HPGE DETECTOR APPLICATION ON MONITORING ENVIRONMENTAL SAMPLES AROUND THE ACCELERATOR

Yadong Ding, Qingbin Wang, Zhongjian Ma, Qingjiang Zhang, MingyangYan
IHEP, CAS, Beijing 100049, China

Abstract

Massive experimental works are aimed to clarify the structure of detector including CT with X ray machine, determining the thickness of dead layer with collimating radioactive source and ect. Measuring structure and size of the detector by X-ray computed tomography, measuring the dead layer thickness of detector's front surface and side surface though collimated point source method, scanning the dead layer distribution of the entire detector. A finite element analysis software name CST is used to simulate electric field distribution of the HPGe detector. Calibrating the efficiency of HPGe detector by means of point source and soil standard matter, A Monte Carlo software called MCNP is used to simulate detector efficiency preliminarily according to the structure parameters of the factory, optimizing and verifying simulated results on the basis of measured results. At last, the comparison of the simulated and the experimental data showed very good agreement.

INTRODUCTION

Due to its high resolution, HPGe detectors are able to distinguish between photons of very close energies, which are widely used for analysis of gamma emitters radioisotopes.[1] Moreover, it does not require chemical separation and can be measured in bulk form. Hence, it is very suitable for environmental sample monitoring, even for induced radioactivity and activation analysis.

Nevertheless, the experimental determination of the response function for HPGe detector presents some difficulties. It demands a large number of gamma emitters in order to account for the energy range of interest. And, the samples will be measured in the same counting geometry as standard sources.[2-3] While, there are so many different types, shapes and materials samples to be analyzed. It is impossible to calibrate detector's efficiency for each type of sample.

Fortunately, Monte Carlo simulation of detector systems is become an alternative or complement to experimental efficiency calibration.[4-6] However, when calculating detector responses, full energy peak efficiency, for HPGe detectors through Monte Carlo simulation, one often observes a discrepancy between calculated and empirical data. It is generally considered that this deviation is probably originated from three aspects, including the structure and size of the detector, the thickness of the dead layer, the distribution of electric field.

PARAMETERS OF THE HPGE DETECTOR

Detector system

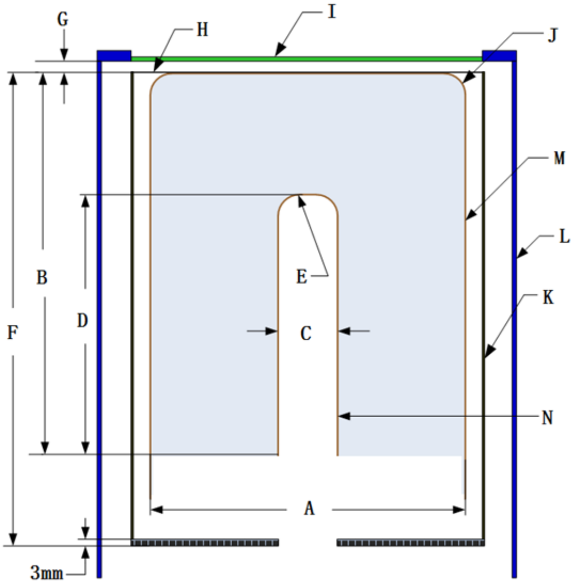

Figure 1: Structure schematic of HPGe detector.

According to the geometry of the crystal, there are planar, coaxial, well three types of HPGe detectors. In this study, a PopTop n-type closed-end bulletized HPGe detector used was manufactured by ORTEC and specified as having a 50% efficiency relative a 3in. ×3in. NaI(Tl) detector at 1.33MeV.

Definitions and materials of HPGe detector are shown in Figure 1, as follows. A: crystal diameter 64mm, B: crystal length 73.7mm, C: hole diameter 8.6mm, D: hole depth 65.4mm, E: nominal radius 5mm, F: cup length 105mm, G: space 4mm, H: Al/Mylar 0.03mm/0.03mm, I: Be 0.5mm, J: nominal radius 8mm, K: Al 0.8mm, L: Al 1mm, M: Ge/B dead layer 0.3μm, N: Ge/Li dead layer 700μm.

