BNL-112741-2016

Array of High-Granularity Position-Sensitive Virtual Frisch-Grid Detectors

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Presented at the NA-22 Independent Review
Brookhaven National Laboratory, Upton, NY
October 5-6, 2016

October 5, 2016

**Nonproliferation and National Security Department
Radiation Detector and Nonproliferation R&D
Brookhaven National Laboratory
Upton, NY 11973
www.bnl.gov**

**U.S. Department of Energy
USDOE National Nuclear Security Administration (NNSA),
Office of Nonproliferation and Verification Research and Development (NA-22)**

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Accession Number: 93684

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Array of High-Granularity Position-Sensitive Virtual Frisch-Grid Detectors (BL16-CZTFrischGrid-PD2Kb)

Presented to Independent Review Committee
October 5th, 2016

Principal Investigator: Aleksey Bolotnikov

Research team

- Brookhaven National Laboratory (BNL)
- PIs: A. Bolotnikov, G. De Geronimo and R. James
- BNL team: A. Hossain, G. Camarda, R. Gul, L. Ocampo, G. Yang, Y. Cui (NNS), V. Emerson, J. Fried (Instrumentation Division) and G. Mahler (mechanical designer)
- Students: M. Petryk, S. Cheng, A. McGilloway, C. Cherches, M. Siegel and R. Gallagher
- Subcontractors: Redlen and eV Products

The project is at the end of the second year

Outline of today's presentations

- Project overview (Aleksey Bolotnikov)
 - Project background, goals, and objectives
 - Progress to date
 - Results
 - Current plan and challenges:
 - Array housing
 - ASIC and electronic boards
- ASIC development – Emerson Vernon
- Detector and ASIC boards development – Yonggang Cui
- Evaluation of pad response function (PRF) – Luis Ocampo
- Summary – A. Bolotnikov
- Demonstration of our current 4x4 array prototype (Bldg. 815)

Project overview

- Goal: To develop a gamma-ray camera based on the arrays of 3D position-sensitive virtual Frisch-grid CdZnTe(CZT) detectors
- Motivation: To overcome the high cost and low availability of large-volume CZT crystals for making field deployable high-resolution gamma ray detectors
- Benefits: Our new design allows us to achieve high detection performance while using typical-grade low cost CZT crystals which cuts the overall cost of the proposed instrument
- Applications: The arrays can be used in compact hand-held instruments or large-area gamma cameras that will enhance detection capability for nonproliferation and national security

Array baseline module specification

A basic module consists of 4x4 detectors, which are read out by a single ASIC; the array's size is dictated by ASIC constrain and requirement to minimize parasitic capacitances

Baseline Array Specification

Dimensions	4x4 array of 6x6x20 mm ³ detectors (thickness optionally up to 40 mm)
Energy range	10 – 3000 keV
Energy resolution	<1% FWHM at 662 keV at < 25 °C; <2% at 50 °C
Position resolution	<1 mm (can be improved with pad response functions)
Power per module	< 200 mW per module
Current crystal cost	\$900 per 5.9x5.9x19.5 mm ³ crystal (Redlen, cut from the material rejected by other customers, the price can be reduced at least ½ for high-volume orders) \$250 (eV Products) for the same size crystals But Redlen crystals are more cost effective!

Comparison with H3D

	Basic 4x4 array (20 mm thick)	H3D (15 mm thick CZT)
Detector size (mm ³)	23x23x19.5	20x20x15
Making thicker detectors?	Up to 40 mm	???
Cost per crystal (\$)	500-1000 (Redlen) 250 (eV)	N/A
Total detector cost (\$)	14,400 (7,000)	8,000-20,000 ???
Cost per area (\$/cm ²)	2,590 (1,295)	2-5,000
Energy resolution (%FWHM @ 662 keV)	<1% (guarantee) 0.7% (best)	<1% (guarantee) 0.5% (best), inherently better
3D position resolution	<0.5 mm (potentially 0.1 mm)	0.5 mm
Number of readout channels	48 (ASIC)	121 (ASIC)
CZT crystals suppliers	Redlen, eV Products	Redlen
CZT material grade	Regular quality, recycling crystals rejected by other customers (H3D, medical)	Selected (premium)
Operation modes	Spectroscopy, imaging, handheld, arrays	Spectroscopy, imaging, handheld, arrays

We are not competing with H3D, there are applications for both systems.
H3D represents an advanced technology but its cost is higher

Comparison of the spectra measured with H3D pixelated and a virtual Frisch-grid detectors

20x20x15 mm³ 3D position-sensitive detector with 1.7-mm pixel sizes

Developed by Z. He et al.

