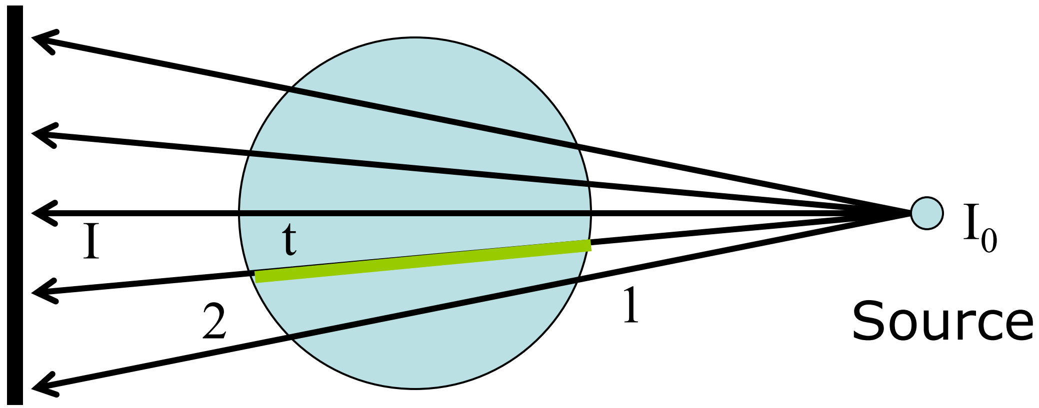
Lecture 2: Medical Applications of Nuclear Physics

- Projection Imaging
- Tomographic Imaging CT/PET/SPECT

Projection Imaging

Projection Imaging: External source



Film or X-ray detector

- Intensity at screen: $I = I_0 \exp\left(-\int_1^2 \mu dt\right)$
- μ = attenuation coefficient within region.
- Measurement at screen gives line integral:

$$\int_1^2 \mu dt = \ln\left(\frac{I_0}{I}\right)$$

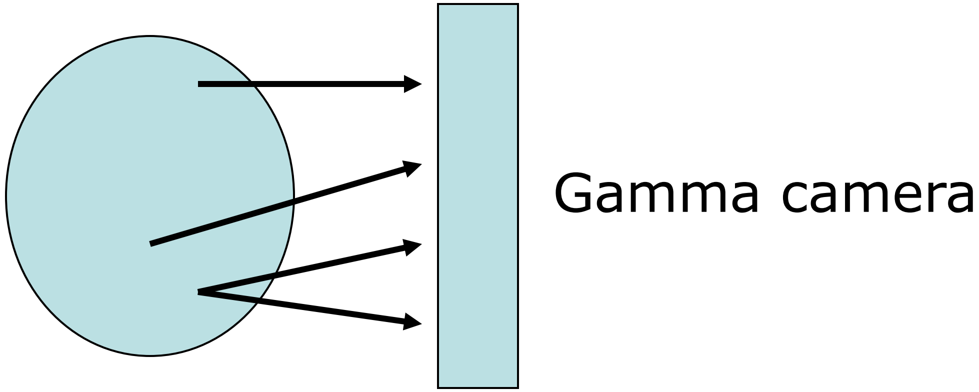
- No resolution in depth
- Need ~1% variation in μ in ~1cm for image contrast

Conventional X-ray image

- Energy of radiation is compromise between:
  - Penetration – minimises radiation dose
  - Contrast – need enough absorption to achieve the image
- X-rays yield an anatomical image $\rightarrow$ location of organs

Projection imaging: Internal source

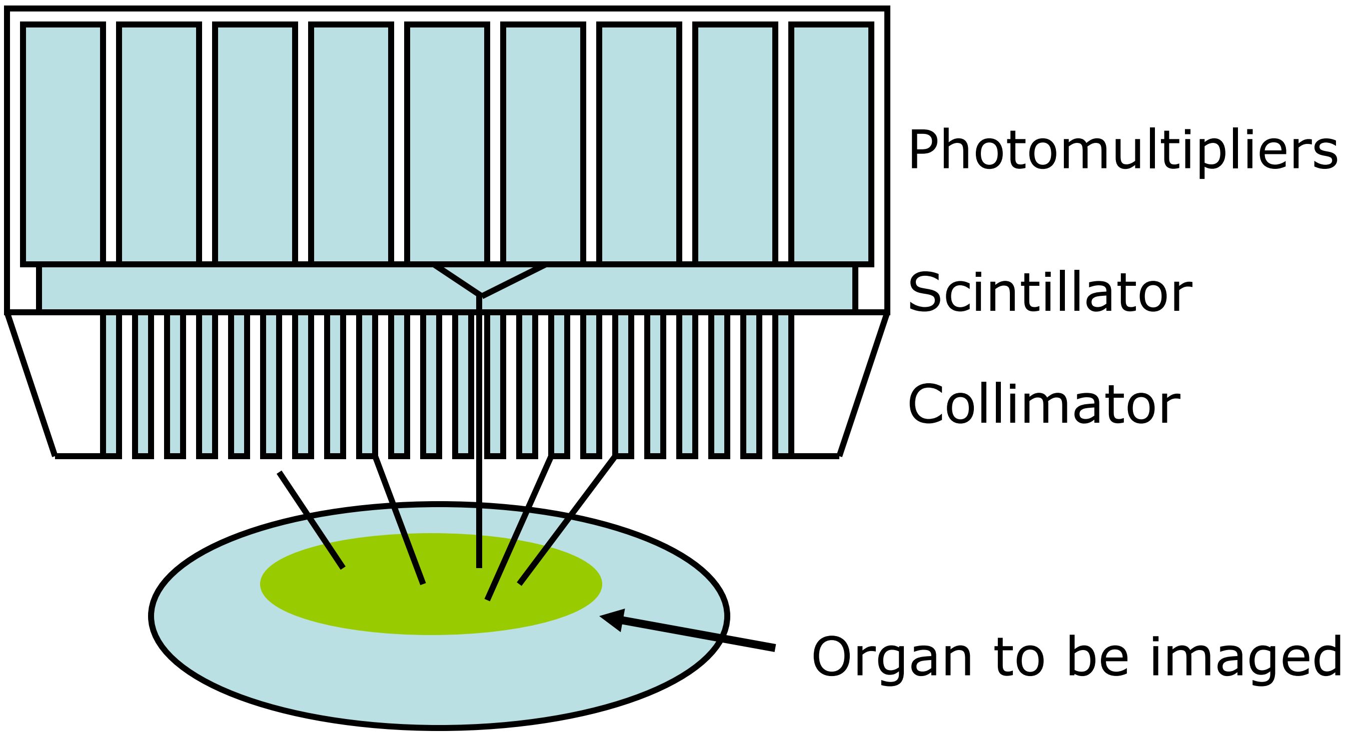
- Map distribution of absorbed radiotracer in body or organ with a position sensitive detector – a gamma camera.



- Ideal source:
  - No β emission (less dose to patient)
  - $t_{1/2}$ scan time (less dose to patient)
  - E_γ~100 to 200 keV $\rightarrow$ good photopeak absorption
- Example: Iodine – selectively taken up by the thyroid $\rightarrow$ used to measure thyroid size and efficiency.

Isotope	Source	$t_{1/2}$	$E\beta$(kev)	$E\gamma$(kev)
^{131}I	Reactor	8d	606	364 (64%)
^{123}I	Cyclotron	13h	No	159 (84%)

Projection imaging: Gamma camera



- Typically: 30cm × 2cm NaI(Tl) scintillator
- Spatial resolution ~ a few mm
- Use of large collimator not efficient → relatively large radiation dose given to patient.

Radiation Risk Perspective (mSv)

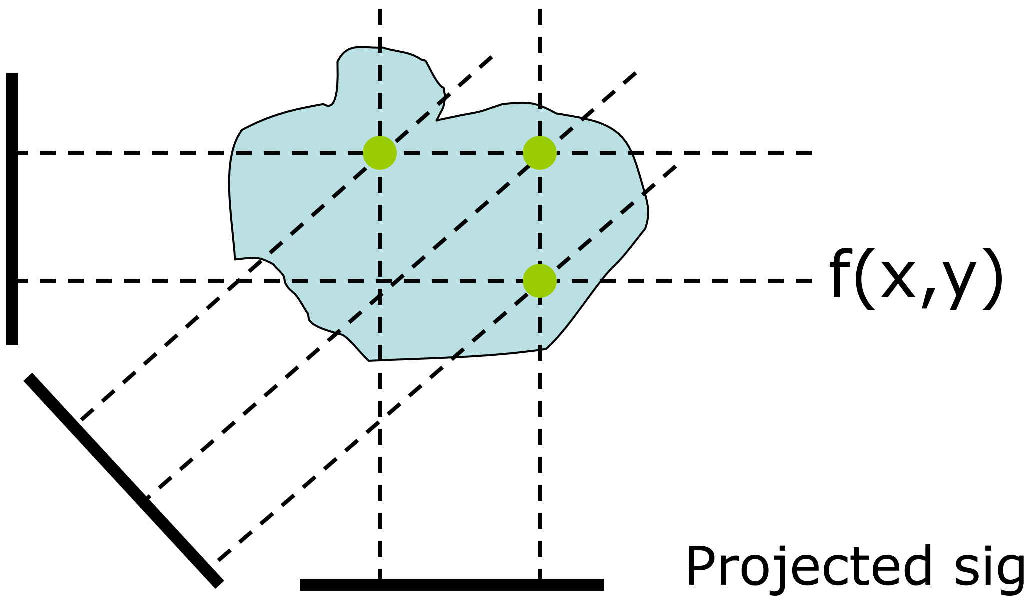
Background radiation (all sources)	~2-2.6/year
Commercial Air Travel	.01/1000 mile
Chest x-ray (2 view)	0.1
CT	1-10
SPECT	10-40
PET F-18 DG viability (10 mCi)	8

Computed Tomography

How to image in 2 and 3 dimensions...

Computed Tomography

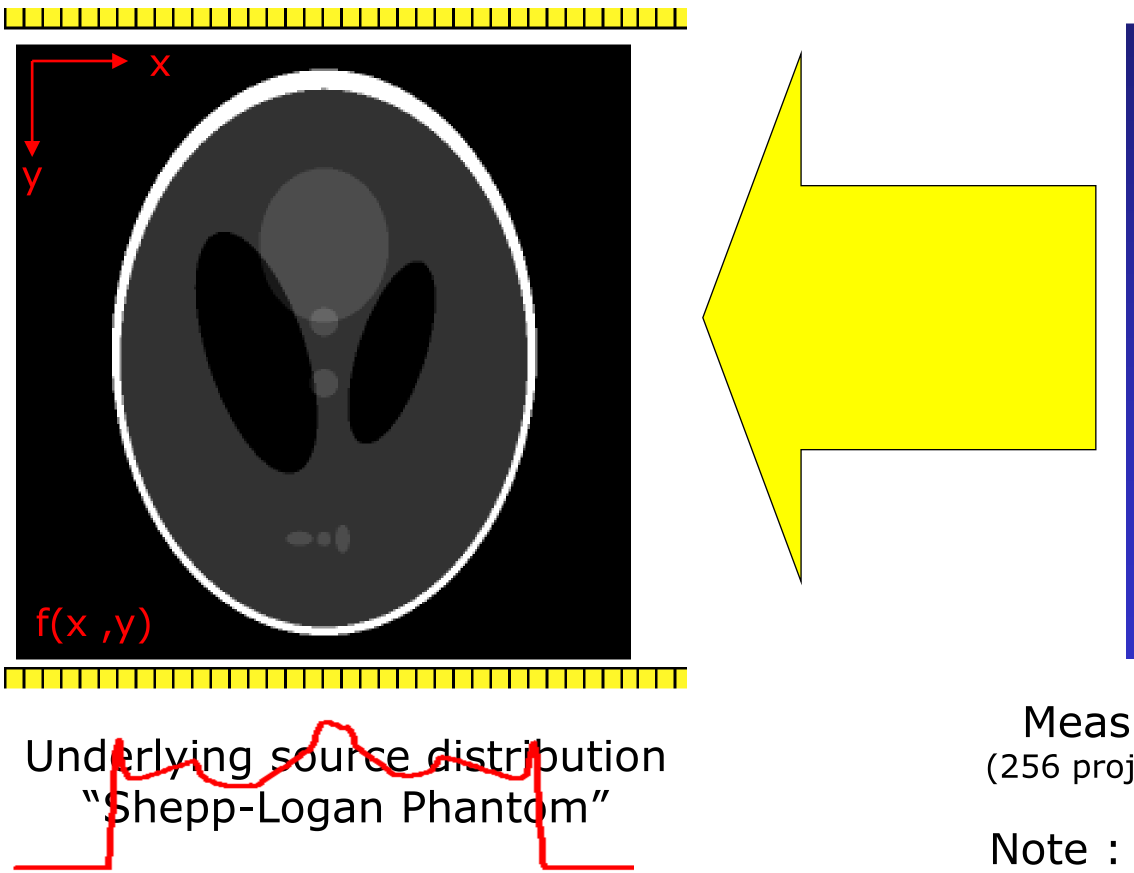
- For simplicity consider 2D reconstruction from 1D projected images of a function f(x,y)



- Different projections contain different information about f(x,y).

