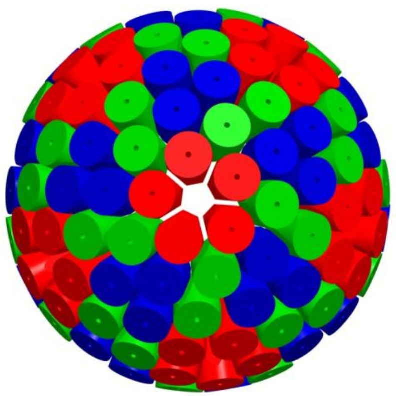
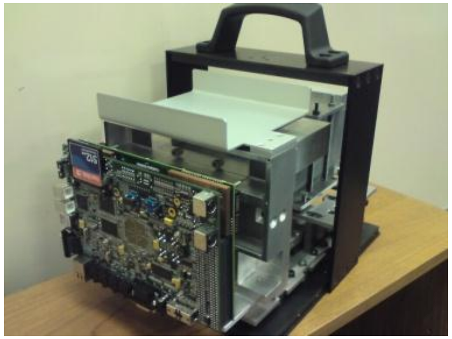
Position Sensitive Detectors for Nuclear Structure Physics and their Applications





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

Content of the Talk

- Introduction to Nuclear physics
- Types of array
  - TIGRESS array
  - AGATA
  - AIDA
- Applications of detectors spun off from NP
- Conclusion

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Nucleus is unique, strongly interacting many-body system

- UK Nuclear Physicists are involved with investigating
  - Nuclear Structure
  - Nuclear Astrophysics
  - Hadron physics
  - Phases of nuclear matter
  - Theory
- Experiments require semiconductor instrumentation development
- A natural path of this evolving instrumentation has been on designing and implementing position sensitive detectors
- Position sensitive detectors for nuclear structure, nuclear medical imaging and portable spectrometers for use in security and decommissioning

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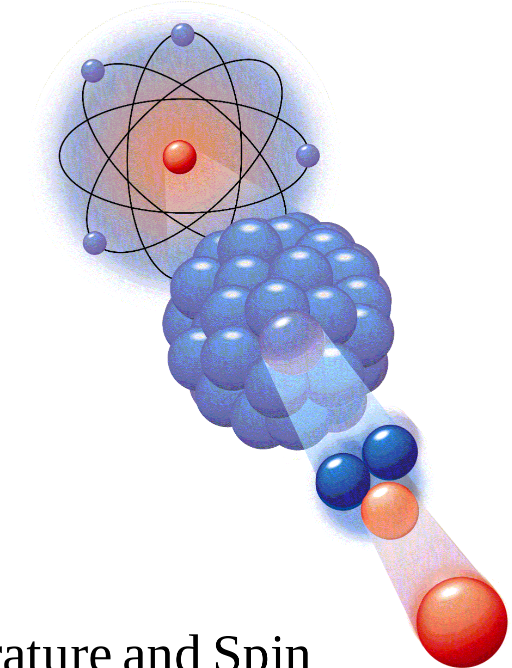
Questions being Investigated in NS Field

Nuclear Physics Research – very diverse



Modern nuclear physics aims at extending our understanding of the atomic nucleus in two key directions:

towards smaller distances by investigating the structure of the constituents of nuclei – nucleons and mesons

towards larger scales by exploring the very limits of matter – Isospin N/Z (neutron-rich), Mass (superheavy nuclei), Temperature and Spin

In parallel nuclear physicists apply this understanding to other areas of scientific study (e.g. nuclear astrophysics – production of elements and the energy sources in stars and explosive astrophysical sites) or to everyday applications (e.g. nuclear medicine – diagnostic or treatment purposes, homeland security, environmental monitoring)

Precision γ-ray spectroscopy with large position sensitive detectors arrays

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Experimental Conditions and Challenges

FAIR
SPIRAL2
SPES
REX-ISOLDE
EURISOL
ECOS

- Low intensity
- High backgrounds
- Large Doppler broadening
- High counting rates
- High γ-ray multiplicities

High efficiency
High sensitivity
High throughput
Ancillary detectors

Need instrumentation

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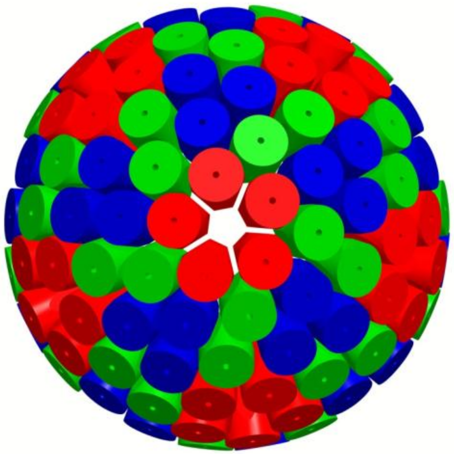
Where we work
Lots of activity and opportunities
Accelerator facilities

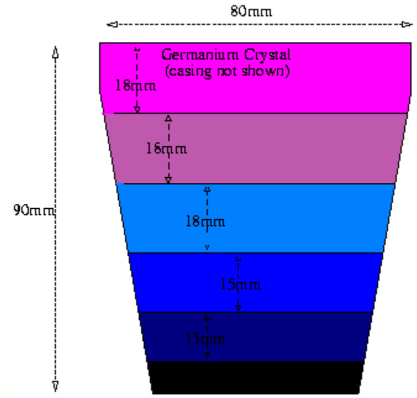
No UK Facility!

Position Sensitive Detectors in NP

- Highly segmented detectors are used in conjunction with pulse shape analysis and gamma ray tracking to get a better insight into the structure of atomic nuclei

AGATA
ADVANCED GAMMA
TRACKING ARRAY





GRETINA

- Using signal decomposition planar detectors have the possibility of better position resolution

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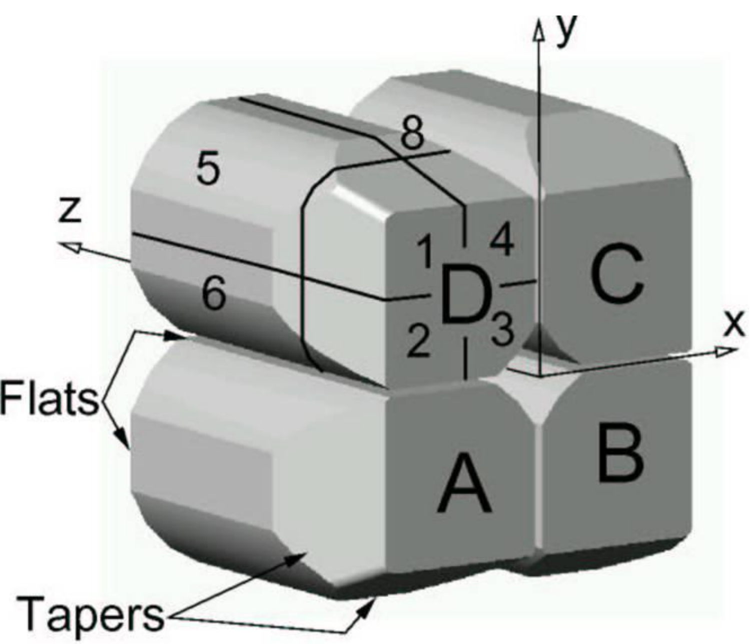
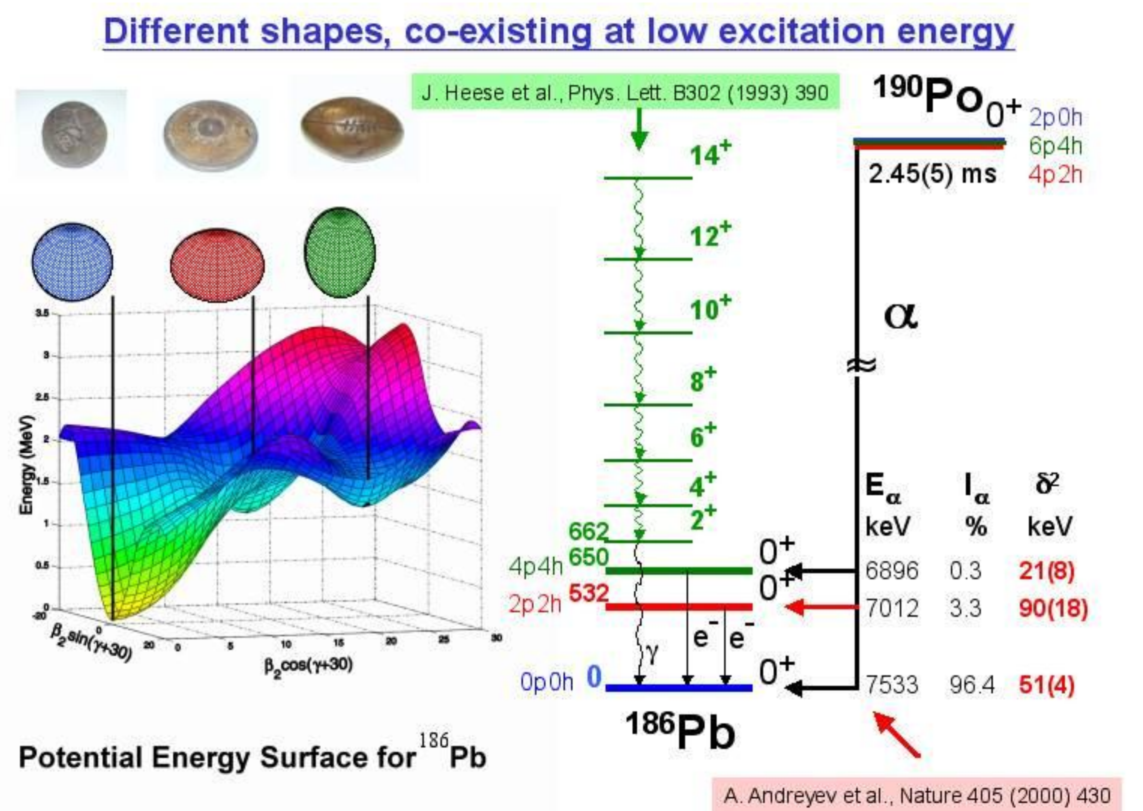
TIGRESS

- The TRIUMF ISAC Gamma Ray Escaped Suppressed Spectrometer – TIGRESS - was one of the first segmented arrays being used in NP
- Each detector four HPGe crystals electronically segmented x8
- Compton suppression achieved with BGO
- Coulex experiments, d,p reaction and fusion evaporation reactions investigated with stable and radioactive beams





