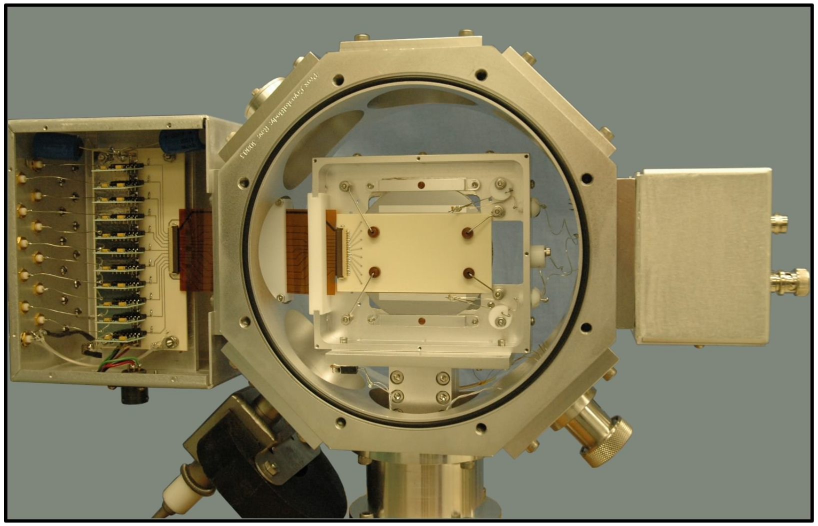
Semiconductor detectors with optimized proximity signal readout

DOE Phase II SBIR DE-SC0009676



PI: Dr Stephen Asztalos, XIA LLC

LBNL Lead: Dr Mark Amman

Outline

- Company Background
- Technology Review
- Phase I effort
- Phase II work plan
- Commercialization

Company Background

Who we are

XIA LLC produces advanced **X-ray and gamma-ray detector electronics and related instruments** with applications in research, industry, and homeland security.

Located in the San Francisco Bay Area with ~20 employees

Products range from 2"x3" OEM circuit boards to 3'x3'x2' detector assemblies, $500-50,000

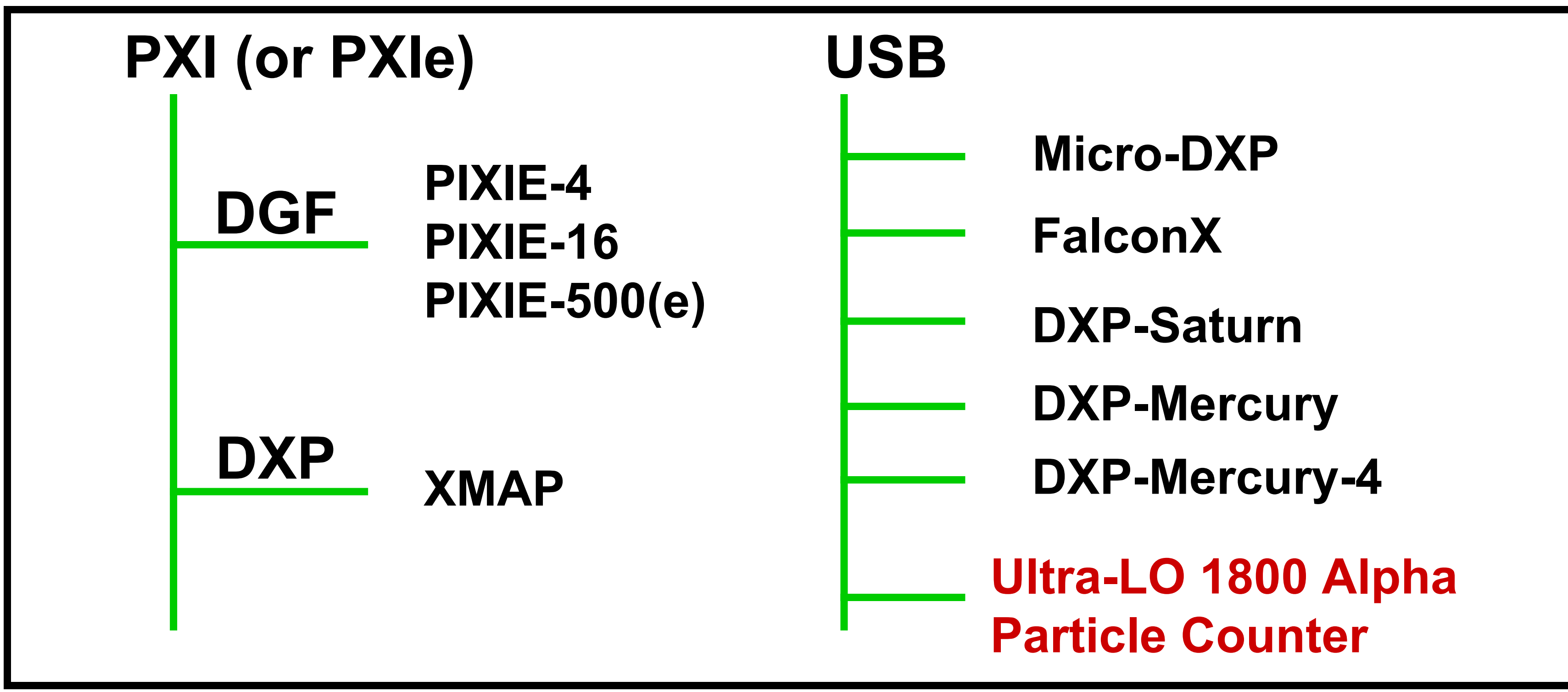
Two main product lines:

DGF Gamma ray processors (higher precision, coincidence, waveforms) for HPGe, scintillators, silicon strip detectors

DXP X-ray processors (higher throughput, fast mapping) for Si(Li), HPGe, silicon drift detectors

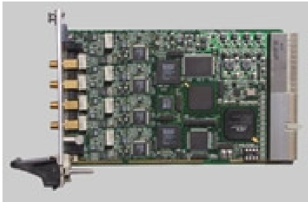
What we do

- Replacing analog multi-module electronics with all-digital pulse processing in FPGA and/or DSP.
- Early products were pulse processing modules based on CAMAC standard; now most instruments are based on PXI (or PXIe) standard or are standalone USB devices.



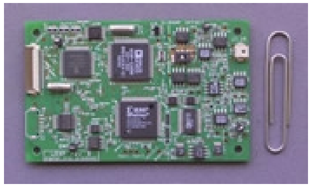
What we sell

Falcon-X



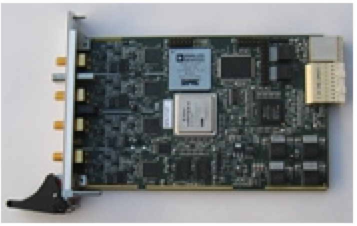
DXP XMAP

DXP Mercury

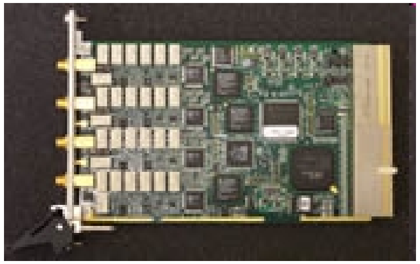


Micro-DXP

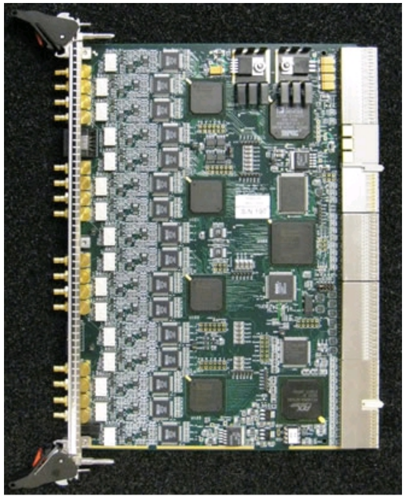
DXP Saturn



DGF Pixie-500 Express



DGF Pixie-4



DGF Pixie-16

Ultra-LO 1800

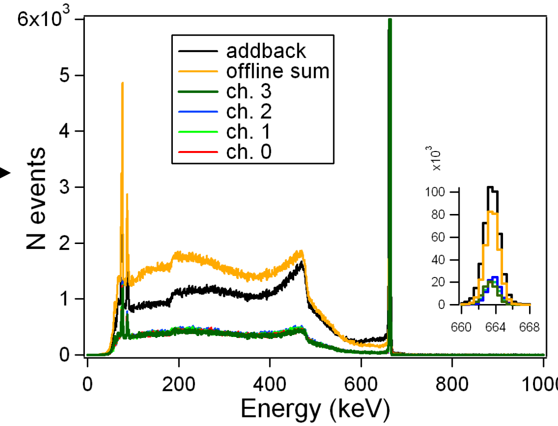
PhosWatch

DXP Mercury-4-OEM

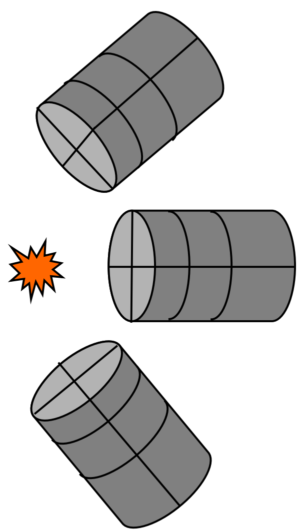
Sample Applications

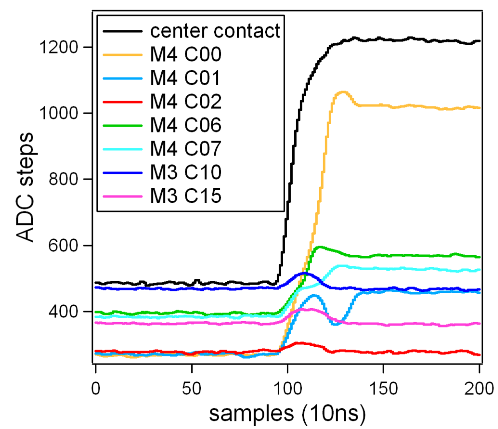
Instruments That Advance The Art

Compact clover readout system with single Pixie-4



HPGe detector array, gamma ray tracking with multiple Pixie-16





SBIR Successes

Agency	Grant Number	Year	Project Title	Award Amount	Sales & Revenue as of 12/31/2012
DOE SBIR	DE-FG03-2ER81311	1992	Digital Processing Electronics for X-ray detector Arrays	$550k	**~$2.2m**
NIH SBIR	5R44-CA69972-03	1995	High Speed Detector for Mammography Calibration	$825k	**~15.5m**
DOE SBIR	DE-FG03-7ER82510	1998	Digital Processors for GRETA Detectors	$825k	**~2.5m**
DOE SBIR	DE-FG02-1ER83320	2001	Processing Electronics for Beta-Gamma-Gamma Detection	$875k	**~10.8m**
				$3.075 m	**~$31.0m**

More recent SBIR Projects (partial list)

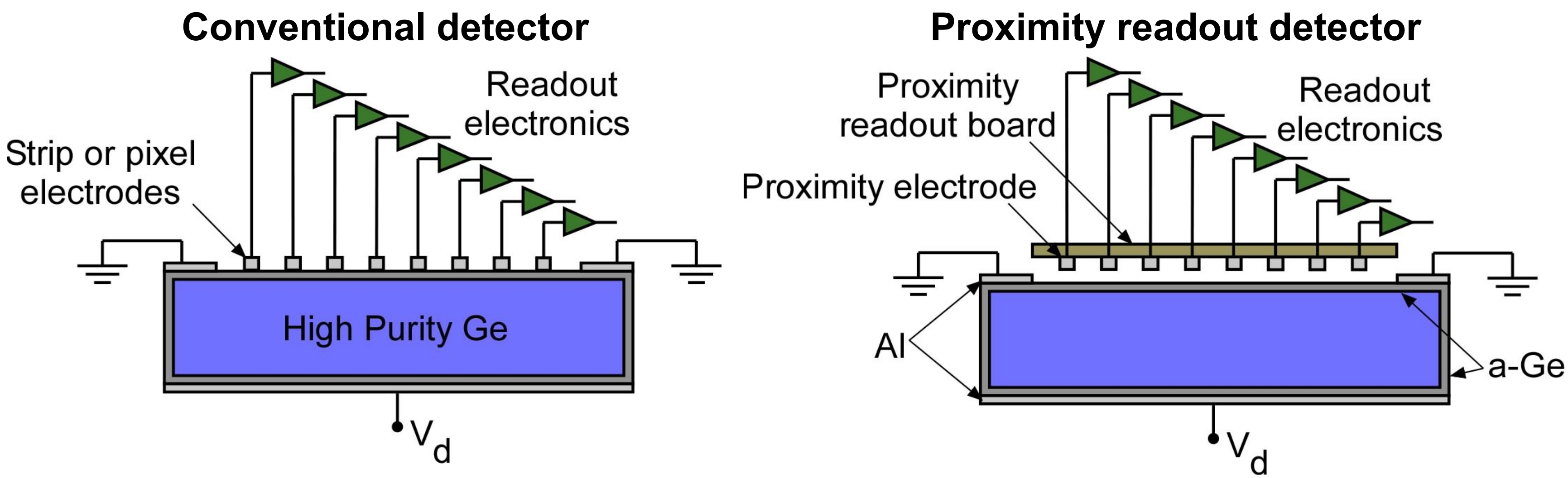
Instruments That Advance The Art

Agency	Year	Project Title	Award Amount
DOE SBIR	2013	Proximity charge sensing readout in HPGe detectors	$1.15m
DOE SBIR	2012	High density low cost readout electronics for large scale radiation detectors (see tomorrow's talk)	$1.15m
DOE SBIR	2011	Silicon Drift Detectors for High Resolution Radioxenon Measurements	$953k
DOE SBIR	2007	Electronics for Large Superconducting Tunnel Junction Detector Arrays for Synchrotron Soft X-ray Research	$1.1m
DOE SBIR	2005	Low Level Radioactive Xenon Monitoring by Phoswich Detector System	$875k

Technology Review

Revisited an old idea

Proximity Electrode Signal Readout: Move readout electrodes from the detector surface to a readout board placed very near the detector surface…



… and maintain the field in detector through simplified detector electrodes and a resistive film surface coating consisting of amorphous Ge (a-Ge)

1. "Position-Sensitive Semiconductor Detector for Gamma Rays," R. Kurz, D. Protic, R. Reinartz, and G. Riepe, IEEE Trans. Nucl. Sci **24**, 255, (1977).
2. "Proximity Charge Sensing with Semiconductor Detectors," P. N. Luke, C. S. Tindall, and M. Amman, IEEE Trans. Nucl. Sci. **56**, 808 (2009).
3. "Proximity Electrode Signal Readout of High-Purity Ge Detectors," M. Amman, A. Priest, P. N. Luke, S. Asztalos et al., IEEE Trans. Nucl. Sci. **60**, 1213 (2013).

