Imaging and locating radioactive isotopes for security

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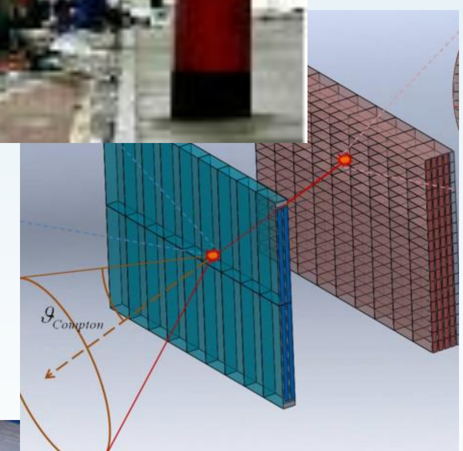
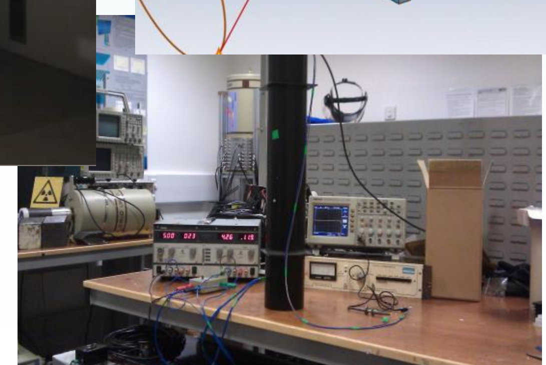
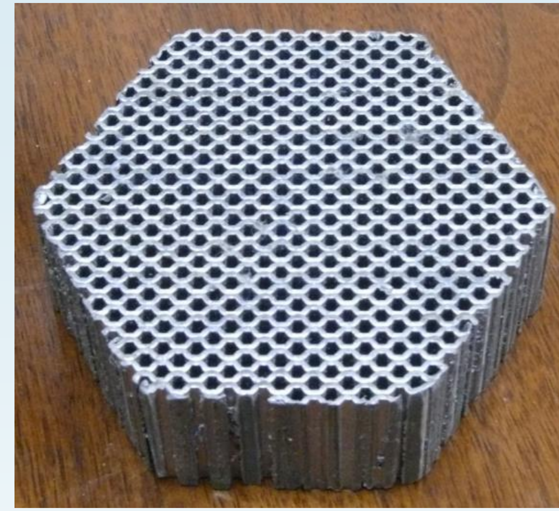
Outline

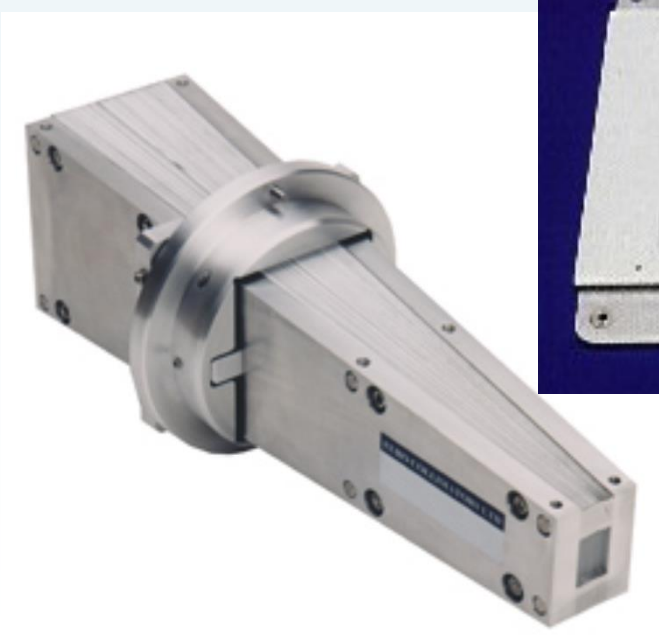
- Mapping radioisotope distributions using physical collimation
  - *RadScan 600*
  - *Coded aperture collimation*
- Mapping radioisotope distributions using electronic collimation
  - *Compton cameras*
  - *Neutron scatter cameras*
- Locating radioisotopes
  - RadICAL & RadICAL Stack

