

**TOSHIBA**

# Cosmic-ray-muon Scattering for Nuclear Applications

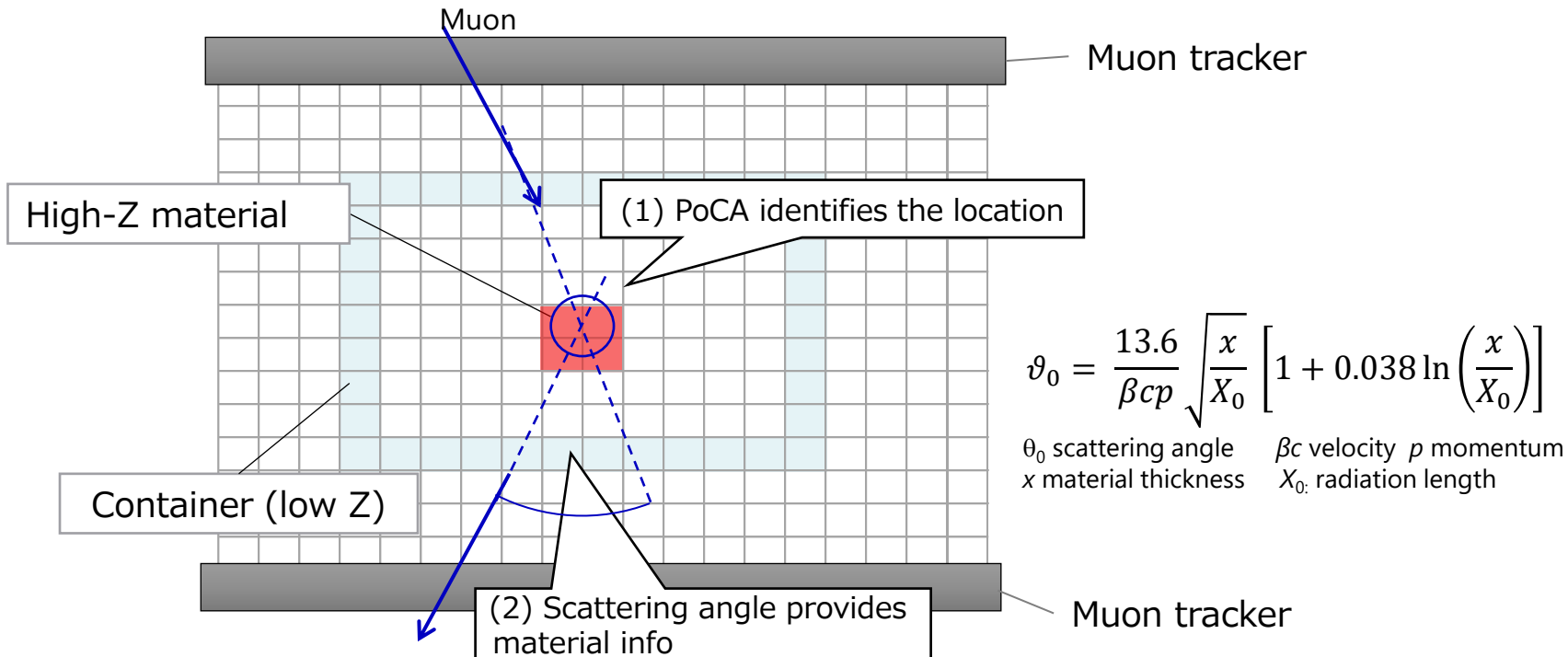
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Toshiba Corporation

