Applications of gamma-ray detectors

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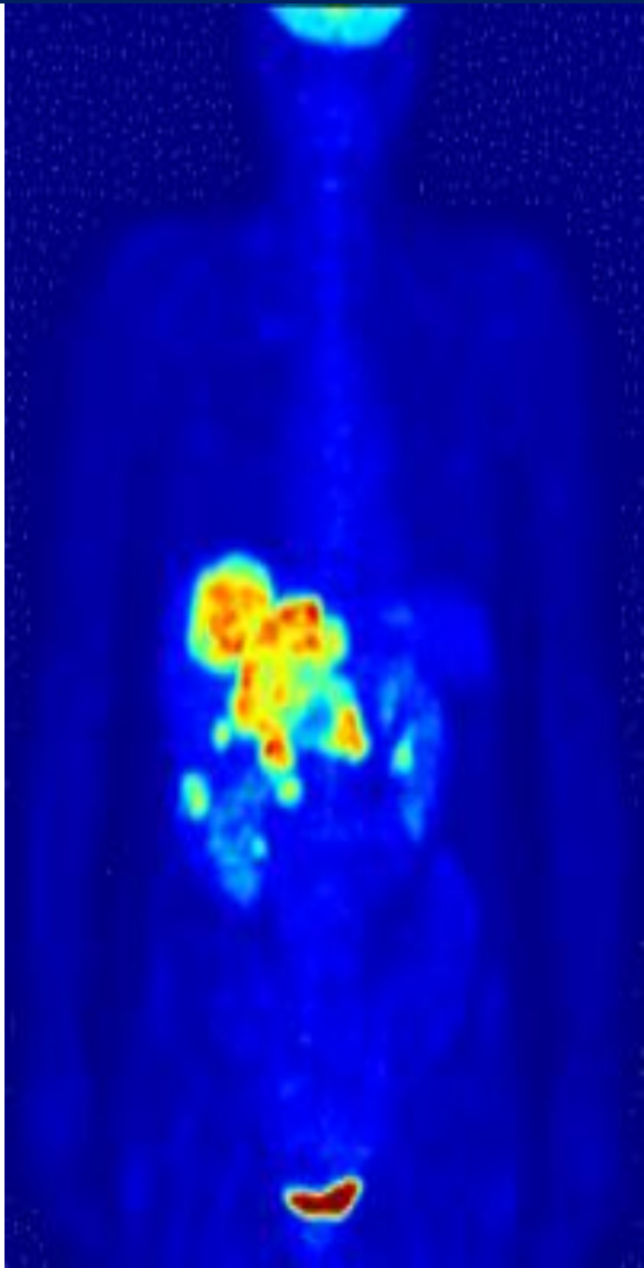
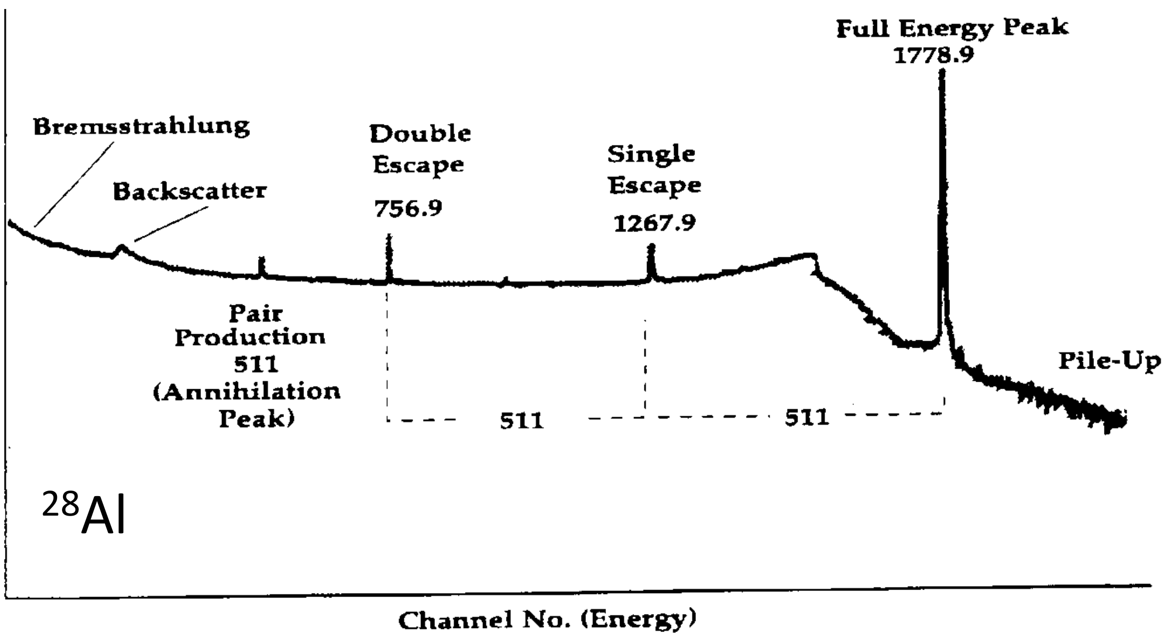
Outline

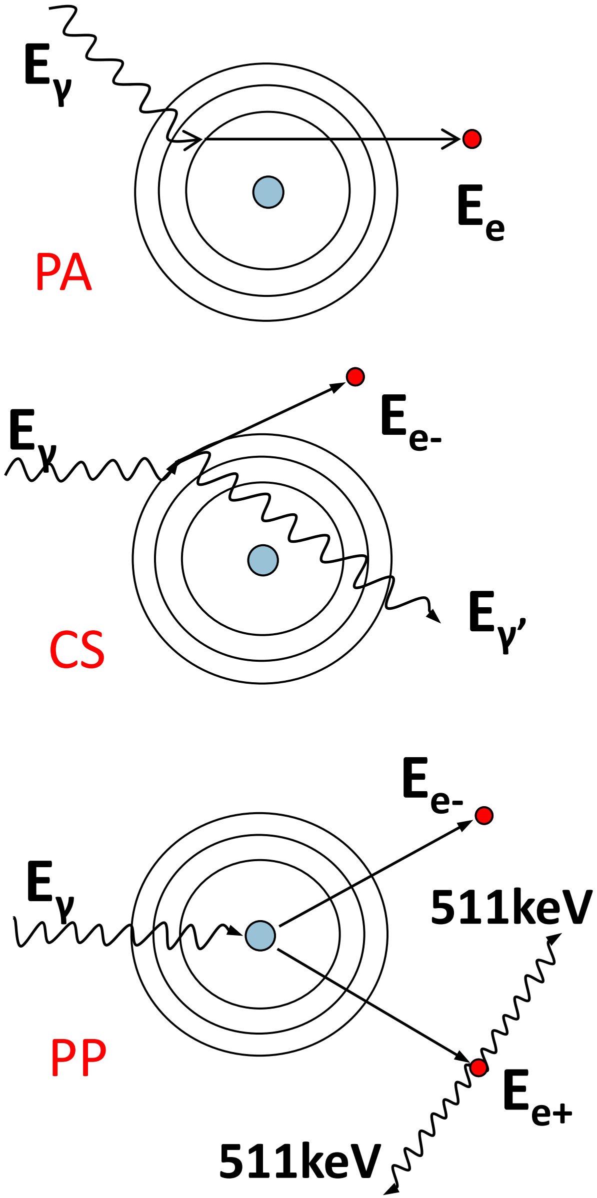
- Gamma-ray detectors
- Compton imaging
  - Example data
  - Liverpool projects
- Positron Emission Tomography (PET)



Gamma-ray detectors

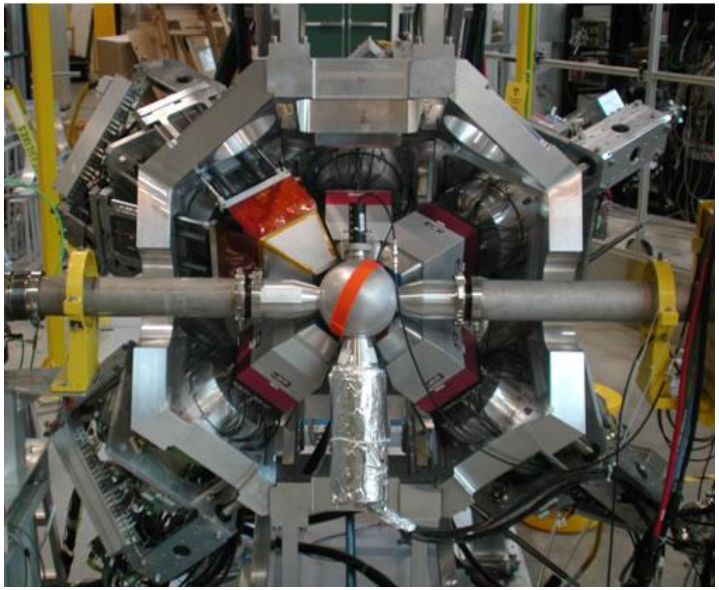
Provide a response from transfer of energy from incident gamma rays to electrons in the detector via Photoelectric absorption, Compton scattering and pair production





Gamma-ray detectors

- Semiconductor detectors, e.g. HPGe, Si, CZT
  - Excellent energy resolution – HPGe ideal for spectroscopy
  - Good efficiency
  - Insensitive to magnetic fields



- Scintillation detectors, e.g. CsI, BGO, $LaBr_3$
  - Very efficient (good for Compton suppression)
  - Relatively poor energy resolution
  - Cheap and robust – good for applications
  - PMTs sensitive to magnetic fields

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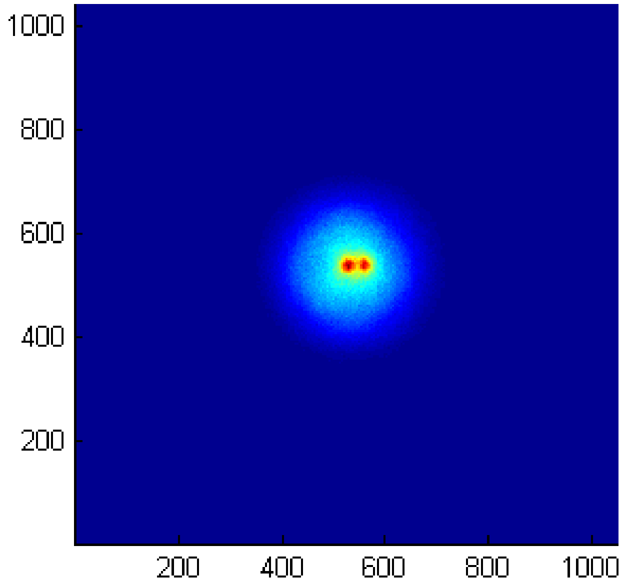
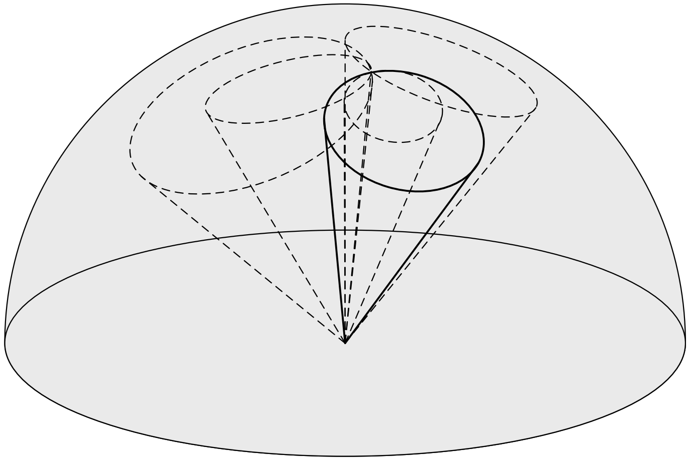
Compton imaging



- Used to detect sources of gamma radiation
- Can locate radiation via imaging methods
- Can identify what the source of radiation is via gamma-ray spectroscopy
- The system has a wide range of view so is possible to locate radiation at different scales – in a lorry, in a room, in a body
- Can be used to image radiation for vehicles in transit

Compton imaging – some history

- Compton imaging not a new concept
- Astrophysicists have been using this method since the 1970’s
- Low energy, near field applications have some challenging limitations:
  - Detectors with very low noise properties
  - Read-out electronics with very high readout capabilities
  - Advanced image reconstruction algorithms, including computing power
- Developments here have led to a resurgence in research activity



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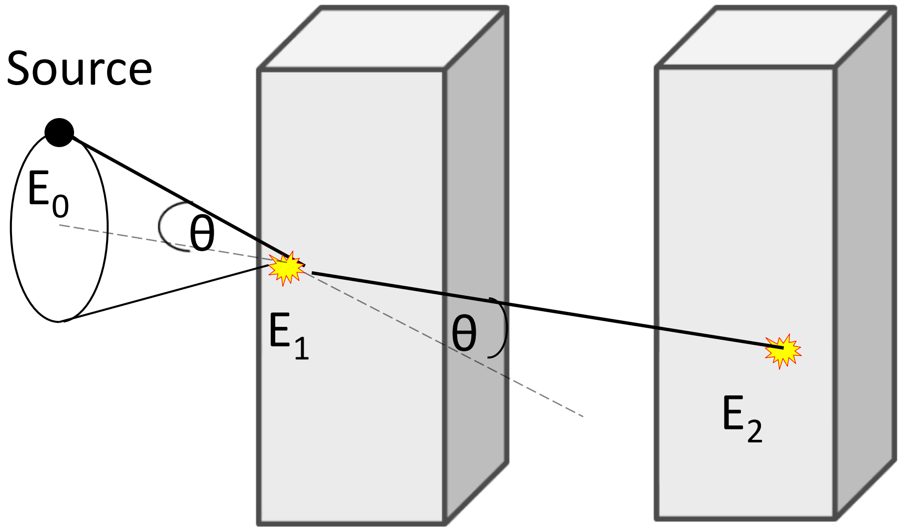
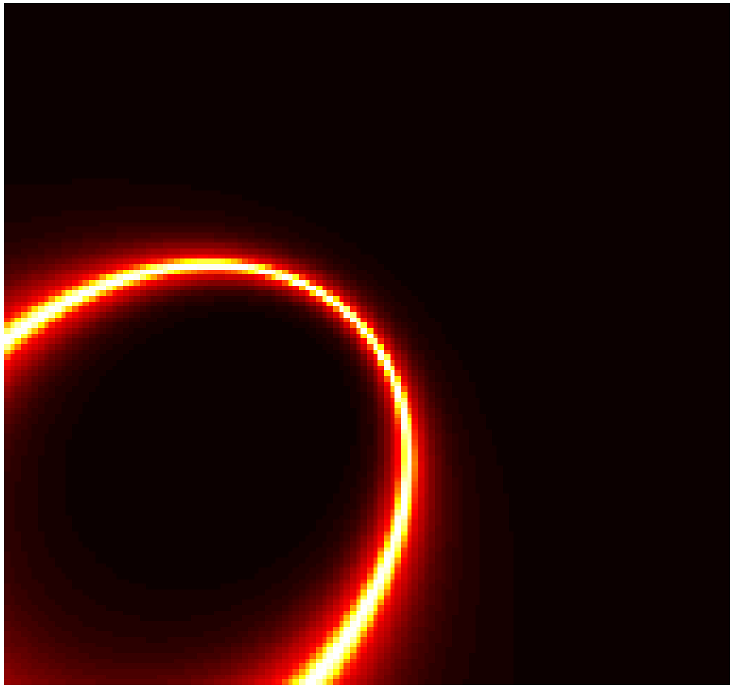
How does it work?

- Gamma rays interact in both detectors (scatterer and absorber)
- The path for each gamma ray is reconstructed as a cone
- Source located at max cone overlap





$$\cos\vartheta = 1 - m_e c^2\left(\frac{1}{E_1} - \frac{1}{E_0}\right)$$

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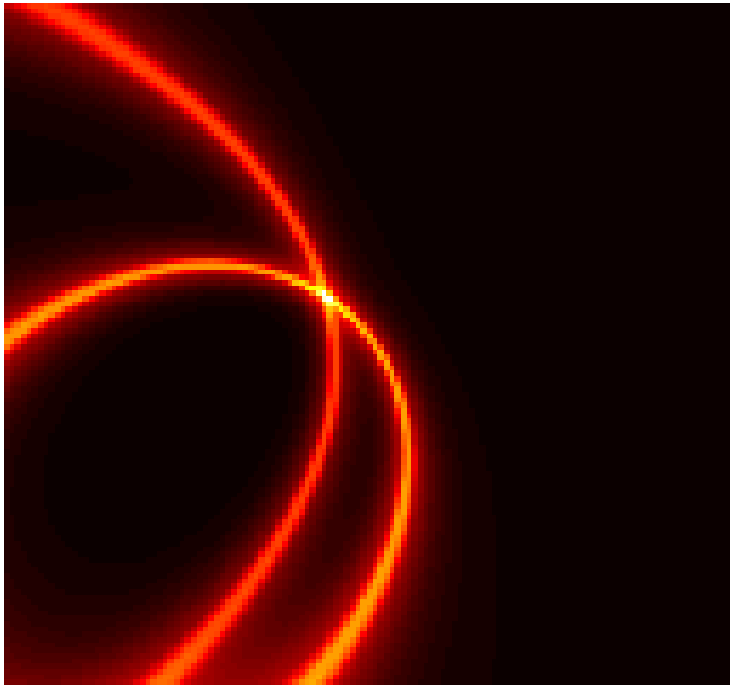
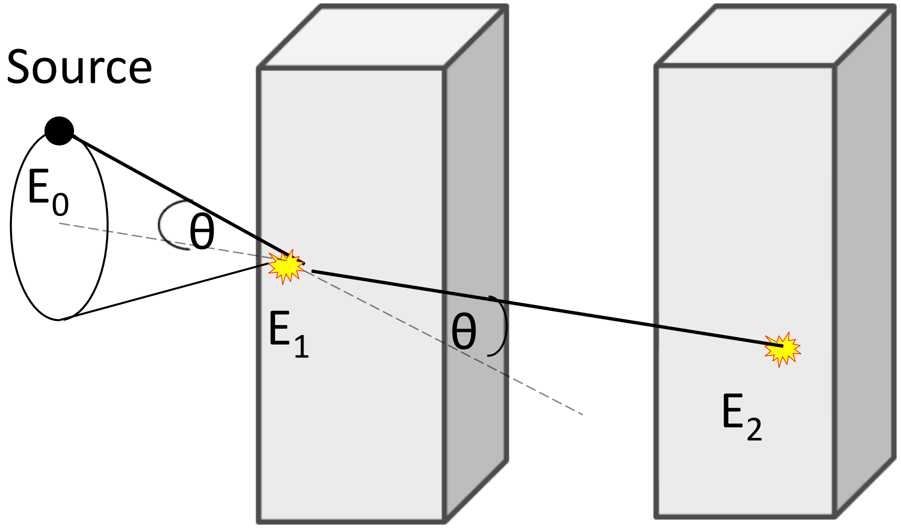


$$\cos\vartheta = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E_0} \right)$$