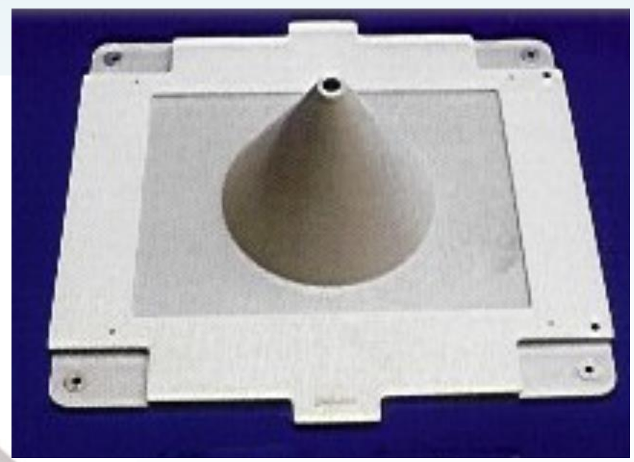


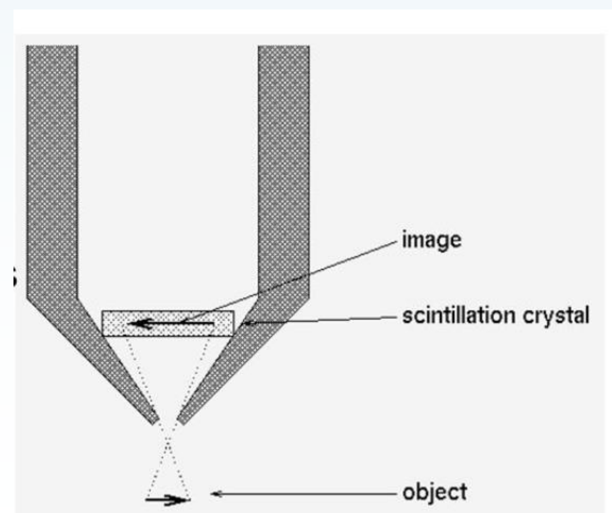


Mapping using Simple Physical collimators





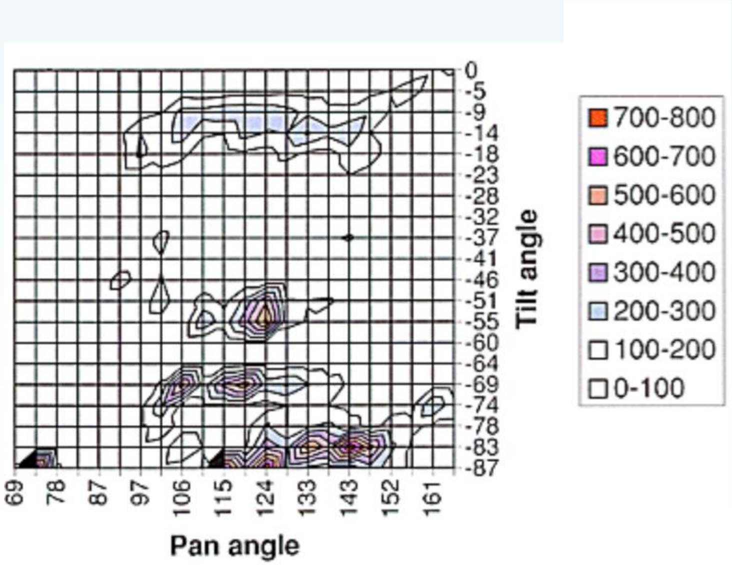




Simple Physical Collimators

RadScan 600 – *single 'parallel' hole collimator*

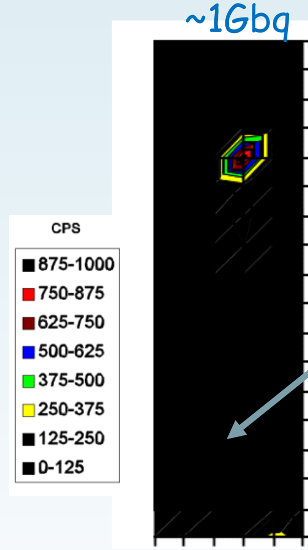
- Inspection Head:
  - Cs:Tl scintillator and silicon photo diode detector (20 x 25-mm)
  - Truncated cone shield/collimator combination made of tungsten (with 2,4, and 9 degree opening angles)
- Mounted on a pan & tilt mechanism so that it can scan a required area
- Advantages
  - Simple point & shoot operation
- Disdavantages
  - Heavy (125kg)
  - Slow, static sources only (~10s per point in typical operational conditions)



RadScan 600 results – fuel store

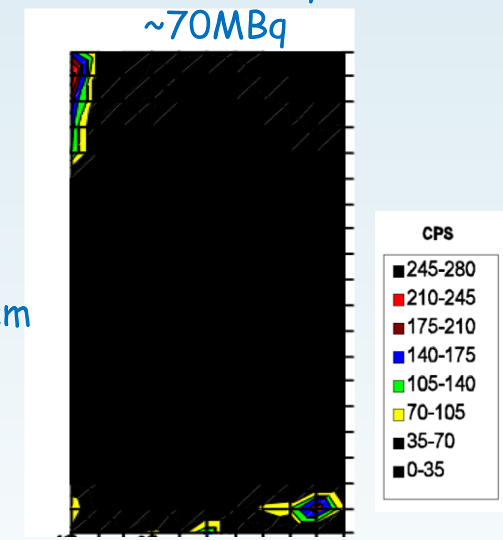
The Hanford Site C is a decommissioned nuclear production complex on the Columbia River in the U.S. state of Washington.

Max activity ~1Gbq



25x25cm pixels

Max activity ~70MBq



Area ~5 x 1m
Distance ~ 3m
Aquisition ~ 10s per point
Total time ~15mins

Area ~6 x 3m
Distance ~ 1.5m
Aquisition ~ 10s per point
Total time ~36mins

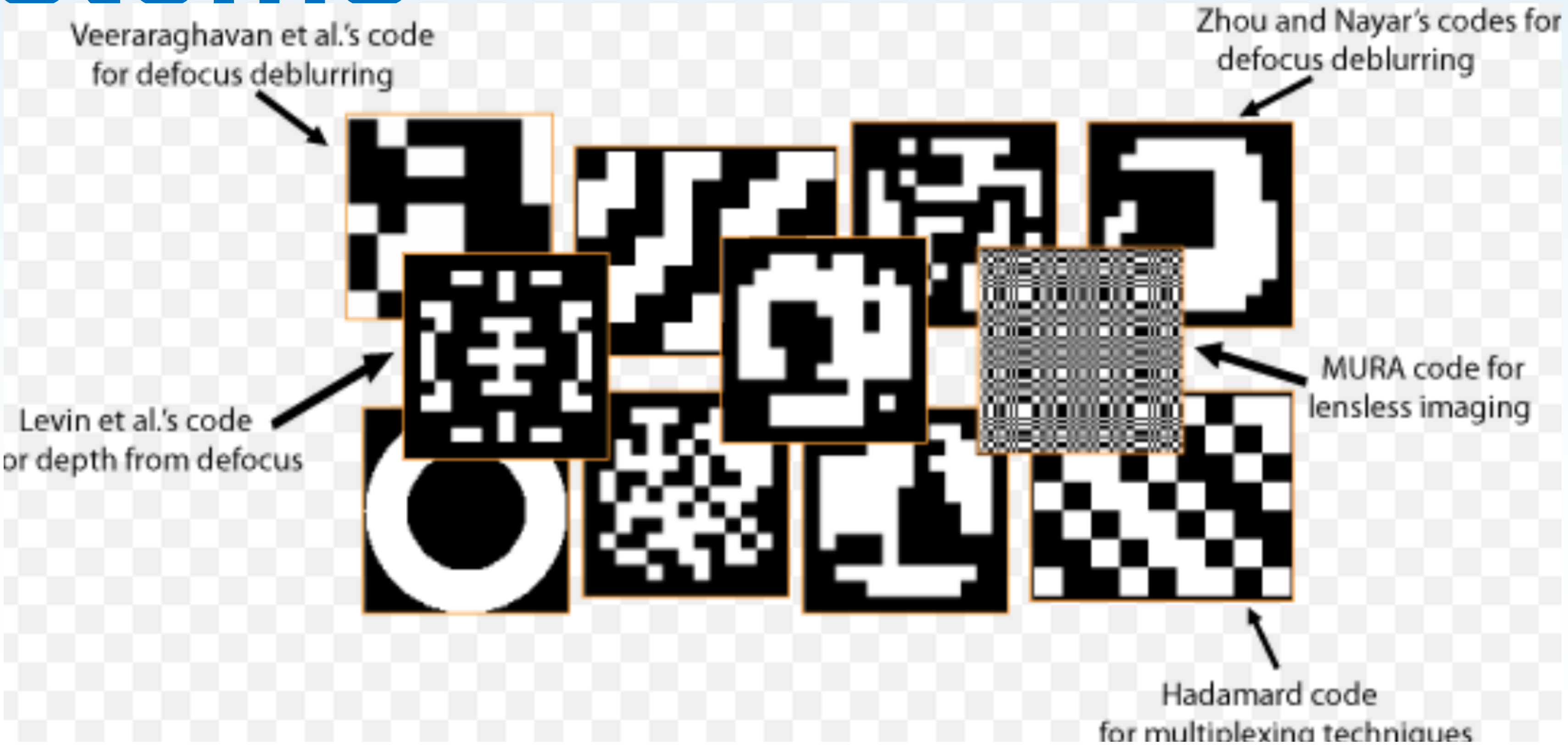
RadScan application

1. Two areas in the fuel store were scanned for contamination
2. Calibration of the system to Cs-137 gives 600cps is 300MBq at 2m

