Science and Technology Facilities Council

Design and development of a gamma radiation detector system for source localisation and mapping

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IAEA International Atomic Energy Agency

UNIVERSITY of York

Introduction

Interaction of gamma rays with matter

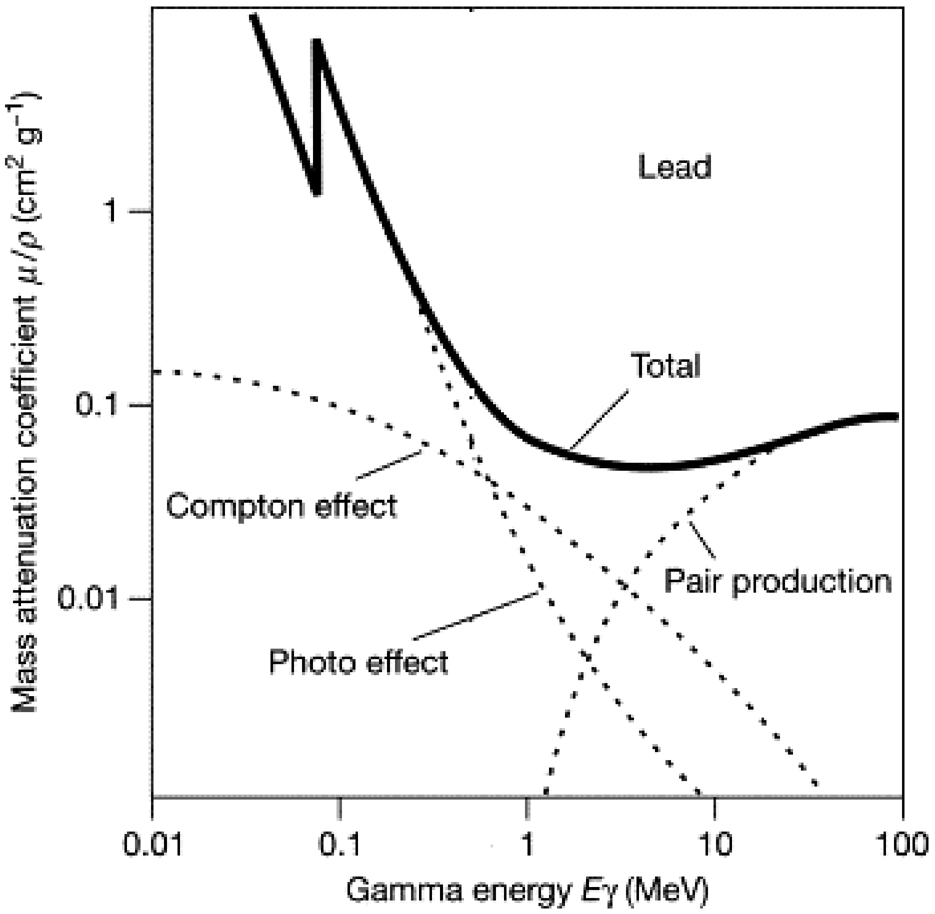


Fig.1. The mass attenuation coefficient of lead (Pb) as a function of gamma energy in MeV

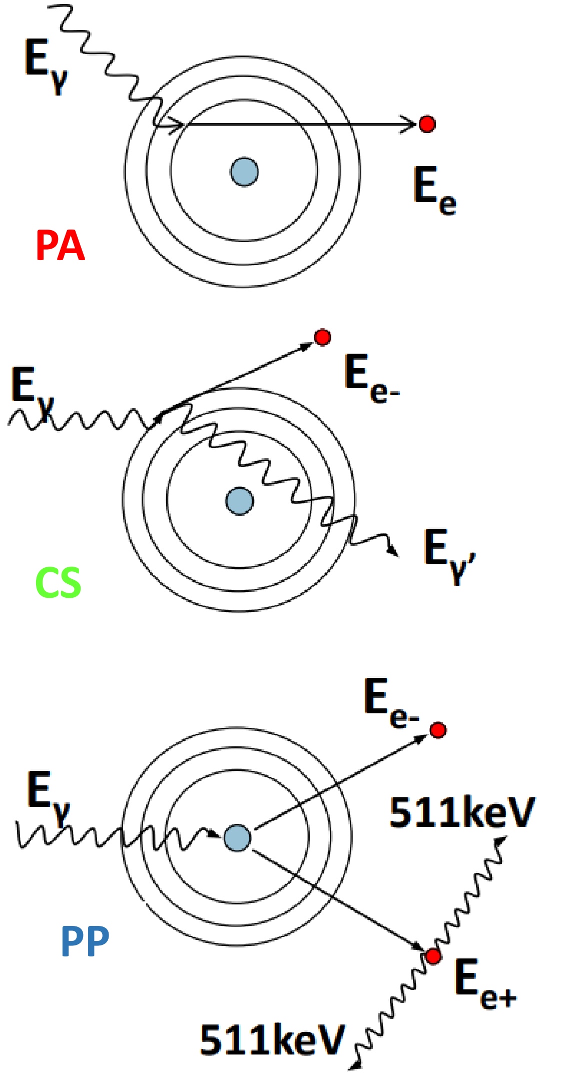
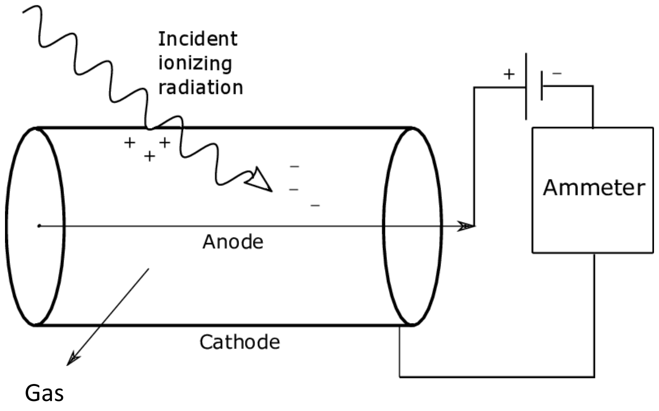
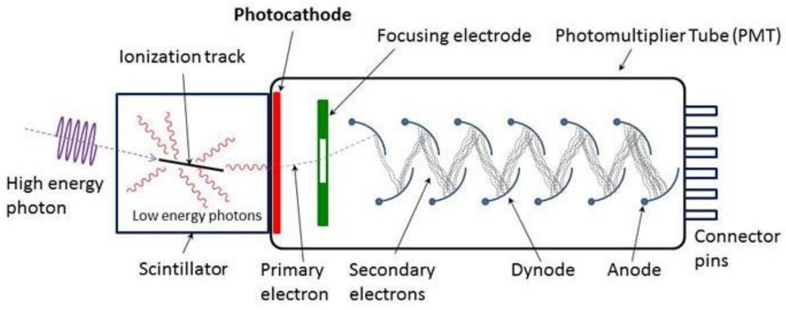
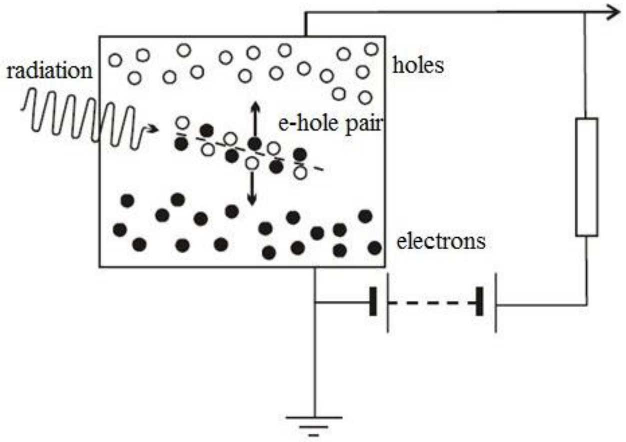


Fig.2. Gamma ray interaction mechanisms

G. R. Gilmore, (1996)., Practical Gamma-ray Spectrometry, Second. John Wiley & Sons, pg. 26.

Types of gamma radiation detectors

<table>
<tr><td>a) Gas-filled detectors</td><td>b) Scintillation detectors</td><td>c) Semiconductor detectors</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>• Simple, robust, lower sensitivity and resolution</td><td>• High sensitivity, good energy resolution. Performance can be affected by temperature variations.</td><td>• Excellent resolution.
• Expensive, as some like HPGe, may require cooling by liquid nitrogen.</td></tr>
</table>

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Monira, S., & Brücken, E. (2020). Charging-up Behaviour of MicroPattern Gaseous Detectors.
https://commons.wikimedia.org/wiki/File:PhotoMultiplierTubeAndScintillator.jpg

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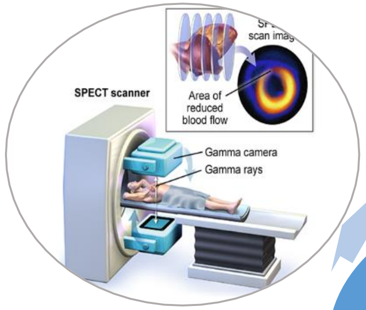
“Making the invisible, visible”

Fukushima clean-up

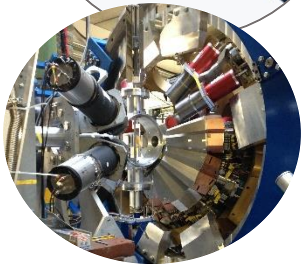
Medical Imaging and Diagnostics



Radiation waste sorting and management

Applications

Scientific Research (Astrophysics and Nuclear Physics experiments)



Industrial Applications

Homeland security

https://www.iaea.org/newscenter/news/off-site-environmental-remediation-in-fukushima-co
https://www.onestopndt.com/ndt-articles/gamma-radiography-testing

Current Work

- Design a detector system that can accurately localise and map out a volume of source.

