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Title: Muon tomography at LANL

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MUON TOMOGRAPHY AT LANL

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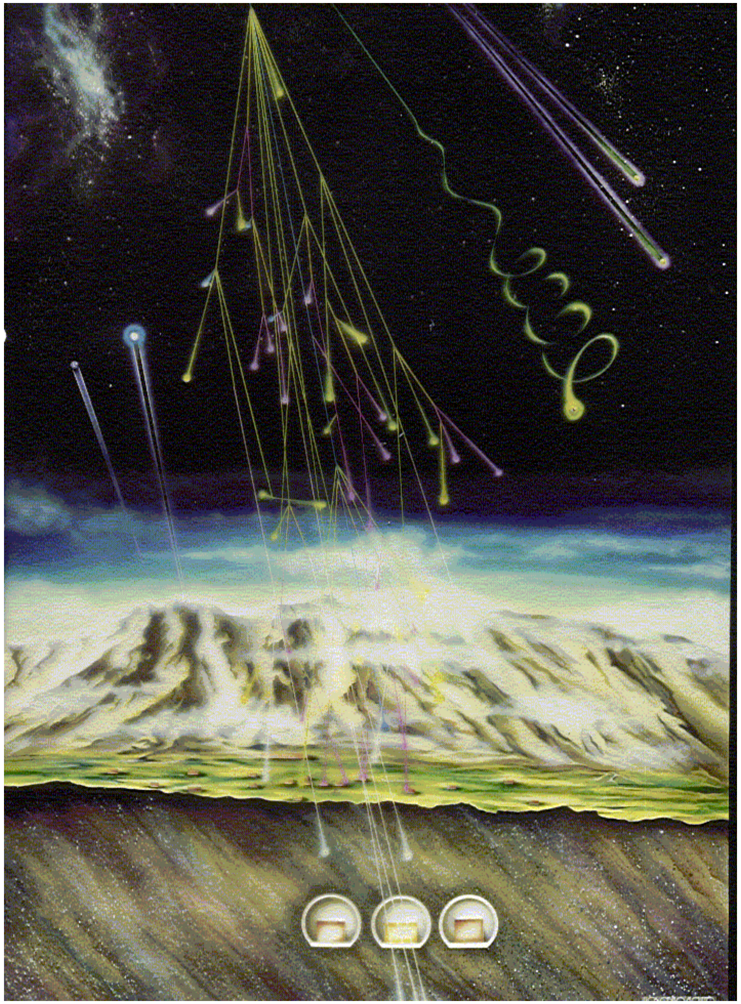
Natural muon source: cosmic rays

- Cosmic rays (protons) interact with atmospheric nuclei and produce abundant flux of pions, which decay into muons and neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

- Average energy of cosmic muons: 3-4 GeV
- They reach the earth at a rate ~1/cm^2/minute

Particle	Mass (MeV)
$e^\pm$	0.5
$\mu^\pm$	105
p/n	940

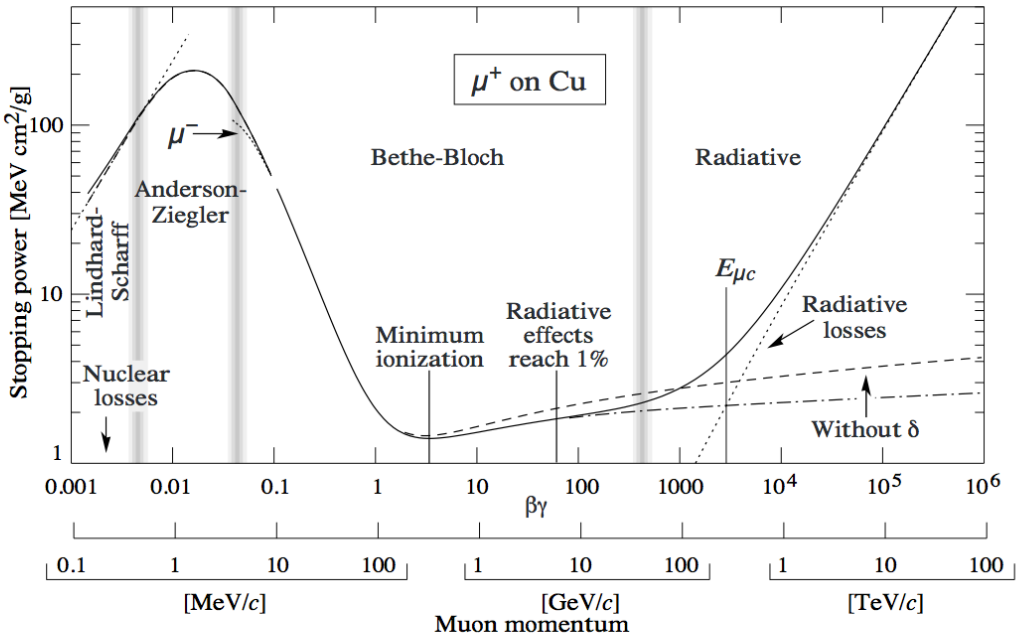


Muon interactions in matter

- CR μs lose energy primarily by **ionization**

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

- Average energy: 3-4 GeV
- **dE/dx ≅ 2 MeV g^{-1} cm^2** for minimum ionizing particles (MIPs)
- A few GeV muon typically ranges out in meters



Muon interactions in matter

- They are deflected by **multiple Coulomb scattering** (MCS) on nuclei

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

$$\theta_0 = \frac{14.1MeV}{pc\beta}\sqrt{\frac{l}{X_0}}$$

material thickness in units of X_0

radiation length for material

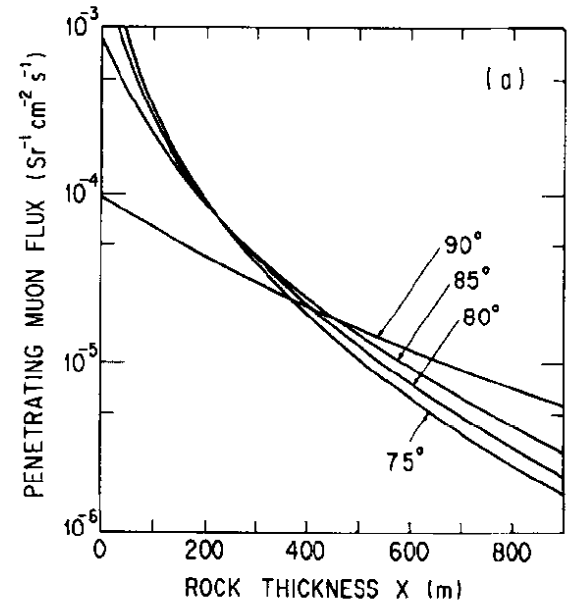
$$\frac{1}{X_0} = \frac{Z/(Z+1)\ln(287/\sqrt{Z})}{A \cdot 716.4g \cdot cm^{-2}}$$

MCS allows discrimination of different materials with similar densities!

