LA-UR-17-28587
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Title: Cosmic Ray Radiography/Tomography

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Intended for: Recent Developments in muon radiography, 2017-09-25/2017-09-29 (Vienna, Austria)

Issued: 2017-10-17 (rev.1)

Cosmic Ray Radiography/Tomography*

Mt. Tsukuba

Cephren's pyramid

Fukushima reactors

Chris Morris (for the muRad team)

Los Alamos National Laboratory

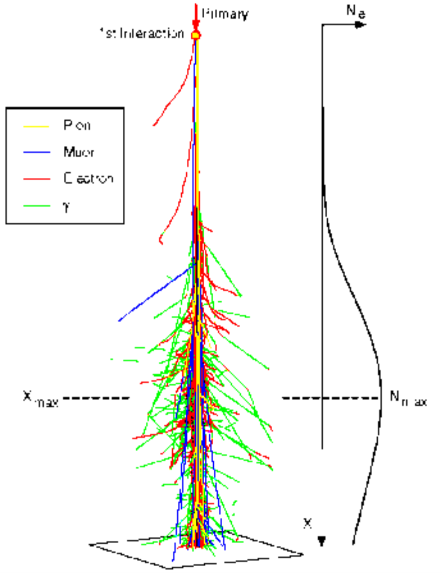
25-September-2017

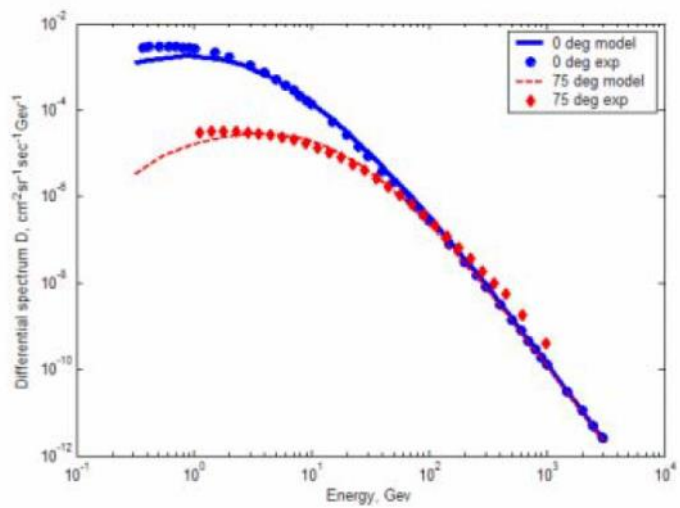
The cosmic ray flux of about ~1 particle per cm^2 per minute at the earth's surface is composed predominately of mu-mesons ($\mu^{\pm}$). E. P. George was the first use cosmic ray muons for radiography. George measured the stopping rate of muons in order to determine the overburden of a mine tunnel. This technique has since been used for a variety of geological and archeological investigations] We have researched using the multiple scattering of muons for radiography. In addition to providing much more sensitivity than stopping, multiple scattering provides 3-d information, enabling tomography. I will discus the technology and applications from the perspective of the Los Alamos research program.

*Currently funded by DNN R&D (NA-221) , NNSA, U. S. Department of Energy

What are Cosmic rays

- Mean energy of a few GeV, highly penetrating.
  - Muons interact only through Coulomb and weak forces.
  - $dE/dx \approx 2.0$ MeV/g/cm^2.
  - 4 GeV muons have a range of ~6.7 m in concrete.
- Muon flux.
  - 10,000 muons/m^2/min at the earth's surface. 1/thumbnail/minute
- Strong angular dependence.
  - Muon flux roughly scales with $\cos^2\theta$ where θ is the zenith angle.



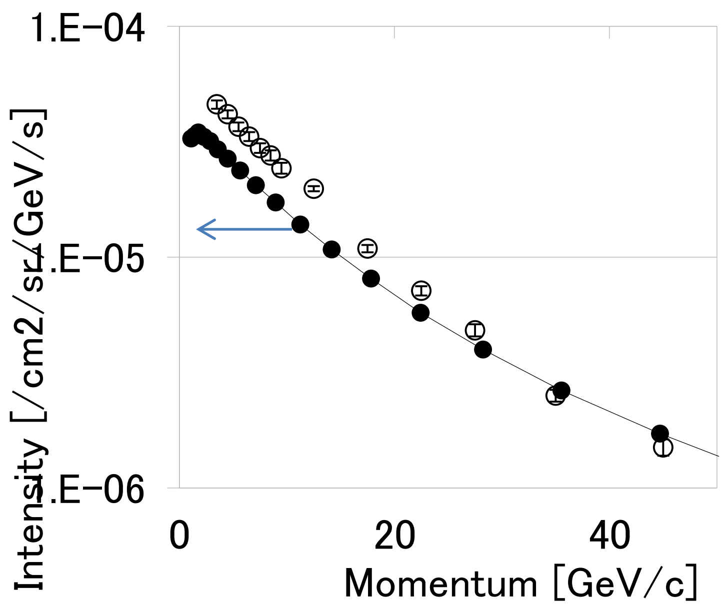


Energy spectrum of cosmic-ray muons.

,

Energy Loss

$$\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln(\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



Multiple Scattering

$$\frac{dN}{d\theta} = \frac{1}{2\pi\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} d\Omega$$

$$\theta_0 = \frac{14.1}{p\beta}\sqrt{\frac{L}{X_0}}$$

$$X_0 = \frac{K}{A}\left\{Z^2\left[L_{rad} - f(Z)\right] + ZL'_{rad}\right\}$$

	dx/dE cm/GeV	x cm
Reactor Core	731.9	8.7
Concrete	254.1	15.8
Fe	88.4	9.5
water	502.5	36.0

Stopping cosmic ray radiography

Commonwealth Engineer, July 1, 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.

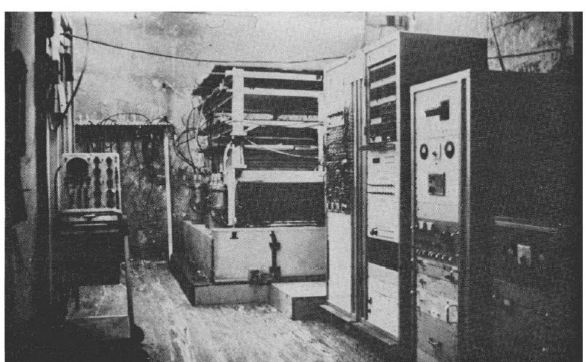
Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

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

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy,



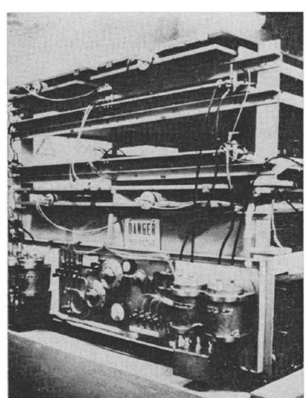


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid. Fig. 7 (right). The detection apparatus containing the spark chambers.

6 FEBRUARY 1970 — 835

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Nuclear Instruments and Methods in Physics Research A 356 (1995) 585–595

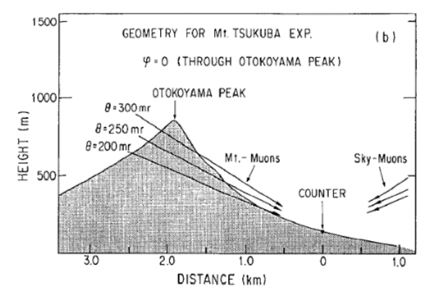
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

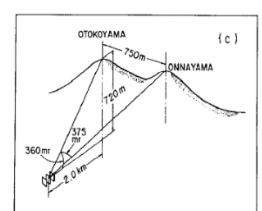
Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction

K. Nagamine [a,b,*], M. Iwasaki [a], K. Shimomura [a], K. Ishida [b]

[a] Meson Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo, Japan
[b] Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan

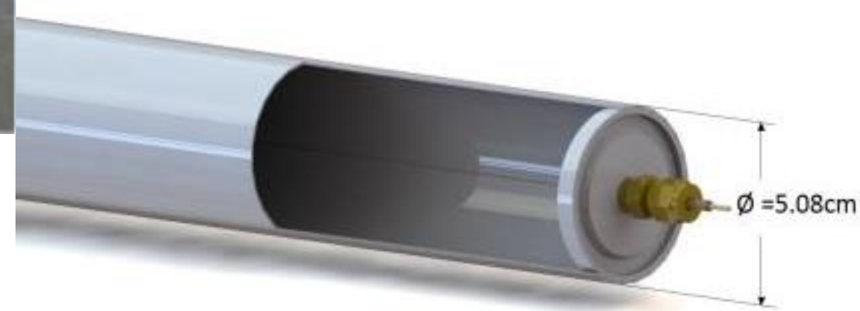
Received 4 July 1994; revised form received 12 September 1994





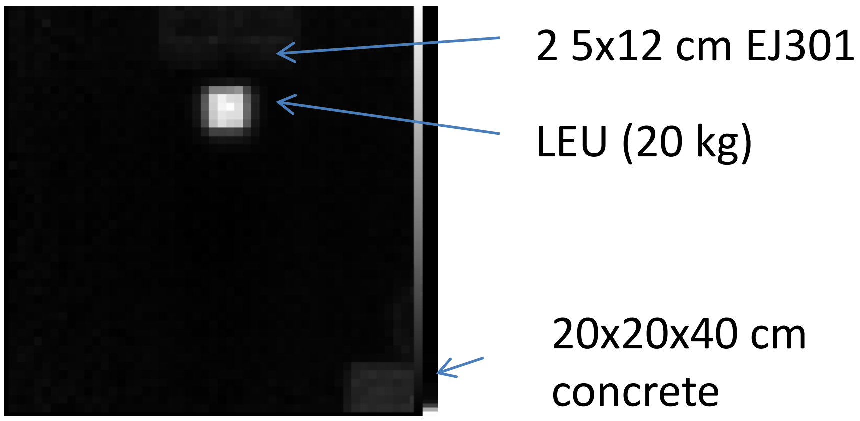
Our detector: the Mini Muon Tracker

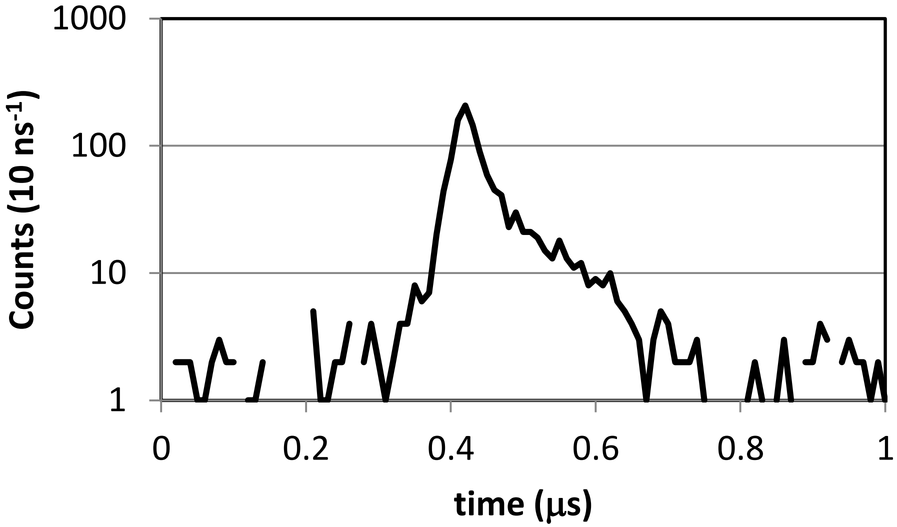
- 576 drift tubes arranged in X and Y layers
- Trackers size: 120 cm x 120 cm x 60 cm



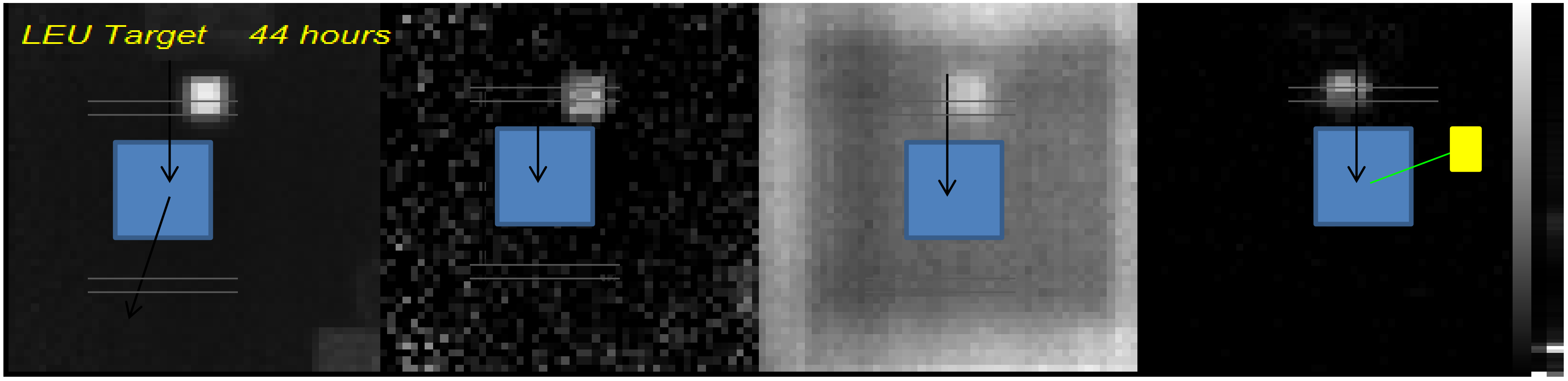
Gas mixture: 47.5% Ar, 42.5% CF_4, 7.5% C_2H_6, 2.5% He
Al tubes, gold-plated anode wire, 30-µm diameter

Four different kinds of radiography



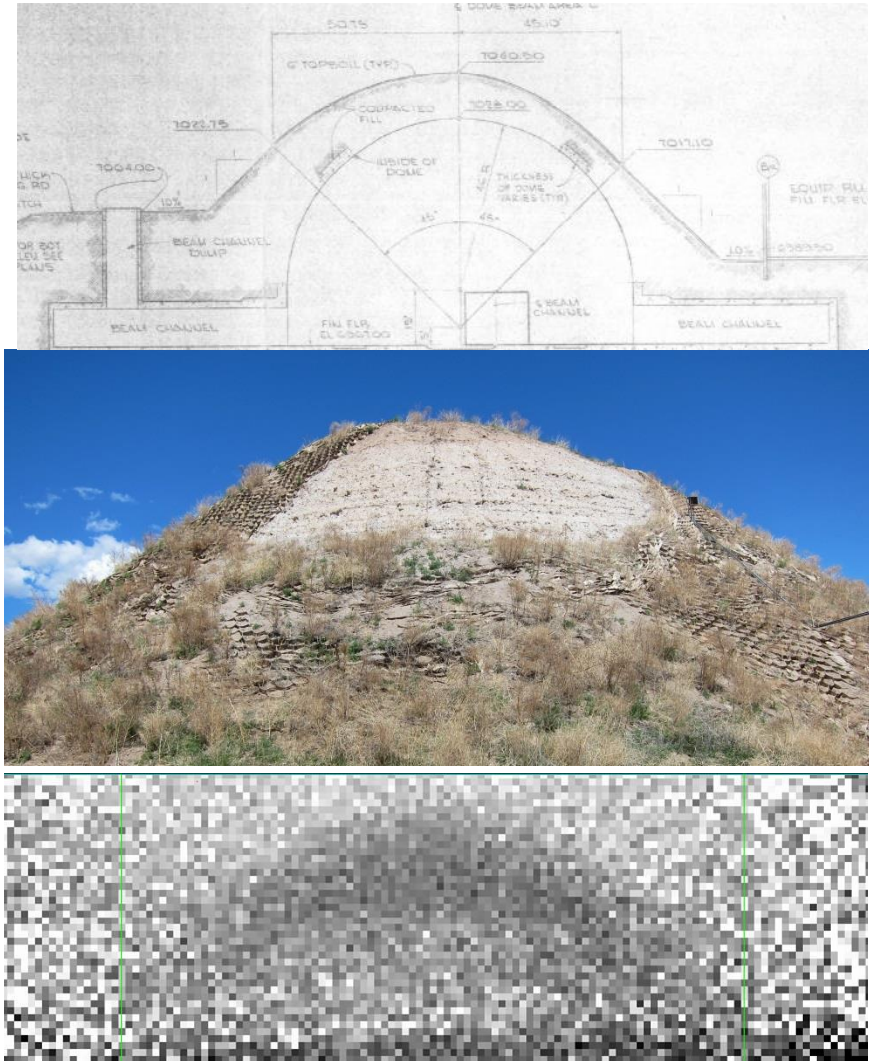


Scattering (RL) Ln(N/N$_0$) Stopped (hr-1) Tagged(hr-1)