Advantages

Sub-strip/pixel position resolution

- Multiple electrodes detect charge (integrated, not transient) → simple "interpolation" is possible to achieve sub-electrode pitch positions

Simplified detector fabrication

- Electrode fabrication and interconnect issues are moved from detector to circuit board (well-established board fabrication processes, differential thermal contraction issue of pixel bump bonding avoided, …)

Greater flexibility in detector design

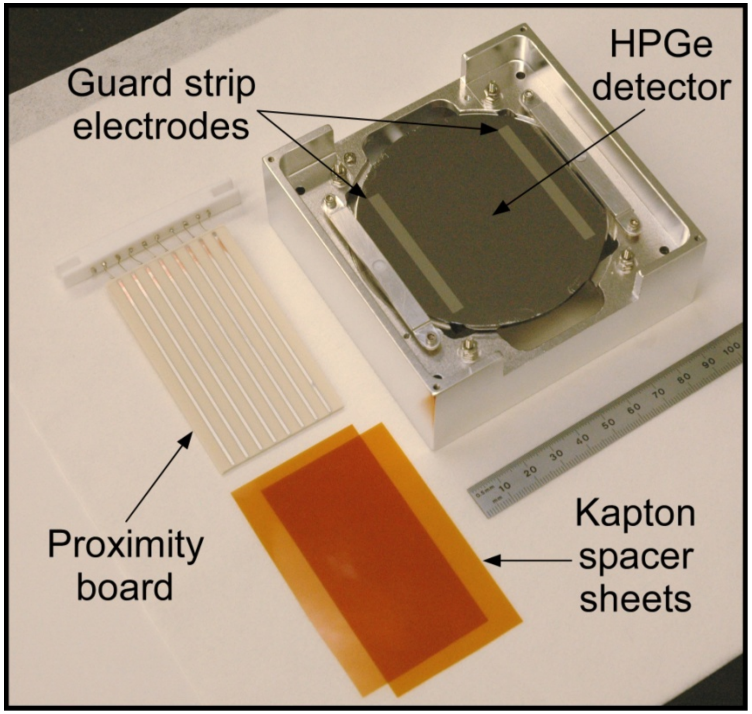
- Strip, pixel, single-sided orthogonal-strip, … not limited to single layer planar designs
- Readout configuration can be changed without refabricating the detector

Primary objective of current project: *Demonstrate and explore the advantages of the proximity readout technique as applied to HPGe gamma ray detectors*

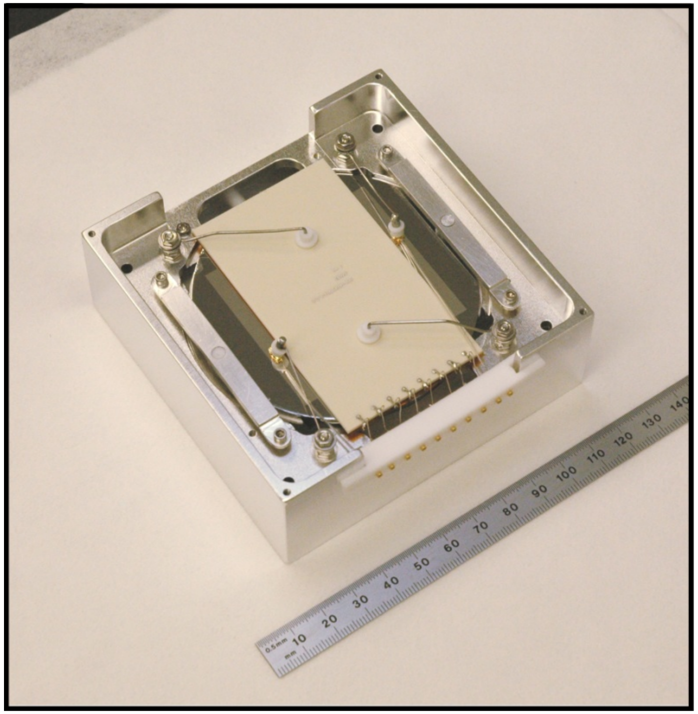
Phase I results

1-D detector development

Energy measurement and sub-strip pitch position resolution demonstrated on multiple HPGe 1-D position resolution detectors, for example (single-sided strip readout):

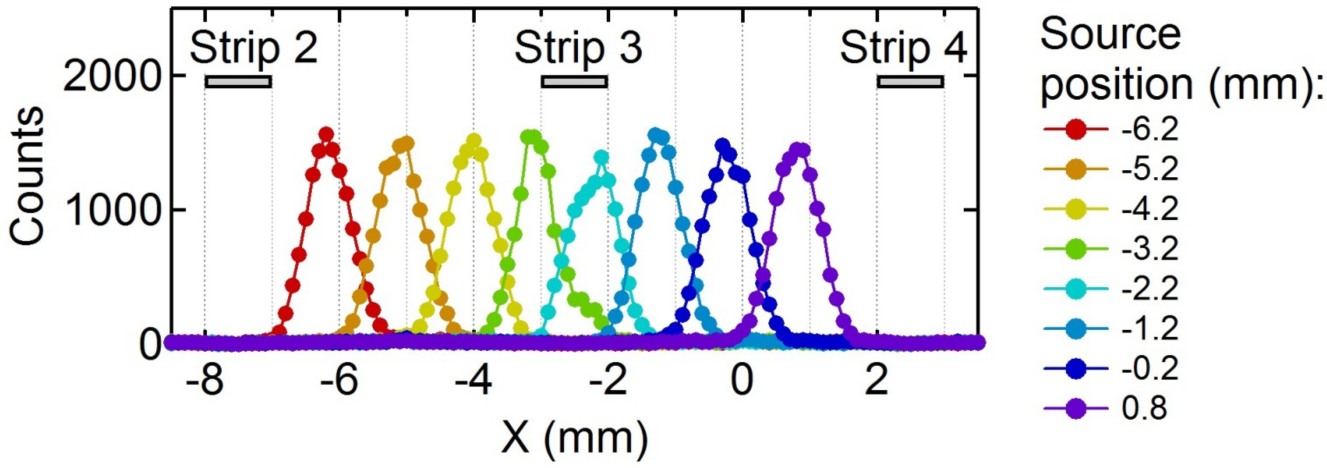


1-d strip proximity charge sensing readout detector prior to assembly

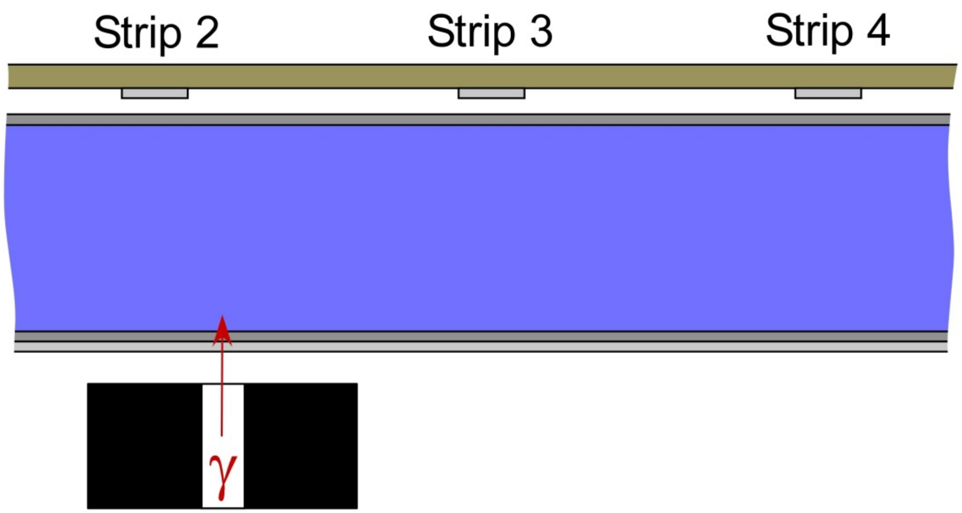


Assembled proximity readout detector

1-D Position Readout



Gamma-ray event position histograms reconstructed from data acquired with a prototype proximity electrode detector



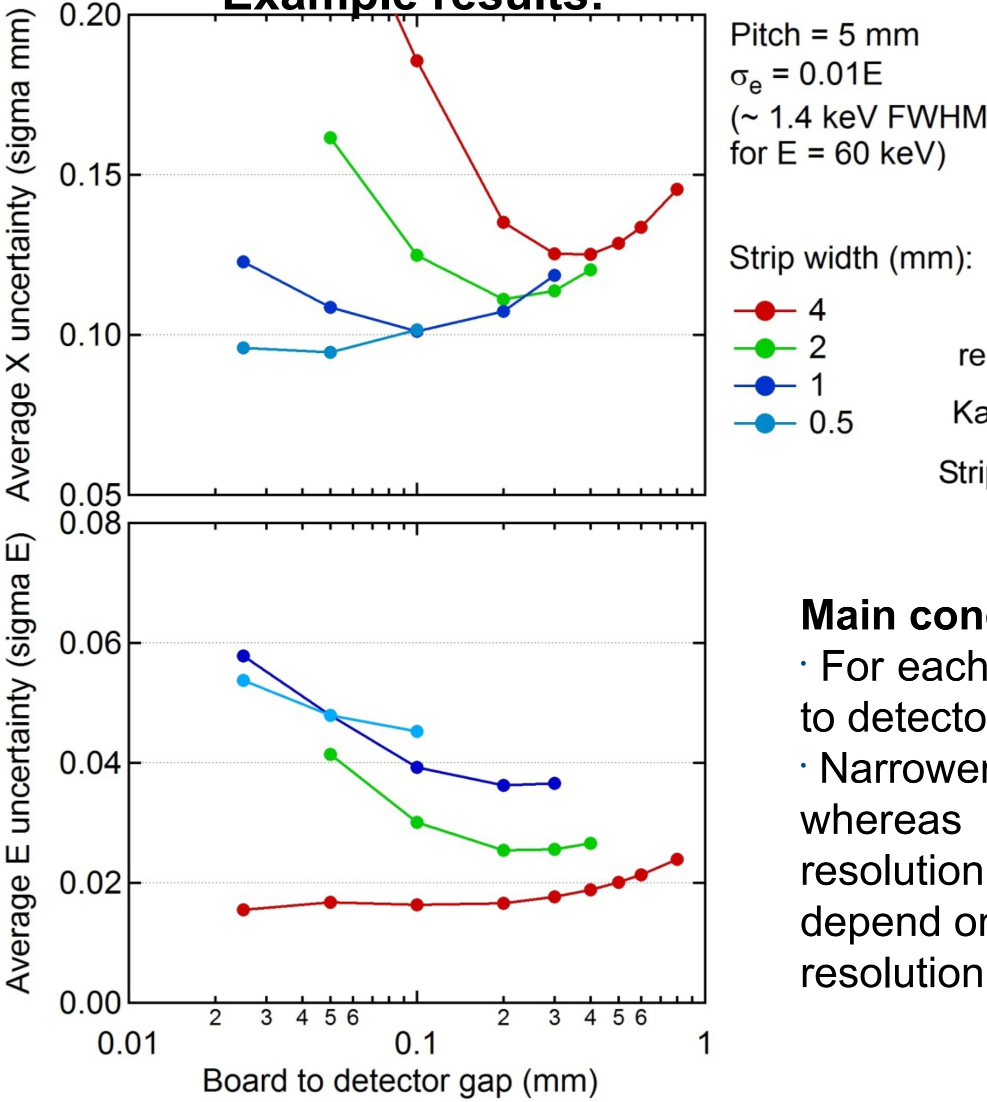
An Am-241 source, collimated to about 1 mm FWHM, was used for these measurements. The histograms are from data sets acquired at eight different source locations.

The position resolution is clearly much better than the strip pitch.

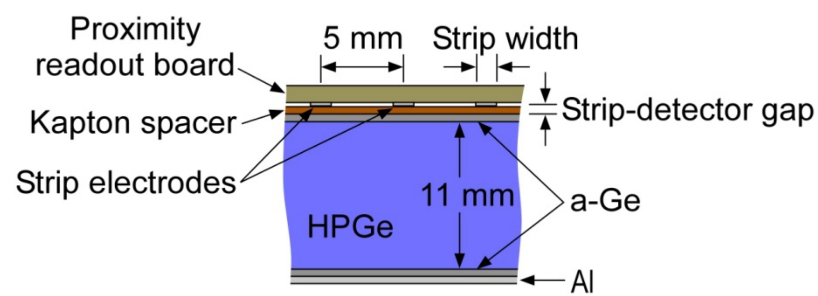
Design Optimization

Instruments That Advance The Art

Example results:



Monte Carlo method implemented to assess the impact of noise on position and energy resolution of strip proximity electrodes

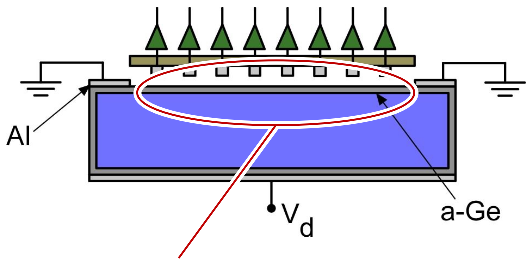


Main conclusions:

- For each strip width, there is an optimum board to detector gap.
- Narrower strips are better for position resolution whereas wider strips are better for energy resolution. The optimum design will therefore depend on the relative importance of the position resolution versus the energy resolution.

Phase II work plan

Phase II work plan



a-Ge resistivity, charge carrier injection, and stability affect performance

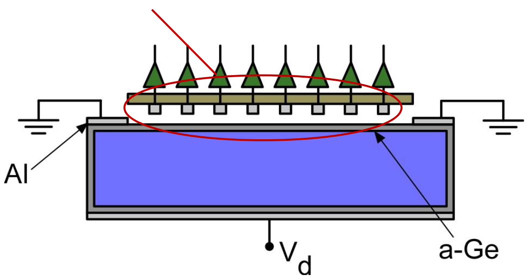
- Optimize cryosat

  Built new cryostat with low noise flex cabling, improved preamplifiers

- Optimization of amorphous-Ge (a-Ge) film for use on proximity surface

  Evaluated various a-Ge deposition processes using simple device structures

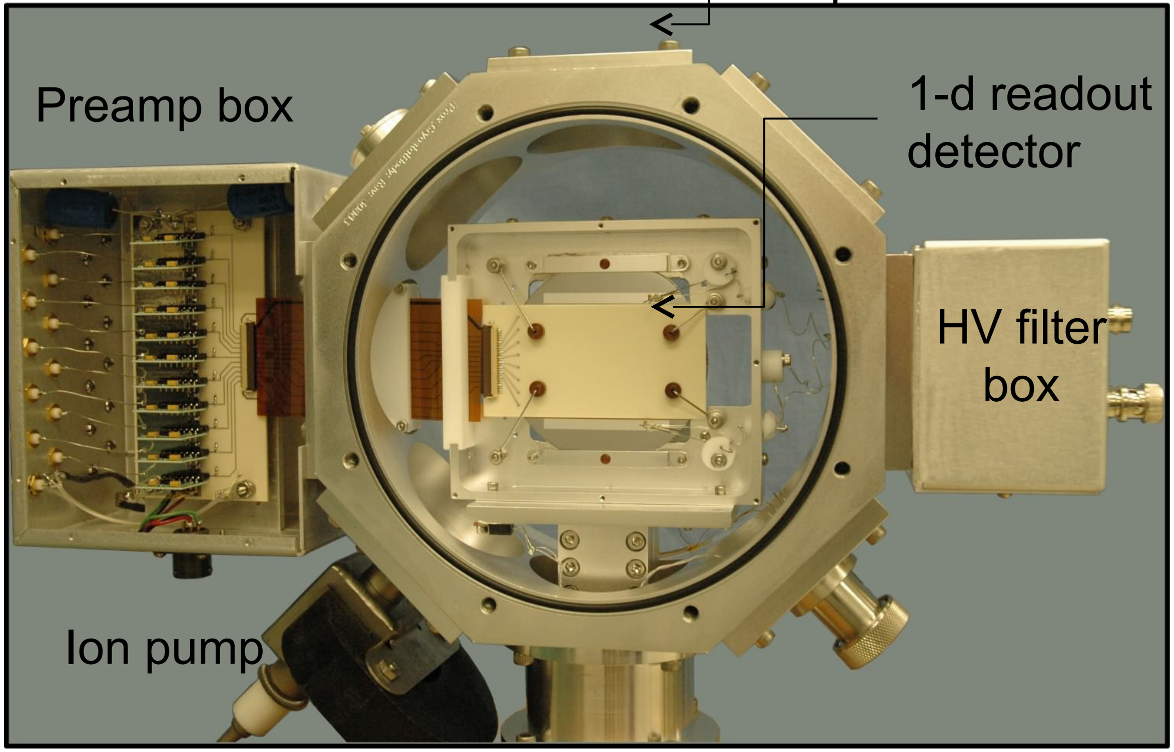
Proximity electrode geometry affects performance



- Extension to 2-d position measurement

- Production and characterization of complete detector system with 2-d position readout capability

Improved Detector System

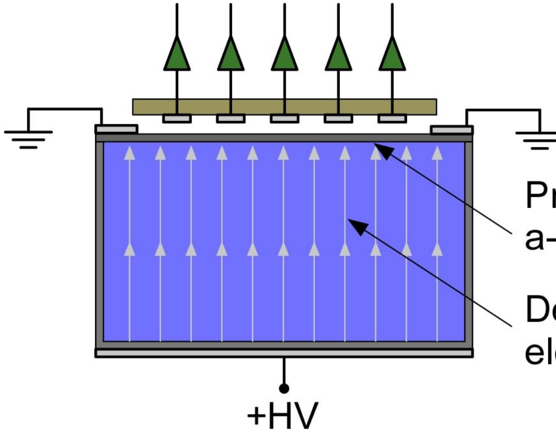


- Multiple flexcircuit electrical feedthroughs (previously demonstrated to have low microphonics)
- Port configuration provides ability to reconfigure for different detector designs including 2-d readout
- Leverages existing parts produced for other projects