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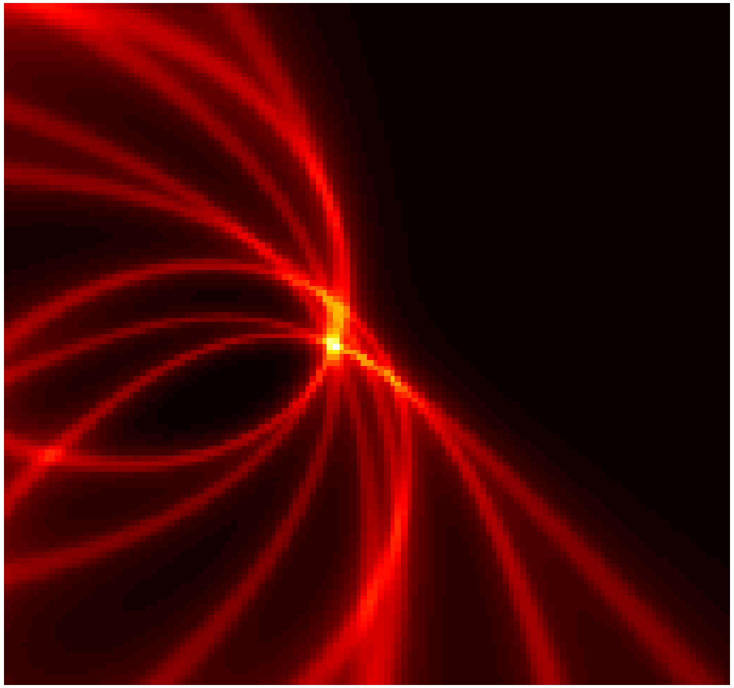

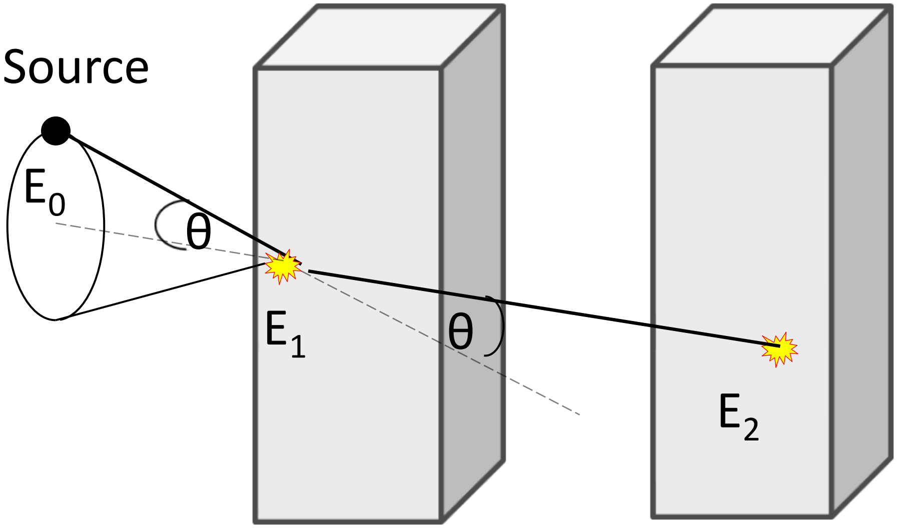

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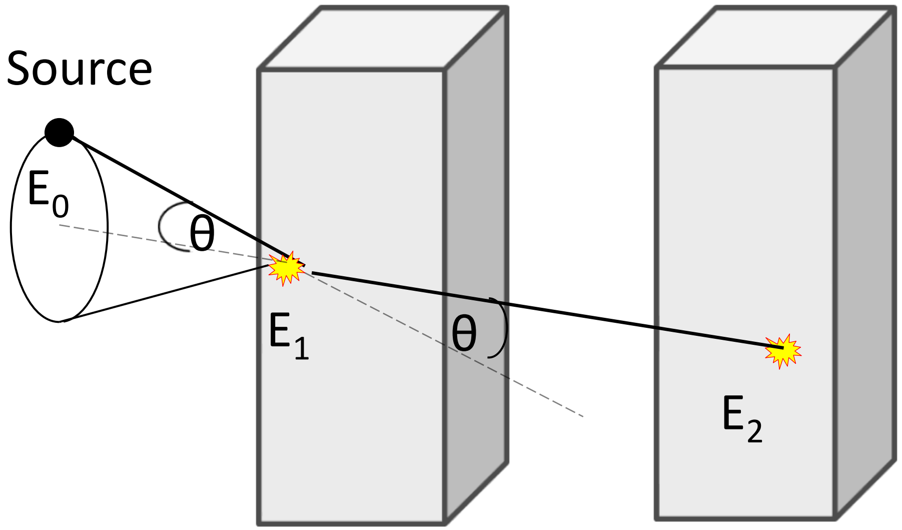

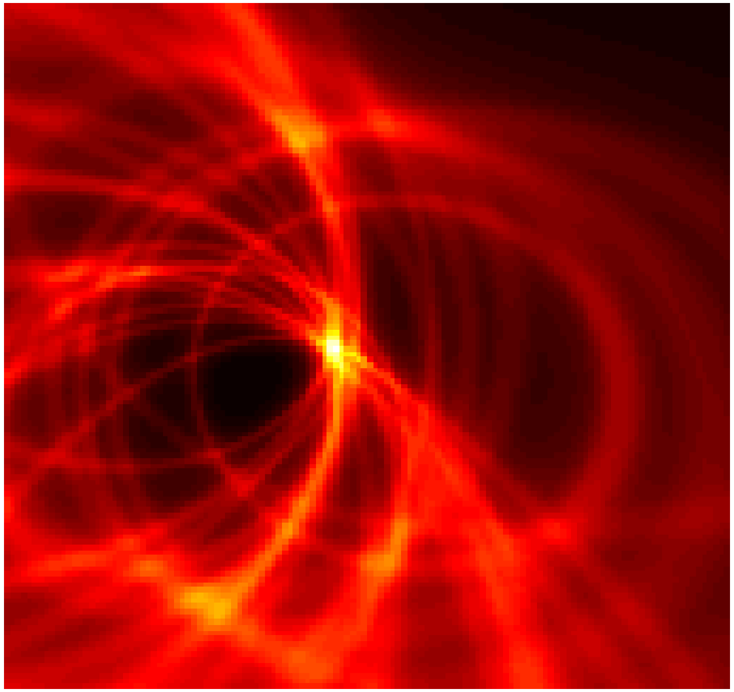

$$\cos\vartheta = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E_0} \right)$$

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What makes a good system?

- Sensitivity of a Compton camera is a factor of:
  - Detector materials: Compton scattering cross-section in scatterer and Photoelectric absorption cross-section in absorber[1]
  - Detector thicknesses
  - Configuration geometry
  - Low energy noise thresholds
- Quality of the reconstructed image is a factor of :
  - Detector energy and position resolution
  - Doppler broadening

Semiconductor Detectors ☺

1. L J Harkness et al, *Optimisation of a dual head semiconductor Compton camera using Geant4,* NIMA (2009) 604, 351-351

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Example data

- Two HPGe SmartPET detectors in Compton imaging mode
- 2.5cm separation between cans
- Multi-isotope imaging:
  - ^{137}Cs point sources 662keV
  - ^{22}Na line source 511keV and 1274keV
- Measurements at multiple angles, (varying 5° to 15° increments across a 20° to 110° range)

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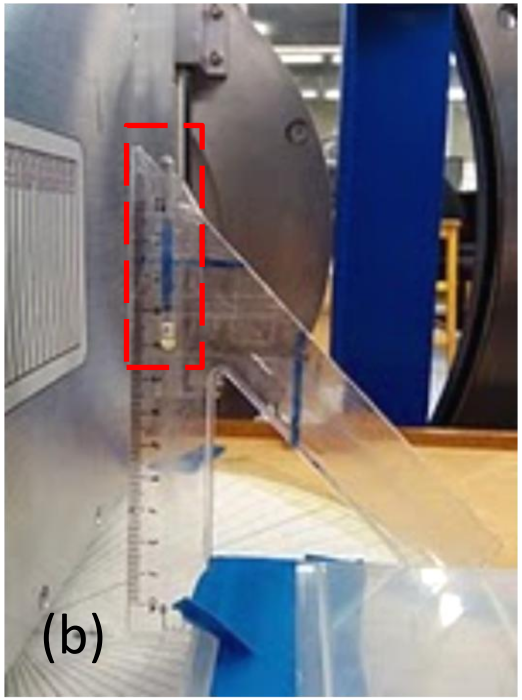
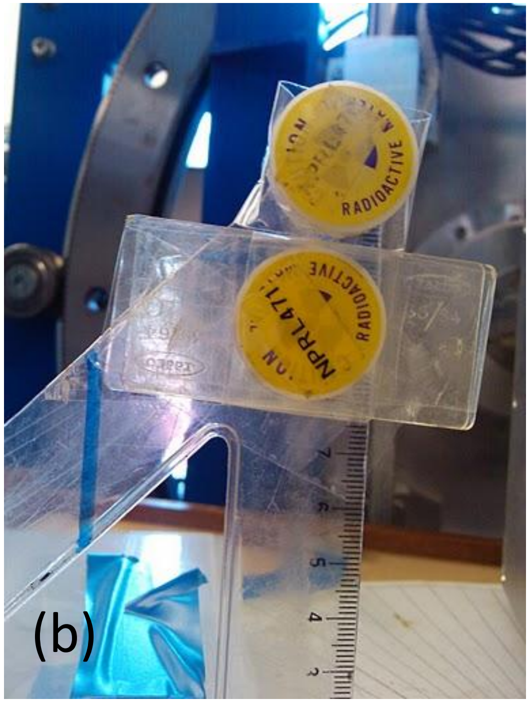
Example data sets

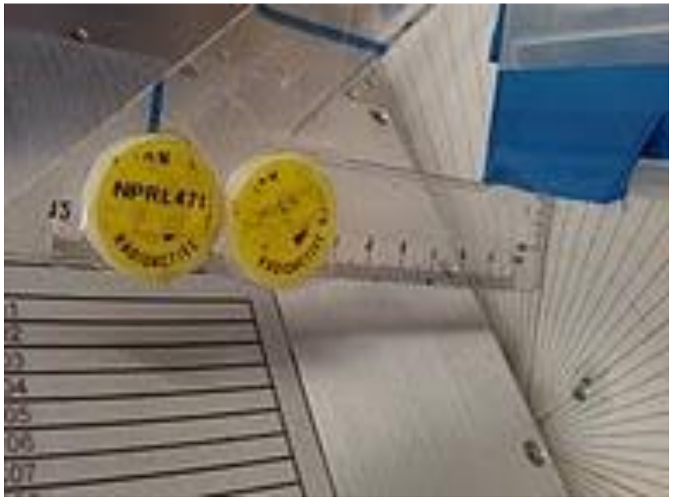
(a) Two ^{137}Cs point sources, separated by 2.8 cm

(b) One ^{22}Na line source, separated by 1cm from two ^{137}Cs point sources separated 2.8cm from each other

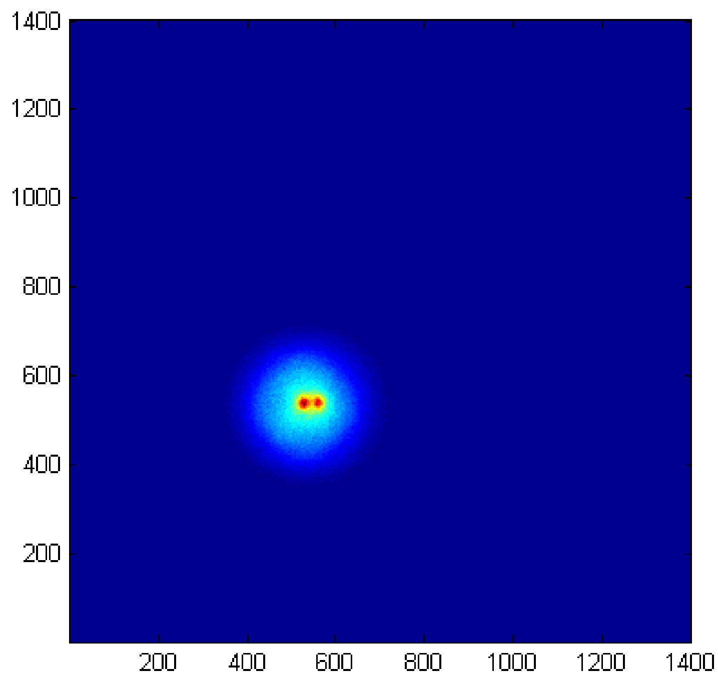


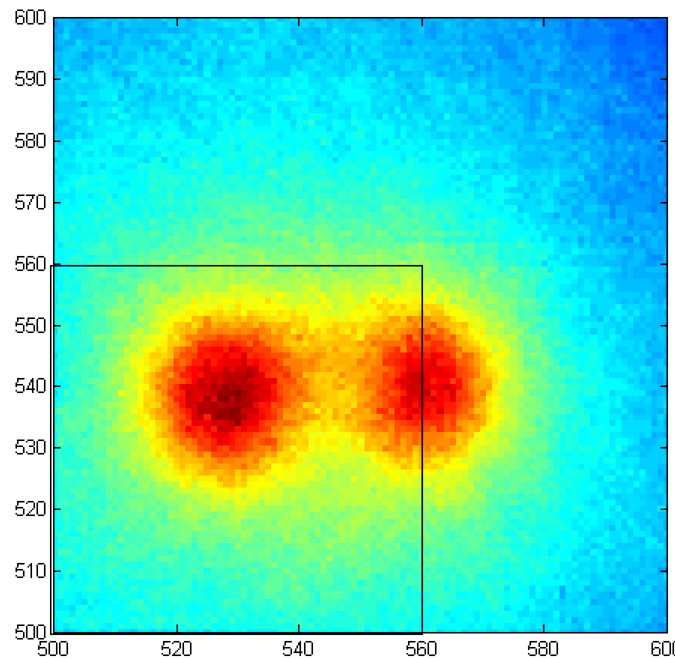


Results: Two ^{137}Cs point sources separated by 2.8 cm



- ✓ Two sources 5 cm from scatterer
- ✓ Fold [1,1,1,1] addback spectrum generated
- ✓ 10 keV gate set around the 662 keV addback photopeak





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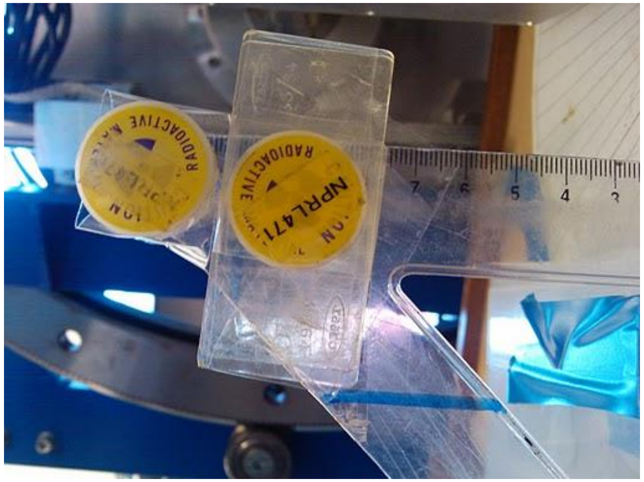
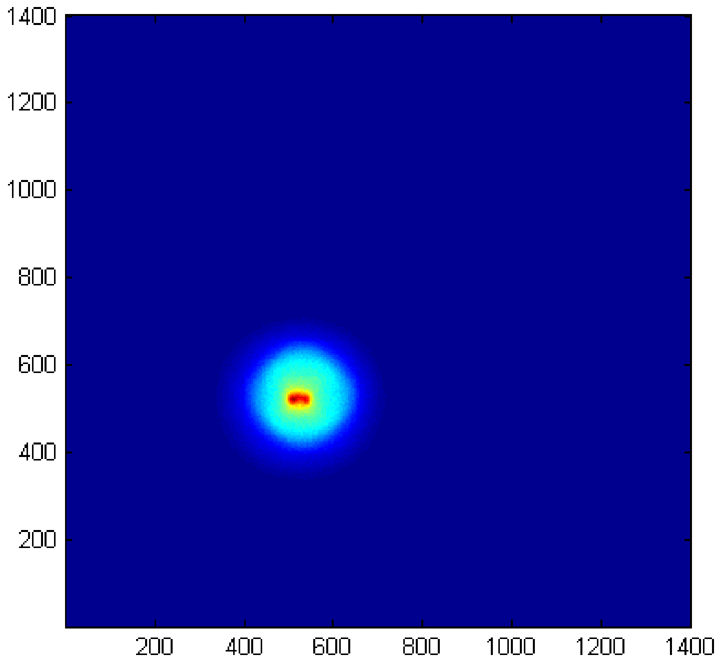
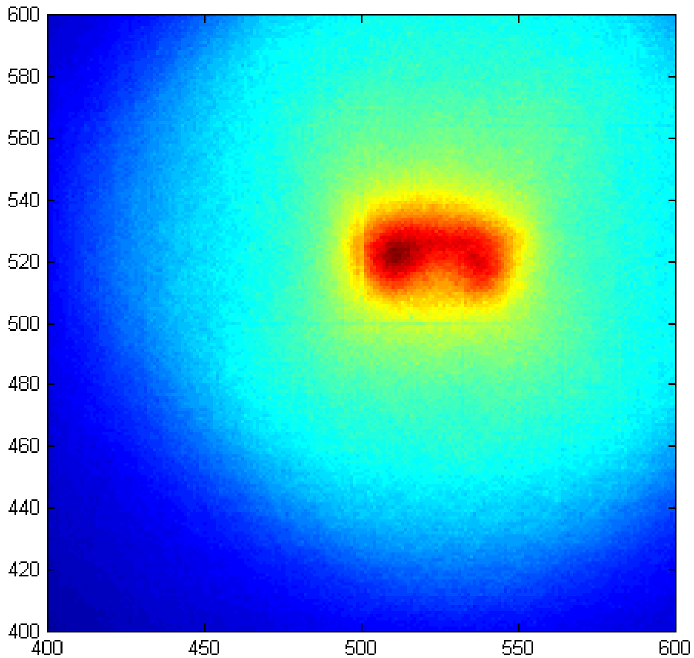
Results: One ^{22}Na line source and two ^{137}Cs point sources

