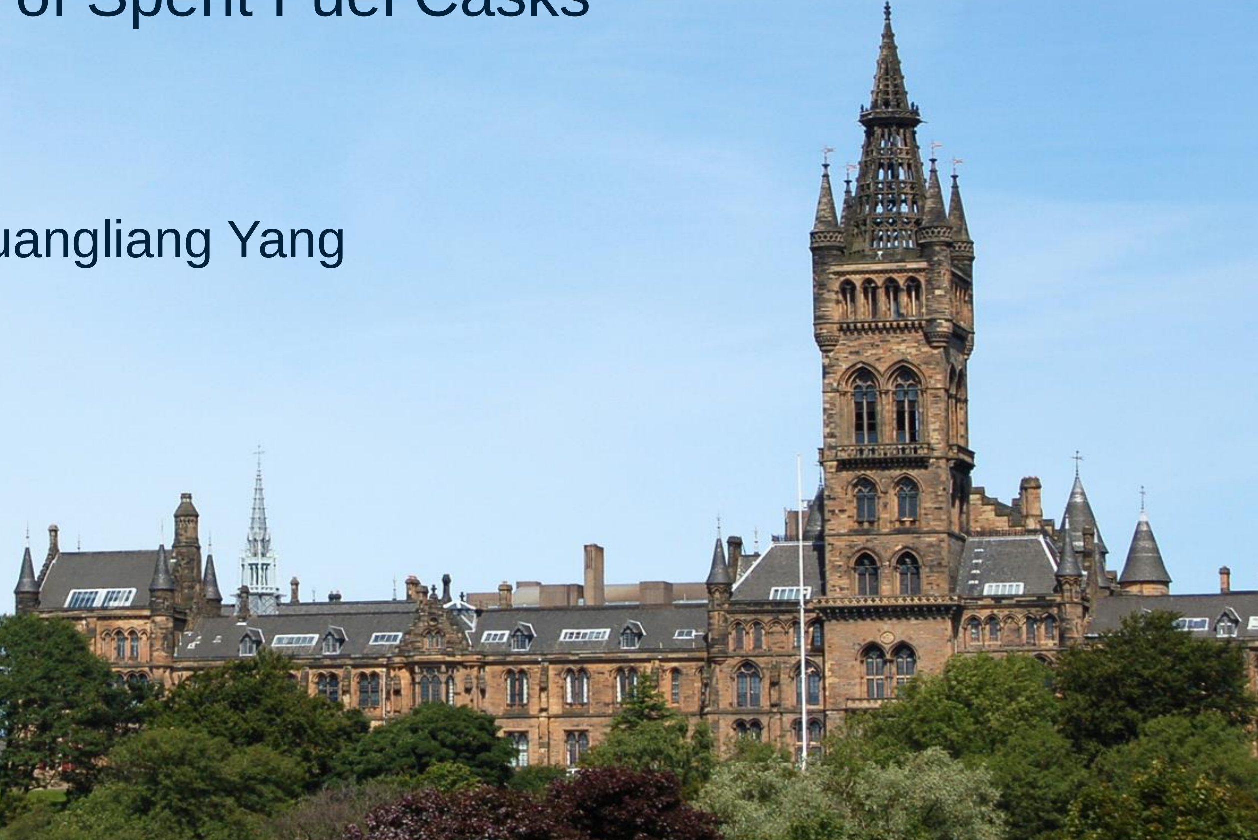
Geant4 Simulation of Multimodal Detector System for Tomographic Imaging of Spent Fuel Casks

University of Glasgow

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Guangliang Yang

Tuesday 11th October 2022



The multimodal tomographic imaging system.

- This multimodal imaging system includes the muon, gamma, and neutron tomography imaging sub systems.

- Muon tomography imaging has an excellent penetrating power, which enables it to detect the absence of spent fuel.

- Gamma and neutron can provide fingerprints for the nuclear materials.

Why need to be multimodal?

- The difficulty faced by muon tomography imaging is that it does not possess the capability to discriminate the spent fuel and the fresh fuel as they have the same density and atomic number.
- Due to the heavy shielding for the spent fuel casks, very little radiation can leave the casks, and the imaging time needed for a high-quality image is correspondingly very long.
- By combining the attenuation and multiple scattering muon imaging, it is possible to discriminate the material according to their average atomic number

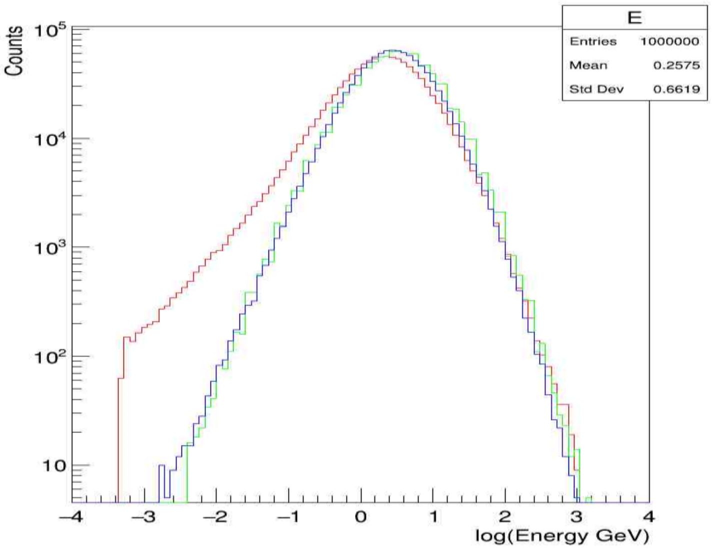
Work tasks

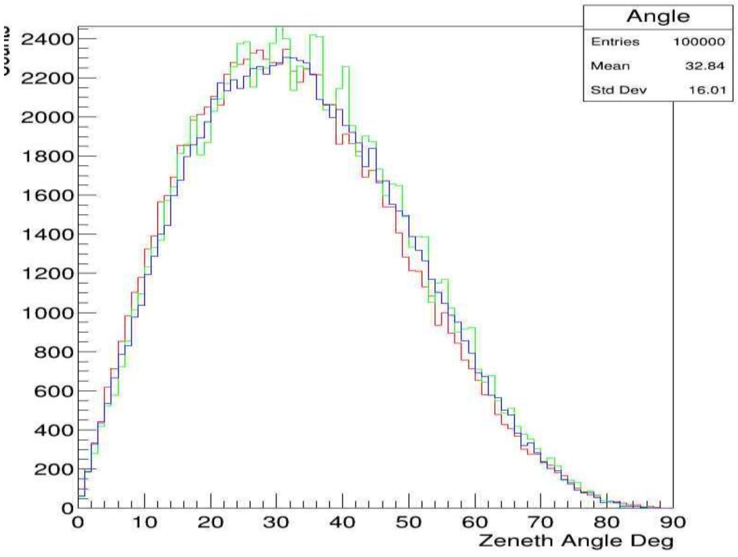
- The first task is to develop a Geant4 simulation framework;

- the second task is to verify the simulation code and run the simulation code to generate data.

G4 Simulation: Event Generator

- Muon: three muon event generator were integrated into G4 simulation code, which are CRY, EcoMug, and the muon Generator developed by S. Chatzidakis.
- Gamma: gamma energy was sample from a histogram, which histogram can be provider by user.
- Neutron: LLNL fission library 2.0.2 was used.





