International Workshop on Muography 2023 (MUOGRAPHERS 2023)

Investigation of the Impact of Magnetic Fields on Scattering Muography Images

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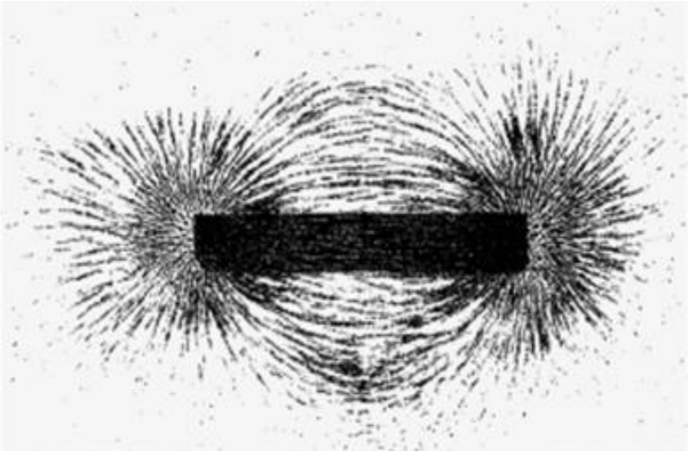
UCLouvain

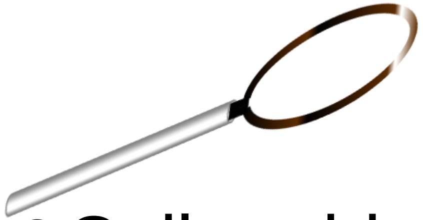
2023/06/21

■ Magnet or magnetic field measurement techniques are limited.

● Magnetic flux can be figured out only where iron sand presents.



● A Hall device probing
(local measurement)



●Coil probing
(time dependent one only)

Cosmic-ray muon has potential!!

- **Charged particle**: Lorentz force deflects muons into specific direction in contrast to scattering.
- **High penetrating power**: Probe insertion is not necessary and we can measure magnetic fields placed inside some targets.
- **Wide field of view** facilitates large-scale measurements.
- **Natural radiation**

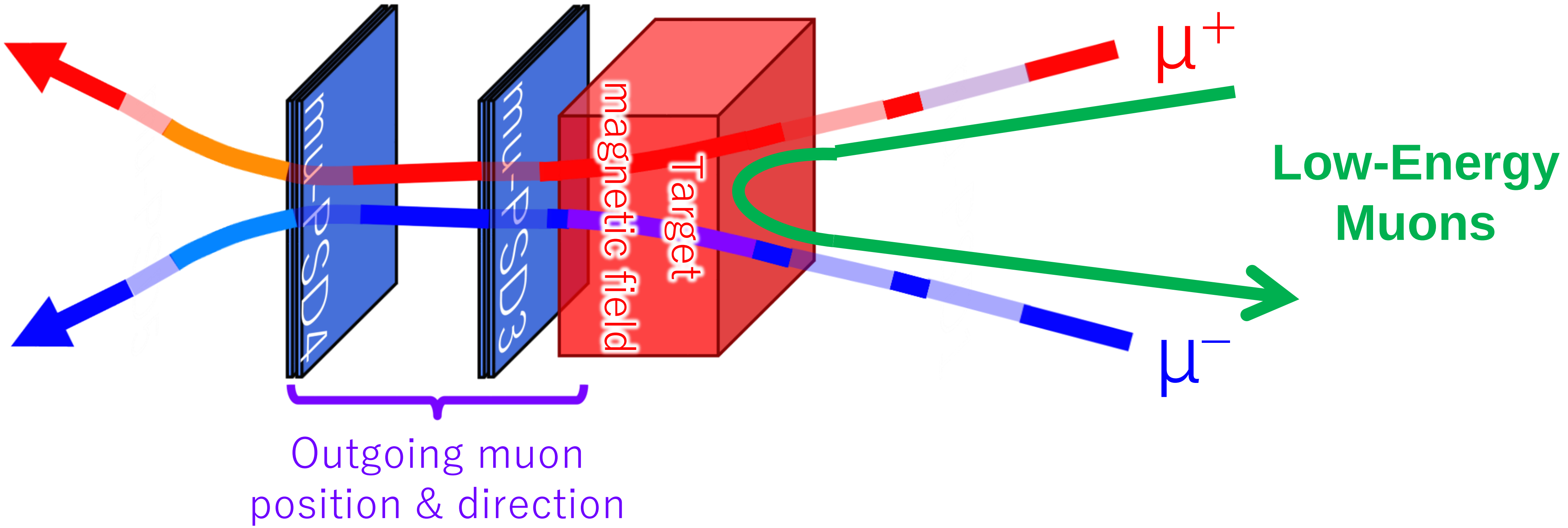
Magnetic Field Imaging by Cosmic-ray Muon

