1 Collimator simulations for development of a scanning system

The *Compex* project comprises the development and study of a novel HPGe detector set-up. In its' beauty it will consists of five *Compex* Clovers, i.e. five groups of four crystals brought together within a capsule. In nuclear spectroscopy experiments where very exotic structures are to be studied it is necessary to employ a high resolution HPGe detectors. In addition these detectors need to be compact. The compact and exotic together brings *Compex*. In order to confidently discover new physics and propose new nuclear structure properties it is of utmost importance to know the characteristics of the detectors, especially if it is a new type of detector. In this regard it is hence essential to characterise the *Compex* set-up in detail.

The characterisation of HPGe crystals is achieved with a scanning system. There exists some different scanning systems [1, 2, 3]. All systems utilise a collimator in some way. In the traditional scanning system, cf. Figure a γ-beam is directed to one end of the crystal in a right angle. Surrounded on the sides of the crystal other γ-detectors, such as scintillators, are placed. With the help of slits 90° Compton scattered γ-rays with a specific energy can be gated on. The origin of such signals can be narrowed down to a small region in the crystal and therefore its properties here can be known. By doing this for many regions one scans a complete crystal and studies:

- Energy resolution
- Signal amplitude
- Rise time

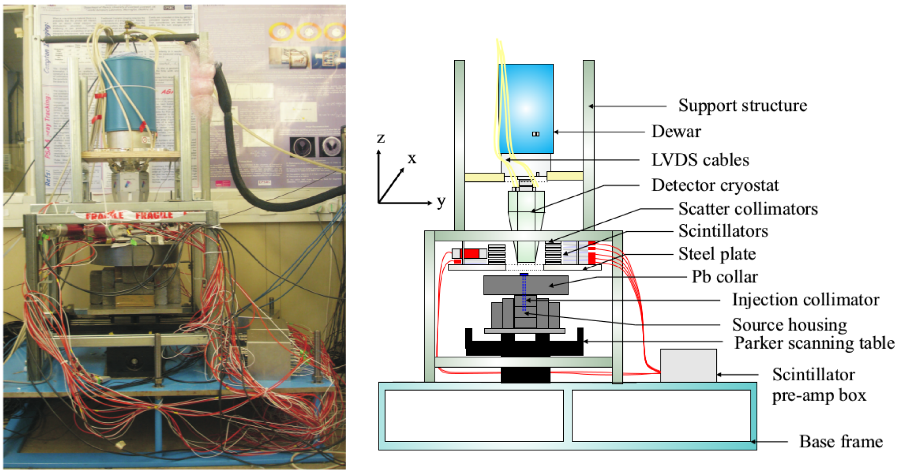

Figure 1: Liverpool scanning table [1]

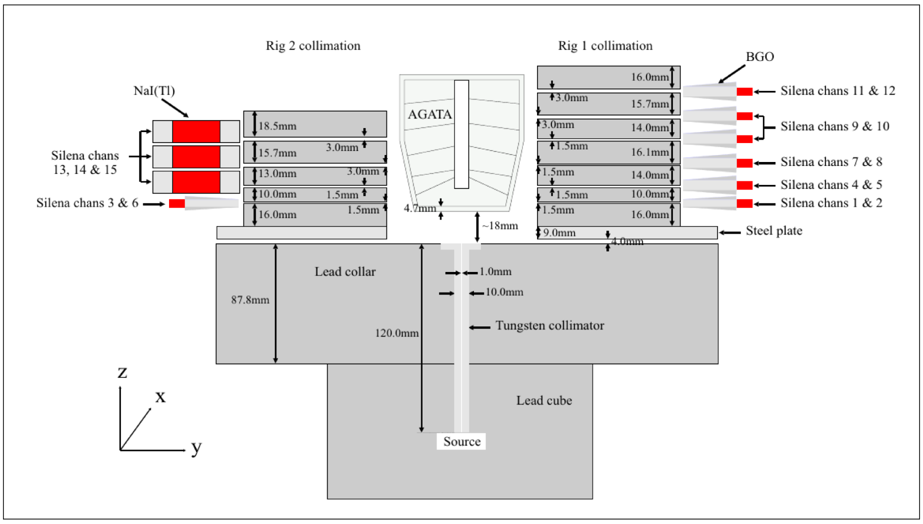

Figure 2: Measures of the Liverpool scanning table [1]

