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High-Efficiency CdZnTe Position-Sensitive VFG Gamma-Ray Detectors for Safeguards Applications

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DISCLAIMER

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1. INTRODUCTION

The goal of this project is to incorporate a Cadmium-Zinc-Telluride (CdZnTe or CZT) detector (with 1% or better resolution) into a bench-top prototype for isotope identification and related safeguards applications. The bench-top system is based on a 2x2 array of 6x6x20 mm^3 position-sensitive virtual Frisch-grid (VFG) CZT detectors. The key features of the array are that it allows for the use of average-grade CZT material with a moderate content of defects, and yet it provides high-energy resolution, 1% FWHM at 662 keV, large effective area, and low-power consumption. The development of this type of 3D detector and new instruments incorporating them is motivated by the high cost and low availability of large, > 1 cm^3, CZT crystals suitable for making multi-pixel detectors with acceptable energy resolution and efficiency.

The end product will incorporate the 2x2 detector array into a modified version of the nanoRaider, which is a compact gamma-ray detection instrument manufactured by FLIR Corporation that employs relatively poor performing CZT hemispheric detectors (i.e., 3%-FWHM CZT detectors). The new instrument (called "nanoRaider II") will significantly improve the accuracy and efficiency, as compared to the nanoRaider, for in-field analysis of nuclear materials and detection of undeclared activities during IAEA inspections. Since the nanoRaider is used currently by the IAEA as part of its Complementary Access toolkit, we expect relatively quick acceptance of the nanoRaider II for safeguards use.

The nanoRaider II will impact the following items in the IAEA's Long-Term R&D Plan, 2012-2023: 2.2 (elemental and isotopic signatures of fuel cycle processes); 2.3 (detect signatures of undeclared activity and improve analysis); and 2.6 (detect process emanations). The high energy-resolution capability of the nanoRaider II also has applicability to 3.2 (fissile content of metal mixtures containing actinides Np, Am, etc.).

2. MAJOR TASKS

Task	Deliverable and Status	Lead	Deadline
Analysis of IAEA needs, detector requirements	Report (Complete)	LANL	12/15/14
Familiarization with the HM-5 and nanoRaider device architectures	Status update (Complete)	BNL	12/31/14
Integration of a 2x2 detector array	Status update and data	BNL	05/15/14

	with integrated system (Complete)		
Demonstrate data with BNL's VFG detectors and data-acquisition system and FLIR's software for energy spectra and isotope ID	Complete	BNL	07/31/14
Conduct tests on bench-top unit	Test plan and final report (Complete)	BNL	10/2/15

3. RESULTS AND DISCUSSIONS

During this year we concentrated on proving the proposed technology and optimizing specific design features for a new VFG-based handheld instrument. We investigated energy resolution, efficiency, stability, the capability for dose-rate measurements, multi-modality for gamma-ray and neutron detection, and the mechanical design. An agreement with FLIR was reached on many specific design features of the new instrument.

<u>Energy Resolution:</u>

We tested over 30 VFG detectors of different geometrical dimensions and different temperature conditions. We demonstrated that by using correction techniques the instrument can provide excellent energy resolution of 0.5-1.5% FWHM at 662 keV over a wide temperature range. It is important to mention that such energy resolutions cannot be achieved with the detectors used in FLIR's current CZT-based instrument – the nanoRaider. The nanoRaider uses commercial detectors provided by eV Products, which have an energy resolution of about 2.5% or worse. Not all detectors used in the existing nanoRaider can provide performance even at the 2.5% FWHM level.

Fig. 1 illustrates the temperature dependence of the energy resolution measured for one of the new VFG 6x6x20 mm^3 detectors at different bias voltages: 2000, 3000, and 4000 V. It shows that the detectors provide the energy resolution below 1.5% at 662 keV over a wide range of temperatures from 5 to 45 ^{0}C. They can operate at reduced cathode biases but with some modest performance loss at high temperatures. The optimal cathode bias is expected to be around 3000 V. As seen from the plots, the energy resolution is governed primarily by the electronic noise which, in turn, depends on the ambient temperature.