G4 Simulation: Detector Construction

- For gamma and neutron, ideal detector was used.
- For muon, drift detector system was used.

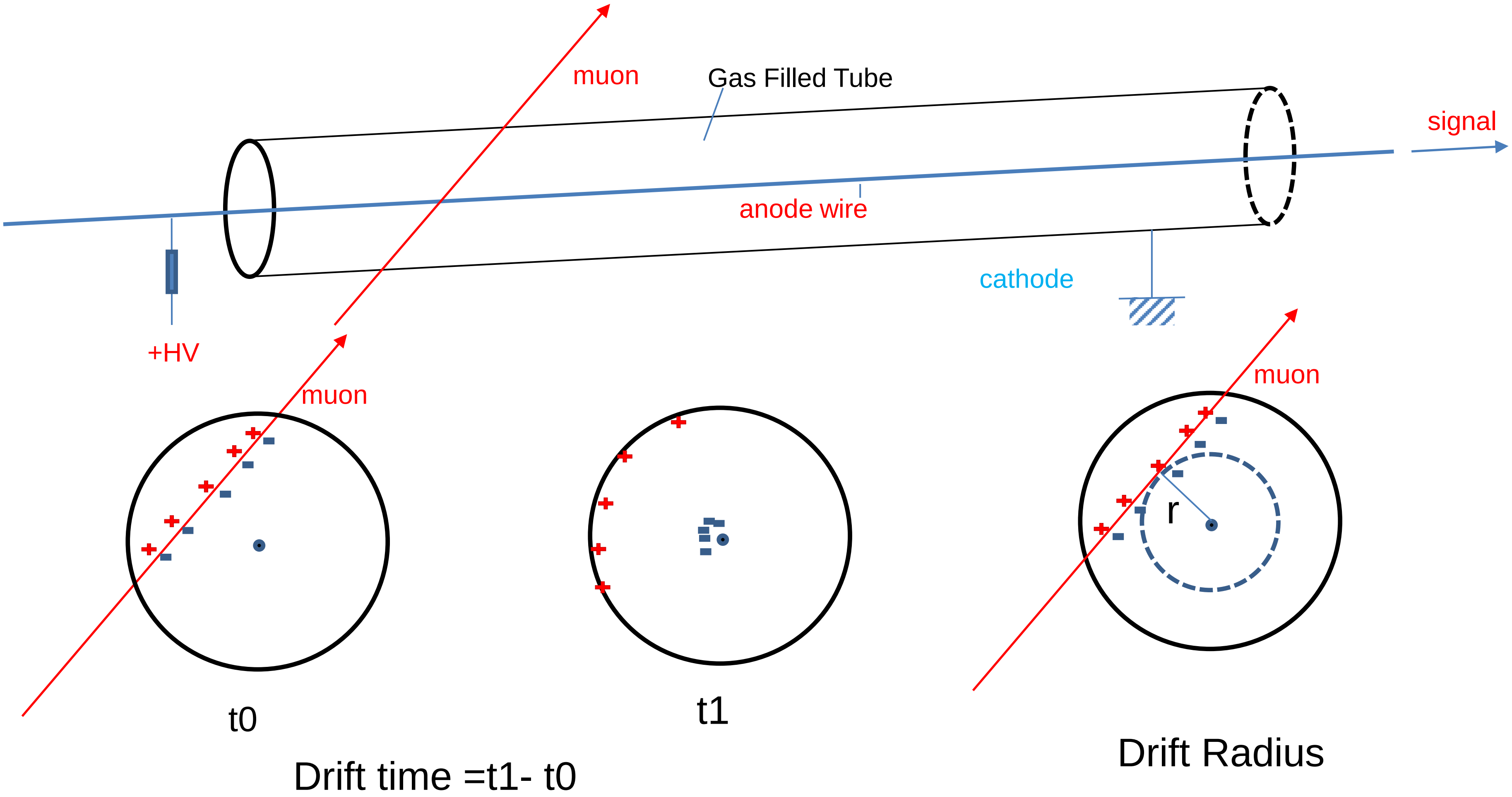
1st muon tomography detector, Los Alamos 2003
(Green at al., 2006)

Decision Sciences prototype MMPDS™
(Milner et al., 2012)

