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***Upgrading FLIR NanoRaider with the next
Generation of CdZnTe Detectors***

Goal – Integrate VFG detectors into FLIR R200

Advanced Virtual Grid ASIC (AVG-ASIC)

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Nonproliferation and National Security Department

Brookhaven National Laboratory

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Upgrading FLIR NanoRaider With The Next Generation of CdZnTe Detectors

Goal - Integrate VFG detectors into FLIR R200

Advanced Virtual Grid ASIC (AVG-ASIC).

*Department of Nonproliferation and National Security
Instrumentation Division*

Upgrading FLIR NanoRaider with the next generation of CdZnTe detectors

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June 10, 2016

Outline

1. Project motivation, goals and its current status
2. Development of position-sensitive virtual Frisch-grid detectors and which we proposed for nanoRaider
3. Emerson Vernon will describe ASIC developments for CZT detectors
4. Yonggang Cui will update on the electronics development for the detector prototype

Motivation

- NanoRaider is a very successful instrument commonly used by nuclear inspectors
- It employs the hemispherical detectors, which have the simplest design ever proposed for CZT detectors
- Because of this simplicity and robust data processing algorithms, FLIR were able to make a very reliable and user-friendly instrument... but its energy resolution is limited by $\sim 2.5\%$ at 662 keV (poor based on the modern requirements to CZT detector)

In order to successfully compete with emerging technologies, FLIR needs to upgrade their nanoRaider with new detectors

Arrays of position-sensitive virtual Frisch-grid detectors could be a good choice to replace the hemispherical detectors

Apollo detector by H3D Inc.

Handheld Imaging Spectrometers

Apollo is a high-efficiency radio-isotope identification device (RIID) with better than 1% FWHM energy resolution and gamma-ray imaging

2x2 array of 20x20x15 mm³ Redlen detectors

An unbeatable feature of pixelated detectors is low electronic noise

But...

The H3D detector relies on using the best selected CZT crystals

How many such crystals with < 1% are available?

At what cost?

How reliable are detectors?

eV Products (KromeK) SPECT-Image (similar to H3D)

*eV-CZT® Detector Module
(Shown with 20x20x15mm CZT)*

Energy resolution is <2% at 662 keV

Project goals

- The goal of this project is to upgrade the FLIR's NanoRaider with a 2x2 array of position-sensitive virtual Frisch-grid detectors recently developed at BNL
- During this year we will integrate and demonstrate a benchtop prototype of the instrument using existing components and a readout system from another projects
- BNL Tasks:
 - Design and fabricate an adapter that enables a nanoRaider controller to communicate with BNL ASIC
 - We are currently in process of signing CRADA with FLIR which allows FLIR to use ASIC and a software for raw data processing
- FLIR Tasks:
 - integrate a benchtop unit with a HV power supply, DAQ, and a user interface

Crystal defects is the main limiting factor of CZT detectors

- CZT has several advantages as a detector medium:
 - High atomic number and high density (important for detecting of the gamma-rays)
 - Wide bandgap, 1.57 eV, high-resistivity at room temperature, $>3 \times 10^{10}$ Ohm-cm
 - Relatively low the W-value (4.6 eV, e.g., Si: 3.6 eV)
 - High energy resolution, $<0.5\%$ at 662 keV $<1.5\%$ at 60 keV
 - Energy resolution is primarily limited by the leakage current
- The feasibility and performances of CZT detectors have been demonstrated by many researchers using different detector designs
- However, the large-volume spectroscopic detectors are still very expensive and not easily available for practical applications
- The reason: response non-uniformities caused by crystal defects that are present even in the best quality material available today

Defects in detector-grade CZT crystals

- BNL has unique experimental facilities to test CZT material and detectors
 - We identified three types of defects in commercial detector-grade CZT material (despite all efforts to improve its quality) :
 - Subgrain boundaries, or walls of dislocation (most common defects that can be tolerated in many applications)
 - Te inclusions (present in eV-Products material)
 - Prismatic defects, also known as “scars” left after annealing (present in Redlen crystals)
- } Very harmful
- It is hard for vendors to specify contents of the defects in their crystals because they cannot reveal them directly; this is the major problem for vendors and users

Charge trapping due to subgrain boundaries measured with a highly-collimated X-ray beam

X-ray response map,
5 μm step
(low-angle boundary)

Output signal variations are small, ~1%

X-ray diffraction topography of
a 10x15 mm² area of a 2-mm
thick planar detectors