Other scanning techniques are the pulse shape comparison scan and the mix of PSCS and γ-ray imaging. A first intention is to characterise the *Compex* crystals with the traditional technique. To be able to do this one needs a collimator. Important properties of the collimator are:

- Divergence of γ-rays
- Scattering efficiency (full energy efficiency)
- Transmittance or required source activity to obtain a desired count rate in the detector

The divergence of the beam governs the postion precision that is possible to obtain. The scattering efficiency determines the amount of γ-rays that exit the collimator which have full energy. It is an important quantity since scattered particles increase the general divergence of the beam and cannot be used when the γ-ray energy is used. The transmittance governs the count rate in the detector and hence in the continuation duration of the measurements. A known transmittance enables a well chosen source activity to obtain a desired detector count rate.

The simplest collimator is a volume with a cylinder hole where the volume can absorb γ-rays which are emitted badly. By adjusting the diameter of the cylinder the beam divergence can easily be determined. The scattering efficiency is not trivial to know. The idea of integrating cones on top of the cylinder was told to be a preferable configuration concerning the scattering efficiency. In this small project the performance of different collimators have been studied to determine the suitable collimator in use within the *Compex* project.

2 Geometry definition

The base geometry:

World $1 \times 1 \times 1$ m^3, air

Cylinder Outer radius 10 cm, length 10 cm, lead. If needed an inner diameter of 1 or 1.5 mm. Placed towards the $+\hat{z}$ starting in $z = 0$.

Integrated cones N integrated cones were placed within the mother volume cylinder, with a set inner diameter to match that of the mother and an outer diameter which varied for optimised performance. The cones were placed in such a way that the complete cylinder in $+\hat{z}$ was filled and the direction of the cones was varied with a 180° rotation. The tip of the cones in the same direction of the beam was by far the best and if not otherwise mentioned (denoted flipped), it was employed.

Integrated cylinders N integrated cylinders were placed within the mother volume cylinder now with an inner diameter set to zero. Cylinders, first one with a diameter of 1 mm and then $N - 1$ with a varied increasing diameter for best performance, were placed such that the cylinder with the smallest diameter was at the exit of the collimator.

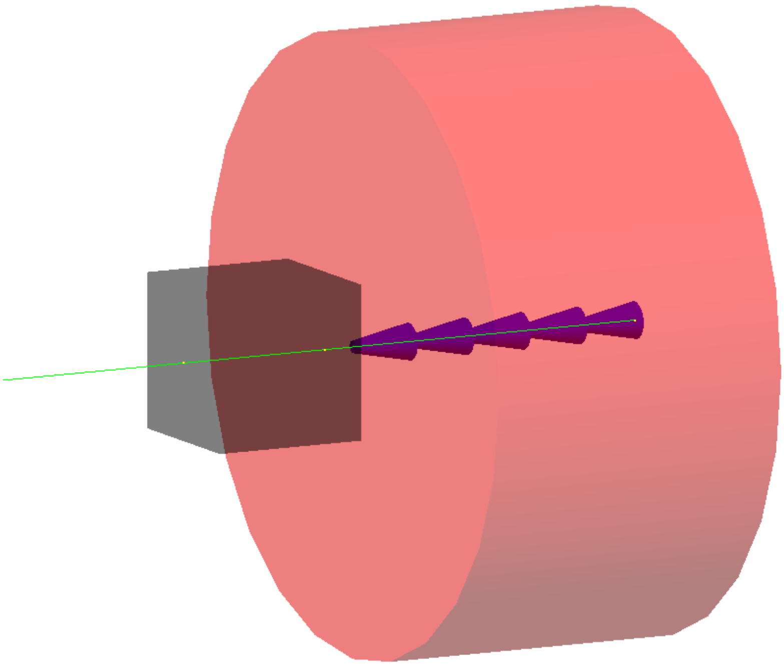

Figure 3: Geometry

3 Physics model

- G4EmStandardPhysics

4 Method

4.1 Primary generator

The primary generator in Geant4 was set as follows:

