

On Improving Nuclear Fuel Imaging Using Position Sensitive Detectors

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What is nuclear fuel imaging and why?

- Nuclear fuel for fission reactors is usually Uranium dioxide in pellets form.
- Pellets are inserted into fuel rods made of zirconium alloy (stainless steel).
- Nuclear fuel assemblies are a collection of fuel rods in various patterns.
- Spent nuclear fuel assemblies (SFA) will have to be stored safely in geological long-term repositories.
- Posiva developed depository for nuclear waste at Olkiluoto, Eurajoki.
- Before disposal SFA's have to be examined (nuclear safeguards).



Images (top and right): © Westinghouse

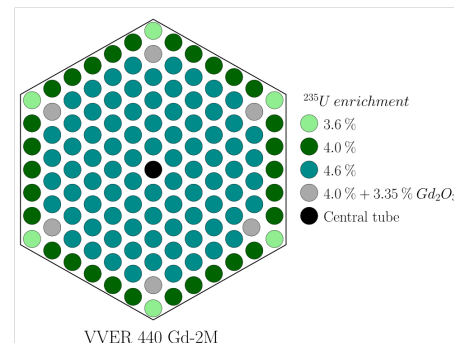
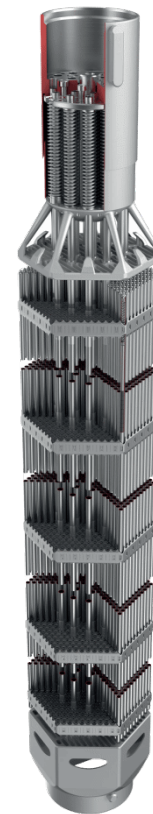


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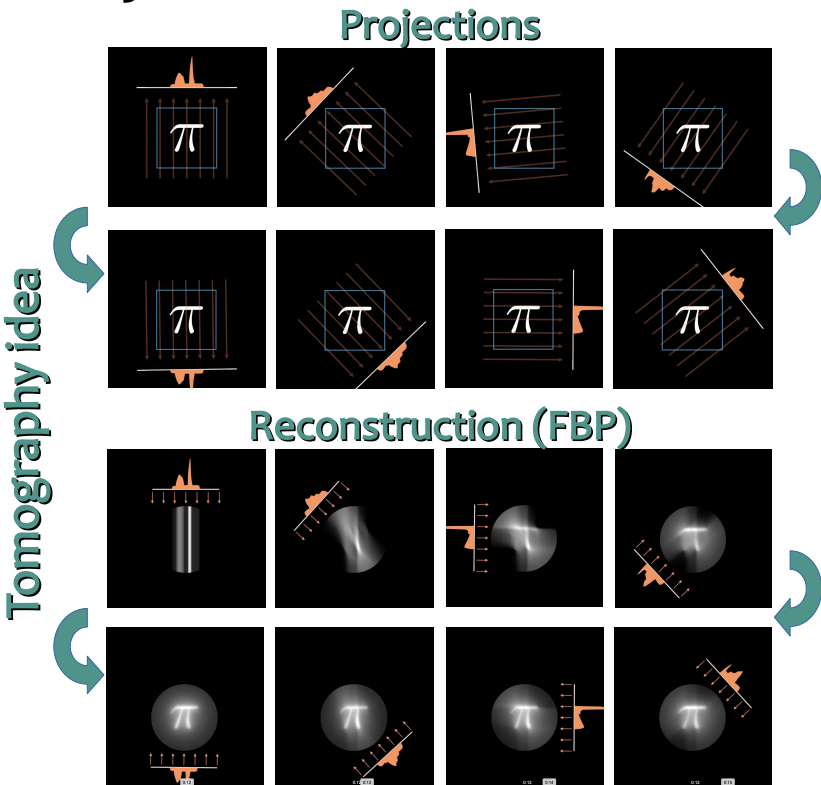


What is nuclear fuel imaging and why?

- After usage SFAs contain many radionuclides.
- Most abundant radionuclides with Gamma emissions (after e.g. 20 years cool down time):

Nuclide	Half life [a]	Gamma emissions [keV] (Br)
Cs-137	30.02	662 (85)
Cs-134	2.06	605 (98), 796 (86)
Eu-154	8.60	1274 (35), 723 (20), etc

