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Title: Muon Tomography at Los Alamos

Author(s): Perry, John O.

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Muon Tomography at Los Alamos

John Perry, P-25, LANL
Threat Reduction Team

Los Alamos
NATIONAL LABORATORY
EST.1943

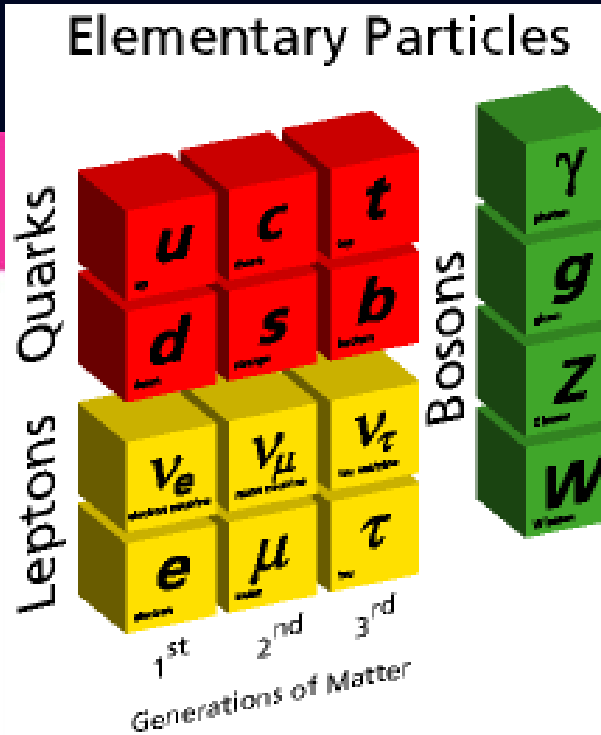
A Matter of Teamwork

- Threat reduction team and muon team
  - Chris Morris, John Perry, Jeff Wang, Joe Fabritius, Daniel Poulson, Elena Guardincerri, Matt Durham, Jeff Bacon, Alexei Klimenko, and more!
- Many Sponsors
  - DTRA, DOS, DOE
- Collaborators
  - DSIC, NSTec, Toshiba

Outline

- Cosmic-ray muon background
- Mini Muon Tracker (MMT)
- Muon interactions with matter
  - Energy loss
  - Multiple Coulomb scattering
  - Muon induced fission
- Horizontal reactor imaging - Fukushima
  - Mock reactor
  - Fukushima simulations and measurements
  - UNMRR measurements
  - Japan NCA measurements
  - Next steps to Fukushima
- Carbon fiber tubes and the future of muon tomography

What is a Muon?



τ

Tauon

Mass	1,780 MeV/c²
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/ Antimatter	M

μ

Muon

Mass	106 MeV/c²
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/ Antimatter	M

e

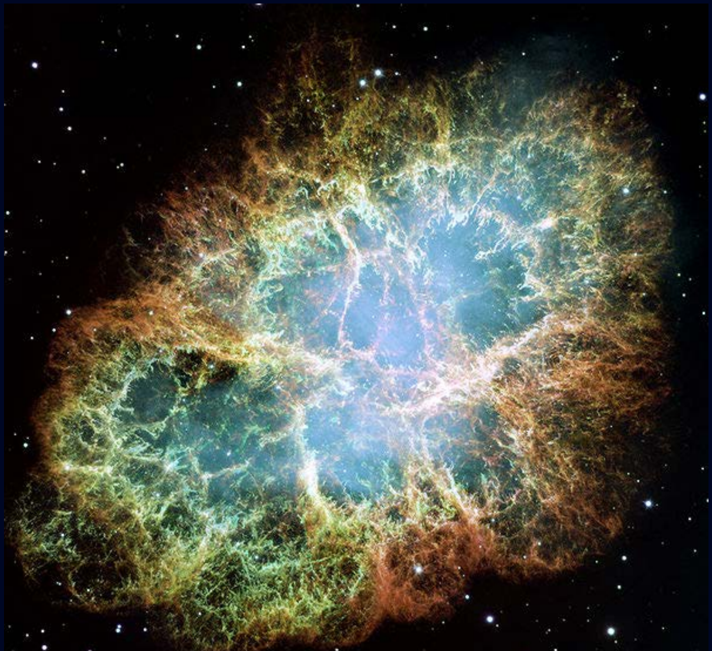
Electron

Mass	0.511 MeV/c²
Charge	-1 e
Lepton Number	1
Baryon Number	0
Matter/ Antimatter	M

Cosmic Rays: Where Do They Come From?

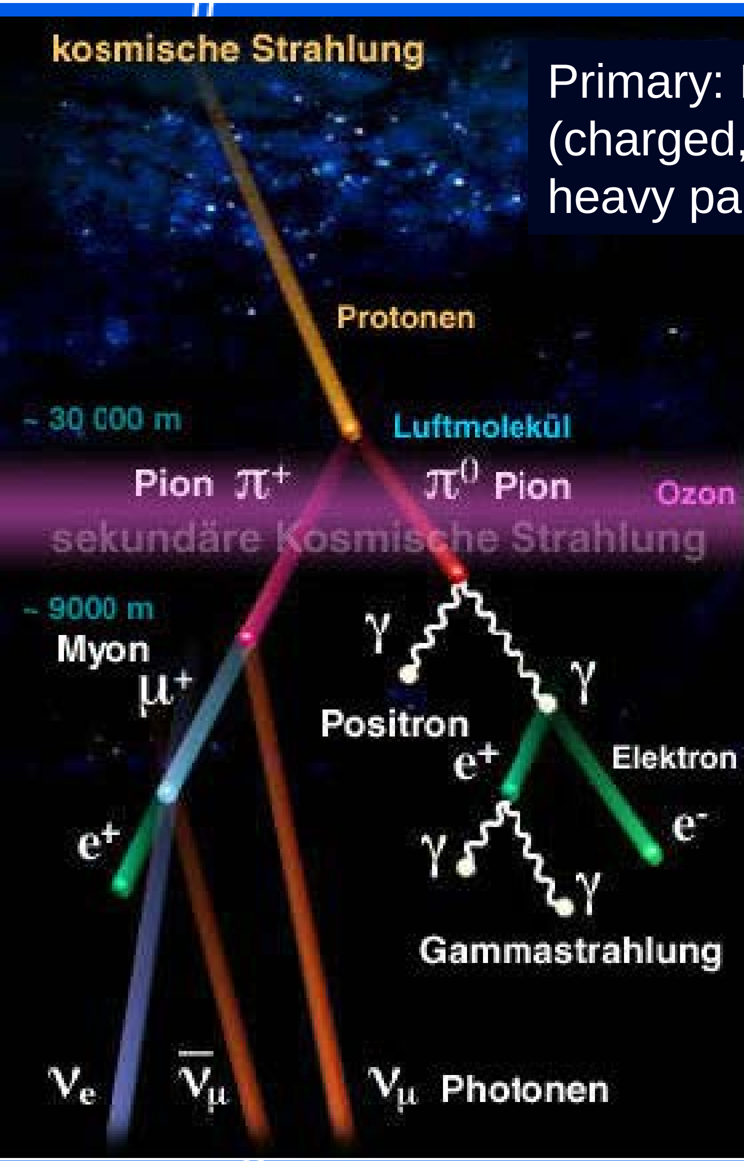
- Discovered by Victor Hess in 1912
- Consist of mainly protons, electrons, and ions
- Ray acceleration can occur in strong magnetic fields from supernova blast wave remnants
- Energies range from MeV to beyond TeV

Victor Hess (1883 – 1964)
Nobel Prize in Physics 1936



Crab Nebula (SNR 1054 remnant)

Cosmic Rays Conversion In Atmosphere



Primary: Mostly **protons** (charged, strongly interacting heavy particles, ~99%)

Secondary: Mostly **muons** (charged, EM-interacting heavy particles, ~70%) and electrons (charged, EM-interacting, light particles, ~30%). Neutrinos are weakly interacting and can be ignored.

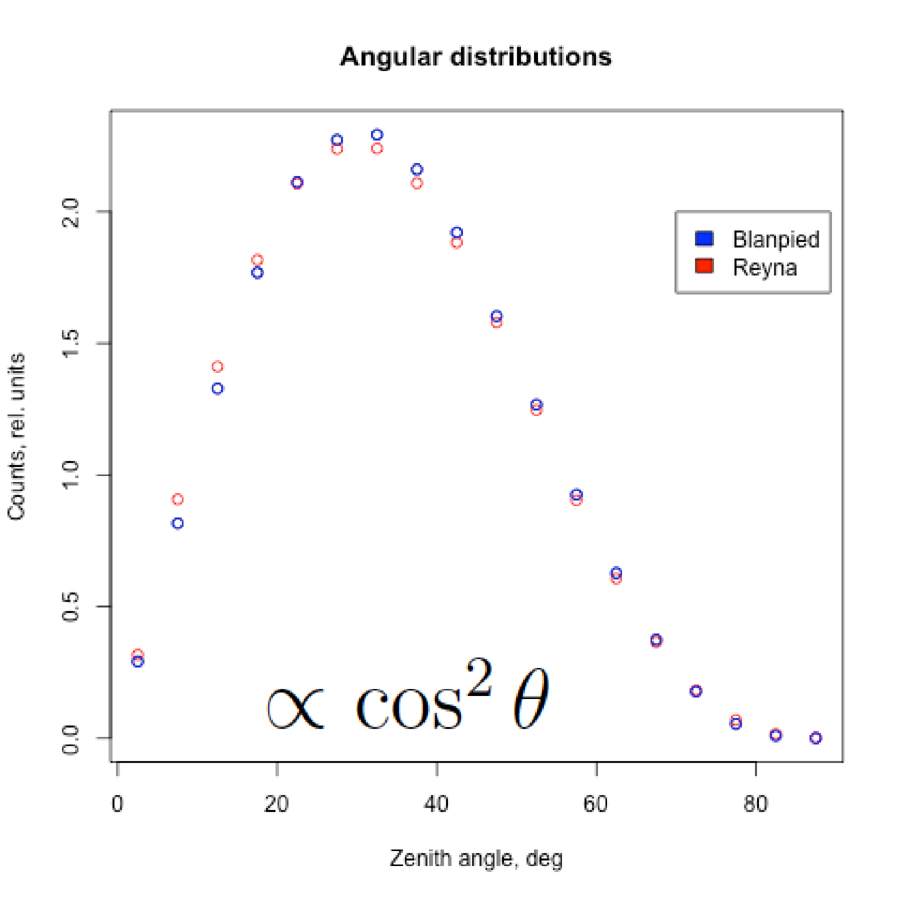
Rate at sea level:

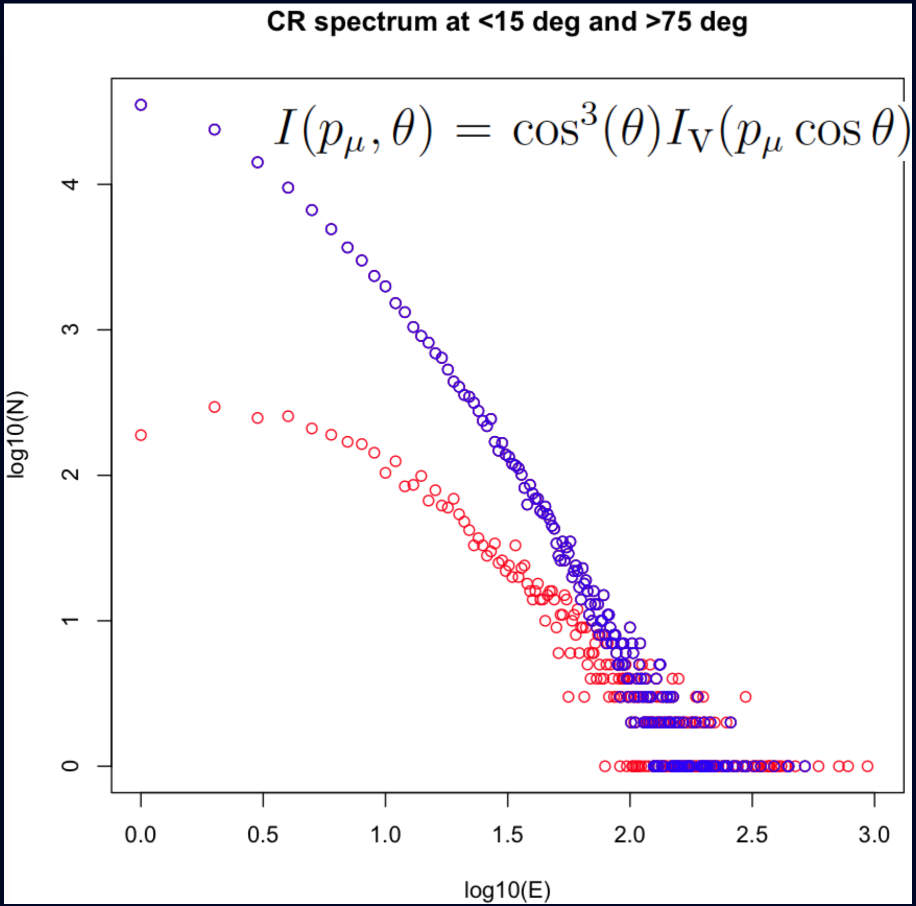
~1 per minute through your fingernail

~1 per second through your open hand

~ 10,000 per sq. meter per minute

Muon Flux and Spectrum as a Function of Zenith Angle





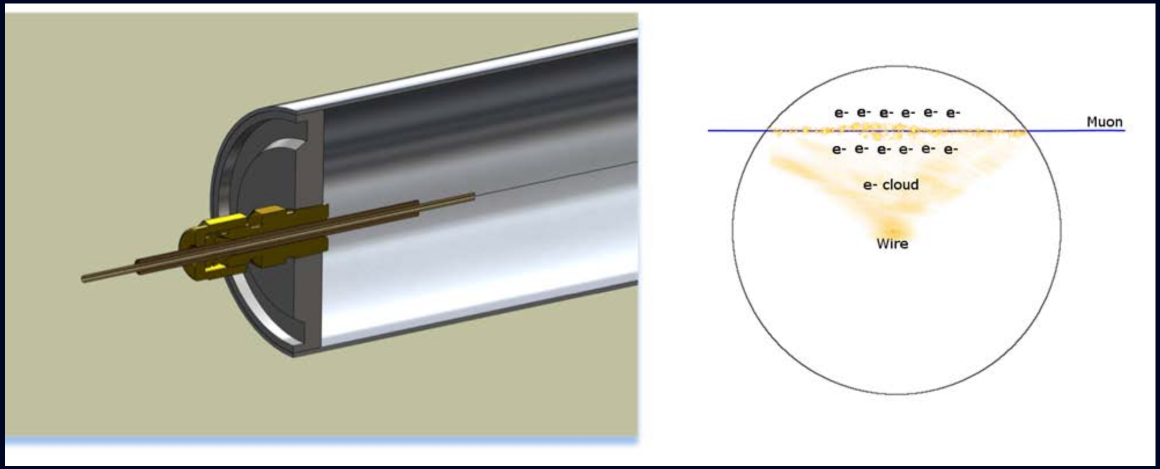
Mini Muon Tracker (MMT) For Muon Tomography

- 576 4-foot long and 2-inch diameter aluminum drift tubes
- Each tracker set has 3 x-y pairs of double planes, for a 12-fold tracking coincidence, in and out
- Supports additional input signals in the form of TTL pulses
- Neutron detectors studied
  - He-3 tubes with poly
  - He-4 tubes
  - Plastic bar scintillators
  - EJ-301 liquid scintillators
- Resolution of ~3 mm for spherical objects

“In” Tracker

“Out” Tracker

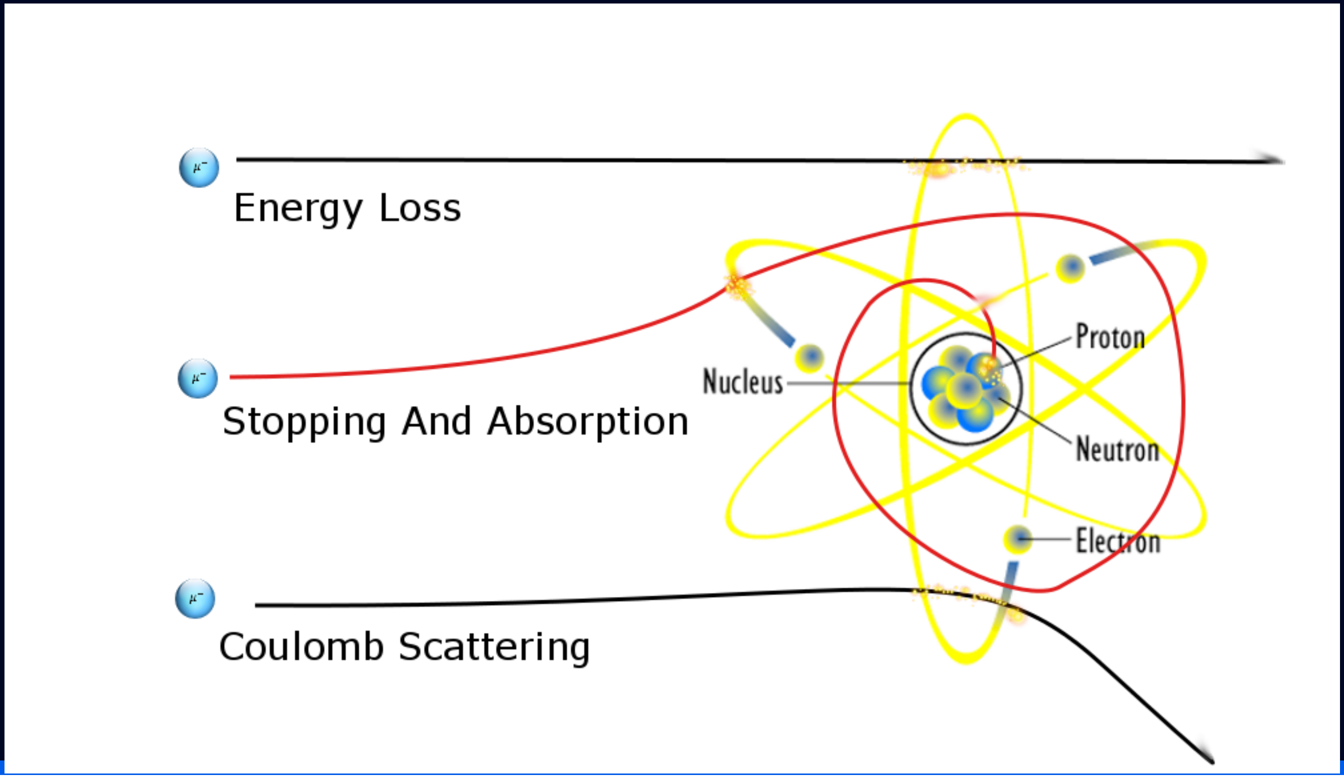
Drift Tube Schematic



<u>Figure</u> 13 – Drift tube design cutaway (left) and diagram of a charged particle passing through that drift tube (right). This drift tube detector is a gas filled aluminum tube with a Swagelok fitting that anchors a wire between both ends of the tube. When a charged particle passes through the tube, it creates electron and ion pairs (ions omitted in right figure). The cloud of electrons drifts to the wire creating a signal.

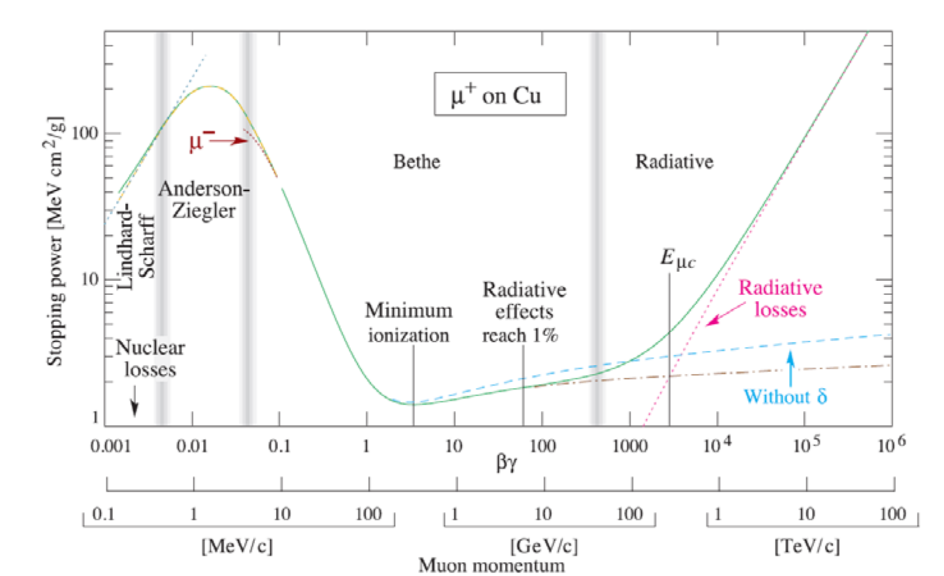
Muon Interactions In Materials

- Energy loss
- Multiple scattering
- Stopping and absorption



Muon Energy Loss

- Average energy of the cosmic-ray muon is 3-4 GeV
  - Minimally ionizing
- Stopping power increases exponentially for low energy muons
- Stopping power and the ionization process is only weakly Z dependent and is more dependent on density
- Energy loss and ionization is the basis of transmission radiography



Stopping power for positive muons in copper over nine orders of magnitude in momentum. The different dominant physical processes, such as radiative losses and ionization, are shown.

Muon = 105.66 MeV/c^2

Cosmic-Ray Muons Penetrate Large Objects

Searching for Hidden Chambers in Pyramids

Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

Luis Alvarez, et. al.
Science **167**, 832 (1970)

Arturo Menchaca, et. al. see

http://www.msnbc.msn.com/id/4540266/

Muon transmission radiography – Well established since the mid 1900s

Predicting Volcanic Eruptions

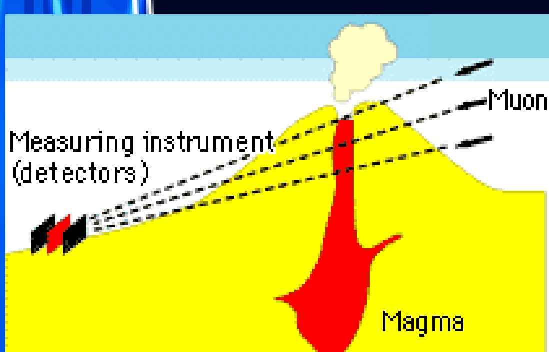


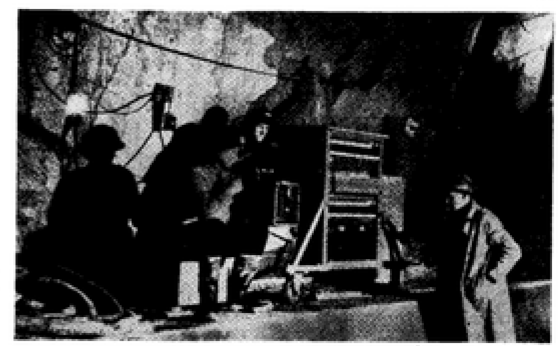
Figure 4: Analyzing the internal structure of a volcanic zone using muons

Tanaka, Nagamine, et. al.
Nuclear Instruments and Methods A **507**:3, 657 (2003)

Measuring Tunnel Overburden

Commonwealth Engineer, July 1, 1955 E.P. George 1955 455

Cosmic Rays Measure Overburden of Tunnel



● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

By Dr. E. P. George
University of Sydney, N.S.W.