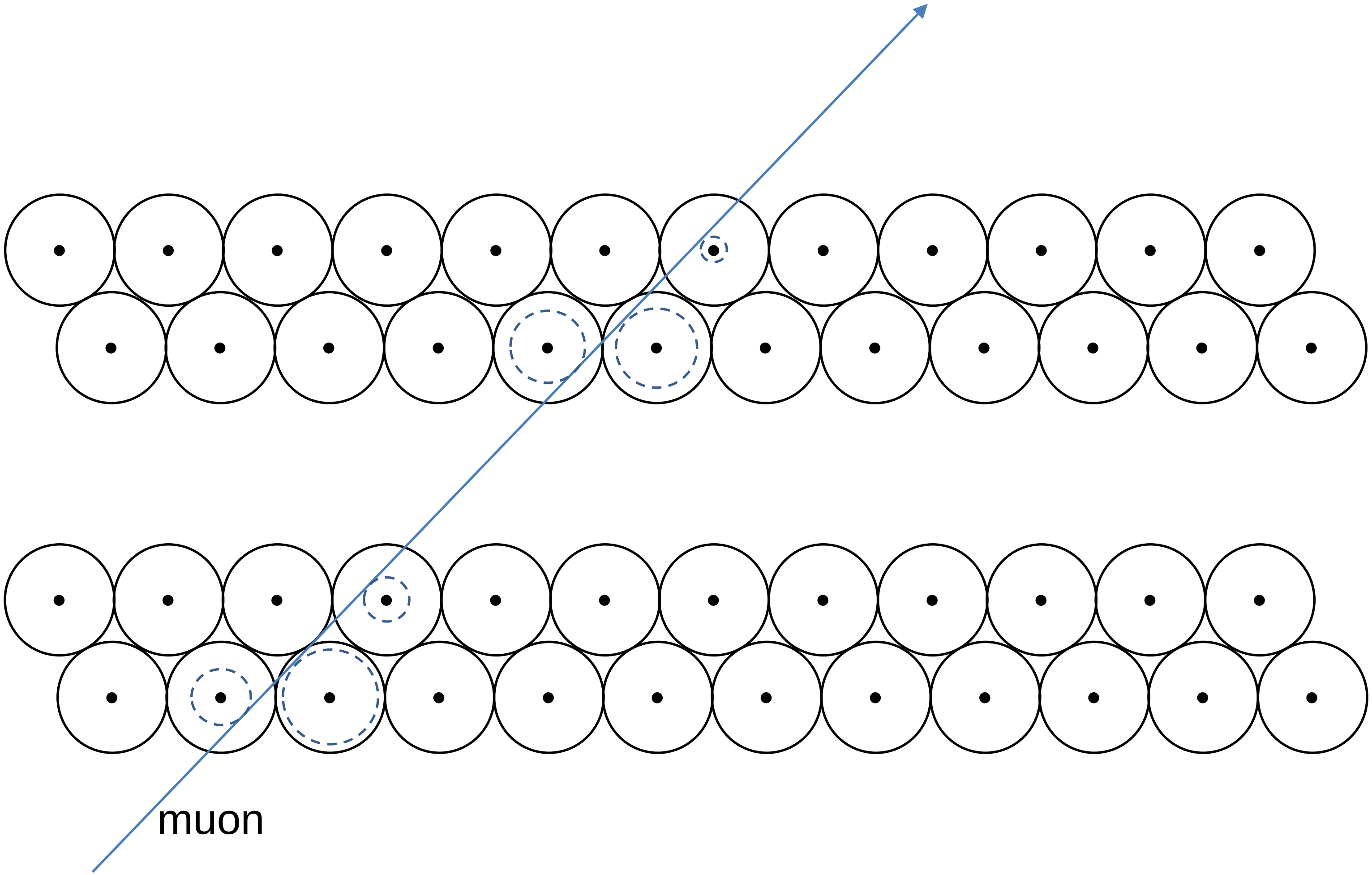
G4 Simulation: Event Analysis

- For gamma and neutron, the information about momentum direction, time, hitting position are extracted from the ideal detector. (i.e. read from the G4 results)
- For Muon, detailed drift detector analysis was implemented.
  - Task 1, drift radius calculation, add uncertainty to the calculated drift radius.
  - Task 2, find out muon hit patterns, eliminate noise event.
  - Task 3, reduce the effect of delta ray on the muon tracks.

Principle of drift detector



How to measure Muon tracks

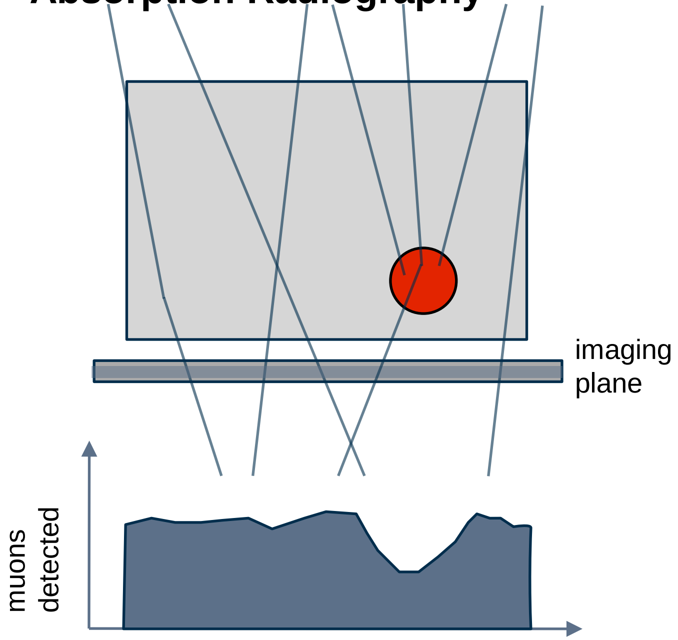


G4 Simulation: multiple scattering model

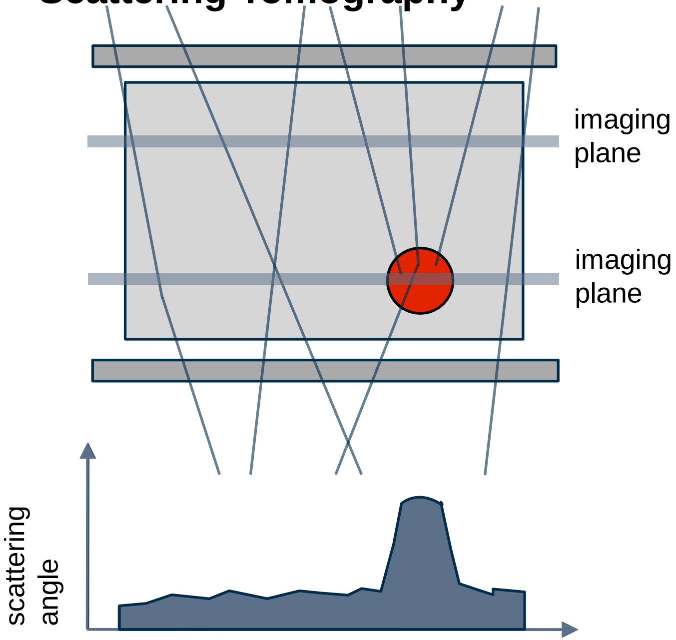
- The multiple scattering model can be chosen from the WentzelVI combined scattering model, the Urban MSC model, and the single scattering model.
- The WentzelVI combined scattering model is the current Geant4 default multiple scattering model.
- The Urban multiple scattering model was the previous default MSC model.
- The single scattering model is the gold standard, which can be used to verify all the other models.

Image reconstruction Methods

Absorption Radiography



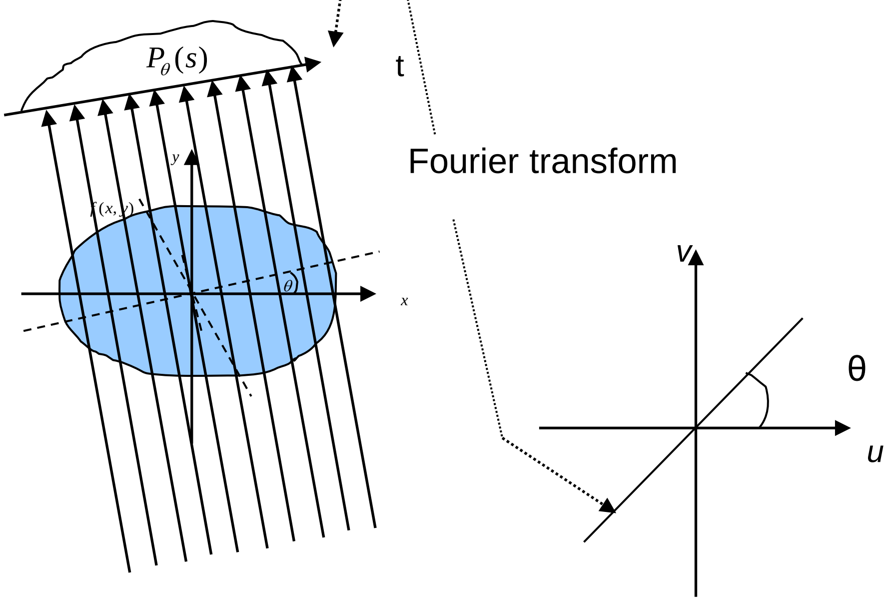
Scattering Tomography



Higher density material absorbs muons and material with higher atomic number Z scatters muons through larger angles. It is possible combine all available information to improve the image quality.

The Fourier Slice Theorem

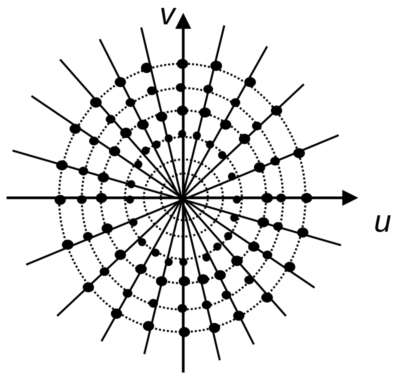
The Fourier Slice theorem relates the Fourier transform of the object along a radial line.