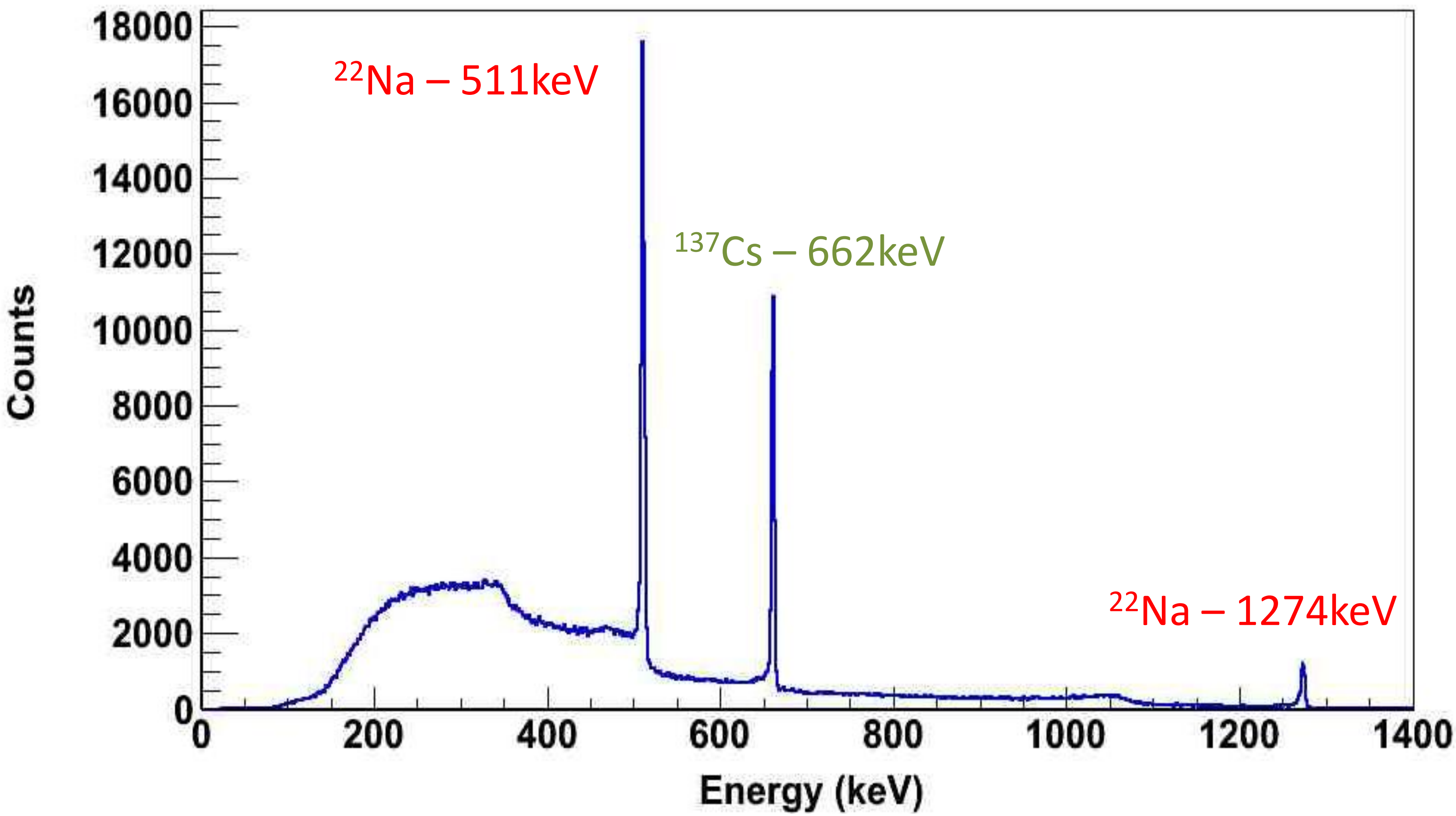


- ✓ Two ^{137}Cs sources sep 2.8cm and one ^{22}Na line source 8 cm from scatterer
- ✓ Fold [1,1,1,1] addback spectrum generated
- ✓ Two 10 keV gates set around the 511 keV and 662 keV addback photopeaks

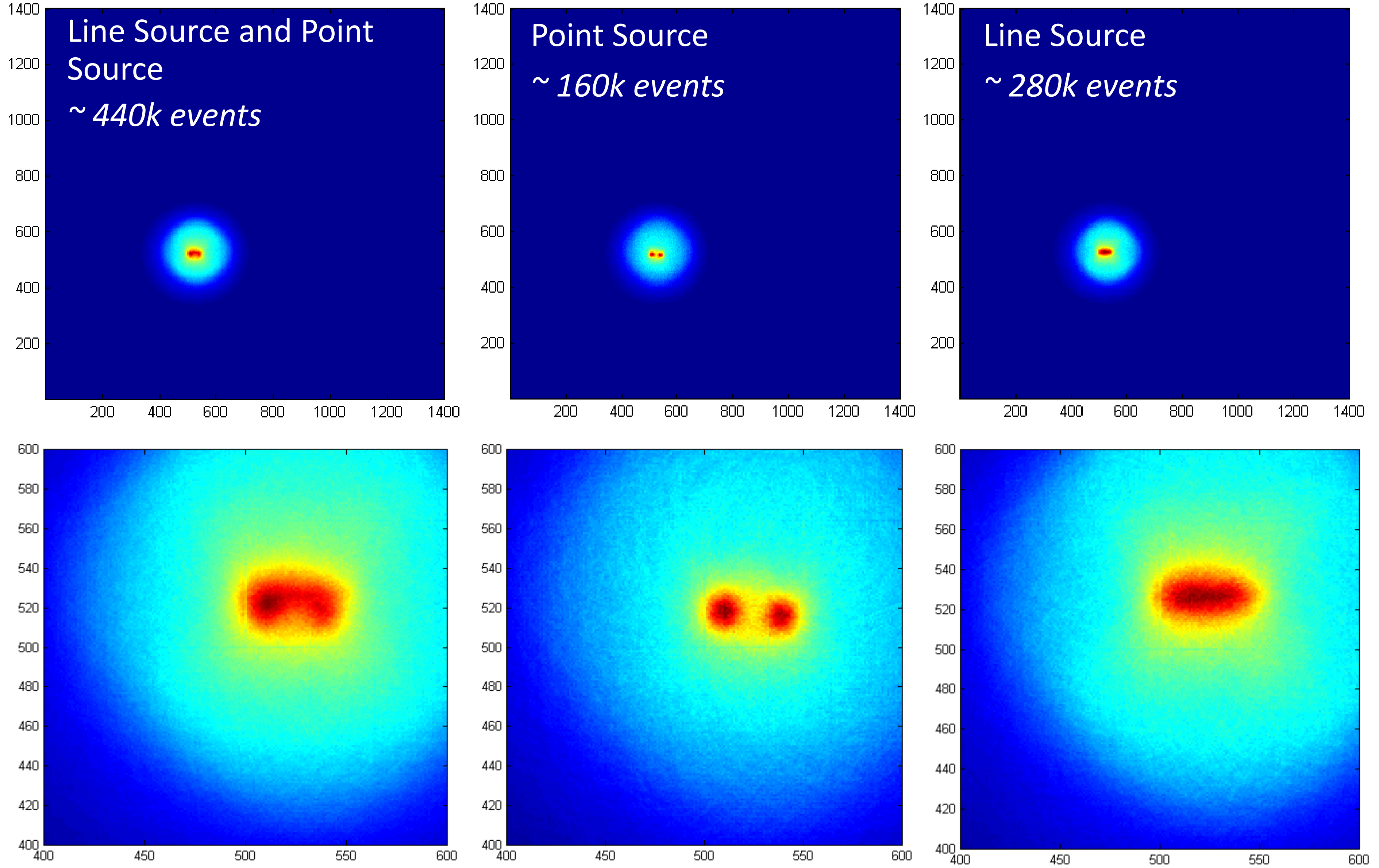




Multi-isotope imaging



Let's break it down...



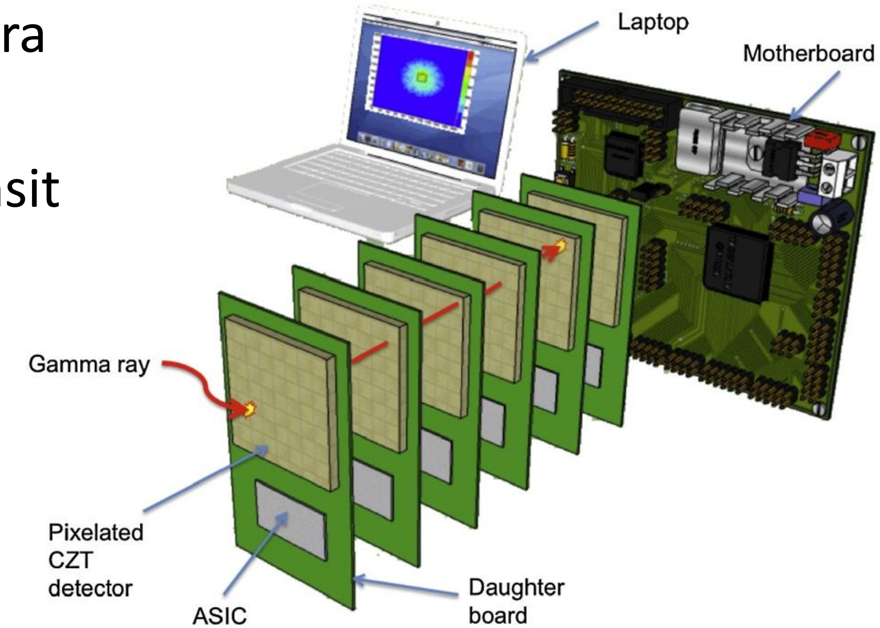
Can image quality be improved?

- Contributions to Compton camera image quality include[1]:
  - Doppler Broadening
  - Energy Resolution
  - Position Resolution
  - Geometrical configuration
- Doppler broadening is a property of the detector material
- Energy resolution is characteristic of the detectors
- Position resolution can be improved beyond electrode segmentation
- Development of image reconstruction algorithms

1. L J Harkness et al, *Design Considerations of a Compton camera for Low Energy Medical Imaging,* AIP Conf Proc (2009) 1194, 90-95

Compton imaging projects at Liverpool

- **AWE project** : imaging across a wide energy range – threat reduction
- **PorGamRays**: a portable device (room temperature detectors)
- **NNL Collaboration**: coupled with an optical image
- **GammaKeV**: a robust portable camera
- **Distinguish**: imaging of goods in transit
- **ProSPECTus**: nuclear medicine



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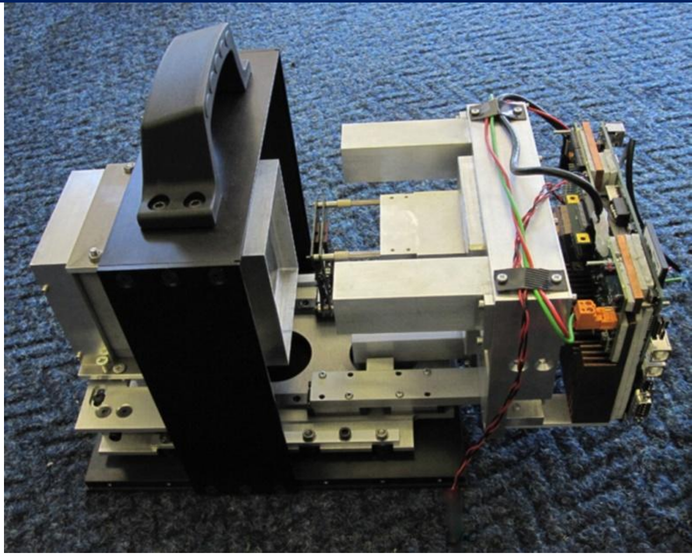
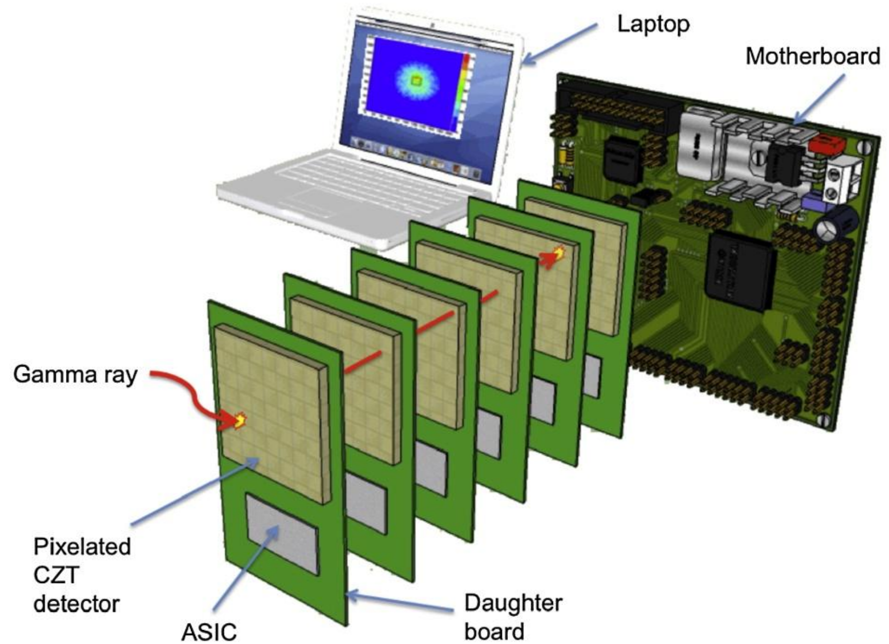
Nuclear decommissioning and security

- PorGamRays – room temperature, small area, semiconductor detectors portable for "in the field" measurements
- NNL project – real time gamma ray imaging coupled with optical images from a camera
- GammaKeV – imaging of gamma rays from the reactor of a nuclear submarine





Security applications

• Monitoring luggage at airports, and cargo at shipping docks is important

• The luggage is passed through **x-ray scanners**

• The radiation is used to image what is inside containers without opening them

• Can identify objects through their **shape** and **density**

Security applications

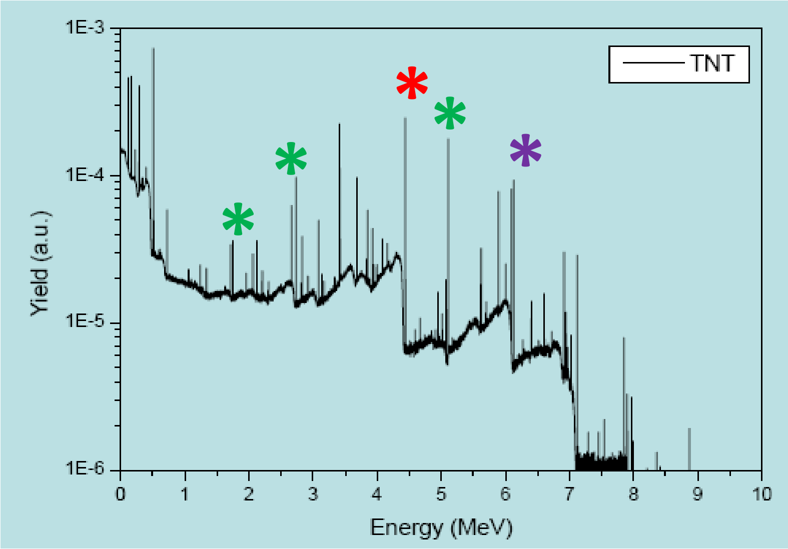
• Useful to identify specific materials, e.g. drugs and explosives

• Research at UoL Physics Dept: Detection of gamma-rays from neutron activated materials

• Can both form an image and produce a **gamma-ray spectrum**

• The peaks in the gamma-ray spectrum contain elemental information: what is inside?

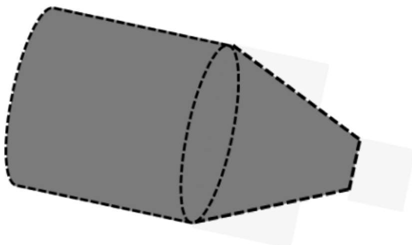
• Explosives and drugs contain combinations of light elements e.g. Oxygen (6.1 MeV), carbon, (4.4 MeV) nitrogen (1.64, 2.31, 5.11 MeV)



Security – new research

Martin Jones

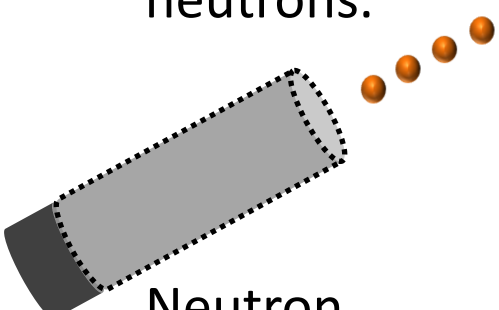
Neutron detector



Inelastic scattering.

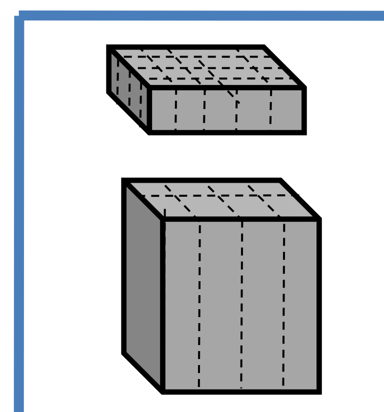
Characteristic gamma rays emitted

14MeV pulsed neutrons.



