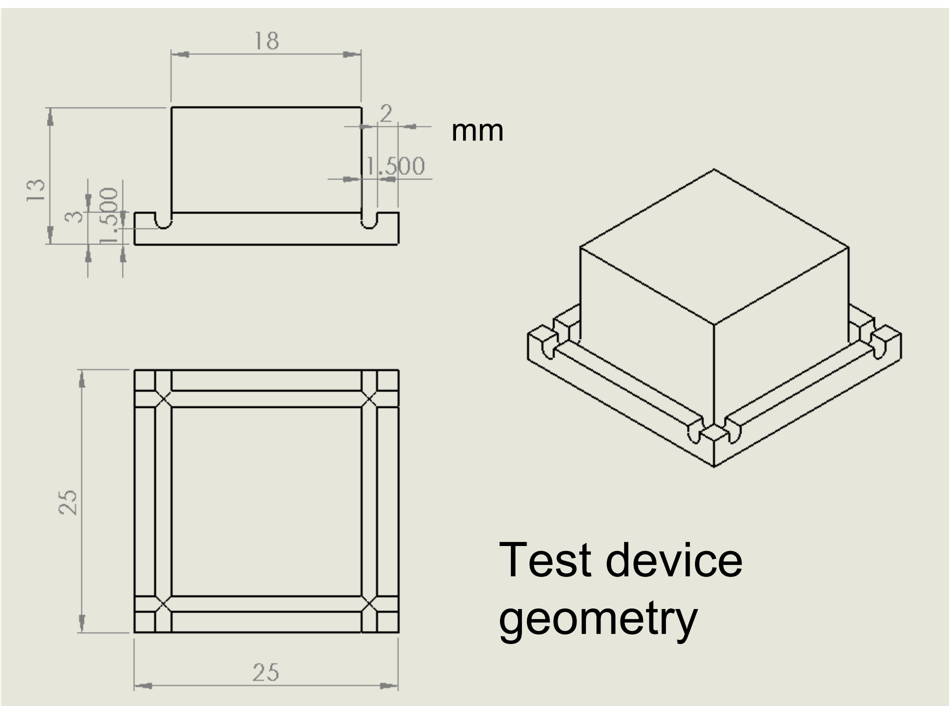
Observations:

- Depends on side processing (sputter recipe and pre-sputter treatment), impurity concentration, and typeness, W.L. Hansen, E.E. Haller, G.S. Hubbard, IEEE TNS 27, 247 (1980)
- Reduced surface channels at low T
- Sometimes leads to edge strips with substantial leakage current
- Strong channel appears to be the source of large leakage currents and detector breakdown failure
- Incomplete coating of sides has led to detector failure
- NCT a-Ge/Ge(p)/a-Si configuration suffers more from this than a-Ge/Ge(p)/ a-Ge configuration (~ same side coating?)
- High impurity p-type HPGe material suffers more from this than low impurity based on results from NCT detectors

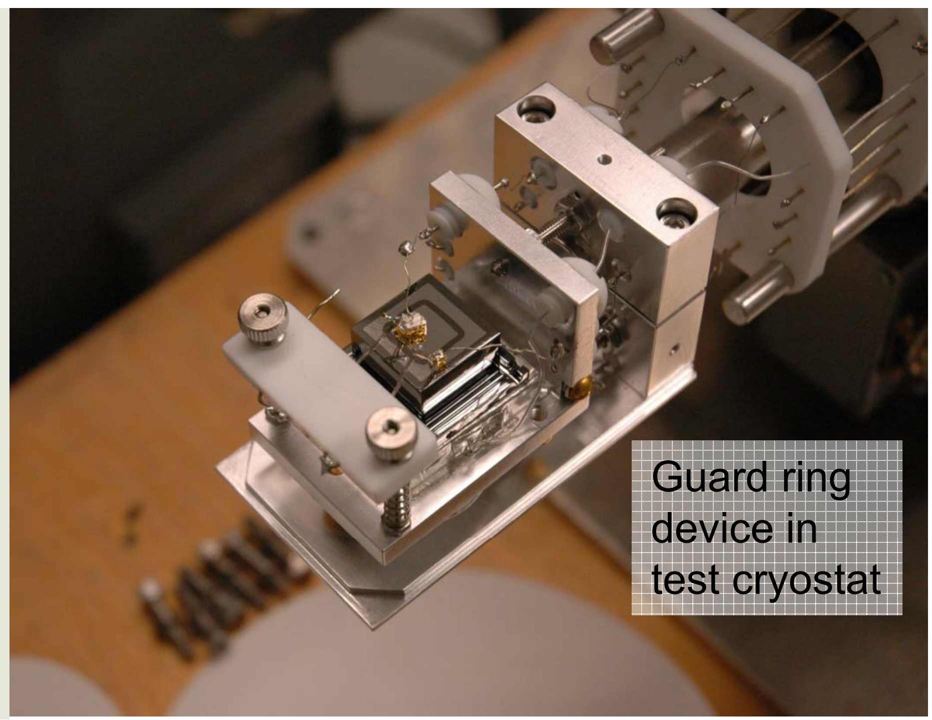
Reproducibility? Impact of geometry, T cycling, …