Optimization of a-Ge Film

Key to success is the resistivity of the proximity surface:

- Resistivity must low enough so that surface charge will not build up and distort the electric field
- Resistivity must be high enough so that the surface layer will not screen the radiation-generated charge from the proximity electrodes

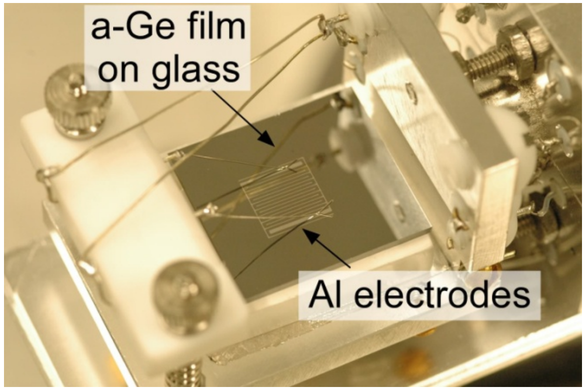


Target ~10^9 Ω/square → ~10 ms time constant for a typical 10 pF detector capacitance

Conclusions from sputtered a-Ge thin film resistivity measurements at low temperatures:

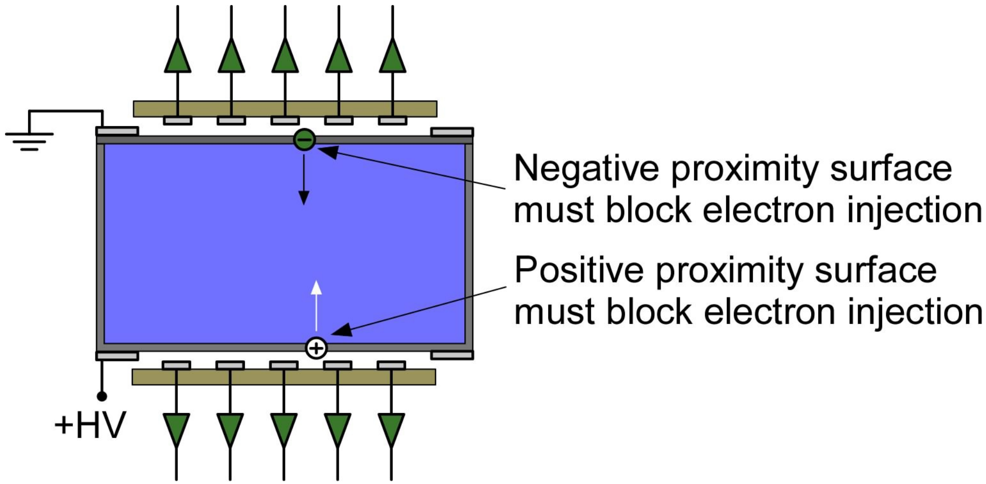
- Hydrogen (residual H2O vapor) must be minimized in the sputter chamber otherwise the resistivity is too large
- Clean vacuum system, high purity Ar sputter gas, long pump down times, and bake outs used to achieve lower resistivity films

a-Ge film test sample loaded into a variable T cryostat



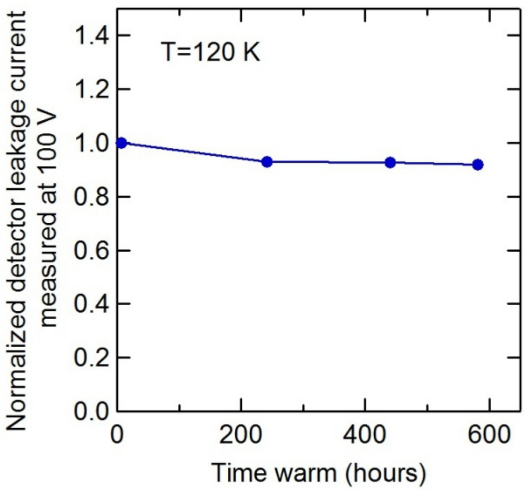
Characterize the a-Ge Film

In addition to optimized resistivity, the a-Ge film must also form a low charge injection electrical contact to the HPGe so that low leakage current (low electronic noise) is achieved, and its properties must be stable with time (room temperature storage)

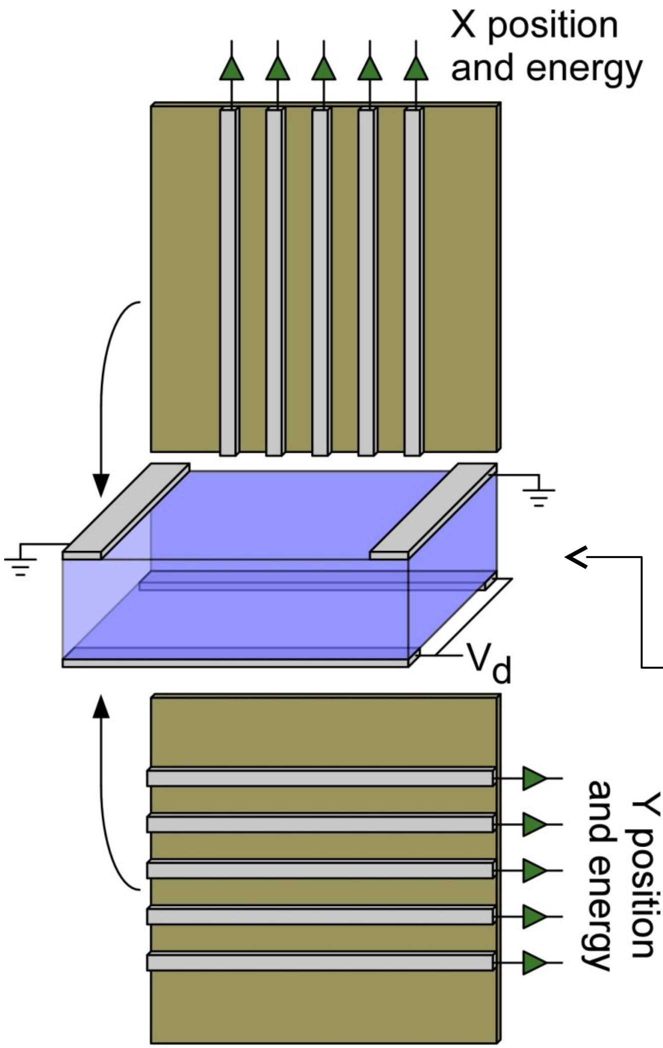


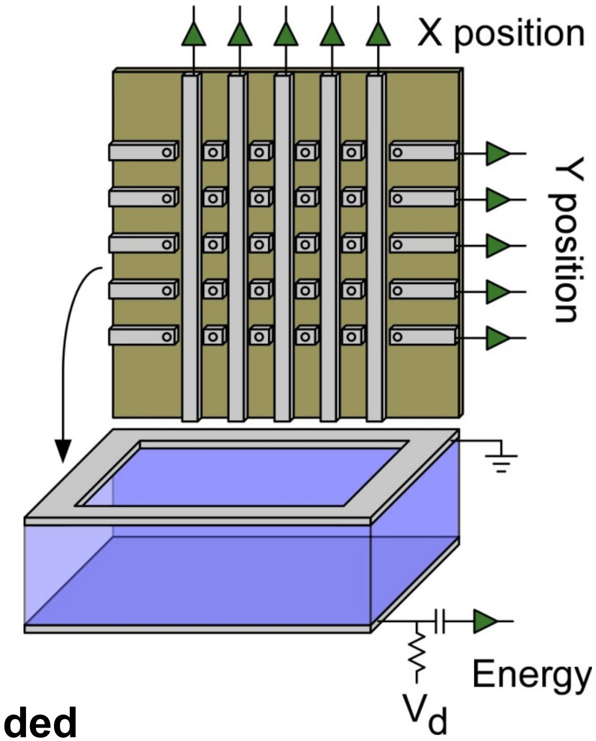
Conclusions from small detector leakage current measurements at various temperatures:

- a-Ge sputtered in pure Ar with little residual H2O appears to be a good blocking contact of both hole and electron injection even at elevated temperatures (~< 1pA/cm2 at 110 K)
- Leakage current stability with room temperature storage still under study, but initial measurements indicate that the target a-Ge sputtering process produces stable characteristics



2-D Position Readout Designs



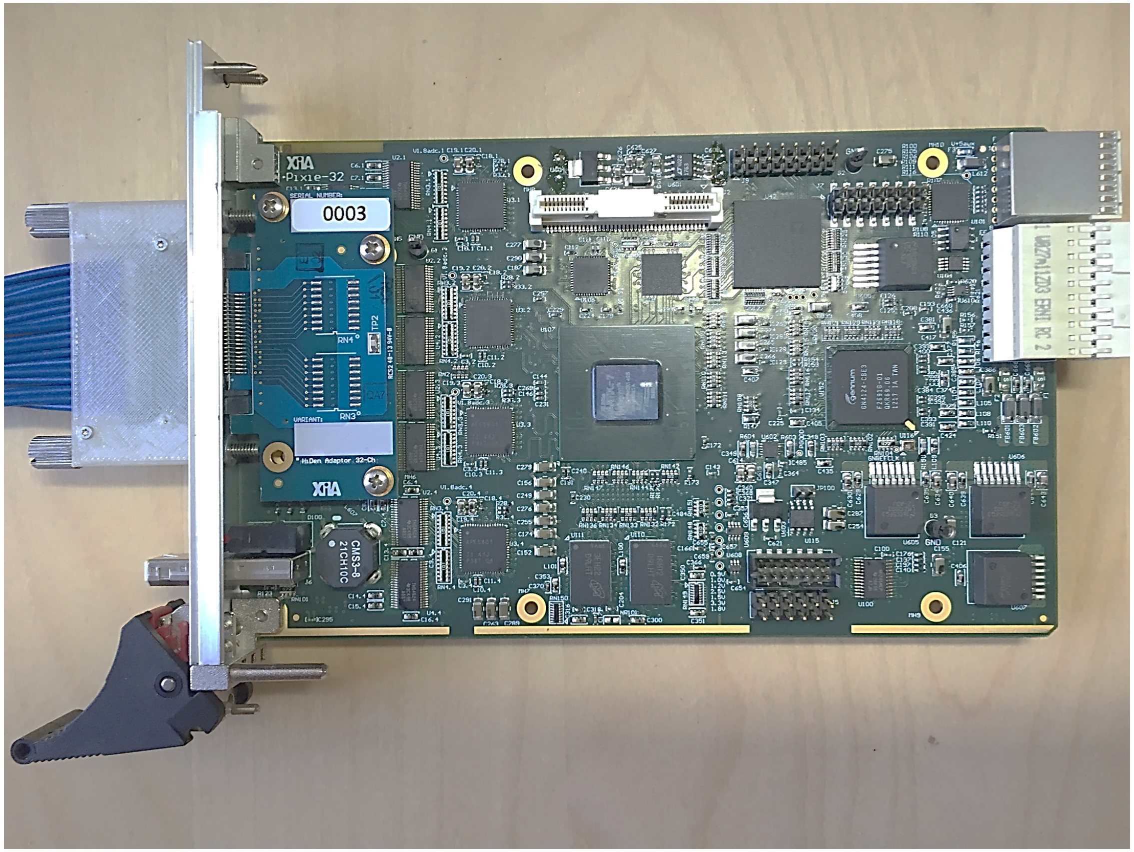


Double-sided
Advantages: simple position measurement
Disadvantages: more complex energy measurement, a-Ge film must be optimized for both detector contacts

Single-sided
Advantages: simple energy measurement
Disadvantages: complex position measurement

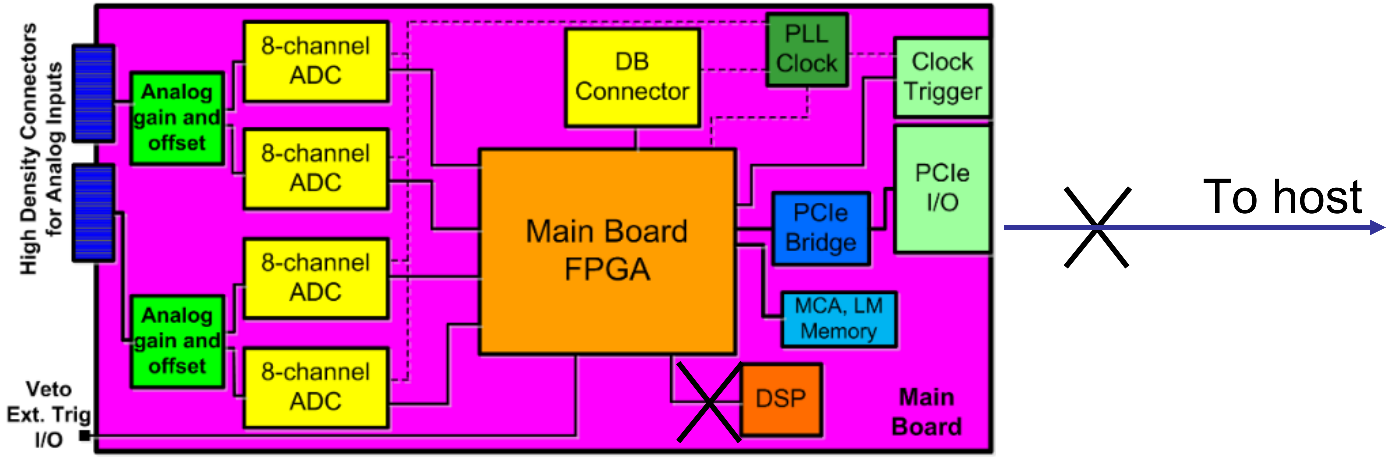
Electronics

- Resources on the XIA Pixie-4 likely insufficient to handle complex calculations required to extract position and energy resolution in real time.
- The 20+ channels envisioned in the final design provided an opportunity to further develop our 32 channel board.



2-D Detector Design - Electronics
32 Channel HiDen XIA board

- Design and built under another XIA Phase II project, but no host and no DSP interface



- HPGe quality energy resolution (<2 keV @1.3MeV, <1.2 keV @ 122 keV)
- Sub-nanosecond timing resolution
- Nonlinearity < 0.5 keV
- Digitization at 12-14 bit, 65-125 MSPS
- x4 PCI Express interface (max 800 MB/s to PC)
- 3U PXI module
- 600 MHz Blackfin DSP
- 256 MB SDRAM for list mode data

Commercialization

Staged commercialization approach

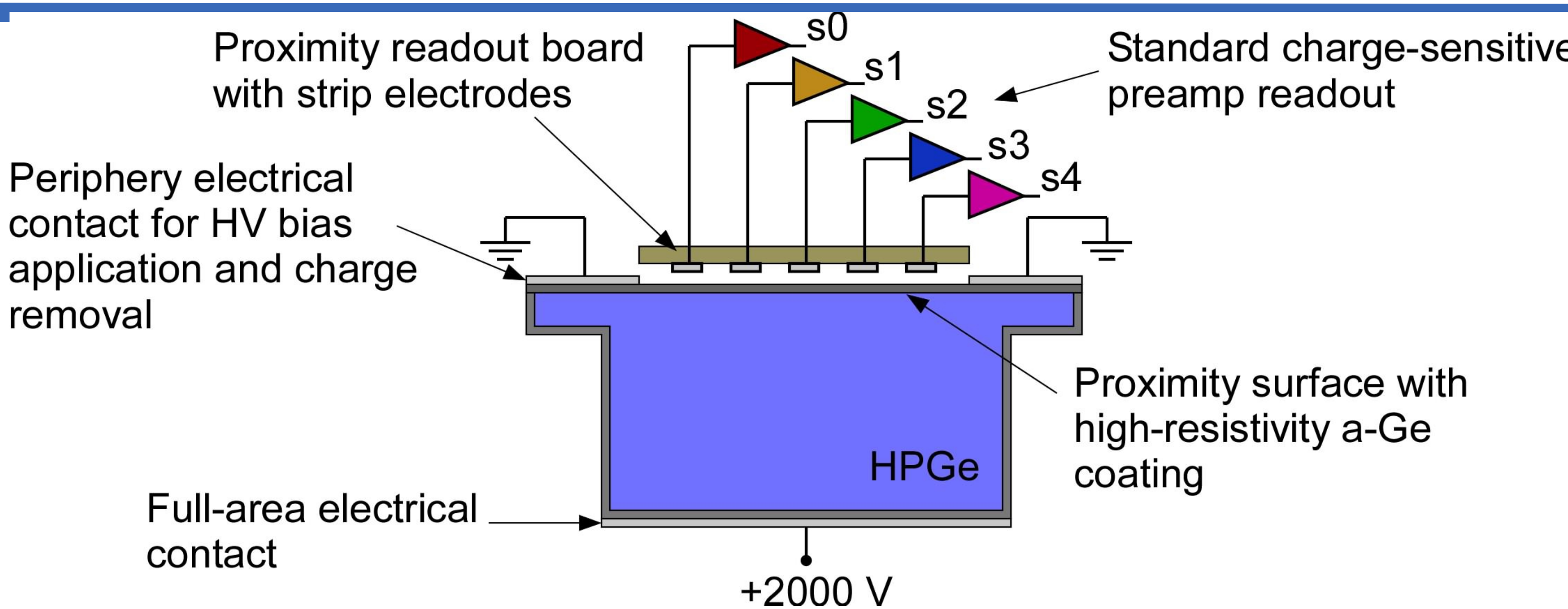
- Test device at end user facilities (e,g. NSCL)
- Replace a fraction of existing detectors withing DOE NP complex with LBNL as supplier
- Transfer final process to Ortec
- Develop interest in medical and mining markets
- Branch out to silicon devices

