Design of a collimator–detector system for tomographic measurement of nuclear fuel, using the Monte Carlo simulation code GEANT

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ABSTRACT

This study is a part of an on–going project which aims at performing tomographic measurements on irradiated nuclear fuel assemblies. The goal of the project is to determine the distribution of the ^{140}Ba activity in order to verify new calculations regarding the thermal power distribution. We here decribe the basic feature of a test setup, namely the collimator–detector system. This system will be designed from simulations using the GEANT code. Preliminary results show that iron is an adequate material for the collimator in the test setup.

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1 INTRODUCTION

In the nuclear fission process ^{140}Ba is produced. The ^{140}Ba decays through β^- emission to ^{140}La. By β^- emission ^{140}La decays to ^{140}Ce which, in turn, decays by emission of 1596 keV gamma radiation. Measuring this radiation the power outtake from the fission process can be obtained. The nuclear fuel assembly consists of rods containing the fuel. Rotating and measuring gamma-radiation from a small part of the nuclear fuel assembly the power outtake from each rod can be obtained. This is the tomographic measuring method.The tomographic measurement method requires a collimator–detector system see fig 1. The collimator–detector system will consist of collimator and detectors. The collimator–detector system should be designed so that only gamma radiation from a small, well defined section of the assembly

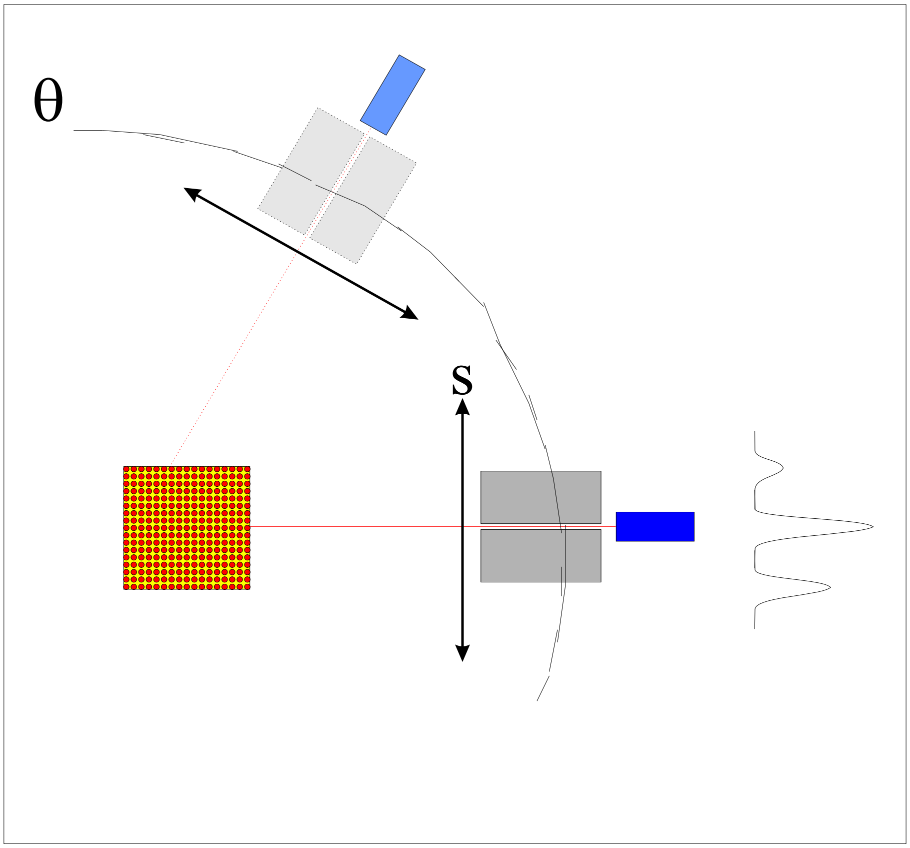

Figure 1: *Schematic picture of the measured nuclear fuel assembly and the collimator–detector system. The picture also shows how the collimator–detector system will be rotated around the assembly to perform a tomographic measurement.*

will hit the detector and also prevent crosstalk between the detectors. This can be achieved with narrow collimator slits in the collimator.

Before building the real experimental setup a test will be performed with a dummy setup. It is for this dummy setup the response of a collimator–detector system has been simulated. For the dummy setup, ^{137}Cs is used as radiation source which emit gamma with an energy of 662 keV.

2 SIMULATION CODE

The simulations were performed by using the Monte Carlo program GEANT version 3.21. The geometric concept of GEANT is an empty volume, in which volumes of arbitrary materials appropriate for the case of interest may be defined. Using a ray–tracing method,the energy deposition of gamma rays, can be calculated in the various parts of the volume. The initial gamma rays are in general randomly generated but may be directed towards specific points.

User defined inputs are: the geometry for the system studied, the radiation kinematics at a starting point, the physical properties of the material used in the various parts of the volumes and the location and orientation of the various volumes.

In addition to the user inputs, default routines describing and calculating energy loss in the various materials, cross section and radiation properties are implemented.

A detailed account for the GEANT code is found in [1].