# Muon Scattering Imaging Develop at LANL

(1) Location of scatterer identified by point-of-closest-approach

(2) Scattering angle provides material info

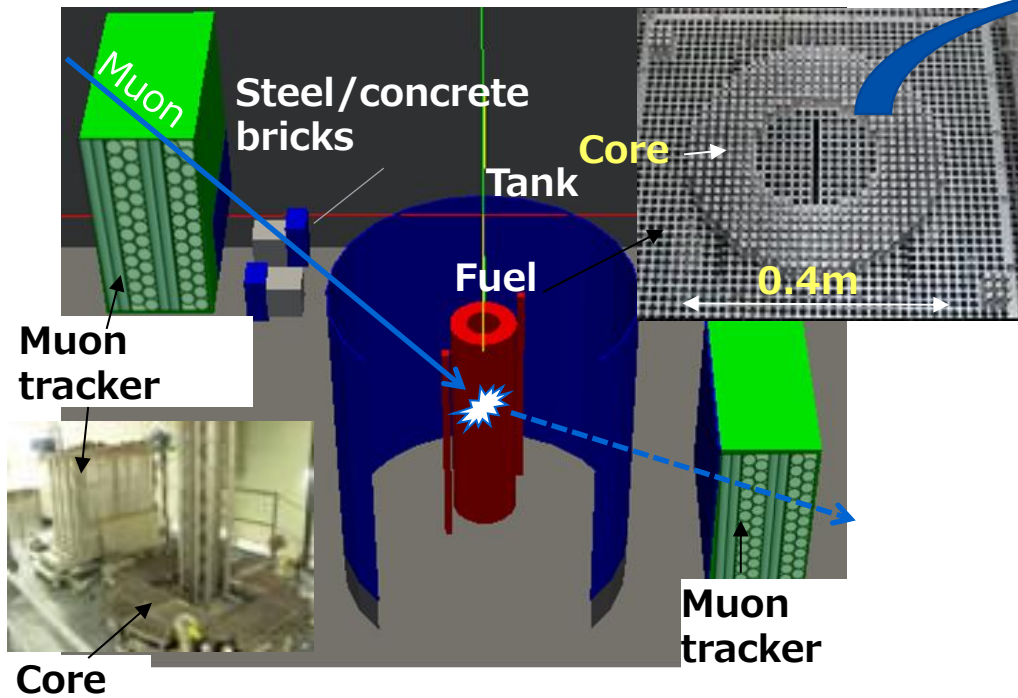
- Scattering angle approximately scales with atomic number



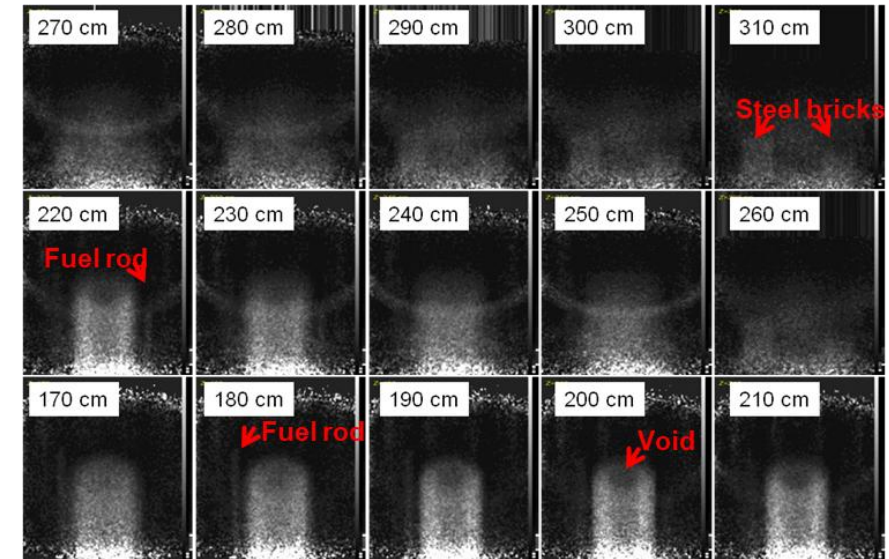
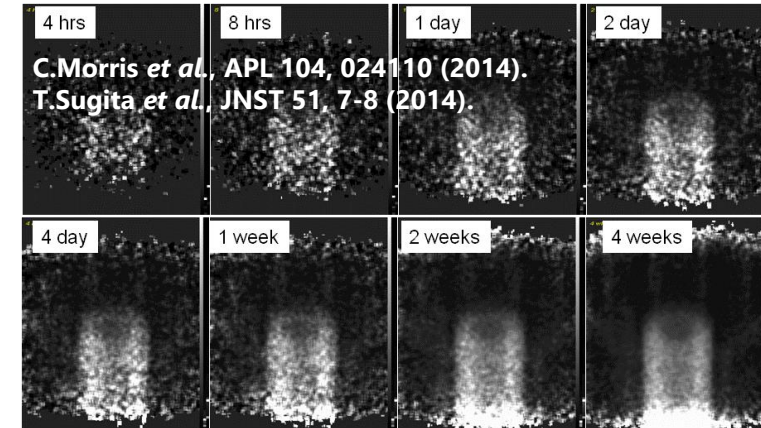
**Muon scattering angle provides material information**

# Reactor Imaging at TOSHIBA Nuclear Critical Assembly

- Technical demo with “real” reactor core at TOSHIBA’s research reactor.
- Mini Muon Tracker of 1.2m x 1.2m size shipped from LANL and was installed to NCA.