— Magic-μ —

Patent: MAGNETIC FIELD STRUCTURE IMAGING USING MUONS, 2022, WO2023031265

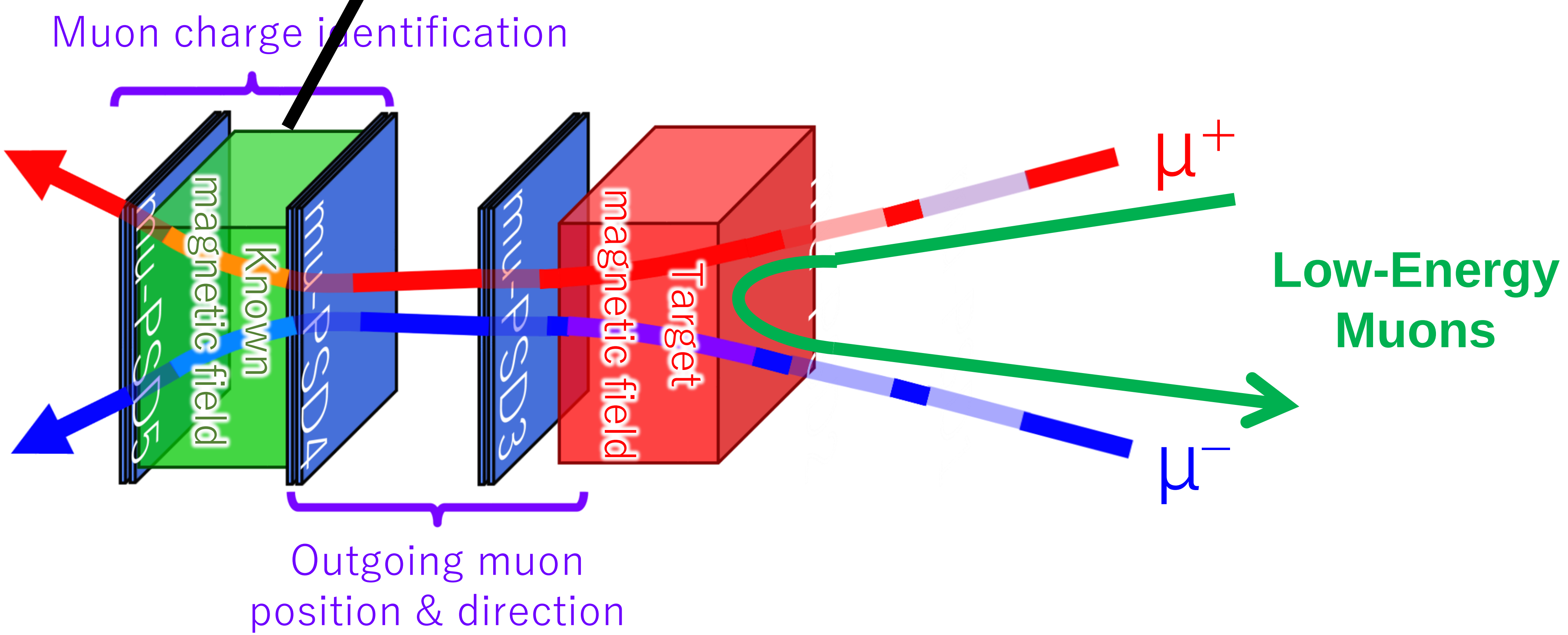
Conceptual designs

- Huge and strong magnetic fields such as **Fusion reactors**
- Background measurement (Magnet OFF) or precise simulation must be possible.
- We need just qualitative measurement.