Innovative Technology Report, DOE/EM-0390, 1998

Slow as the scene needs to be raster scanned to build up an image

Mapping using Coded aperture systems



Coded Aperture Collimators

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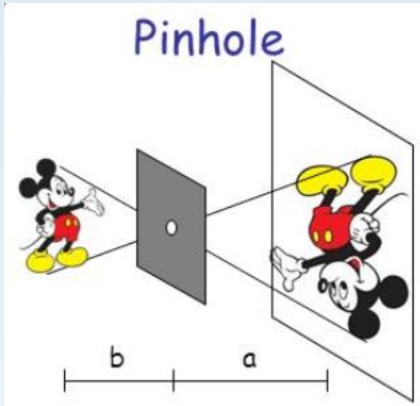
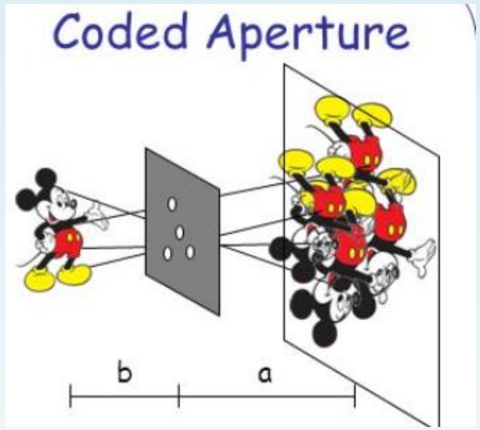
BASICS

- Single hole casts one shadow but is inefficient
- Multiple holes more efficient but complex shadow is cast





Coded aperture:
Uniformly Redundant arrays (URA) generally used in standard or modified form.

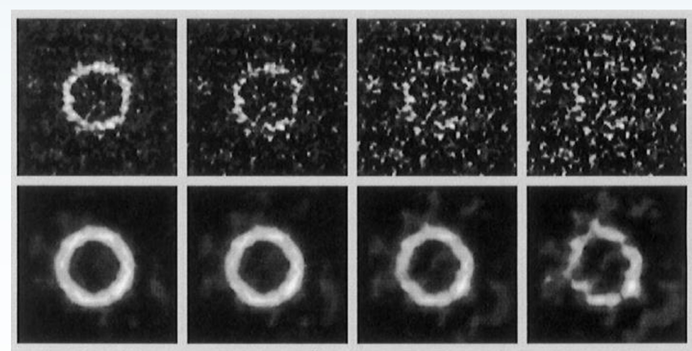
PERFORMANCE COMPARISON

Camera:
- CsI:Tl (1-3mm thick) x 40mm dia
- Image intensifier +CCD

Sensitivity:
- 100MBq at 10m gives SNR>5 in 900s

Single hole

Coded aperture



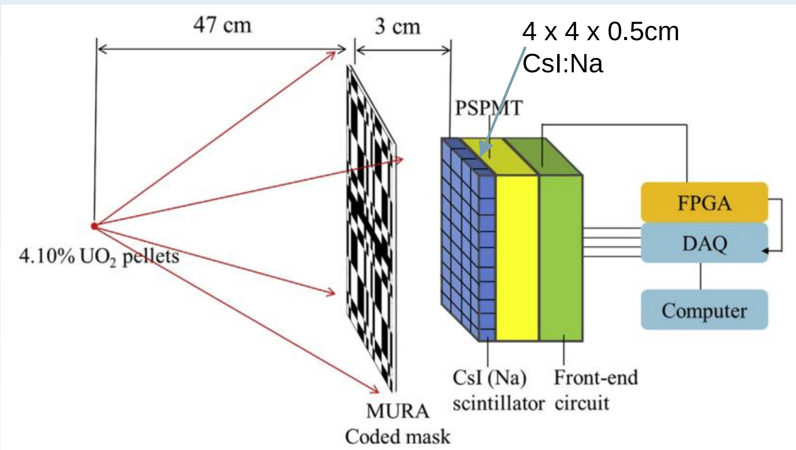
Relative time 8, 4, 2 and 1 going from left to right

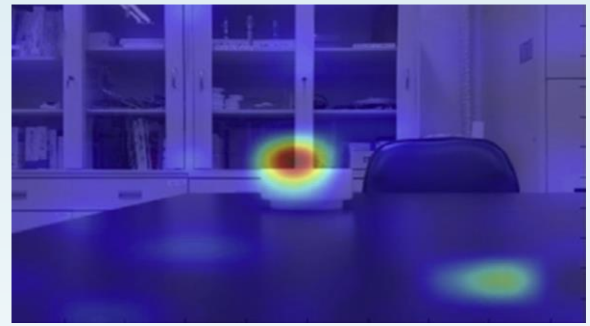
Ivanov O, et al.,NIMA,<u>422</u>,729-734,1999

Coded Aperture Collimators

EXAMPLE

Estimation of time required to find critical mass of ^{235}U





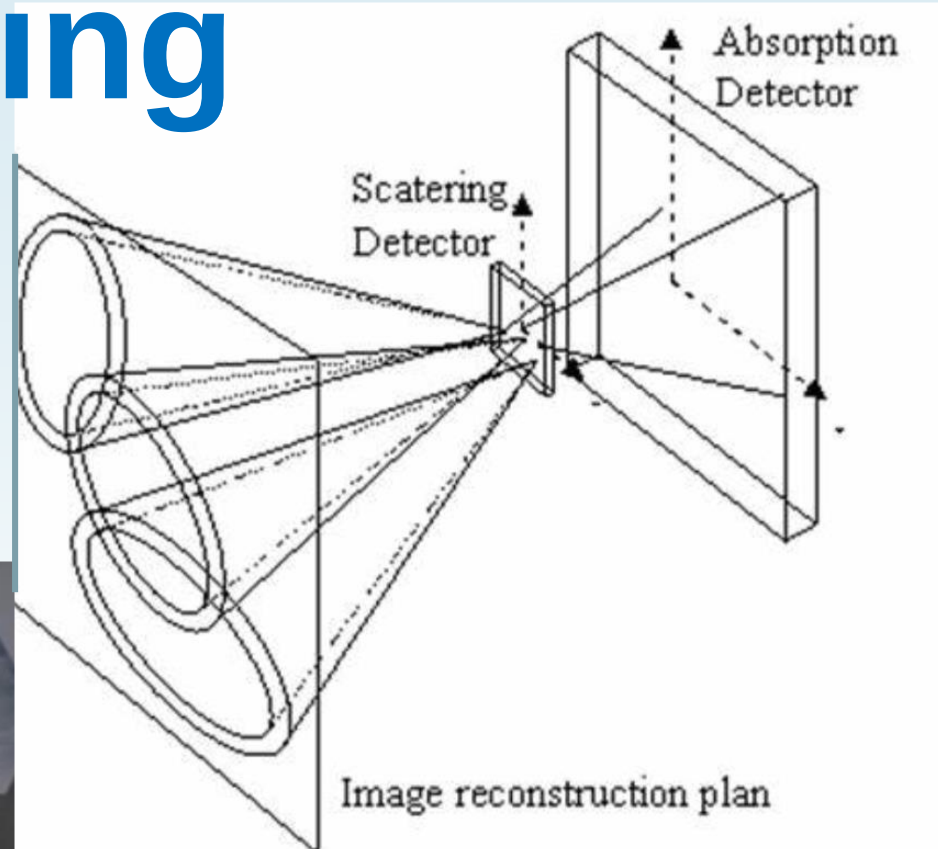
Imaging characteristic X-rays from UO_2 using 'anti-mask' subtraction algorithm