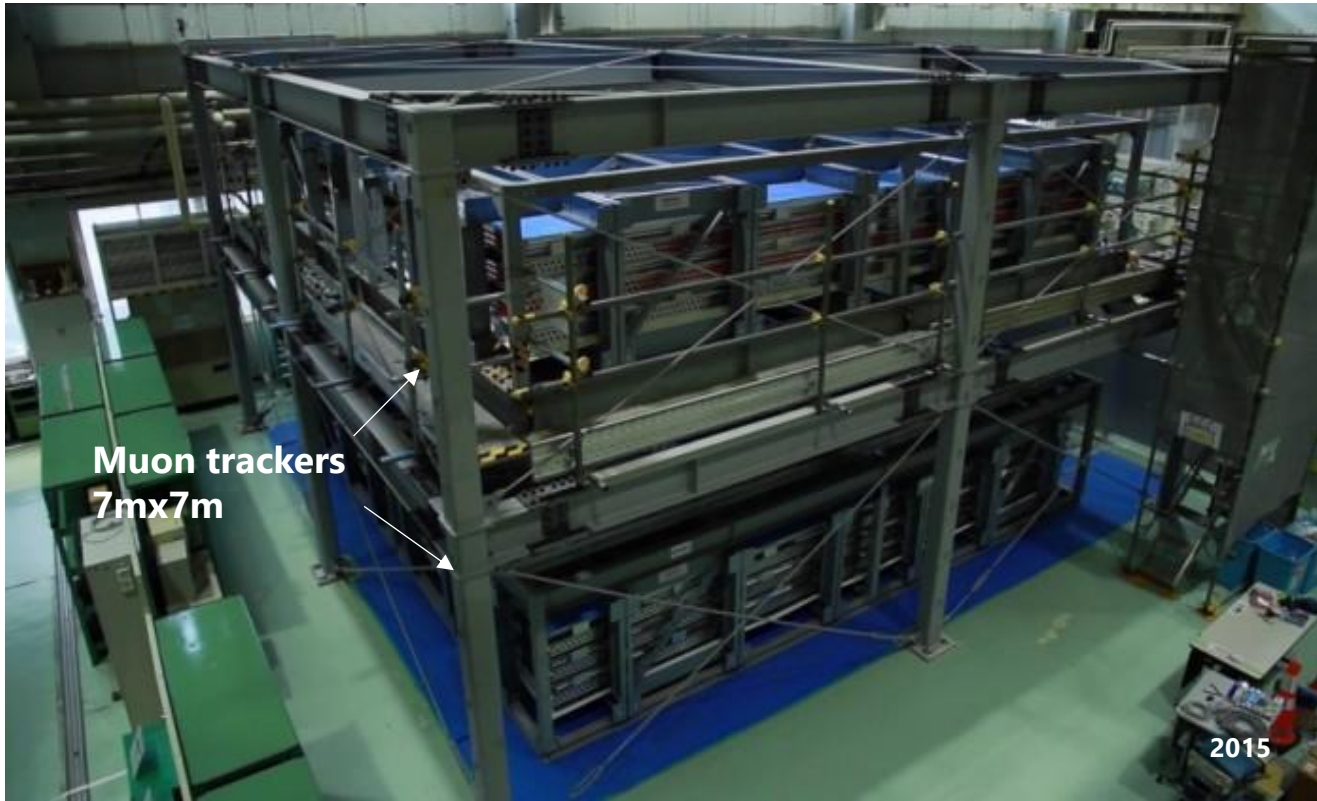


TOSHIBA Nuclear Critical Assembly (Kawasaki, Japan)



World's first muon reactor imaging with real  $UO_2$  core

## Muon Trackers Developed at TOSHIBA



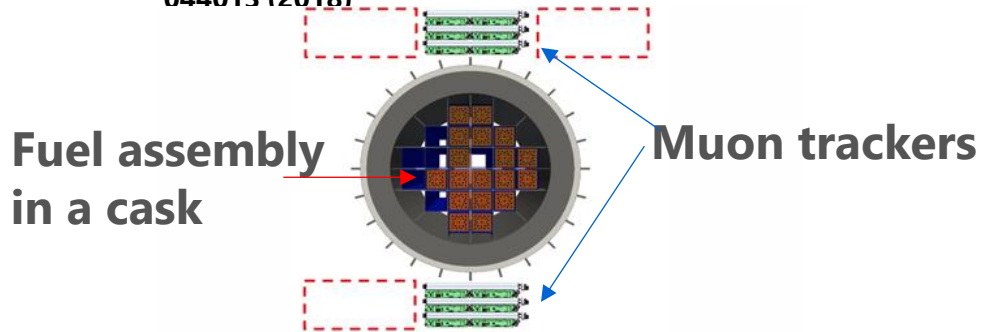
- 7m x 7m muon tracker for reactor imaging
  - Collaborative effort with LANL and DSIC
  - 6,720 drift tubes used
  - Can operate under radiation environment of  $50 \mu\text{Sv/h}$

Fukushima Daiichi muon imaging project was carried out as a part of "Project of Decommissioning and Contaminated Water Management" supported by Ministry of Economy, Trade and Industry, Japan.

