A Prototype Scintillating-Fibre Tracker for the Cosmic-ray Muon Tomography of Legacy Nuclear Waste Containers

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Muon and Neutrino Radiography 2013 (MNR2013)
Detector and Electronics Workshop
Friday 26th July 2013

Presentation Overview

- UK legacy nuclear waste and the Glasgow MT project
- Glasgow MT detector
  - Design characteristics
  - Construction
  - Performance studies
  - Simulation studies
- Image reconstruction
- Preliminary results and simulation verification
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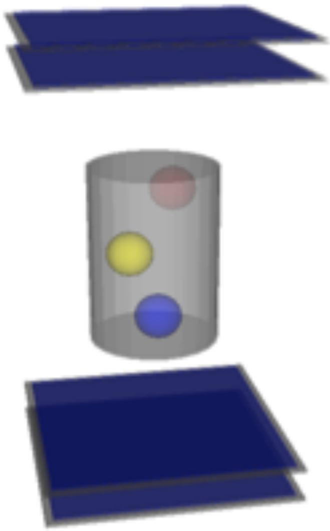

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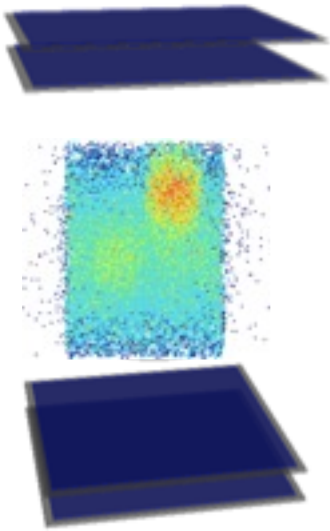

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UK Legacy Nuclear Waste

- Currently, there are 8 nuclear power plant facilities operational in the UK
  - 1 Magnox reactor, 6 advanced gas-cooled reactor sites and 1 pressurised-water reactor
  - Government policy is to undertake reactor new-build at several sites within the UK
- A consequence nuclear power is the generation of low-, intermediate- and high-level waste products
  - Legacy silos and waste ponds
  - ILW waste containers (see below)

- The UK's nuclear waste reprocessing is currently performed at Sellafield, Cumbria in the north-west of England
- On Sellafield's site significant volumes of ILW and HLW are stored in highly-engineered structures
- In order to characterise this current (and legacy) waste, techniques to clearly understand waste performance and storage parameters are essential
- Development of characterisation techniques (such as MT) assist in mitigating the risks inherent with long-term storage of these materials

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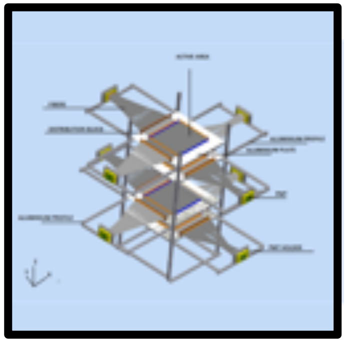
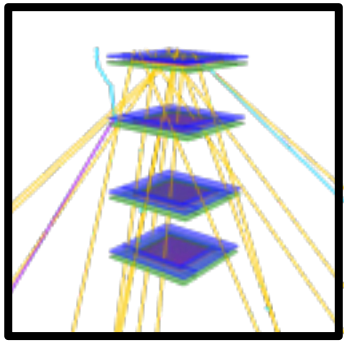
The Glasgow Muon Tomography Project

- Industrial collaboration with UK National Nuclear Laboratory (NNL) undertaken on behalf of Sellafield Ltd. (and the UK Nuclear Decommissioning Authority)

Sellafield Ltd NDA Nuclear Decommissioning Authority NATIONAL NUCLEAR LABORATORY





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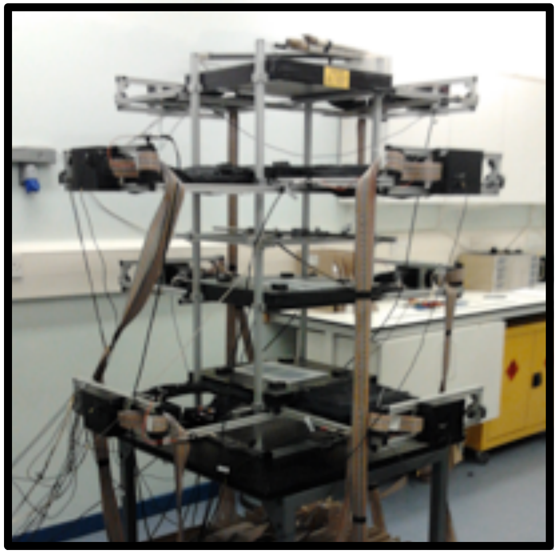
  Could a scintillating-fibre MT system be used in the non-destructive assay of legacy nuclear waste containers at Sellafield?



- Small-scale prototype designed and constructed in Glasgow after initial simulation studies confirmed the potential of the technology

- First imaging results on a test setup of objects are presented here

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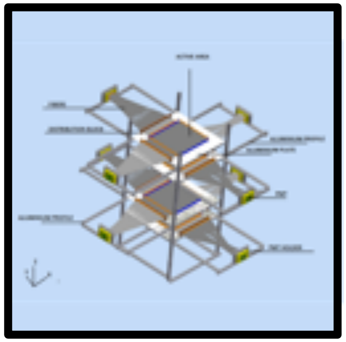

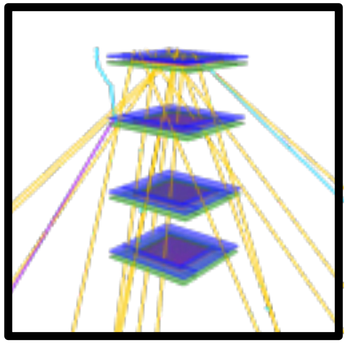

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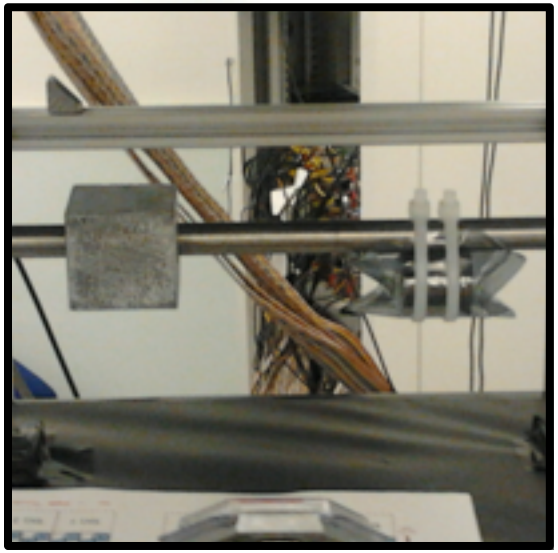

