Geometrical optimisation of a segmented HPGe detector for spectroscopic gamma emission tomography—A simulation study

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A B S T R A C T

Segmented coaxial HPGe (High Purity Germanium) detectors have recently been shown to be feasible for Gamma Emission Tomography (GET). This type of detector allows for a combination of high efficiency and high energy resolution in gamma spectrometry of irradiated nuclear fuel. The ultimate aim of developing segmented HPGe for GET measurements is to achieve a high spatial resolution to facilitate imaging of rod-internal features and interrogation of smaller irradiated fuel samples.

In this work, we present the optimisation of a segmented HPGe detector through a simulation study using the Monte Carlo particle transport code MCNP. Constraints to each dimension of the detector were identified, from manufacturing limitations and requirements arising from the use of a finite-sized collimator slit. In particular, a relationship between the minimum inner radius of the coaxial detector and the segments azimuthal dimension was derived based on the identified constraints. Segment azimuthal and radial dimensions have been varied (based on the derived relationship between the azimuthal and radial dimension) and the full energy efficiency and misidentification rate were evaluated to obtain the optimal dimensions. The optimal ranges of the segment dimensions were determined.

1. Introduction

Gamma Emission Tomography (GET) is a non-intrusive technique to image the interiors of gamma-emitting objects. During GET measurements, gamma-ray intensities from such objects are measured at various positions and from these, the internal activity distribution may be reconstructed using dedicated software [1–4]. If these measurements are carried out spectroscopically, the spatial distribution of various radioactive nuclides can be deduced. This, in turn, offers a valuable experimental tool in e.g. nuclear fuel development where the nuclide distribution in a fuel rod represents how various fuel parameters such as burnup, power, etc. are spatially distributed [5].

Various GET setups, exhibiting a moderate spatial resolution, have been utilised for specific objectives [3,6,7]. However, to facilitate studies of rod-internal phenomena [8] such as fission product migration, pellet cladding interactions, rod bow and swelling, fuel fragmentation, fission gas release measurements, etc., a spatial resolution in the order of 0.1 mm is desirable.

As detailed in Ref. [8], a segmented HPGe detector (Fig. 1) for GET measurements was proposed consisting of a single monolithic germanium crystal where a number of electrodes electronically define the segmentation of the detector. Each of these segments is coupled to a collimator slit to obtain the desired spatial resolution. The idea with segmented HPGe detectors is not new, they have been used for nuclear structure studies such as AGATA [9], GRETINA [10]. However, to our knowledge, none has been used for GET in nuclear fuel applications so far.

The work presented in Ref. [8] represents the first stage in an ongoing project where the feasibility of using segmented HPGe detectors in post-irradiation examination (PIE) will be studied with the aim to construct a prototype instrument. The present work is in that regard the second stage where geometrical considerations have been taken into account to infer their impact on detection efficiency and suppression of crosstalk events between segments, here called the misidentification rate. As is described below, these two figure of merits is somewhat conflicting, which governs the optimisation strategy where the detector dimensions and the specific segmentation pattern are varied to maximise and minimise these figure of merits, respectively.

The simulations used in the present work were performed using the Monte Carlo particle transport code MCNP-6.2 [11] with gamma-ray energies ranging from 662 keV to 1596 keV i.e. covering activities of nuclides of primary interest for fuel development. The optimisation addressed solely the detector while auxiliary equipment such as collimators was only treated partially.
acquisition and system integration will be subjects in forthcoming work.

2. The proposed segmented HPGe detector

2.1. Design, working principle, and scope for possible use

The proposed segmented HPGe detector is an electronically segmented detector, i.e. a single monolithic high purity true coaxial germanium crystal where the outer electrode is segmented to obtain spatially resolved detection elements as shown in Fig. 1. The segmentation is made both in the azimuthal (θ) and the axial (z) direction. In the θ direction, the detector is segmented in two functionally different regions; the pair of small pie-shaped regions as shown in Fig. 1, named “scattering segments”, and the remaining pair of the large pie-shaped regions named “energy deposition segment”. The scattering segments are further divided in the z-direction into 18 segments, where each acts as an individual detector.

