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Design and Performance Testing of a Linear Array of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors for Uranium Enrichment Measurements

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Design and Performance Testing of a Linear Array of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors for Uranium Enrichment Measurements

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***Abstract*— Arrays of position-sensitive virtual Frisch-grid CdZnTe (CZT) detectors with enhanced energy resolution have been proposed for spectroscopy and imaging of gamma-ray sources in different applications. The flexibility of the array design, which can employ CZT crystals with thicknesses up to several centimeters in the direction of electron drift, allows for integration into different kinds of field-portable instruments. These can include small hand-held devices, compact gamma cameras and large field-of-view imaging systems. In this work, we present results for a small linear array of such detectors optimized for the low-energy region, 50-400 keV gamma-rays, which is principally intended for incorporation into hand-held instruments. There are many potential application areas for such instruments, including uranium enrichment measurements, storage monitoring, dosimetry and other safeguards-related tasks that can benefit from compactness and isotope-identification capability. The array described here provides a relatively large area with a minimum number of readout channels, which potentially allows the developers to avoid using an ASIC-based electronic readout by substituting it with hybrid preamplifiers followed by digitizers. The array prototype consists of six (5x5.7x25 mm^3) CZT detectors positioned in a line facing the source to achieve a maximum exposure area (~10 cm^2). Each detector is furnished with 5 mm-wide charge-sensing pads placed near the anode. The pad signals are converted into X-Y coordinates for each interaction event, which are combined with the cathode signals (for determining the Z coordinates) to give 3D positional information for all interaction points. This information is used to correct the response non-uniformity caused by material inhomogeneity, which therefore allows the usage of standard-grade (unselected) CZT crystals, while achieving high-resolution spectroscopic performance for the instrument. In this presentation we describe the design of the array, the results from detailed laboratory tests, and preliminary results from measurements taken during a field test.**

***Index Terms*—CdZnTe, high-granularity detectors, 3D position-sensitive virtual Frisch-grid detectors, crystal defects, charge-loss correction**

I. INTRODUCTION

Arrays of position-sensitive virtual Frisch-grid (VFG) CdZnTe (CZT) detectors offer high detection efficiency, high energy resolution and a capability to correct response non-uniformity [1,2] which allows the developers to use standard-grade (unselected) material, while retaining high performance. Previously we demonstrated the feasibility of using position-sensitive VFG detectors with thicknesses up to 5 cm and array prototypes consisting of small numbers of detectors coupled with a front-end ASIC resulting in an energy resolution of <1% FWHM at 662 keV after corrections. The second prototype was a 4x4 array with an energy resolution of ~0.9% FWHM at 662 keV after corrections with a position resolution <500µm [3]. The arrays provide performance and functionality comparable to 3D pixilated detectors but at a lesser cost. The potential applications of the arrays, which can be configured into detection planes with different geometrical form factors and dimensions, includes nuclear security, non-proliferation, safeguards, medical imaging, X- and gamma- ray astronomy, and other areas which require spectroscopy and imaging of gamma-ray sources in a wide dynamic range, from ~10 keV up to several MeV. In this work, we present the results from testing a small linear array of six position-sensitive VFG detectors optimized for usage in compact handheld instruments for uranium enrichment measurements, storage monitoring, dosimetry and other safeguards-related tasks.

The virtual Frisch-grid design was originally proposed for a noble gas ionization chamber with a long drift region [4]. This design approach was also adopted for CZT (and some other semiconductor detectors) and was used in CAPture™ [5], hemispherical [6], Frisch-ring [7], and capacitive Frisch-grid [8] detectors. In our detectors, the virtual Frisch-grid shielding effect is achieved by using 4 charge-sensing pads attached to the side surfaces near the anode. These non-contacting, virtually grounded electrodes play similar roles as those used in Frisch-grid [7] and capacitive Frisch-ring [8] detectors. The difference is that we also use the pads for position sensing. The signal readouts from the pads are converted into X-Y coordinates, while the drift time and the cathode-to-anode ratio, C/A, is used to determine the Z coordinate associated with the location of each interaction event.