Space Domain

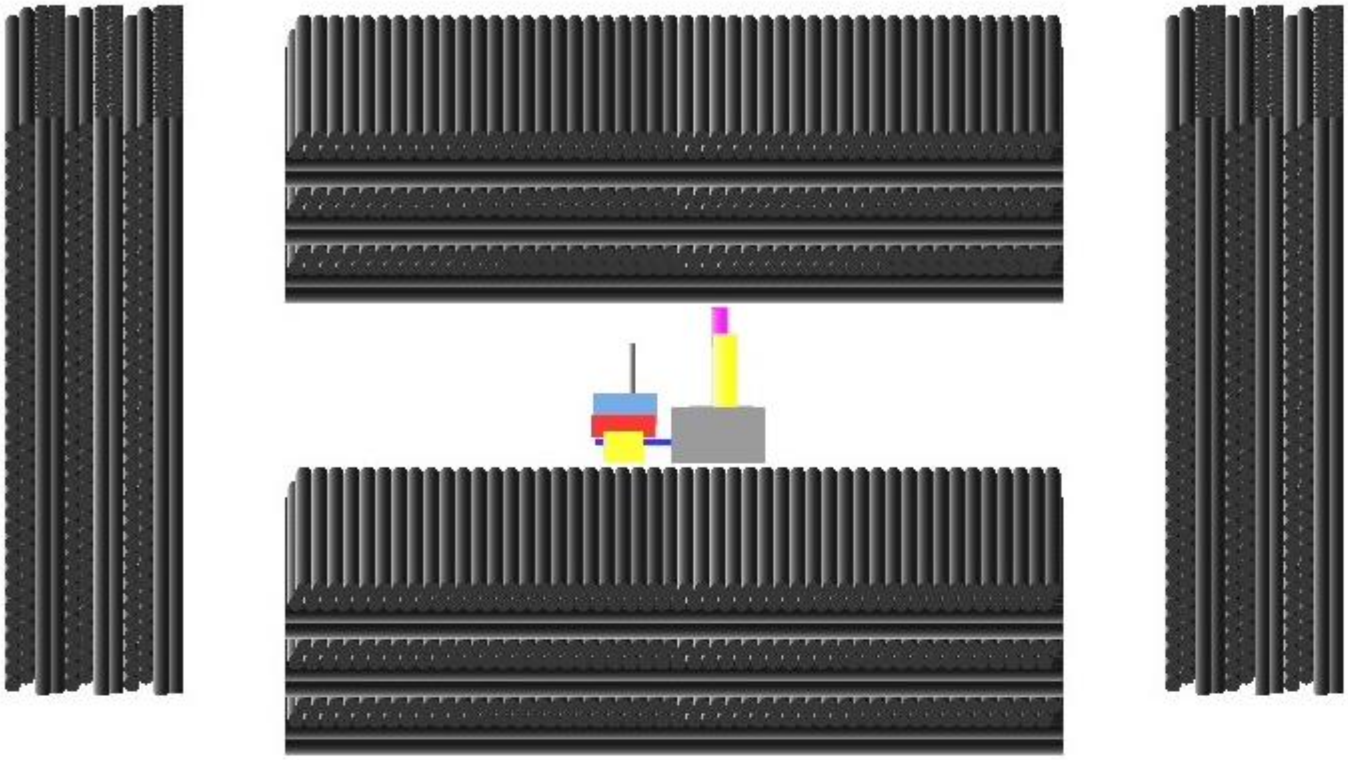
Frequency Domain

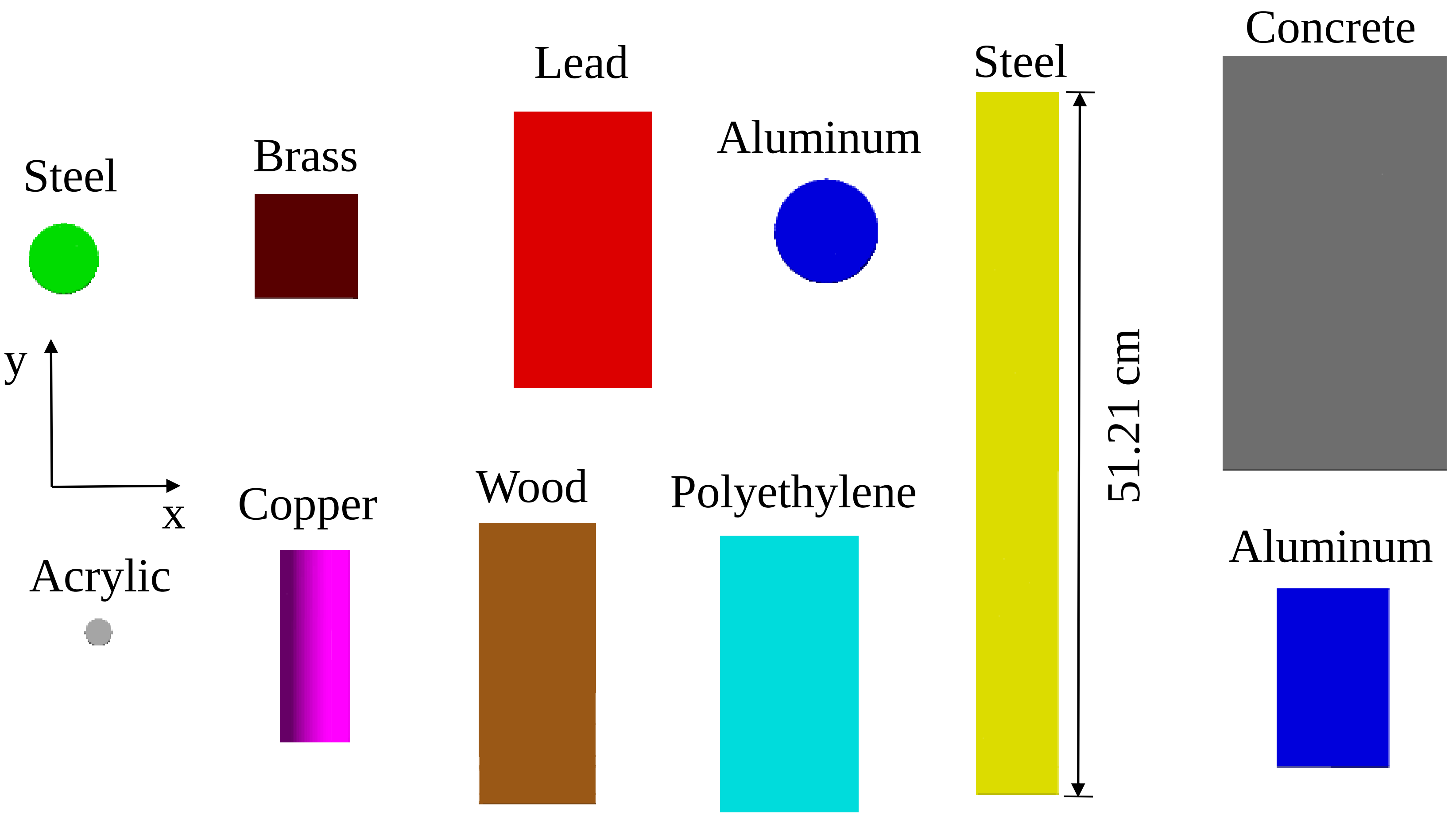
Collection of projections of an object at a number of angles



For the reconstruction to be made it is common to determine the values onto a square grid by linear interpolation from the radial points. But for high frequencies the points are further apart resulting in image degradation.