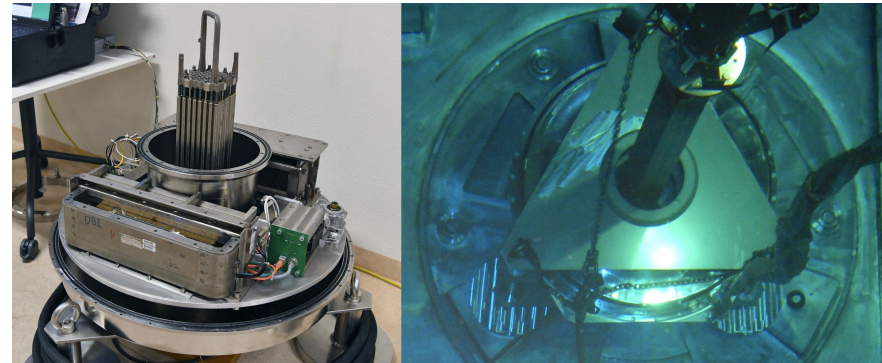
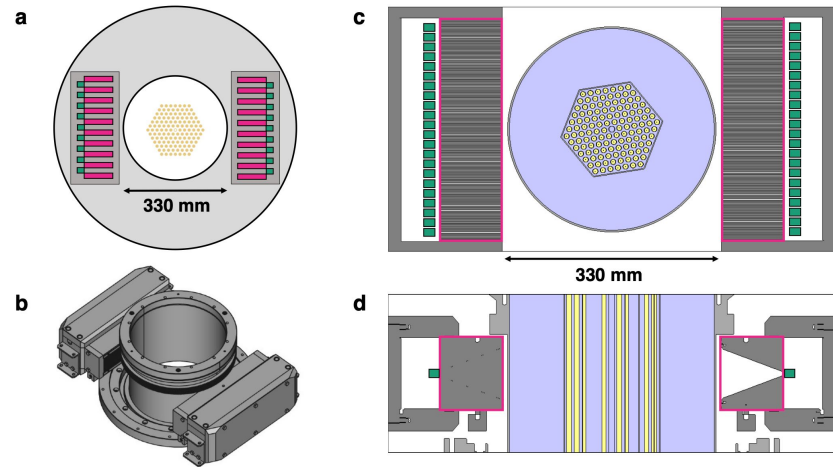
- Examination of SFA's is done among others by Passive Gamma Emission Tomography (PGET)
- Similar to medical SPECT imaging the object itself is the emitter of high energetic photons.
- We need:
 - a line camera for recording emitted gammas from SFA,
 - a collimator,
 - a mechanic for recording at different angles around SFA,
 - a tomographic reconstruction of the image (inverse problem).



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The PGET device

- Approved for safeguard inspections by IAEA in 2017.
- Sensing elements: Small Cadmium Zinc Telluride crystals behind tungsten collimator. Size: $3.5 \times 3.5 \times 1.75 \text{ mm}^3$; Energy resolution: of 10 keV at 662 keV.
- Collimator of 10 cm thickness with tapered slits from 70 mm to 5 mm at crystal. Slit width 1.5 mm with pitch of 4 mm.
- 2 opposite detector units with 2 mm offset.
- Watertight rotating mechanics with hole for SFA.
- Rather simple but fast DAQ system sensing energy windows.



Images taken from thesis of Riina Virta, drawings ©Tobias Kähkönen, photos ©Dean Calma/IAEA and Fortum.

The PGET device in action

(The material and info on following slides is taken from Riina Virta's doctoral thesis, <http://hdl.handle.net/10138/575149>)

- Since 2017 PGET measurements have been performed at Finnish nuclear power plants.
- Validation of method by scanning SFAs in deep water pools.
- Possibility to scan SFA vertically.
- Single measurements last about 5 min.
- Using energy windows around 650-700 keV (Cs-137 photopeak) and 1200-1300 keV (Eu-154 photopeak).

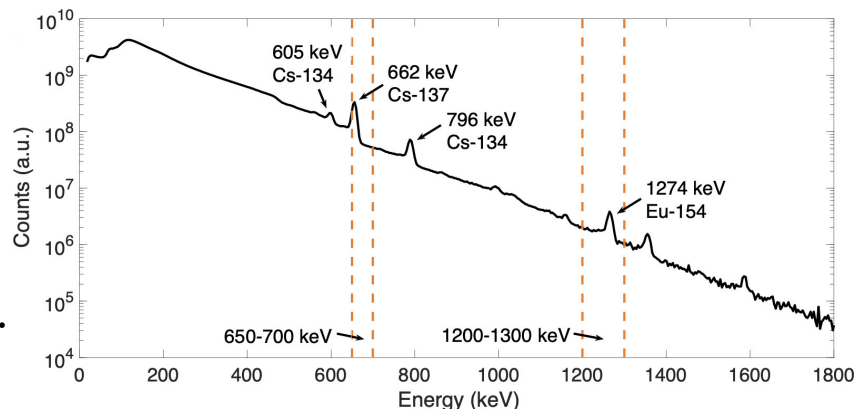
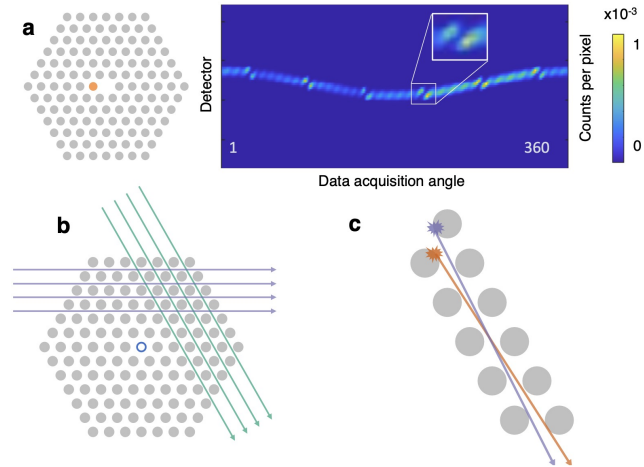


Photo © TVO

The PGET reconstruction

- For illustration imagine a single fuel rod in a SFA.
- A 360° scan results in a sinogram (a).
- Challenge: Emitted photons from rods in centre are heavily attenuated.
- See through directions (b) exist that help sensing inner rods (c).
- Solving of inverse problem not trivial (FBP will not perform well).
- PGET algorithm:
 - ➔ Initial FBP to determine configuration of fuel assembly.
 - ➔ Iterative method using a forward model with both attenuation and emission (grid as prior).
 - ➔ Minimisation with least square method.
 - ➔ Classification using trained support vector machine.