Type G4ParticleGun

Particle Gamma-photons

Position $(0, 0, 0)$

Energy 661.7 keV to resemble a ^{137}Cs source

Direction $(u_x, u_y, 1)$ where:

$$u_x = r \cdot \cos\theta \tag{1}$$
$$u_x = r \cdot \sin\theta \tag{2}$$
$$\theta = \text{uniform random number} : [0, 2\pi] \tag{3}$$
$$r = 0.1 \cdot \sqrt{\text{uniform random number} : [0, 1]} \tag{4}$$

4.2 Run

Multithread 4 parallel processes

Events $2 \cdot 10^6$

4.3 Detectors

For the final analysis a box scoring mesh with the following settings was created:

Size $5 \times 5 \times 0.01$ cm^3

Location $(0, 0, 150.0)$ mm

Binning 500×500

I.e. it was set 5 cm from the collimator exit to resemble a real *Compex* crystal scanning.

For the detailed examination with the too large inner diameter the following box scoring mesh was used:

Size $2 \times 2 \times 0.1$ cm^3

Location $(0, 0, 100.5)$ mm

Binning 200×200

I.e. it was set directly on top of the collimator exit.

A sensitive detector was set up to create an energy spectrum. It was placed 5 cm away from the collimator exit and only stored the full energy of the incoming photons.

4.4 Analysis

The flux (first time cm^{-2}) in number of γ-rays was scored with one of the built-in Geant4 scorers. Besides this, the sensitive detector scored the energy of the incoming photons and stored the energies in a histogram. The scattering efficiency was determined as the ratio of the number of full energy γ-rays and the total detected in the sensitive detector. The beam divergence was determined as 3σ of the 2D flux. Finally, the required activity was calculated on the basis of the number of full energy γ-rays detected and the solid angle coverage:

$$\Omega = \frac{\pi 15^2}{4\pi \cdot 150^2} \tag{5}$$

5 Results

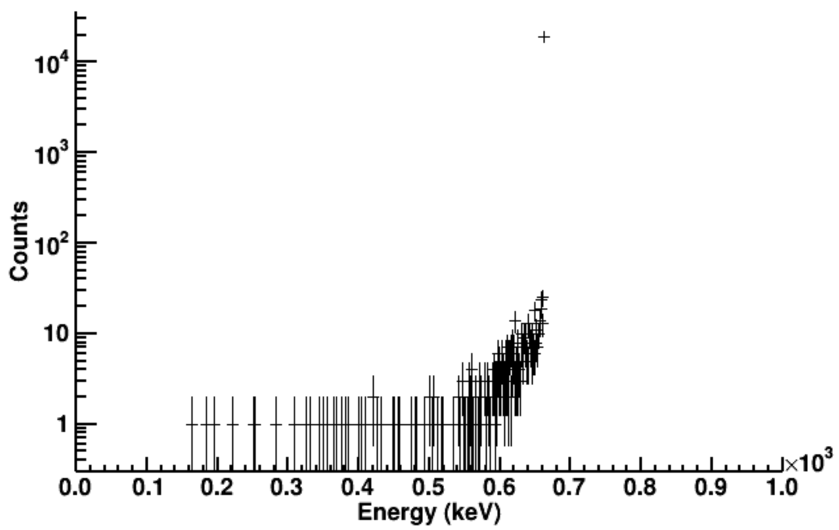

Figure 4: Spectrum for integrated cones (i).