Sinogram / Radon Transform

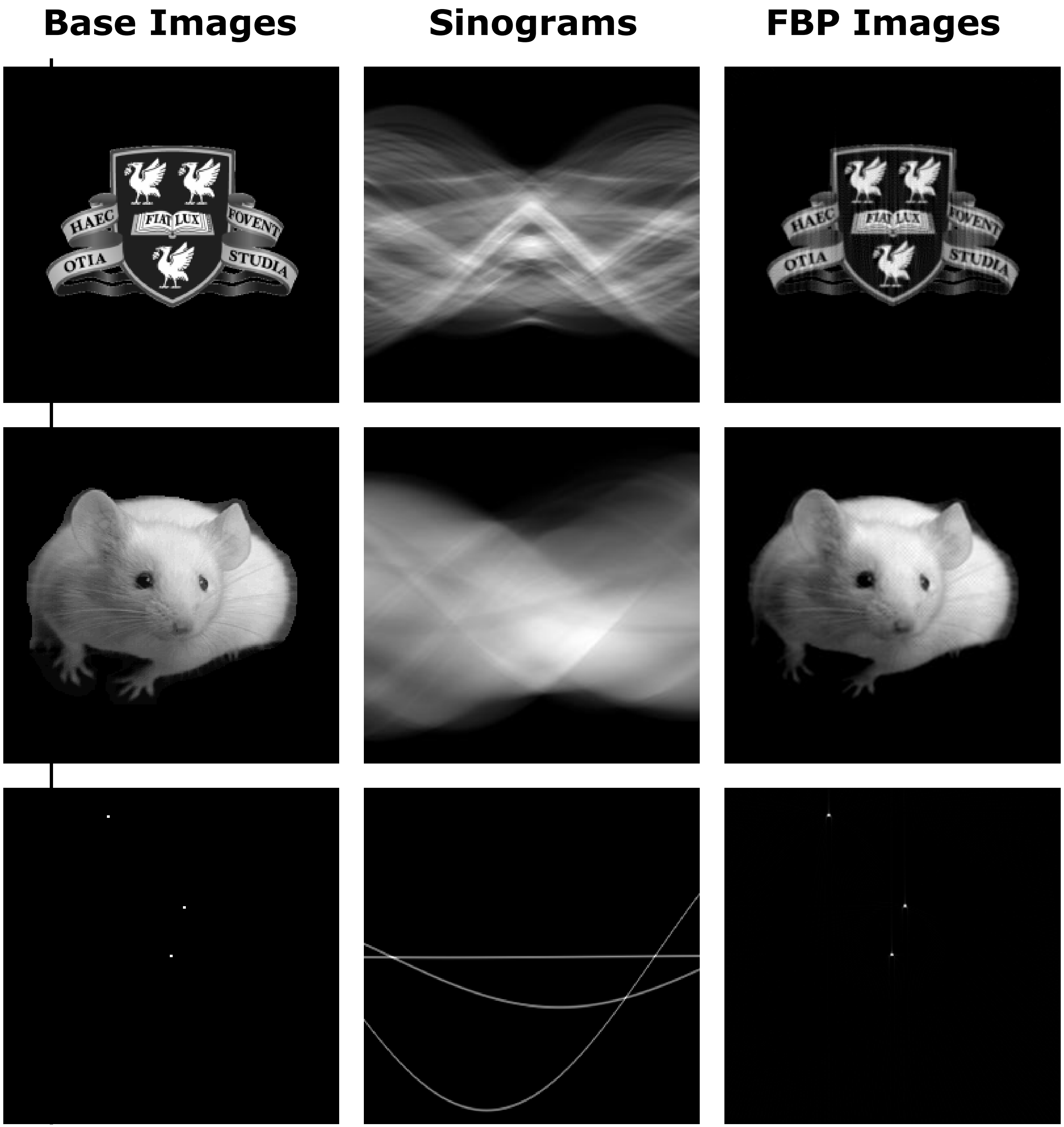
- The sinogram is
  - Measure of intensity as a function of projection, θ and position, r
  - Often seen plotted as a 2d grey scale image



Underlying source distribution
“Shepp-Logan Phantom”

Measured result – **“Sinogram”**
(256 projections, 363 positions per projection)

Note : We measure from 0 to 180°



All three FBP images were produced using:

* 256 x 256 sinogram
* Ramp Filter
* Linear Interpolation

Different Imaging Methods

- Analytic Reconstruction
  - Simple Back-Projection (SBP)
  - Filtered Back-Projection (FBP)
  - Fourier Transform Reconstruction

- Classical Iterative Reconstruction
  - Least Squares Iterative Techniques (LSIT)
  - Algebraic Reconstruction Techniques (ART)
  - Simultaneous Iterative Reconstruction Techniques (SIRT)
  - Gradient and Conjugate gradient

- New Iterative Reconstruction
  - Maximum Likelihood Expectation Maximization (ML-EM)
  - Ordered Subset Expectation Maximization (OS-EM)
  - List-Mode Maximum Likelihood (LM-ML)

Analytic vs Iterative

- **Analytic Reconstruction**
  - Try to solve directly from the projection data (radon transform / sinogram)
  - Single “pass” approach – Not as computer intensive.
- **Iterative Reconstruction**
  - Start with an initial “guess” of the source distribution (uniform)
  - Forward-project this estimate along measured projections and compare.
  - Update the estimate based on the comparison.
  - Continue until some convergence criteria is met.
  - Much (much!) more computer processor and memory intensive.
  - Allows the physics of the system to be included in the calculations.
  - Result is less dependant on how the data was collected
  - Method copes better than FBP with noisy data and small numbers of projections and/or positions

FBP Algorithm (Analytic)

- Fourier transform each projection into frequency domain.
- Multiply by a "filter" such as a Ramp filter.
- Inverse Fourier transform back to spatial domain to give a filtered sinogram.

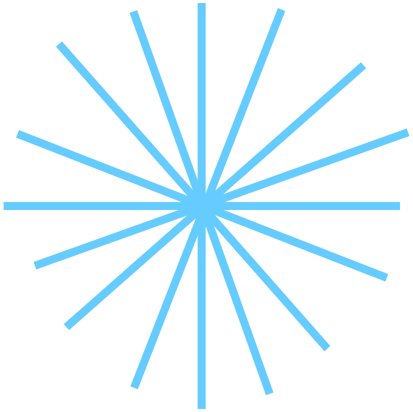
$$f_{BP}(x, y) = \int p(x\cos\theta + y\sin\theta, \theta)\,d\theta$$

$$f_{BP}(x, y) = \sum_{0}^{N-1} p(x\cos\theta + y\sin\theta, \theta)\Delta\theta$$

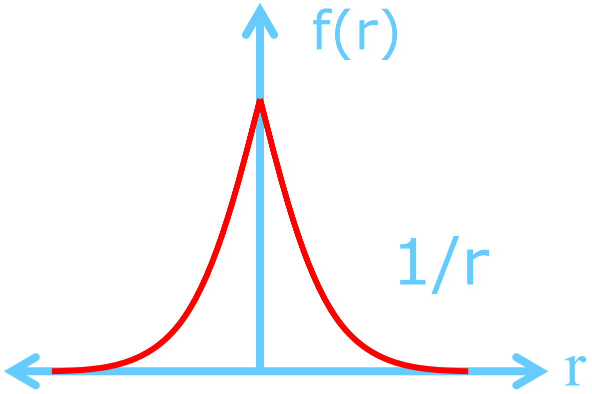
Simple Back-projection

Filtered Back-projection

Why do we need a filter?



Point source



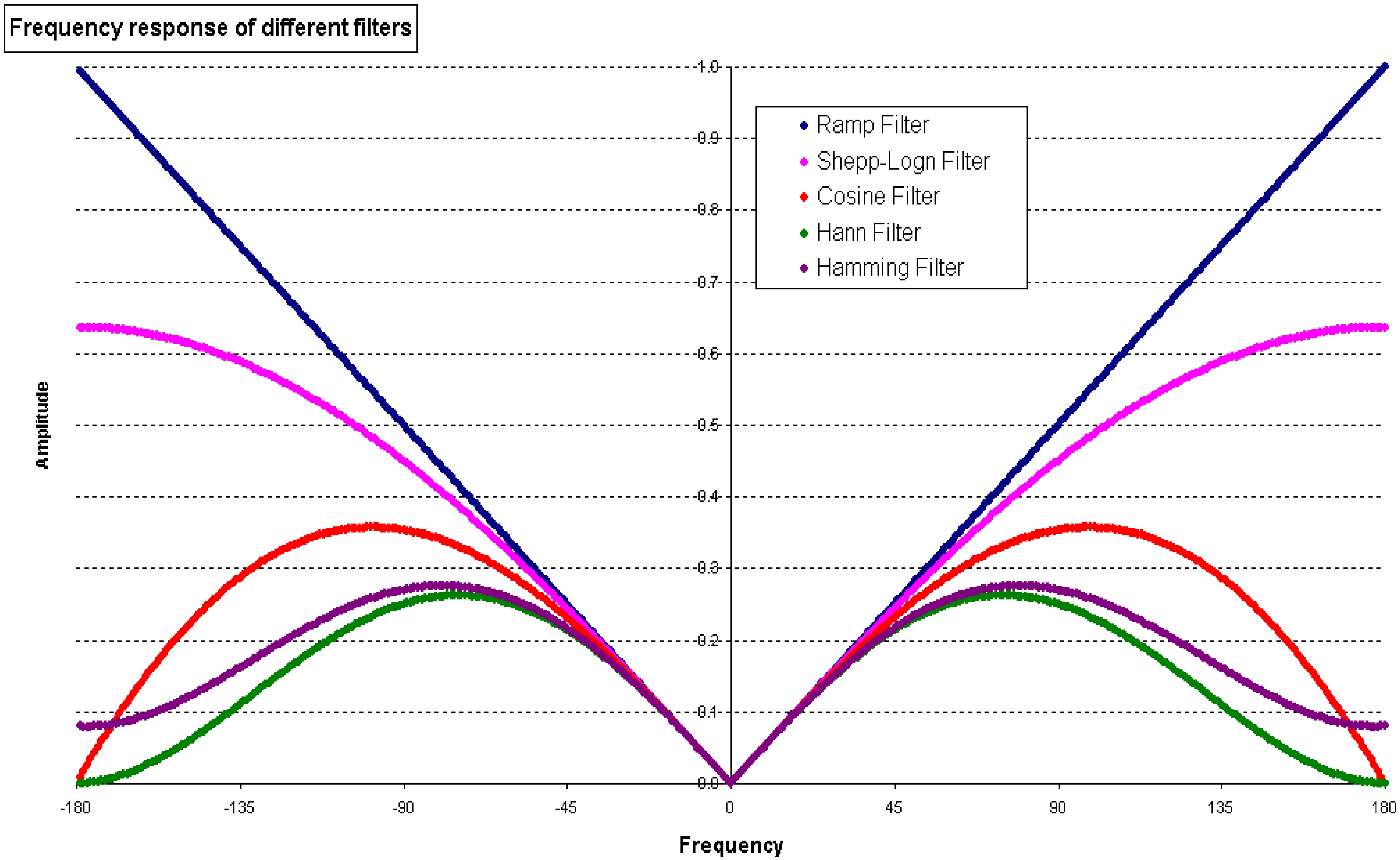
- Reconstruction of a point source by simple back-projection gives a “star like” pattern.
- Lots of angles $\rightarrow$ density of lines $\propto$ 1/r
- Obtain blurred image

→ Corrected by applying a filter

FBP Filters

A Ramp filter is theoretically the ideal filter to use, but real data contains noise and the ramp filter can enhance high frequency noise.

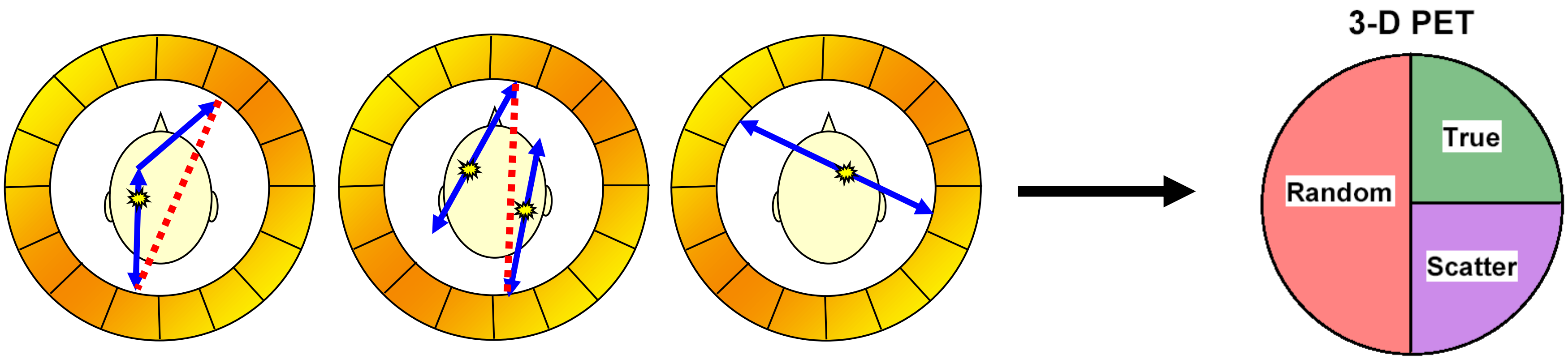
No single filter is the answer, it is very dependent of the system and data quality



Computed Tomography

PET Case study (SmartPET)

The motivation behind the project



Scattered Coincidence **Random Coincidence** **True Coincidence**

- Existing technology relies on BGO scintillator technology.
  - Limited position resolution.
  - High patient dose requirement.
  - Poor energy resolution only accept photopeak events.
  - Will not function in large magnetic field.
- SPECT applications utilising Compton Camera techniques.