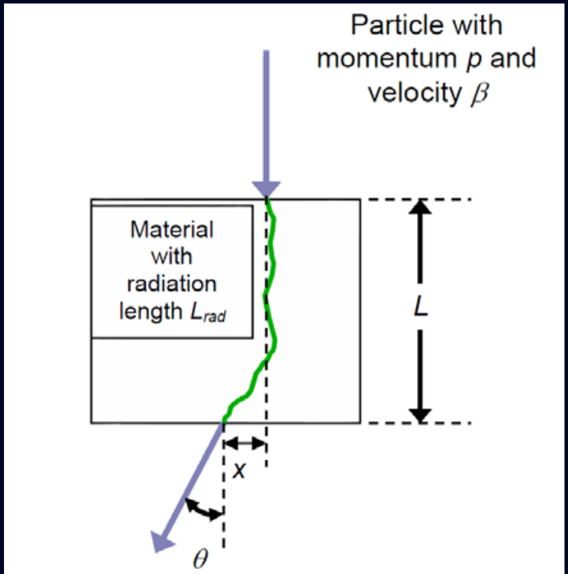
Multiple Coulomb Scattering

- Multiple Coulomb scattering produces angular diffusion which is useful for tomography
- Linear Z dependence of scattering angle width due to inverse dependence on radiation length

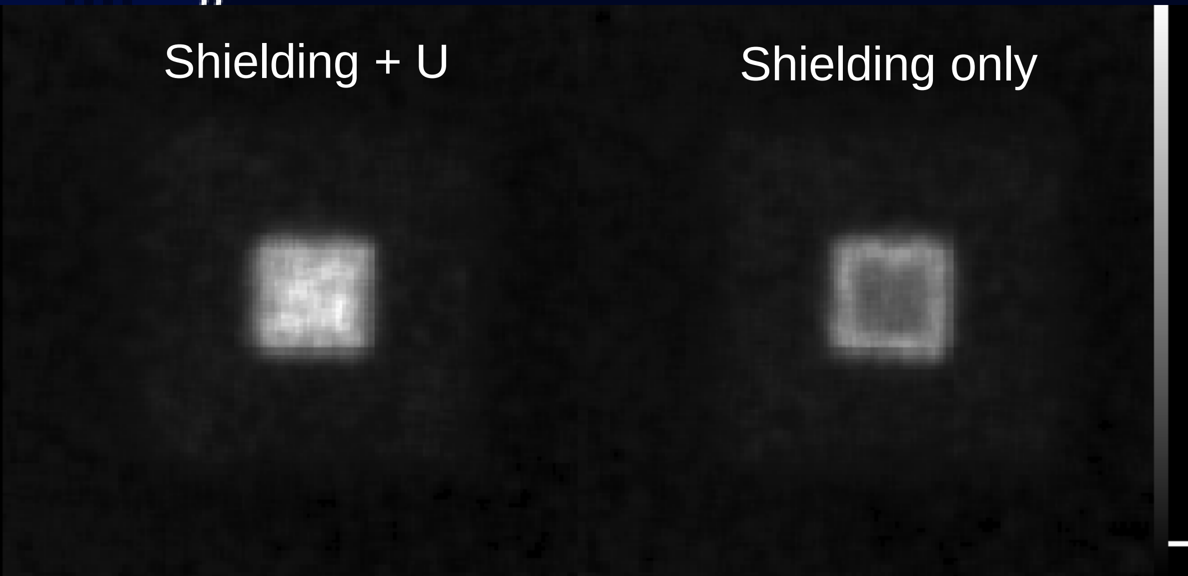
$$\frac{dN}{d\Theta} \propto \Theta \exp\left(-\frac{\Theta^2}{2\Theta_0^2}\right)$$

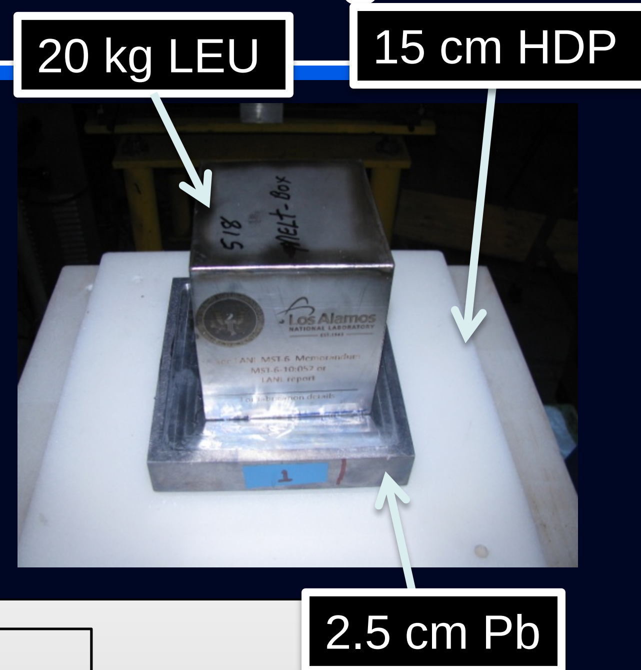
$$\Theta_0 = \frac{13.6\, MeV}{\beta c p}\sqrt{\frac{L}{L_0}}\left[1 + 0.038 \ln \frac{L}{L_0}\right]$$

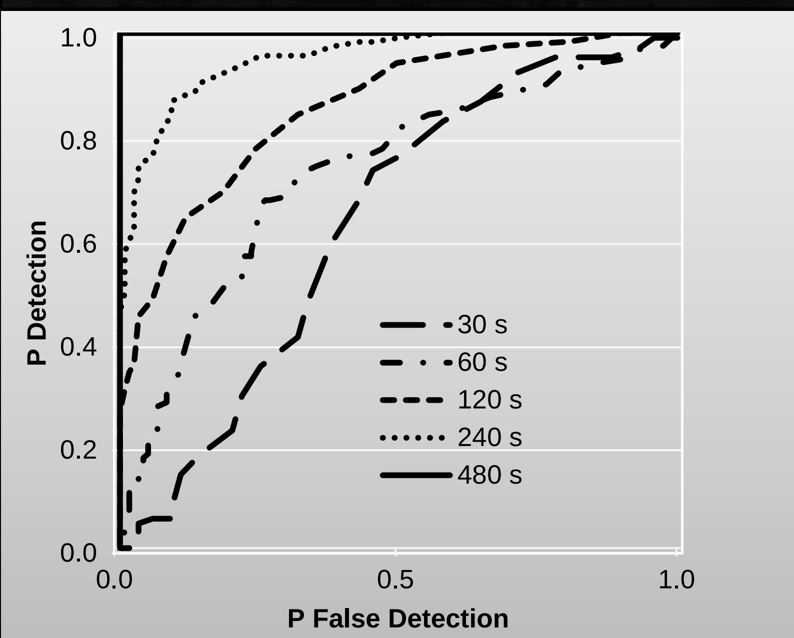
$$\lambda_{mat} = \Theta_0^2 \cong \left(\frac{13.6\, MeV}{p}\right)^2 \frac{1}{L_{0,mat}}$$

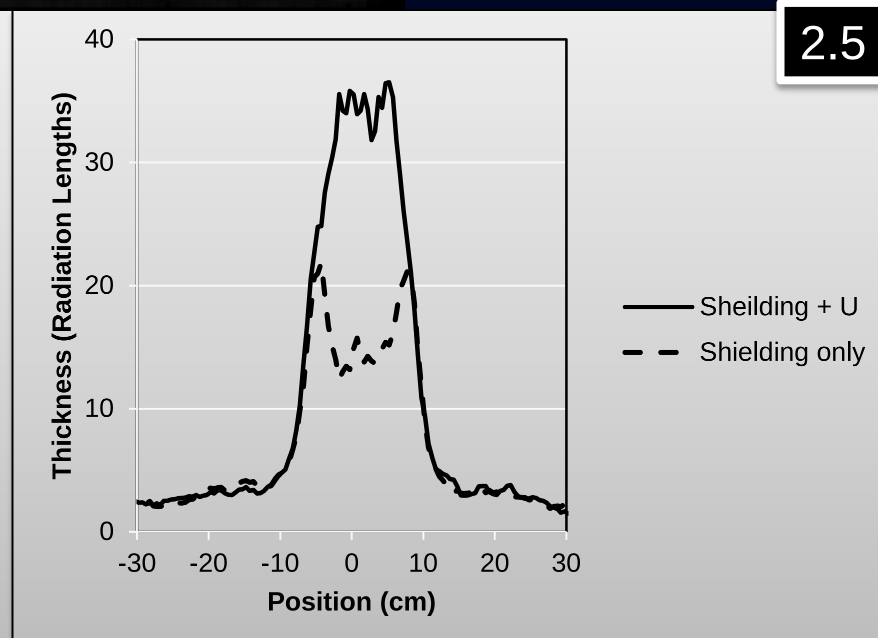


Muon Radiography: Multiple Scattering Demo

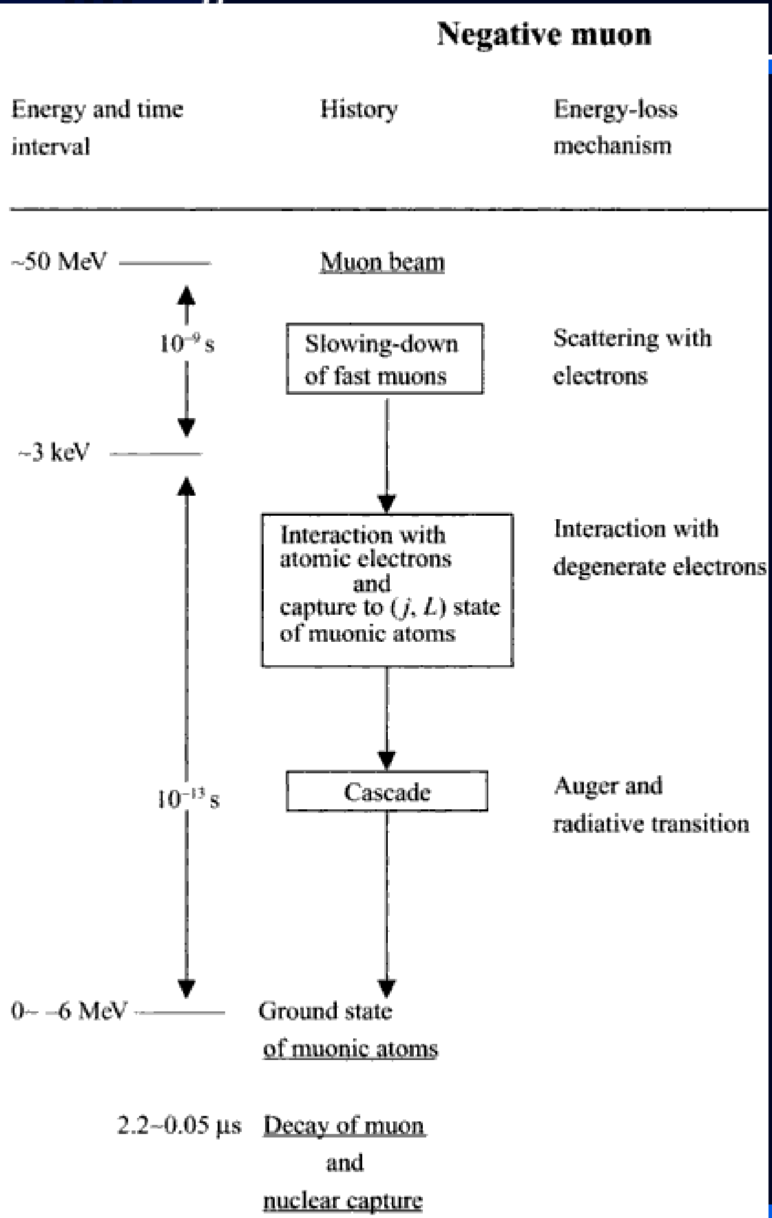








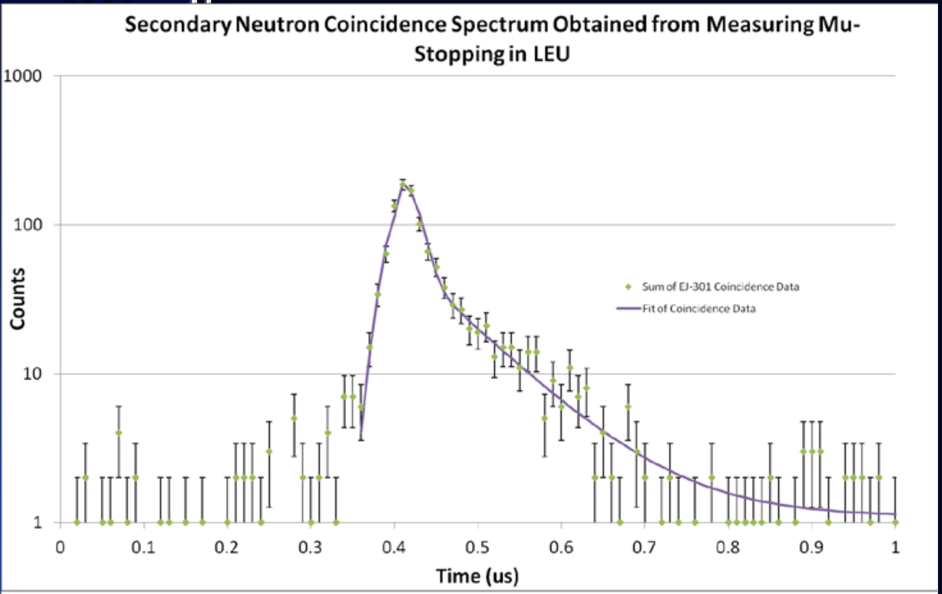
What Muons Do When They Stop

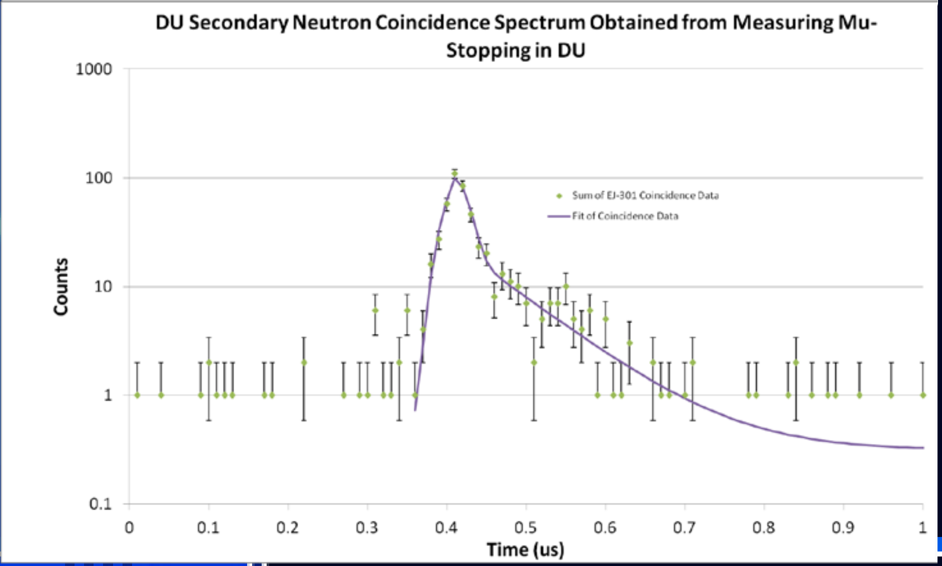


- Cosmic-ray muons: ~60% positive, ~40% negative
- Both absorption and scattering depend on macro properties of materials.
- When stopped, positive muons decay with a lifetime

  $\tau_{1/2} = 2.2\mu s$
- Negative muons descend through atomic orbits and are captured by nuclei
- Fission resultants - gamma and neutron flux - are useful for improving muon radiography SNR!