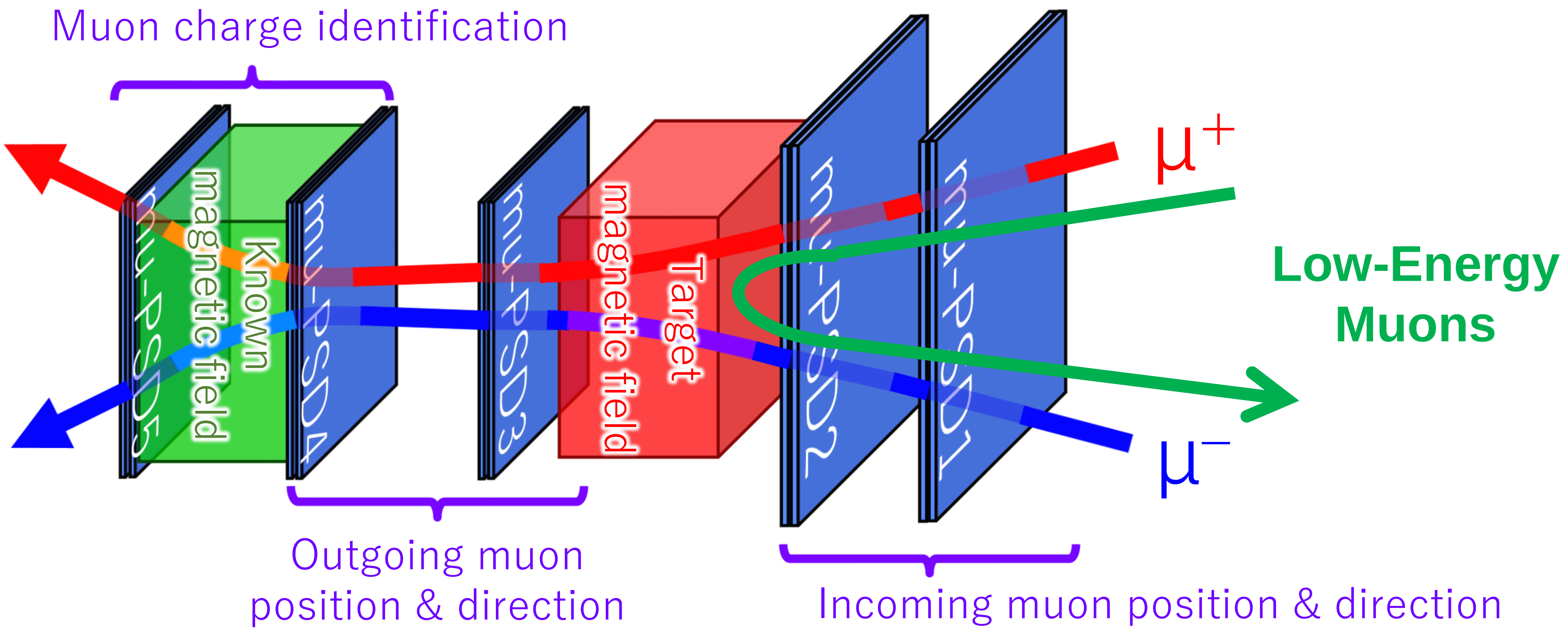
- **1 m** magnetic field of **1 T**, muons up to **180 MeV** will be **completely deflected back**. These constitute **3.5%** of the muon flux.

Addition to the normal muography setup allows for enhanced magnetic field information.



- A 20 cm thick magnet of 0.2 T can distinguish + and - muons of energy of 130 MeV.

