



U.S. DEPARTMENT
of **ENERGY**

X-ray and Gamma-Ray Detector Capabilities at BNL

From detector materials to readout, calibration, and fieldable
systems

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Mirion Connect 2026



@BrookhavenLab

A brief note before we start

I am giving this presentation on behalf of the BNL Instrumentation team.

I joined the Instrumentation Department full time in January, so this is also an opportunity for me to share — with great appreciation — the breadth and quality of the work that the team has been developing across detector materials, sensors, readout, calibration, and integrated systems.

I also sharing here contact for the key people leading the work in these areas.

BNL Instrumentation: the capability platform

Part 1

BNL Instrumentation: from concepts to fielded systems

Full-lifecycle instrumentation

BNL can take detector concepts from initial R&D through prototyping, characterization, production engineering, deployment, and operation of real systems.

Why this matters

- Faster iteration across materials, sensors, readout, and packaging.
- Feedback from tests and fielded systems into the next detector generation.
- Accountability across the full path from idea to deployed instrument.

Relevant to Mirion

- New detector materials and architectures.
- Low-noise electronics and waveform readout.
- Calibration, algorithms (AI), and response correction.
- Environmental and radiation testing.

Detector systems across energy scales and environments

Breadth

- Optical, near-IR, x-ray, gamma-ray, neutron, and RF instrumentation.
- Ground, underground, accelerator, reactor, and space applications (extreme environments typical for nuclear reactors).
- Sensors, readout, mechanics, thermal control, firmware, and data processing.

This talk

- Gamma-ray semiconductors: CZT, TlBr, CsPbBr₃.
- Soft x-ray photon science with skipper CCDs.
- High-Z detectors for direct x-ray imaging and CMOS/ASIC integration.

Connecting theme

BNL's value is the ability to connect material behavior, sensor architecture, readout, calibration, and deployment environment.

BNL platform for x-ray and gamma-ray detector development

- Long-running room-temperature semiconductor detector program.
- Materials characterization at NSLS-II and CFN.
- Radiation-effects studies with charged-particle and neutron beams, including NSRL.
- Low-noise electronics and microelectronic integration.



Center for Functional Nanomaterials



Charged-particle beam



Talk map: three parts

1. BNL platform

Full-cycle detector and instrument development: materials, devices, electronics, calibration, packaging, and test facilities.

2. Gamma detectors

Mostly Aleksey's CZT/TIBr/VFG material: room-temperature spectroscopy, imaging arrays, defects, and field examples.

3. Soft x-rays

Mostly Gio's material: skipper CCDs for photon science, TIBr direct-conversion imaging, and pixel/ASIC readout.

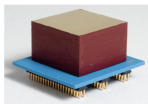
Gamma-ray detectors: room-temperature semiconductors and VFG arrays

Part 2

Room-temperature semiconductor detectors

- High-Z, high-density materials enable efficient gamma-ray absorption.
- Wide bandgap and high resistivity support room-temperature operation.
- CZT is mature; TlBr and lead-halide perovskites are promising emerging directions.
- Main practical barrier: crystal defects and response non-uniformity.

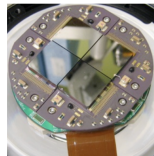
H3D CZT detector



eV CZT crystals



NuStar focal plane detector



TlBr detectors from RMD



A 3×3×6mm³ RMD fabricated CsPbBr₃



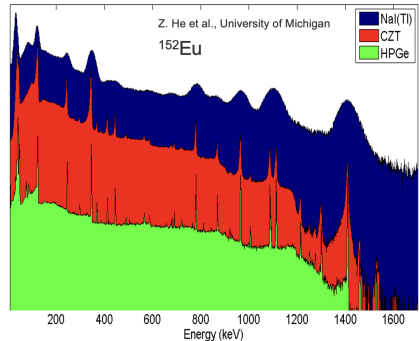
Neusoft Medical Systems

SPECT system Redlen CZT

BNL contact: Aleksay Bolotnikov

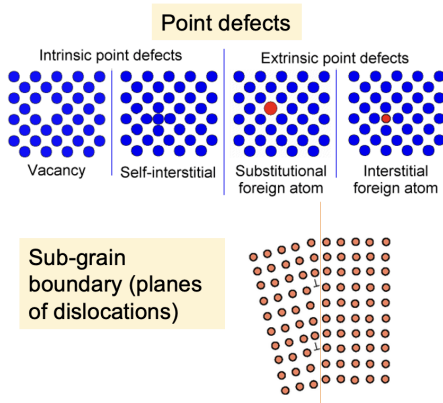
Performance context: CZT between scintillators and HPGe

- HPGe remains the resolution benchmark, but requires cryogenic operation.
- CZT can approach HPGe-like spectroscopy while operating near room temperature.
- High-quality CZT systems reach about 1% FWHM at 662 keV; best selected devices are below that.
- Practical performance space between scintillators and HPGe.



