Advances in semiconductor sensors, Gamma-ray imaging systems

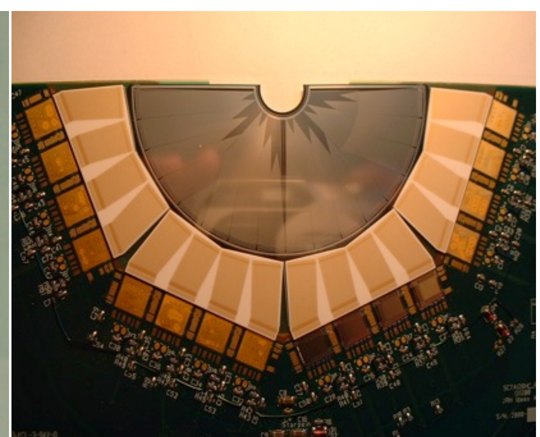
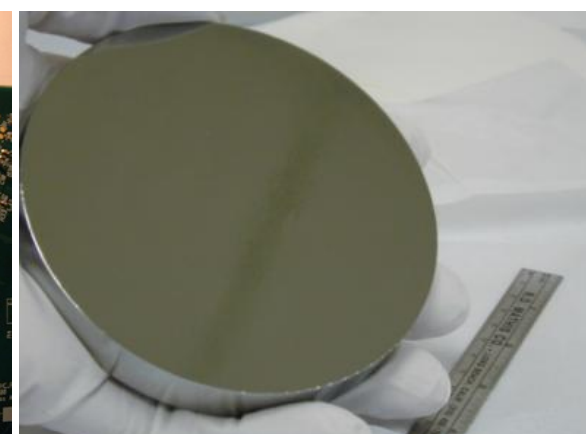
Science & Technology Facilities Council

UNIVERSITY OF LIVERPOOL

Dr Andy Boston
ajboston@liv.ac.uk

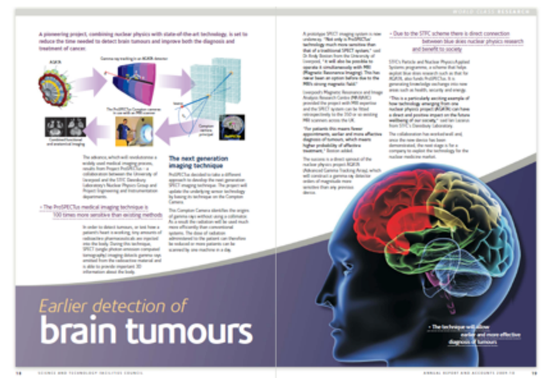
Outline of presentation

- **Focus on ionising radiation and gamma-rays**
  - What are the challenges?
  - What detector technology can we consider?
  - Select example projects & links to fundamental research
  - The future prospects

Sensors: Knowledge Exchange

Direct application in medical security and energy areas as evidenced by funding from: CLASP/PNPAS, EPSRC/TSB, NERC, MRC, NHS, NNL (NDA), AWE



PROSPECTUS

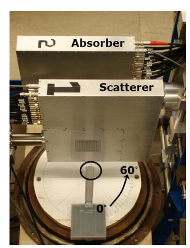
- Novel SPECT imaging system

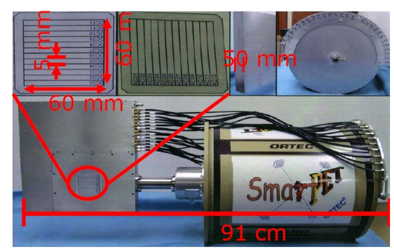
NNL

- Nuclear Decommissioning applications

NERC

- Radionuclide Transport





All projects are collaborations some with industrial partners. All involve contributions from parts of STFC.

What are the challenges?

- **In <u>Nuclear Medicine</u>:**
  - Know the **energy**
  - Want the **location** over a small field of view
  - Need to cope with **high count rates**
  - Multimodality applications (eg PET/CT)
  - Image fusion

What are the challenges?

- **In Nuclear Security and Environmental :**
  - Don't know the **energy** & a broad range
  - Want the **location** over a large field of view
  - Need to cope with **wide range of count rates**
  - Image fusion

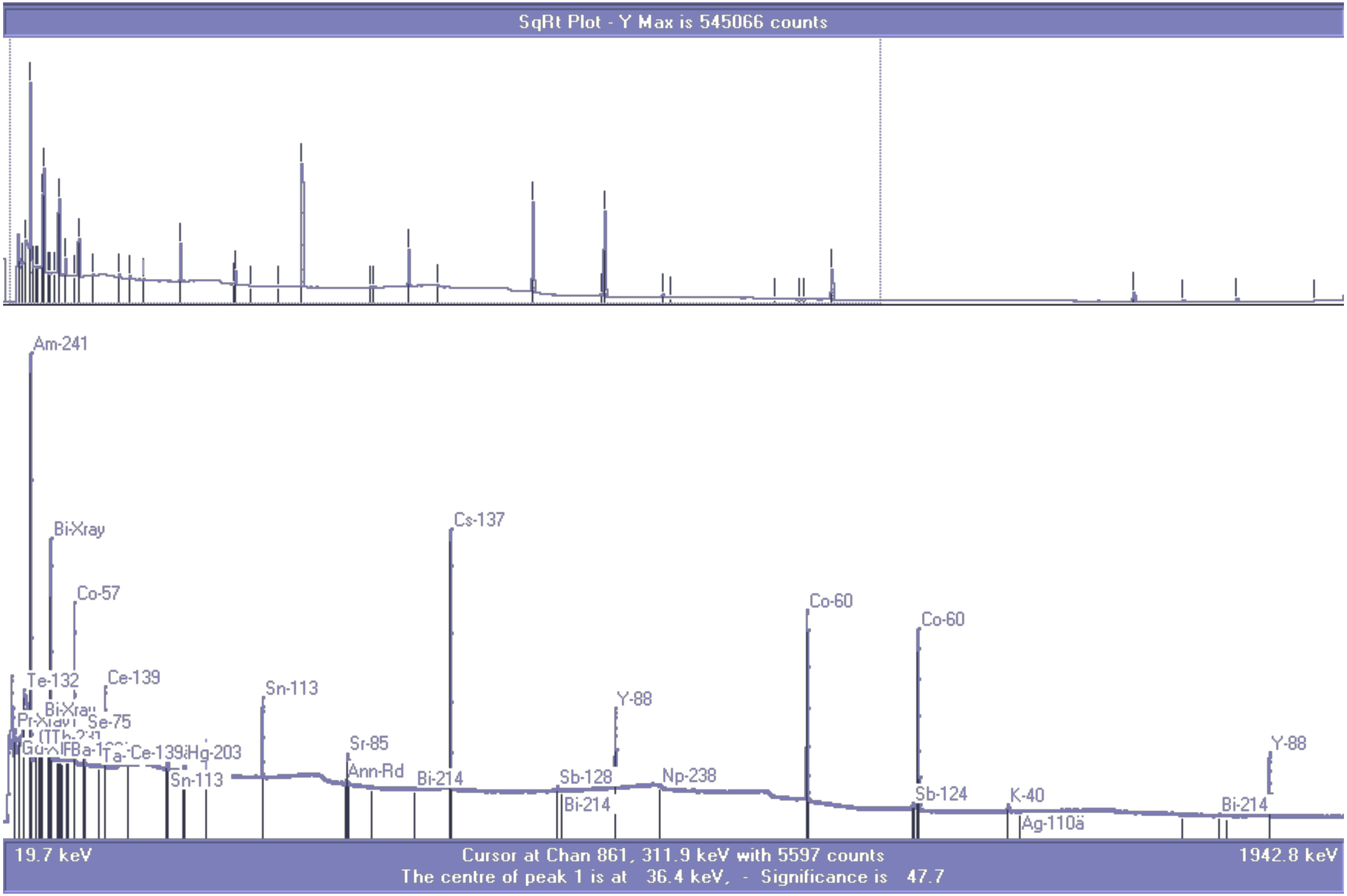
What are the detector requirements?

- **Need to know the location of the radiation:**
  - Use a mechanical collimator (Anger Camera)
  - Use positron annihilation for LoRs
  - Use other electronic collimation
- **Range of energies:**
  - Medical 141 keV – 511 keV
  - Security 60 keV – 2 MeV
- **Operating environment:**
  - B-fields? Microphonics? High temperature?

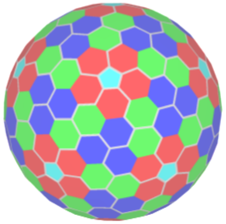
What are the detector requirements?

- **Ideally would want:**
  - Good energy resolution (Good light yield/charge collection) < few %
  - High efficiency (High Z)
  - Position resolution
  - Timing resolution
- **Detector materials:**
  - Semiconductors (Si, Ge, CdZnTe)
  - Scintillators ($LaBr_3$, CsI(Tl), NaI(Tl), BaFl, BGO, LYSO…)

High resolution Gamma spectrometry

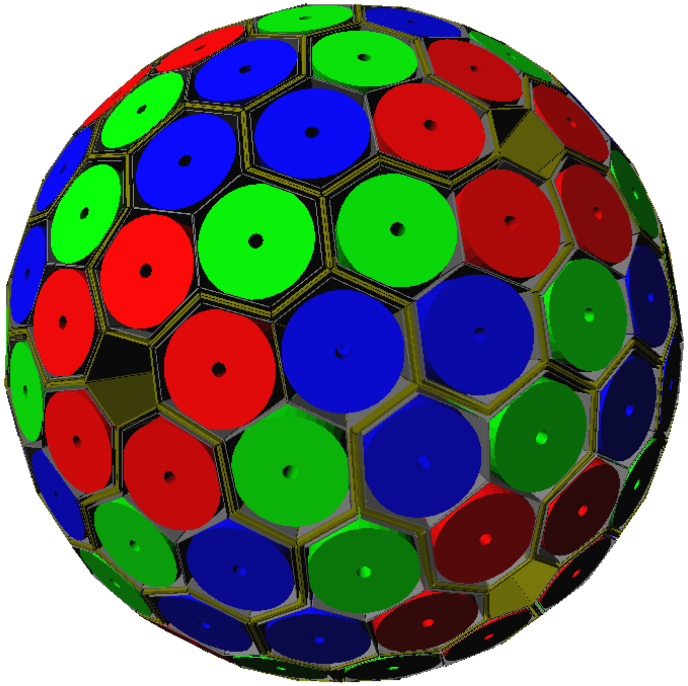


The AGATA Spectrometer



Steering Committee Chairperson: G. De Angeles INFN LNL
vice-Chairperson: Faizal Azeaz

12 Countries
>40 Institutions



Main features of AGATA

Efficiency: 43% (M_γ=1) 28% (M_γ=30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

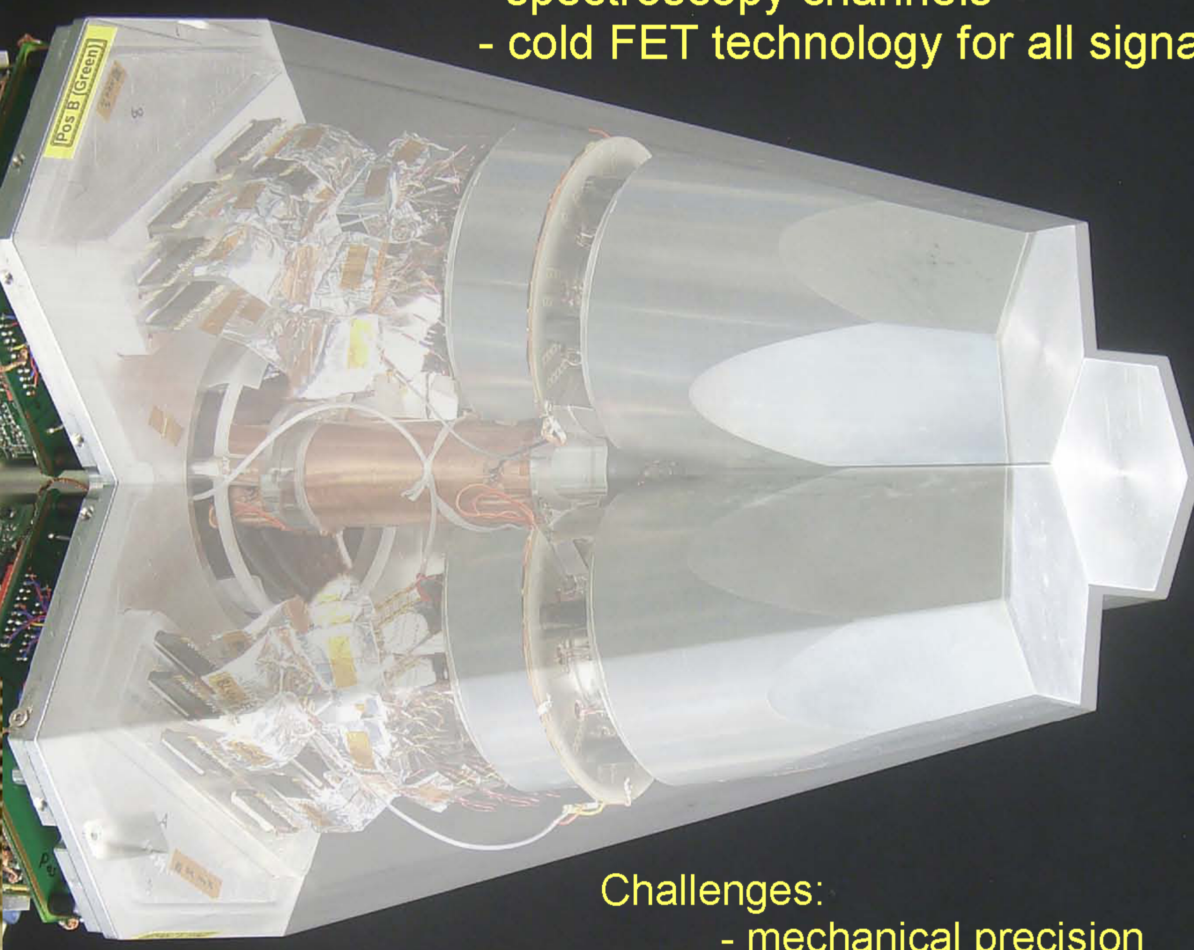
Peak/Total: 58% (M_γ=1) 49% (M_γ=30)
today ~55% 40%