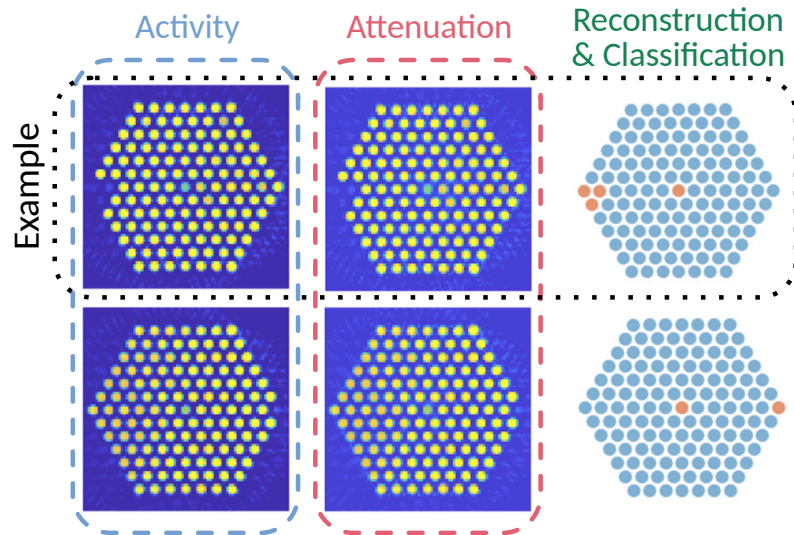


Levenberg Marquardt algorithm:

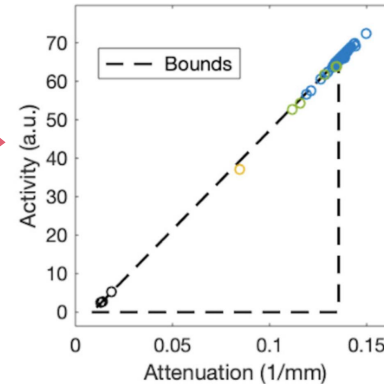
$$\begin{aligned}
 & \min_{\lambda, \mu, c} \left\{ \begin{array}{l} \text{forward projection } \|H(\mu)\lambda - C(c)s\|_2^2 \\ \text{measured sinogram} \end{array} \right. \\
 & + \underbrace{\alpha_\lambda \|R_\lambda \lambda\|_2^2 + \alpha_\mu \|R_\mu \mu\|_2^2}_{\text{a priori information}} \\
 & + \alpha_c \|\log(c)\|_2^2 + \alpha_s \|\mathbf{1}^T (s - C(c)s)\|_2^2 \Big\} \\
 & \text{regularisation terms}
 \end{aligned}$$

The PGET reconstruction and classification

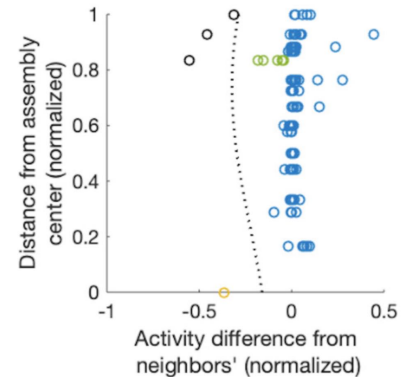
- Example from measurement campaign at Loviisa powerplant.
- Fuel type VVER-440, BU 55.0 Gwd/tU, CT 6.8a.
- 360 angles, 924 ms projection time per angle.
- Energy window 650 – 700 keV for 662 keV emission from Cs-137.
- 3 missing rods plus central water channel.



Activity –
attenuation plane



Trained support
vector machine for
classification



From [R. Virta et al, ESARDA Bulletin 61:10-21, 2020.](#)

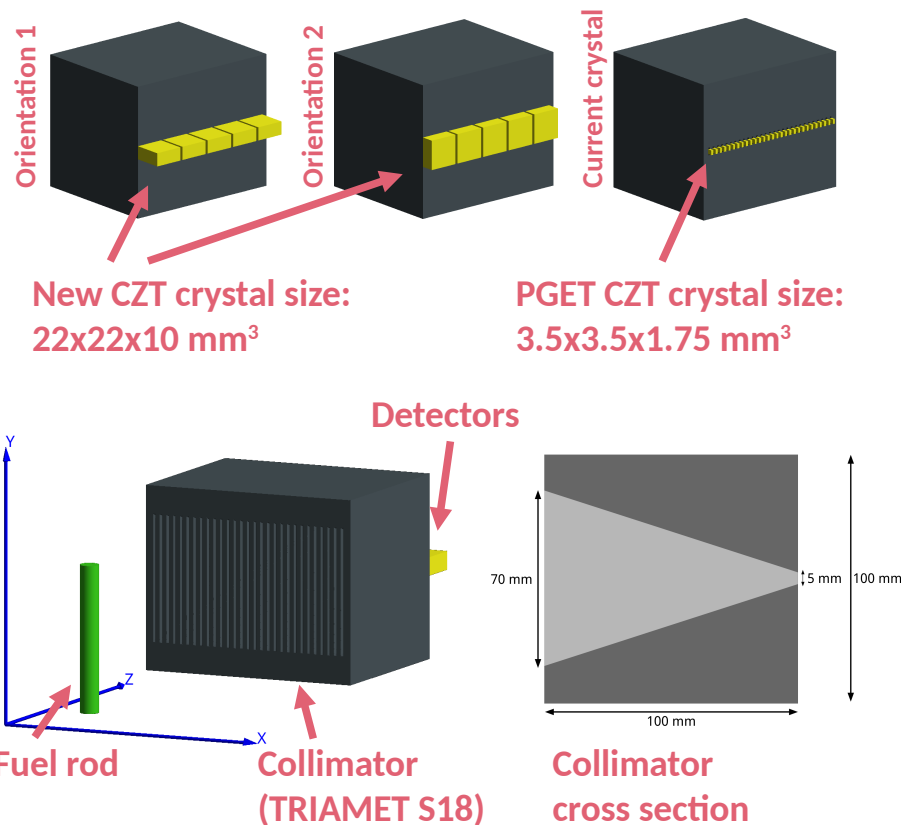
The POSEIDON project

(Funded by NKS, Nordic Nuclear Safety Research)