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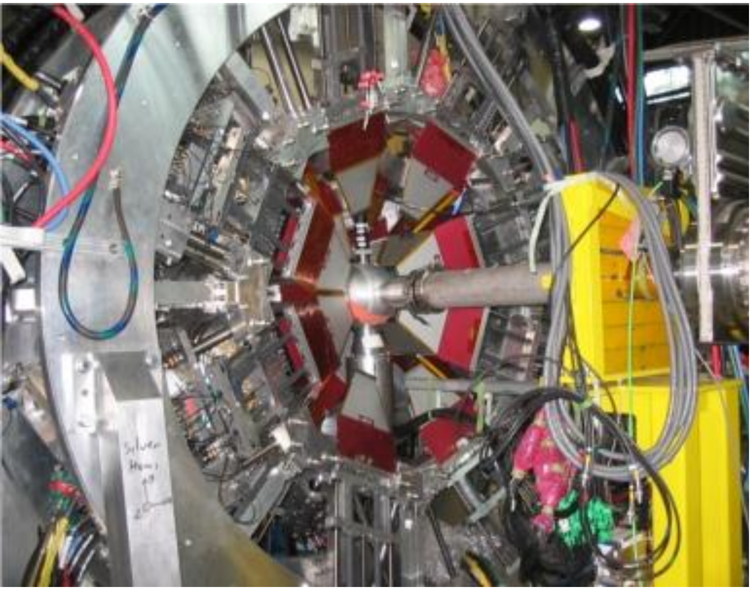
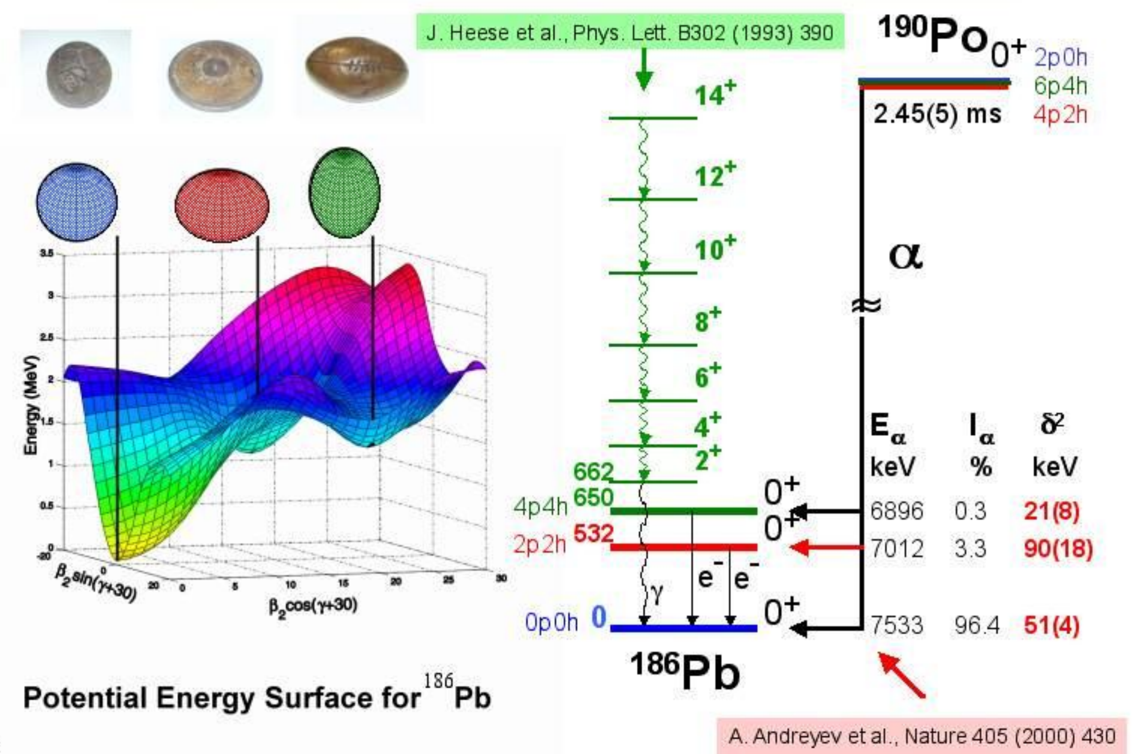


Different shapes, co-existing at low excitation energy



Future Arrays

- Next generation γ-ray spectrometer based on **gamma-ray tracking**
- First "real" 4π germanium array ➔ no Compton suppression shields
- Versatile spectrometer with very high efficiency and excellent spectrum quality for radioactive and high intensity stable beams
- **Advanced GAmma Tracking Array - AGATA**

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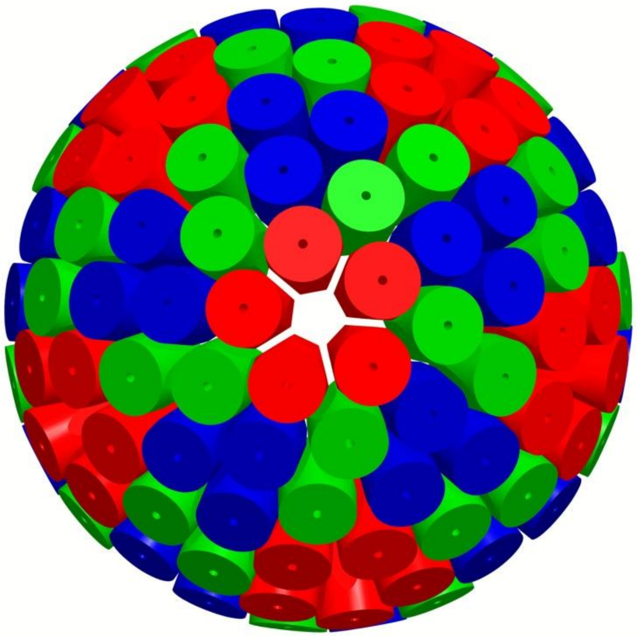
AGATA
(Design and characteristics)

4π γ-array for Nuclear Physics Experiments at European accelerators providing radioactive and stable beams



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%

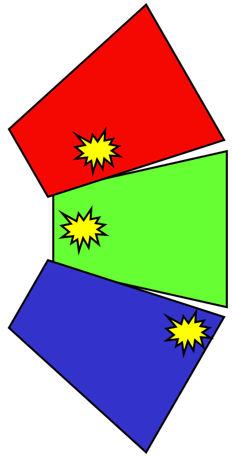
Angular Resolution: ~1º →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

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

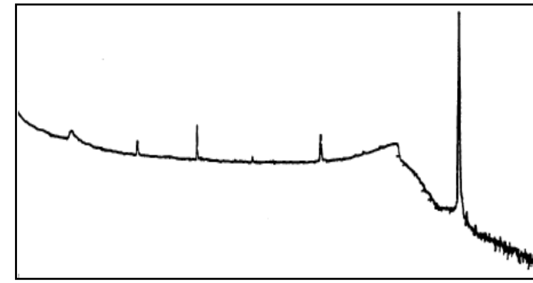
- 180 large volume **36-fold** segmented Ge crystals in 60 triple-clusters , 12 pentagonals
- Shell of Ge with inner radius of 23.5cm will consist of 230kg of Germanium
- Solid angle coverage of 80%
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow operation of Ge detectors in position sensitive mode → γ-ray tracking

The Concept

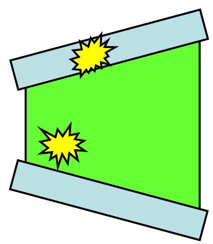
Without Compton suppression shields

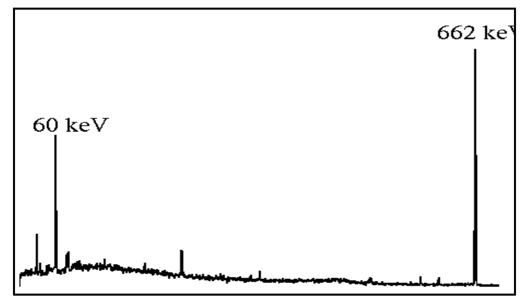


Compton continuum.
=> Large peak to total ratio



With BGO shielding

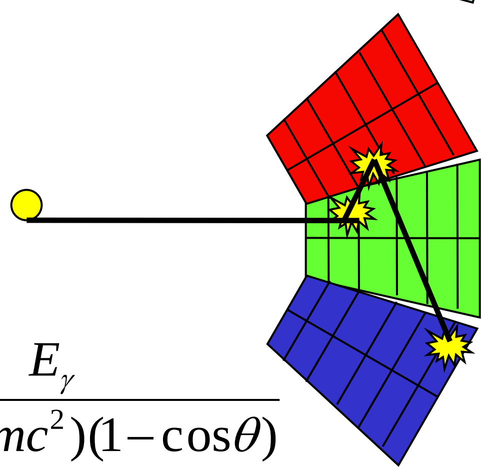




Less solid angle coverage
=> Big drop in efficiency

With highly segmented detectors

$$E_{\gamma}' = \frac{E_{\gamma}}{1+(E_{\gamma}/mc^2)(1-\cos\theta)}$$



Path of γ-ray reconstructed to form full energy event
=> Compton continuum reduced
=> Excellent efficiency ~50% @1MeV
=> Greatly improved angular resolution (~1^0) to reduce Doppler effects

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Position Sensitive Detectors

Highly segmented detectors

$$E_\gamma' = \frac{E_\gamma}{1 + (E_\gamma / mc^2)(1 - \cos\theta)}$$

- Each event **x, y, z, t, E**
- x, y, z **determined with PSA** (IC + RC)
- **Experimental** pulse shapes are **compared to theoretical** basis
  - Impossible to scan 180 detectors
  - Simulation can be adapted as neutron damage occurs
- Tracking: Compton scatter formula relates scatter angle to energy deposited
  - Allows reconstruction of FEE
  - Increases P/T
  - Optimum use of HPGe coverage

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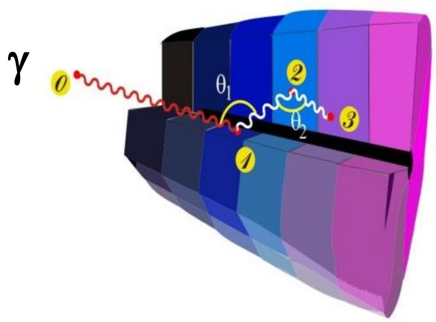
Ingredients of γ-Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

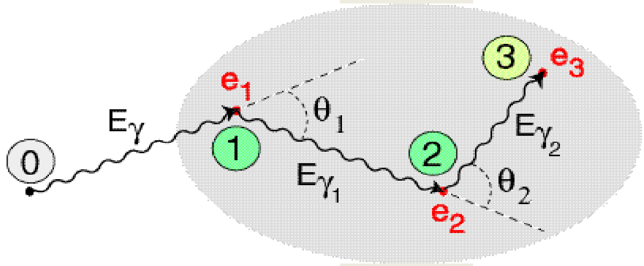
Pulse Shape Analysis to decompose recorded waves

Identified interaction

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

4

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



reconstructed γ-rays

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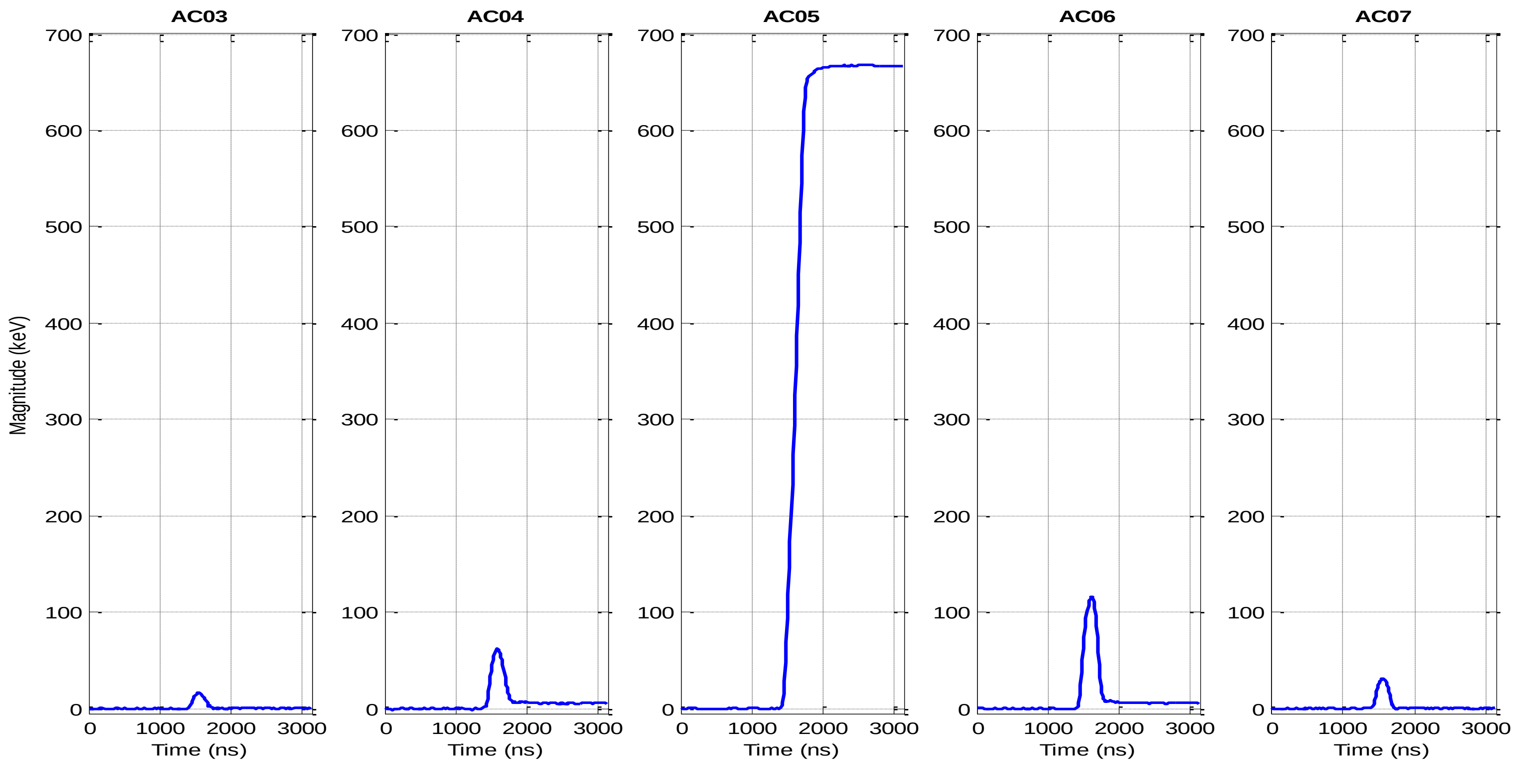
Pulse Shape Analysis (PSA): X Y position