Transmission radiography

Tunnel detection and imaging using seismic tools and cosmic-ray muon radiography

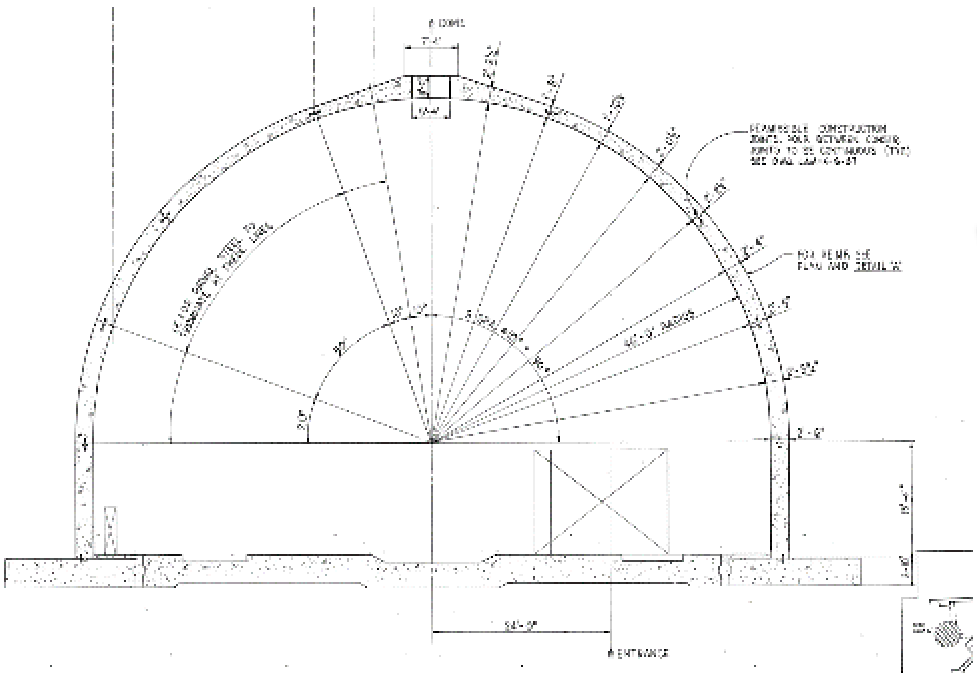


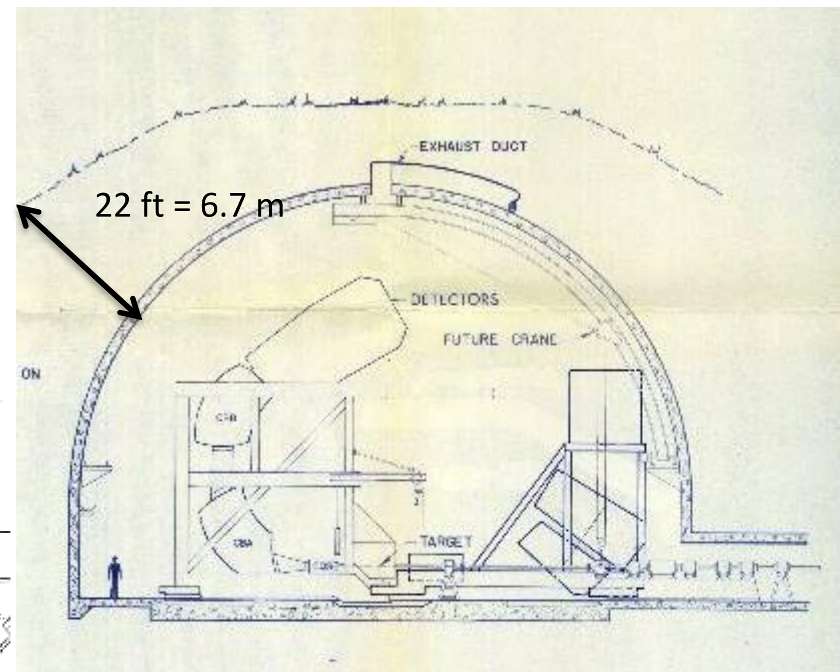
With day-month exposure time single sided muon imaging can look through thick structures.

- Data can be taken with passive detectors such as nuclear emulsions, plastic track detectors, or image plates. (research is needed to develop the last two options)
- Using data from our drift tube tracker we have developed algorithms for both single sided imaging and scattering imaging using integrating detectors.

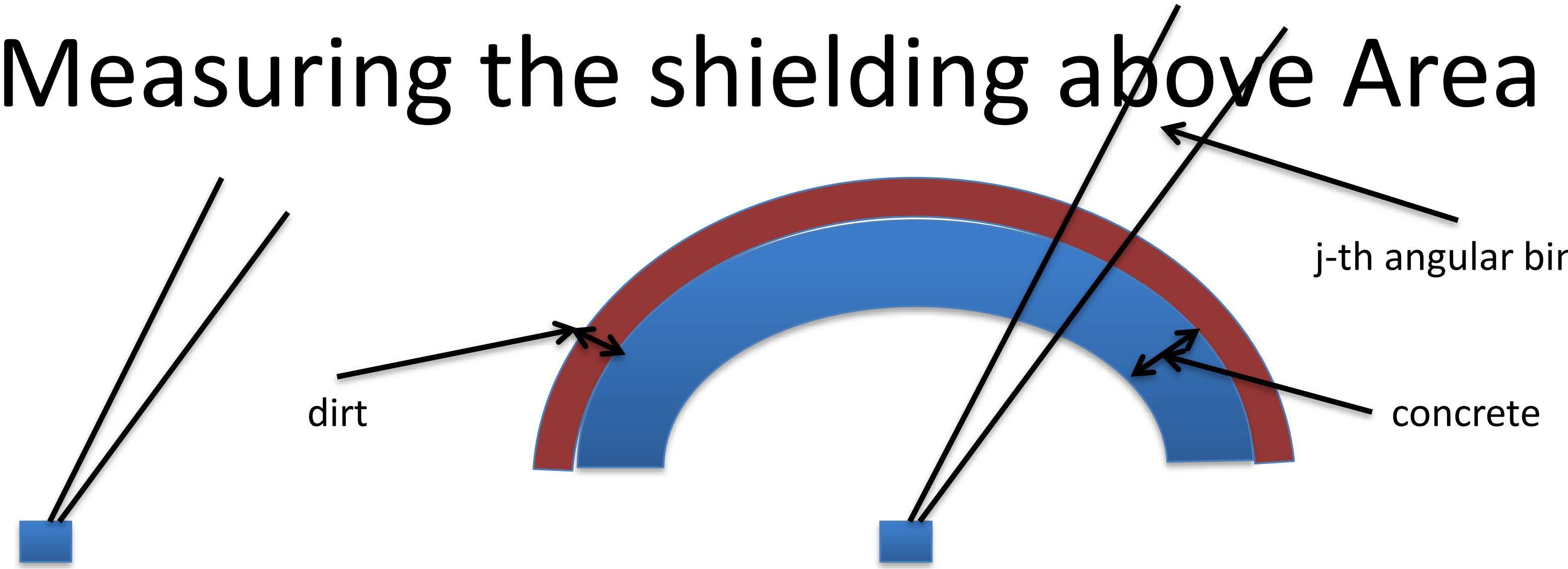
Over the past 30 years soils has washed of the area C dome, a primary beam area at LANSCE

- We have recently use our detector to make simple measurements of the overburden





Measuring the shielding above Area C



- Measure muon flux in angular bins inside and outside the dome provides muon attenuation
- A measurement of muon attenuation provides the amount of matter, or "range" R (density times length) traversed by the particles along their path. If R_j is the range of a muon travelling along a path j, then

known/needed

$$R_j = t_{concrete,j} \times r_{concrete} + t_{dirt,j} \times r_{dirt}$$

from data

unknown

from drawings

Calculating the ranges

- Effect of overburden is to remove lower energy muons
- The relationship between the minimum energy E_{min} that a muon must possess to traverse a material without being absorbed and its range R is tabulated for a set of elements and materials:

$$E_{\min} = E_{\min}(R) \quad (1)$$

- The number of muons surviving the passage through that material is given by

$$N_{underground}(\theta) = \epsilon \cdot \int_{E_{\min}}^{\infty} f(\theta, E)\, dE \qquad N_{surf}(\theta) = \epsilon \cdot \int_{0}^{\infty} f(\theta, E)\, dE$$

where $f(\theta,E)$ is the flux of muons expected on the surface

- Taking the ratio cancels out detector's efficiency
- Obtained E_{min} from

From CRY

measured

$$\frac{N_{underground}(\theta)}{N_{surf}(\theta)} = \frac{\int_{E_{\min}}^{\infty} f(\theta, E)\, dE}{\int_{0}^{\infty} f(\theta, E)\, dE} \quad (2)$$

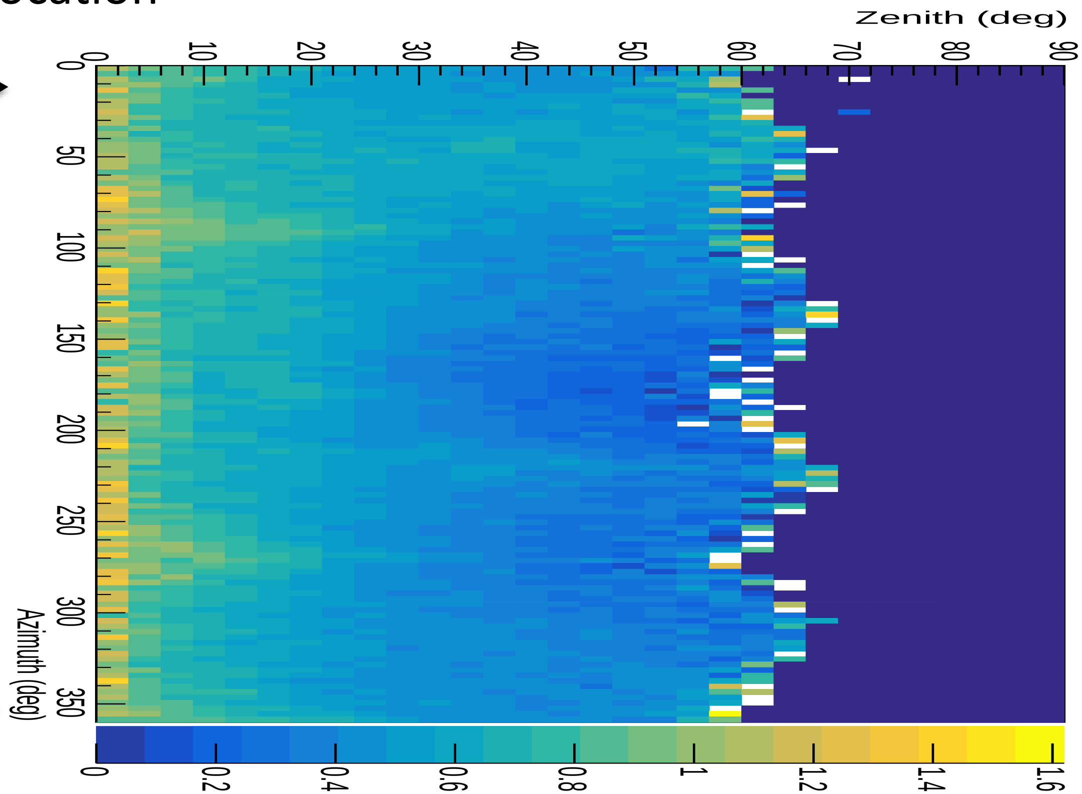
- Using $f(\theta,E)$ provided by the Cosmic-Ray Shower Monte Carlo software
- Determine E_{min} from (2) and R from (1)

Results: muon attenuation length

- Muons attenuation length as a function of the direction, as seen from the MMT location