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II. ARRAY DESIGN

The array consisted of six VFG detectors fabricated from 5x5.7x25 mm^3 CZT crystals acquired from Redlen, Inc. The number of crystals was dictated by size of the detector board, which we adopted from our previous project [3]. The detectors have a simple design. Each crystal, furnished with two gold contacts on the top and bottom surfaces (the anode and the cathode) is encapsulated inside the ultra-thin polyester shell for electrical insulation and mechanical protection of the detector, as we previously described [2]. The shell tightly envelops the crystal and holds in place two CuBe flat-spring contacts on the cathode and the anode faces. Four 5-mm wide pads, cut from copper adhesive foil, are attached over the shell near the anode side.

The detectors were placed vertically on the detector board and gently pressed from the top using the cathode board having the decoupling capacitors and resistors. The anode spring contacts touch the designated anode pads on the board, while the charge-sensing pads are soldered to the board contacts. The signals generated by the incident photons on the anodes, cathodes and 4 position-sensing pads are routed to the corresponding front ASIC inputs (charge-sensitive preamplifiers). The decoupling circuitries are required for reading the signals from cathodes, which are biased at 2500-3000 V. Fig. 1 shows the image of the fully assembled array consisting of 6 detectors squeezed between the cathode and the detector boards.

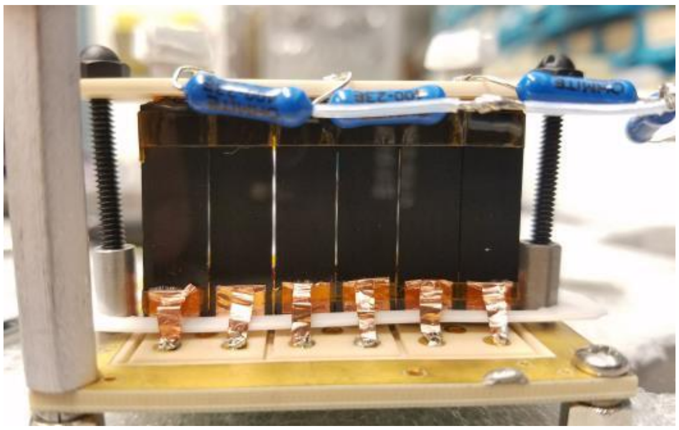

Figure 1. Frontal view of the linear array with one side of pads connected to the PCB board.

The detector board, with the detectors on the front and the multipin connectors on the opposite side, was plugged into the motherboard inside the test box (see Fig. 2). The motherboard also carries the ultra-stable low-voltage passive converters supplying power to the ASIC chips, two analog-to-digital converters (ADCs) for digitizing the peak amplitudes from all channels, the Field Programmable Gate Array (FPGA) for processing the data and communicating with the ASICs and the USB port [10-12].

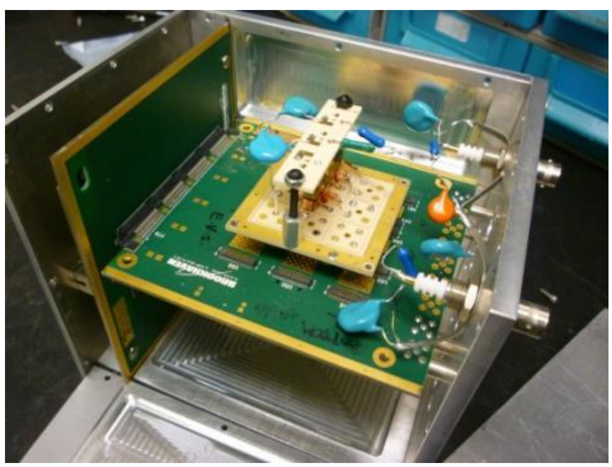

Figure 2. Linear Array mounted to the circuit board inside the aluminum test box.

The AVG1 ASIC used in these measurements [2] allowed us to capture the signals from individual cathodes, anodes and pads which would require 36 readout channels in the case of 6 detector arrays. The ASIC was developed for conventional VFG detectors and employs the same design implemented for H3D pixelated detectors [10-12]. The AVG ASIC has 6 inputs for the negative polarity signals induced on the cathodes and 36 channels with slightly shifted baseline so both polarity signals, which are generated in the pixelated detector, can be captured. These 36 inputs could be used for reading the positive signals generated on the anodes and the negative signals on the pads. The only limitation of the current AVG ASIC is that it has a limited dynamic range for the negative signals. Thus, if the deposited energies are >1 MeV some fraction of the pad signals will be clipped and