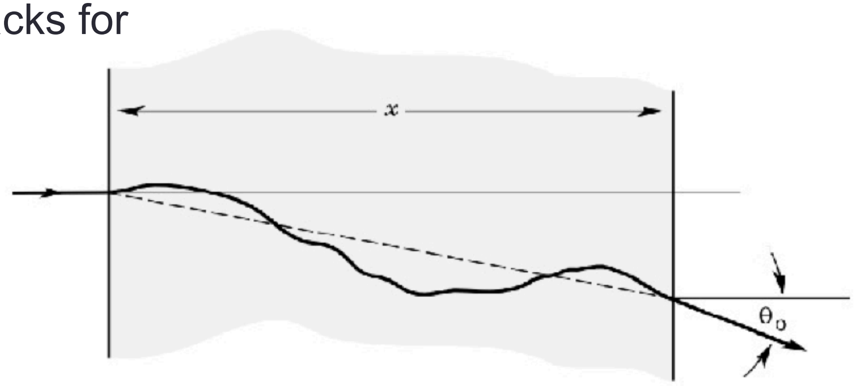
Material	Radiation length X_0
Air	304 m
Water	36 cm
Shielding concrete	10.7 cm
Nylon	36.7 cm
Aluminium (Al)	8.9 cm
Silicon (Si)	9.36 cm
Iron (Fe)	1.76 cm
Lead (Pb)	0.56 cm
Uranium (U)	0.32 cm

Stopping versus multiple scattering

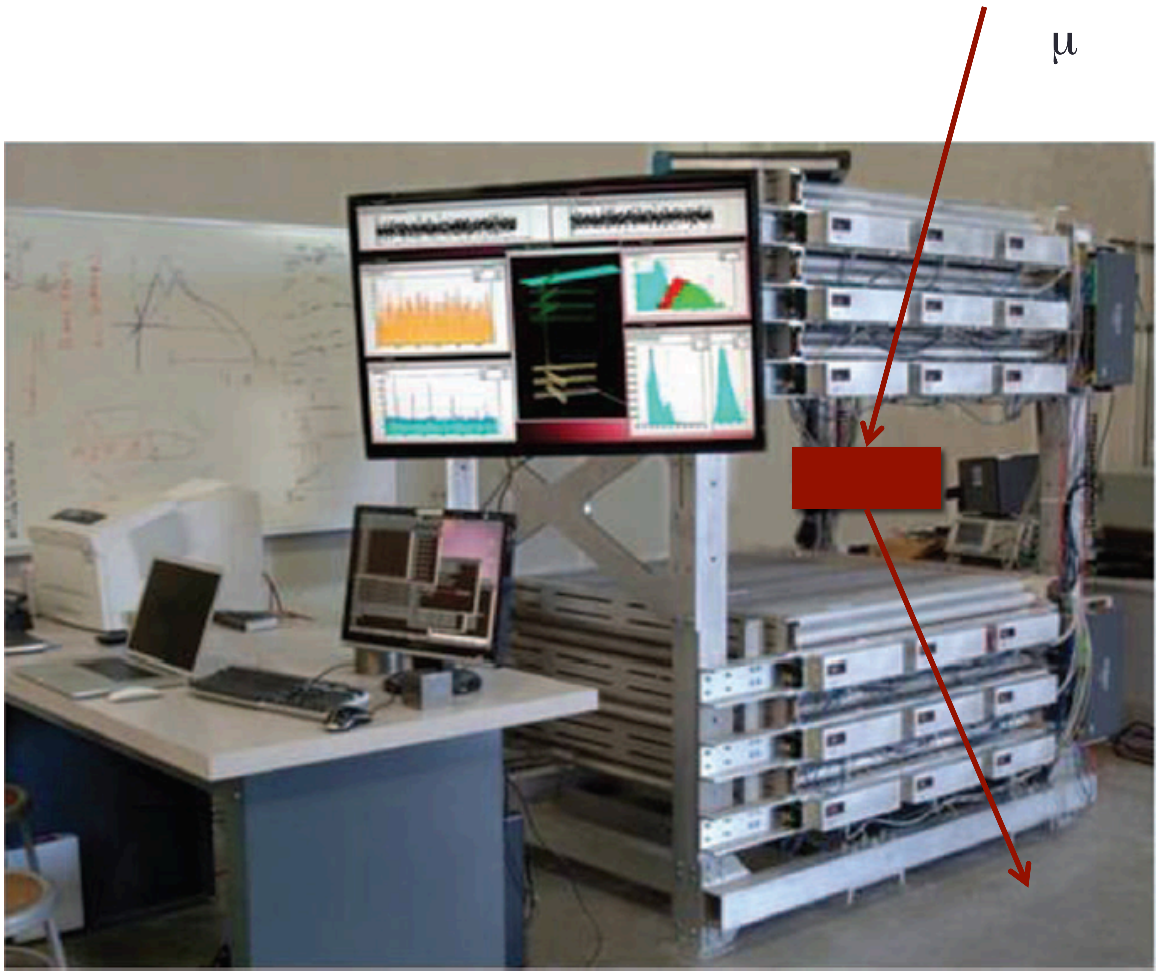
- **Stopping**: measure muon attenuation through the sample due to energy loss through ionization
  - One tracker only
  - Incident flux must be known



- **Multiple scattering**
  - Uses two trackers to measure in and out tracks for individual μs
  - Material identification

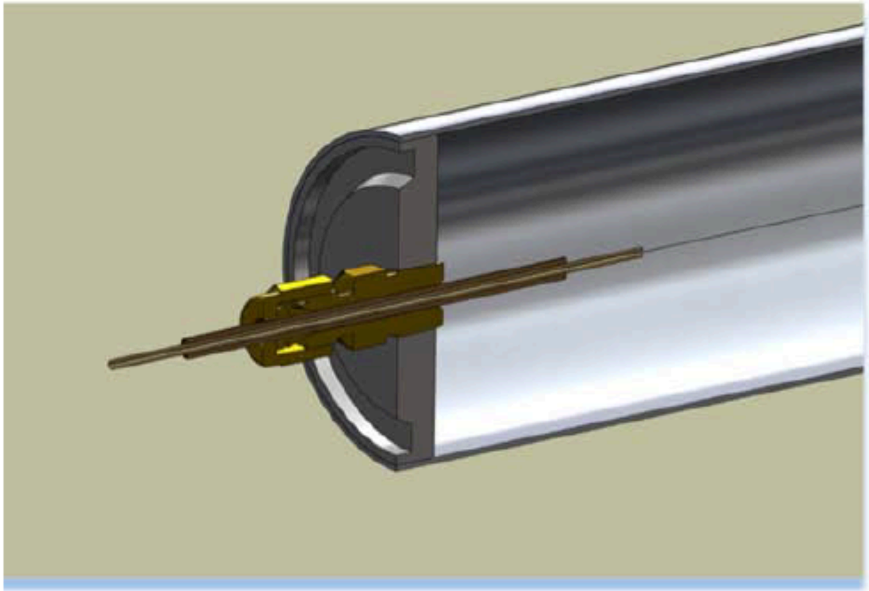


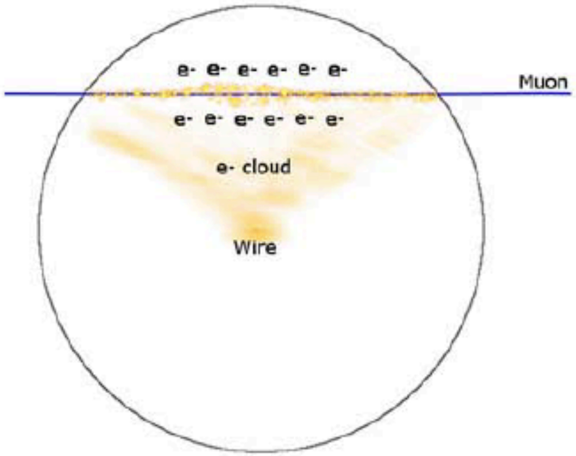
Our detector: the Mini Muon Tracker



- 576 tubes
- Sample placed between 2 supermodules
- Final resolution (0.63 ± 0.02) cm