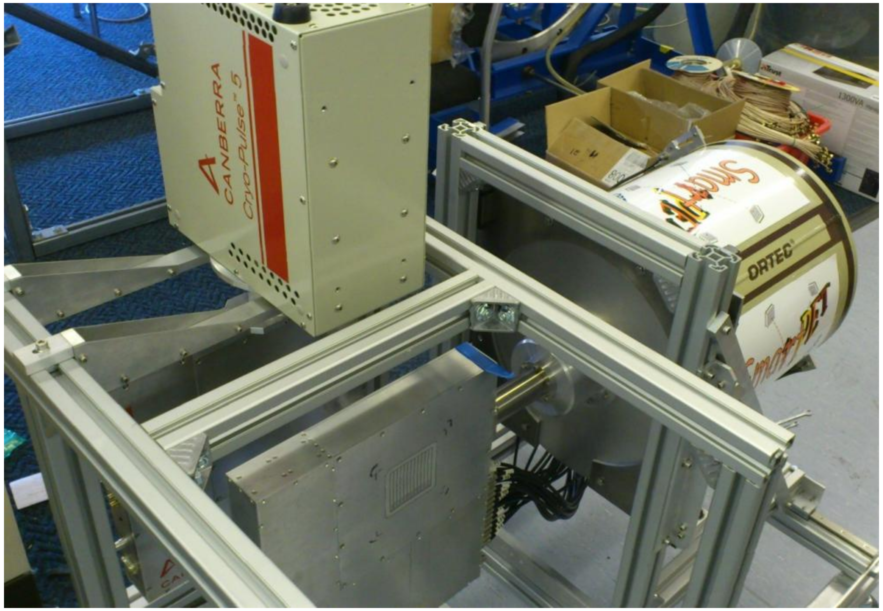
Neutron generator

Detection & imaging **(Compton Camera)**



AWE project

- Development of an imaging device in the detection of illicit nuclear materials
- Energy range 59.4 keV to 2 MeV
- 3 detectors:
  - 5mm HPGe scatter detector (medium to high energy)
  - 8 mm Si(Li) scatter detector (low energy)
  - 20 mm SmartPET HPGe absorber detector (all energies)



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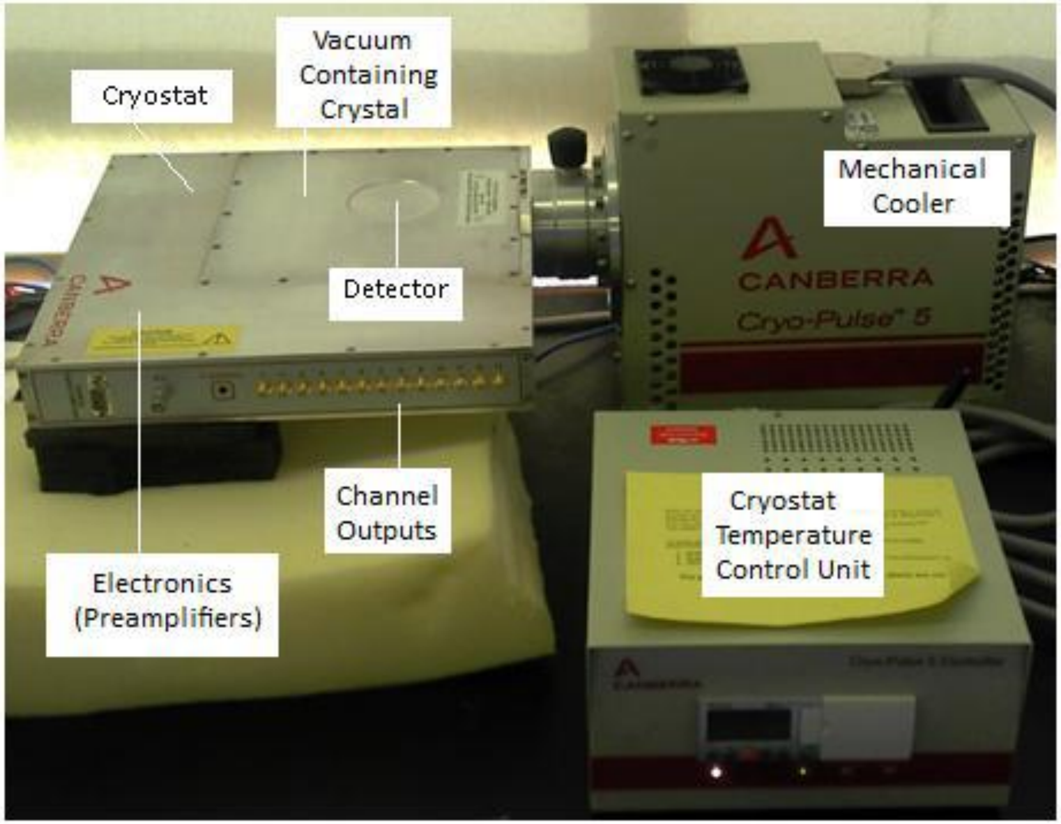
AWE project Si(Li) detector

- Canberra Si(Li) DSSD detector 13 strips on each face
- 8 mm thick, 66 mm diameter
- Cryogenically cooled using a CryoPulse CP5 cooler



- Energy resolution of all strips measured to be (1.4 to 1.6) keV at 59.4 keV using ^{241}Am (excluding channel 14)

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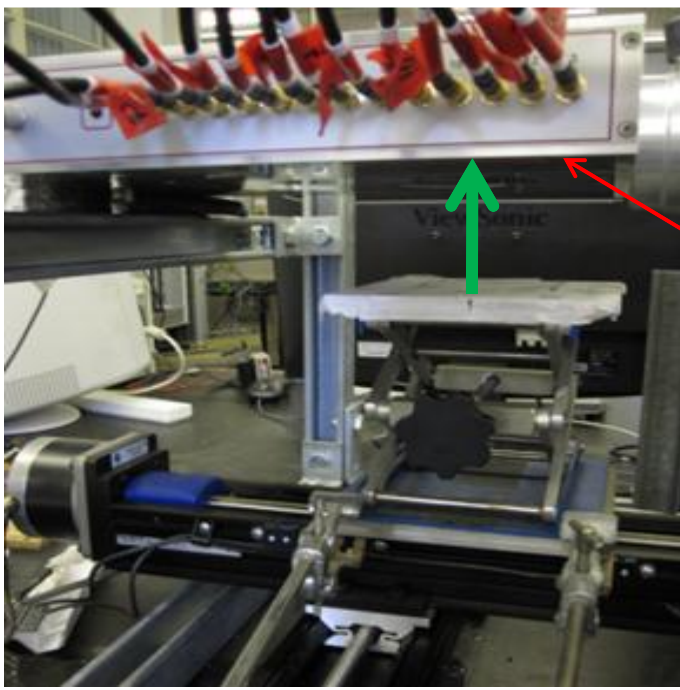
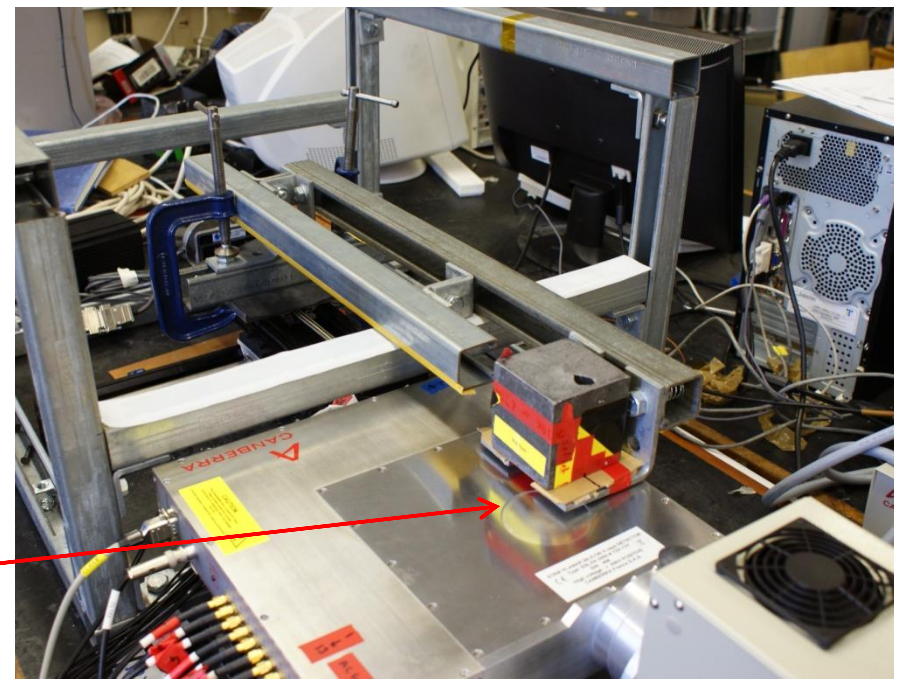
^{241}Am surface scan of Si(Li)

- 1 mm collimated ^{241}Am source scanned in 1 mm steps with a duration ~40s across the AC face, DC face and detector side
- Data recorded using GRETINA cards



DC face

AC face



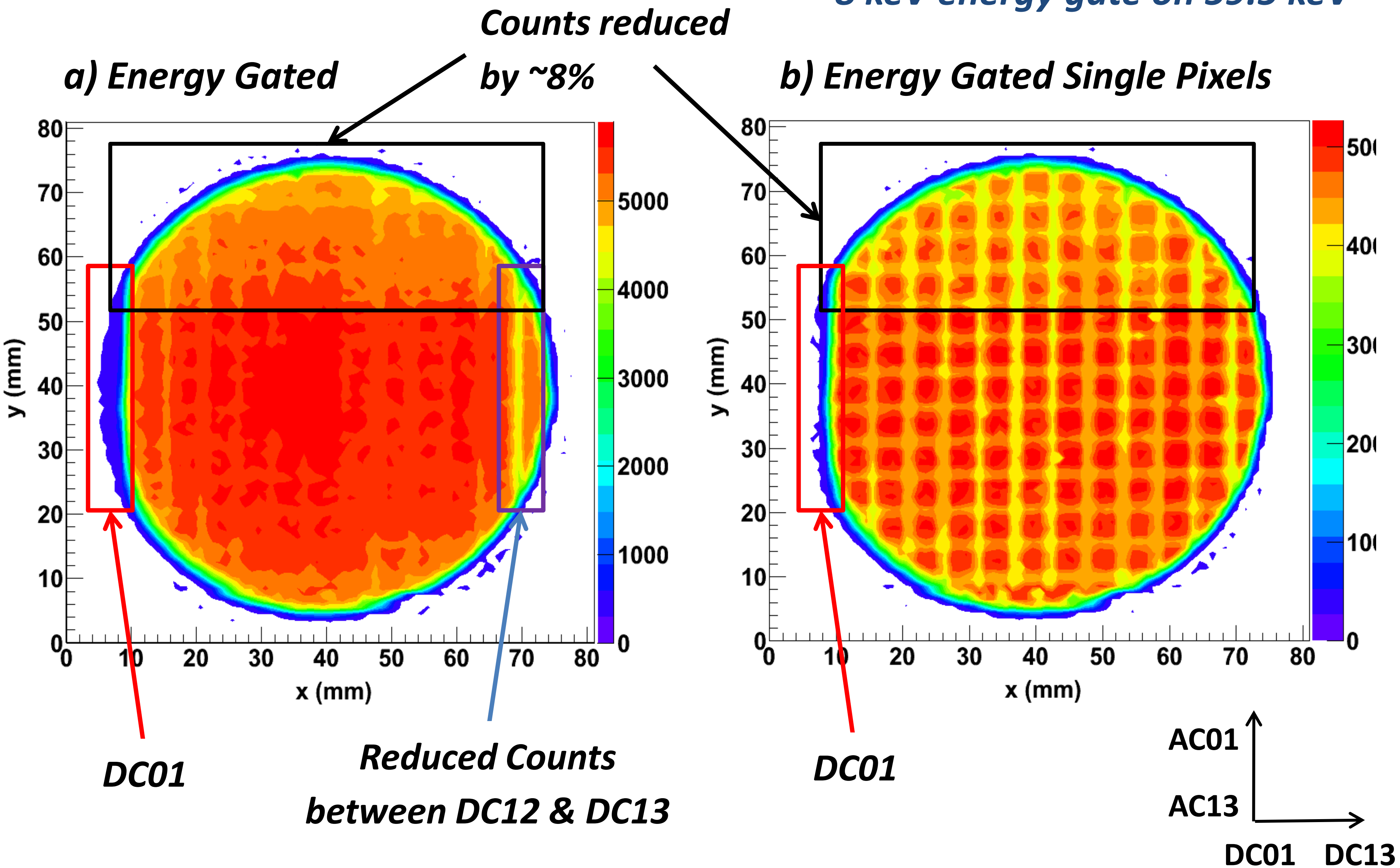
DC Surface scan

AC Surface scan

AC face intensity plots

L J Harkness et. Al, JINST (accepted)

8 keV energy gate on 59.5 keV

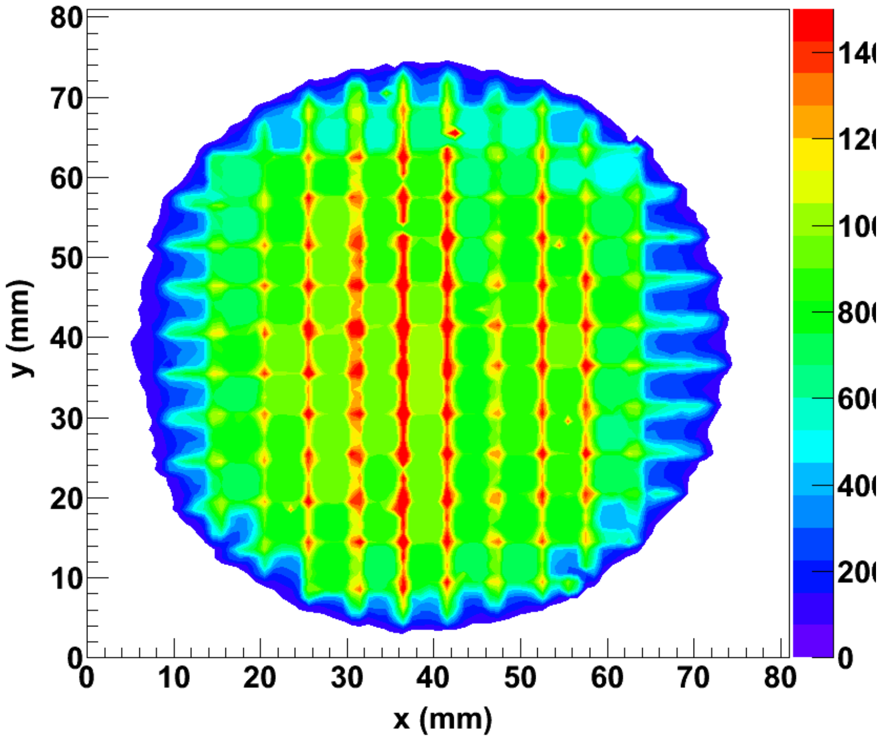


Multiple pixel intensity plots

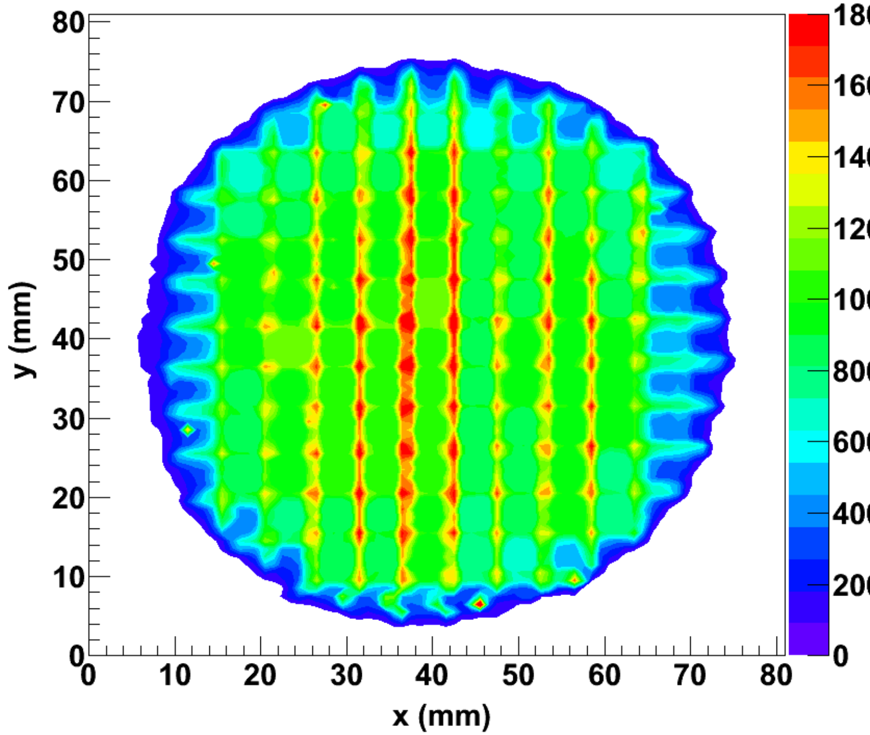
L J Harkness et. Al, JINST (accepted)