Status – Detector Fabrication I

- **Fabrication of small test detectors**
  - **Mechanical crystal preparation**
  - **Sputtering and thermal evaporation film deposition**
- **Confirmed results of previous studies**

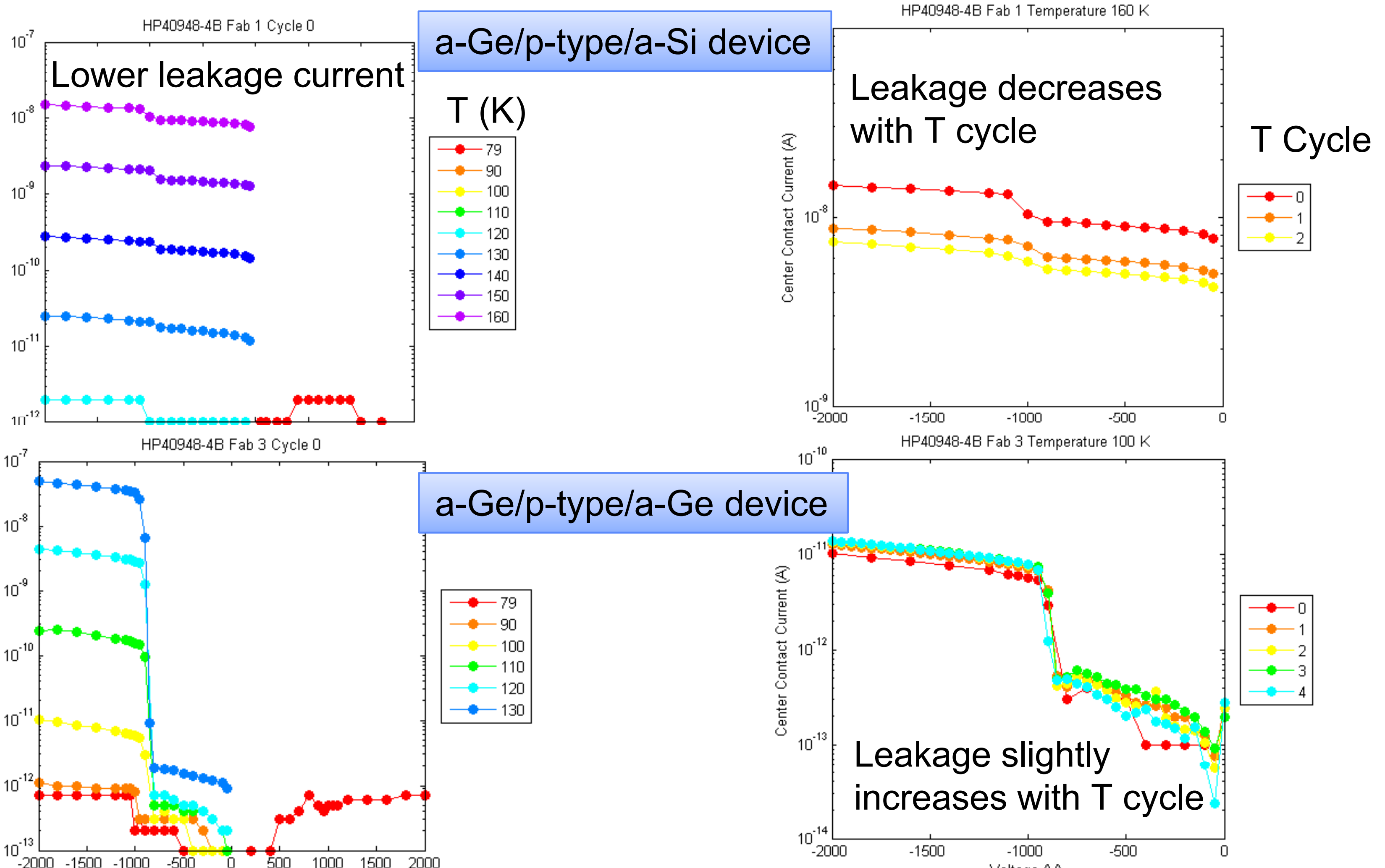


Test device geometry