Neutron Coincidence Spectrum and Lifetime of Mu- Capture in Uranium Cubes

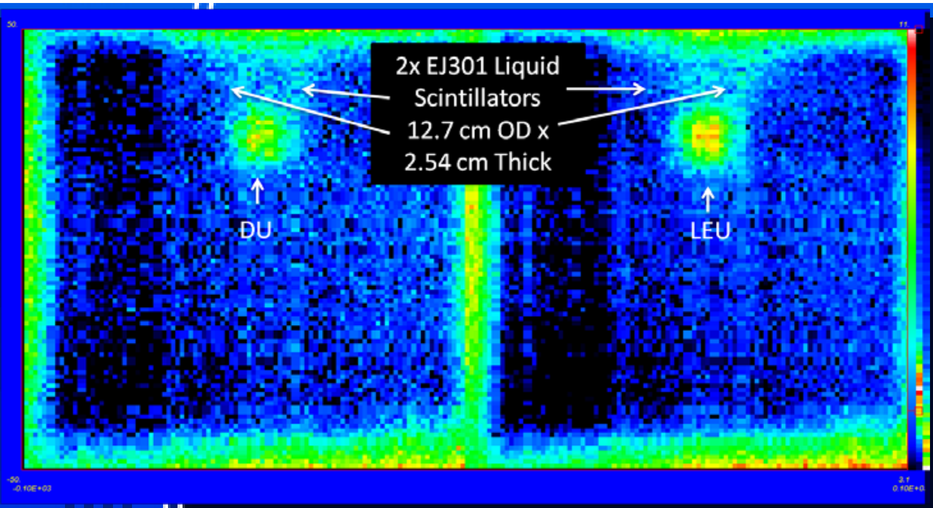




- The neutron coincidence data has two features: prompt (Gaussian timing resolution) and delayed (exponential lifetime)
- Log-likelihood ratio fit
  - Minimized a model consisting of a Gaussian, exponential, and constant
- Measured lifetime of mu- capture in uranium
  - Literature: 72 ns in U-235 and 77 ns in U-238

	DU - Minimized Fit	DU - 1 Sigma	LEU - Minimized Fit	LEU - 1 Sigma
Background (counts)	0.3	0.3	1.1	1.1
Gaussian Amplitude (counts)	75	75	133	133
Gaussian Width (ns)	16	16	18	18
Exponential Amplitude (counts)	24	24	57	57
Exponential Lifetime (ns)	80	137	82	116
Peak Center (ns)	410	410	410	410
Degrees of Freedom	87	87	87	87
Summed Log-Likelihood	81	168	87	164
Lifetime Uncertainty (ns)	57	57	34	34

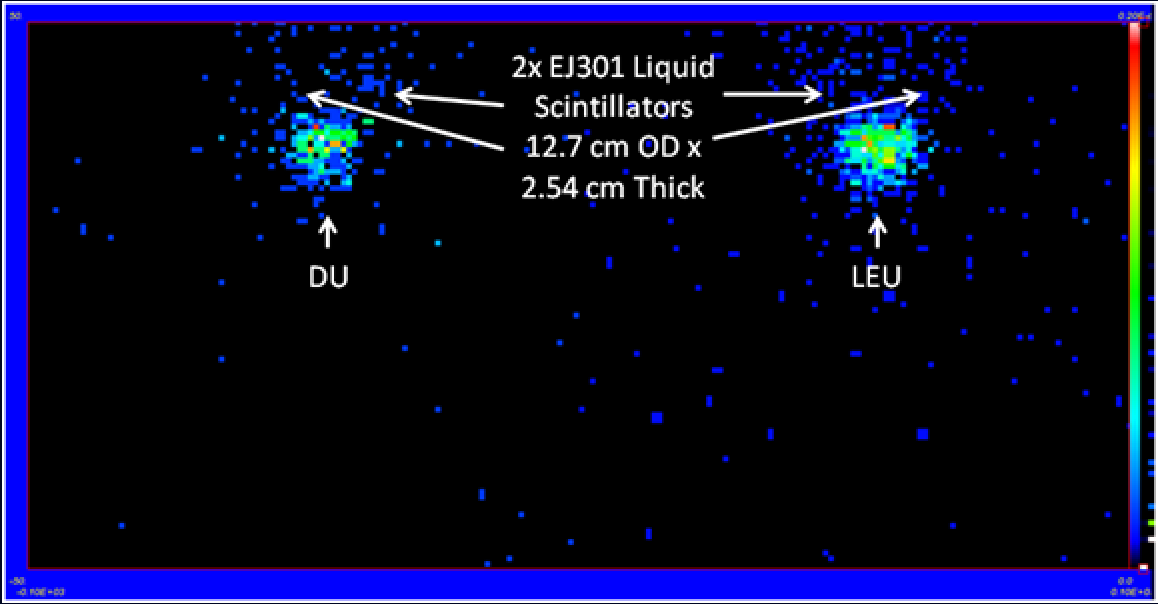
Tagging Stopped Muons with Coincident Neutrons



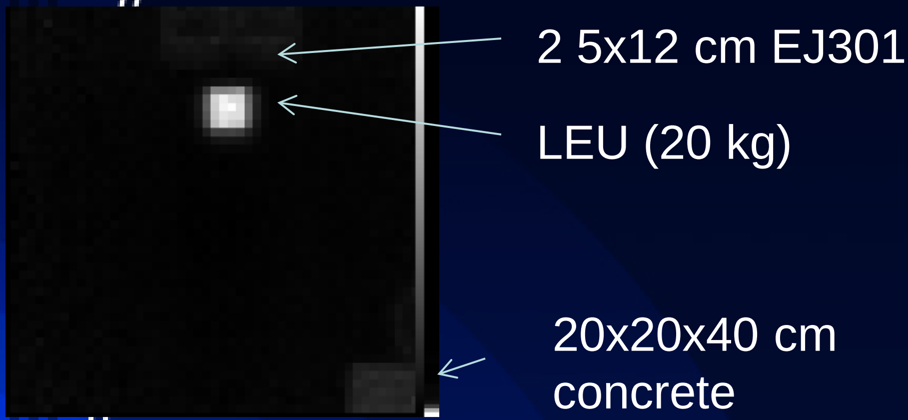
A coincidence window, between EJ-301 detectors and muon tracks, of 350-650 ns is used to create a tagged stopped radiography of the uranium cubes.