the position will not be evaluated correctly. We found that the effect of the pad signal clipping become notable for the gamma rays above 1 MeV. We are currently developing a new ASIC that will have a wider dynamic range for the negative signals.
To calculate the normalized X and Y coordinates, we used the center of gravity method:

$$X = \frac{A_x^1}{A_x^1 + A_x^2} \qquad (7)$$

and

$$Y = \frac{A_y^1}{A_y^1 + A_y^2}, \qquad (8)$$

where A_x^1, A_x^2, A_y^1 and A_y^2 are signal amplitudes measured from the pairs of opposite pads along the X and Y directions. For the Z coordinate we used the C/A ratio. As we described previously [2], this approximation is sufficient for correcting the response non-uniformity. The measured X-Y-Z values constitute a configuration space, which correlates to the spatial variations in the measured anode signals. Thus, by segmenting the X-Y-Z space into small voxels we can sort out the signals corresponding to each of them and apply a charge-loss correction accordingly using a 3-dimensional correction matrix (CM) generated during calibration [2]. For comparison purposes, we also apply drift-time corrections, along the Z direction, which are called 1D corrections.

Our main goal was to evaluate the temperature stability of the array in the field under real conditions. To protect the detector and electronics from the moisture that can easily condense during the temperature cycling, we fabricated a special plastic enclosure, made of VeroBlackPlus RGD875, that hermetically seals the entire system: the detector and electronics (see Fig. 3). The enclosure also allowed us to control the temperature in both the lab and field environments. For this purpose, we use a massive aluminum flange to seal the enclosure and dissipate heat. When the test box is placed inside the enclosure the flange touches a copper block firmly bolted to the backside cover of the test box used for conducting the heat generated by the readout electronics and FPGA. Considering the high-temperature conditions expected for the field measurements, we attached a commercial 40W Peltier cooler to the outer flange to maintain a reasonably stable temperature, +/-1 °C, for the detectors. As we show next, he main temperature instability does not come from the ASIC, but the temperature dependence of the charge collection efficiency of the detectors was found to be significant enough to affect the energy resolution if the temperature was not kept stable within ~1.0-1.5 degrees. Using an environmental enclosure and the cooler, we measured the detector responses at different temperatures between 15 and 40 °C. We found that the detectors could operate at a temperature close to 30 °C without significantly affecting the energy resolution. Above 30 °C the resolution degrades and approaches 2% at 662 keV at 40 °C. We took only a few measurements at temperatures above 35 °C because, as we discovered, some of the detectors kept at high bias for several days at elevated temperatures suddenly became leaky and needed to be replaced. To avoid damaging the detectors, we took fewer measurements at temperatures above 35 °C. We note that we fabricated and used such a bulky environmental enclosure for the entire test box as it was the simplest (low cost) solution in preparation for the field tests. In the actual instrument, only the detectors and front-end electronics require environmental protection. Furthermore, as is seen in Fig. 3, the enclosure has specially designed slots for attaching the shielding tungsten plates and the front tungsten window, if necessary.

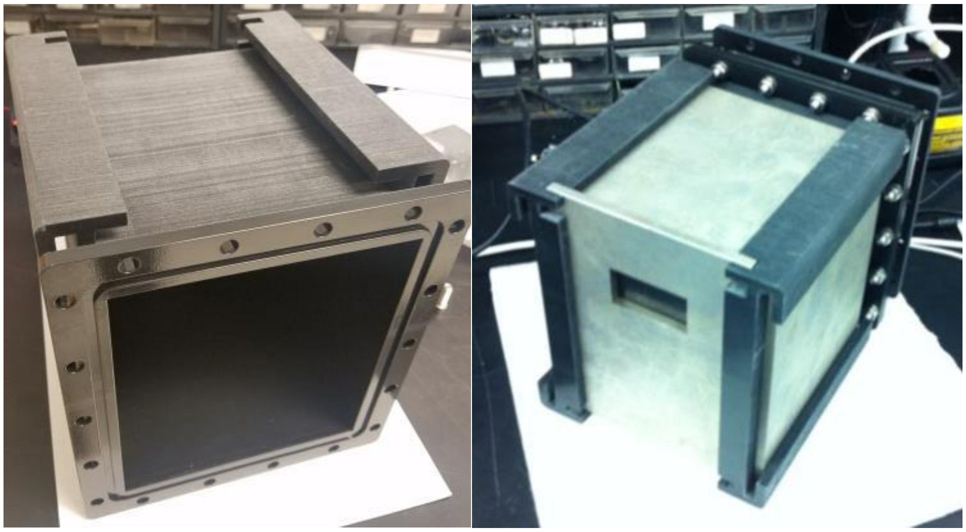

Figure 3. (a) A 3D printed plastic waterproof enclosure. (b) Plastic waterproof enclosure with tungsten plates surrounding it.