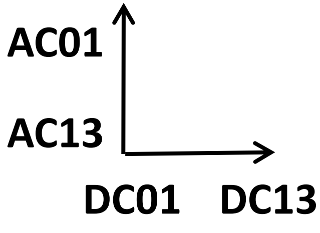
8 keV energy gate on 59.5 keV

a) DC surface scan



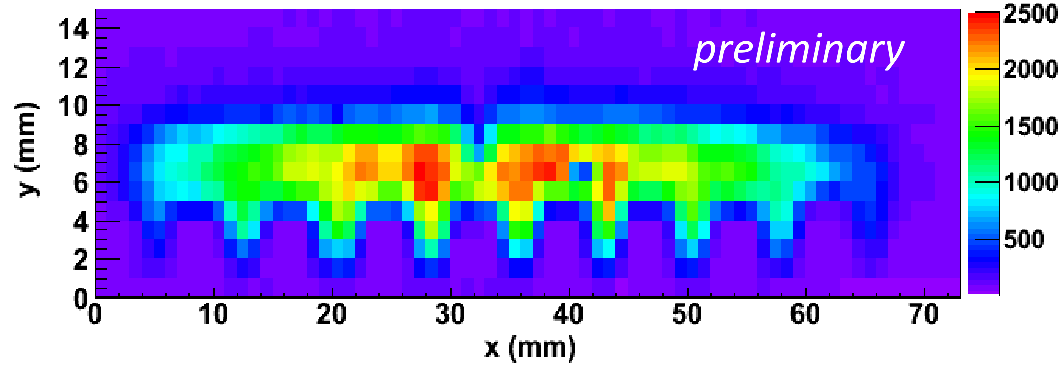
b) AC surface scan



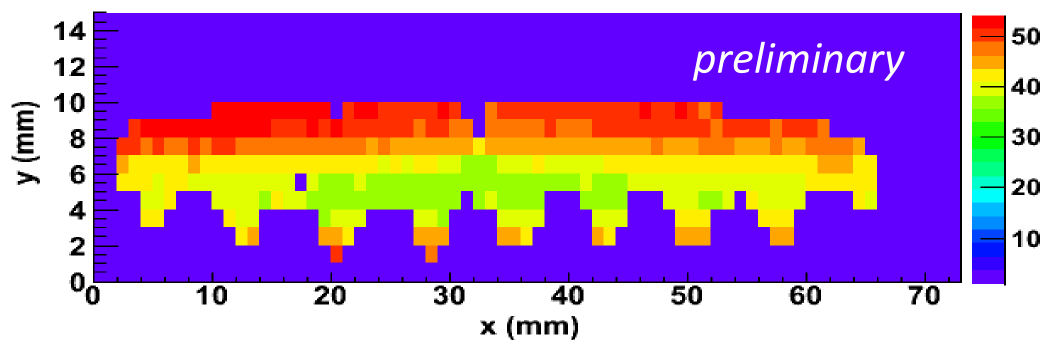


Side scan intensity plots

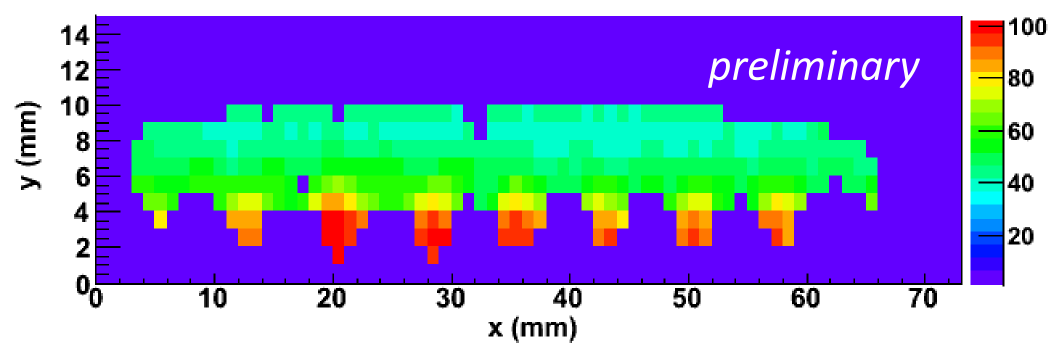
a) Single pixel energy gated intensity map



b) Single pixel energy gated t30 map, AC contacts



c) Single pixel energy gated t30 map, DC contacts



AWE project

- Characterisation of Si(Li) detector underway to determine PSA parameters
- Investigation of charge collection properties of Si(Li) detector ongoing
- Compton camera data currently being taken with the Si(Li) detector and SmartPET HPGe absorber detector (A. Sweeney)

- Characterisation of 5mm HPGe detector to determine PSA parameters
- Compton camera data will be taken with the 5mm HPGe detector and SmartPET HPGe absorber detector

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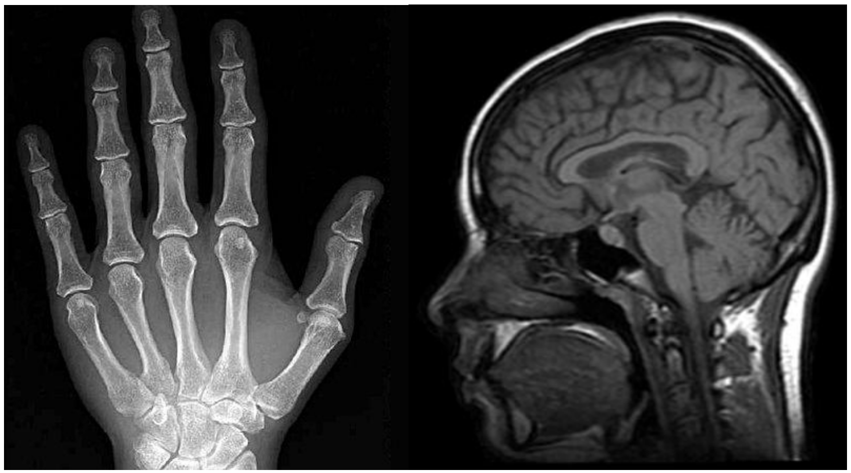
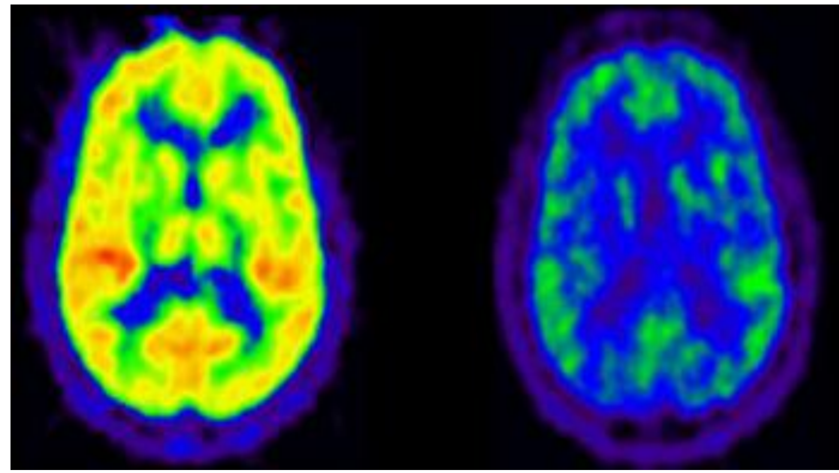
Conventional medical imaging

Anatomical Imaging



- **X-rays**
- **CT** – Computed Tomography
- **MRI** – Magnetic Resonance Imaging

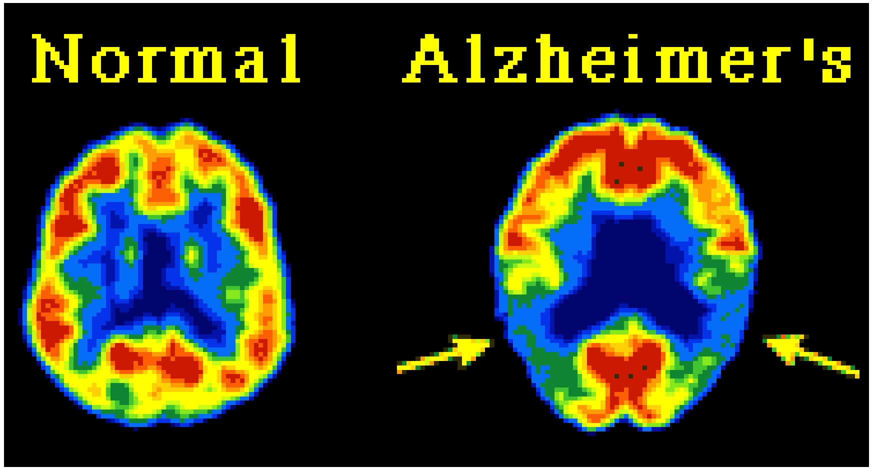
Functional Imaging

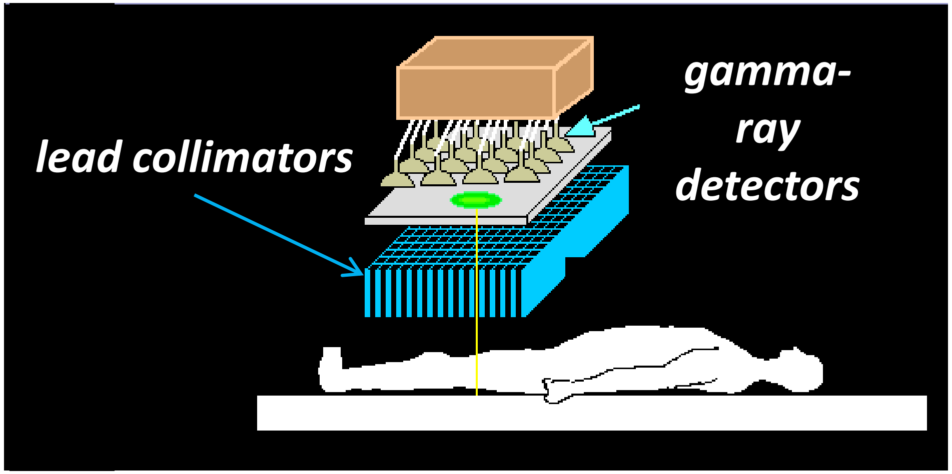


- **SPECT** – Single Photon Emission Computed Tomography
- **PET** – Positron Emission Tomography

Nuclear medical Imaging: SPECT

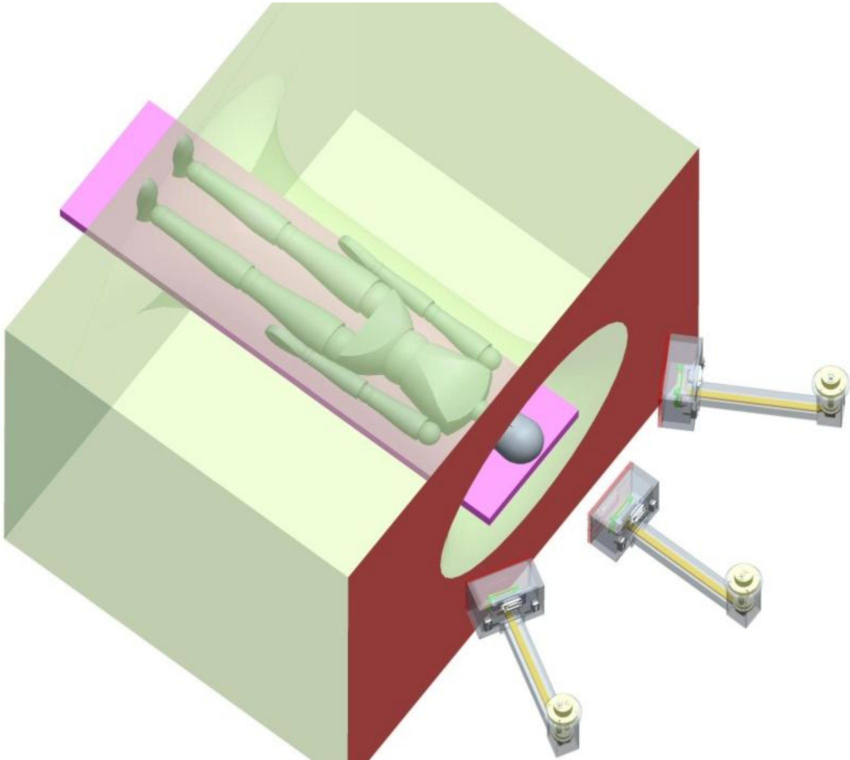
- Nuclear imaging used to study biological functions: **SPECT**
- Inject a radioactive biological compound to patient, **^{99m}Tc**
- Compound travels to organ of interest (e.g. tumour)
- Single gamma rays emitted from compound, detected by a gamma camera which has a mechanical collimator and gamma-ray detectors





SPECT research

ProSPECTus



- £1.1 million project
- Prototype system
- High-sensitivity alternative to SPECT
- A Compton camera used instead of a gamma camera
- Semiconductor detectors

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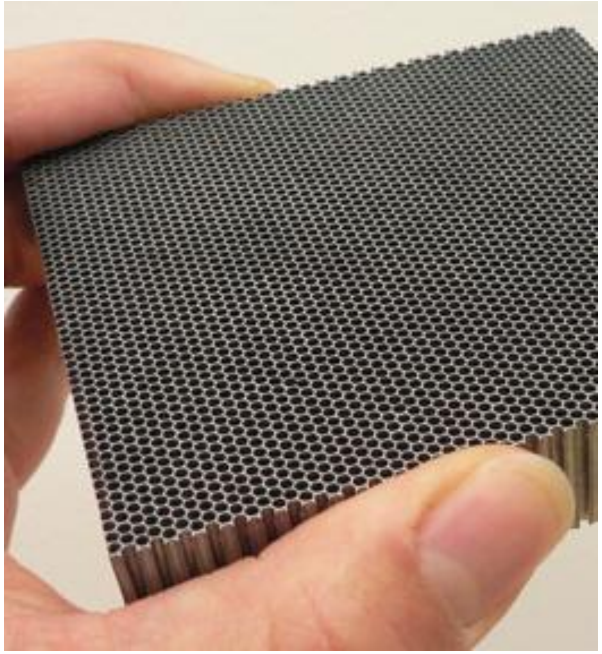
Science & Technology Facilities Council

Why ProSPECTus?

Conventional SPECT is limited by:

- Compromise between sensitivity and image resolution
- Maximum gamma ray energy limit
- Collimator bulky and heavy
- Existing detector readout technology incompatible with magnetic fields



Small animal SPECT collimator
http://www.nuclearfields.com

- Dual-isotope imaging difficult due to poor energy resolution of scintillator detectors

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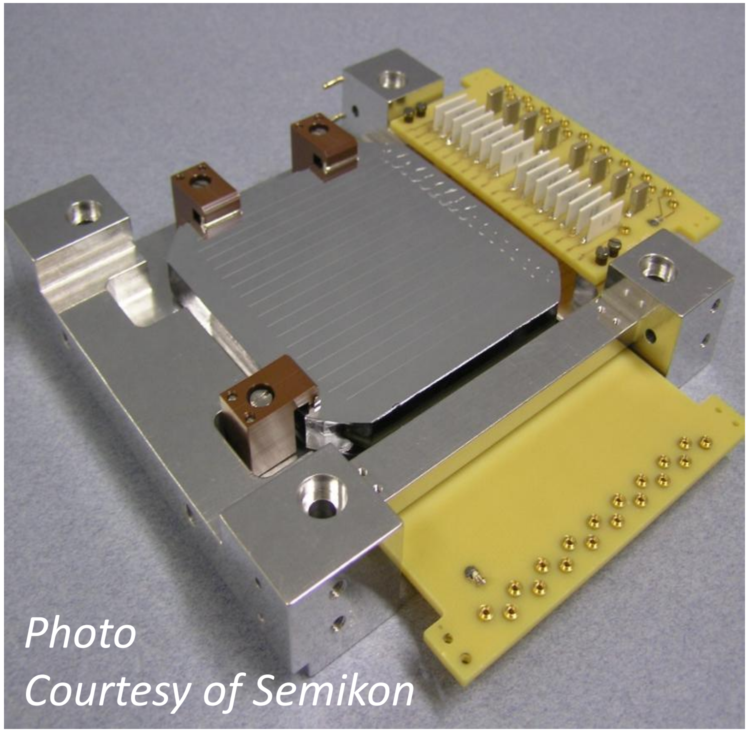
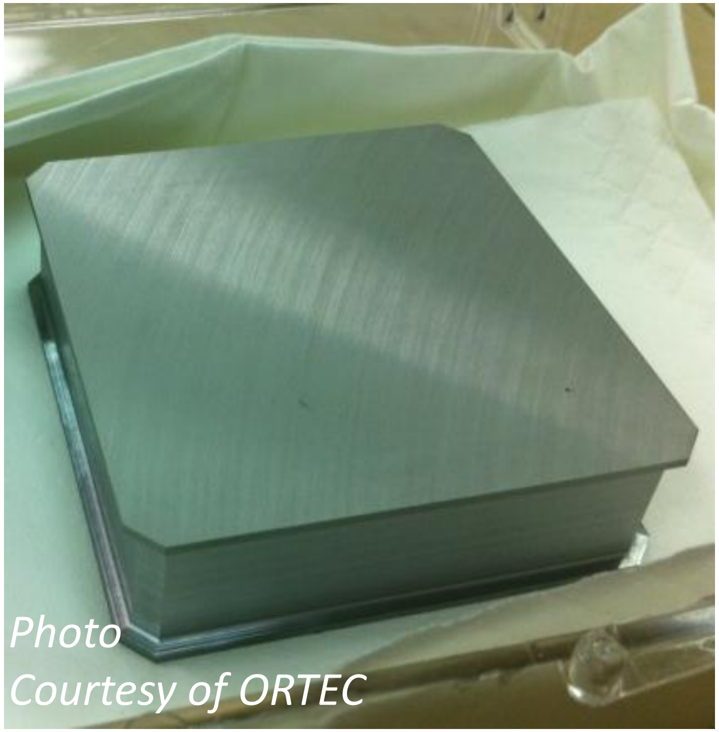
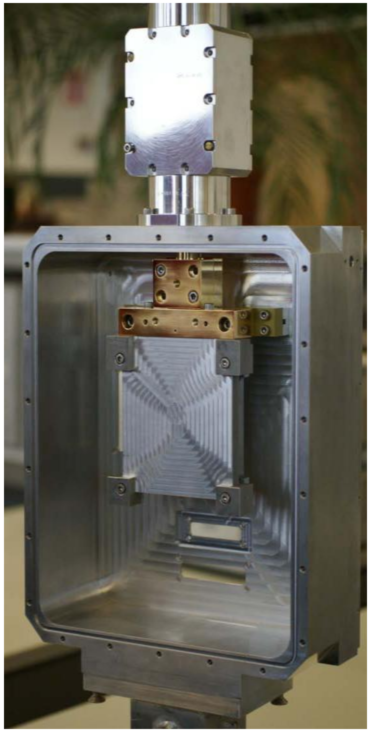
ProSPECTus



- Planar Si(Li) detector
- (60 x 60 x 9) mm crystal
- 15 strips on each detector face, 4mm pitch



- Planar HPGe detector
- (60 x 60 x 20) mm crystal
- 12 strips on each detector face, 5mm pitch