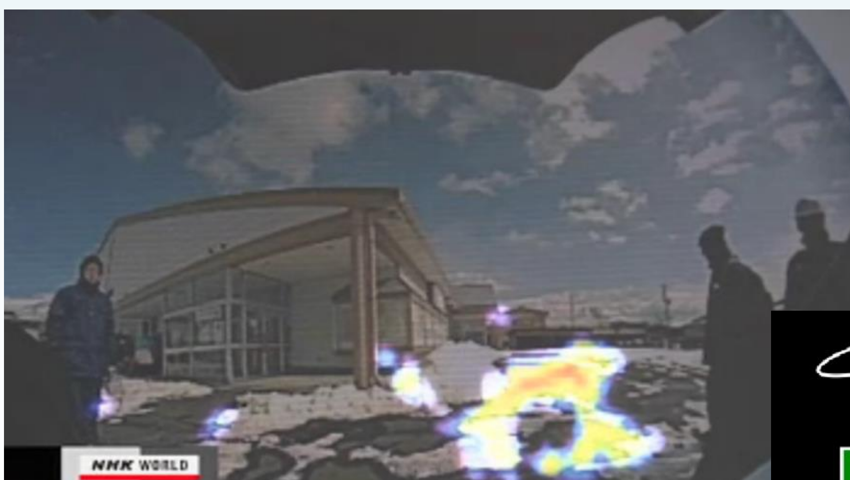
Estimation of the required detection time and count rate for the critical mass of ^{235}U at a 10-m distance from the camera.

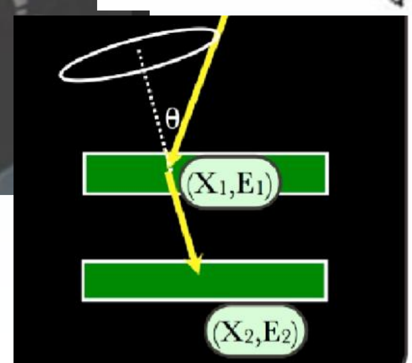
Critical mass without neutron reflector (=50 kg)		Critical mass with neutron reflector (=15 kg)	
Required time (s)	Count rates (cps)	Required time (s)	Count rates (cps)
199.4 s	30.9 cps	448.9 s	13.8 cps

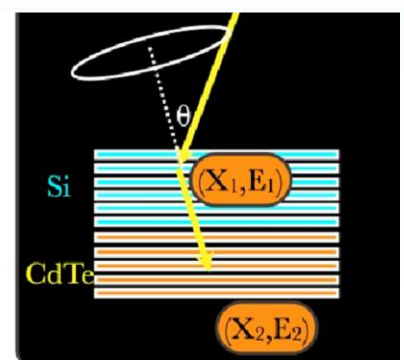
Taewoong L, et al, Nuclear Engineering and Technology 50, (2018), 923-928

Mapping using Electronic collimators









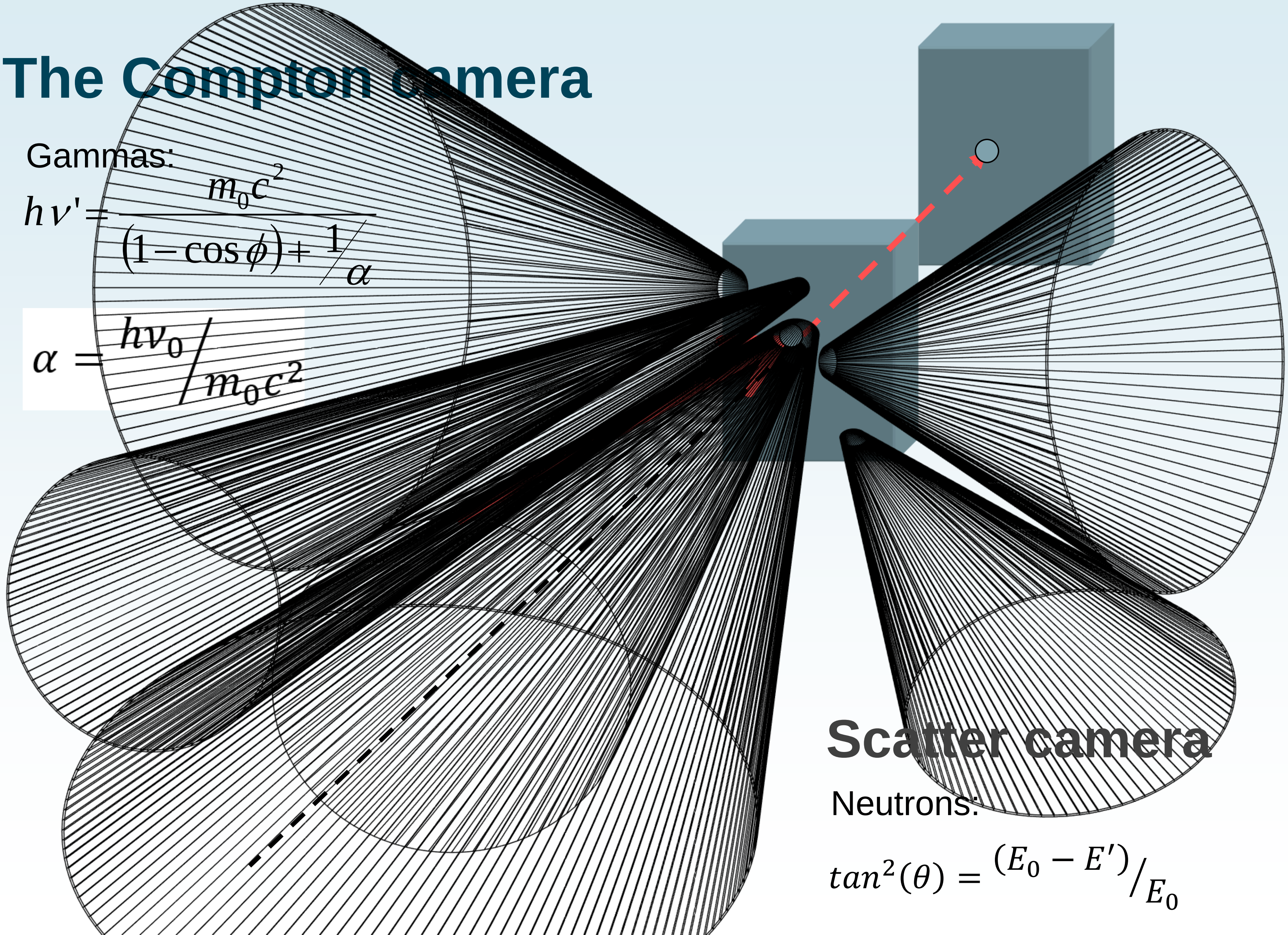
Gamma imaging using Compton cameras

The Compton camera

Gammas:

$$h\nu' = \frac{m_0 c^2}{(1-\cos\phi) + \frac{1}{\alpha}}$$

$$\alpha = {h\nu_0}/{m_0 c^2}$$



Scatter camera

Neutrons:

$$tan^2(\theta) = {(E_0 - E')}/{E_0}$$

Gamma imaging using Compton cameras

EXAMPLE 1 – decommissioning

The problem:

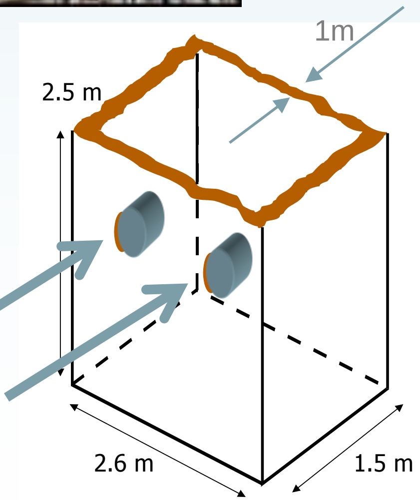
decommissioning 3 small cells used to create radiotherapy sources at Sellafield.
Estimated activity of several GBq.

The solution:

a small format, flexible geometry Compton camera that could collect data through 1m thick walls

Cell 3 – 1m thick concrete walls

Access points for detector arrays. Detectors were placed at different points and at different orientations to simulate a large camera



Gamma imaging using Compton cameras

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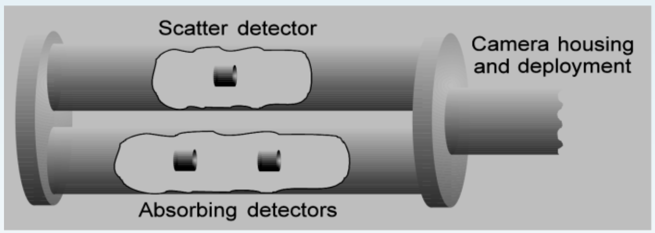
Camera design:
- environment required simple design
- 3 NaI:Tl sensors per unit
- 2 units used at any one time
- housed in 60mm dia. thin walled steel tubing

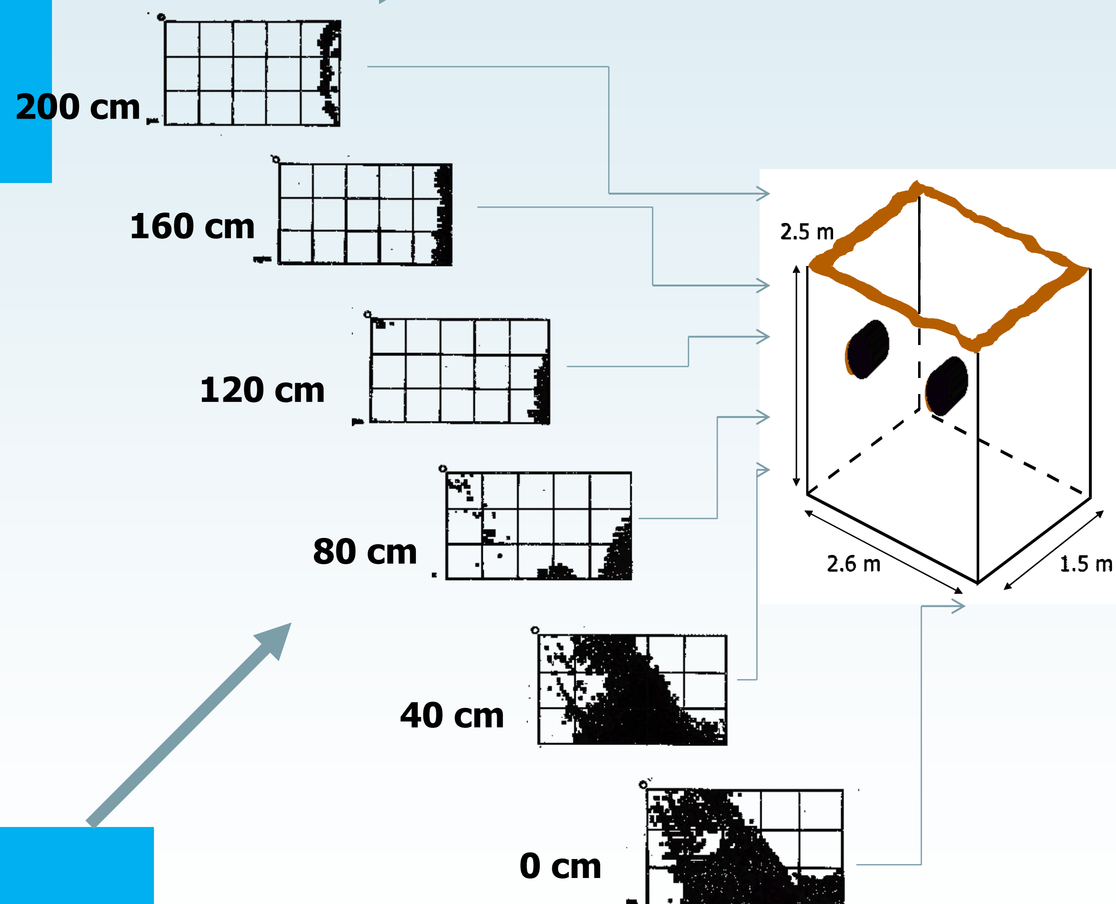


Two sensor arrays each containing 3 detectors. Each element was $5mm^3$ NaI:Tl

Process:
- Gamma flux $\sim 5x10^3\ s^{-1}cm^{-2}$
- Six orientations and six depths
- Total acquisition time 360s

Results:
Volume reconstruction displayed as gamma intensity recorded at different planes above the floor

Note unexpected activity high on the walls



1997 IEEE NUCLEAR SCIENCE SYMPOSIUM - CONFERENCE RECORD, VOLS 1 & 2 Pages: 365-368 Published: 1998

Gamma imaging using Compton cameras

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EXAMPLE 2 – support for first responders to a 'dirty bomb' attack

The problem:

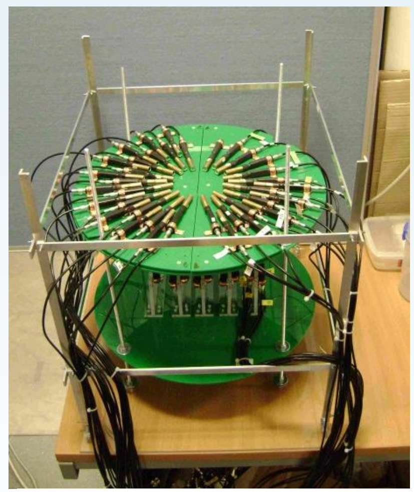
March 25, 2009 (The Times)

Rising threat of dirty bomb attack on UK, says Jacqui Smith

A terrorist attack on Britain with chemical, nuclear or biological weapons is now "more realistic" because of the increasing theft of materials used to make a dirty bomb, the Government warned yesterday.