III. TEST RESULTS

The calibration for each detector was done at several temperatures and using several gamma-ray lines. For calibration we collected the pulse-height spectra from known gamma-ray sources and used them to evaluate the channels' baselines, gains and the 3D correction matrixes for each detector. For presenting the results, we collected additional data sets (not used for calibration) to avoid any correlation effect. Fig. 4 shows 3 rows of the spectra: after applying 3D corrections (top), 1D (middle) correction only, and the raw data (bottom) measured from a fresh fuel rod, ~93% ^{235}U, located ~40 cm from the detector plane. The measurements were taken at a temperature of ~19 °C. The same cathode bias of 2750 V was applied to all detectors. Fig. 5 shows the combined spectra after 3D and 1D corrections, correspondingly. The energy resolution was found to be 1.9 % FWHM at 186 keV, which is very good for such big detectors with an area of 5x7 mm^2. If we only apply a 1D correction, the energy resolution is only ~3%. We note that the electronic noise (due to leakage current) is the major factor limiting the energy resolution of these detectors.

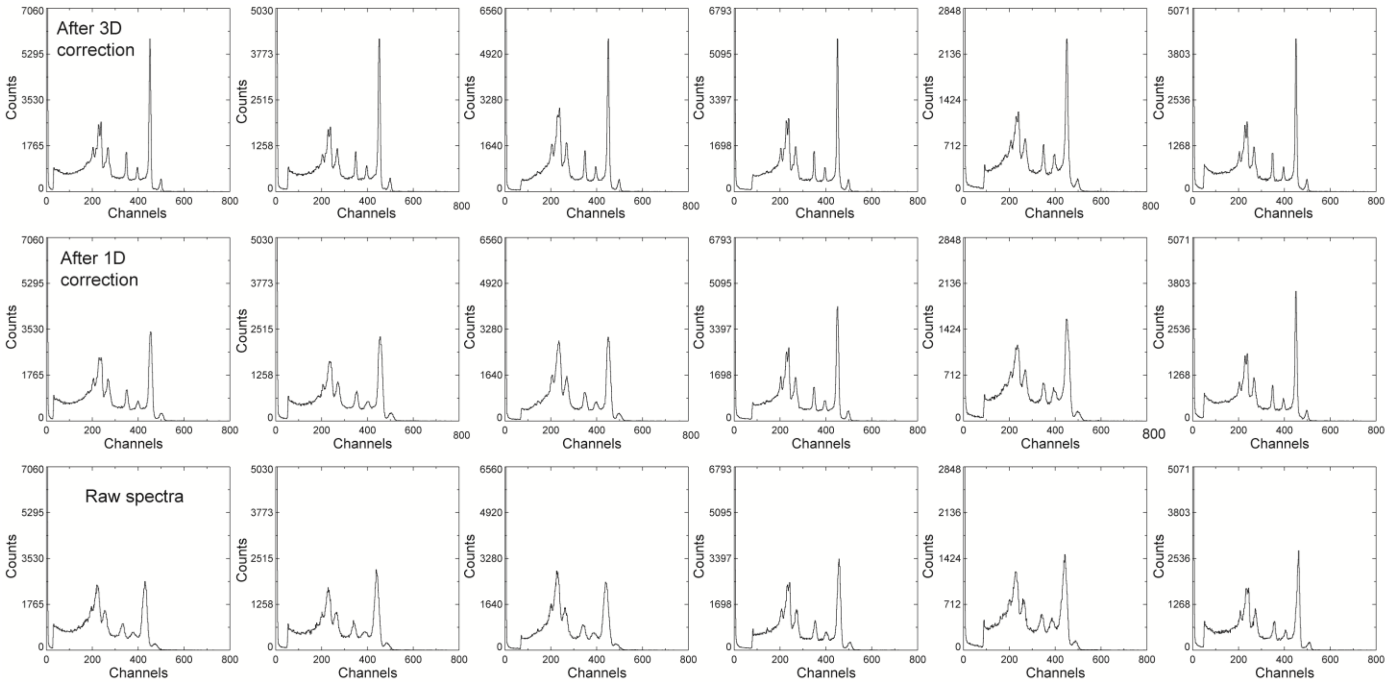

Figure 4. The pulse-height spectra measured at 19°C and corrected using calibration data measured at the same temperature.