Common PET isotopes

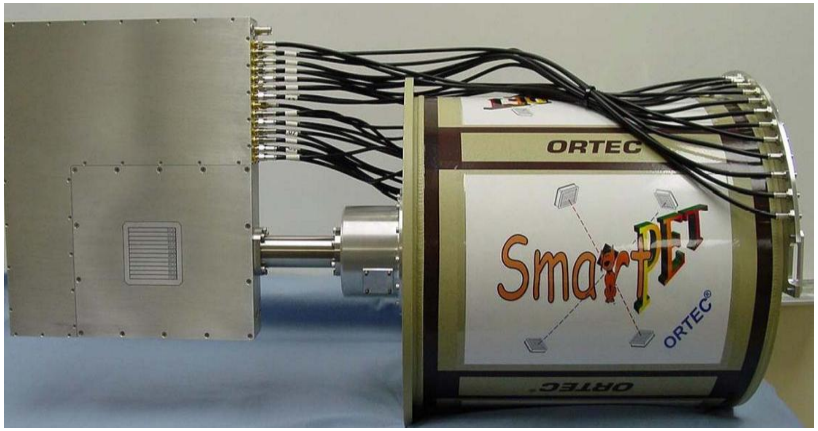
Isotope ($t_{1/2}$)	Reactions	Radio pharmaceutical	Diagnostic use
^{11}C (20.3m)	$^{14}N(p,\alpha)^{11}C$	Methylspiperone Acetate methionine	Brain Heart metabolism Cancer detection
^{13}N (10.0m)	$^{16}O(p,\alpha)^{13}N$ $^{13}C(p,n)^{13}N$	Ammonia Amino acids	Heart blood flow Protein synthesis
^{15}O (2.0m)	$^{14}N(d,n)^{15}O$ $^{16}O(p,pn)^{15}O$	O_2 CO	Brain blood flow Oxygen metabolism Blood volume
^{18}F (110m)	$^{18}O(p,n)^{18}F$ $^{20}Ne(d,\alpha)^{18}F$	2-deoxy-2-fluoro-D-glucose (FDG) Flurodopa	Glucose metabolism Brain

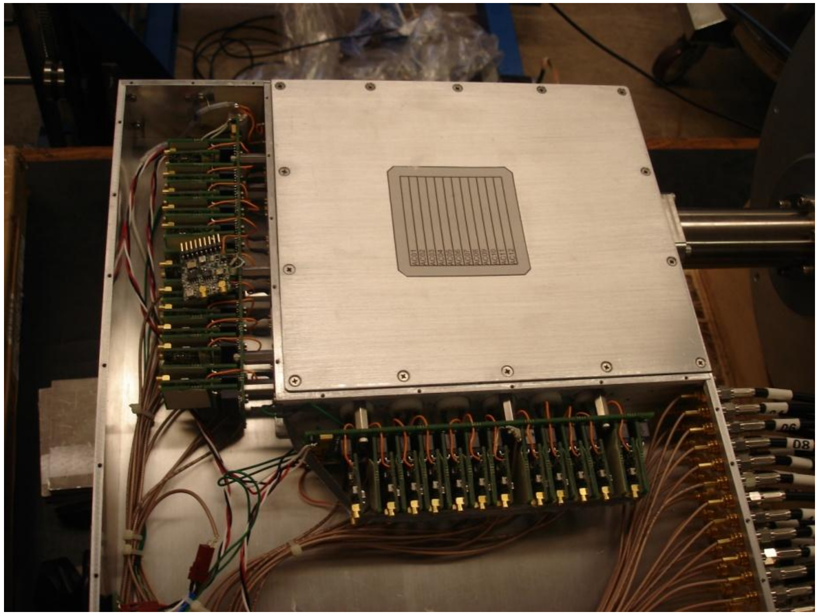
PET isotopes: Positron range

Isotope	E_{max}(MeV)	Max. range (mm)	FWHM (mm)
^{11}C	0.96	4.2	0.28
^{13}N	1.20	5.4	0.35
^{15}O	1.74	8.4	1.22
^{18}F	0.63	2.6	0.22
^{82}Rb	3.15	17.1	2.60

- PET assumes that the point of positron emission corresponds to the location of the atom from which it originated.
- Continuous range of energies of positron.
- Error induced in spatial resolution depends on direction of travel.

Double Sided HPGe Strip Detectors





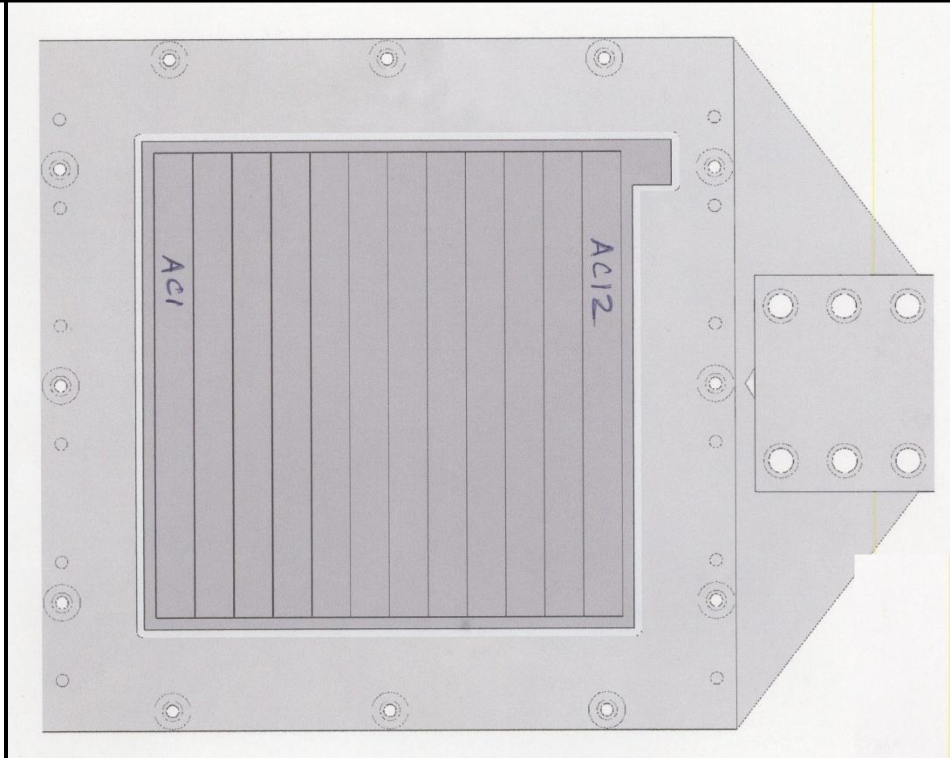
- o 60mm x 60mm x 20mm active area
- o 7mm x 20mm guard ring
- o 12 x 12 orthogonal strips
  - 5mm pitch
  - 5mm x 5mm x 20mm voxels
- o 1mm Aluminium entrance window
- o Thin contact technology
- o Fast charge sensitive preamplifiers

Energy resolution:

1.5 keV@122 keV & 3.25keV FWHM at 511keV

Intrinsic photopeak efficiency – 19% at 511keV

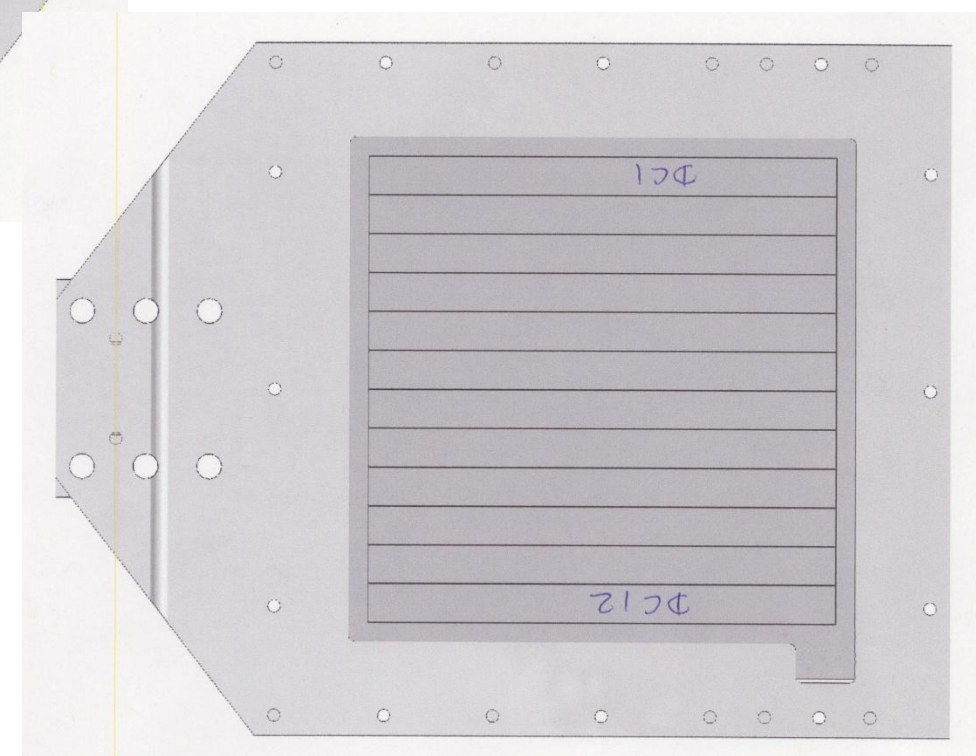
The SmartPET DSGSD detectors



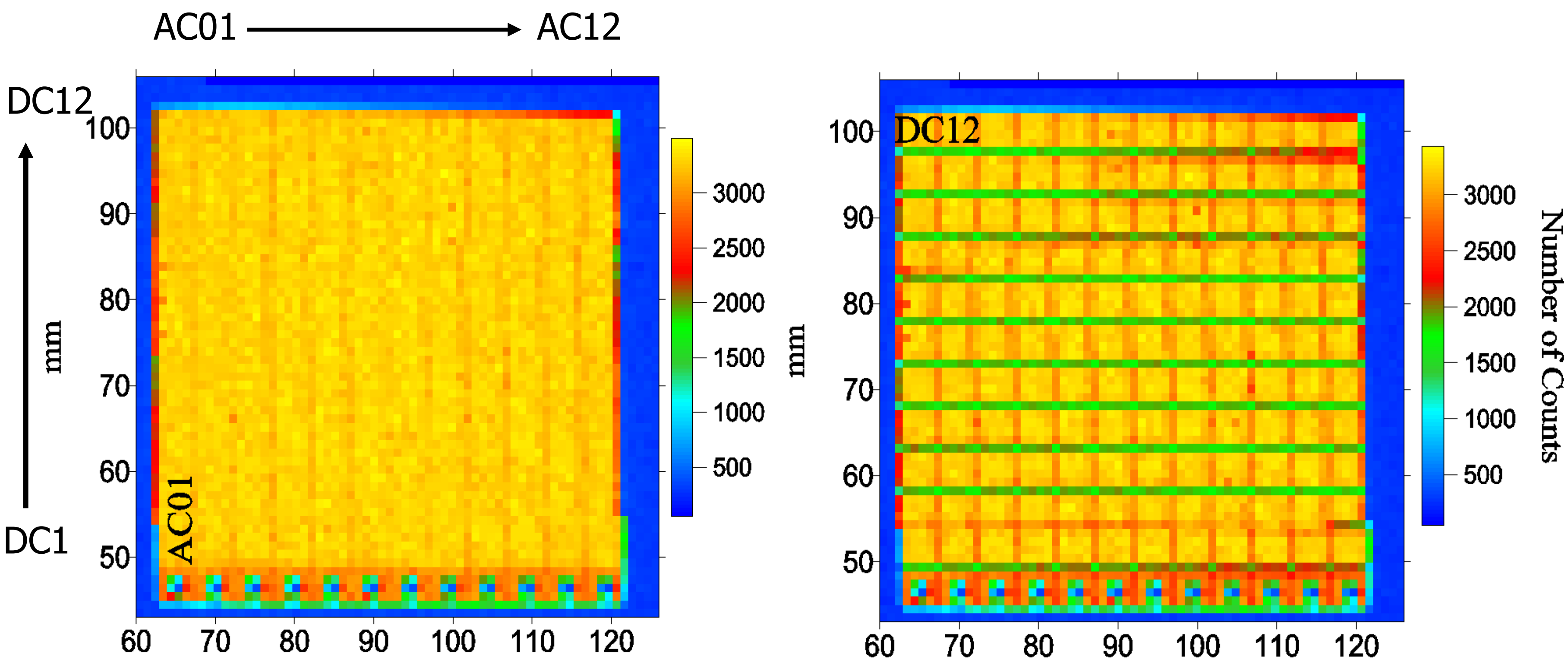
Detector Specification

- Depletion at -1300V, Operation at -1800V
- 12 x12 Segmentation, 5mm strip pitch
- 1mm thick Aluminium entrance window