6x6x15 mm³ virtual Frisch-grid device offering cost reduction

Progress to date

- Demonstrated the feasibility of position-sensitive VFG detectors by testing individual detectors and small array prototypes (important milestone!)
- Optimized designs for detectors and detectors housing
- Acquired most of the required detectors from Redlen and eV Products (important milestone!)
- Assembled and tested detectors using crystals from both vendors and compared their performance → Best selected detectors have the same performance but Redlen detectors are more cost effective
- Modified the design of the existing AVG ASIC to fit the requirements for the new detectors (ASIC simulation is complete, the layout is in progress)
- Developed software for data processing and demonstrated the capability of VFG detectors to correct response non-uniformity
- Carry out IR transmission microscopy, I-V curve, and X-ray diffraction topography measurements and correlated detectors performance with crystal defects

Root of the problem

Subgrain boundaries, dislocation networks, and secondary phases are major defects in commercial CZT crystals (revealed by X-ray diffraction topography)

These defects cause small variations in detector response resulting in small photopeak broadening

In most cases these defects can be corrected by using position-sensitive high-granularity detectors!

Operation principle of position-sensitive virtual Frisch-grid detectors

Position-sensitive virtual Frisch-grid detector

- The arrays consist of small area, $6 \times 6 \text{ mm}^2$, but long, up to 5 cm, CZT crystals (bars)
- Such crystals have much higher production-yield and lower cost than crystals used for large pixelated detectors
- 4 position-sensing pads (non-contacting electrodes) attached to the side surfaces near the anode; the pads signals provide X-Y coordinates
- The cathode signals are used to measure drift times to evaluate Z coordinates, like in TPC;
- C/A ratio gives independent estimates for Z
- Virtually grounded pads produce the Frisch-grid effect (as if a real grid were placed inside the detector)

CZT bars

Very first Virtual Frisch-grid detector proposed for imaging and spectroscopy of gamma ray sources

This design (drift cell) was originally proposed for noble gas detectors by V. Dmitrenko et al. This idea was later applied to CZT detectors by G. Montemont (LETI) and D. McGregor (Kansas State University)

Response measured from a virtual Frisch-grid detector (^{137}Cs source)

Operation principle is identical to the classic gas ionization chamber with a real grid

Position of the virtual Frisch grid

Nearly constant response from the drift region

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

Illustration of virtual Frisch-grid effect

Pulse-height spectra measured with shielded and unshielded 5x5x10 mm³ detector

Unshielded Shielded

Vs.

Aluminum tape
used as shielding
electrode

Position sensitivity

^{241}Am source
6x6x15 mm³ detector
Tungsten slit collimator (~1-mm) was placed near the cathode

6x6 mm²

We used the simplest (linear) approximation for the pads response function (this causes small distortion of the slits image)

We use the high-granularity position information to correct the response non-uniformities caused by crystal defects

Pads response functions: *Pads signal amplitude vs. (x,y)*

Schematic drawing of a position-sensitive VFG detector

Amplitudes A_x^1 and A_x^2 are used to evaluate x , while A_y^1 and A_y^2 are used to evaluate y

Response function

$$A = R(x, y)$$

The reverse response functions give 2 independent estimates for X and 2 estimates for Y coordinates for

$$X_1 = R^{-1}(A_x^1, A_y^1, A_y^2)$$

$$X_2 = L - R^{-1}(A_x^2, A_y^1, A_y^2)$$

$$X = \frac{X_1 W_1 + X_2 W_2}{W_1 + W_2}$$

$$W = \frac{1}{\sigma_x^2}$$

$$\sigma_x^2 = \left(\frac{\partial R}{\partial A} \right)^2 \sigma_A^2$$

If assume a linear approximation for the response function: $X = \frac{A_x^1}{A_x^1 + A_x^2}$

Evaluation of the response functions, R , and inverse response functions, R^{-1}

- The response functions can be measured using our pulsed laser system
- Alternatively, they can be evaluated during the calibration with the uncollimated gamma ray source
- As a starting point we use a linear approximation (first order)

Second order approximation

Using position information to correct response non-uniformities

- Because defects locations are fixed, the response variation is caused by random distributions of interaction points → Such variations can be corrected if the locations of interaction points are known with sufficient accuracy
- Position information allows us to virtually segment a detector into small voxels and equalize responses from each voxel
- A 3D correction matrix (lookup table) is generated during calibration

Raw spectrum

Responses from individual voxels

After equalizing responses from individual voxels

Examples of pulse-height spectra before and after correcting response non-uniformities

7x7x20 mm³ Redlen crystal

Cathode bias 3000 V

Improvement of spectral response after 3D corrections

¹³⁷Cs

⁶⁰Co

¹³³Ba

Best spectra measured from 20-mm thick detectors (after 3D corrections)

These results demonstrate the increased efficiency for
detecting energetic gamma rays

Detector fabrication

Sheet of copper
springs used for
electrical
connection

Assembling first array prototypes

- We are using the existing test box and DAQ system originally developed by the Instrumentation Division for the Polaris project
- Our current ASIC is a modification of the H3D ASIC

Pictures of experimental setup

We employed existing readout electronics and ASIC developed during our previous project (CZT arrays)

40-mm thick detector

Backside view of the detector board

Test box

Current ASIC:

36 anode and 9 cathode inputs

Its architecture is identical to the H3D ASIC.