It was proposed in [8] to use a multi-slit collimator with its slits aligned with the face of respective scattering segments, see Fig. 2. The detector operation requires that the collimator slits directly irradiate only the scattering segments, and not the energy deposition segments, to allow for correct localisation of the event. Further on, a high-speed multichannel digitiser was envisioned for reading out the signals individually from each segment and the inner unsegmented core electrode. Further on, a high-speed multichannel digitiser was envisioned for reading out the signals individually from each segment and the inner unsegmented core electrode. In Ref. [8], two different methods for analysing the digitiser data were evaluated and for this work method 2 was applied. This method implies that an event is discarded if a neighbouring scattering segment registers an event in coincidence with the first event. Thereby, events that could erroneously be assigned to more than one collimator slit are discarded.

Although the ultimate aim is to have a versatile detector which can be used to measure a variety of irradiated nuclear fuel, in the foreseeable future the intended use is for the measurement of irradiation tested fuel rods. We anticipate no constraints on the dimensions of the fuel to be measured even though it would typically vary from a few cm to a few decimetres (dm) in height, while the diameter of the rodlets could range from a few mm up to 1 cm. Also, rigs with multiple rodlets are used, of typically about 1 dm rig diameter/width. No space constraints of practical importance are anticipated for the whole setup (including collimator, fuel fixture etc.). Similarly, the activity of the irradiated fuel intended to be measured can also vary substantially, (including collimator, fuel fixture etc.).

Table 1: Collimator dimensions used in the simulations.

| Collimator external dimensions: |  |
|-------------------------------|---|
| Length                        | 300 mm |
| Width                         | 100 mm |
| Height                        | 100 mm |

| Collimator slit dimensions: |  |
|-------------------------------|  |
| Height                        | 4 mm  |
| Width                         | 1 mm  |

Table 2: Detector dimensions and their constraints.

| Detector length             | ≤ 90 mm (manufacturing limitation) |
|-------------------------------|-----------------------------------|
| Outer diameter               | ≤ 80 mm (manufacturing limitation) |
| Azimuthal angle of the       | 26°–60° (investigated range) |
| scattering segment (2θ)      |                                   |
| Inner radius                 | 6 – 15 mm (investigated range)    |
| Scattering segment width     | ≥ 5 mm (manufacturing limitation)  |

2.2. General considerations

The results of Ref. [8] suggested that a segmented HPGe detector could be feasible with a detection efficiency in the range of 19%–28% and with a negligible misidentification rate. However, the investigated segmentation pattern was the first iteration and had not been subject to optimisation.

While the optimisation of the collimator slits is not the scope of this paper, some words about the collimator geometry may be in place. As the geometry of the detector segments, for all practical means, may be regarded as fixed, while it is connected to the geometry of the collimator, it is essential to find a reasonably general layout for the collimator to adapt an envisioned instrument to a variety of experimental cases. The work presented in [8] together with some previously performed GET measurements [3,5–7] guided the present work to fix the collimator dimensions needed for the simulations. The main collimator dimensions adopted in this work are presented in Table 1.

From a simulation study, the length of the collimator, made of Densimet® (93% tungsten), was set to 300 mm. This length offers an adequate shielding from a planar source of height 500 mm and width 10 mm. The transmission of 662 keV, 1063 keV, and 1596 keV gamma-rays through 300 mm Densimet® was shown to be about $7 \times 10^{-21}$, $1 \times 10^{-13}$, and $2 \times 10^{-10}$, respectively. The face-to-face distance between the collimator and the detector was fixed at 40 mm, providing space for detector casing etc. It should be noted, however, that multiple collimators of varied dimensions would be preferable in an actual setup, since the activity of nuclear fuel may vary by many orders of magnitude, depending on burnup and decay time.

2.3. Detector geometry

One of the figures of merit is the detection efficiency and it is straightforward to argue for using as large active detector volume as possible. There are, however, practical limitations on the dimensions governing the volume. For example, from the manufacturer of such segmented detectors [12] it was learned that a germanium crystal of size 90 mm (length) x 80 mm (outer diameter) is currently the maximum dimensions where there is manufacturing experience of segmented detectors and this case was therefore chosen for this study.

The number of scattering segments in the z-direction is fixed by the width of the segments and from the manufacturer’s advice [8], a segment width no smaller than 5 mm should be used, implying that 18 segments are possible. Table 2 summarises the main dimensions considered.

To optimise the azimuthal angle, 2θ, of the scattering segment (see Fig. 1) and the inner radius of the detector, one may recall the principle of operation of the segmented detector during a GET measurement mentioned in Section 2.1. In principle, the collimated beams of photons from the collimator (Fig. 2) must only hit the corresponding scattering segments while the energy deposition segments should not be in the direct beam path. This implies that the inner radius of the segmented detector should be equal to or greater than a minimum value, imposed by the collimated beam height.