Horizontal direction

Vertical direction



$$Attn = -\ln \frac{N_{underground}(q,f)}{F_{surf}(q,f)}$$

Muon tomography of a canyon wall above a 1950's tunnel

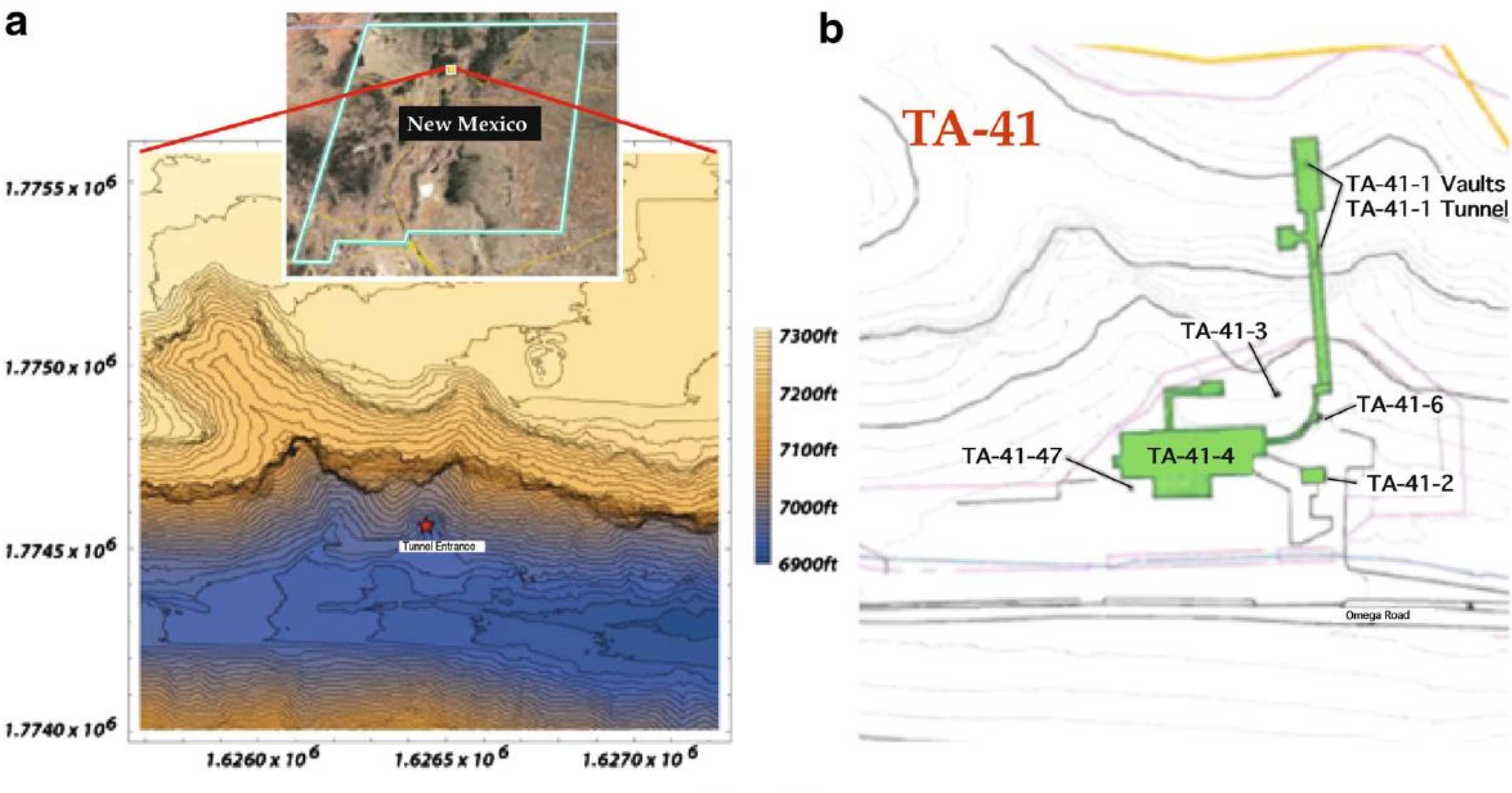


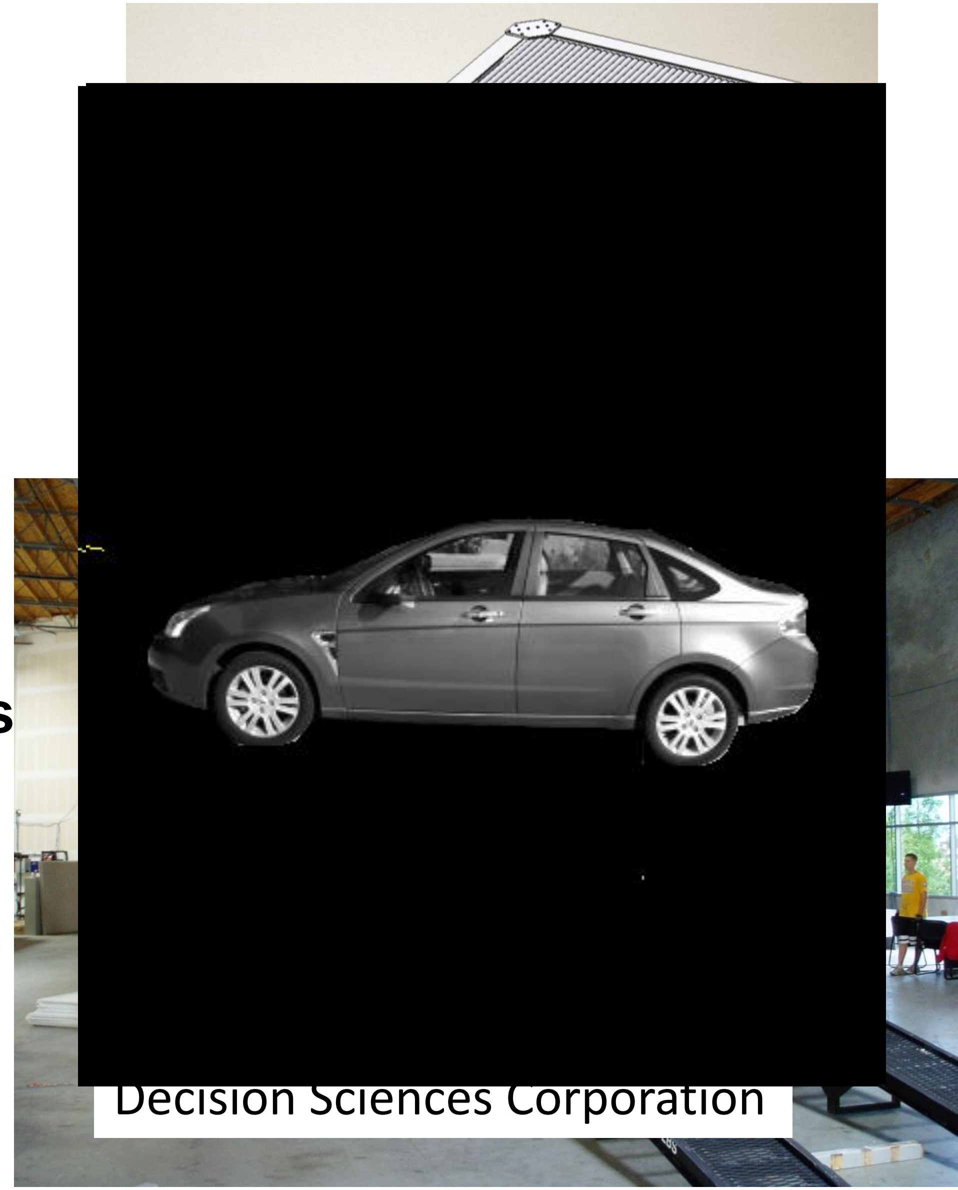
Figure 1

Pure Appl. Geophys. 174 (2017), 2133–2141

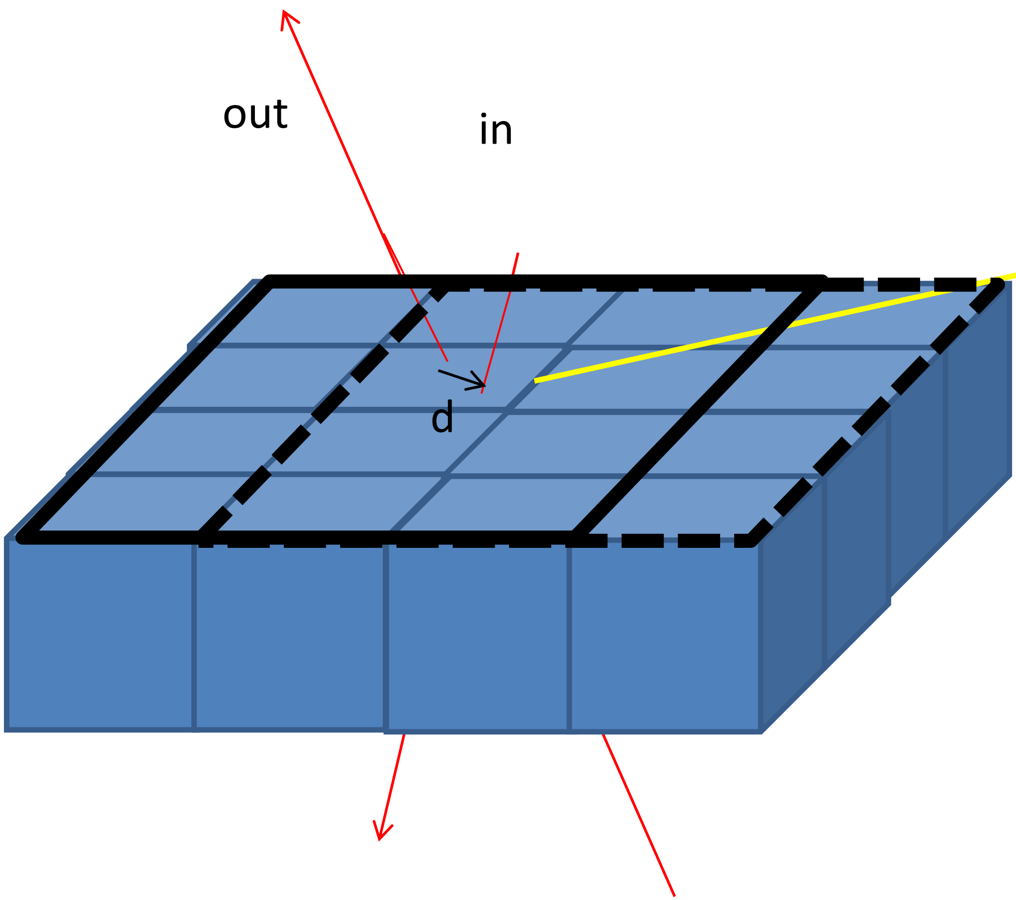
Scattering radiography

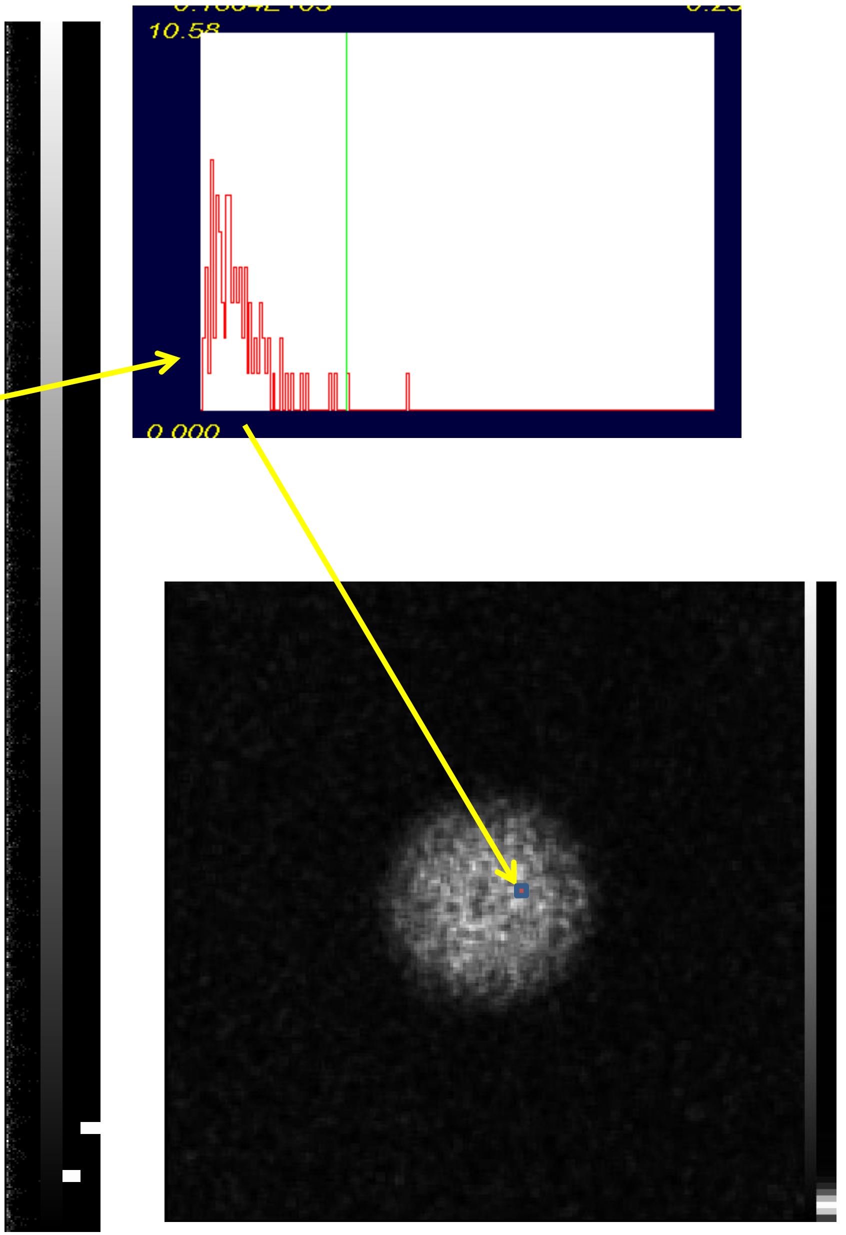
Scattering cosmic ray radiography

- **Technical approach:**
  - **Measure passive radiation**
  - **Use muons to generate "scattering density" image**
    - » Built in momentum measurement
    - » Automatic calibration using flux through empty detector
  - **Combine signals to identify threats**
- **Advantages over other methods**
  - **No radiation**
  - **Simple technology**
  - **Inexpensive**
  - **Can penetrate thick cargos**
  - **Automatic Identification**



Generating Scattering Images





If(d<rmin) then
increment h(I,j,k,θ)

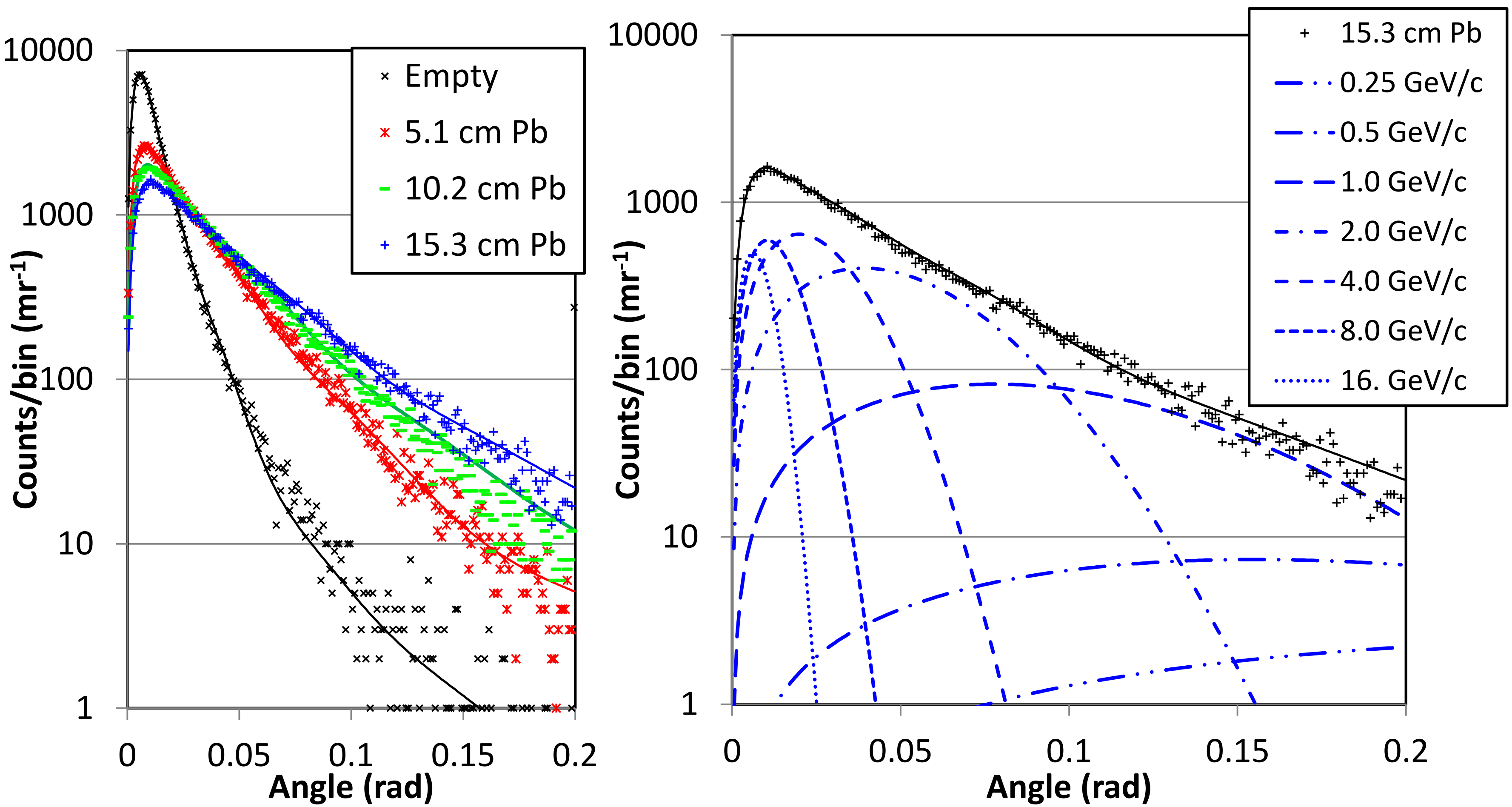
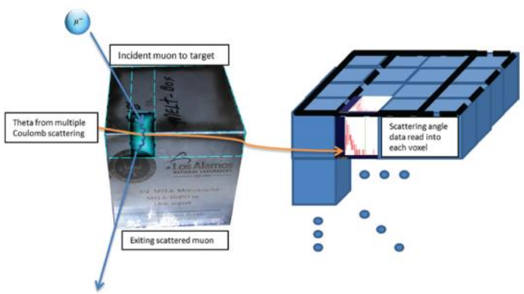


Figure 6) Left) Measured angular distributions for various thickness of lead (points) and the fit (lines) for various thicknesses of lead. Right) The decomposition of the fit into energy groups. Empty shows the angular distribution with no object in the scanner.