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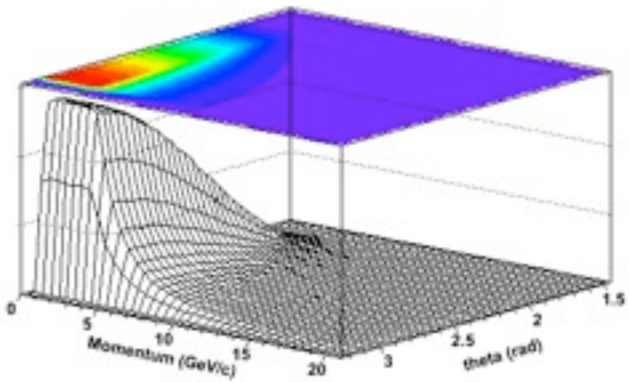
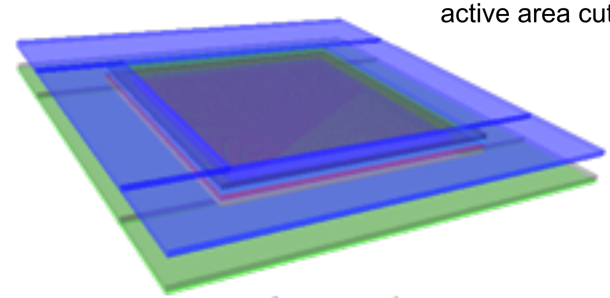
The Glasgow MT Detector:
Muon Event Generator and GEANT4 Simulation Studies



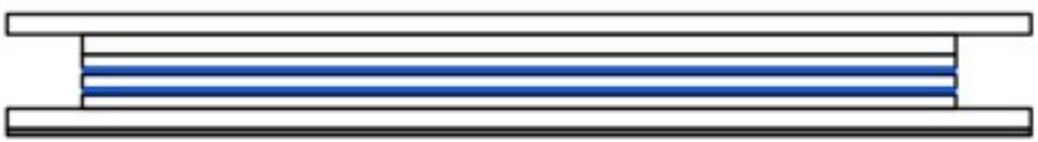
- Cosmic-ray muons are generated by a standalone code based on well established and accurately measured properties:
  - Mean momentum, p_{mean} of 3.35 GeV/c with $p^{-2.7}$ slope at high momenta
  - The angular distribution has a characteristic $\cos^2 \theta$ dependence
  - Muon flux of approximately $1 cm^{-2} min^{-1}$

top-down view of the module shows the active area cut out

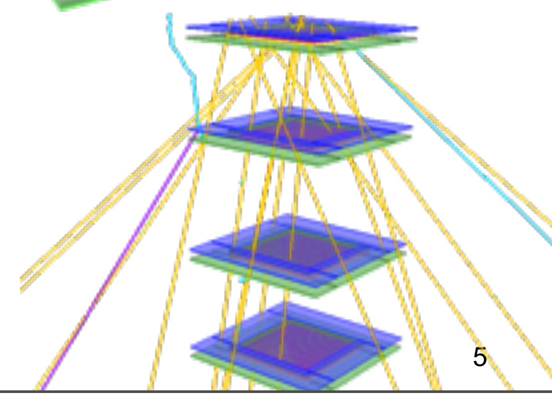


- GEANT4, developed at CERN, is the '*industry standard*' detector simulation framework in particle and nuclear physics

- 'Active' components of the module 'sandwich' structure and materials accurately modelled in GEANT4