Image charge asymmetry varies as a function of
lateral interaction position

- Calibration of asymmetry response

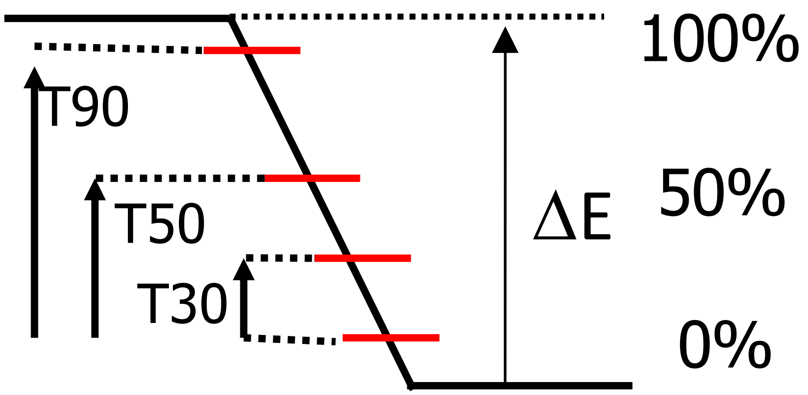
Pixilation 5x5x20mm becomes 1mm^3

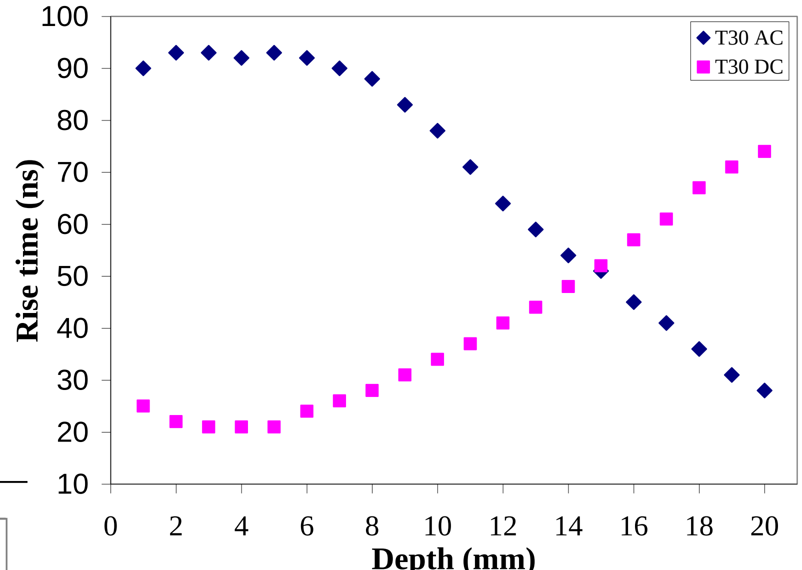
$$Asymmetry = \frac{Area_{left} - Area_{right}}{Area_{left} + Area_{right}}$$

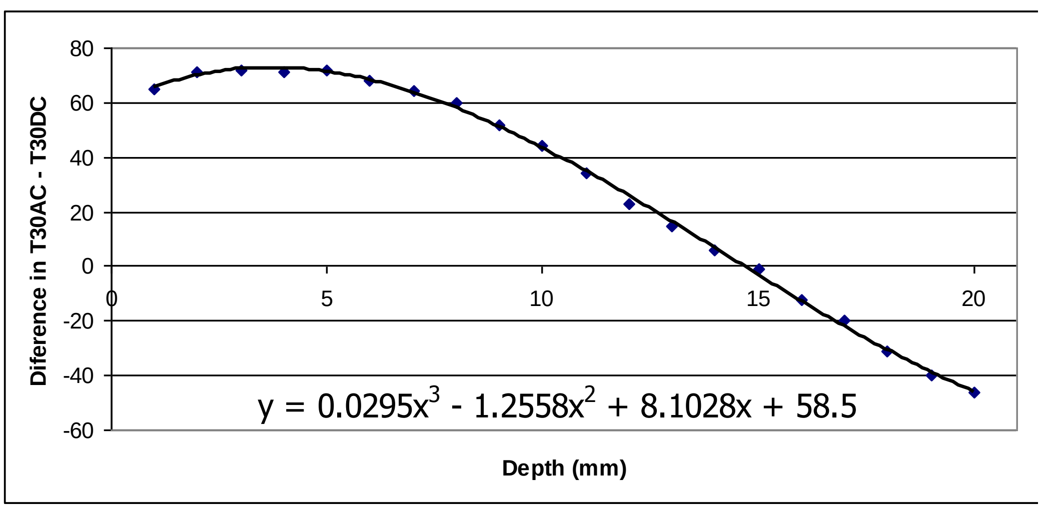


Pulse Shape Analysis (PSA): DoI

- Location of the depth of interaction position within detector gathered by parameterisation of the information from the pulse shape







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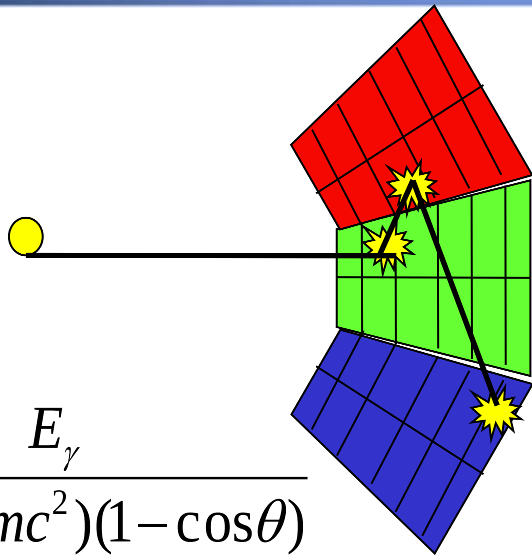
Gamma Ray Tracking

With highly segmented detectors



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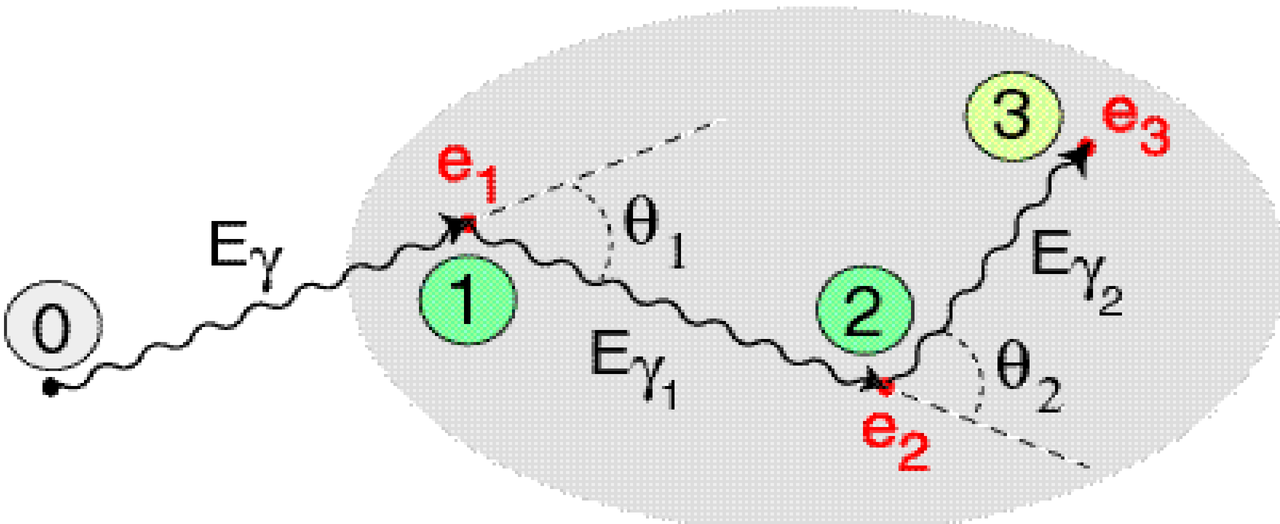

- Basic assumptions w.r.t. energy and Klein Nishina
  - 1st interaction deposits most energy
  - Scatter will be forward focused

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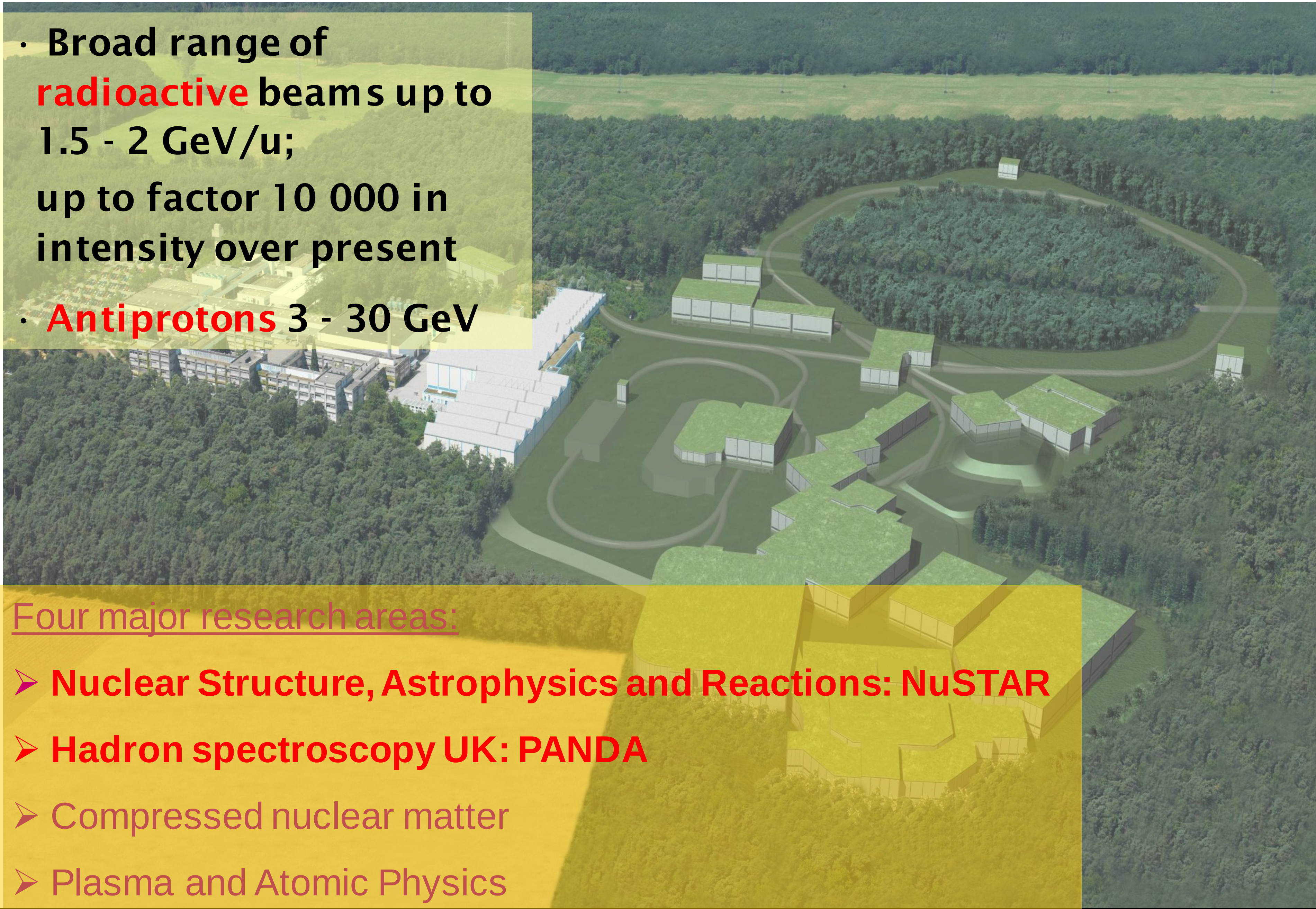
FAIR: Facility for Antiproton and Ion Research



- Broad range of radioactive beams up to 1.5 - 2 GeV/u;
  up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