Detection of a 5 cm tungsten cube (2.3 kg)



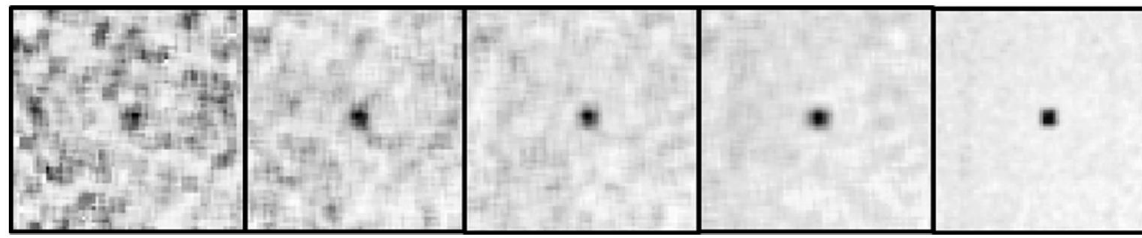
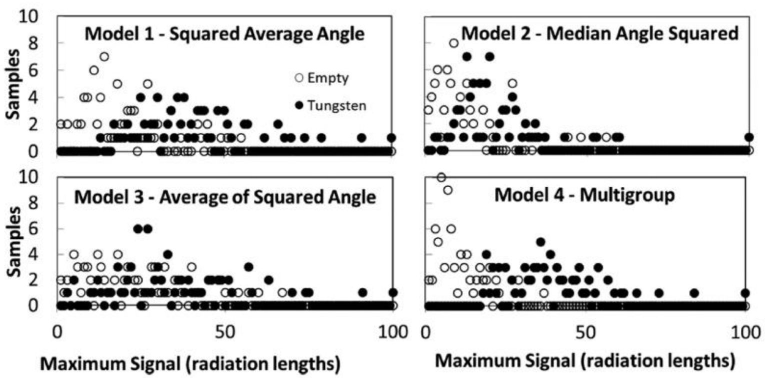
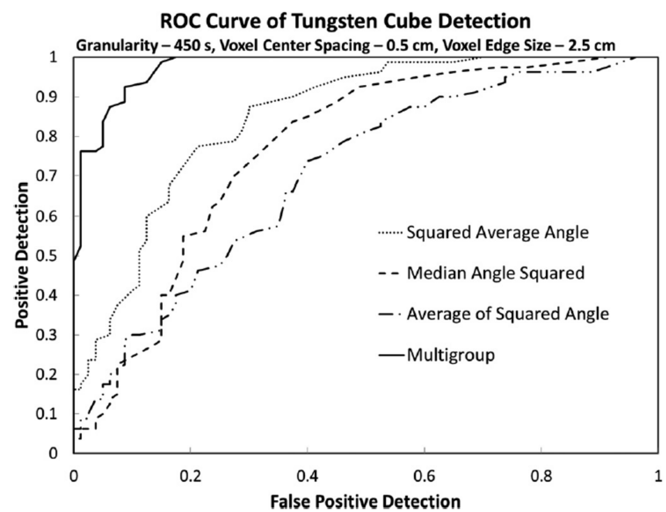


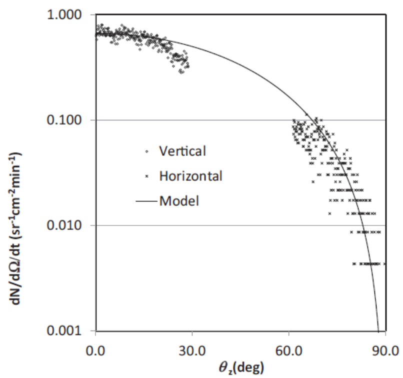
FIG. 2. Muon tomography of a tungsten cube (5 cm edge) measured with the MMT. The reconstruction was created using the multigroup method. Five images are shown of the cube with increasing exposure (from left to right: 1 min, 5 min, 15 min, 1 h, and 10 h).

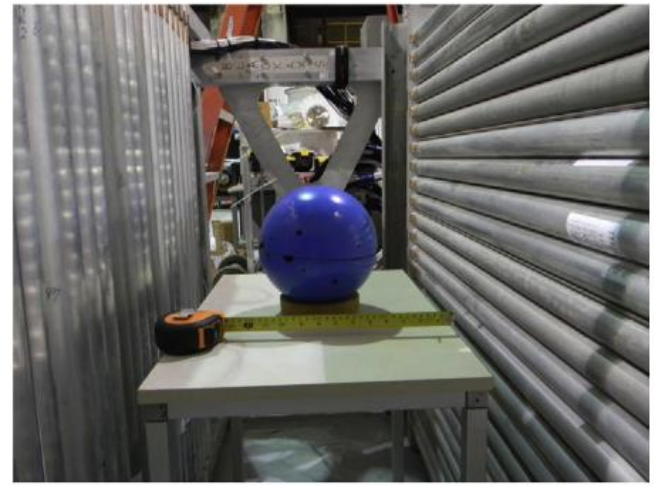


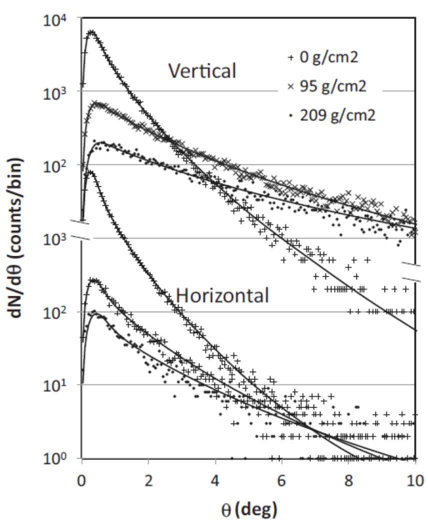


Quantitative muon tomography

$$\frac{dN}{d\Omega dt} = 0.66\cos^2(\theta_Z)(\mathrm{sr}^{-1}\mathrm{cm}^{-2}\mathrm{min}^{-1}),$$

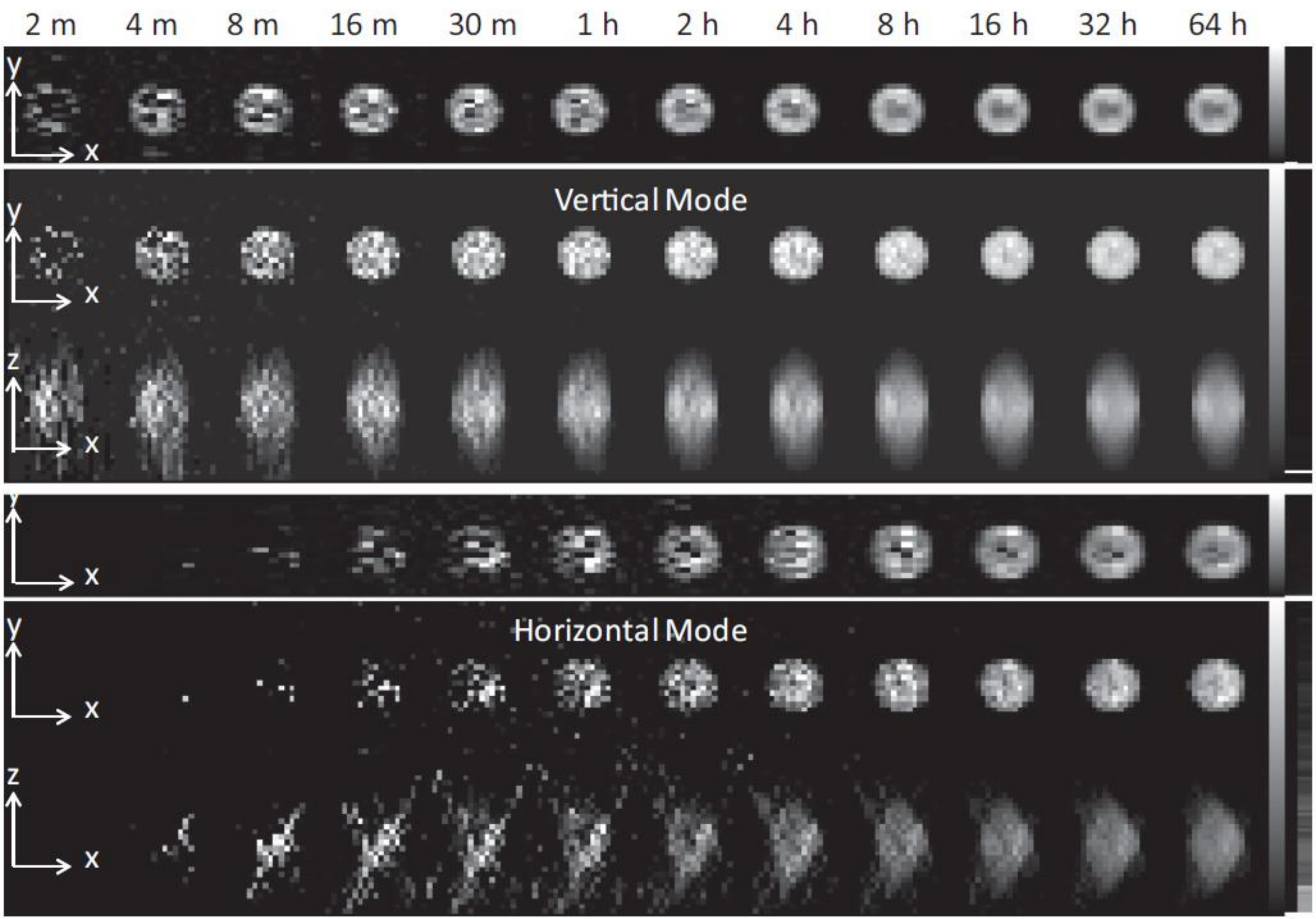






Nuclear Instruments and Methods in Physics Research B 330 (2014) 42–46

Tomography of an 20 cm diameter lead shell



Detecting Internal Structure

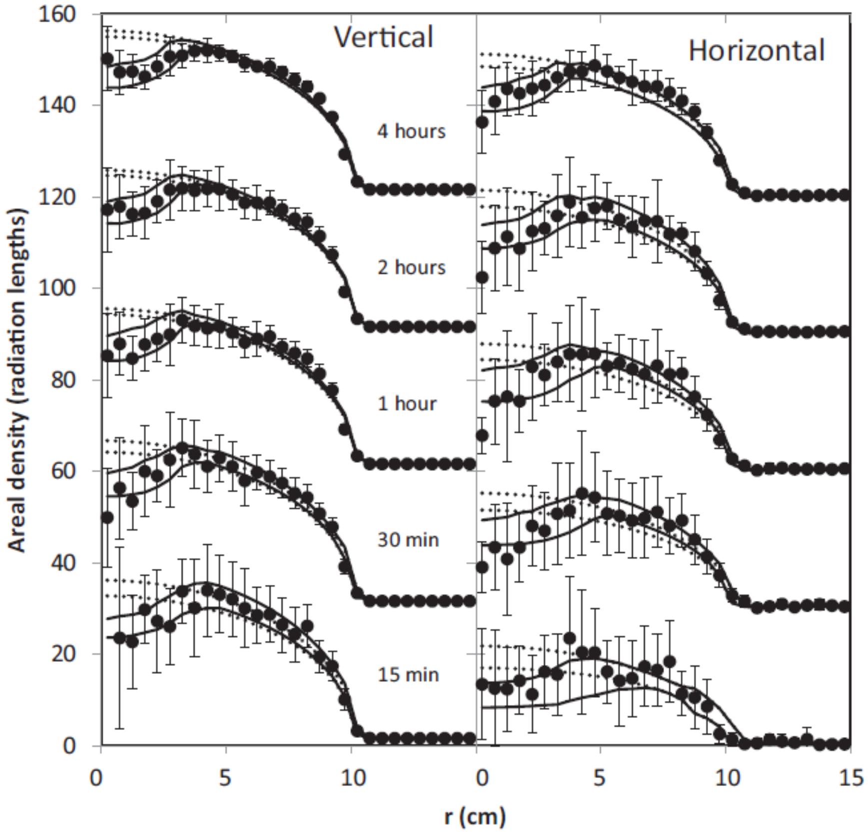
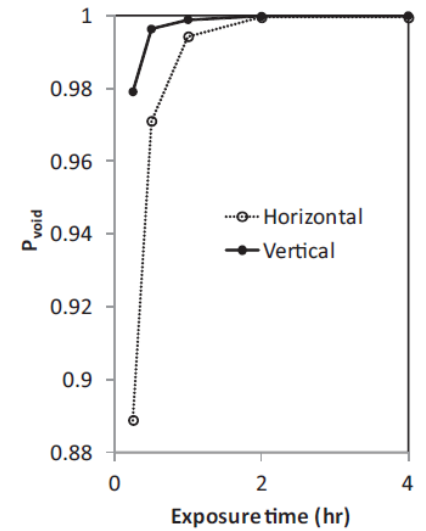
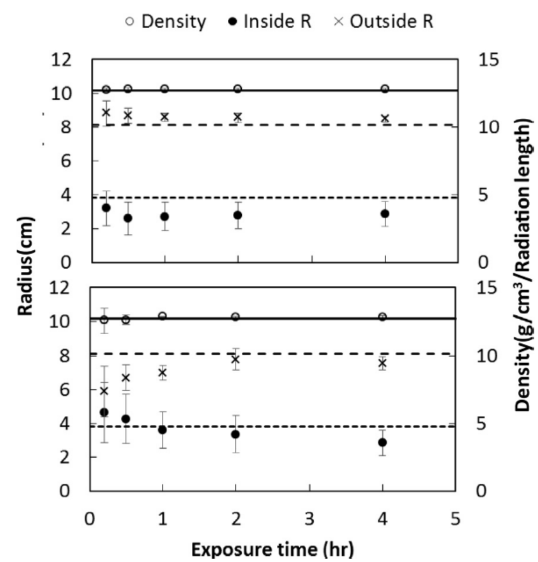
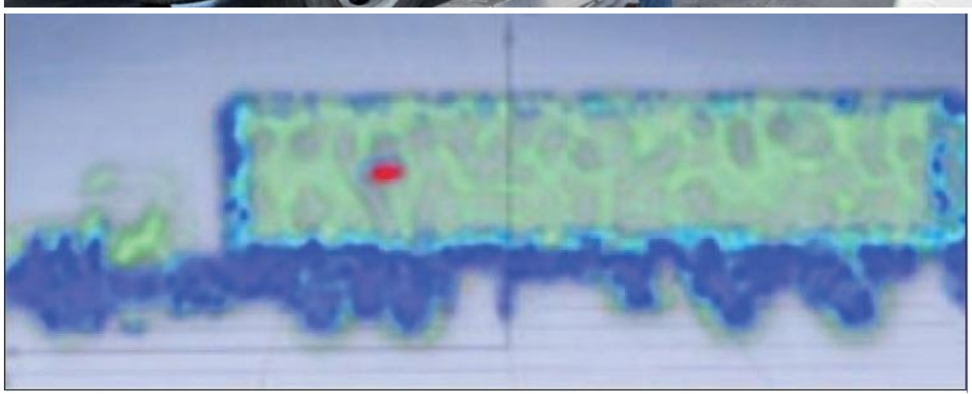


Fig. 5. Radiation length weighted areal density obtained in vertical (left) and horizontal (right) viewing modes. The data points show the mean value from 15 independent runs. The error bars are the standard deviation from the 15 runs. The curves show the ±1 standard deviation bounds from the mean for fits to the data with (solid) and without (dash) a central void.





