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U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

Office of Defense Nuclear Nonproliferation Research & Development

Nuclear Weapons and Material Security (WMS) Team Program Review
WMS2013

Array of Virtual Frisch-Grid CZT Detectors with Common Cathode Readout for Correcting Charge Trapping and Rejecting Incomplete Charge Collection

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BROOKHAVEN NATIONAL LABORATORY

Research team

- Brookhaven National Laboratory (BNL)
- PIs: A. Bolotnikov, G. De Geronimo and Ralph James
- BNL team: A. Hossain, G. Camarda, G. Yang (NNS), V. Emerson, J. Fried (Instrumentation) and G. Mahler (mechanical engineer)
- Students: M. Marshall, I. Andrews, M. Petryk, and J. Butcher
- Subcontractors: S. Soldner (eV Products) and H. Chen (Redlen)

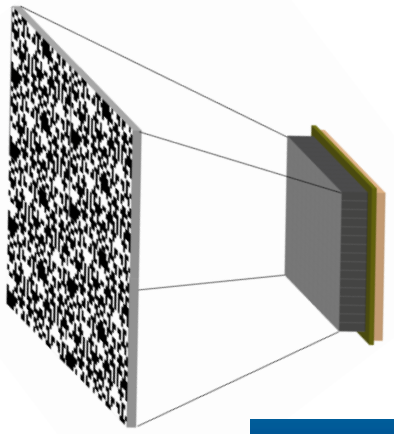
- Three-year project
- Budget: $550K per year

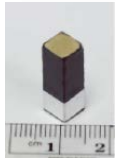
Project goal and objectives

- **Goal:** Develop and integrate an array of virtual Frisch-grid CZT detectors and readout electronics
- **Motivation** for the project: To overcome the high cost and low availability of large-volume CZT crystals by making arrays of small but higher production-yield crystals
- **Array description**: The array is a high-energy-resolution, position-sensitive detector that can be coupled with a coded aperture mask and used for spectroscopy and imaging of gamma rays
- The array provides functionality and performance comparable to the array of 3D sensitive pixelated detectors.
- Because of the capabilities for charge-loss correction and rejection of incomplete charge-collection (ICC) events, the array can utilize off-the-shelf CZT crystals readily available from vendors at lower cost.

Large-area detecting plane coupled with a coded aperture mask for long-range detection

Portable, battery-powered spectrometers





Target parameters of a single array module

- The array consists of 2x2 detector modules
- Each module is a 6x6 array of 6x6x15 mm^3 virtual-Frisch-grid detectors mounted on a fanout substrate and front-end ASIC

A detector module specification:

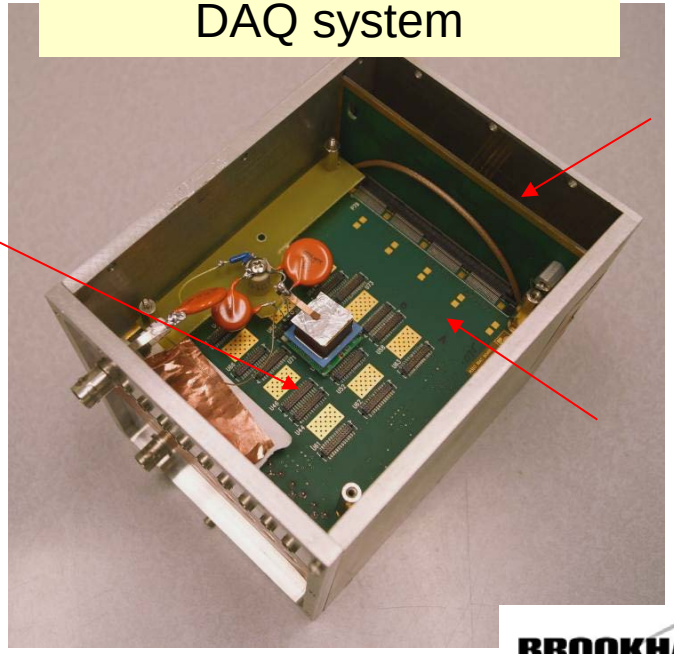
Dimensions:	6x6 array of 6x6x15 mm^3 crystals
Detector area:	13 cm^2
Detector volume:	29 cm^3
Energy range:	20 – 2000 keV
Energy resolution:	<1.3% at 662 keV (< 1% with selected detectors)
X-Y resolution:	6 mm (potentially <1 mm)
Z resolution:	0.5 mm (based on the drift time or C/A ratio)
Power per module:	<0.5 W per module
Communication:	USB
Cost per crystal:	$990 (it can be reduced by at least ½)
Features:	Compton reconstruction, rejection of ICC events

Objectives

1. Fabricate a 12x12 detector array consisting of 2x2 modules
2. Modify the existing H3D ASIC (originally developed for 3D pixelated detectors) to fit to the array's requirements
3. Fabricate the new ASIC (36 anodes and 9 cathodes)
4. Integrate a bench-top system and test with a coded aperture mask

Important: We will reuse the existing readout board and DAQ developed for 3D pixelated detectors (Polaris)

Existing test box and DAQ system



The 6x6 array modules will fit to the connectors on this board

We will make a more compact box and boards' configuration

The H3D ASIC was developed by BNL Instrumentation Division in collaboration with the University of Michigan for DTRA

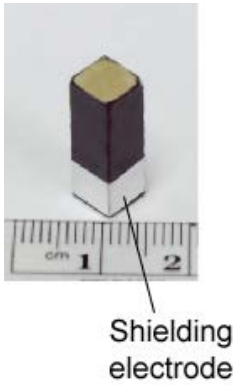
Progress to date

- Acquired 90 CZT crystals (from Endicott Interconnects and Redlen) and characterized them (IR microscopy and X-ray diffraction topography)
- Fabricated and tested 2x2, 2x4, and 3x3 array prototypes with a common cathode using the existing readout system based on the H3D ASIC
- Tested the designs for the virtual Frisch-grid detectors and the array:
  - potential interference between the anodes' and cathodes' wires and between the adjacent cathodes
  - reliability of the spring contacts
  - HV tests
- Modified the design of the existing H3D ASIC and started the new ASIC layout
- Validated the algorithm for rejecting incomplete charge collection (ICC) events for single- and multiple-detector events
- Demonstrated a sub-millimeter spatial resolution for the virtual Frisch-grid detector with sensing strips

The current project tasks (through December 2013)

- Electronics:
  - Complete ASIC layout and submit it for fabrication
  - Design and fabricate the interposer for the detector module
- Detector fabrication:
  - Assemble and test 90 virtual Frisch-grid detectors (with assistance from several students)
- System integration:
  - Design and fabricate the fanout substrates for the array modules and ASIC interposers
  - Design and fabricate the housing for the detector modules
  - Assemble a 3-array module, integrate the system and test electronics
- Software and data processing algorithms development

Virtual-Frisch grid detector design

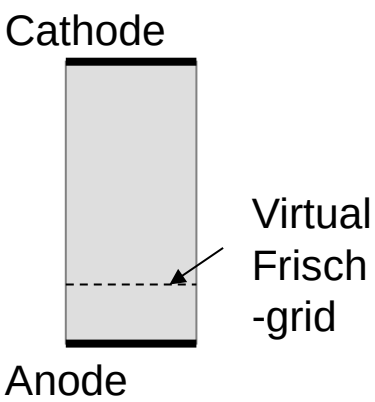


(1) Long detectors - up to 20 mm. This allows us to:

- Use a narrow (~5-mm wide) shielding electrode placed near the anode without compromising the anode shielding

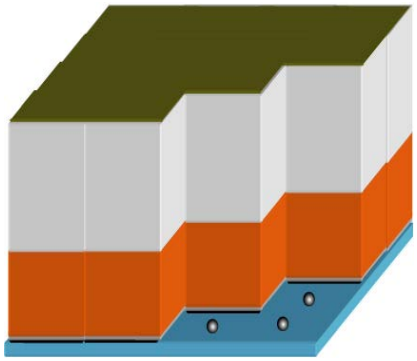
(2) Connect the cathode of 2x2, 3x3 or even 4x4 detectors together to make a common cathode; use cathode signals to measure electron drift times and interaction depths to:

- Correct for the electron trapping
- Reject the incomplete charge collection events (ICC) including the events interacting near the anode (inside the collection region)