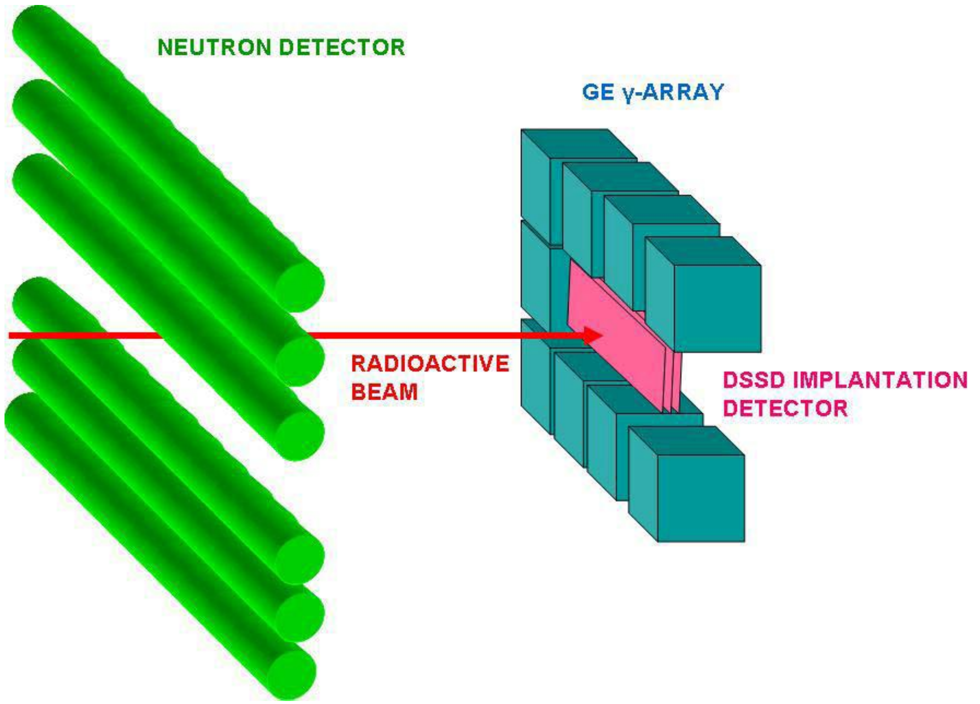
Four major research areas:

- **Nuclear Structure, Astrophysics and Reactions: NuSTAR**
- **Hadron spectroscopy UK: PANDA**
- Compressed nuclear matter
- Plasma and Atomic Physics

Advanced Implantation Detector Array

AIDA for use at DESPEC at FAIR

- SuperFRS, Low Energy Branch (LEB)
- Exotic nuclei – energies ~ 50 – 200MeV/u
- Implanted into multi-plane, highly segmented DSSD array
- Implant – decay correlations
- Multi-GeV DSSD implantation events
- Observe subsequent p, 2p, α, β, γ, βp, βn … low energy (~MeV) decays
- Measure half lives, branching ratios, decay energies …
- Tag interesting events for gamma and neutron detector arrays



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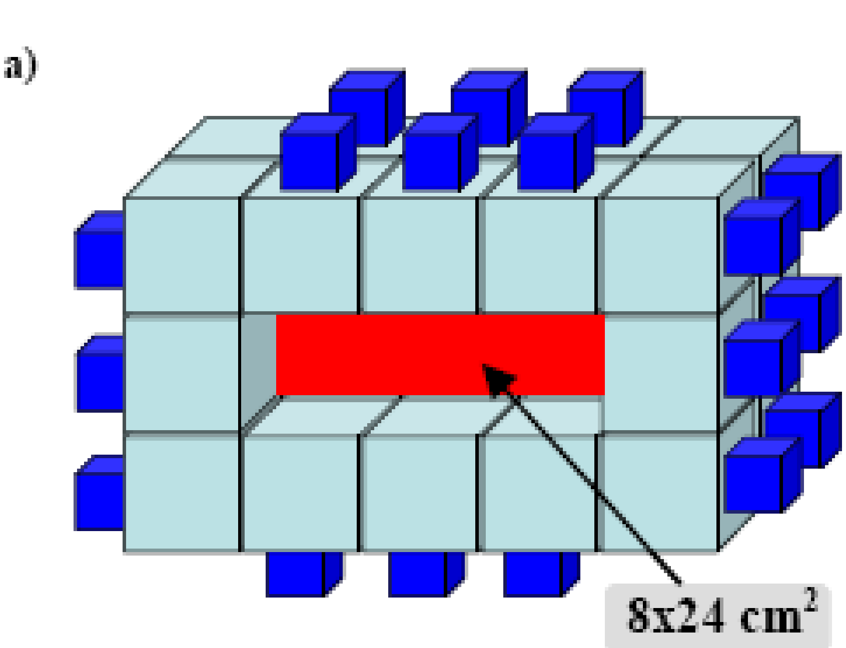
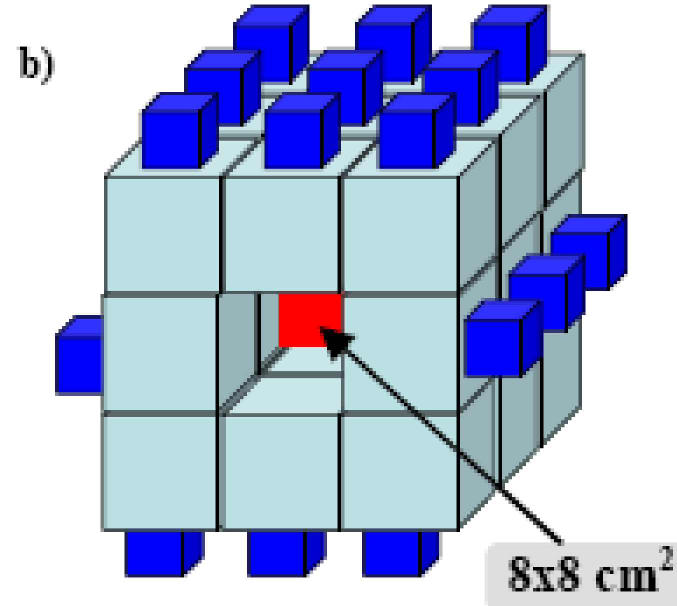
Implantation DSSD Configurations





Two configurations proposed:

a) 8cm x 24cm
"cocktail" mode
many isotopes measured simultaneously

b) 8cm x 8cm
concentrate on particular isotope(s)
high efficiency mode using:
- total absorption spectrometer
- moderated neutron detector array

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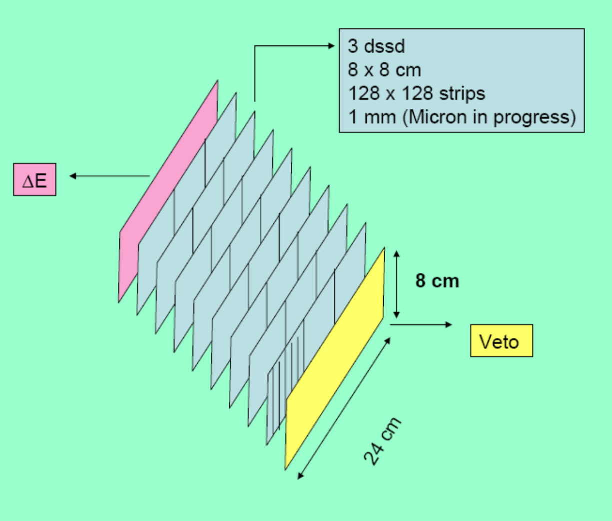
AIDA: DSSD Array Design

- **8cm x 8cm** DSSDs
  common wafer design for 8cm x 24cm and 8cm x 8cm configurations
- **8cm x 24cm**
  3 adjacent wafers – horizontal strips series bonded

- 128 p+n junction strips, 128 n+n ohmic strips per wafer



- strip pitch 625μm
- wafer thickness 1mm
- ΔE, Veto and up to 6 intermediate planes
  4096 channels (8cm x 24cm)
- overall package sizes (silicon, PCB, connectors, enclosure …)
  ~ 10cm x 26cm x 4cm or ~ 10cm x 10cm x 4cm

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Implantation – Decay Correlation

- DSSD strips identify where (x,y) and when (t_0) ions implanted
- Correlate with upstream detectors to identify implanted ion type
- Correlate with subsequent decay(s) at same position (x,y) at times t_1(,t_2, …)
- Observation of a series of correlations enables determination of energy distribution and half-life of radioactive decay

- Require average time between implants at position (x,y) >> decay half-life depends on DSSD segmentation and implantation rate/profile
- Implantation profile

  $\sigma_x \sim \sigma_y \sim 2cm, \sigma_z \sim 1mm$
- Implantation rate (8cm x 24cm) ~ 10kHz, ~ kHz per isotope (say)
- Longest half life to be observed ~ seconds

Implies quasi-pixel dimensions ~ 0.5mm x 0.5mm

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Applications

- Medical Imaging – 3D functional image of cancers or neurological diseases < 600keV
  - Positron Emission Tomography (PET)
  - Single Photon Emission Computed Tomography (SPECT)
- Energy range 60keV – 20MeV
- Security – 3D spectroscopic image to show what and where
  - Distinguish
  - PorGamRays
- Environmental imaging
  - BAE systems
  - AWE – Threat reduction
- Nuclear decommissioning
  - NNL

Most use Compton Camera method – 3D imaging

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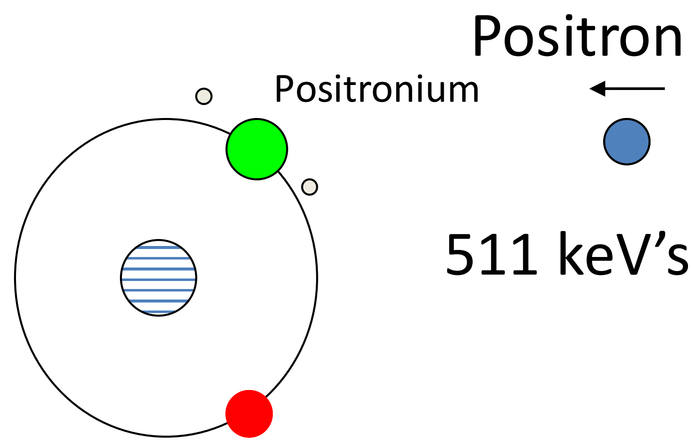
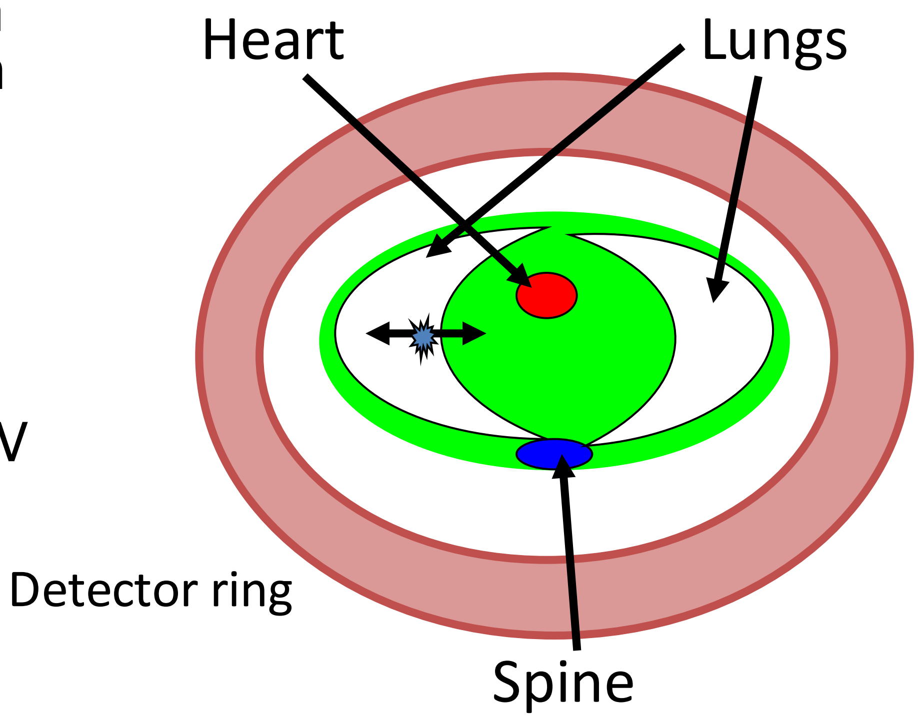
What is Positron Emission Tomography?