Decision Sciences First Installed Commercial Muon Scanner at Freeport in the Bahamas



Muon tomography can be used to search for nuclear contraband in cargo.

- Less than one minute scanning time to detect 20 kg of U
- Combining scattering and stopping can discriminate materials (explosives from cigarettes etc.)

Summary

- Cosmic rays (muons) can be used for imaging
- Stopping can be used to image thick structures (1000 g/cm^2). Measures electron density. Precision ~1000/$\sqrt{N}$ g/cm^2
- Scattering can image thinner objects. Precision ~$x/\sqrt{2N}$
- More later

Cosmic Ray Radiography/Tomography-Part 2*

Toshiba NCA

Assembly at Yokahama

Fuel Cask at INL

Chris Morris (for the muRad team)

Los Alamos National Laboratory

25-September-2017

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*Currently funded by DNN R&D (NA-221) , NNSA, U. S. Department of Energy

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Energy Loss

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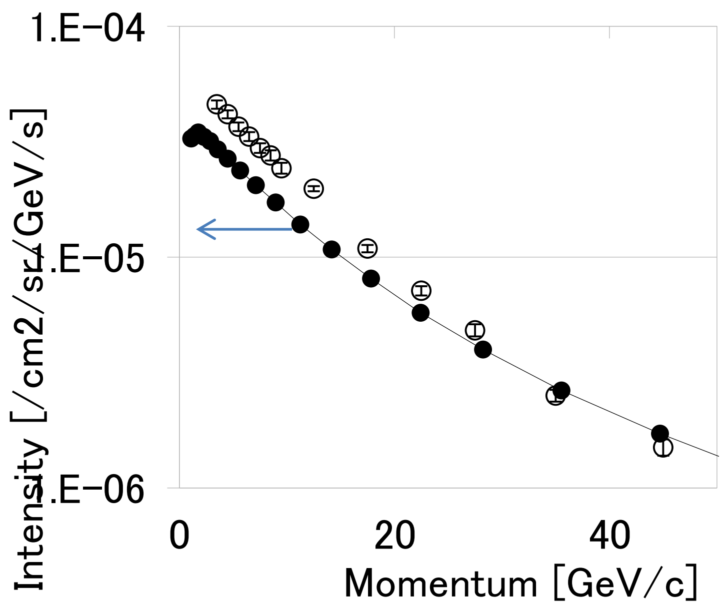


Multiple Scattering

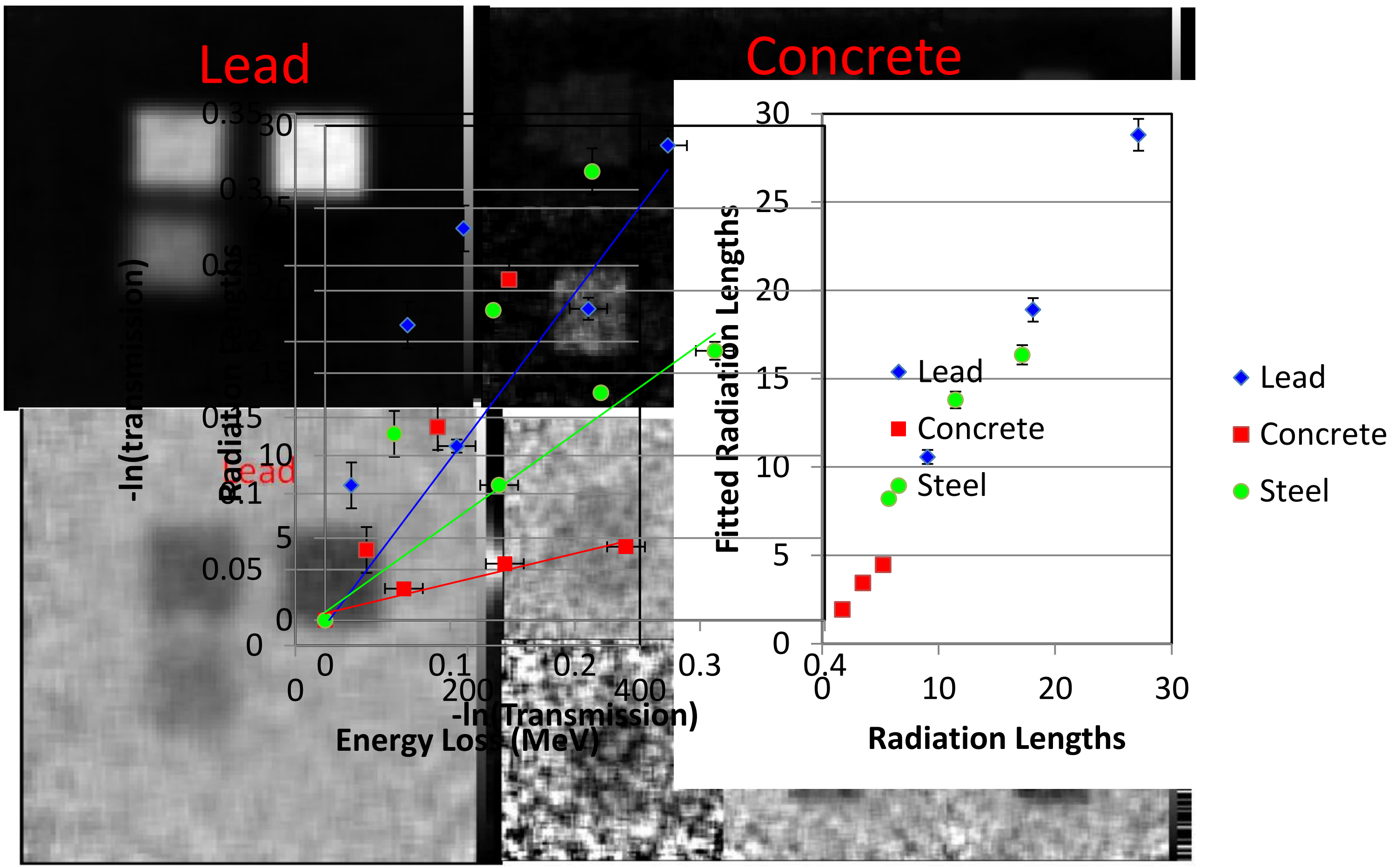
$$\frac{dN}{d\theta} = \frac{1}{2\pi\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} d\Omega$$

$$\theta_0 = \frac{14.1}{p\beta} \sqrt{\frac{L}{X_0}}$$

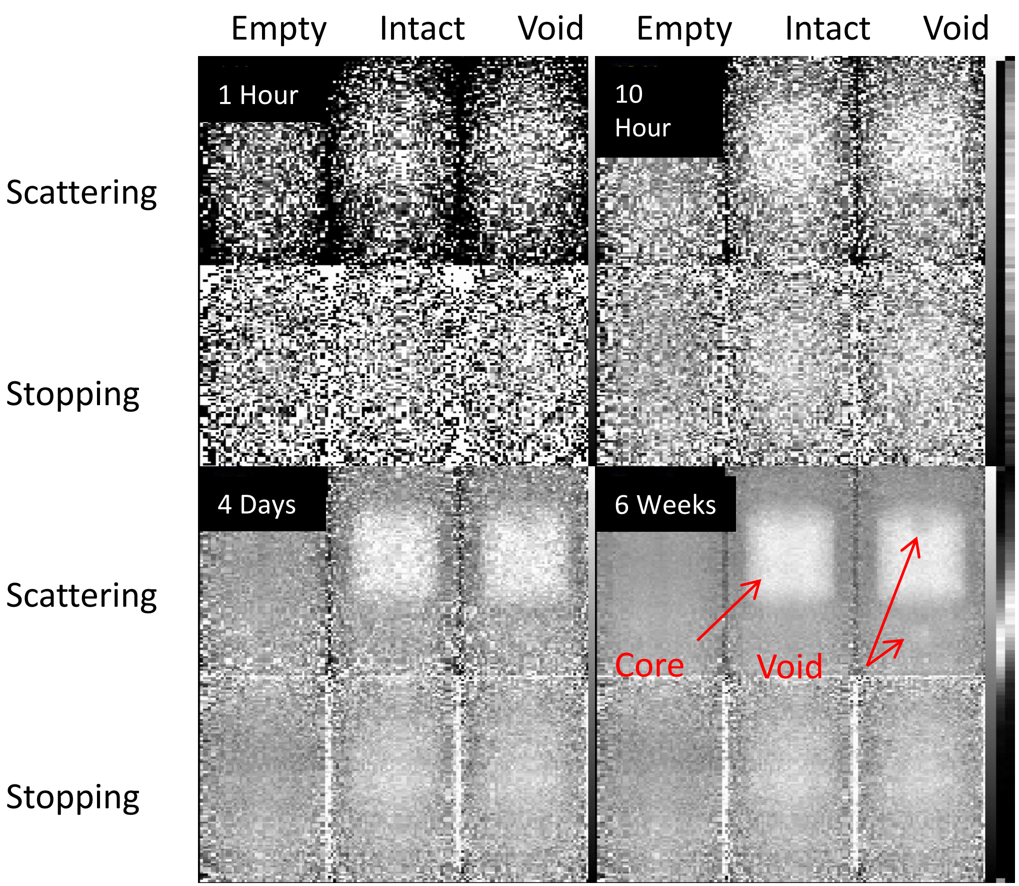
$$X_0 = \frac{K}{A} \left\{ Z^2 \left[L_{rad} - f(Z) \right] + Z L'_{rad} \right\}$$

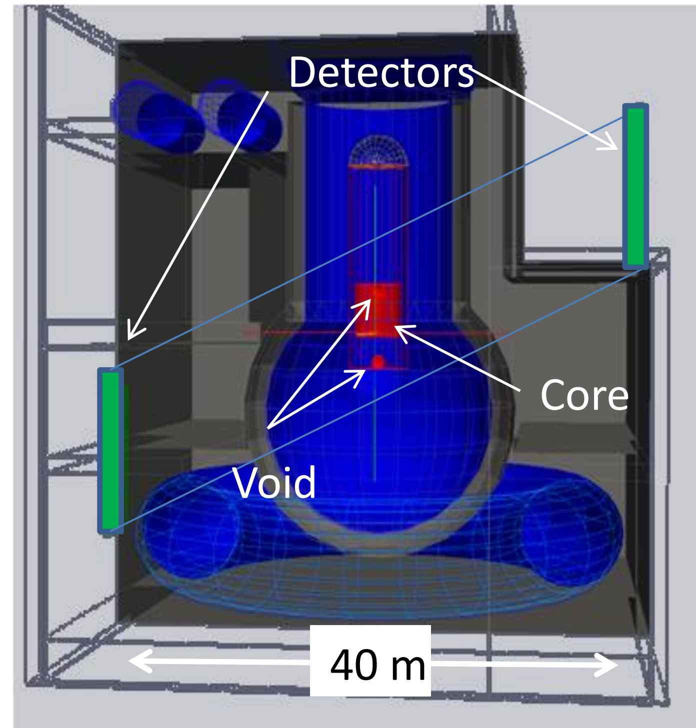
	dx/dE cm/GeV	x cm
Reactor Core	731.9	8.7
Concrete	254.1	15.8
Fe	88.4	9.5
water	502.5	36.0

Material Identification



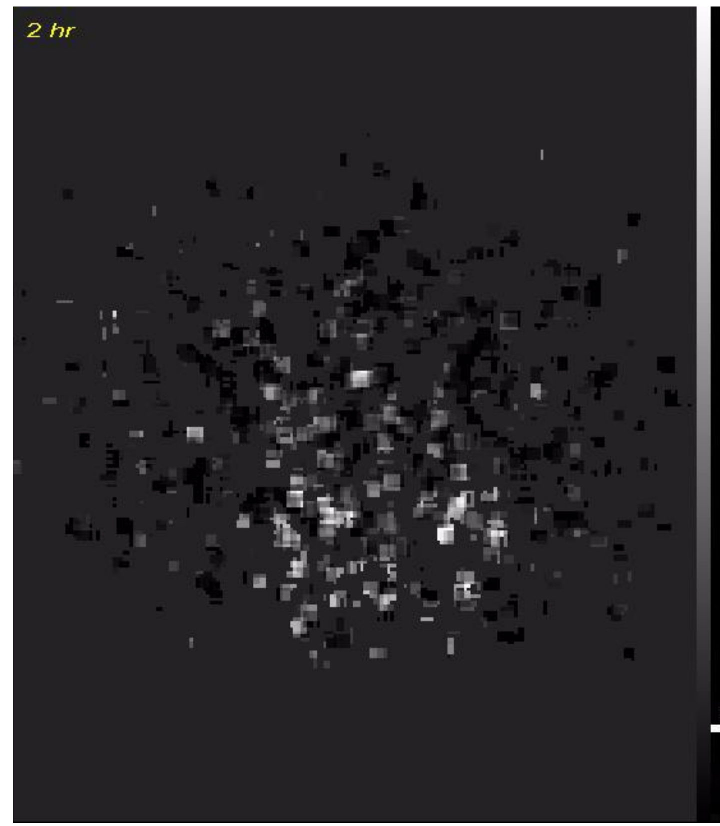
GEANT Simulation of Radiography of Fukushima reactors (Toshiba)