- ^{40}K, a naturally occurring radioisotope found in potassium rich materials such as fertilisers will be used in this study as a radiation source.

- Directional detection of the 1460 keV γ-rays from the decay of ^{40}K can help localise and map out the sources.

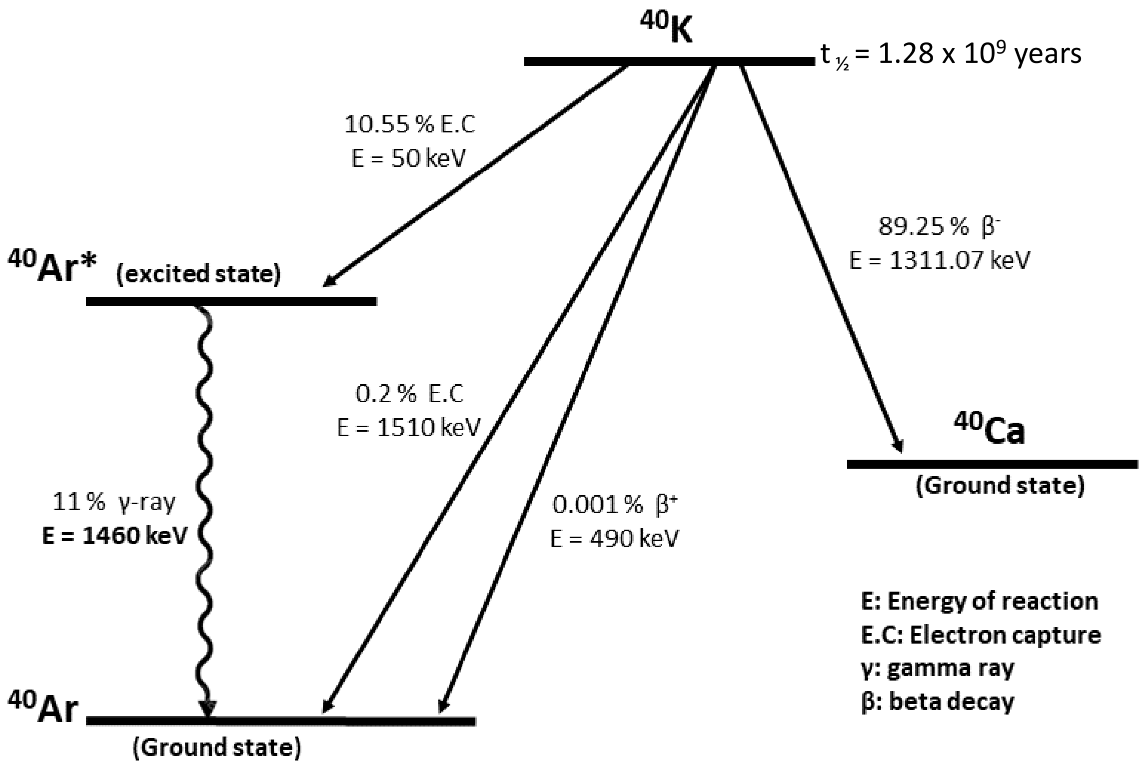


Fig.5. Decay scheme of ^{40}K

Leutz, H., Schulz, G., and Wenninger, H.: The decay of potassium-40, Z. Phys., 187, 151–164, https://doi.org/10.1007/BF01387190, 1965.

Techniques for source localisation

1. Compton cameras

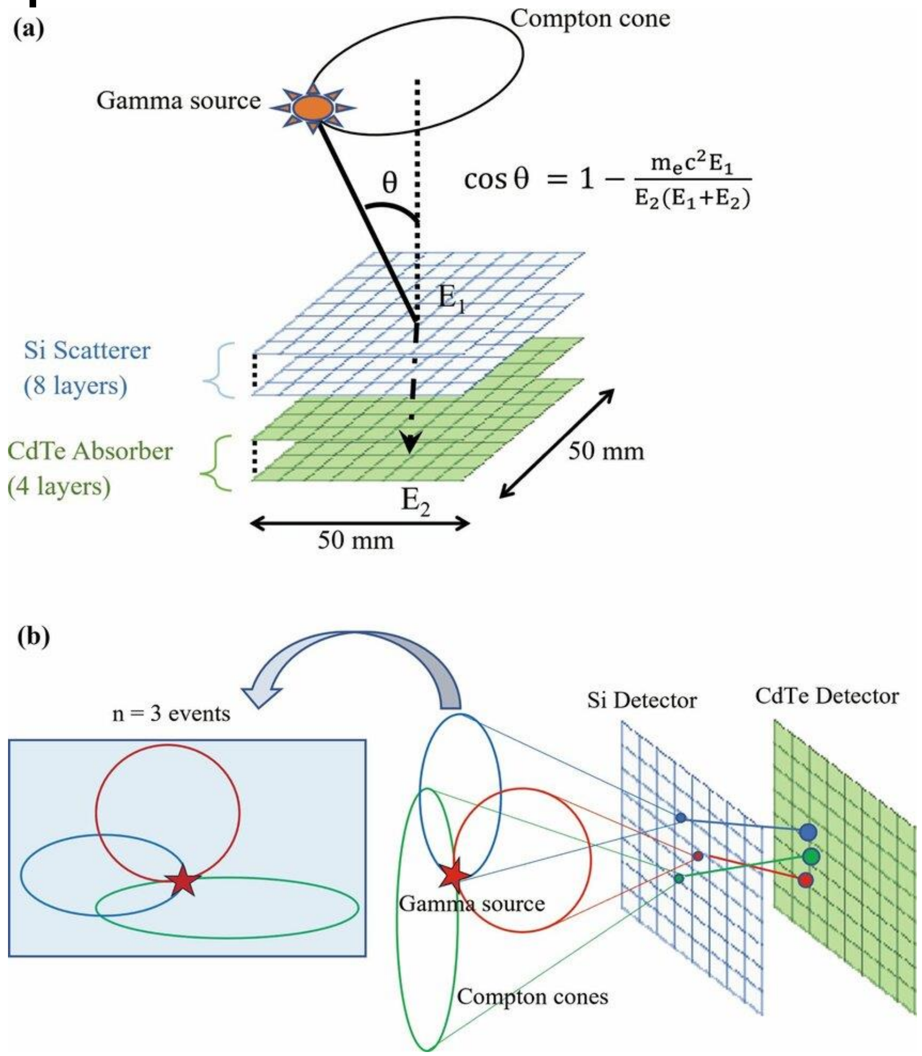


Fig.6. Schematic illustration of a general Compton camera (**a**); Compton cones of each event are superimposed to locate the γ-ray source (**b**).

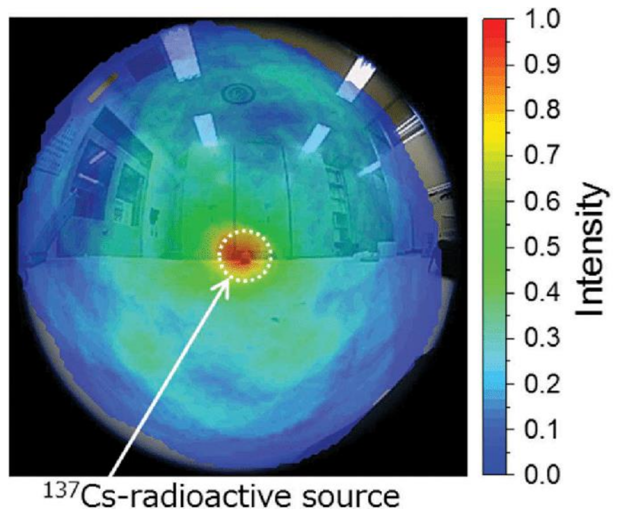


Fig.7. Reconstructed radiation image of a ^{137}Cs radioactive point source obtained using a compact Compton camera.

