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Low-Cost 3D Position-Sensitive CZT High-Granularity Detectors

Aleksey Bolotnikov

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Low-cost 3D position-sensitive CZT high-granularity detectors (BL16_HighGran_PD3Ja)

Presented to Independent Review Committee
October 6th, 2016

Principal Investigator: Aleksey Bolotnikov

Outline of today's presentations

- Project overview (Aleksey Bolotnikov)
 - Project background, goals, and objectives
 - Progress to date
 - Results
 - Current tasks and challenges:
 - Evaluate pixel response functions and incorporate them into position reconstruction algorithm
 - Evaluate position resolution in 3D pixelated detectors
- Results from testing 3D CZT Detectors using a pulsed laser system – L. Ocampo
- Development of waveform-digitizing H3DD ASIC – A. D'Andragora
- Feasibility studies of ultra-thick (up to 5 cm) CZT detectors – A. Bolotnikov
- What limits the maximum thickness of CZT detectors? (Pockels effect measurements) – G. Yang
- Testing Hemispherical CZT Detectors – A. Hossain
- Summary – A. Bolotnikov
- Lab tour in Bldg. 815 (if time permits)

Research team

- Brookhaven National Laboratory (BNL)
- PIs: A. Bolotnikov, A. Hossain, G. De Geronimo and R. James
- BNL team: G. Camarda, Y. Cui, R. Gul, L. Ocampo, G. Yang, V. Dedic (NNS), V. Emerson, J. Fried (Instrumentation Division)
- Students: M. Petryk, S. Cheng, A. McGilloway, C. Cherches, M. Siegel and R. Gallagher
- Subcontractors: Redlen Technologies, eV Products and CapeSym Inc.
- The project is at the end of its second year

Project overview

- Goal: Enhance the performance and reduce the production cost of large-volume CdZnTe (CZT) detectors particularly pixelated detectors (because they represent the most advanced technology for spectroscopy and imaging of gamma ray sources)
- Motivation: Today's CZT detectors (e.g., Hemispherical, CPG, H3D) rely on using the highest quality crystals to achieve the high-performance; such crystals have low production yield, low availability, and are very expensive
- Technical approach: use high spatial resolution position sensing to enable CZT detectors to correct response non-uniformities caused by crystal defects
- Benefits: Proposed technology will allow us to utilize off-the-shelf unselected CZT crystals, so increasing their availability and reducing the cost of CZT detectors

Capability improvement to be addressed

- ▶ This project addresses the area 2Jc – “development of new concepts in the low-cost radiation detectors with small form factor and improved efficiency” and 2Ja – “new concepts in photon detection hardware and data analysis”
- ▶ Enabling CZT detectors to correct response non-uniformities caused by crystal defects will allow us to use CZT crystals with relaxed quality requirements higher production yield and reduced cost

Root of the problem is material defects present in commercial detector-grade CZT crystals

Three types of the extended defects still are present in today's commercial detector-grade CZT material:

- Subgrain boundaries (or walls of dislocations)
- Te inclusions (eV)
- Prismatic dislocation defects, also known as star-shape defects and scars (remnants of big Te inclusions after Cd annealing) (Redlen)
- Vendors cannot specify contents of the defects in their crystals because they cannot reveal them directly; this is the major problem for vendors and users
- Most effective techniques (all available at BNL) to screen crystal defects are:
 - White beam X-ray diffraction topography
 - IR microscopy
 - High-spatial resolution X-ray response mapping
 - Chemical etching

Example of sub-grain boundaries in CZT crystal

X-ray diffraction map revealing sub-grain boundaries with high and low density of dislocations

- Roles of sub-grain boundaries:
 - (1) The primary cause for carrier trapping by subgrain boundaries is impurities and Te accumulated within the dislocation cores
 - (2) In addition, the sub-grain boundaries and their networks can cause local variations of the electric field

Our X-ray response mapping revealed that the amount of charge loss as electron cloud crosses such boundaries is typically very small, 1-2%.