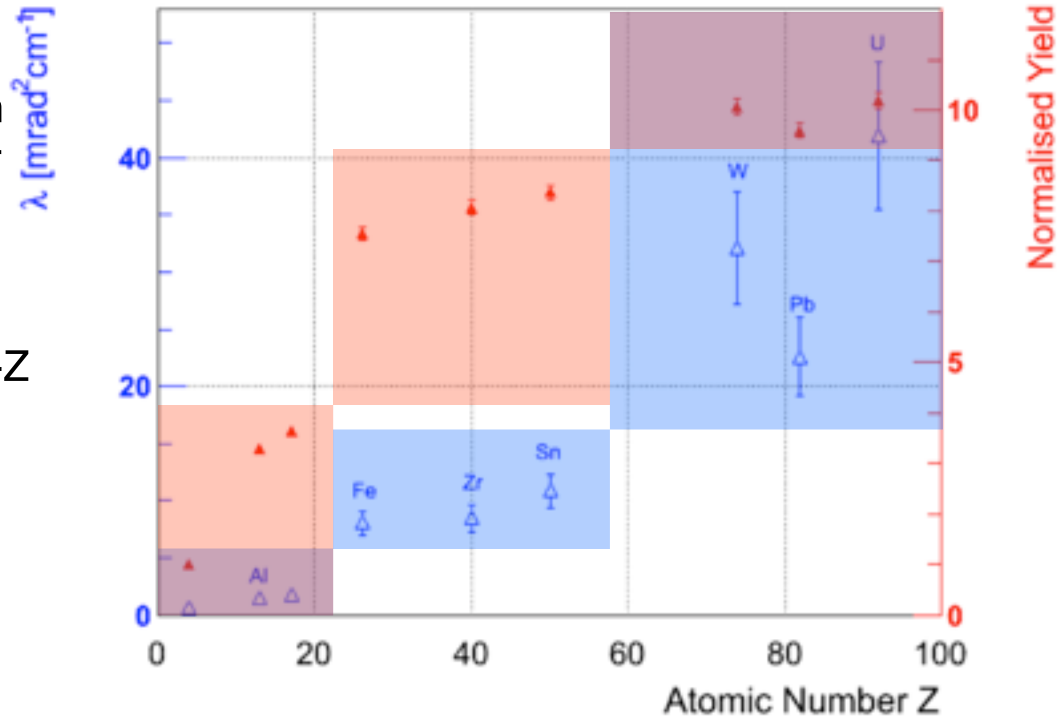


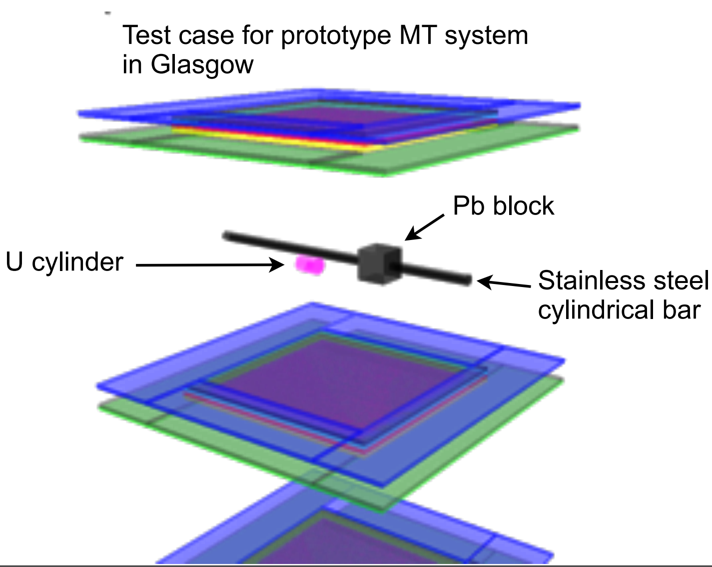
with 'V'-shaped grooves in X-plane (top-side) and Y-plane (under-side)



The Glasgow Detector:
More GEANT4 Simulation Studies

- Expected material discrimination obtained from GEANT4 simulations studies performed in an air matrix:
  - 10x10x10cm^3 blocks of material with 1 day muon exposure
  - Clear separation of low-, medium- and high-Z materials using scattering parameters



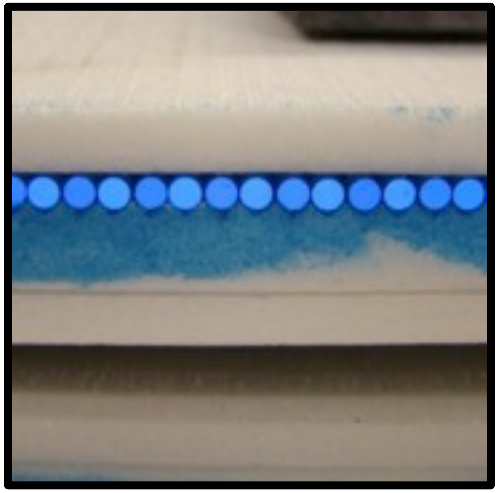


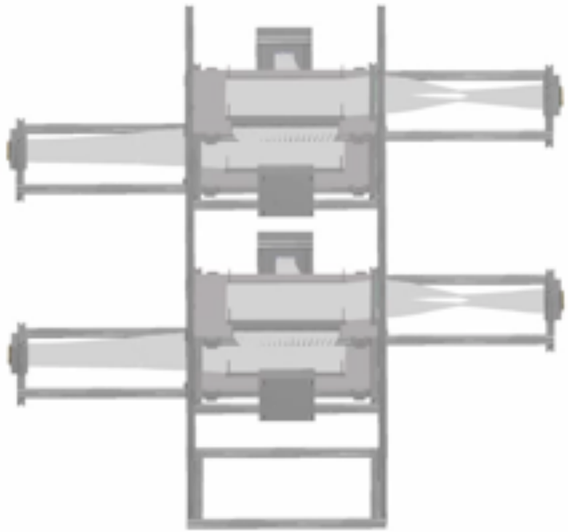
- Experimental test setup in Glasgow simulated (shown opposite without top module)
- Data taking commenced 2012 to verify the initial, promising simulation results

The Glasgow Detector:
Module Construction

- Prototype detector setup consists of four tracking modules
  - 2 orthogonal layers of 128 scintillating fibres
  - 'Sandwich' structure with flat and machine-grooved Rohacell® (polymethyacrylimide) support sheets and Aluminium baseplate

  - Layers bonded with optical glue
  - Tedlar® and nylon tubing ensure light-tightness





- Fibres held in place by custom-made distribution blocks at edges of Aluminium baseplate and PMT
- All four modules held in place in an Aluminium-profile stand with alignment pins in each module

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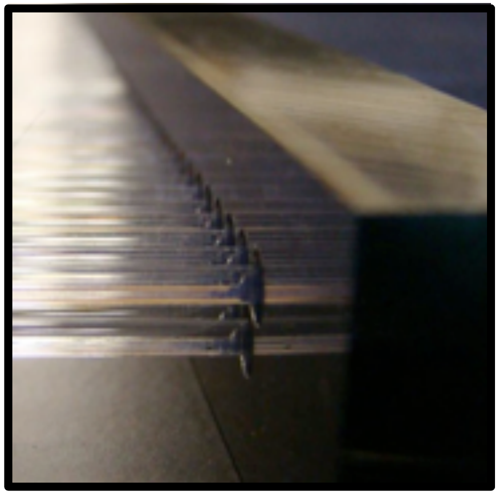

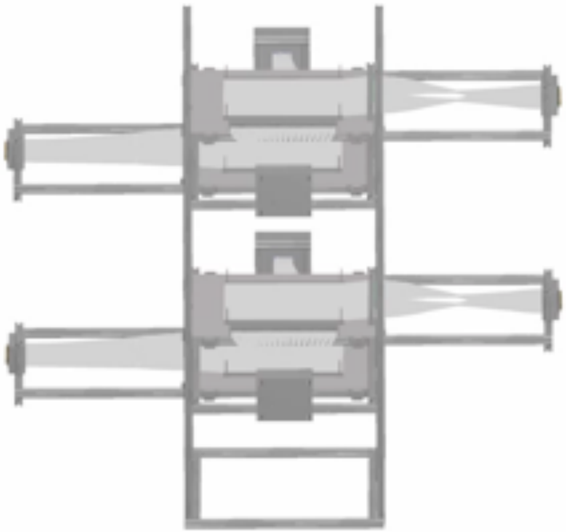

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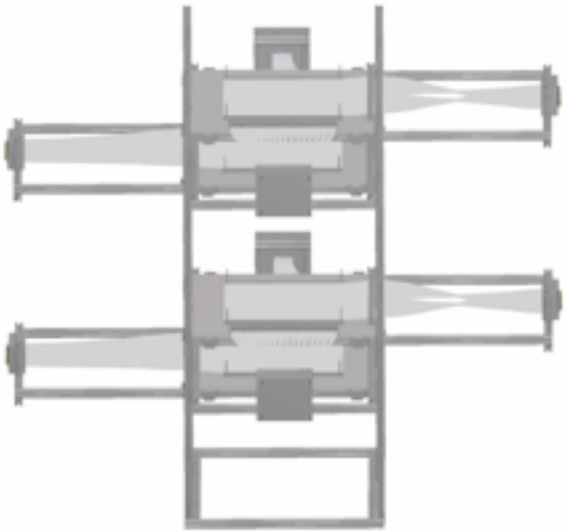