To determine the minimum radius, the optical field of view was used as a starting point. The optical field of view is defined as the region that can be reached by straight lines through the collimator slit, see Fig. 3. This assumes an ideal collimator and neglects the presence of scattered gamma-rays and transmission of uncollided radiation through the collimator material. Therefore, a margin was applied to the calculated minimum radius to account for possible gamma-ray flux outside the optical field of view. Once the optimal value on the minimum radius was obtained, it was varied around this value in order to infer its effect on the efficiency and on the misidentification rate as is discussed in Section 3.2.

From Fig. 3 one can obtain an expression for the minimum inner radius in terms of the azimuthal angle of the scattering segment, collimator dimensions, and other relevant parameters. Using basic geometry
the following expression for the minimum radius is obtained:

$$ r_{\text{min}} = \left( \frac{h}{\sin \theta} + \frac{hd}{L} + \frac{hR}{L} \right) \left( \frac{\sin \theta - h}{L \cos \theta} \right) $$

where:
- $L$ = length of the collimator,
- $h$ = height of the collimator slit,
- $d$ = face-to-face distance between the collimator and the detector,
- $R$ = outer radius of the detector,
- $\theta$ = half azimuthal angle of the scattering segment,
- $r_{\text{min}}$ = minimum inner radius of the detector.

3. Simulation study

The Monte Carlo N-Particle transport code MCNP-6.2 [11] was used to obtain the efficiency and the misidentification rate for the segmented HPGe detector. Simulations were performed by varying the azimuthal angle of the scattering segment and using the corresponding minimum inner radius as given by (1) with a +5% margin added. For the intrinsic full energy efficiency case, each simulation was performed twice, once for the 662 keV photons, and another for the 1596 keV photons. To evaluate the intrinsic full energy efficiency in each simulation, $10^7$ and $10^8$ photon tracks were simulated for the evaluation of efficiency and the misidentification rate respectively. The other dimensions of the detector were kept fixed at the values presented in Section 2. To simulate a realistic HPGe detector, a 1 mm thick aluminium end cap and a dead layer of thickness 0.3 μm [13] (assuming an n-type germanium crystal with a thin +p outer contact) were included in all simulations.

Using various tools included in MCNP, simulated measured spectra were obtained on which an anti-coincidence/coincidence condition was applied. In all simulations, both photon and electron transport was used. The number of tracks simulated in each simulation were enough to pass all ten statistical checks performed by MCNP.

3.1. Detection efficiency and misidentification rate

Pulse height spectra were obtained by irradiating the centrally located detector segment and from these spectra the intrinsic full energy efficiency and the misidentification rate was determined. The full energy efficiency, $E$, was calculated by using the probability of full energy deposition, $P_i$, in the scattering segment pair $i$ in union
The inner radius, \( r \), of the detector is equal to a minimum value and this ensures that the energy deposition segments do not fall into the optical field of view. (a) Schematic illustration of the optical field of view. (b) Zoomed-in view of the right side of (a). Point ‘b’ in the figure indicates the intersection location of the optical lines with the boundary of the scattering segment.

with the energy deposition segments per incident photon. Where index \( i \) corresponds to the target segment pair of the radiation source in the simulation. To save the computational time required, the evaluation of the efficiency was conducted in such a way that the direction of the photon beam spanned only the optical field of view as depicted in Fig. 3. The total misidentification rate was evaluated by summing the \( P_i \) for all the remaining 17 scattering segment pairs which were not directly irradiated by the source and hence any full energy event in these segments corresponds to a misidentification event. Further, dividing this sum by the sum of \( P_i \) for all the scattering segment pairs \( (i = 1, 2, 3...18) \), the total misidentification rate, \( M \), was obtained as normalised to per full energy event in the detector, Eq. (2).

\[
\text{Total Misidentification Rate, } M = \frac{\sum_{i=1}^{18} P_i}{\sum_{i=1}^{18} P_i}
\]  

(2)

Index \( j \) stands for the target scattering segment pair which is excluded from the sum in the numerator since it does not represent a misidentification. The coincidence/anti-coincidence condition is applied in the simulations to obtain \( P_i \) in the following way:

1. A pulse in one scattering segment is counted also if there is a coincident pulse in any of the energy deposition segments, and in this case the pulses are summed.
2. If there are coincident pulses in any neighbouring scattering segments, the pulses are discarded.