Schematic of the array

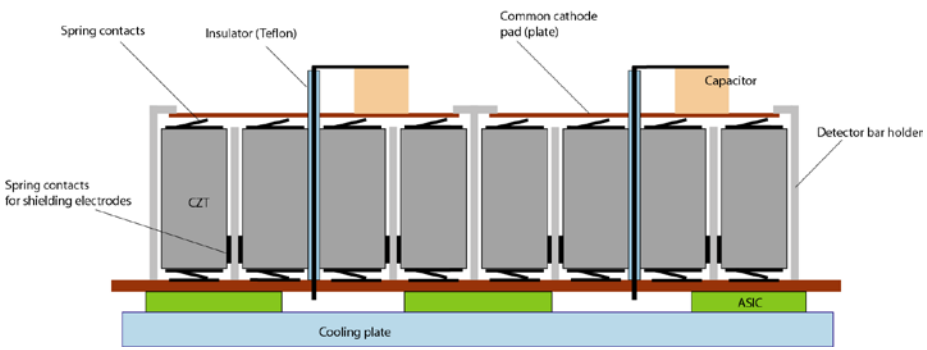
Common cathode



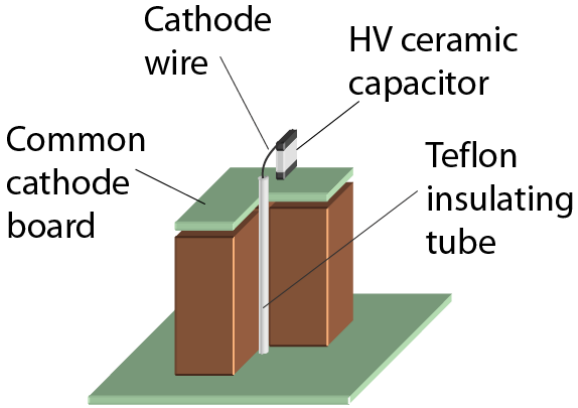
Fanout substrate

Schematic of the array's design

Schematic of the array



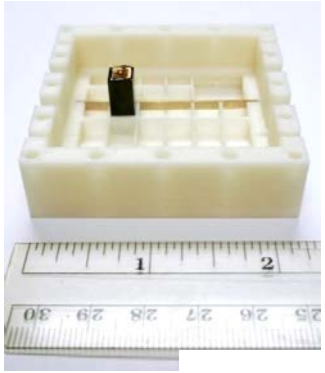
Detectors are grouped in 2x2 sub-arrays with a common cathode



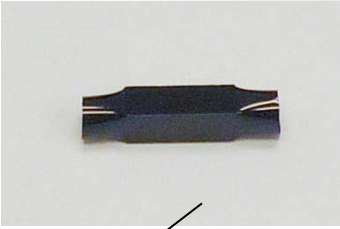
Challenges resolved regarding this design:

- Evaluated possible interferences between the anodes' and cathodes' wires and between the adjacent cathodes
- Evaluated the reliability of the spring contacts
- Completed the HV tests of the material used for fabrication of the holder

Prototype of the detector housing

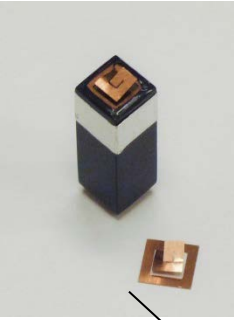


Testing of the array prototypes



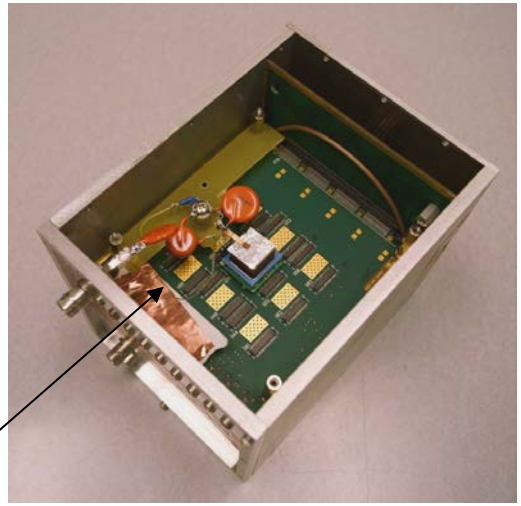
Detector encapsulated inside a thin polyester shell

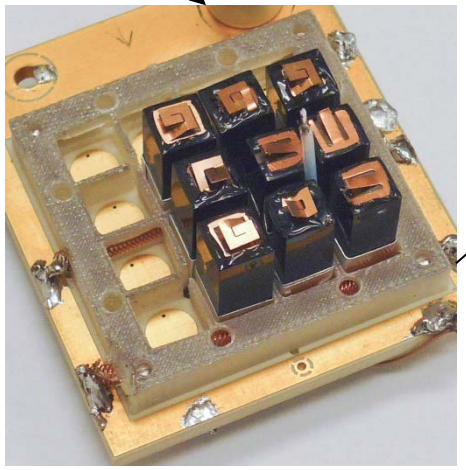
Test box containing readout electronics and connectors for evaluating pixel detectors or arrays



Assembled detector with two spring-loaded contacts

Array mounted on a substrate





We could easily rearrange the detectors for making 2x2, 2x4, 3x3 and 4x4 arrays

Cathode bias: 2500 V; cathode and anode peaking time: 1 μs

Cooling is important: we use an environmental chamber to stabilize the temperature at 18 C

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Readout electronics

National Nuclear Security Administration
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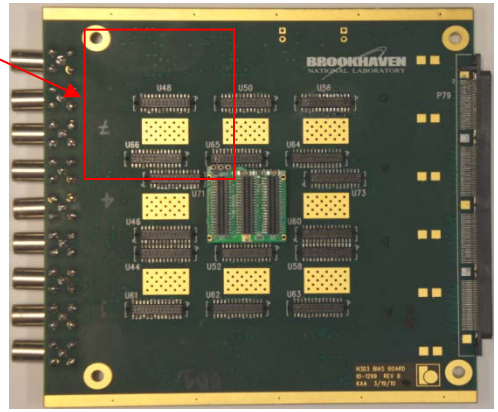
Readout electronics consists of 4 components:

- ASIC
- ASIC interposing board
- Analog Mother Board
- DAQ (with optical communication, Giga-bit Ethernet, and USB)

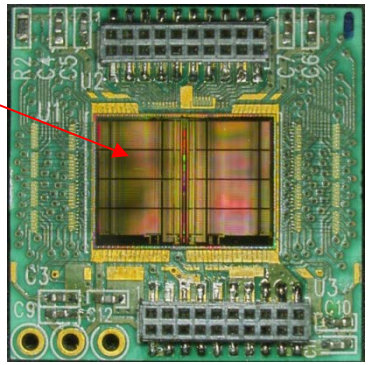
Array module position

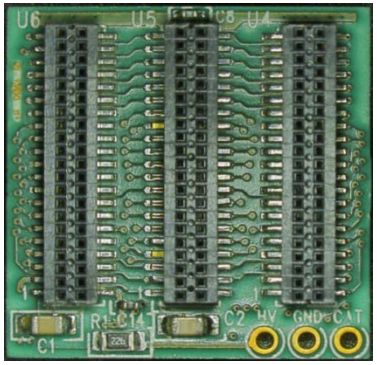
Analog Mother Board



The ASIC board will also be modified

ASIC



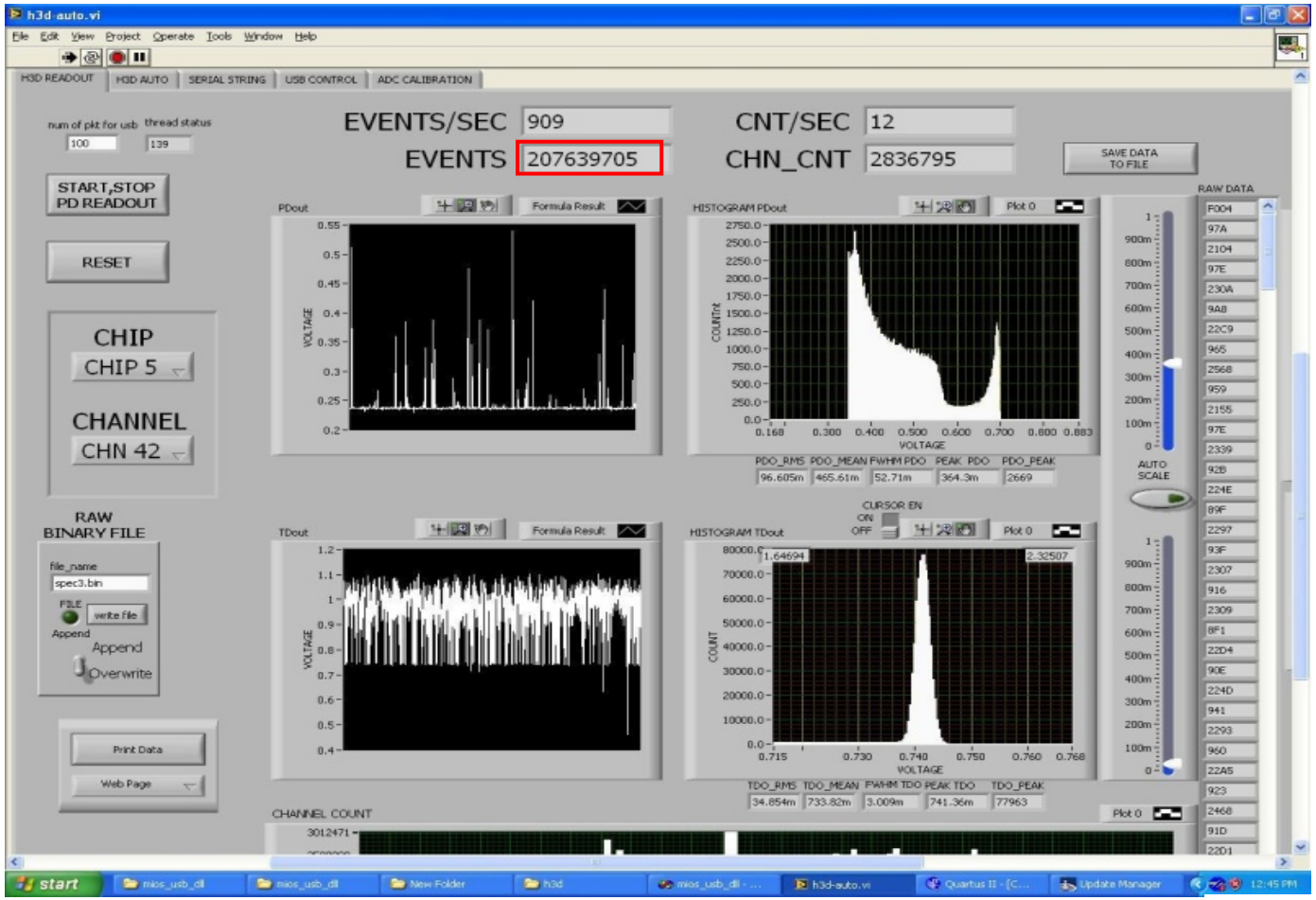


DAQ

Developed at BNL Instrumentation Division in collaboration with the University of Michigan.

