Simulation of Imaging Using Accelerated Muon Beams.

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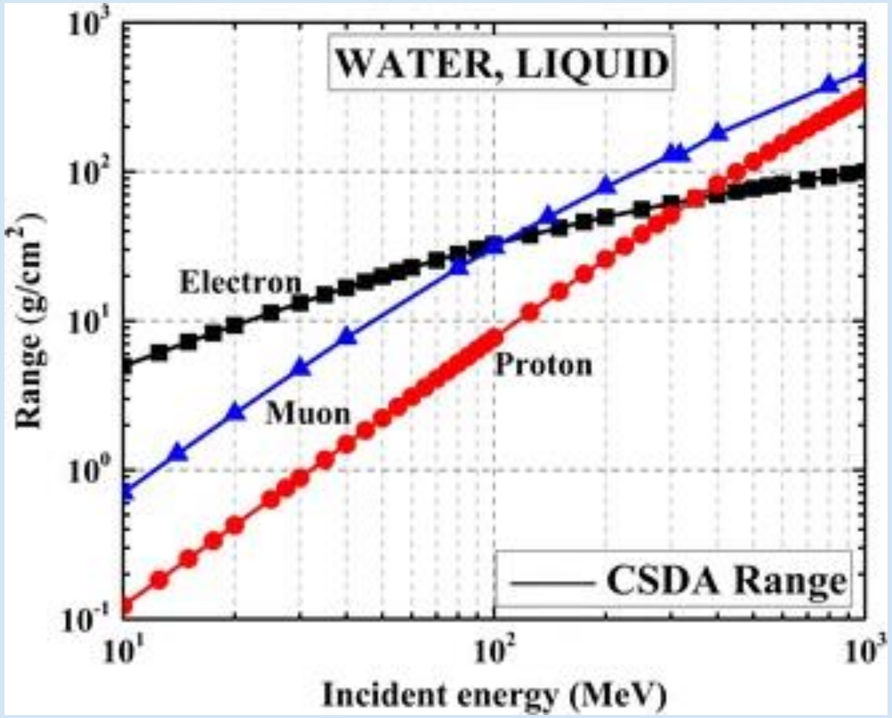
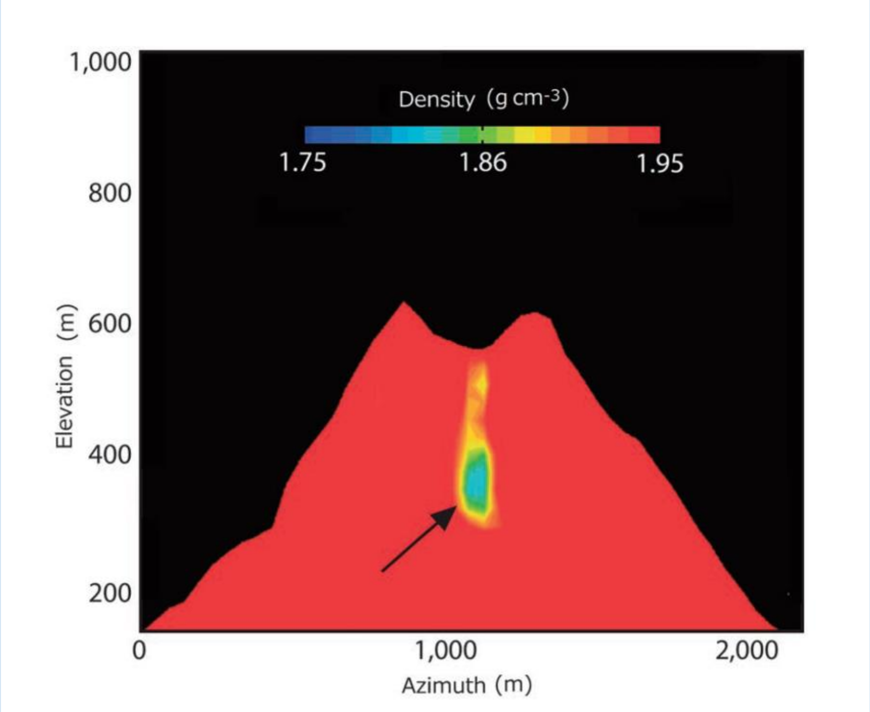
Contents

Muon

- Elementary particle of intermediate mass (105 MeV/c^2) between electron (0.5 MeV/c^2) and proton (940 MeV/c^2).
- Cosmic-ray muons have been widely used for imaging application due to their strong penetrating power.

