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Position-sensitive detectors for nuclear fuel imaging (POSEIDON)

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Abstract

The passive gamma emission tomography (PGET) device presently used for spent fuel safeguards inspections uses very small cadmium-zinc-telluride (CZT) detectors. Better imaging performance is possible using larger detectors, provided that these detectors are position-sensitive. Such detectors add the option to use Compton imaging to obtain axial imaging information. In the NKS_R_2022_136A project "POSEIDON", a pilot feasibility study of a PGET device that makes use of a state-of-the-art 3D position-sensitive semiconductor detectors (both germanium and CZT are considered) has been performed. The Monte Carlo radiation transport software package Geant4 was used to simulate the performance of a small scale PGET device. The performance of small and large CZT detectors was compared. The total detection efficiency for the large CZT detector is almost 30 times larger. The fraction of the events, in which the full energy of the initial photon is deposited, is only 12% for the small and 40% for the large CZT detectors. The ratio of ideal Compton imaging events for large and small CZT detectors is close to 200. All of this shows the immense improvement that is possible when using large instead of small CZT crystals.
The experiments performed in Uppsala and Helsinki with two different position-sensitive germanium detectors provide proof-of-principle evidence that excellent imaging is possible with a large detector covering multiple collimator slits and demonstrate that it is possible to combine multi-slit imaging in one direction with Compton imaging in the perpendicular direction.

Key words

passive gamma emission tomography, PGET, position-sensitive detector, semiconductor detector, CZT detector, germanium detector, Compton imaging, spent fuel

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Final Report from the NKS-R POSEIDON Activity

(Contract: NKS-R-2022-136)

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1. Introduction

The PGET device for the inspection of spent nuclear fuel assemblies (SFA) was developed between 2004 and 2014 under the IAEA JNT 1510 project, in cooperation with the IAEA Member State Support Programs from Finland, Sweden, Hungary and the European Commission. The PGET device is based on a collimator consisting of a linear array of narrow slits, with a relatively small CZT detector behind each slit (Mayorov et al., 2017, Virta et al., 2022). The detectors have a good energy resolution, enabling to collect tomographic data in four user-defined energy windows. Because of the small detectors, the probability that a gamma ray is fully absorbed, providing ideal imaging information, is small. Large CZT detectors would have a higher probability for detecting the full-energy of gamma rays, increasing the sensitivity and image quality of the PGET device. However, a large CZT detector would cover more than one collimator slit, requiring position sensitivity to determine through which slit a gamma ray travelled in order to maintain image spatial resolution.

We are studying the performance of a PGET device that uses state-of-the-art 3D position-sensitive semiconductor gamma ray detectors. There are two relevant detector materials: germanium and CZT. The imaging detector technology being developed is also useful for other than safeguards applications, such as the non-invasive post-irradiation examination of nuclear fuel to characterise its important properties (Holcombe et al., 2015).

Next to using the position sensitivity along the direction of the collimator, which gives transaxial position information, we are investigating to what extent Compton imaging can provide information on the origin of a gamma ray along the axis of an SFA. This opens the prospect of creating 3D images with the PGET device in a single axial position, adding axial information to the 2D transaxial images that are at the moment possible.

In this report, we summarize the activities performed under the POSEIDON project NKS-R-2022-136, which ran from June 2022 to May 2023. A Monte Carlo (MC) model of the PGET device was set up using the Geant4 framework. The MC model was used to simulate the performance of both large position-sensitive CZT detectors and small CZT detectors as installed in the PGET device. The performance of these detectors was compared. Tomographic measurements with a position-sensitive germanium detector and rod-shaped Cs-137 sources mimicking spent fuel were performed at Uppsala University. Compton imaging was demonstrated with a germanium imaging spectrometer and a Cs-137 point source at the University of Helsinki.

2. PGET device

The combined efforts of multiple stakeholders of the IAEA Support Programme task JNT 1510: "Prototype of passive gamma emission tomography (PGET)" culminated at the end of 2017 in IAEA approval to use the PGET instrument in inspections (Figure 1).

Figure 1. The inside of the PGET device is visible with the water-tight cover removed. Left: A 1D gamma camera is positioned before and behind the central hole into which a spent fuel assembly to be investigated is lowered. The gamma cameras are mounted on a common platform which rotates around the central hole for tomographic imaging. Right: view of the front face of the collimator slits.