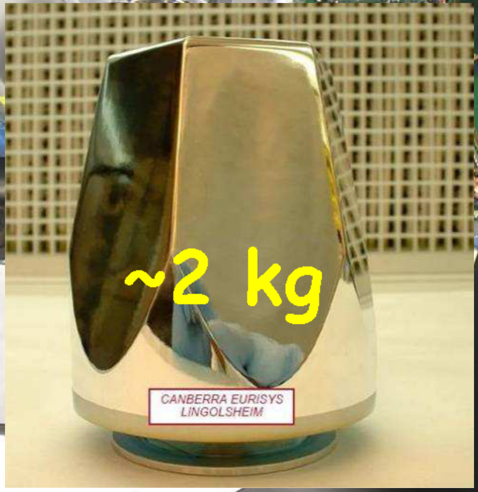
Angular Resolution: ~1º →
FWHM (1 MeV, v/c=50%) ~ 6 keV
today ~40 keV

Rates: 3 MHz (M_γ=1) 300 kHz (M_γ=30)
today 1 MHz 20 kHz

Asymmetric AGATA Triple Cryostat

- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals





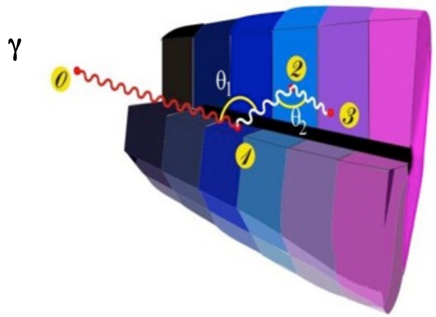
Challenges:

- mechanical precision
- LN2 consumption
- microphonics
- noise, high frequencies

Ingredients of γ-Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

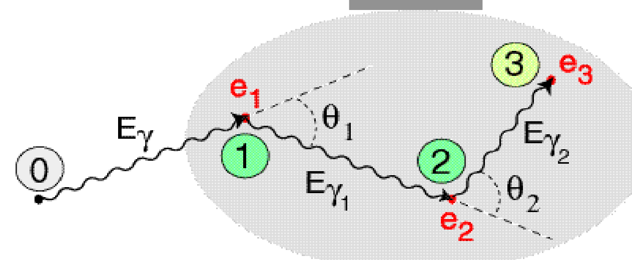
Pulse Shape Analysis to decompose recorded waves

Identified interaction

$(x,y,z,E,t)_i$

4

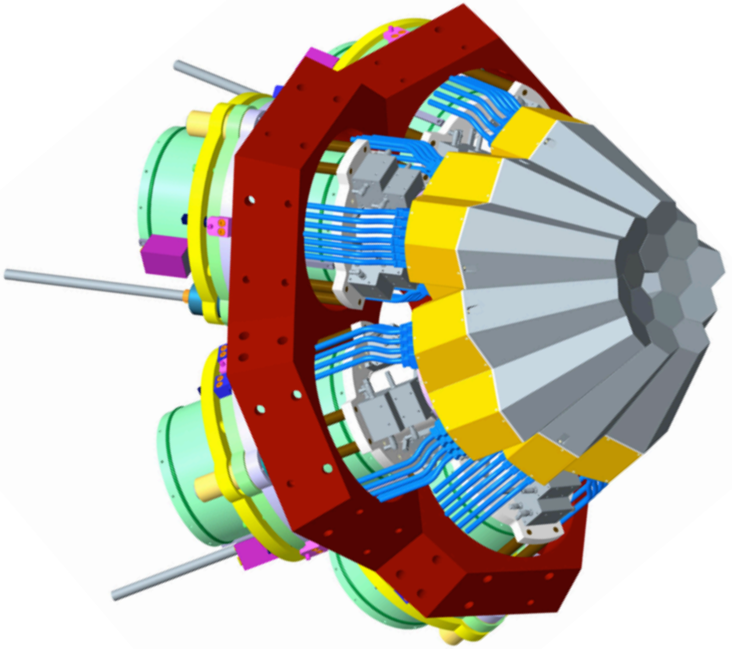
Reconstruction of tracks e.g. by evaluation of permutations of interaction points