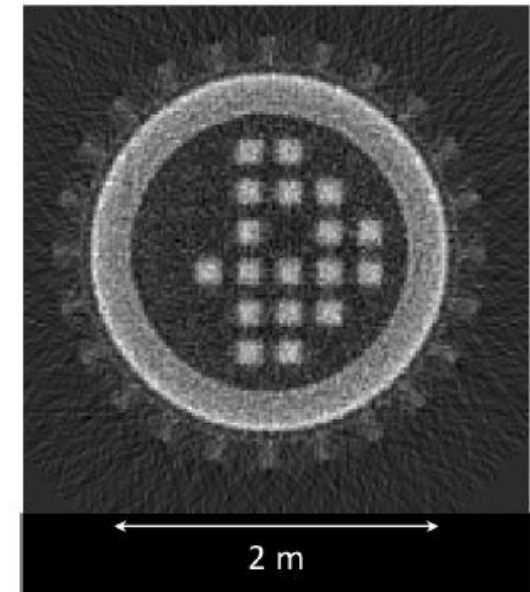
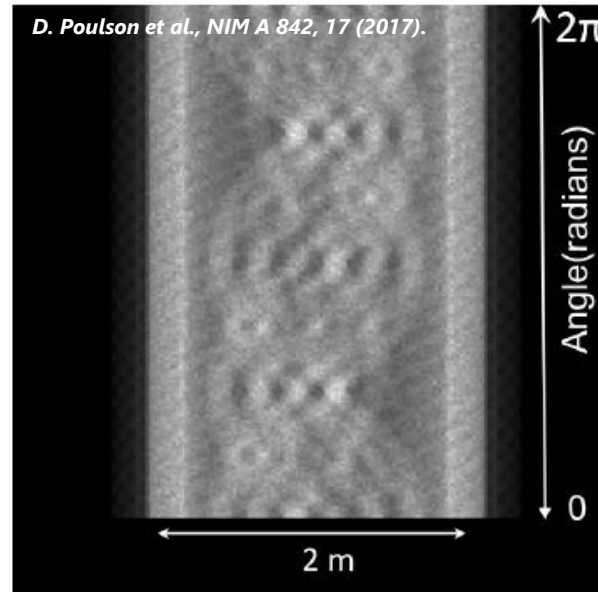


LANL news 2018

J.M Durham et al., *Physical Review Applied* 9, 044013 (2018)