Software development

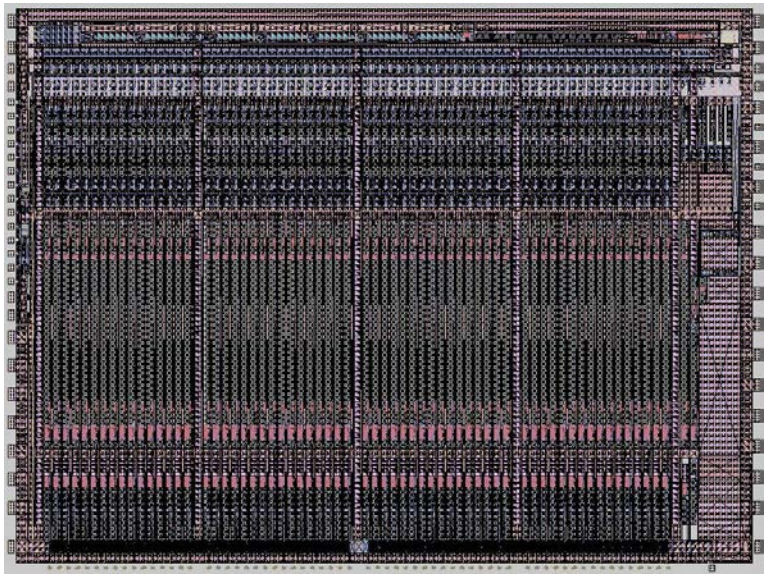
The IDL code based on the LabView interface



The ASIC fabrication scheduler

- Complete the new ASIC design - end of May 2013
- Complete the ASIC layout - end of September 2013
- ASIC fabrication - October-December 2013
- Test the ASIC, submit the revised ASIC (if necessary) - through October 2014

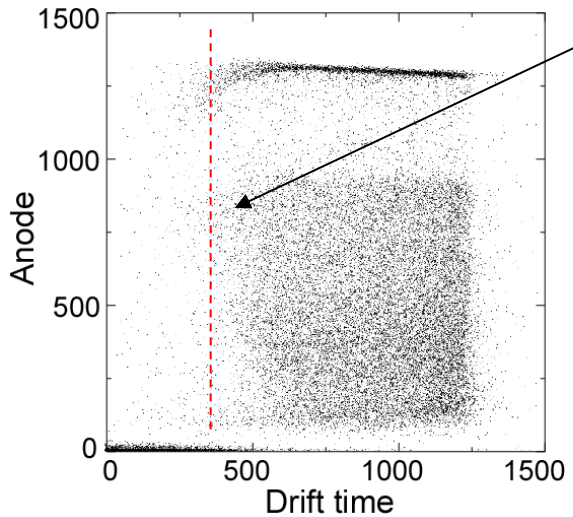
Preliminary ASIC layout



- The risk associated with this task is low because the new ASIC is based on the existing design with minor modifications
- The new ASIC will have 36 anodes and 9 cathodes

Response from a 6x6x15 mm³ virtual Frisch-grid detector

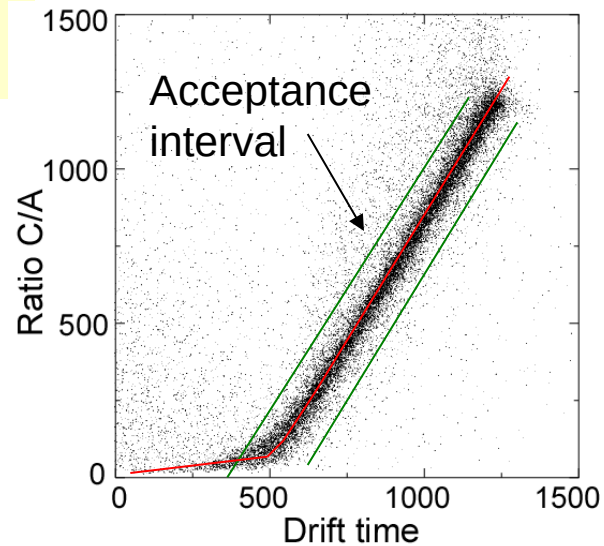
Anode vs. Drift time



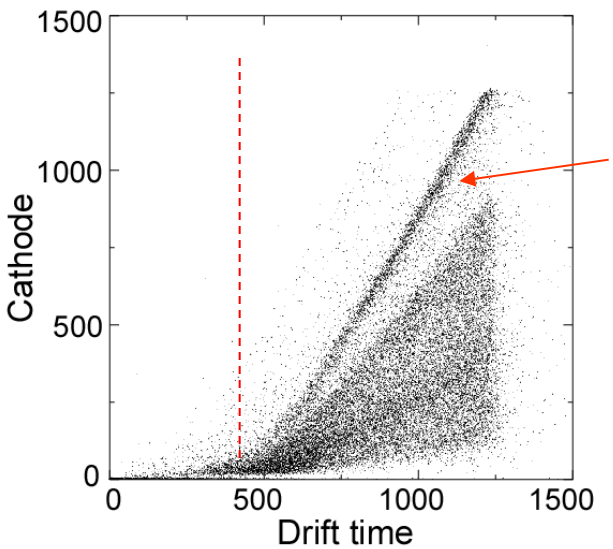
Position of the virtual Frisch grid

Nearly constant response from the drift region

Ratio C/A vs. Drift time



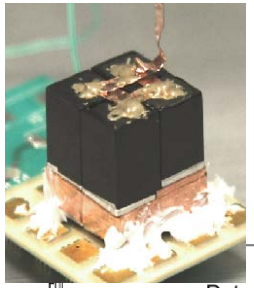
Cathode vs. Drift time



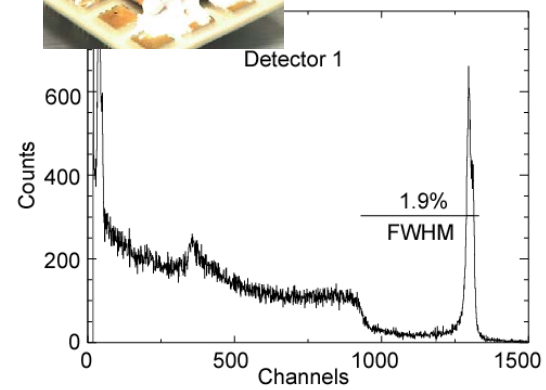
Almost linear response from the drift region like in a classic gas ionization chamber

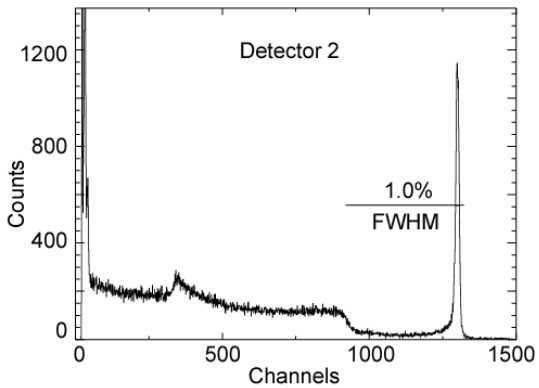
C/A vs. T is used to reject the ICC events. The red curve is a cathode signal induced by a unit charge vs. drift time