The solution:

- Wide Area Radiation Detector - WARD
- Two arrays of $5mm^3$ CZT sensors
- Adjustable geometry
- Custom DAQ system



98 CZT pixel camera

Individual sensor

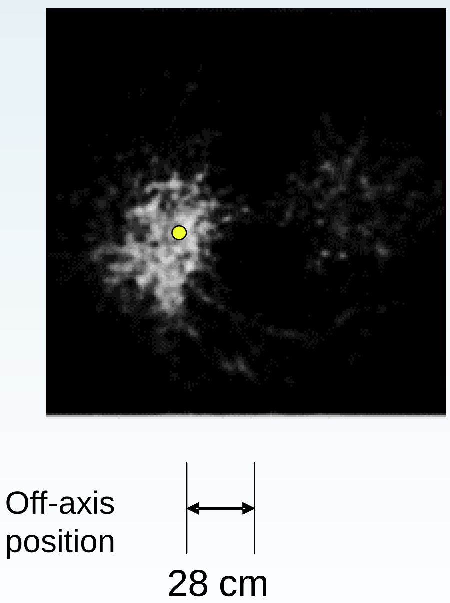
CZT crystal

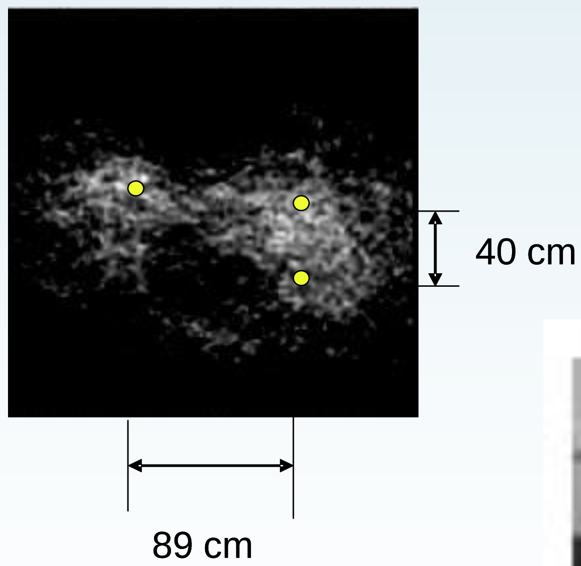
A joint project between UCL, St Barts, e2v and CAST (now DSTL)

Gamma imaging using Compton cameras

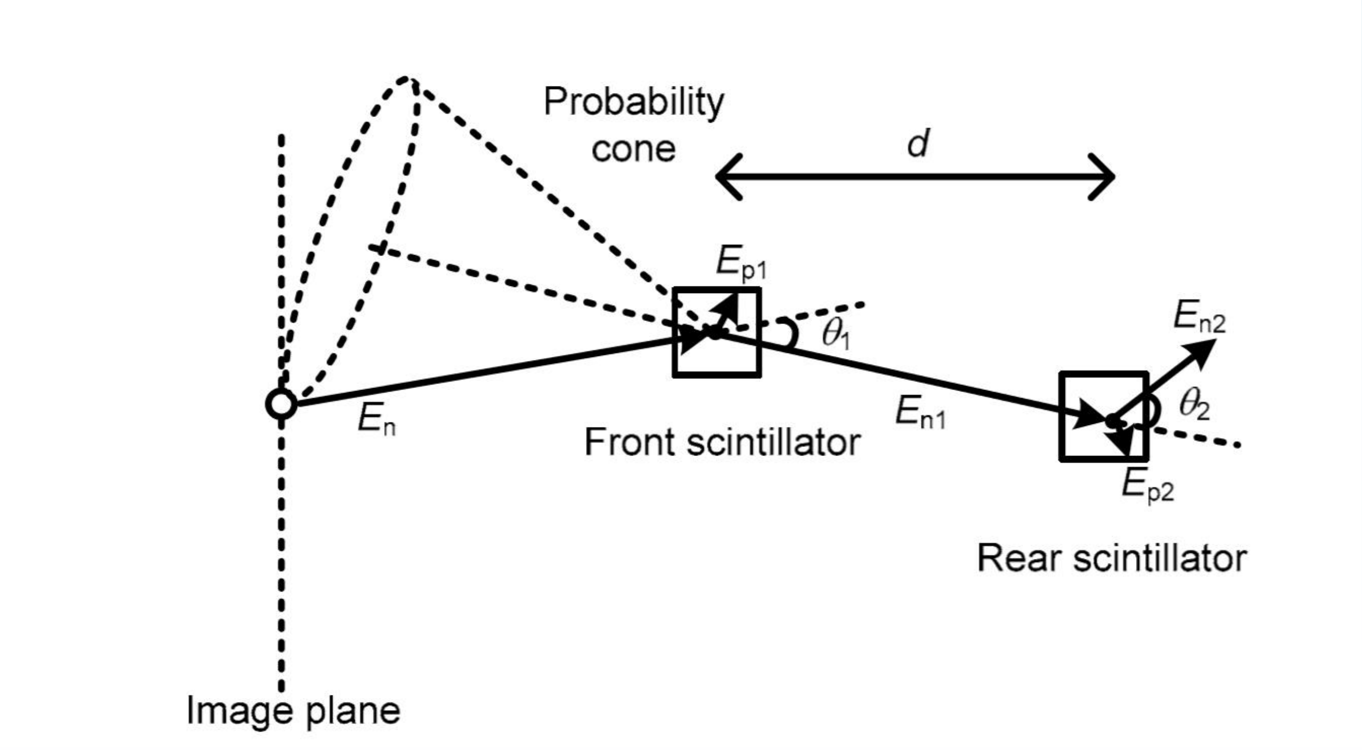
PERFORMANCE

- Experiments carried out at CAST
- All sources (^{137}Cs) imaged at distances > 2m
- Gamma flux of ~1-3 $s^{-1}cm^{-2}$ at the camera face
- Acquisition time of 1000s