Structure parameter

In order to verify the physical dimensions of the crystal, as well as accurately determine the actual position of the crystal within the aluminium casing, the detector was scanned by X-ray computed tomography.

The length and diameter of the crystal determined from X-ray image match the data provided by the manufacturer, to within a few tenth of a millimetre. The length is a little difficult to accurately determine since the cylindrical shape of the crystal projection on the X-ray image gives a curved front projection when the beam is not exactly parallel to the front of the crystal. The radius of the bulletizing at the front of the crystal was determined to be almost same as indicated on the blueprints. The crystal-to-end cap distance is significantly larger than the nominal value, was estimated to be 5mm.

Dead layer thickness

Dead layer exists on the surface of the entire crystal, which could be expressed as front, side, back and inner four different regions. The total thickness of dead layer is considered in two terms: the actual DL in which charge collection efficiency is zero, photons interacting there yield no pulse, the partially active layer, which is a zone of low collection efficiency.

A radioactive source and a lead source collimator are used to measure the thickness of dead layer. The energy of source should be low enough to ensure that the number of photons penetrated the central hole of crystal is negligible. A source collimator was designed to position in different ways, so the photons emitted from the source could hit the HPGe detector surface at different angles of incidence relative the crystal surface. Full energy peak count for different angles of incidence were recorded for 59.54keV photons from a ^{241}Am source.

The thickness of the dead layer could be calculated from the relative change in the count between different angles. Take 45° and 90° for example, the ratio between the two measurements is given by Eq.1 below. When measuring on the front of the detector, the attenuation of Mylar should be considered.

$$\begin{aligned}\frac{N_{45}}{N_{90}} &= \exp\left(-\mu_{\mathrm{Al}} d_{\mathrm{Al}}(\sqrt{2}-1)\right)\\ &\times \exp\left(-\mu_{\mathrm{Ge}} d_{\mathrm{Ge}}(\sqrt{2}-1)\right)\\ &\times \exp\left(-\mu_{\mathrm{Be}} d_{\mathrm{Be}}(\sqrt{2}-1)\right) \qquad (1)\end{aligned}$$

In Equation 1, N_{45} is the count rate at 45° and N_{90} is the count rate at 90°; μ_{Al}, μ_{Ge} and μ_{Be} are the linear attenuation coefficients for aluminium, germanium and beryllium; d_{Al}, d_{Ge} and d_{Be} are the thickness of aluminium, germanium and beryllium.

Scanning the detector

The detector was scanned by the above-mentioned source collimator, which is to investigate the uniformity of crystal surface. The lead collimator was perpendicular to the surface of the detector. The scanning was done along four parallel lines of detector housing (east, west, south, north) on the side, the scanning was done along two mutually perpendicular lines (east to west, south to north) on the front. Peak count rates were recorded at 5mm intervals. The scanning results are shown in Figure 2 and Figure 3.

According to the calculated results, the dead layer of front surface and side surface of the detector is not completely uniformity.

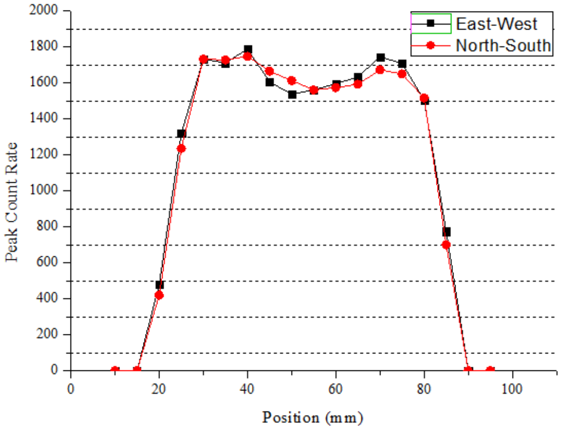

Figure 2: Scanning results of front dead layer.