3 SIMULATED GEOMETRIES

In this section, the various geometries used in the simulation will be discussed. Two cases have been considered:

(A) One collimator + one detector
(B) Four collimators + four detectors

Case A was considered in order to get acquaintance with the GEANT code. By extending case A to four collimators, a more realistic geometry was achieved, case B.

3.1 CASE A

The geometry for this case is shown in figs. 2 and 3. The collimator

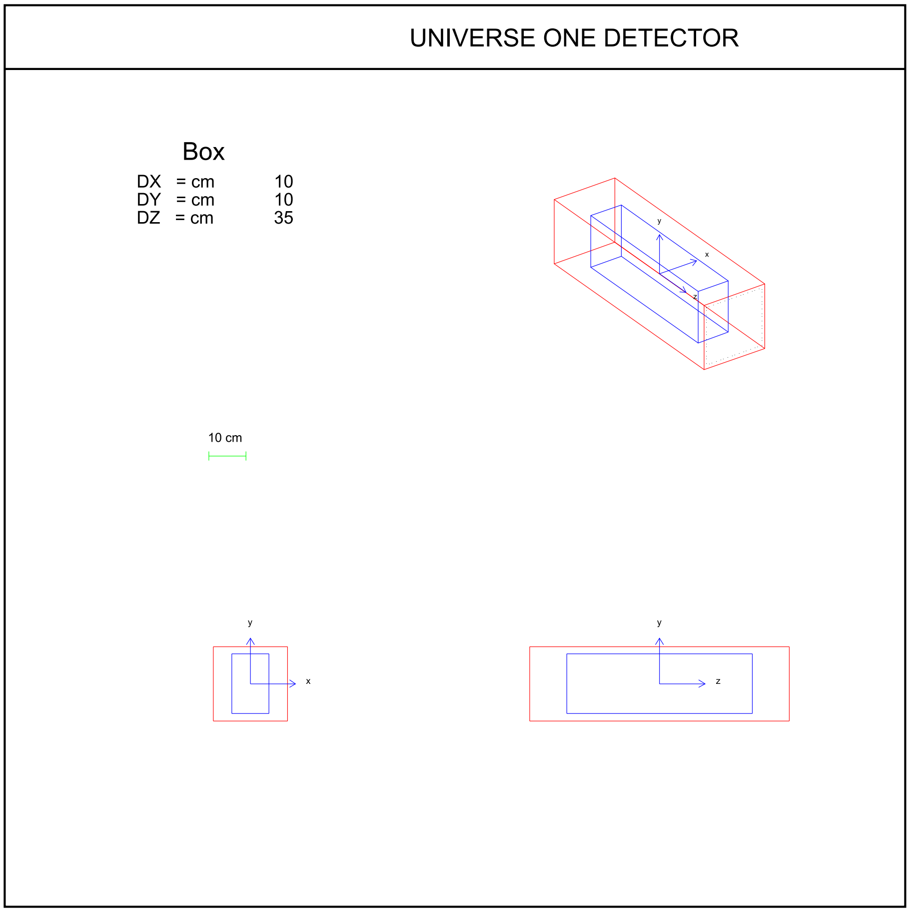

Figure 2: *The position of the collimator inside the GEANT volume. The doted line is a radiating plane that radiates gammas towards the collimator–detector system*

consists of an iron block of $20\times20\times50$ cm^3 containing a collimator slit and a volume for the detector. The width of the collimator slit was 2 mm and the height and length were 3 cm and 30 cm, respectively. The geometry of the detector is a circular plate with 3 cm radius and 1 cm width. Position and geometry of the detector are shown in figs. 4 and 5. Using this geometry some preliminary function tests were performed in order to conclude that all routines were properly implemented.

3.2 CASE B

In this case the collimator–detector system was divided into four parts, each part containing one collimator slit and one detector. The dimensions for each