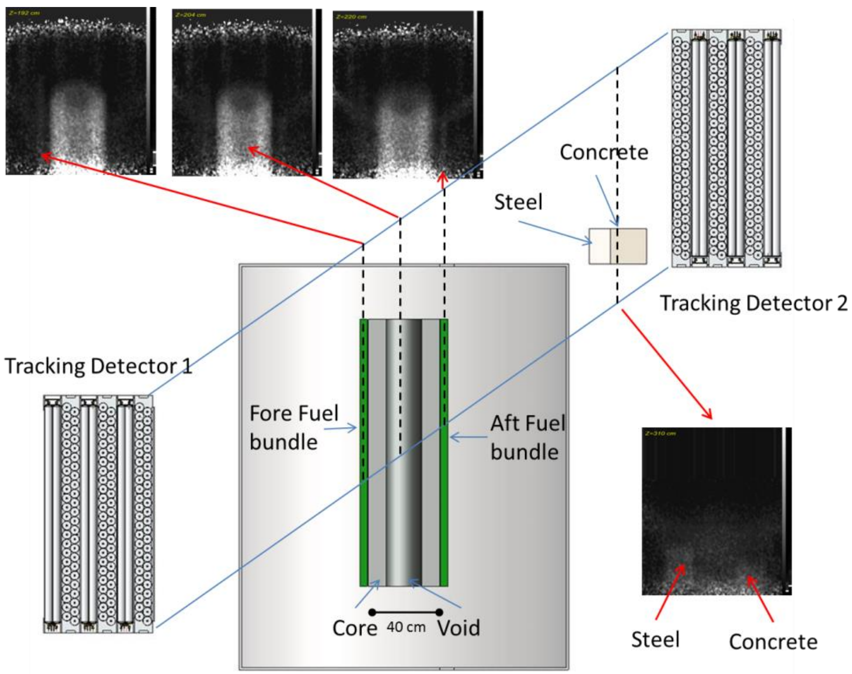


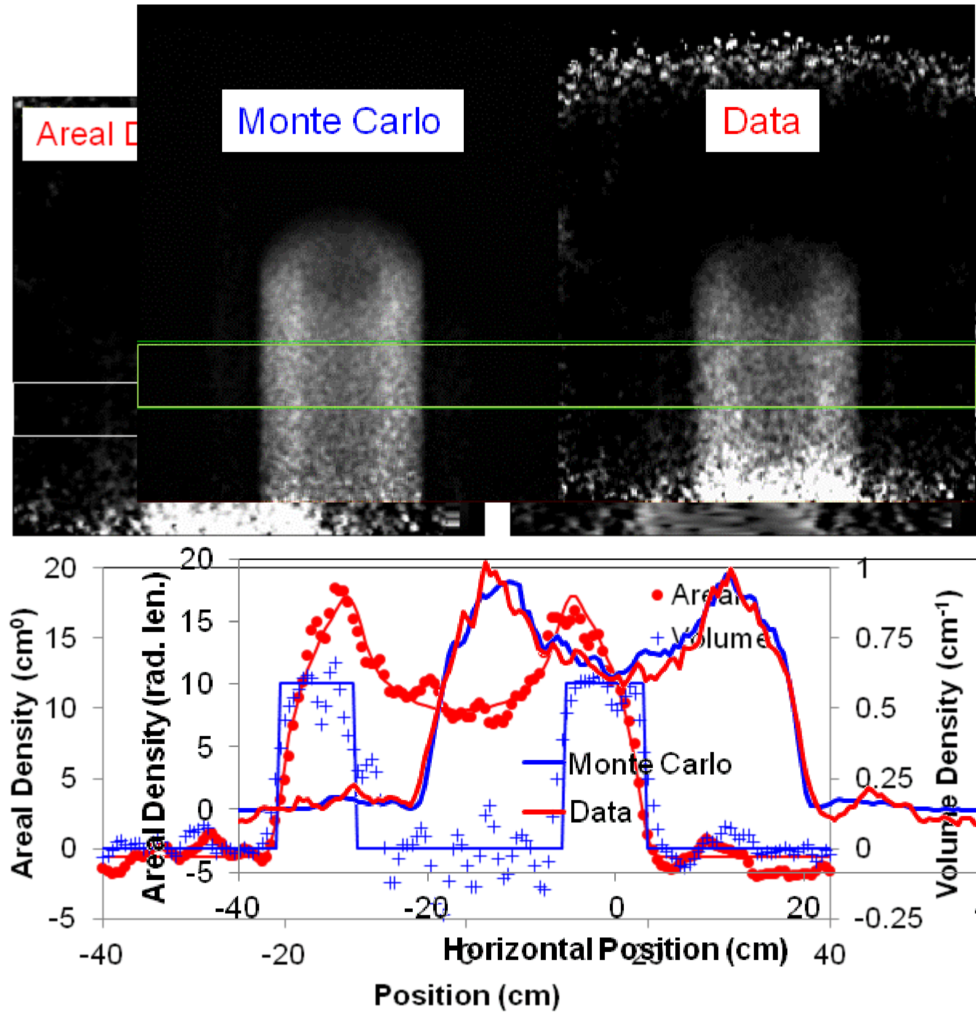
- Scattering Cosmic radiography can be used to image the damaged cores
- Stopping radiography is much more difficult

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



NCA Results

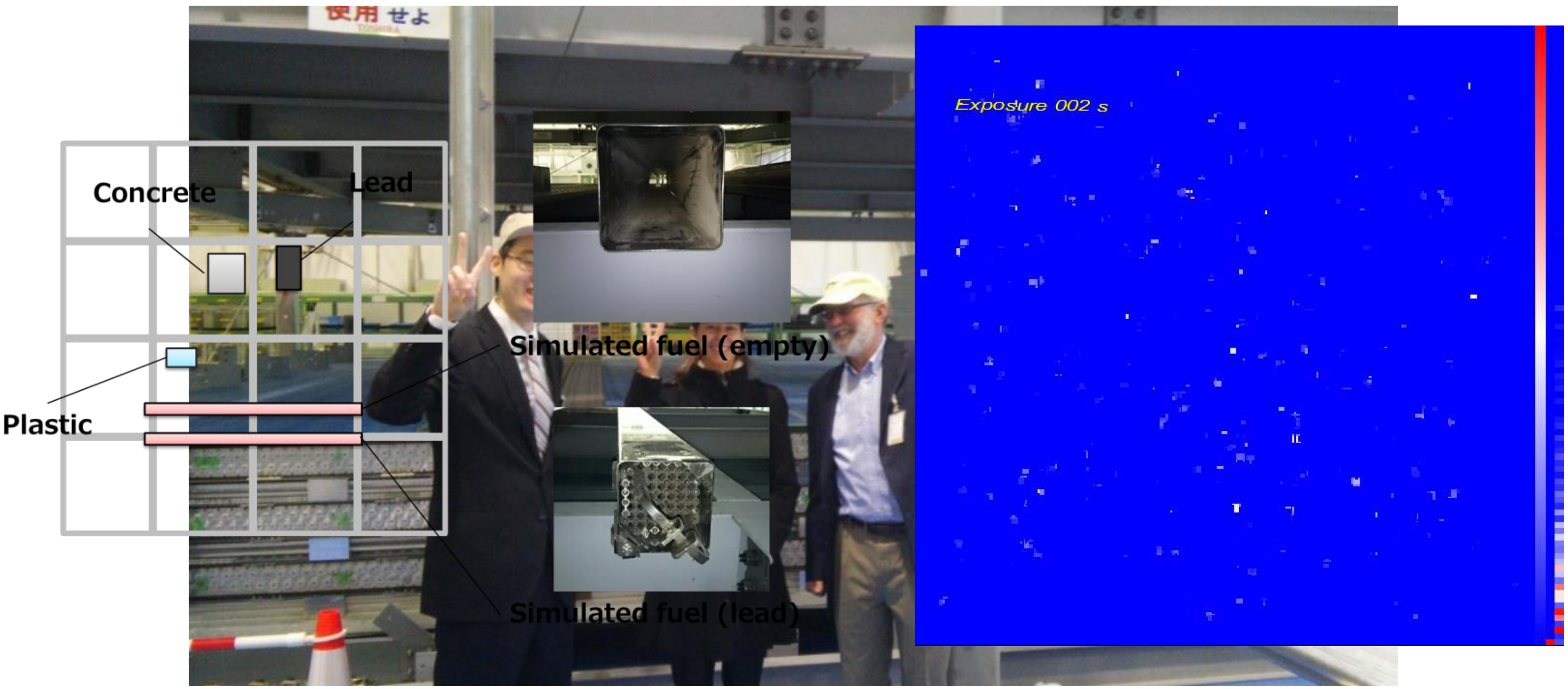

Concrete
Steel
Tracking Detector 2
Tracking Detector 1
Fore Fuel bundle
Aft Fuel bundle
Core
40 cm
Void
Steel
Concrete


Monte Carlo
Data
Monte Carlo
Data
Areal Density (cm^0)
Horizontal Position (cm)
Position (cm)

Fukushima Status

Assembly in February at Yokahama

5 minute exposure

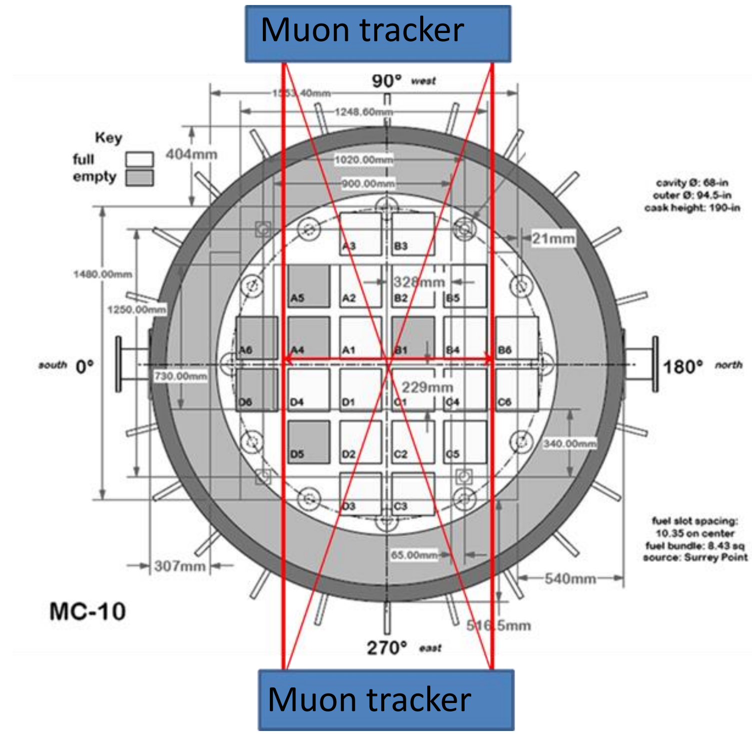


Fuel cask imaging

Fuel cask imaging for NA-22

Muon trackers in weatherproof enclosures. One side elevated to increase muon flux through both detectors (falls off as ~$\cos^2\Theta$).

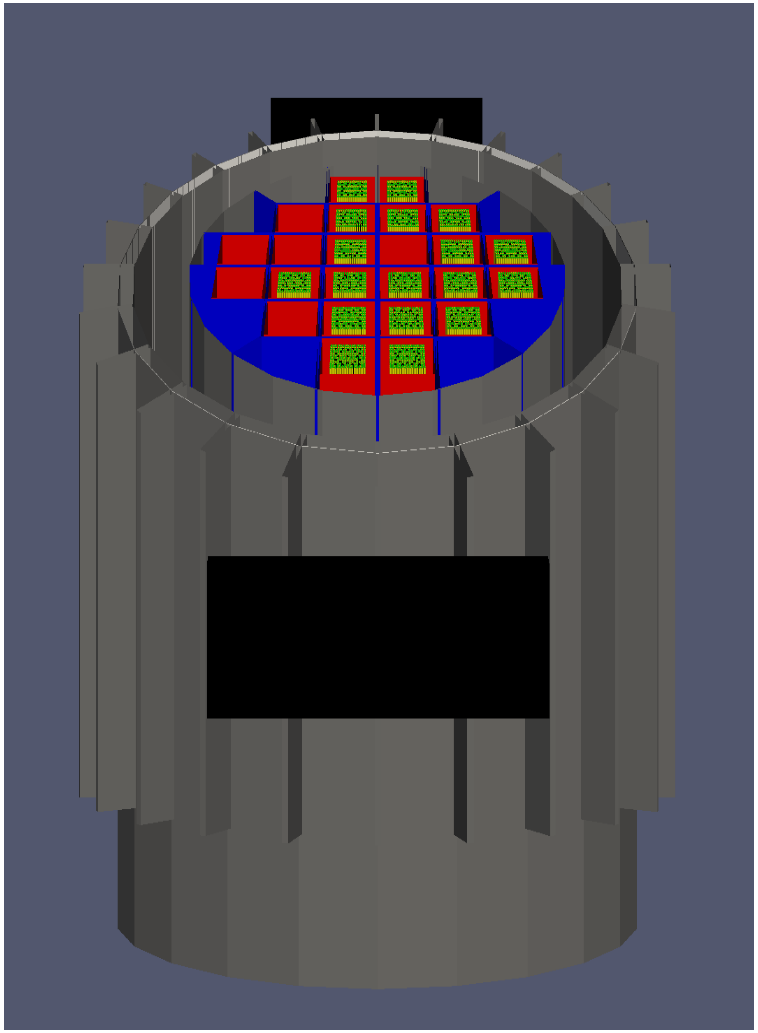
Westinghouse MC-10 cask

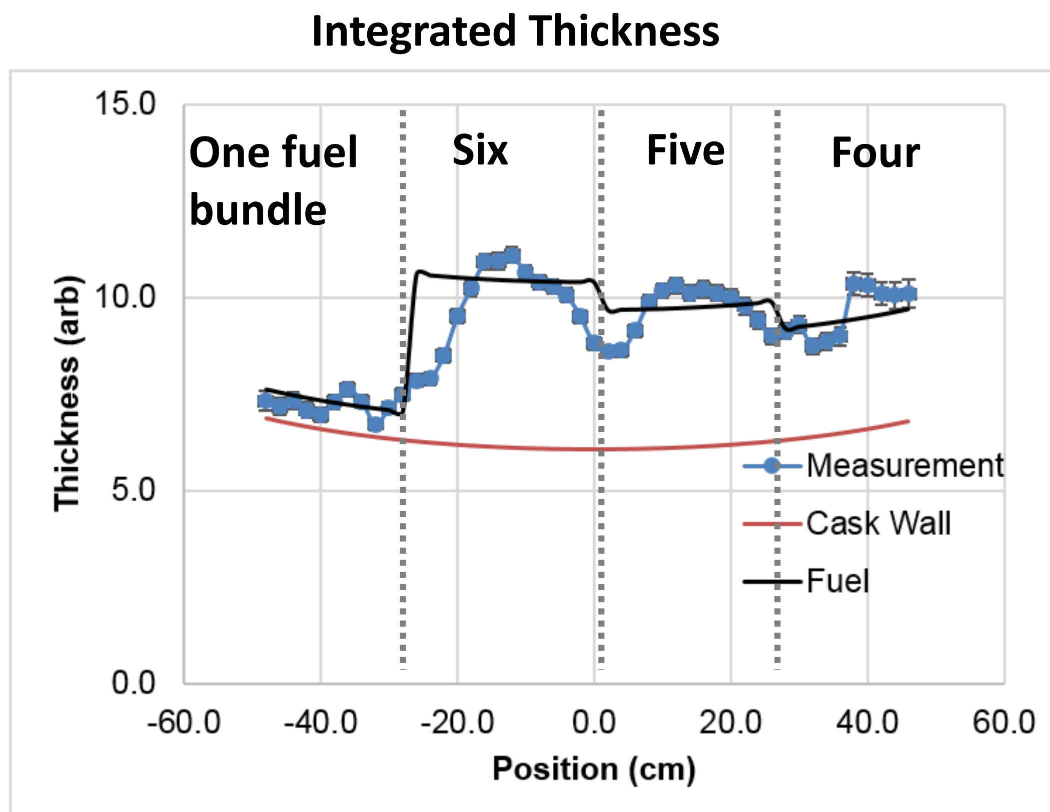


Cask loading profile. Several fuel bundles are missing. The bundles are high-burnup PWR fuel, removed from commercial plants in early 80s.