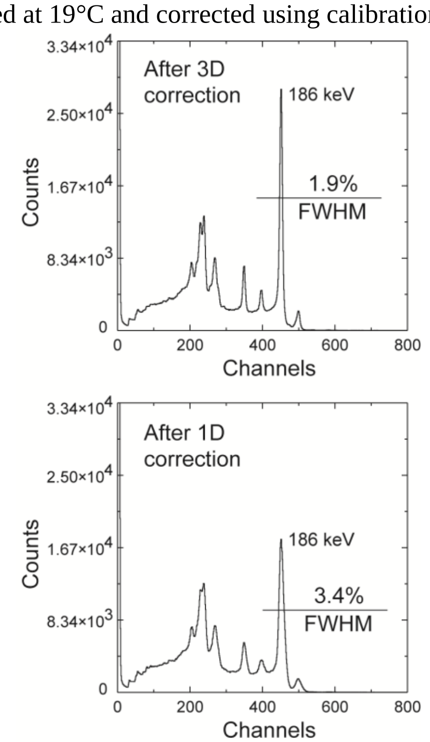

Figure 5. The combined spectra, for ^{235}U, from all 6 detectors after (top) and before (bottom) 3D corrections.

In preparation for the field test, the detectors were disassembled before being transported and reassembled at Savannah River National Laboratory (SRNL). The whole detector array was calibrated using the standard U-sources with a range of enrichments. We also used the same data to generate the new calibration files for detector baselines and gains. As an example,

Fig. 6 shows the pulse-height spectra measured from a NIST-446 source at SRNL. The energy resolution is in the range 1.7-2.2 FWHM % at 186 keV.

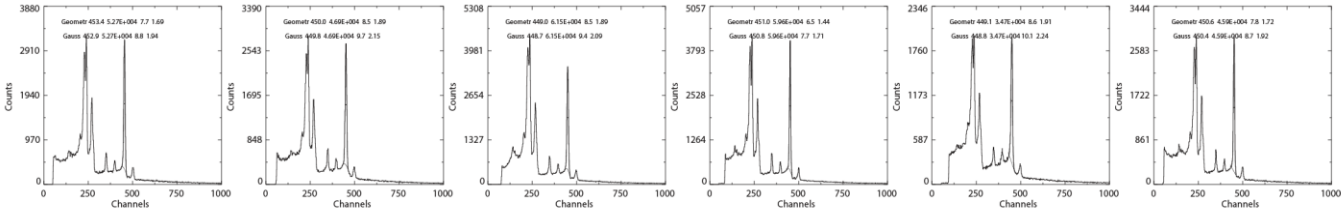

Figure 6. The pulse-height spectra measured from a NIST-446 source at SRNL.

The field test was carried out at the Westinghouse Fuel Fabrication Facility (WFFF) in Columbia, South Carolina. During the field measurements we kept the temperature of the detectors in the range 18-19°C. All detectors worked well without showing any degradation over time. We did not observe any effects related to the outside humidity and temperature. The outside temperature was in the range of 28-35°C (early in the morning and midday) and humidity was nearly 90%. Several UF_6 cylinders were measured at the same location as shown in Fig. 7 with minor readjustments as casks were switched around.

Fig. 8 shows an example of the spectra measured from one of the UF_6 cylinders. The first row contains the 3D corrected spectra. The second row contains the spectra after the drift-time corrections (1D correction). The third row shows the raw data. Recalibrating the detector gains using the collected data we were able to slightly improve the spectra shown in the fourth row. The combined data is shown in Fig. 9 with the respective FWHM for each case. The improvement in resolution is shown to be upwards of 1%. Overall, the data for the cylinders measured at the WFFF can be analyzed to develop the CZT detector array into an enrichment meter device. The results of this analysis are shown in Fig. 10 where the count rate values for the 185.7-keV gamma ray are plotted as a function of the declared enrichment. The graph shows that the trend is quite linear with a strong deviation at the cylinder with a declared value of 4.4% enrichment. This low count rate behavior was also observed in the measurements performed earlier in the year.