Guard ring device in test cryostat

Status – Detector Fabrication II

- **Preliminary Results**

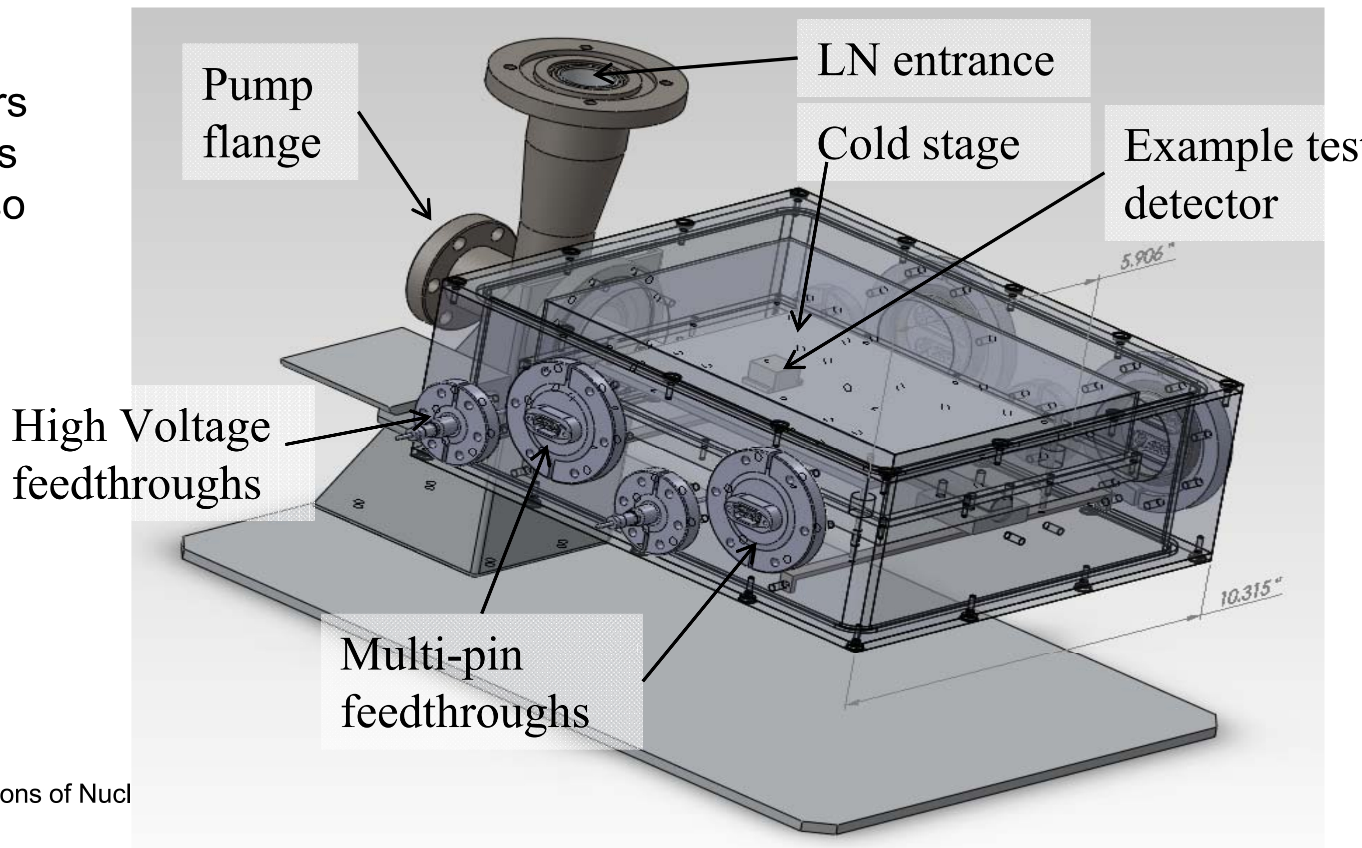


Future – Detector Fabrication

- **Systematic study of detector fabrication processes**
  - **Multi-detector cryostat (temperature variable)**
