Resurrected from the dead: Full characterization of an old HPGe detector using γ-ray and CT tomographies coupled to standard calibration techniques and simulations

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V. Angelopoulou[1], E. Kouvaris[1], V. Lagaki[1], T.J. Mertzimekis[1,*], P. Papagiannis[2]

[1] *Department of Physics, Zografou Campus, 15784, University of Athens, Greece*
[2] *Medical Physics Lab, School of Medicine, 11527, University of Athens, Greece*

Abstract   A decommissioned co-axial HPGe detector has been recently acquired and returned to operational mode in an effort to build an environmental radiation spectrometer at the University of Athens. The new counting station, GEROS (Germanium for Environmental RadiOactivity Studies), was fully characterized prior to operation to obtain detailed information on its linear response, efficiency and energy resolution. In addition to using point-like calibration sources (^{60}Co, ^{137}Cs, ^{152}Eu and ^{226}Ra), several bulk sample geometries were calibrated by means of an IAEA standard, focusing on soils, sediments and solid materials.

In lieu of deteailed technical specifications, the crystal integrity, especially in regards to the dead layer known to build up over the years was studied by means of γ-ray tomography. The 3D geometry of the crystal was fully reconstructed considering the absorption coefficients, and the dead layer thickness was estimated. The overall crystal alignment inside the case was also checked. The results were verified by placing GEROS inside a medical CT scanner and irradiating it to obtain detailed longitudinal and transverse sections.

The results were combined to provide input data for subsequent MCNP5 simulations. Good overall agreement between simulations and measurements was achieved. Despite some expected loss of resolution, the detector was found to perform substantially well.

Keywords   HPGe detector, efficiency, γ-ray tomography, CT scanning, MCNP

INTRODUCTION

It is very common to examine the operational characteristics of a High-Purity Ge detector before its normal operation for γ-spectroscopy studies. There have been several works in the past on the efficiency, linearity and resolution of HPGe detectors used in a variety of applications and fundamental studies. In the present paper, a p-type, 20% (nominal) HPGe detector, of coaxial crystal geometry was acquired after staying in activity for an unknown number of years (est. over 20). The HPGe given the name GEROS (Germanium for Environmental RadiOactivity Studies) was accompanied by very limited technical specifications provided by the original manufacturer [1]. The experimental and simulation studies to fully characterize the detector, so as it could resume its normal operation for research and educational purposes, is described in this work.

METHODOLOGY

Standard Calibration Techniques

The detector was checked for its linearity, energy resolution and absolute efficiency using various point-like sources. ^{60}Co, ^{137}Cs, ^{152}Eu and ^{226}Ra sources were placed in front of

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* email: tmertzi@phys.uoa.gr

the window of the detector at distances of 10, 15 and 20 cm. The detector operated at 1400 V, connected to standard electronics. 4k-chn spectra were recorded in DAQ for 1 h per measurement and analyzed with SpectrW [2]. The detector linearity was checked in terms of energy vs. channel correspondence, where a second-order polynomial function was used for the fit. The energy resolution (FWHM) was fitted also as a polynomial function of energy, while data for the detection efficiency were fitted with two functions, common in literature [3,4] and a "homemade" two-exponential term equation.

Fig. 1. The bulk samples and the IAEA reference material (left), and the set up (right)

In addition, as GEROS' intended use is environmental radioactivity measurements, its efficiency was measured with five bulk samples of different cylindrical geometries, all containing quantities of an IAEA reference material (IAEA-154) of known specific activity. The low-activity samples were placed directly on the detector window (Fig. 1) mounted in a specially manufactured holder to maximize counting rates. From the measured counting rates of each sample (average measurement time 24 h), the conversion factors to actual specific activity have been determined.

Gamma-ray Tomography

Next, the study focused on determining the full geometry of the co-axial crystal, the exact mounting position inside the aluminum cup and the estimation of the active volume. Build-up of a dead layer is well known to occur in HPGe crystal surfaces when there is absence of bias, allowing Li ions to drift inside the bulk volume and destroy the superconducting properties. The above questions were tackled by performing a systematic γ-tomography study.