Algorithms used

- Simple back-projection (SBP)
- Filtered back-projection (FBP)
- Maximum Likelihood Expectation Maximization (MLEM)

1. Parajuli, R. K., Sakai, M., Arakawa, K., Kubota, Y., Kubo, N., & Tashiro, M. (2021). Carbon range verification with 718 keV Compton imaging. *Scientific Reports*, *11*(1), 21696.
2. Sato, Y., Terasaka, Y., Utsugi, W., Kikuchi, H., Kiyooka, H., & Torii, T. (2019). Radiation imaging using a compact Compton camera mounted on a crawler robot inside reactor buildings of Fukushima Daiichi Nuclear Power Station. *Journal of Nuclear Science and Technology*, *56*(9-10), 801-808..

2. Multiple detector systems

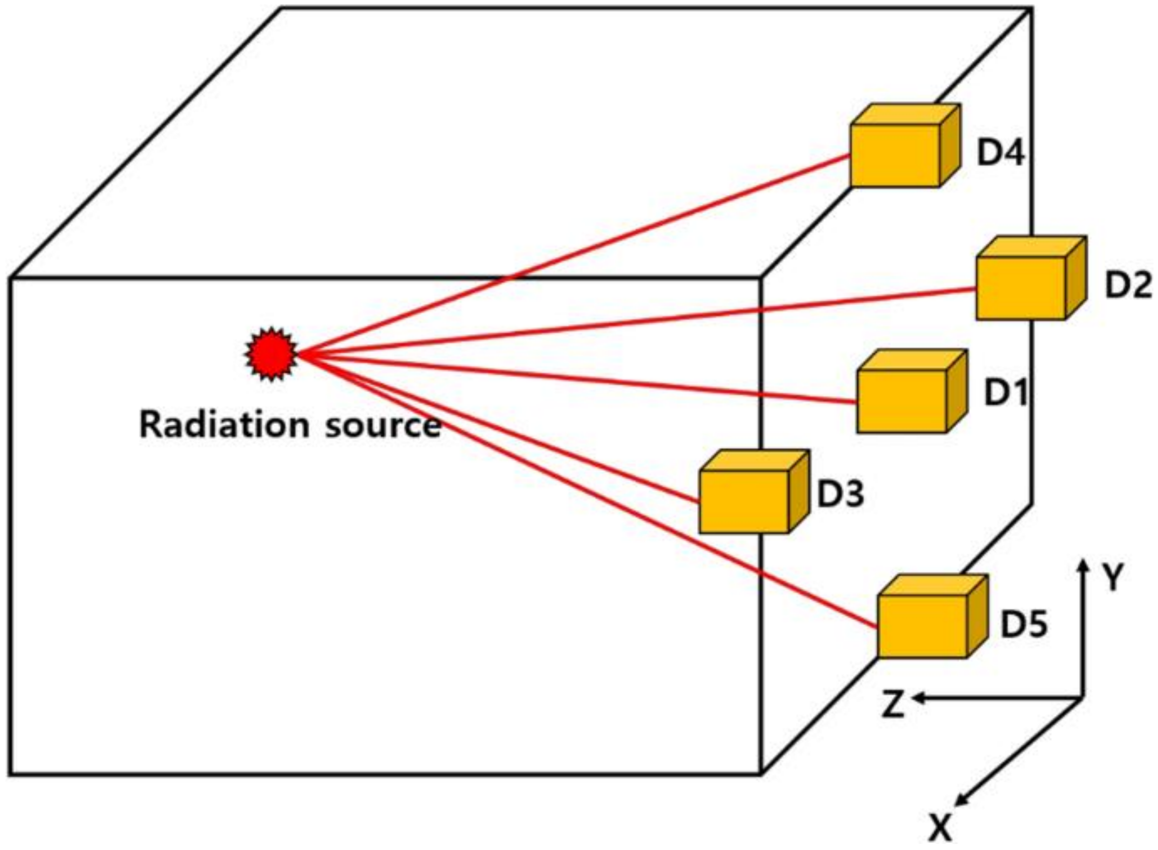


Fig.8 Schematic diagram of the radiation source position tracking system using multiple radiation spectroscopy detectors

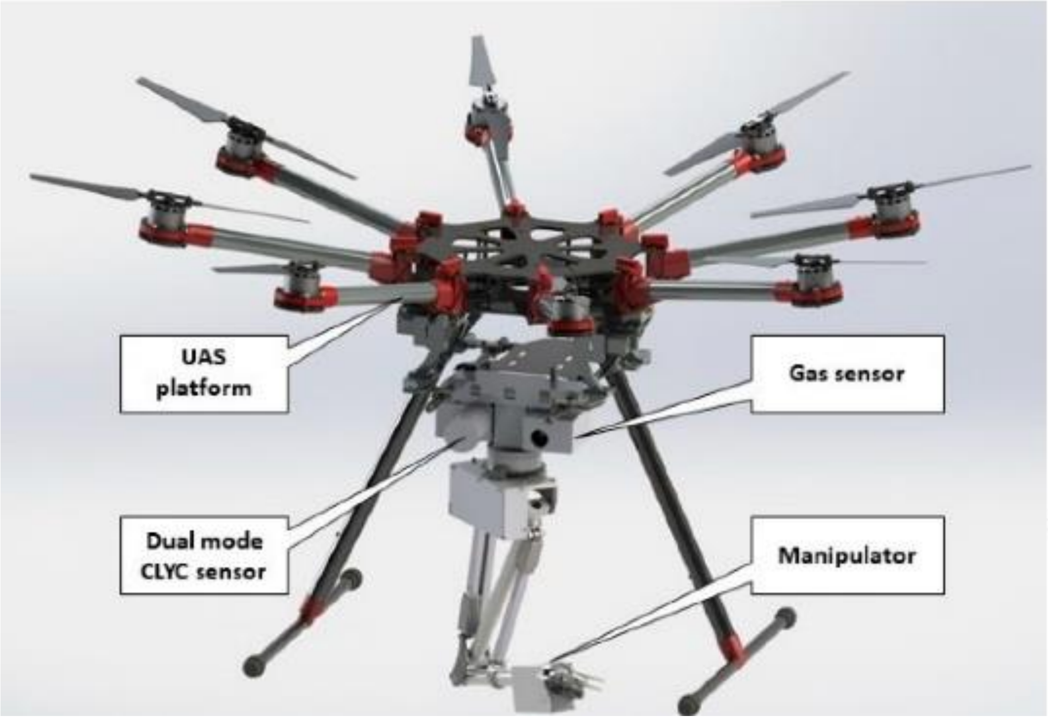
Methods used

- Triangulation

The radiation intensity is inversely proportional to the square of the distance

Lee, S. J., & Baek, C. H. (2022). Radiation source position tracking system using multiple radiation spectroscopy detectors. *Journal of the Korean Physical Society*, *81*(1), 18-23.

3. Mobile platforms e.g. radiation detectors mounted on autonomous robots, cars and drones.



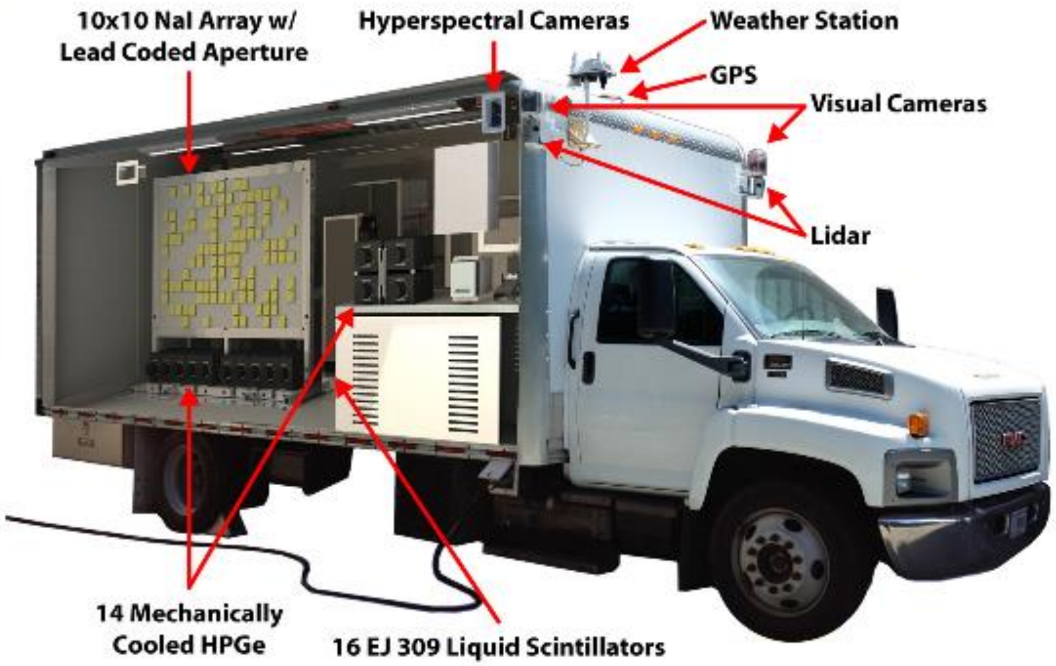


Fig.9 Drone used for monitoring, mapping, and source localization purposes (a); Radiological multi-sensor analysis platform (RadMap) system carried by a truck (b).