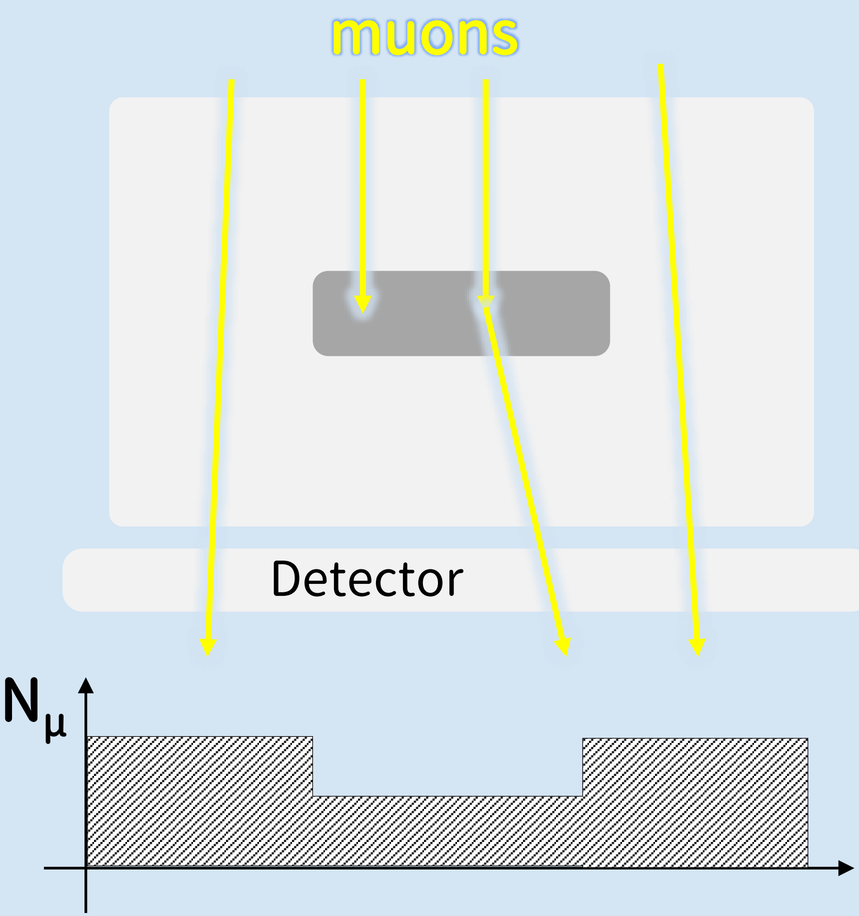




https://doi.org/10.3769/radioisotopes.65.305

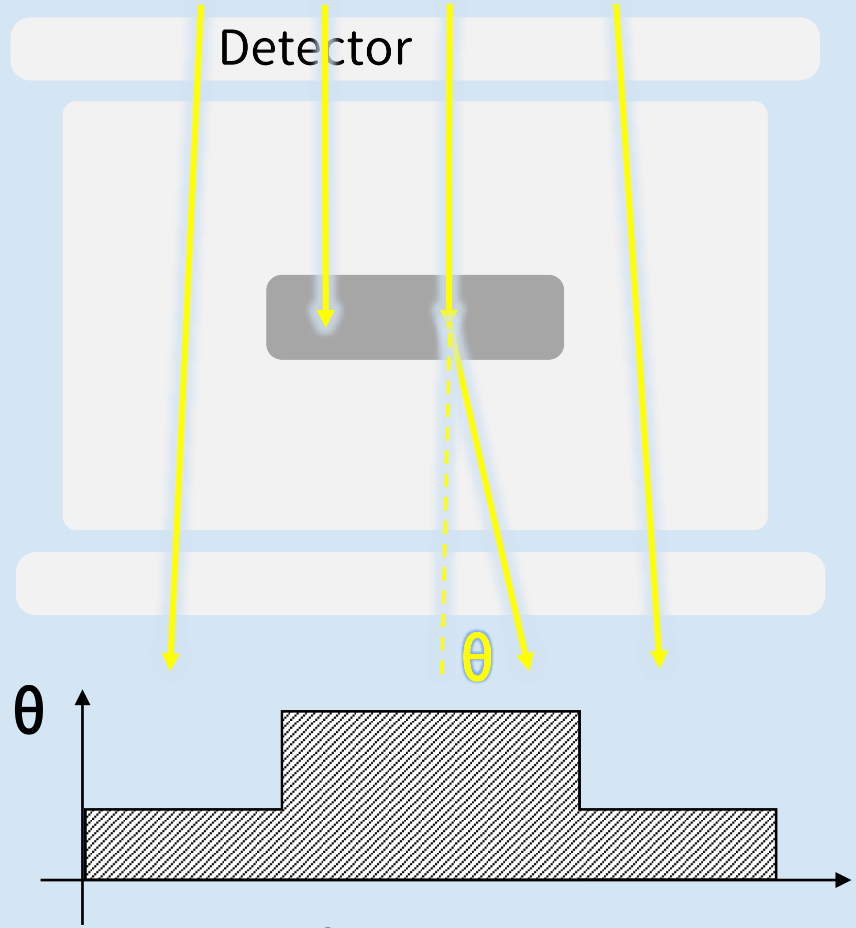
Radiography & Tomography

Absorption radiography



☺ Larger structure
☹ Resolution degradation due to scattering

Scattering tomography

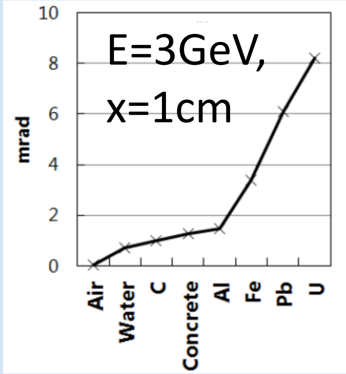


☺ identify materials and its position.