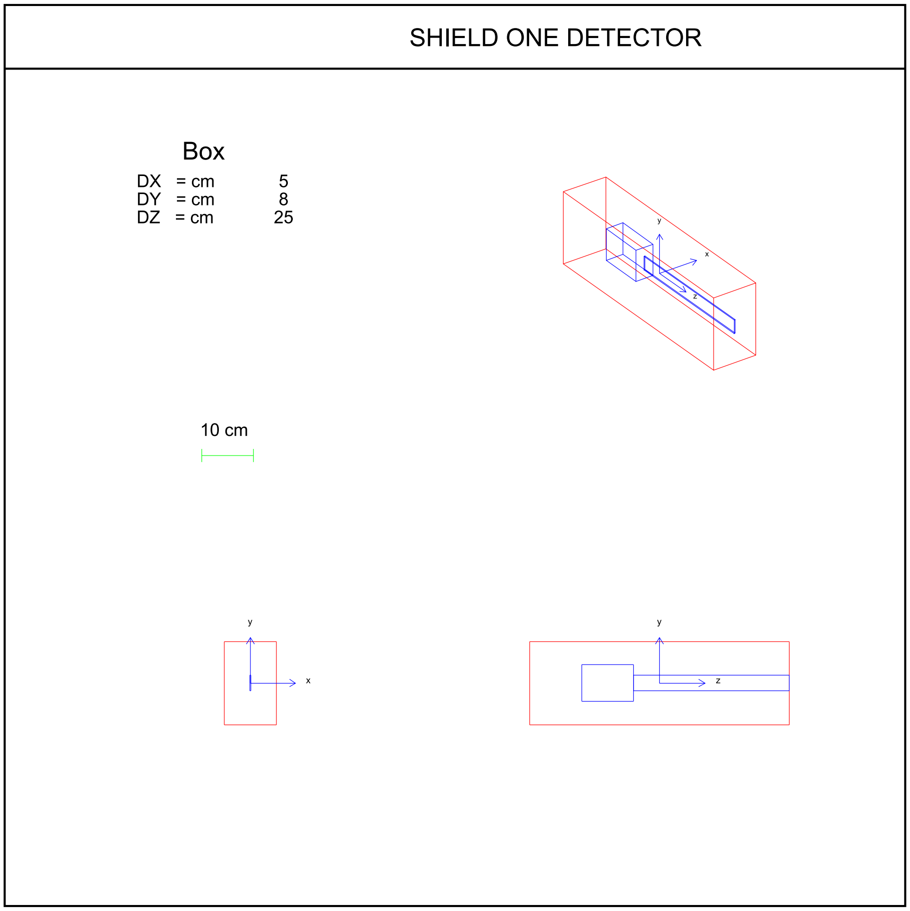

Figure 3: *The inner structure of the collimator, with collimator slit and volume for the detector.*

part were height 10 cm, width 4.0 cm and length 40 cm. Each of these parts were then divided into four new parts of 10 cm length. Three of these parts contained the collimator slits and the fourth the volume for the detector, see Figure 6. This was done in order to determine the amount of radiation that was absorbed in different parts of the collimator. To prevent back scattering into the detectors all collimator material behind the detectors are removed. This can be seen in Figure 7. No calculations were made to check this effect. The geometry and location of the detectors were the same as in case A. The only difference was that the width of the collimator and the detector volume were smaller in order to keep the distance between the centers of the two outer detectors to 12 cm. All four detectors was of the same size and material.

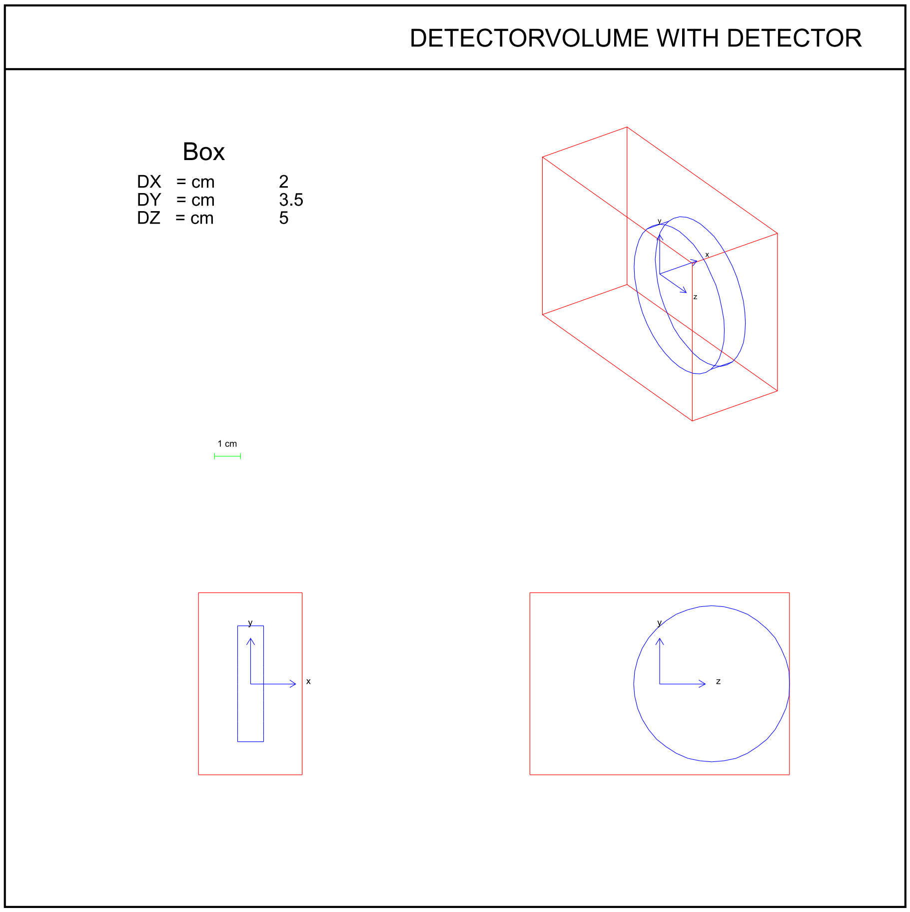

Figure 4: *The position and orientation of the detector element in the detector volume*

4 SIMULATIONS

Three aspects of the collimator-detector system were investigated:

1. The efficiency of the collimator. This means the collimator´s ability to prevent unwanted gamma radiation to reach the detector
2. The possibility that a gamma ray scattered in one of the detectors will reach a neighbouring detector and how to prevent such crosstalk.
3. Detector response.