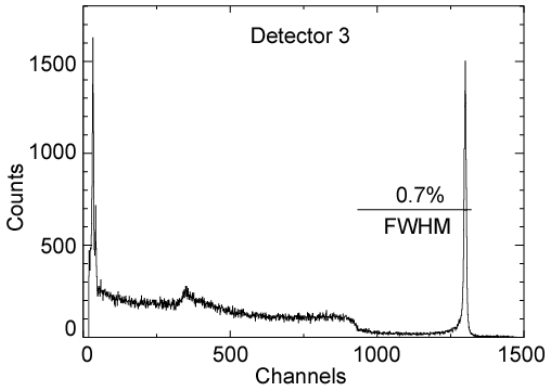
Results from a 2x2 array prototype

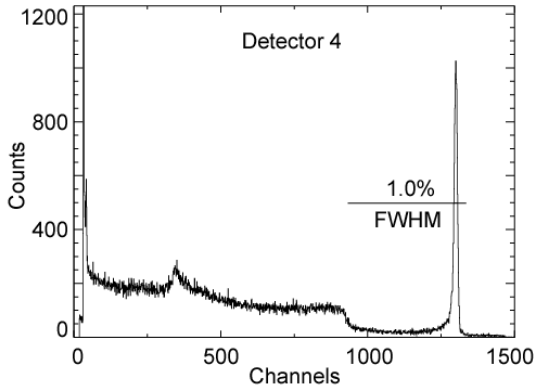


2x2 array prototype
of 6x6x15 mm^3 virtual
Frisch-grid detectors

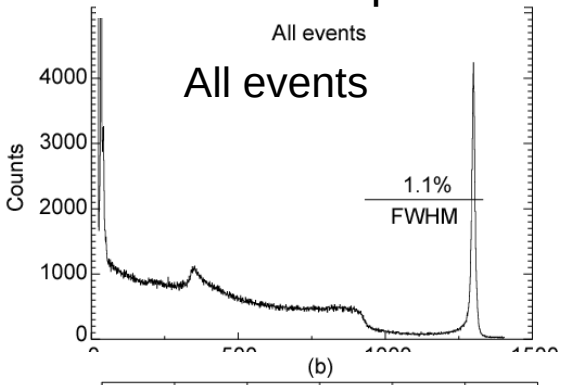




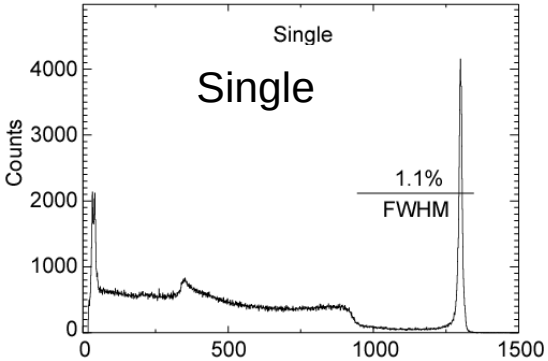




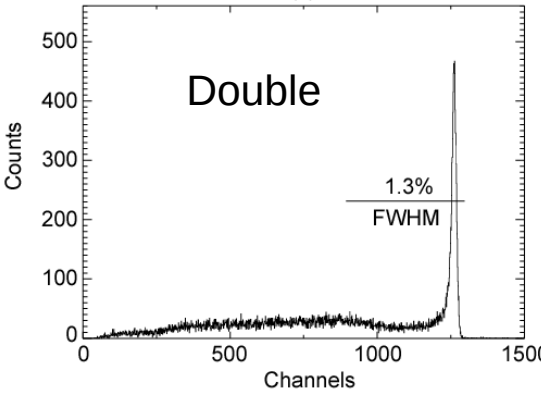
Combined spectra



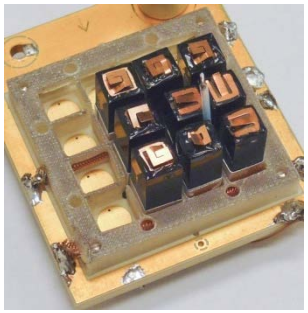
(b)



(c)

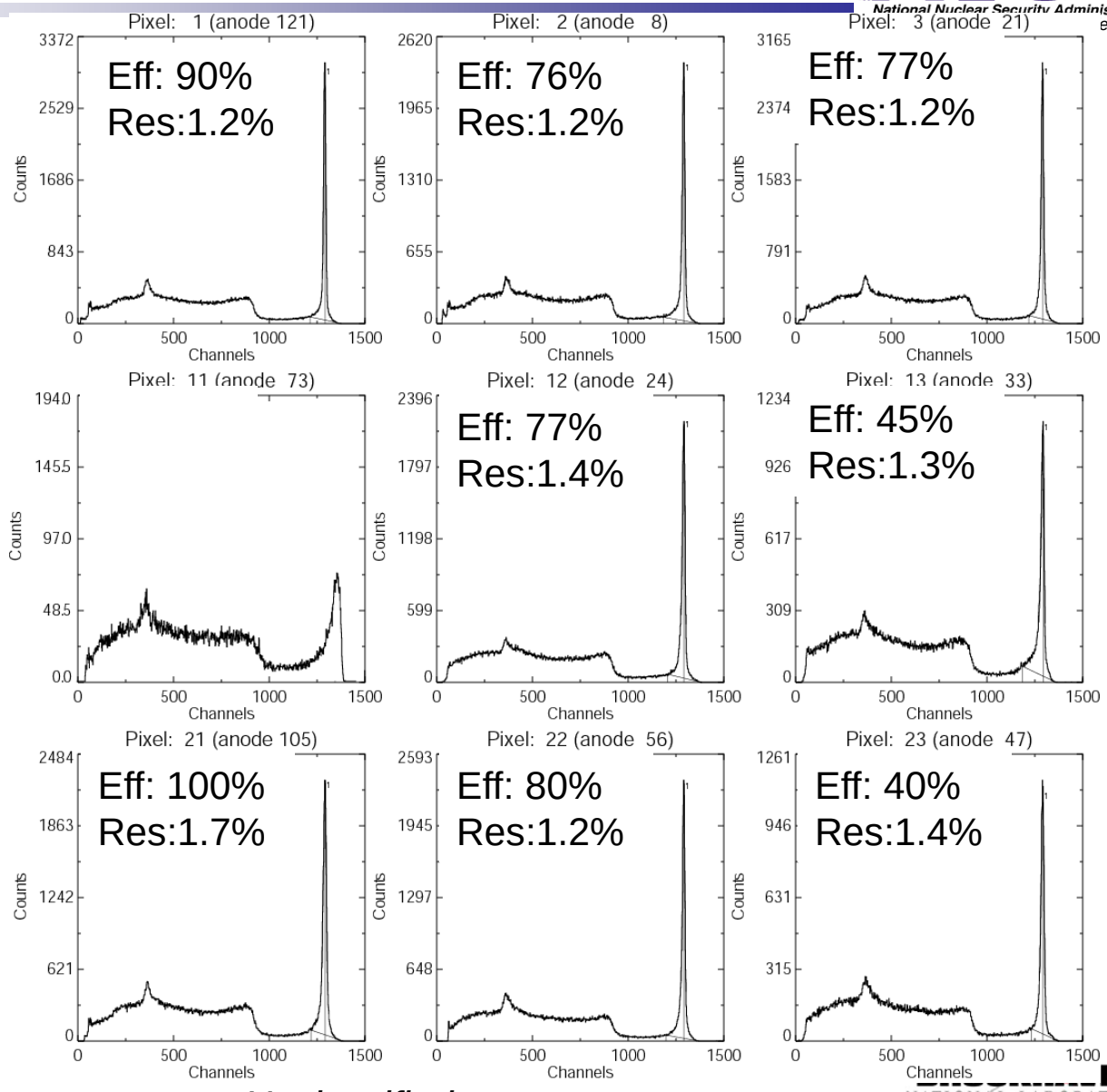


3x3 array: spectra after ICC rejection



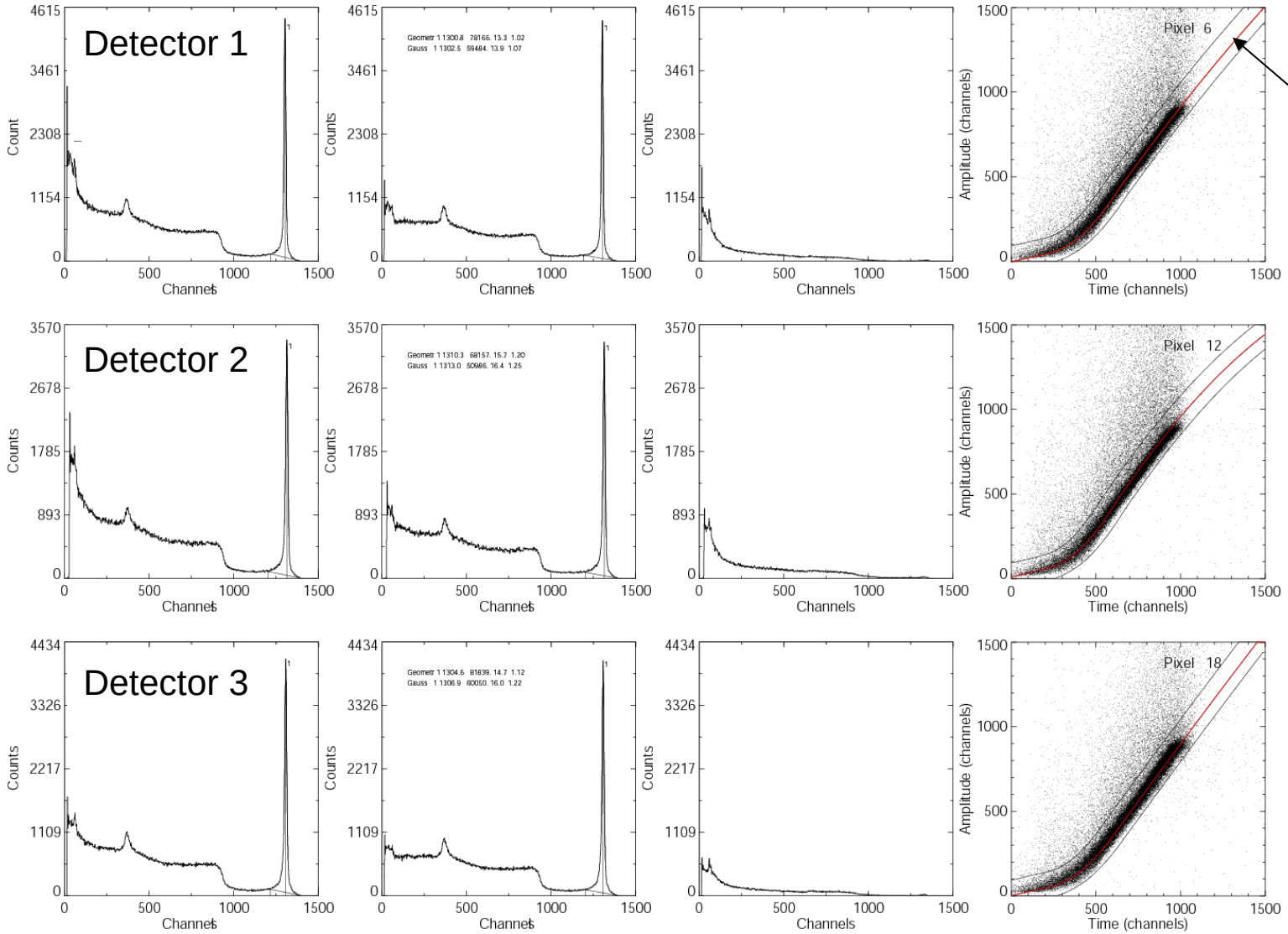
Numbers indicate relative photopeak efficiency and energy resolution (FWHM) at 662 keV