Marques, L., Vale, A., & Vaz, P. (2021). State-of-the-art mobile radiation detection systems for different scenarios. *Sensors*, *21*(4), 1051.

Research Work Approach

- Perform GEANT4 Monte Carlo simulation to inform the detector design and some parameters of the experimental setup.

- Build a gamma radiation detector, optimise its performance and carry out some experimental work using the different methods of source localisation.

Experimental setup design

- Use 10 cm acrylic cubes to model a wall of potassium-rich fertiliser with some parts made from non-radioactive material like sand.
- The radiation detector will be mounted on a robotic arm and scan over the entire area of the wall.
- The robotic arm provide position data which will be overlaid to the radiometric data to generate 2D radiation maps.

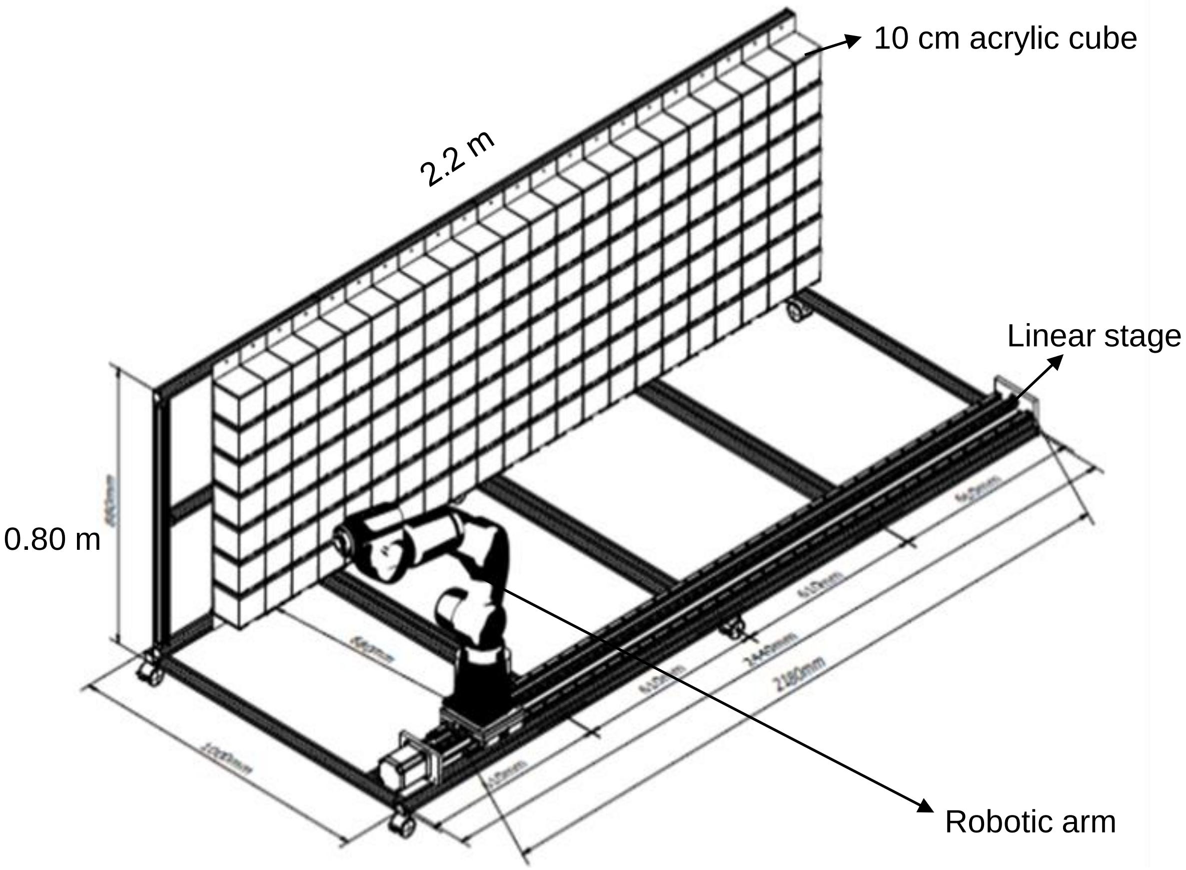


Fig.10. Experimental setup for localising a spread-out (volume) source

Actual Experimental setup

Detector selection

Things to consider:

- High detection efficiency
- Good energy resolution and spatial resolution
- Compact and portable

GEANT4 Monte Carlo simulations

Preliminary Results

Simulations performed to:

- Determine the optimal detector geometry and material.

Bismuth Germanate $Bi_4Ge_3O_{12}$ (BGO)
12% resolution at 662 keV

Caesium Iodide (CsI) – 6% resolution at 662 keV

Plastic scintillator - 13.2 % at 477 keV photoelectrons from Cs-137 gamma-ray source

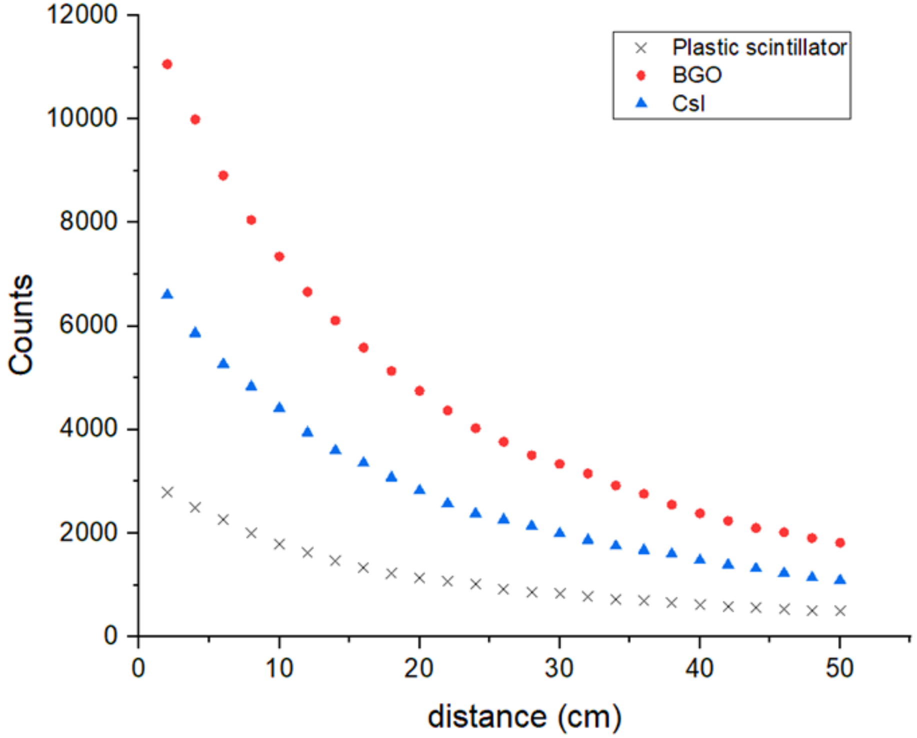


Fig.11 A plot showing a comparison between plastic, BGO and CsI detectors, where the number counts are plotted as a function of source-detector distance