All simulations were preformed by using gamma radiation with an energy of 662 keV.

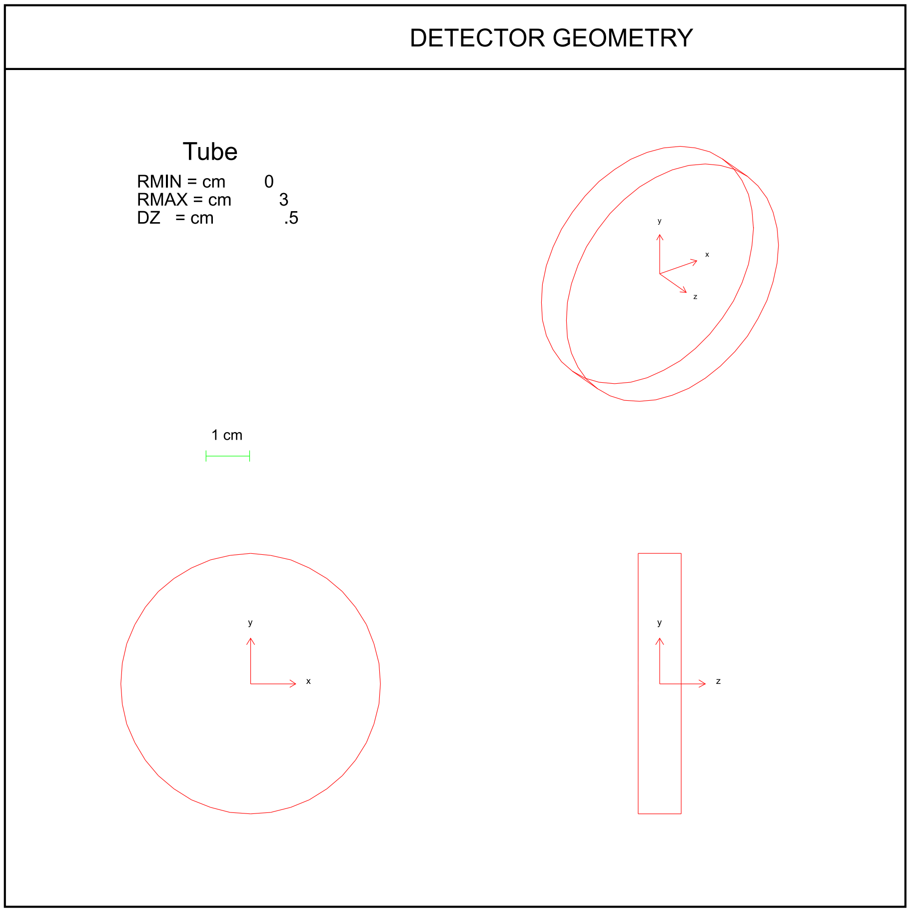

Figure 5: *The geometry of the detector element. A circular plate with 3 cm radius and 1 cm width.*

4.1 COLLIMATOR EFFICIENCY

In this context it may be possible to first perform a simple calculation of the expected count rate in the detectors. The following estimate was adopted. Assuming an ideal collimator and a radiating area A_1 at a distance R from the detector, see fig 8. Let the area for the collimator slit be A_3. Then the radiation from area A_2 can only hit the detector assuming an ideal collimator. Using the notation from fig 8 x and y can be calculated according to