  - **Change process with regard to**
    - **Surface treatment**
    - **Sputter process (gas composition, pressure, temperature,…)**

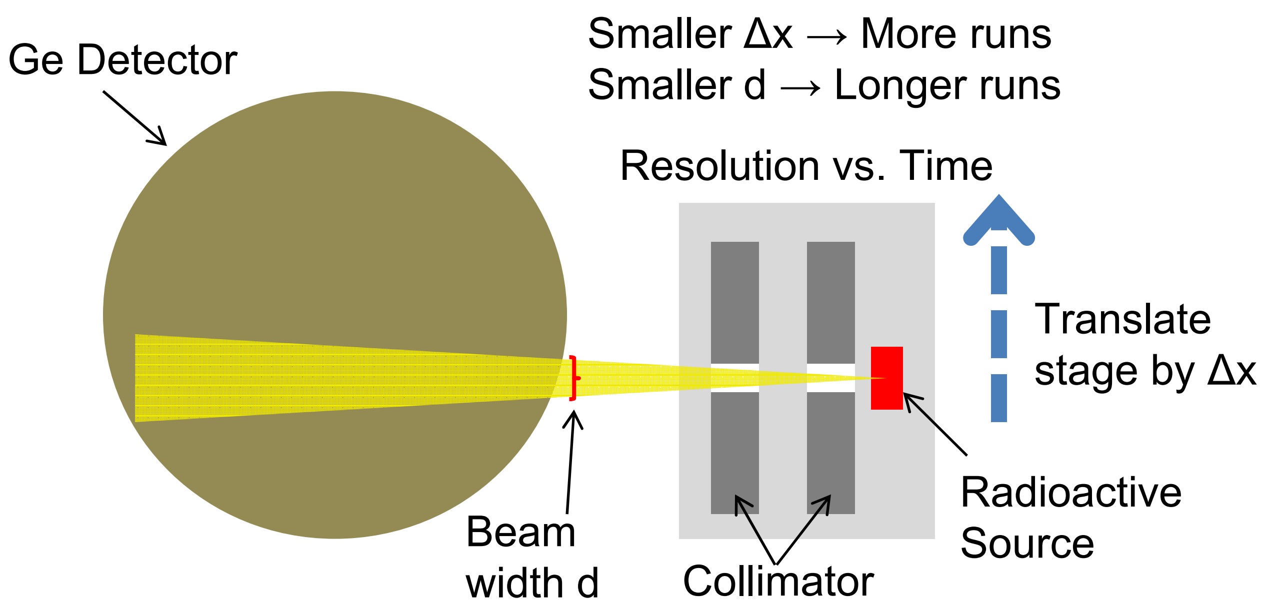
<u>Modular Design</u>
-Many small detectors of various geometries
-Larger detectors also possible

