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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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DISCLAIMER

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

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Introduction

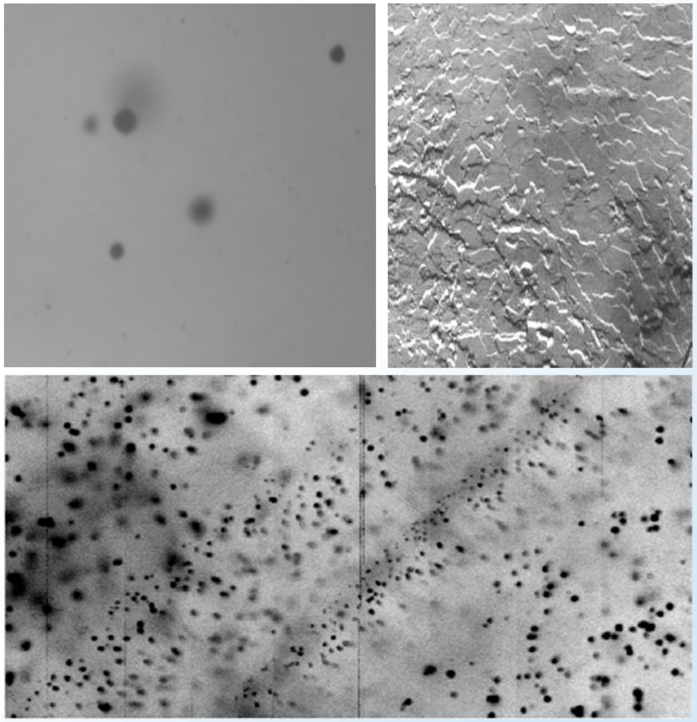
- Presentation is focused on the design and testing of the array.
- The flexibility of the array design allows for integration into different kinds of field-portable instruments.
- These can include small hand-held devices, compact gamma cameras and large field-of-view imaging systems.
- There are many 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 linear array has been optimized for the low-energy region, 50-400 keV gamma-rays, which is principally intended for incorporation into hand-held instruments to be used as an enrichment meter device.

Commercial CZT

- CZT crystals are very costly!
  High-quality and relatively "defect-free" CZT crystals are difficult to produce.

- Several types of defects still are present in today's commercial CZT material:
  - Impurities-related trapping centers
  - Telluride inclusions
  - Sub-grain boundaries

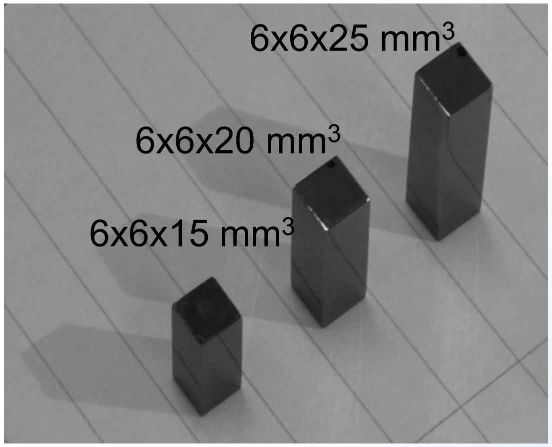
- It is hard for vendors to specify contents of defects in their crystals because they cannot reveal them directly; this is the major problem for vendors and users.



X-ray Diffraction Topography

Position-sensitive virtual Frisch-grid detectors

- Majority of CZT detectors used for gamma-ray spectroscopy operate as virtual Frisch-grid devices (3-terminal, CAPture, hemispherical, Frisch-ring, capacitive Frisch-grid, pixelated…)
- The main distinguishing feature of our detectors is their geometry; we use bar-shaped crystals with a large aspect ratio and small, ~6x6 mm^2, cross-section
- Arrays of such bars can substitute for big CZT crystals which are expensive and difficult to produce
- In contrast, the bars can be produced economically, using 6-7 mm thick CZT wafers, which are mass produced by vendors for medical and baggage scanners

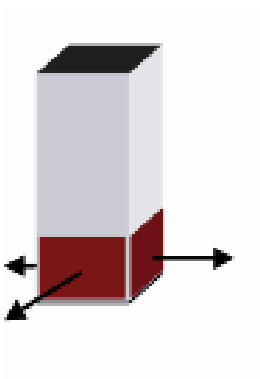


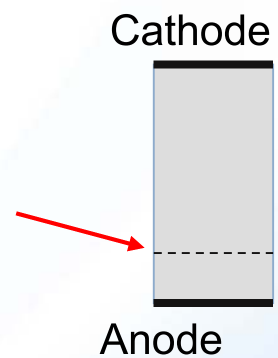
CZT bars cut from the standard mass-produced production CZT wafers

Such bars are available from eV-Products Inc. and Redlen Technologies Inc.