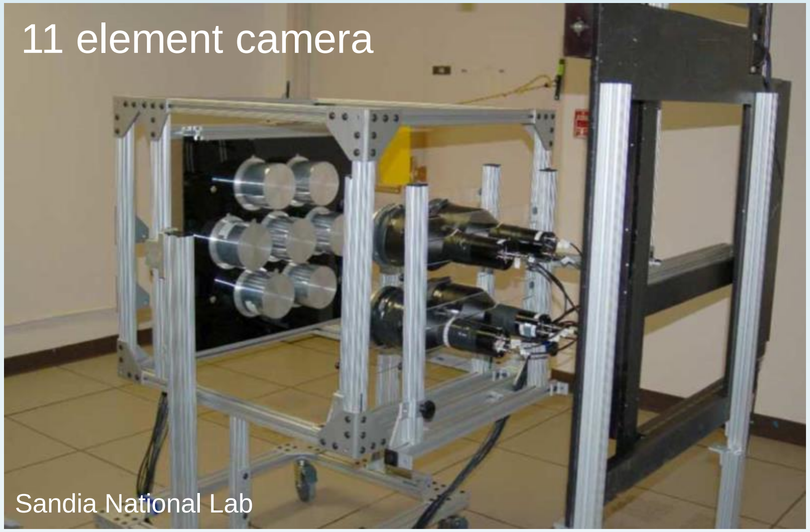




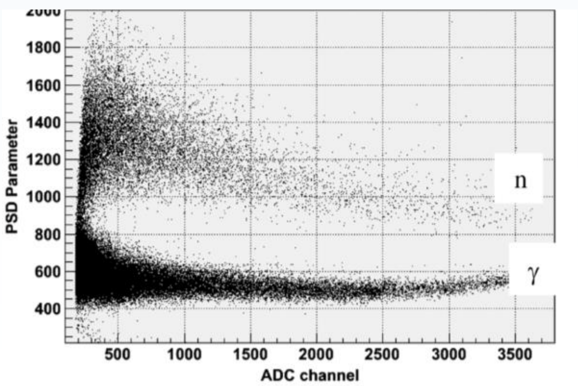
Mapping using Electronic collimators – neutron scatter cameras



Neutron imaging using scatter cameras



Camera design:
- Front plane - four 5"x2"
- Back plane – seven 5x4"
- scintillator - EJ301 with PSD performance



PERFORMANCE:

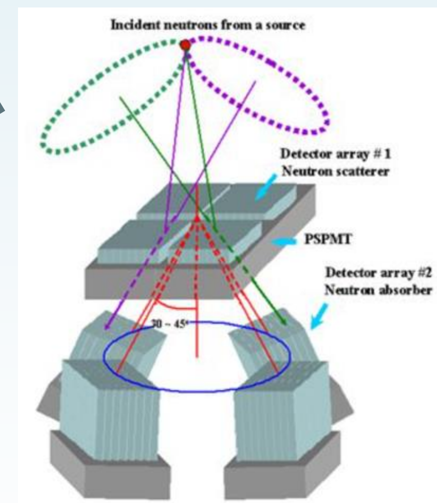
IAEA significant quantity equivalent of ^{252}Cf at ~5m inside tanker detected in 300s
Unshielded at 30m took 2hrs.

Mascarenhas N., et al., IEEE trans Nuc. Sci., 56, 2009

Isotope mapping with RadICAL

Physical collimators are heavy and some lead to complex reconstruction

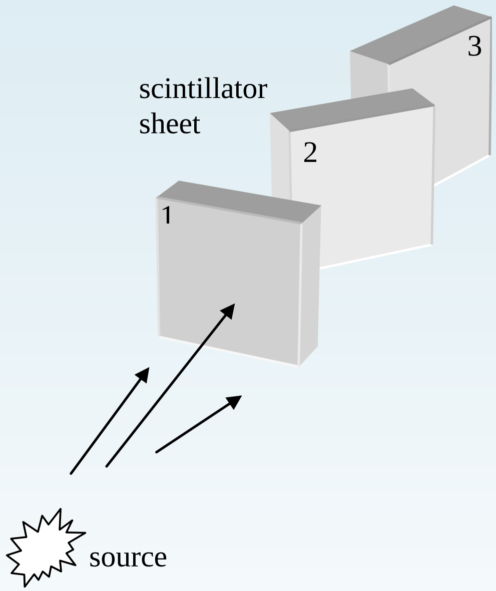
Electronic collimators are complex to operate and to reconstruct the image



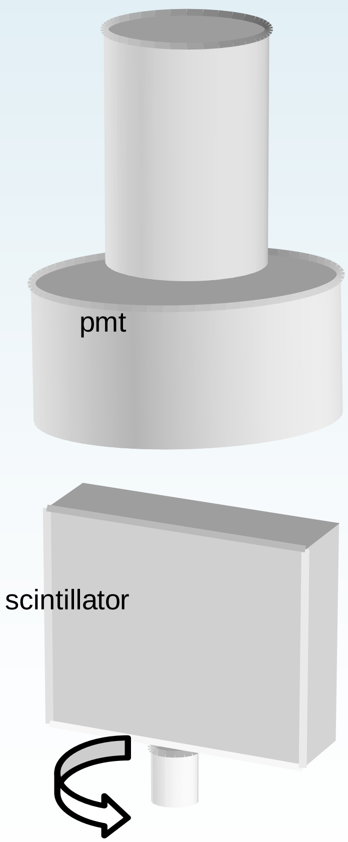
A simpler approach….

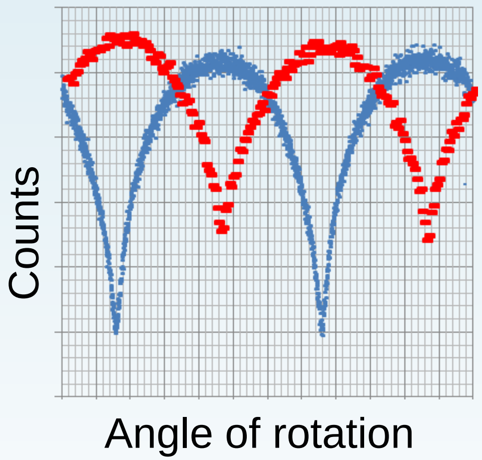
Isotope mapping with RadICAL

Basic concept



Rotating a scintillator records a variation in output and hence locates the source





Energy deposited in a scintillator and hence output depends upon the area and depth presented to a source

Response from two different isotopes positioned in different directions from the detector