Essential for testing process parameters at an acceptable rate

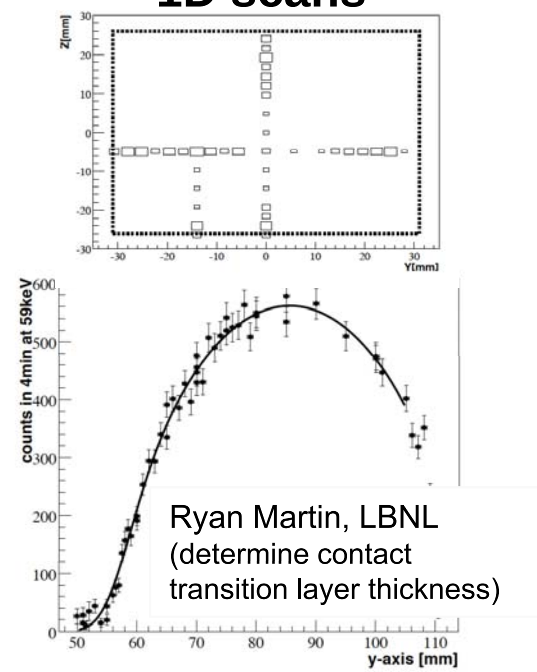


Status – Detector Characterization
Signal response – Linear 1D/ 2D scan

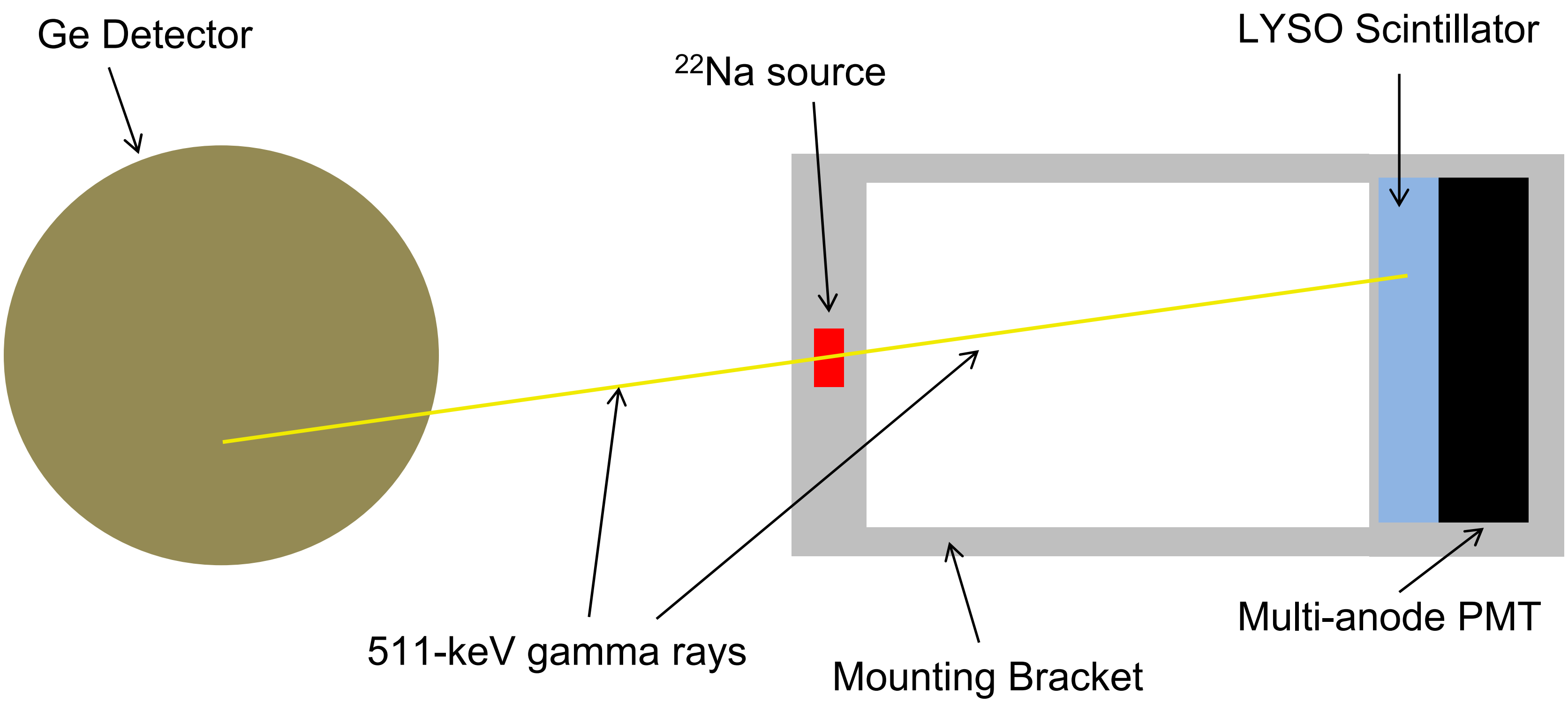
- **Need to understand position-dependent response of new detector configurations**
- **Collimated scanning takes time**
  - **Direct tradeoff between resolution and time**
  - **Collimated coincidence scanning takes even more time**