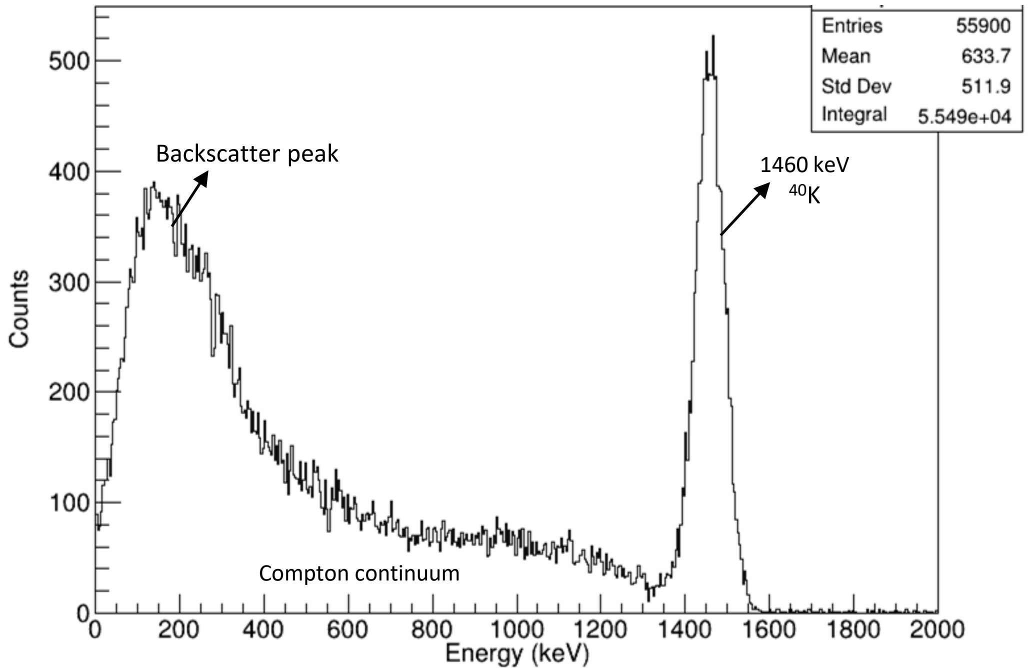


Fig.12 Energy spectrum of 1460 keV gamma rays from a 2cm thick cuboid BGO detector

Moszynski M, Kapusta M, Wolski D, Szawlowski M, Klamra W. Energy resolution of scintillation detectors readout with large area avalanche photodiodes and photomultipliers. IEEE Trans Nucl Sci. 1998; 45: 472–7

Kim, D. G., Lee, S., Park, J., Son, J., Kim, T. H., Kim, Y. H., ... & Kim, Y. K. (2020). Performance of 3D printed plastic scintillators for gamma-ray detection. *Nuclear Engineering and Technology*, *52*(12), 2910-2917.

GEANT4 Monte Carlo simulations cont.…

Preliminary Results

- A 50 cm x 50 cm x 10 cm wall was simulated, along with 9 source locations.
- To determine the accuracy of the detector in mapping/localising the source positions.

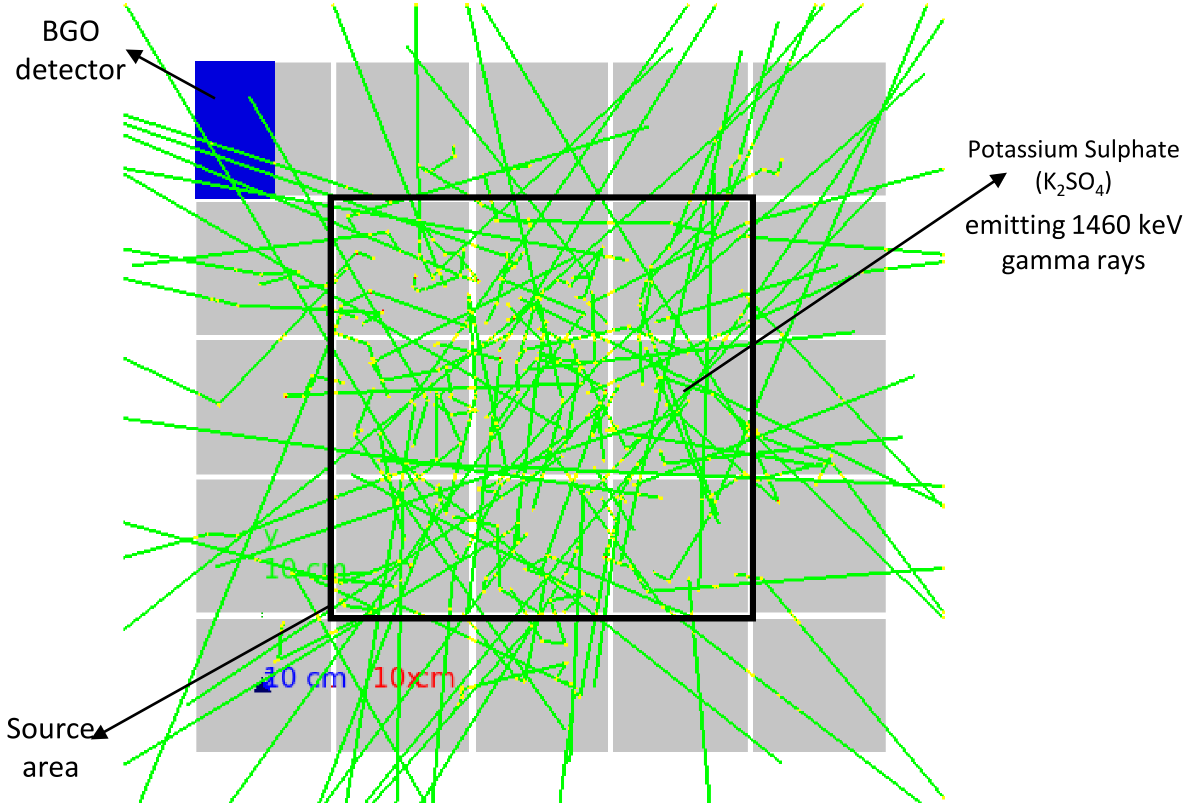


Fig.13 GEANT4 simulation of 1460 keV gamma rays from multiple volumes of potassium sulphate fertiliser, simulated 3 million events, evenly distributed

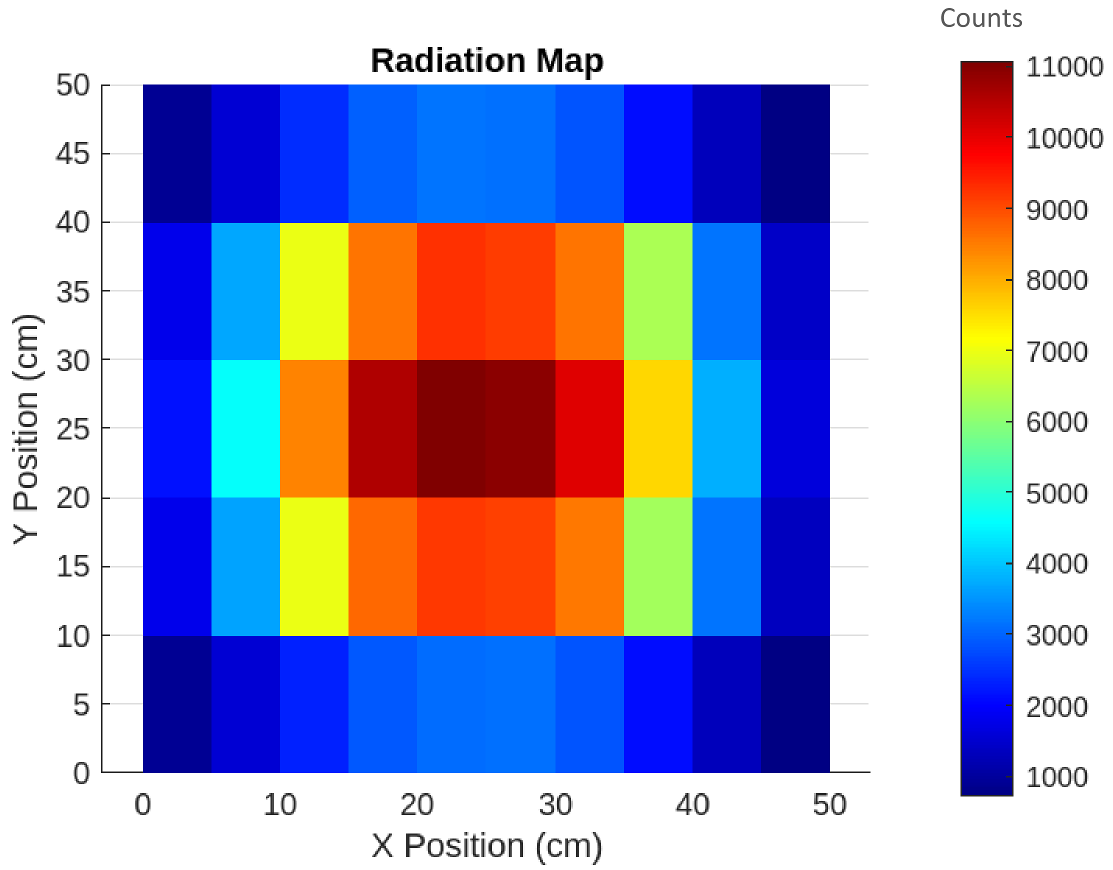


Fig.14 Radiation map generated at 2 cm source-detector distance

Determining the spatial resolution

Preliminary Results

Based on the BGO detector's intrinsic resolution, a noise level of 1-2 mm is reasonable. The spatial resolution can be calculated from the hit positions.