For those measurements, a new set up was constructed. GEROS was placed on a X-Y motion platform. A custom collimator made out of four 5 cm x 5 cm Pb bricks was put together to shape a 3 mm x 3 mm hole, which was initially placed coaxially to the HPGe crystal with the help of an alignment laser (see Fig. 2). A weak ^{134}Cs source (t½ = 2.0652 y) was placed behind the hole of the collimator. On the window of the detector there was a predefined grid of positions, which was used to specify the coordinates of the collimated γ-rays spot. As the X-platform was manually moved to a new grid position, the γ-rays irradiated a different part of the crystal.
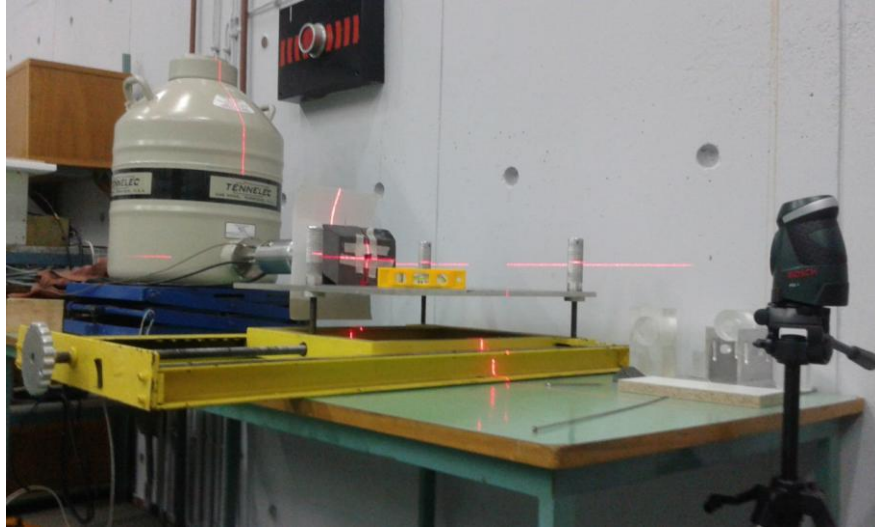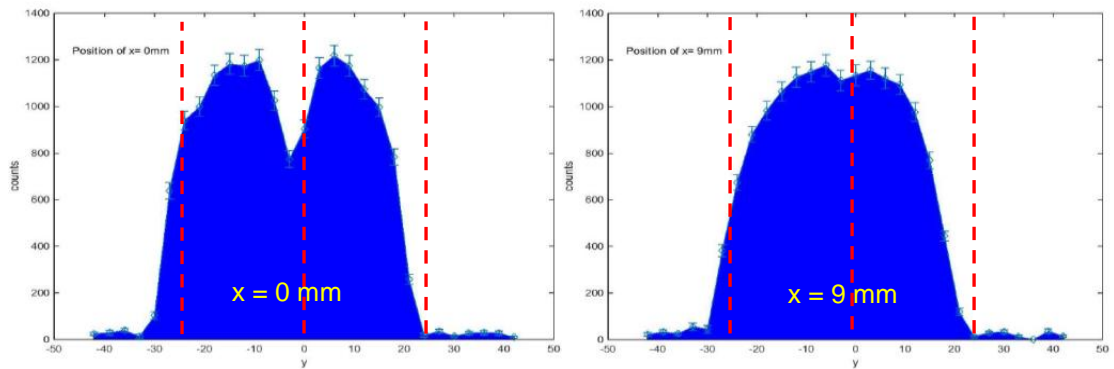
Fig. 2. The experimental set up for γ-ray tomography