A full description of the first prototype and results from the tests can be found in (Honkamaa et al., 2014). The most recent detailed description of the device is of a refurbished version of the prototype (White et al., 2018). The PGET prototype is a multi CZT gamma ray detector designed for gamma ray imaging of nuclear fuel. It entails two detector banks, each containing 87 CZT gamma ray detectors of dimensions 3.5×3.5×1.75 mm^3. The CZT gamma ray detectors are located behind a 10-cm-thick tungsten parallel-slit collimator in each bank and mounted on a common platform inside a water-tight enclosure. The collimator slit pitch is 4 mm and each opening is 1.5 mm wide. The collimator opening is angled so that the opening is 70 mm tall at the front of the collimator, decreasing to 5 mm at the back. The CZT gamma ray detectors are located behind the collimator slits and are oriented such that a 1.75×3.5 mm^2 side covers the 1.5×5 mm^2 opening.

3. Monte-Carlo model of a PGET device

A Monte-Carlo model of a small-scale PGET device consisting of six objects was implemented using Geant4 (defined in *src/PGETDetectorConstructor.cc*), see Figure 2. Table 1 lists the names, the materials, the construction methods and the main dimensions of these objects. Note that the column labelled *Construction in Geant4* shows the sequence of operations used to create each object, while the column labelled *Main Dimensions* shows the overall dimensions of each object. The simulations generate a list mode file containing the interaction times, interaction positions (x, y, z) and the energy and deposited energy of the primary gamma rays as well as the secondary photons and electrons.

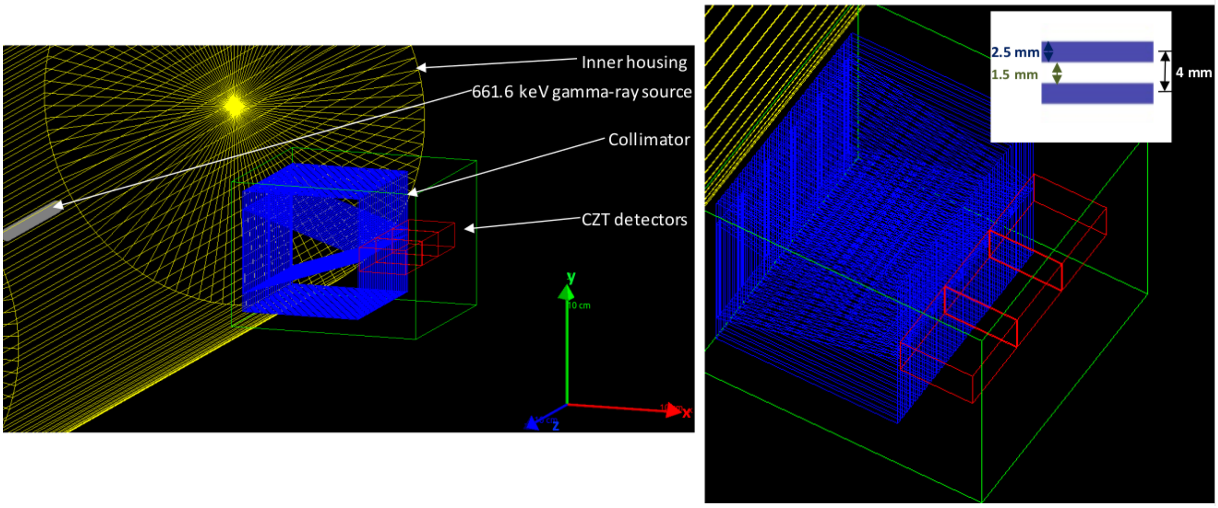

Figure 2. Objects modelled in Geant4 to simulate the smaller-scale PGET device. A source of 661.6 keV gamma rays (as emitted by the main fission product Cs-137) is implemented. Large CZT detectors (red outlines) are 306 mm away from the gamma ray source.

The initial gamma ray and the secondary particle interactions are created by Geant4. The physical photon interaction processes considered in the model are the four major interaction types: photo-electric effect, Rayleigh scattering, Compton scattering, and positron-electron pair production. An energy cut-off was used to improve the code performance, not tracking particles with a kinetic energy lower than this limit, assuming they deposit their energy locally.