Figure 7. Placement and measuring point of UF_6 cask with the linear array detector. The rightmost image displays the changing of casks in between measurements.

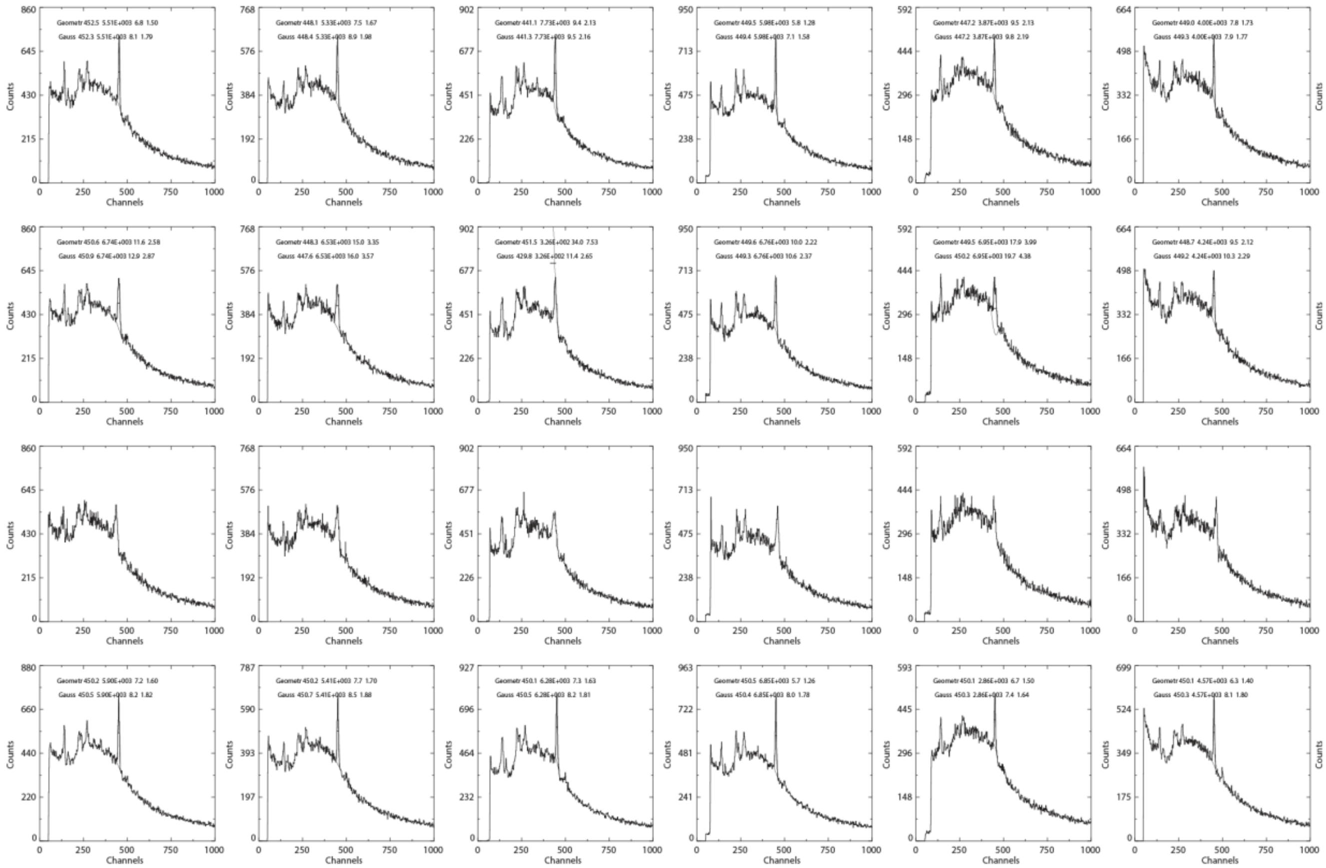

Figure 8. Spectra measured from one of the UF_6 cylinders. The first row contains the 3D corrected spectra. The second row contains the spectra after the drift-time corrections (1D correction). The third row shows the raw data. Recalibrating the detector gains using the collected data we were able to slightly improve the spectra (fourth row). The collection time was 15 minutes.