In total, 710 10-min long measurements were performed, scanning the full window of the aluminum cup, with a step of 3 mm for each direction. The 604.7 keV (I% = 97.62%) and 795.9 keV (I% = 85.53%) ^{134}Cs peaks were analyzed in the spectra.
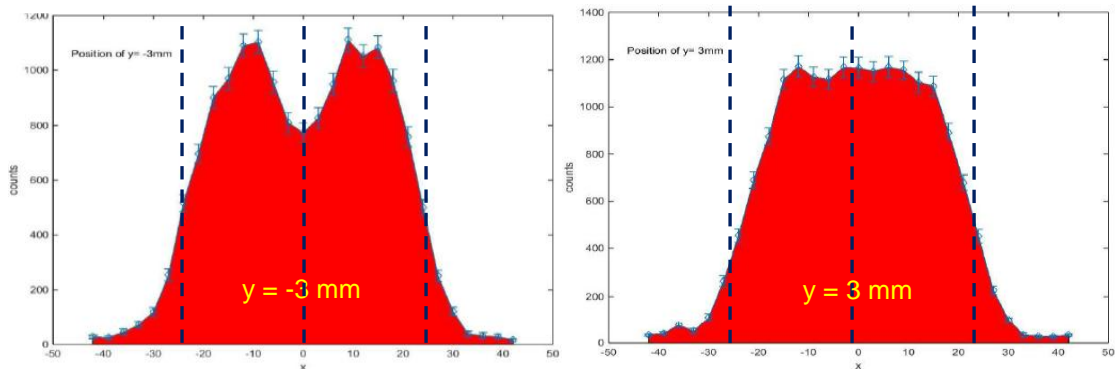
a)

b)

Fig. 3. Diagrams of counts a) vertical and b) horizontal scanning. The dashed lines indicate the nominal center and outer bounds of the crystal.

Diagrams of counts vs. X and Y positions were drawn as seen in Fig. 3. In the expected co-axial geometry, the different thickness of the Ge layer absorbing the emitted source photons would result in a non-uniform distribution of counts in X and Y scans.

By combining all 2D diagrams, a 3D model of the crystal was reconstructed (Fig. 4). It is important to clarify that the 3D model does not show the actual shape of the crystal, but the absorbed energy of the γ-rays penetrating the crystal, throughout its whole volume. In essence, it is the reconstruction of the absorption coefficient 3D map, which is however inversely related to the geometry of the crystal.

With further study of the results, the center, the tilt and the dimensions of the crystal could be estimated in good detail. The center was determined by creating a plot of minimum to maximum recorded counts (N_{min}/N_{max}), around the area where the hole was expected, for each dimension of the X and Y axes. The data were fitted with a Gaussian function to determine the minimum point of the ratio, signifying the minimum position of the absorption coefficient, and thus the center of the crystal.

An asymmetry in the Y axis is apparent in Fig. 3, near the edges of the graphs, that concerns the orientation of the crystal inside the cup. The edges have been used to estimate the internal and external diameter of the crystal. The data near the edges were initialy fitted with a sigmoid function. Keeping in mind that the geometry of the crystal is coaxial, the internal diameter was estimated by measuring the distance between the mean values of the two curves that appear around the center. In analogy to that, the external diameter was estimated for the two curves at the edges. This procedure was repeated for both dimensions and the diameters were calculated.

CT scanning

To complete the investigation of the detector's internal structure and geometry, GEROS was placed in a medical CT scanner (X-ray Computed Tomography) in Lefkos Stavros Hospital. A complete tomography at various X-ray energies (40-120 keV) was performed and the study resulted in detailed determination of the crystal's outer dimensions and exact positioning.
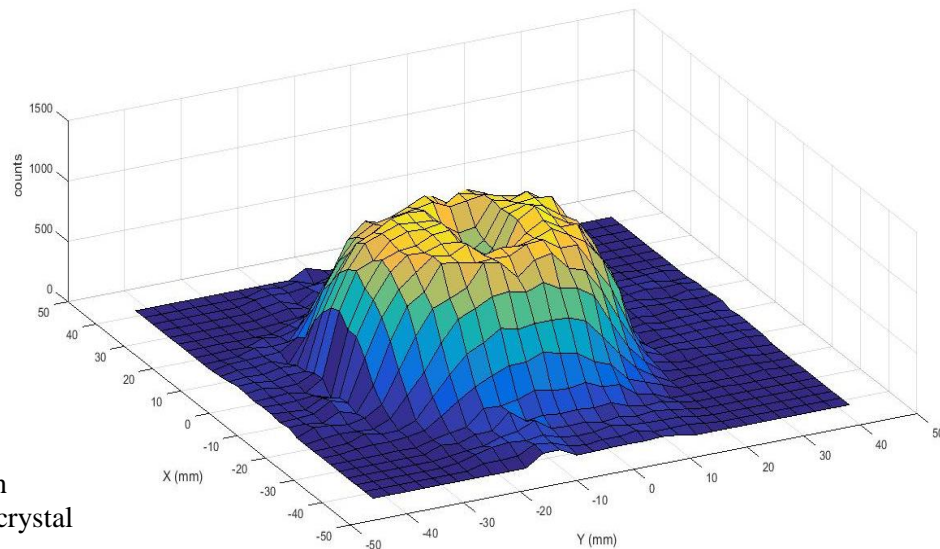