- Radionuclide decays by positron emission, β^+
- Positron emitted with initial kinetic energy
- Positron will slow down in medium
- Comes in to close contact with a free or weakly bound electron and for a very short time they become a Positronium atom, with the positron as the nucleus
- As the positron is antimatter to the electron catastrophic annihilation occurs
- Energy of each particle released in process as two back to back 511 keV photons to conserve momentum





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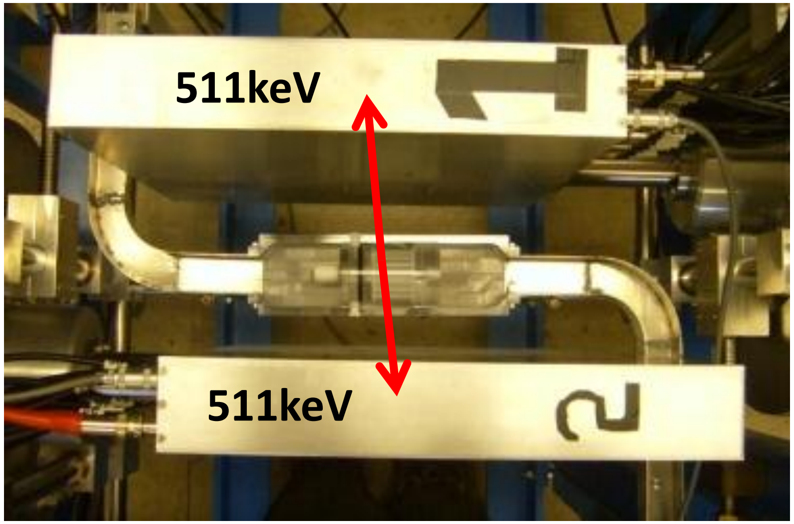
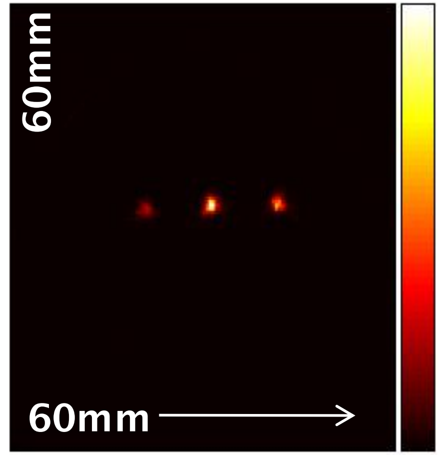
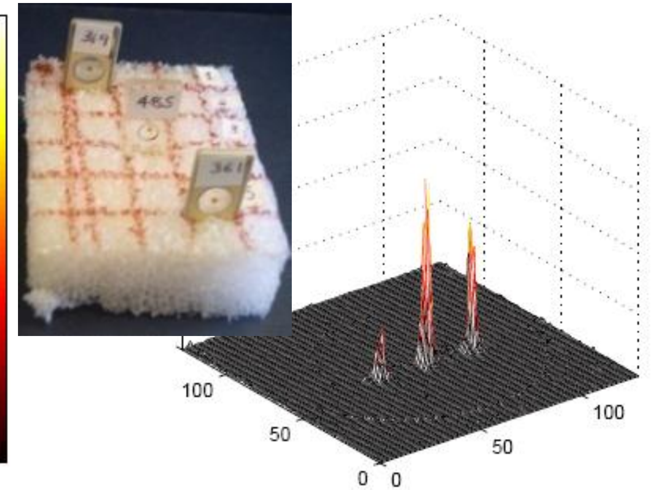
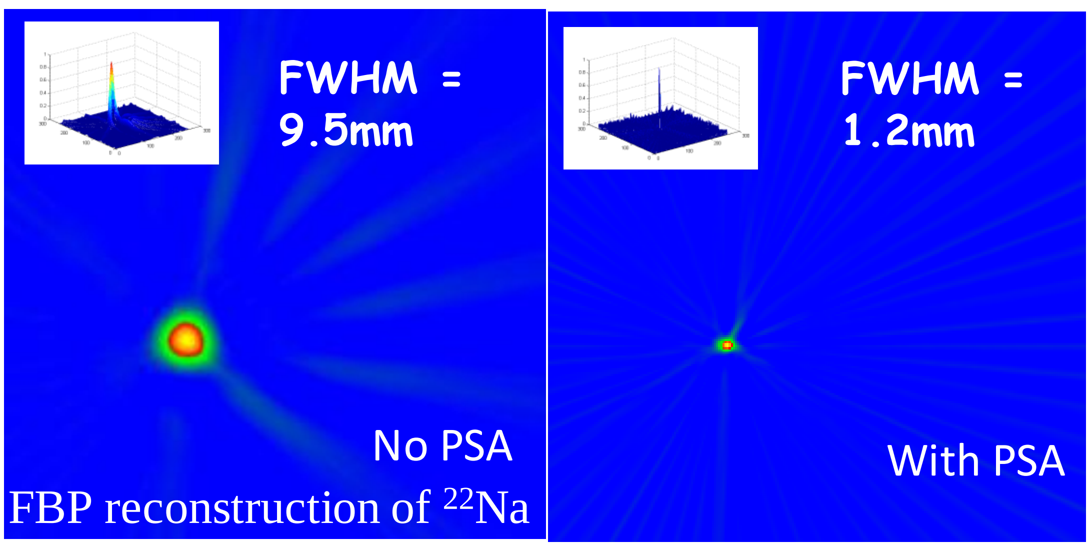
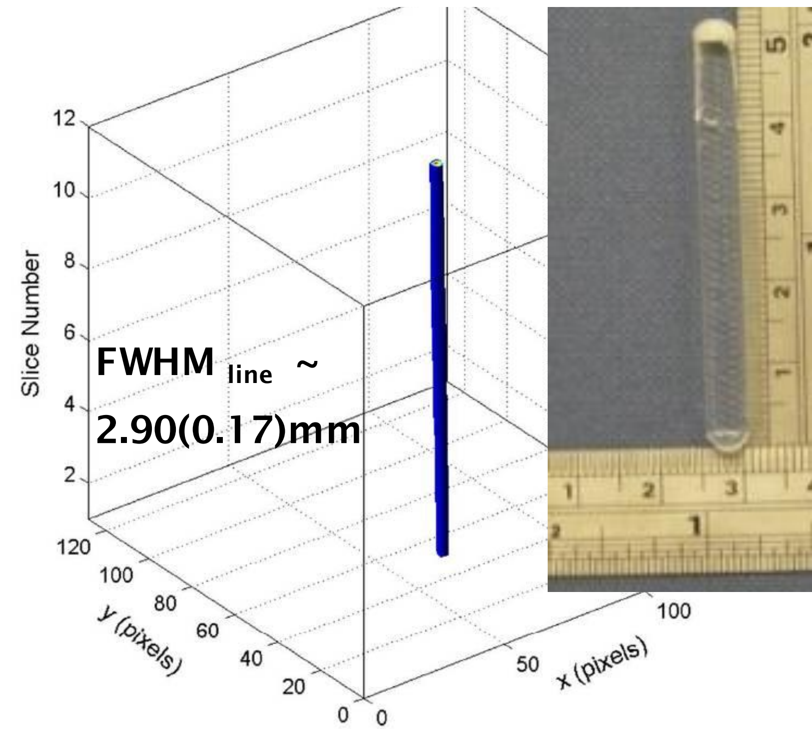
PET Imaging with SmartPET











NIM A606 issue 3 (2009) 523-532
NIM A604 Issue 1-2 (2009) 343-346

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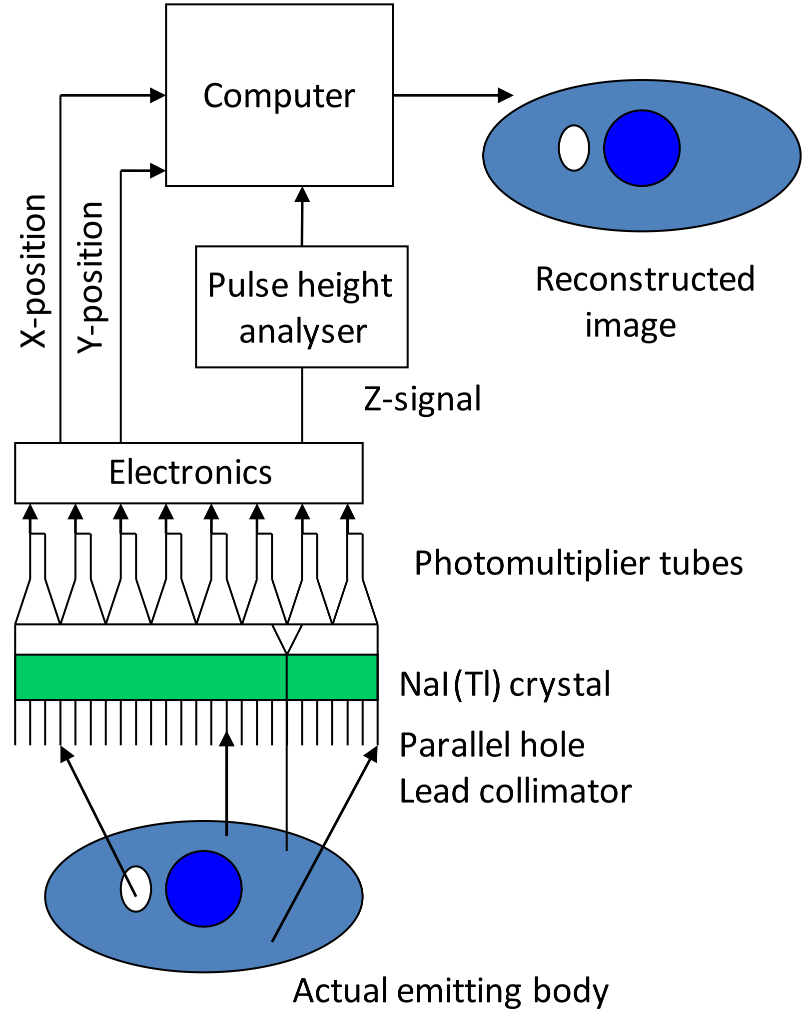
What is Single Photon Emission CT?

- Currently a gamma camera is used,
  - **Scintillator material**
  - **Mechanical collimation**
- Limitations;
  - Sensitivity due to presence of collimators
  - Energy resolution – only single energies can be imaged or well separated energies
  - Energy of gamma ray used must be kept low - 140keV ^{99m}Tc
  - Aberrations because of rotation misalignment
  - Large number of events needed to create image to get acceptable signal to noise ratio



Will not operate in magnetic field

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SPECT Imaging

- How can we remove this requirement for collimation?
  - Use position sensitive segmented semiconductor detectors which inherently have electronic collimation
    - Finer position of interaction information
    - Greater sensitivity ~100x
    - Greater range of energies (60keV – 2MeV)
      - Opens up other radioisotopes for use in medical imaging but can also use system in non medical imaging capacity
  - Use Compton camera process
- Volumetric 3D image – No rotation
- Can use semiconductors in magnetic field – MRI co-registry possible

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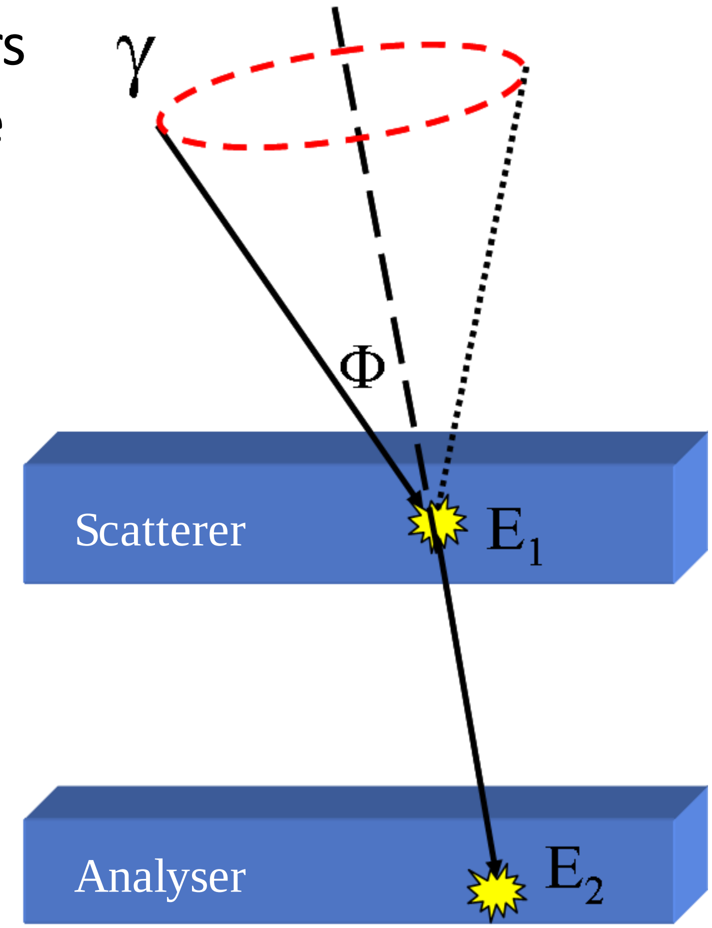
Compton Camera Principles