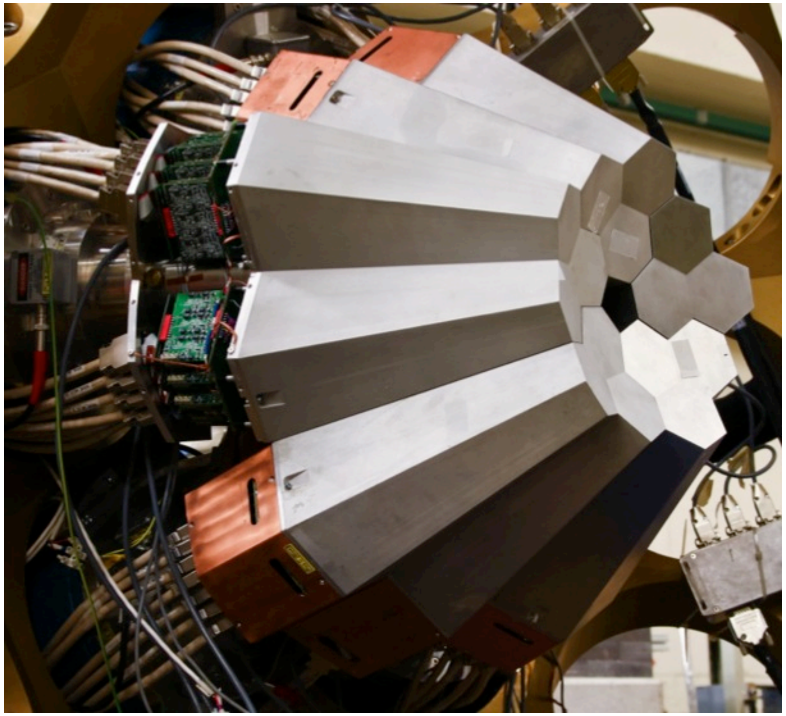


reconstructed γ-rays

The AGATA Demonstrator

Objective of the final R&D phase 2003-2008





From Design to Reality

AGATA's Deployment

Intense stable beams

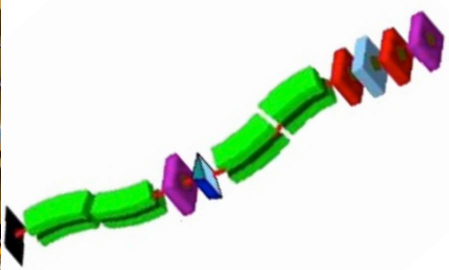
2010 → INFN LNL
15 detectors

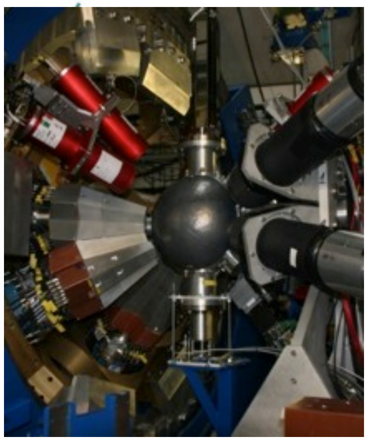
AGATA D.+PRISMA

Total Eff $_{Nominal}$. ~2.6%

Fast Fragmentation beams

2012 2014→ GSI/FAIR
25 detectors



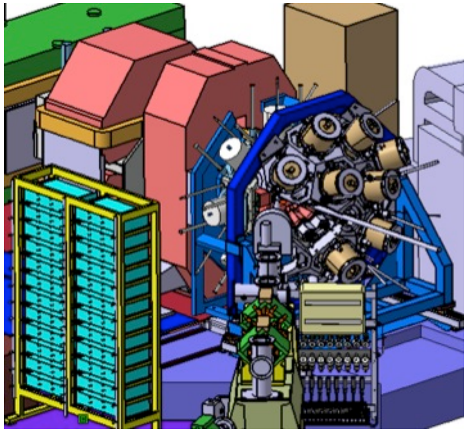


AGATA @ FRS

Total Eff. (β=0.5) ~ 10%

ISOL and stable beams

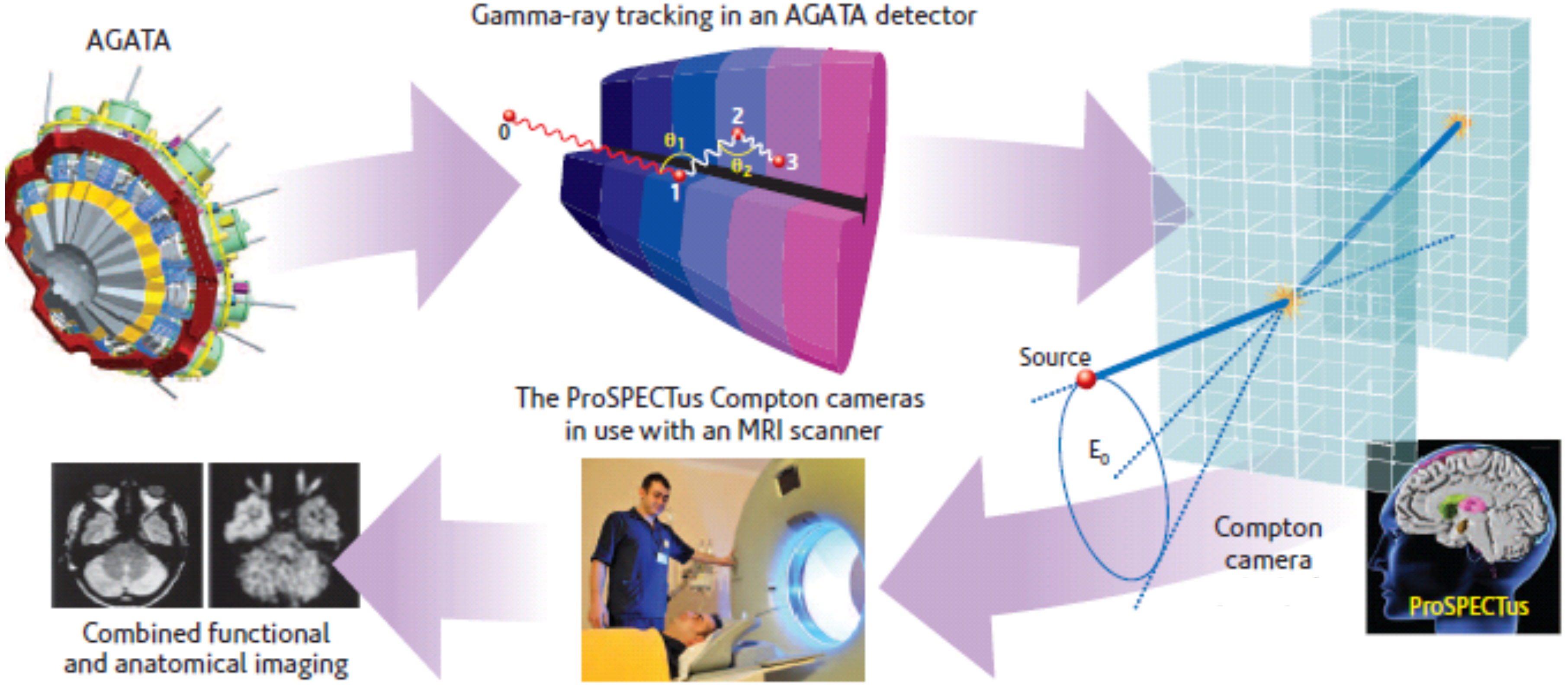
2014- 16→ GANIL/SPIRAL
45 detectors



AGATA @GANIL

Total Eff ~ 8% to 14%

From AGATA to Application



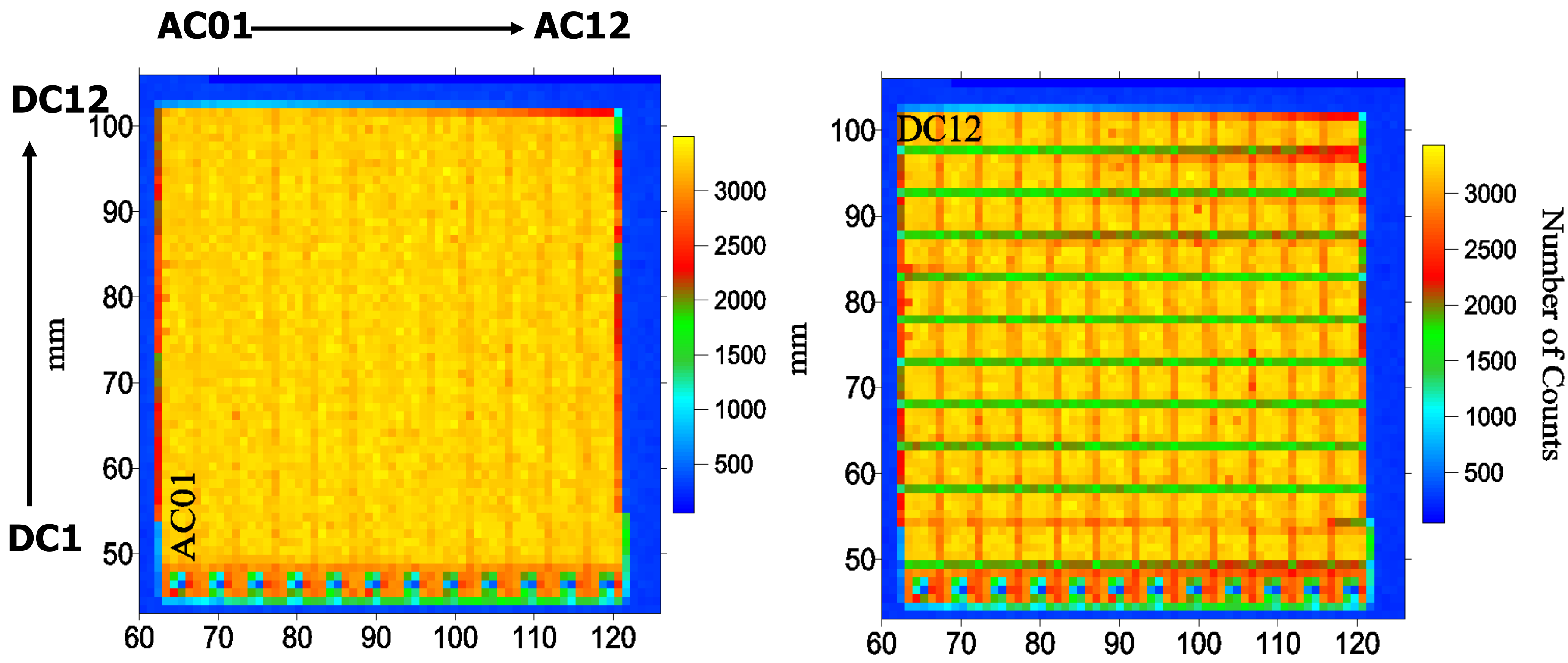
Science & Technology Facilities Council

Typical system configuration

- Double sided strip detectors
- RC Charge preamps (100 - 200mV/MeV)
- Caen V1724 8 channel digitizers with 100Mhz / 14 bit
- Custom written firmware providing circular buffer, trigger, energy, timestamp
- Optical readout
- Timestamp, list mode trace data recorded to disk and/or processed in real time

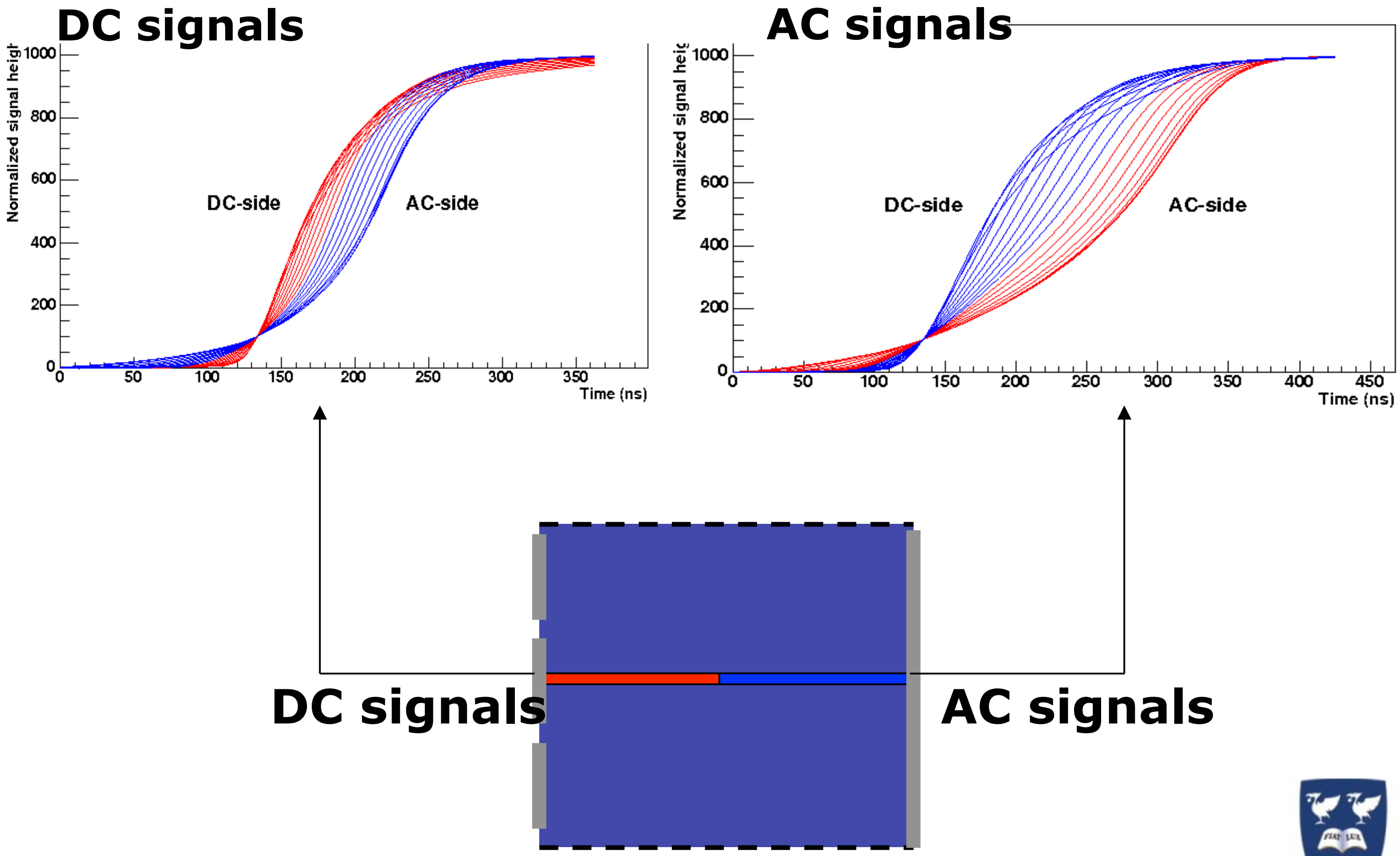
- Also use “desktop digitizer” and V1730 16 channel board.

Am-241 AC x-y surface intensity distribution



- **The results are presented for 60 keV with 2 minutes of data per position.**

Typical detector depth response



ProSPECTus

Next generation Single Photon Emission Computed Tomography

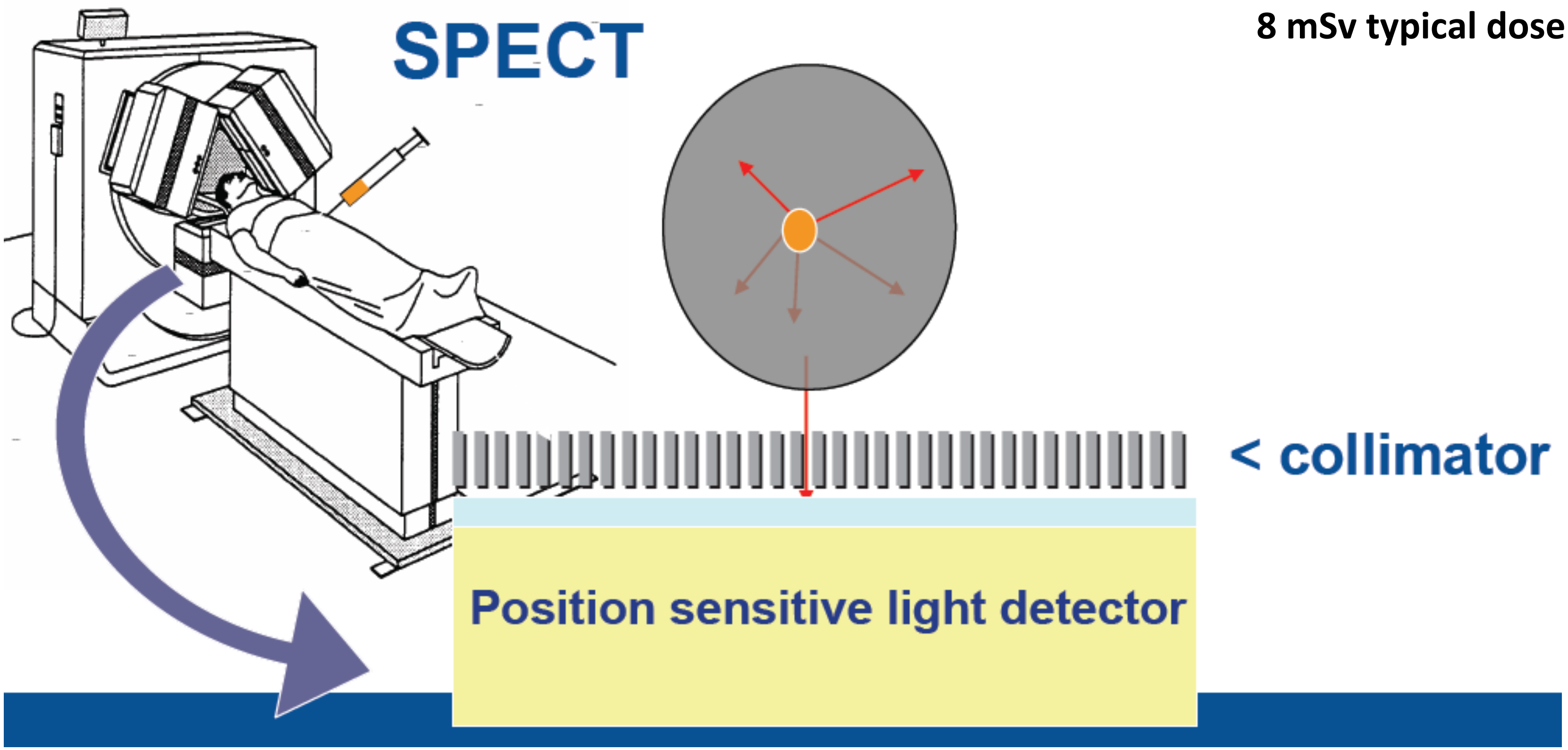
Nuclear Physics Group, Dept of Physics, University of Liverpool, Nuclear Physics & Technology Groups, STFC Daresbury Laboratory, MARIARC & Royal Liverpool University NHS Trust, CCC NHS Foundation Trust

UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

What is SPECT?

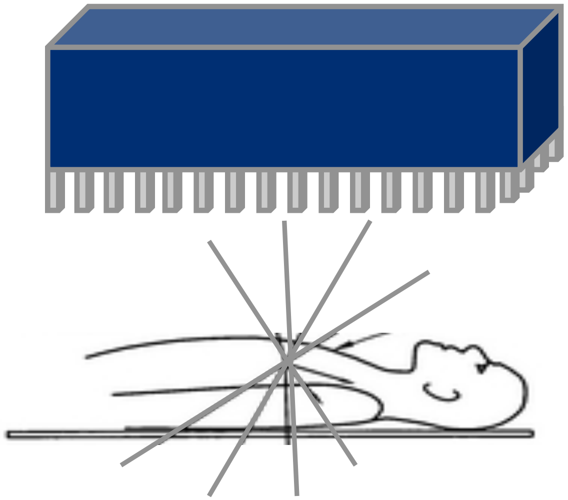
8 mSv typical dose



Functional imaging modality

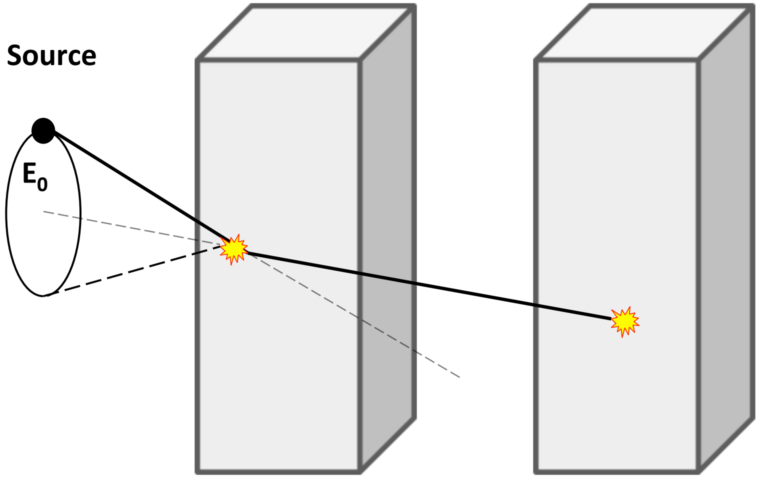
What's different?