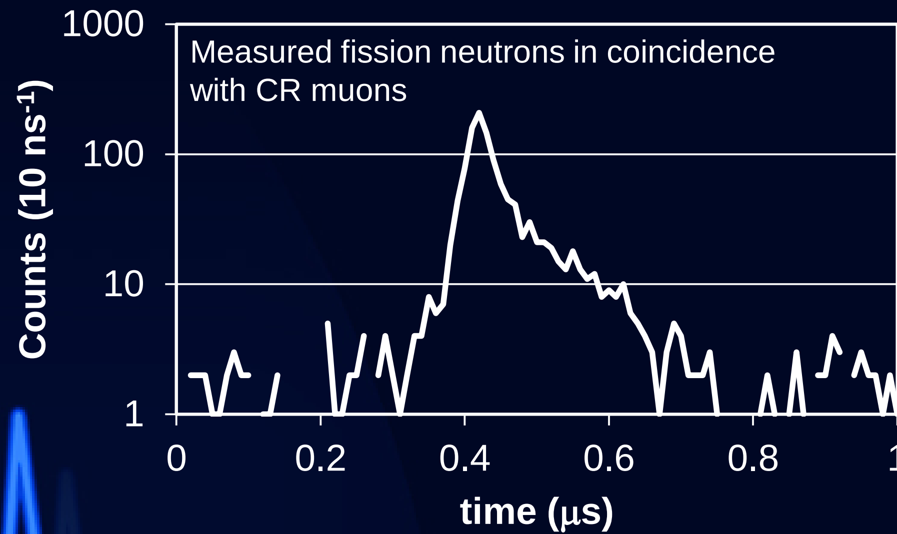
Stopped Track Image

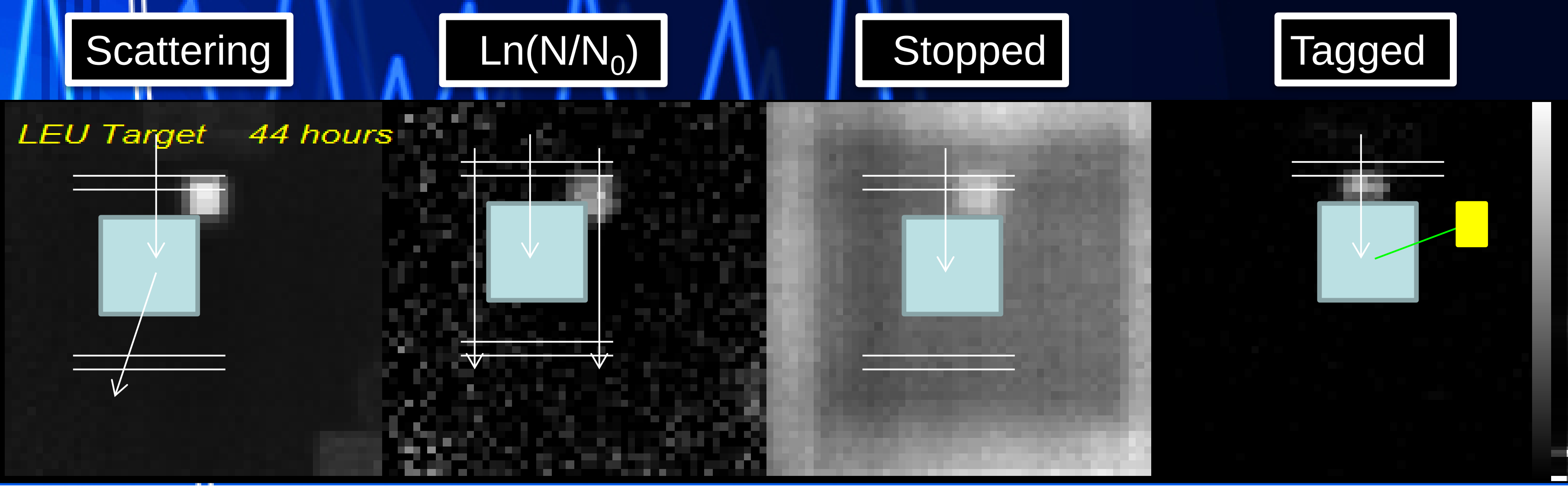
Tagged Stopped Tracks



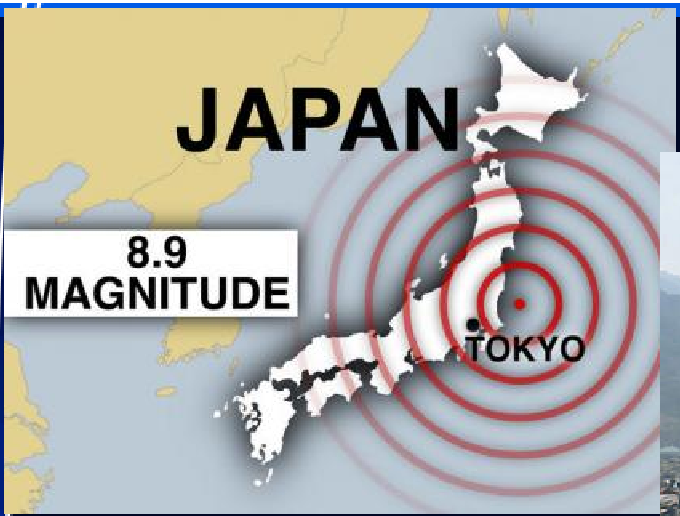
Four Different Kinds of Radiography





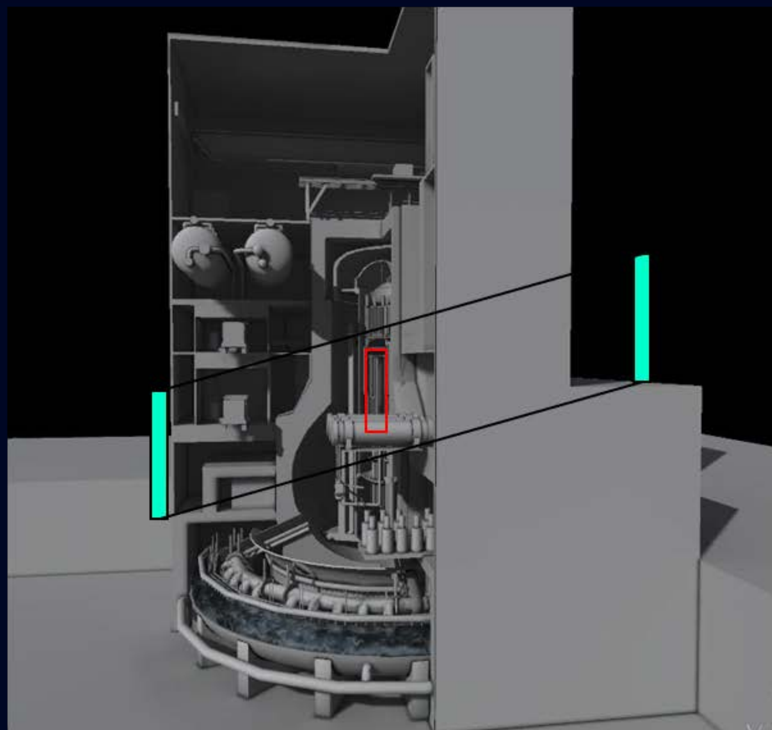


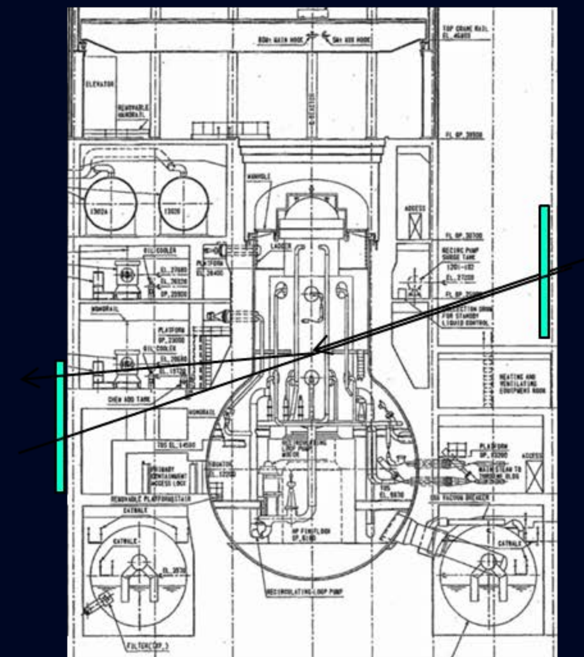
Fukushima-Daiichi Nuclear Disaster



11 March 2011: Tōhoku earthquake and tsunami

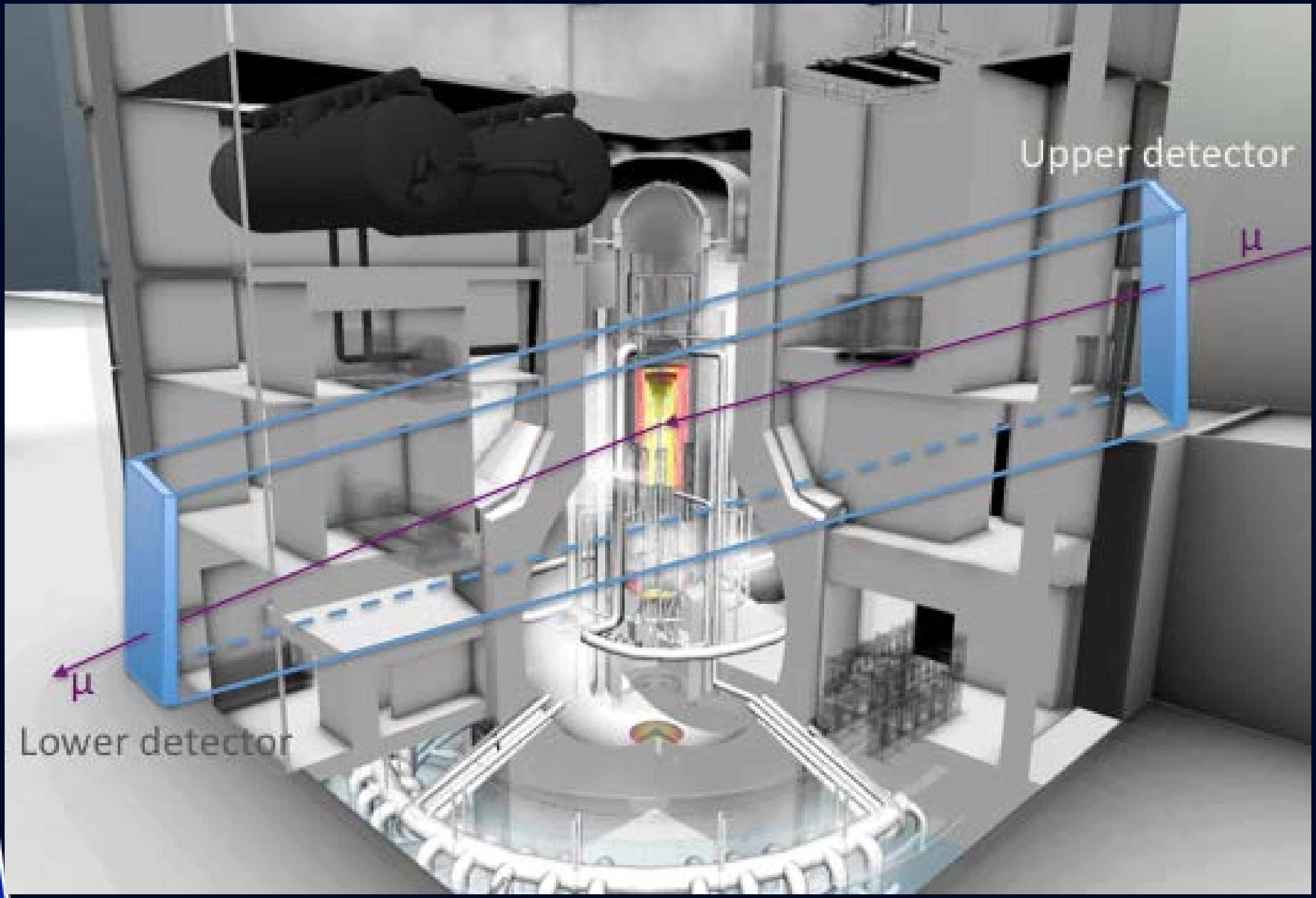
Deployment of Muon Tomography at a Nuclear Reactor



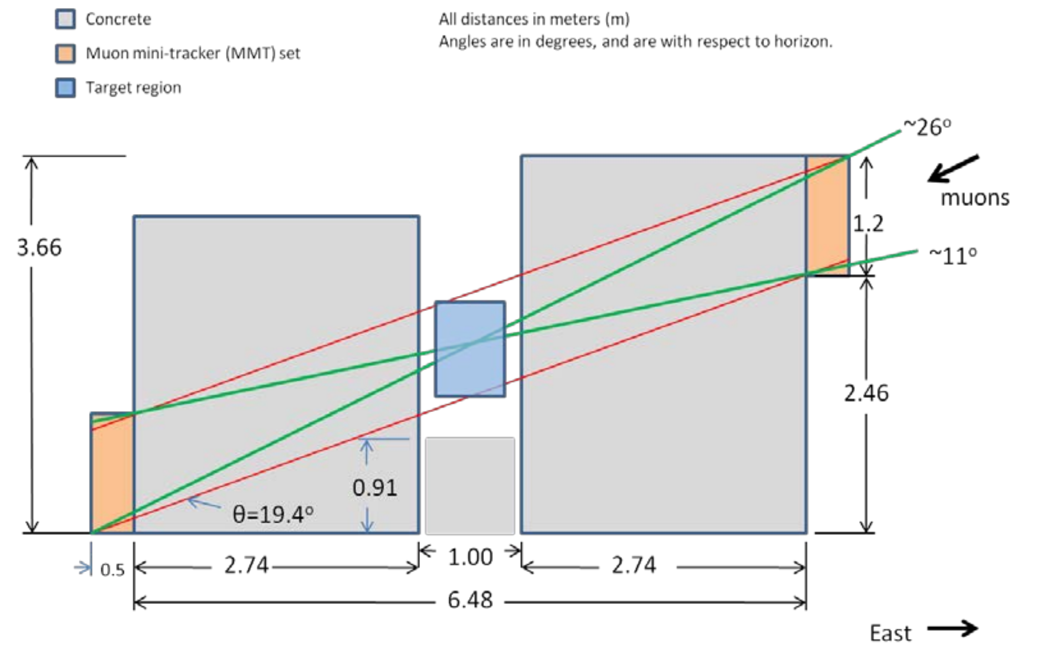


Deployment of a muon tomography system in a nuclear reactor imaging configuration. The detector planes (teal boxes) are oriented vertically and placed on either side of the reactor. The near horizontal muons are measured as they pass through the reactor. An image is reconstructed showing details of the core and other components that are found in the field of view (red box).