- Collaboration of **Uppsala University** (Sweden), **Svafo** (Studsvik, Sweden), **IDEAS** (Oslo, Norway) and the **Helsinki Institute of Physics** (HIP).
- **Team** (alphabetical order): Peter Andersson, Mihaela Bezak, Peter Dendooven, Sofia Godø, Stefan Jarl Holm, Ramsey Al Jebali, Matti Kalliokoski, Aage Kalsæg, Mounia Laassiri, Gustav Pettersson, Anders Puranen, Vikram Rathore, Santeri Saariokari and myself.
- **Goal:** Improving PGET using position-sensitive and large Cadmium Zinc Telluride (CZT) detectors.
- **Main objectives:** Do large position sensitive CZT detectors perform better than the current small detectors in the PGET system? Can we utilise 1274 keV gamma rays from Eu-154?
- Also part of the POSEIDON project: Can commercial gamma-ray imagers be used for nuclear waste characterisation?

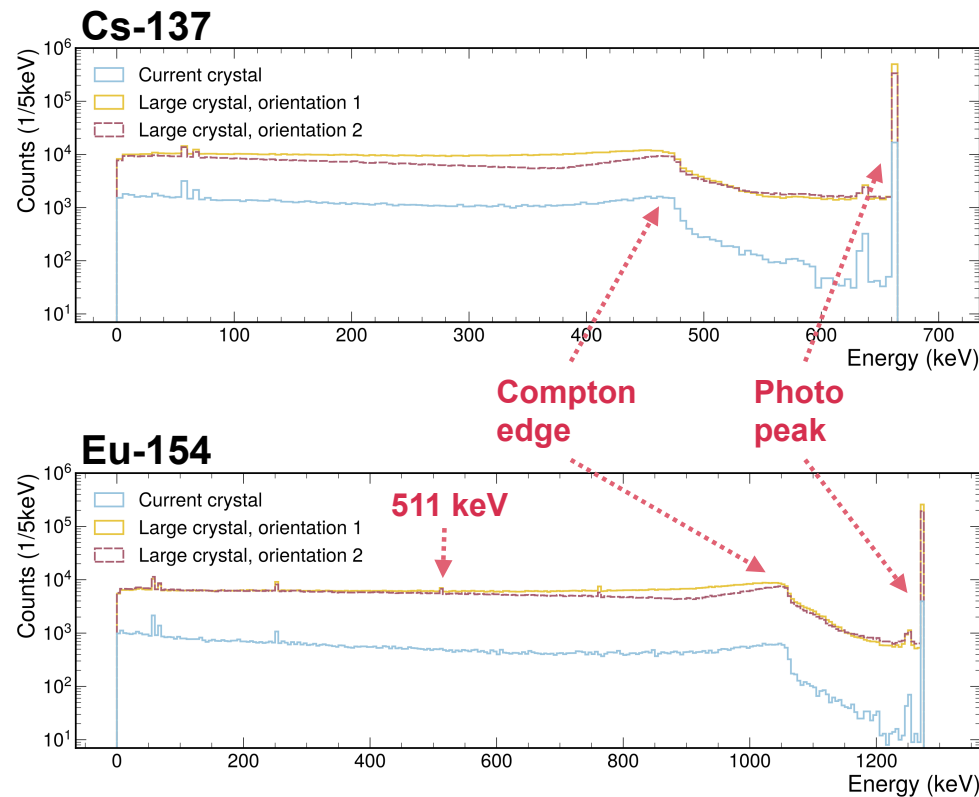
Approach by simulation

- We know that absorption efficiency of small CZT crystals as used in PGET is low. This is especially suboptimal for imaging rod positions in centre of SFAs.
- We used the GEANT4 toolkit and implemented a PGET-like system using larger CZT crystals in two different orientations as well as the present one.
- For the large CZT detector we follow the design from the IDEAS GDS-100 detector.
- Study questions:
 - Are large position sensitive CZT detectors better performing?
 - Can 1274 keV gamma emissions from Eu-154 be used (less prominent than 662 keV from Cs-137 but less attenuated by fuel rods)?
 - Can Compton imaging be utilised?



Results

- Disclaimer: this is not full detector simulation at present stage.
- 200 million gamma photons per run.
- Event definition: all interactions from one primary gamma ray.
- Results:
 - Energy spectra are shown for 662 keV (Cs-137) and 1274 keV (Eu-154).
 - Typical features visible, e.g. photopeaks, Compton edges, escape peaks, etc.
 - Height of photo peak increases substantially for larger crystals.
 - Photo peak to Compton ratio: 10.4 (current crystals), 41.4 (orientation 1) and 35.9 (orientation 2).