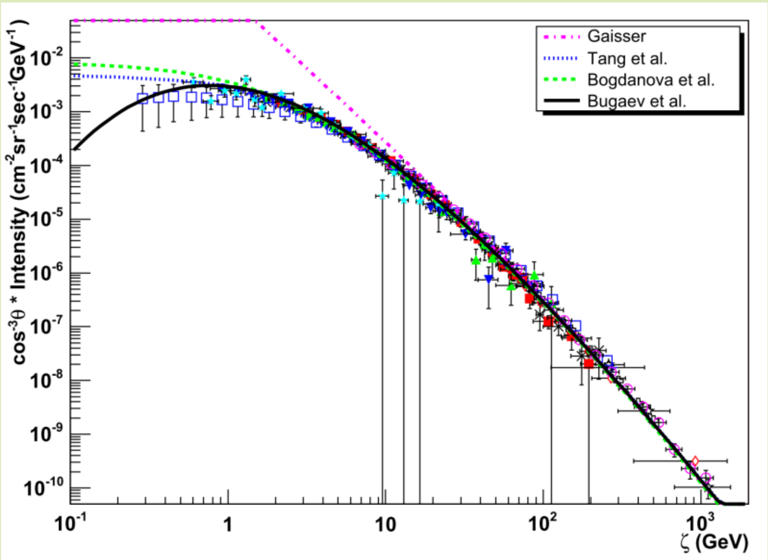
Cosmic-ray vs Beam Muons

$$\theta \propto \sqrt{x/X_0}/E$$

x : path length
X_0 : radiation length

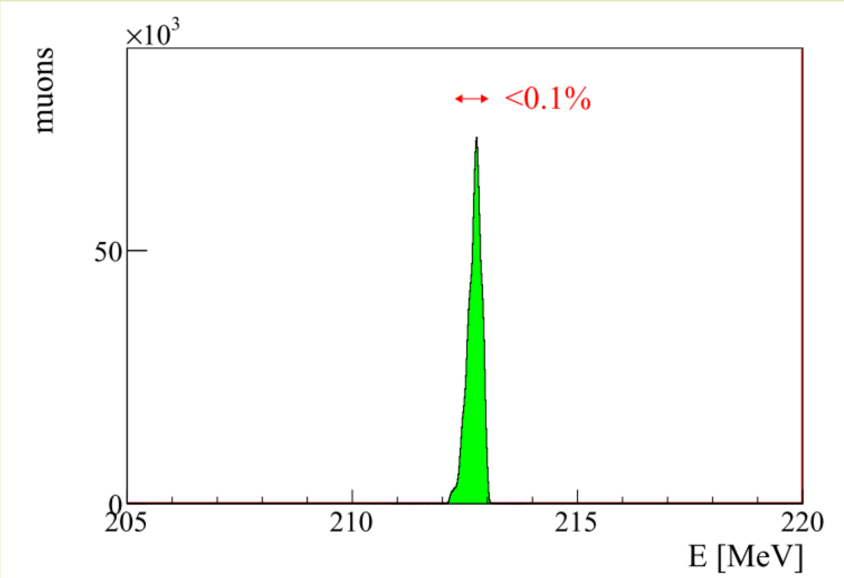


Cosmic-ray



sub-GeV to sub-TeV

Beam muons



ΔE << 1%

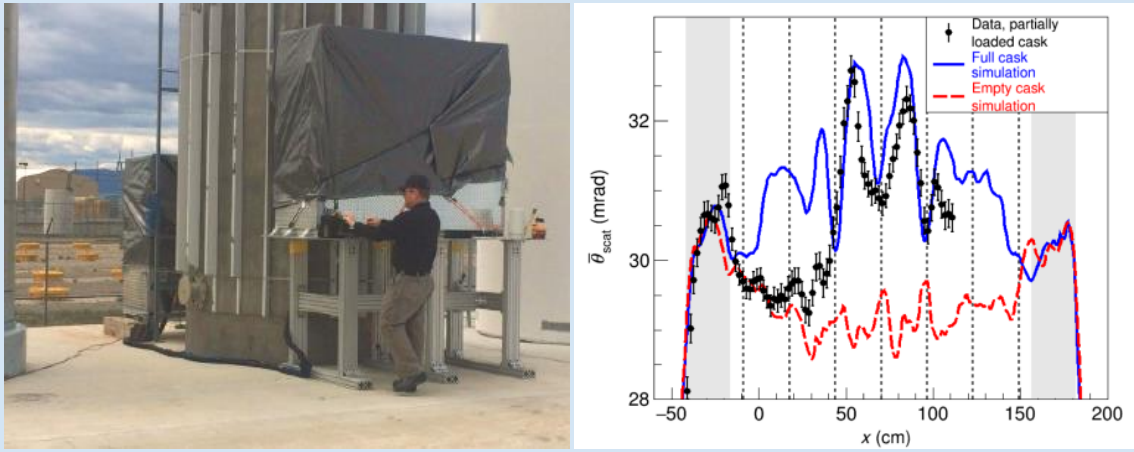
Beam muons should provide powerful imaging capabilities.

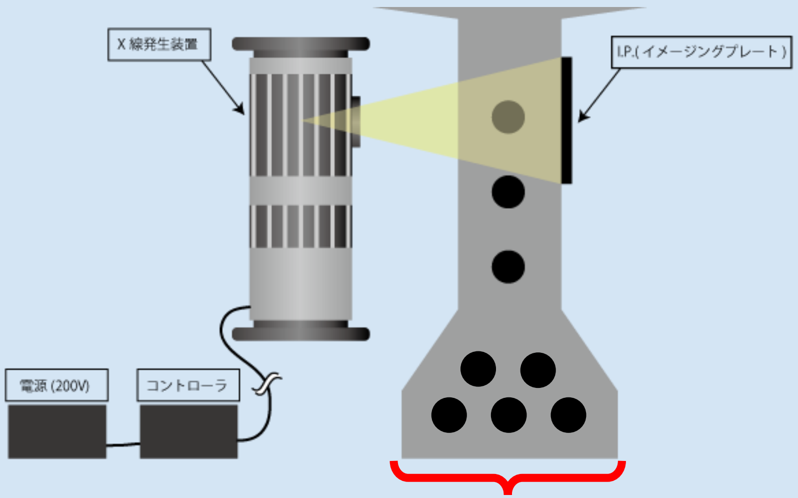
Simulation for Potential Applications

1. Dry cask storage
   - better resolution with less time, compared to that with cosmic-ray.
   - potential to detect small amounts/types (Pu/U) of nuclear, impossible with cosmic rays.
2. Prestressed concrete
   - inspection impossible with conventional methods such as X-ray, ultrasound etc.

inspection on the PC steel

cask scan with cosmic-ray [~90 days]