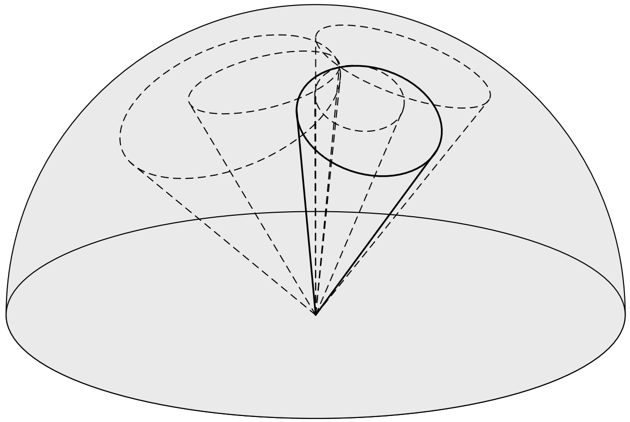
NIM A580 Volume 2 (2007) 929-933
IEEE conference proceedings (2009) 624-628

- 2 position sensitive detectors
- Energy information from the detectors allows the creation of a cone, the base of which represents the possible sites of origin

$$E_0 = E_1 + E_2$$



- Image created from many events, with the location of the source where most cone overlaps occur

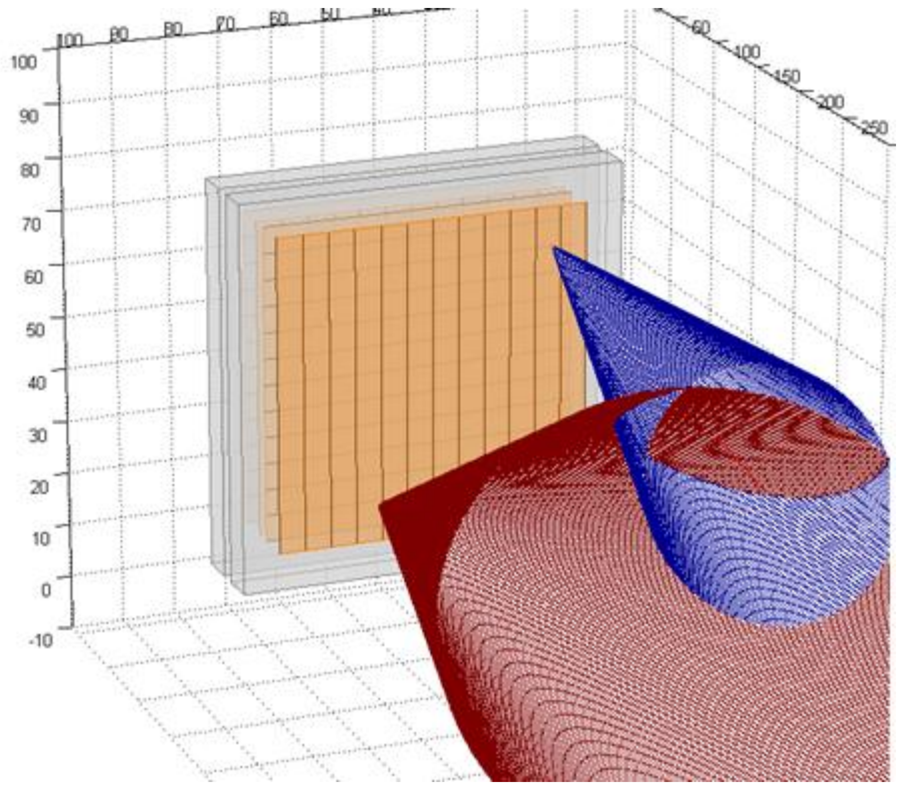


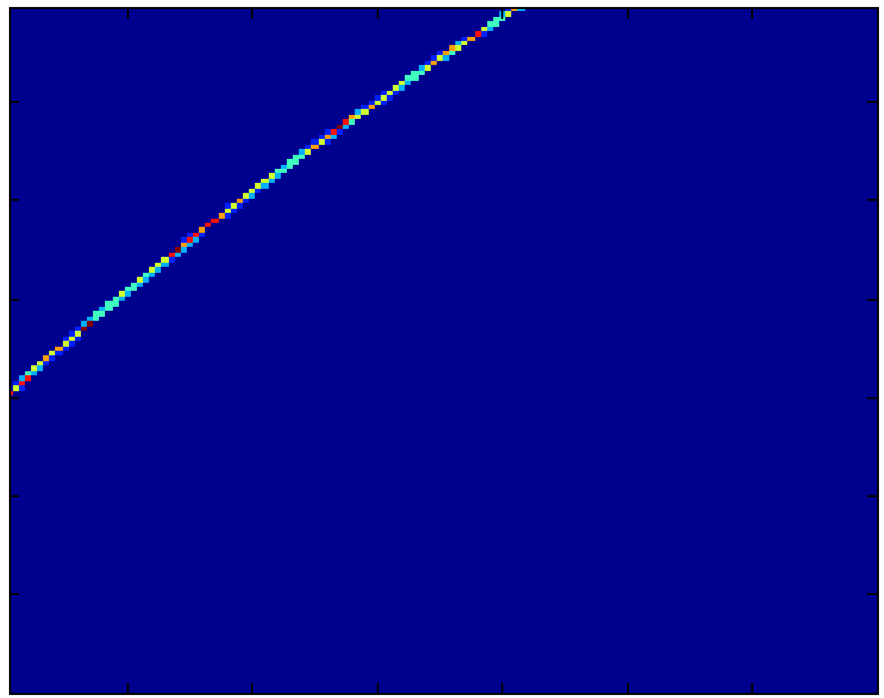
$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Image Reconstruction

- Matlab output of the system
- Two SmartPET detectors

- Projection of cones in z plane
- Overlapping gives emission position





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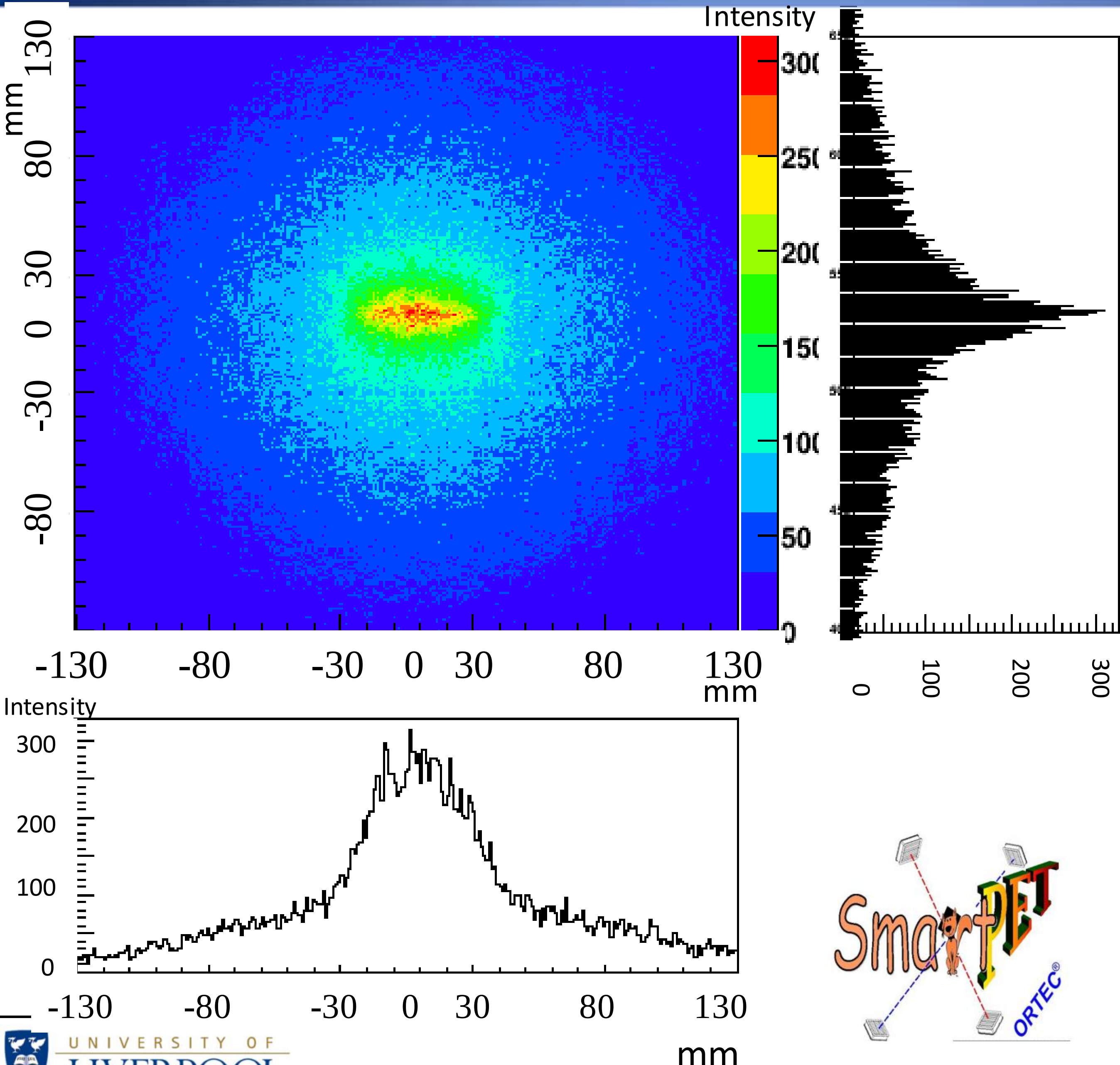
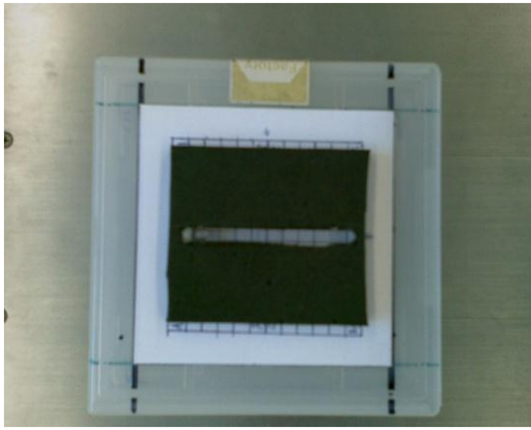
Line Source



- Line source – Glass vial 50 x 2.5mm ^{22}Na
- Analytic reconstruction
  x = 52mm
  y = 4 mm