1D scans



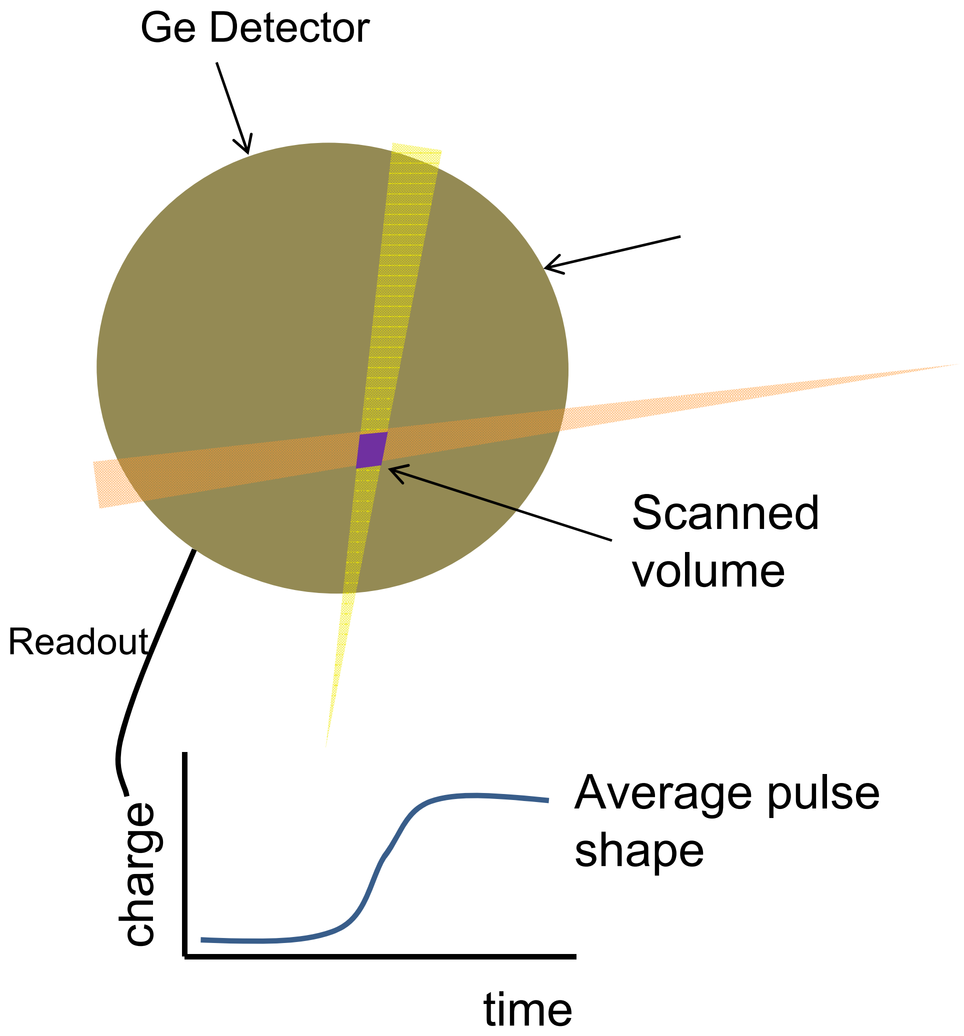
Status – Detector Characterization
Signal response – 3D coincidence mapping



-Positions of Ge detector, ^{22}Na source, and scintillator are known and fixed
-Source emits positrons
  -Short positron range
  -Annihilation leads to collinear, oppositely oriented 511-keV gamma rays

Domingo-Pardo, NIM, 643, 79 (2011)