- Warm FET configuration, 300mV/MeV pre-amps
- Average energy resolution ~ 1.5keV FWHM @ 122keV



Am-241 AC x-y surface intensity distribution



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

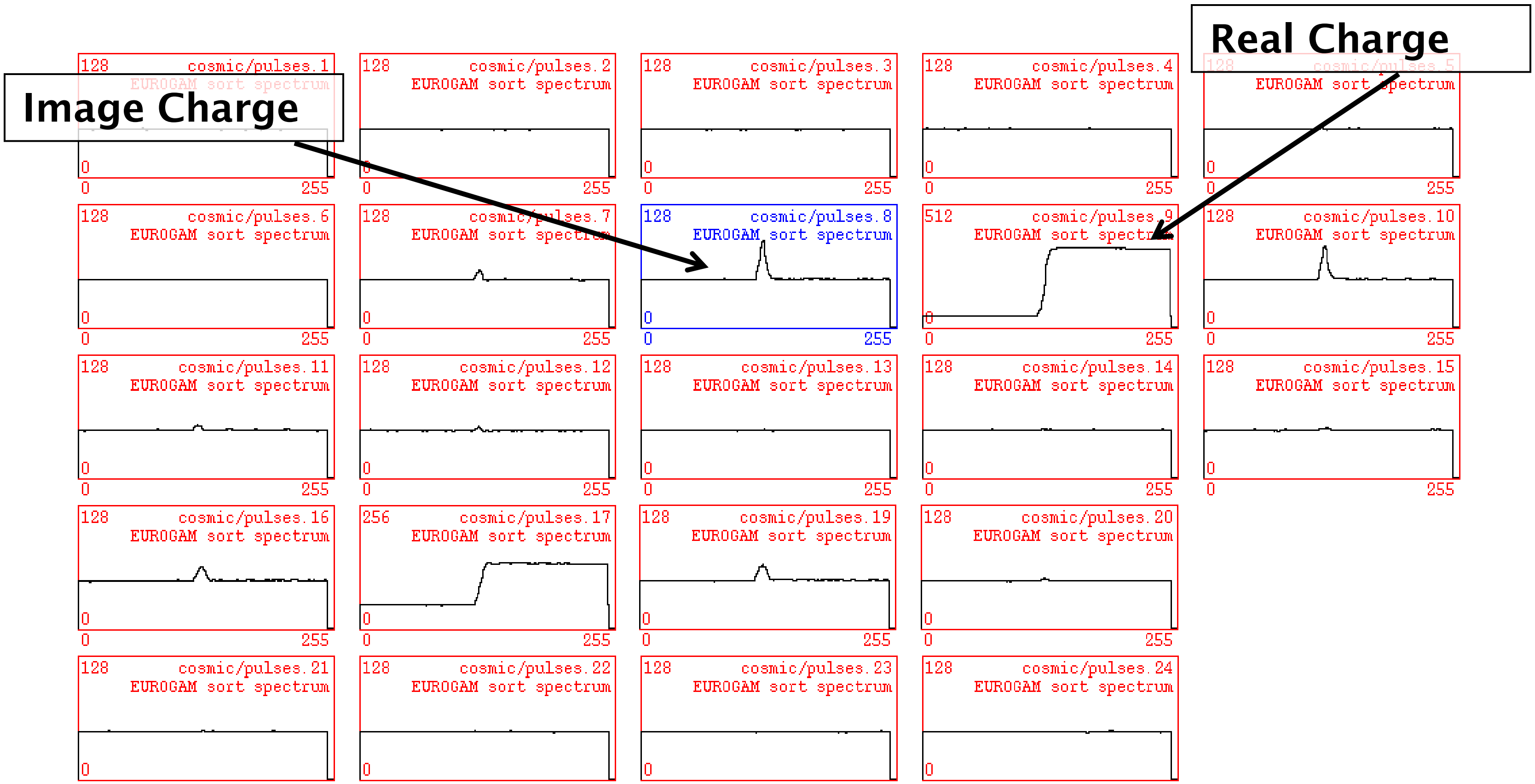
The SmartPET System

Detector Separation – 130mm
Absolute PET Sensitivity – 0.99% (CFOV point source)

Pulse Shape Analysis

PSA techniques developed through characterisation measurements

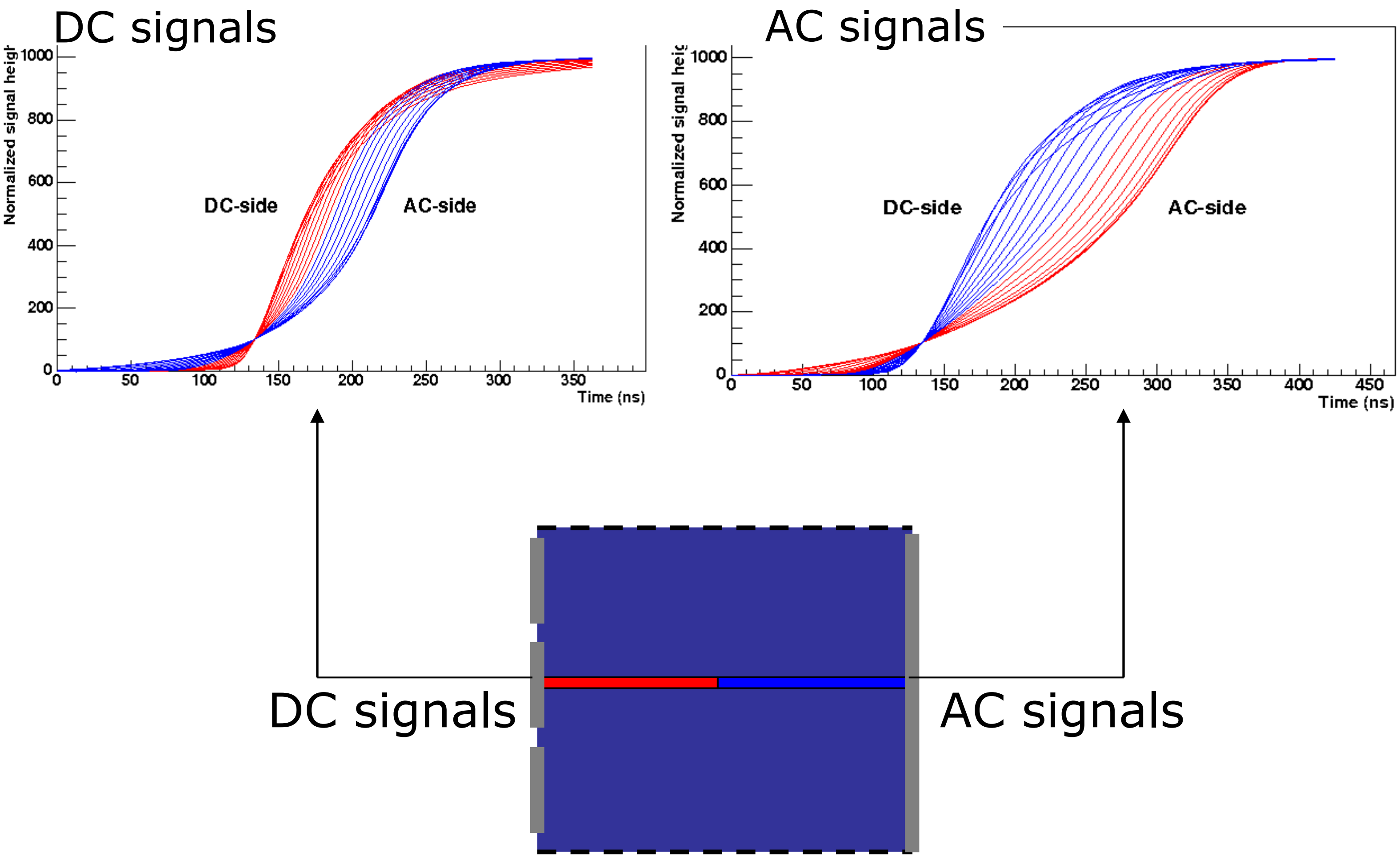
Calibration of variation in detector pulse shape response with position



Parameterisation of these pulse shapes provides increased position sensitivity

SmartPET detector depth response

"superpulse" pulse shapes for ^{137}Cs events versus depth

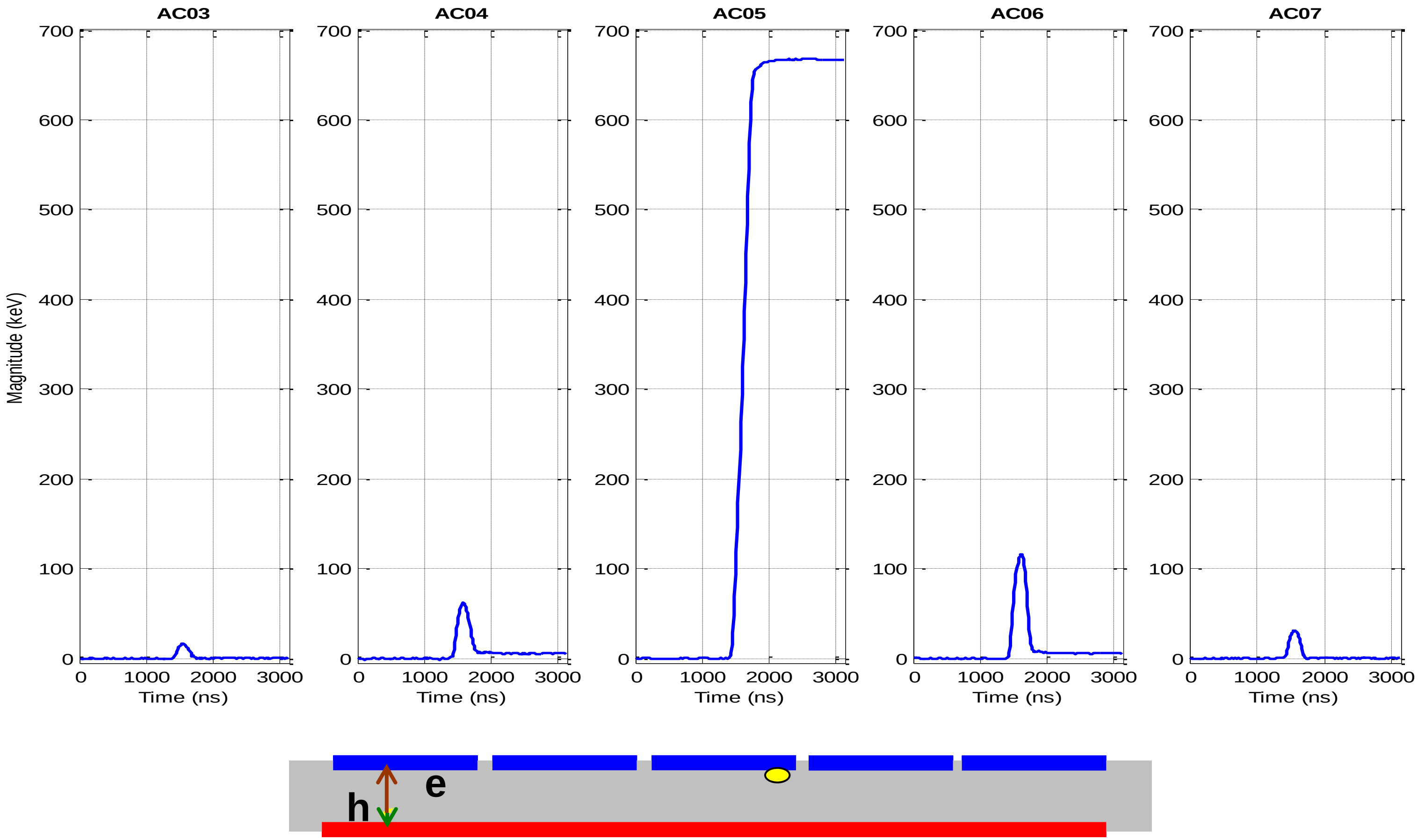


Position Sensitivity

Image charge asymmetry varies as a function of lateral interaction position

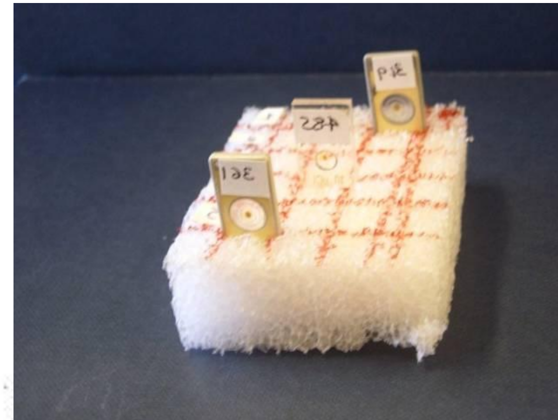
- Calibration of asymmetry response

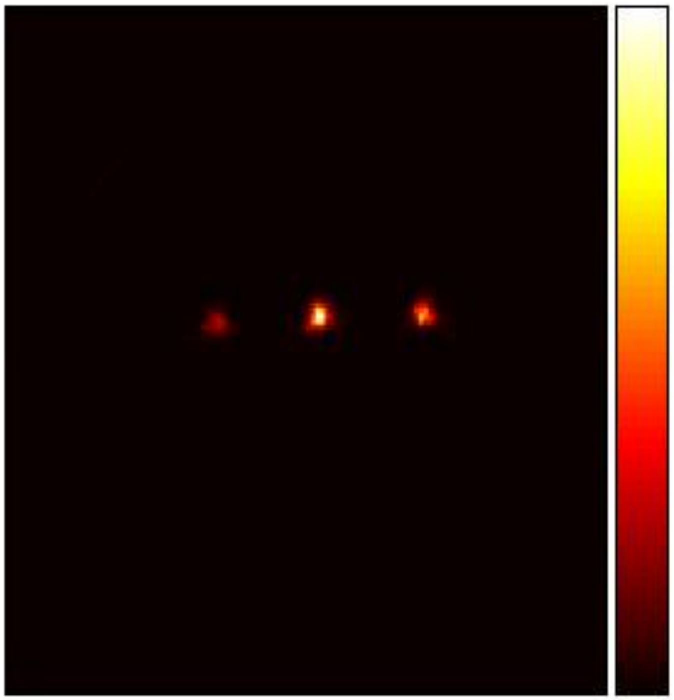
$$Asymmetry = \frac{Area_{left} - Area_{right}}{Area_{left} + Area_{right}}$$