Core challenge: defects limit practical instruments

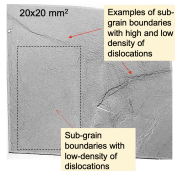
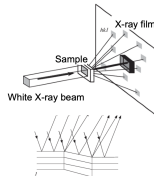
- Point defects, dislocations, sub-grain boundaries, and inclusions degrade energy and position resolution.
- Vendor prescreening is limited, so material selection and device-level correction matter.
- BNL can identify defects, map detector response, and correct residual non-uniformity.



BNL characterization: linking defects to response

- IR transmission imaging reveals Te inclusions.
- X-ray diffraction topography reveals sub-grain boundaries and dislocation networks.
- High-spatial-resolution x-ray mapping links local defects to detector response.
- These tools reduce risk in detector procurement and integration.
- BNL played critical role in improving CZT and TlBr by providing feedback to the vendors (Redlen, eV, RMD)

Schematics of the White-Beam X-ray Diffraction Topography setup at NSLS II

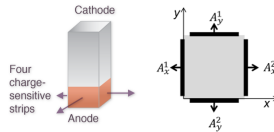


CZT sample characterized for the NuStar focal plane CZT detector.

Position-sensitive virtual Frisch-grid detector design

- Bar-shaped crystals with large aspect ratio.
- Virtual Frisch-grid effect provides electrostatic shielding and improves spectroscopy.
- Position-sensitive pads provide 3D event information.
- Low channel count makes large-volume arrays attractive.

Schematic of PS-VFG detector



Center-of-gravity formulas

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

10x10x32 mm³

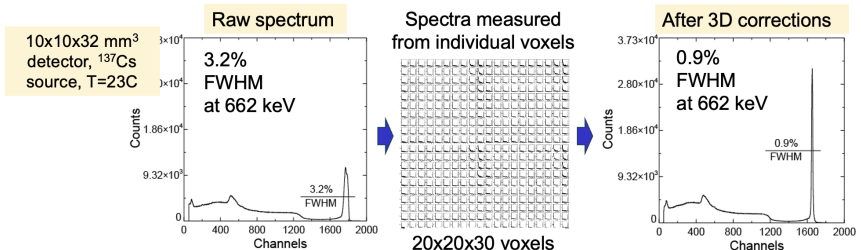


5x5x12 mm³



Key differentiator: 3D correction of non-uniformity

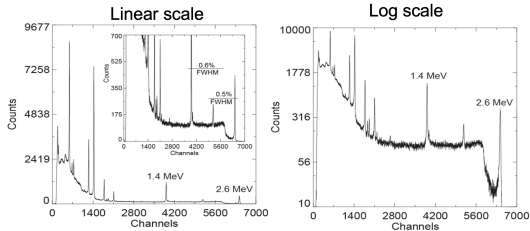
- 3D position information lets the detector volume be divided into voxels.
- Each voxel response can be equalized before summing events.
- This can recover strong spectroscopy from standard-grade material.
- Corrections can be done in coordinates or directly in signal-amplitude space.



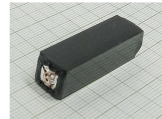
Large-volume CZT bars: high efficiency with few channels

- Example: $10 \times 10 \times 32 \text{ mm}^3$ CZT detector

U-232 source through 5-mm lead, bias is 3700V
Gamma ray lines with energies up to 2.6 MeV



$10 \times 10 \times 32 \text{ mm}^3$



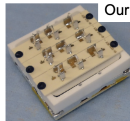
- 3 cm^3 detector requires 5 readout channels only 3D position resolution is $< 1 \text{ mm}$
- High detection efficiency for gamma rays

A. Bolotnikov, J. MacKenzie, E. Chen, F. J. Kumar, S. Taherion, G. Carini, G. De Geronimo, J. Fried, Kihyun Kim L. Ocampo Girado, E. Vernon, R. B. James, "Performance of $8 \times 8 \times 32$ and $10 \times 10 \times 32 \text{ mm}^3$ CdZnTe position-sensitive virtual Frisch-grid detectors for high-energy gamma-ray cameras", Nucl. Instr. Meth. A969, p. 164005, 2020.