Imaging Reactor Core with Near-Horizontal Muons

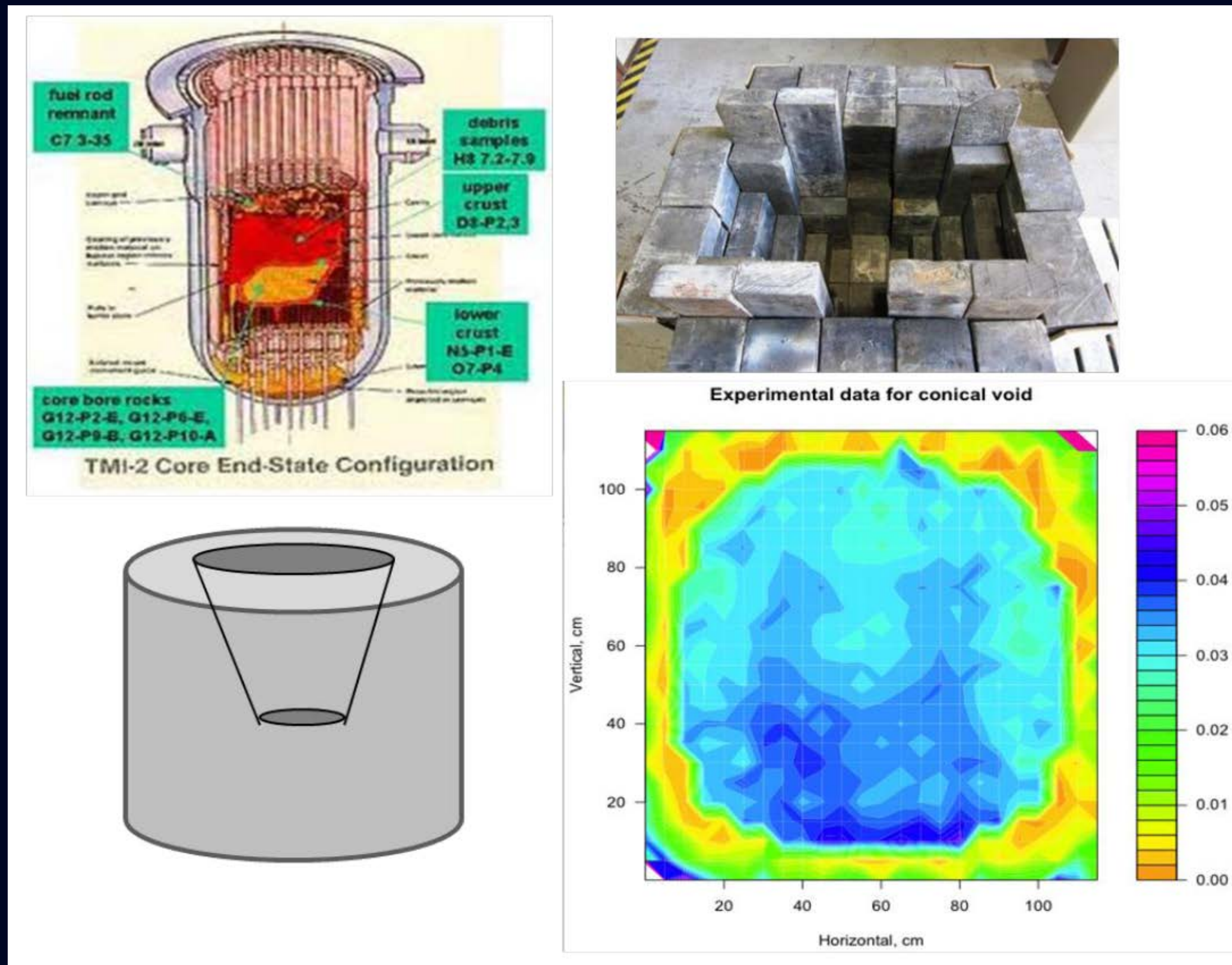


Reactor Mockup Experiment Layout



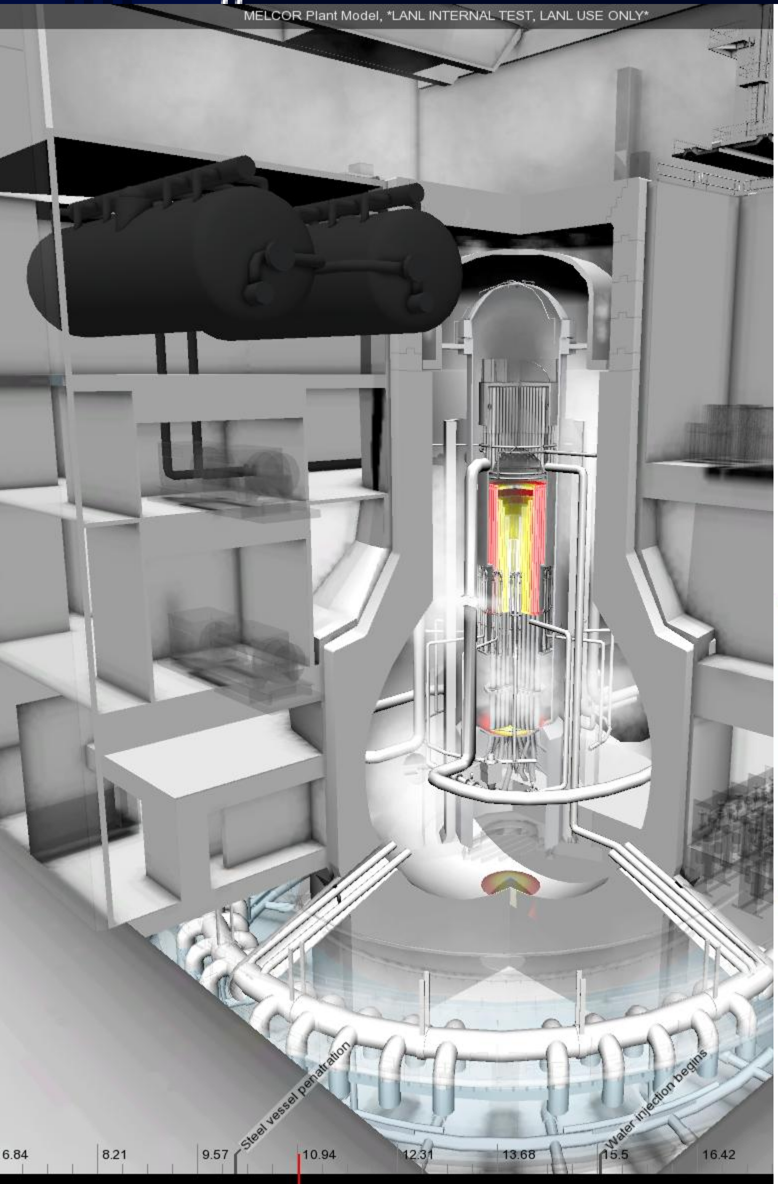
Experimental drawing of reactor mock-up (top) and photograph (bottom). In the photograph, 2.74 meters of concrete surrounds a stack of lead on each side. The MMT detector planes are oriented on the ends of each slab of concrete (diagramed in orange, top).

Reactor Mockup: Conical Void

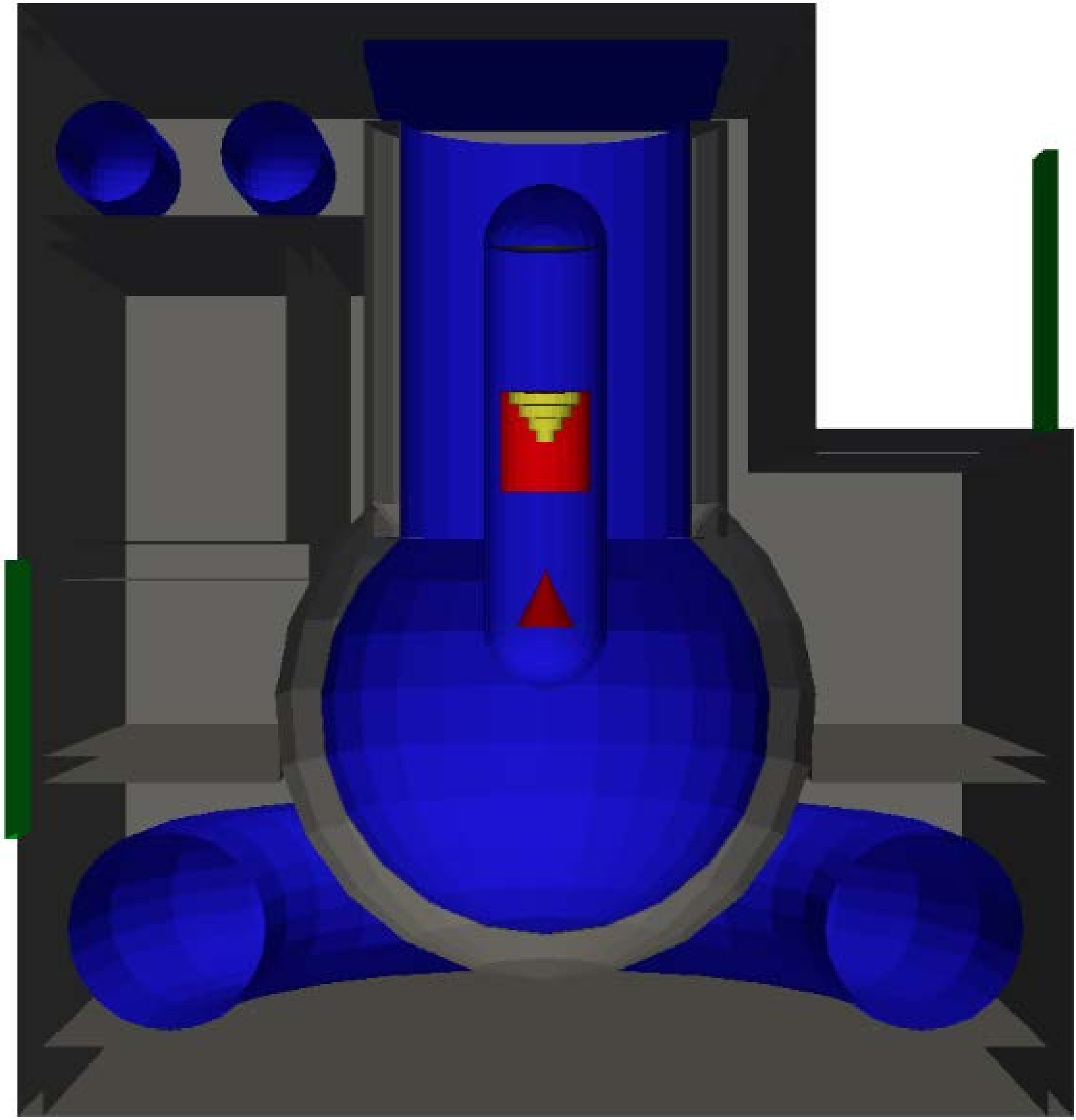


Conical void configuration for a molten reactor mock-up.