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x'_i - xi)^2}$$

x_i – hit positions without noise
x'_i – reconstructed positions with noise
σ_x - spatial resolution
N – number of data points

$$\sigma_{overall} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

σ_x = 0.15 cm
σ_y = 0.15 cm
σ_z = 1.71 cm

$\sigma_{overall}$ = 1.72 cm

The detector is able to resolve points that are at least 1.72 cm apart.

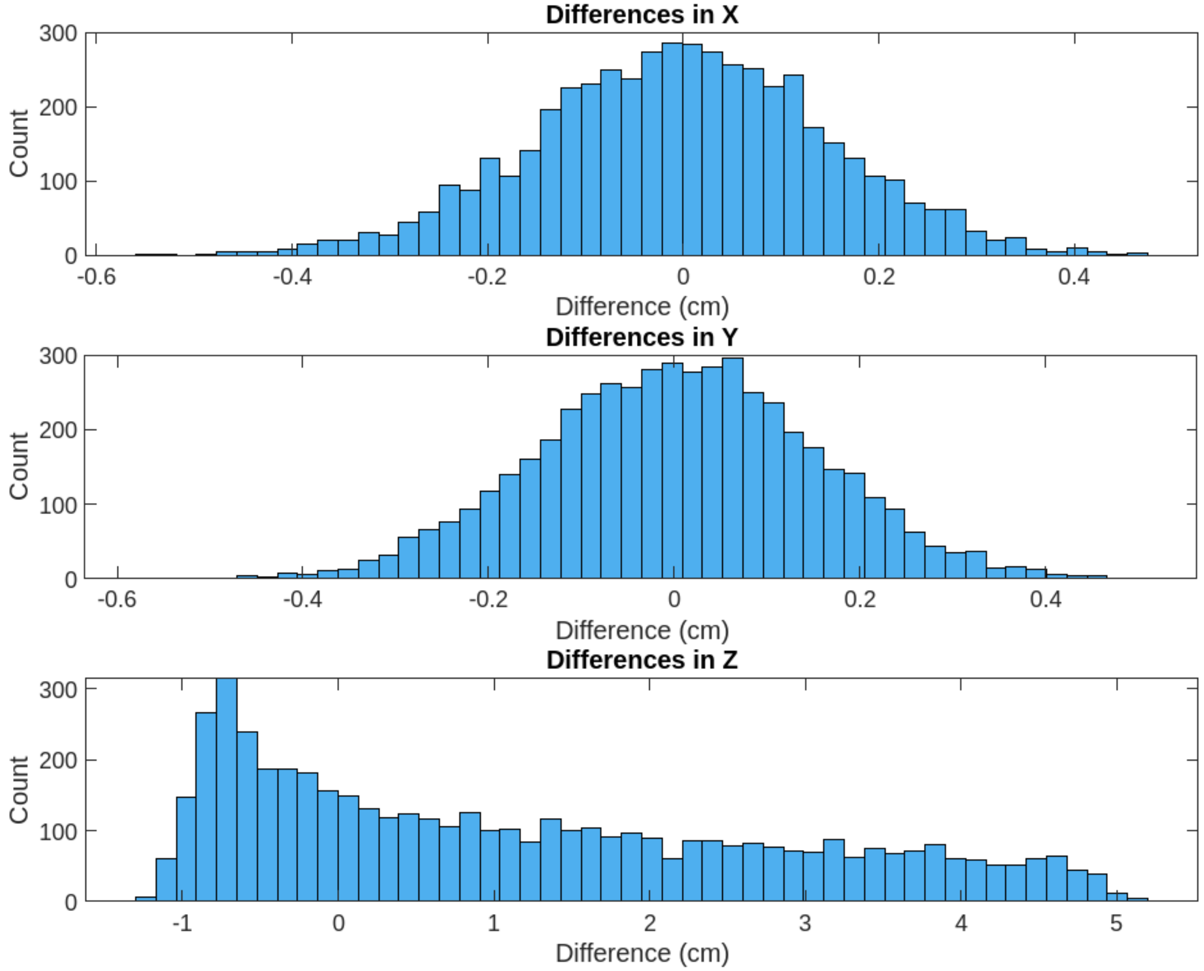


Fig.15. The distribution of the errors between the true and reconstructed positions along each dimension (x, y, and z)

Dadgar, M., Maebe, J., Abi Akl, M., Vervenne, B., & Vandenberghe, S. (2023). A simulation study of the system characteristics for a long axial FOV PET design based on monolithic BGO flat panels compared with a pixelated LSO cylindrical design. *EJNMMI physics*, *10*(1), 75.

Future Work

- Build a BGO detector, optimise its performance and fully characterise it.
- Assemble the experimental set-up and run some tests.
- Generate radiation maps and validate the results using simulations.
- Explore other techniques of source localisation.