To illustrate the performance we can achieve with VFG CZT devices, we collected spectra from several radioactive sources: ^{241}Am, ^{137}Cs, ^{56}Co, ^{60}Co, ^{232}Th, ^{133}Ba, ^{258}Cf (with 0.25-inch lead and 3-inch polyester sheet), and ^{239}Pu. Fig. 2 shows measured energy resolutions of 1.24% at 356 keV, 0.73% at 662 keV, and 0.61% at 1.33 keV, indicating that the electronic noise is the dominant component limiting the detector's energy resolution. These spectra demonstrate the high dynamic range for detecting both low- and high-energy gamma lines.

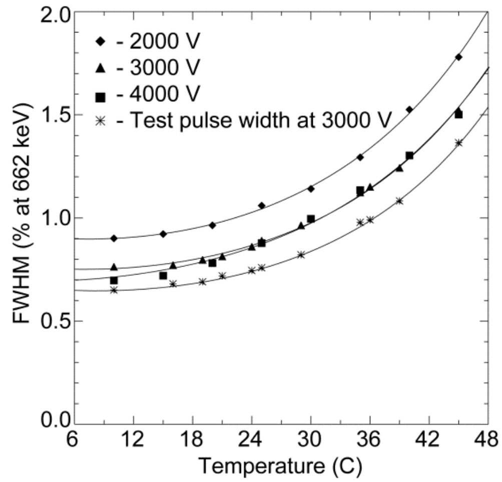


Fig. 1. Temperature dependence of the energy resolution, % FWHM, at 662 keV, measured at three cathode biases: 2000, 3000 and 4000 V. The % FWHM at lower temperatures represents the contribution of the electronic noise.

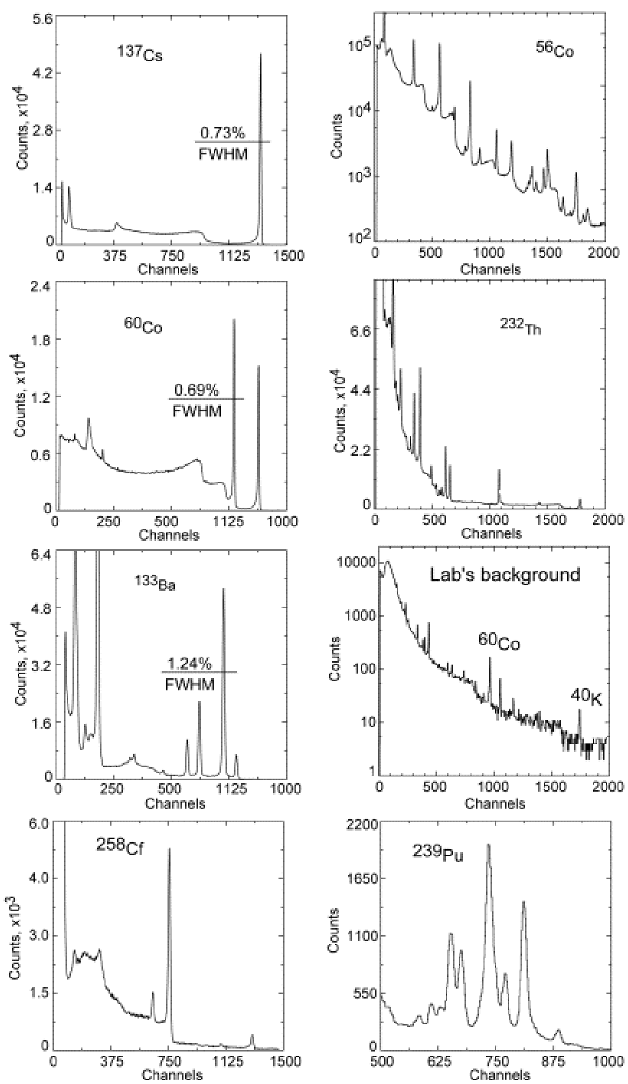


Fig. 2. Pulse-height spectra measured with a 7x7x20 mm^3 position-sensitive VFG detector. Several radioactive sources were placed ~1 inch above the cathode: ^{137}Cs, ^{56}Co, ^{60}Co, ^{232}Th, ^{133}Ba, ^{258}Cf (with 0.25-inch lead and 3-inch polyester sheet), and ^{239}Pu.