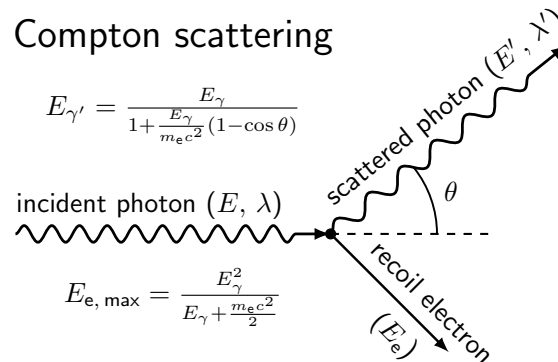


Results

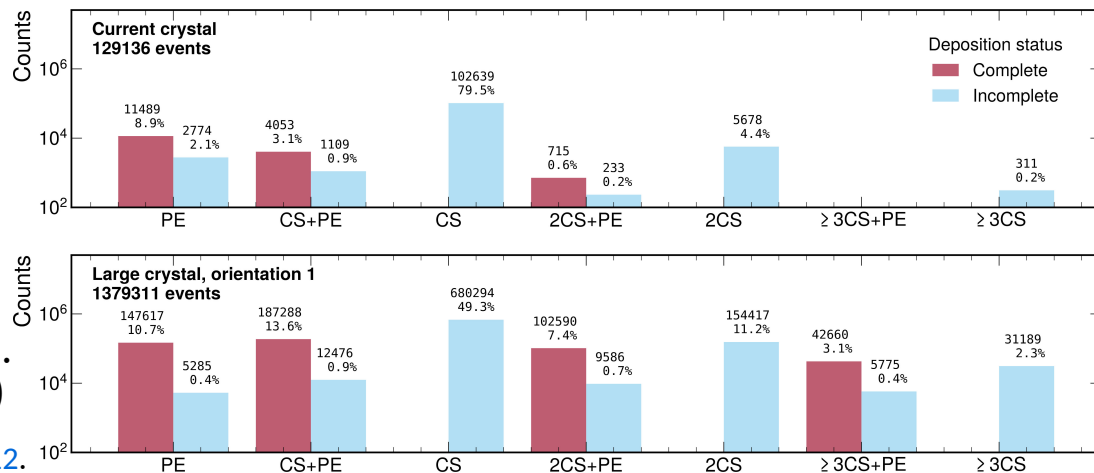
- Having a position sensitive thick CZT we can exercise Compton imaging
- Compton scattering:
 - Inelastic photon matter interaction;
 - Recoil electron energy depends on scattering angle of photon;
 - Scattered photon can escape or interact.
- Golden event: Incoming photon undergoes Compton scattering followed by photoelectric absorption of scattered photon.
- Graphic: Process frequency in CZT crystals for 662 keV photons. (PE: photoelectric, CS: Compton)

Compton scattering

$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e c^2} (1 - \cos \theta)}$$



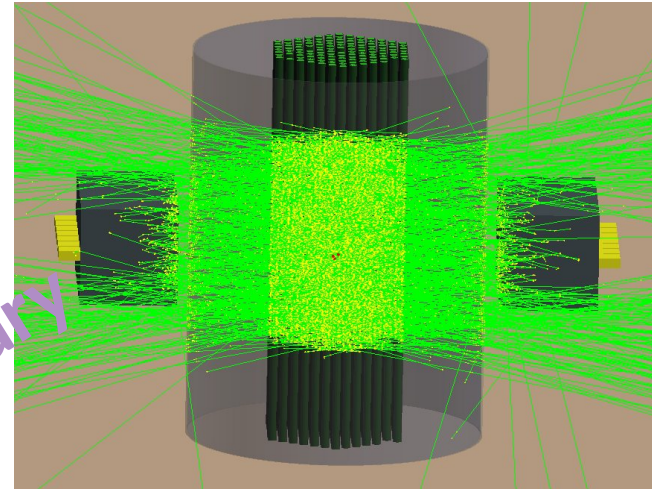
$$E_{e, \max} = \frac{E_{\gamma}^2}{E_{\gamma} + \frac{m_e c^2}{2}}$$



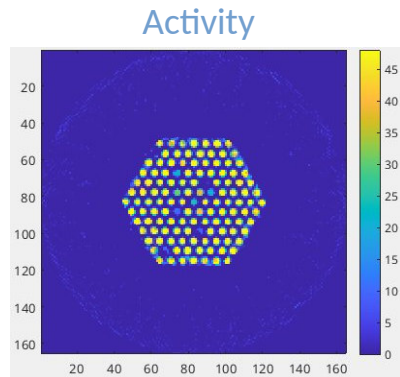
More info: [S. Saariokari et al 2025 JINST 20 C03012](#).

Tomography

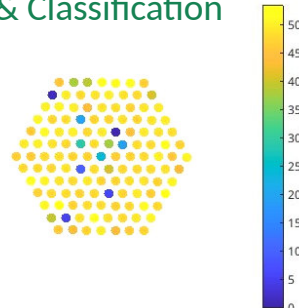
- Full PGET tomographic GEANT4 simulation for large CZT detectors.
- VVER-440 fuel assembly with 3 missing rods emitting 662 keV and 1274 keV gamma-rays.
- Full 360 degree scan in 1-degree steps.
- 2 billion events per angle.
- Image reconstruction based on “iterative reconstruction method” (HY, STUK).