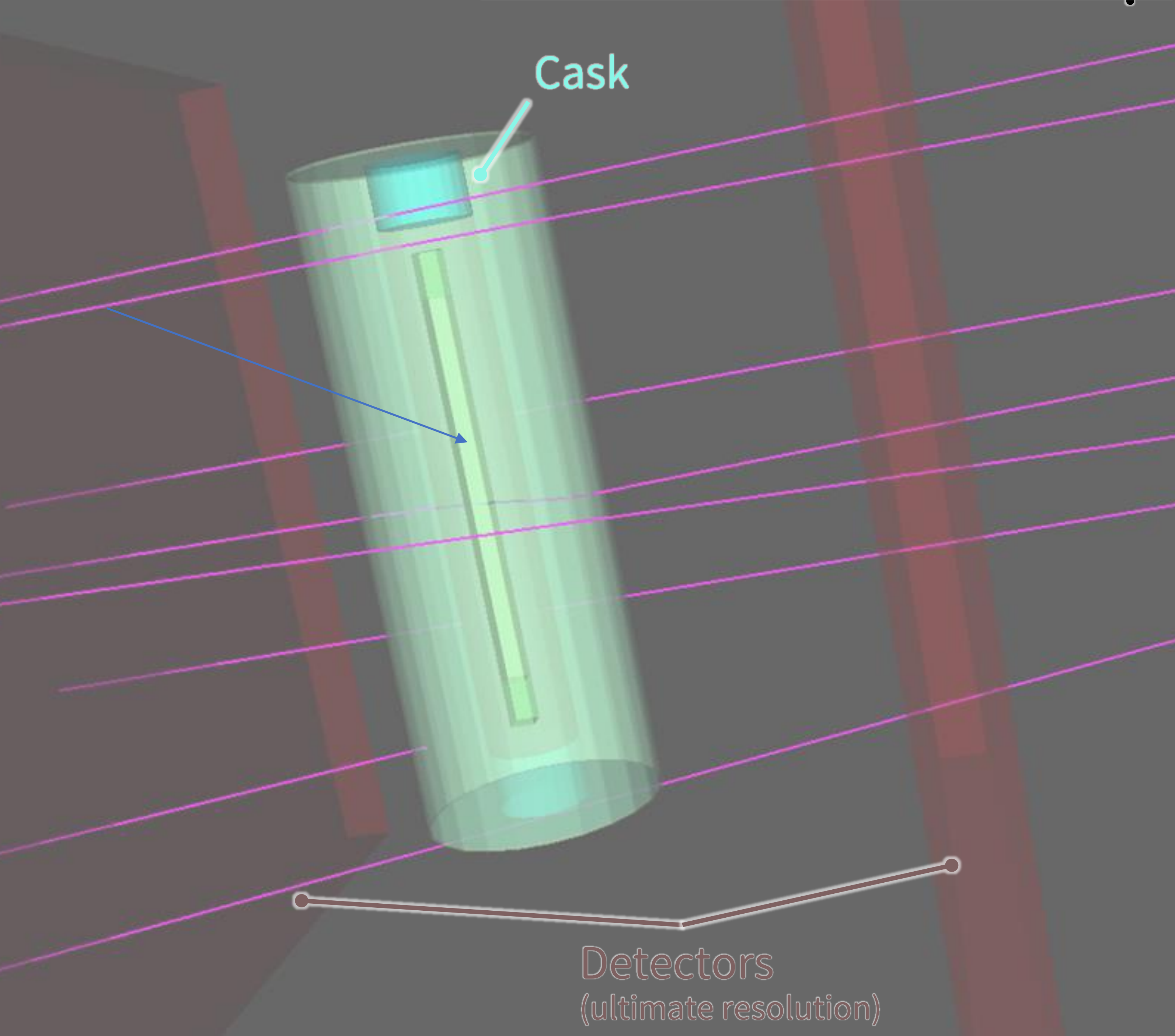


difficult with X-ray

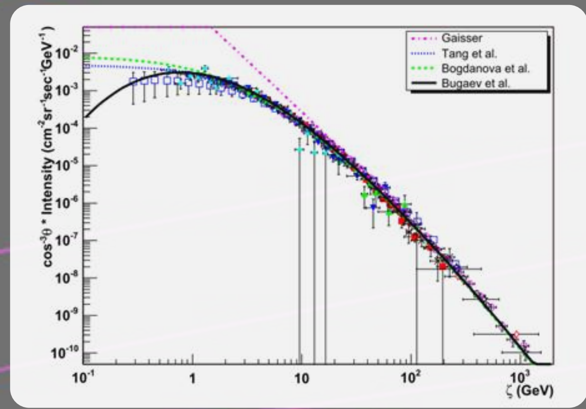
J.M Durham et al., Physical Review Applied 9, 044013 (2018)

http://www.kokusai-se.co.jp/technology/technology03.html

Simulation setup



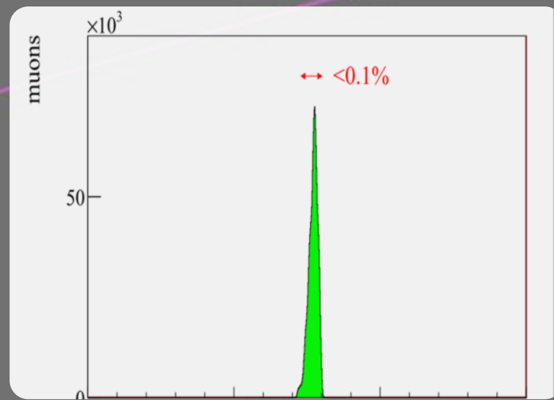
Cosmic-ray muons



D. Reyna, arXiv:hep-ph/0604145v2

OR

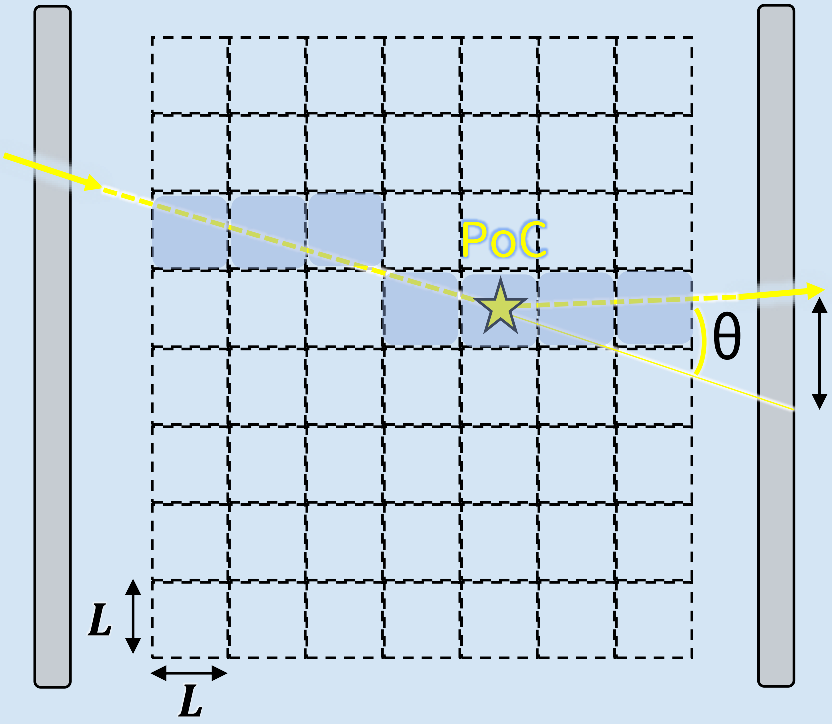
Beam muons



$E = 3$ GeV, $\Delta E = 0.1$ %

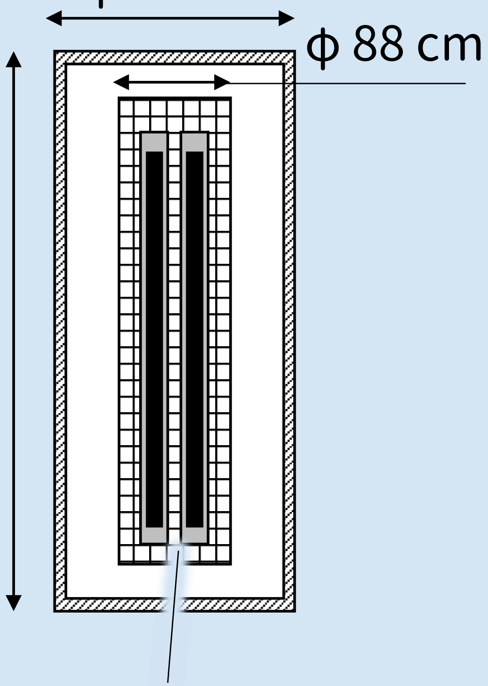
Analysis Method

- Point of closest approach (PoCA) is adopted.
  - In addition, displacement method [H. Miyadera et al., AIP Advances 3 (2013) 052133] is used to avoid bias in scattering intensity at deeper sites in some results.