Conventional SPECT



- Gamma rays detected by a gamma camera
- Inefficient detection method
- Incompatible with MRI
- 2D information

Compton camera

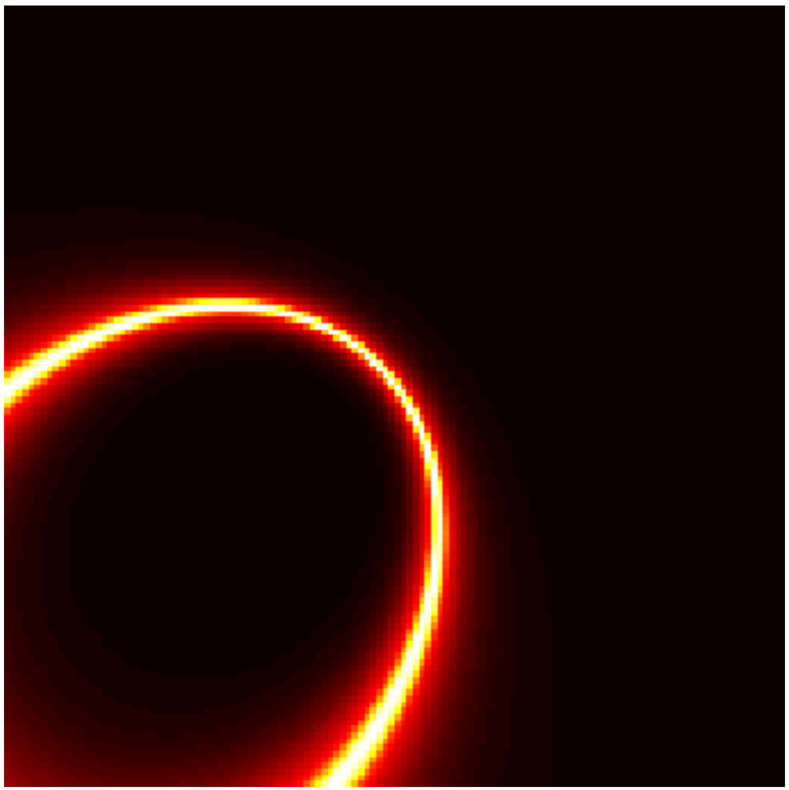


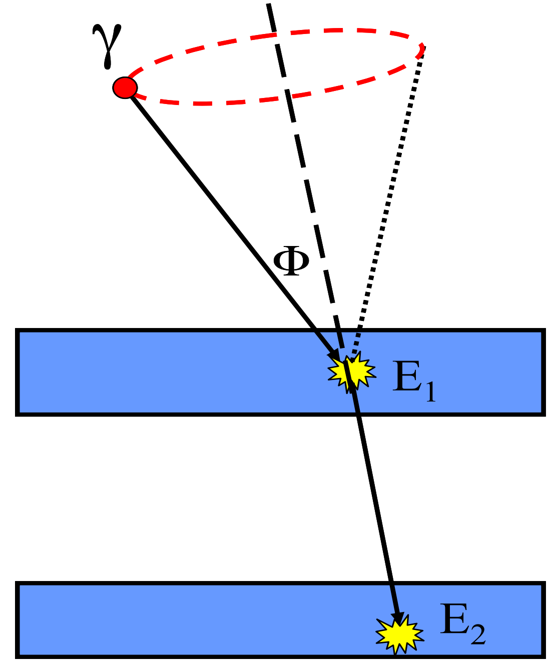
- Gamma rays detected by a Compton camera
- Positions and energies of interactions used to locate the source
- 3D information.

Factors that limit the performance of a Compton Imager:
Energy resolution, Detector position resolution, Doppler Broadening