Image of chemically etched CZT surface

~5x5 mm²

Region with low dislocations density boundaries

Prismatic defects are remnants of Te inclusions after Cd annealing (THM samples)

Image of the etched CZT surface revealing prismatic dislocations

X-ray response map

(a)

(b)

Prismatic dislocations are very detrimental as a cause for non-uniform charge collection.

Roles of the “big” and “small” defects

Big defects like big Te inclusions or “scars” are responsible for incomplete charge collection (ICC) events

Such defects cause the photopeak efficiency loss (the total efficiency is unchanged)

Such events can be identified by using the C/A ratio and **rejected!**

Brookhaven Science Associates

Small defects like low-dislocation density subgrain boundaries cause variations in detector responses resulting in small photopeak broadening

In many cases these defects can be corrected by using position-sensitive detectors!

Using position information to correct response non-uniformities

- Because defect 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

- Previously we demonstrated the feasibility of this approach in the cases of virtual Frisch-grid detectors, in this project we propose to apply this approach to large-volume pixelated detectors

How we can achieve position resolution in CZT detectors

Use non-collecting position sensing strips (pads)

Case of pixelated detectors

- Require using sensing strips for steering electrodes
- Difficult to fabricate

I. Kuvvetli, M. A. J. van Pamelan and C. Budtz-Jørgensen, NIMA 403, 390, 1997.

Position sensing pads suit better in the case of Virtual Frisch-grid detectors

Specifically in pixelated detectors

Use charge sharing to evaluate X-Y coordinates

- Require small pixels to ensure a majority of charge sharing events
- It works well to correct response non-uniformities
- We demonstrated the feasibility of this approach in our previous project (see our publication: A. Bolotnikov et al., NIMA, 805, 41, 2016)

Use signals from adjacent pixels to evaluate X-Y coordinates

- Allows use large pixels with conventional patterns
- But...transient signals are weak
- In the past, researchers did not use time-correlated signal amplitudes → we proposed a novel algorithm to address these issues
- 0.6-mm spatial resolution was reported by Z. He team

W. Warburton, in Proc. Materials Research Soc. Symp., 1997, vol. 487, 531

Objectives

- (1) Use high-position sensitivity to improve the performance of large-volume 3D pixelated detectors with *conventional* contacts patterns:
 - Implement a novel position reconstruction algorithm based on time-correlated signals captured from adjacent pixels to obtain sub-pixel position resolution
 - Find an optimal pixel size to achieve high position resolution with a minimum number of readout channels
 - Demonstrate the feasibility to correct response non-uniformity caused by crystal defects
- (2) Apply a similar approach to improve the performance of other type large-volume CZT detectors with conventional and new designs, e.g., hemispherical and virtual Frisch-grid

Progress to-date

- Objective 1 (large-volume pixelated detectors):
 - Developed a model for simulating signals generated in pixelated detectors and demonstrated importance of using the time-correlated signals from adjacent pixels for achieving sub-pixel resolution
 - Developed a test station based on a focused pulsed laser for measuring signals induced in CZT detectors
 - Acquired 12 large-volume pixelated detectors needed for project (from eV Products and Redlen) with different thicknesses (5, 10, and 15 mm) and pixel sizes: 1.4, 1.72, and 2.8 mm
 - Currently we are testing these detectors using both the gamma ray sources and the pulsed laser to find the optimal algorithm for processing digitized signals captured from neighboring pixels (this is the main task of the project)
- Objective 2: (other CZT devices)
 - Demonstrated the feasibility of ultra-thick (up to 5 cm) detectors
 - Working together with our industrial partner (CapeSym) to improve the performance of hemispherical detectors

Experimental setups for testing 3D pixelated and other types of detectors using gamma sources

Developed and used two experimental setups:

- (1) A test box for testing different types of detectors by reading signal waveforms with hybrid charge-sensitive preamplifiers (eV Products)
- (2) Fast pulsed laser station for simulating integration events inside CZT detectors (know the exact location, trigger)

Set up for taking measurements with gamma ray and alpha-particle sources
A pixelated detector under the test was plugged into the motherboard mounted on the translation stages

Redlen detector

eV Products detector

Pulsed laser station for testing CZT detectors

Wavelength: 650 nm
beam size: 10 and 50 μm

How to achieve sub-pixel position resolution in large-volume pixelated detectors

Signal after charge-sensitive preamplifier generated by the pulsed laser pointed at the central pixel (central and 8 neighboring pixels)

- Our approach is based on using time-correlated sample amplitudes taken from digitized signals and pixel response functions (PRF)
- Plugging these sample amplitudes into the inversed response functions we can evaluate electron cloud positions at a particular time
- We can repeat this calculations for several correlated samples (from a certain time interval) to improve accuracy and minimize electronic noise
- This approach requires using a waveform digitizing ASIC (using such ASICs is common trend now)

Using response function to evaluate position

R^{-1} is inverse response function

Two estimates for X and Y positions:

$$X_1 = R(A_i)$$

$$X_2 = L - R(A_i)$$

$$X_1 = R(A_x^1)$$

$$X_2 = L - R(A_x^2)$$

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

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

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

If assume a linear approximation for the response function:

$$X = \frac{A_x^1}{A_x^1 + A_x^2}$$

We can evaluate X for each time!

Using time-correlated versus uncorrelated signal amplitudes

Amplitude correlations between Right-Left and Bottom-Upper pixels as a laser beam moves across a central pixel

Use shaped signals(uncorrelated)

Weak correlation

Use time-correlated sample amplitudes and linear approximation of the response function

Stronger correlation means a better spatial resolution

Image of the beam

Current work and technical challenges

- Current Tasks:
 - Continue testing the pixelated detectors to optimize signal processing algorithm for evaluating X-Y coordinates
 - Evaluate theoretically and experimentally the pixel response functions
 - Investigate response functions and evaluate the position resolution using pixelated detector with different pixel sizes (1.4, 1.72, and 2.8 mm) and different thicknesses (5, 10, and 15 mm)
 - Optimize detector geometry that would provide the best position resolution
 - Evaluate the contribution of electronic noise: measure spatial resolution at for different photon energies
 - Continue investigating and improving performance of CZT detectors with different designs (particularly hemispherical and virtual Frisch-grid)
- Future plans: Using our experience in digital signal processing to implement a waveform digitizing ASIC (will be available in next FY)

Using the fast pulsed laser for testing 3D pixelated detectors

Luis Ocampo

Graduate Student Assistant

Ph.D. Candidate Nuclear engineering– Penn State

Pixelated Detector

121 pixels – 1.72 mm size

Grid Selection

Signals & Sub-pixel resolution

Sub-pixel resolution

- Correlates each signal in a space-time domain to trace electron clouds
- Reconstruct the XY coordinates with high accuracy.

However, charge signal induced on a pixel is greatly reduced when it is shared among surrounding pixels.