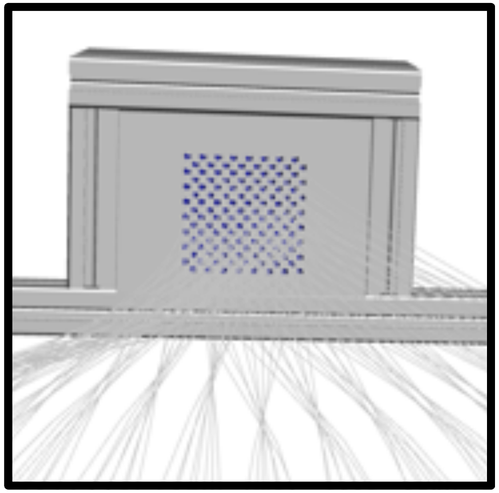

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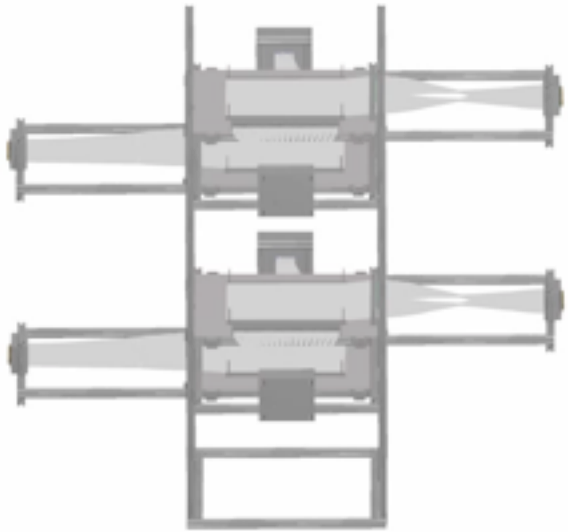

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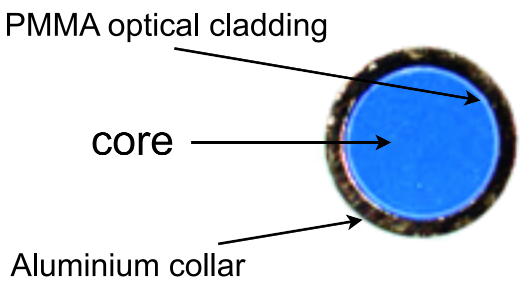
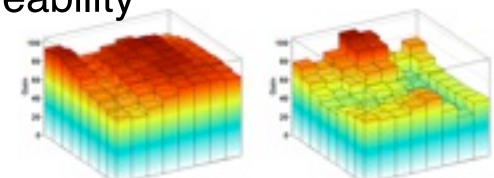
Detector Components:
Scintillating Fibres and Hamamatsu H8500 MAPMTs



- SAINT-GOBAIN scintillating fibres used
  - 2mm pitch with active core of 97% width
  - Polystyrene-based core with PMMA (polymethylmethacrylate) optical cladding (3% width)
- Polished fibre (shown opposite)
- Aluminium collars glued on to ensure uniform contact with PMT
- Chosen for their robustness and scaleability



PMT relative-gain maps

- HAMAMATSU H8500 MAPMT (8x8 array segmented anode)
- 2 fibres multiplexed to one pixel via a dedicated coupling scheme to ensure successful fibre identification
- PMTs gain-tested at operational voltages
- Custom-built PCB boards used to read-out to 32-channel CAEN QDC units

Hamamatsu
H8500 MAPMT (front view)

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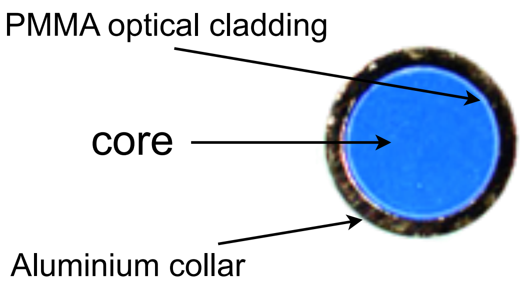

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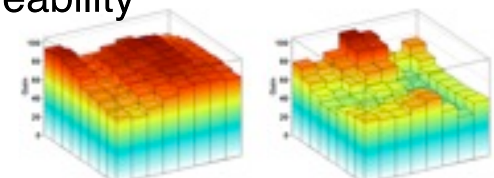

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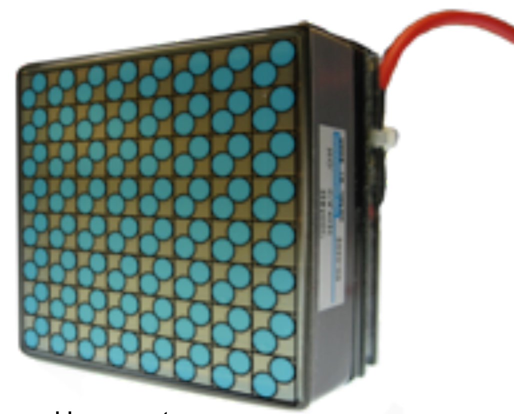
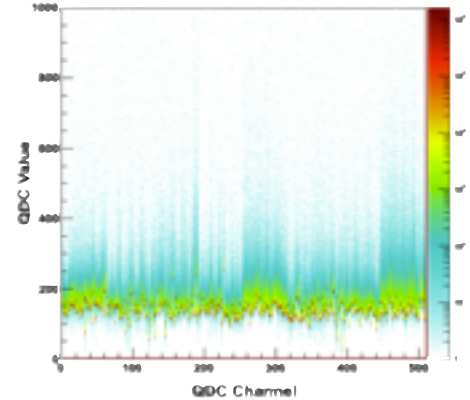
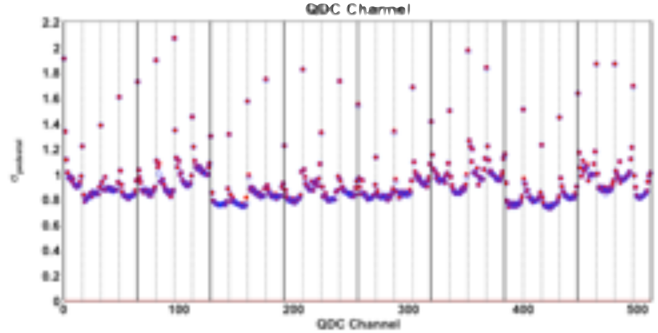