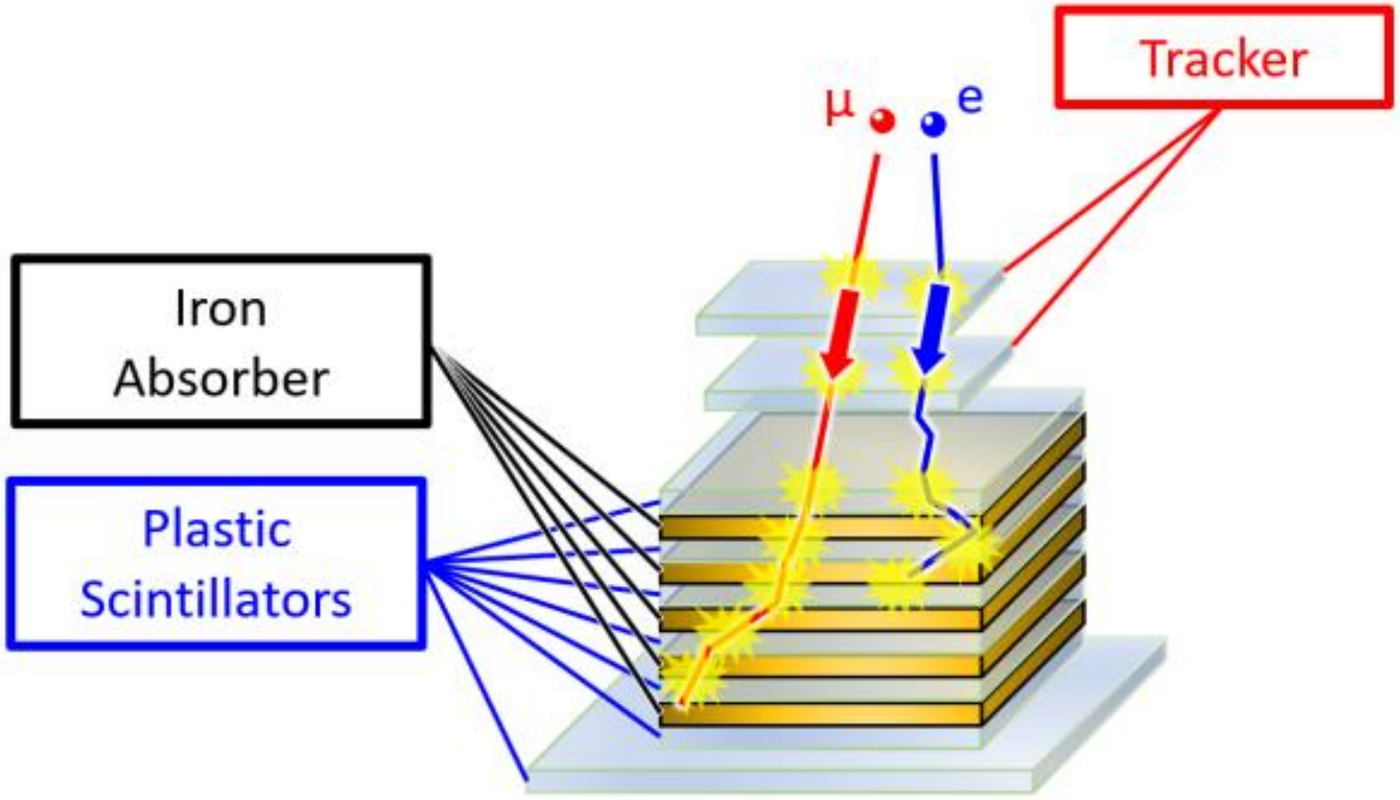
- For small-size targets such as **electric car motor** developments!