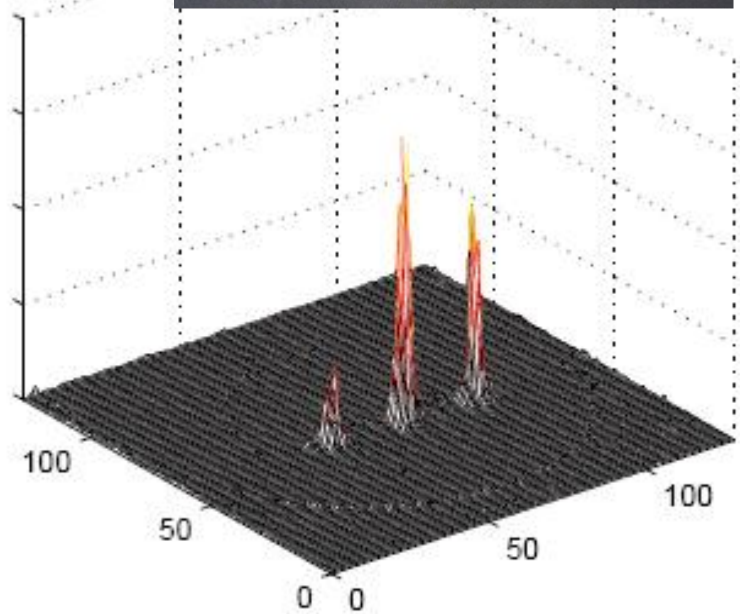


Point Source Imaging

Three ^{22}Na point source have been imaged with the SmartPET system







From MLEM reconstruction the point sources display FHWM of ~1.4mm

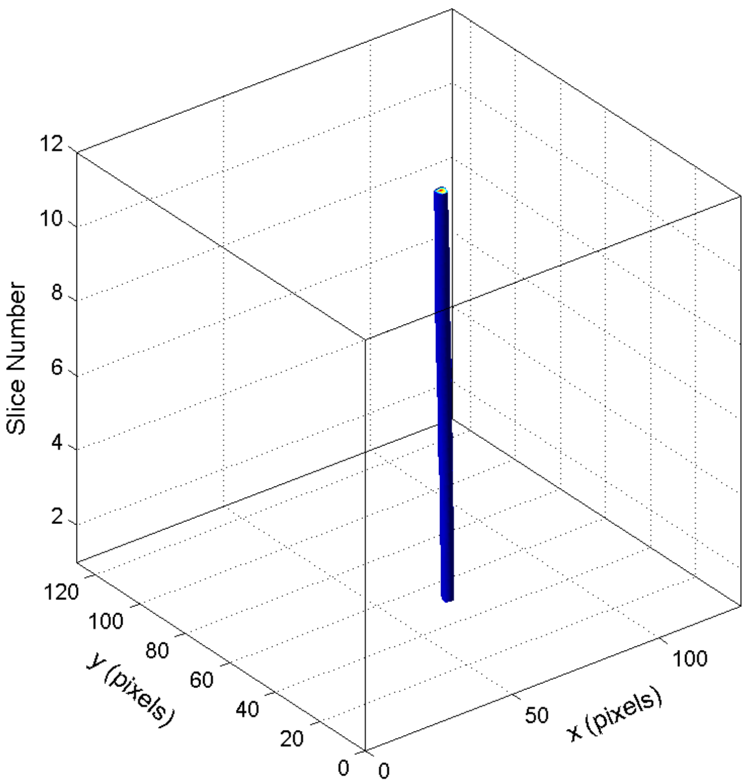
Over 60% of events processed

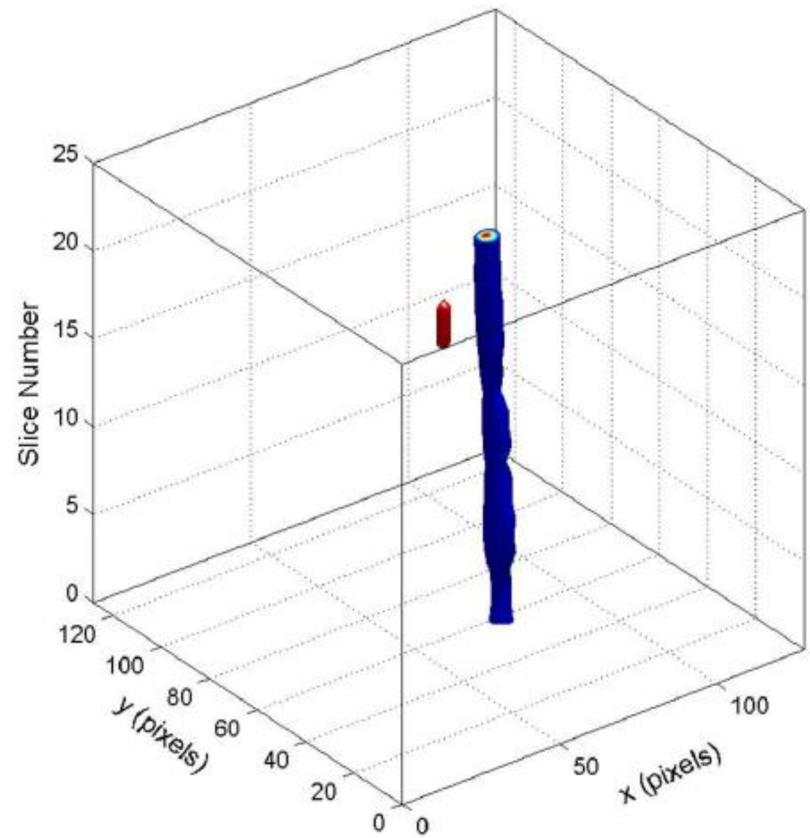
Point Source Imaging

Imaging of a ^{22}Na line source

- 50mm long x ~2.5mm internal diameter

Single pixel hits with MLEM reconstruction

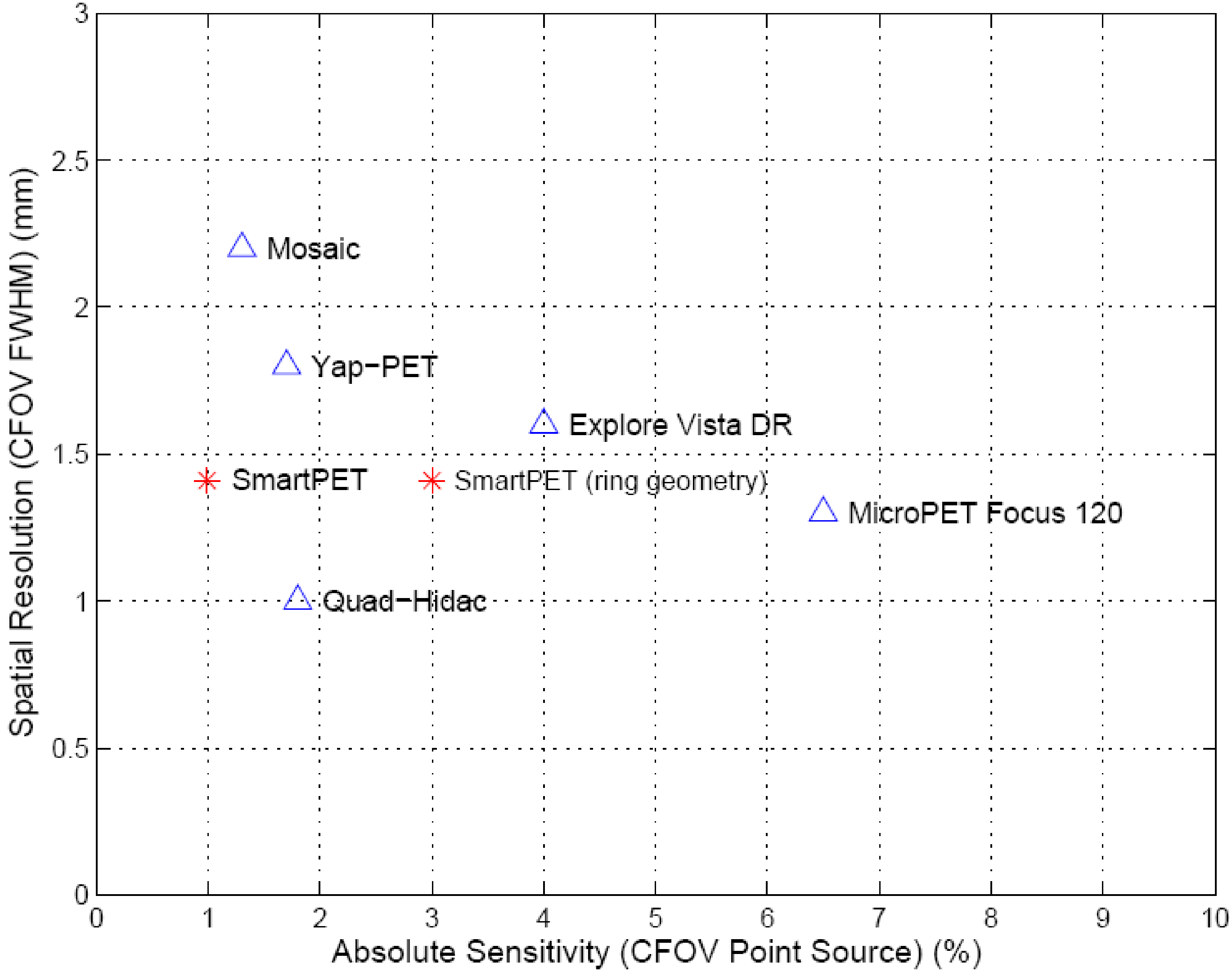




FWHM $_{line}$ ~ 2.90(0.17)mm

FWHM $_{point}$ ~ 1.60(0.17)mm

System Performance



Larobina et al.
Current medical imaging reviews 2006, 2, 187-192

Computed Tomography

SPECT Case study (ProSPECTuS)