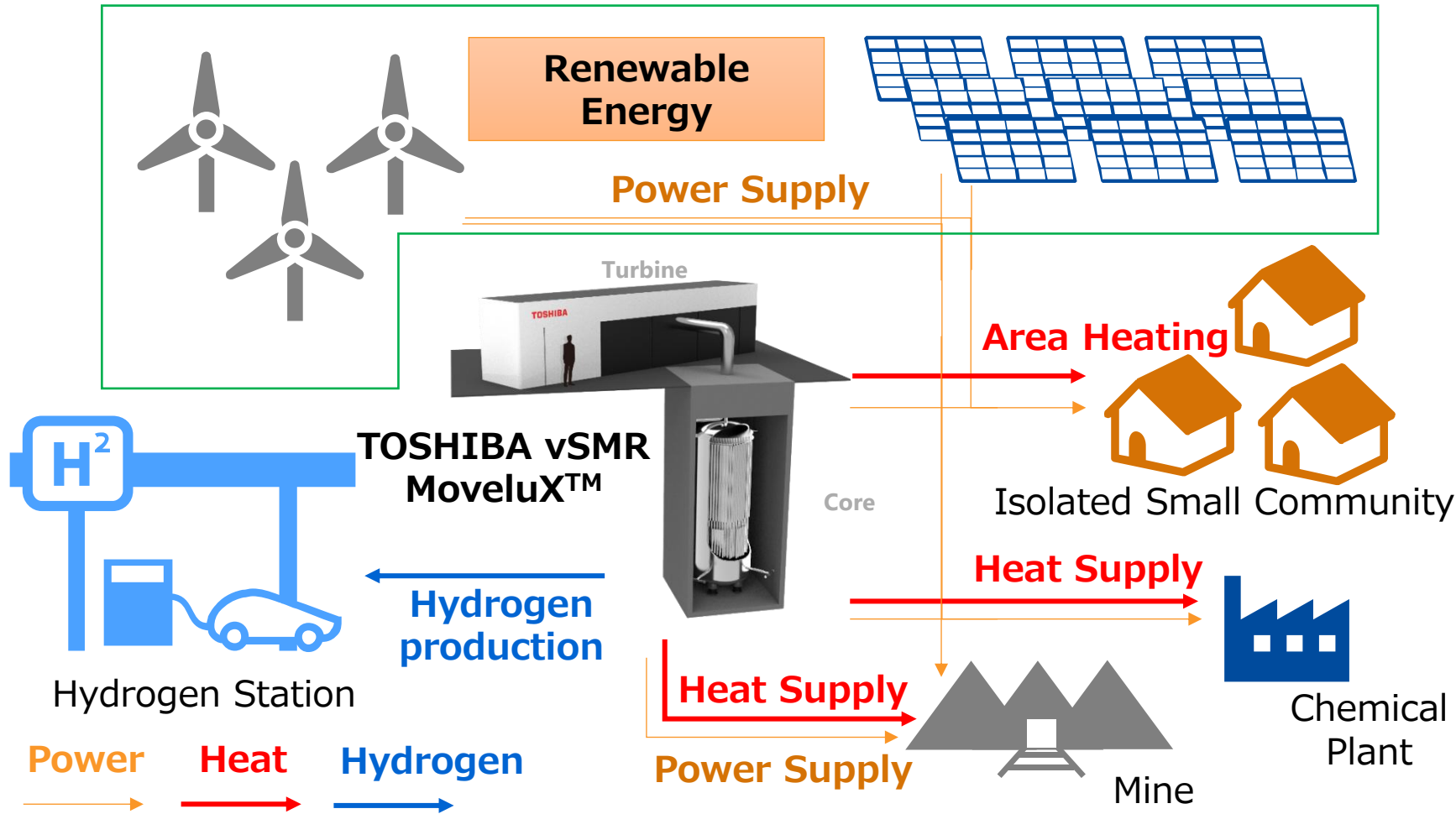


Most of the plutonium on earth is stored in steel dry-storage casks of a few meter in diameter  
Fuel assemblies inside a dry cask can be imaged by muon scattering imaging



Muon technology capable of identifying fuel assemblies inside a cask

# Small Modular Reactor



## Specifications of TOSHIBA MovelluX

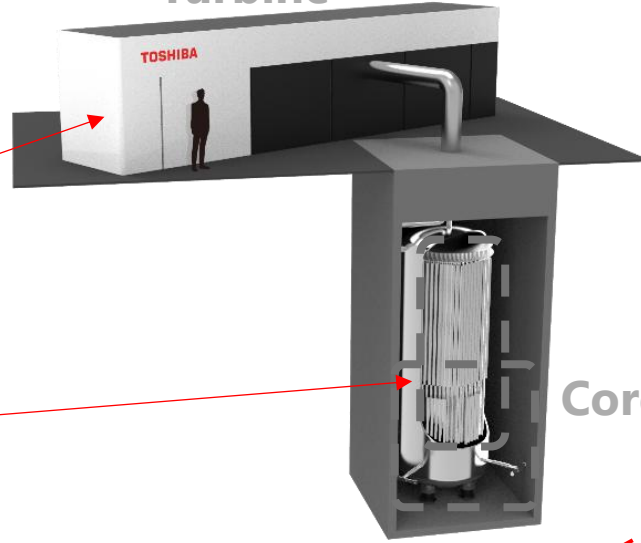
Moderator	Solid (CaH <sub>2</sub> )
Core heat removal	Heat pipe
Thermal output	10 MW
Temperature	700 °C (Heat pipe)
Pressure	1 atm
Fuel	Silicide (4.99 wt%)
RPV diameter/height	2.0 m/5.0m (includes heat exchanger)
Duration of operation	20 years (without exchanging fuel)