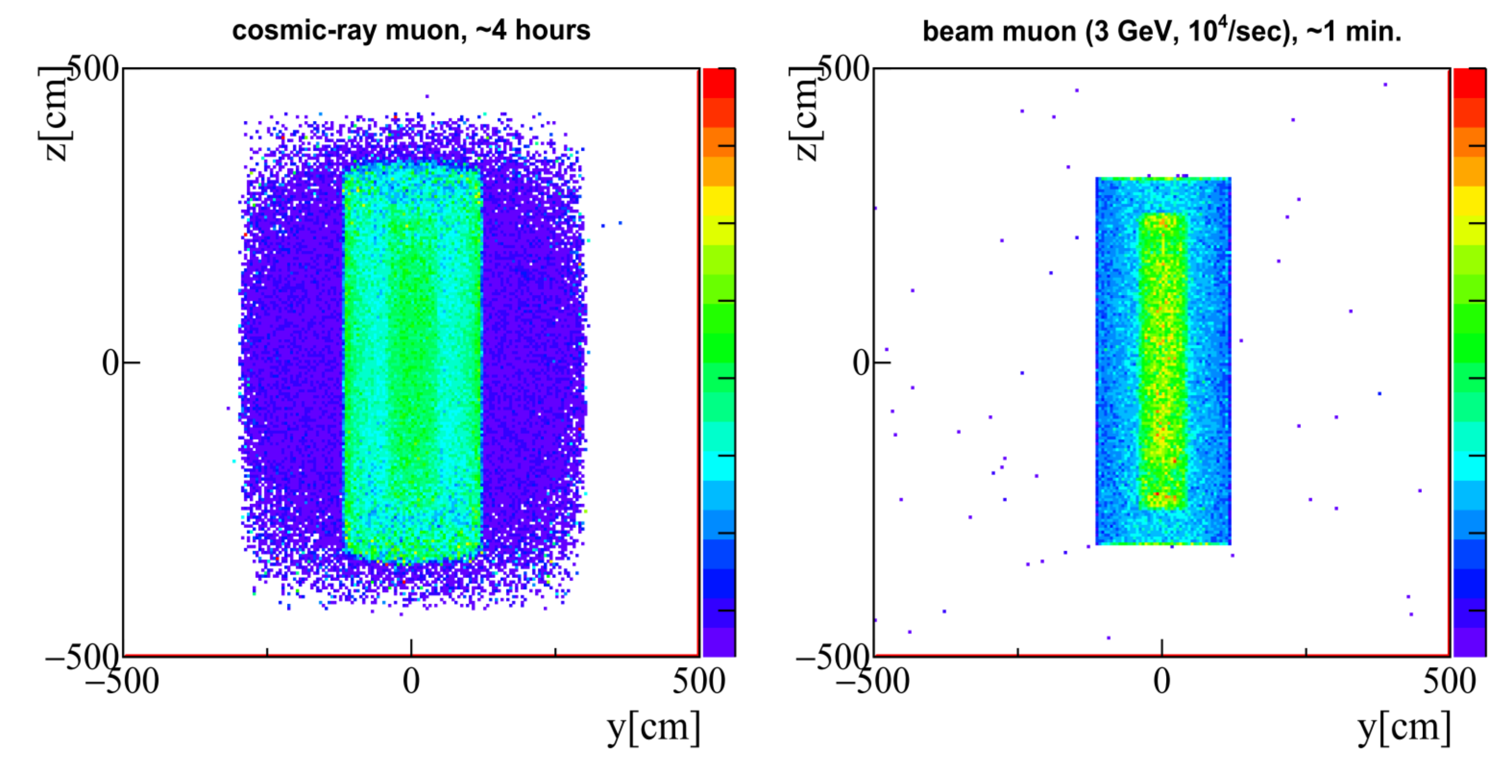


- Extrapolate detected muon directions and get PoC as scattering point.
- Add θ^2 to the signal counter of the PoC pixel ($\boldsymbol{S_i}$).
- Increment the counter for pixels ($\boldsymbol{C_i}$) along the path.
- scattering density of i'th pixel (λ_i) is calculated to be $\lambda_i = \sum_\mu \boldsymbol{S_i} / \sum_\mu \boldsymbol{C_i} / \boldsymbol{L}$
- displacement between original track and scattered one is also calculated.

Result



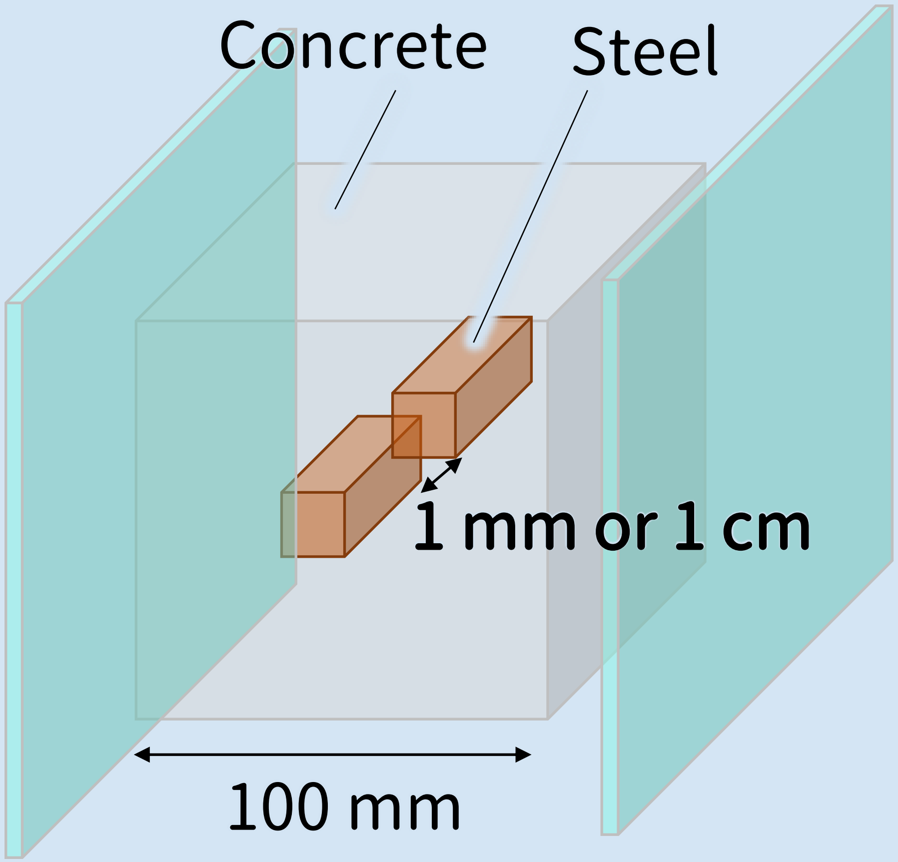
Fuel assembly (UO_2:Zry) inside the container (Steel)