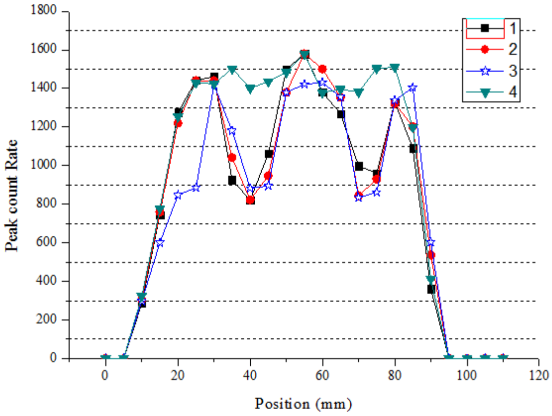

Figure 3: Scanning results of side dead layer.

Influence of the electrical field

In order to give an intuitive analysis of the electric field distribution, a finite element analysis software (Ansoft-Maxwell 3D) is used to simulate this detector. The simulation result is shown in Figure 4.

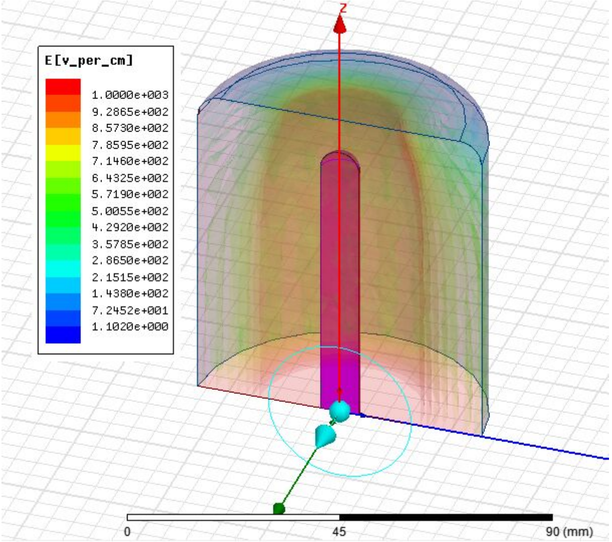

Figure 4: Electric field distribution on the cross section of the detector.

SIMULATION AND VERIFICATION OF DETECTOR EFFICIENCY

Preliminary simulation

Physical model of detector was constructed according to the dimensions provided by manufacturer. In efficiency experiment, two kinds of radioactive source were applied on detector calibration. Point standard sources, were placed on the axis of the detector, and had a distance of 25cm away from detector. Reference material of soil was packed in polyethylene sample box, and lay on the detector. The filling height was 6.605cm, and the filling radius was 3.5cm. The diameter and height of sample box are 7.5cm and 7.0cm. Densities of two materials could be separately calculated though the data of mass and volume, and the composition of two materials was analysed by X-ray fluorescence. Based on the above parameters, efficiencies were preliminarily calculated by MCNP programme. The simulated results are listed on Table 1 and Table 2.

Table 1: Simulated Efficiency and Experimental Efficiency of Point Sources

Energy (keV)	Simulated efficiency	Experimental efficiency	relative deviation
59.541	3.41E-03	2.53E-03	34.54%
778.905	1.03E-03	8.99E-04	14.83%
1408.013	6.82E-04	5.91E-04	15.40%

Table 2: Simulated Efficiency and Experimental Efficiency of Soil Standard Sample

Energy (keV)	Simulated efficiency	Experimental efficiency	relative deviation
59.5409	3.46E-03	0.02835	21.91%
661.657	1.55E-02	0.014361	7.72%
1173.228	1.05E-02	0.009247	11.34%
1332.492	9.71E-03	0.008476	14.56%

Optimization simulation

The dead layer has an effect on the detection efficiency of γ rays. From the linear attenuation curves, low energy γ ray has a weak power to penetrate substance, perhaps only a few millimeters. The front dead layer lead low efficiency to low energy γ ray. High energy γ ray has a strong force to penetrate matter, even be able to penetrate the entire detector, so efficiency of high energy photons mainly determined by the side dead layer. Medium energy γ ray can penetrate about a few centimeters, and its efficiency is affected by the inner dead layer.

Simulation was carried out in the case of point sources. The thickness range of front dead layer and side dead layer is present ahead. Adjusting the thickness gradually, until the calculated results agreed with the experimental results. The thicknesses of front, side, inner dead layer are 0.15mm, 1.2mm and 1.28mm. After adjusting, experimental efficiency and calculated efficiency are in good agreement, the maximum deviation is within 2%, and the results are shown in Figure 5.