Status – Detector Characterization
Signal response – 3D coincidence scan

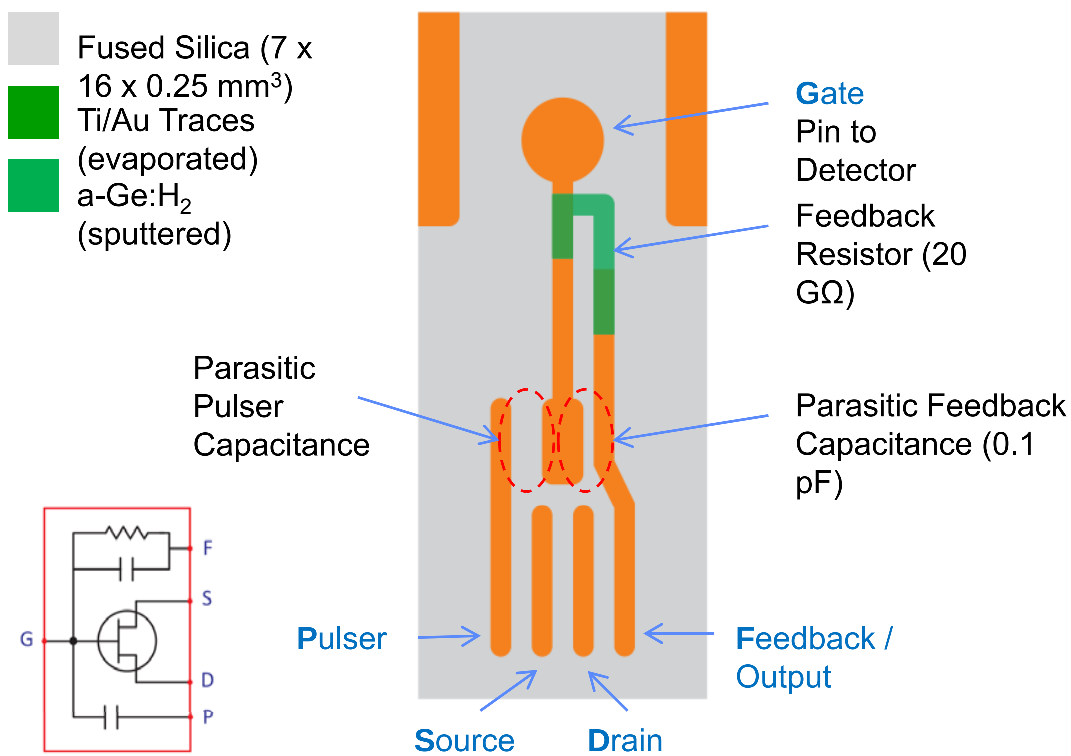


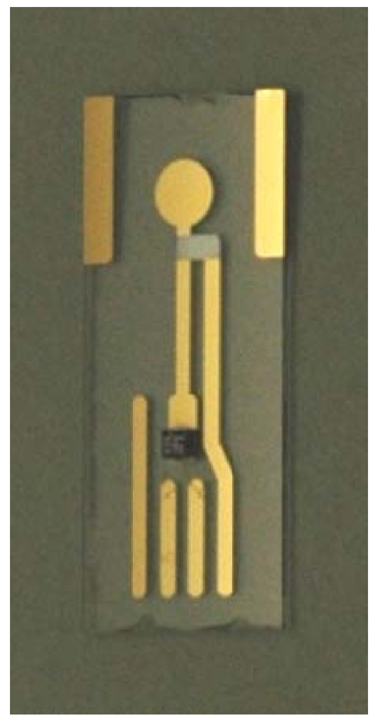
- Combined perpendicular data sets give defined volume
- Some prior knowledge of Ge detector response is required
- Assumes unique position-dependent response
- Similar pulses from two cones assumed to be same location
- Average waveform gives expected position-dependent response

Domingo-Pardo, NIM, 643, 79 (2011)