Photoefficiency was evaluated on the basis of the number of events under the photopeaks



Rejecting ICC events (single detector events)

Original spectra | Accepted | Rejected | Events distribution in *R vs. t* space



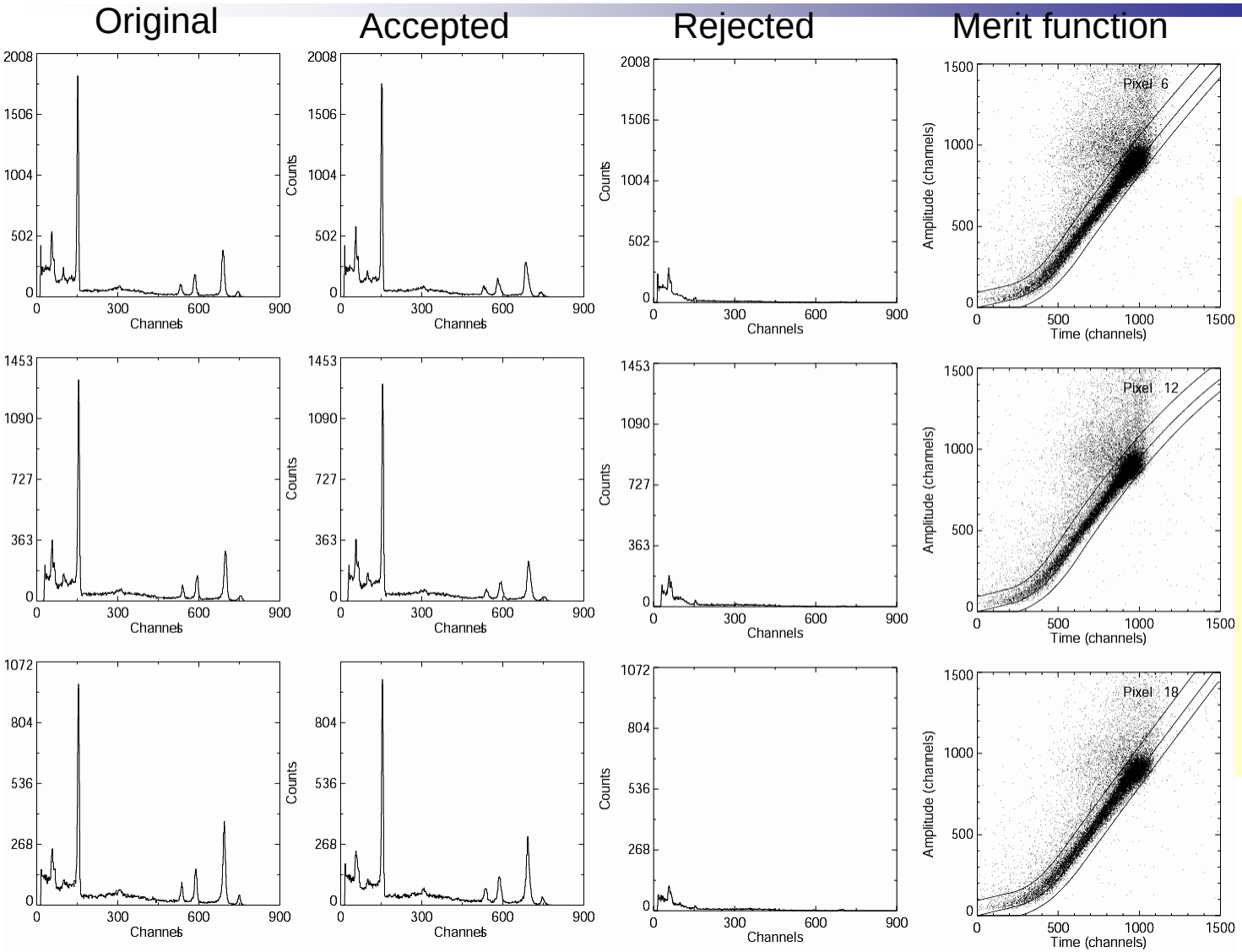
The correlation function *is* defined as the ratio

$R(t)=C/A$

It was evaluated selecting the photopeak events (^{137}Cs source) and plotting them as *C/A vs. t.*

Applied soft rejection constraints

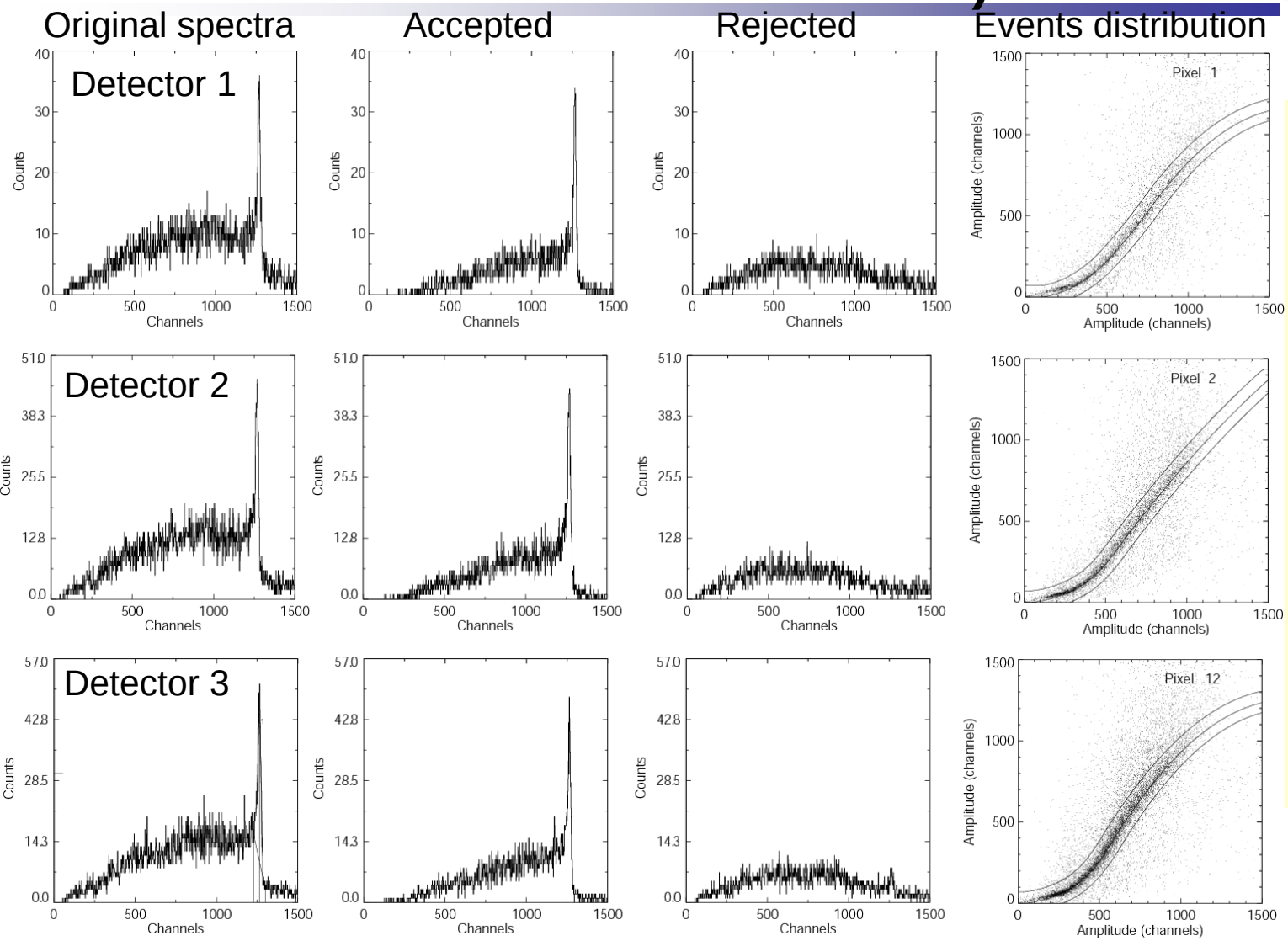
Rejecting ICC events in the case of ^{133}Ba source



We use the same merit function obtained for high-energy gamma rays (662 keV)!