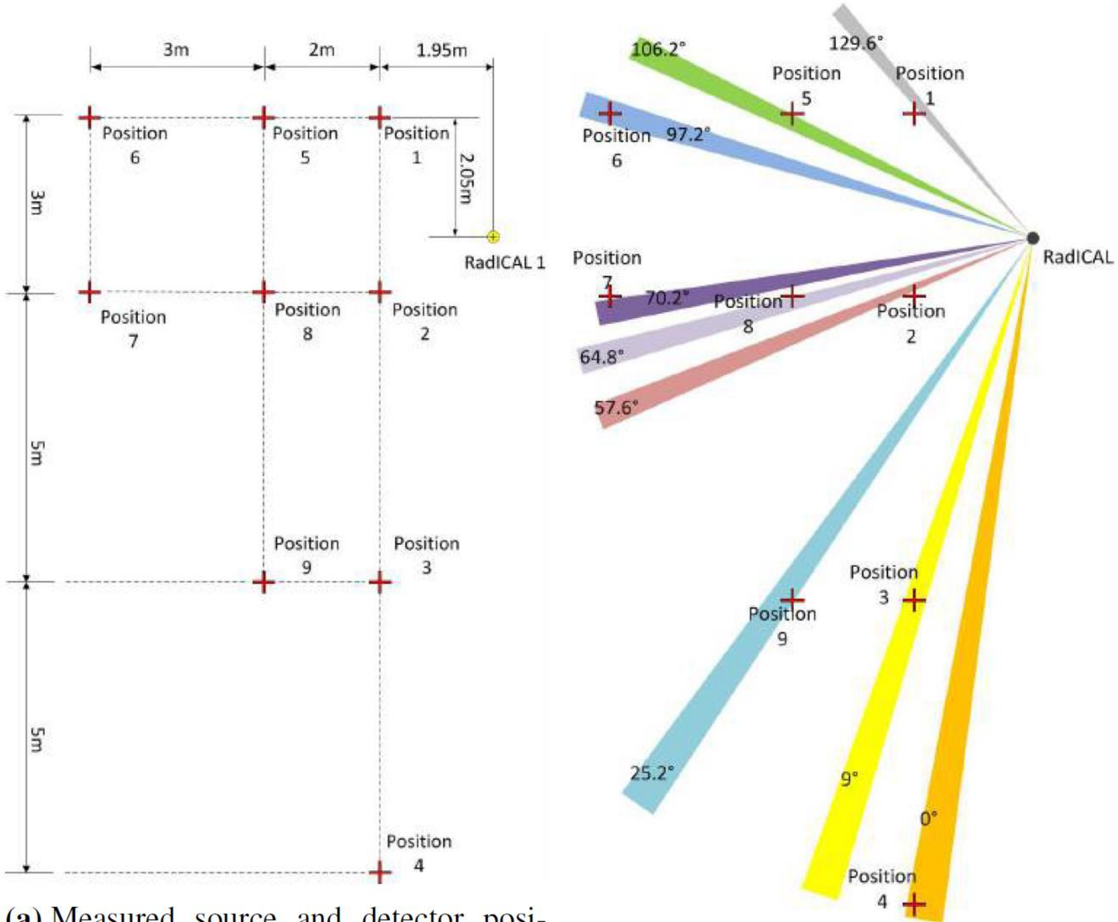
Randall G et al 2014 JINST Art:P10011

Isotope mapping with RadICAL

PERFORMANCE

Static radiation fields
500 MBq Cs-137 at different positions over a 7 x 13 m area. Total acquisition time 200s

Mean error in location direction was 1.6^0



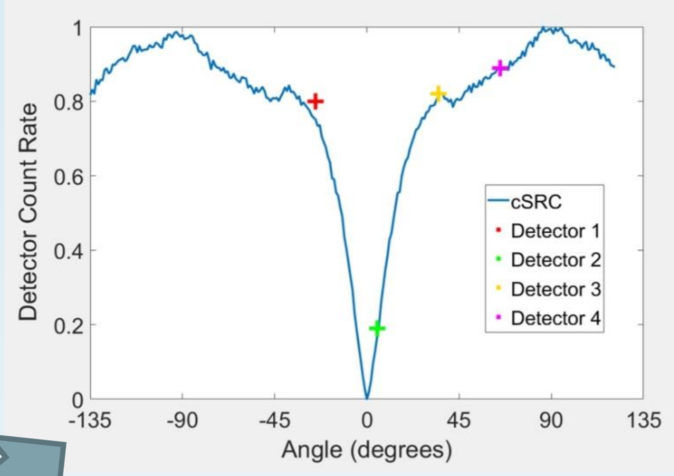
(a) Measured source and detector positions.

(b) Measured and detected positions.

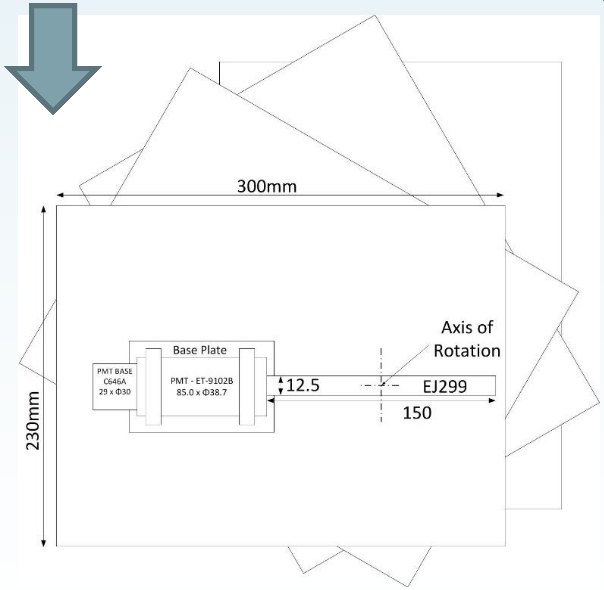
Randall G., PhD Thesis, University College London, 2017

2. Isotope mapping with RadICAL

Dynamic radiation fields - If speed is important then the readout from a stack of fixed detectors can be compared with a standard response curve to find the location



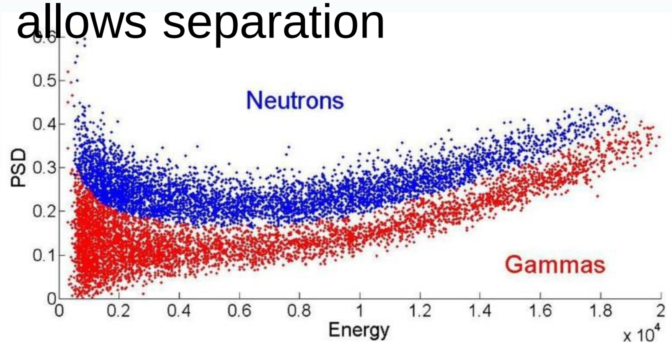
Mean error in location direction was 3.6^0



A 4 detector RadICAL stack

Randall G, et al (2019) submitted to JINST.

Mixed radiation fields - if mixed fields (neutrons & gammas) are being investigated then changing the scintillator (often to Gd loaded materials) and using PSD techniques allows separation



Conclusions

- Different approaches have been described
- Collimators are heavy and a distinct disadvantage
- Efficiency improvements come with coded apertures
- Electronic collimation is complex particularly with large area detectors
- RadICAL has many adavantages – no collimator, simple electronics – but performance with distributed sources still under investigation