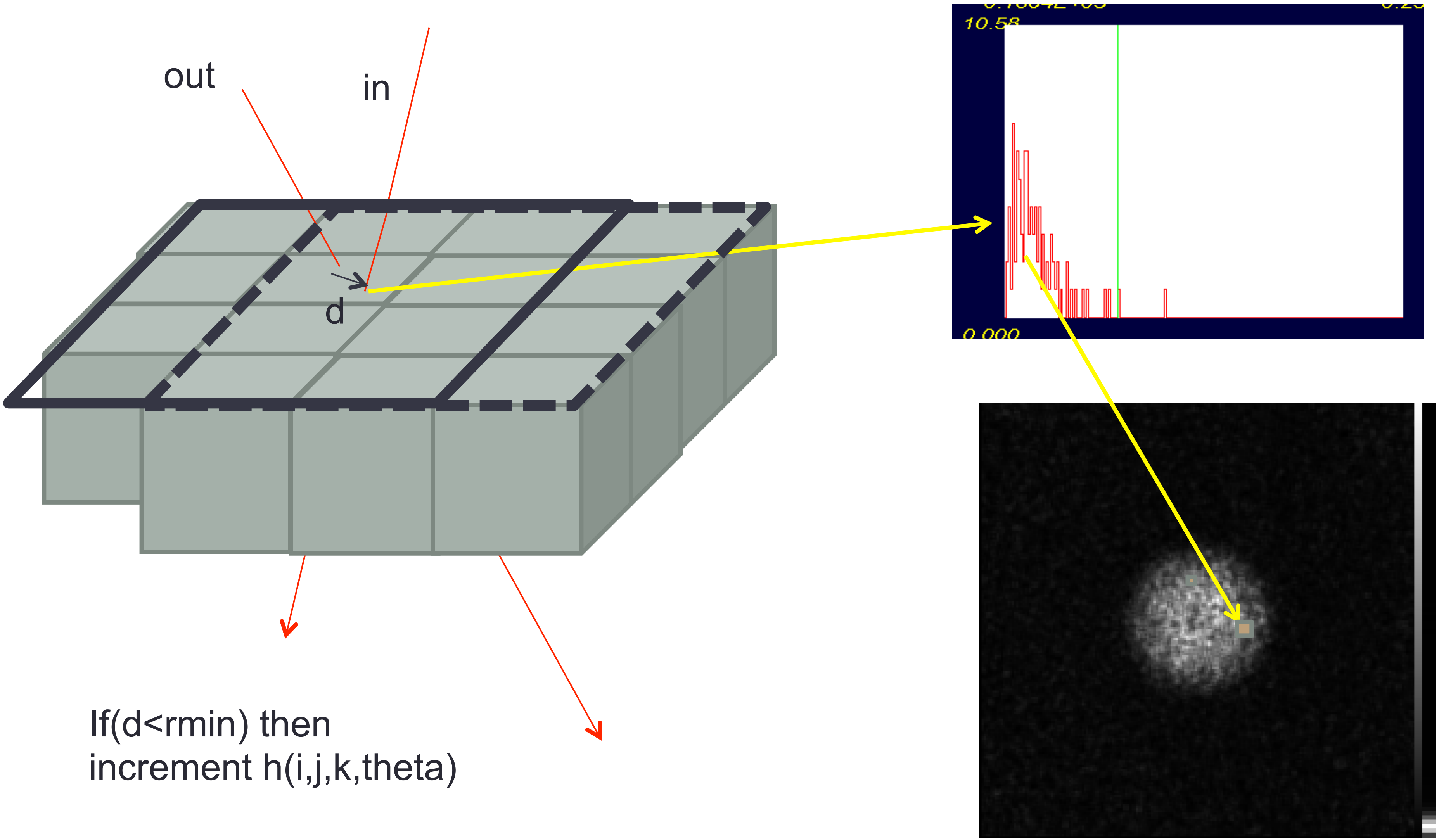
Our drift tubes





- The passage of a charged particles through the gas liberates electrons from its atoms
- The electrons drift to the central wire (anode) producing an electric signal
- Gas mixture: 50% Ar, 44% CF_4, and 6% C_2H_6
- Al tubes, gold-plated anode wire, 30-μm diameter

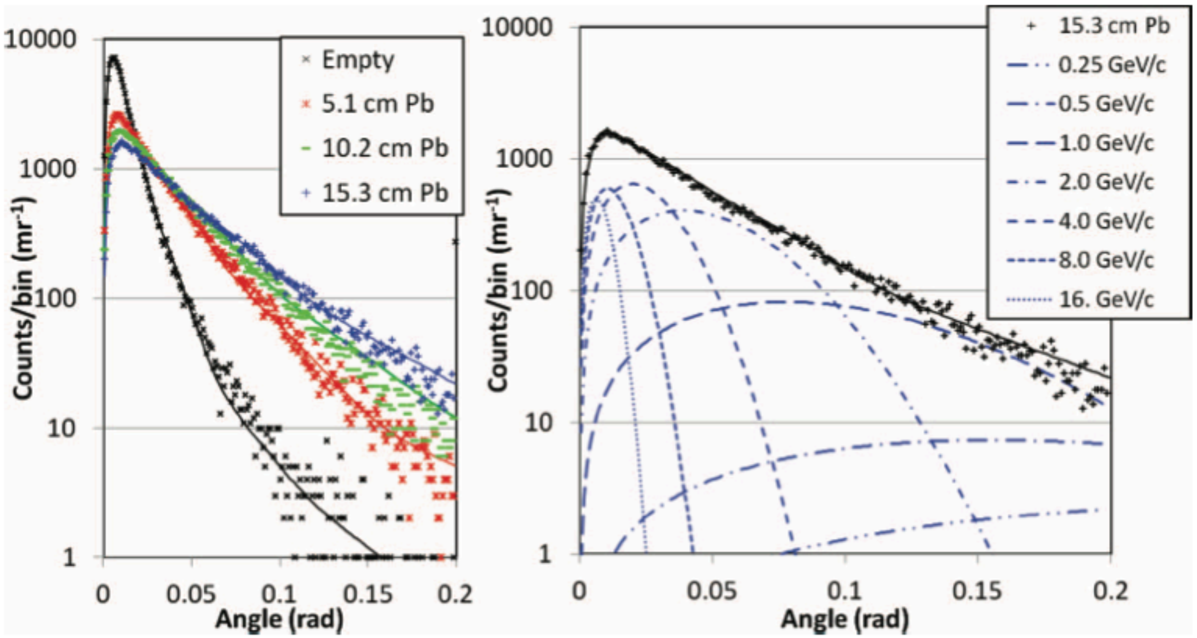
Generating scattering images



If(d<rmin) then
increment h(i,j,k,theta)

Generating scattering images

- Cosmic muons have a broad momentum distribution
- Scattering distribution for each voxel fitted with a model that uses multiple momentum groups p_i to approximate the muon spectrum with



$$\frac{dN}{d\theta} = \sin(\theta) \sum \frac{A_i}{\theta_{0i}{}^2} e^{-\frac{\theta^2}{2\theta_{0i}{}^2}}$$