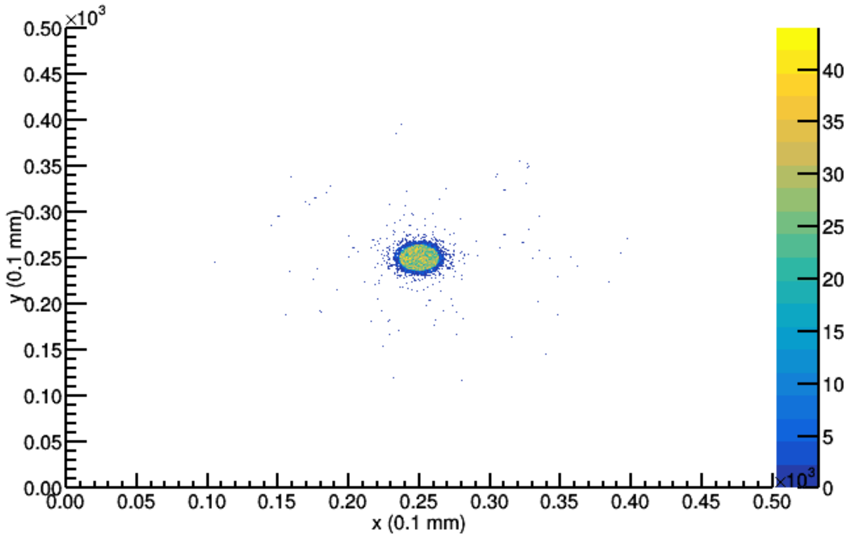

Figure 5: Divergence for integrated cones (i).

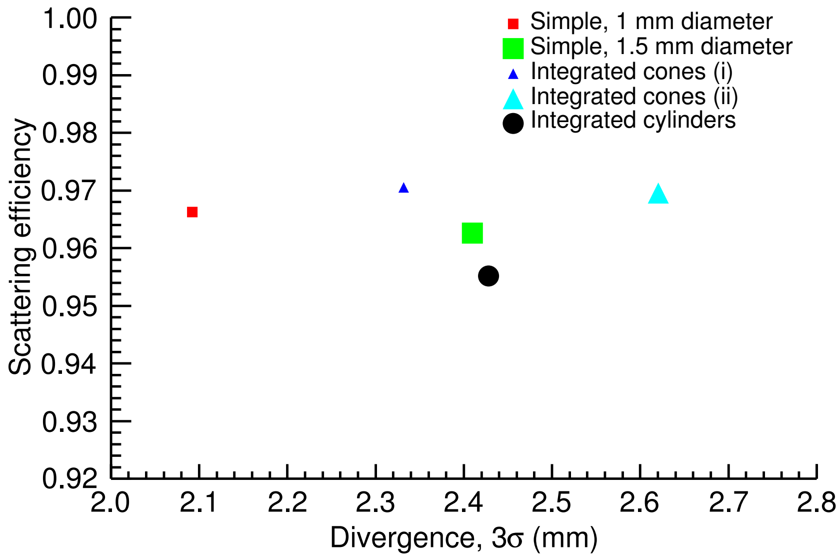

Figure 6: Results

Simple, 1 mm diameter A cylindrical collimator with diameter 1 mm.

Simple, 1.5 mm diameter A cylindrical collimator with diameter 1.5 mm.

Integrated cones (i) 5 cones (20 mm length) with an inner diameter of 1 mm and an outer of 1.4 mm.

Integrated cones (ii) 5 cones (20 mm length) with an inner diameter of 1.5 mm and an outer of 1.9 mm.

Integrated cylinders 5 cylinders (20 mm length) where the last one had a diameter of 1 mm and the rest an increasing diameter of 0.05 mm.

The required activity to achieve a count rate of 1 kHz for the first configuration is about 130 MBq.

6 Conclusion

It seems true that a collimator with integrated cones actually is able to increase the scattering efficiency, but it largely depends on the dimensions of the cones. However, many factors speak against such a configuration:

- The scattering efficiency is only increased marginally.
- The scattering efficiency is already close to maximum with the conventional collimator type.
- The beam divergence increases.
- It is unclear of whether it is possible to manufacture such a structure.