Hamamatsu
H8500 MAPMT (front view)

The Glasgow Detector:
Data-taking and Performance Studies

- Multi-fold trigger on Dynode-12 signals from the detector PMTs
- Highest gain-corrected QDC signal above pedestal chosen as ‘hit’
- Only events with a hit in each layer are analysed
- Narrow pedestals across the 512 QDC channels
- PMT characterisation and cross-talk investigations completed.
- Relative gain-maps obtained via laser scan
- Multiplicities (~1.5 clusters per 1[8] event across all PMTs)
- Detector performance stable over long time periods
- Alignment optimisation undertaken to compensate for minor structural misalignments (less than 5mm)





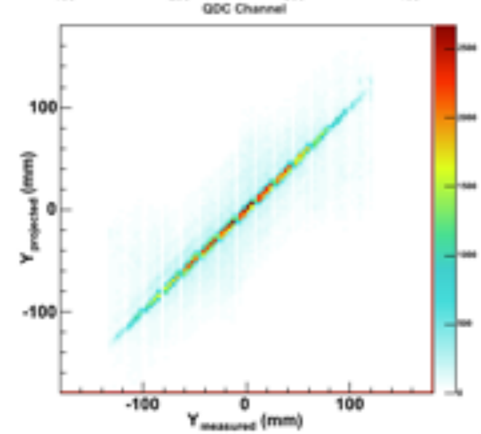


Image Reconstruction:

Maximum Likelihood Expectation Maximisation (ML-EM)

L. Schultz *et al.*, "*Statistical Reconstruction for Cosmic Ray Muon Tomography*" - IEEE Transactions on Image Processing **16** (2007)

- Imaging volume is split into small volume elements called voxels
- Prior knowledge of the Point of Closest Approach (PoCA) is needed
- This method provides information on every voxel the muon is assumed to have passed through.
- The scattering likelihood of the *i*th muon in the *j*th voxel is expressed as:

$$S_{ij}^{(n)} = f(\Delta x, \Delta\theta_x, L_{ij}, T_{ij}, \lambda_j^{(n)})$$

- where Δx and $\Delta\theta_x$ are the spatial and angular deviations of the track (in the x direction) due to scattering, L_{ij} is the pathlength in the voxel, T_{ij} is the 3-D pathlength from the voxel exit point to the exit point from the imaging volume (shown opposite) and $\lambda_j^{(n)}$ is the λ value of the current iteration.
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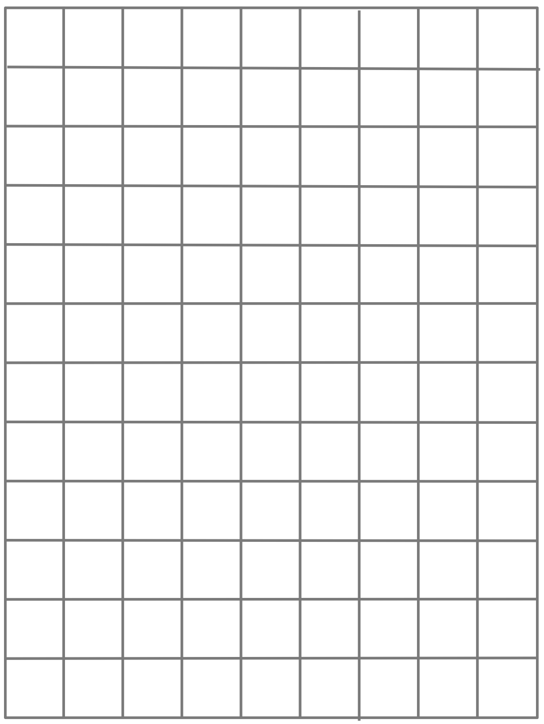

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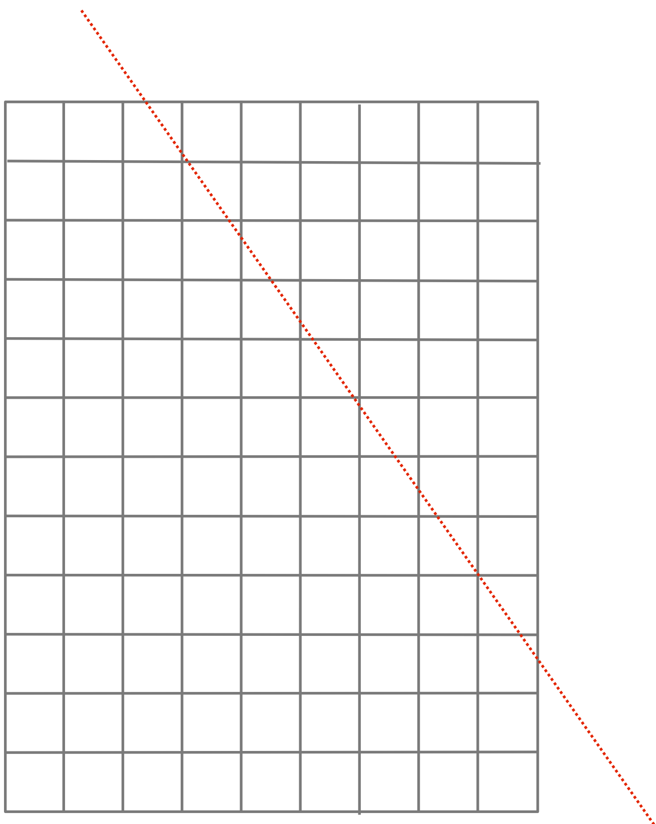
track from top modules



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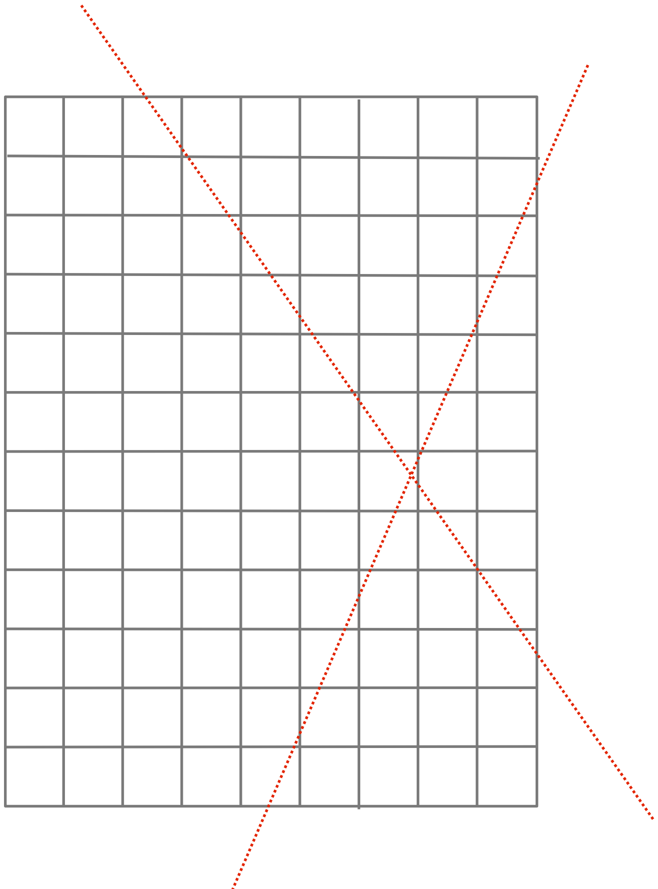

