3D Position-Sensitive Semiconductor Detectors for Nuclear Fuel Imaging

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On behalf of the POSEIDON team, University of Helsinki & Uppsala University

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Self-intro

- **BSc in physics**
  Thesis title: Ionizing Radiation and Radioprotection
  Supervisor: Prof. R. Cherkaoui El Moursli
- **MSc in Security of Computer Networks and Embedded Systems (Sécu.RISE)**
  Thesis title: Development of Wavelet Based Tools for Processing and Characterising the γ-ray Spectrometry
  Supervisor: Prof. M. Jedra & Dr. E. M. Hamzaoui
- **Ph.D. in Physics and Nuclear Instrumentation**
  Thesis title: Neutron Signals Nonnegative Tensor Blind Source Separation: Application to Neutron/Gamma Discrimination
  Supervisor: Prof. R. Cherkaoui El Moursli & Dr. E. M. Hamzaoui
- **Postdoctoral researcher at University of Helsinki, Helsinki, Finland**
  Activity name: POSEIDON - Position-sensitive detectors for nuclear fuel imaging
- **Visiting researcher, BNL, Instrumentation Division, jun. 18, 2023 - Now**
  Project summary: Study the usage of Cadmium-Zinc-Telluride (CZT) and germanium detectors for position-sensitive gamma-ray detection for 3D imaging with Passive Gamma Emission Tomography.

Nuclear safeguards

nuclear safeguards are activities by which the International Atomic Energy Agency (IAEA) can verify that a State is living up to its international commitments not to use nuclear programmes for nuclear-weapons purposes.

two ways:

- by providing credible assurances that States are honouring their international obligations, thus helping to build international confidence;
- by being able to detect any misuse of nuclear material or technology early on, thereby alerting the world to potential proliferation.

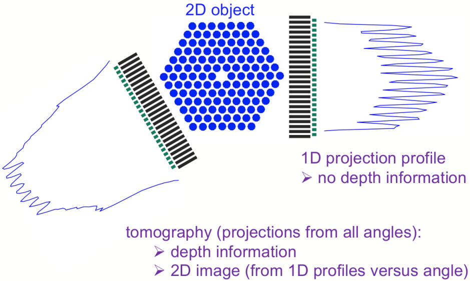
pictures: IAEA

better objective methods (technology) to detect misuse help to build international confidence.

What is tomography?

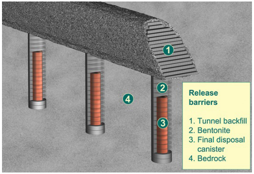
From http://en.wikipedia.org on 03-21-2023:
"**Tomography** refers to imaging by sections or sectioning, through the use of any kind of penetrating wave. A device used in tomography is called a **tomograph**, while the image produced is a **tomogram**."

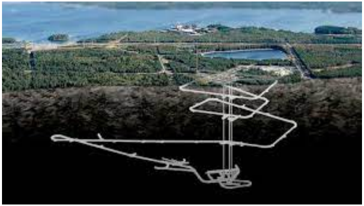
Emission: Using gamma radiation emitted from the object.



Spent fuel disposal in Finland? [1]

- disposal of spent fuel in the geological repository "ONKALO" starting in the mid-2020's
- fuel is not retrievable after disposal → safeguards verification before encapsulation

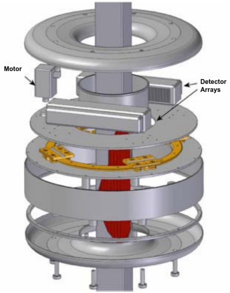




pictures: Posiva.fi [2]

Background

- Passive Gamma Emission Tomography (PGET)
- Similar idea as in medical SPECT
- PGET strength: ability to image activity of single fuel pins
- Research on PGET started in the 1980's
- IAEA Member States Safeguard Support Programmes, under JNT 1510 in 2004
- Approved by IAEA for inspections in 2017
- Now a third version in use R. Backholm et al., the first commercial one T. White et al. & M. Mayorov et al.



Rendering of the PGET instrument design including the housing and fuel assembly in the interrogation chamber [T. Honkamaa et al., Proc. Symp. International Safeguards, Vienna, 2014].

Why PGET!

JNT 1955 Phase I Technical Report
L.E. Smith et al., PNNL Tech. Rep. PNNL-25995, 2016
S. Jacobsson Svärd et al., ESARDA Bulletin 55 (2017) 10

Objective 1 - Independent pin counting for verification of item integrity

- completely **independent of a-priori information about the assembly**
- primary performance question:
  can missing or substituted pins be confidently detected?