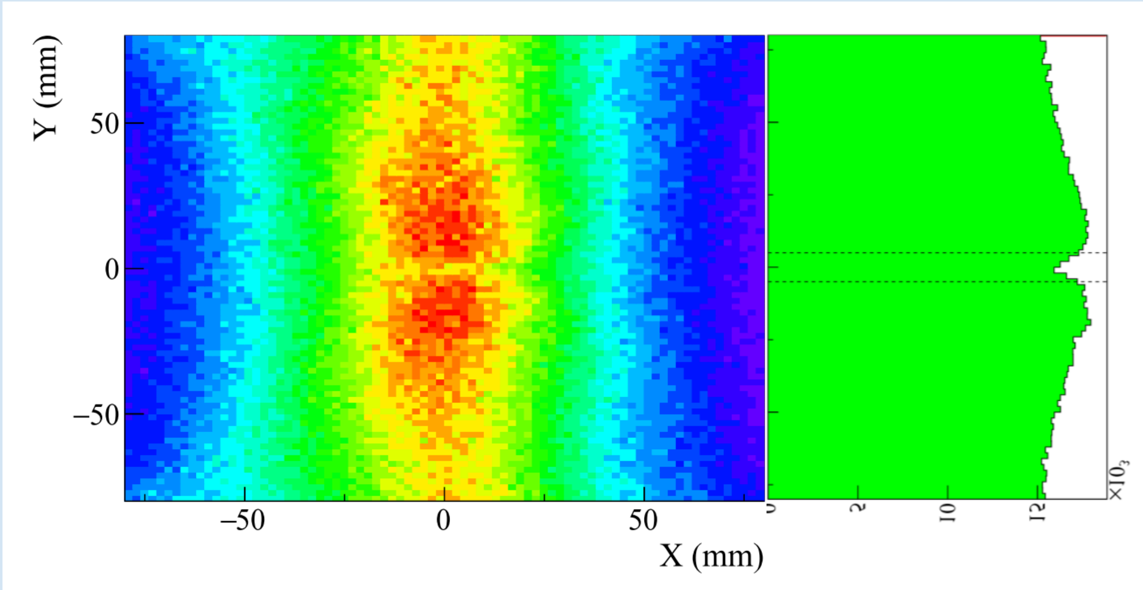
The fuel container can be seen clearly with less time.

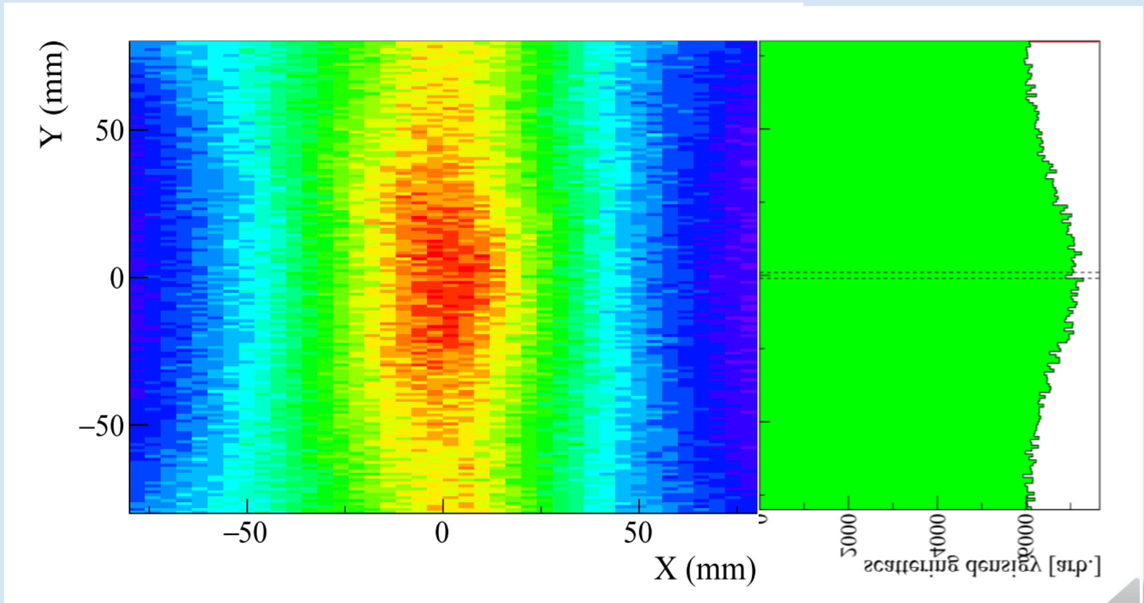
Beam muon has better resolution with less time.