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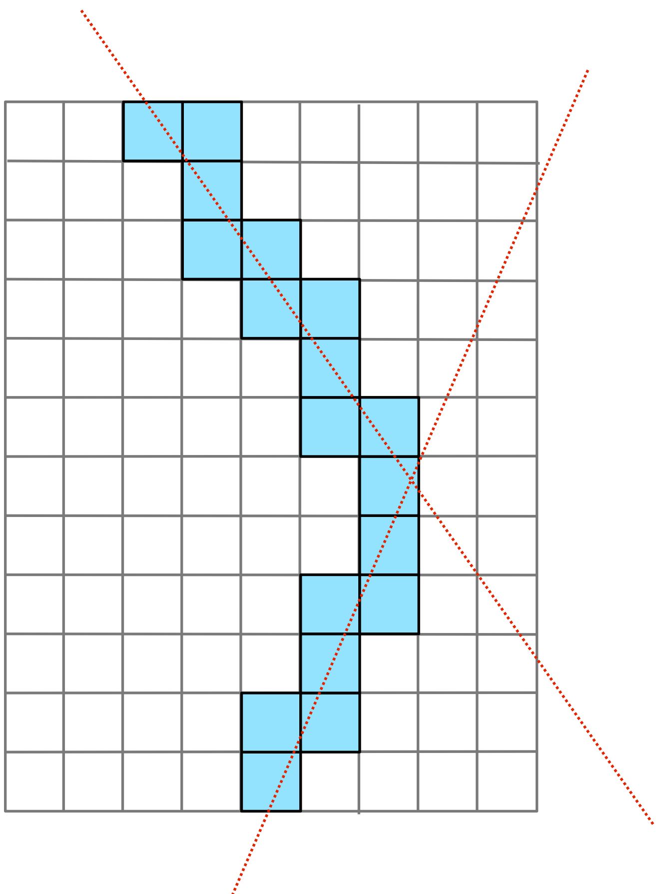

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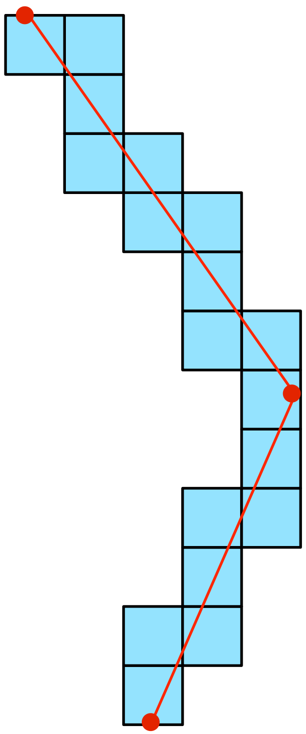

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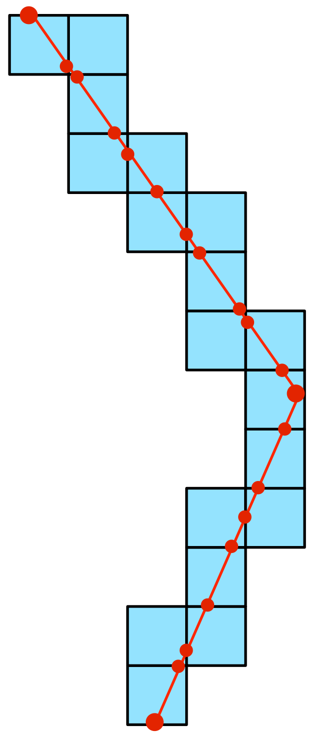

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- The scattering likelihood of the *i*th muon in the *j*th voxel is expressed as:

$$S_{ij}^{(n)} = f(\Delta x, \Delta\theta_x, L_{ij}, T_{ij}, \lambda_j^{(n)})$$

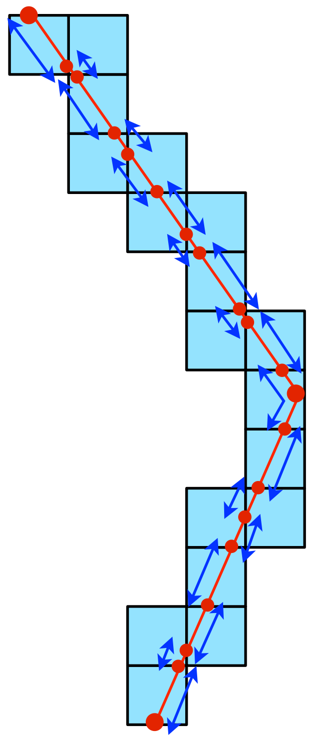
- where Δx and $\Delta\theta_x$ are the spatial and angular deviations of the track (in the x direction) due to scattering, L_{ij} is the pathlength in the voxel, T_{ij} is the 3-D pathlength from the voxel exit point to the exit point from the imaging volume (shown opposite) and $\lambda_j^{(n)}$ is the λ value of the current iteration.
- The λ value of the next iteration is determined as:

$$\lambda_j^{(n+1)} = \frac{1}{M_j}\sum_i S_{ij}^{(n)}$$

- Iteration continues until convergence, i.e. the most likely value has been found.