When comparing the five different electromagnetic (EM) physics lists, results show that the energy deposited in the CZT detectors is not strongly dependent on the choice of EM physics list. The default EM physics model (*emstandard_opt0*) gives nearly identical results as the *emstandard_opt1*, *emstandard_opt2*, *emstandard_opt*3and *emstandard_opt4* lists. In this work, the *G4EmStandardPhysics_option4()* model has been used because it is deemed to be the most accurate EM physics constructor for R&D and detector performance studies.

We created an additional class *PGETActionInitialization* which is needed to instantiate the user action classes *PGETPrimaryGeneratorAction*, *PGETRunAction*, *PGETEventAction*, *PGETTrackingAction* and *PGETSteppingAction*.

Table 1. Main dimensions and construction properties of elements included in the Monte-Carlo model of the PGET device created using Geant4. Φ is the diameter and L the length of a tube.

Object	Material	Construction in Geant4	Main Dimensions
Detector	CdZnTe 45% Cd, 5% Zn, 50% Te	G4Box	$3.5 \times 3.5 \times 1.75$ mm^3
Collimator	Triamet-S18 95% W, 3.5% Ni, 1.5% Cu	G4SubtractionSolid [G4Box & G4Trd]	$100 \times 100 \times 122$ mm^3
Bank	Air	G4Box	$160 \times 120 \times 150$ mm^3
γ-ray source	γ-ray	G4Tubs	Φ = 10 mm, L = 122 mm
Inner housing	Air	G4Tubs	Φ = 33 cm, L = 1 m
World volume	Air	G4Box	$3 \times 3 \times 3$ m^3

In the simulations, the main dimensions and construction properties of small and large CZT detectors are presented in order to compare the total detection efficiency and the fraction of detector events in which the full energy of the initial photon is deposited. In both simulation cases, the array of CZT detectors fully covers the length of the tungsten collimator.

4. Results of the simulations

4.1. Geant4 Interaction Times, Positions and Energies

As mentioned in section 3, a simulation results in a list mode file. The information relevant for establishing basic detector performance and Compton imaging is extracted from these files. Using the *GetTrackID()* function provided in Geant4, when an event interacted in the detector volume by Compton or photoelectric effects, primary tracks were recorded having ID = 1, while secondary tracks were recorded having ID > 1. The ID was used as a flag to track secondary gamma rays and electrons originating from the same primary event.

Figure 3 shows the energy spectra of the large and small CZT detector. The energy spectrum of the large CZT detector, $40\times20\times40$ mm^3 (blue line), is similar to that of the small CZT detector, $3.5\times3.5\times1.75$ mm^3 (red line). The dimensions of the large detector corresponds to the largest commercially available CZT crystals. For both detectors, the expected features are clearly observed: full energy peak at 661.6 keV; the Compton edge at 475 keV and the group of tungsten X-rays escaping from the nearby collimator ($K_{\alpha2}$ escape 58.30 keV, $K_{\alpha1}$ escape 59.32 keV and K_{β} escape at 67.24 keV).

PGETEventAction is created to get the photon hit collection and to save it into histograms to an output text file for further analysis. Additional developed software was required to extract the relevant information from this file, i.e. information that mimics the data that would be obtained by use of a real detector.

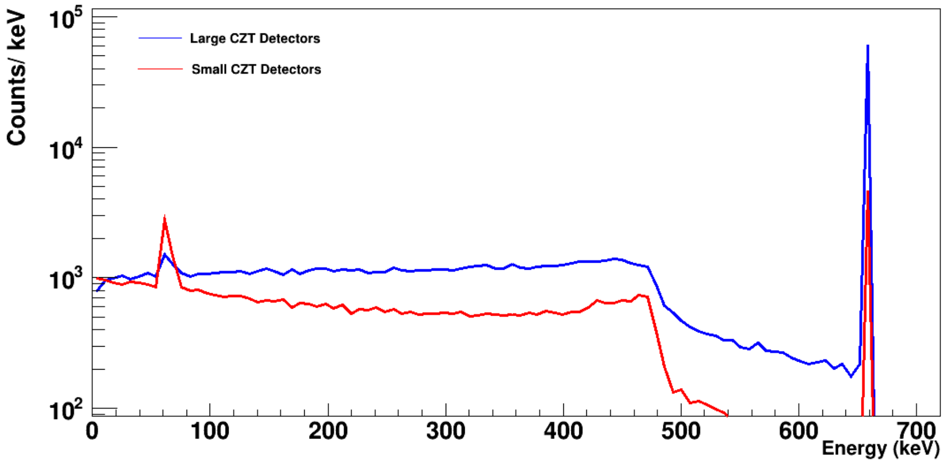

Figure 3. Energy spectra obtained from the simulated CZT detectors for the large CZT (Blue line) and small CZT (red line) detectors.