Operation principle of position-sensitive virtual Frisch-grid detectors

- Small area, 6x6 mm^2, but long, up to 5 cm, CZT crystals (bars)
- 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.
- C/A ratio gives independent estimates for Z.
- Virtually grounded pads produce the Frisch-grid effect (as if a real grid was placed inside the detector)

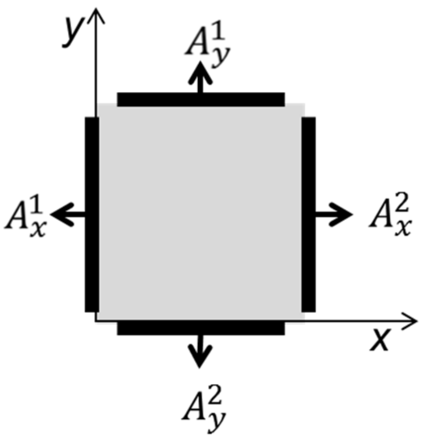




We use position information to correct the response non-uniformities caused by crystal defects

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)

Adding position-sensitive pads to conventional VFG design



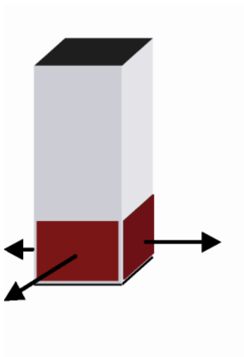
- In a simplest approach we use the center of gravity method to evaluate X-Y coordinates
- This approach causes image distortion, especially near the edges
- A better approach is to use pad response functions
- In this case signals from only two orthogonal pads can be used to evaluate position