$$x = R \tan\theta - l_1 = R\frac{l_1}{l_3} - l_1 \tag{1}$$

$$y = R \tan\gamma - l_2 = R\frac{l_2}{l_3} - l_2 \tag{2}$$

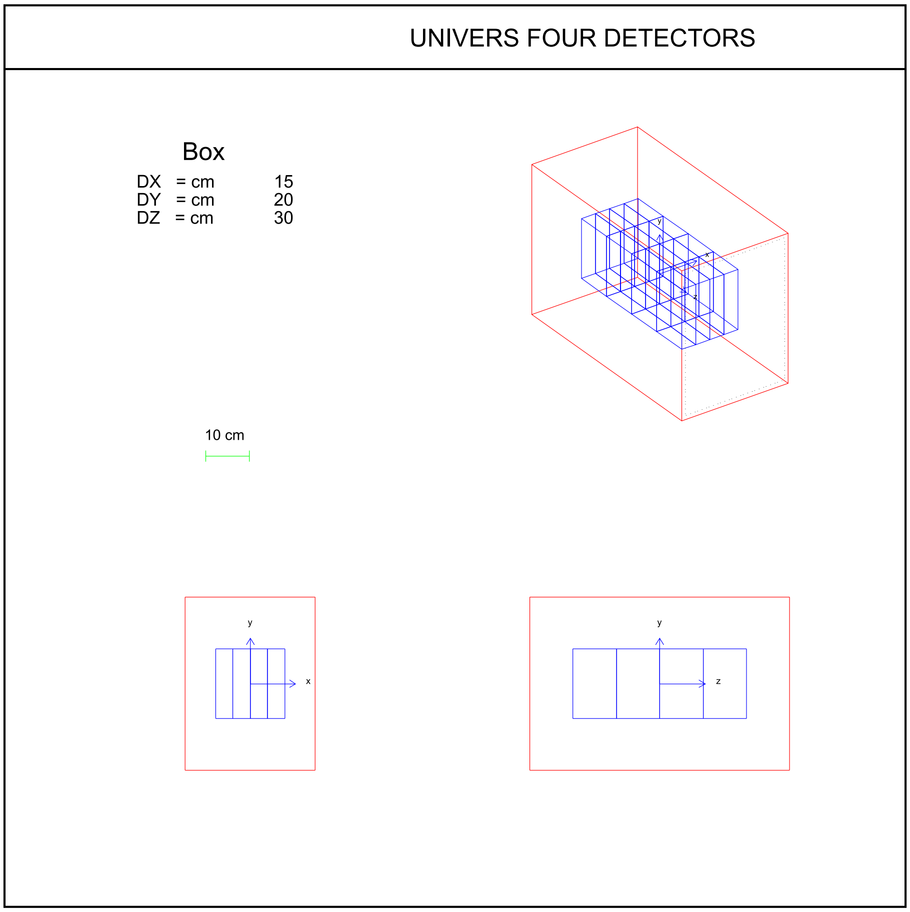

Figure 6: *The 16 parts in which the collimator is divided. 12 parts containing the collimator slits and four parts containing the volume for the detectors. The doted line is a radiating plane that radiates gammas towards the collimator–detector system.*

Hence

$$A_2 = (l_1 + 2x) \times (l_2 + 2y) \tag{3}$$

If $R \gg \sqrt{A_3}$ and $A_1 \gg A_2$ then a approximation for the ratio between the solid angles for A_3 and a sphere is

$$\Delta\Omega = \frac{A_3}{4\pi R^2} \tag{4}$$

This then gives that the probability that a photon generated in a random direction in the area A_1 will hit the detector is

$$P = \frac{A_2}{A_1}\frac{A_3}{4\pi R^2} \tag{5}$$

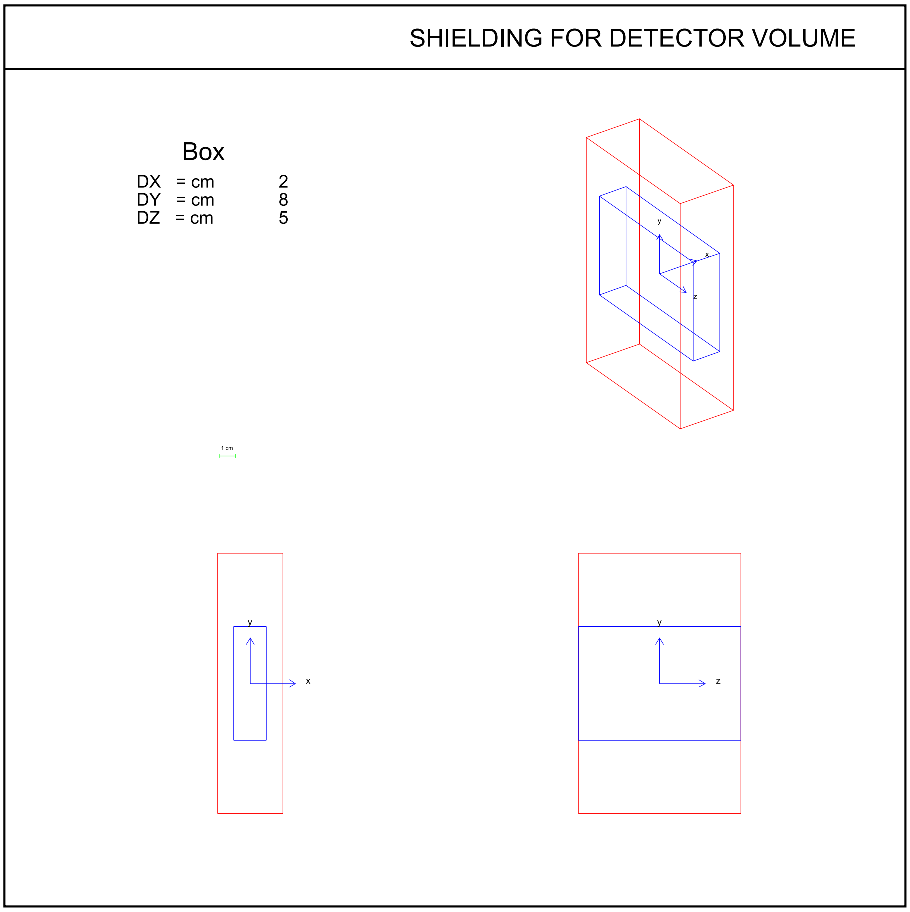

Figure 7: *The part of the collimator that contains the detector volume. All the collimator material behind the detector is removed to prevent from back scattering into the detector*

Since the gamma rays are emitted in the solid angle of a half sphere towards the collimator–detector system this gives

$$P = \frac{A_2}{A_1}\frac{A_3}{2\pi R^2} \tag{6}$$

In this simulation 10^8 events were calculated. The gamma rays were emitted isotropically towards the collimator–detector system from a plane, with dimensions 30×40 cm^2, at a distance of 40 cm from the detectors.