Modeling of the Core Melting

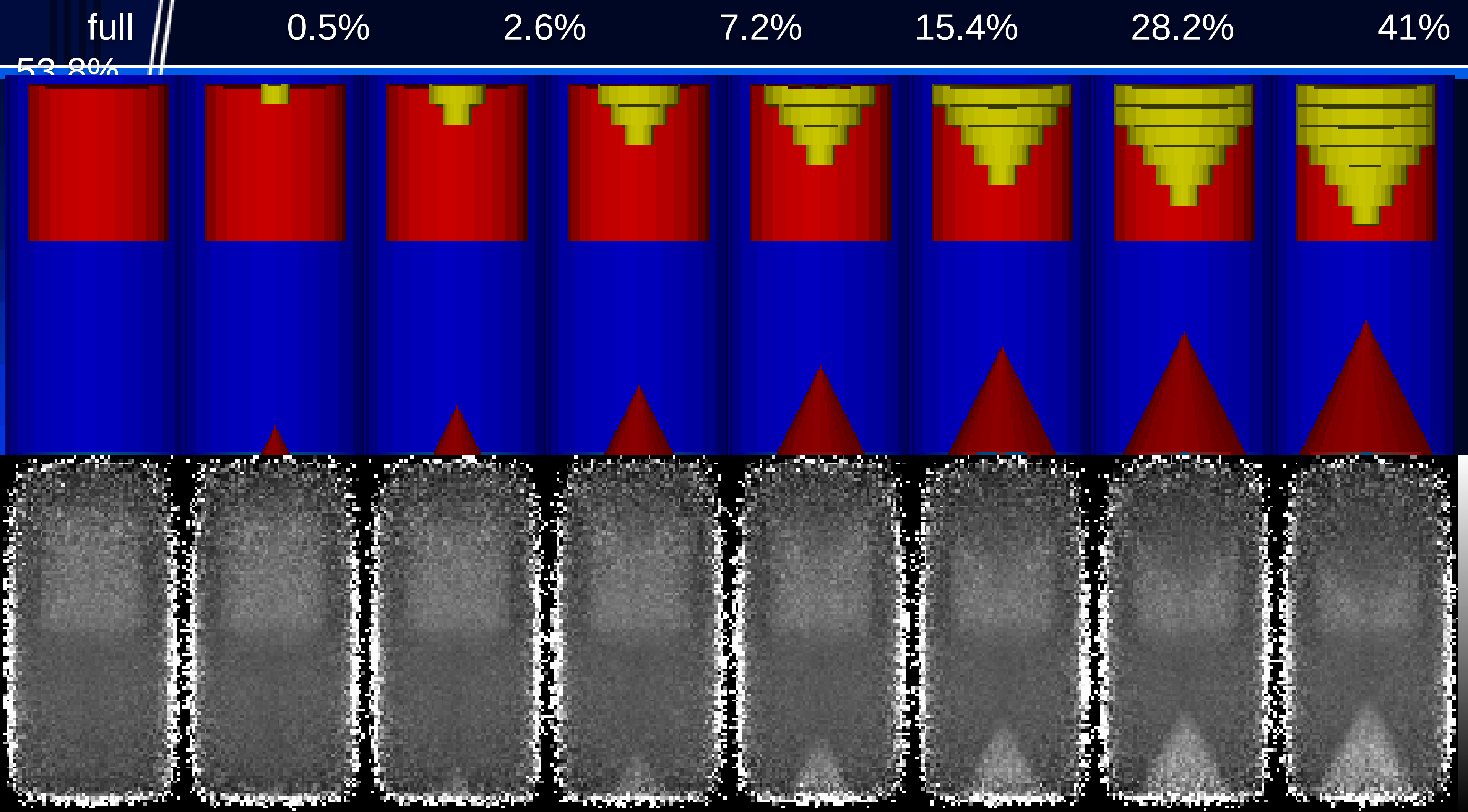


3D imaging by the VISIBLE team

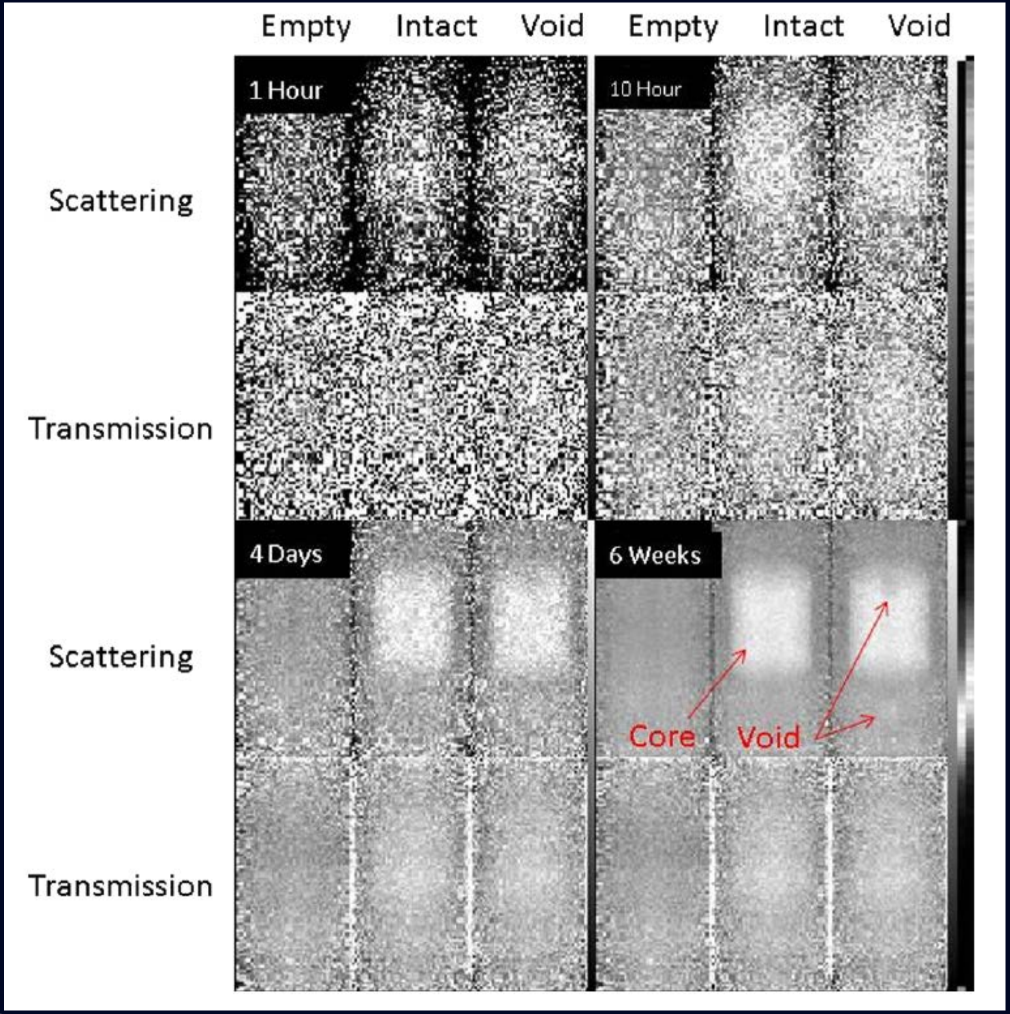


Our simplified GEANT4 model

Modeling of Melting Core



Imaging a Core with Multiple Scattering as Compared to Transmission



Reactor reconstructions at different exposure times.

In scattering radiography, the reactor core can be detected after about 10 hours of exposure.

After four days, a 1 m diameter (1%) void can be detected when compared to an intact core.

After 6 weeks, the void is clear and the missing material can be observed.

Fukushima Experiment-May 2012

Drift Tube Detectors Work in High-Radiation Field

May 25, 2012 – Fukushima Daiichi Nuclear plant

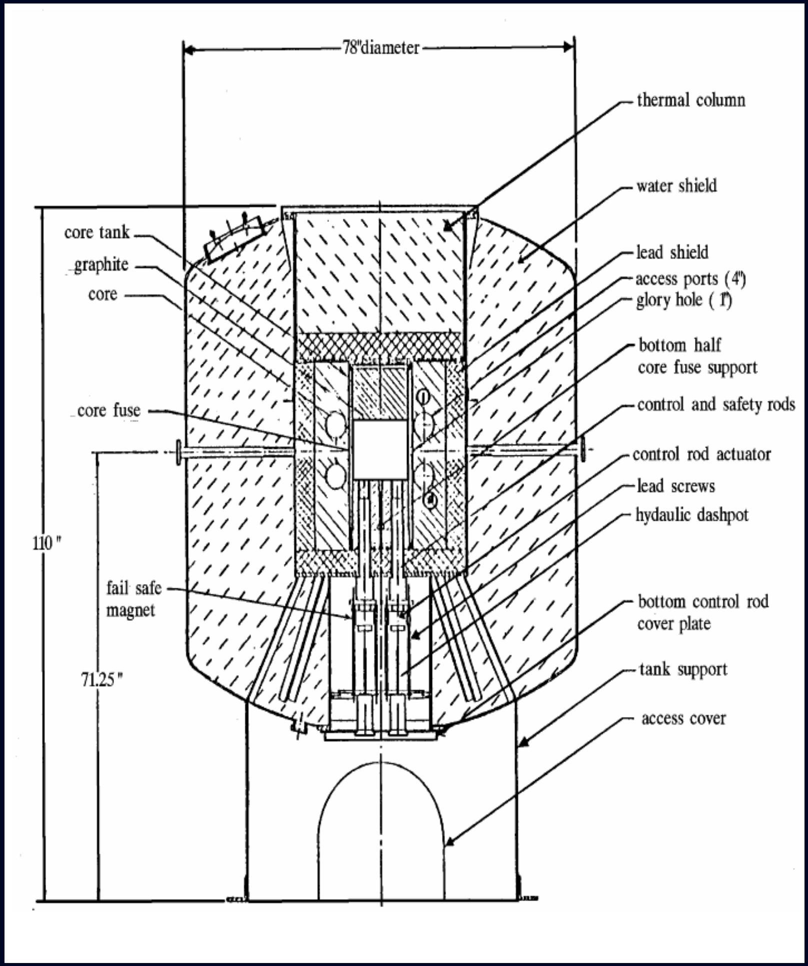
UNMRR Imaging Objectives

- Image a research reactor remotely and autonomously over several months
  - Use lessons learned for future Fukushima imaging
- Validate Geant4 models by comparing data to simulation
  - Flux analysis
  - Abel inversion image analysis
- Validate muon tomography reconstruction algorithms in NewDisplay

Upper MMT supermodule installed at UNMRR

UNMRR Background – Elevation View

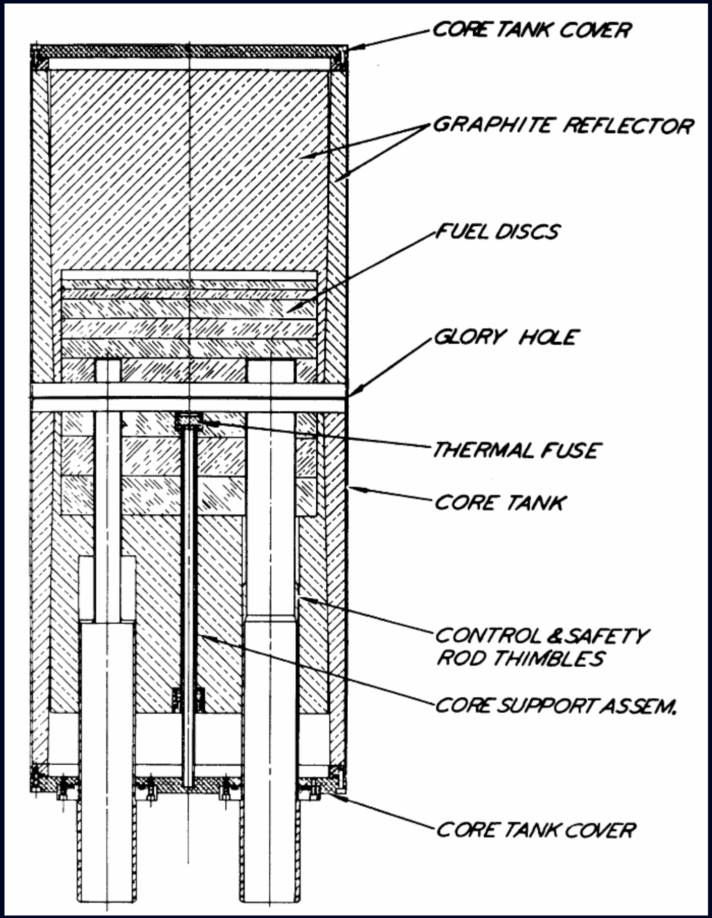
- AGN-201m
  - 5 watts of power controlled by rod insertion
  - Steel water vessel
  - Steel thermal column containing water and lead
  - Lead shielded
  - Graphite reflected
  - Several access ports
- Concrete housing not shown in diagram
  - 60 cm thick on the side with supermodule 1
  - 40 cm thick on other sides



Elevation view of AGN-201M

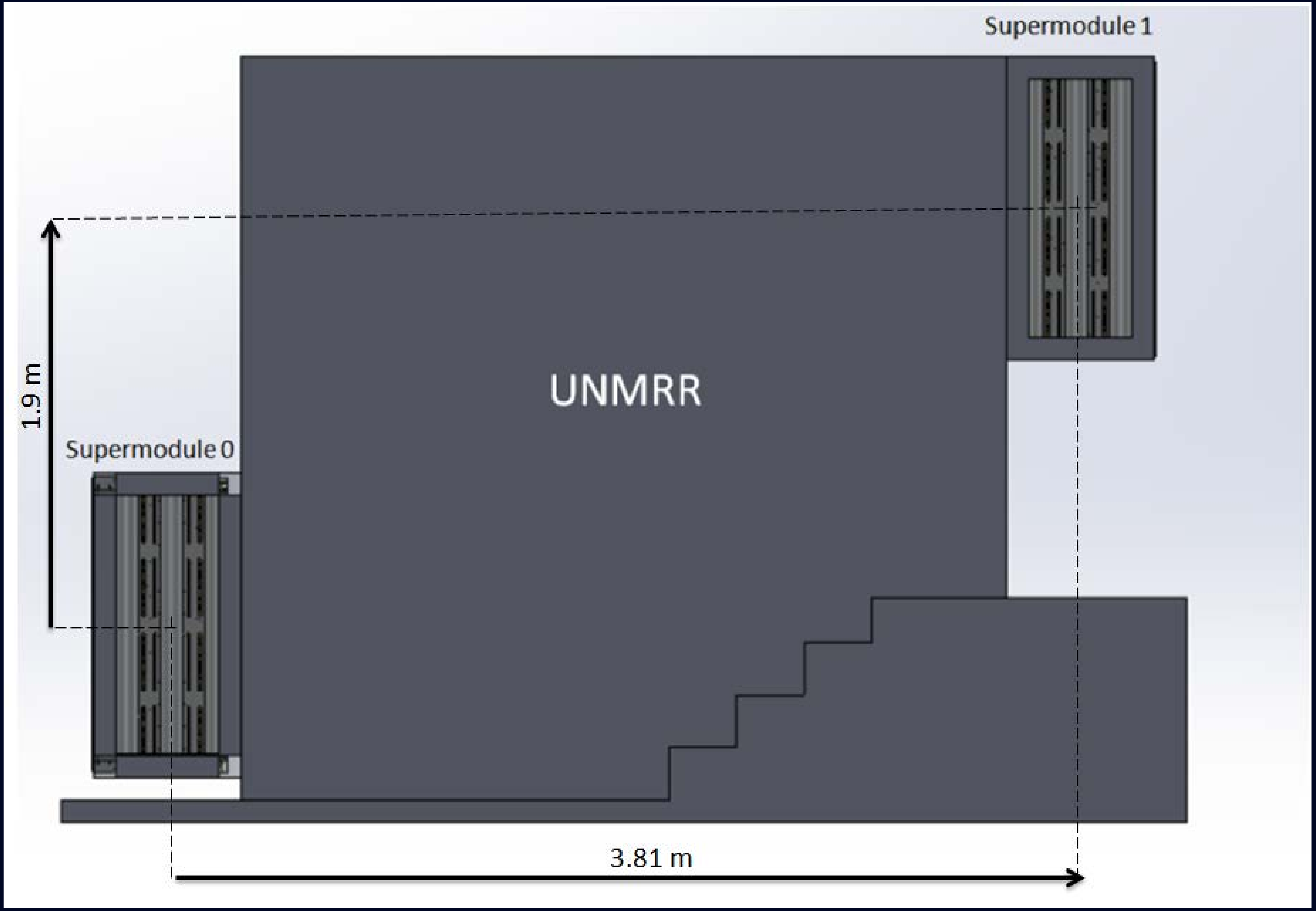
UNMRR Background – Core Profile

- Core built with cylindrical plates
  - Polyethylene loaded with 19.5% UO_2
  - U-235 amounts to 666.9 g total
  - 4 cm thick
  - 25.6 cm OD
- Four fuel control rods are used to bring reactor critical
- Core fuse made of polystyrene melts to separate halves in event of power excursion