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

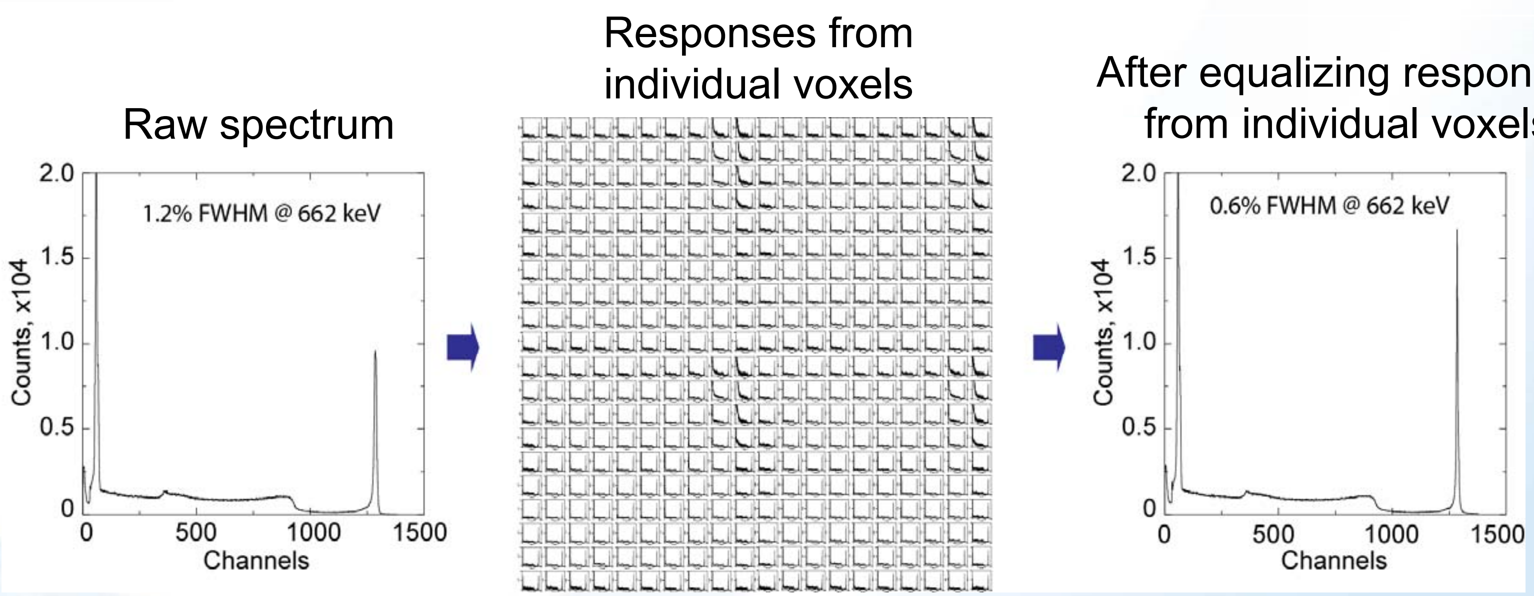
$$Y = \frac{A_y^2}{A_y^1 + A_y^2}$$

- The main advantage of position-sensitive VFG detectors is their ability to correct response non-uniformity caused by crystal defects
- This allows for using less expensive, unselected (standard grade) crystals to reduce cost and improve instrument performance

Position-sensitive virtual Frisch-grid detectors (CZT drift detectors)



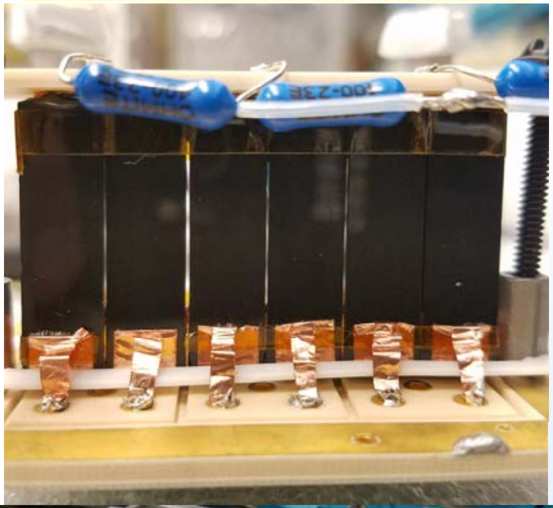
- Position information allows us to virtually segment a detector into small voxels and equalize responses from each voxel
- A 3D correction matrix (lookup table) is generated during calibration and used to correct measured signals

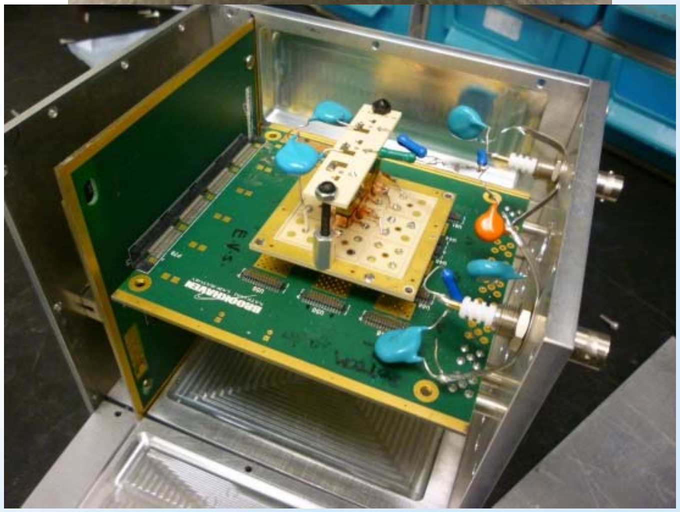


Linear Array Design

- The array consisted of six VFG detectors fabricated from 5x7x25 mm^3 CZT crystals acquired from Redlen, Inc.
- The detectors have a simple design:
  - Two gold contacts on the top and bottom surfaces (the anode and the cathode).
  - Encapsulated inside the ultra-thin polyester shell for electrical insulation and mechanical protection of the detector.
  - 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