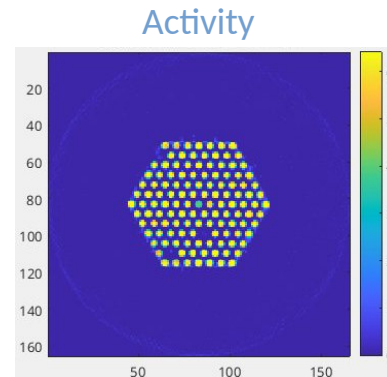
preliminary



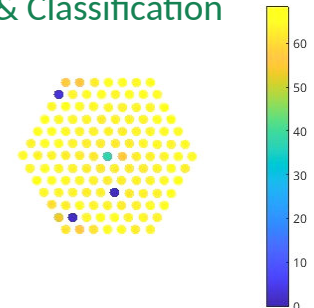
Reconstruction & Classification



From small
to large CZT
crystals

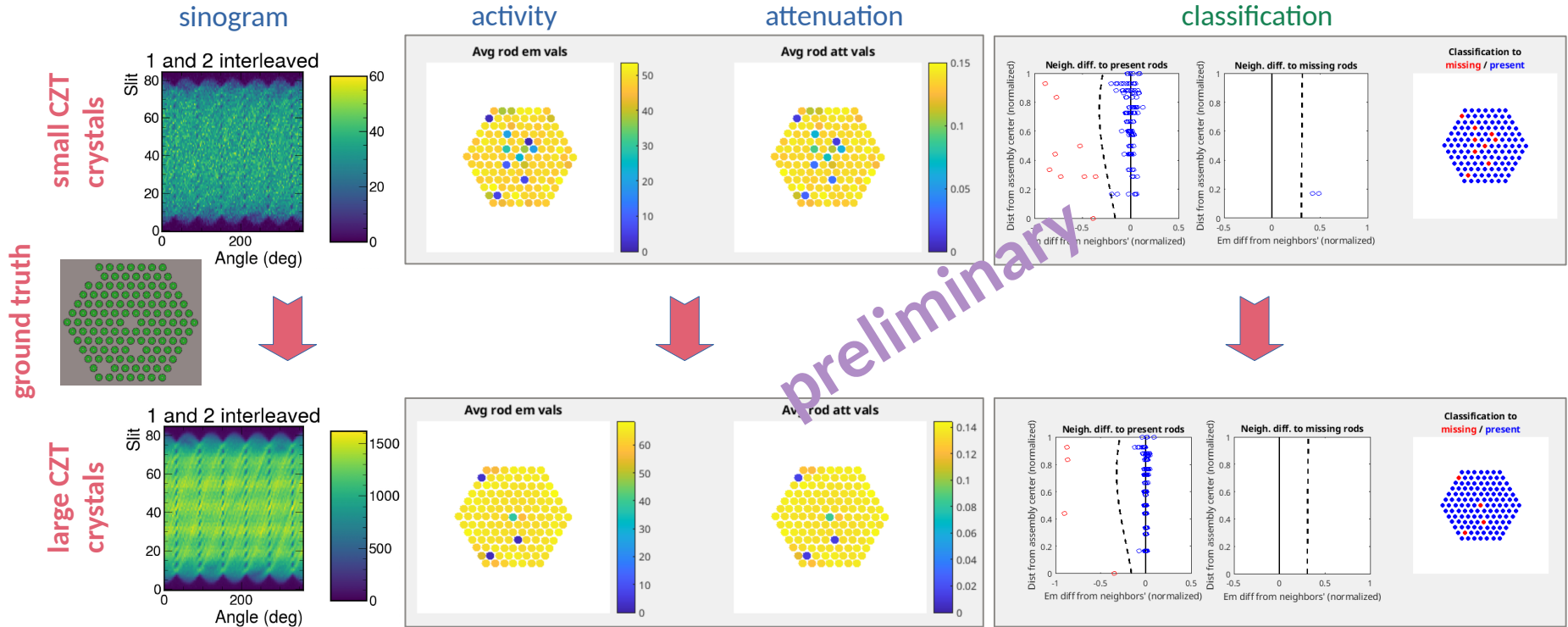


Reconstruction & Classification



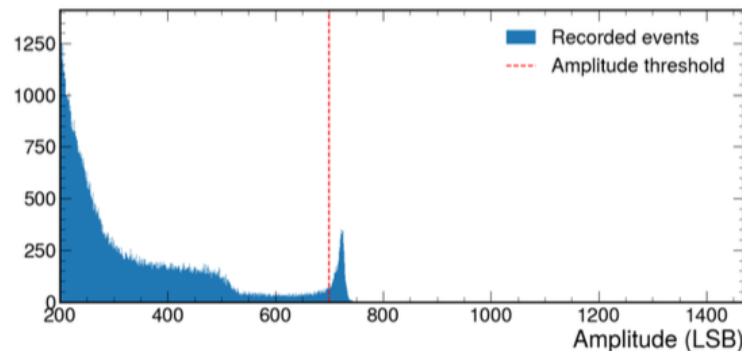
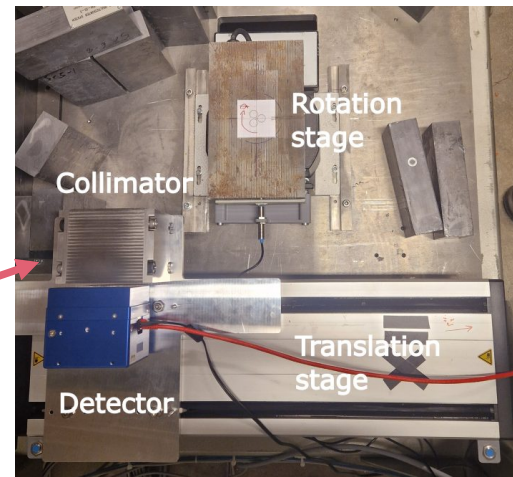
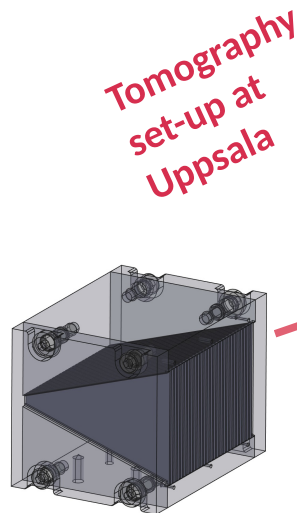
Tomography

- Simulation results for Eu-154 gamma rays of 1274 keV.