Detector dimensions and efficiency

The largest single-crystal CZT detector reported in the literature has a drift distance (i.e., detector thickness) of 15 mm. The emergence of position-sensitive VFG detectors allows for thicker detectors. From the standpoint of efficiency, especially for high-energy gamma-rays, it is always beneficial to use thicker detectors to ensure good stopping power. Although BNL has already established new records for detector efficiency (up to 25 mm) with lab prototypes, an agreement was reached to use 20-mm-thick detectors in the new VFG-based instrument (i.e., the nanoRaider II). This will allow for higher efficiency and establish a new state-of-the-art for CZT-based instruments with regard to the detector thickness.

Another important factor is the cross-sectional area of the detectors. Here, there was some flexibility due to the trade-offs associated with cost and availability. The principal supplier (Redlen) prefers to cut its 75-mm-diameter wafers into 6-mm-thick slabs, since their principal product (for nuclear medicine) requires 5-6-mm thick detectors. Hence, cost and availability push toward 5x5x20-mm^3 VFG detectors. However, Redlen is willing to cut detectors into larger cross sections if a set-up fee is paid. We agreed to use detector elements with a size of (5-7 mm) x (5-7 mm) x 20 mm.

Stability study:

It was previously demonstrated by other researchers that the stability of CZT instruments surpasses that of NaI. Detectors can stably operate for years without any observable changes in their original characteristics. In our lab we tested VFG detectors for weeks, sometimes for months, and we did not observe any change. Aging studies of VFG detectors are continuing.

Count rate measurements:

We demonstrated experimentally that the 2x2 module of VFG detectors and readout can operate at a count rate up to $5x10^3$ count/sec. Note that this is the maximum count rate we were able to achieve by putting together several available radioactive sources, and the detector module is expected to work well at even higher count rates.

Neutron Measurements:

The option of neutron measurements with a He-3 tube was desirable as an add-on. The same tube now in use with the nanoRaider would be used in the nanoRaider II. We also tested the possibility of using VFG CZT detectors for neutron detection. In these measurements, we employed a Cf-252 source to determine the sensitivity of the VFG detectors to thermal neutrons. The fast neutrons from the Cf-252 source were thermalized by 25-mm-thick polyethylene in front of the VFG detector. Despite a very low activity of our neutron source, <5 μCi, we were able to observe well-distinguishable peaks associated with neutrons in the pulse-height spectra, confirming the ability to see gamma-ray and neutrons simultaneously.

Testing 2x2 array prototypes:

We assembled and tested four 2x2 arrays using 20- and 25-mm-thick detectors. As an example, Fig. 3 shows a 2x2 array assembled with 20-mm long crystals.

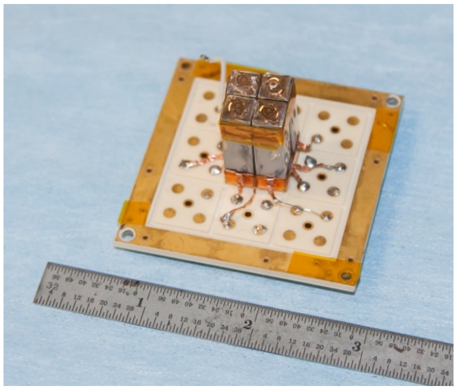


Fig. 3. A 2x2 array prototype of 7x7x20 mm^3 VFG detectors.