Energy Determination using Multi-layer Muon Energy Spectrometer

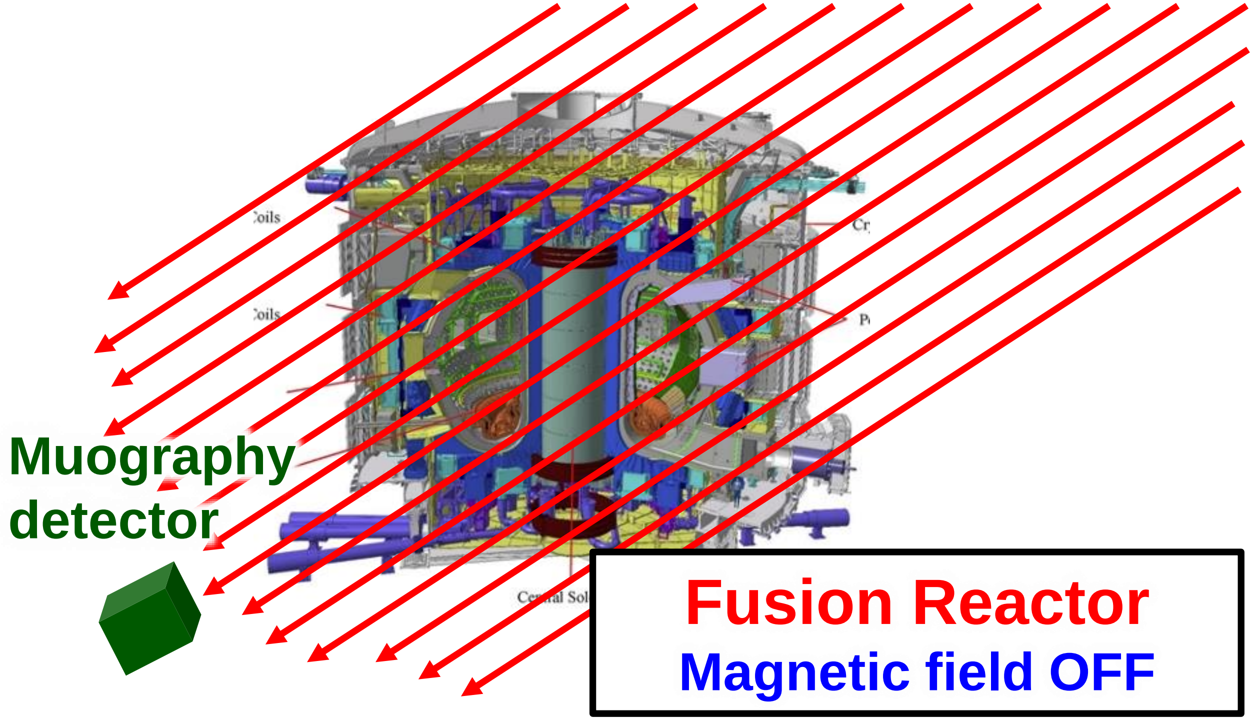
- Composed of layers of **iron plates** and **plastic scintillators**.
- Iron plates interact with muons causing them to **lose energy**.
- Plastic scintillators **detect** these particles, and we can estimate the energy.

Energy up to of 1 GeV can be determined using multi-layer detector (90 cm thick) analyzed by machine learning