Next steps

- Further optimization of a-Ge through basic device fabrication and measurements
- Performance study of the 1-d readout detector in the new cryostat/readout electronics system
- Simulations of the 2-d readout configurations to assess performance potential
- Material quality verification of high purity Ge crystals to be used for the 2-d readout detector (simple planar detector fabrication and evaluation)
- Large-area 2-d proximity readout detector fabrication and integration into the test system
- 2-d proximity readout detector evaluation

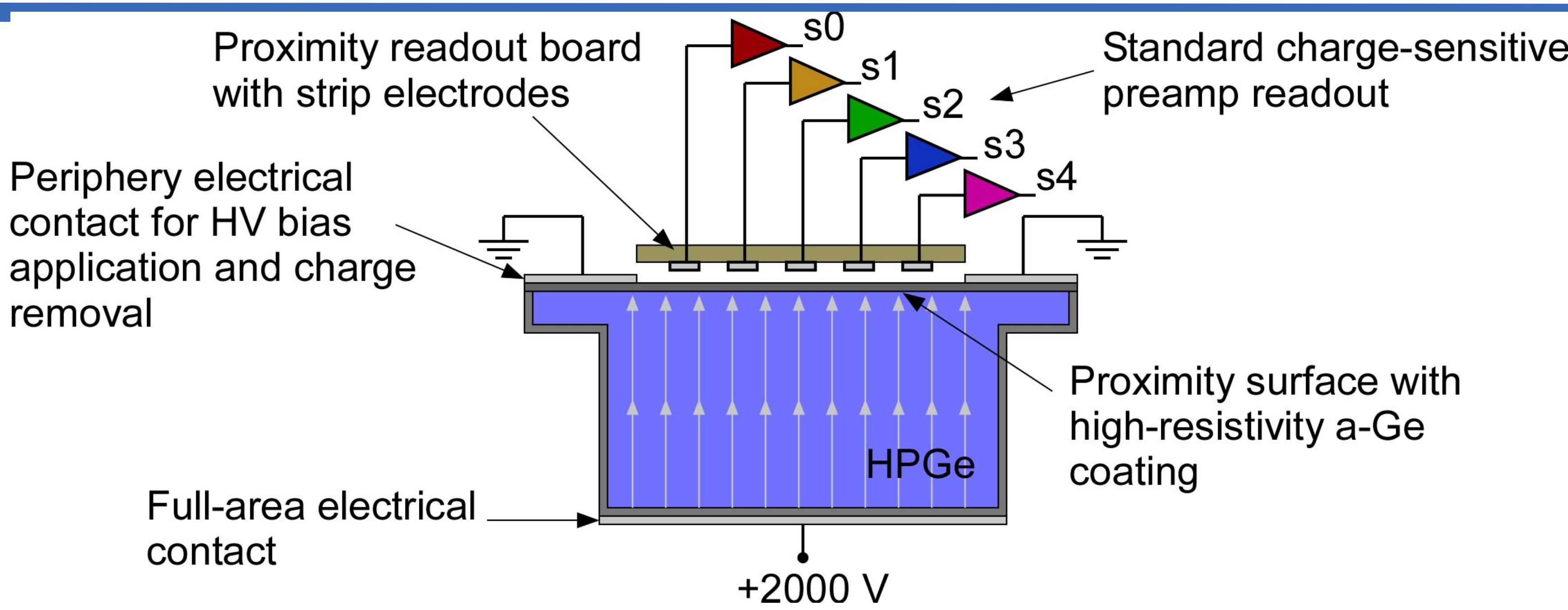
Backup Slides

Proximity electrode signal readout



- Signal readout electrodes in close proximity but not electrically connected to detector
- Concept not new but now want to develop for HPGe readout
- Example related work:
  - Gas ionization detectors: G. Battistoni, et al., NIM152, 423 (1978).
  - CdZnTe CPG edge compensation: P. N. Luke, et al., IEEE TNS 44, 713 (1997).
  - Semiconductor detector readout: P. N. Luke, et al., IEEE TNS 56, 808 (2009).

Proximity electrode signal readout



Key to success is the proximity surface:

- Resistivity must low enough so that surface charge will not build up and distort field
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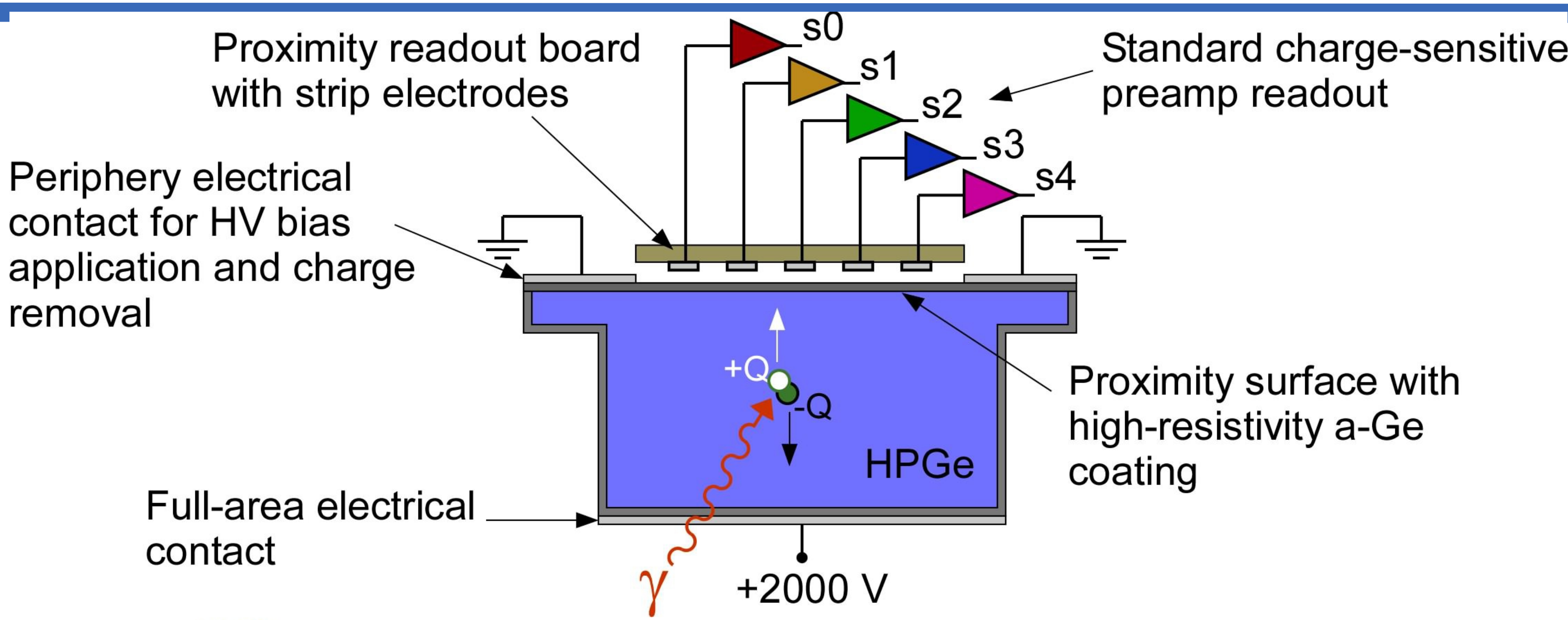
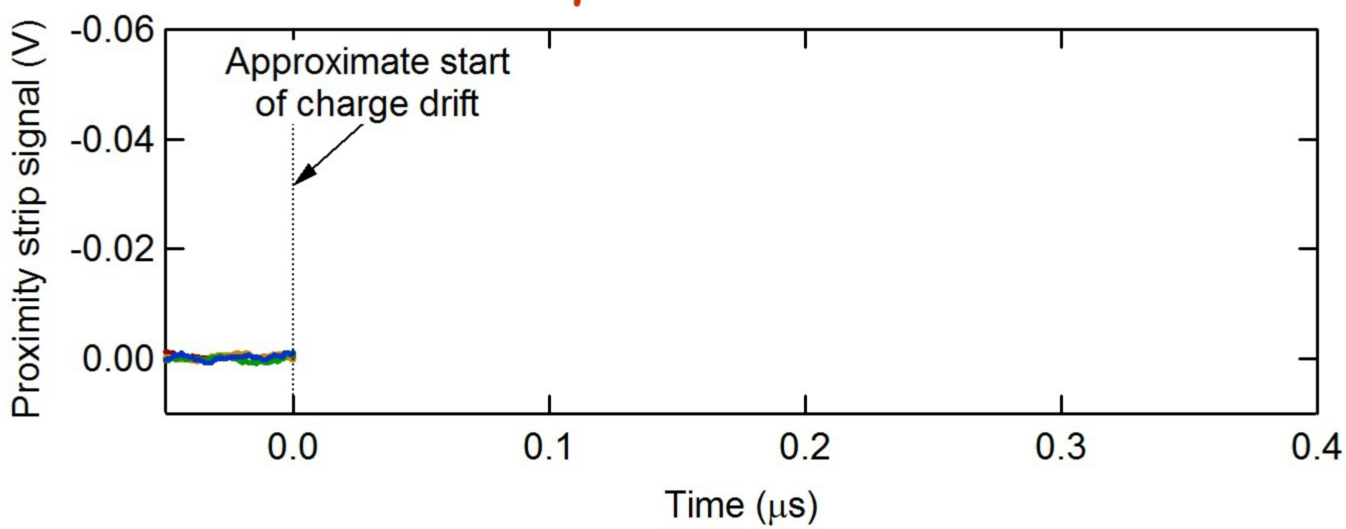
~109 ⌈ /□ → ~10 ms time constant for a typical 10 pF detector capacitance