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

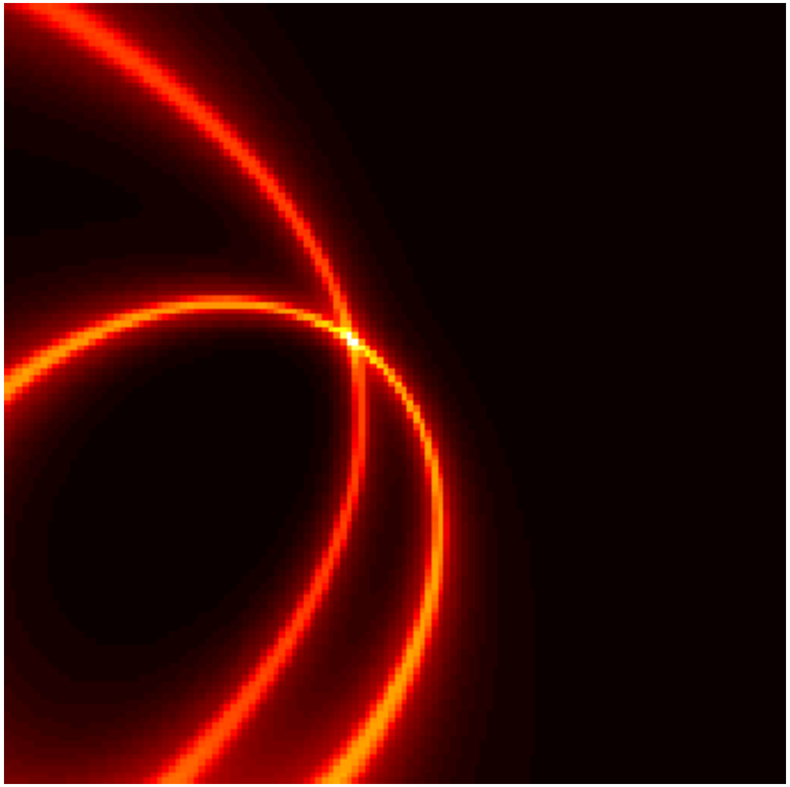


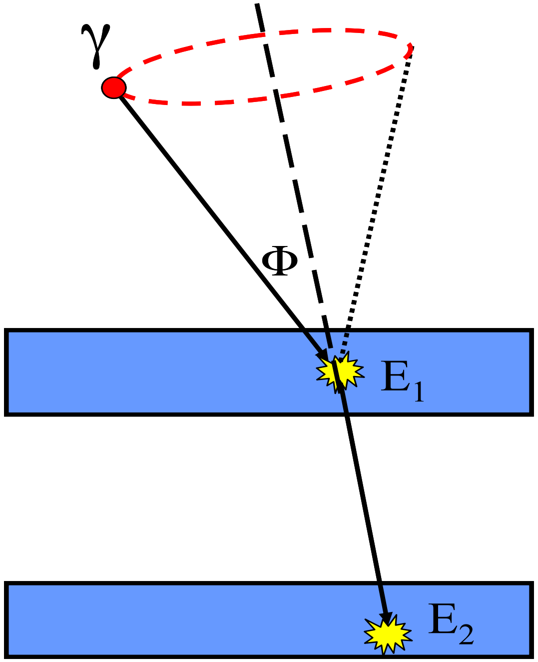


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

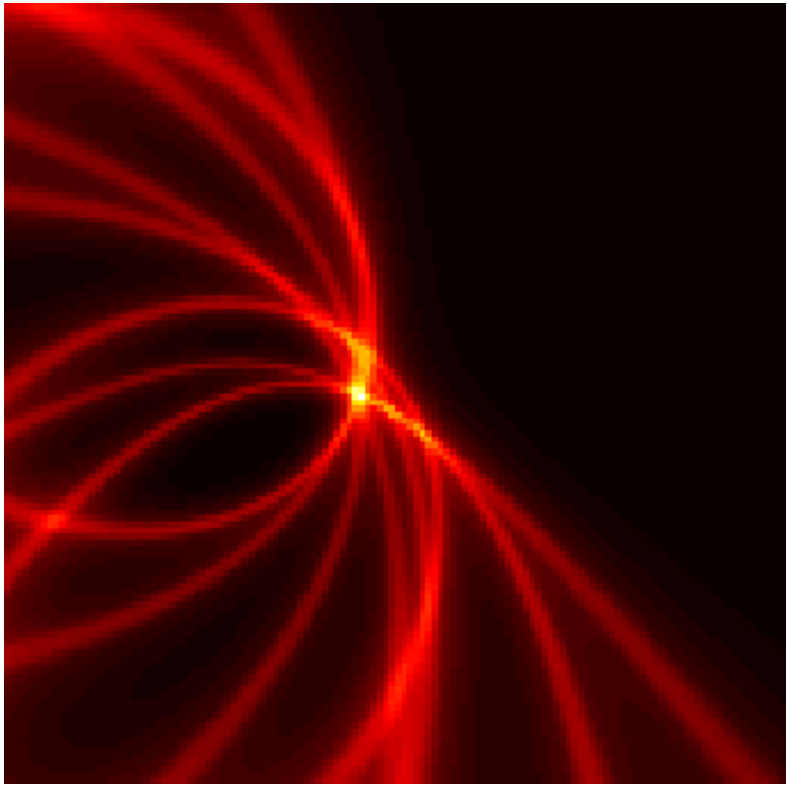


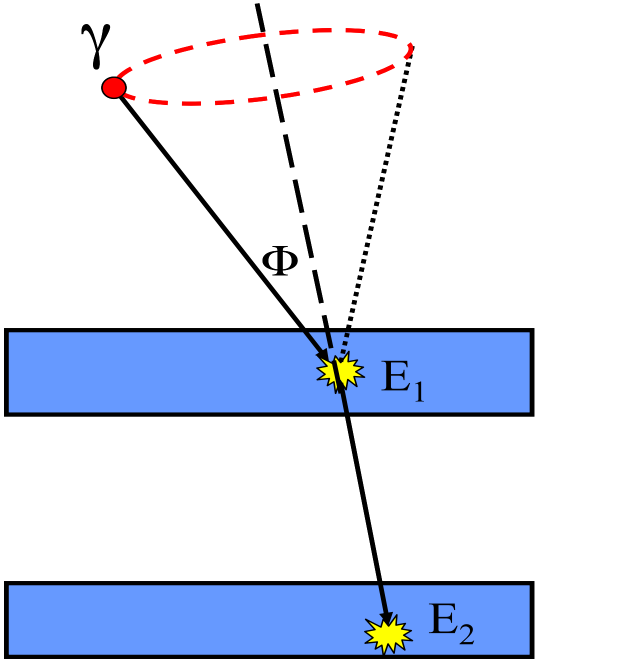


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

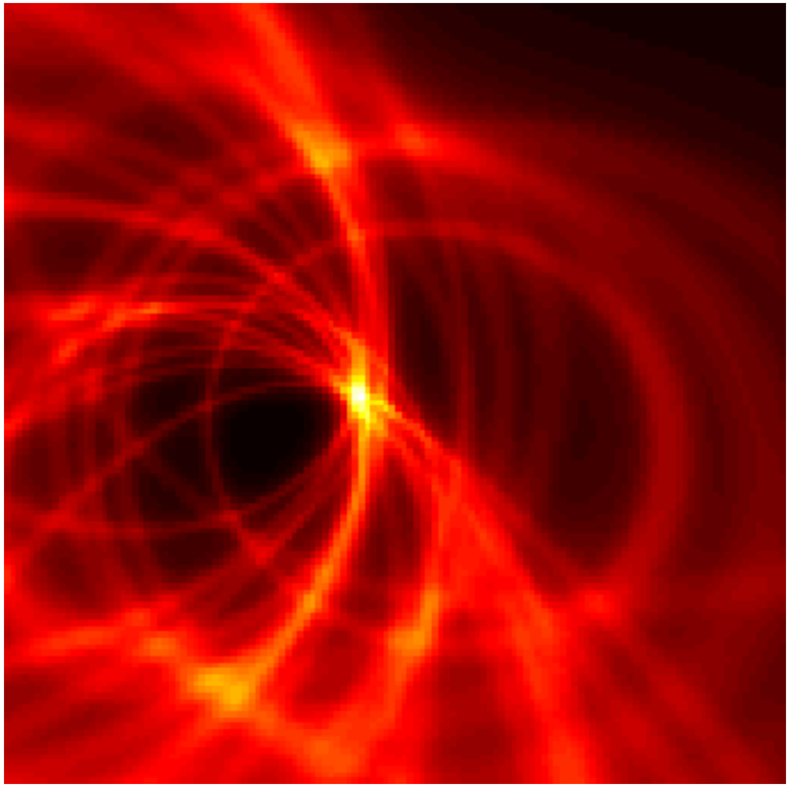


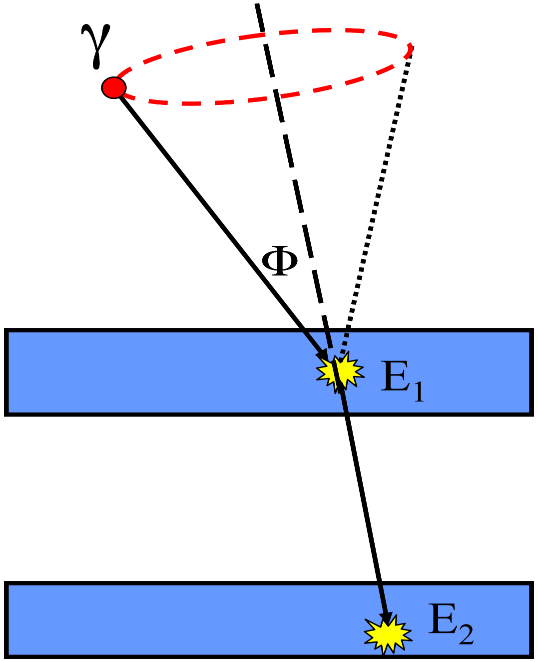


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space

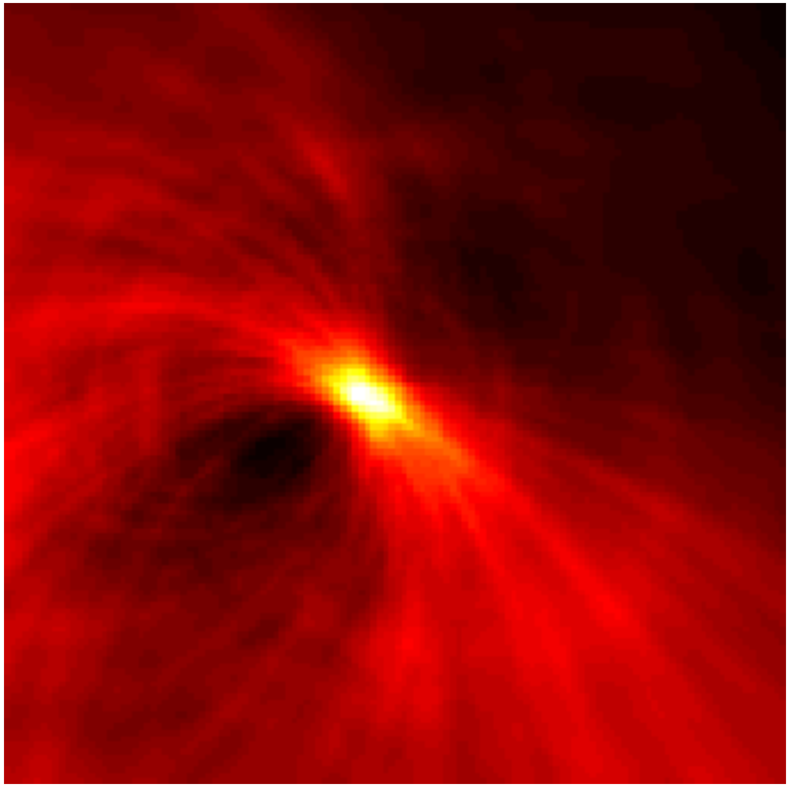


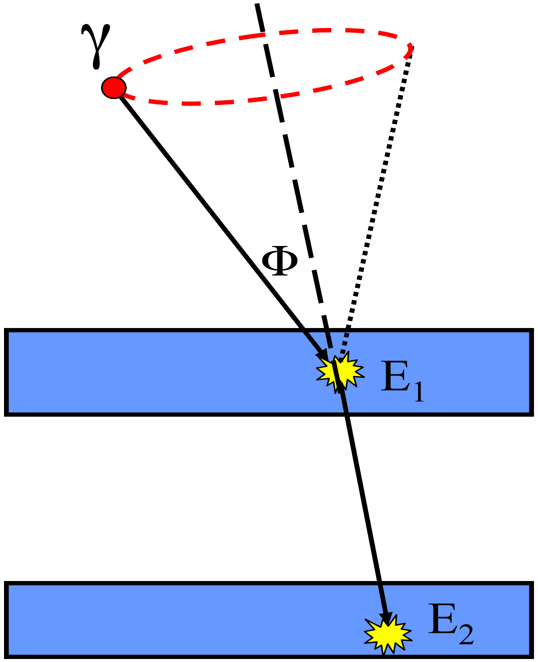


$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Research : Compton Imaging

- Compton *Cones of Response* projected into image space





$$\cos\phi = 1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)$$

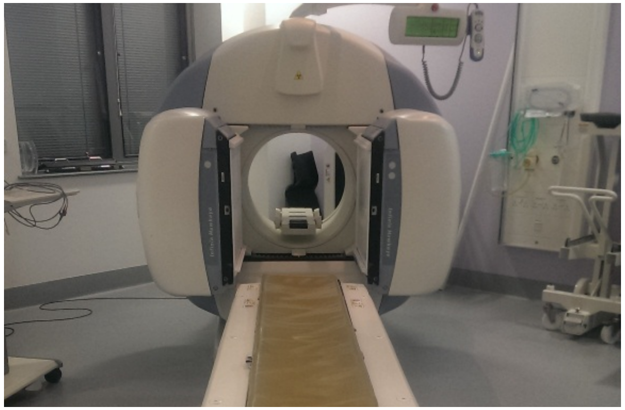
UNIVERSITY OF LIVERPOOL

Image Reconstruction Algorithms

- **Sensors have excellent energy & position information.**
- **Uniformity of sensor response**
- **Optimise existing:**
  - Analytical
  - Iterative
  - Stochastic
- **Requirement for GPU acceleration**

MTRL: Medical Teaching and Research Laboratory

SPECT/CT:



Converted a lab to host a refurbished SPECT/CT scanner in partnership with STFC Daresbury Laboratory and Royal Liverpool University Hospital.

Uses - training medical physics students and research.

MTRL Timeline

- **Autumn 2012- discussions with Liverpool University, Royal Hospital, STFC Futures.**
- **Dec 2012- Futures offer funding for lab refit.**
- **Jan 2013- Clear equipment from lab T3**
- **Mar 2013- Install lead shielding on walls and doors, new floor, rewire, paint, fit air con, fit personnel safety system.**
- **Early 2014 obtain & install scanner**
- **SPECT/CT**
- **2014 first students**

Funded by STFC Futures (refit laboratory) and University of Liverpool (purchase used scanner) Expert advice from Royal Liverpool Hospital

ProSPECTus: Next generation SPECT

- Detector head sensitivity maximised for ^{99m}Tc 141 keV gamma rays (also works at higher energies e.g. ^{131}I 364keV).
- Sensitivity is a factor of 10 improvement over LEHR collimated SPECT detector heads.
- Multi-isotope imaging in single acquisition
- Wide energy range with one system
- 2 semiconductor detectors housed in 1 cryostat
- MRI-compatible

Security & Environmental Imaging

- SNMs and other threats
- Raster scanning
- Coded aperture systems (low energy)
- Focus on wide FOV and variety of stand off distances
- Compton cameras

A three dimensional gamma-ray vision system

NDA Funded

Science & Technology Facilities Council

NATIONAL NUCLEAR LABORATORY

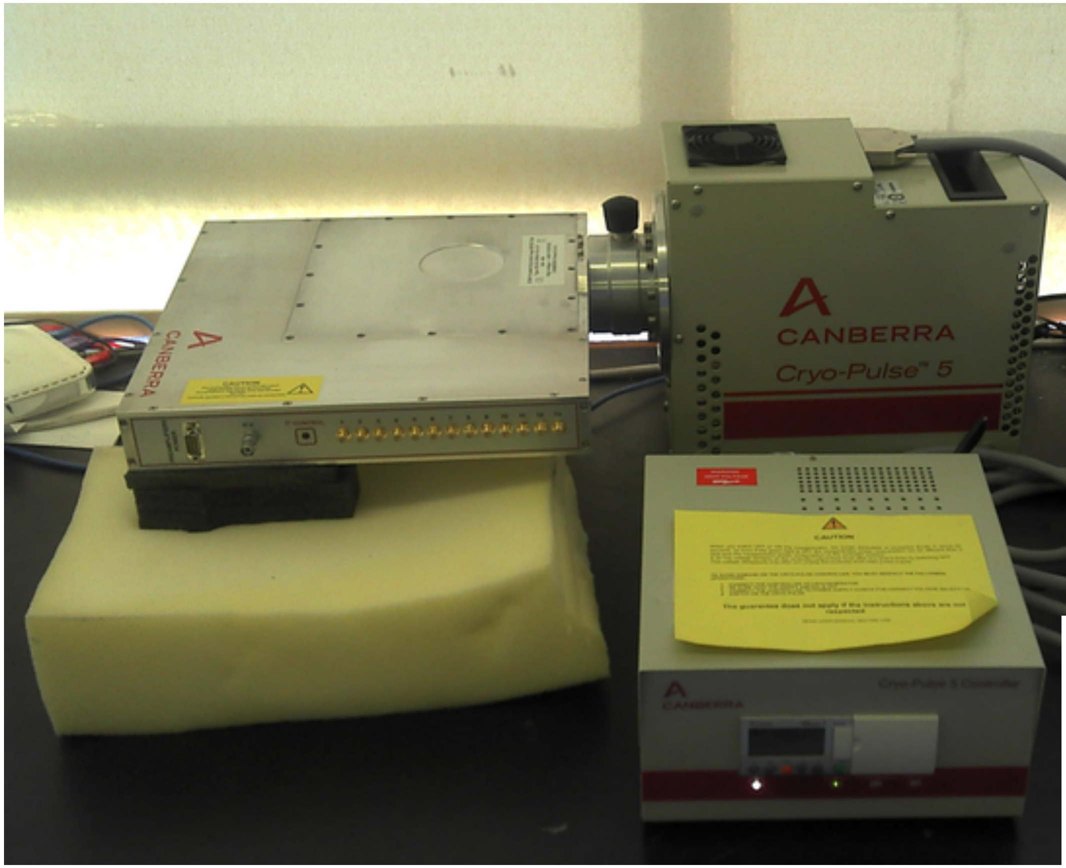
UNIVERSITY OF LIVERPOOL

Location and Identification…

Courtesy K. Vetter LBL (work @ LLNL)

- The ability to locate and identify radioactive material with high precision
- Quantification of waste into low/intermediate/high brackets
- Wide range of activities from ~37kBq -> MBq
- There are many open challenges and opportunities

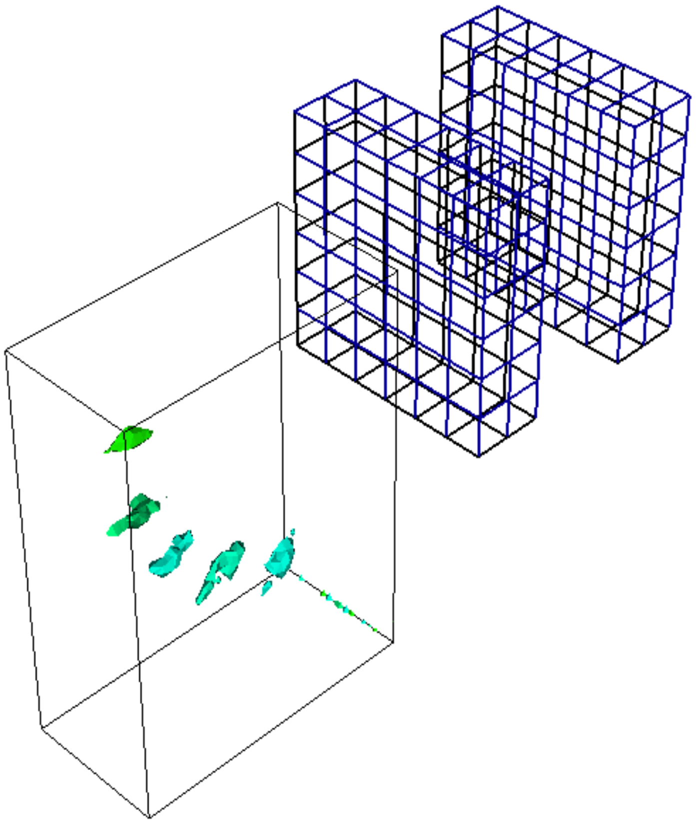
Si(Li) + Ge Cryogenic solutions



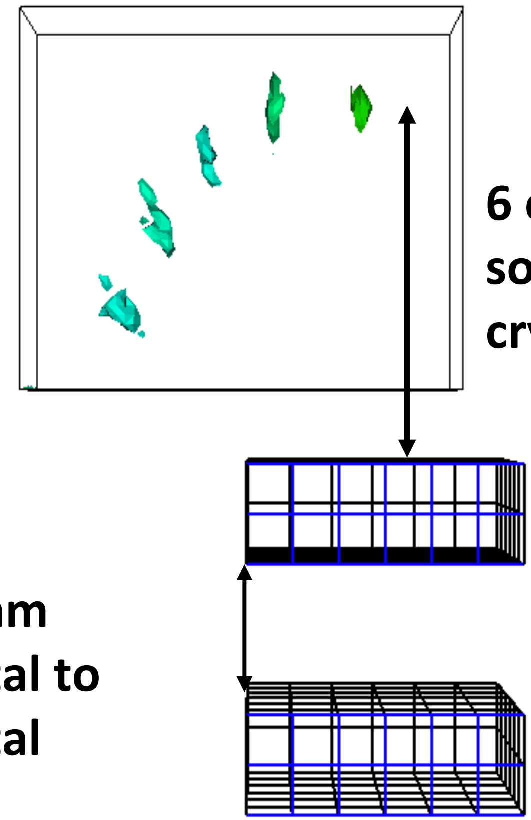
- **Mechanically cooled**
- **Battery powered**
- **Work in collaboration with Canberra**