Array integration: from detector bars to instruments

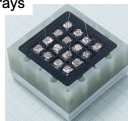
BNL has modular CZT bar arrays, read out with BNL ASICs and commercial waveform systems. Performance demonstrated over a broad energy range: below 200 keV through MeV gamma rays.

6x6 array of 5x5x15 mm³ detectors

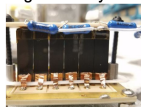


Our first arrays

4x4 array of 6x6x20 mm³ detectors



Linear array of 6 5x7x25 mm³ detectors for low energy gamma rays

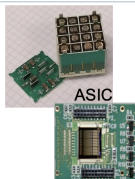


2x2 array of 6x6x20 mm³ detectors for handheld instruments



Second generation

NASA crate of 4x4 6x6x20 mm³ detectors readout by BNL's AVG2 ASIC



10-crate array for AMEGO and [GECCO](#) telescopes prototypes currently under testing by NASA

BNL system



IDEAS GDS-100 system



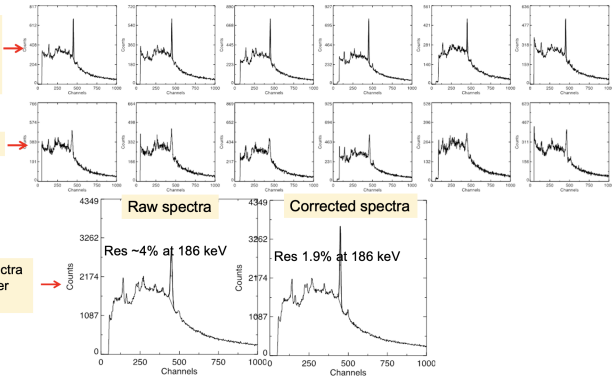
Application example: uranium enrichment measurement

- Linear CZT array deployed for UF_6 cylinder measurements.
- Environmental packaging included shielding and thermal control.
- 3D corrections improved the 186 keV line from about 4% raw to 1.6–2.0% FWHM.
- Strong example of detector physics translating into safeguards instrumentation.

After 3D corrections
Resolution: 1.6-
2.0% FWHM at 186
keV

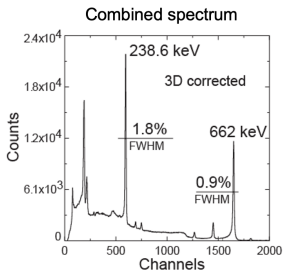
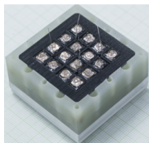
Raw data

Combined spectra
before and after
corrections



Spectra measured with the 4x4 array from 232U and 137Cs

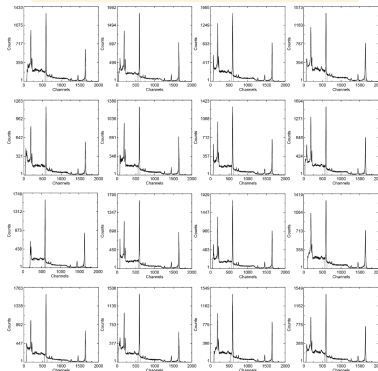
4x4 array of 6x6x20 mm³ detectors



Arrays show good performance in a wide energy range
< 2% at < 200 keV and <1% at 662 keV

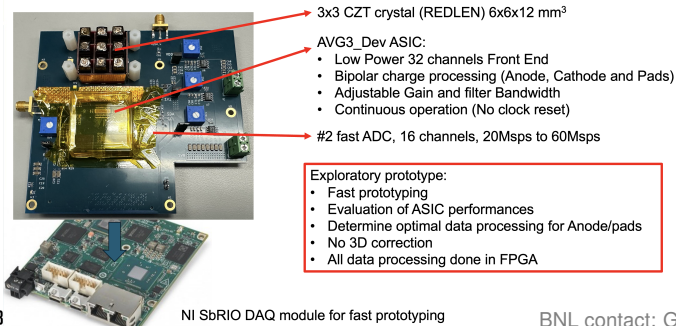
The energy resolution is limited by the electronic noise
due to large detector capacitor and leakage current