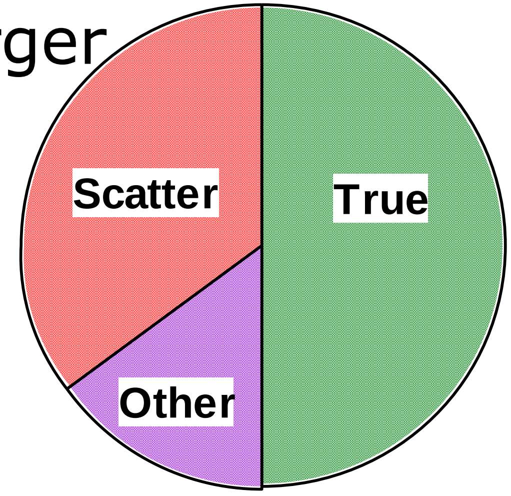
SPECT : Problems/Opportunities

Technical

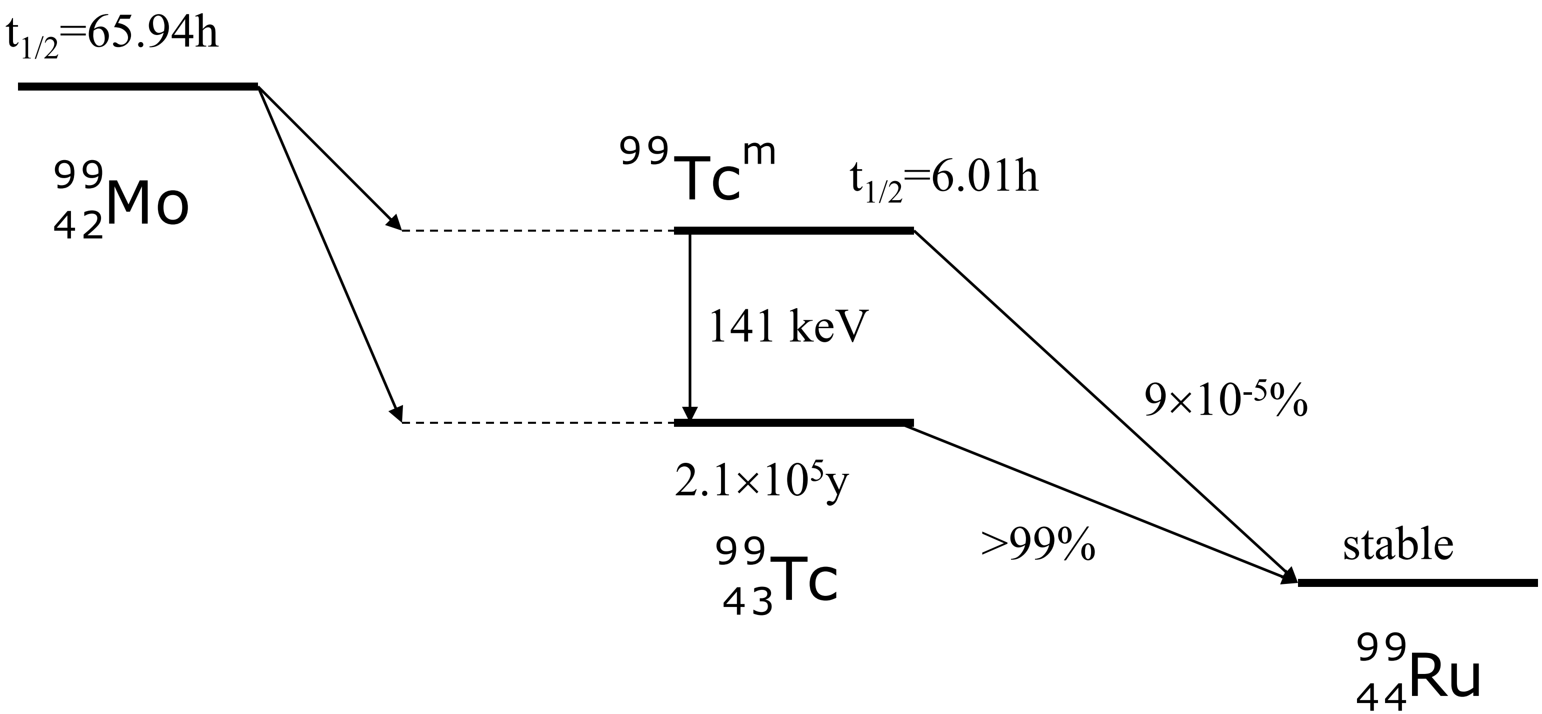
- Collimator Limits Spatial Resolution & Efficiency
- Collimator is heavy and bulky
- Energy of radioisotope limited to low energy

- NaI:Tl Dominant for >40 Years...
- MRI → Existing PMTs will not easily operate

- Would like to be able to image a larger fraction of events.



Technetium-99m

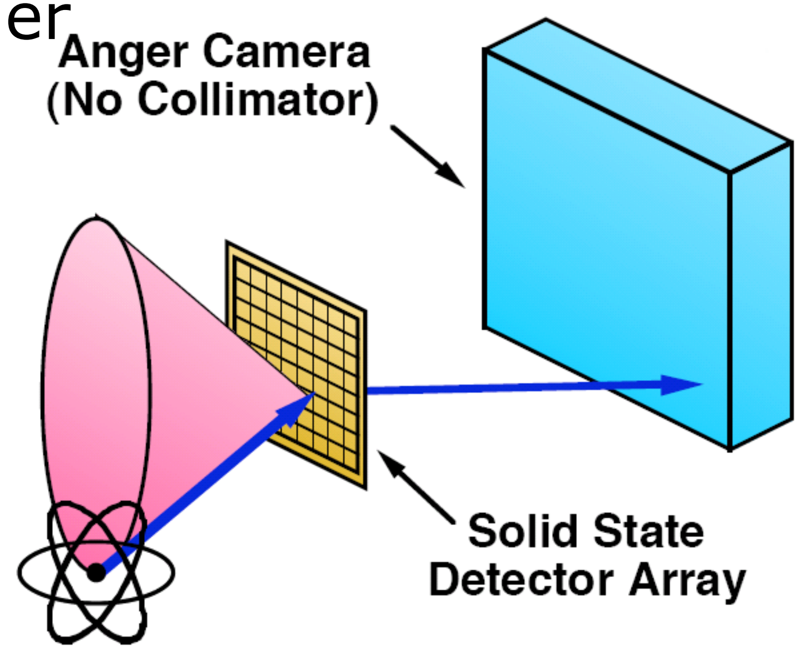


- Supplied in a generator consisting of ^{99}Mo absorbed onto alumina (66 hour $t_{1/2}$).
- Container allows liquid introduced at top to be collected at bottom. Needs replacing weekly.
- Conventionally imaged with gamma camera.

Eur J Nucl Med Mol Imaging (2009) 36:1371–1374

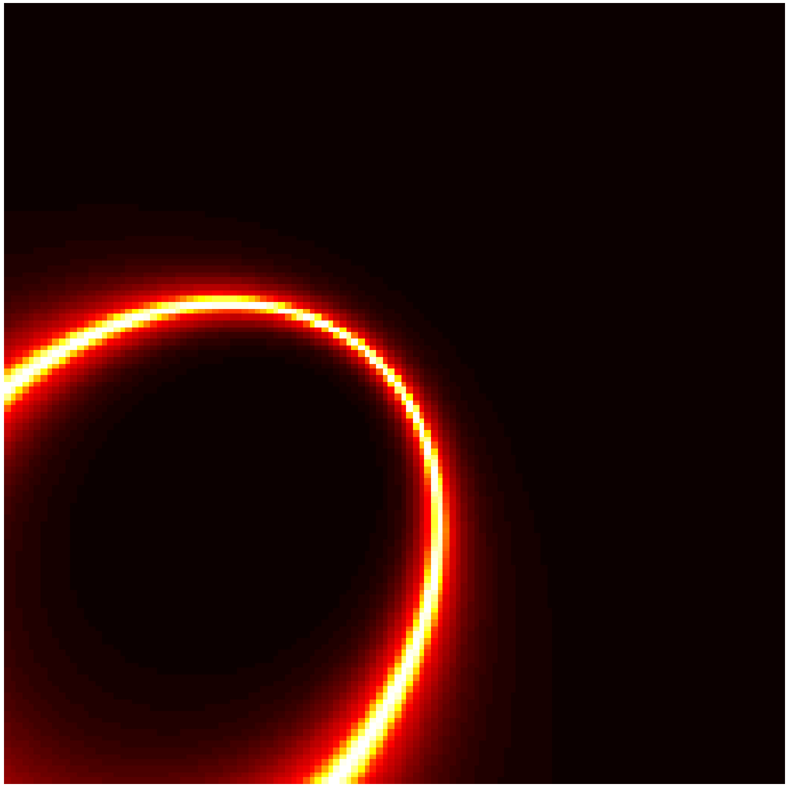
ProSPECTus is a Compton Imager

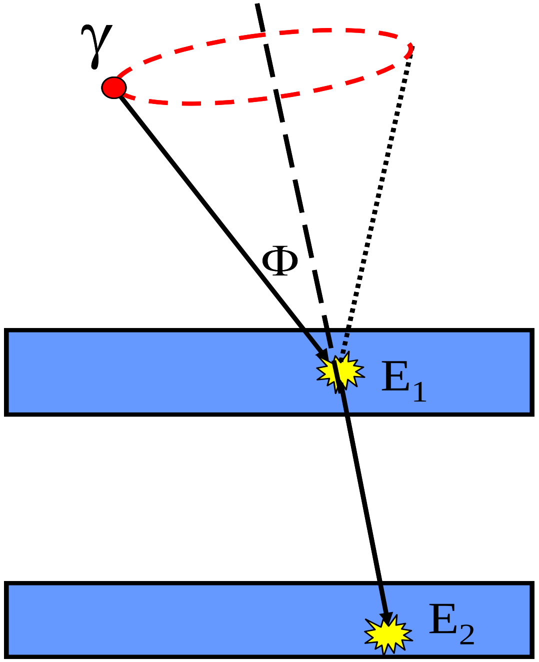
- Radical change → No mechanical collimator
- Utilising Si(Li) + CZT/Ge semiconductor sensors
- Pixellated technology and existing ASIC
- Position resolution 7-10mm → 2-3mm
- Sensitivity factor ~100 larger
- Simultaneous SPECT/MRI



Compton Imaging

- Compton *Cones of Response* projected into image space





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

Compton Imaging

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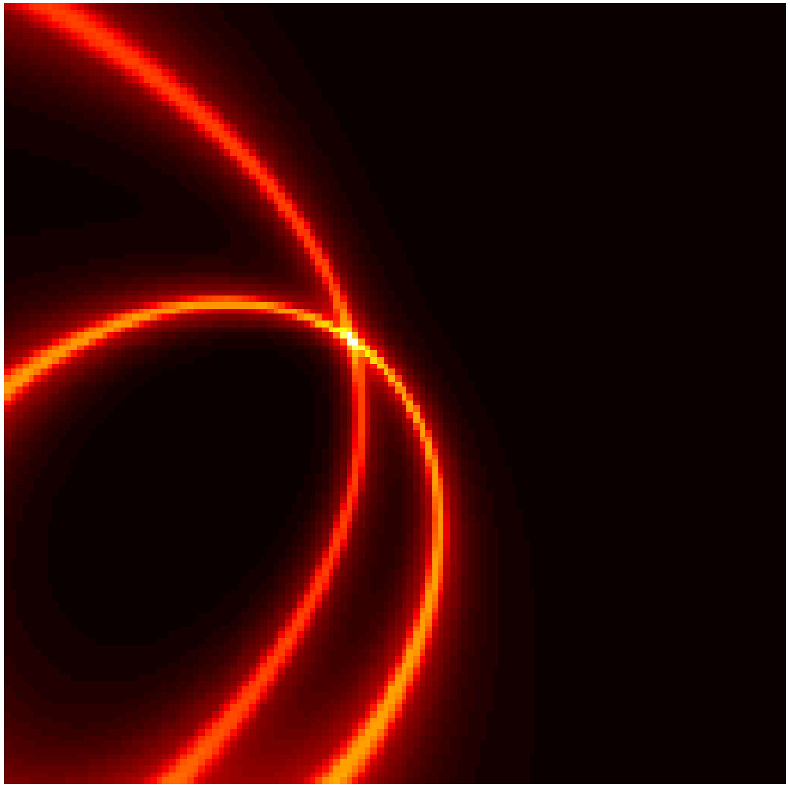

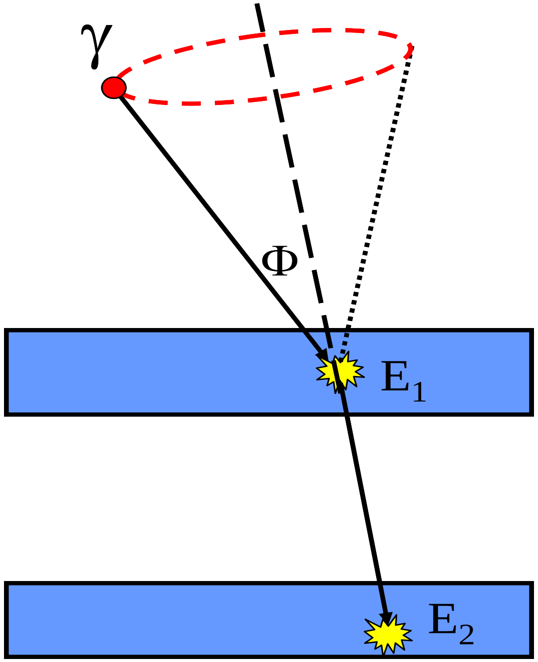

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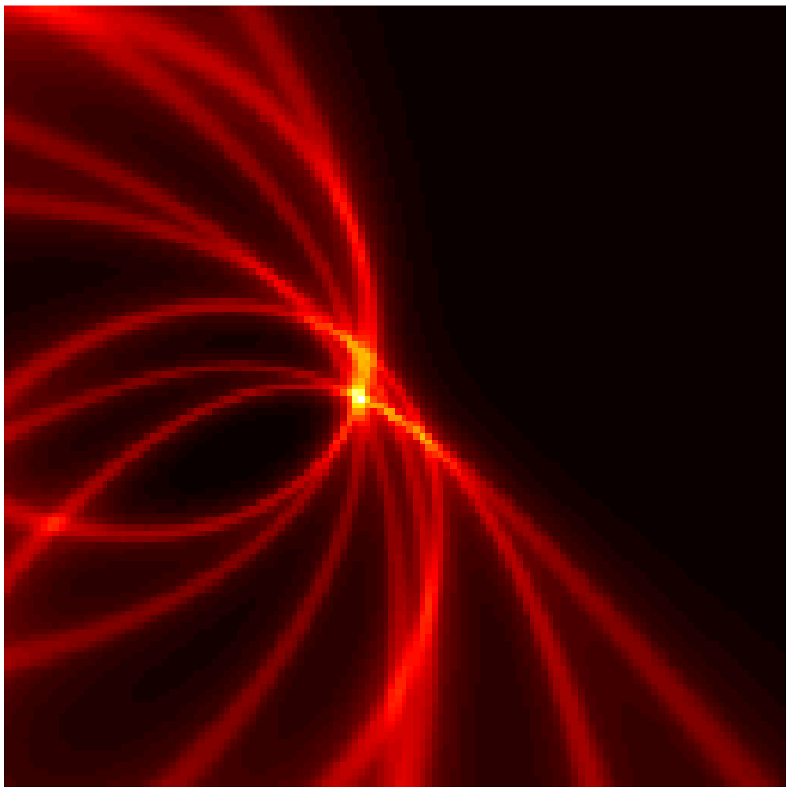