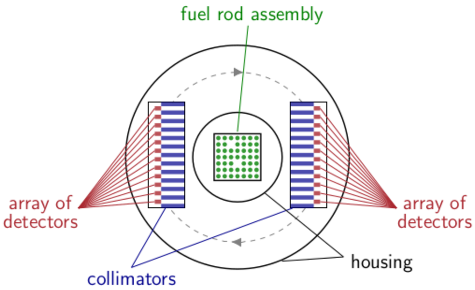
→ qualitative imaging

Objective 2 - Pin-by-pin characterization for detection of anomalies

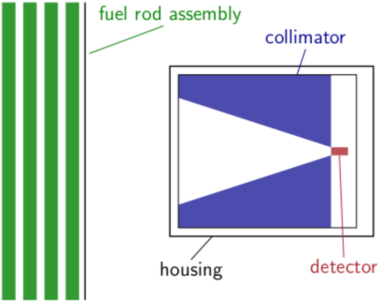
- quantitative assessment of individual pin properties
  e.g. isotopic concentrations to derive burnup and cooling time
- **prior information could be incorporated** (e.g. in order to correct for self-attenuation)
  operator-declared information on e.g. fuel assembly type and geometry
  fuel geometry information inferred from the tomographic analysis itself

→ quantitative imaging

PGET measurement device



(a) Transaxial cross section, collimators in the horizontal direction



(b) Vertical cross section, collimators in the vertical direction

R. Backholm et al., Inverse Problems and Imaging 14(2020)317
for details see references [3-5]

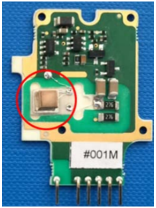
PGET measurement device

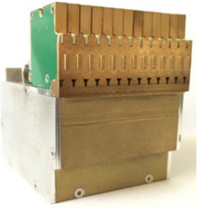
collimator: 1.5 mm slits, 4 mm pitch

360 degree rotation

Why CdZnTe (CZT)!

- Detection of gamma rays in the MeV region is important for nonproliferation and nuclear security missions
- It is also of great interest for gamma-ray astronomy: cosmic gamma rays in this range are least explored because of the low sensitivity of the existing instruments
- Achieving the high sensitivity in the MeV range requires detecting media with high Z and density, that can also provide high energy and position resolutions
- Today, CZT-based arrays can satisfy these requirements, and therefore, become attractive for ground and space telescopes

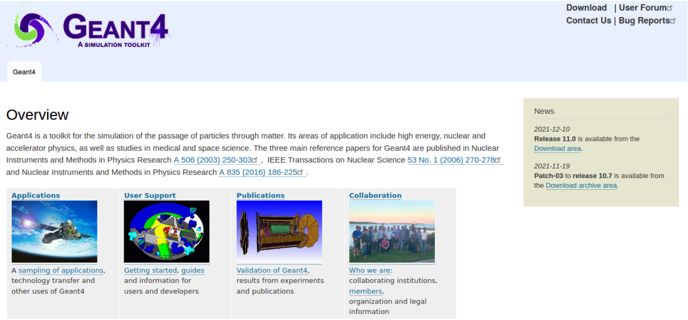




A front-end board (FEB) with CZT detector circled in red (top), and a back-end electronics board populated with 13 FEBs (bottom).

Why Geant4?!

- It's freely accessible;
- Traditional MC's work with cycles and generations;
- Geant4 tracks particles in "real" time.



geant4 web cern

C++, modular architecture, multi-threaded, trivially parallel on multi-nodes, source available
User modifies + extends User Classes, even System Classes, not input card driven Engines for geometry, materials, physics, tracking, history recording, visualisation, analaysis.