This means that the rejection algorithm can be applied for the whole energy range

Rejecting ICC events (three detector events)



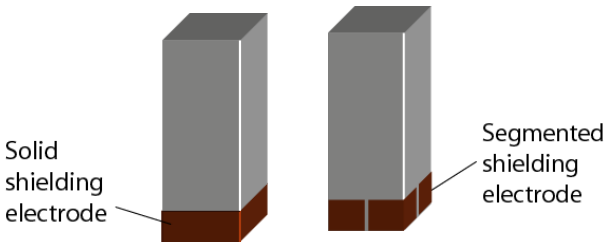
The merit functions were obtained by using the relationship

$$C_i / A_i = \frac{CR_i(T_i)}{\sum A_j R_j(T_j)}$$

Where *Ri(Ti)* is a correlation function measured for single-point interaction events

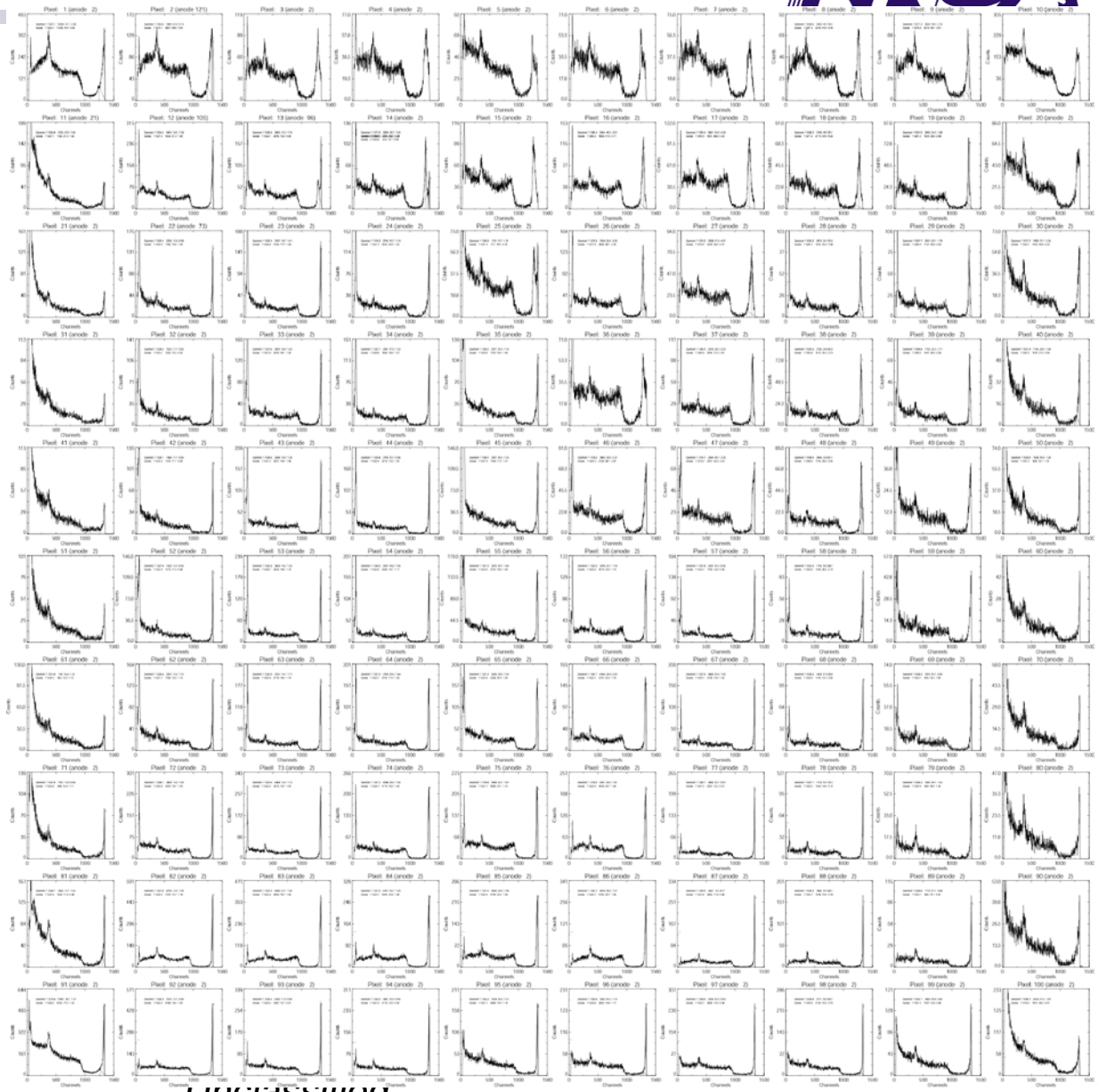
Future development

Position sensitive virtual Frisch-grid detector



Preliminary results

- Using 4 signals from the strips we electronically segmented the anode of a 6x6x15 mm^3 detector (10x10 segments)
- Spectra are plotted for each of 100 0.6x0.6 mm^2 segments
- No charge sharing complications!



Publications

PEER-REVIEWED PUBLICATIONS:

(1) J. Butcher, M. Hamade, M. Petryk, A. E. Bolotnikov, G. S. Camarda Y. Cui, A. Hossain, K. H. Kim, G. Yang and R. B. James, “Drift-time variations in CdZnTe detectors measured with alpha particles: Their correlation with detector response”, Proceedings of the 2012 SORMA conference, submitted May 2012.

(2) A. E. Bolotnikov, J. Butcher, G. S. Camarda, Y. Cui, G. De Geronimo, J. Fried, A. Hossain, K. H. Kim, M. Marshall, M. Petryk, E. Vernon, G. Yang, and R. B. James, “Comparison of analog and digital readout electronics on the processing of charge-sharing events in pixelated CdZnTe detectors”, IEEE Trans. on Nucl. Science, submitted December 2012.

(3) A. E. Bolotnikov, J. Butcher, G. S. Camarda, Y. Cui, G. De Geronimo, J. Fried, P. M. Fochuk, A. Hossain, K. H. Kim, O. V. Kopach, G. Mahler, M. Marshall, B. McCall, M. Petryk, E. Vernon, G. Yang, and R. B. James, “Testing arrays of virtual Frisch-grid CdZnTe detectors using the fourth generation of H3D ASIC”, IEEE Trans. on Nucl. Science, submitted December 2012.

PRESENTATIONS:

(1) A. E. Bolotnikov, G. S. Camarda, Y. Cui, G. De Geronimo, A. Hossain, K.H. Kim, G. Yang, E. Vernon, and R. B. James, “New Results of Testing an Array of Virtual Frisch-Grid Detectors Using a 3D-ASIC Readout System”, Invited Talk, 19th International Conference on Room-Temperature Semiconductor Radiation Detectors, October 30, 2012, Anaheim, CA.

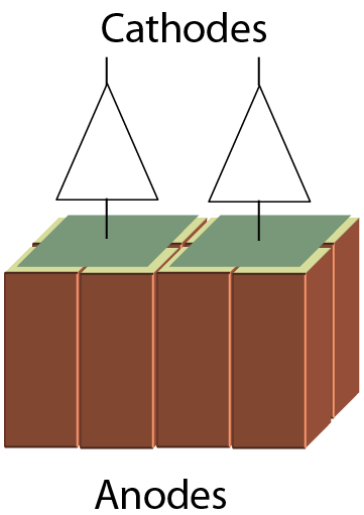
(2) G. S. Camarda, A. E. Bolotnikov, Y. Cui, A. Hossain, K. H. Kim, G. Yang, and R. B. James, “Influence of Surface Preparation of Bar-Shaped Crystals on Detector Performance”, SPIE Conference on Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XIV, August 13, 2012, San Diego, CA.

Conclusions

- The project is progressing according to schedule
- The hardware of a bench-top system and ASIC will be completed by December 2013
- The whole system will be completed and tested by October 2014
- Demonstrated feasibility of a virtual Frisch-grid detector array with a common cathode
- Acquired and characterized 60 CZT crystals (fabricated detectors during the summer with help from students)
- Demonstrated an ICC rejection algorithm in the case of single and multiple interaction-point events
- Proposed a new design for virtual Frisch-grid detectors that can potentially improve spatial resolution down to < 1 mm; this should significantly enhance the array's capabilities for imaging applications

Results from testing of 2x4 array with two common cathodes: Spectra from ^{137}Cs source