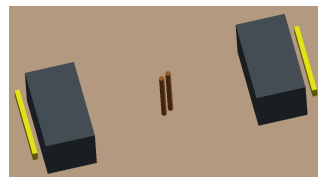
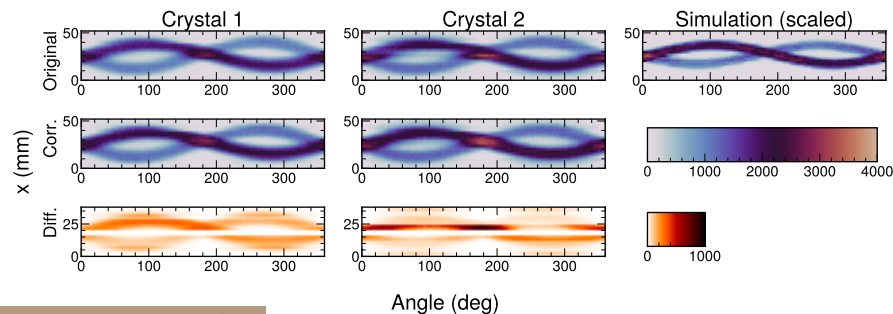
Tomographic measurements

- Performed at Uppsala University using:
 - 1) Bettan tomographic setup with rotational and translational stage.
 - 2) IDEAS GDS-100 system using large CZT crystals ($22 \times 22 \times 10 \text{ mm}^3$).
 - 3) 1D multi-slit tungsten collimator (Triamet S18, similar to PGET).
 - 4) Mockup fuel rods of titanium filled with bronze granulate containing Cs-137.
- Two rods (activity ratio of 0.55 ± 0.02) were placed on stage with 14 mm separation.
- Full 360° rotation in 3° steps and translational stepping for sub-slit precision and to overcome limited detector coverage in space. Mimicking IAEA procedure.

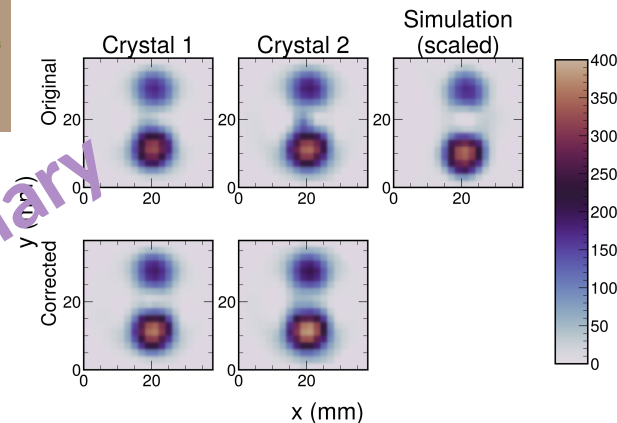


Tomographic measurements

- For analysis photo peak intensities per pixel and single-slit intensities were studied to produce calibration factors.
- GEANT4 simulations were performed with geometry similar to the Bettan setup. 
- Sinograms were studied (top right).
- Reconstruction uses simple FBP algorithm with Hann filter (bottom right).
- Applying gain correction to crystals makes reconstruction more uniform.
- Simulation in good agreement with measurement including fuel rod activity.
- Analysis concerning Compton imaging still open.



Geometry of GEANT4 simulation



Gamma-ray imagers and nuclear waste characterisation

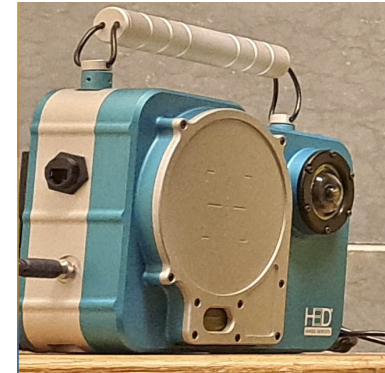
- Two commercial gamma-imagers:
 - GeGI:** High purity position sensitive germanium detector,
 - H420:** Position sensitive detector using thick CZT crystals.
- Both use optical cameras to visualise position of emitting sources.
- Both are Compton imaging capable.