It may be noted that, in the simulations, events corresponding to partial energy deposit are not counted, which is a fair representation of the situation in actual measurements where only the full-energy peaks are analysed. However, in reality, these events will still contribute to a background and as well as to dead time and pile-up.

3.2. Effect of varying the inner radius around the minimum value

The detection efficiency and the misidentification rate are coupled to the detector’s inner radius, which in turn is governed by the collimator properties. Therefore, an additional set of simulations were performed where a realistic collimator was simulated to account for contributions from photons that have passed through the collimator material. The collimator was modelled in front of the detector as...
per the dimensions given in Table 1. The collimator slit was aligned with the central scattering segment pair, and a surface source, slightly larger than the collimator slit, was located at the opposite end of the collimator. The emission of photons from the source was directed towards the collimator with a divergence of 1° from the surface normal, which is larger than the angular divergence of the optical cone of view of 0.76° in order to save computational time. Four azimuthal angles were chosen to study the detector performance. These angles were 32°, 33°, 34°, and 35°, for which the detection efficiency was found to be almost constant in the simulations performed without the collimator. For each angle, the inner radius was varied from −20% to +20% around the minimum value and the detector performance in terms of detection efficiency and total misidentification rate was evaluated. Anti-coincidence/coincidence conditions were then applied in the manner described in Section 3.1.

Because a substantial fraction of the starting photons did not reach the detector, only the number of photons that hit the detector surface were taken into consideration. To obtain the detection efficiency and the misidentification rate, 10⁷ and 10¹⁰ photon tracks were simulated, respectively. Again, all ten statistical checks performed by MCNP were fulfilled in each simulation. In Fig. 4, an overview of the geometry is shown.

4. Simulation results

4.1. Detection efficiency as a function of the azimuthal angle

The detection efficiency was evaluated for the detection element as described in Section 3.1, by varying the azimuthal angle of the scattering segment from 26° to 60°. Two different source energies, 662 keV and 1596 keV were used separately for each case. In these simulations, a margin of 5% over the minimum inner radius was added to the inner radius. Fig. 5 shows the variation of the detection efficiency and the detection volume for the various azimuthal angle values. The detection efficiency for 662 keV photons varies from a value of approximately 21% to 25% and remains almost constant over azimuthal angle values between 32° and 35°. The obtained values of the efficiency for 662 keV photons at 32°, 33°, 34°, and 35° are approximately 25%. Similarly, for 1596 keV photons the efficiency varies from a value of approximately 11% to 13%. As seen in Fig. 5, the detector volume can relatively well explain the efficiency variations for 662 keV gamma rays, while for 1596 keV gamma rays, the detector volume is insufficient to explain the variation in efficiency.

4.2. Misidentification rate as a function of the azimuthal angle

To evaluate the misidentification rate, simulations were performed for the same range of azimuthal angles as in the efficiency calculations, i.e. 26° to 60°. Only the central scattering segment pair was irradiated by the source in the simulations, therefore, any full energy event registered in the remaining scattering segment pairs was classified as misidentification according to the acceptance requirements discussed in Section 3.1. The result is shown in Fig. 6 where the number of full energy events in each scattering segment pair has been normalised to the total number of full energy events in the whole detector. It can be inferred from Fig. 6 that most of the full energy events are recorded in the correct central scattering segment and only a few misidentification events occurred, mostly in the neighbouring segments. Further on, the analysis gave that the variation in the total misidentification rate over the entire range of azimuthal angles was 1.0 – 1.1 per-mille. The cause of these misidentified events was found to be coherent scattering. This was confirmed by simulating a test case with coherent scattering disabled in the gamma-ray transport, where the misidentified events disappeared.

4.3. The inner radius effect on detection efficiency and misidentification rate

In Fig. 7, the dependency of detection efficiency and total misidentification rate on varying the inner radius is shown. As can be seen, the detection efficiency varies approximately 4 per cent units over the range of the inner radius values. Similarly, the total misidentification rate varies between 2.4 – 3.0 per-mille in a limited range around the minimal inner radius but increases for smaller values. The +5% margin used as a base case seems therefore motivated and also allows for taking into account the manufacturing tolerances of about 0.5 mm.