Prestressed Concrete with Cosmic-ray



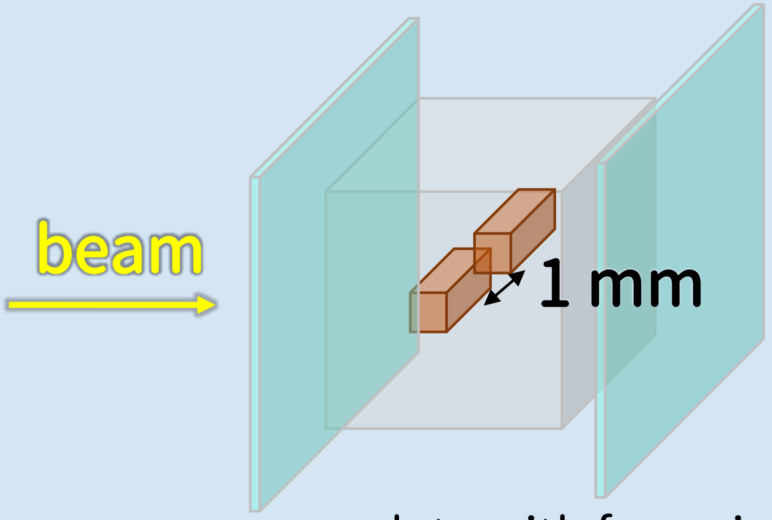
data with several tens of days



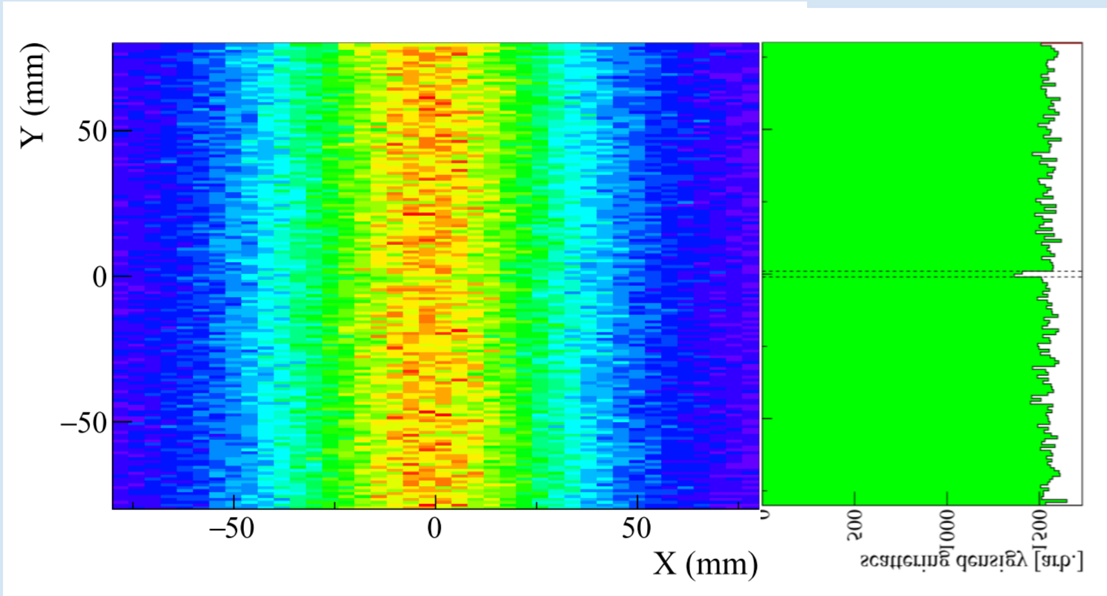


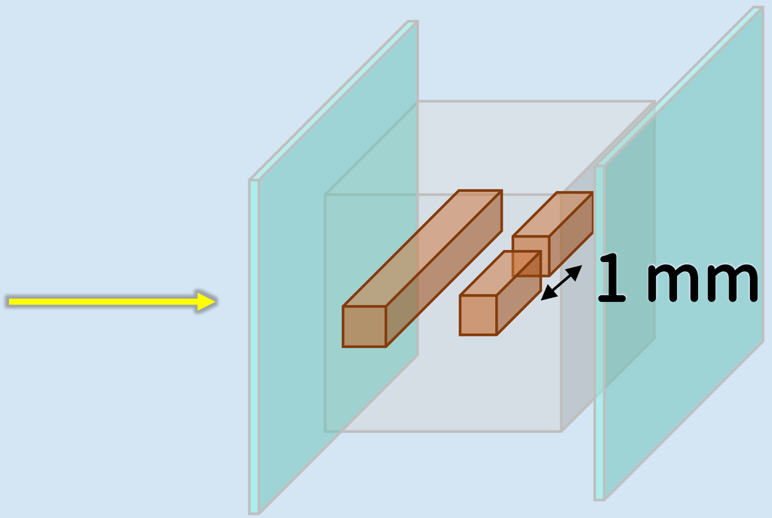
~1-cm defect can be detected.