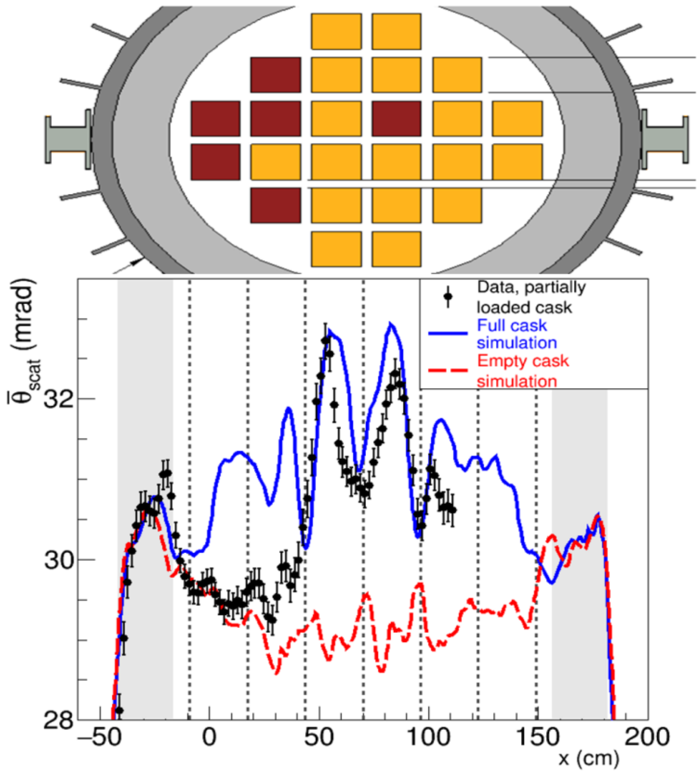
Count time: 100 hrs

Preliminary Results





Most recent run

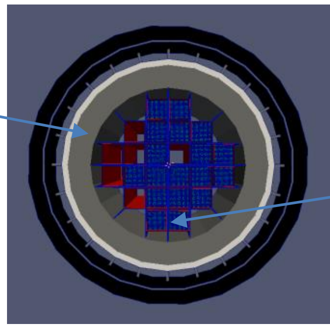


Problems

- Detector voltage too low
- Lost clock sync for ~1/2 of data
- Wind moved detectors

Fuel cask tomography

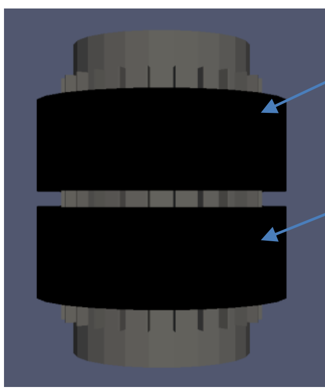
Top View



Cask wall (steel)

Fuel slots

Side view

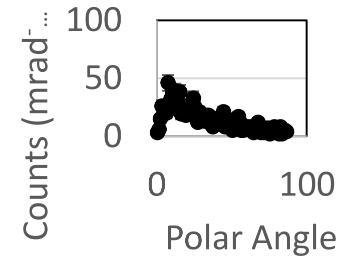


Input detector

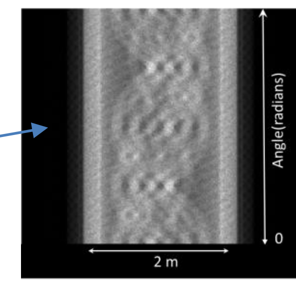
Output detector

- Generate trajectory through the cask with Geant. About 1 day of exposure.
- Construct a histogram of scattering angle for each pixel in a sinogram. Integrate in the vertical direction.
- Fit the scattering angle distribution to get the areal density using the calibrated multi group method. Enter into a 2-d histogram.
- Apply filtered back projection tomography to obtain a cross section of scattering length density. Empty slots are visible with 20 σ significance

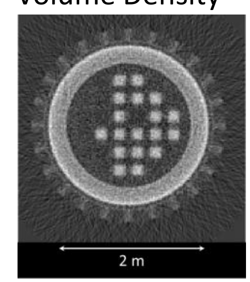
Multi-group fit for a typical sonogram pixel



Sinogram



Volume Density



Model fitting can reduce the amount of data required

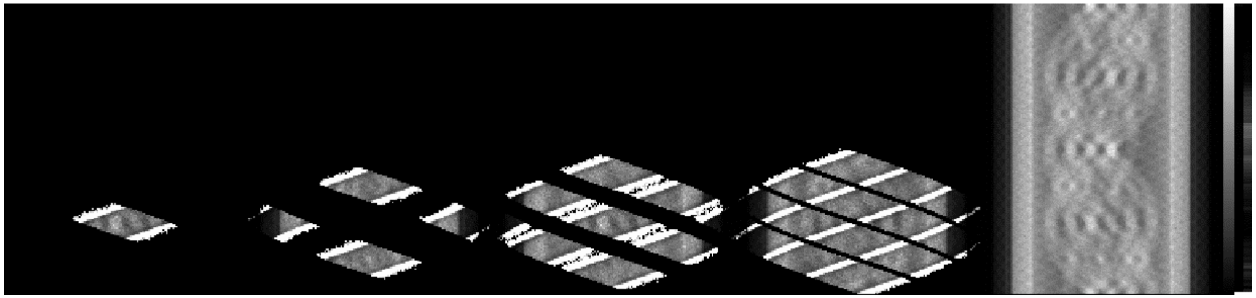


Figure 1) from left to right n=1,2,3,4 and the full data set.

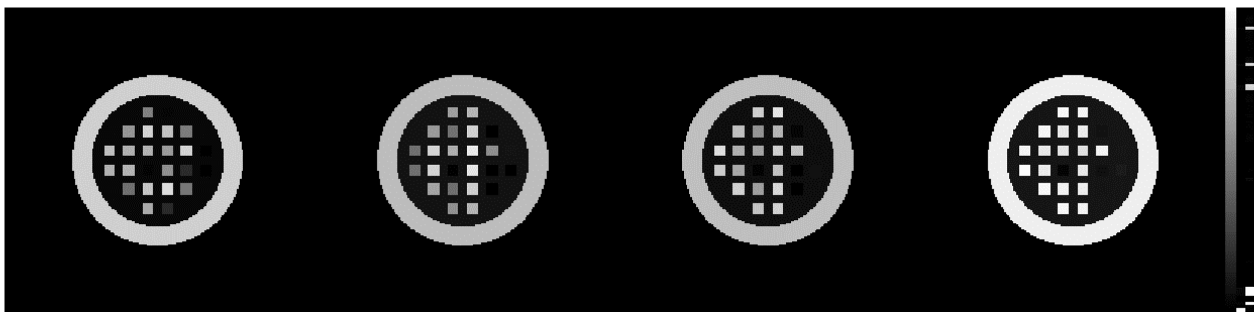


Figure 1) Densities obtained from the partial data sets compared to the full data set. These are for n=2,3,4 and full from left to right. The n=1 data is under constrained without further constraints, since there is no data for the cask wall.

then

$$\rho_k = \sum_i p_{ki} a_i \,. \qquad 1$$

One can form a X^2 as

$$\mathrm{X}^2 = \sum_k (\rho_k - y_k)^2 \,, \qquad 2$$

where y_k is the measured sinogram. The index k runs over both angles and position in the sinogram. The *a*'s are found by solving:

$$\frac{d\mathrm{X}^2}{da_j} = 0 = \sum_k 2\left(\sum_i p_{ki} a_j - y_k\right) p_{kj} \,. \qquad 3$$

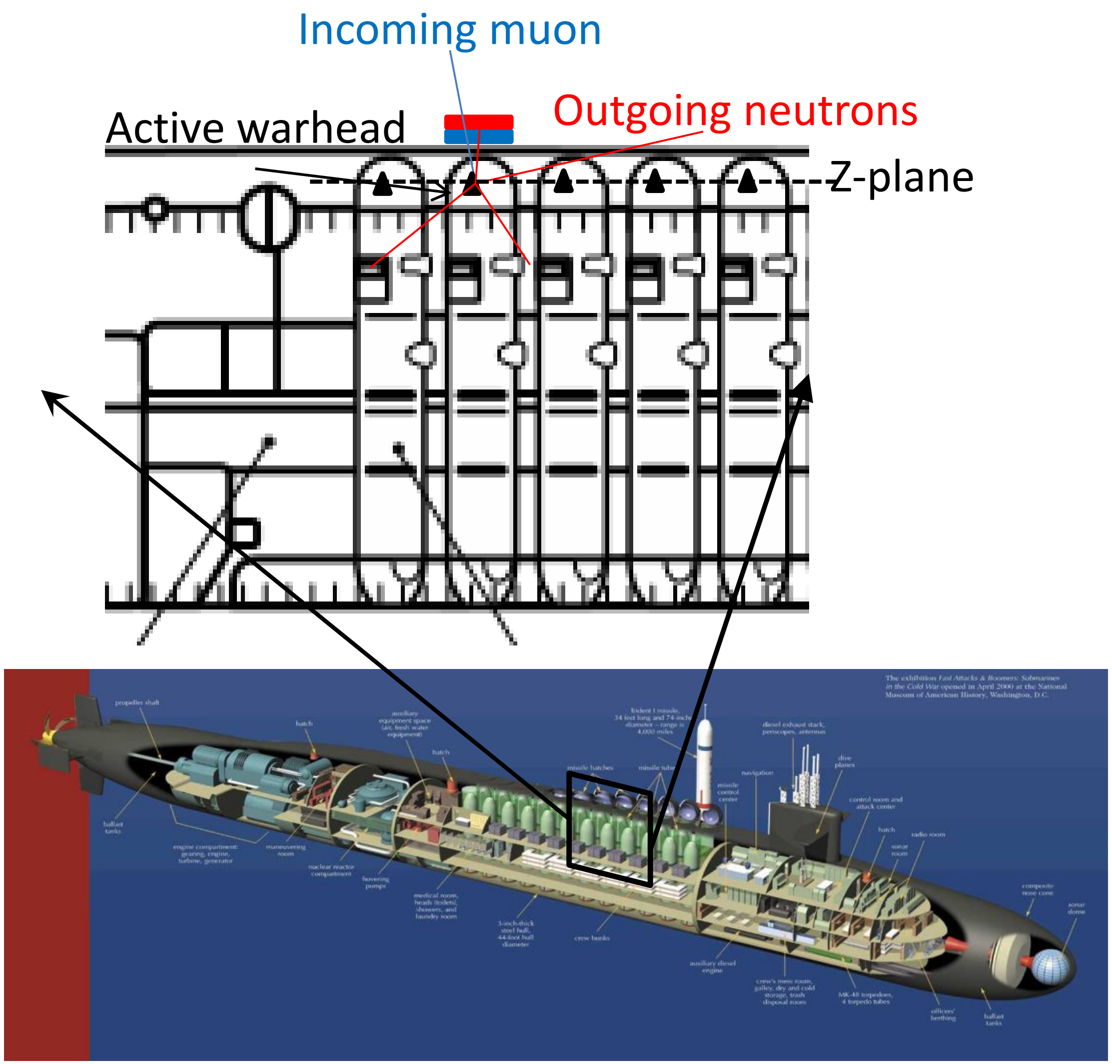
Path forward

Proposal to NA22

- Larger detectors
  - $R=2^2\times1.5^2$
- No need to move the detectors

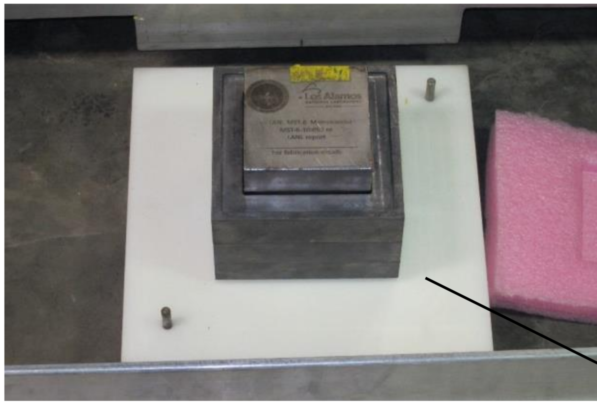
Other things

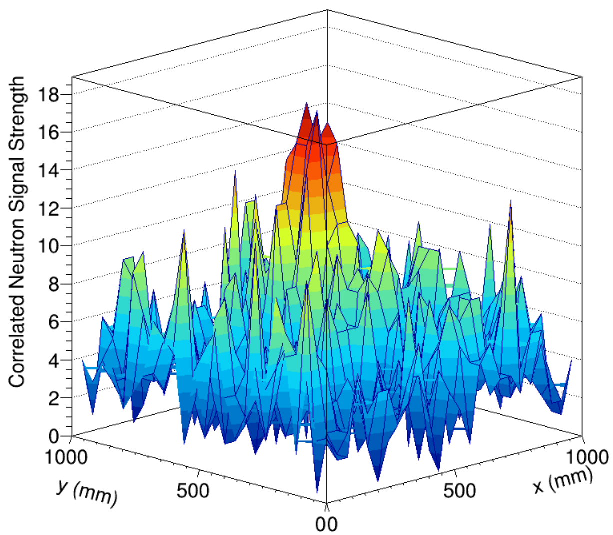
A new method of passive counting of nuclear missile warheads –work for the Defense Threat Reduction Agency and the State Department



- Use the interaction of stopped μ^-,
- $\mu^- + A \rightarrow (A-1) + n + \nu_\mu$.
- For nuclei with atomic number above Mg this decay mode dominates.
- In Fissile material neutron are amplified.
- Incoming muons can be tagged by outgoing neutrons to detect nuclear warheads
- May be other uses such as secondary cargo inspection

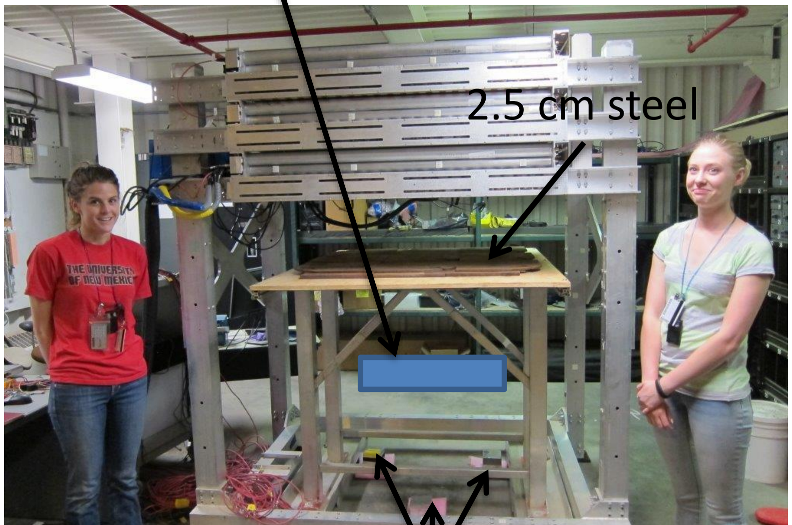
Single sided imaging



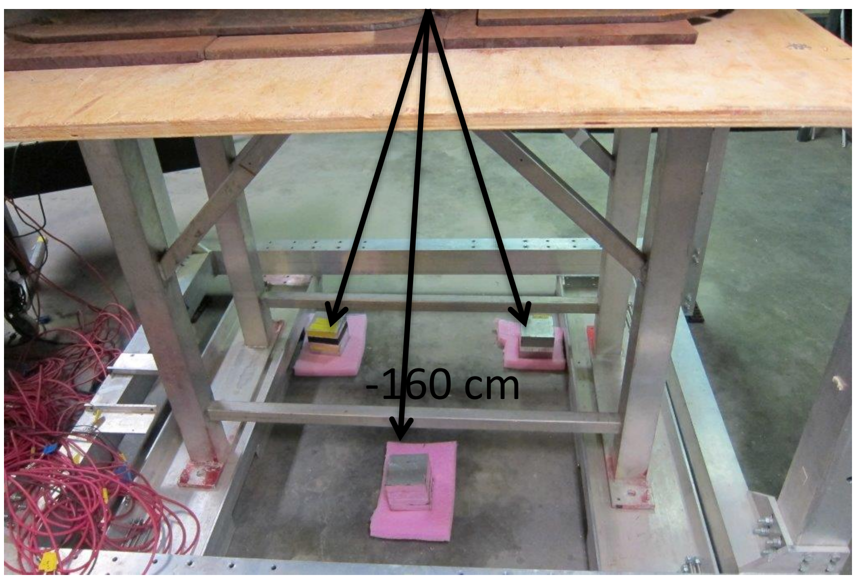


Unambigious detection of shielded uranium with single sided cosmic ray muon imaging