The correct signal magnitude is regained by adding the neighbor signals together

Simulation

Simulation - Neighbors

Pixel 2 Pixel 3 Pixel 4

Pixel 5 Pixel 1 Pixel 6

Pixel 7 Pixel 8 Pixel 9

Experimental Approach

Uncovered CZT detector – 2 mm Pixels

Pulse laser system with a 62 micron beam

Continuous beam
focused on the detector
surface

Pre-amplification of Signals

20 x 20 x 15 mm crystal with pin connections

Pre-amplifiers connected to 3x3 grid selected in the pixelated detector

Experimental Approach

Pulse laser system with a 10 micron beam fiber

Experimental vs. Simulated

Signal Propagation

Pixel 2	Pixel 3	Pixel 4
Pixel 5	Pixel 1	Pixel 6
Pixel 7	Pixel 8	Pixel 9

Signal Propagation – 5 pixels

Data Processing

First Results

Line width gives
the position
resolution

Total induced signal as Gaussian distribution

Measure the response function of each pixel in order to calibrate

Future Work

- Current Tasks:
 - Continue testing the pixelated detectors to optimize signal processing algorithm for evaluating X-Y coordinates
 - Evaluate theoretically and experimentally the pixel response functions
 - Investigate detectors with different pixel sizes: 1.4, 1.72, and 2.8 mm
 - Investigate and improve performance of CZT detectors with different designs (particularly hemispherical and virtual Frisch-grid)
- Technical Challenges:
 - Local variations of the electric field can affect the ability to correct response non-uniformities
 - Electronic noise issue

Development of waveform-digitizing H3DD ASIC

Alessio D'Andragora
Instrumentation Division

Digital 3D PSD technique – H3DD ASIC

Collaboration with DTRA and University of Michigan

- H3DD ASIC measures whole waveform on each signal
- Waveform is digitally sampled and stored
- Advanced algorithms can extract information from the stored data
-
- Waveforms can be analyzed with powerful signal processing techniques, thus achieving higher resolution

ASIC Architecture

Digital interface (CMOS & SLVS)

Channel Architecture

- Energy resolution < 1 keV
- Energy range up to 9 MeV
- Dynamic range up to 10,000 (dual-gain architecture)
- Programmable gain
- Programmable anti-aliasing filter
- Low-noise event discriminator
- High-resolution waveform sampling
- Record depth up to 256 samples
- Programmable pre-and post-trigger
- Sampling rate up to 200 Ms/s
- Readout rate up to 100Ms/s
- Multiple trigger and readout more (token/addressing)
- Power dissipation ~1.8 mW/channel

Waveform Sampling - Simulations

Physical Layout

13.5mm

Physical layout is being optimized, post layout simulation in progress

Feasibility studies of ultra-thick CZT detectors

A. Bolotnikov

Testing ultra thick 30-, 40-, 50-mm Redlen detectors

- The goal of these measurements was to investigate how thick CZT detectors can be made
- For these measurements we used THM crystals grown by Redlen assembled as position-sensitive virtual Frisch-grid detectors
 - We tested 6 detectors of each group (except for 50-mm thick for which we tested 3 samples)
 - Before corrections, the energy resolutions were between 3% to 20% at 662 keV.

After corrections, the resolutions improved to 0.8-1.7% for ALL tested detectors

Best results from 20-, 30-, and 40-mm thick detectors

Z correction

XYZ correction

FWHM maps

Selected areas

20 mm

Before

After

30 mm

Before

After

40 mm

Peak-position maps revealed sub-grain boundaries?

Distribution of photopeak peak positions (response map) before X-Y corrections

5x5 mm²

Image of the etched surface revealing sub-grain boundaries and prismatic defects

~5x5 mm²

Resolve sub-grain boundaries →

Using the charge-sensing pads, we can achieve spatial resolution <100 μm!

Results from 50-mm thick Redlen detector

- Due to charging effect the electric field may rapidly decay towards the anode → the high bias is required
- The max applied bias was 9000 V (leakage current limit)

- The FWHM map is very uniform → prismatic defect were not observed
- The photopeak broadening is likely due to low electric field near the anode

Out of 3 tested 50-mm thick detectors only one showed the good response! A 50 mm thickness could be the limit for CZT detectors?