Image Reconstruction:
Maximum Likelihood Expectation Maximisation (ML-EM)

L. Schultz *et al.*, "*Statistical Reconstruction for Cosmic Ray Muon Tomography*" - IEEE Transactions on Image Processing **16** (2007)



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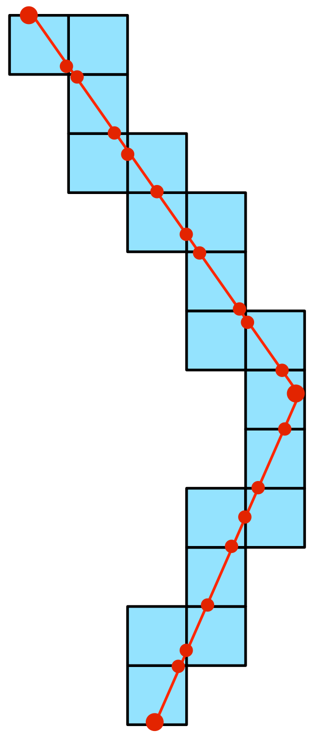

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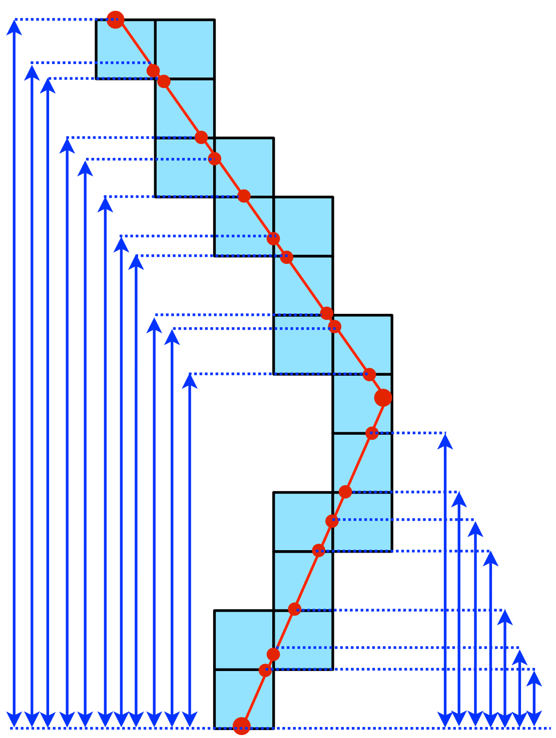

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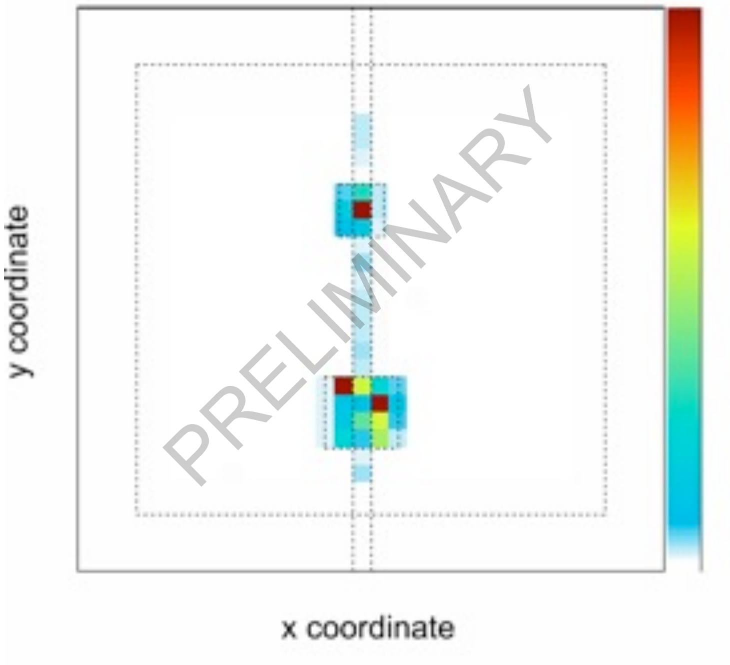
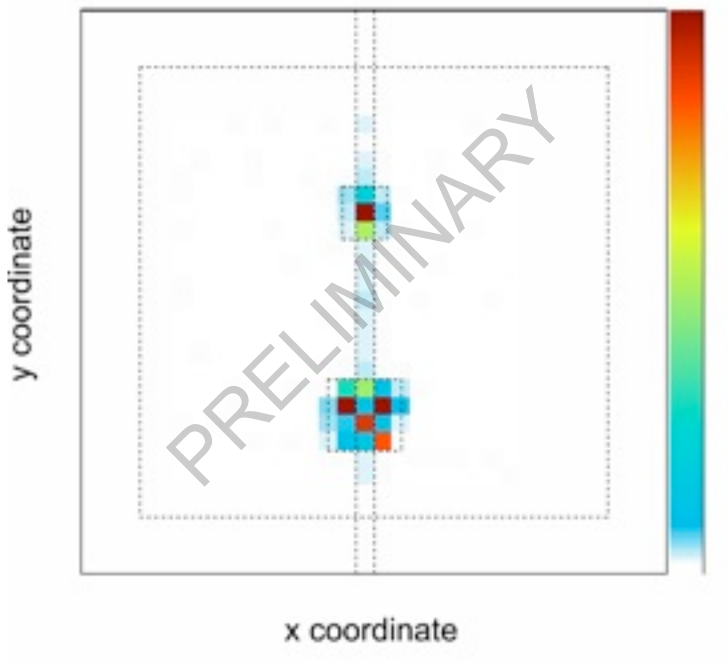
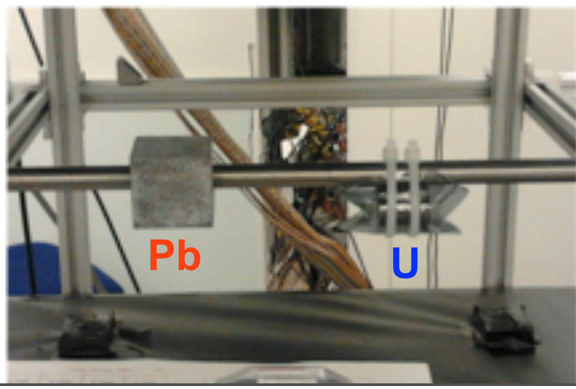
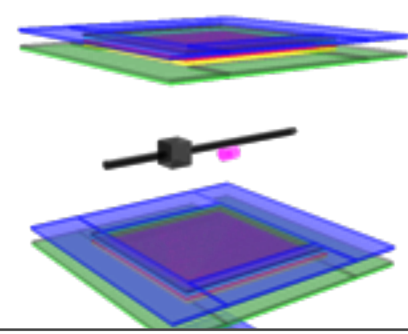
Data	Simulation