Grand vision: "Ubuntu POSEIDON"

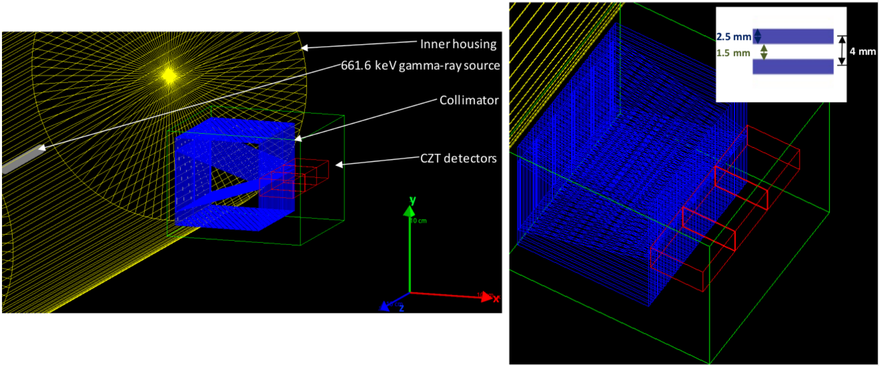
Simulate the entire PGET, using only open source code;
Allow anyone to innovate, verify, improve on PGET modelling.

> The model will be quite generic & parametrized such that various scenarios can be easily implemented!

Verification of modeled PGET using code-to-code verification and using available experimental data (phdsco.com/products/gegi, available at the HIP Detector Laboratory).

Smaller-scale simulation– Proof of concept

A Monte-Carlo model of the PGET device consisting of six objects, as described in Figure below, was implemented using Geant4 in order to generate interaction positions and energies.



Objects modeled in Geant4 to simulate the smaller-scale PGET device (E_γ=661.6 keV) CZT detectors 306mm away from γ-ray source.

Physics list:

Physics lists are based on:

1. Transportation (required for every particle which is tracked in a simulation)
2. EM physics

Constructor	Components	Comments
G4EmStandardPhysics_option4()	Standard models when applicable	The most accurate standard [It is recommended for R&D and detector performance studies]

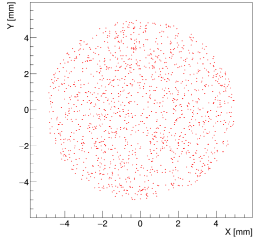
Primary Generator:

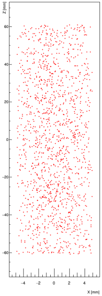
The classical convention represents each particle's position by its Cartesian coordinates (x, y, z), the direction by a unit vector with three components (u, v, w). In this current work, the position will be described by the cylindrical coordinates (R, ψ, z), and the direction will be described by two angles: (θ, ϕ).

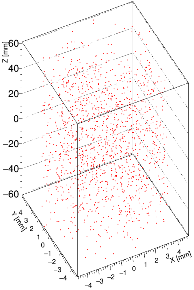
$$\text{Pi}\ (x, y, z, u, v, w) \rightarrow \text{Pi}\ (R, \psi, z, \theta, \phi)$$

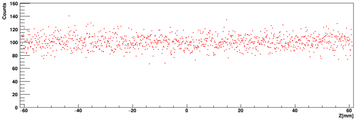
For the production runs, **10 million events** were used to obtain the histograms and eventually spectra!

1D, 2D & 3D reconstructions of 10×10^3 points representing the spatial source distribution of the primary 661.6 keV γ -rays







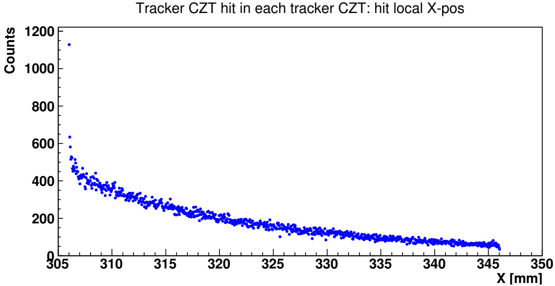


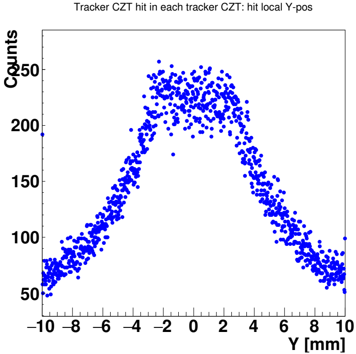
The primary kinematic is a cylindrical particle randomly shooted from the fillingsTubs.
The type of the particle and its energy are set in PGETPrimaryGeneratorAction (661.6 keV γ -ray)

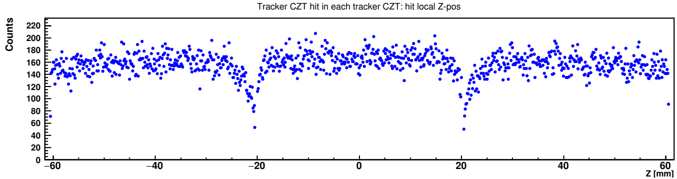
Hit and sensitive detector classes (PGETCZTHit, PGETCZTSD) were implemented to account the following information when a particle track passed through the detector:

- Time when a particle hits CZT detectors
- Hit global position (the position in the world volume frame)
- Event No, Track No and Step No
- processName
- Energy deposited in CZT detectors (= the accumulated deposit from all particles)
- ...