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THANK YOU…

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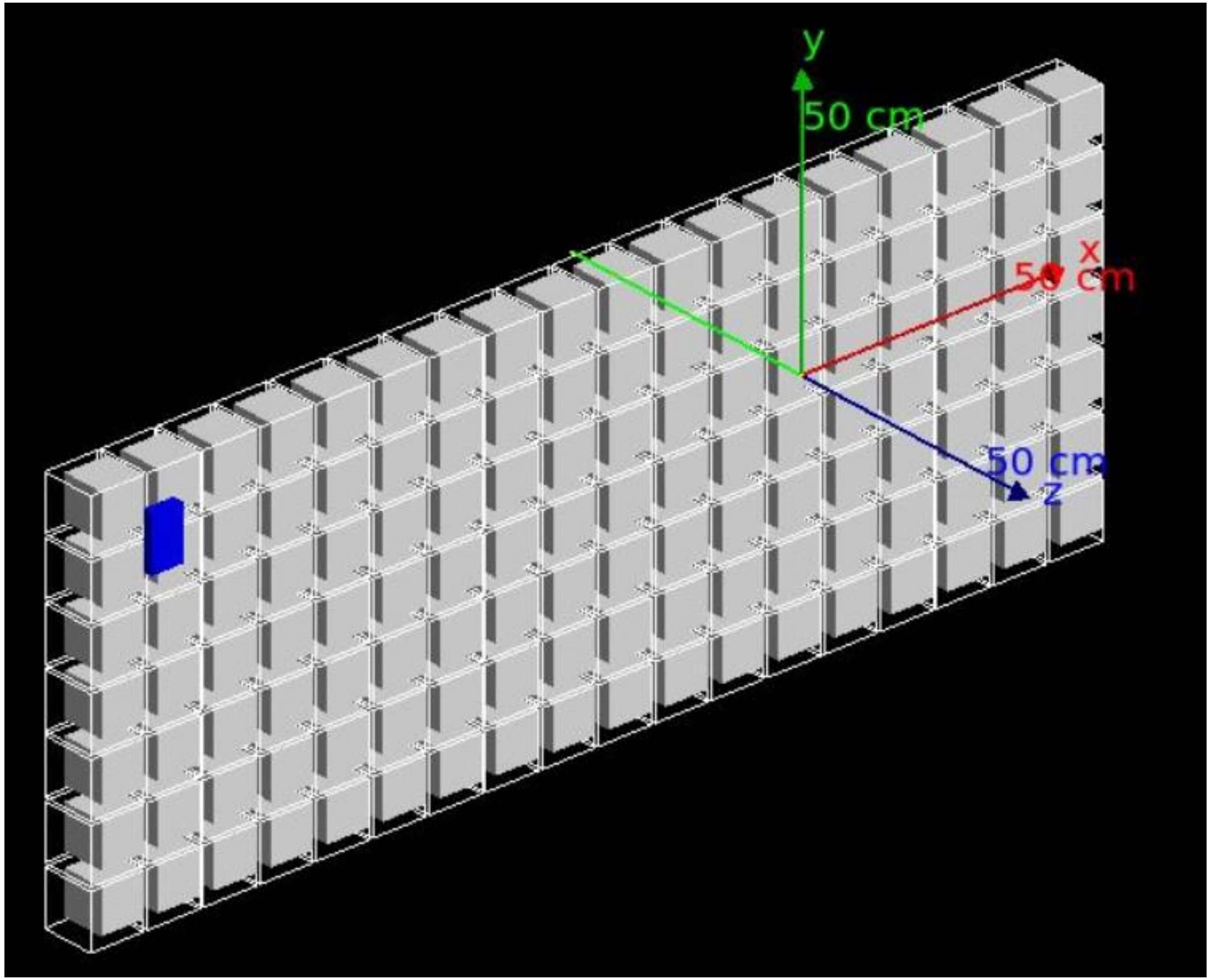
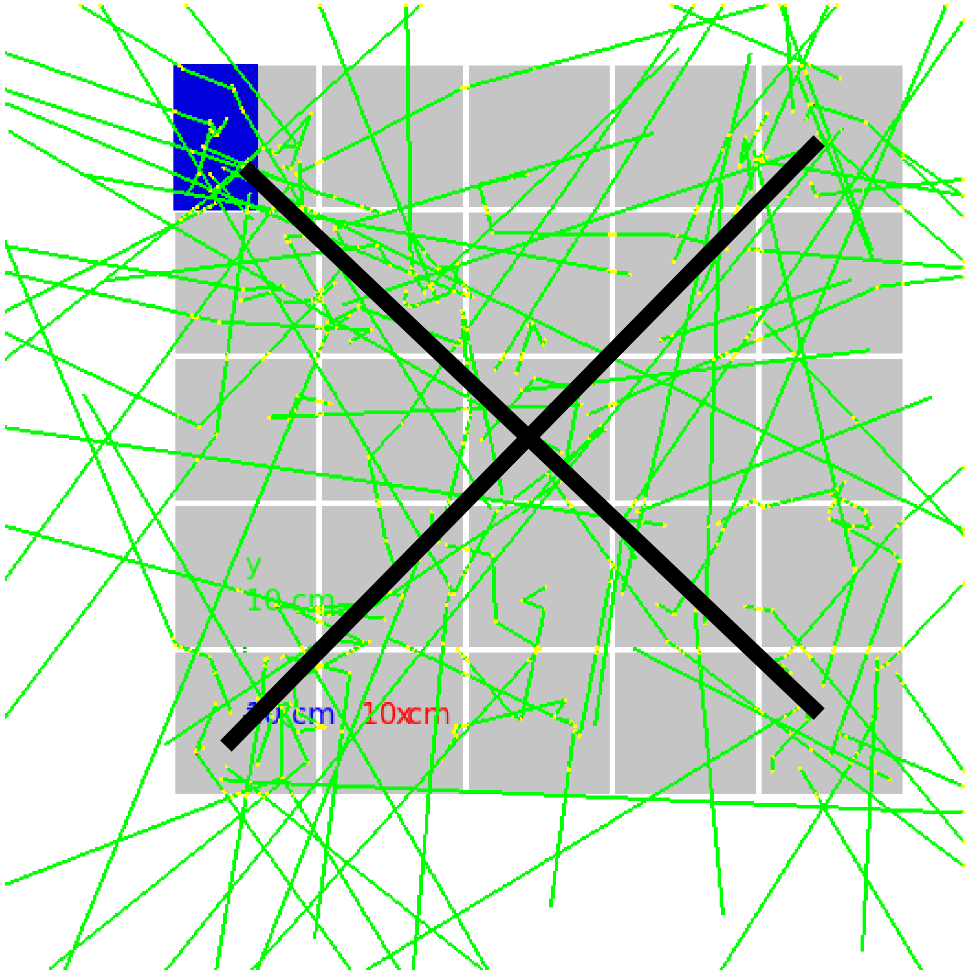
Back up slides

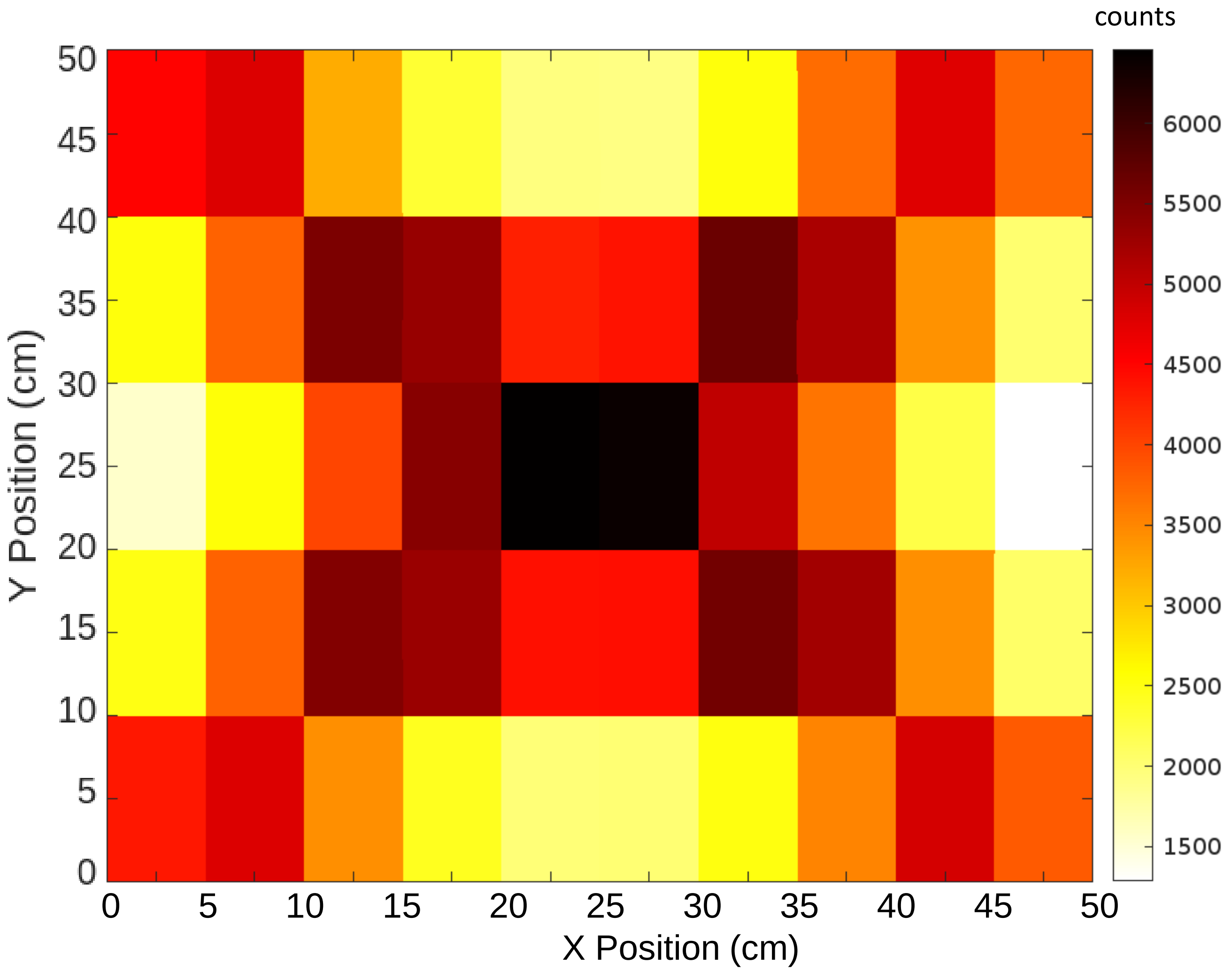
GEANT4 Monte Carlo simulations (Experimental setup)



- The fertiliser wall, acrylic boxes and radiation detector can be simulated in GEANT4.
- Different source locations can be simulated and the detector can be placed in different positions depending on the desired step lengths in order to do the mapping.
- The volume sources can be set to have uniform number of events.
- Gamma rays are emitted at random within the volume of source.