4x4 array of 6x6x20 mm³ detectors read out with AVG2 ASIC

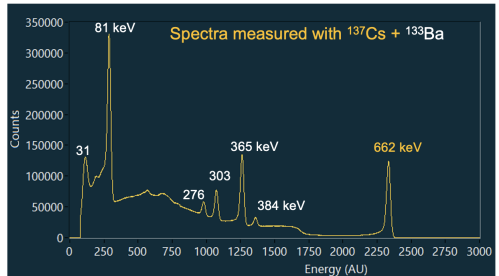
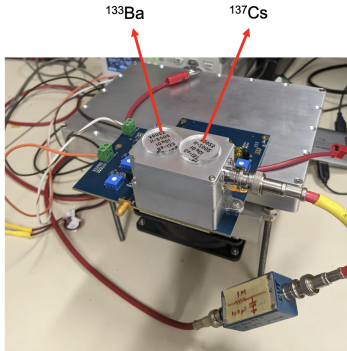


Large dynamic range readout for CZT gamma arrays

- BNL's AVG3 readout path targets low-power, low-noise waveform capture for CZT bars.
- Gamma-ray instruments require fine spectroscopy near hundreds of keV and very large signals up to tens of MeV.
- Development path includes gain selection/compression and FPGA-based waveform processing.



Large dynamic range readout for CZT gamma arrays



Measurement time 48 hours , 3000 energy bins

X-rays: photon science, high-Z imaging, and pixel readout

Part 3

Hard x-rays above 20 keV: why high-Z direct conversion

- Silicon cameras lose absorption efficiency as photon energy increases.
- Thick scintillators improve efficiency but degrade spatial resolution.
- Direct high-Z sensors can combine absorption, spatial resolution, and integration with pixel readout.
- BNL/RMD work is exploring TlBr films and crystals as high-Z x-ray sensors.

TlBr films: direct x-ray imaging on ROICs

- Attractive for hard x-rays because of high effective Z, high density, and high intrinsic resistivity.
- Film deposition opens a possible “integration-less” path onto readout chips.
- First integration with a commercial charge-integrating ROIC produced direct x-ray images.

First attempt of integration with ROIC -> Brilliance 1M from KA Imaging (7.8um pixel)



- Detection Area ~ 1cm x 1cm
- ITO top contact
- 100um TlBr film
- KA Imaging barrier Layer

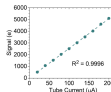
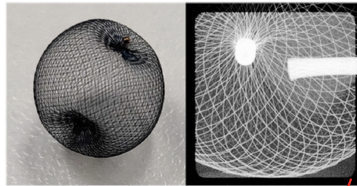
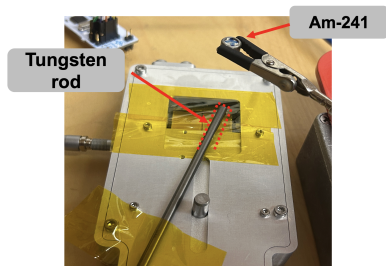


Image of a brain stent
Wire $\varnothing = 20\mu\text{m}$

Edge of the Pt Contact

TlBr on Timepix3: early imaging and the remaining problem

- Timepix3 provides fine pixels, event-driven readout, and timing capability. BNL/RMD/UCB (SBIR) prototypes coupled TlBr crystal and film sensors to Timepix3. A tungsten shadow was observed with a single-crystal sensor, demonstrating x-ray response.
- Current limitation: response non-uniformity and barrier-layer/material optimization.

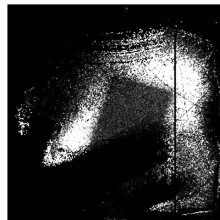


- Test setup with tungsten rod and Am-241 Source

Mono-crystallin Sensor Biased at $\sim -20V$



- No shadow



- Shadow

Custom readout ASICs for spectroscopic x-ray pixels

- BNL ASIC work targets hybrid pixel detectors with precision spectroscopy.
- HEXID concept: finely segmented CZT sensor, 150 μm pitch, low input capacitance, and low-noise front end.
- Architecture is designed for spectral imaging rather than simple frame imaging.
- This bridges detector material and deployable x-ray instruments.