Geat4 Simulation of the Los Alamos GMT

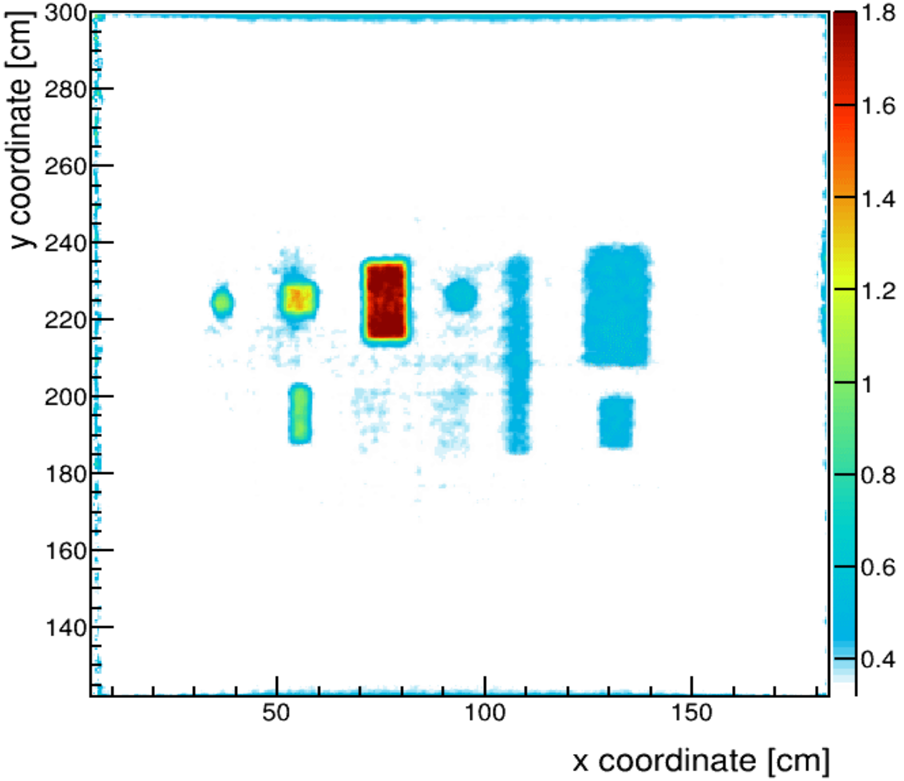



Concrete
Lead
Steel
Aluminum
Steel
Brass
y
x
51.21 cm
Copper
Wood
Polyethylene
Aluminum
Acrylic

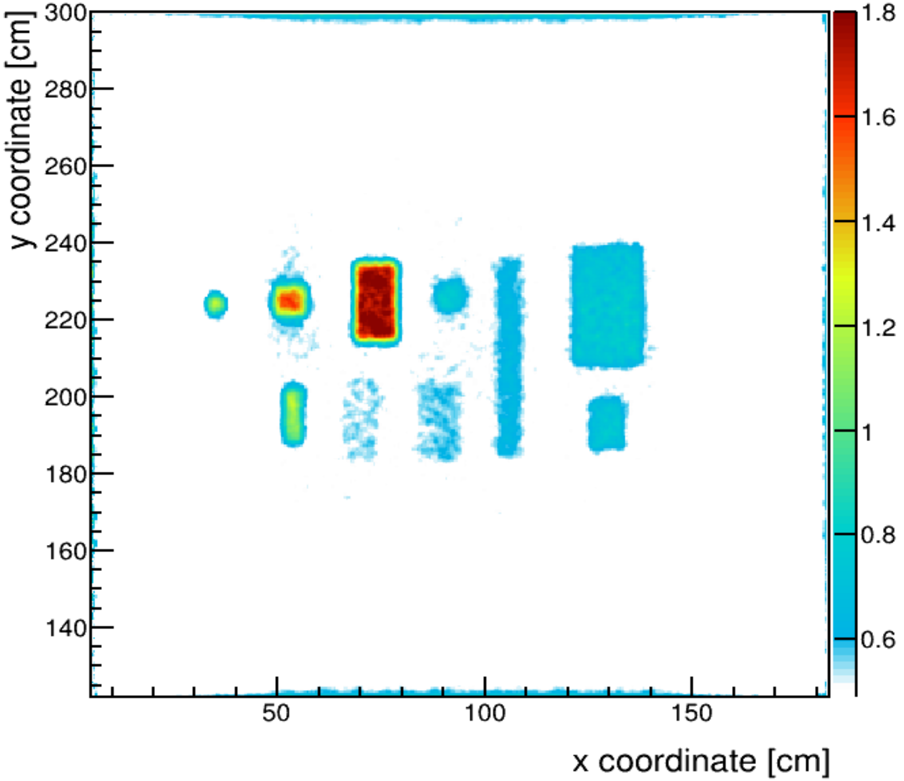
Scan 1

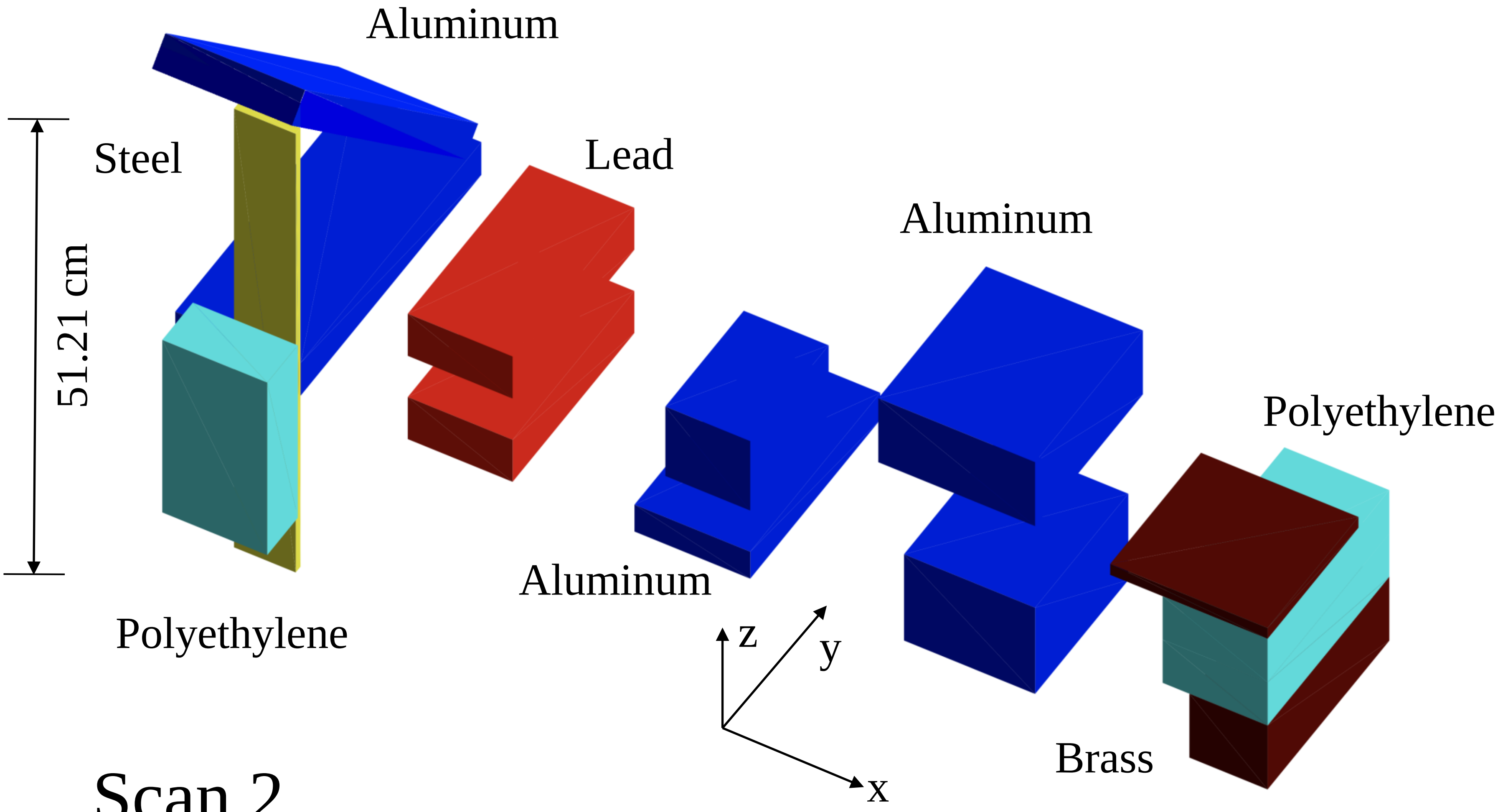
z = 108 cm. Slice thickness : 6 cm
60M simulated/measured muons