Compton Camera measurements (Ge/Ge)

E = 1408 keV, 30 keV gate



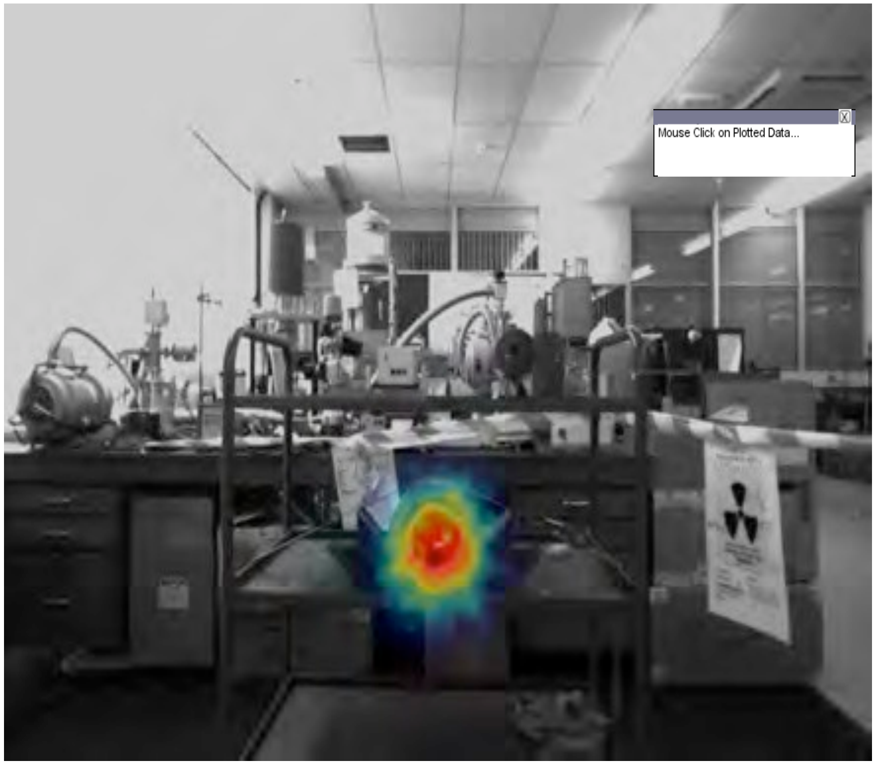
FWHM ~ 8mm: full 3D

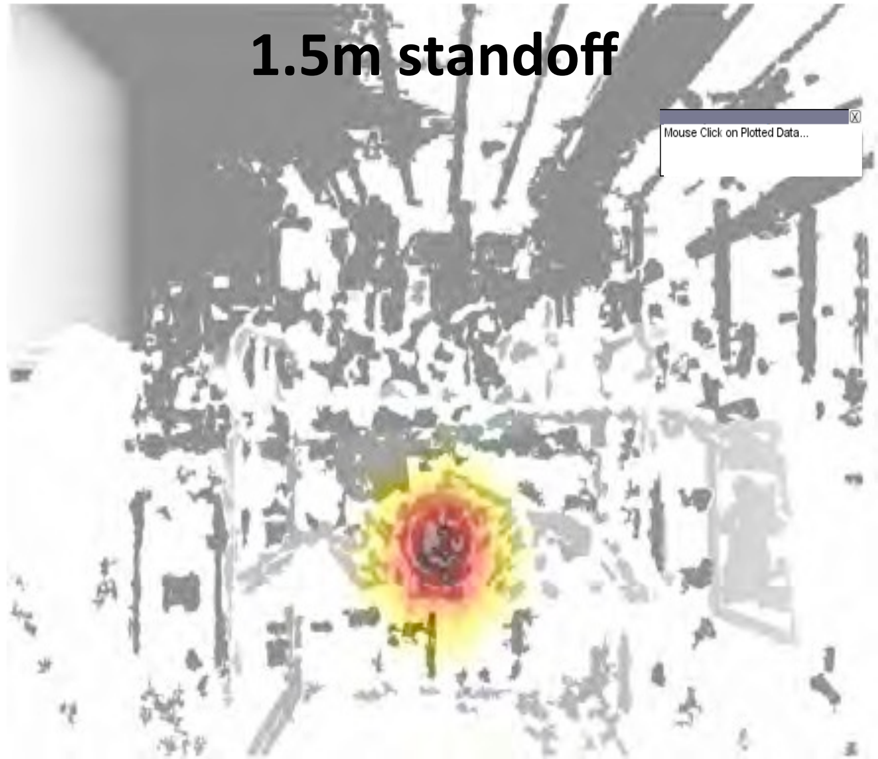


No PSA (5x5x20)

Iterative reconstruction

The potential: 3D Gamma & Optical Stereoscopic image fusion





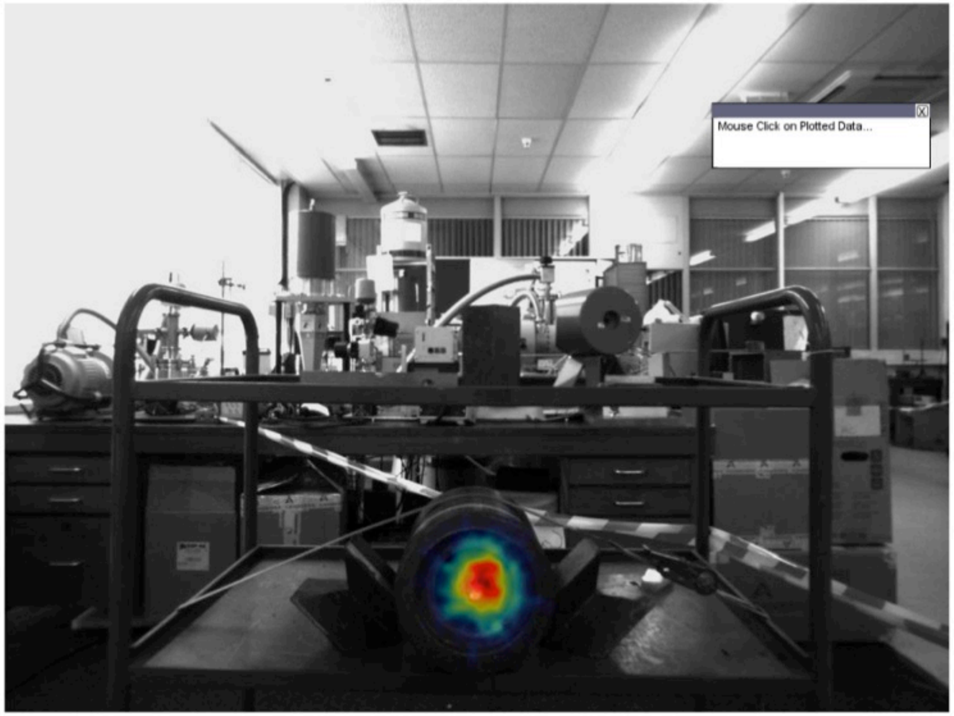
1.5m standoff

NATIONAL NUCLEAR LABORATORY

Science & Technology Facilities Council

A Compton Camera provides 3D source location

The potential: 3D Gamma & Optical Stereoscopic image fusion



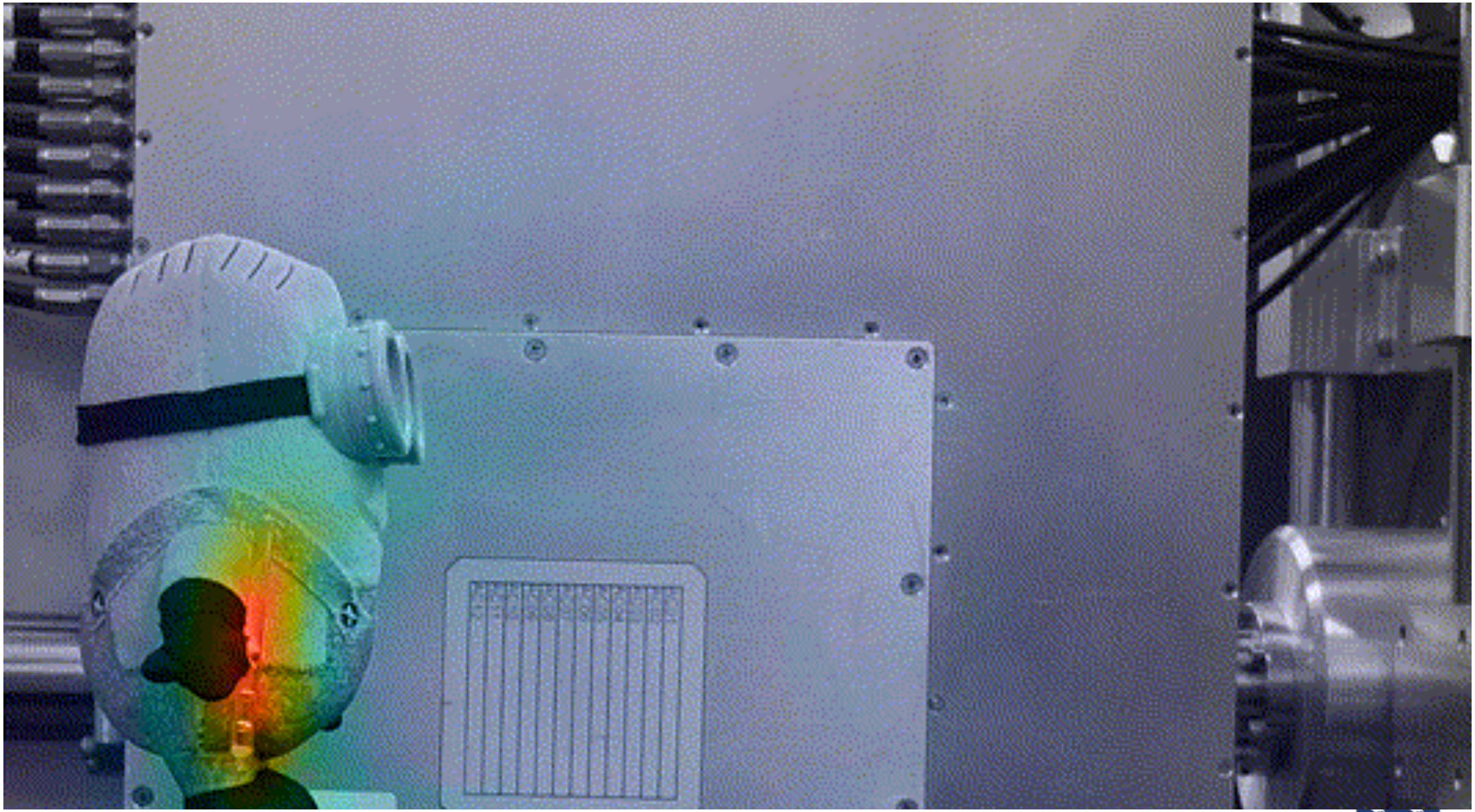
1.5m standoff

NATIONAL NUCLEAR LABORATORY

Science & Technology Facilities Council

A Compton Camera provides 3D source location

Real time imaging



Typical limit of detection

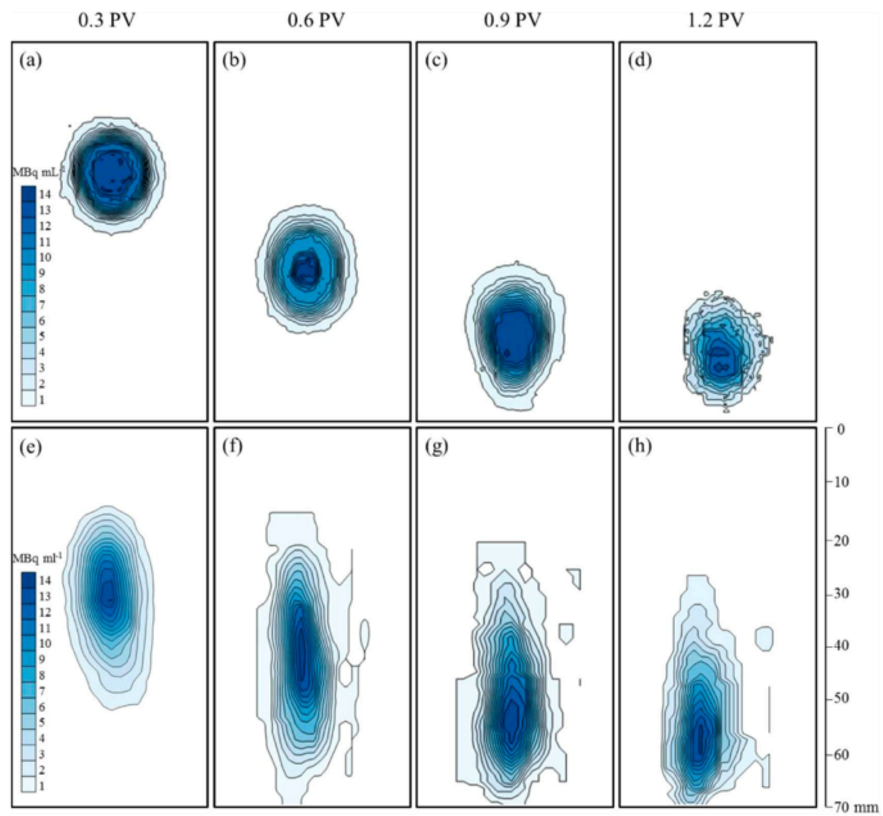
- For a stand-of distance of 1m
- Measurement time of 1 minute
- A full field limit of detection of
  - 4kBq for ^{137}Cs,
  - 10kBq for ^{60}Co
  - 10kBq for ^{241}Am
- 3 dimensional phase space gating
- Background reduction from the whole field of view
- Theoretically x10 reduction possible