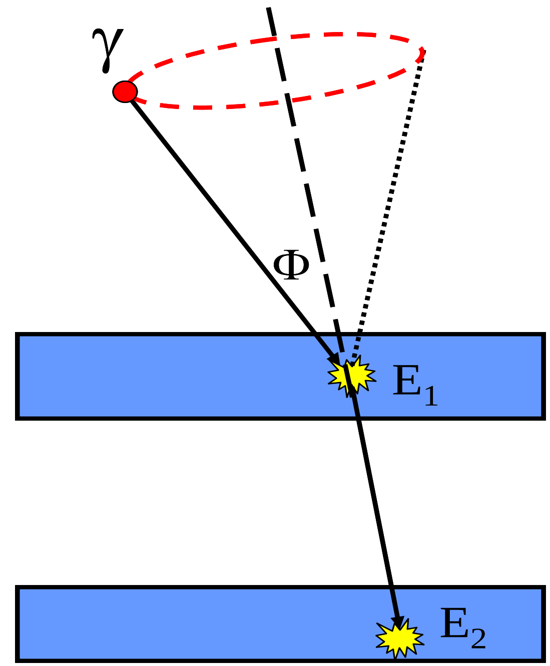

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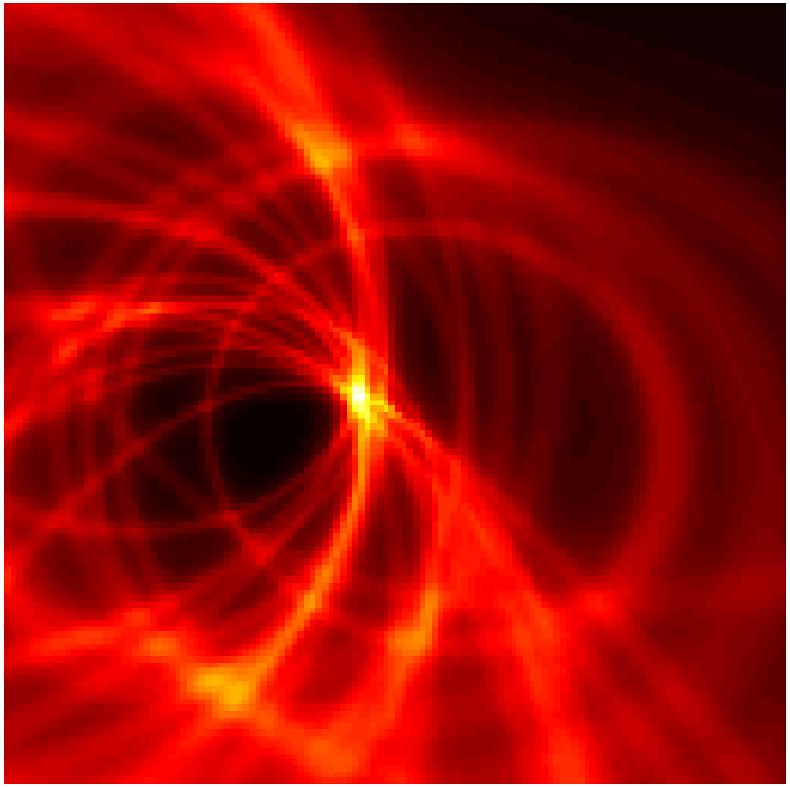

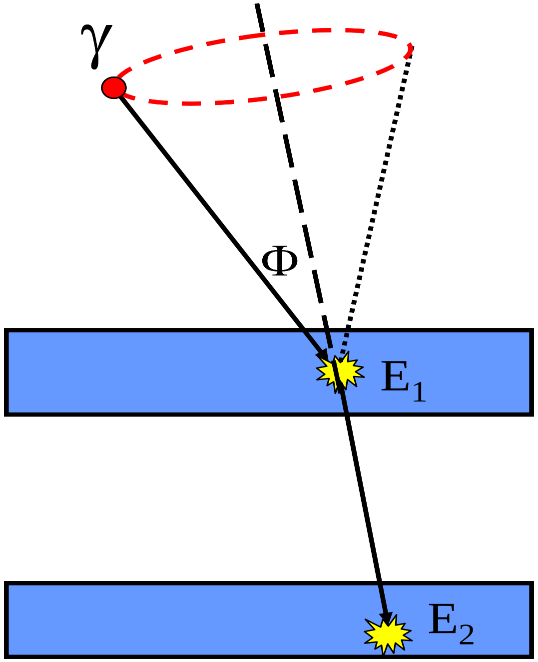

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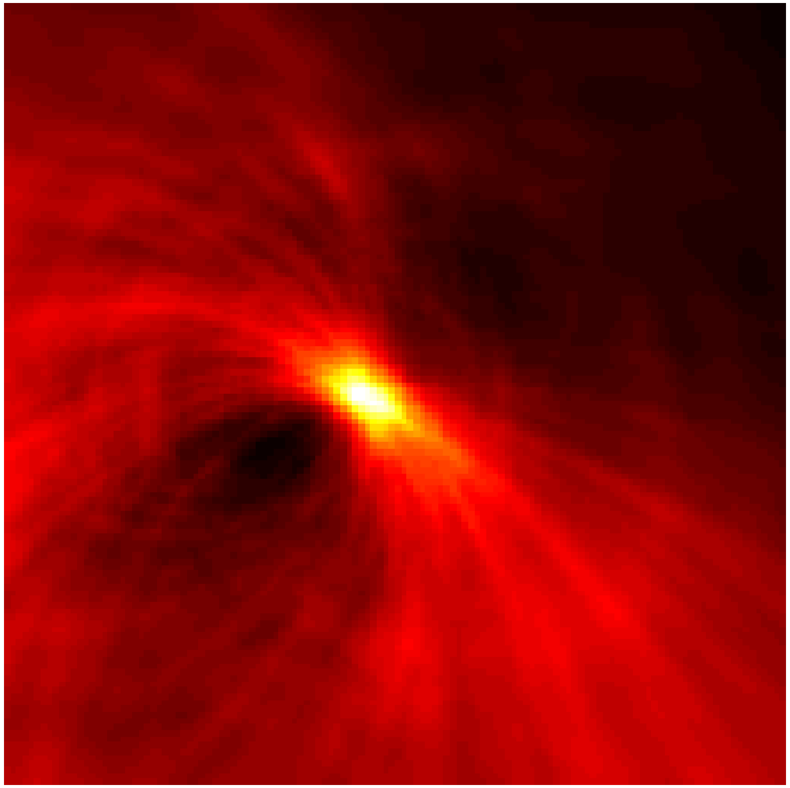

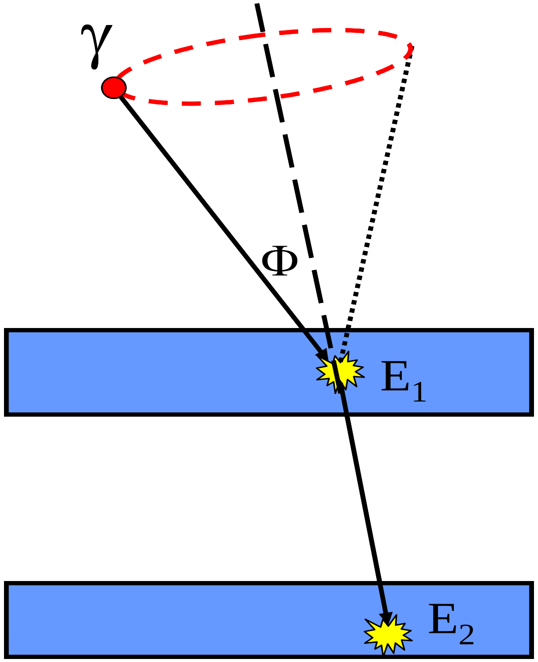

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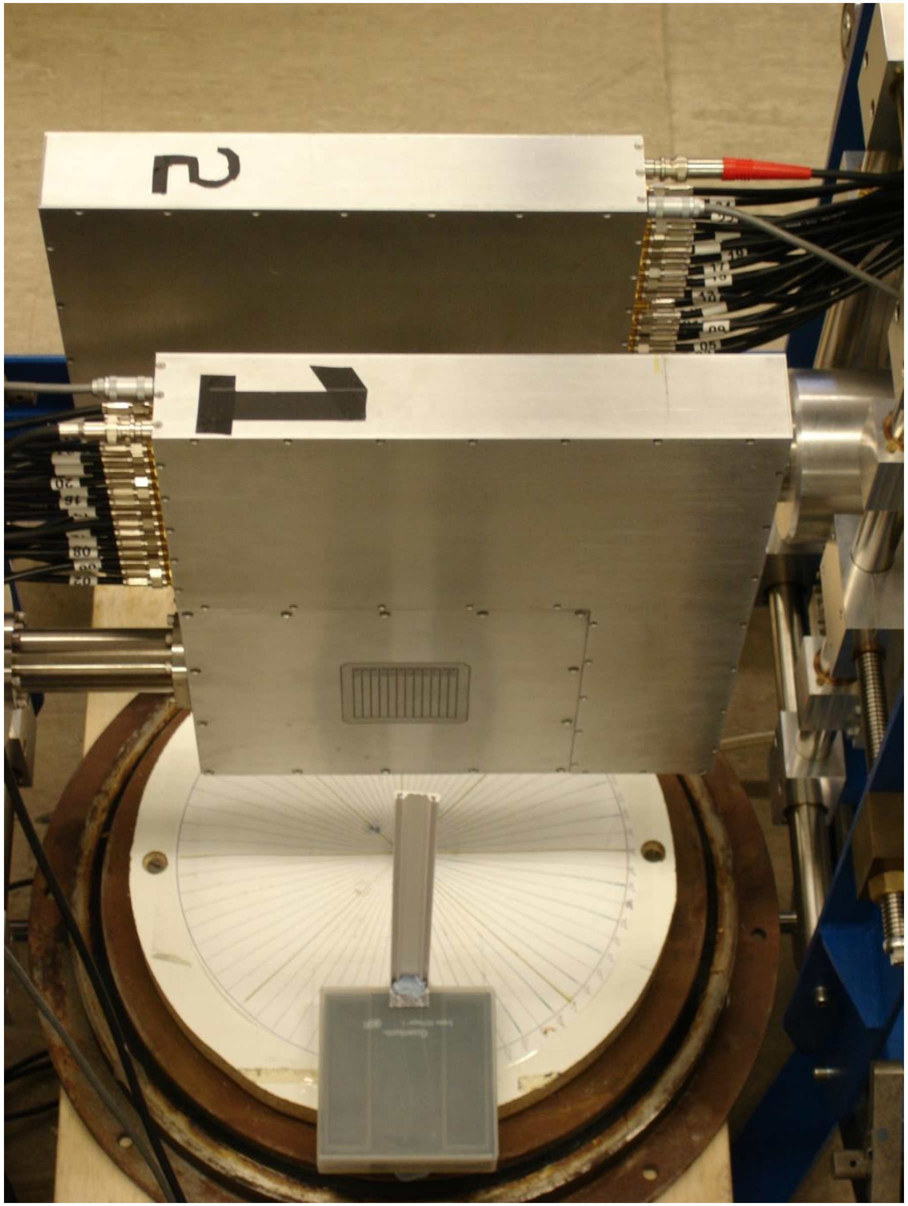
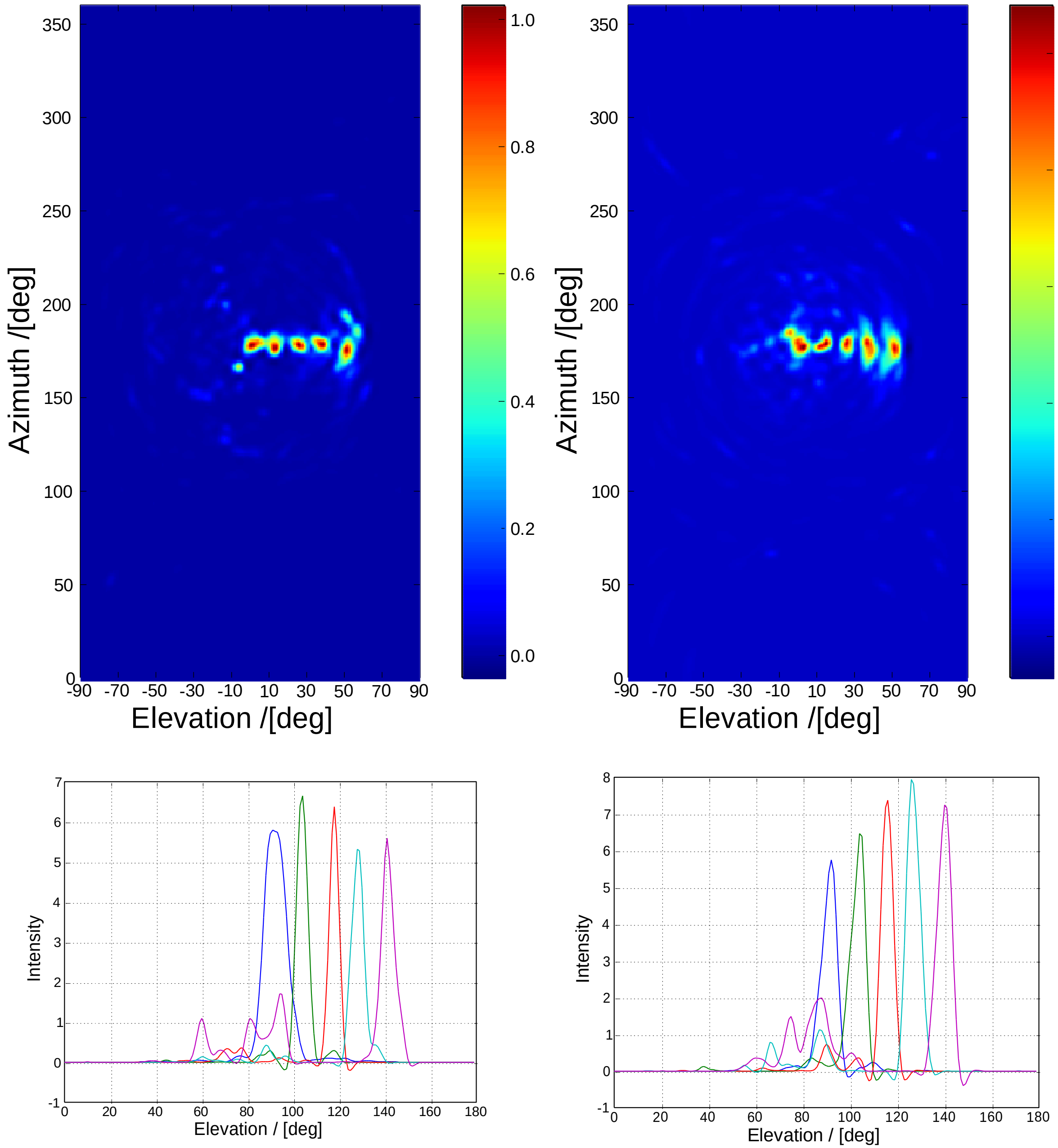
Compton Imaging