■ Effect of magnetic field on muography images

Absorption

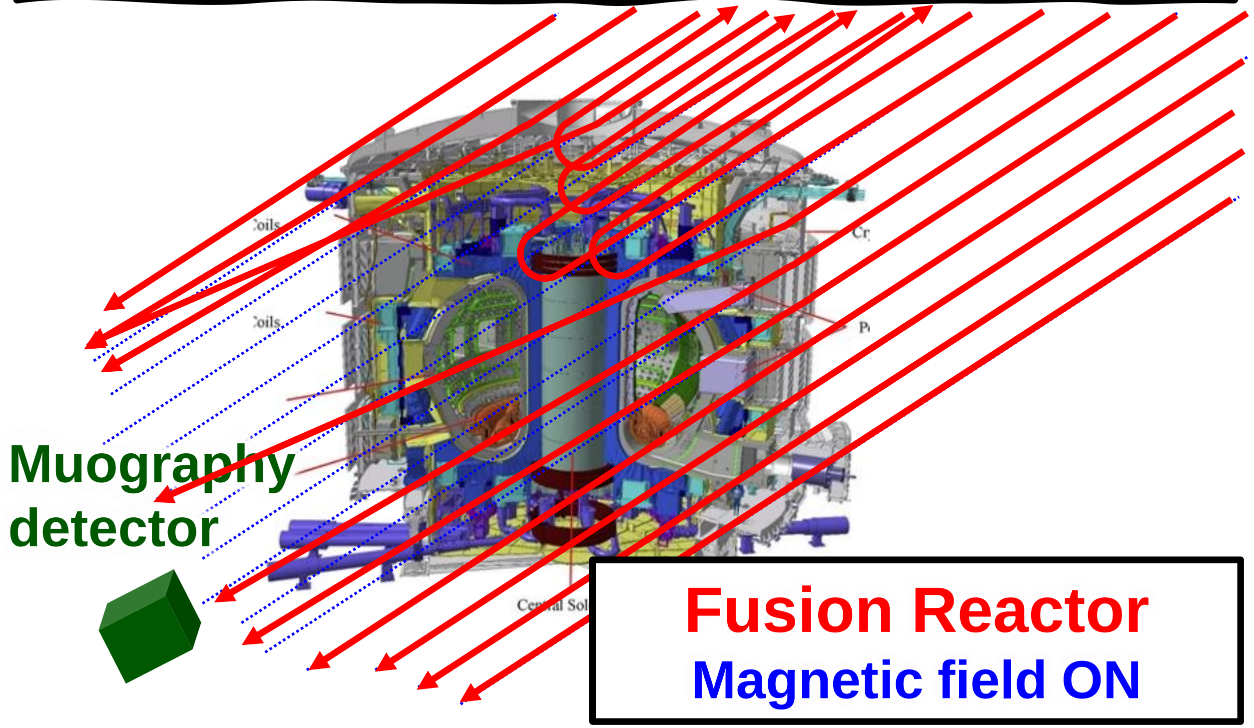


Muon trajectories are almost straight lines if there is no magnetic field

Scattering

■ Effect of magnetic field on muography images

Absorption

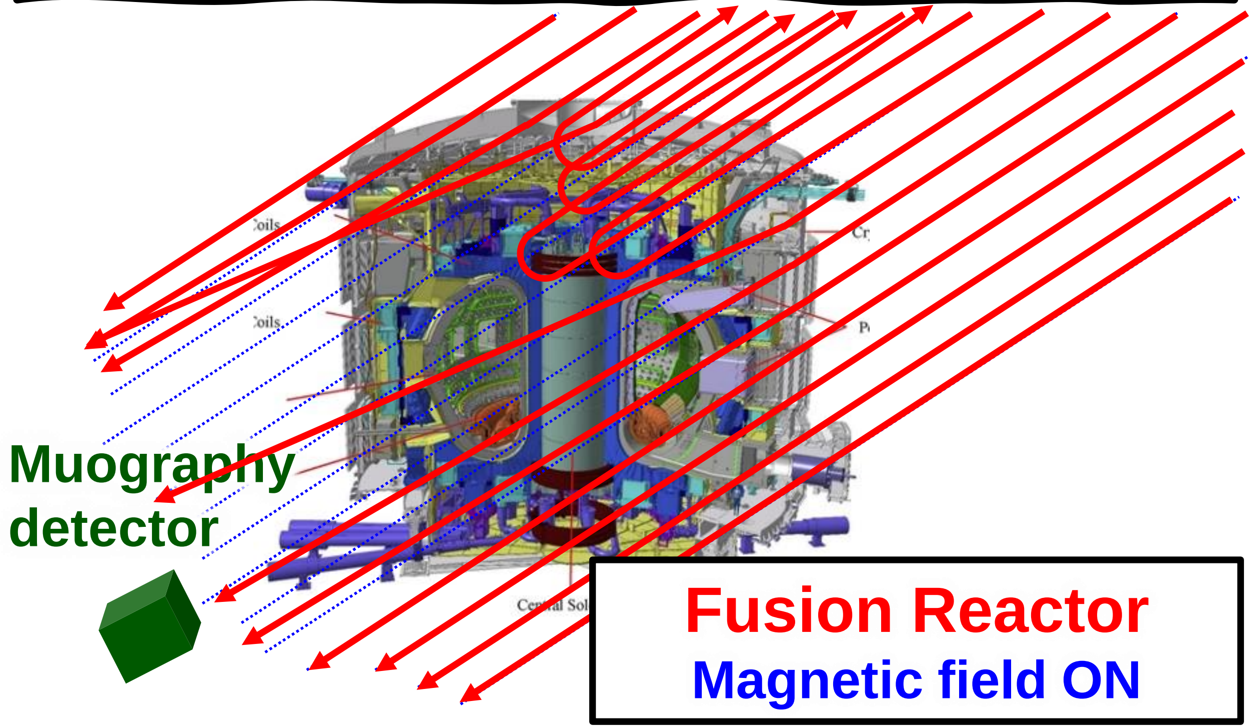


Muography images are distorted and vanished by deflection and reflection of muon.