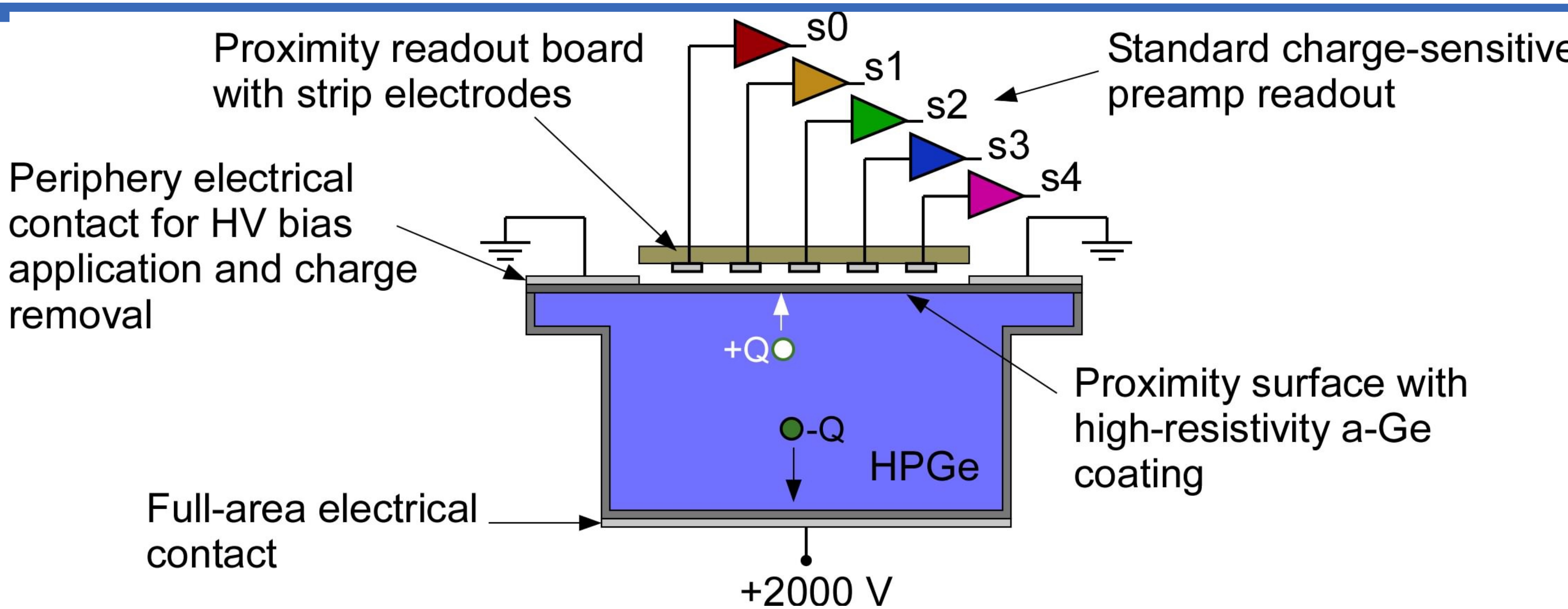
Proximity electrode signal readout

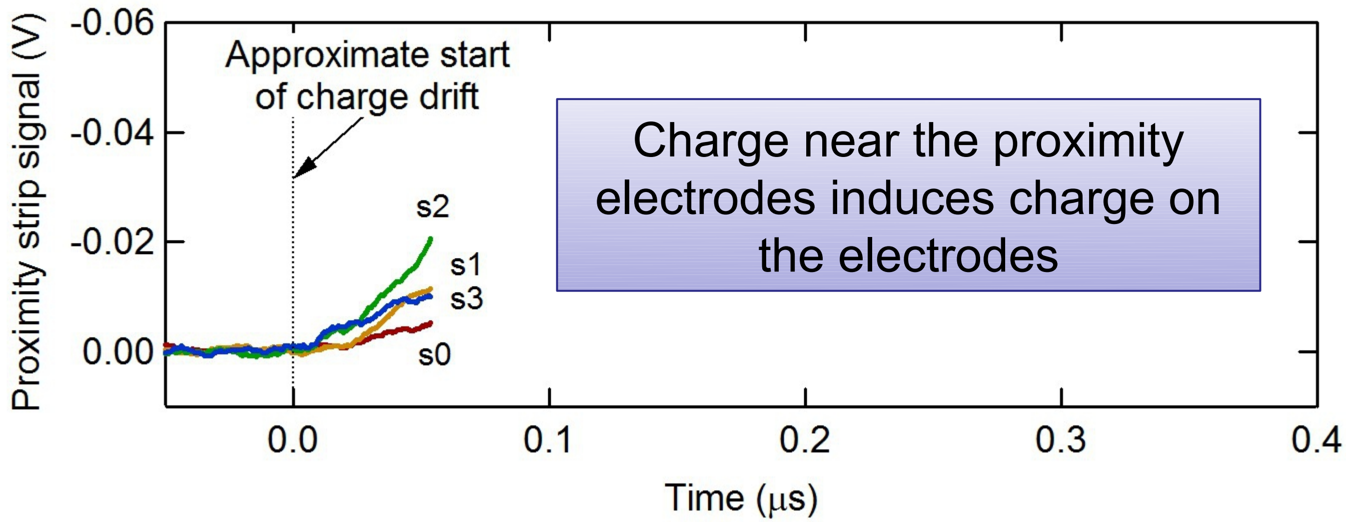




Measured signals from single event with a Cs-137 source

Proximity electrode signal readout





Measured signals from single event with a Cs-137 source

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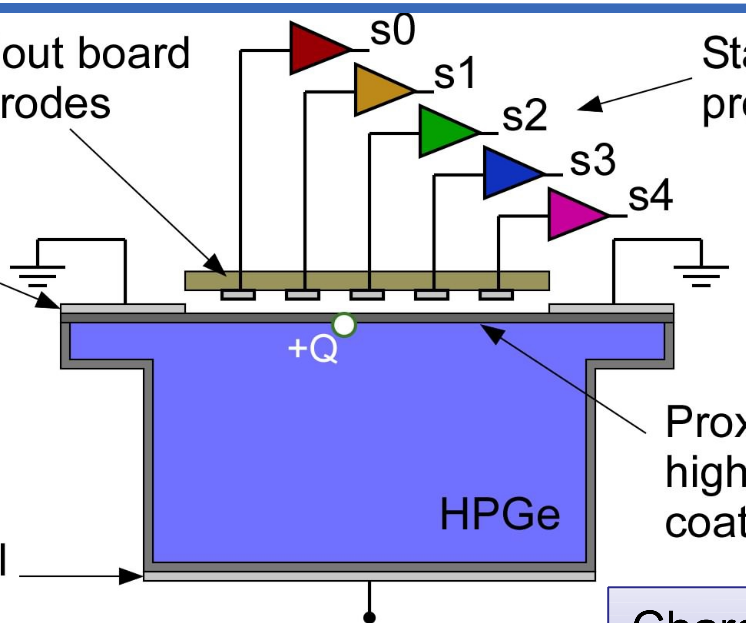
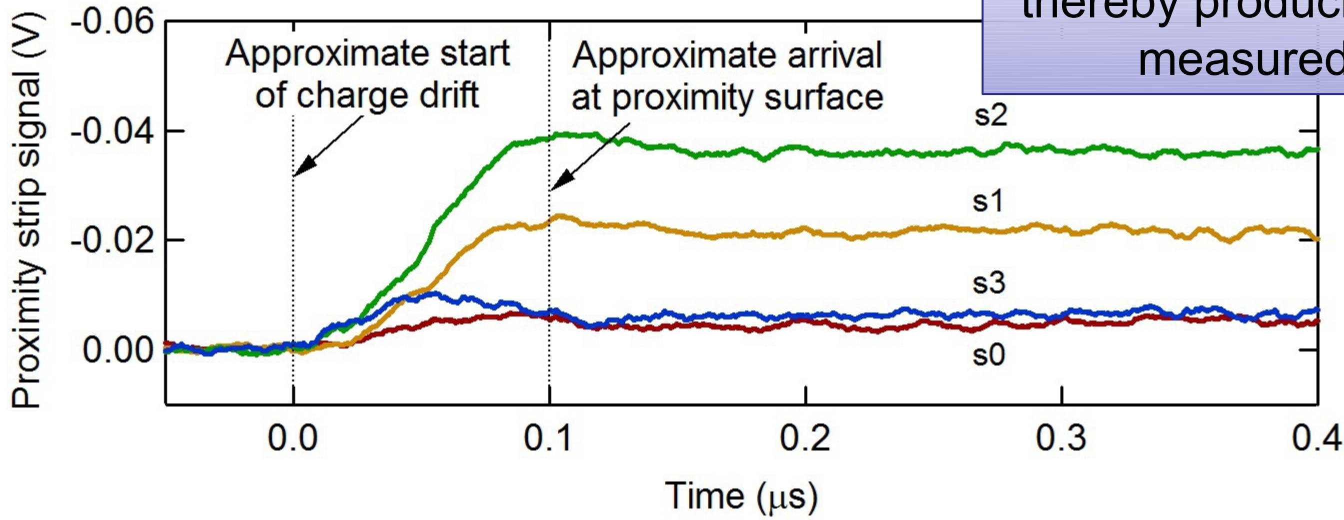
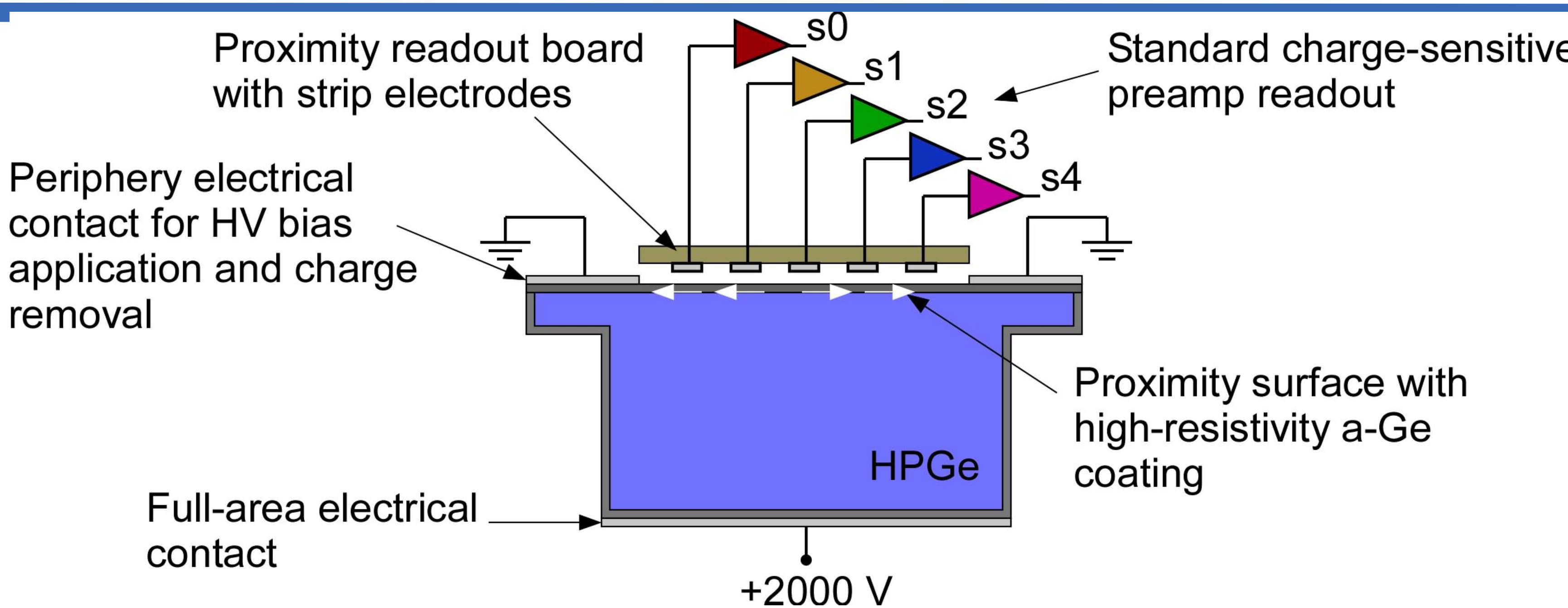


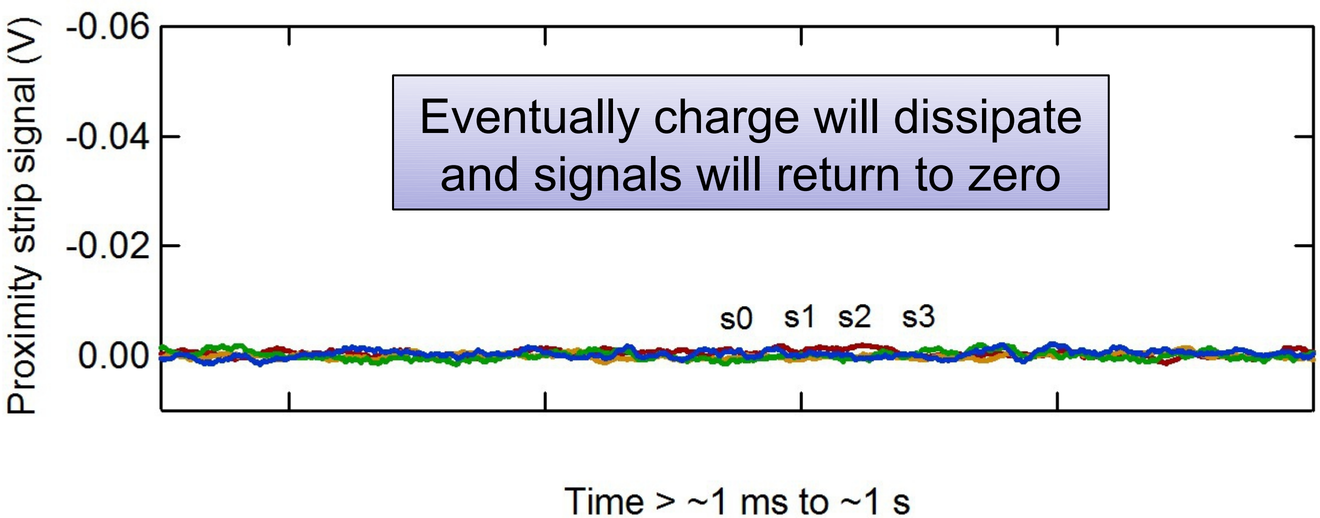
Charge momentarily remains thereby producing an easily measured signal



Measured signals from single event with a Cs-137 source

Proximity electrode signal readout





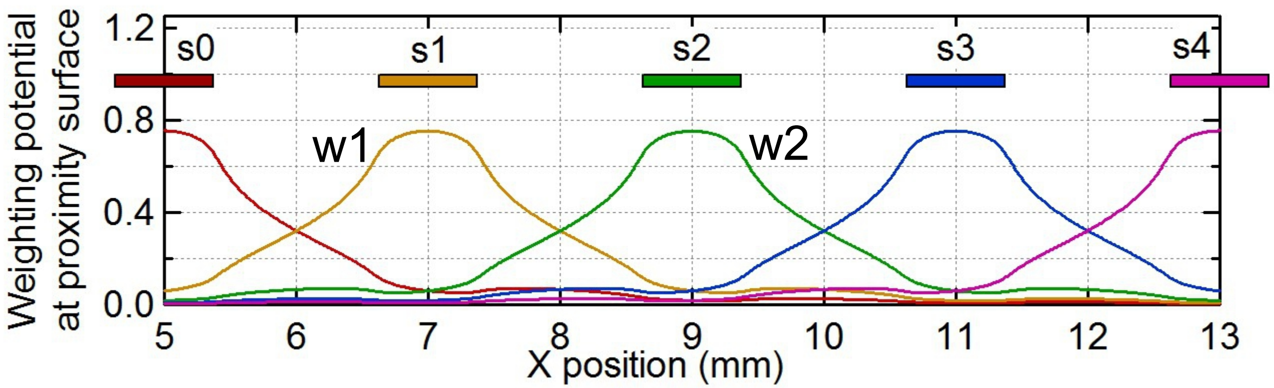
Position and energy determination

Instruments That Advance The Art

Since no single electrode completely collects all of the event charge, the proximity method does not directly measure energy (or position at the sub-electrode-pitch level)

Fine position and energy must be calculated based on signals from multiple electrodes

Utilize weighting potential of each electrode calculated at the proximity surface = induced charge on electrode for a unit charge sitting at the proximity surface



Position and energy determination

Method 1: Rely on knowledge of geometry to calculate weighting potentials at the proximity surface (= induced charge on strip due to unit charge at surface)

1. Determine x from pulse height ratio and calculated weighting potential ratio
   Localize to strip based on pulse height comparison
   Localize further based on solution to:

$$\frac{w_2(x)}{w_1(x)} = \frac{p_2}{p_1}$$

2. Determine E from x, w2(x), and p2 :

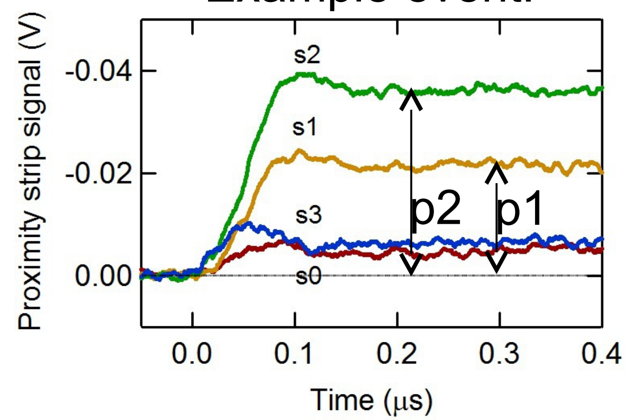
$$E = \frac{p_2}{w_2(x)} C_2$$

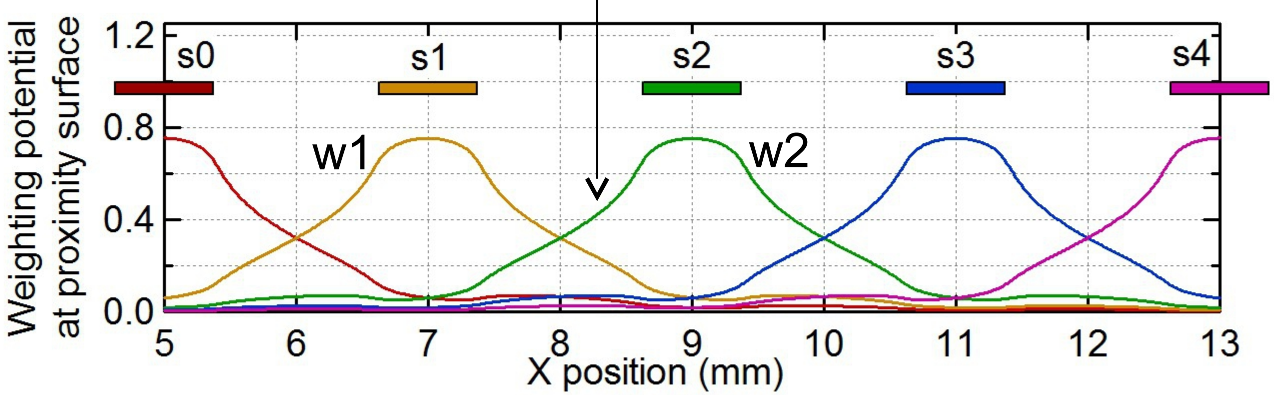
Determined through channel energy calibration

$$\frac{w_2}{w_1} = \frac{p_2}{p_1}$$

$$\Rightarrow x = 8.3\,\text{mm}$$

Example event:





Position and energy determination

Method 2: Use flood illumination data and expected spatially uniform event distribution to obtain “weighting potential”

1. Determine “weighting potential” ratio required to produce a flat x histogram
2. Determine x from pulse height ratio and extracted “weighting potential” ratio
3. Determine “weighting potential” using pulse height histograms generated for specific x values, peak location gives the “weighting potential”
4. Determine E from x, extracted “weighting potential”, and pulse height

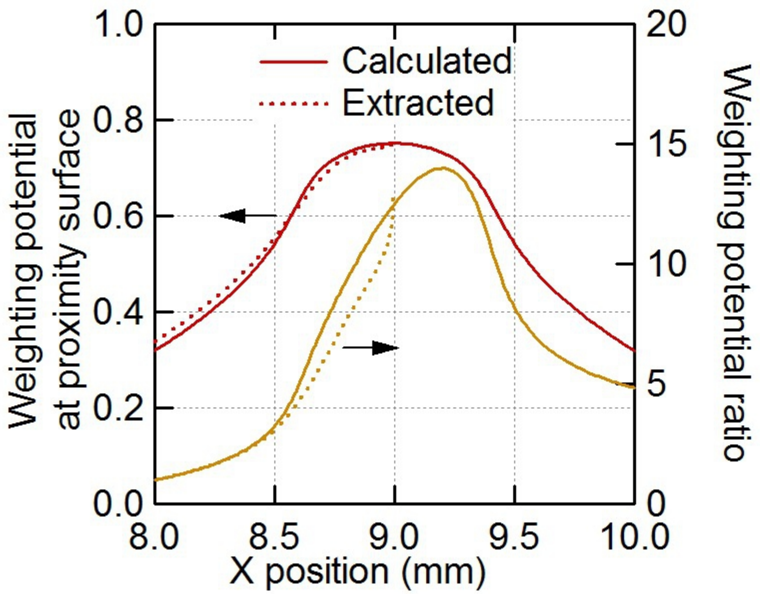
$$x = \frac{d}{2} \frac{\int_1^{r} H(r)\,dr}{\int_1^{r_{max}} H(r)\,dr}$$

Using this, numerically determined r(x) = w2/w1(x)