4.2 CROSSTALK

To determine the magnitude of this effect it was assumed that the gamma rays hit only one of the four detectors. By checking the amount of the gamma

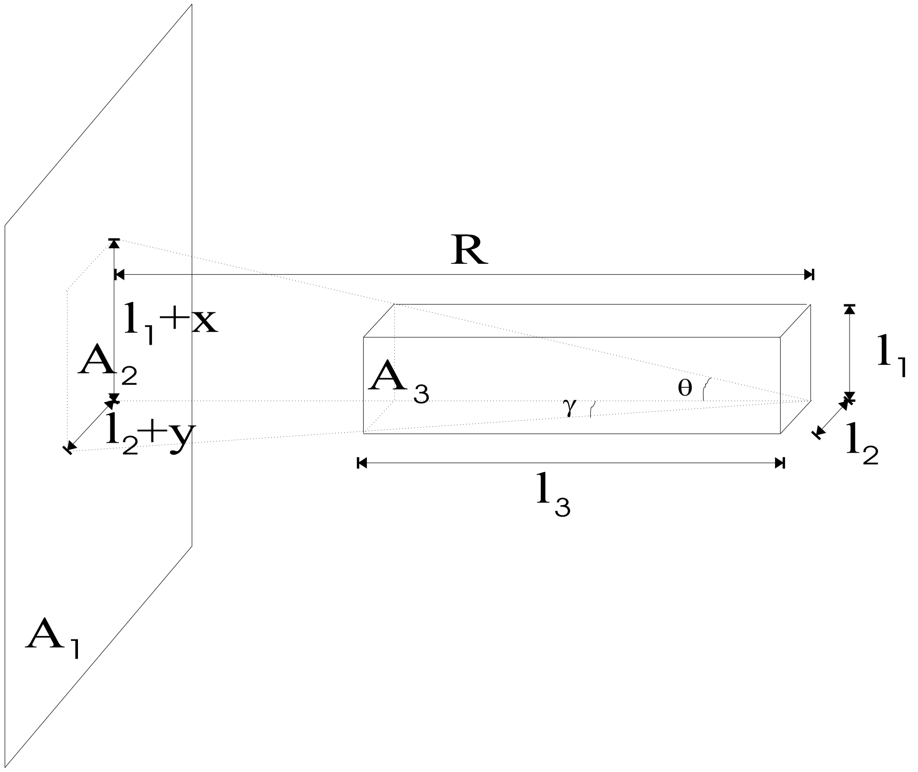

Figure 8: *A_1 area of the radiating plate and A_3 area of the collimator opening. Radiation from area A_2 can only hit the detector assuming an ideal collimator. R distance between the detector and the radiating plate.*

rays that were scattered from this detector into the other ones it was possible to define a measure of the crosstalk. This measure was defined as the ratio between the number of events scattered out from one detector into another and the number of events incident on the first detector.To get satisfactory statistics 100000 events were calculated.

4.3 DETECTOR RESPONSE

It is not possible to introduce line broadening due to the resolution of a detector using GEANT. For this reason, the response funtion of fig 9 was convoluted to a normal distribution curve. The Box–Müller method [2] was used to generate normally distributed random numbers and a resolution of 10% was used for the detectors. This resolution is appropriate for the detectors of the planned setup.