Scattering

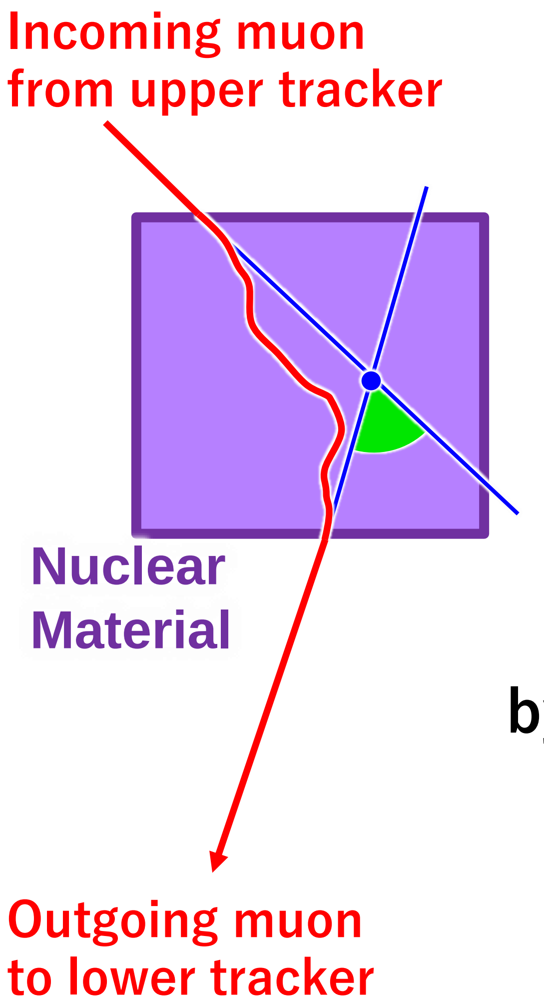
■ Effect of magnetic field on muography images

Absorption



Muography images are distorted and vanished by deflection and reflection of muon.

Scattering



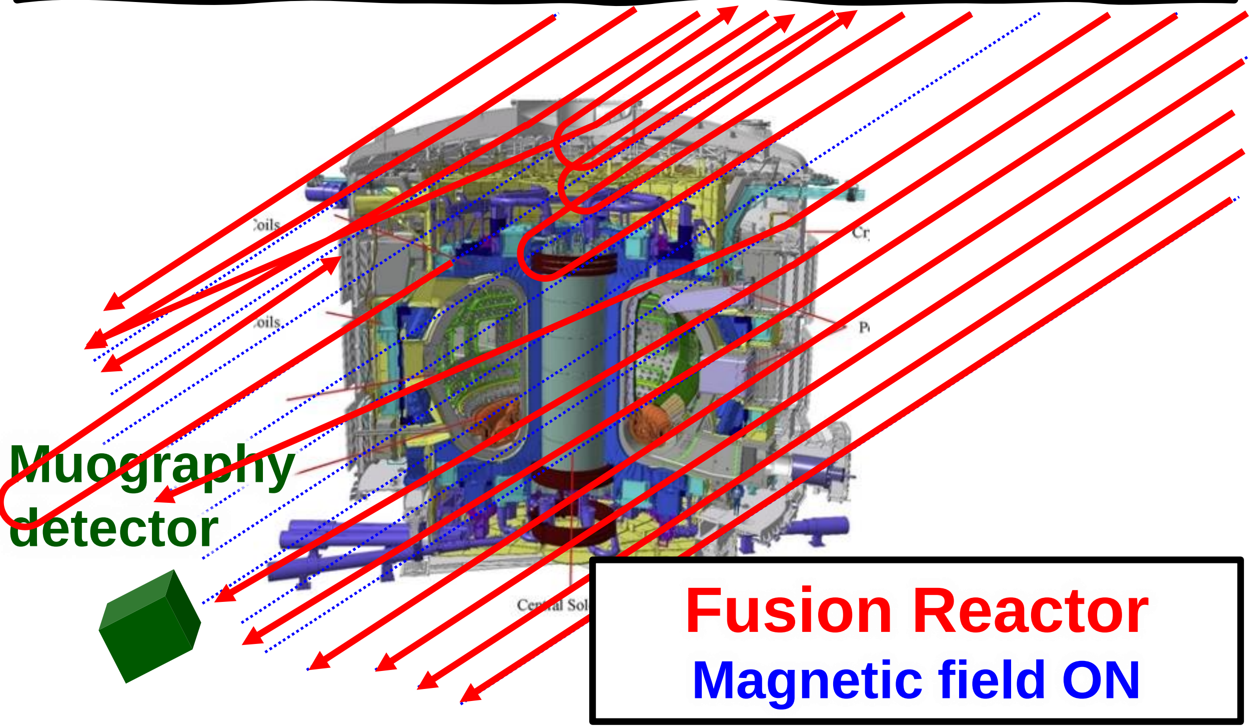
Scattering muography estimates

1. a PoCA position
   and
2. a scattering angle

by incoming and outgoing muon directions for each event.