Linear array prototype of 5x7x25 mm^3 detectors

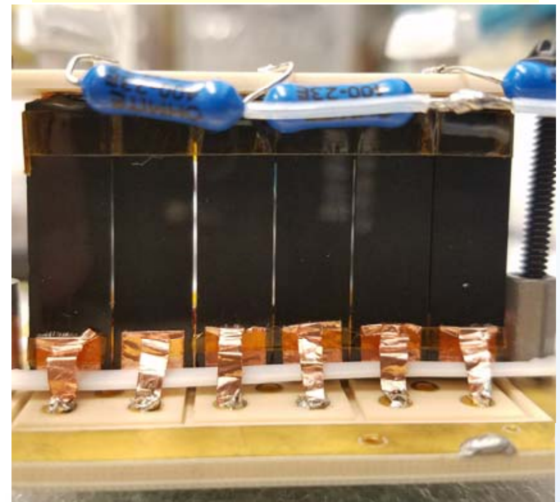


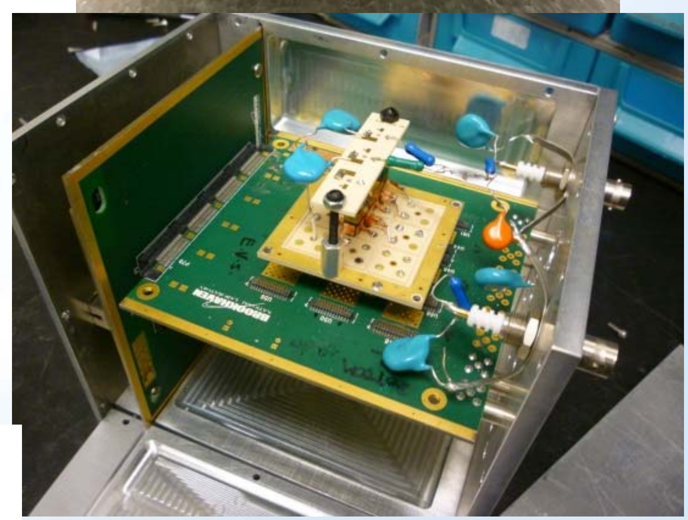


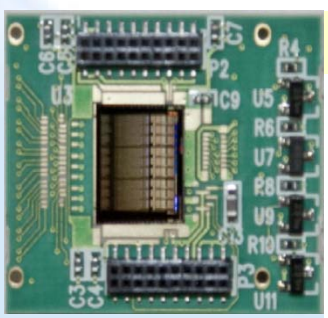
Linear Array Design & Set Up

- The signals generated by the incident photons on the anodes, cathodes and 4 position-sensing pads are routed to the corresponding front ASIC inputs
- Biased at 2500-3000 V.
- The detector board was plugged into the motherboard inside the test box.
- The motherboard also carries:
  - 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
  - Field Programmable Gate Array (FPGA) for processing the data and communicating with the ASICs and the USB port