Detector	GeGI	H420
Manufacturer	PHDS Co.	H3D Inc.
Active material	germanium	CZT
Size	90 mm diameter 11 mm thick 67 cm ³ active volume	4 crystals each 22x22x10 mm ³ > 19 cm ³ active volume
Segmentation	16 anode and 16 cathode strips orthogonal with 5 mm pitch	11x11 pixels on anode 1 cathode
Energy resolution	< 0.3% (< 2.1 keV)	≤ 1.1% (≤ 7.3 keV)
Spatial resolution	1.5 mm in 3D	0.5 mm in 3D
Weight & dimensions	26x20x14 cm ³ 6.8 kg	24x9.5x18 cm ³ 3.6 kg

GeGI

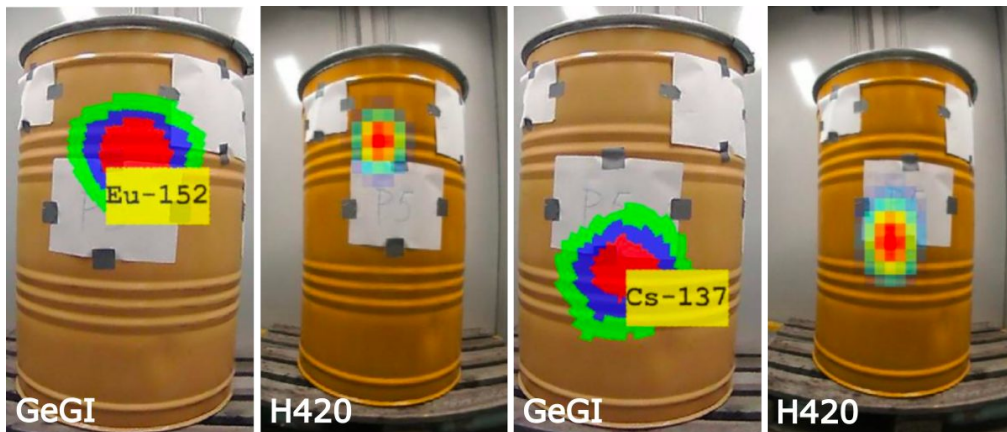


H420



Gamma-ray imagers and nuclear waste characterisation

- Measurements at SVAFO.
- Performed in shielded chamber.
- Real waste-drum with insert structures containing contaminated and active nuclear waste.
- Drums were studied from 4 different angles (90° steps) at distance of 80 cm.



HPGe gamma
spectrometer

H420



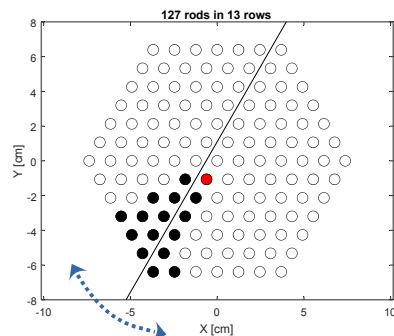
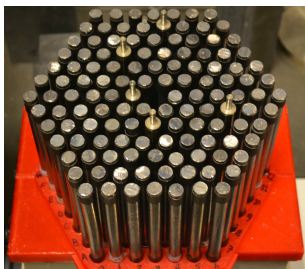
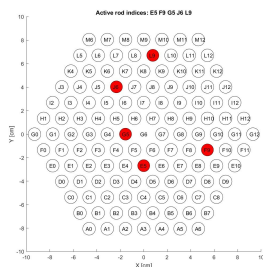
GeGI

Waste drum

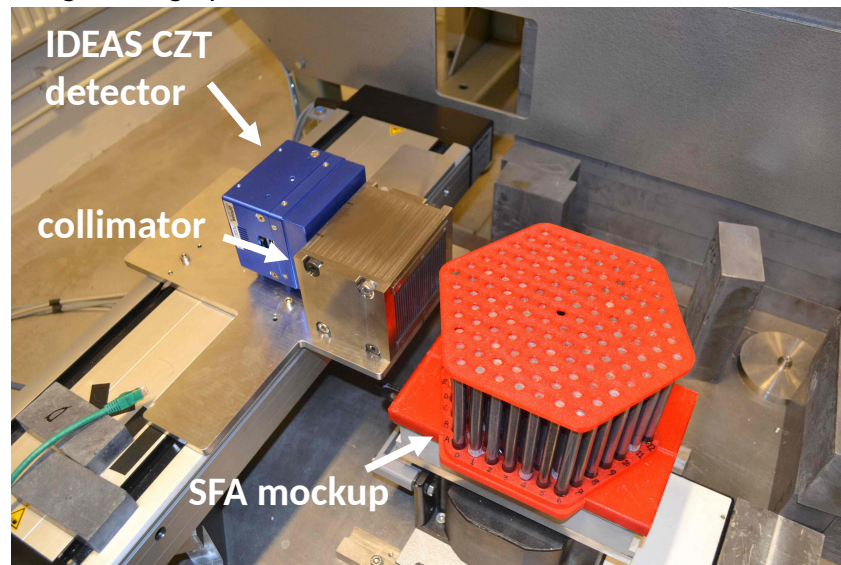
- Both imagers performed well to identify and localise nuclear waste inside drum.
- Coded aperture in H420 helps for radionuclides with low energetic emission.

Outlook

- New measurements at Bettan in Uppsala last week.
- Focus on see-through angles.
- Using full VVER-440 mock-up assembly consisting mostly of lead rods with several “fuel” rods added.



Images and graphics: Peter Andersson



- Main measurements:
 - ↳ Scanning small segment with sub degree precision.
 - ↳ Full tomographic scans with several active “fuel” rods.
- Analysis has just started. Stay tuned!

Conclusions

- We studied possible hardware improvements to the present PGET device:
 - We showed that larger position sensitive CZT crystals can be used for tomographic scans → good agreement with simulation results.
 - Compton imaging - a work in progress - needs more measurements for meaningful conclusions.
- Commercial Compton imagers perform well to study the content of nuclear waste drums.
- Last week we performed more measurements at Bettan/Uppsala:
 - Emphasis on more realistic SFA with focus on see-through angle study. Stay tuned!