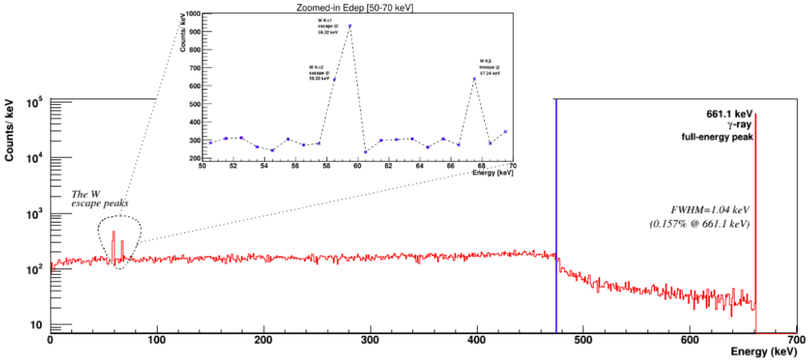
CZT hits: Xpos, Ypos and Zpos







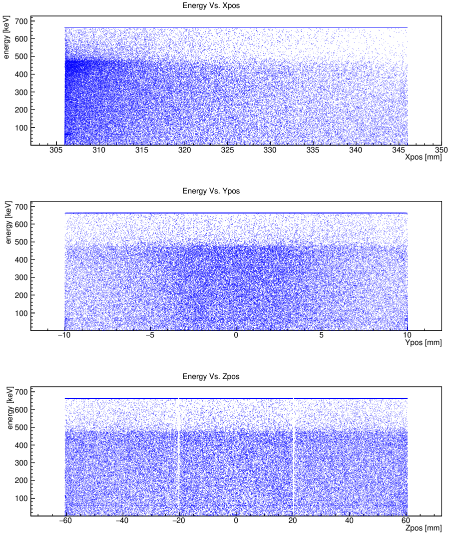
Energy deposition map



The expected features are observed: full energy peak at 661.6 keV; Compton edge at 475 keV and W X-rays (escaping from the nearby collimator) around 50-70 keV.

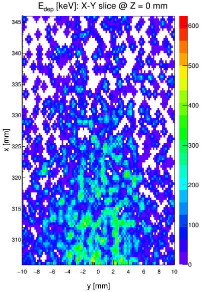
The W X-ray lines (W $K_{\alpha 2}$ escape 58.30 keV, W $K_{\alpha 1}$ escape 59.32 keV and W K_{β} escape at 67.24 keV) are clearly visible.

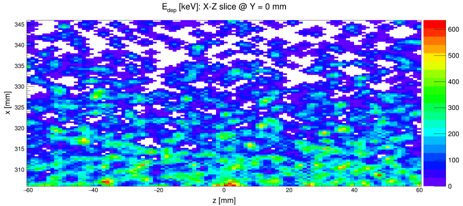
Energy deposited vs. Xpos, Ypos and Zpos

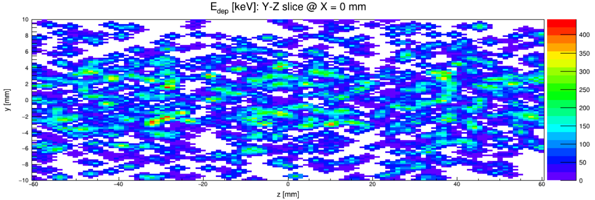


Energy deposited for 10 million 661.6 keV γ-ray vs. Xpos (top), Ypos (middle) and Zpos (bottom).

2D energy deposited in CZTs







Energy deposits within CZTs [keV], for 10 million 661.6 keV γ-ray, shown in a x-y slice for z=0 (upper left), a x-z slice for y=0 (upper right) and a y-z slice for x=0 (bottom).