As can be seen in Fig. 7, the detection efficiency is decreasing with the inner radius which needs some considerations regarding the margin used. Larger margins imply a decreased active detector volume and, hence, a decreased detection efficiency. On the other hand, the larger the margin, the smaller the risk for misidentification, since gamma rays passing near the minimum inner radius may have been transmitted through the collimator corners, and could thereby bypass the target scattering segment that is vital to correctly localise the event. Consequently, there is a conflict between obtaining high detection efficiency and low misidentification rate, when selecting the margin over the minimum radius. From this, the base case of +5% margin may therefore be justified as a reasonable compromise.

5. Summary of optimal detector dimensions

The choice of optimum azimuthal angle could hypothetically be based on a Figure-of-Merit (FoM), which emphasises the performance of the detector in terms of both high efficiency and low misidentification rate, such as the ratio of the efficiency and the misidentification rate. However, since the misidentification rate was found as negligible for all azimuthal angles simulated, it was decided to simply base the optimisation of the azimuthal angle on the optimal efficiency. Consequently, the figure of merit that was maximised, was defined as FoM=\(E_{\times 5\%}\) (Efficiency at the inner radius with +5% margin over the minimum value). In this case, 32° appears as the optimum value for the azimuthal angle. A summary of the optimum configuration for the detector dimensions is given in Table 3.

6. Study of performance of as-optimised detector geometry

For the as-optimised detector geometry (Table 3), the intrinsic efficiency curve was obtained by simulation of photons with varied energy hitting the central scattering segment. The efficiency curve is shown in Fig. 8 (total and full-energy intrinsic efficiency).

The finite width (in the z-direction) of the boundaries between the respective scattering segments [14] could potentially increase cross-talk between the segments, which would lower the detection efficiency. The approximate width of the boundary as provided by one of the manufacturers of such segmented detectors [15] was 0.5 mm, but the actual width may vary in the final manufactured detector. Therefore, an experimental calibration may be needed, as reported in [14], to acquire the efficiency and the misidentification rate of each segment.

In an attempt to quantify this effect, simulations were performed by reducing the width of the scattering segment from 5 mm to 4.8 mm, 4.6 mm, and 4.4 mm, implying a segment boundary width of 0.2 mm, 0.4 mm, and 0.6 mm respectively (total width of the boundaries at both sides of a scattering segment). The results from the simulations are shown in Fig. 9. As shown in the figure, only a small effect on the efficiency and the misidentification rate was observed as caused by finite segment boundaries. Because the chosen read-out method discards crosstalk events, one would anticipate an unacceptable decrease in the detection efficiency in the event of undesired electronic cross-talk between neighbouring segments. In that case, the use of a trigger acting on the net pulse may be introduced to mitigate these detrimental effects on the efficiency, but this would imply an increase
Fig. 4. Plotted geometry in MCNP. This was modelled for the simulations to observe the effect on the full energy efficiency and the total misidentification rate by varying the inner radius around the minimum value. The source was located at the left-hand side of the collimator slit.

Fig. 5. The detection efficiency and the detection volume for various values of the azimuthal angle of the scattering segment ($2\theta$). The error bars represent the 1-sigma estimated uncertainties in the values from the MCNP results.

Fig. 6. Normalised number of 662 keV events (number of full energy events in a particular scattering segment/total full energy events in all scattering segments) is plotted vs the identified segment. Here 0 on the $x$-axis refers to the central scattering segment which was irradiated with the photon source and numbers on either side of 0 refer to the neighbouring scattering segments.

of the misidentification rate, since some real events may be interpreted as cross-talk if depositing energy below the trigger level. Therefore, an analysis was done to investigate the effect on the detection efficiency and the misidentification rate of such a trigger and the result is shown in Fig. 10. In this analysis, the trigger level represents the maximum amount of energy allowed in neighbouring scattering segments before an event is discarded. With a trigger level of 100 keV, the efficiency, assuming no cross-talk, increased from 25% to 28% for 662 keV gamma photons. Because more events with the uncertain origin are accepted,
Fig. 7. Effect of varying the inner radius around the minimum value for 662 keV gamma rays. The inner radius is varied from −20% to +20% around the minimum value and the intrinsic full energy efficiency and total misidentification rate were evaluated for four different azimuthal angles. (a) $\theta = 32^\circ$, (b) $\theta = 33^\circ$, (c) $\theta = 34^\circ$, and (d) $\theta = 35^\circ$. The error bars represent the estimated 1-sigma uncertainties in the values from the MCNP results.

Fig. 8. Variation in the detection efficiency for the different photon energy, for the optimised detector configuration.