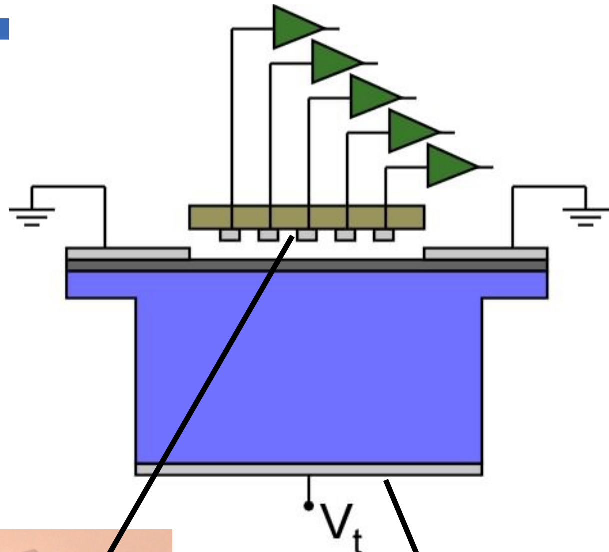
$H(r) =$ pulse height ratio histogram

$$r = \frac{p_2}{p_1} = \frac{w_2}{w_1}$$

$d =$ strip pitch



Single-sided strip proximity detectors

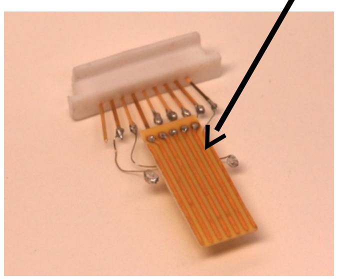


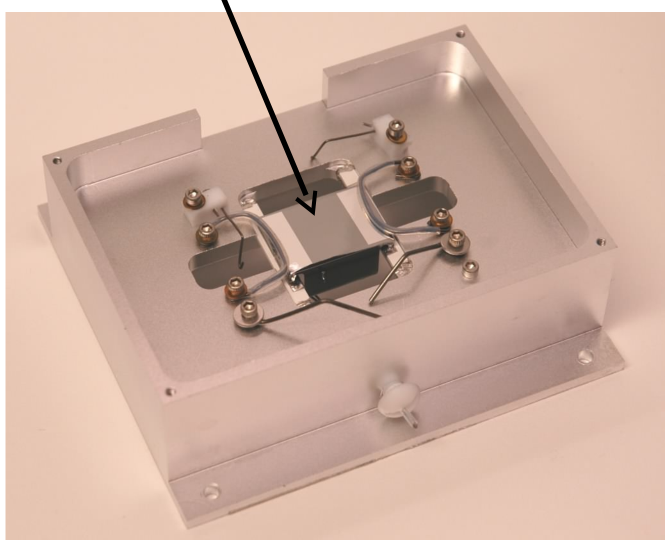
Proximity electrodes:

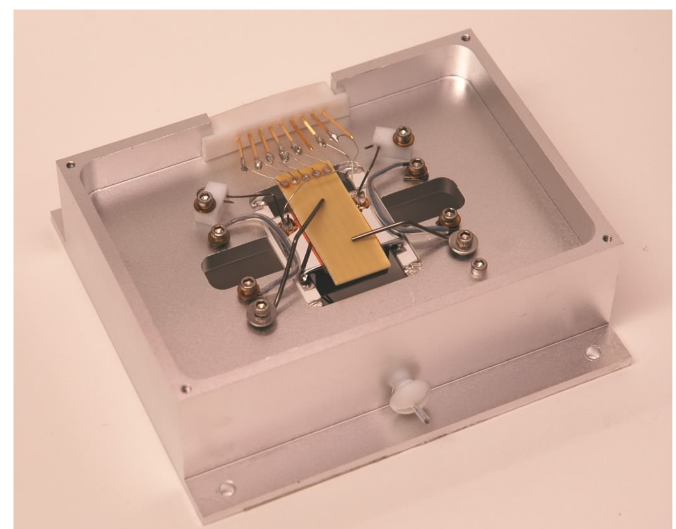
- ~1 mm width and gap
- Spaced ~2 mil from detector with Kapton

Detectors:

- 10 mm thick, 18 x 18 mm2 area
- 12 mm gap between guard strips



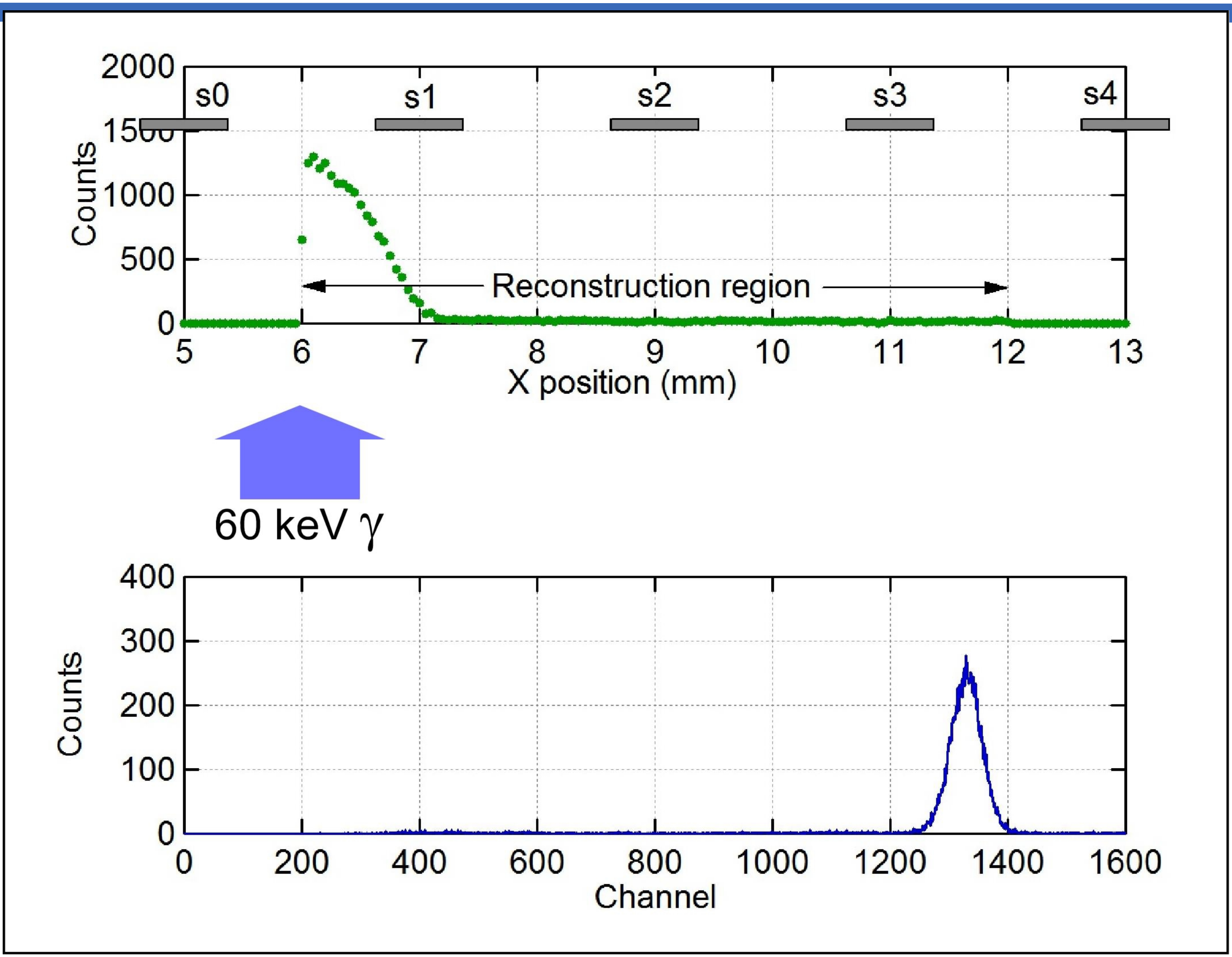




Scanned Source Measurements

Position

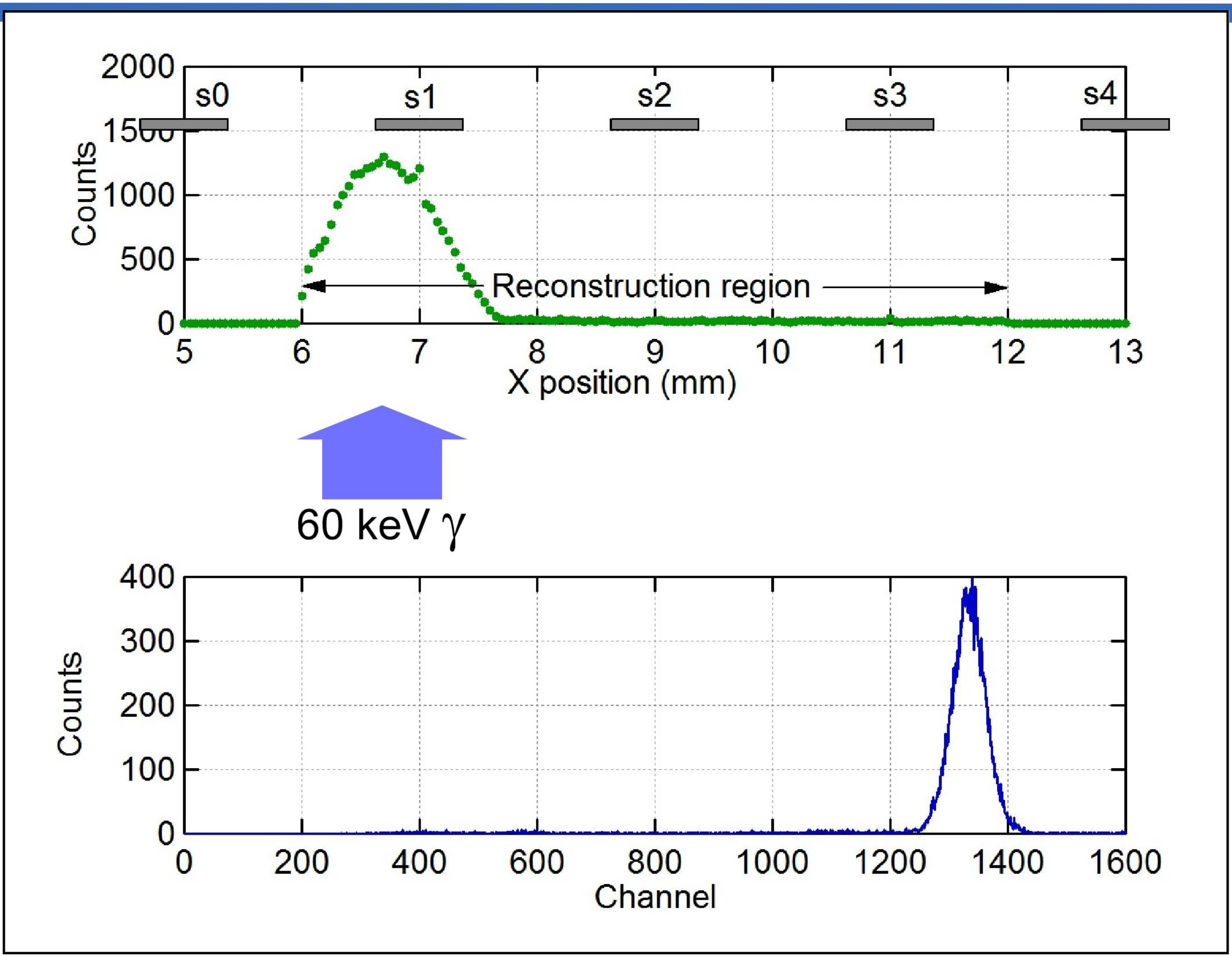
Energy



Scanned Source Measurements

Position

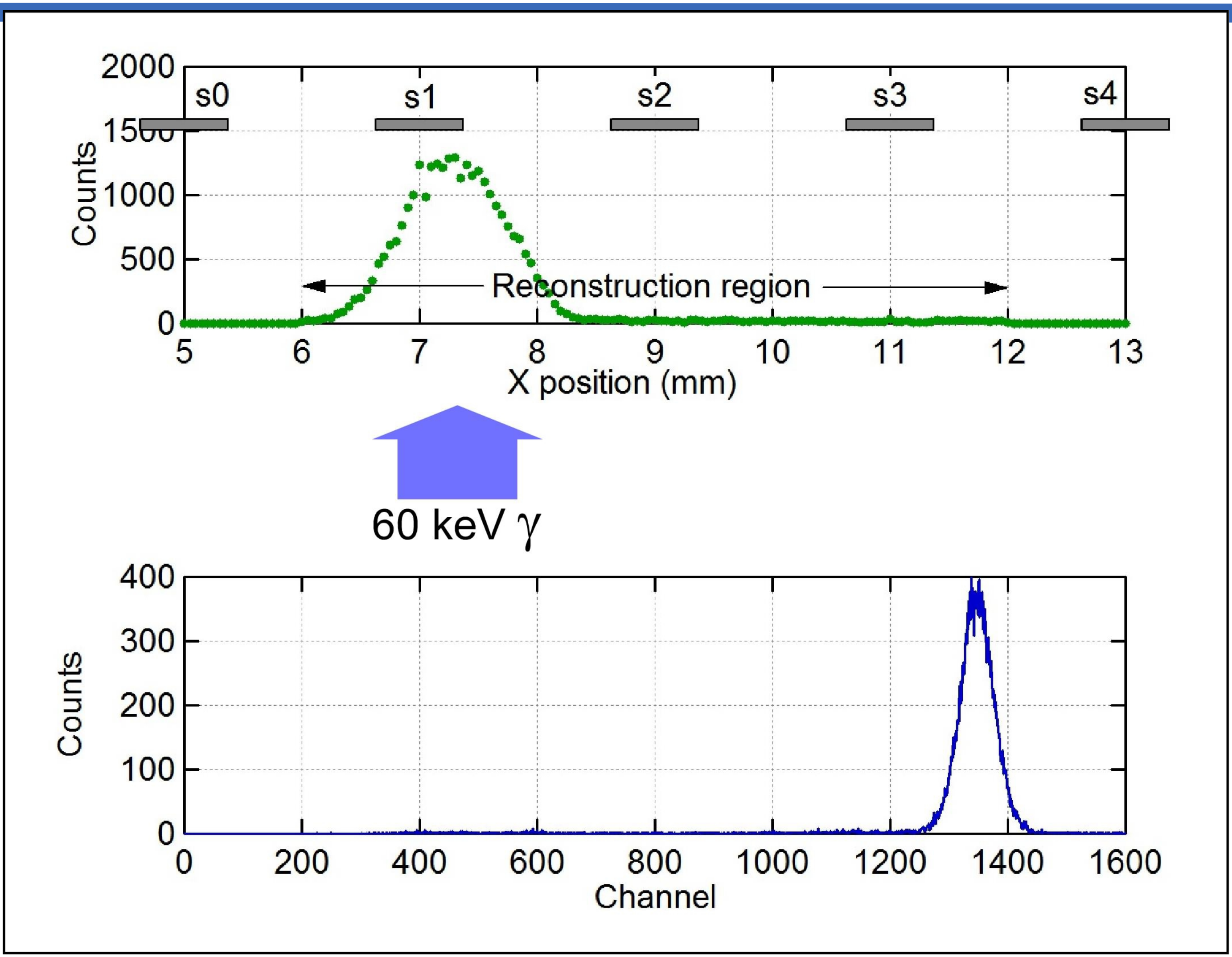
Energy



Scanned Source Measurements

Position

Energy



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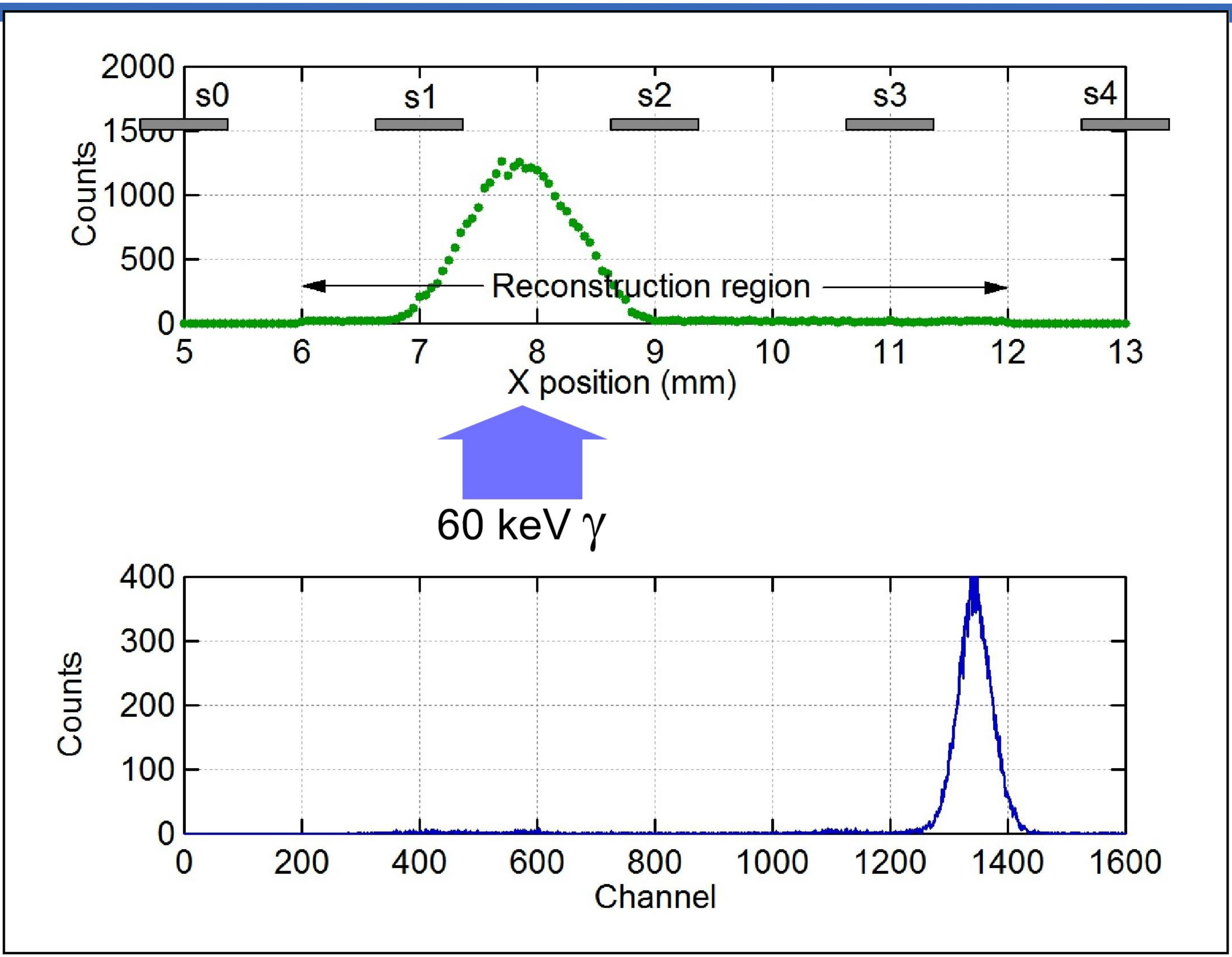
Position

Energy



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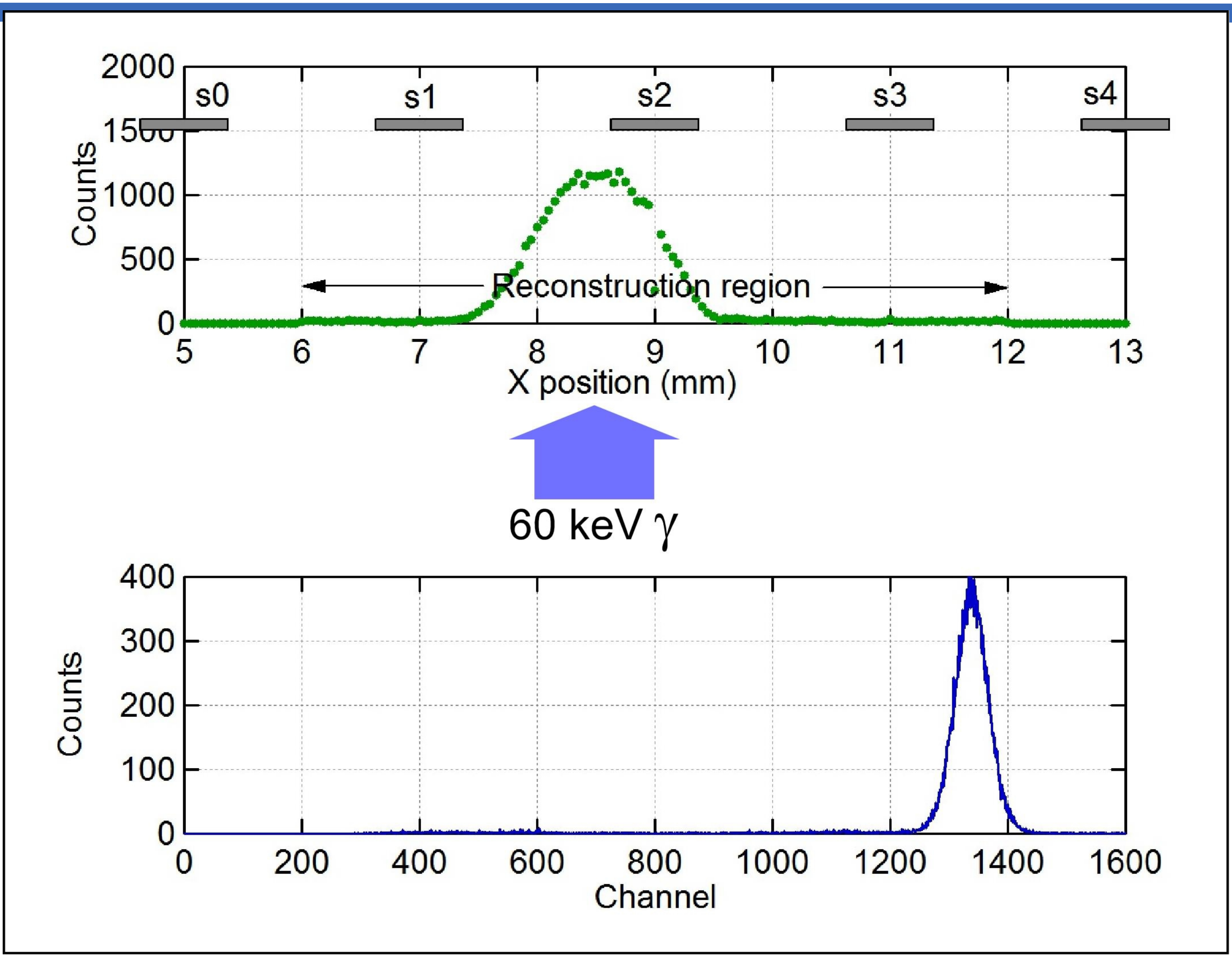
Position

Energy



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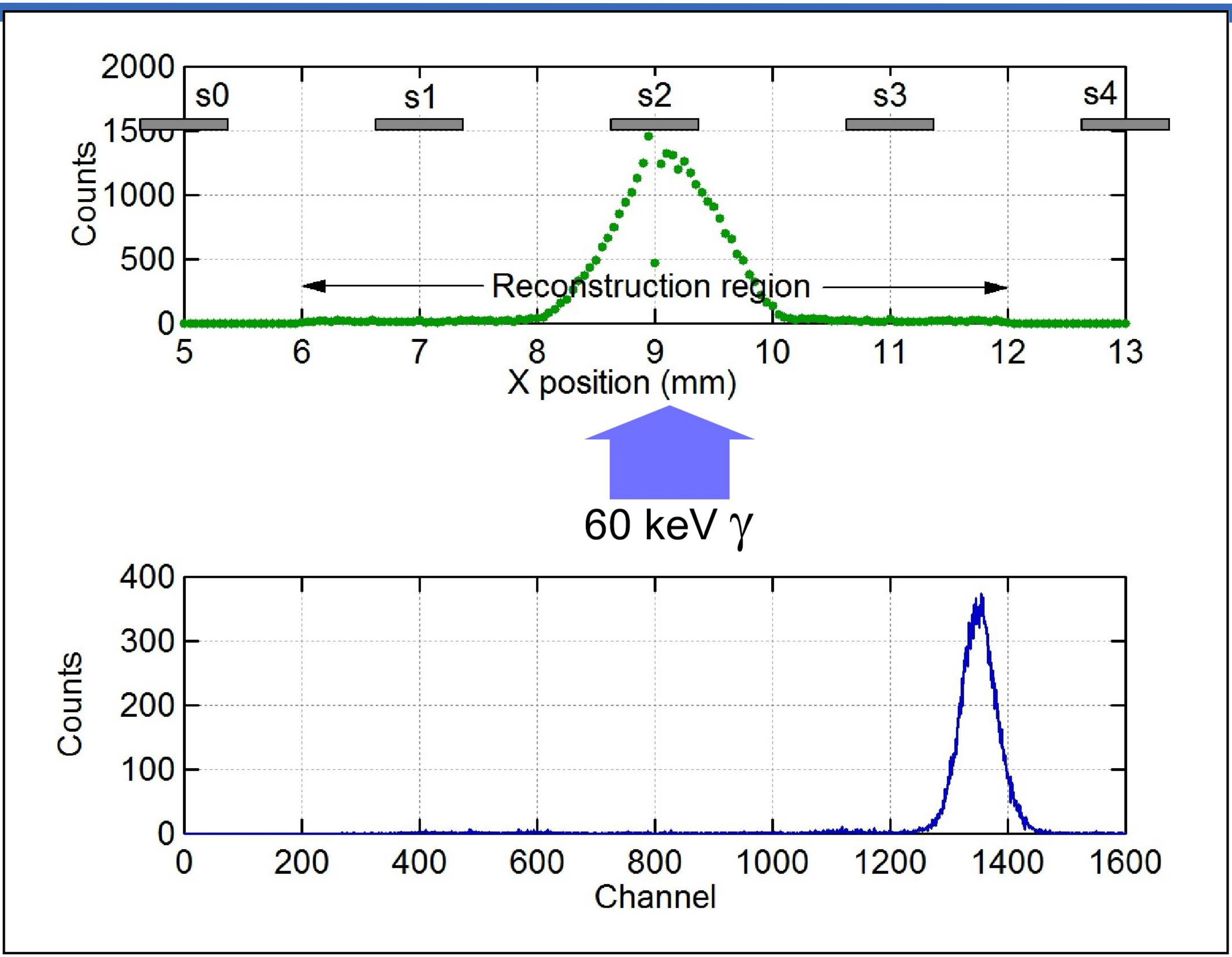
Position

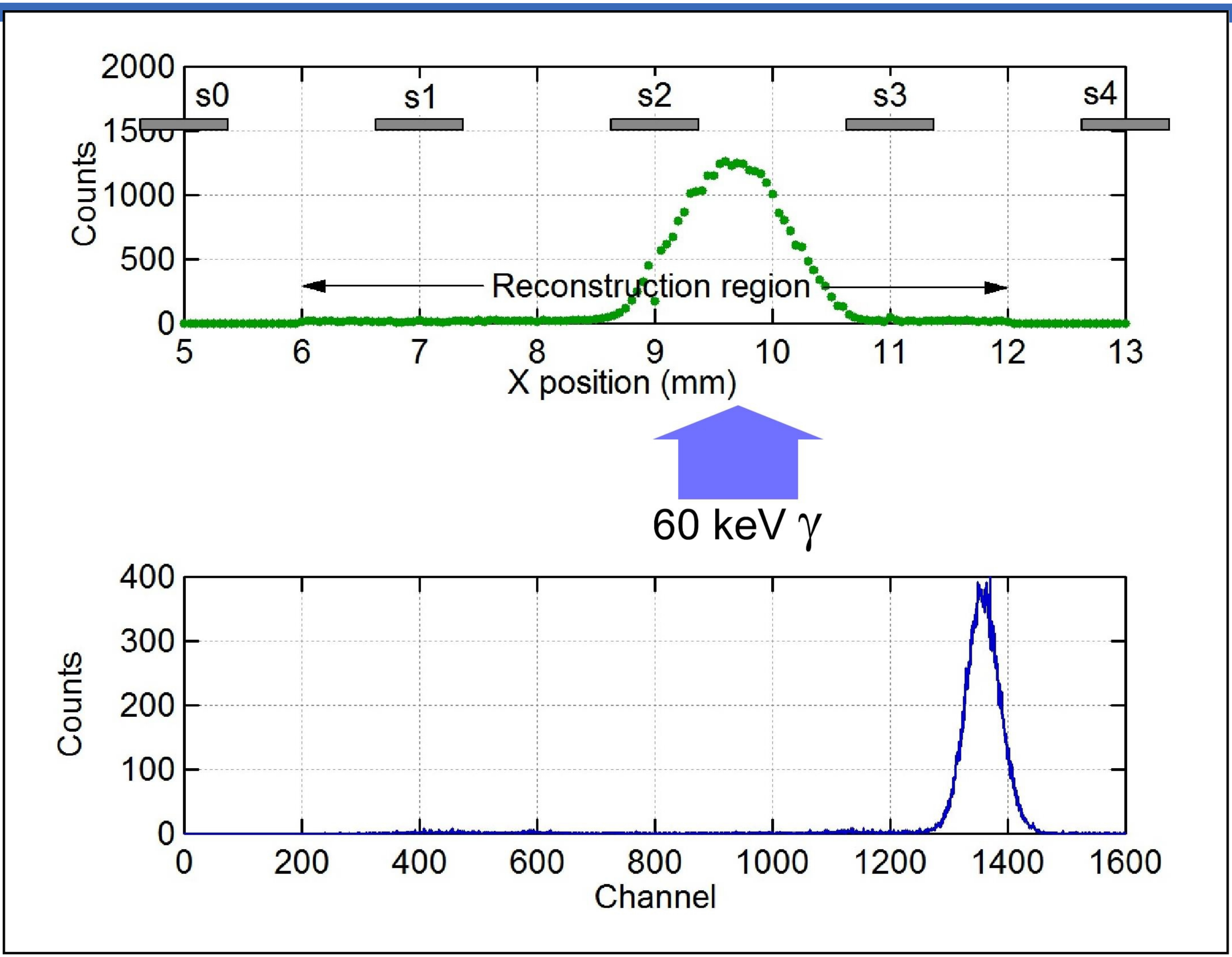
Energy



Scanned Source Measurements

Position

Energy



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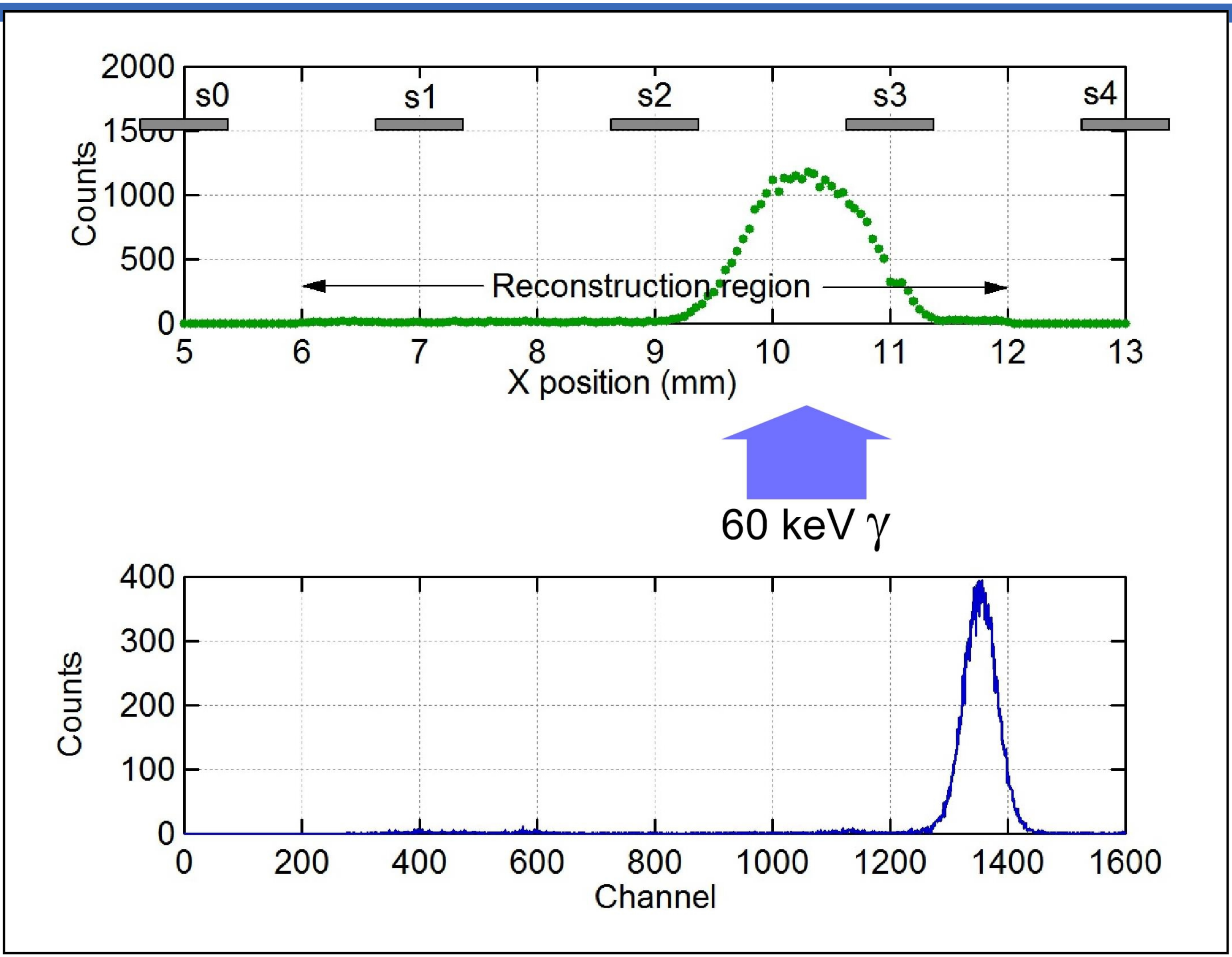
Position