Status – Detector Readout - Concept

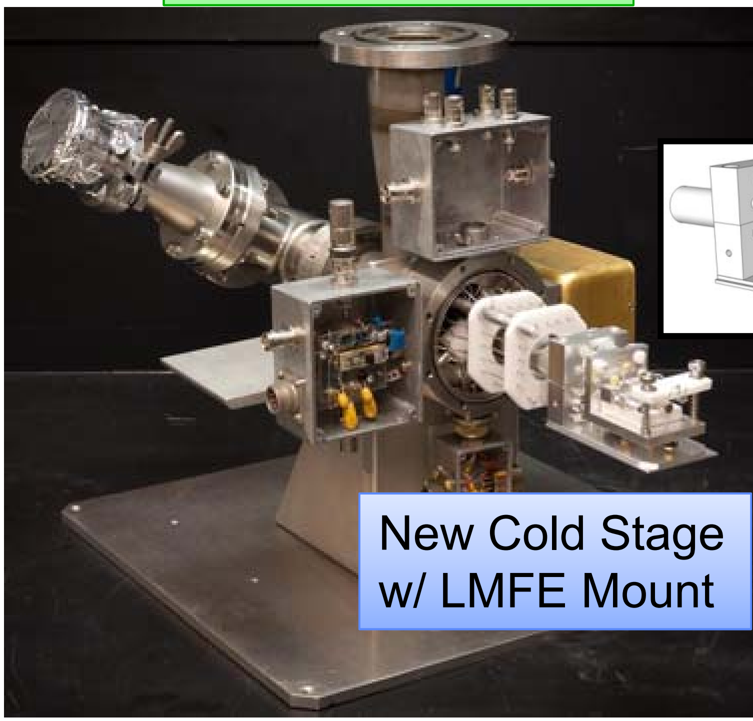
- **In order to develop and evaluate the low noise performance of point contact detectors, a low-mass and ultra-low noise front-end is being refined (similar to MAJORANA Low-Mass Front-End)**

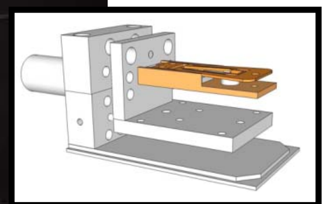




Status – Detector Readout – Test System

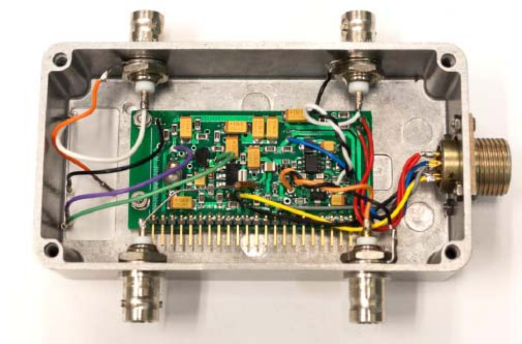
LMFE Test Cryostat



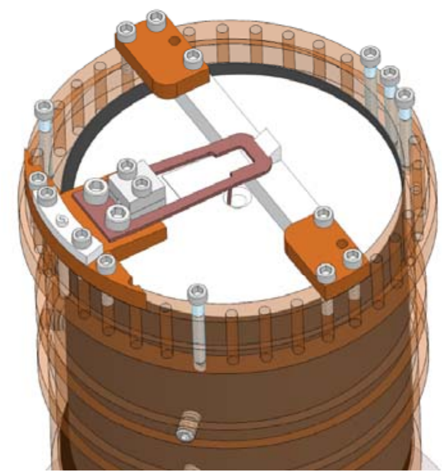


New Cold Stage w/ LMFE Mount

A rapid test environment for temperature-dependent testing of LMFE performance.



Low-Noise Preamplifier



Future:
Design for 60x60 mm point contact detector to be fabricated with low-noise readout and improved fabrication process

Summary & Outlook

- **Summary**
  - **Detector fabrication baseline established**
    - **Production and characterization of small (and large) HPGe detectors initiated**
  - **Multi-detector cryostat is being built**
  - **Detector characterization system available and upgrade being built**
  - **Modeling and simulation environment established**
  - **Detector readout development ongoing**
- **Outlook**
  - **Systematic measurements and improvements in the fabrication of HPGe detectors including theoretical studies on contacts and surfaces**
  - **Large detector demonstration to come later …**