X-ray response map,
10 μm step
(high-angle boundary)

The primary cause for carrier trapping by subgrain boundaries is impurities and Te accumulated within the dislocation cores

In addition, the sub-grain boundaries and their networks can cause local variations of the electric field

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

Image of the etched CZT surface revealing prismatic dislocations

X-ray response map

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

High-granularity position-sensitive detectors

- Because defects locations are fixed, the response variations are caused by random distribution of the interaction points inside detectors → can be corrected if locations of interaction points are known for each event
- Position information allows us to virtually segment the detector's volume into a large number of small voxels (e.g., 30x30x50 voxels) and equalize responses from each voxel

- Benefits: (1) We can utilize off-the-shelf unselected crystals available at low cost and use bigger crystals, (2) use thicker crystals (up to 5 cm), (3) apply smaller HV, (4) use simpler detector designs.

Commonly used CZT gamma ray detectors have limited ability to correct response non-uniformities

CPG detector
20x20x15 mm³

First demonstrated P. Luke

Drift-time
correction
only

20x20x15 mm³ 3D position-
sensitive detector with ~2-
mm pixel sizes

Developed by Z. He et al.

3D
correction
but with a
coarse
spatial
resolution

These detectors rely on the highest quality CZT crystals to achieve the high performance → Such crystals have low production yields and are very expensive!

Because of defects the maximum thickness of today's CZT detectors is 15 mm!

Hemispherical detectors

15x15x10 mm³
hemispherical detector

Disadvantages of hemispherical detectors:
Detector's geometry is not optimal
Inability to correct the response non-uniformities

Arrays of virtual Frisch-grid (drift) detectors

- To overcome the high cost and low availability of big CZT crystals we propose arrays of small cross-section, $6 \times 6 \text{ mm}^2$, but long, up to 5 cm, detectors (bars)
- Such crystals have much higher production-yield and lower cost than crystals used for big pixelated detectors
- Bars' cost: \$250 (eV) vs. \$1000 (Redlen), cut from the crystals rejected by other costumers
- The bars can be configured either as planar or as position-sensitive detectors:

CZT bars

Planar

Position-sensitive

We placed a single 5-mm wide non-contacting electrode or 4 charge-sensing pads for position sensing

The cathode signals are used to measure drift times (or C/A ration) to evacuate Z coordinate, like in TPC

Both the shieling electrode and pads produce the virtual Frisch-grid effect (as if a real grid were placed inside the detector)

Schematic of the array with the common cathode

Fanout board

Pulse-height spectra measured with shielded and unshielded detector prototypes

Unshielded

Vs.

Shielded

How we fabricate detectors and arrays

We developed a reliable procedure for detector fabrication and array assembling

Place a detector inside an ultra-thin polyester shrink tube

For insulation and mechanical protection we use the ultra-thin polyester shrink tube (Advanced Polymer, Inc.)

Volume Resistivity: 10^{18} Ohm-cm,
Surface Resistivity: 10^{14} Ohm/square,
Thickness: 100 μ m.

Seal one side with a rubber band and deep into hot water

Without position sensing

Position sensitive

or

Array of conventional (planar) virtual Frisch-grid detectors

- 2 6x6 arrays (detector modules) were integrated into the system and tested
- For the first array we carefully selected the best 36 crystals out of ~100 acquired from eV Products and Redlen
- For the second we used randomly chosen (unselected) crystals

Fully assembled 6x6 array

Integrated unit with partially filled array

^{137}Cs spectra (selected 36 best detectors)

For the first array we used only the best (selected) crystals

Bias: 3000 V,
Temperature: 19 C

Very uniform response of
Redlen detectors
(resolution: 0.8-1.3%
FWHM) at 662 keV

Combined spectra from 36 selected detectors (without position sensing)

Electronic noise: 2 keV FWHM at 3000 V
Resolution is determined by crystal performance

With high-quality crystals it is not difficult to achieve the high performance

Unfortunately, such crystals have low production yields and very expensive!

Results from the second array (typical unselected detectors)

- For the second array, we used unselected crystals
- We achieved an overall resolution of 1.4% FWHM at 662 keV with a broader range of peak-widths measured for individual detectors
- This clearly demonstrates that signal corrections are necessary to recover performance and increase acceptance rates of CZT crystals
- Only high-granularity position sensitive detectors can provide such capabilities

Testing position-sensitive virtual Frisch-grid detectors and arrays

2x2 array of 20-mm thick detectors

Testing a single detector

4x4 array of 20-mm long detectors

- We employed existing readout electronics and the analog ASIC developed for the first generation of arrays
- First we accumulated a big data set used to calibrate the response matrix, then we used a different data set to plot the results (avoid data correlations!)