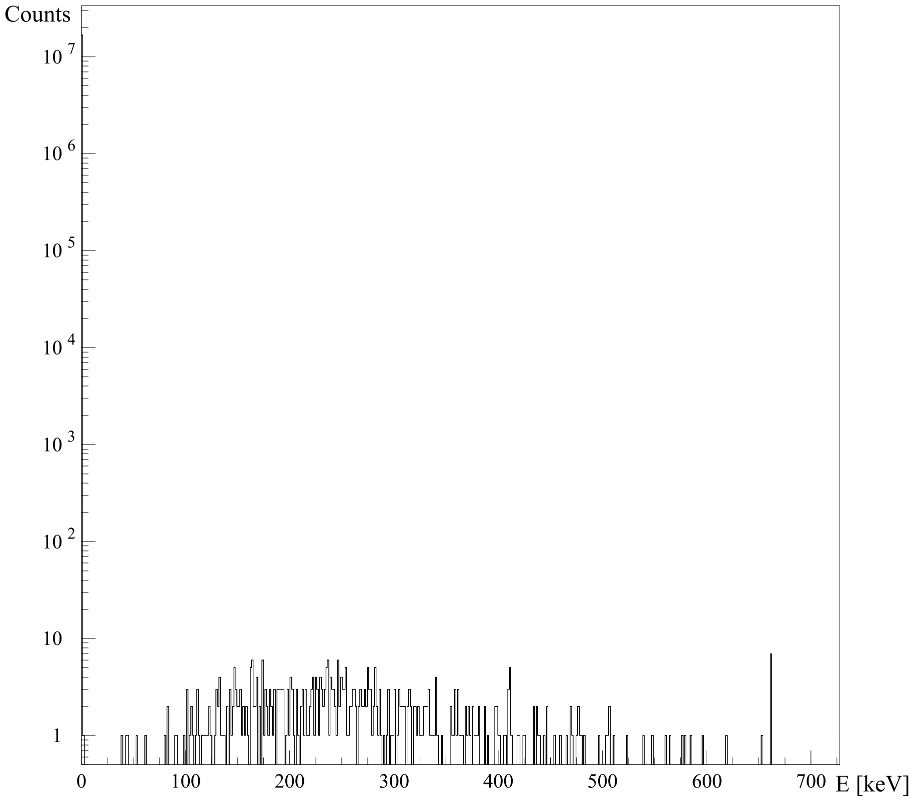

Figure 9: *The energy deposit of gamma rays that hit one of the detectors*

5 RESULTS

5.1 COLLIMATOR EFFICIENCY

Calculating the probability P of equation 6 using the values from section 3 and 4, $A_1 = 1200$ cm^2, $A_2 = 1.67$ cm^2, $A_3 = 0.6$ cm^2 and $R = 40$ cm, gives:

$$P = \frac{1.67}{1200}\frac{0.6}{2\pi 40^2} \approx 8 \times 10^{-8} \tag{7}$$

Multiplying P with the 10^8 gamma rays that are emitted from the radiating plate gives 8 hits/detector. As can be seen from fig.9, six gamma rays with an energy of 662 keV will hit the detector. Thus, the results from the theoretical estimation and the simulation are in the same order of magnitude.

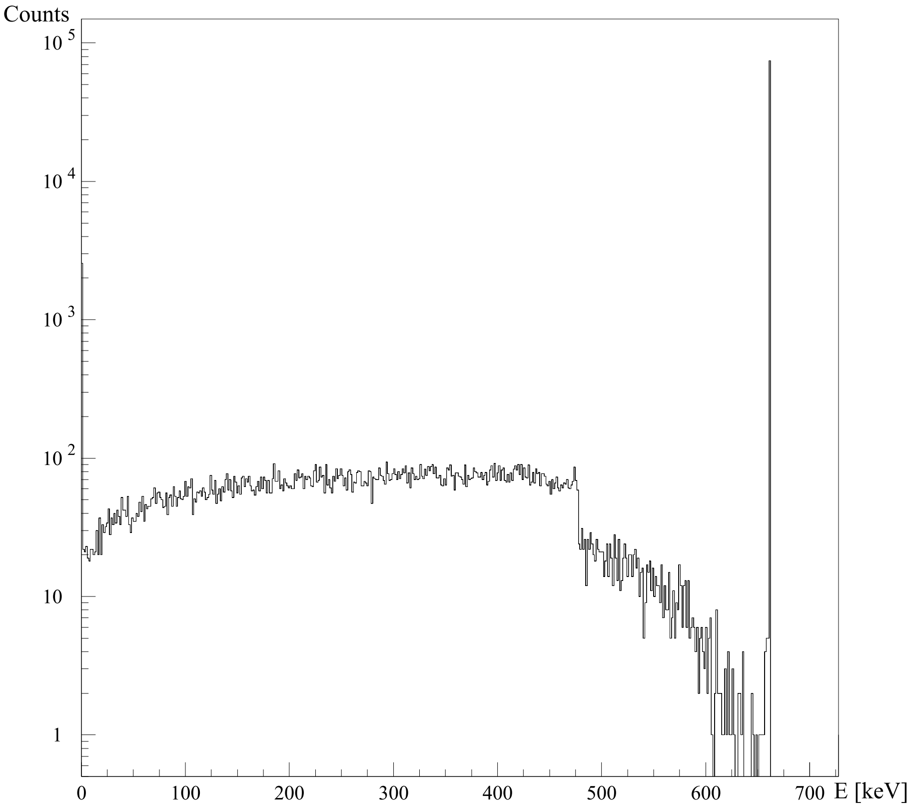

Figure 10: *The response function for the radiated detector.*

5.2 CROSSTALK

Sum over all hits in figs. 10 and 11 gives a result of 89960 hits in the radiated detector and 882 hits in the neighbouring detector. The ratio, R, between these quantities gives

$$R = \frac{882}{89960} \approx 1 \times 10^{-2} \tag{8}$$

Hence, 1% of the gamma rays are scattered into the neighbouring detector. An improvement was achieved if 2 cm of hevymet were inserted between the detectors. The ratio R then decreased to less then 1 per thousand.