Energy



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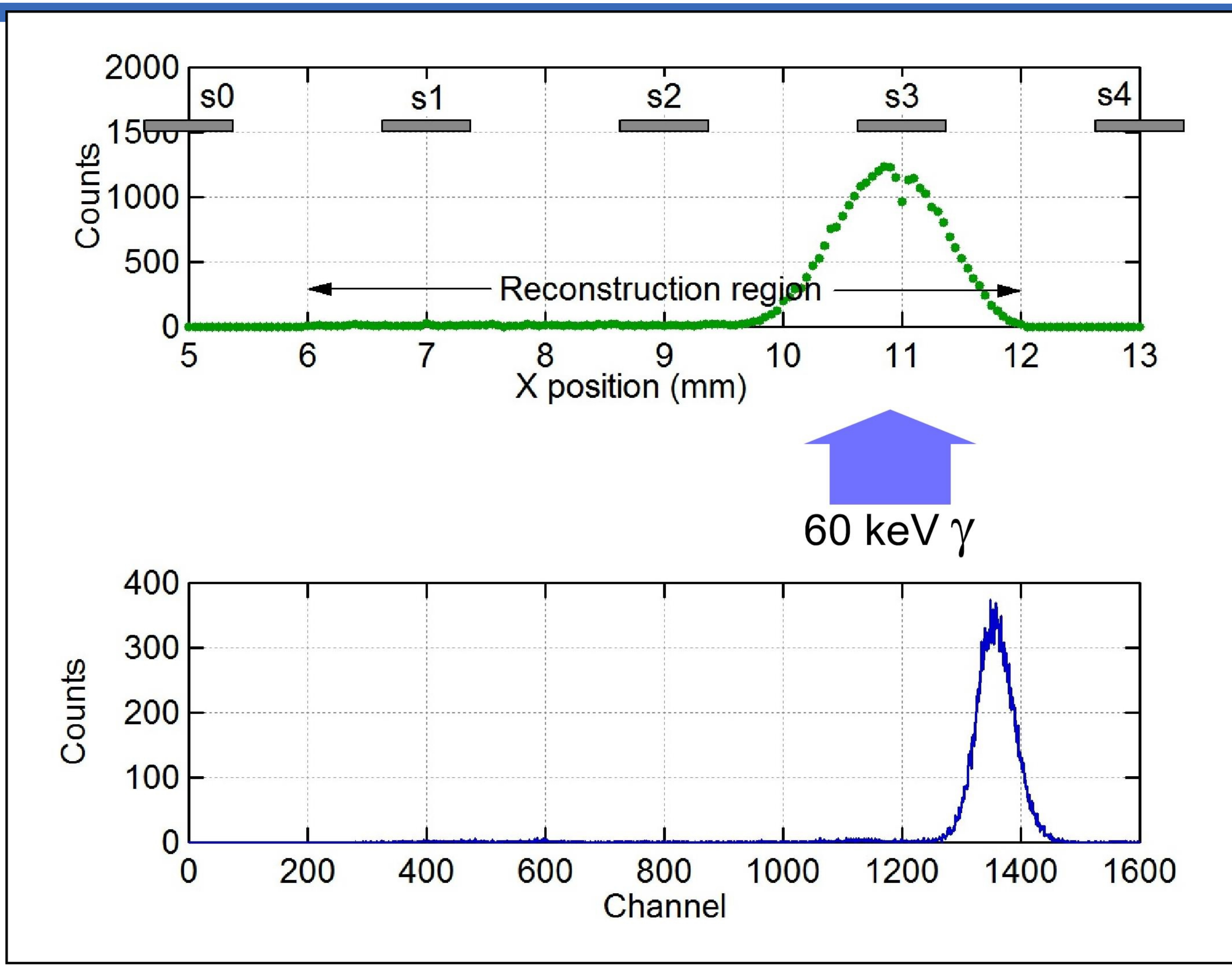
Position

Energy



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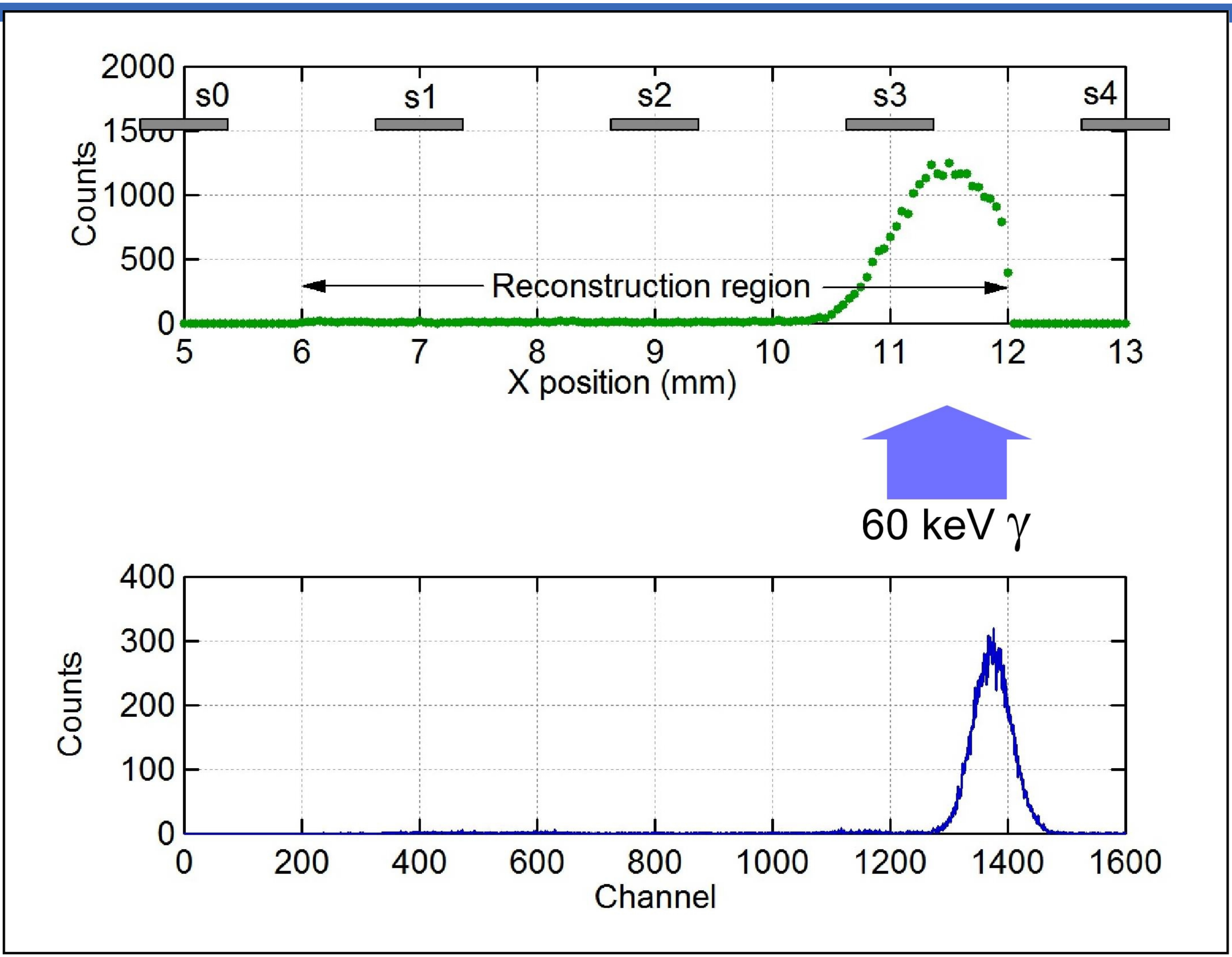
Position

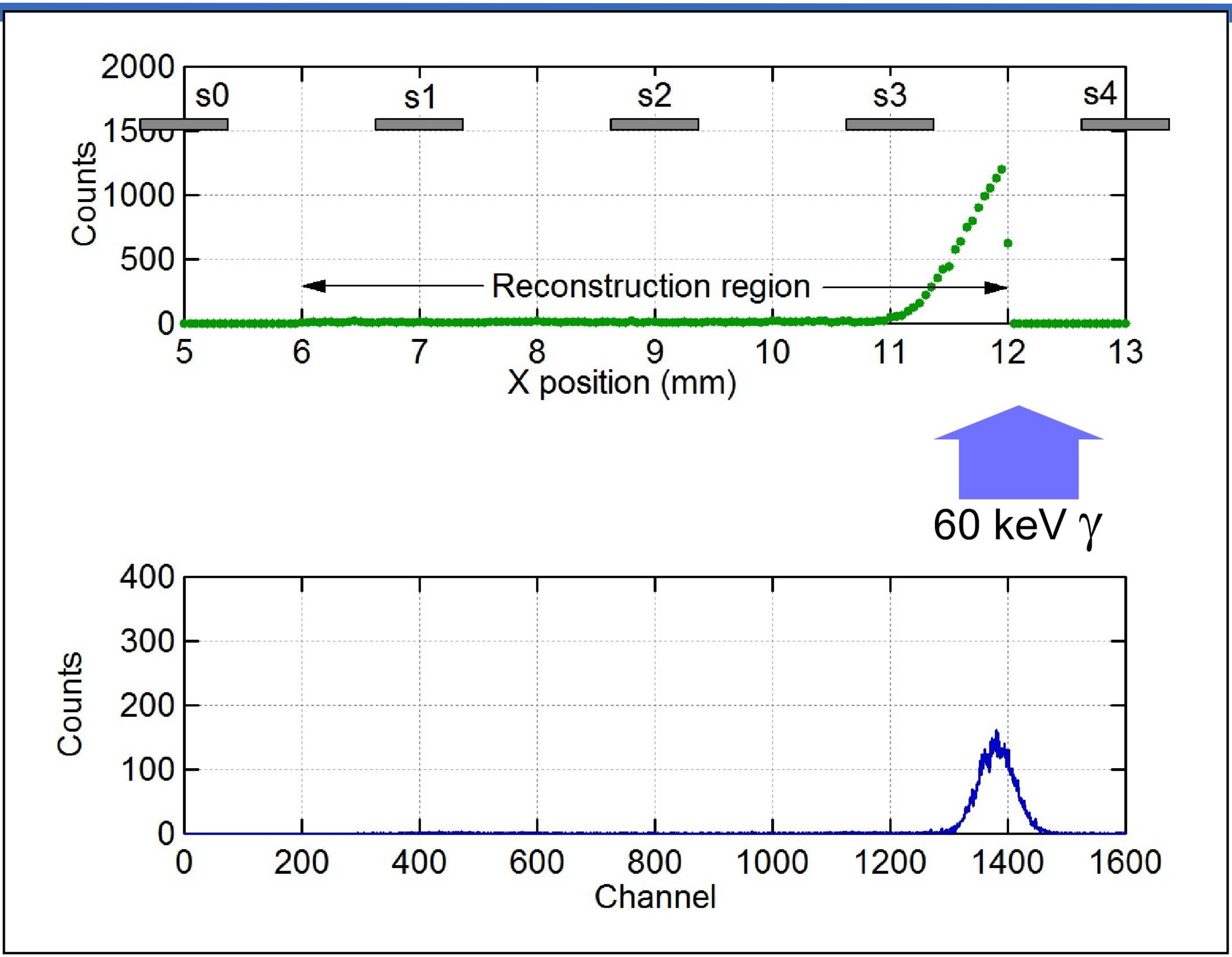
Energy



Scanned Source Measurements

Position

Energy



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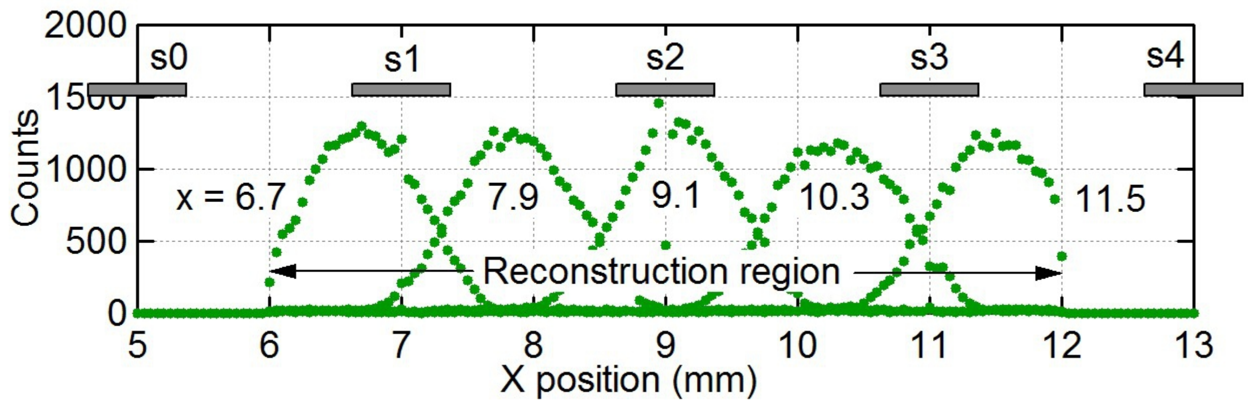
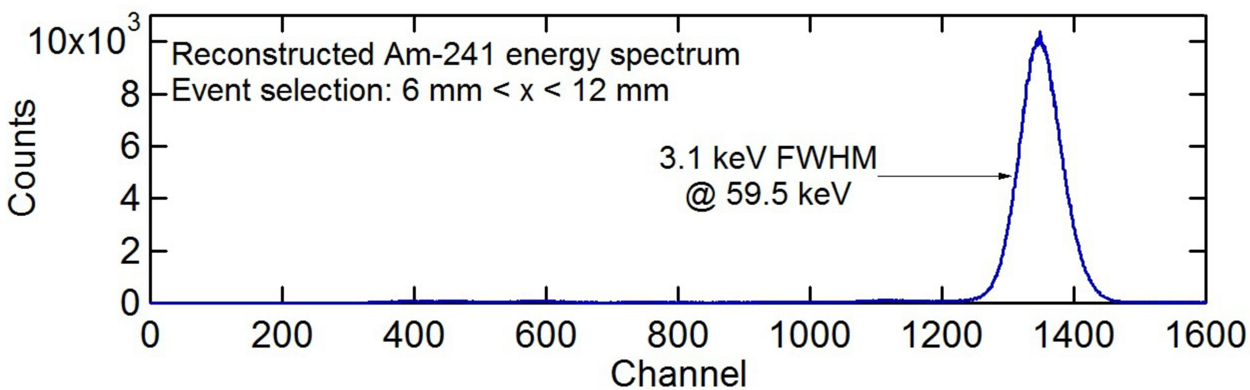
Position



Sub-strip-pitch position resolution achieved!

Energy



Single channel electronic noise ~ 1.5 keV

Part of peak width is from summation (~quadrature) of noise from multiple channels

Spatial non-uniformities in the charge sensing will also contribute