Results from testing of 6x6x15 mm³ position-sensitive VFG detectors fabricated from different quality crystals

Raw spectra

After drift-time correction

After segmenting the detectors into 60x60x30 voxels

We tested over 50 detectors with different dimensions from different suppliers, and we always achieved much better performances!

Spectra after corrections

7x7x20 mm³ detector biased at 3000 V

Increased efficiency allows detection of energetic gamma rays

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

We used *unselected* CZT detectors cut from 6-mm-thick CZT wafers based on the best guess of the vendor – no prior screening

- We tested 6 detectors of each group (except for 50-mm thick for which we tested 2 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, 40, and 50 mm thick detectors

Raw spectra 3D correction - FWHM maps - Selected areas

20 mm

30 mm

40 mm

50 mm

Prismatic defects

Spectra from the first 4x4 array of 20-mm long position-sensitive CZT drift detectors

Before

We used all readout channels available in the current ASIC, 45 channels

After

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

A very important milestone!

2x2 array for the nanoRaider

- We assembled two detector modules for the benchtop prototype (crystals for these detectors were cut from CZT material rejected by other customers)
- Each module is 2x2 array of 6x6x20 and 7x7x20 mm³ crystals
- Both detector modules were tested in the laboratory

2x2 module layout

4 anodes
1 common cathode
8 channels for 16 sensing pads
Total: 24 readout channels

As a temporary solution we use a current 36-channel ASIC developed for the conventional (planar) virtual Frisch-grid detectors

Detector boards

Simple fabrication process

Cs-137 spectra measured with the first array

Array 1 (6x6x20 mm³)

Bias 3000 V

Temperature 18 C

Raw data

After 3D corrections

Combined spectrum after corrections

Cs-137 spectra measured with the second array

Array 2 (7x7x20 mm³)

Bias 2700 V

Temperature 18 C

Combined spectrum after corrections

Reduction of voltage bias had practically no effect on module performance

Array 2 (7x7x20 mm³)

Bias 2000 V

Temperature 18 C

Raw data

After 3D corrections

Combined spectrum after corrections

We can make thicker detectors biased at lower voltages

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

Can operated at reduced bias but the electric field must be above a certain limit (~ 1000 V/cm) to attain $<1\%$ resolution (~ 2500 V/cm in pixel detectors)

Temperature dependence of energy resolution

20-mm long detector
Bias 3000 V

Correction matrixes were evaluated at each temperature

These measurements show that the energy resolution of these detectors is mainly determined by the leakage current

We proposed a new detector design to reduce the leakage current

Stability of the correction matrix

We demonstrated that the correction matrix (look up table) is very weekly depends on photon energies and temperature

The spectrum was taken at 21 C and processed using correction matrix measured at 21 and 35 C

Matrix measured at 21 C

Matrix measured at 35 C

The same correction matrix can be used for different energies

Conclusions

- Advantages of position-sensitive virtual Frisch-grid detectors:
 - 3D correction of the response non-uniformities
 - Employ unselected low-cost CZT crystals usually cut from large production volume (standard) detectors rejected by other customers
 - Simple and robust design
 - Low fabrication cost
 - Employ thicker crystals up to 5 cm (thickness of H3D is 15 mm)
 - Energy resolution $\sim 1\%$ (depending on temperature)
 - High detection efficiency and good energy resolution means the high sensitivity (in the lab conditions, an array of 12 $6 \times 6 \times 20$ mm³ detectors can detect a 12 μCi ^{137}Cs source at a distance of 1 m in ~ 30 sec)
 - Can operate at lower biases than typical CZT detectors with same thicknesses
 - Arrays require a smaller number of readout channels than H3D
 - 3D position sensitivity allows for making directional and gamma-imaging instruments

Goal - Integrate VFG detectors into FLIR R200

VFG Detectors

Readout ASIC board

Bias Board

Acquisition Board

FLIR R200

Work Plan

Status

- ❖ New adaptor board has been designed and fabricated.
 - Purchase order was placed this week to have the boards assembled.
 - We worked with FLIR closely on this project to make sure that the adaptor board will fit into R200 device.
 - FLIR is modifying their acquisition board of R200 to the new VFG-based devices.
- ❖ A bridge board was designed so we can test the adaptor board with BNL's existing acquisition system.
 - The bridge board will also be used to verify the performance of VFG detector array.
 - The board is being fabricated by PCB manufacturer.