Readout system of H3D ASIC was developed by the BNL's Instrumentation Division in collaboration with the University of Michigan

ASIC board

2x2 array of 20-mm thick detectors

Typical charge signals (after preamps) generated on the cathode, anode, and sensing pads

Testing small array prototypes

Use ASIC from the previous project

With this ASIC we could read signals from 12 detectors

γ

4x4 module layout

12 anodes

3 cathodes

24 sensing pads

Total: 36 anode and 3 cathode channels

Brookhaven Science Associates

2x2 array of 20-mm thick detectors

Office of International Nuclear Safeguards (NA-241) is interested in using this technology for compact handheld instruments

We are currently funded by NA-241 to develop, in collaboration with FLIR, a prototype based on a 2x2 array of 20-mm thick position-sensitive VFG detectors GSFC/NASA proposed to use these detectors for a high-energy calorimeter

Using signals from 2 and 3 pads (instead of 4) to resolve the ambiguity problem

4 pads corrections

3 pads corrections

Testing Redlen crystals (array of 12 6x6x20 mm³ detectors)

Typical resolution is 0.8% at 662 keV after 3D corrections

Raw data (no corrections)

After 3D corrections

These results demonstrate that we can make arrays and read the signal from a large number of position-sensitive detectors.

A very important milestone!

Testing Redlen crystals

Improvement: energy resolution from 1.8% down to 0.8% after 3D corrections

After Drift-Time Corrections

After 3D

Testing eV Products crystals

Typical energy resolution is (1.5-2.0)% at 662 keV after 3D corrections

Raw data (no corrections)

After 3D Corrections

Testing eV Product detectors

Improvement: energy resolution from 1.8% after 3D corrections

After drift-time Corrections

After 3D Corrections

In the case of eV detectors, the 3D correction does not work as good as in the case of Redlen crystals → Effect of Te inclusions and current ASIC limitation

Correlations between Te inclusions and detector response

Correlations between Te inclusions and detector response

X-ray response map of a 10-mm thick detector

X-ray response map measured for a 10x10x10 mm³ detector with a high concentration of Te inclusions and a grain boundary

Temperature dependence of energy resolution

Temperature dependence of the energy resolution
Measured for a 20-mm long detector
Cathode bias: 3000 V

Energy resolution is primarily limited by electronic noise

Because the detector anode has a larger area, 6x6 mm², it causes higher leakage current and larger detector capacitance

Here H3D detectors have some advantage because of the smaller anode contacts (smaller input capacitance and leakage current)

Detectors can operate at reduced cathode bias

Dependence of energy resolution vs. applied bias, measured for a 20-mm-thick detector

20-mm thick detectors can be operated at reduced bias, but the electric field must be above a certain limit (~ 1000 V/cm) to attain $<1\%$ resolution !

This suggests that the response non-uniformity is related to the local variations of the electric field

Potential edge-effect problem in large aspect ratio VFG detectors

Edge effect due to the large geometrical aspect ratio of detectors

Due to charged deep levels, the electric field slightly decreases toward the anode $\rightarrow$ naturally focusing field!

Current work and technical challenges

- Current Tasks:
 - Finalize designs and fabricate detector housing, detector board, and interposer board (Yonggang)
 - Fabricate ASIC (Everson)
 - We will reuse the existing DAQ and test box
 - Evaluate (theoretically and experimentally) pads response functions
 - Integrate 4 arrays into a benchtop instrument and evaluate its performance in two modes: as coded aperture and Compton imagers
- Technical Challenges:
 - Implement an improved position reconstruction algorithm based on actual pad response functions (currently we use a linear approximation)
 - Investigate limitations caused by Te inclusions in eV crystals
 - Develop calibration procedure

Mechanical model of the array module

4x4 6x6x20 mm³ detector module without a top cover

Detector array

(the spring contacts on the top and on the bottom are not shown)

Spring contacts for pads to be directly soldered to the detector board

Detector board

Interposer

ASIC board

Connectors for plugging into the ASIC board

Directors are suspended between two rigged boards and will be able to withstand mechanical and temperature shocks