Linear array prototype of $5x7x25\ mm^3$ detectors





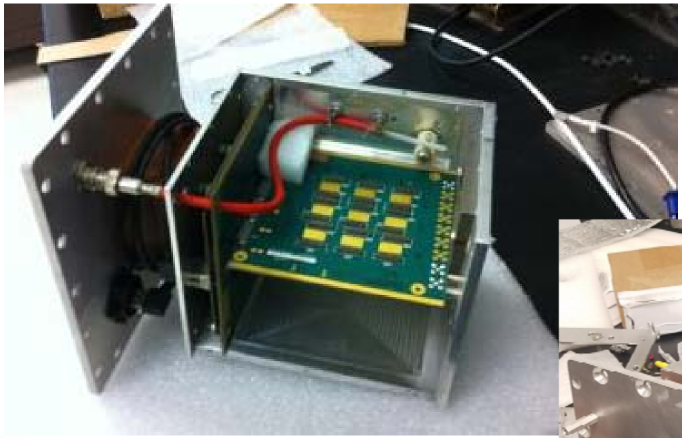


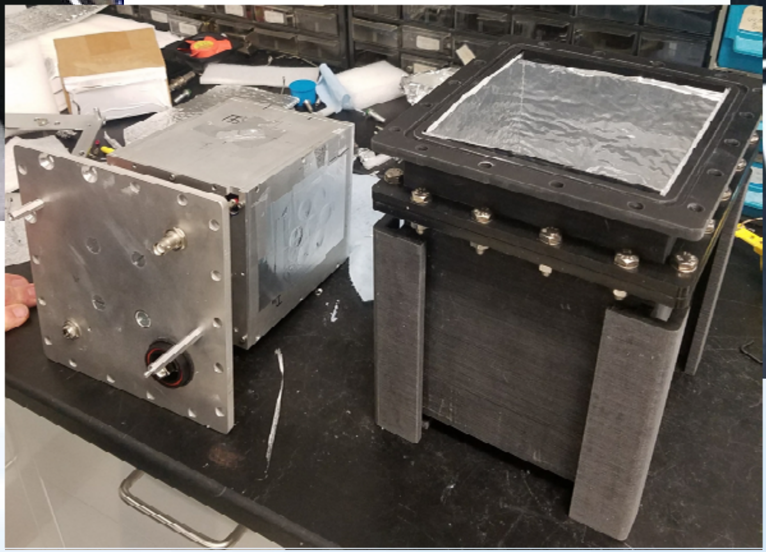
ASIC and ASIC board

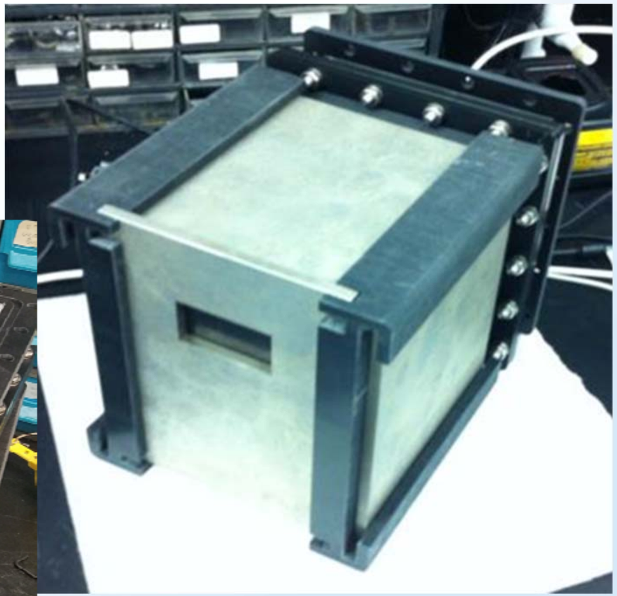
Current ASIC (AVG1 designed by E. Vernon): 36 anode and 9 cathode inputs
currently developing a new ASIC with a wider dynamic range for the negative signals.

Preparing for the field test

- Designed a new case to seal the detector and protect from humidity.
- Added aluminum flange to seal the enclosure and dissipate heat
- The flange touches a copper block bolted to the backside cover of the test box to conduct the heat generated by the readout electronics and FPGA.
- Added a 40W Peltier cooler and a fan to further control temperature.
- Added tungsten shielding to reduce background.