72 SMR designs and concepts globally

# Muon Scattering Imaging for SMR Operation and Maintenance

SMR

Turbine



## Turbine

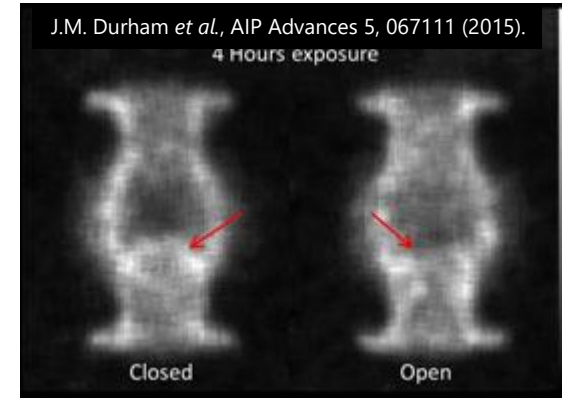
- Pipe thinning online measurement

## Core

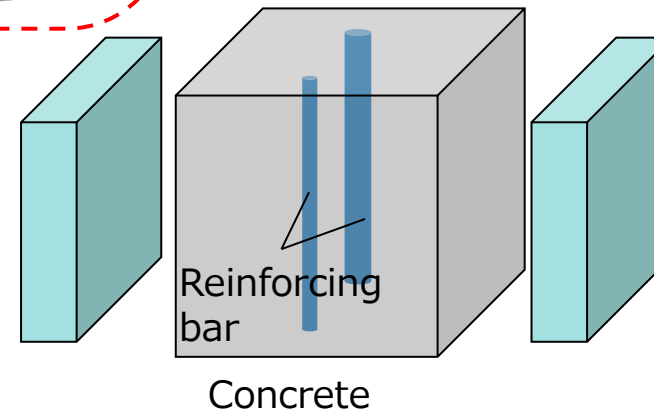
- Nuclear security
- Burnup monitor

## Building

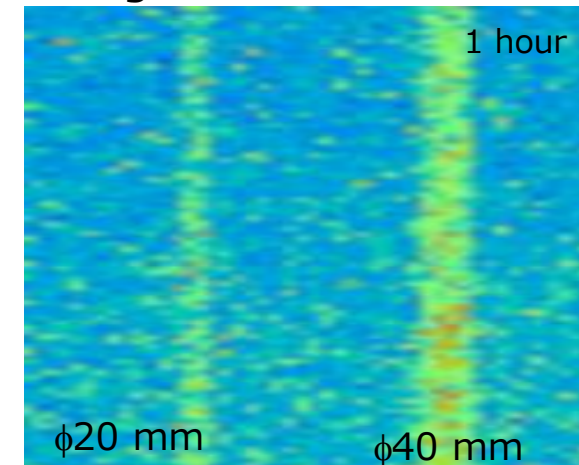
- Reinforced concrete



Valve imaging at industrial plant

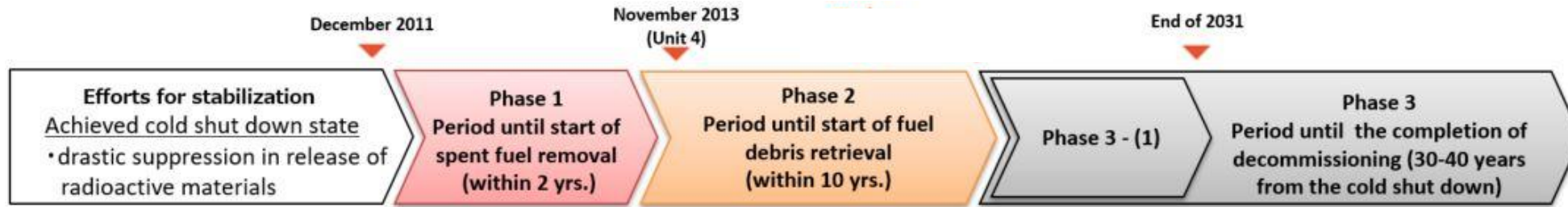


Reinforcing bar in 20-cm concrete



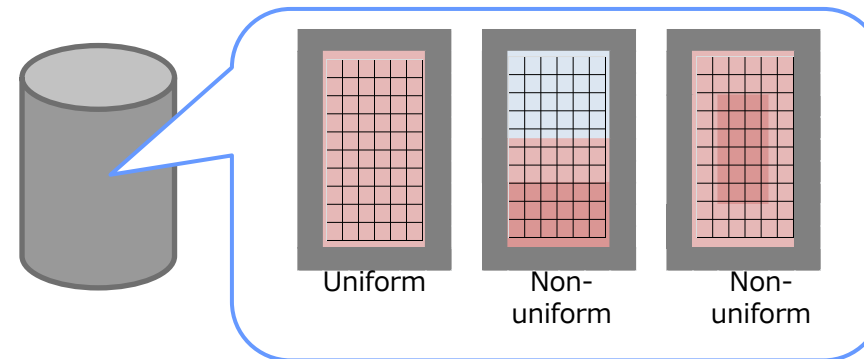