Several test measurements were carried out with these arrays to investigate their energy resolutions, stability of the correction matrix, and different charge-correction schemes. Fig. 4 shows the pulse-height spectra measured with a 2x2 array prototype of 7x7x20 mm^3 position-sensitive VFG detectors. In this example, we used four strips to evaluate the positions of the interaction points.

Minimizing the number of readout channels:

One of our tasks was to reduce the total number of readout channels. For this reason, we proposed to connect adjacent sensing pads together. In this case, to avoid ambiguity caused by the multiple interaction events in adjacent detectors, we could use only two strips to locate the positions of interaction points. Fig. 5 demonstrates that we can implement this design simplification without degrading array performance. As shown in Fig. 5, the corrected spectra are similar to those from Fig. 4, indicating that two orthogonal strips can be used to evaluate positions in the cases when two or more interactions occur in adjacent detectors. In general, any of four pairs of orthogonal strips can be used for positioning. Depending on the locations of the interaction points, we have to select those that allow us to resolve any ambiguity of the strip signals.

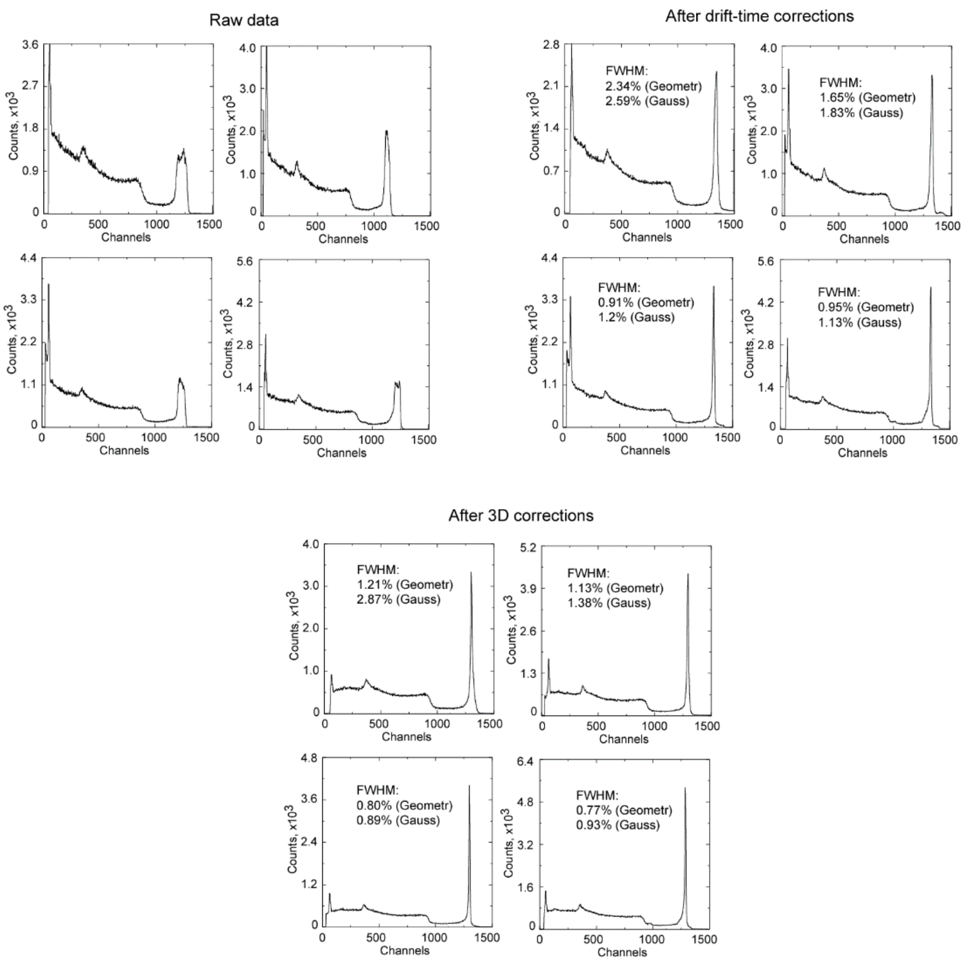


Fig. 4. Pulse-height spectra measured with the 2x2 array prototype of 7x7x20 mm^3 position-sensitive VFG detectors. The crystals used in the array were acquired from eV Products. In this array, we use the readout sharing approach: every two adjacent strips shared a single readout channel. Only single detector events were selected. Four position-sensing strips were used to evaluate the position of each event.