Advanced Virtual Grid ASIC (AVG-ASIC)

June 10, 2016

Principal Investigators:

Emerson Vernon and Gianluigi De Geronimo

Outline

Original 3D ASIC

- 3D ASIC Design Motivation
- ASIC for 3D Position Sensitive Detectors
- ASIC Architecture
- Front-end Interface
- Prototype
- System Readout

Towards AVG

- Advanced Virtual-Frisch Grid (AVG) ASIC Development
- Preamp Signals for Virtual Frisch Grid Detectors
- Current ASIC Development
- Conclusion and Future Work

3D ASIC Design Motivation

CdZnTe $1.5 \times 1.5 \times 1 \text{ cm}^3$, $11 \times 11 = 121$ pixels

- + High x- and gamma-ray detection, room temperature, compact
- + Source imaging, directionality (Compton scattering)
- Poor hole mobility, electron trapping, non-uniformities

3D position-sensitive concept - Prof. Zhong He, Univ. of Michigan

•Combines

- small-pixel effect
- depth sensing

•Extracted Information

- energy and timing at anodes
- energy and timing at cathode

•Applied correction

- corrects each volumetric pixel (voxel)

Readout requires an Application-Specific Integrated Circuit (ASIC)

ASIC with readout for 128 anodes and 2 cathodes

- Low-noise charge amplification
- Signal processing (amplitude, timing)
- High-speed multiplexing
- Low power

ASIC for 3D Position Sensitive Detectors

3D position-sensitive concept

Developed by BNL Instrumentation Division in collaboration with the University of Michigan for DTRA (DoD).

Instrumentation Division : Gianluigi De Geronimo, Emerson Vernon, Jack Fried, Kim Ackley, John Triolo, and Don Pinelli.

ASIC Architecture

- 130 channels (128 anodes, 2 cathodes), 330 mW
- Energy and timing measurement
- LVDS digital interface, multiplexed analog outputs
- Test pulse and test ramp generators
- Temperature sensor and analog monitors

Front-end Interface

- ASIC size 12.9 mm x 9.3 mm
- Board size 22 mm x 22 mm
- Wire-bond

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

Prototype

Analog Mother Board

DAQ

- Regulators and ADCs
- LVDS signal chain to DAQ
- Optical communication
- Giga-bit Ethernet
- USB

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

System Readout

- Sparse readout
- Two channels with data
- Capability to readout the neighbors

- Amplitude and timing data
- Real time Histogram with statistics
- Capability to monitor all channels

Advanced Virtual-Frisch Grid (AVG) ASIC Development

ASIC for 3D Position Sensitive Detectors

- 128 Anode channels
- 2 Cathode channels
- Size: 13 x 10 mm²
- 300,000 transistors
- CMOS 250 nm

Advanced Virtual Frisch-Grid ASIC (AVG ASIC)

- 36 Anode channels
- 9 Cathode channels
- Size: 7.4 x 8.7 mm²
- 220,000 transistors
- CMOS 250 nm

AVG technology is being adopted by FLIR Systems

Preamp Signals for Virtual Frisch Grid Detectors

Drift time
→ ←

- Readout requires an ASIC with 3D Position Sensing
- A waveform digitizing ASIC would be best
- The pad signals can substitute for the cathode signal

Current ASIC Development

NA-22 Project

- Develop an Array of Position Sensitive Virtual Frisch Grid Detectors
- Develop an ASIC to read out position sensitive Virtual Frisch-Grid detectors
- The AVG ASIC will be modified to implement an analog position sensing readout

Analog 3D PSD

- Readout pulse amplitude and timing from each electrode
- Use bi-parametric data to reconstruct the event

Digital ASIC Collaboration with DTRA and the University of Michigan**

Digital 3D PSD

- Waveform is digitally sampled and stored
- Advanced algorithms can extract information from the stored data
- Higher resolution can be achieved with pad and neighbor information

** This ASIC is under research and development

Conclusion and Future Work

- The current AVG ASIC successfully demonstrated the Virtual Frisch-Grid concept
- The AVG ASIC will be modified and optimized for analog position sensitive Virtual Frisch-Grid detectors
- Risks associated with the modifications are low
- This project will benefit from the waveform digitizing ASIC currently under development

Questions