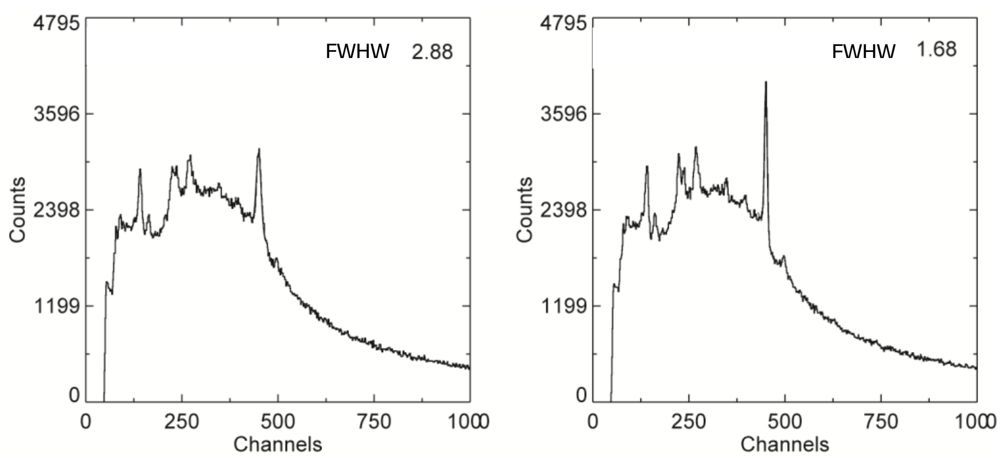

Figure 9. Combined spectra from the UF_6 cylinder data shown in Fig.8. The leftmost image shows the raw spectra with an approximate resolution of 2.88%. The rightmost image shows the 3D corrected spectra with an improved resolution of approximately 1.68%.

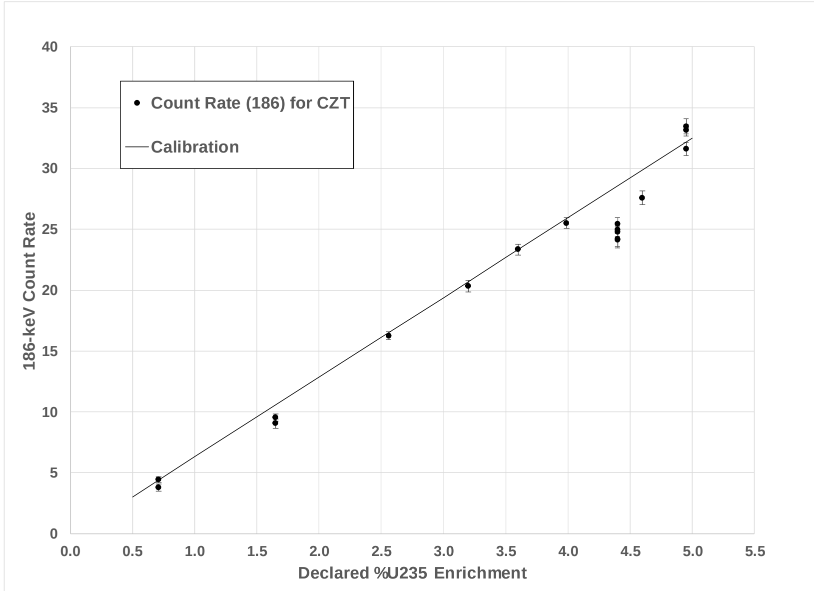

Figure 10. Measured count rate values for the 185.7-keV gamma ray as a function of the declared enrichment.

IV. CONCLUSIONS

We investigated the performance of a linear array composed of six position-sensitive VFG detectors optimized for usage in compact handheld instruments. Our main goal was to evaluate the array under realistic field conditions. The array responses were measured at different temperatures between 15 and 40 °C in a controlled environment. The detectors could operate at a temperature close to 30 °C without significantly affecting the energy resolution. Above 30 °C the resolution degrades and approaches 2% at 662 keV at 40 °C. The results also showed that the correction matrix, used to perform the 3D corrections is independent of temperature over this range. Furthermore, the results illustrate the importance of temperature stability for the detectors within +/-1 degree °C. Lastly, it is optimal to use the correction matrix generated at a temperature that is close to or lower than the temperature at which measurements will be taken. After applying corrections, the energy resolution was found to be 1.9 % FWHM at 186 keV. At a higher energy, the resolution can be as good as 0.8 % at 662 keV. These resolution improvements can significantly enhance the performance of compact handheld instruments.