Fig. 4. A 3D reconstruction model of the crystal

RESULTS AND DISCUSSION

Standard Calibration Techniques

In Fig. 5 the linearity, energy resolution and absolute efficiency curves are depicted. The fit with a function $F(x)=Cx^2+Bx+A$ has produced the values A=9.2 keV, B=0.6435 keV/chn

and $C=9.2 \times 10^{-8}$ keV/chn^2. The excellent agreement between fit and data, as well as the tiny value of C, confirms the linearity of the detector.
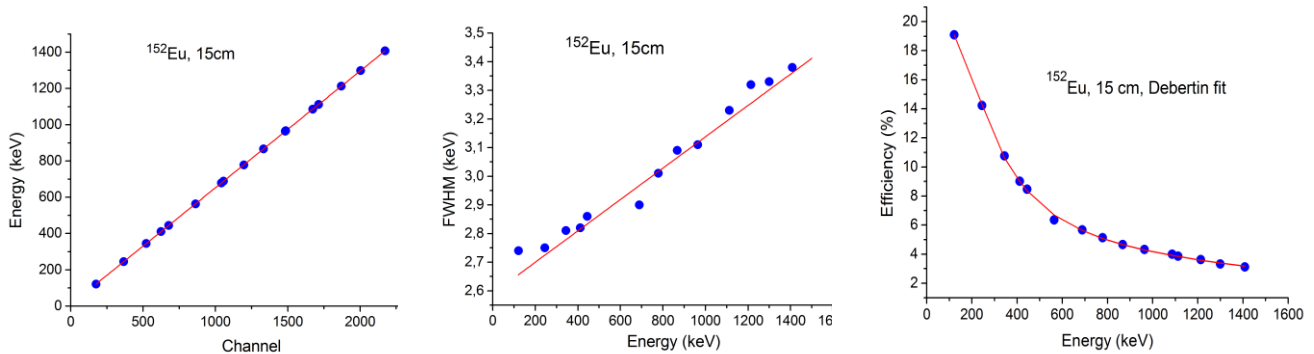

Fig. 5. Linearity (left), energy resolution (middle) and absolute efficiency (right) curves deduced from a ^{152}Eu source placed at 15 cm from the detector's window and fitted with Debertin's equation

From the value of FWHM at 1332 keV, equal to 3.3 keV, a significant degradation of the resolution is evident when compared to the manufacturer's original value (2.06 keV). Despite this loss of resolution, attributed to the long inactivity, GEROS can still be used reliably for environmental studies. Moreover, the absolute efficiency curve is typical for a detector of its kind (in Fig. 5 a Debertin fit is shown) and is in the order of 3-5% for most of naturally occurring isotopes (^{238}U series, ^{40}K etc).

The results of GEROS calibration using the IAEA reference material for several sample geometries produced the conversion factors shown in Table 1. It has to be noted that the IAEA standard is only rich in ^{137}Cs and ^{40}K. In the future, standards of different composition will be used additionally.

Table 1. The conversion factor between counting rate and specific activity for the bulk samples

Mass (gr)		Radioisotope	$t_{1/2}$	Conversion factor
Net weight	*Mixed weight*			
3.245	8.788	^{137}Cs	30.08	4.2699
		^{40}K	$1.28 \cdot 10^9$	3.1979
2.956	9.003	^{137}Cs	30.08	3.3924
		^{40}K	$1.28 \cdot 10^9$	3.4519
19.781	34.095	^{137}Cs	30.08	0.3568
		^{40}K	$1.28 \cdot 10^9$	0.0911
32.736	61.445	^{137}Cs	30.08	0.1806
		^{40}K	$1.28 \cdot 10^9$	0.0350
92.48	107.062	^{137}Cs	30.08	0.0614
		^{40}K	$1.28 \cdot 10^9$	0.0068

Gamma ray Tomography

The exact position of the crystal's center was pursued in terms of finding the minima of the ratio N_{min}/N_{max}. Gaussian fits were performed on these ratios (Fig. 6) suggesting a minimum exists at (0,-2 mm), hinting a crystal displacement.