Measurements of the electron mu-tau product using 40-mm-thick VFG detectors

Using digital oscilloscope we could select the photoabsorption events (662 keV) interacting near the cathode and measure the electron drift time

Bias: 5000 V

Drift time: 3.3 μs

Anode amplitude: 69 mV

(used for calibration, $A_0=69$ mV)

$$A = A_0 \exp\left(-\frac{t}{\tau}\right)$$

$$\tau = \frac{t}{\ln\left(\frac{A_0}{A}\right)}$$

Bias: 200 V

Drift time: 135 μs

If $A_0/A < 3$ then drift time gives the low limit for the electron lifetime)

Anode amplitude: $A=38$ mV

Lifetime: 220 μs
Mu-tau: $2 \times 10^{-1} \text{ cm}^2/\text{V}$!

The mu-tau product of today's CZT is ~ 10 times higher than commonly thought $\rightarrow > 5\text{-cm}$ thick detectors are feasible

This raises the bar to a higher level for all other alternative materials proposed today to replace CZT

**Using Pockels effect to measure the electric field
of CZT detectors**

**What limits the maximum thickness of CZT
detectors?**

Ge Yang

Potential factors limiting CZT detector thickness

- Three factors can limit the size/thickness of CZT detectors: electron lifetime, response non-uniformities and ability to apply a sufficiently strong electric field over the entire length of the crystal

Electron lifetime

- The amount of charge loss correlates with the drift time and can be corrected if the latter is measured.
- If we allow 10% of the charge loss (which can be corrected without introducing additional noise) and assuming the mu-tau value of $10^{-1} \text{ cm}^2/\text{V}$, then a drift time of $\sim 10\text{-}\mu\text{s}$ and $\sim 10\text{-cm}$ -thick detectors are possible!

Response non-uniformities

- The amount of charge loss correlates to the electron cloud drift paths (or X-Y-Z coordinates) and potentially can be corrected if position-sensitive detectors are used.
- We demonstrated that we accurately correct such variations in 5-cm thick CZT detectors

Ability to apply a sufficiently strong field

- The electric field strength decays towards the anode due to ionization of deep levels. $\rightarrow$
- Achieving the minimum required electric field can limit the detector thickness?

Our hypothesis was that the max CZT thickness was primarily limited by the inability to apply sufficiently strong electric field over the entire length of the detector! We used the Pockels effect to verify this.

Pockels effect (PE) measurement

An effective technique to study the internal electric field in CZT detectors

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

50-mm long detector

Cathode

Drift region

Virtual Frisch-grid

Anode

Bias 6000 V
Time bin size 20 ns

Cathode

Pad signal

Fast (normal) component of the anode signal

Slow component of the anode signal

Peak corresponds to the electron cloud reaching the sensing pads

Pockels images of two tested 50-mm long detectors

Cathode bias 8 KV

A

Linear scale

C

Detector 1

Detector 2

Log scale

Detector 1

Detector 2

Electric field strength decays towards the anode

The field is very low near the anode (no spectrum was observed from detector 1)
50-mm thickness could be the limit for CZT detectors

Electric field profiles of two tested 50-mm long detectors

Testing Hemispheric CZT Detectors

Anwar Hossain

Motivation

- ☐ The hemispherical detector is another cost-effective promising alternative to large aspect ratio devices;
- ☐ It provides excellent energy resolution with the simplest geometry;
- ☐ Require simple readout electronics compared to other leading CZT detectors;
- ☐ Charge-loss correction may be worthy, which has not been attempted yet.

Spectral response of a hemispheric detector supplied by CapeSym.

D. S. Bale & C. Szeles, *SPIE Proc.*, vol. 6319 (2006)

Signal Collection and Correction Process

Drift-time was measured by capturing waveforms of both anode and cathode signals at preamplifier outputs.

Acquired digitized waveform of detector signals for correction process.

Correlation
between the anode
signals and drift
times

Drift time (channels)

Drift time Correction

Improvement in energy resolution was achieved after drift time correction.

To improve the energy resolution further, we need to apply 3D correction.

Position-sensitive hemispheric detector

- Introduce the sensing strips concept into hemispheric detector to correct incomplete charge collection for improving energy resolution;
- Need to modify the design without compromising the detector's performance;
- Design modification of hemispheric detector is a challenge.