$$\theta_{0i} = \frac{14.1}{p_i} \sqrt{\frac{l}{X_0}},$$

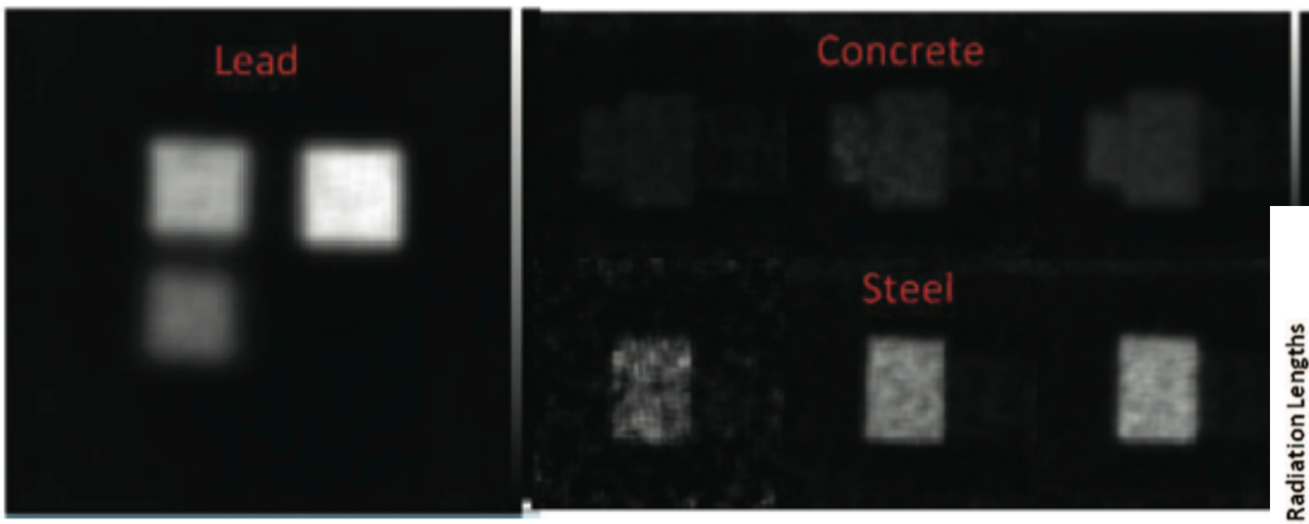
AIP Advances **3**, 082128 (2013)

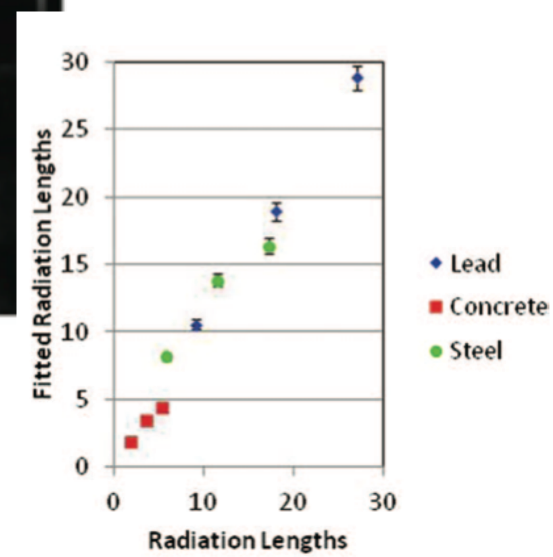
Left) Measured angular distributions for various thickness of lead (points) and the fit (lines) Right) The decomposition of the fit into energy groups. Empty shows the angular distribution with no object in the scanner.

Generating scattering images

- With the amplitudes fixed by the global fit a maximum likelihood fit of the angular distribution for each voxel, where l/X_0 is the only free parameter, is used to obtain a radiation length image

AIP Advances **2**, 042128 (2012)



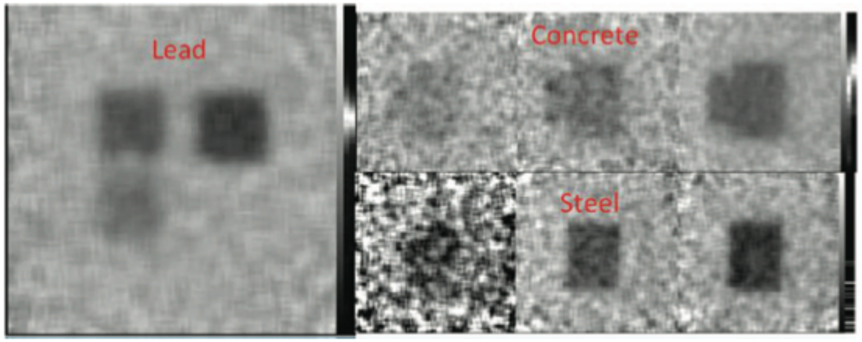


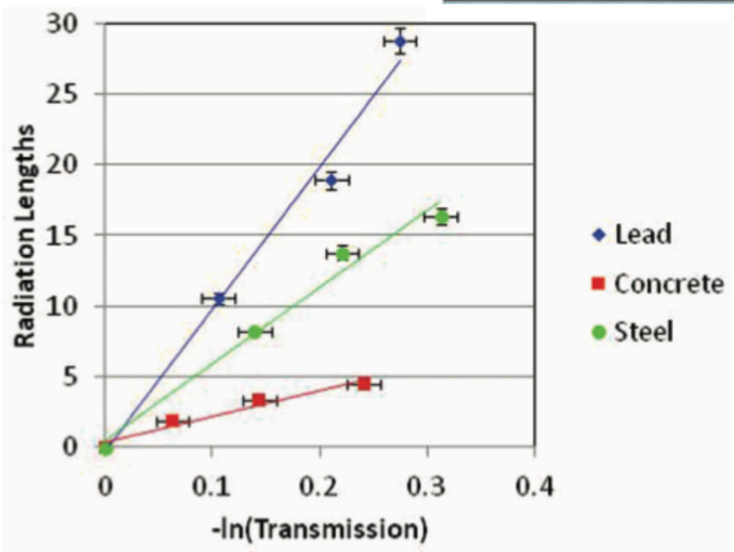
three thicknesses each of lead, concrete and steel

Material identification

- When multiple scattering data are combined with attenuation data material identification can be obtained

ln (N/N_0)





AIP Advances **2**, 042128 (2012)

Commercial application: Decision Sciences

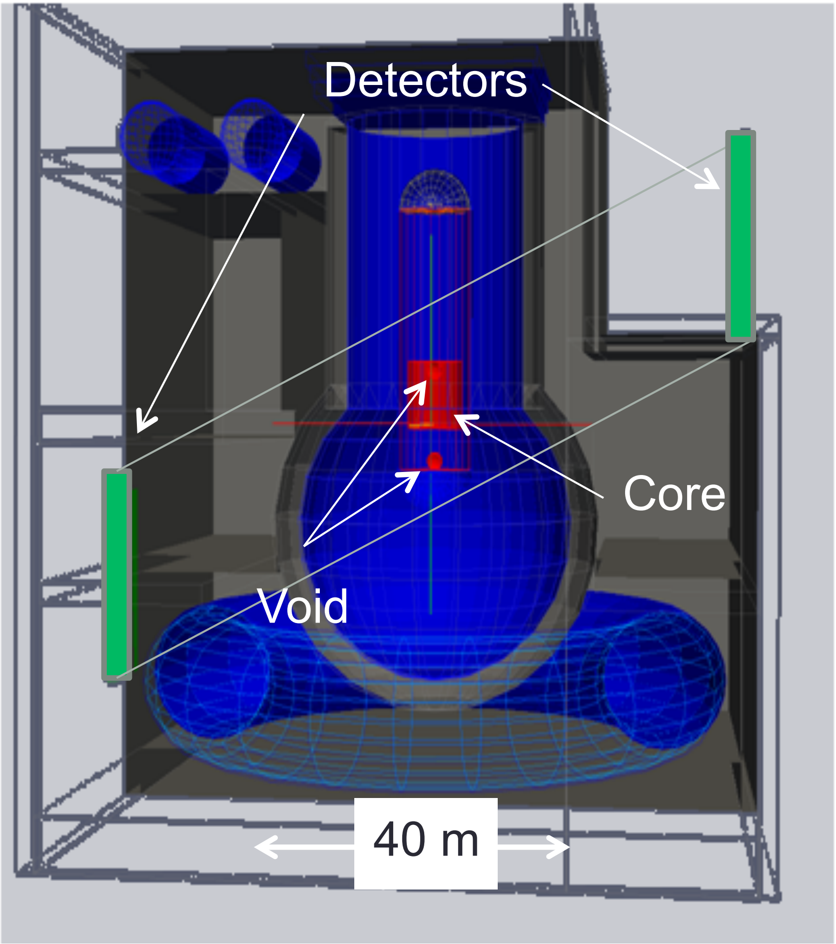
- First test scanner installed at Freeport, Bahamas