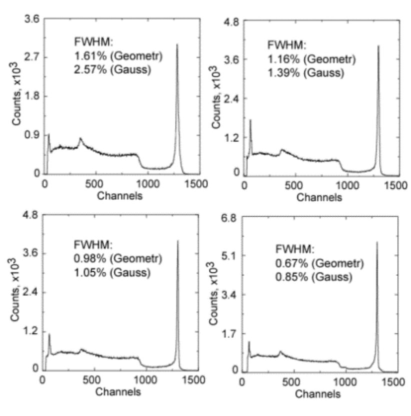


Fig. 5. Pulse-height spectra measured after reducing the number of readout channels by using one pair of strips instead of two. The performance was not degraded.

Mechanical design and electronics:

Based on discussions with the DOE Office of Nuclear Verification (NA-241) and FLIR, we decided to deploy a 2x2 VFG detector array. Each individual detector has dimensions of 6x6x20 mm^3. In order to demonstrate the performance of such a 2x2 VFG array, we designed a new detector substrate that can interface with our existing readout electronics. Fig. 6 shows the layout design of the new substrate. Four VFG detectors of cross-sectional area ranging from 5x5 mm^2 to 7x7 mm^2 can be hosted on this substrate. Such 2x2 detector arrays can be processed by our existing electronics system. Thus we used four shorter connectors to interface with BNL's readout electronics, which allowed us to route most traces right underneath the detector array, enabling a compact design of the module. The substrate is being fabricated and is scheduled for delivery to BNL on Oct. 6, 2015. Meanwhile, we have acquired all the components (sensing pads and connectors) and fabricated all VFG detectors needed for assembly and testing.

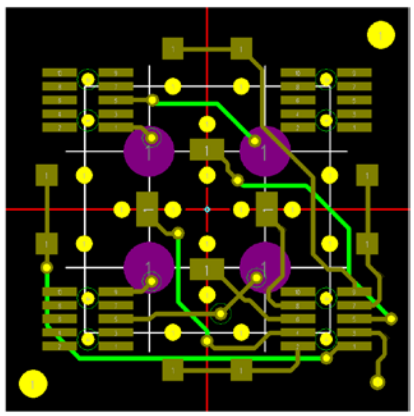
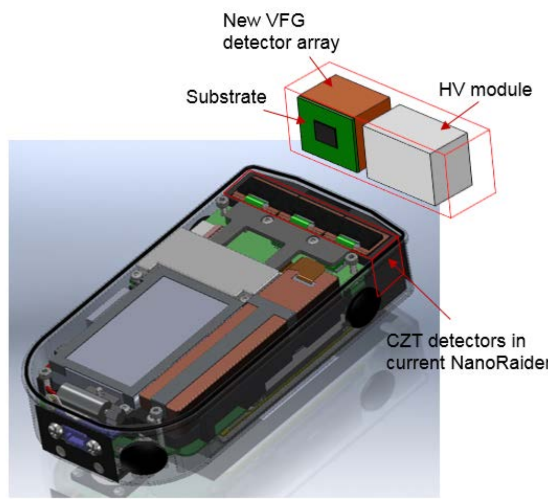


Fig. 6. Layout drawing of the new substrate for 2x2 VFG detector array.