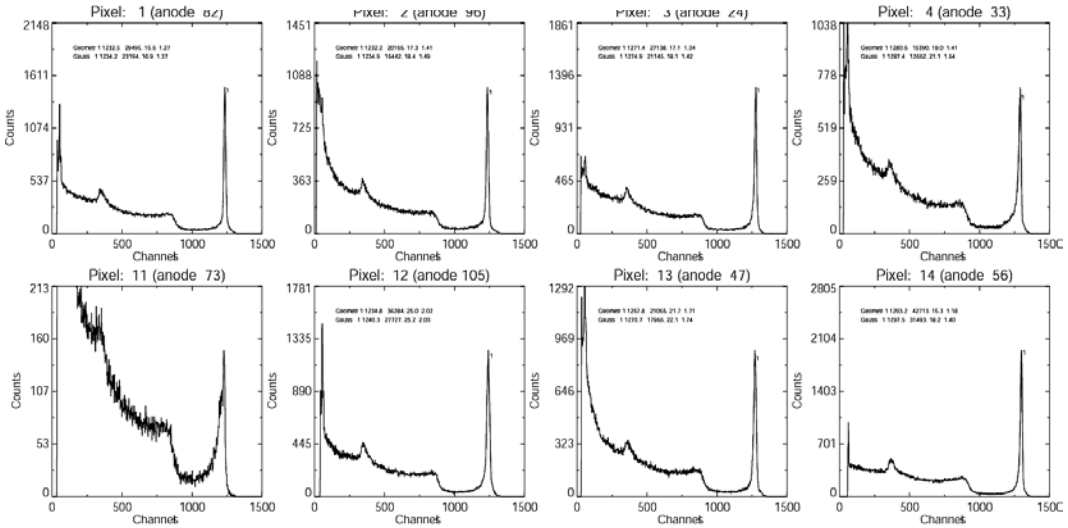
2x4 array with two common cathodes



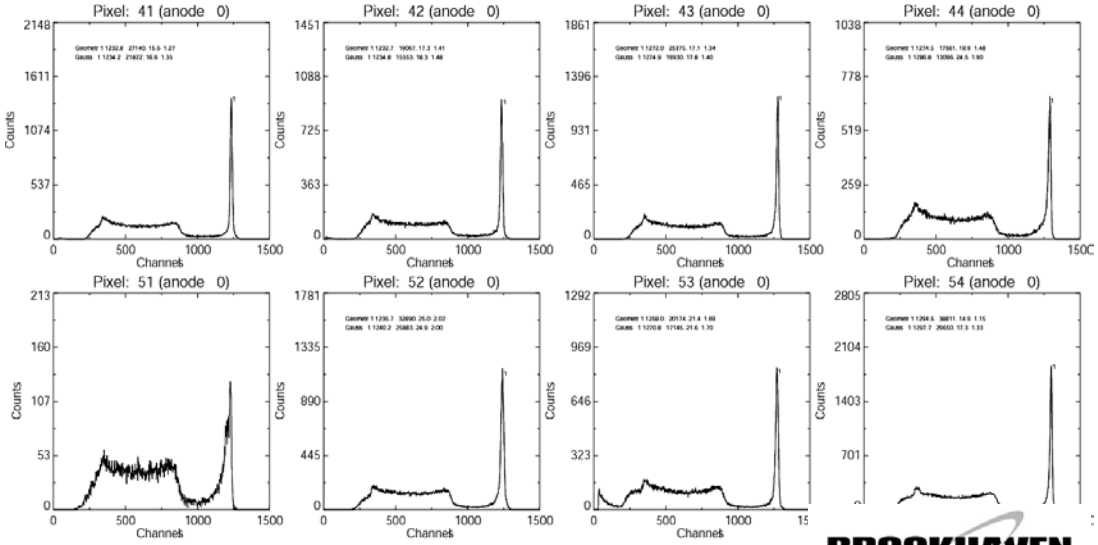
No interference between the cathode wires and anodes and common cathodes

Energy resolution is in the range of 1.2-1.7% FWHM at 662 keV

After charge-loss correction

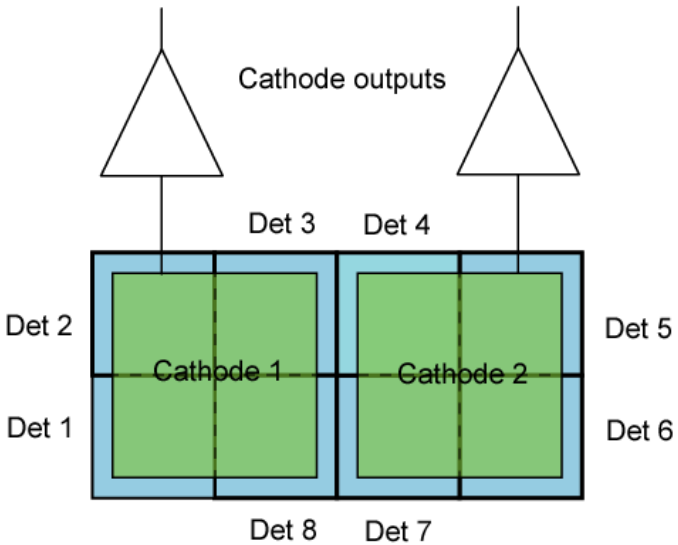


After rejecting ICC events

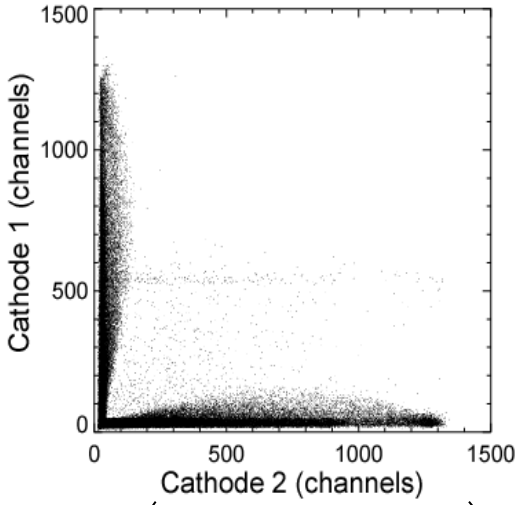


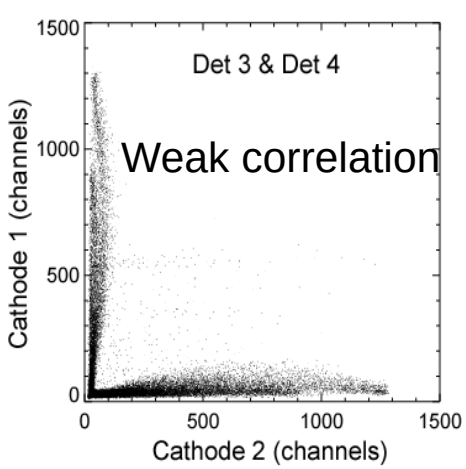
Results from testing of 2x4 array with two common cathodes

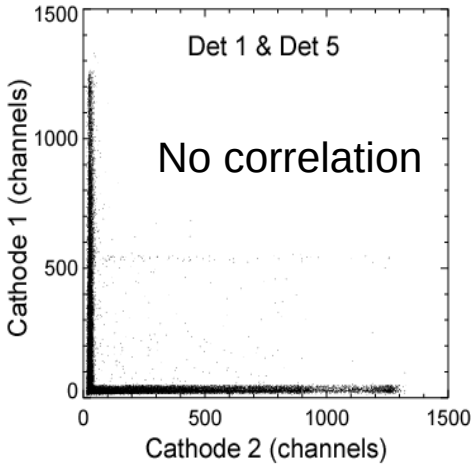
2x4 array with two common cathodes



All events





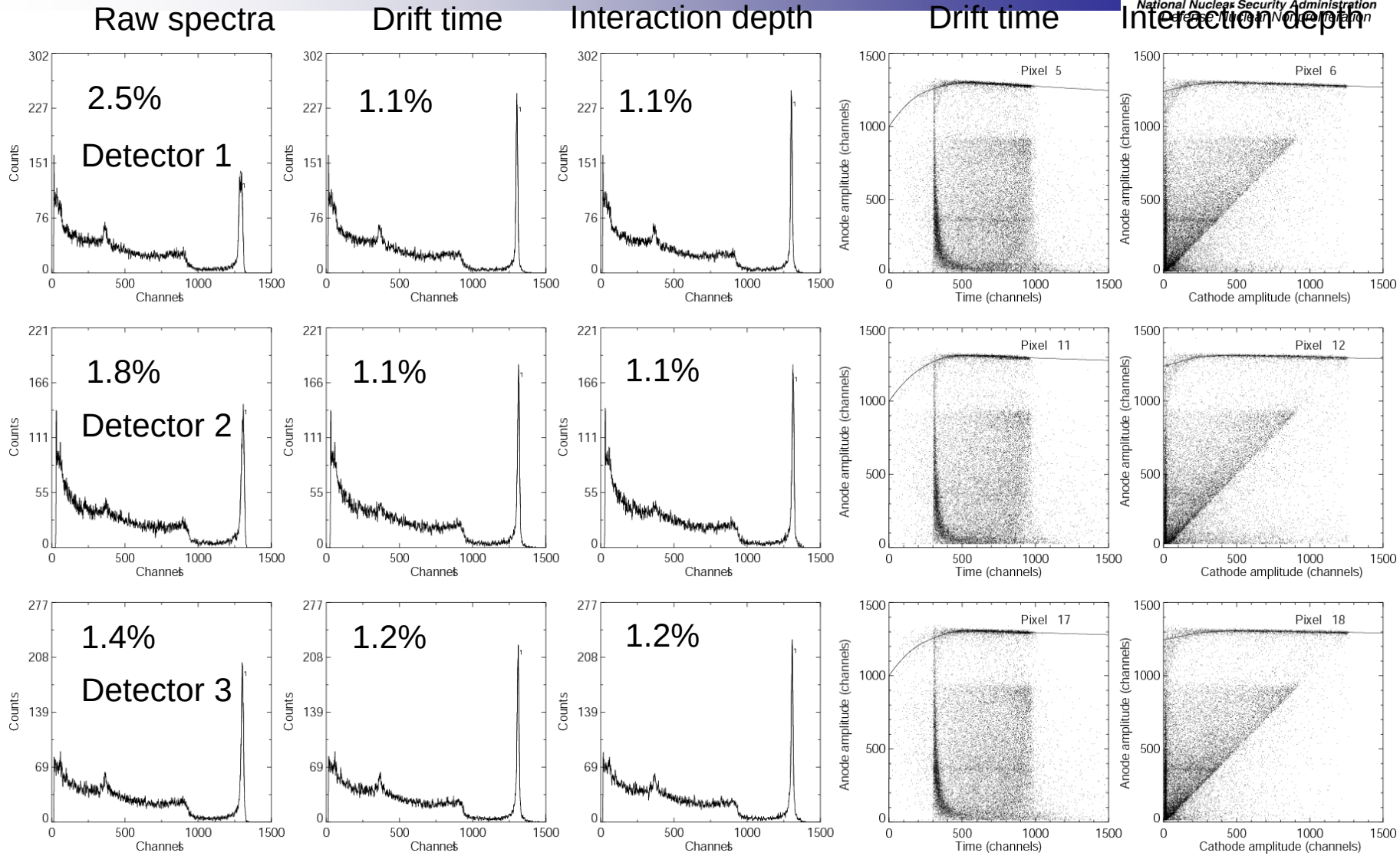


Use a ^{137}Cs source for these measurements

A small cross-talk is seen

Nevertheless, this has no effect on the performance!