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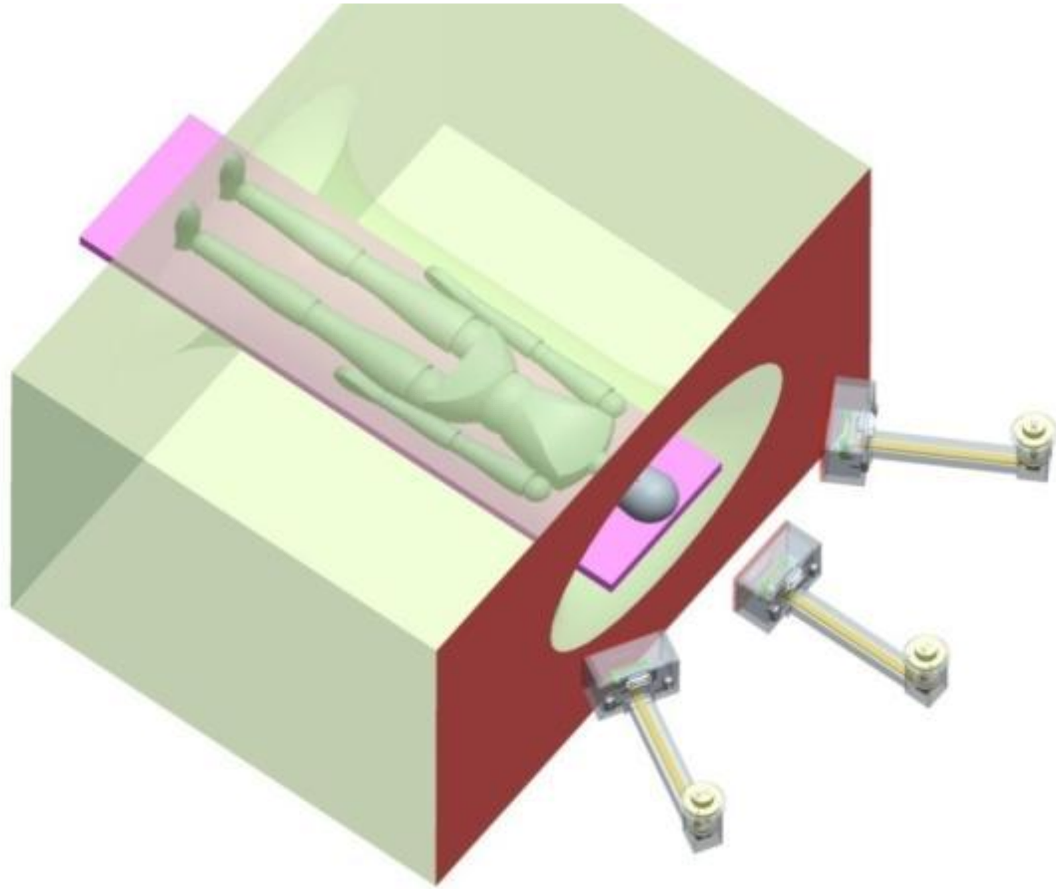
ProSPECTus

- Interdisciplinary project with physicists, MARIARC, Royal Liverpool University Hospital
- £1.1M knowledge exchange project
- Compton camera for SPECT with capabilities in MRI scanner
  - 9mm Si(Li) scatterer
  - 20mm HPGe analyser
- Siemens MAGNETOM 1.5T symphony scanner



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Security: The Distinguish Project

- Explosives (illicit substances) contain characteristic combinations of light elements

  - carbon, nitrogen, oxygen, hydrogen

- Emission of characteristic gamma rays stimulated by neutron interrogation

  - Oxygen : 6.13MeV

  - Carbon : 4.43MeV

  - Nitrogen : 5.11MeV, 2.31MeV, 1.64MeV

- Pulsed Fast Neutron Analysis (PFNA)

  - gamma-ray detection and imaging

  - digital processing techniques

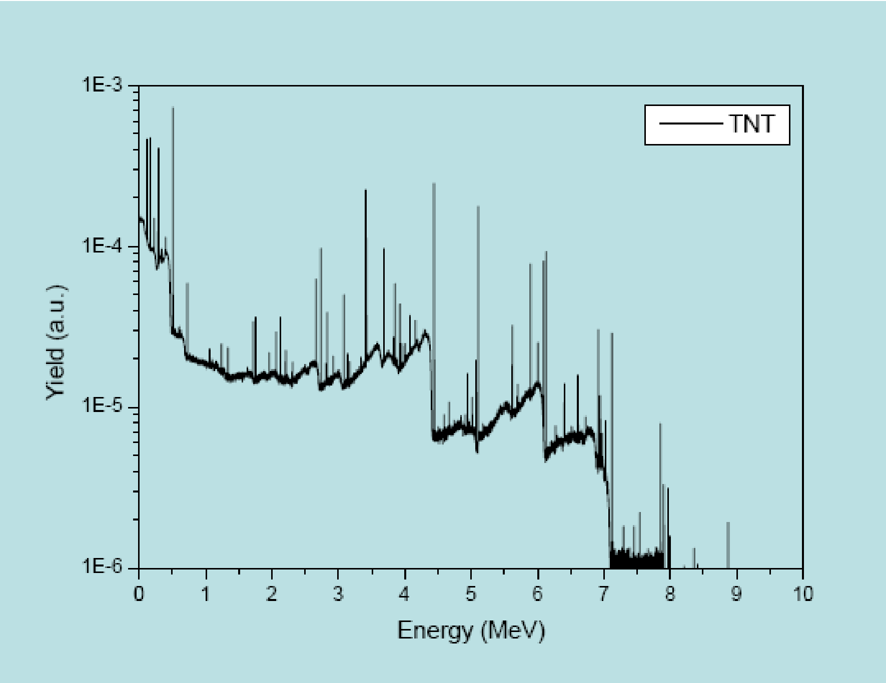
Material Identification

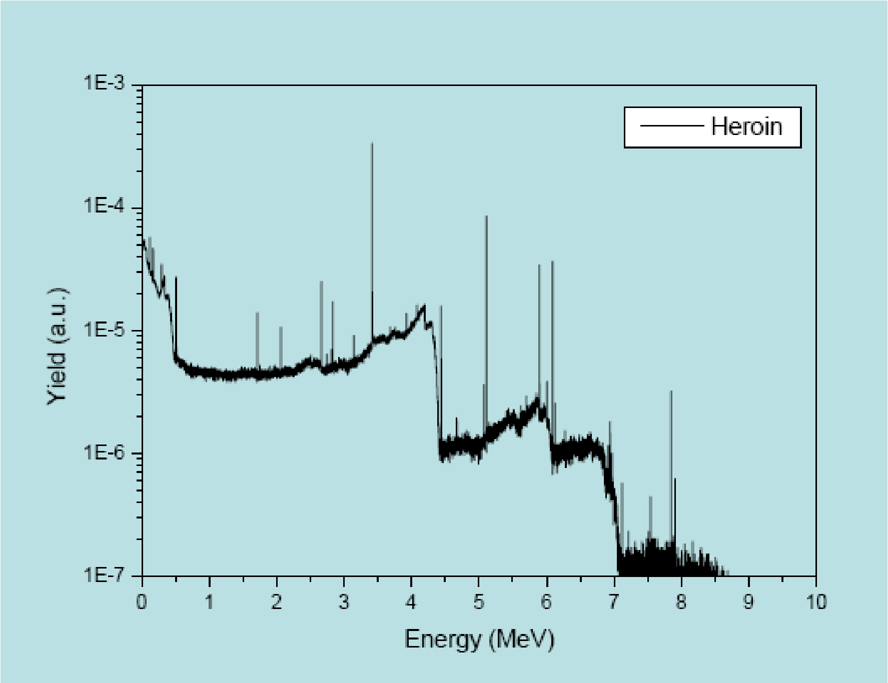
- Identification of illicit material primarily through ***gamma-ray fingerprinting***

  - capture gamma rays

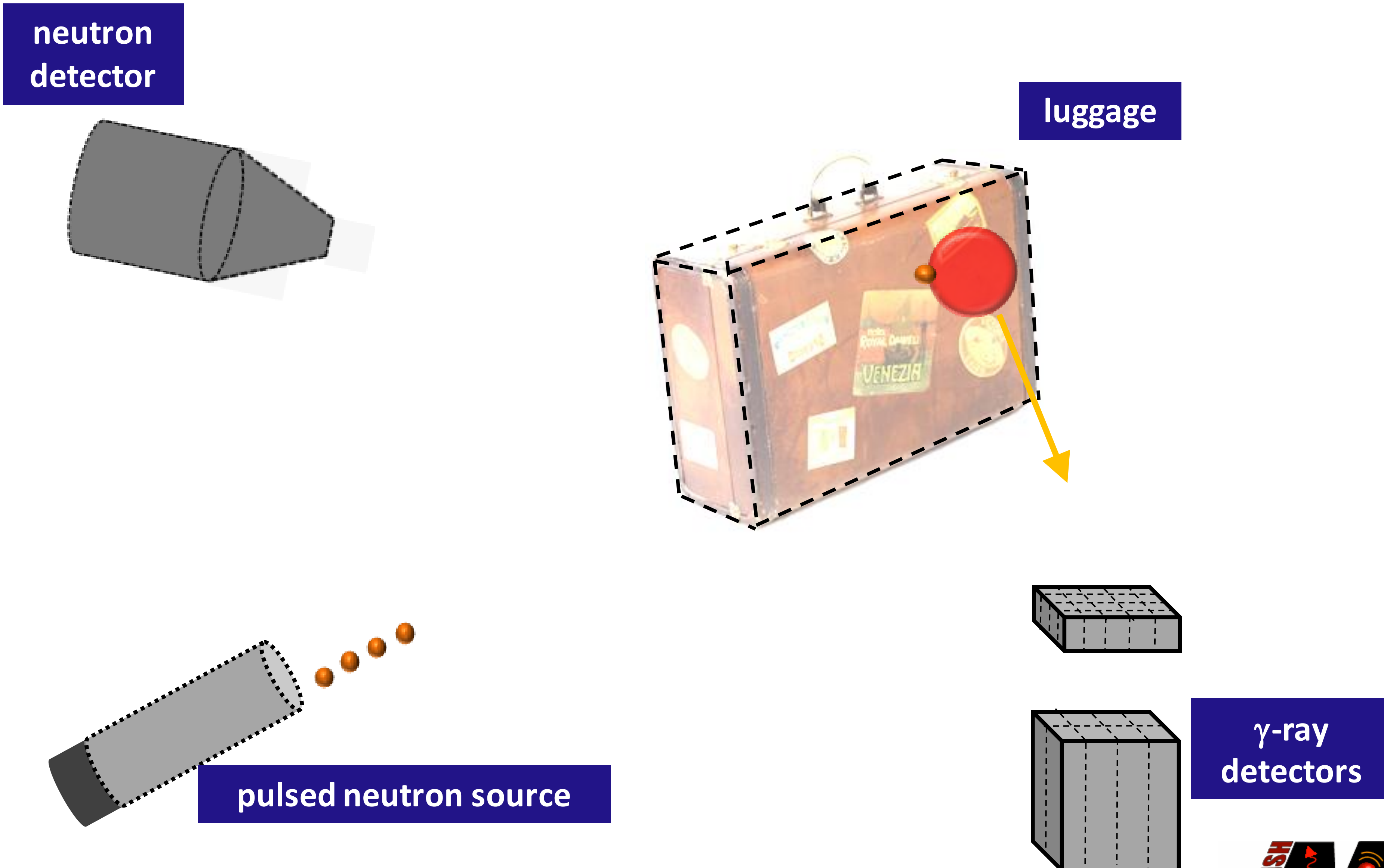
  - inelastic scatter gamma rays

- Characteristic prompt gamma rays from light elements





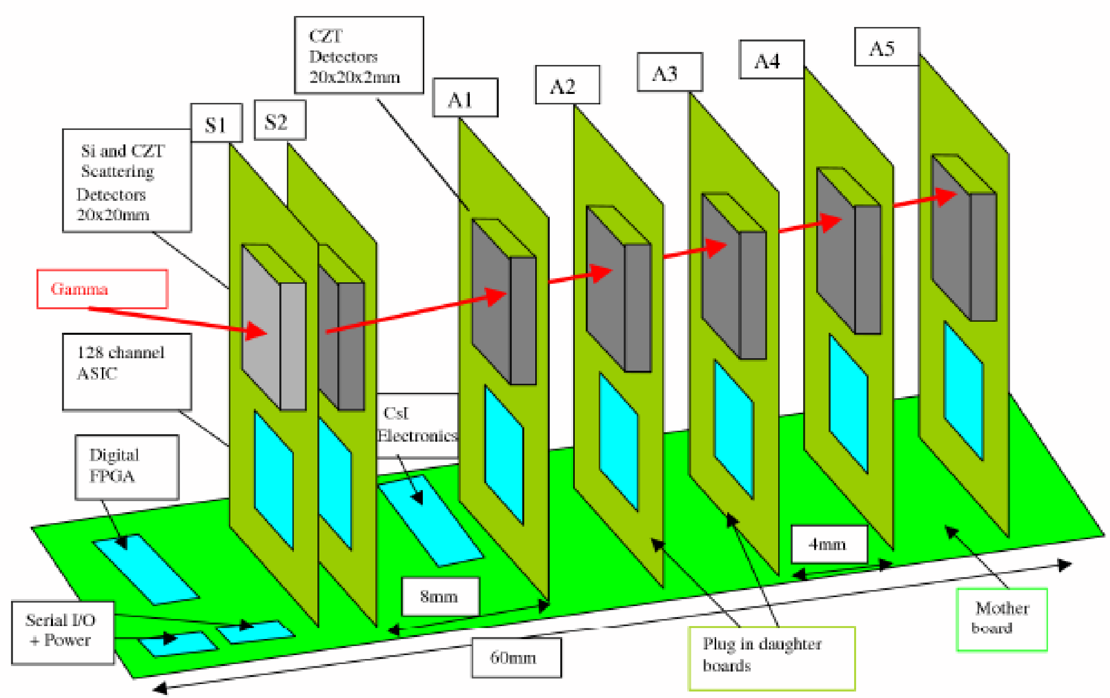
The Concept


neutron detector
luggage
pulsed neutron source
γ-ray detectors
VENEZIA

Environmental and Decommissioning Assaying

- What, where, how much?
- BAE submarine nuclear reactor, terrorist threat reduction, national nuclear laboratory
- Produce images to gauge possible contamination using a portable gamma ray spectrometer
- Layers of CZT