4.2. Event types and energy deposited

For the analysis we select events in which an interaction with the CZT sensitive detectors happened, resulting in either full or no full energy deposition. We classify events in nine types according to the following scheme:

- PE: The primary γ underwent a photoelectric effect
- CS+PE: The primary γ underwent a single Compton scattering followed by photoelectric effect
- CS: The primary γ underwent a single Compton scattering
- 2CS+PE: The primary γ underwent 2 Compton scatterings followed by photoelectric effect
- 2CS: The primary γ underwent 2 Compton scatterings
- 3CS+PE: The primary γ underwent 3 Compton scatterings followed by photoelectric effect
- 3CS: The primary γ underwent 3 Compton scatterings
- >3CS+PE: The primary γ underwent more than 3 Compton scatterings followed by photoelectric effect
- >3CS: The primary γ underwent more than 3 Compton scatterings

The percentage of each of the nine types of events for both detectors is given in Table 2. For both detectors, the values are calculated relative to the total number of events interacting in the detectors. For full energy deposition, about 15% of events are of type CS+PE in case of large CZT detectors and about 2.5% of events are of type CS+PE in case of small CZT detectors. For no full energy deposition, about 35% of events are of type CS in case of large CZT detectors and about 73% of events are of type CS in case of small CZT detectors.

Table 2. Percentage of events as a function of the energy deposited and classified according to the interaction history. The results for both the large and small CZT detectors are given. For both detectors, the values are calculated relative to the total number of events interacting in the detectors.

		PE (%)	CS + PE (%)	CS (%)	2 CS + PE (%)	2 CS (%)	3 CS+PE (%)	3 CS (%)	>3 CS+ PE (%)	>3 CS (%)
Large CZT	Full energy deposition	9.19	14.87	0.00	10.36	0.00	4.32	0.00	1.60	0.00
	No full energy deposition	7.10	2.54	34.74	1.26	10.53	0.40	2.40	0.13	0.53
Small CZT	Full energy deposition	8.22	2.46	0.00	0.44	0.00	0.04	0.00	0.01	0.00
	No full energy deposition	9.65	2.29	73.23	0.22	3.34	0.01	0.12	0.007	0.007

In the large CZT detectors, the total detection efficiency is almost 30 times larger than that of the small CZT detectors. The fraction of detector events in which the full energy of the initial photon is deposited is only 12% for the small detectors, but 40% for the large detectors. Combining these two factors, we conclude that large detectors are very promising for imaging characteristics in terms of full energy detection efficiency. For Compton imaging, the "golden" events, containing the highest quality imaging information, are those in which a Compton scatter is followed by photoelectric effect with a full energy deposition. The ratio of such golden events for large and small CZT detectors is 30×(14.87/2.46)=181 ! This shows the immense improvement that is possible when using large instead of small CZT crystals.

5. Experiments

Two experiments, one in Uppsala and one in Helsinki, each using a position-sensitive germanium detector, were carried out.

5.1. Experiment in Uppsala

A two-week experiment was performed at Uppsala with the position-sensitive germanium detector using the tomography test bench "Bettan" (Jansson et al., 2013) to perform tomographic imaging of rod-shaped Cs-137 sources as mock-up nuclear fuel rods. The test bench, see Figure 4, consisted of three mock-up rods placed on a rotating magnetic table, keeping the rods upright and stable, and a lateral motion table on which the collimator-detector system was mounted to collect projection data at every rotation angle. The germanium detector covers six collimator slits. These experiments confirmed the viability of utilizing a large position-sensitive detector to cover multiple collimator slits, enabling identification of the entrance slit through which each individual gamma ray travelled by use of the position information of the list mode data generated by the detector's data acquisition system. Figure 5 shows the reconstructed tomographic image, showing the three rods with various activities in fine detail. A detailed description of these measurements can be found in Rathore et al., 2023.