Furthermore, a closer look at Fig. 3, considering the orientation of the crystal, suggests a slight tilt of the crystal inside the aluminum cup. Specifically, while comparing the two scans at the estimated center in both dimensions, the crystal appears to be symmetrical towards the x axis, whereas in the y axis there is a profound asymmetry. This is in agreement with the γ rays penetrating more material on the negative side of the y axis than on the positive, an observation that could only be explained by a tilt.

An important structural detail in the co-axial type is the existence of an internal hole in the cylindrical shape of Ge (resembling a "Π" shape in side view). The size of this inner (missing) cylinder was not known beforehand. However it is important information as it affects the total active volume of the detector. In Fig. 8, sigmoidal curves were used to determine the radius of the inner cylinder, but also the outer (active) diameter of the crystal. It is important to note that the latter result excludes the dead layer of the crystal. The results are summarized in Table 2.
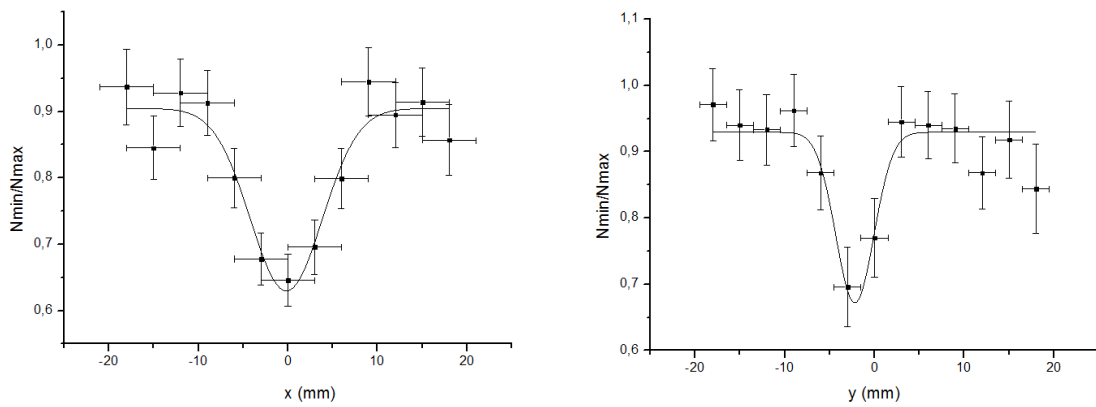

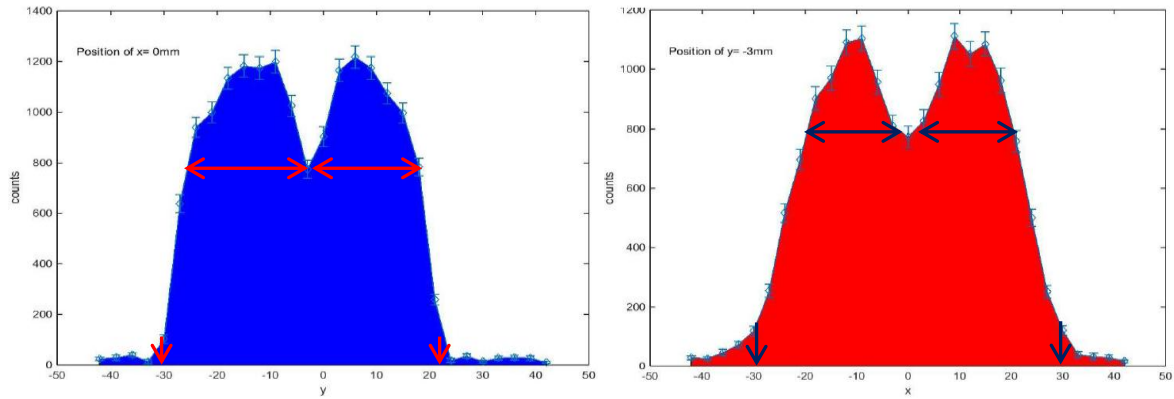**Fig. 6**. Gaussian fits to locate the mimima in X and Y scans.