GMT Scan 1



Simulation Scan 1

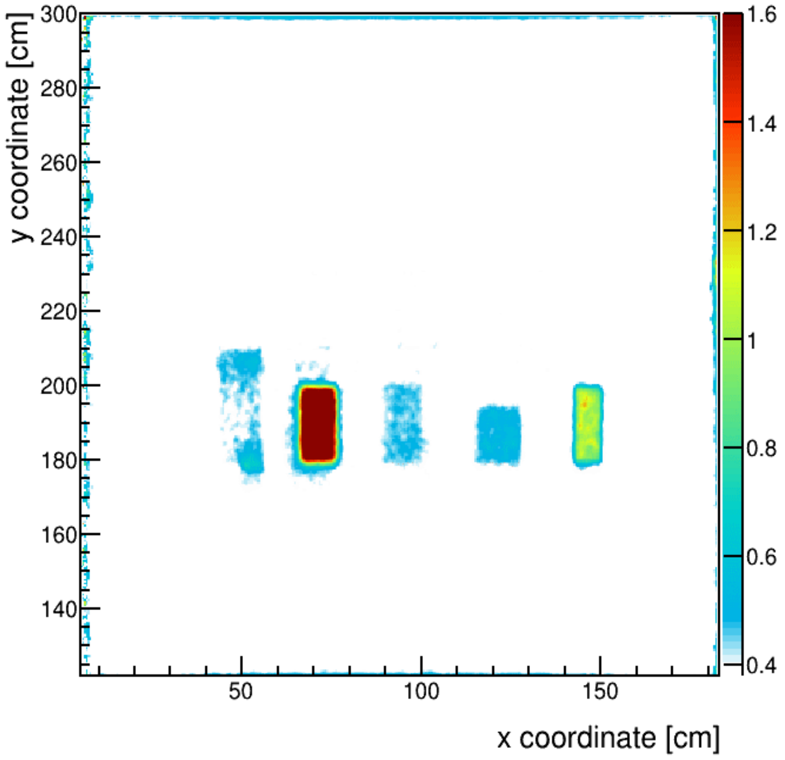



Aluminum
Steel
Lead
Aluminum
51.21 cm
Polyethylene
Aluminum
Polyethylene
Brass
z
y
x