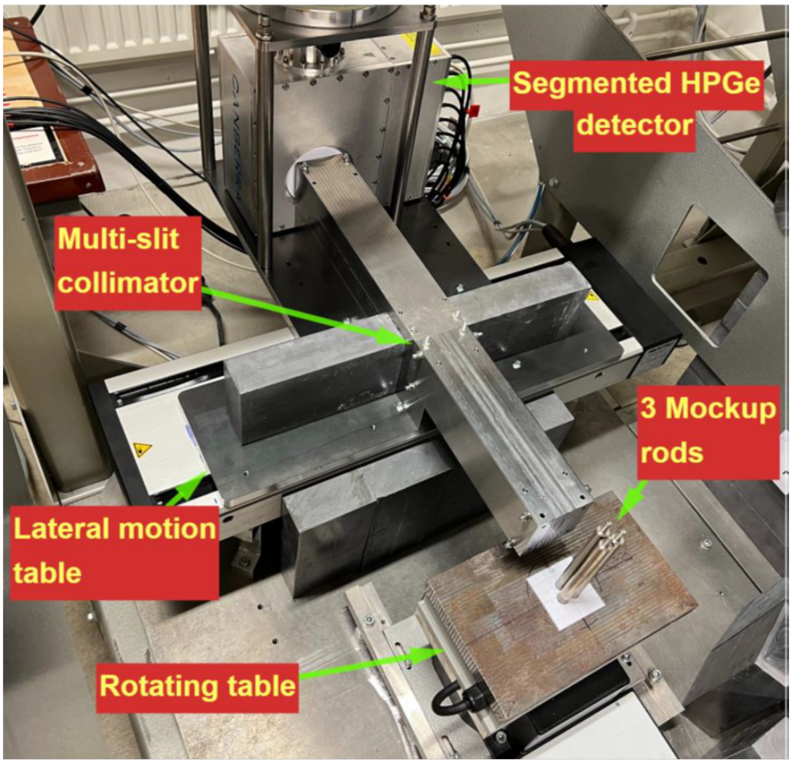

Figure 4. BETTAN test bench for tomography with a position sensitive germanium detector and a multi-slit collimator. Figure from Rathore et al., 2023.

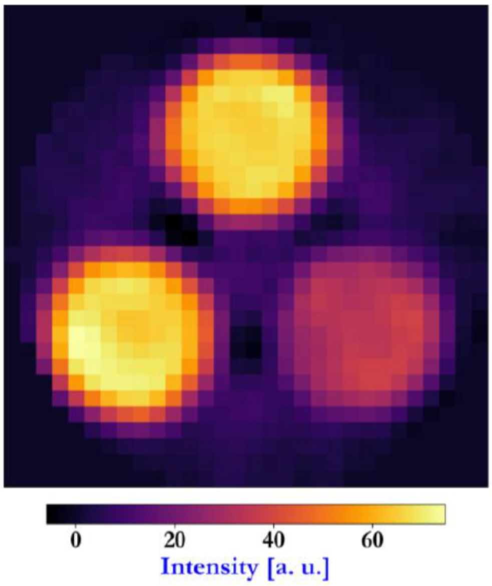

Figure 5. Tomographic image depicting the test object of three mock-up fuel rods collected with a large position-sensitive germanium detector. The images were reconstructed using the filtered backprojection algorithm employing the Hann filter. Figure from Rathore et al., 2023.

5.2. Experiment in Helsinki

This experiment was aimed at studying the feasibility of achieving improved axial resolution, no longer limited by the size of the axial field of view of the collimator, by utilising 3D position-sensitive detectors behind the collimator.

A GeGI germanium gamma imaging spectrometer (phdsco.com/products/gegi) available at the Helsinki Institute of Physics was used to study and analyse axial information from Compton images. The GeGI-imager is a portable detector that has a 90 mm diameter × 11 mm thick high purity germanium sensor with segmented readout. The readout is divided in 32 strips with 16 on each side of the crystal. The measurements were made with a point-like Cs-137 source with an activity of 3.9 MBq. The source was placed at 40 cm from the device, see Figure 6**.**

Measurements were made without any collimator between source and GeGI device and with a slit collimator made with lead bricks. The device was operated in Compton imaging mode. The collected data was stored in list mode to obtain individual event information for each strip. Measurement times of 10 minutes were used.

Figure 6. GeGI measurement setup. The Cs-137 source is placed behind the lead bricks for shielding purposes.