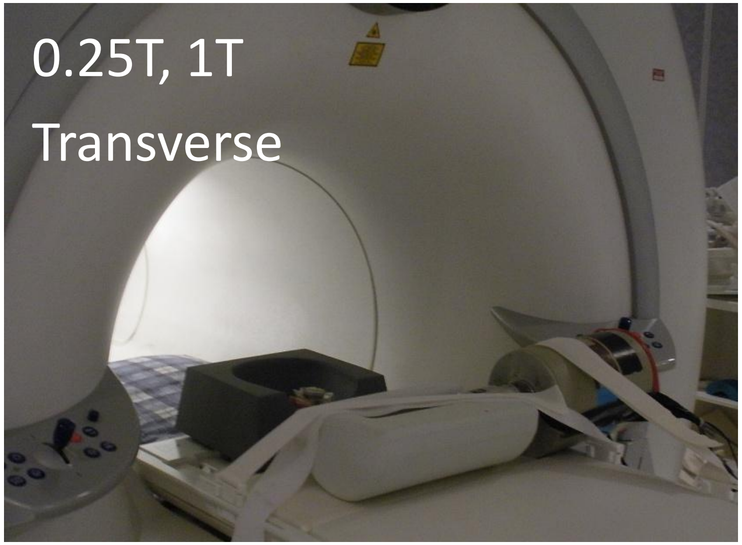


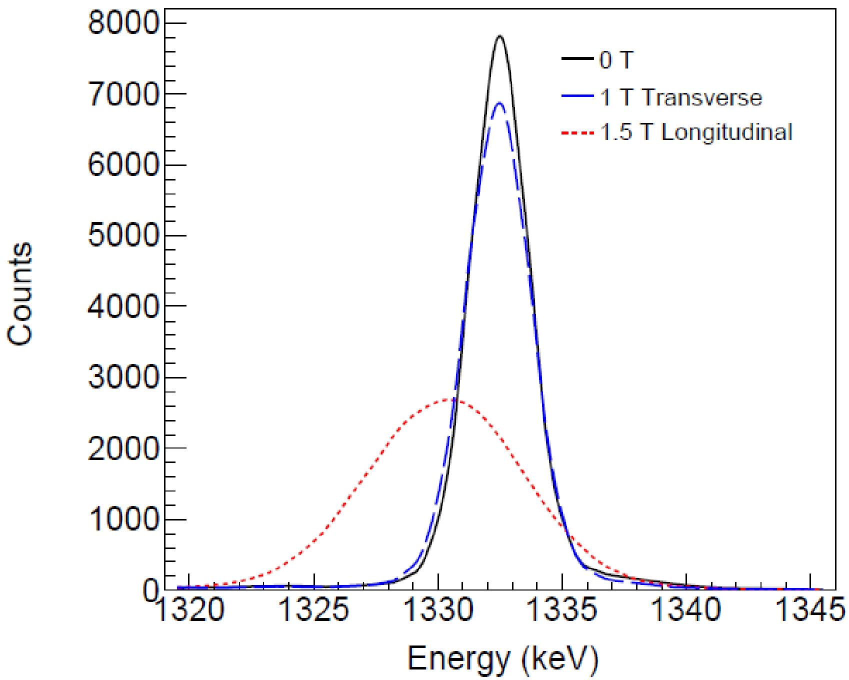
- Custom-built cryostat
- MRI compatible

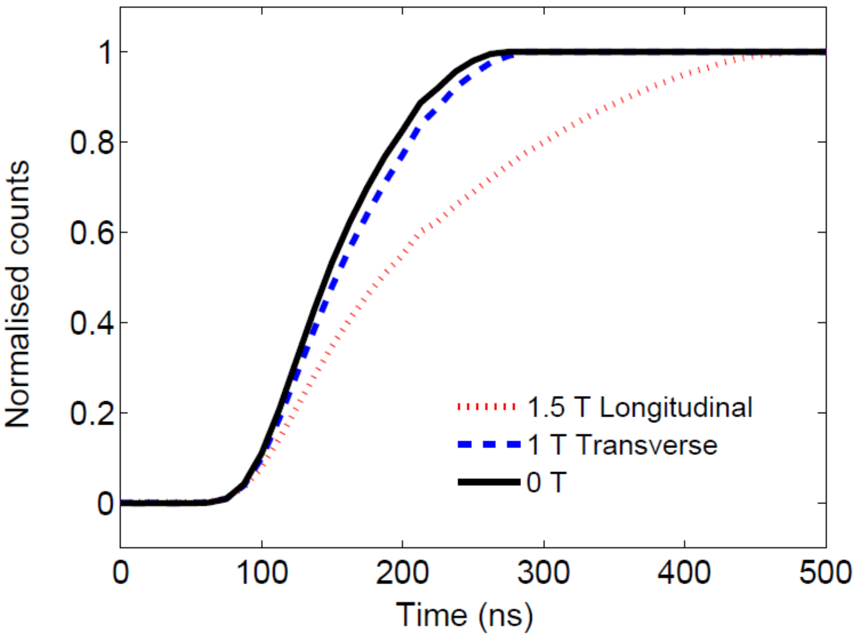
MRI investigation

L J Harkness et. al, NIM A (2011) 638, 67-73

- TESSA coaxial HPGe detector
- 1.5 T Siemens Symphony MRI Scanner
- Data acquired for 2 B field orientations: longitudinal and transverse
- Pulser and Sources: (80keV->1332keV)

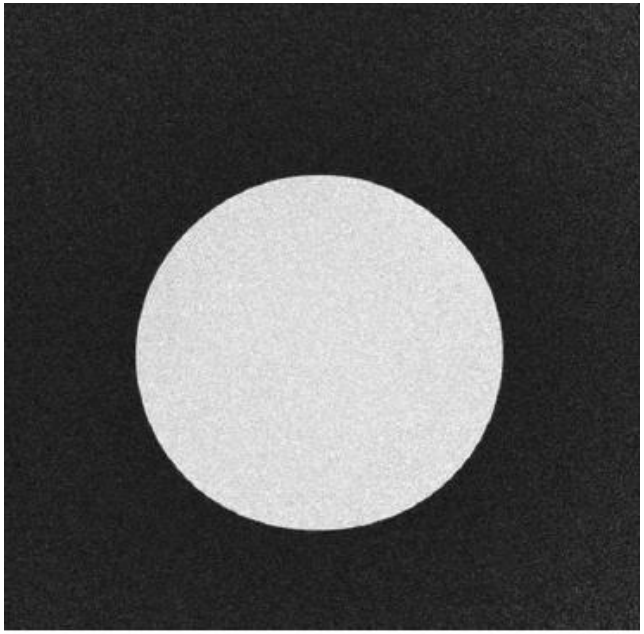




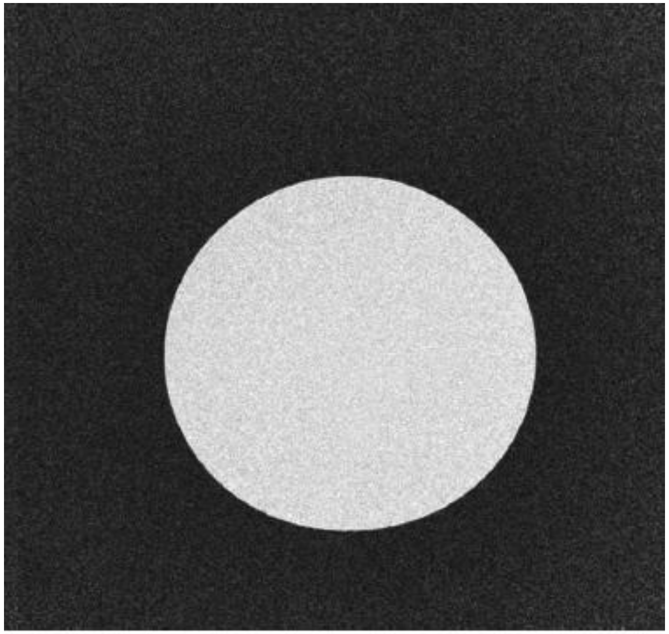


MRI images

L J Harkness et. al, NIM A (2011) 638, 67-73



Calibration Image

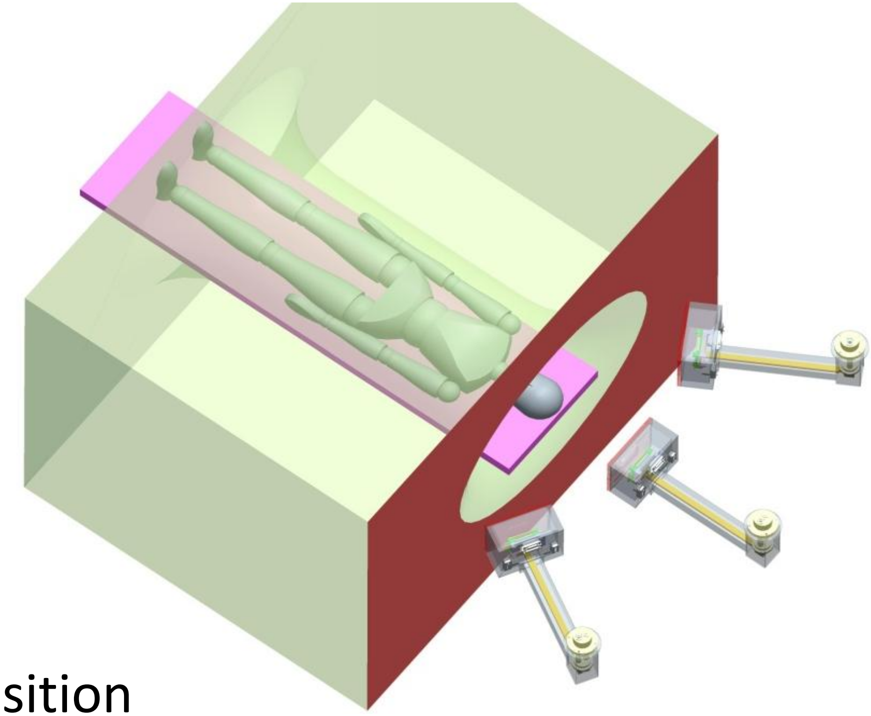


TESSA at bore entrance

- Phantom – cylinder of distilled water
- TESSA detector doesn’t degrade MRI image quality
- MRI imaging doesn’t further degrade TESSA energy spectra

ProSPECTus – an improvement?

- Sensitivity maximised for 141 keV gamma rays – 1 in every 30 used instead of 1 in every 3000 used in LEHR collimated SPECT
- Lower dose to patient or shorter data acquisition times
- Multi-isotope imaging in single acquisition
- Wide energy range with one system
- Compatible with MRI systems



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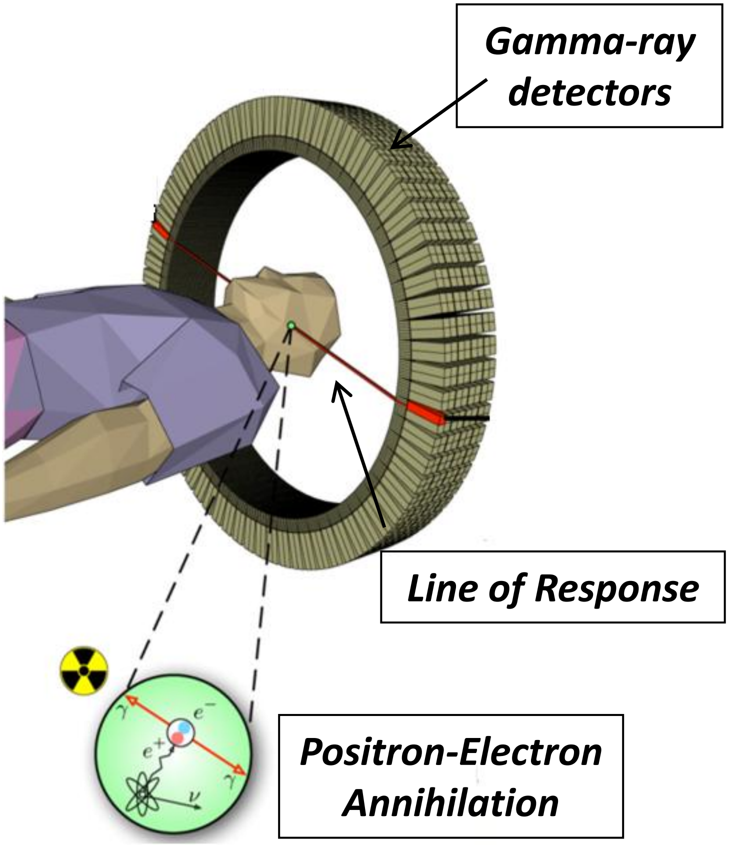
Nuclear medical imaging: PET

- Nuclear imaging used to study biological functions: **PET**
- Inject a radioactive biological compound to patient, **^{18}F – FDG**
- Compound travels to organ of interest (e.g. tumour)
- Positron emitted, annihilates in body
- Two gamma rays emitted from annihilation, back-to back
- Gamma rays detected outside body – Line of Response **LOR**
- Overlapping LOR's shows location of the radiation



Conventional PET

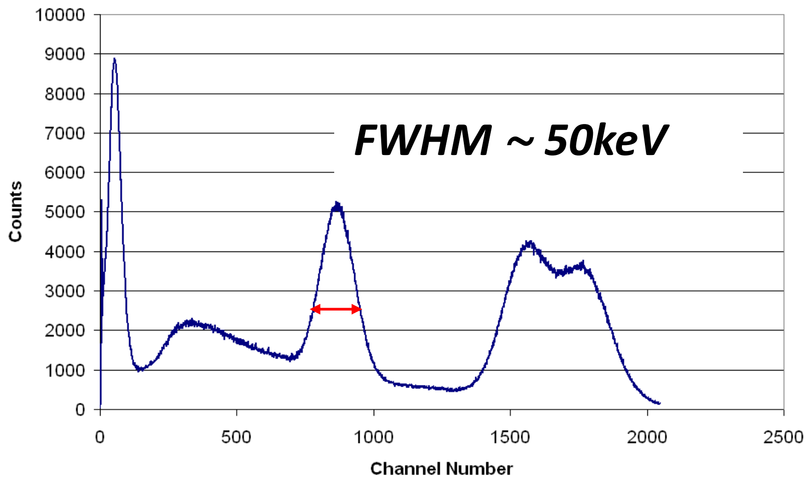
- Scintillation detectors typically employed, e.g. NaI

  ✓ high stopping power

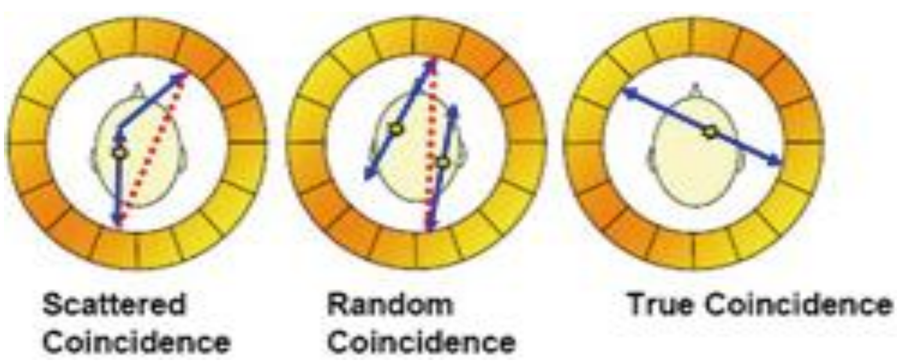
  ✗ poor energy resolution

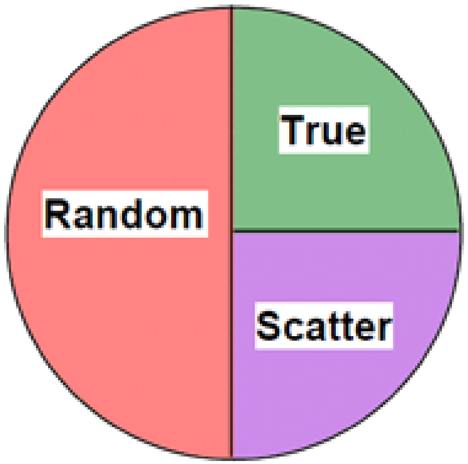
  ✗ limited position resolution

  ✗ PMTs sensitive to MRI fields



- Detectors with better energy resolution would improve discrimination of scattered coincident events





SmartPET motivation

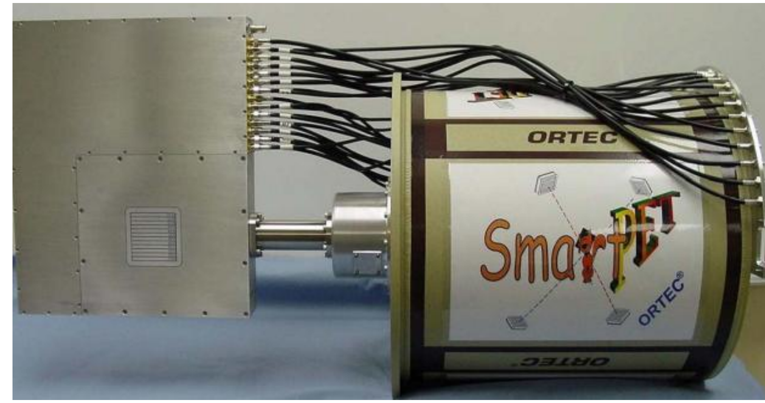
Current Standards	**SmartPET**
Scintillation detectors	2 HPGe planar detectors
Poor energy resolution	Excellent energy resolution
Limited position resolution	Enhanced position resolution through **PSA**
PMTs unable to function in B field	Complimentary with MRI

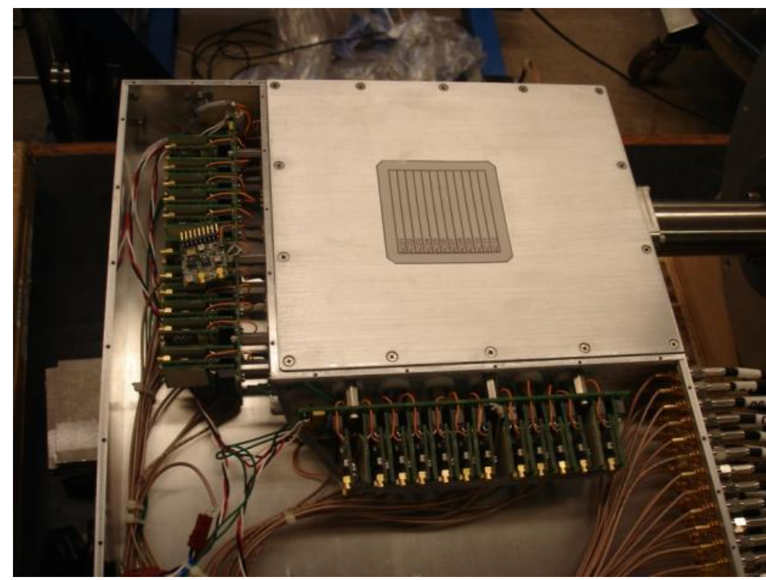
SmartPET

- Two double sided HPGe strip detectors
- (60 x 60 x 20) mm active area
- 12 x 12 orthogonal strips