Comparison small and large CZT detectors

- events with energy deposition in the CZT detectors were:
  - classified according to the type of interactions
  - split into events in which the full 661.6 keV is deposited and those in which a lower energy is deposited
- The table below shows the fraction of events according to this classification, relative to the total number of events for each detector separately. Pe: photoelectric effect, CS: compton scattering. For example 2 CS+PE is an event in which 2 Compton scatterings are followed by an interaction with the photoelectric effect.

	event type	PE (%)	CS+PE (%)	CS (%)	2 CS+PE (%)	2 CS (%)	3 CS+PE (%)	3 CS (%)	>3 CS+PE (%)	>3 CS (%)
large CZT	full energy	9.19	14.87	0.00	10.36	0.00	4.32	0.00	1.60	0.00
	no full energy	7.10	2.54	34.74	1.26	10.53	0.40	2.40	0.13	0.53
small CZT	full energy	8.22	2.46	0.00	0.44	0.00	0.04	0.00	0.01	0.00
	no full energy	9.65	2.29	73.23	0.22	3.34	0.01	0.12	0.007	0.007

Comparison small and large CZT detectors

- $$\frac{\text{total detection efficiency } \textbf{large} \text{ CZT detector}}{\text{total detection efficiency } \textbf{small} \text{ CZT detector}} \approx 30$$
- fraction of detector events with full initial photon energy desposition:
  - 12% for the small detectors, 40% for the large detectors
- For Compton imaging, the "golden" events, caintaining the highest quality imaging information, are those in wich Compton scatter is followed by photoelectric effect (CS+PE) in the table (previous slide) with a full energy deposition. The ratio of such golden events for large and small CZT detectors is 30 x (14.87/2.46)=181!
- The simulation results show the great improvement that is possible when using large instead small CZT detectors.

Summary and ongoing work

- The simulations show quantitatively the great benefit for imaging that can be achieved by using large semiconductor detectors.
- The experiments provide proof-of-principle evidence that:
  - excellent imaging is possible with a large detector covering multiple collimator slits
  - it is possible to combine multi-slit imaging in one direction with Compton imaging in the perpendicular direction.
- Future development includes:
  - simulating various real-life applications in detail
  - more complicated and extensive measurements with the available position-sensitive germanium detectors
  - extensive measurements with a large position-sensitive CZT detector

References

1 posiva.fi/en

2 Backholm, R, Bubba, TA, Bélanger-Champagne, C, Helin, T, Dendooven, P, Siltanen, S. 2020. Simultaneous reconstruction of emission and attenuation in passive gamma emission tomography of spent nuclear fuel. Inverse Problems & Imaging 14, 317-337

3 Mayorov, M, White, T, Lebrun, A, Brutscher, J, Keubler, J, Birnbaum, A, Ivanov, V, Honkamaa, T, Peura, P & Dahlberg, J. 2017. Gamma Emission Tomography for the Inspection of Spent Nuclear Fuel. 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), Atlanta, GA, USA.

4 White, T, Mayorov, M, Lebrun, A, Peura, P, Honkamaa, T, Dahlberg, J, Keubler, J, Ivanov, V & Turunen, A. 2018. Application of Passive Gamma Emission Tomography (PGET) for the verification of spent nuclear fuel. Proceedings of the INMM 59th Annual Meeting, Baltimore, Maryland, USA.

5 Virta, R, Bubba, TA, Moring, M, Siltanen, S, Honkamaa, T & Dendooven, P. 2022. Improved Passive Gamma Emission Tomography image quality in the central region of spent nuclear fuel. Scientific Reports. 12: 12473.

6 Jansson, P, Jacobsson Svärd, S, Grape, S & Håkansson A. A laboratory device for developing analysis tools and methods for gamma emission tomography of nuclear fuel. 2013. Proceedings of the ESARDA Symposium 2013 and 35th Annual Meeting, Bruges, Belgium.

7 Rathore V, Senis, L, Holm, SJ, Andersson Sundén, E, Håkansson, A, Laassiri, M, Dendooven, P & Andersson, P. 2023. First experimental demonstration of the use of a novel planar segmented HPGe detector for gamma emission tomography of mockup fuel rods. submitted manuscript

8 Rathore, V, Senis, L, Håkansson, A, Sundén, EA & Andersson, P. Experimental evaluation of the performance of a novel planar segmented HPGe detector for use in gamma emission tomography. Nucl. Instrum. Meth. Phys. Res. A. 1049: 168073.

9 phdsco.com/products/gegi

Thank you for your attention!

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