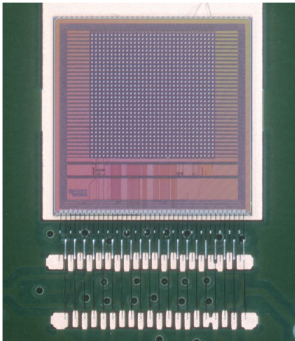
ASICs for Spectroscopy

3FI (photon science)

32 x 32 100um pixels

Sensor: Silicon

Energy Range: up to 18 keV

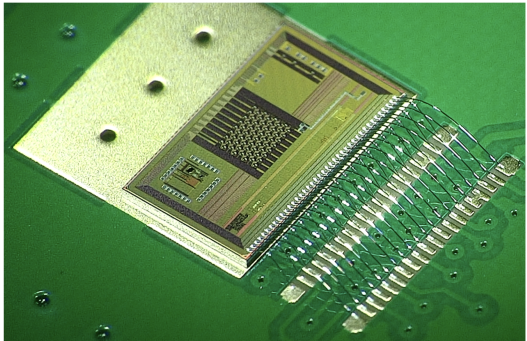


HEXID (gamma ray astronomy)

8 x 8 150um pixels hexagonal

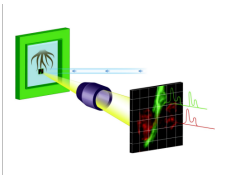
Sensor: CZT

Energy Range: High Gain up to 18 keV, Low Gain up to 180keV

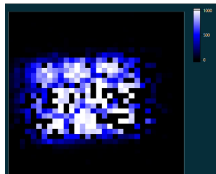


First 3FI beamtime at NSLS-II

Event Driven in Action



3FI



Moving slits



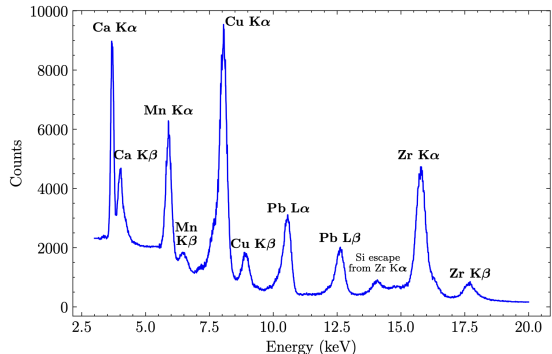
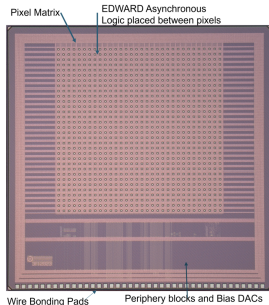
Event-driven image reconstruction

3FI performance

"Evaluation of a Full Field Fluorescence Imager with Synchrotron Radiation"

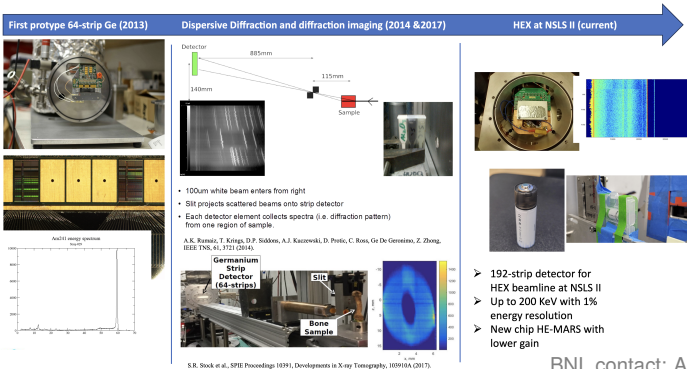
Piotr Maj, et al, arXiv:2507.14425, (2025)

"...308 eV full width at half maximum (FWHM) energy resolution at 8.04 keV, that corresponds to 30 e- rms equivalent noise charge (ENC) and 138 eV FWHM energy resolution at 3.69 keV (16 e- rms ENC) were obtained, for Cu and Ca $K\alpha$ lines, respectively.."



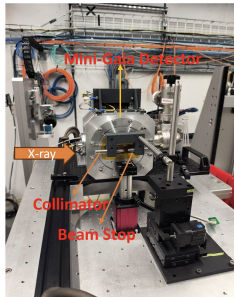
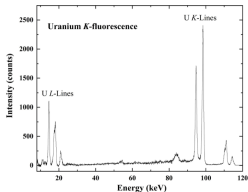
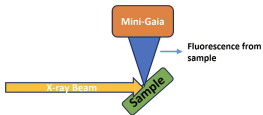
Germanium detectors

Germanium provides higher stopping power than silicon and excellent spectroscopic performance for hard x-rays. BNL has developed strip and pixel Ge detector systems for NSLS-II beamline applications. 192-strip Ge detectors have been used at HEX and other synchrotron beamlines, with spectroscopy up to about 200 keV. MARS/HE-MARS ASICs provide low-noise amplitude and timing readout for Ge sensor arrays.