5.3 DETECTOR RESPONSE

The energy resolution for one detector is shown in fig.12. From fig.12 the height of the photopeak and the Compton continuum are 1650 and 85 hits respectively. Hence the ratio between the photopeak and the Compton con-

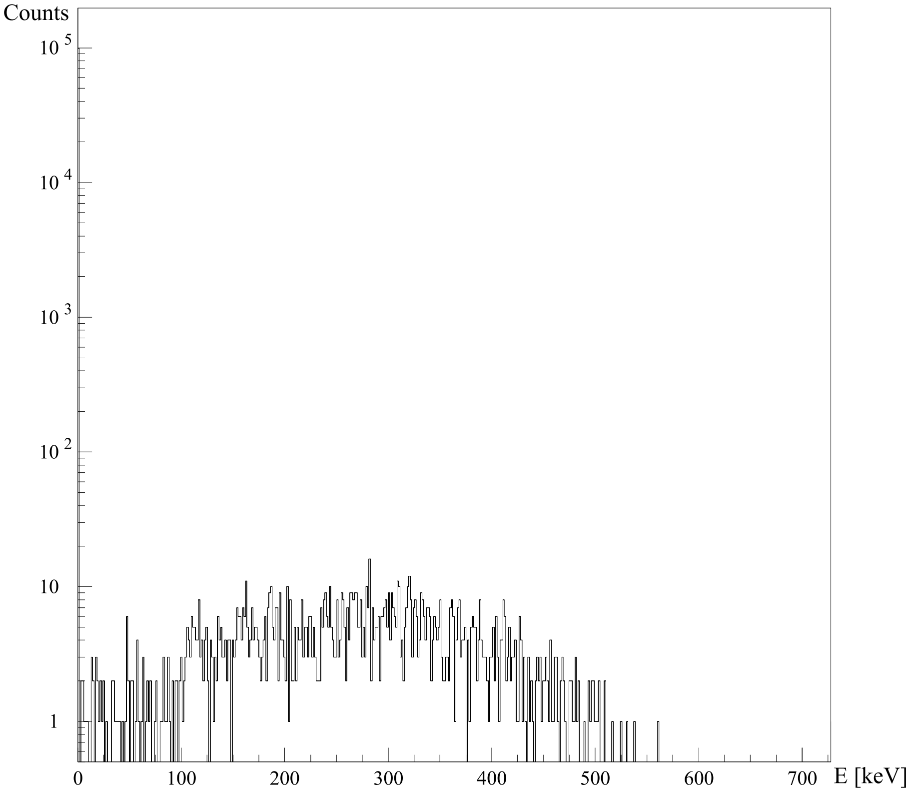

Figure 11: *The energy distribution of the radiation that is scattered into one of the neighbouring detector.*

tinuum is

$$\frac{photopeak}{Comptoncontinuum} \approx \frac{1650}{85} \approx 19 \qquad (9)$$

6 CONCLUSIONS

In the collimator–detector system the crosstalk between detectors may contribute to the overall uncertainty of the area evaluation of the spectrum peaks. This contribution will be too large if iron only is used as collimator material. Thus, through insertion of hevymet between the detectors the contribution can be reduced to an acceptable level. The conclusions from the simulations are that iron is a suitable material for the collimator–detector system if hevymet is inserted between the detectors.

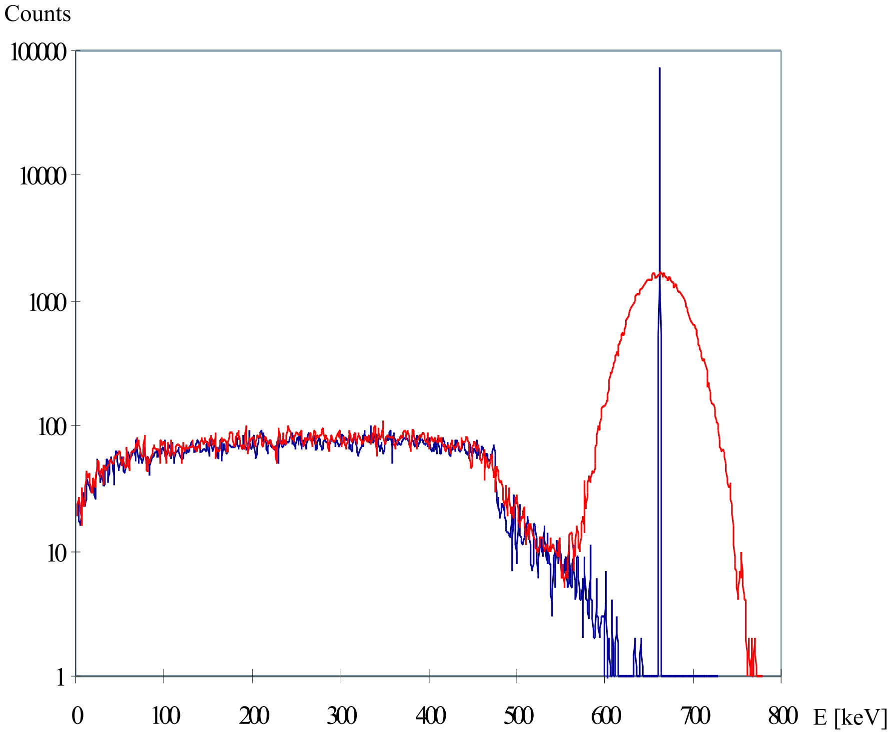

Figure 12: *The GEANT response function of one detector together with a convoluted normal distribution with a width of 10%.*

7 ACKNOWLEDGMENTS

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