Radiography of Fukushima reactors

- 11 March 2011 Tohoku Great Earthquake (9.0 magnitude)
- The three operating reactors (1,2,3) at Fukushima melted down
- Clean up estimated to take 40 years
- 2 weeks after the earthquake Dr. Cas Milner suggesting using muon scattering to look at the cores
- Toshiba is currently assembling the two supermodules (7 x 7 m^2)
- Once tested they will be moved to Fukushima around unit #2
- Installation in situ in June 2015
- Goals:
  - Evaluation of debris distribution -> evaluation of debris distribution
  - Assessment of the damage to the fuel assembly -> R&D on debris-removal equipment

LANL MC simulations

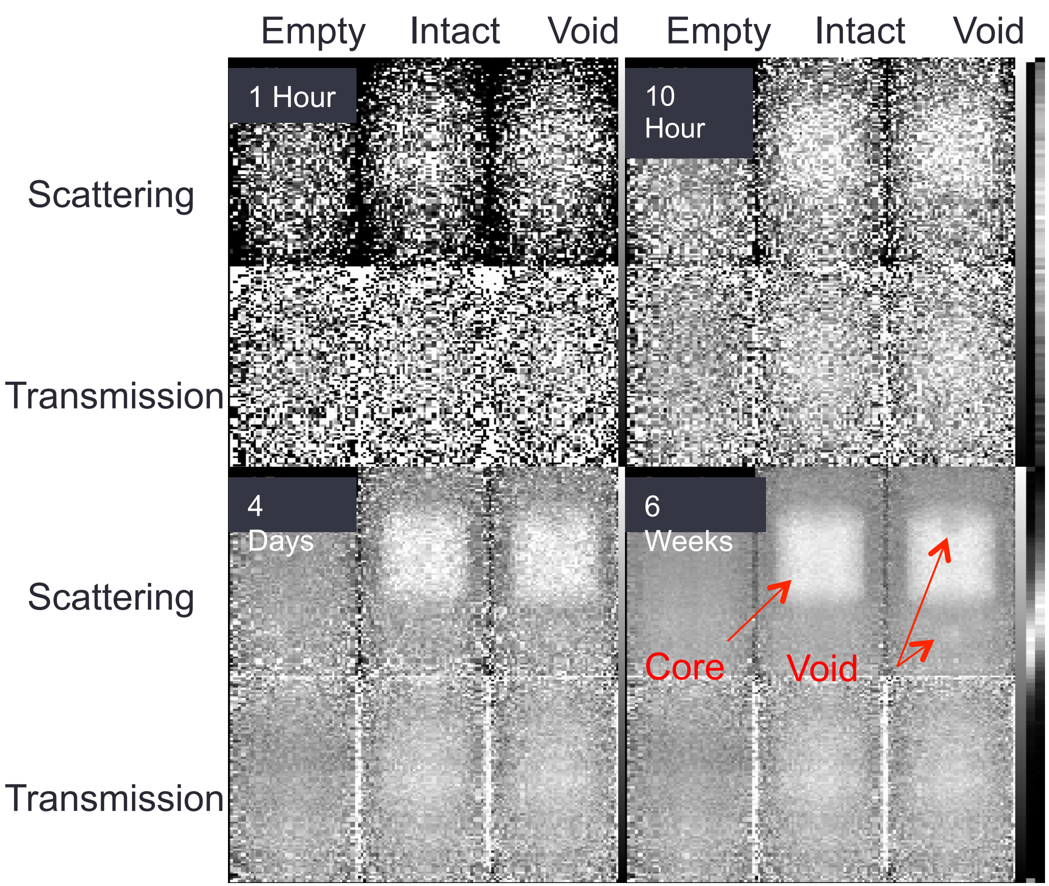
- Geant4 model of the unit #1 including all major structures, the reactor build- ing, the containment vessel, and the pressure vessel.
- 50 m^2 detectors placed as shown Simulated scenarios:
  - Intact core
  - 1 m^2 diameter (1%) material removed from the core and placed in the bottom of the pressure vessel
  - No core



PRL 109, 152501 (2012)

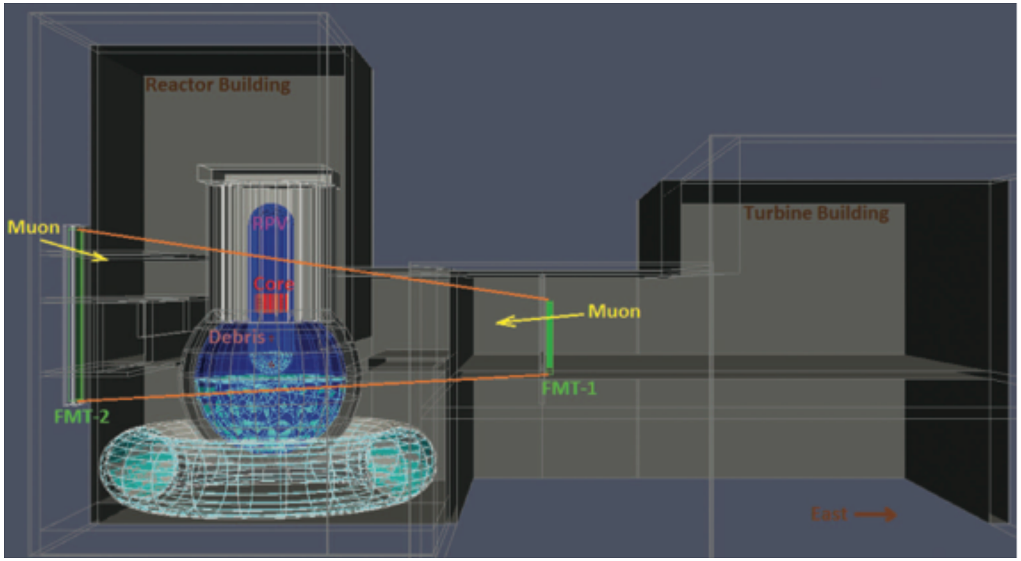
LANL MC simulations

- For transmission radiography:
- 1 h: the difference in scattering between the images with and without the core is visible
- 10 hours: the reactor core is visible in the scattering image
- 4 days: the 1 m diameter void is visible in the core
- 6 weeks: both the void and the resulting sphere of core material below the core are clearly visible

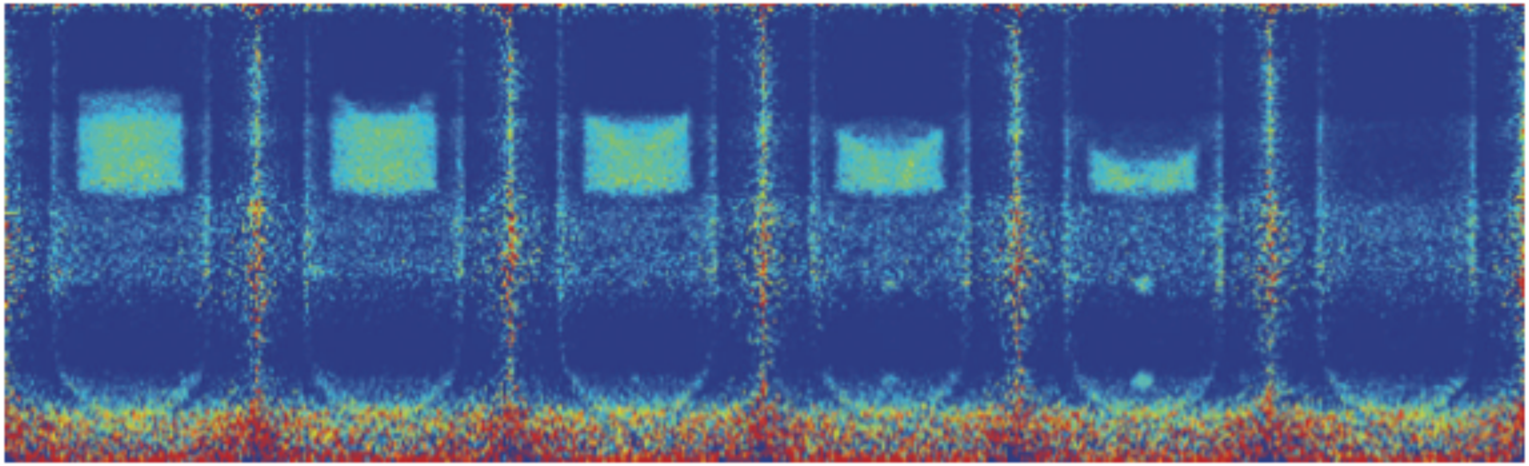


PRL 109, 152501 (2012)