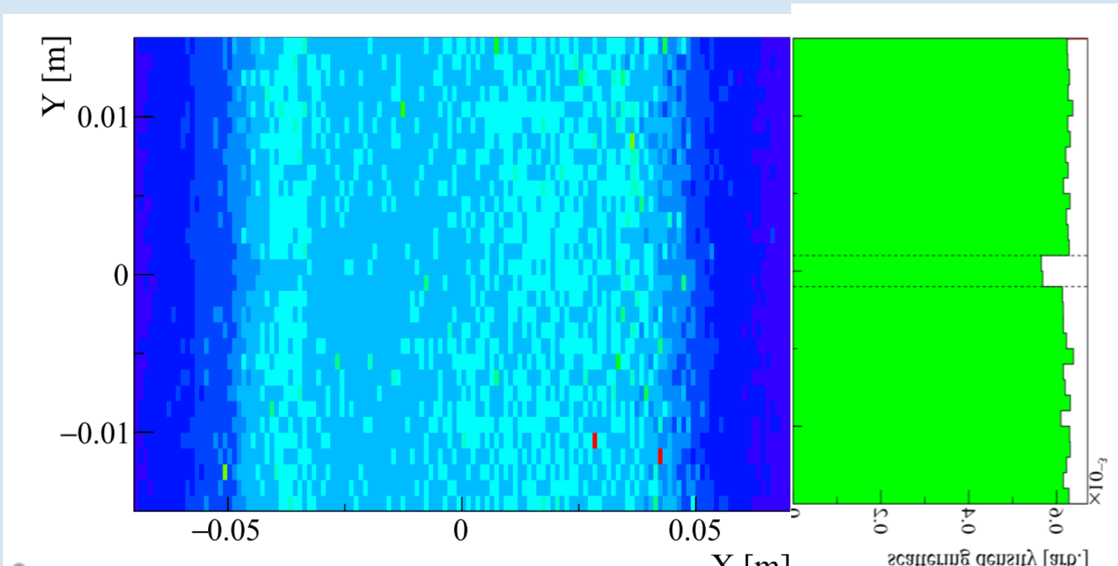
with Beam Muons



data with few minutes





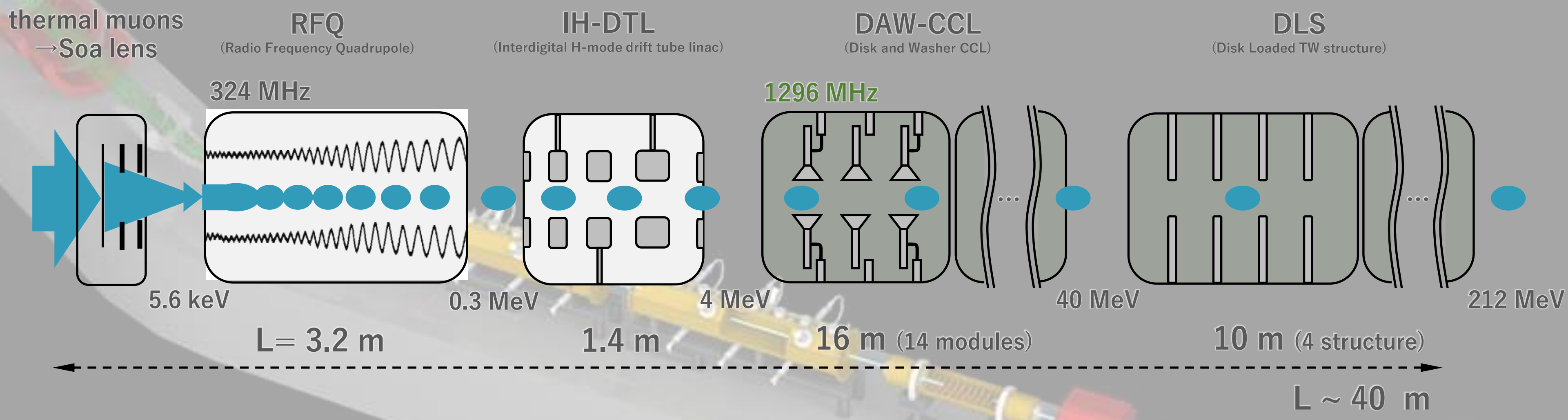


~1 mm vacancy can be detected,
even if it's on the far side of the structure

not clear separation of the two steel bars due to the PoCA method, assuming scattering at a single point, and further analytical studies are needed.

Prospects for Muon Accelerator

- Muon linac, accelerating muons from thermal energy to near the speed of light, will start construction soon to measure g-2.



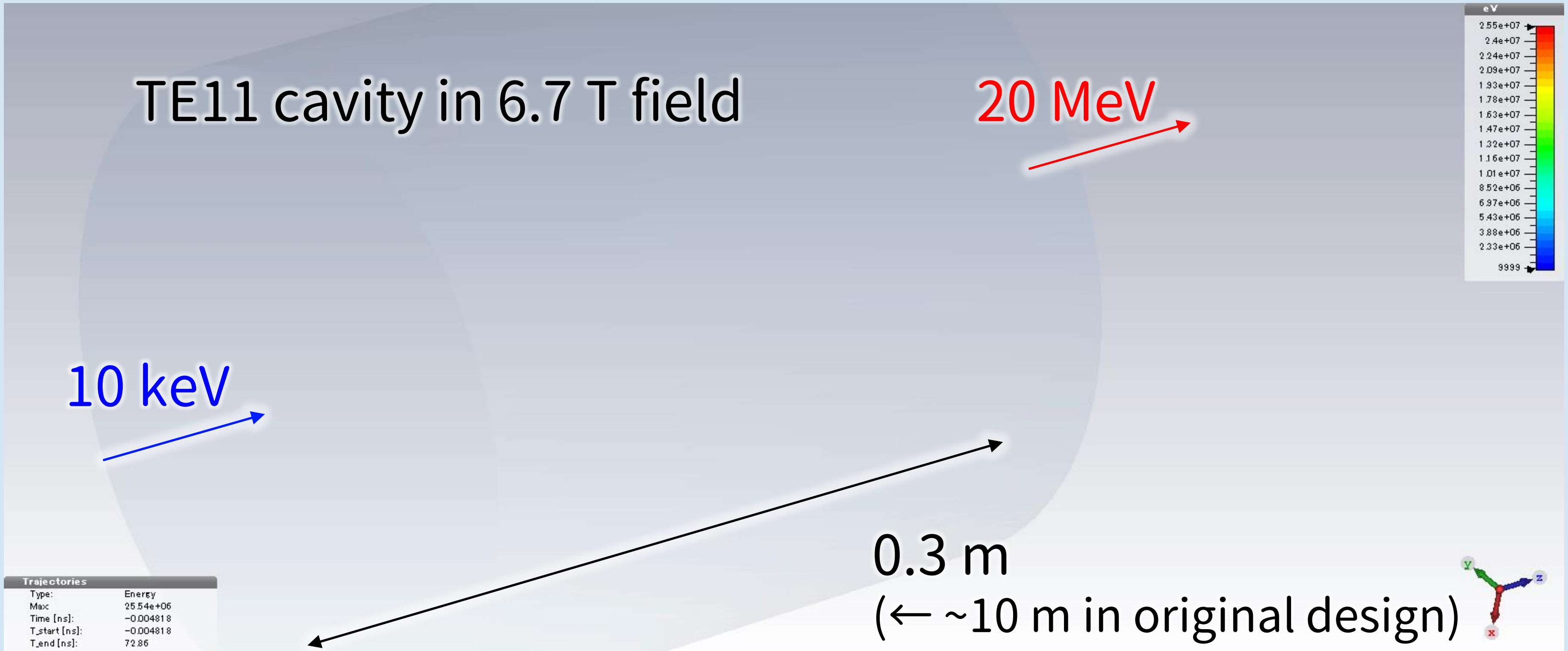
Energy [MeV]	212
Intensity [/s]	10^6
Repetition [Hz]	25
Pulse length [nsec]	10
Normalized ε_t [π mm mrad]	1.5
Δp [%]	0.1

- The experiment (J-PARC E34) receives approval in PACs and high priority in KEK PIP2016.
- Budge request from KEK to MEXT.
- KAKENHI "Specially Promoted Research" has been approved for partial construction of the experiment.

Cont'd

- To enable the inspection of roads and other infrastructure, intensive research and development is being done for more compact accelerators. One of the bottlenecks is low velocity part of muon acceleration.

Simulation for automatic cyclotron resonance acceleration for low velocity muon



Summary

- Cosmic-ray muons have been widely used in imaging. Recent progress in muon accelerators is expected to expand the possibilities of imaging with beam muons, which enables us to perform clearer imaging in less time.
- Simulation studies for two possible applications (dry cask and PC) were reported, which show potential of the imaging with beam muons.
- Muon accelerator will start soon at J-PARC. Further studies for more compact acceleration is on-going.