Typical design of a Hemispheric detector

Position-sensitive Virtual
Frisch-grid detector

Virtual Frisch-grid CZT Detector (size $\sim 7 \times 7 \times 20$ mm³) sensing pads at four side walls for x-y-z positional information.

E-field distribution and its effect

- ❑ Material defects may lead to charge carriers terminating in inactive region;
- ❑ An inaccurate design and detector fabrication may also cause incomplete charge collection.
- ❑ Design modification of hemispheric detector is a challenge.

Hemispheric pattern

Spectral response

E-field lines terminate away from anode –

possible reasons may be

- Surface conductivity
- Crystalline defects
- Detector design and fabrication

Incomplete charge collection may lead to lower energy tail and reduced peak-to-noise ratio.

Design Modification and Detector Performance

Acquired anode and cathode signals of detector signals for correction process.

Attach virtual anode to reject the charges accumulate inactive region to improve the peak-to-noise ratio.

Possible designs

To attach sensing strips, we consider two possible designs

Design 1

Attach sensing strip directly on the side surfaces

after modifying the cathode into a cage.

In this case, we need to apply high voltage to collect positional signals.

Disadvantage:

Applying high bias raised leakage current significantly.

Design 2

Attach sensing strips on top of insulating layer similar to position-sensitive VFG detector.

Disadvantage:

Detector fabrication is a critical as the gap between electrodes and sensing pad is small that may induce noise into the system.

Sensing Strips in Hemispheric Detector

- Acquire spectral response after modified the electrode design;
- Acquired signals from anode, cathode and four sensing strips, although leakage current increased while connected to strips.

Detector with four sensing strips

Summary

- Hemispherical detector can be another promising member in 3D position-sensitive detector technology;
- Demonstrated the feasibility of design modification and able to accomplish the charge-loss correction;
- Need to optimize the design for introducing sensing pads. It is challenging but possible to implement.

Future Plan

- **Fabricate and test a larger volume (20x20x10 mm³) CZT crystals;**
- **Optimize the electrodes pattern to attach sensing pads;**
- **Modify the existing algorithm to analyze digitized waveforms for incomplete charge correction.**

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. A.E. Bolotnikov, K. Ackley, G. S. Camarda, Y. Cui, J. F. Eger, G. De Geronimo, C. Finfrook, 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)
4. Aleksey Bolotnikov, Giuseppe S. Camarda, Eric Chen, Rubi Gul, Vaclav Dedic, Gianluigi Geronimo, Jack Fried, Anwar Hossain, Jason MacKenzie, Lous Ocampo, Paul Sellin, Saeid Taherion, Emerson Vernon, Ge Yang, Uri El-hanany, and Ralph James, "Use of the drift-time method to measure the electron lifetime in long-drift-length CdZnTe detectors", accepted for publishing in Journal Applied Physics (2016)

Take-away messages

- This is a feasibility study project with the main objective to enhance position resolution of large-volume pixelated detectors with conventional pixel patterns (like in H3D devices) and to enable them to correct response non-uniformities caused by crystal defects
- The main benefits of this approach are: (1) Improve position resolution and imaging capability; (2) Proposed technology will allow us to utilize off-the-shelf unselected CZT crystals, so increasing their availability and reducing the cost of CZT detectors
- Developed a pulsed laser test system for measuring signals induced in CZT detectors and acquired large-volume pixelated detectors with different thicknesses and pixel sizes
- Currently we are testing these detectors with a goal to optimize the algorithm for processing digitized signals captured from neighboring pixels (this is the main task of the project)
- Our technical approach is to use the time-correlated signals from adjacent pixels and the pixel response functions to achieve high spatial resolution
- We also demonstrated the feasibility of ultra-thick (up to 5 cm) detectors and the high mu-tau product of today's CZT crystals
- Working together with our industrial partner (CapeSym) to improve the performance of hemispherical detectors

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