The manufacturing possible integrated cylinder configuration did not improve on the scattering efficiency, either. The beam divergence is rather not a measure of the spread of the beam but more a measure of leakage γ-rays making it through the lead block.

Several further configurations were investigated to see if they possibly could better optimise a collimator. These were:

- Integrated cones with the end coned removed.
- Integrated cones separated a set distance.
- Integrated cones flipped.
- Integrated cylinders separated a set distance.

Several different dimensions were examined for the different configurations (see notes.txt in 2nd_analysis).

6.1 Improvements

Possible improvements to the simulation:

- Employ a biasing technique (reversed Monte Carlo, geometry based importance biasing)

7 Shielding

Since a very strong source is to be used, ~ 1 GBq, sufficient shielding is essential to avert any radiation damages. To evaluate the amount of shielding necessary Geant4 simulations were performed.

7.1 Geometry

The geometry employed was very similar to the one above. The material of the cylinder was changed to wolfram and an inner diameter of 1 mm was used. An additional sensitive volume was placed with the following properties:

Side box $1 \times 1 \times 0.00001$ cm^3, air. Placed just on top of the cylinder collimator in $+\hat{y}$ and moved a little in $\hat{z}$ such that it was completely covered by the cylinder from the source.

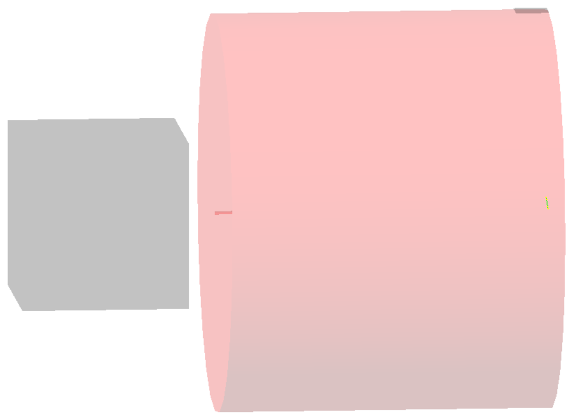

Figure 7: Geometry

7.2 Method

7.2.1 Primary generator and run

The primary generator in Geant4 was set as follows:

Particle Gamma-photons

Primary vertex $(0, 0, 0)$

Energy 661.7 keV to resemble a ^{137}Cs source

Direction $(u_x, 1, u_z)$ where:

$$u_x = r \cdot \cos\theta \tag{6}$$

$$u_z = r \cdot \sin\theta \tag{7}$$

$$\theta = \text{uniform random number} : [0, \pi] \tag{8}$$

$$r = 0.25 \cdot \sqrt{\text{uniform random number} : [0, 1]} \tag{9}$$

7.2.2 Analysis

The box was set as a sensitive detector and the energy of the γ-rays entering the volume was stored in a histogram (just like above). In the analysis only the total histogram entries were used for the final calculations.

7.3 Results

The number of counts obtained with a cylinder diameter of 6 cm was 1400. Translated into the count rate per cm^2 for a 1 GBq source (see 2nd_analysis/math.py) it corresponds to:

Count rate 120 Bq/cm^2

Count rate around collimator 20 kBq (based on the above number, which is exaggerated since that varies over the cylinder surface)

7.4 Conclusion

A diameter of 6 cm seems to reduce the radiation exposure around the collimator to viable levels. For additional safety measures it will be covered with another 4 cm heavy met around the cylinder and on top and this will imply almost 100 % shielding.

References

[1] M. Dimmock. *Characterisation of AGATA Symmetric Prototype Detectors*. PhD thesis, University of Liverpool, 2008.

[2] F. Crespi et al. A novel technique for the characterization of a hpge detector response based on pulse shape comparison. *Nuclear Instruments and Methods in Physics Research Section A*, 2008.

[3] C. Domingo-Pardo. A novel γ-ray imaging method for the pulse-shape characterization of position sensitive semiconductor radiation detectors. *Nuclear Instruments and Methods in Physics Research, Section A*, 2010.