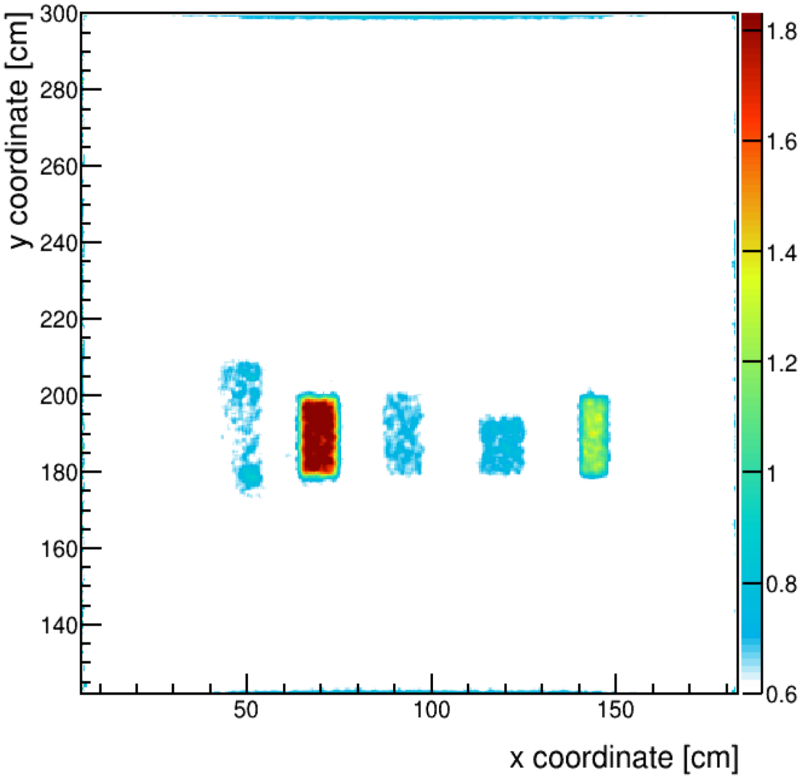
Scan 2

z = 108 cm. Slice thickness : 3 cm
60M simulated/measured muons

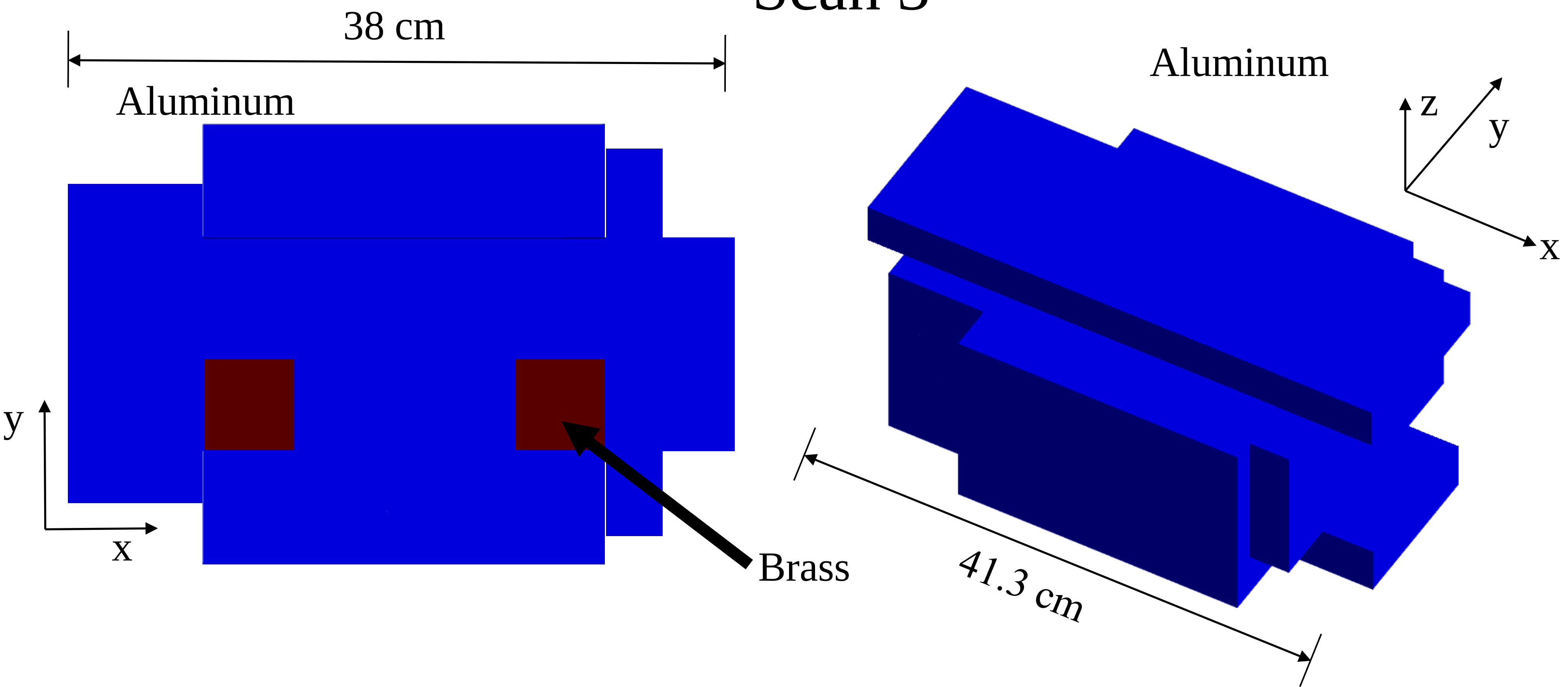
GMT Scan 2



Simulation Scan 2

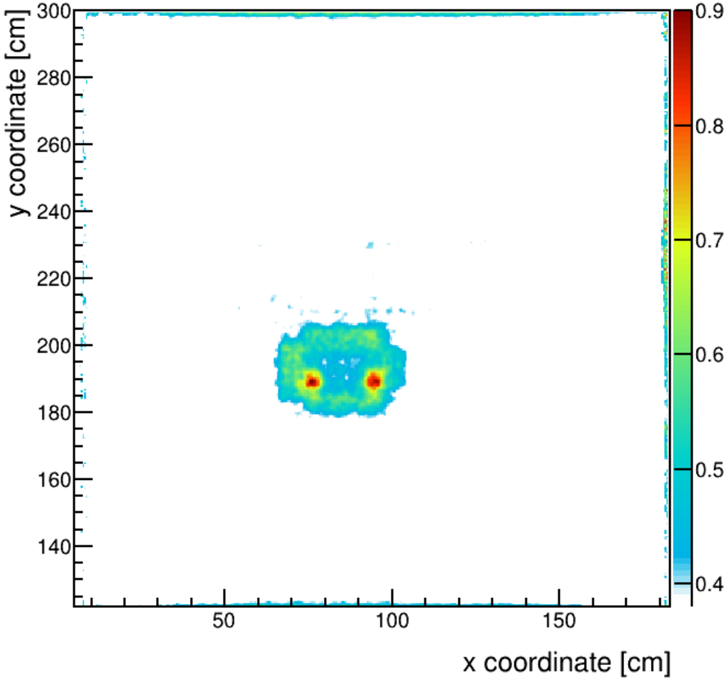


Scan 3

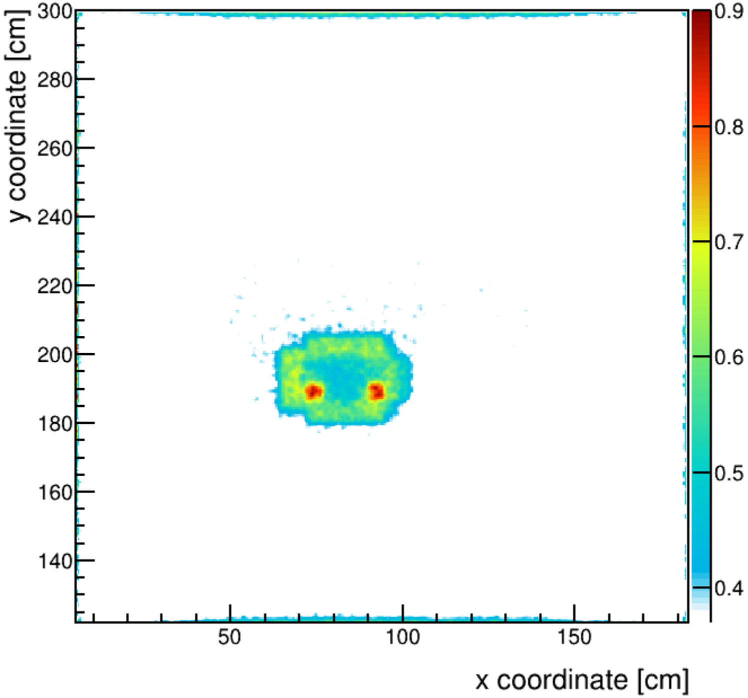


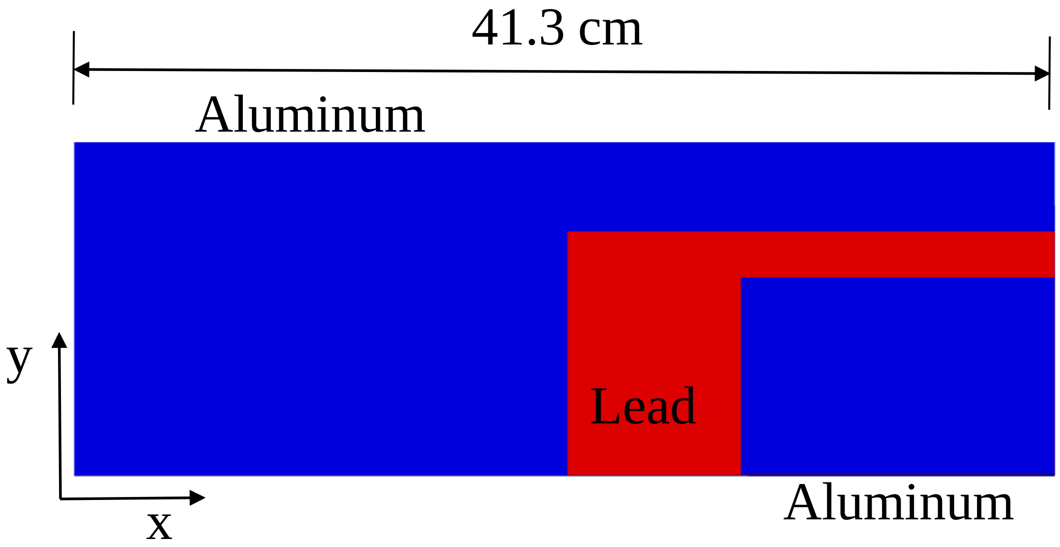
z = 108 cm. Slice thickness : 6 cm
60/50M simulated/measured muons