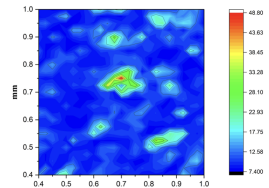


Mini-Gaia: germanium pixel arrays

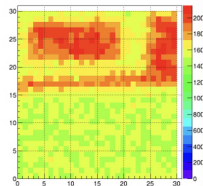
Mini-Gaia is a Ge version of the Maia concept for rapid, event-based fluorescence imaging. The goal is K-line imaging of high-Z materials and actinides where silicon detectors lose efficiency. A prototype 96-pixel Ge detector has been integrated with HE-MARS readout and a closed-cycle cryostat.



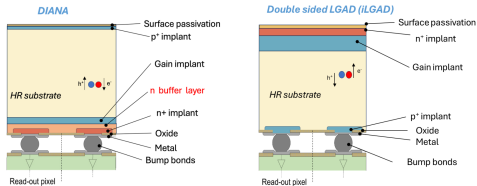
UO₂ sample, fluorescence map



2D Element Map of Au



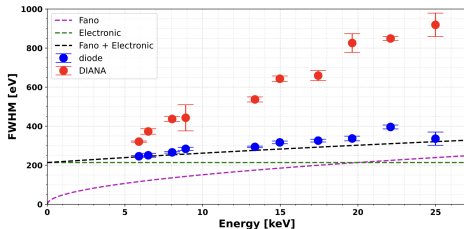
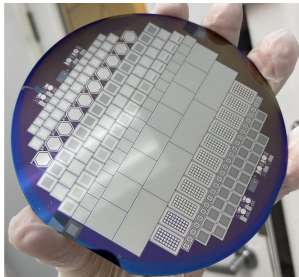
DIANA: LGAD sensors for soft x-ray detection



- Soft x-ray photon science needs high QE and low threshold in the 200 eV–2 keV range.
- DIANA is a BNL LGAD-variant sensor designed to bring hybrid pixel detectors into this regime.
- The gain layer is placed on the readout side, giving uniform gain for shallow soft x-ray absorption.
- A thin entrance window is being developed to improve QE at low photon energies.

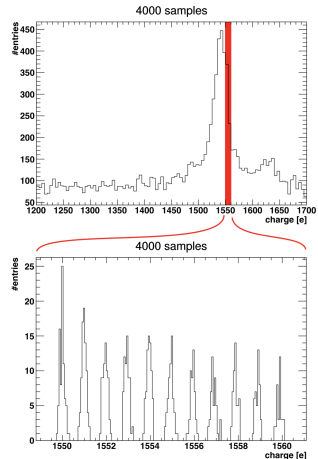
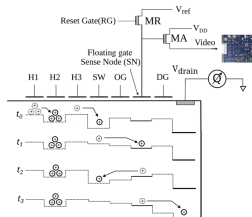
DIANA status: fabricated devices and x-ray response

- DIANA wafers were fabricated in BNL's Class 100 cleanroom.
- First devices show gain-layer depletion around 40 V and multiplication gain of about 3.
- Lab x-ray tests from 5–25 keV demonstrate gain-enhanced response.
- With gain ~ 3 , the estimated detectable threshold improves from about 455 eV to about 150 eV for the tested electronics.



Soft x-ray photon science: skipper CCDs at BNL

- Skipper CCDs enable multiple non-destructive samples of the same pixel charge.
- BNL has installed and is testing a $4k \times 4k$ skipper CCD system.
- Natural fit for photon-starved soft x-ray measurements where very low noise matters more than frame rate.
- Measured single-electron peaks with noise around $0.17 e^-$. Even at the 5.9 keV peak.



Opportunities

Near-term collaboration modes

- Independent characterization of detector materials and devices.
- Prototype readout and signal-processing studies.
- Calibration and correction algorithms for non-uniform detectors.
- Environmental/radiation testing for application-specific systems.