The field test was carried out at a fuel fabrication facility where the outside temperature was in the range of 28-35° and humidity was nearly 90%. Several UF_6 cylinders were measured at the same location (relative to the cylinder) and the temperature of the detectors was kept in the range 18-19°C. All detectors worked well without showing any degradation over time. The combined spectra measured from one cask showed a raw FWHW resolution of 2.88% and after 3D corrections it was improved to 1.68%. The preliminary results from these field test measurements show the capability of a CZT detector array to be developed and used as an enrichment meter device.

REFERENCES

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REFERENCES

[1] A. E. Bolotnikov, G. S. Camarda, Y. Cui, G. De Geronimo, J. Fried, A. Hossain, K. Lee, G. Mahler, M. Maritato, M. Marshall, M. Petryk, U. Roy, E. Vernon, G. Yang and R. B. James, “Use of high-granularity position sensing to correct response non-uniformities of CdZnTe detectors”, Appl. Phys. Lett. 104, p. 263503, 2014.

[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”, Appl. Phys. Lett. 108, p. 093504 (2016).

[3] L. Ocampo Giraldo, A.E. Bolotnikov, G.S. Camarda, S. Cheng, G. De Geronimo, A. McGilloway, J. Fried, D. Hodges, A. Hossain, K. Ünlü, M. Petryk, V. Vidal, E. Vernon, G. Yang, R. B. James, "Arrays of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors: Results From a 4x4 Array Prototype," in IEEE Transactions on Nuclear Science, vol. 64, no. 10, pp. 2698-2705, Oct. 2017.

[4] V. V. Dmitrenko, A. C. Romanuk, Z. M. Uteshev, and V. K. Chernyatin, “Spectrometric applications of an ionization-type drift chamber”, Pribory I Tekhnika Eksperimenta, vol. 1, pp. 51-53, 1982. Translation in Instruments and Experimental Techniques (USA), vol. 25, no. 1, pp. 50-53 (1982).

[5] K. Parnham, C. Szeles, K. G. Lynn, and R. Tjossem, "Performance Improvement of CdZnTe Detectors Using Modified Two-Terminal Electrode Geometry," in Hard X-ray, Gamma-Ray and Neutron Detector Physics, Proceedings of SPIE Vol. 3786, pp. 49-54, 1999.

[6] C. Szeles, D. Bale, J. Grosholz, Jr., G. L. Smith, M. Blostein, and J. Eger, "Fabrication of High Performance CdZnTe Quasi-Hemispherical Gamma-ray CAPture™ Plus Detectors", Hard X-Ray and Gamma-Ray Detector Physics VIII, edited by Larry A. Franks, Arnold Burger, and Ralph B. James, Proceedings of SPIE Vol. 6319 (SPIE, Bellingham, WA, 2006).
[7] D. S. McGregor and R. A. Rojeski, "High-resolution ionization detector and array of such detectors", US Pat. 6175120, 2001.
[8] G. Montemont, M. Arques, L. Verger, and J. Rustique, "A Capacitive Frisch Grid Structure for CdZnTe Detectors", IEEE Trans. Nucl. Sci. 48, pp. 278-281, 2001.
[9] 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, vol. 86, no. 7, 2015.
[10] G. De Geronimo, E. Vernon, K. Ackley, A. Dragone, J. Fried, P. O'Connor, Z. He, C. Herman, and F. Zhang, "Readout ASIC for 3-D position-sensitive detectors," IEEE Trans. Nucl. Sci., vol. 55, no. 3, pp. 1593–1603, 2008.
[11] E. Vernon, K. Ackley, G. De Geronimo, J. Fried, P. O'Connor, Z. He, C. Herman, and F. Zhang, "ASIC for high rate 3-D position sensitive detectors," IEEE Trans. Nucl. Sci., vol. 57, no. 3, pp. 1536–1542, 2010.
[12] F. Zhang, C. Herman, Z. He, G. De Geronimo, E. Vernon, and J. Fried, "Characterization of the H3D ASIC readout system and 6.0 cm^3 3-D position sensitive CdZnTe Detectors," IEEE Trans. Nucl. Sci. 59, pp. 236-242, 2012.