LANL MC simulations

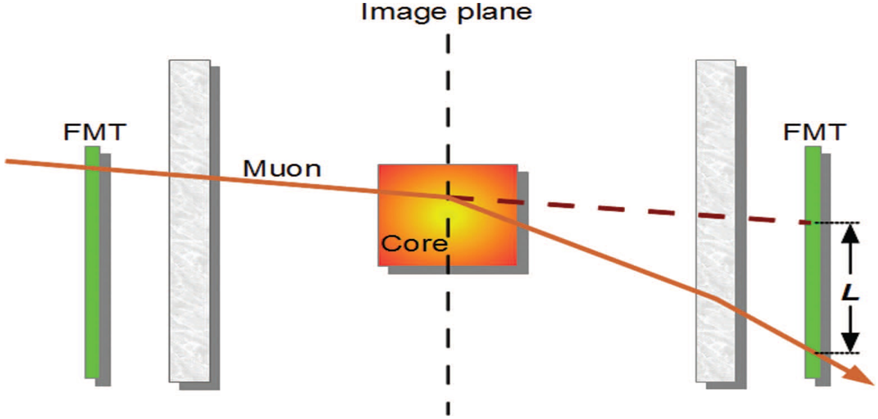


- Unit #2
- 15 x 9m^2 and 5.5 x 22m^2 detectors
- 90 days measurement
- Displacement technique used
- Scenarios:
  - Intact core
  - 10%, 30%, 50%, 70% melted core
  - No core

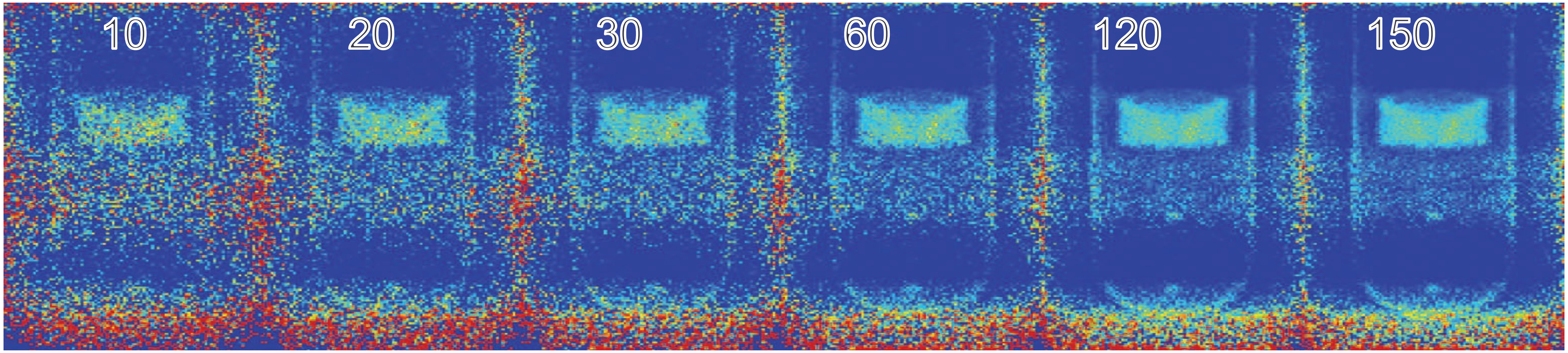


AIP Advances **3**, 052133 (2013)

Displacement Radiography



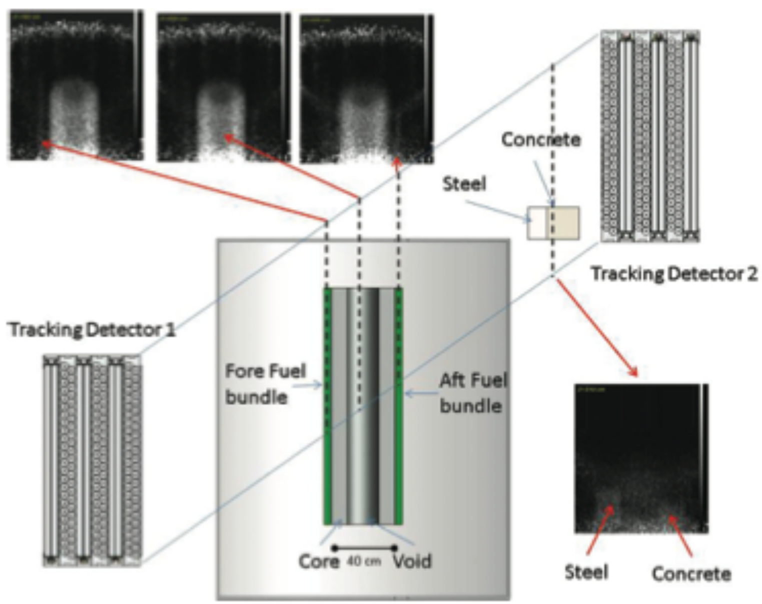
- Muons continuously loose energy.
- For thick objects, the most likely exit energy is zero.
- Exaggerated scattering in the exit overburden reduces sensitivity
- Using the displacement rather than scattering angle reduces this effect.
- Exposure times are reduced by ~40%



50% melted core vs measurement days

AIP Advances **3**, 052133 (2013)

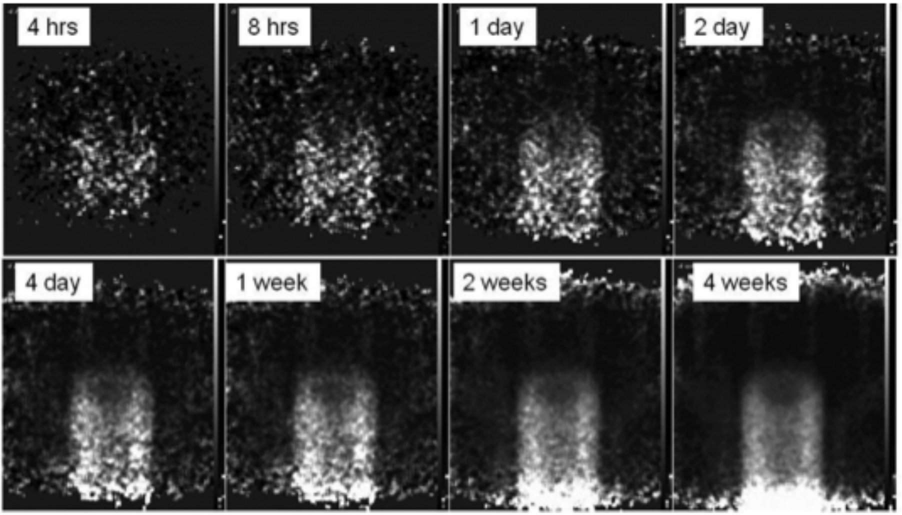
Imaging of the NCA



APPLIED PHYSICS LETTERS 104, 024110 (2014)