ASIC development

Presentation will be given by Emerson Vernon,
Instrumentation Division

- Current ASIC AVG1 → New AVG2 ASIC
- Because we proposed to modify the existing ASIC, the risk associated with this task is low
- New ASIC will have the same architecture
- Introduced small modifications:
 - Total number of channels
 - Optimize shapers for pad channels

Detector board and interposer development

Yonggang Cui, NNS

Compact virtual Frisch-grid detector module

- This task is to implement a compact design of virtual Frisch-grid detector module.
 - Each detector has position-sensing pads for signal correction.
 - Modular design with consideration of DFM (design for manufacturing)

Z-Ray® interposer and stacked structure of VFG module

Stack of VFG module

- The stack cannot be implemented in one PCB board because of the constraint space.
- Z-Ray® interposer allows to reduce the height of an assembled module by 5-10 mm.

Z-Ray® Interposer

Detector board with the spring finger contacts soldered directly to the board

Design of detector board

Top (detector side)

Bottom (Z-Ray® side)

Matching of detector board to Z-Ray® pins

Z-Ray® pins not in use will be removed in assembly.

Using a pulsed laser to measure response functions of the position-sensing pads

Luis Ocampo, Ph.D. student, Penn State, NNS

Laser system components

•650 nm laser – 2mW max

Oscilloscope Signals

Induced Signals

Example of response function measurements

Dependences of pad signal amplitudes (top, bottom, right, left) and the anode amplitudes (center) versus laser beam positions

Publications and Take-away messages

Recent peer-reviewed publications

1. A.E. Bolotnikov, G.S. Camarda, Y. Cui, G. De Geronimo, J. Eger, A. Emerick, J. Fried, A. Hossain, U. Roy, C. Salwen, S. Soldner, E. Vernon, G. Yang and R.B. James, "Use of high-granularity CdZnTe pixelated detectors to correct response non-uniformities caused by defects in crystals", Nuclear Instruments and Methods in Physics Research A, 805, 41–54 (2016)
2. A. E. Bolotnikov, G. S. Camarda, E. Chen, S. Cheng, Y. Cui, R. Gul, R. Gallagher, V. Dedic, G. De Geronimo, L. Ocampo Giraldo, J. Fried, A. Hossain, J. M. MacKenzie, P. Sellin, S. Taherion, E. Vernon, G. Yang, U. El-hanany , and R. B. James, "CdZnTe position-sensitive drift detectors with thicknesses up to 5 cm", Applied Physics Letters, 108, 093504 (2016)
3. W. Lee, A. Bolotnikov, T. Lee, G. Camarda, Y. Cui, R. Gul, A. Hossain, R. Utpal, G. Yang, and R. James, "Mini Compton Camera Based on an Array of Virtual Frisch-Grid CdZnTe Detectors", IEEE Transactions on Nuclear Science, 63, 259-265 (2016)
4. A.E. Bolotnikov, K. Ackley, G. S. Camarda, Y. Cui, J. F. Eger, G. De Geronimo, C. Finfrock, J. Fried, A. Hossain, W. Lee, M. Prokesch, M. Petryk, J. L. Reiber, U. Roy, E. Vernon, G. Yang, and R. B. James, "High-Efficiency CdZnTe Gamma-Ray Detectors" IEEE Transactions on Nuclear Science, 62, 1393-1398 (2015)
5. A. E. Bolotnikov, K. Ackley, G. S. Camarda, C. Cherches, Y. Cui, G. De Geronimo, J. Fried, D. Hodges, A. Hossain, W. Lee, G. Mahler, M. Maritato, M. Petryk, U. Roy, C. Salwen, E. Vernon, G. Yang, and R. B. James, "An array of virtual Frisch-grid CdZnTe detectors and a front-end application-specific integrated circuit for large-area position-sensitive gamma-ray cameras", Review of Scientific Instruments 86, 073114 (2015)

Take-away messages

- Demonstrated the feasibility of the arrays of position-sensitive Virtual Frisch-grid detectors
- Completed design of detectors, the new ASIC, housing, detector board, and interposer
- Anticipate to improve spatial resolution and effectiveness of the 3D correction once the new ASIC becomes available in March of FY 2017
- Acquired CZT crystals from eV and Redlen sufficient to fabricate at least 4 arrays; planning to purchase more crystals from Redlen to replace some of eV crystals
- The most important task is to demonstrate arrays' performance as spectrometers, and Compton and coded-aperture imagers
- The proposed arrays offer a performance level similar to H3D detectors (which are a high industry standard today), while using regular-grade low cost CZT crystals available from several vendors → make less expensive and more widely available room-temperature filed-operating gamma ray detectors for nonproliferation and national security tasks

Acknowledgments

We would like to thank the Office of Defense Nuclear Nonproliferation
Research & Development (DNN R&D) for supporting this work!