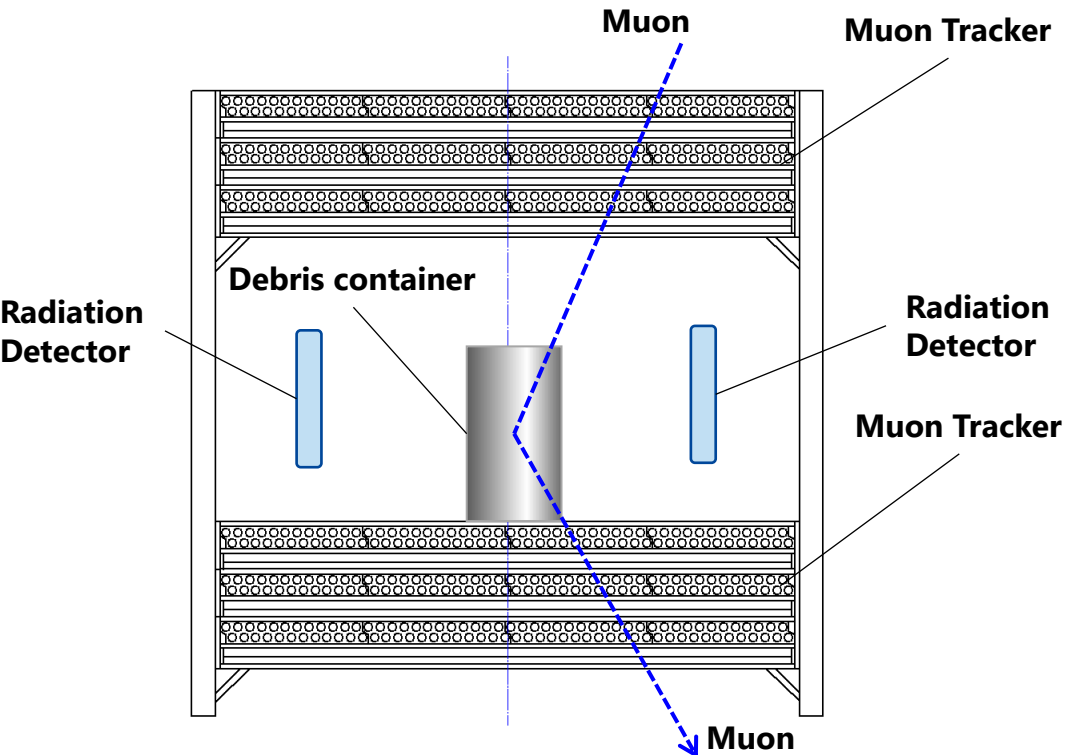
Muon scattering imaging can help operation and maintenance of SMR

# Amount of Nuclear Fuel Needs to be Estimated



Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4  
METI

**It is desirable to measure amounts of nuclear fuel in the removed debris from Fukushima Daiichi**

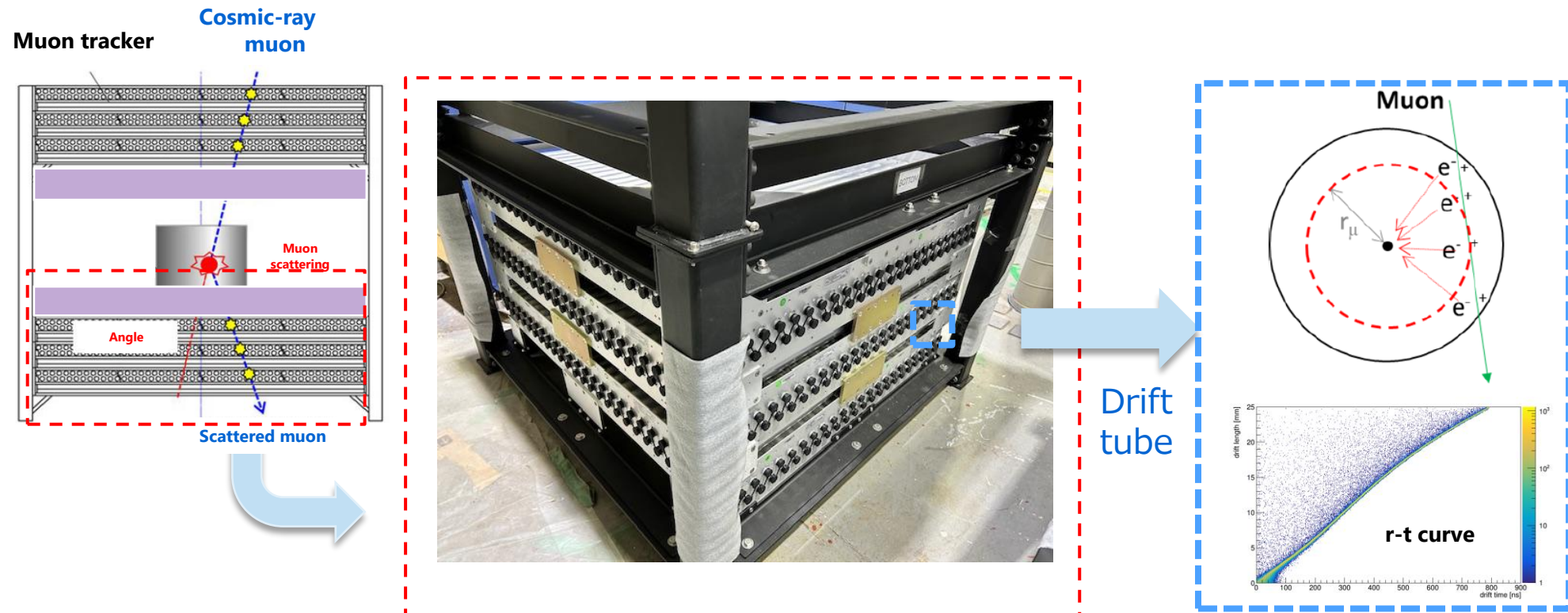


**Can muon scattering measure amount of nuclear fuel?**

## Implemented Measurement Error

All the drift tubes are modeled, and the following errors taken into account in the analysis:

- ✓ Distances of anode wires to the muon track,  $r_\mu$ , converted into drift time considering time resolution.
- ✓ Internal scatterings within the drift tubes simulated.



Prototype detector being assembled for mock-debris demonstration

# Muon Tracking under Radiation Environment

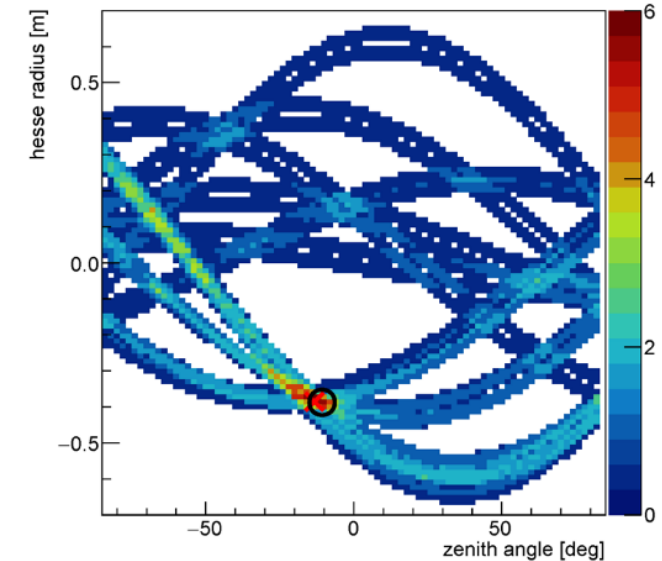
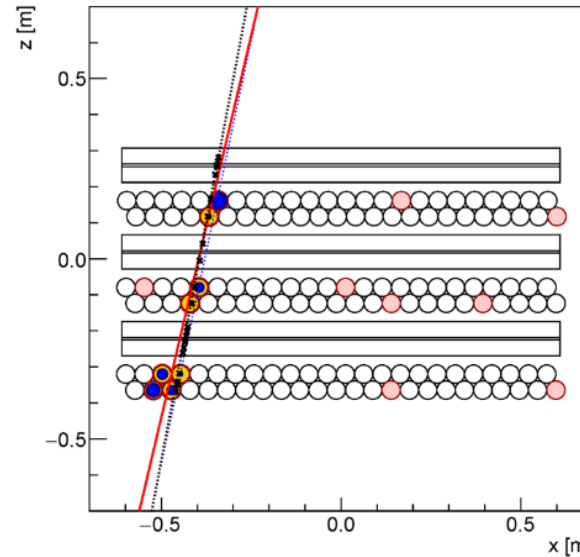
A drift length, a distance to the muon track from the anode wire, is given by

$$\text{drift length} = TR(t_i - t_0)$$

TR is the function that converts a drift time into a drift length. Distances to the muon track from the origin of XZ and YZ planes are given by

$$\begin{aligned}\rho_{XZ} &= x_i \cos \theta_{XZ} + z_i \sin \theta \pm TR(t_i - t_0) \\ \rho_{YZ} &= y_j \cos \theta_{YZ} + z_j \sin \theta \pm TR(t_j - t_0)\end{aligned}$$

where  $x$ ,  $y$  and  $z$  are the location of the anode wire of the drift tube,  $\theta_{XZ}$  and  $\theta_{YZ}$  are the zenith angles of the muon track in the XZ and YZ planes, respectively. The plus-minus symbol is because of the two possible muon tracks. Here, the muon track is obtained by sum voting on  $\rho$ ,  $\theta$  and  $t_0$  since  $\gamma$ -hit drift tubes are not selected in the votes.



Left: track Hough transformation (blue dashed line),  $\chi^2$  minimization of line fit (red solid line) and true muon track (black dashed line).

Right: Hough voting histogram and position obtained by  $\chi^2$  minimization (red cross) and true muon track (black circle). Each drift tube is assumed to suffer 40-kHz noise which corresponds to the  $\gamma$  environment of 200  $\mu\text{Sv/h}$ .

H. Miyadera et al., Applied Optics 63 (2024) A52.

**Muon-track reconstruction using Hough transform developed**

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