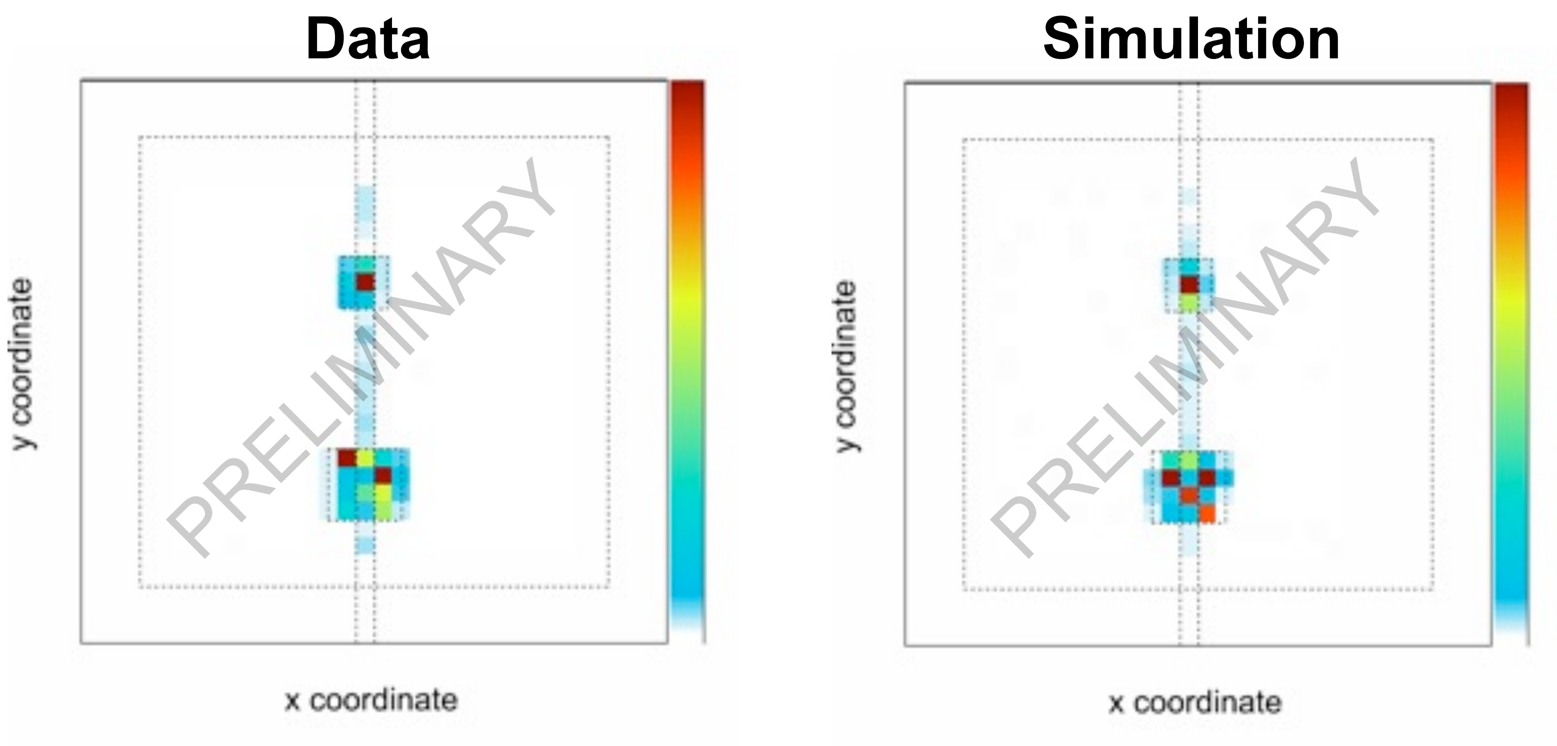








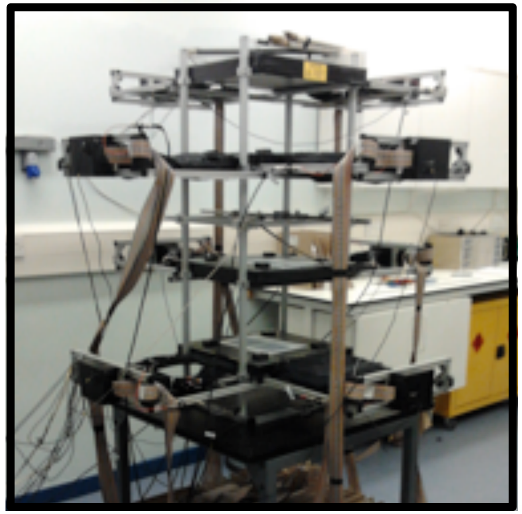
Preliminary Results

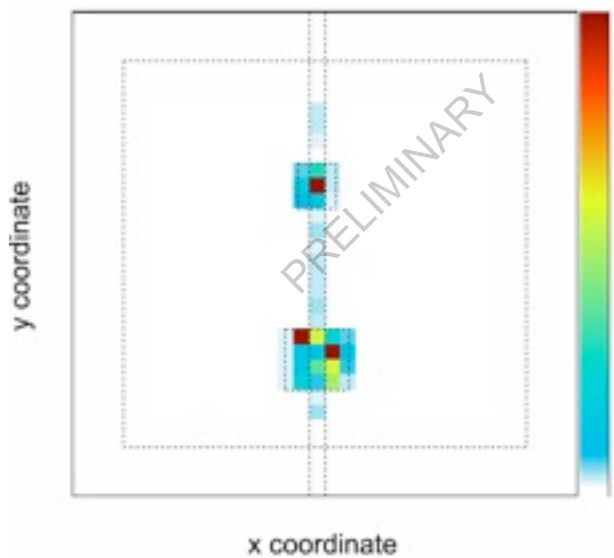


- Excellent agreement between the experimental data taken on the prototype detector and the simulated data
- Clear separation observed between the air, steel bar and the two high-Z materials

Summary

- Muon tomography is increasingly being used in the non-destructive assay of large and/or shielded objects with applications in fields ranging from archaeology to national security
- In collaboration with the UK National Nuclear Laboratory, the Nuclear Physics group at the University of Glasgow has developed and constructed a prototype MT system using scintillating fibres
- First results from this small-scale prototype in Glasgow verify initial simulation and feasibility studies by discriminating between low-, medium- and high-Z materials
- Work underway on the development of a full-scale detector system with a view to imaging legacy waste containers





University of Glasgow

Acknowledgements

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In addition, on behalf of the project, I would like to acknowledge the funding contribution from the NDA and Sellafield Ltd. which enabled this research to be undertaken.

NDA Nuclear Decommissioning Authority

Sellafield Ltd