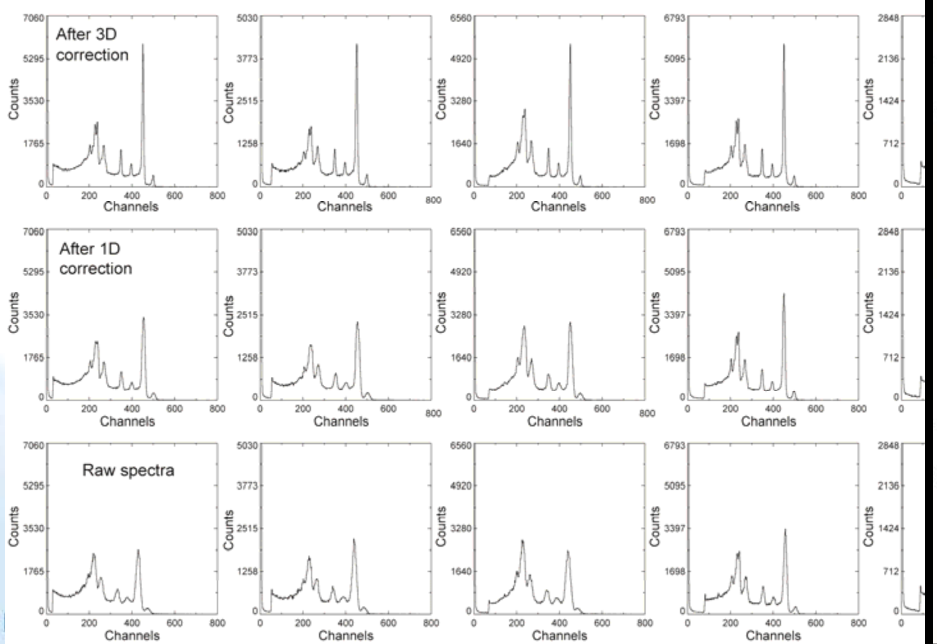


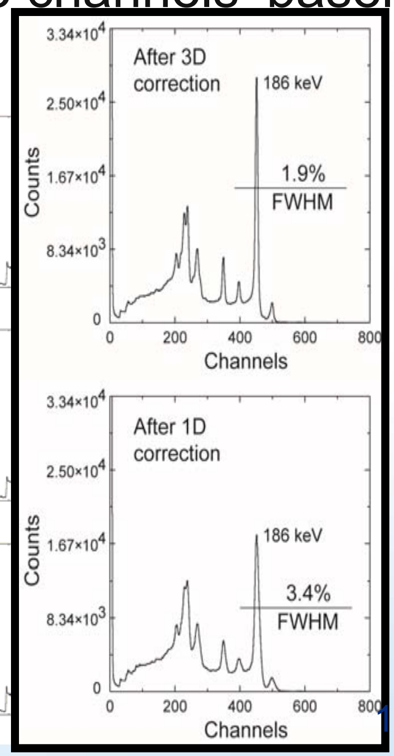
Laboratory Temperature Tests

Using an environmental enclosure, we measured the detector responses at different temperatures between 15 and 40ºC.

We found that the detectors could operate at a temperature close to 30ºC without significantly affecting the energy resolution. Above 30ºC the resolution degrades and approaches 2% at 662 keV at 40ºC.

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 matrices for each detector.





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.

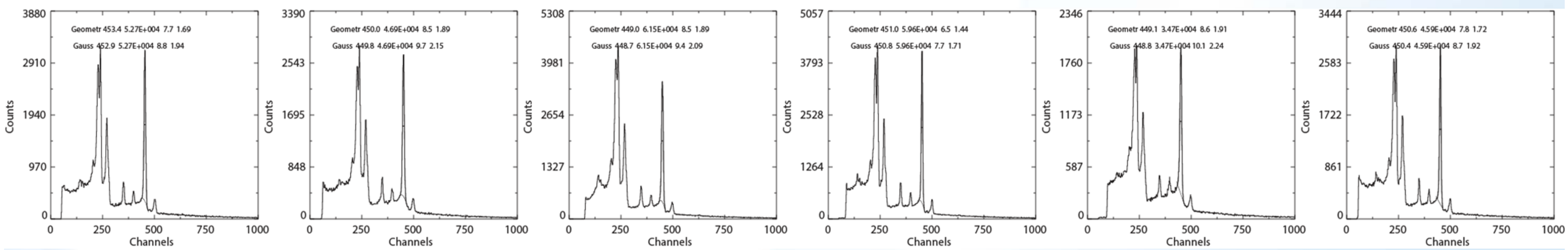
The measurements were taken at a temperature of ~19ºC. The same cathode bias of 2750 V was applied to all detectors.

Field Test Preparations

Detectors were disassembled before being transported and reassembled at Savannah River National Laboratory.