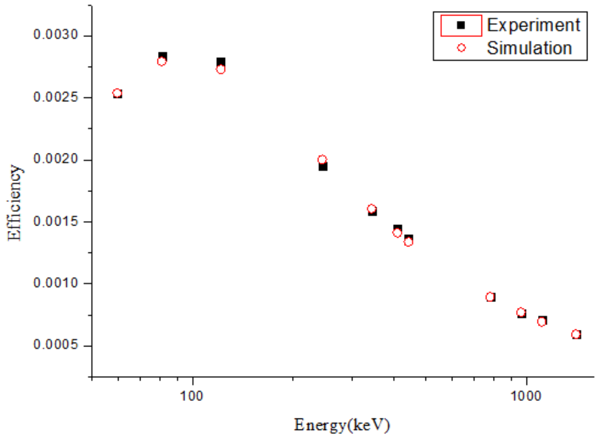

Figure 5: Detector efficiency after adjusting.

Verification simulation

By adjusting the thickness of the afore-mentioned dead layer, so that the simulated efficiency and the experimental efficiency of the detector is within the maximum deviation of 2.0%. Again, using the detector structure after adjusting to simulate efficiency of standard soil sample, where deviations between simulated efficiency and the experimental efficiency are within 4.0%, and the results are shown in Figure 6.

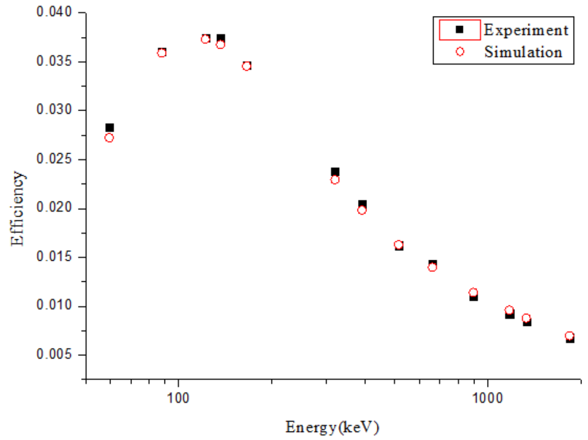

Figure 6: Verification of detector efficiency.

CONCLUSION

In this study, we use MCNP program to simulate photon detection efficiency of HPGe detector application on monitoring environmental samples around the accelerator. Massive experimental works are aimed to clarify the structure of detector including CT with X ray machine, determining the thickness of dead layer with collimating radioactive source. A finite element analysis software name Maxwell is used to simulate electric field distribution of the HPGe detector. The comparison of the simulated and the experimental data showed very good agreement.

REFERENCES

- [1] International Commission on Radiation Units and Measurement (ICRU), “Gamma-Ray Spectrometry in the Environment”, ICRU Report 53, 1994.
- [2] Aline S.E. Santo, Francis G. Wasserman, Claudio C. Conti, “HPGe well detector calibration procedure by MCNP5 Monte Carlo computer code”, *Annals of Nuclear Energy*, 46 (2012) 213-217.
- [3] Chhavi Agarwal, Sanhita Chaudhury, A. Goswami, *et al.*, “Full energy peak efficiency calibration of HPGe detector for point and extended sources using Monte Carlo code”, *J Radioanal Nucl Chem* (2011) 287:701-708.
- [4] Jonas Boson, Goran Agrena, Lennart Johansson, “A detailed investigation of HPGe detector response for improved Monte Carlo efficiency calculations”, *Nuclear Instruments and Methods in Physics Research* A, 587 (2008) 304-314.
- [5] Pavel Dryak, “Experimental and MC determination of HPGe detector efficiency in the 40–2754 keV energy range for measuring point source geometry with the source-to-detector distance of 25 cm”, *Applied Radiation and Isotopes*, 64 (2006) 1346-1349.
- [6] C.C. Conti, I.C.P. Salinas, H. Zylberberg, “A detailed procedure to simulate an HPGe detector with MCNP5”, *Progress in Nuclear Energy*, 66 (2013) 35-40.