We met with FLIR both by a face-to-face meeting and via teleconferences to obtain detailed design information of the nanoRaider. We also discussed the plans with NA-241 program managers and IAEA inspectors to get input from the end-user perspective. Figure 7 (a) shows the current nanoRaider device and (b) illustrates its internal layout and plan for the new nanoRaider II. The current nanoRaider device has three 15x13x5mm^3 CZT detectors (one for spectroscopy and two for counters) in the front. We will replace them with a 2x2 VFG array that has a total volume of 12x12x20 mm^3. The detection efficiency of the new detectors is comparable to the existing device, but the energy resolution will be much better. Because the new detector module is about 15 mm longer than the existing ones in the nanoRaider, we will extend the housing of nanoRaider by 15-20 mm.

In the discussions with FLIR, we learned that interfacing BNL's ASIC with the existing processor in the nanoRaider may be difficult, because the latter is an obsolete component and has very limited input/output ports to new detectors. Because of this, we are considering two approaches right now for the nanoRaider II: (1) we will design a stand-alone detector module with its own digital signal processor. The module will communicate with the nanoRaider II via USB port; and (2) since FLIR is migrating its products to a new FPGA-based platform, we are also considering the design of a detector module that can interface with this new platform. Both approaches are being discussed and evaluated with FLIR right now. We will make a decision soon based on project drivers associated with cost, timing and performance. This recommendation will be provided to NA-241 to seek their input.

(a)



(b)

Figure 7. (a) Photo of the nanoRaider; and (b) Sketch of the proposed nanoRaider II.

4. CONCLUSIONS AND NEXT STEPS

We developed a robust detector module based on the 2x2 array of position-sensitive VFG CZT detectors and BNL-designed readout ASIC for assembling large-area high-energy resolution gamma-ray detection instruments. The array utilizes 6x6x20 mm^3 CZT crystals encapsulated inside ultra-thin polyester shells, and shielding strips placed near the anodes. We demonstrated an energy resolution of 1.0% at FWHM at 662 keV. We showed that the detectors can be grouped into sub-arrays with their cathodes connected to form a single electrode (a common cathode). The signals generated on the common cathodes are then used for electron charge-loss correction in the VFG detectors, and for rejecting incomplete charge-collection events. The position-sensitive side pads were used successfully to correct for material imperfections in CZT detector-grade crystals, which have plagued the technology for many years. We also demonstrated that the use of position-sensitive side pads improves greatly the acceptance rate for useful CZT crystals, and thus the novel design is expected to steadily lower the cost of detectors over the coming few years. Another important feature of the array is the ability to replace individual detectors to match their performances and correct for damage from handling. The detector replacement can be simply slid into the thin-walled honeycomb, and electrically connected via the spring contacts.

The next step emphasizes optimization of the interface of BNL's VFG detector module readout circuit and data-acquisition system to the power supply, software and computer in the nanoRaider, followed by field demonstrations of the new nanoRaider II. These tasks have been proposed for Year 2 (the final year) of the project. During Year 1, we demonstrated an interface by collecting data using BNL's VFG detector array and readout electronics and then loading the data files into FLIR's back-end electronics and software for displaying energy spectra and identifying isotopes. Year 2 focuses on the full integration of the two sub-systems. Through careful analysis of FLIR's nanoRaider system, we discovered that many of the components can be used in the nanoRaider II (e.g., power supply and software for identification), but some of the electronics are of a 10-year vintage and relatively obsolete today. As an example the digital signal processor in the nanoRaider lacks the functionality to adequately handle the signal processing performed by BNL's data acquisition system (DAQ). The easiest and quickest process is to modernize the electronics in the nanoRaider II. A meeting is scheduled in November 2015 to reach a final agreement on those components within the nanoRaider that are nearing the end of their logical lifecycle and may not be appropriate for use in the emerging nanoRaider II. Fortunately, the staff capabilities to modernize the microelectronics in the nanoRaider II exist within the BNL/FLIR team, plus FLIR's commitment of resources to an upgraded instrument grows steadily as new data on the VFG detector module have become available.

5. ACKNOWLEDGEMENTS

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