The collected data was analysed with custom-made python code that allowed to extract the deposited charge in each strip per event over 20 nanosecond time windows. This data was used to calculate the relative Compton angle by selecting only events which fall within 120 ns from each other. The calculated angles were then projected on a plane to obtain the 2D images shown in Figure 7. The image taken without a collimator shows a circle, essentially showing the angular resolution of the Compton imaging setup. For the measurement with the source behind a slit collimator, the effect of the slit is clearly seen: the round image seen without collimator is now "cut" in one direction mimicking the slit collimator. This demonstrates the combination of a slit giving information along one direction with Compton imaging giving information along the perpendicular direction.

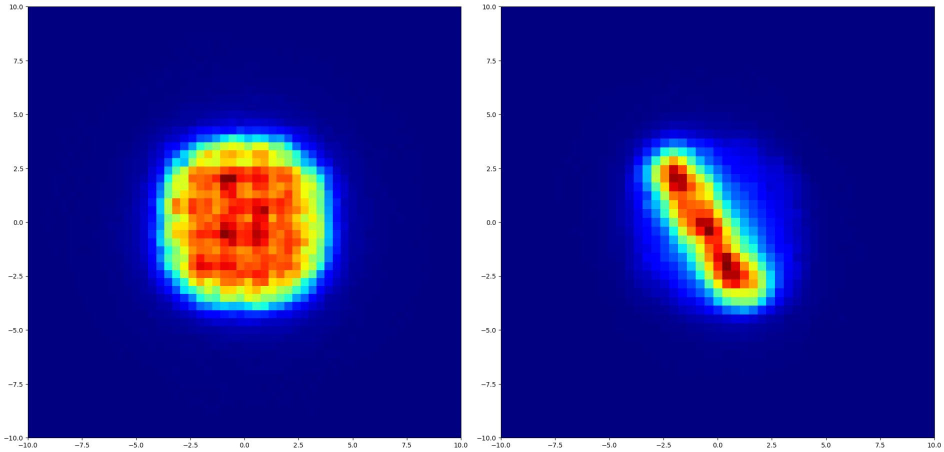

Figure 7. Measured full field Compton image (left) and Compton image when the source is placed behind the slit (right). The tilt in the right image is coming from the orientation of the germanium detector readout strips.

6. Discussion and conclusions

The PGET method has previously been demonstrated to be able to detect partial diversion of nuclear material in a spent nuclear fuel assembly with very high precision. In this work, the comparison of dimensions and construction properties of small and large CZT detectors are presented. On the basis of the results obtained, we conclude the following. In the small CZT detector the probability that a gamma ray emitted from spent fuel (the 661.6 keV gamma ray from Cs-137 is the most important one) is fully absorbed is small. Full absorption is important as these photons provide high-quality radiation images. Detected events in which less than the full energy is detected may be related to photons that have Compton scattered before entering the detector (e.g., inside the fuel, in the pond water or in the collimator) and thus have basically lost their imaging information. A larger fraction of full energy detection is possible using a large CZT detector. However, as the PGET collimators have a pitch of 4 mm, any such detector that is wider than 4 mm and thus covering more than one collimator slit, needs to have position sensitivity in order to know through which collimator slit a detected photon travelled. In the POSEIDON project, we have made a start with investigating the benefits of using state-of-the-art 3D position-sensitive semiconductor detectors (germanium and CZT) in PGET. The use of such detectors will increase the sensitivity, providing better images of weakly emitting objects and/or reducing the measurement time. The PGET collimators have a large vertical acceptance angle such that a roughly 30 cm long axial section of a fuel assembly is imaged at once. Better axial selection is possible by reducing the acceptance angle of the collimator, at the cost of smaller sensitivity and longer measurement times. However, using 3D position-sensitive detectors and the principle of Compton imaging, the vertical angle of the incoming gamma rays can be determined, providing detailed axial scanning with one measurement. In such a system, the excellent energy and spatial resolution of semiconductor detectors is essential. Using a relatively large CZT for PGET has clear benefits. We are looking into quantitative PGET imaging, as well as PGET-like devices for imaging objects other than spent fuel assemblies.

The simulations performed in the POSEIDON project show quantitatively the large benefit for imaging that can be achieved by using large semiconductor detectors. The experiments performed with two different position-sensitive germanium detectors provide proof-of-principle evidence that excellent imaging is possible with a large detector covering multiple collimator slits and demonstrate that 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 and more complicated and extensive measurements with the available germanium detectors and with yet to be acquired large CZT detectors.

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Key words passive gamma emission tomography, PGET, position-sensitive detector, semiconductor detector, CZT detector, germanium detector, Compton imaging, spent fuel

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