- Imaged Toshiba Nuclear Critical assembly reactor
- Core size ~ 1/3 size of commercial power reactor
- MMT detectors outside the water vessel
- 1.5 m long 1cm diameter UO_2 ceramic fuel rods configured in a 40 cm diameter cylinder with a 20 cm void at its center
- 3x3 assemblies of rods placed to the sides in front and behind the cylinder
- ~ 4 weeks of data taken

Imaging of the NCA



- 4h: reactor core visible
- 1d: void at the center visible

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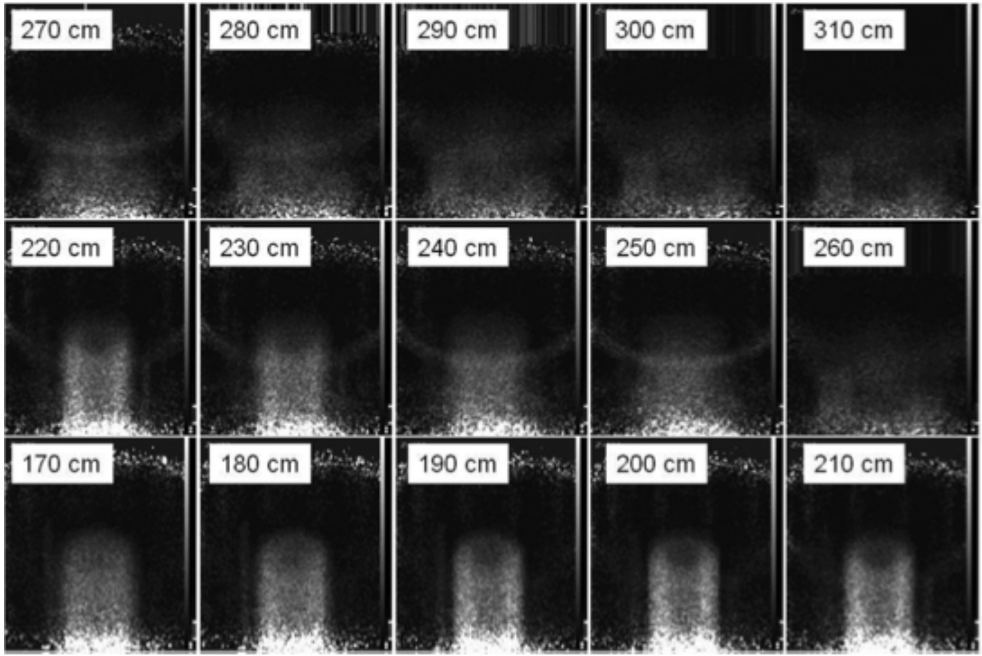
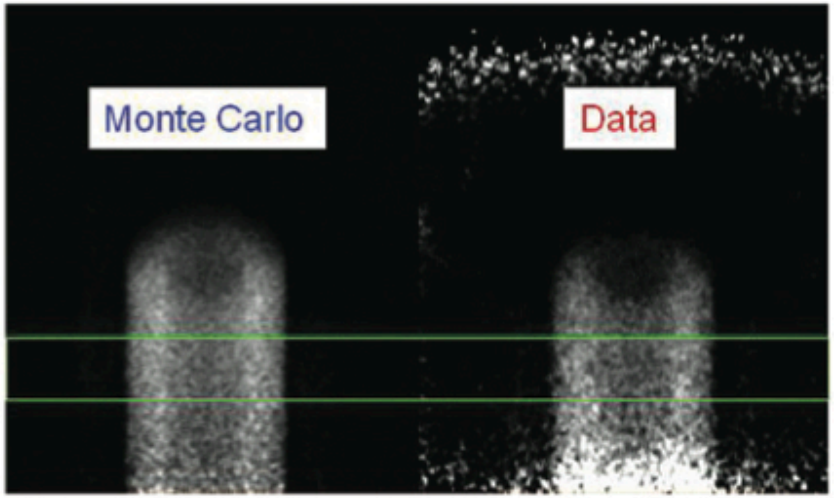
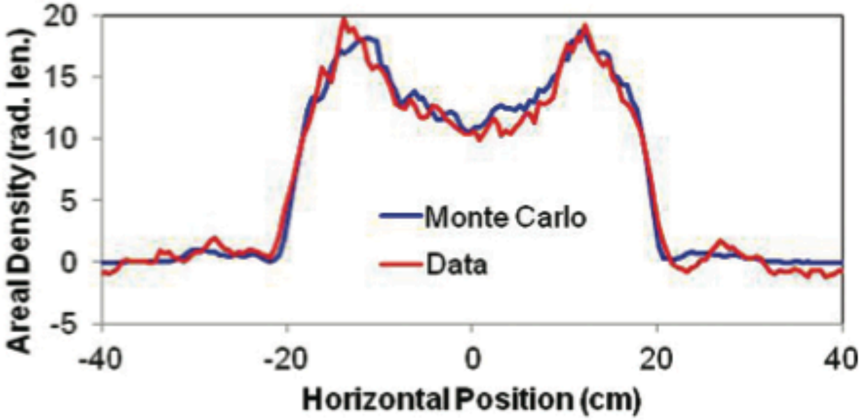
- 180 cm: bundle closest to the lower detector clear
- 200 cm: core best focused
- 220 cm: fuel bundle closest to the upper detector is clear
- 250 cm: flange on the top of the water tank visible
- 310 cm: the steel bricks mounted in front of the upper detectors are in focus



Imaging of the NCA





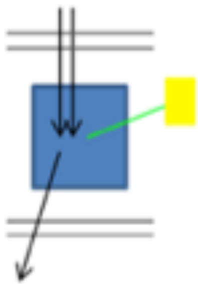
- Quantitative agreement between MC and data within 3%

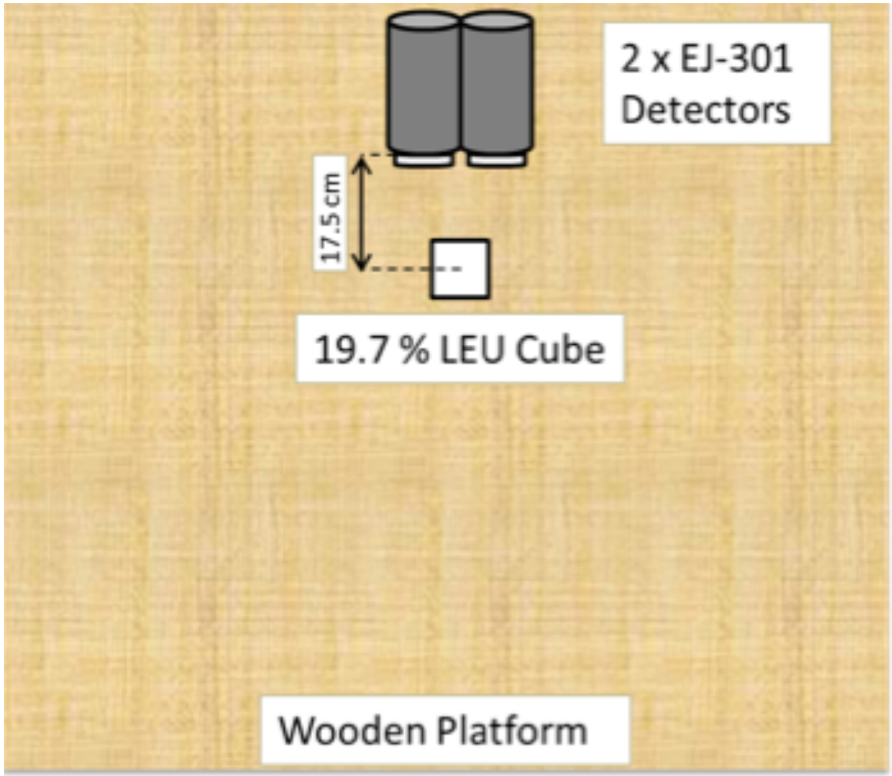
APPLIED PHYSICS LETTERS 104, 024110 (2014)