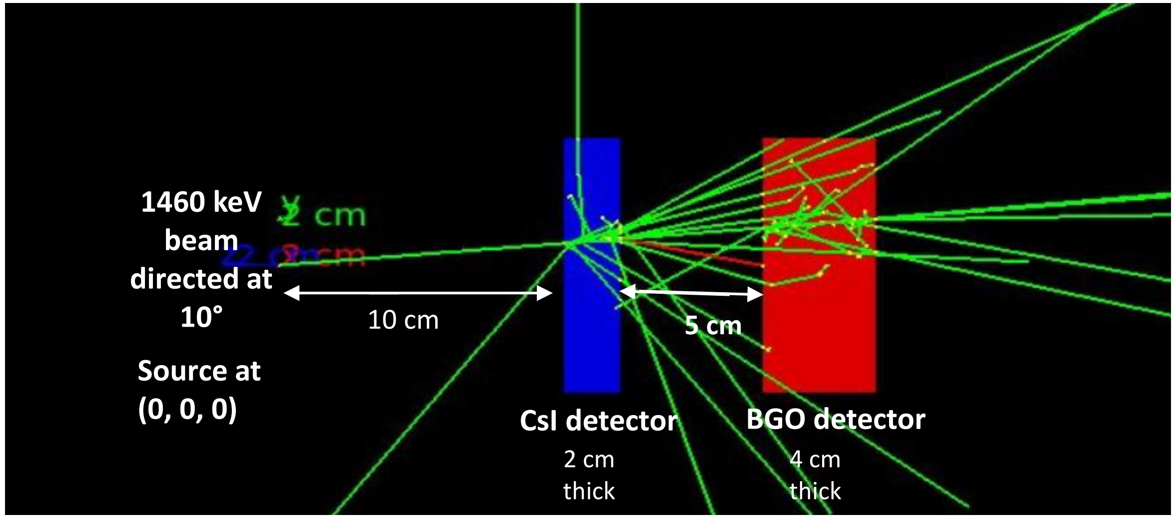
GEANT4 Monte Carlo simulations (pattern explored)

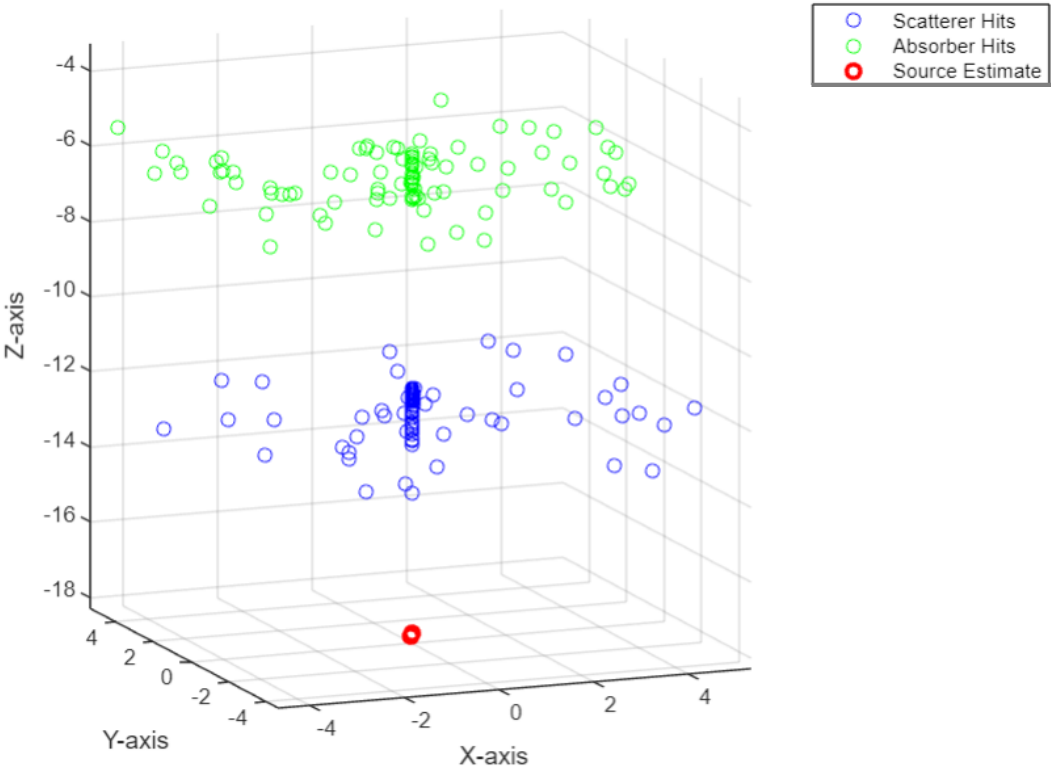




GEANT4 Monte Carlo simulations (Method 2:Compton camera)

A pencil beam placed at the centre of the "world" (0, 0, 0) with an energy of 1460 keV was simulated and directed towards the scatterer detector at an angle of 10°.





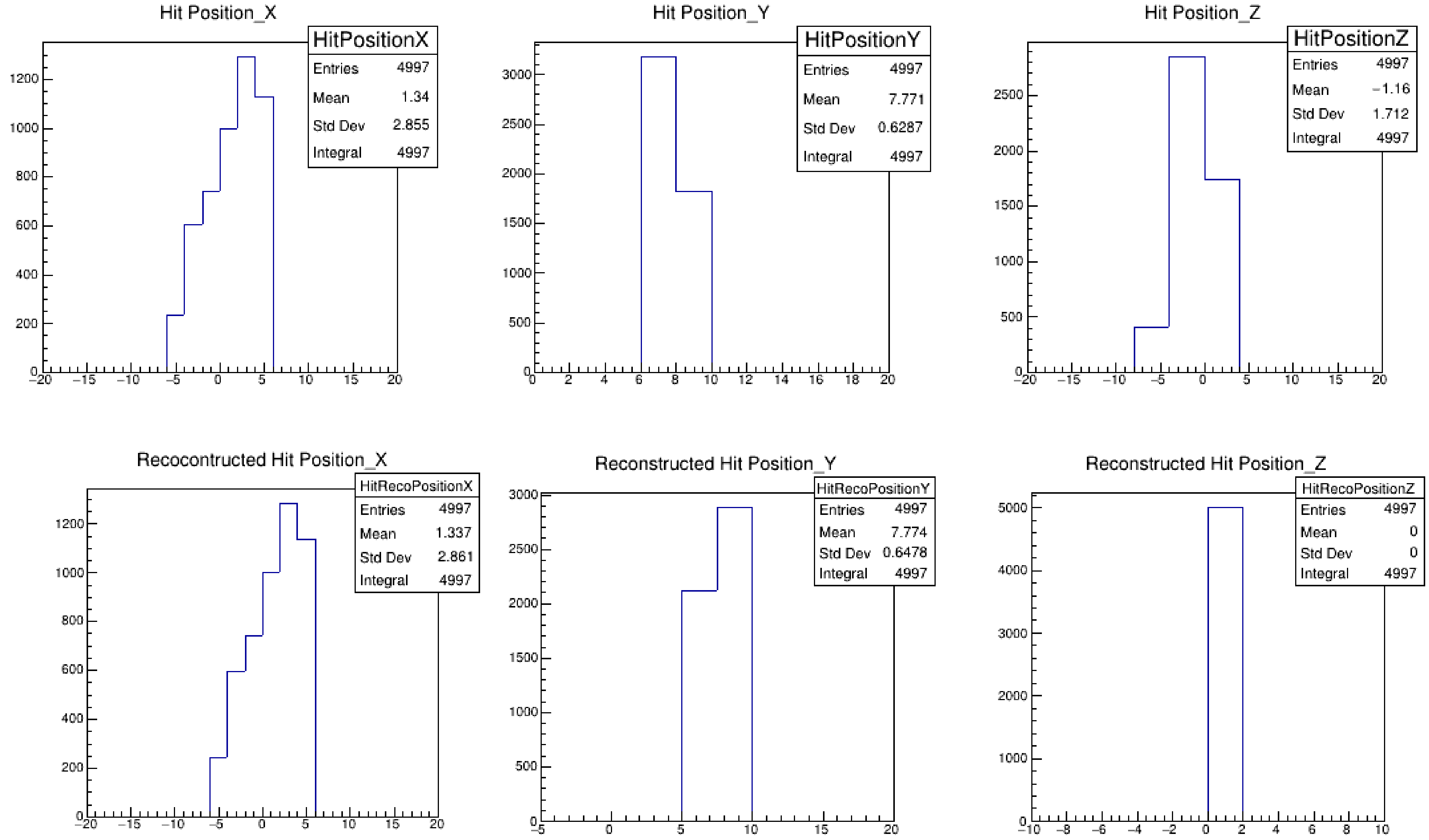
The hit positions were reconstructed and the Maximum Likelihood Estimation algorithm was used to determine the source location.

Command Window

New to MATLAB? See resources for Getting Started.

```
>> example3
Reconstructed Source Position:
   -0.1081   -0.0463  -18.1479
```

Determining the spatial resolution using detector hit positions



True hit position distribution

Hit position distribution after adding noise to the signal

Based on the BGO detector's intrinsic resolution, a noise level of 1-2 mm is reasonable.

Dadgar, M., Maebe, J., Abi Akl, M., Vervenne, B., & Vandenberghe, S. (2023). A simulation study of the system characteristics for a long axial FOV PET design based on monolithic BGO flat panels compared with a pixelated LSO cylindrical design.*EJNMMI physics*,*10*(1), 75.