○ The PorGamRayS project is developing a portable gamma-ray spectrometer with Compton imaging capability (60keV – 2MeV)



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Conclusion

- Innovations to detector technology from Nuclear Physics leads to benefits in society
- Detector development in Nuclear Physics coupled with PSA and gamma ray tracking leads to a better insight into the internal structure of the nucleus
- Applications include medical imaging, secuirty, nuclear decommissioning and environmental assaying
- Different types of position sensitive semiconductor detectors required depending on the application
    - Higher efficiency leads to higher throughput of patient or lower doses
    - 3D image shows what and where in space radioactive material is
-

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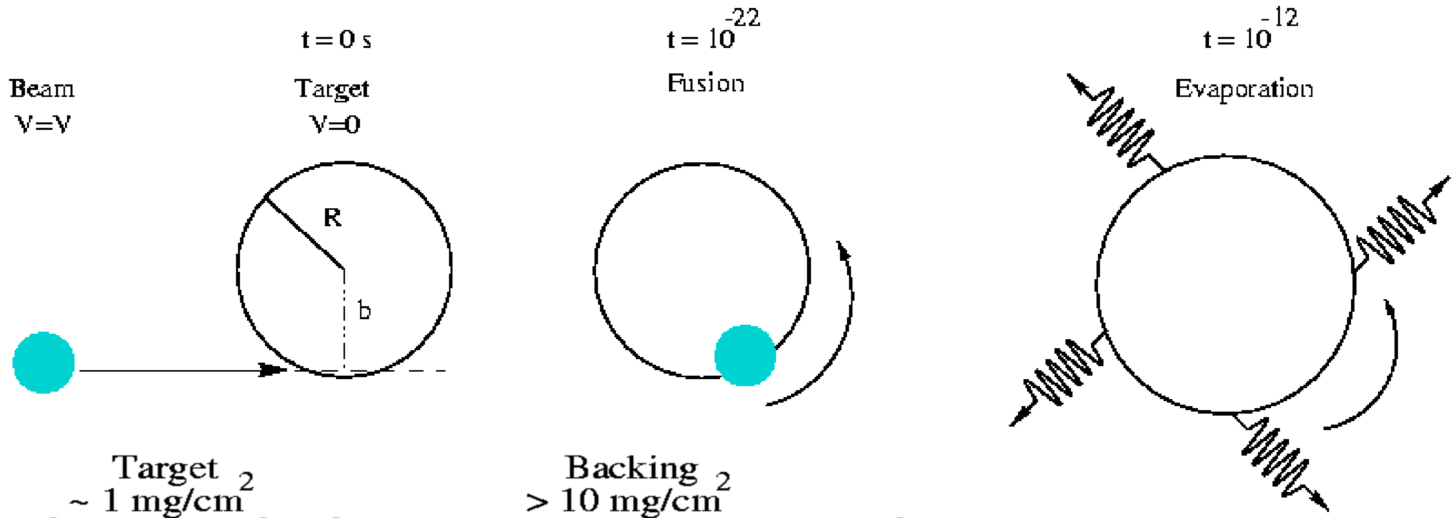
Vancouver CoastalHealth Research Institute
Healthier lives through discovery

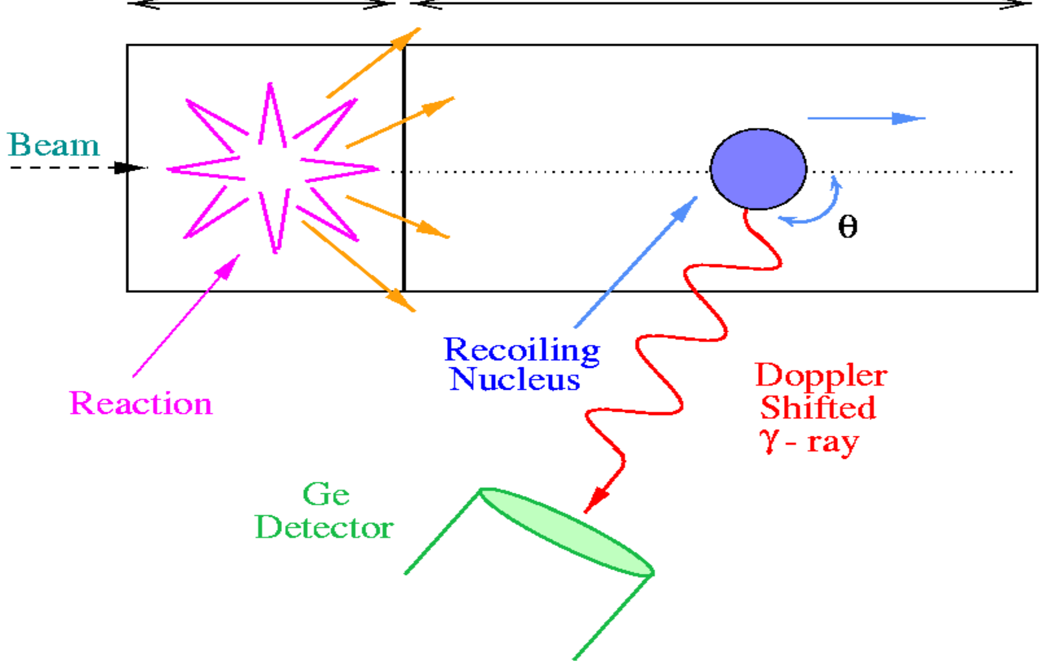
Science & Technology Facilities Council

EPSRC

MRC Medical Research Council

Doppler Broadening





Questions being Investigated

- What are the limits of nuclear existence? What is the heaviest element we can make and where does the neutron-dripline lie?
- Do new forms of collective motion occur far from the valley of the nuclear stability?
- How does nuclear structure evolve at the highest angular momentum just before the fission limit?

- Need powerful state of the art detectors for

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TIGRESS

- TRIUMF ISAC Gamma Ray Escaped Suppressed Spectrometer – TIGRESS
- Versatile γ-ray spectrometer
- Clover detectors – each crystal 8 segments 1 core signal
- BGO detectors around each detector to suppress Compton scattered events
- hcb

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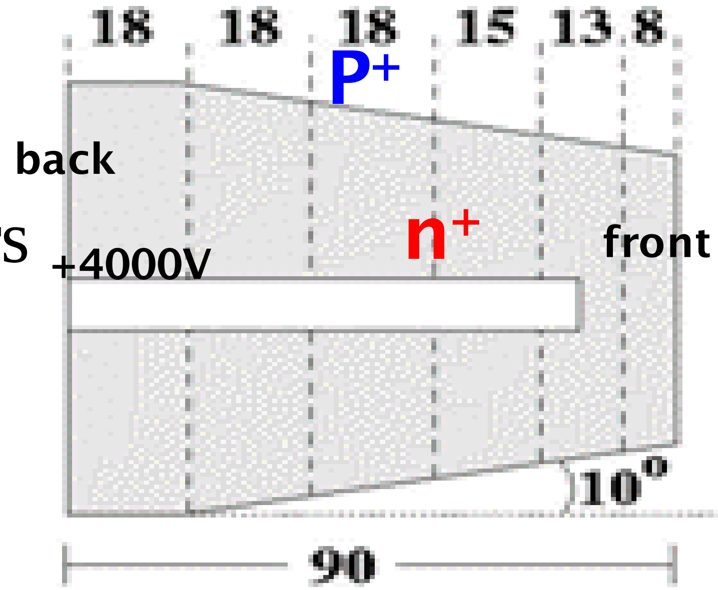
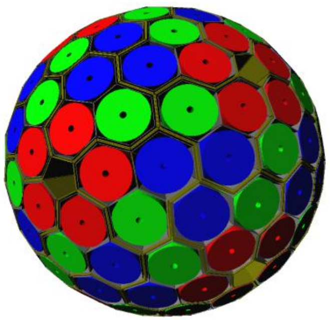
The AGATA Concept

- Spherical array of **180 asymmetric** HPGe detectors
- Each detector has a **36-fold** segmented outer Contact (FWHM ~ 2keV @ 1.3MeV)
- The crystal ;
  - 90mm long
  - 40mm Maximum diameter (10^o taper)
- Completed array - HPGe covers **full 4π solid angle**





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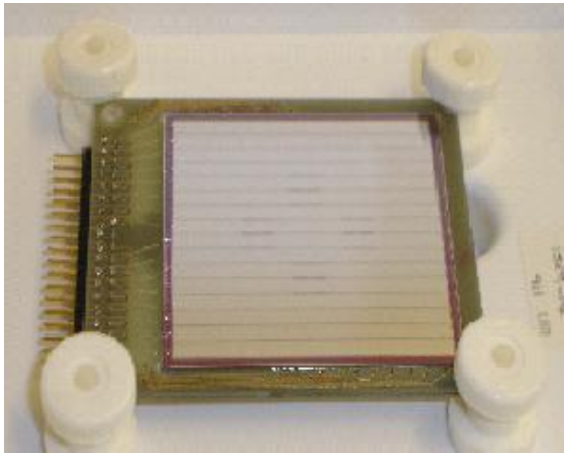
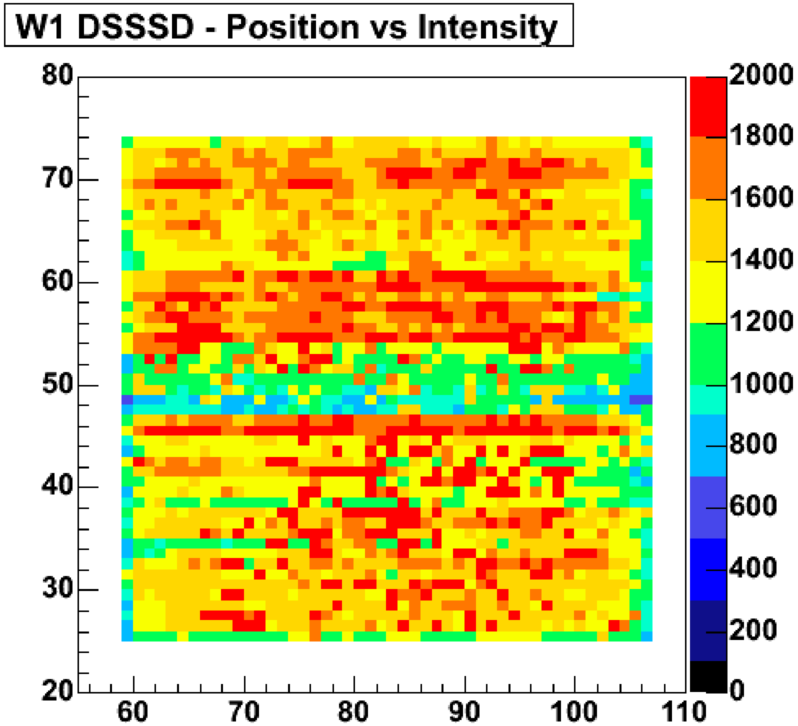
What Next?

- **Replace the scattering SmartPET detector with a Silicon detector**



- Active Volume; 50 x 50 x 0.5mm^3
- 32 strips
- 3mm pitch
- RAL preamps



- Si detector characterised
  - ^{241}Am source – 60keV γ-rays
  - 1mm collimation beam moved 1mm steps in x-y
  - Preamp signal had to be amplified before it would trigger digital system
- With the exception of one channel (Ch25 – not instrumented) uniform response

Types of Image Reconstruction

- **Analytic**
  - Simple back projection of cones
  - Real time
  - Suffers from artefacts
- **Iterative**
  - Yields higher quality images – knowledge of system and how it would respond
  - Not real time – (algorithm development now making realtime a possibility)
- **Stochastic**
  - Significantly improved performance for distributed sources
  - Not real time

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