3x3 array: Illustration of charge–loss correction techniques



Numbers represent energy resolution, %FWHM at 662 keV

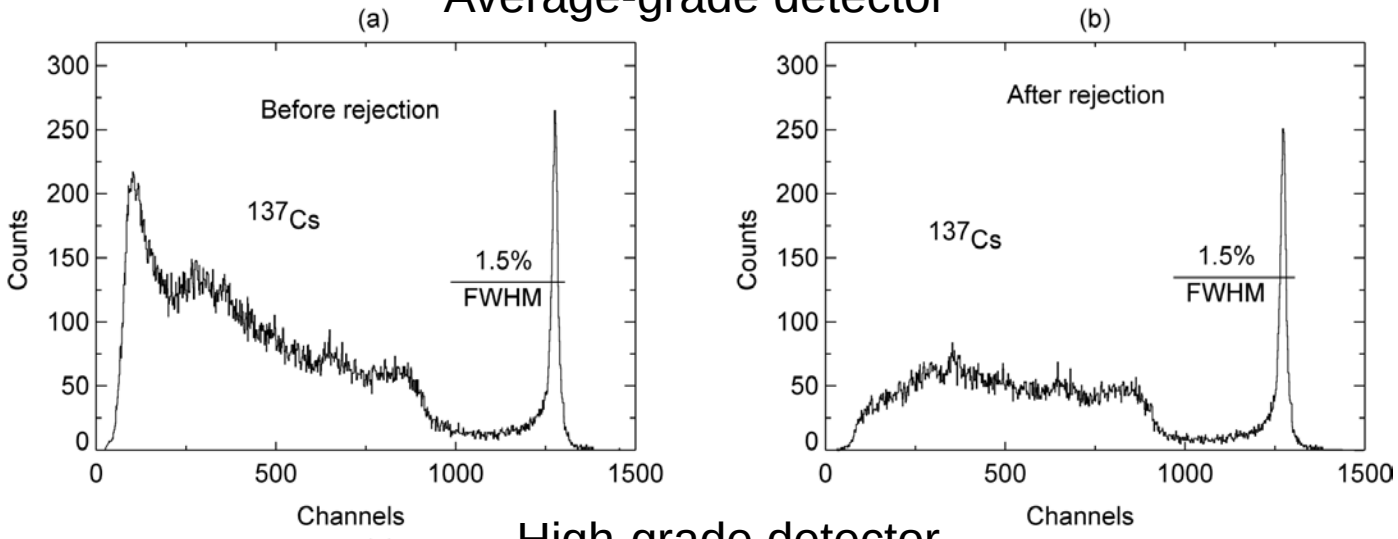
Examples of spectral improvements by rejection of ICC events

ICC events caused by crystal defects and charge trapping at the edges

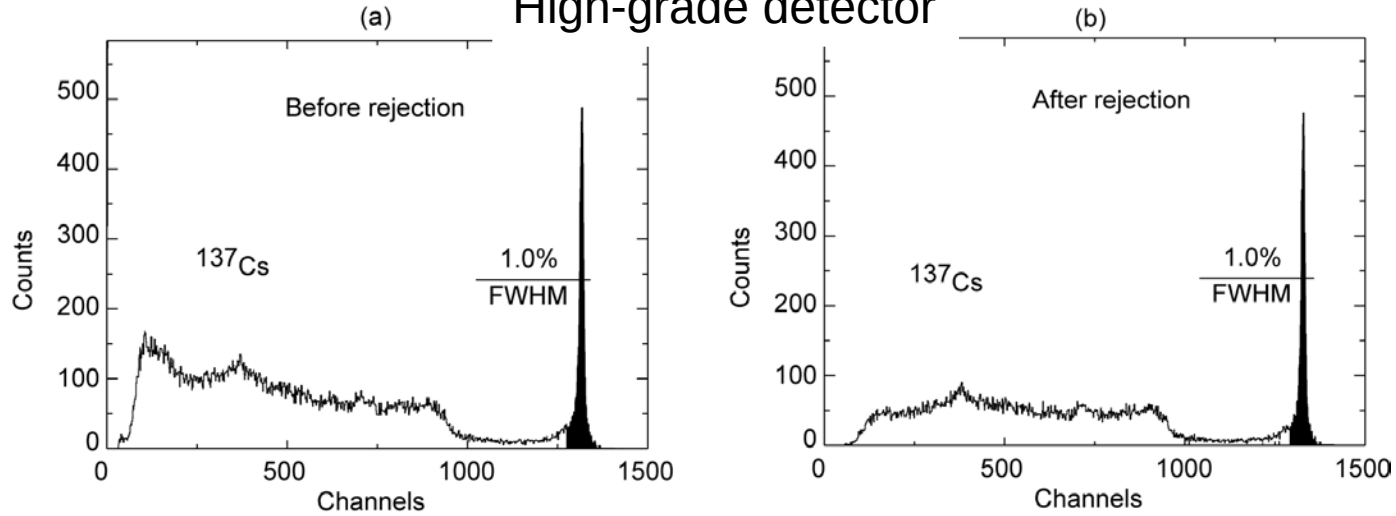
Two 15-mm-long virtual Frisch-grid detectors with different content of defects

Rejection does not affect the photopeaks

Average-grade detector

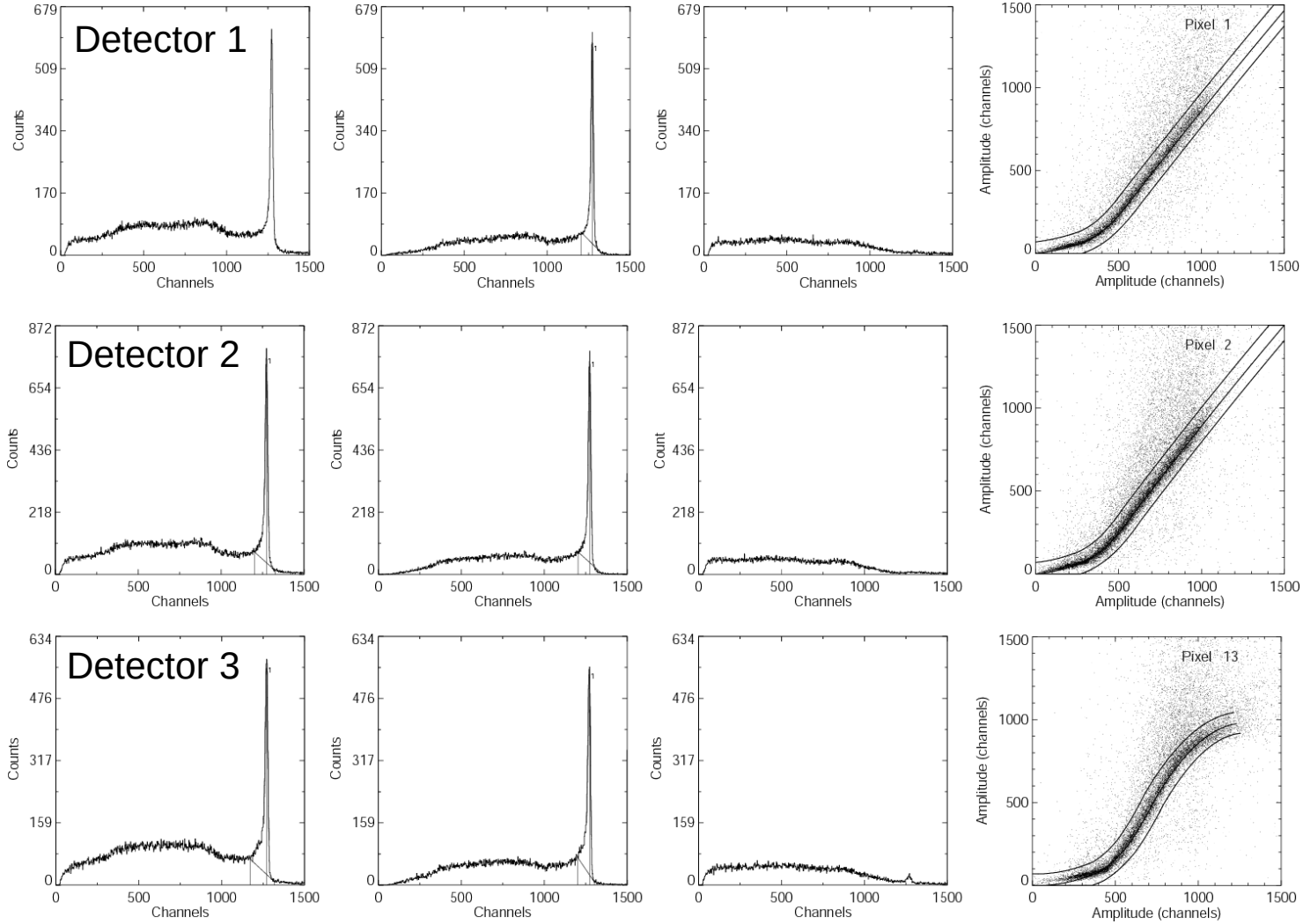


High-grade detector



3x3 array: Rejecting ICC events (*two* interaction point events)

Original spectra | Accepted | Rejected | Events distribution



The merit functions were obtained from

$$C_i / A_i = \frac{CR_i(T_i)}{\sum A_j R_j(T_j)}$$

where *Ri(Ti)* is a correlation function measured for single-point interaction events