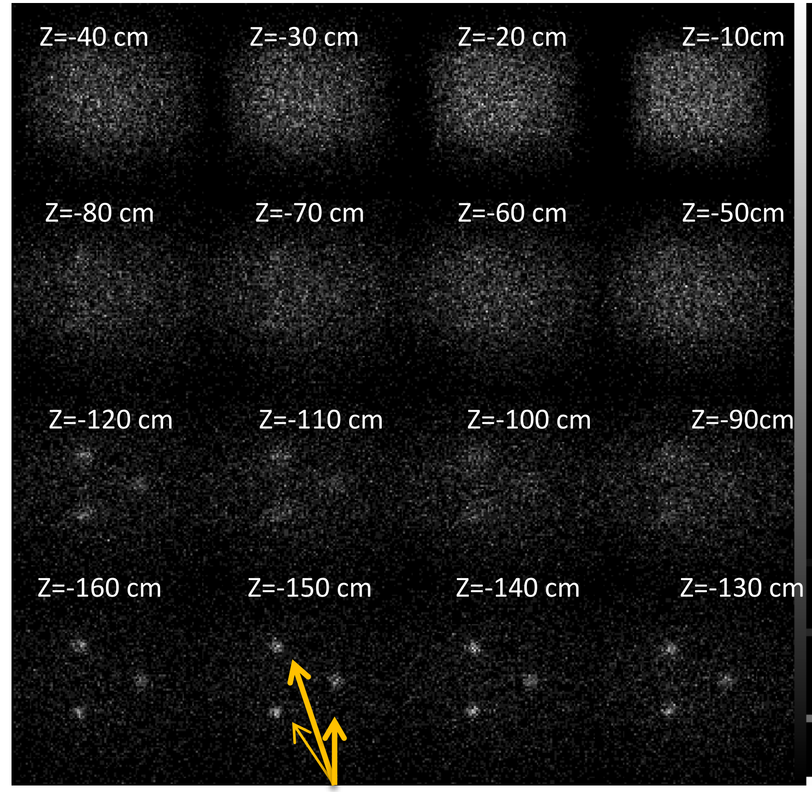
Neutron detectors were on the floor-same average distance as the front of the tracker from the cubes



U cubes

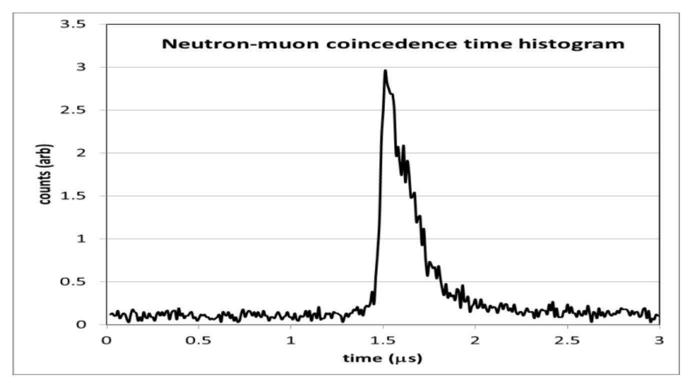


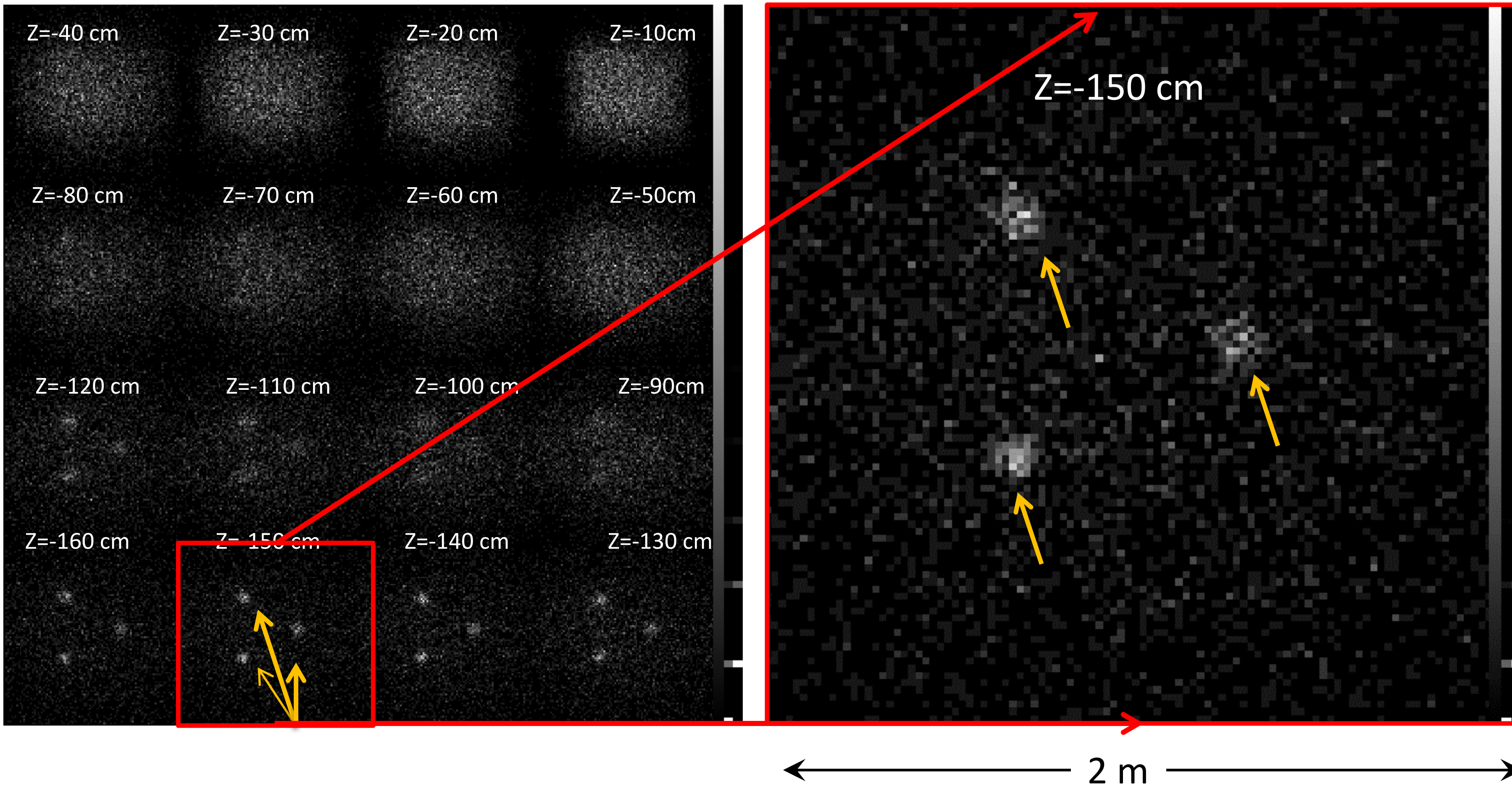
3-d single sided tagged muon laminography image



200 cm

U cubes

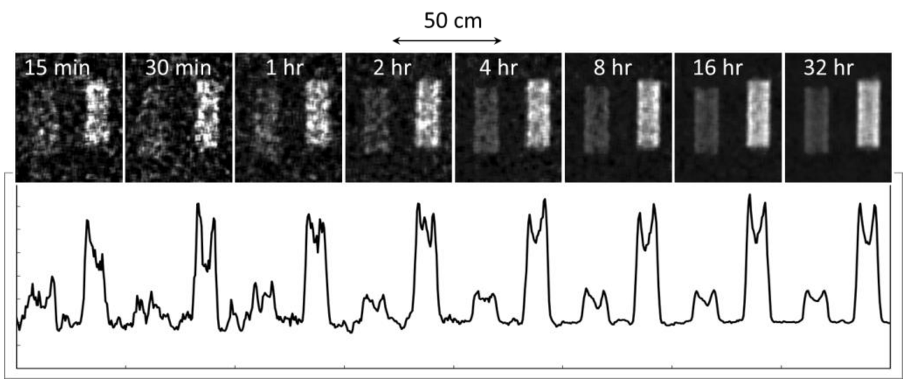


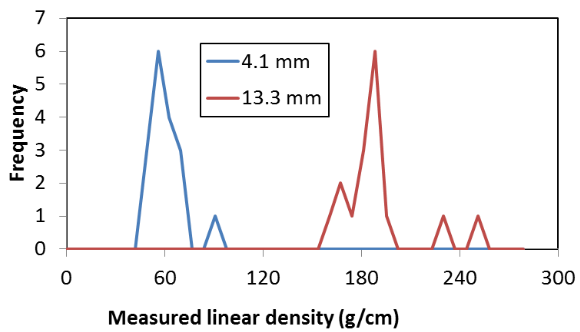


Z=-40 cm
Z=-30 cm
Z=-20 cm
Z=-10cm
Z=-80 cm
Z=-70 cm
Z=-60 cm
Z=-50cm
Z=-120 cm
Z=-110 cm
Z=-100 cm
Z=-90cm
Z=-160 cm
Z=-150 cm
Z=-140 cm
Z=-130 cm
Z=-150 cm
2 m

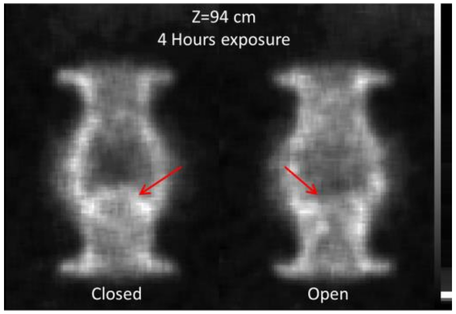
Industrial Radiography

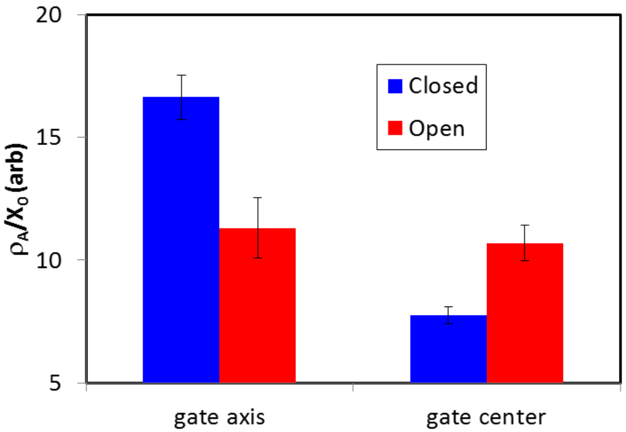
Pipe inspection





Check Valve state

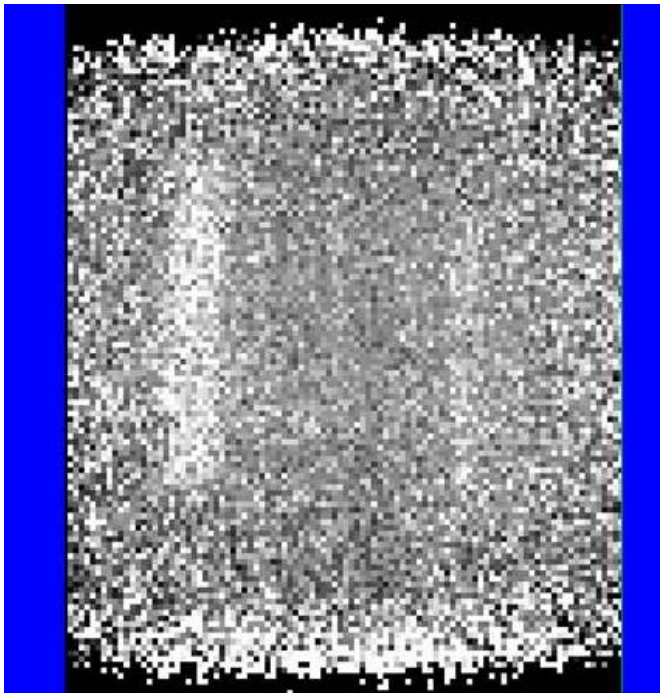


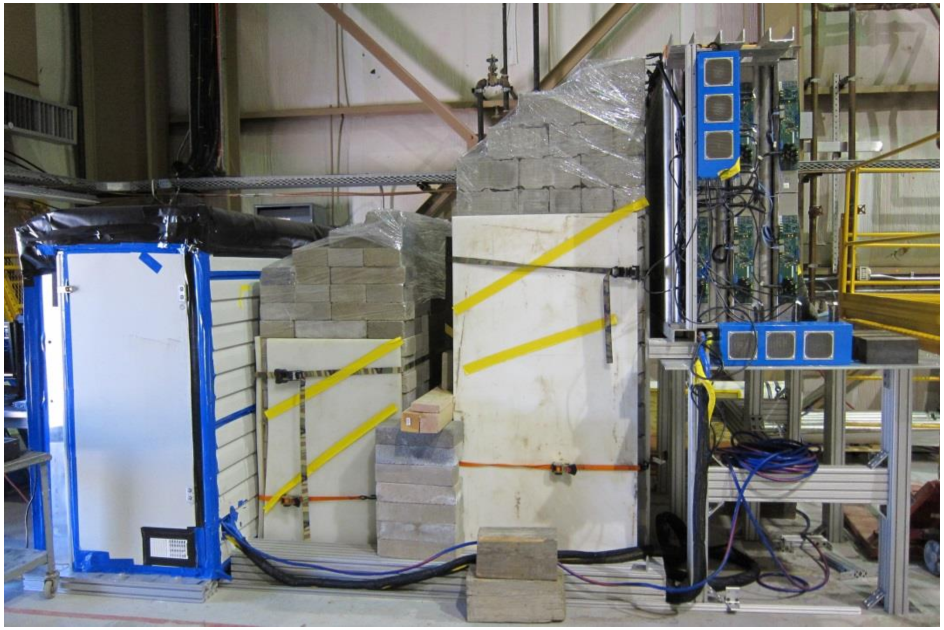


Duomo project for LDRD

Santa Maria del Fiore (Saint Mary of the Flower) church in Florence (Florence Cathedral)
Dome built between 1420 and 1436 by architect Filippo Brunelleschi

Los Alamos in collaboration with Toshiba is studying using muon scattering radiography to shearch for steel chains embedded in the Duomo walls



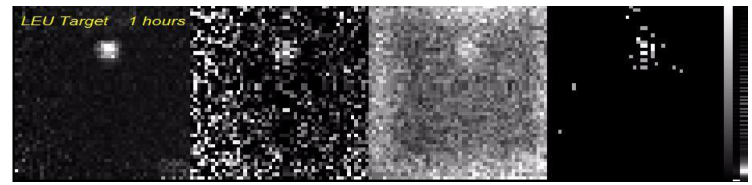


Concrete mock-up wall in the staging area. The thickness of concrete, measured in radiation lengths, is the same as that of the Cupola inner wall.

Summary

- Scattering cosmic ray radiography
  - Apparatus is simple and robust.
  - In use for border protection (Bahamas)
  - Potential for treaty verification
  - Radiography of Fukushima cores
  - Cosmic rays allow precise assessment (~several %) with 8 weeks of exposure

Scattering Stopped Transmission Tagged



20 kg U +Lead box Lead box