Fig. 9. The effect of the finite width of the boundaries between the scattering segments on the efficiency and the misidentification rate using 662 keV gamma photons.
Table 3
Optimum configuration of the detector dimensions. Maximum/minimum manufacturing limits are current values that may change if manufacturing procedures change.

| Detector dimension | Optimum value | Remark |
|--------------------|---------------|--------|
| Length             | 90 mm         | Maximum possible to manufacture based on current manufacturing experience |
| Outer diameter     | 80 mm         | Maximum possible to manufacture based on current manufacturing experience |
| Azimuthal angle of the scattering segment (2\(\theta\)) | 32° | Maximum efficiency |
| Inner radius       | 12.3 mm       | Minimum radius that corresponds to 32° with added +5% margin |
| Scattering segment width | 5 mm | Minimum possible to manufacture based on current manufacturing experience leading to the maximum number of detection elements |

The misidentification rate also increased from 1 per-mille to 50 per-mille. As can be noted, the misidentification rate is not much affected (\(\leq 1\%\)) if a 10 – 20 keV trigger level is used instead. Cross-talk leading to less than that energy being shared with the neighbours is therefore not anticipated to have grave consequences. In particular, since the cross-talk could also be characterised experimentally and accounted for in the analysis of data.

We have also performed simulations to observe the performance of the outermost scattering segments. The intrinsic full-energy efficiency in these segments at 662 keV and 1596 keV was obtained approximately 17% and 8% respectively, which is expected since photons in these segments are more likely to escape before complete absorption. The misidentification rate was found almost negligible at both energies for these outermost segments possibly because of the same reason as for having the low efficiency in these segments.

7. Discussion and outlook

In this simulation study, the geometrical segmentation and outer dimensions of a segmented HPGe detector for measurement on irradiated nuclear fuel were optimised. The dimensions of the collimator and the other experimental parameters were based on foreseeable GET measurement conditions, including 662 keV gamma rays from Cs-137, and the use of a 300 mm long collimator. However, these parameters may change depending on the circumstances and, consequently, the performance of the detector may be affected. Nonetheless, the efficiency and the misidentification rate were found to have limited variation with external settings such as collimator size and positioning. Intrinsic detector properties such as crystal orientation, anisotropic behaviour of the moving charge carriers, and diffusion of charge carriers [16], [17], may introduce cross-talk [18]. In addition, the ability of the analogue front-end electronics to veto cross-talk events is certainly a parameter to take into the investigation in the forthcoming work. The present work represents an attempt to, among other things, study the effect of cross-talk. However, this study comprises only a generic detector and the actual effects may be the subject of future studies, either experimentally or by full-scale pulse shape [19] simulations considering the specific intrinsic crystal properties. Nonetheless, it is anticipated that these properties will not affect the detector performance significantly with the intended use. It was shown in Section 6, that cross-talk amounting to sharing of up to 100 keV causes minor degrading of the misidentification rate. Also, cross-talk has been reported by other authors to be of minor concern for the position resolution in AGATA detectors as reported in a recent study [20], so it may be anticipated that it would be even less important in the application considered in our proposed work since it does not require three-dimensional localisation of the events.
Regarding throughput limitations and high count rate operation, it can be noted that our assumed analysis method discards any event that is not falling within the full energy peak or deposits energy in more than one scattering segment. Therefore, the throughput can be expected to decrease with a high count rate, due to random coincidence events in two or more scattering segments, which would trigger the discard mechanism. Also, random coincidence events in the same scattering segment would move events out from the full energy peak. In this context, it is worth recalling the anticipated use of long and narrow collimator slits, which would cause the opposite challenge, i.e. low count rate. However, in a typical measurement scenario, the expected total spectrum count rate (in the core electrode) will be in the range of 20k – 30k counts/sec which is considered small compared to what a typical HPGe detector and commercially available MCA systems can process. Still, the throughput behaviour of the detector system will be the topic of future studies.

Based on our results it is considered that the segmented HPGe detector is a viable choice for PIE, and the work will continue on its development and the integration of such a detector system in a tomographic setup. More work is planned for the future, which will be directed to perform a selection of measuring parameters in a tomographic scan, such as step length, collimator size, and data acquisition time.

CRediT authorship contribution statement

Vikram Rathore: Conceptualization, Methodology, Writing - original draft, Software, Writing - review & editing, Visualization, Formal analysis, Investigation. Lorenzo Senis: Conceptualization, Writing - review & editing, Validation. Erik Andersson Sundén: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision. Peter Jansson: Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. Peter Andersson: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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