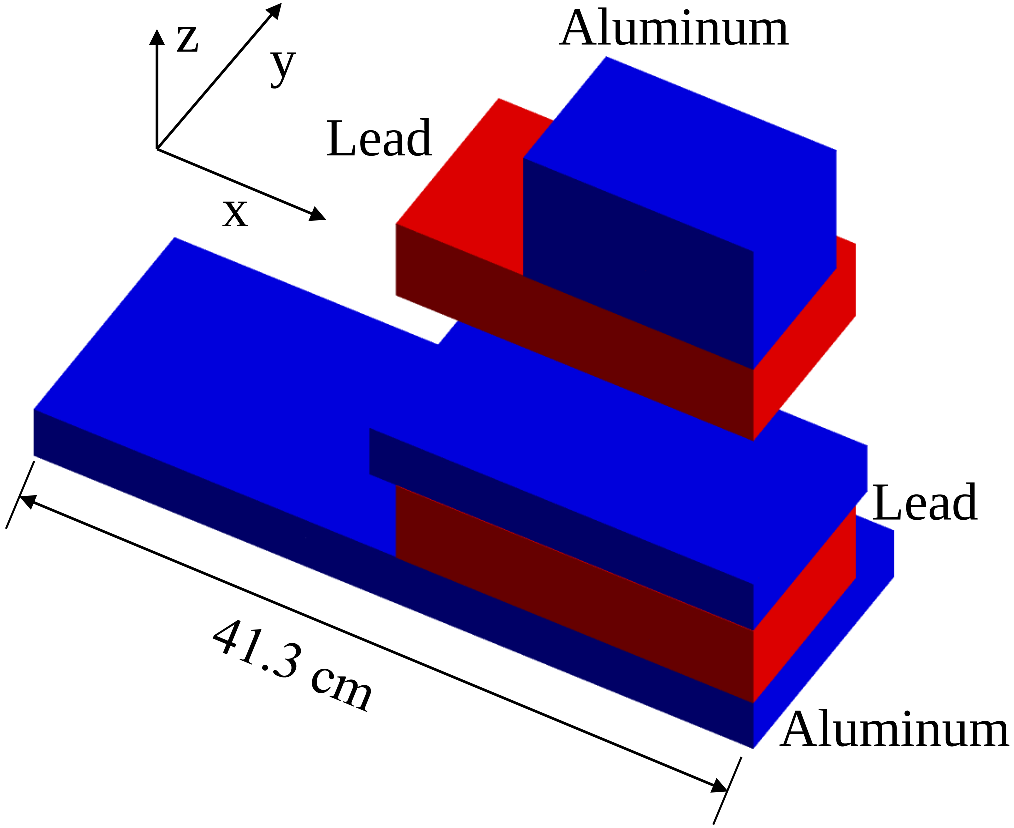
GMT Scan 3



Simulation Scan 3



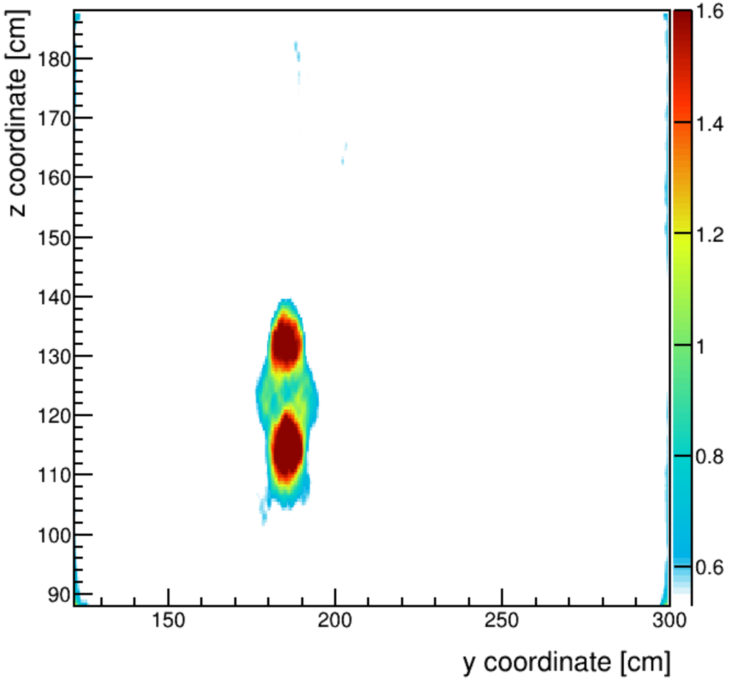

41.3 cm
Aluminum
Lead
Aluminum
y
x


z
y
x
Aluminum
Lead
Lead
Aluminum
41.3 cm

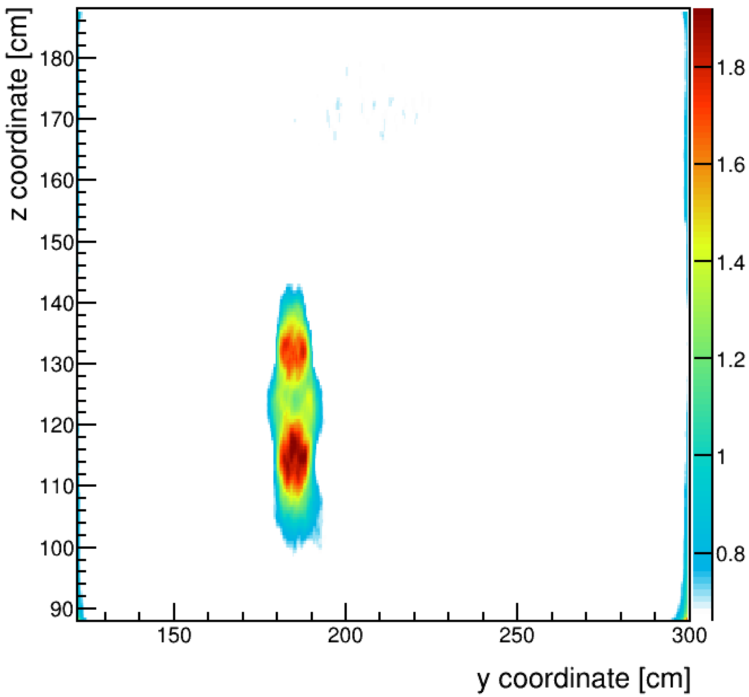
Scan 4

z = 91 cm. Slice thickness : 6 cm
60/41M simulated/measured muons

GMT Scan 4



Simulation Scan 4



Conclusions

A Geant4 simulation framework has been developed, which can be used to simulate muon, gamma and neutron tomography imaging.

This Geant4 simulation framework featured multiple event generators.

A detailed simulation of a drift tube detector system was carried out.

The simulation results was checked against the measured results, which shows excellent agreement.

Thank You !

Geat4 Simulation of MC-10 Cask