Possible joint targets

- Compact isotope identification with improved resolution.
- Large-area or high-efficiency CZT/TlBr modules.
- Safeguards and fuel-cycle measurement systems.
- High-Z direct x-ray imaging and event-driven ASIC readout.

Takeaways

- BNL has a full detector-development chain: materials, devices, readout, algorithms, calibration, and field testing.
- Position-sensitive VFG detectors are a distinctive BNL capability for scalable room-temperature gamma spectroscopy and imaging.
- 3D corrections and defect-aware calibration turn imperfect crystals into practical instruments.
- Active Ge detector effort.
- Soft x-ray skipper CCDs, TlBr direct-conversion imaging, and custom ASICs broaden the x-ray story beyond CZT.

BNL Contact for material in this talk

- Luca Cultrera (lcutrera@bnl.gov) - Department Chair
- Juan Estrada (jestrada@bnl.gov) - Deputy for Research
- Aleksey Bolotnikov (bolotnik@bnl.gov)
- Giovanni Pinaroli (gpinaroli@bnl.gov)
- Abdul Rumaiz (rumaiz@bnl.gov)
- Piotr Maj (pmaj@bnl.gov)

Backup

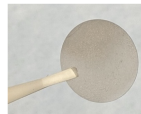
Backup: diamond scintillators for mixed radiation fields

- Diamond has unique properties for radiation detection:
 - radiation hardness
 - very low sensitivity to gamma-rays
 - and fast response
- Conventional diamond detectors rely on charge collection, but this approach requires very high-quality crystals which are expensive, small area, and they suffer from radiation damage
- Our team recently demonstrate an alternative approach using low-cost synthetic polycrystalline diamond materials (films, thin wafers, and powders) as a scintillators for charged particles and thermal neutron detection
- Several prototypes were fabricated from wafers and powders coupled with ^6LiF converters and silicon photomultipliers (SiPMs)
- These sensors can operate in the extreme environments in and around nuclear and fusion reactors, enabling real-time monitoring and verification of nuclear fuel cycles and nuclear materials

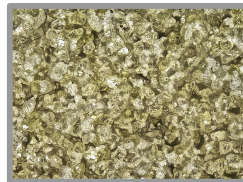
Hyperion
diamond
powder



1-inch 200-micron
polycrystalline diamond disk

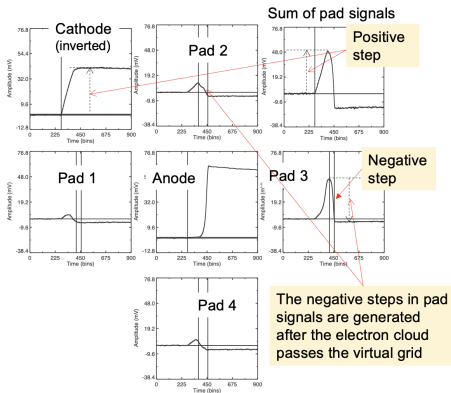


30-um diamond powder layer
bonded to the glass slide



Backup: charge signals and waveform processing

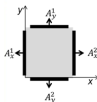
Examples of digitized signals captured from charge sensitive preamplifiers



- Using digital signal processing is paramount for achieving best performance of VFG detectors
- The anode and cathode amplitudes are evaluated using *correlated double sampling*
- Time-synchronized pad signals provide the best estimates for X-Y position
- The sum of the pad signals can substitute for the cathode signals (no decoupling circuitry is needed)
- Conventional signal shaping approach is less effective than waveform

For each event, a VFG detector generates the anode, cathode and 4 pad signals, which we then convert into geometrical coordinates and deposited energy

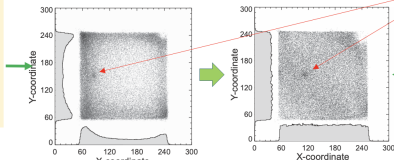
Backup: coordinate reconstruction and modeling



- First, as in the case of response non-uniformities, we normalize the pad signals and convert into two variables using either center-of-gravity formulas or pairs of adjacent pads: $(A_x^1, A_x^2, A_y^1, A_y^2) \rightarrow (\hat{x}, \hat{y})$; $(\hat{x}, \hat{y}) = (A_x^1, A_x^2) \dots$
- Then, we apply 2 *conversion matrices* T_x and T_y (generated during calibration) to find the true X-Y coordinates: $x = T_x(\hat{x}, \hat{y})$ and $y = T_y(\hat{x}, \hat{y})$
- To construct the conversion matrices, we use an uncollimated source to generate event distribution maps in the $(\hat{x}, \hat{y})$ space using center-of-gravity formulas; then we apply an interactive algorithm that locally “stretches” or “compresses” the maps until uniform distributions are achieved