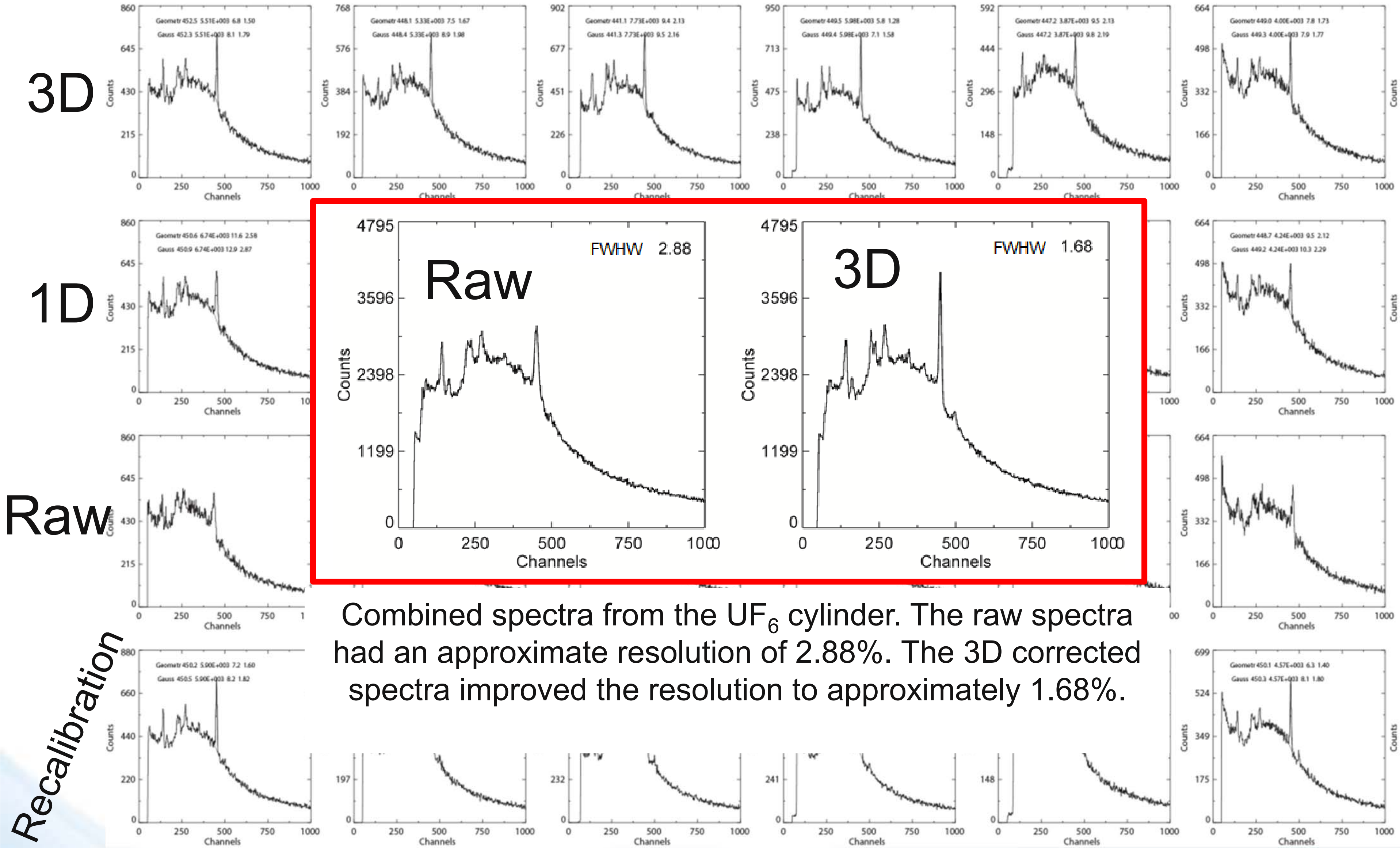
The whole detector array was calibrated at SRNL using the NIST standard U-sources with a range of enrichments. The energy resolution is in the range 1.7-2.2 FWHM % at 186 keV.

Used this data to generate the new calibration files for detector baselines and gains.



Field Test

- Conducted at Westinghouse Fuel Fabrication Facility (Columbia, South Carolina).
- Temperature of the detectors was in the range 18-19ºC.
- All detectors worked well without showing any degradation over time.
- No effects related to the outside humidity and temperature were observed.
- The outside temperature was in the range of 28-35ºC (early in the morning and midday) and humidity was nearly 90%.
- Several UF6 cylinders were measured at the same location relative to the detector array.