Muon induced fission

- Detection and imaging of fissile materials can be performed using muon-induced fission neutrons as trigger
- Potential as treaty verification technique
- When a μ^- encounters the nuclear Coulomb field, it may be captured into an atomic orbital and de-excite into the ground state, emitting x-rays
- In high Z materials they can be captured by a bound proton and produce a neutron and a neutrino, $\mu^- + A \rightarrow n + (A-1)^* + \nu_\mu$
- In fissile nuclei the final nucleus can fission, triggering small fission chains and emitting several neutrons
- This signature can be coupled to muon trajectories and a tagged muon image can be created

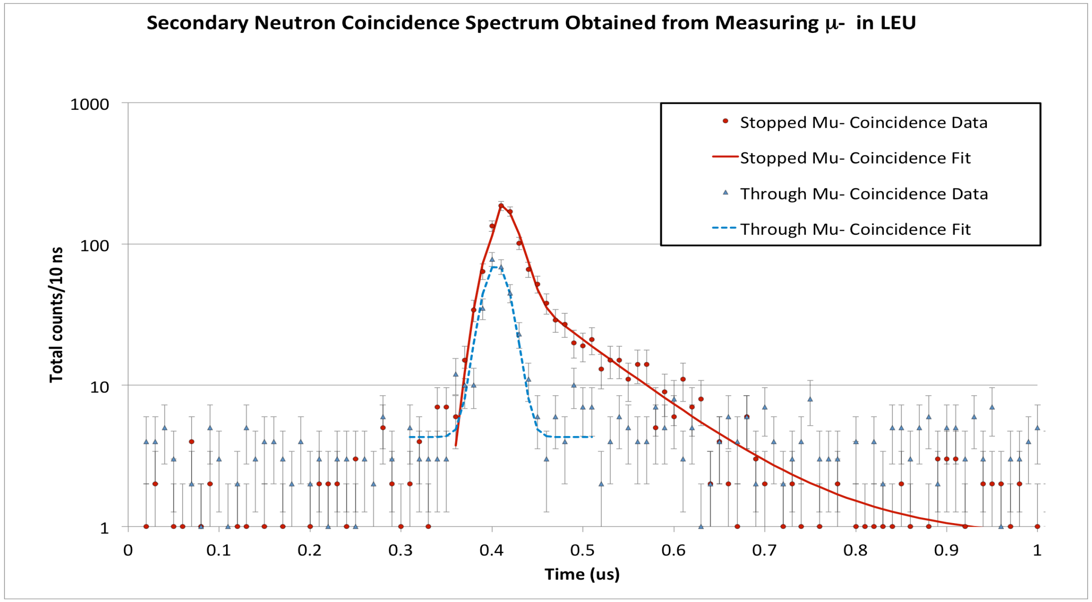
Muon induced fission





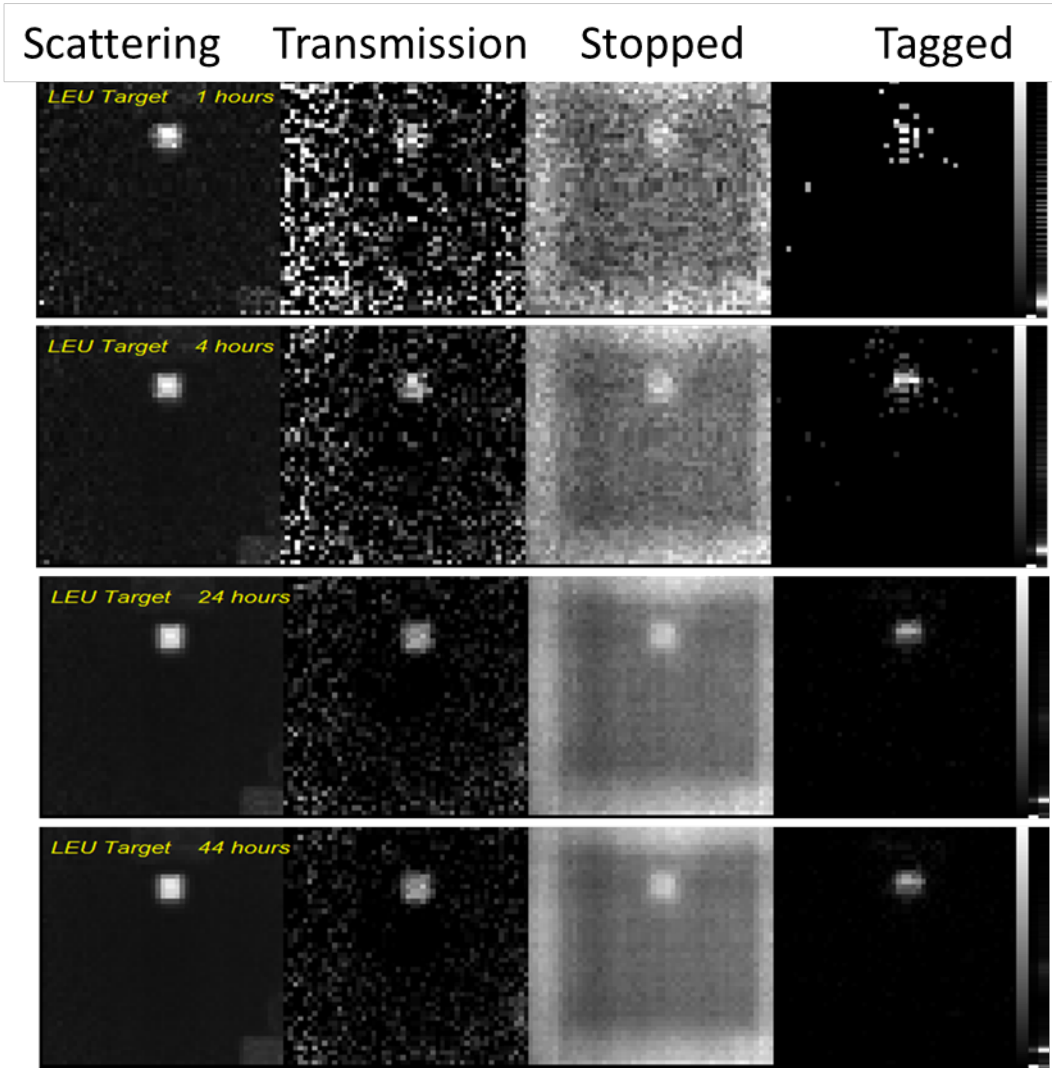
- 12.5 cm diameter by 5 cm deep EJ301 liquid scintillator detectors on a wood plank inside the MMT
- Mesytec NIM module MPD-4 used to discriminate between gammas and neutron signals using PSD
  - Output fed to a dedicated input on the MMT electronics
- 48 h measurement

Muon induced fission



- Spectrum of coincidence time between neutrons and muons
- Fitted time constant: 85 ± 3.3 ns
- Measured lifetime for muonic U atom:
  - 71.6 ± 0.6 ns for ^{235}U
  - 77.2 ± 0.4 ns for ^{238}U

Muon induced fission



- Tagged images show signal-to-noise ratio comparable to the scattering image, although the statistics and position resolution are not as good

Conclusions

- Cosmic ray radiography is simple and works
- The technique is beginning to have commercial applications
- Set-up for the imaging of the Fukushima reactors in construction
- Potential for treaty verification purpose
- Other applications being investigated
  - E.g. Imaging of spent fuel storage dry casks