Events distribution in $(\hat{x}, \hat{y})$ domain generated using the center-of gravity formulas

Events >200 keV from 137Cs source

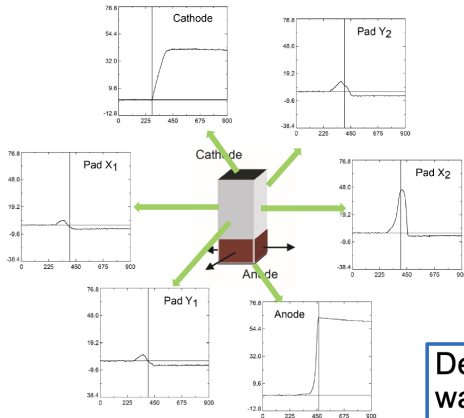


Features due to crystal defects are preserved during reconstruction

Uniform event distribution after completion of the algorithm

During the iterative procedure, at each step, we generate a set of conversion matrices T_x and T_y for both cases of selected signals: pairs or 4 pads

VGf



Bolotnikov et al. (2020)

3-D position measurement

x-position within a pixel

← pulse height ratio of x1 to x2

y-position within a pixel

← pulse height ratio of y1 to y2

z-position within a pixel

← pulse height ratio of anode and cathode

Carrier property

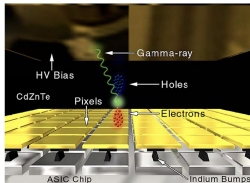
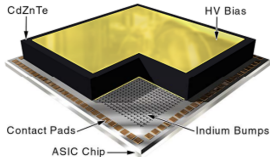
$\Delta T(C-A)$

← carrier drift time & drift velocity

Detailed analysis of waveform captured at each electrode is crucial for precise measurement of gamma-rays.

HEXID: Hyperspectral Energy-resolving X-ray Imaging Detector

Attractive detector solution for the next generation of space-borne Hard X-ray Telescopes[*]



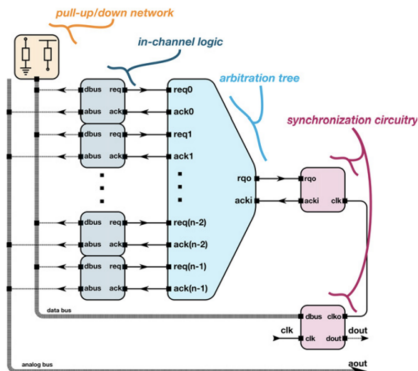
Figures from "Two-Dimensional Integrated Circuits for Hybrid Solid-State Pixel Detector", DOI: 10.1109/NSSMIC.2006.356182

Sensor material	CZT, $W = 4.6$ eV/pair
Sensor thickness	~ 1 mm
Ileak	~ 10 pA
Pixel capacitance	$\sim <150$ fF
Collected Carriers	Electrons
Energy Range	~ 2 keV to ~ 160 keV
ENC	< 20 e ⁻
Pixel Pitch	150 μ m , hexagonal
Detection Area	Target: ~ 12 mm x 10mm (64x80 pixels), Demonstrator: ~ 1.2 mm x 1.2mm (8x8 pixels)
Technology node	65 nm

[*] J. Tang, F. Kislat, H. Krawczynski,; Cadmium Zinc Telluride detectors for a next-generation hard X-ray telescope, <https://doi.org/10.1016/j.astropartphys.2021.102563>.

Event Driven readout: EDWARD (Event Driven with Access and Reset Decoder)

- Spectroscopic pixel detectors are often sparse and asynchronous.
- Event-driven readout reduces wasted bandwidth and dead time compared with frame readout.
- EDWARD architecture provides scalable arbitration and access to individual pixels.
- Event driven readout architecture with non-priority arbitration for radiation detectors, D.S. Gorni et al 2022 JINST 17 C04027



Relevant for high-rate x-ray imaging, hard x-ray spectroscopy, and gamma-ray instruments.

Skipper for X-rays

- Extremely low noise, no gain, no gain dispersion.
- Ongoing efforts on making them faster
- Currently developing faster solutions with non-destructive readout (BNL, FNAL, LBNL, MIT-LL).

will add some materials for this