- 10μCi ^{152}Eu
- 60mm from SPET1
- Source rotated
- Zero degrees in 15º steps up to 60º
- Detector separation
- 3 – 11cm in 2cm steps
- Gates set on energies
- 779, 1408keV
- 2 ^{22}Na sources at different x and y



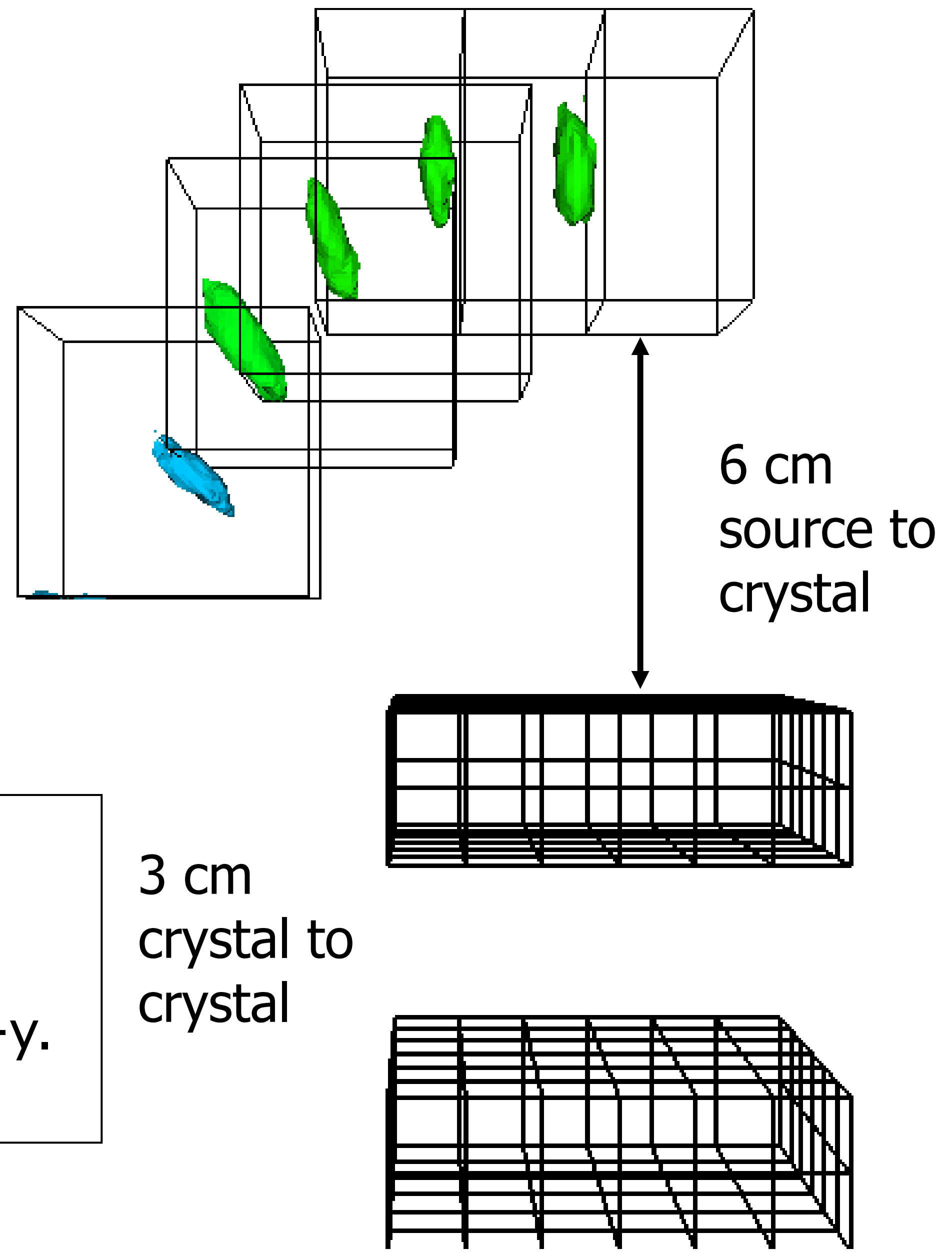
Compton Imaging with HPGe

- 30mm & 50mm separation between scatterer & analyser.
- 1.6cm separation between points
- FWHM ~ 8mm



Imaging Progress : Compton Camera

- ^{152}Eu point source imaging.
- 30 keV gate on 1408 keV.
- 30mm detector separation with 1.6mm position resolution.
- Single interactions in each detector.



Cone beam reconstruction with 10 iterations.

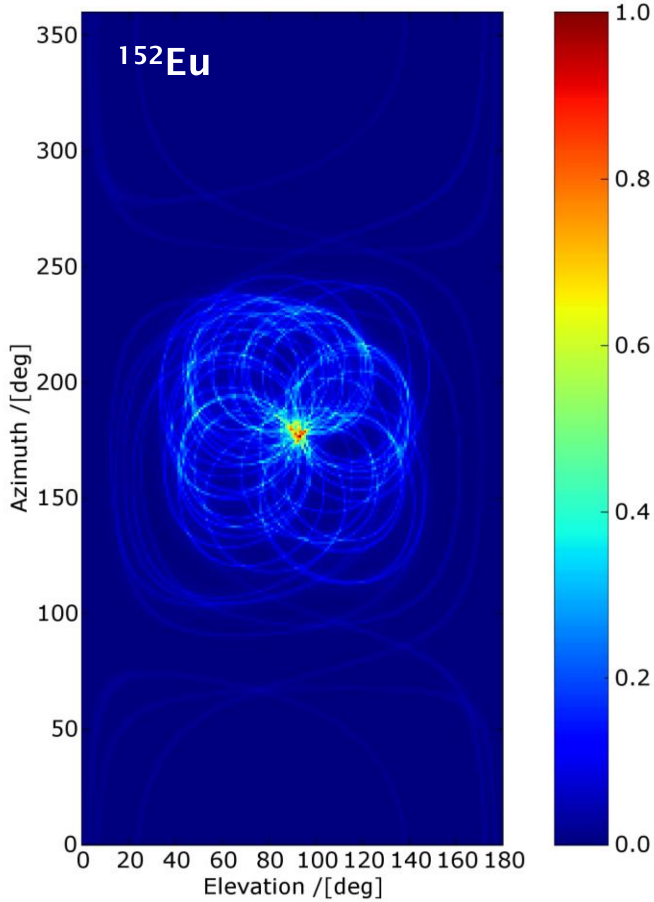
~8mm image resolution x-y.

John Gillam

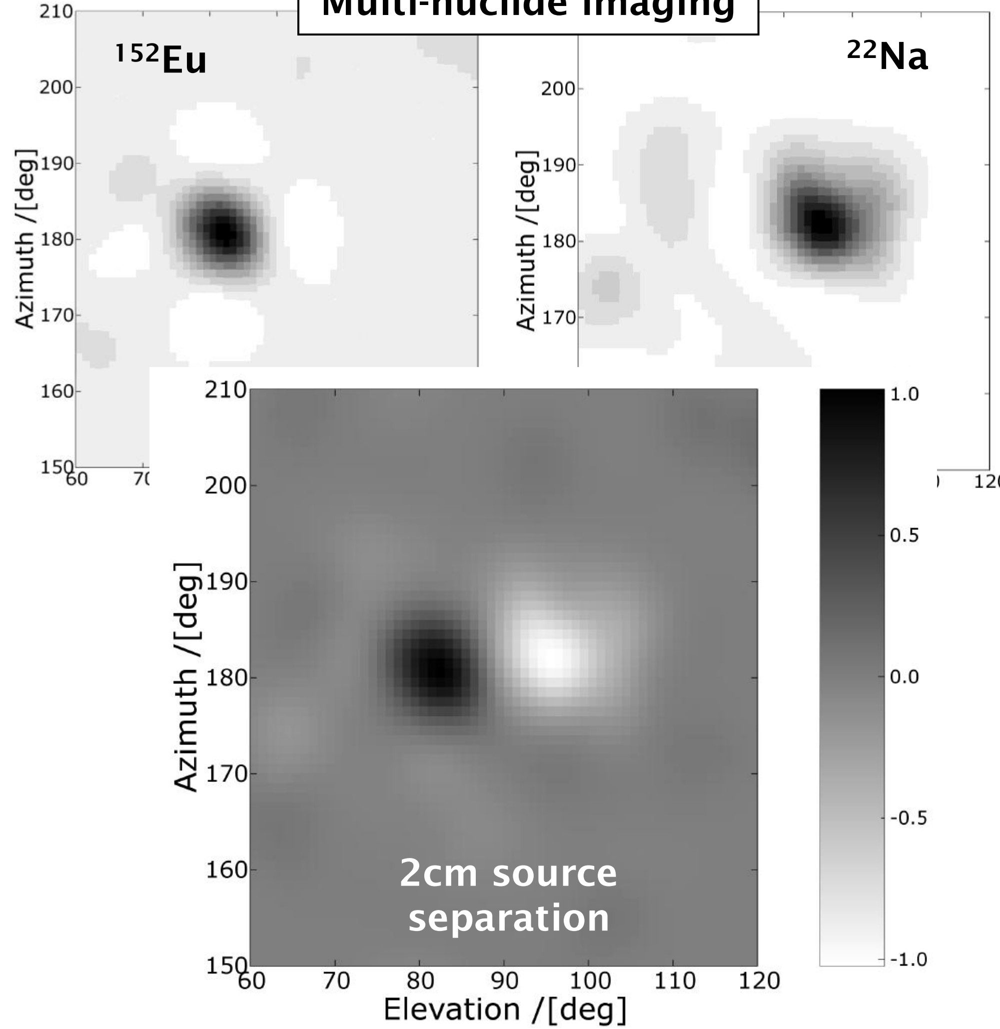
Compton Imaging with SmartPET

Compton Imaging – 2D Imaging

~7° Angular Resolution



Multi-nuclide imaging



Lecture 2: Medical Applications of Nuclear Physics

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- Tomographic Imaging CT/PET/SPECT

http://www.bnmsonline.co.uk

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