  - 5mm x 5mm x 20mm voxels

- Fast charge-sensitive preamplifiers
- Energy resolution < 1.5keV FWHM at 122keV
- Intrinsic photopeak efficiency – 19% at 511keV





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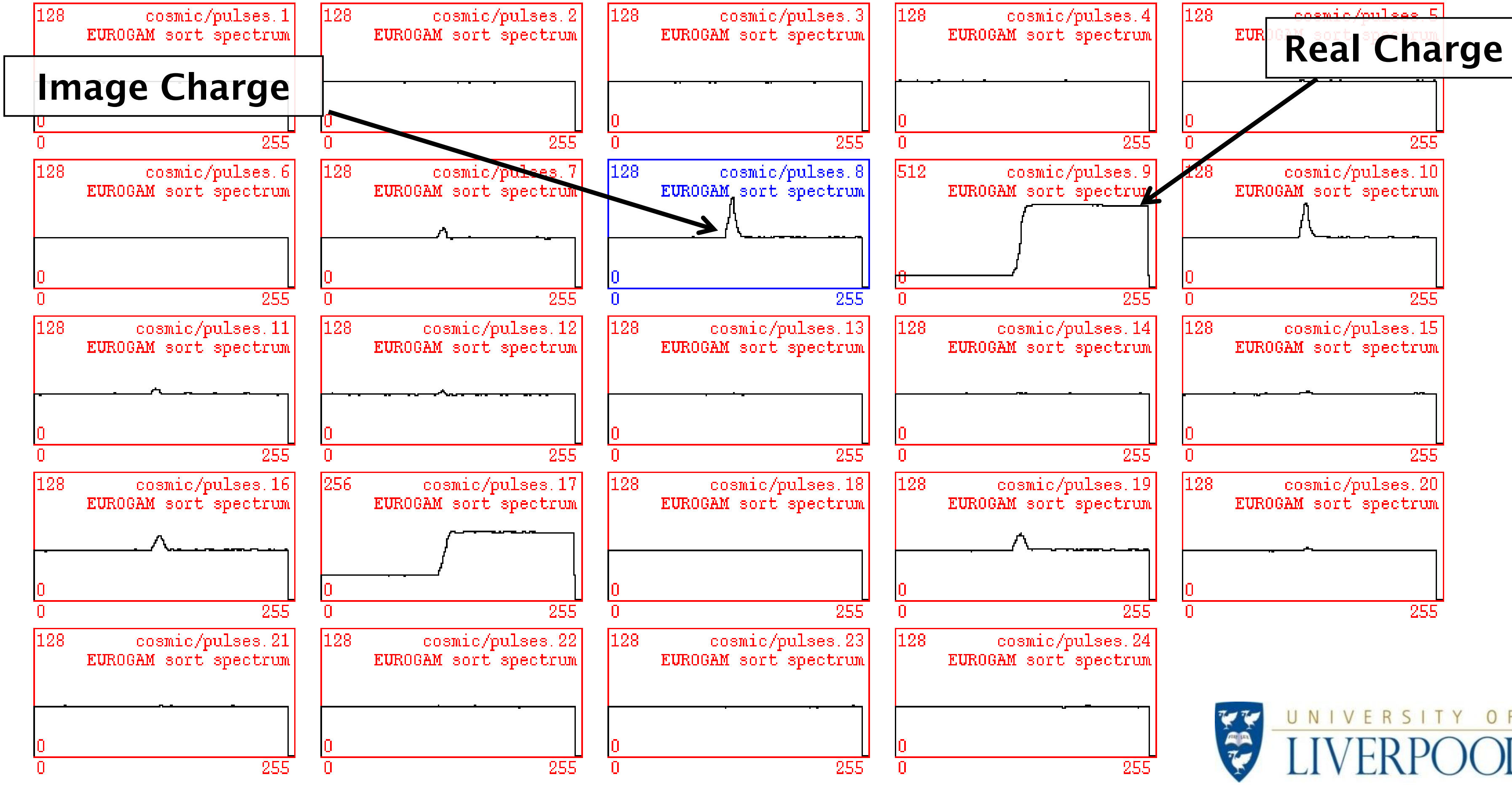
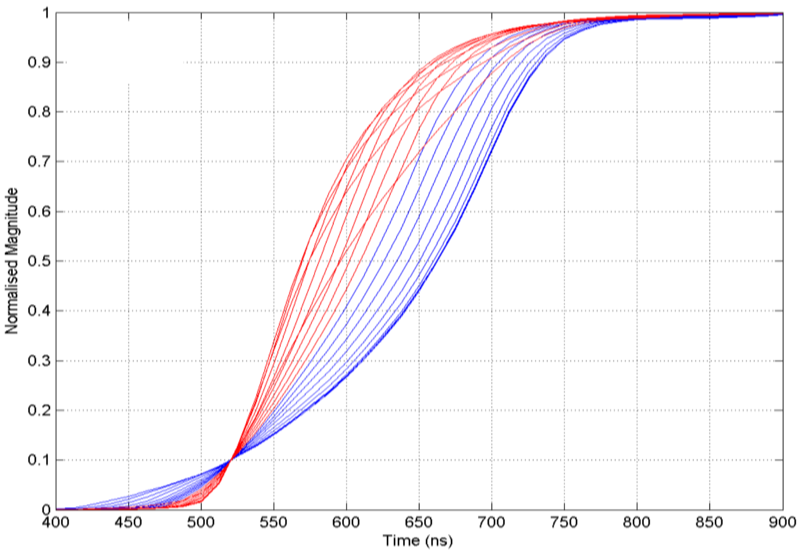
Detector Response

- PSA techniques developed through characterisation measurements
- Calibration of variation in detector pulse shape response with position



Parametric PSA

Dr RJ Cooper



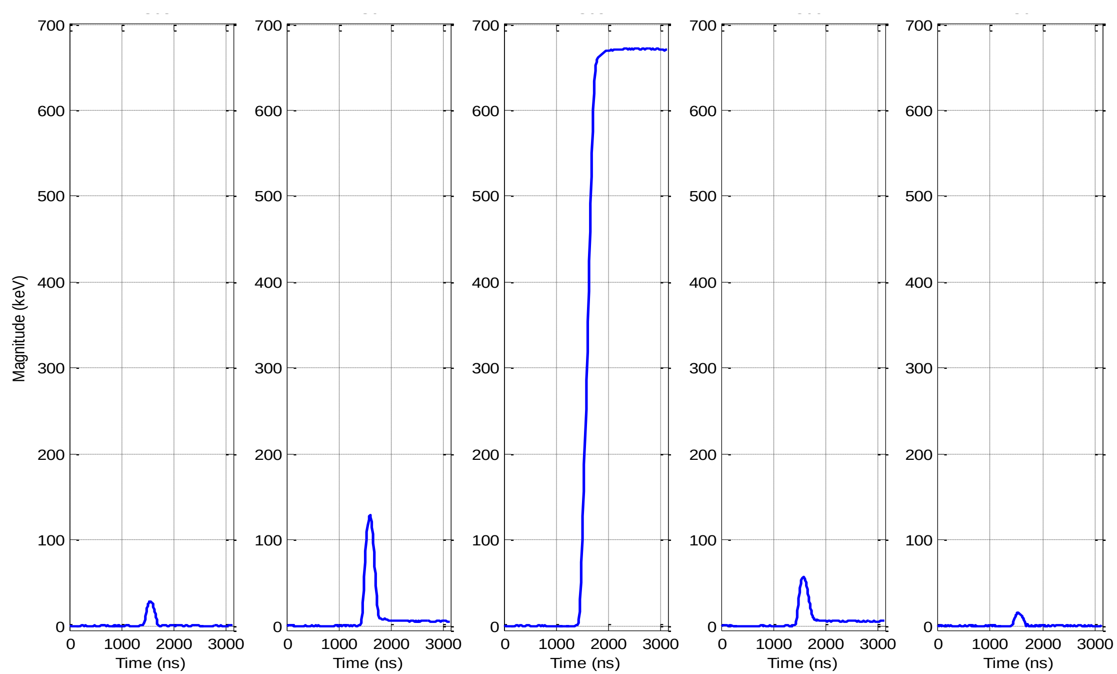
We can calibrate the variation in real charge timing characteristics with interaction position

Risetime analysis

Analyse the variation in image charge area/magnitude

Image charge asymmetry

$$Asymmetry = \frac{Area_{left} - Area_{right}}{Area_{left} + Area_{right}}$$



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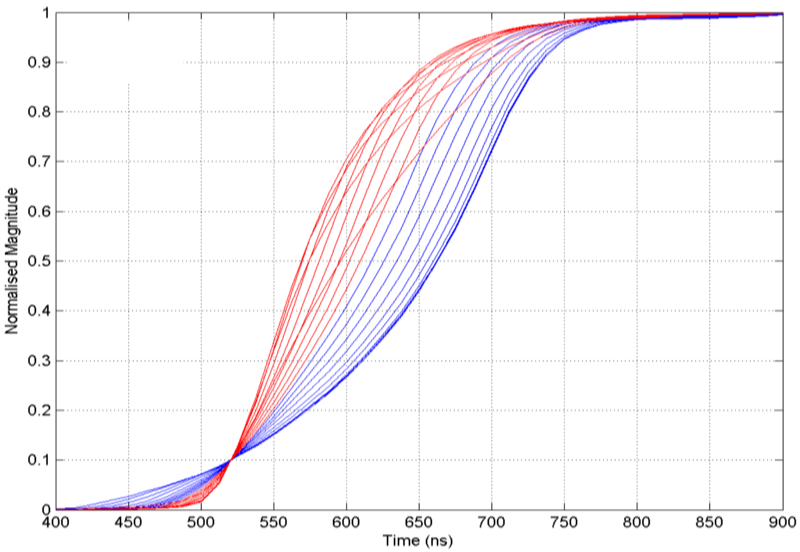

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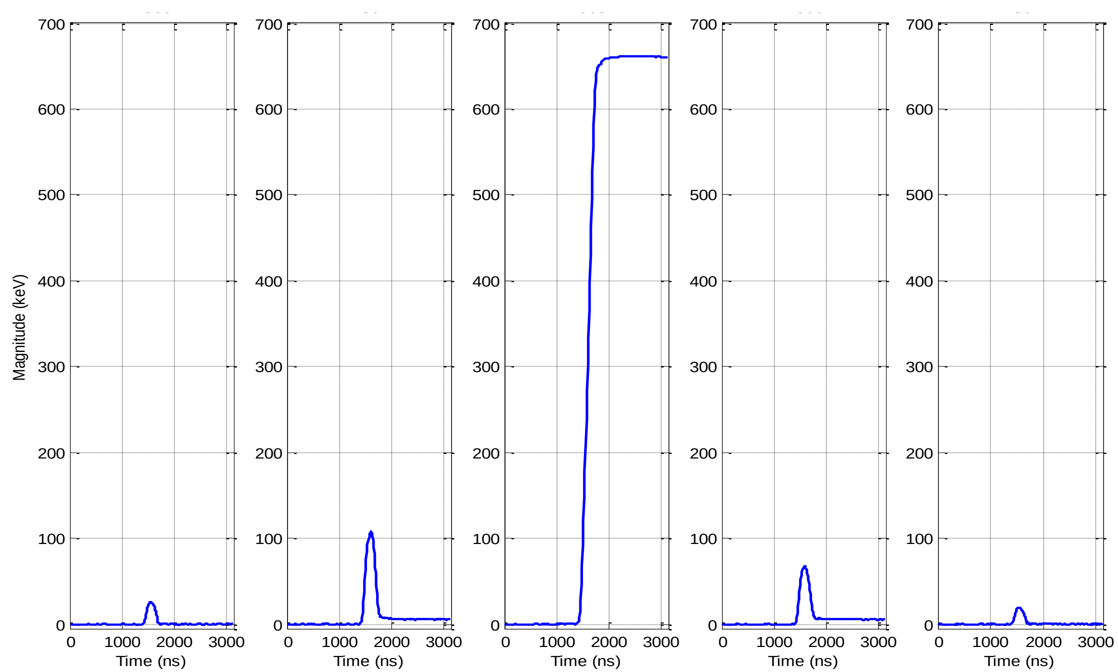

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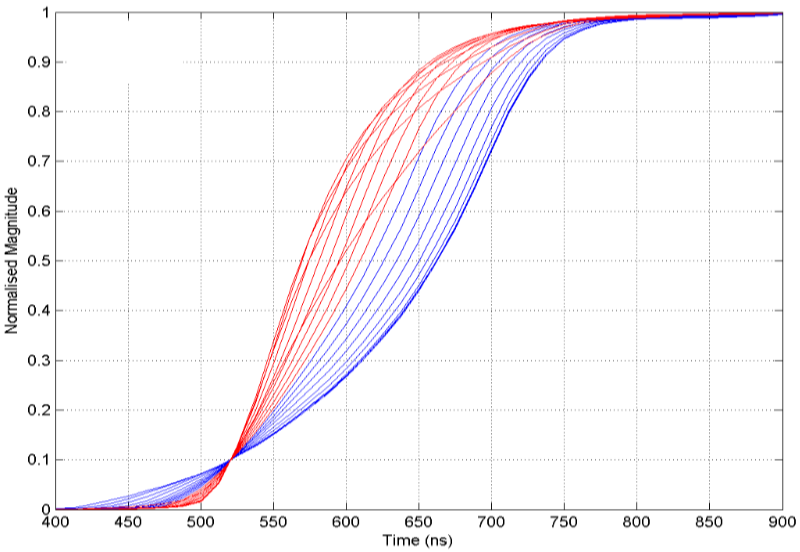

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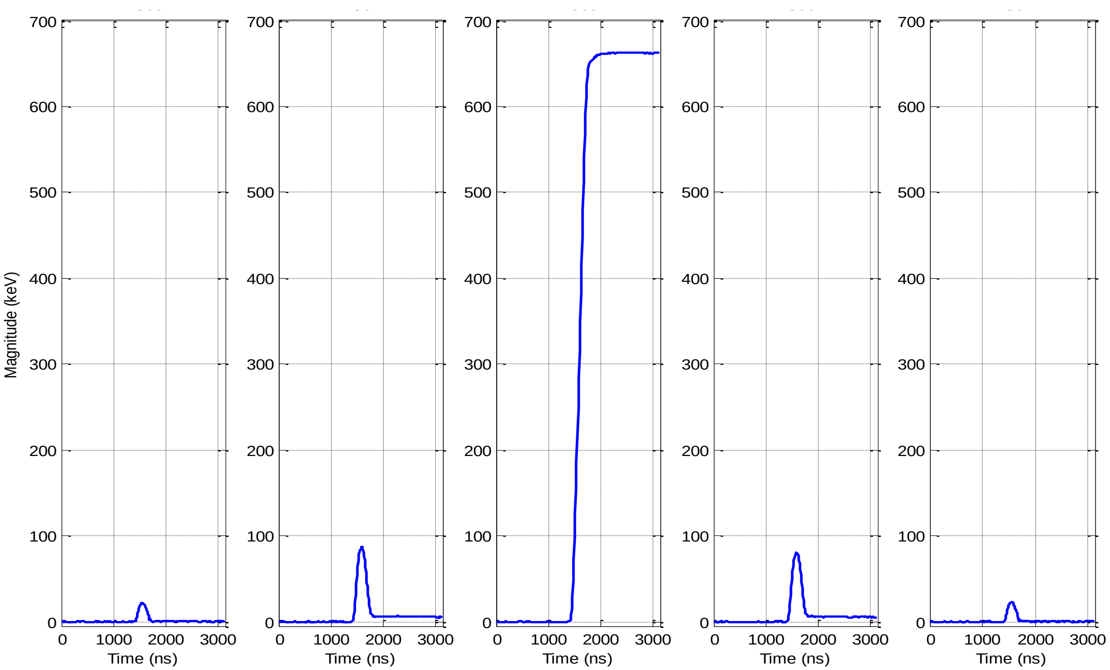

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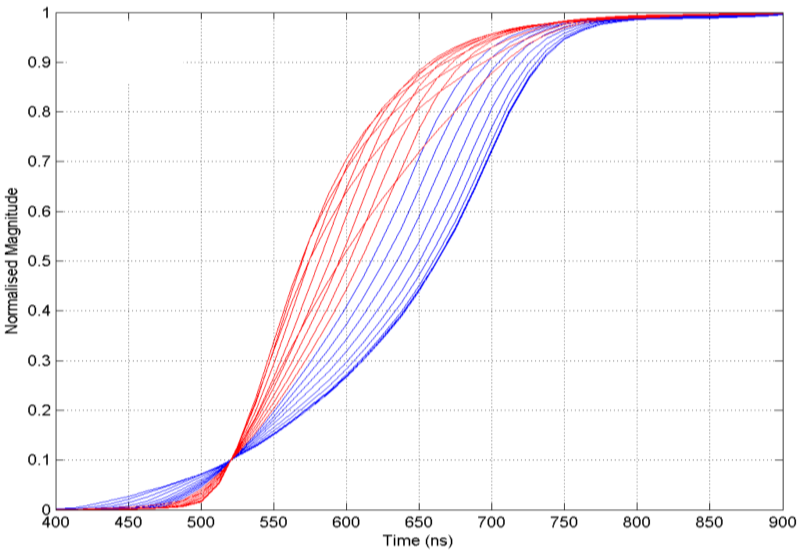