Environmental Compton Camera Development: Imaging Radionuclide Transport in Soils and Geomaterials

NERC Proof of concept award

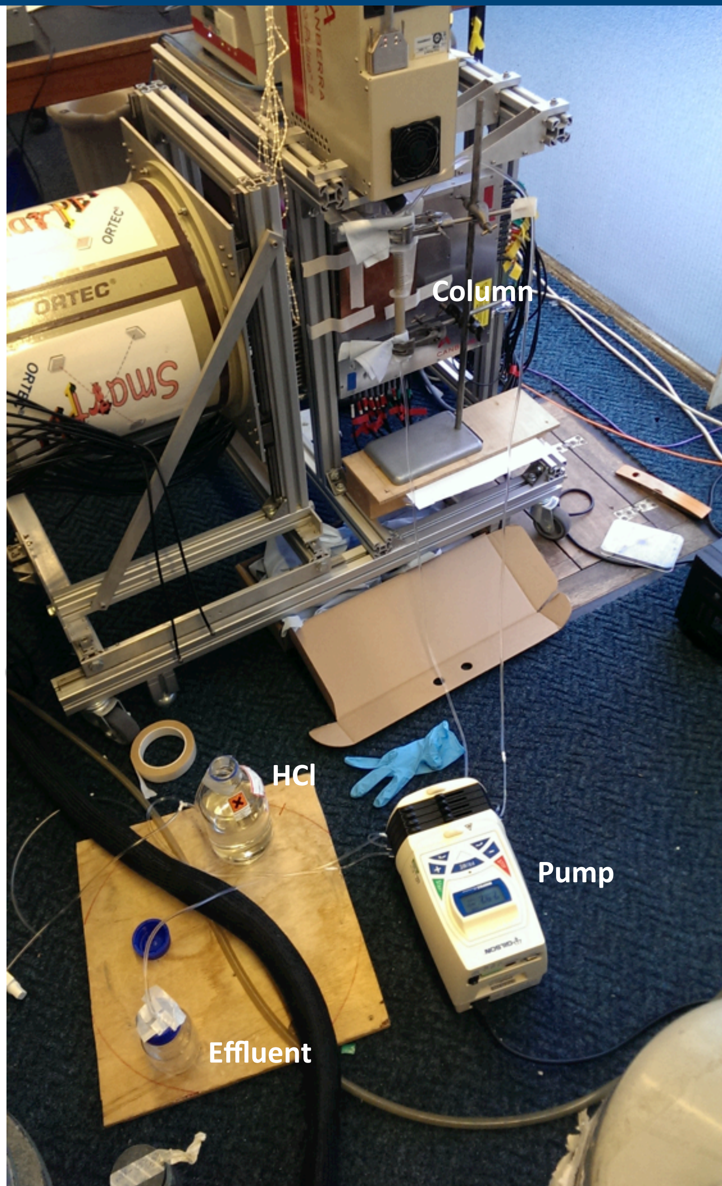
Sample collection from target site

Previous Work: SPECT Gamma-camera

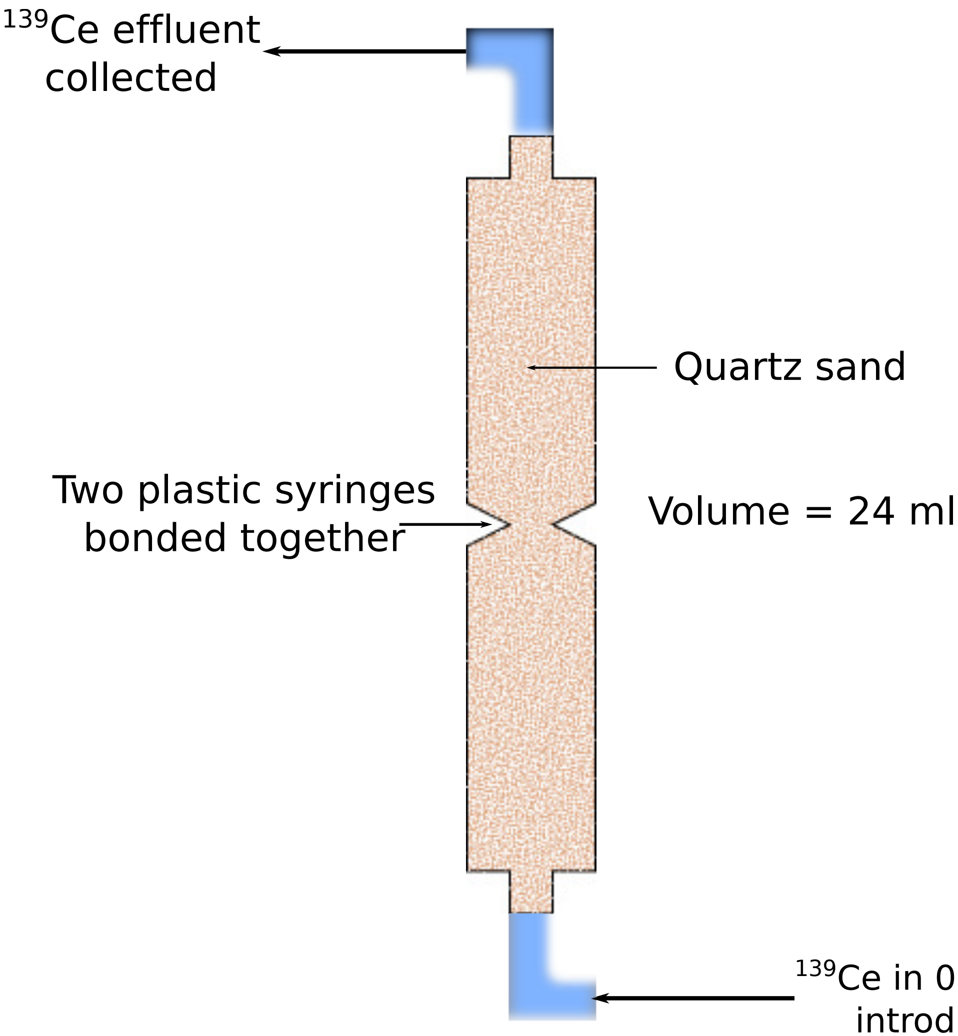


Corkhill *et al*, Environ Sci Technol. Dec 3, 2013; 47(23): 13857–13864

Proof of concept demonstrator

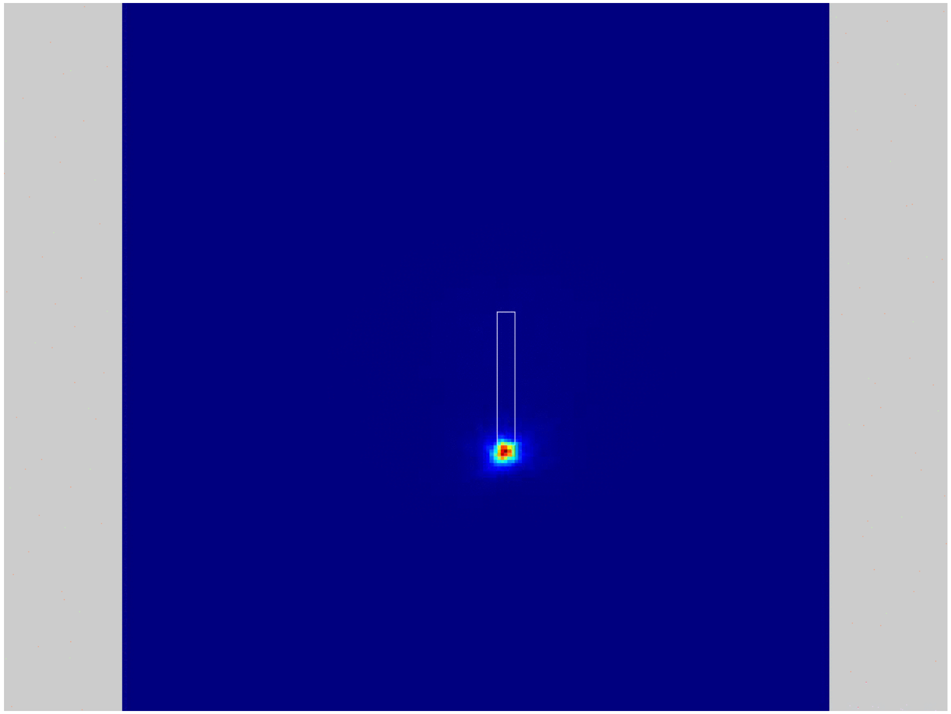


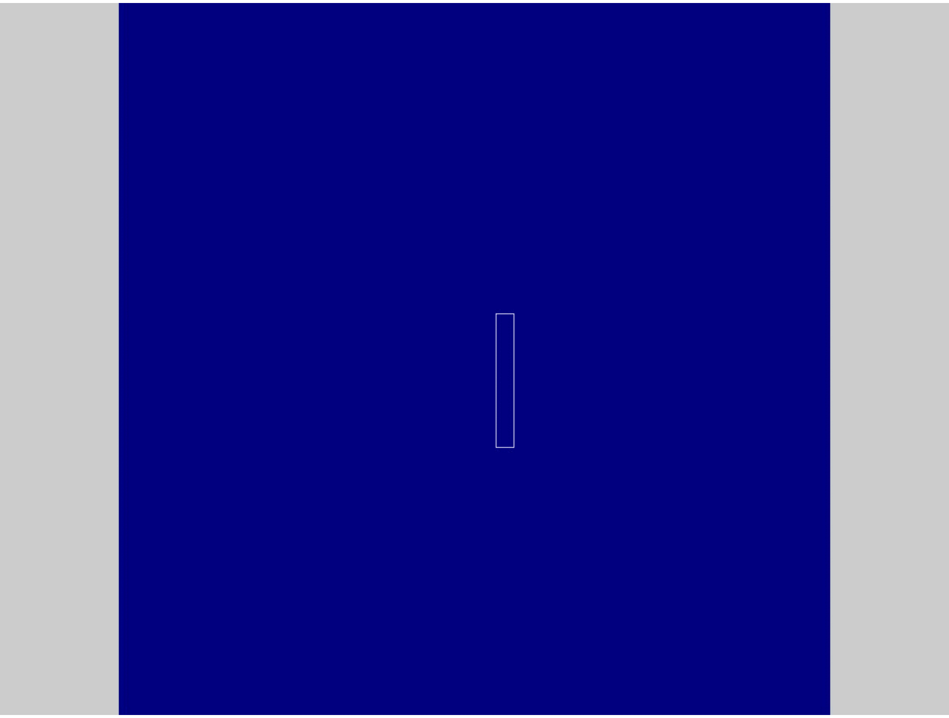
Cerium Sand Column Experiment



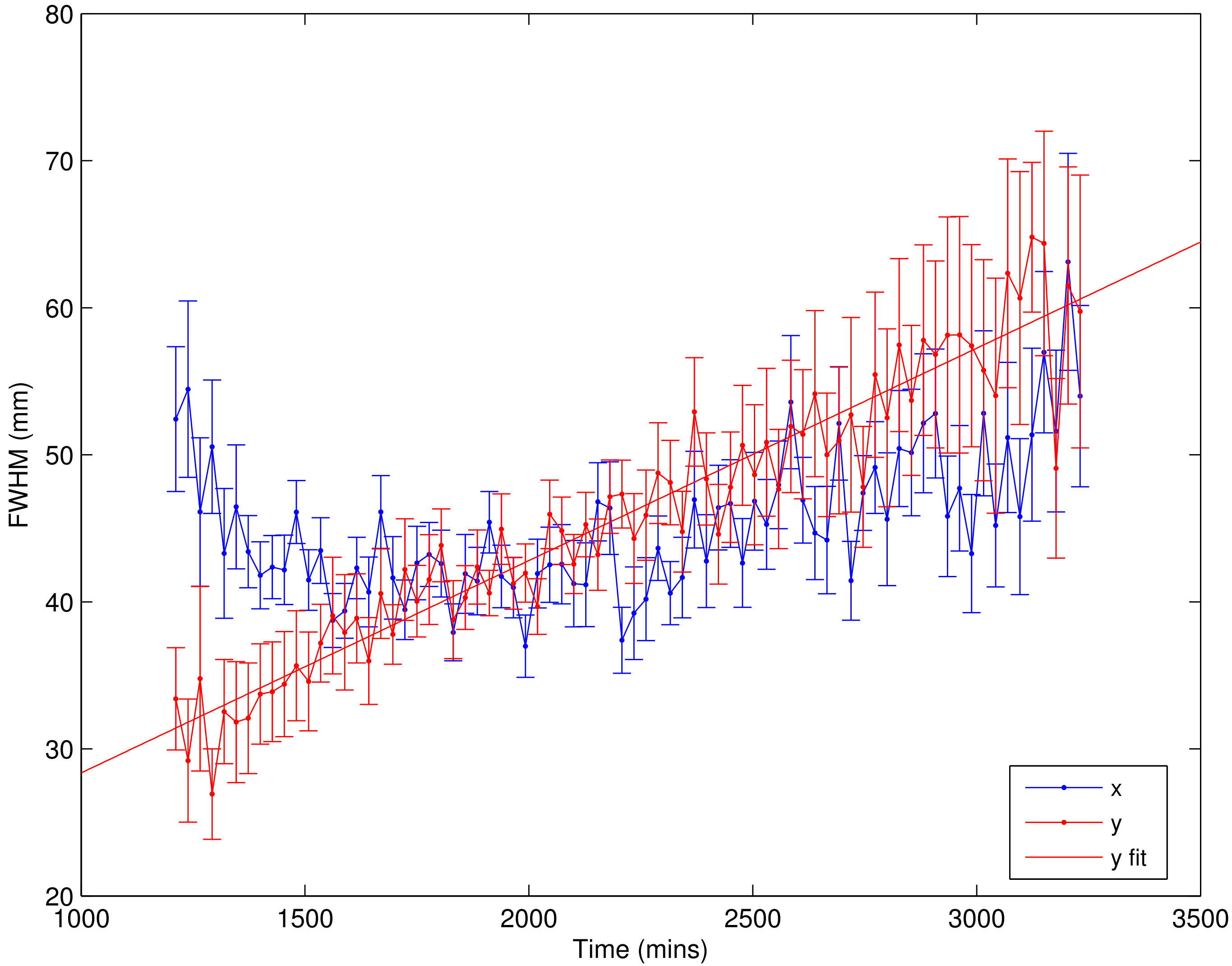
- Higher efficiency
- Wider operational energy range
- Wider imaging field-of-view
- Potential for full 3D imaging

Sand column effluent flow imaged with Ce-139





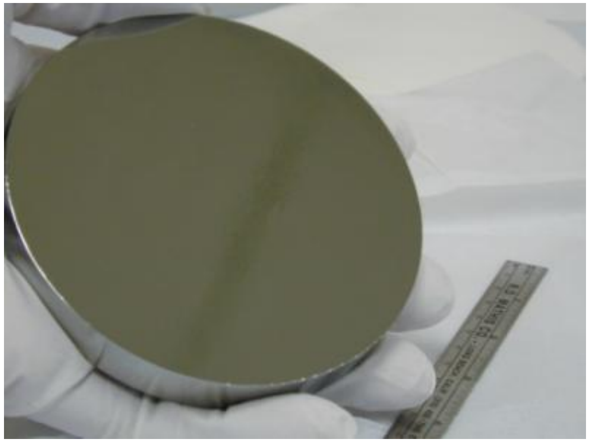
Sand column profile: FWHM v Time



Gamma Ray Imaging Spectrometers

- 10 x imaging sensitivity
- Factor 2 -3 improvement in position resolution
- System locates sources in space (3D) and can identify the isotopes in the material
- Radioactive material found quickly, reducing cost, false alarms and search time – increasing cargo throughput





Improvement of the performance of germanium detectors using pulse shape analysis for industrial and environmental applications

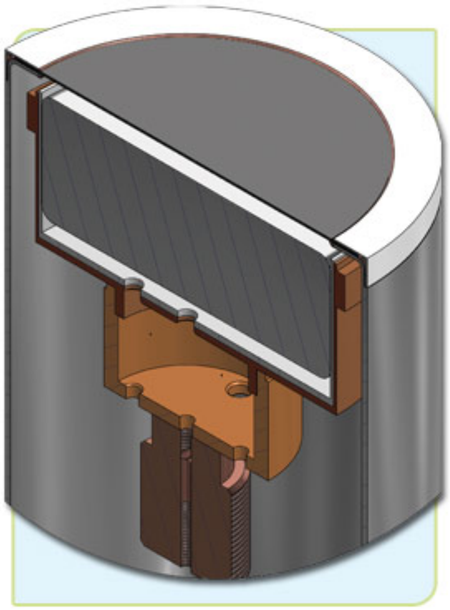
STFC Innovation Partnership Scheme (IPS)

Science & Technology Facilities Council