Fig. 7. Central scaninngs of vertical and horizontal dimensions of the crystal

Despite a difference existing between the values estimated for X and Y scans at first sight, the two values agree well within error. Consequently, the weighted average values were calculated as 9 and 47 mm for the internal and external diameter of the crystal, respectively.

Table 2. The diameter of the hole and the crystal as measured in both dimensions

	Internal Diameter (mm)	External Diameter (mm)
x	8.0 ± 1.5	46.0 ± 1.5
y	12.0 ± 3.0	48.0 ± 3.0

Table 3. Comparing diamensions between the two experimental methods and the nominal values

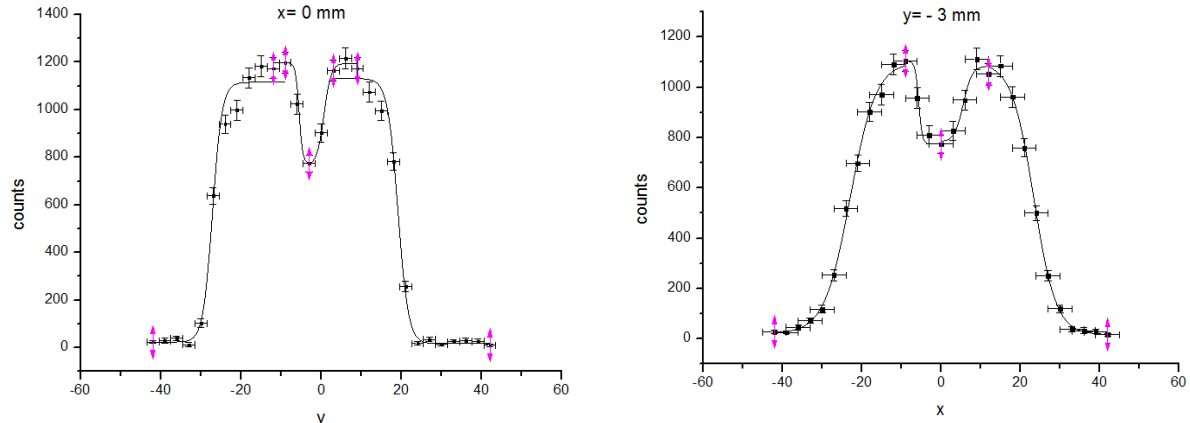|	Manufacturer	γ-ray tomography	CT scanning
Internal diameter (mm)	14	10.0 ± 2.2	N/A
External diameter (mm)	53.6	47.0 ± 2.2	53.4
Length	53.4	N/A	52.5