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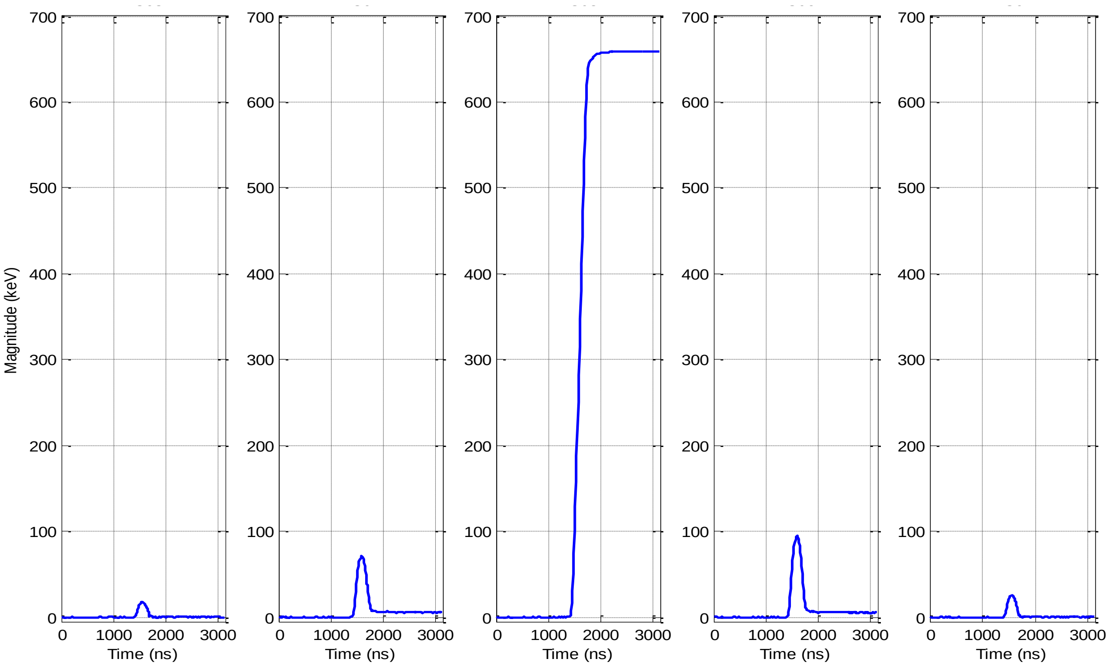

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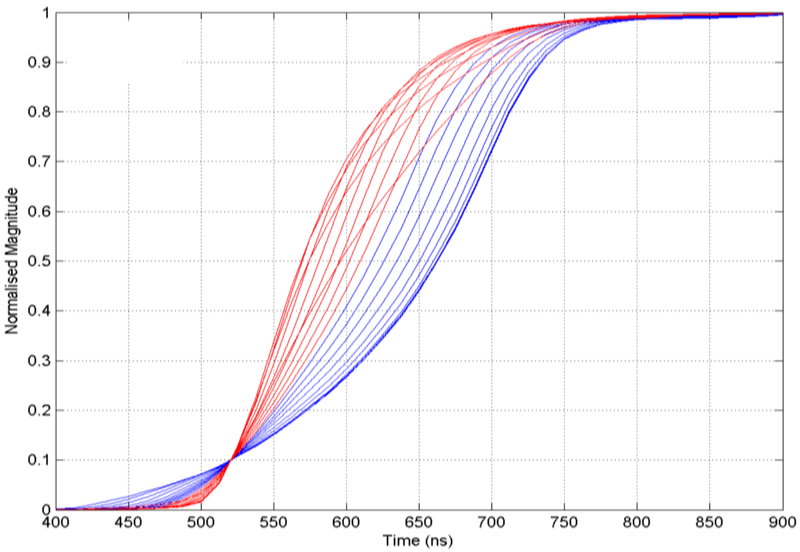

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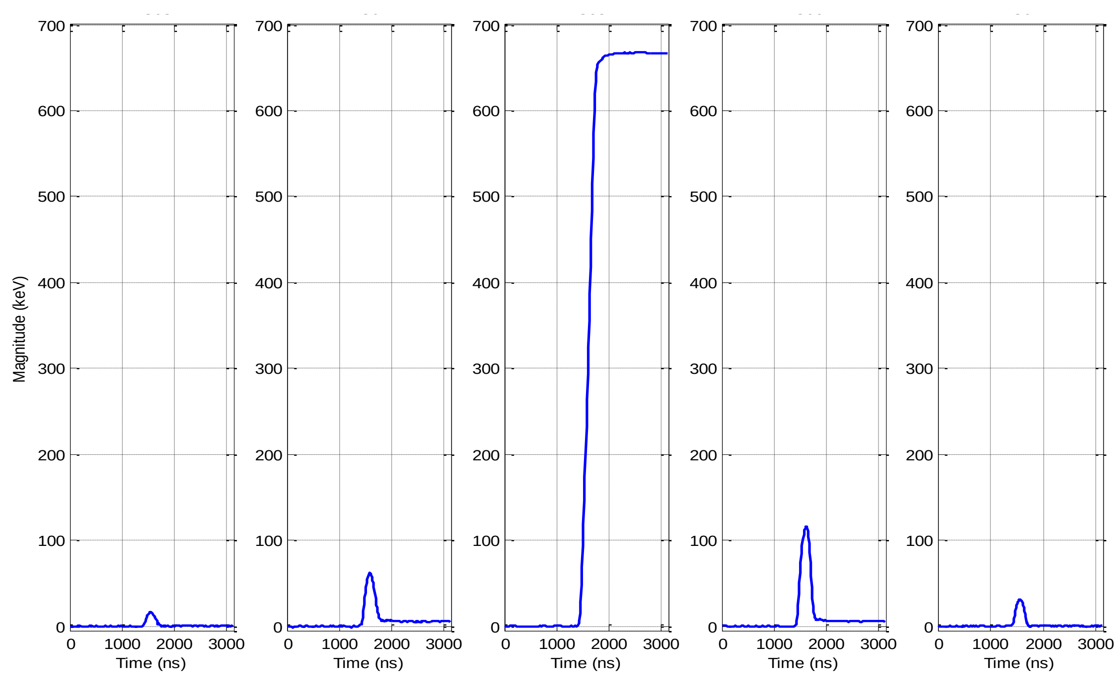

Imaging with SmartPET

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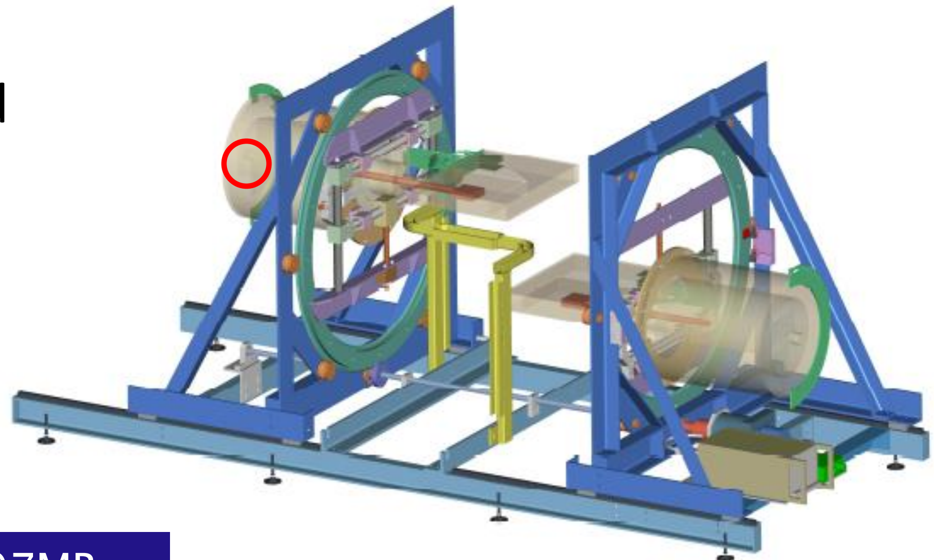
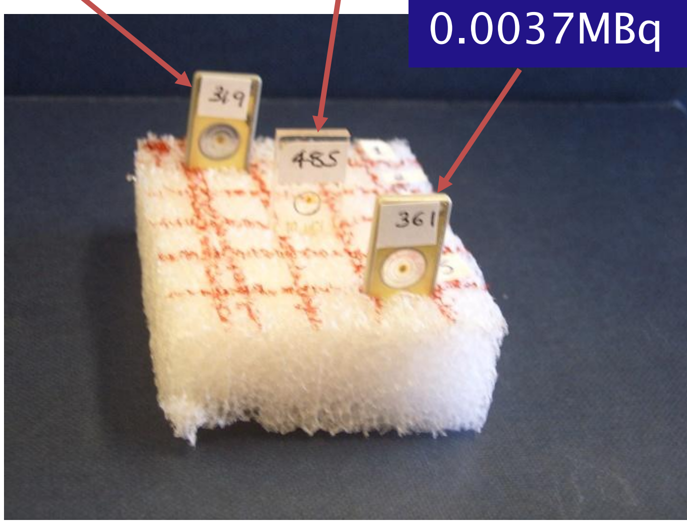
PET data recorded with ^{22}Na point and line sources



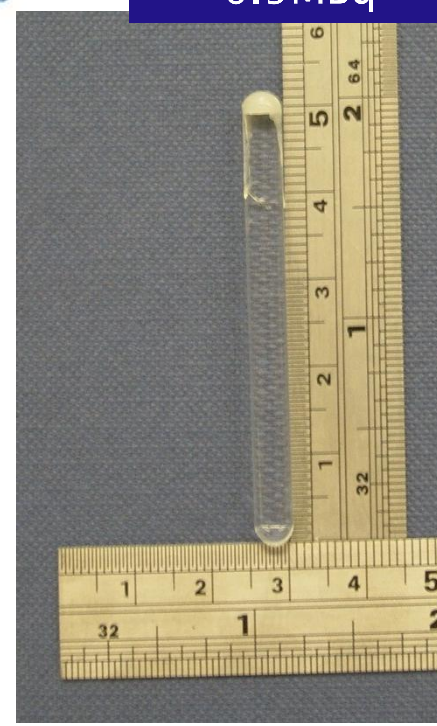
0.0014MBq

0.0307MBq

0.0037MBq



~0.9MBq



Imaging results with SmartPET

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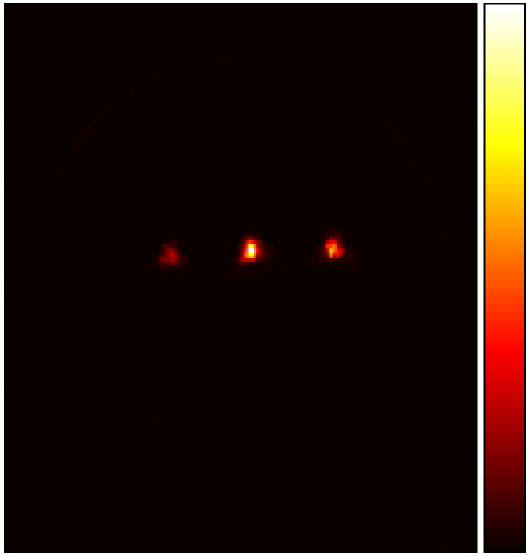
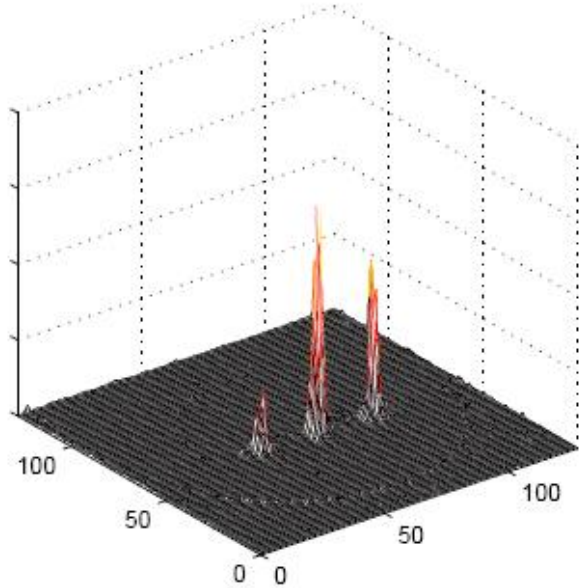
60mm

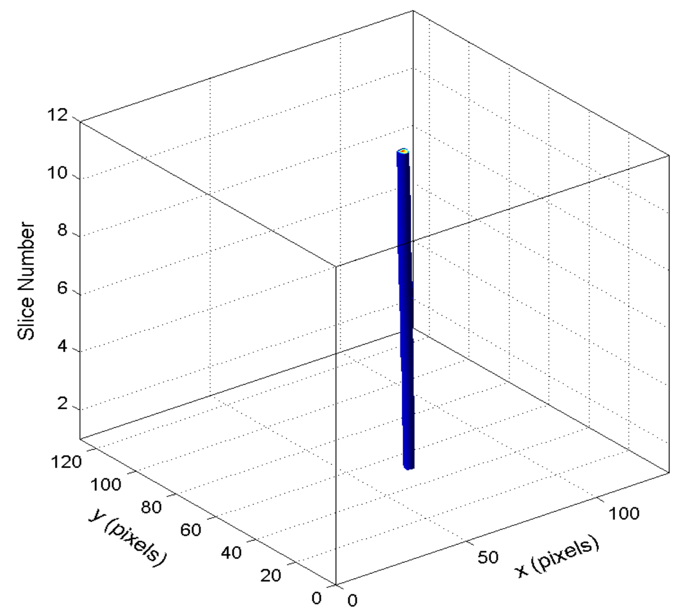


60mm



Point source FWHM ~1.4 mm

Line source FWHM ~2.9 mm (line source has ~ 2.5 mm internal diameter)



Is it any better?

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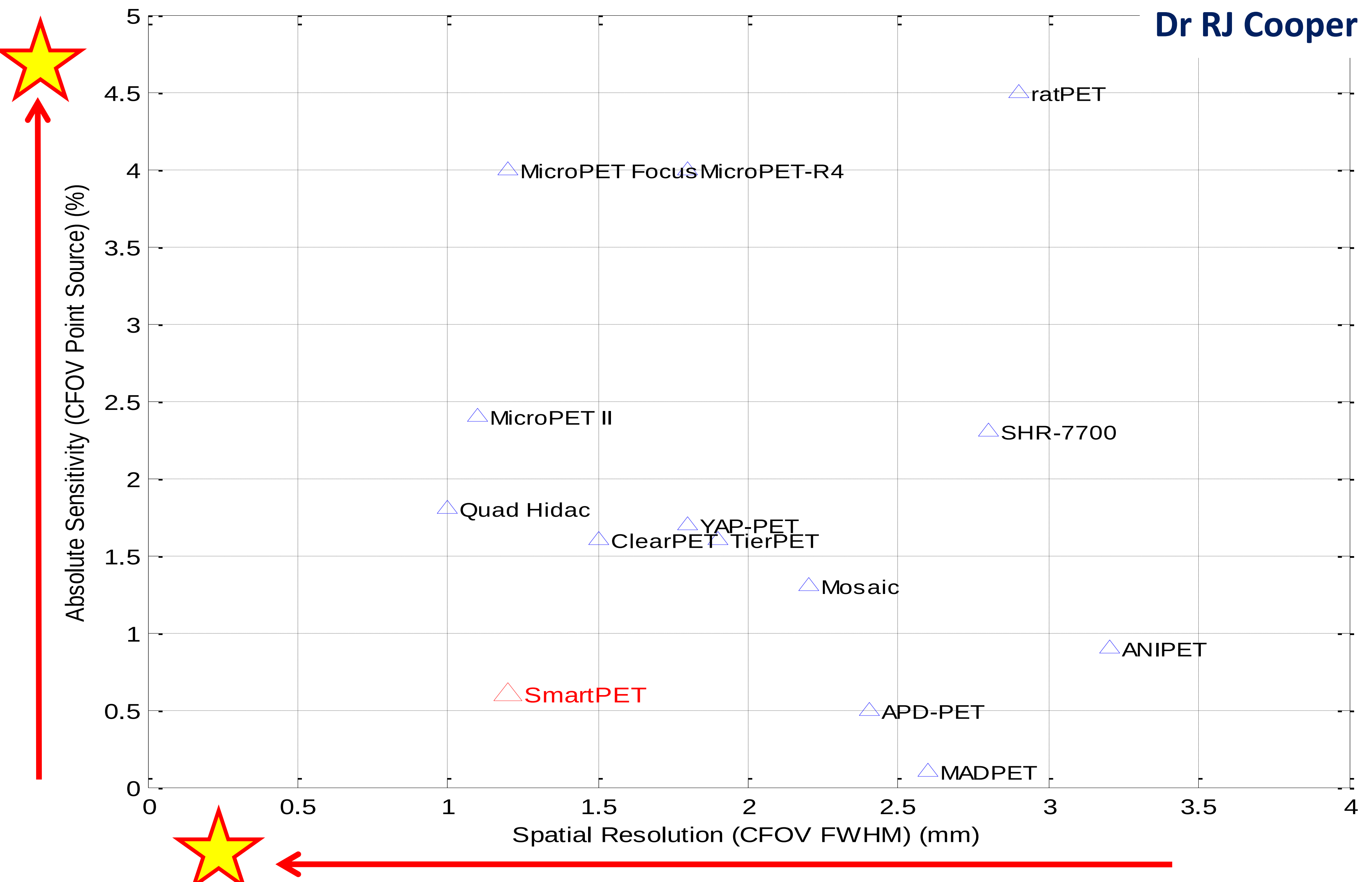

Conclusions

- Gamma-ray detectors such as those used in nuclear structure physics experiments can be used in a number of applied fields
- Existing imaging modalities such as PET can be improved using detectors and techniques developed in blue-skies physics research
- Novel approaches are being developed which are targeted to the growing nuclear imaging industries for homeland security and nuclear decommissioning.

A large number of people have input to this work from the University of Liverpool nuclear instrumentation group and STFC Daresbury Laboratory

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http://ns.ph.liv.ac.uk/imaging-group/

Imaging Group Homepage

Faculty of Science

Introduction

This home page has been produced to give a flavour of the interests the Imaging Group has within the nuclear physics group here at the University of Liverpool. We reside in the Oliver Lodge Laboratory, building number 48 on the University Campus Map.

Our research interests focus on the development of instrumentation for nuclear physics and gamma-ray imaging applications. Information on our current projects can be found by clicking on the links below or those on the left.

» AGATA
The Advanced Gamma Tracking Array (AGATA) project is a European collaboration dedicated to building the ultimate gamma-ray spectrometer for nuclear physics applications.

» Distinguish
The DISTINGUISH project is the development of a system to enable efficient screening of goods in transit. The Liverpool imaging group are adressing the detection and imaging of high energy gamma rays following neutron interrogation.

» PorGamRays
This EPSRC and DTI jointly funded project will develop a prototype portable gamma-ray spectrometer suitable for remote deployment.

» SmartPET
The SmartPET project is the development of a novel small animal Positron Emission Tomography (PET) system based on the use of planar High Purity Germanium (HPGe) detectors and state of the art digital electronics.

» ProSPECTus
The use of position sensitive semiconductor detectors for Single Photon Emission Computed Tomography (SPECT) studies is under investigation.

» GammaKEV
The development of a robust portable Compton Camera.

» NNL
The project aims to develop a gamma-ray sensor, couple it with a 3-D vision system and provide control algorithms for a mechanical manipulator for decommissioning applications.

If you are interested, we have information about our research projects on the web!