Core profile of AGN-201M

Experimental Setup at UNMRR

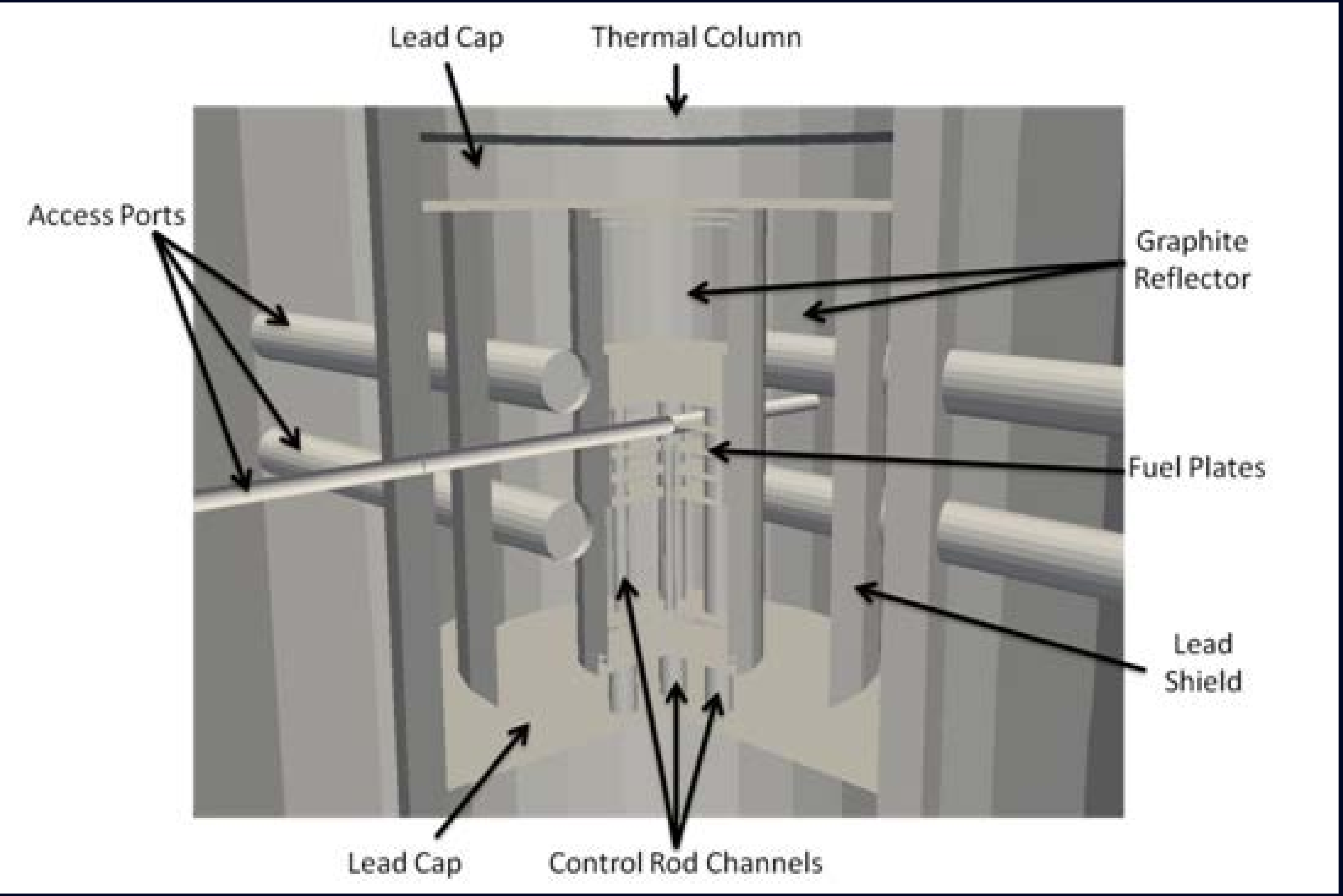


MMT horizontal mode deployment

Simulation Setup for UNMRR Muon Tomography Modeling

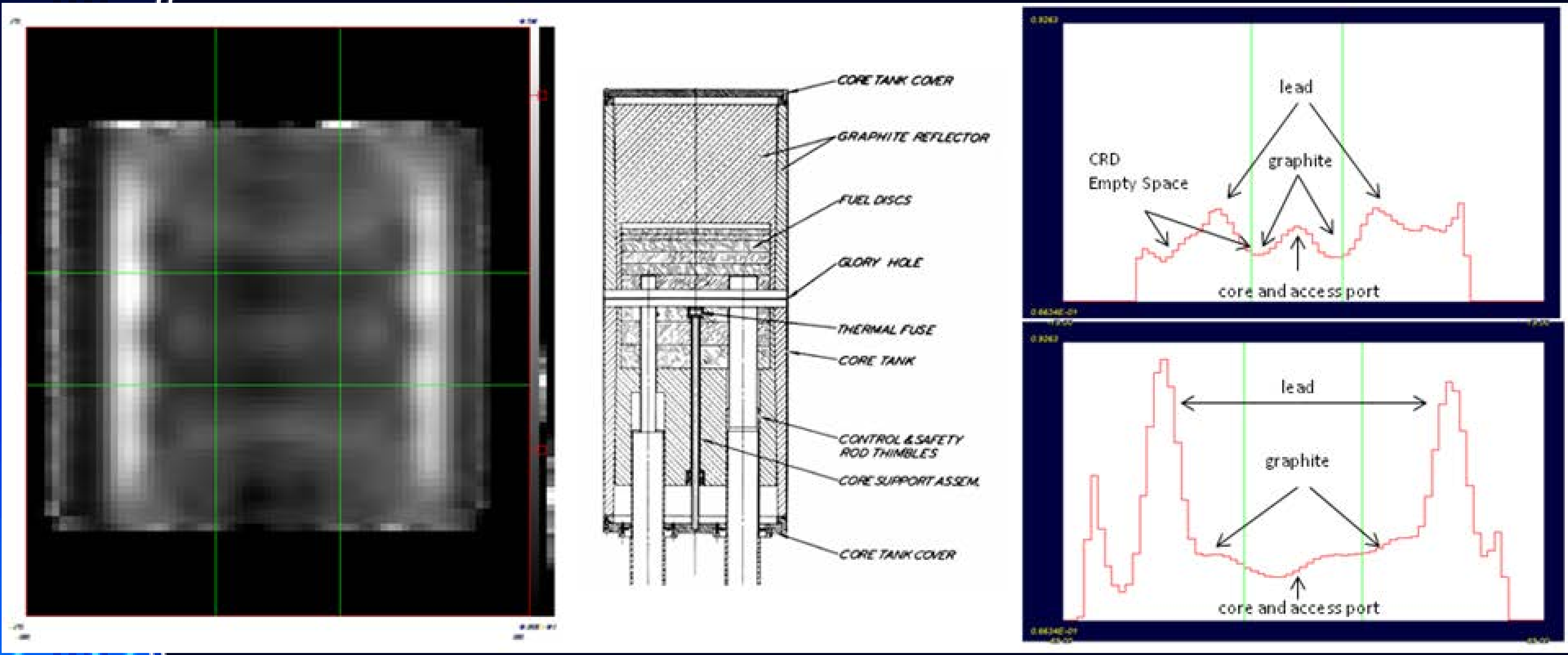
- A model of the UNMRR was built using Geant4
- Model geometry defined in GDML
  - Elevation view diagram (assumed to scale)
  - Core diagram (assumed to scale)
  - AGN-201m user manual
- Simulated cosmic ray muon source with Reyna treatment for angular distribution and Haino-Achard data
- Tracking planes placed at midpoint of each supermodule
- Output tracks written in ROOT

UNMRR Simulation Geometry



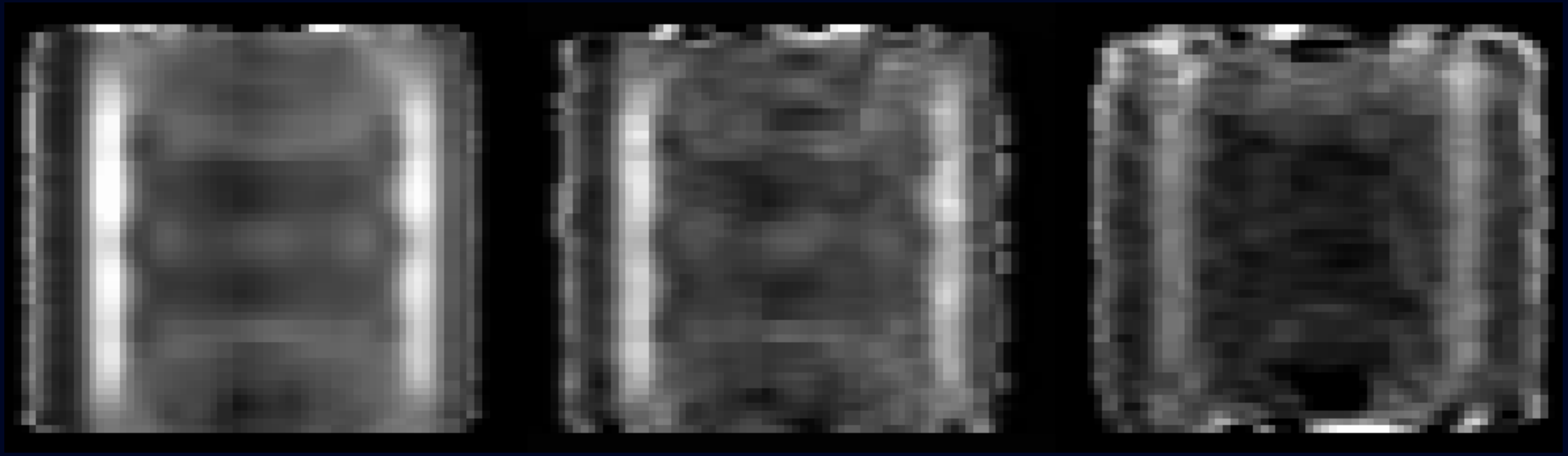
Geant4 simulation geometry of UNMRR. The fuel plates are located in the center and are surrounded by cylinders of graphite. Lead and water cylinders encompass the graphite moderator region. Access ports and drive channels are also included to increase the realism of the simulation.

Analyzing Features of the UNMRR with an Abel Inverted Reconstruction of Simulation



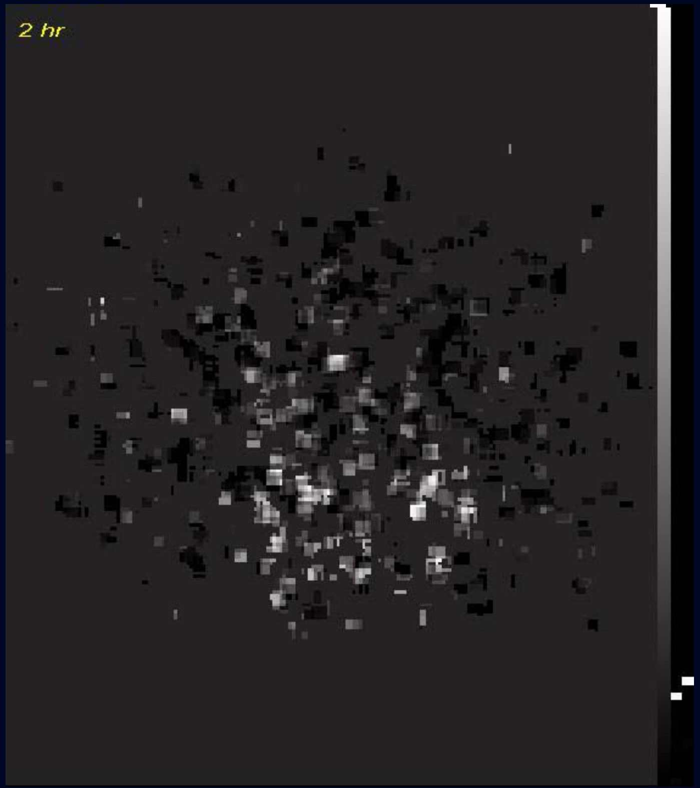
Simulated muon tomography (Abel inverted) showing features of the UNMRR. In the left image, some features are the lead cylindrical housing that shields the core, the graphite components in the center, access port materials, and the core itself. The panels on the right are lineout projections of the zenith (top-right) and azimuth (bottom-right). The core diagram reference is shown in the center.

Abel Inversions of Muon Tomographic Reconstructions from Data and Simulation



Abel inversion reconstructions of the UNMRR at the reactor core plane. A high statistics simulation is shown on the left. A simulation with the same amount of transmission tracks as the data (1.13 million) is shown in the middle. The measurement made at UNM is shown on the right. The high statistics simulation contains approximately 68 times as many tracks as the data. In the images several structures are visible including the core with graphite (center), the lead cylinder shield (outer), and the empty control rod housing (bottom).

Results from Toshiba Nuclear Critical Assembly (NCA) Radiography (350 hrs exposure)



Next Steps to Fukushima

- Collaborating with Toshiba to bring muon tomography to Fukushima
- Working on a WFO agreement to provide consulting services, tracking software and more
- Measurements to begin as soon as 2015

Carbon Fiber Module

Questions?

Contact Information:

John Perry
P-25, LANL
joperry@lanl.gov
505-665-7570