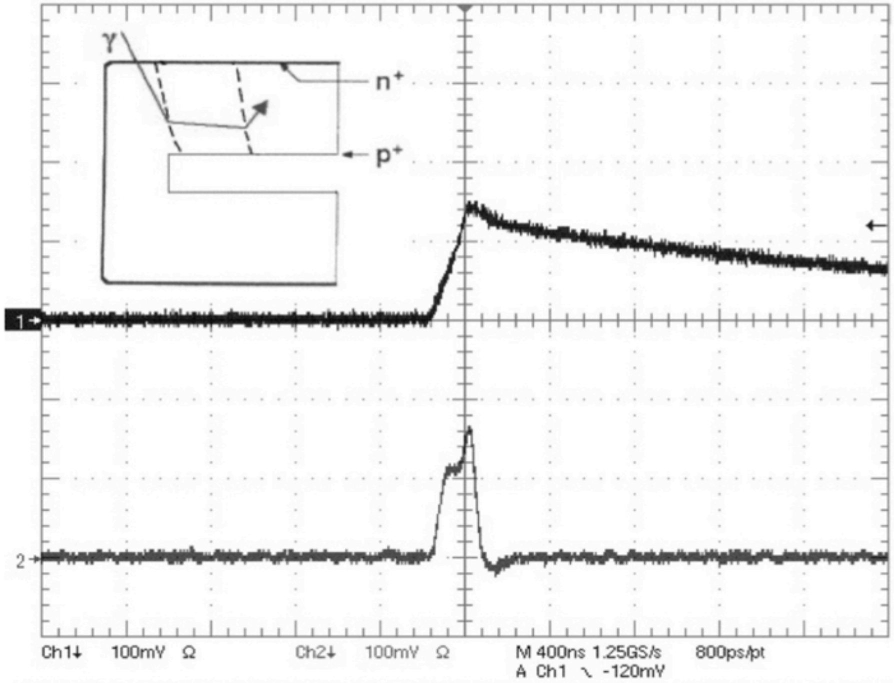
CANBERRA

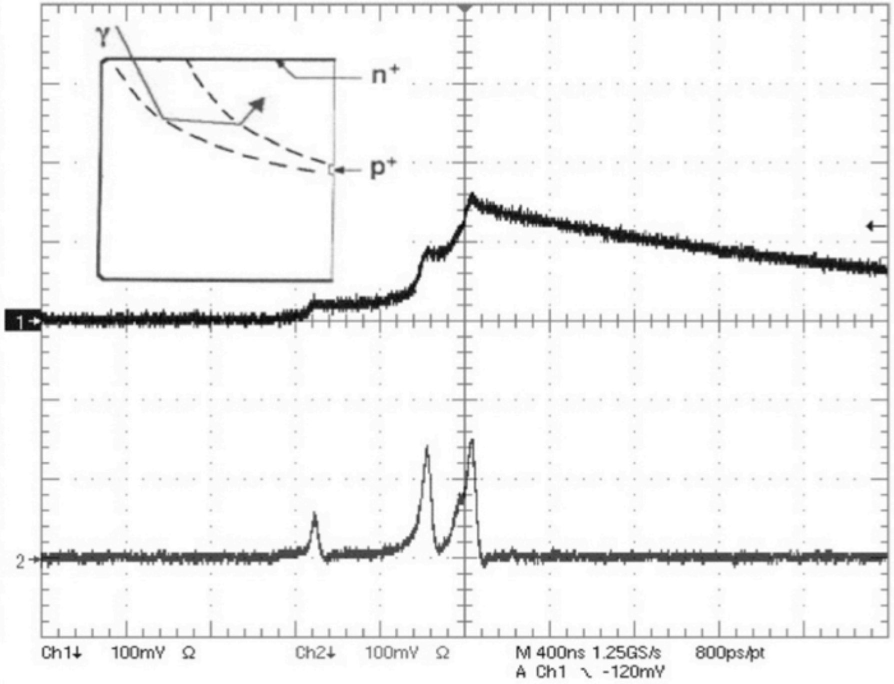
Project aims and objectives

- Project aims to improve minimum detectable activity (MDA) of BEGe detectors by suppressing background events
- Uniquely Identify true coincidence summing
- Investigation will focus on developing algorithms which exploit the position dependent variation in pulse shape for the detector
- Improve the time resolution of the detector



Coax vs BEGe charge pulse shape response

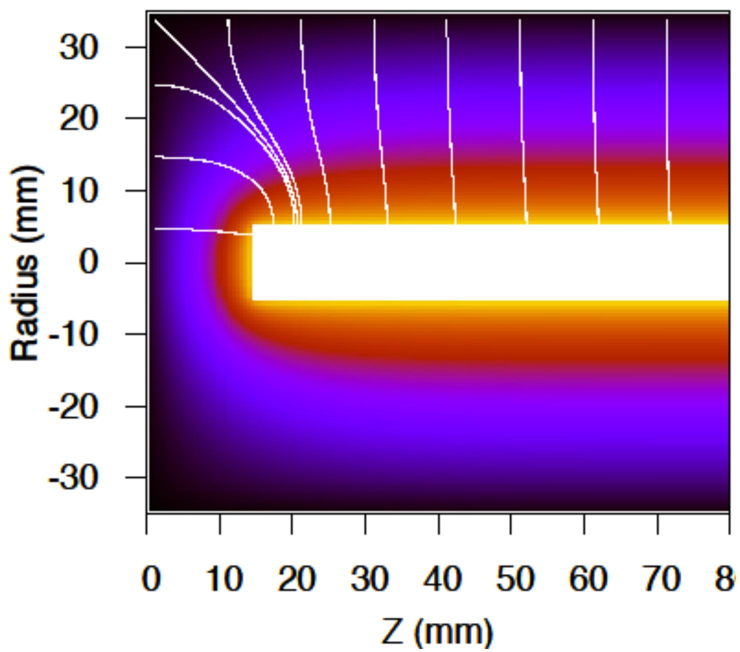




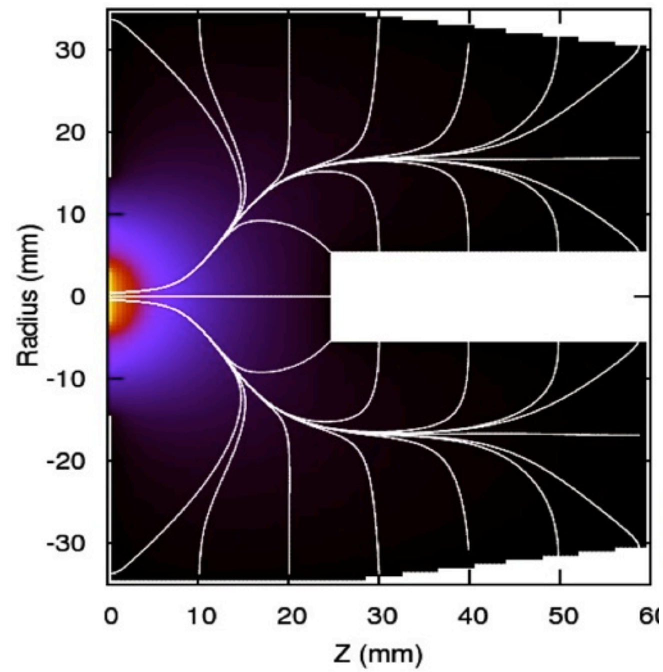
"Inverted Coaxial" Point-Contact Detector

- Drift of charges is radically different from a normal coaxial detector
- Long drift times, up to ~ 2 μs
- Small capacitance gives very low noise
- Can be segmented to give superb position resolution
- Signal time helps to determine drift distance and therefore position

Closed-end Coaxial



Inverted Coaxial



Lots of opportunities exist

- Novel sensors: Point contact imaging detectors
- Image fusion
- Compact, high count rate systems medical imaging
- High sensitivity systems for security imaging
- Autonomous systems
- …..

Advances in semiconductor sensors, Gamma-ray imaging systems

Science & Technology Facilities Council

UNIVERSITY OF LIVERPOOL

Dr Andy Boston

ajboston@liv.ac.uk