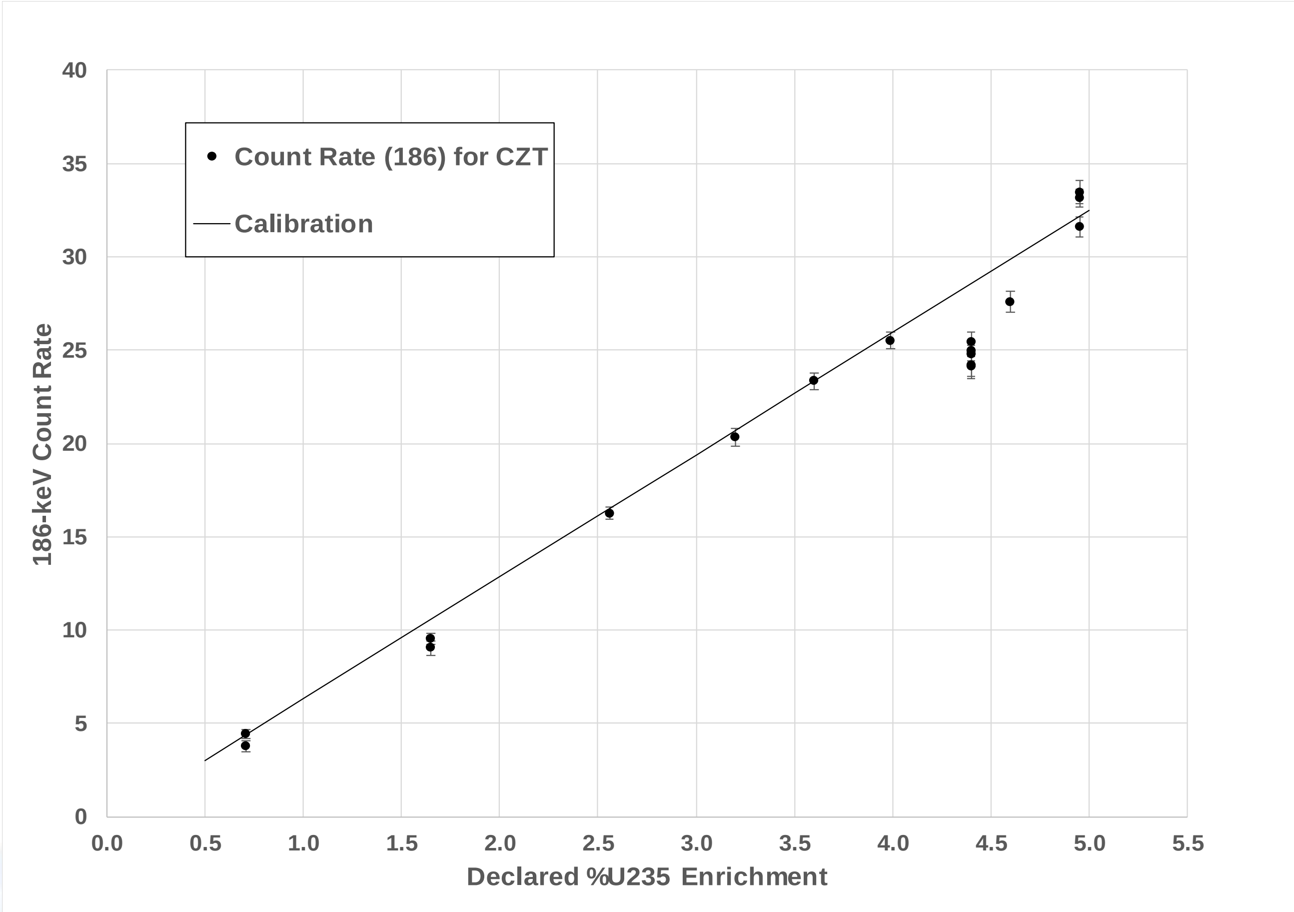


Combined spectra from the UF_6 cylinder. The raw spectra had an approximate resolution of 2.88%. The 3D corrected spectra improved the resolution to approximately 1.68%.

Spectra measured from one of the UF_6 cylinders. The collection time was 15 minutes.

Count Rate vs. Declared Enrichment

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



Conclusion

- We investigated the performance of a linear array composed of six position-sensitive VFG detectors optimized for usage in compact handheld instruments
- The detectors could operate at a temperature close to 30ºC without significantly affecting the energy resolution.
- All detectors worked well without showing any degradation over time.
- The combined spectra measured from one cylinder showed a raw FWHM 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.

Acknowledgements

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Any Questions?