Fig. 8. Sigmoid fit of the central scans of the crystal

CT Scanning

All results mentioned above, extracted by means of γ tomography were subsequently verified by 3D Computer-Aided Tomography (CT). Several slices of the detector were reconstructed producing pictures as the ones illustrated in Fig. 9. The discovered tilt of the crystal was found undoubtedly to exist (side view) inside the aluminum cup. The external diameter was measured at 53.4 mm, however it was impossible to see the hole on the inside, since the X-rays from the CT, even at the maximum available energy, are fully absorbed within some mm after entering the Ge (Z=32) crystal. It is worth noting that the diameter measured with the X-rays matches the nominal value on the text sheet. Comparing it with the 47 mm resulted from the γ-ray tomography, where only the active material can be measured, a difference of 4 mm appears. This points to a rather thick dead layer of 2 mm having formed around its surface due to its prolonged period of inactivity. An additional result of the CT scan is the measurement of the crystal length that could not be deduced by the γ-tomography measurements.
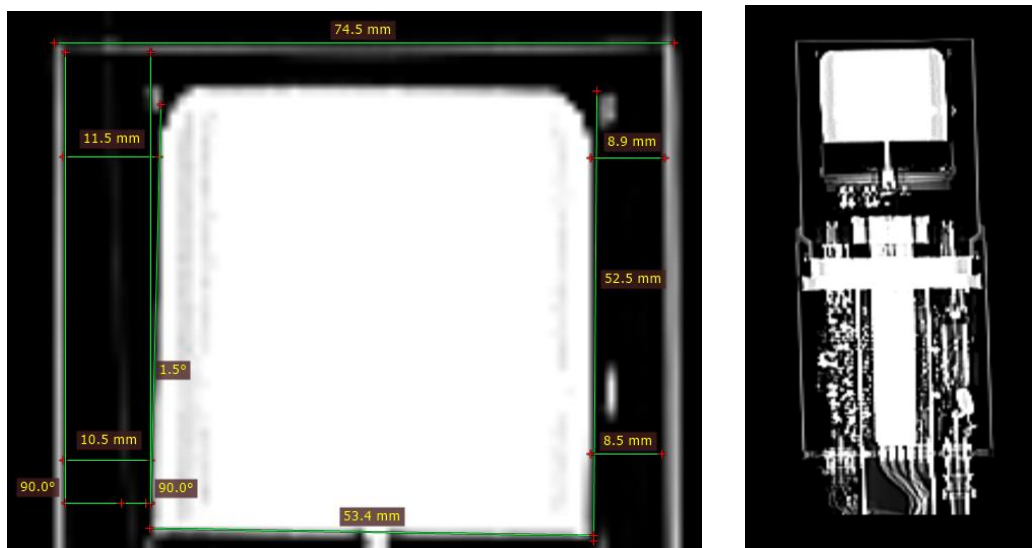

Fig. 9. Side (left) and full view (right) of the detector under X-rays in a medical CT scanner

MCNP Simulations

All extracted information on the geometry and the efficiency of the detector were used to carry out a Monte Carlo simulation using MCNP5 [4]. This work is still in progress, however preliminary results appear in good agreement with the experiment (Fig. 10). Additional simulations will focus on estimating the dead layer thickness and active volume of the Ge crystal.
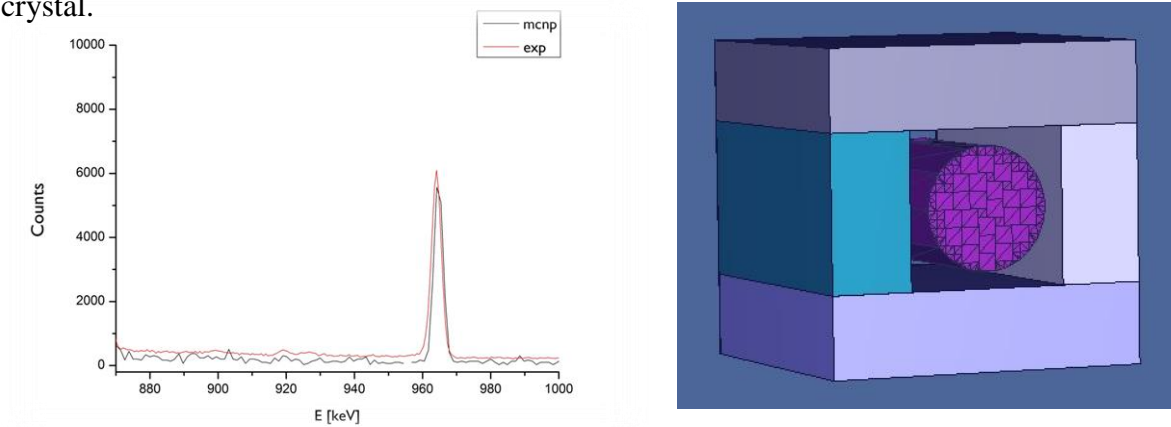

Fig. 10. (Left) Experimental and MCNP-simulated spectra for a randomly selected [152]Eu peak (Right) The model geometry used in MCNP5 simulations

CONCLUSIONS

An old HPGe detector, GEROS, was fully characterized using a combination of experimental techniques, i.e. studies of linearity, energy resolution and absolute efficiency using point-like sources; bulk sample calibrations with an IAEA reference material; γ tomography; and CT scans. The fine geometrical features of the detector have been deduced and cross-verified, while preliminary simulations with MCNP5 show an overall good agreement with the experimental data. Despite its age, GEROS has been found suitable for a research program focused on environmental radioactivity measurements and/or educational activities.

References

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