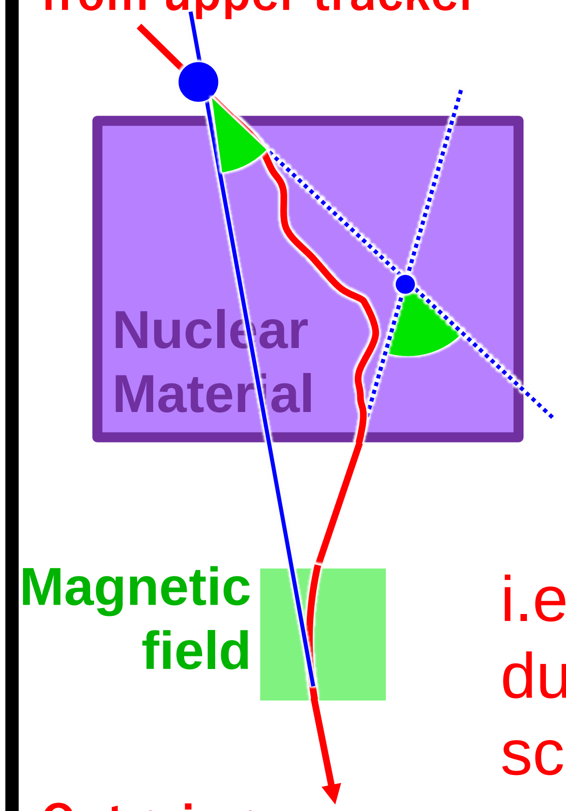
■ Effect of magnetic field on muography images

Absorption



Muography images are distorted and vanished by deflection and reflection of muon.

Scattering



Magnetic field

displaces the PoCA position

and

shifts the scattering angles

i.e., can be a cause of dummy PoCA position and scattering angle

Cosmic-Ray Simulations in PHITS

PHITS
Particle and Heavy Ion Transport code System

Made in Japan (JAEA)

Capable of transporting nearly all particles over wide energy range using Monte Carlo method

- The code and the license is available for **free** upon your request.

  https://phits.jaea.go.jp/howtoget.html

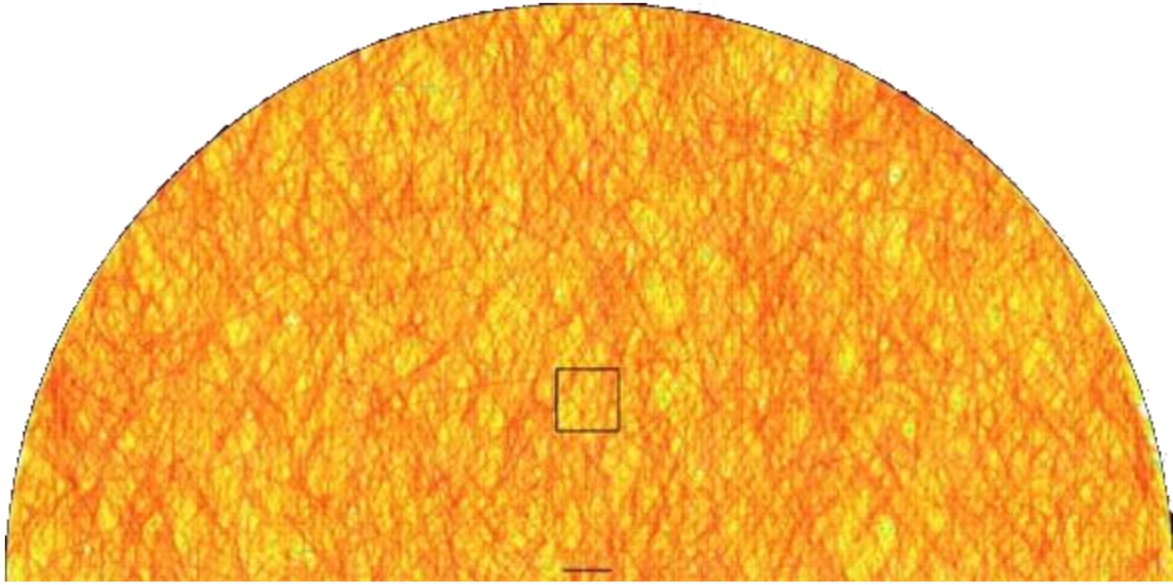
- There are free online tutorials, and you can invite them for face-to-face tutorials.

Cosmic-Ray Simulations in PHITS

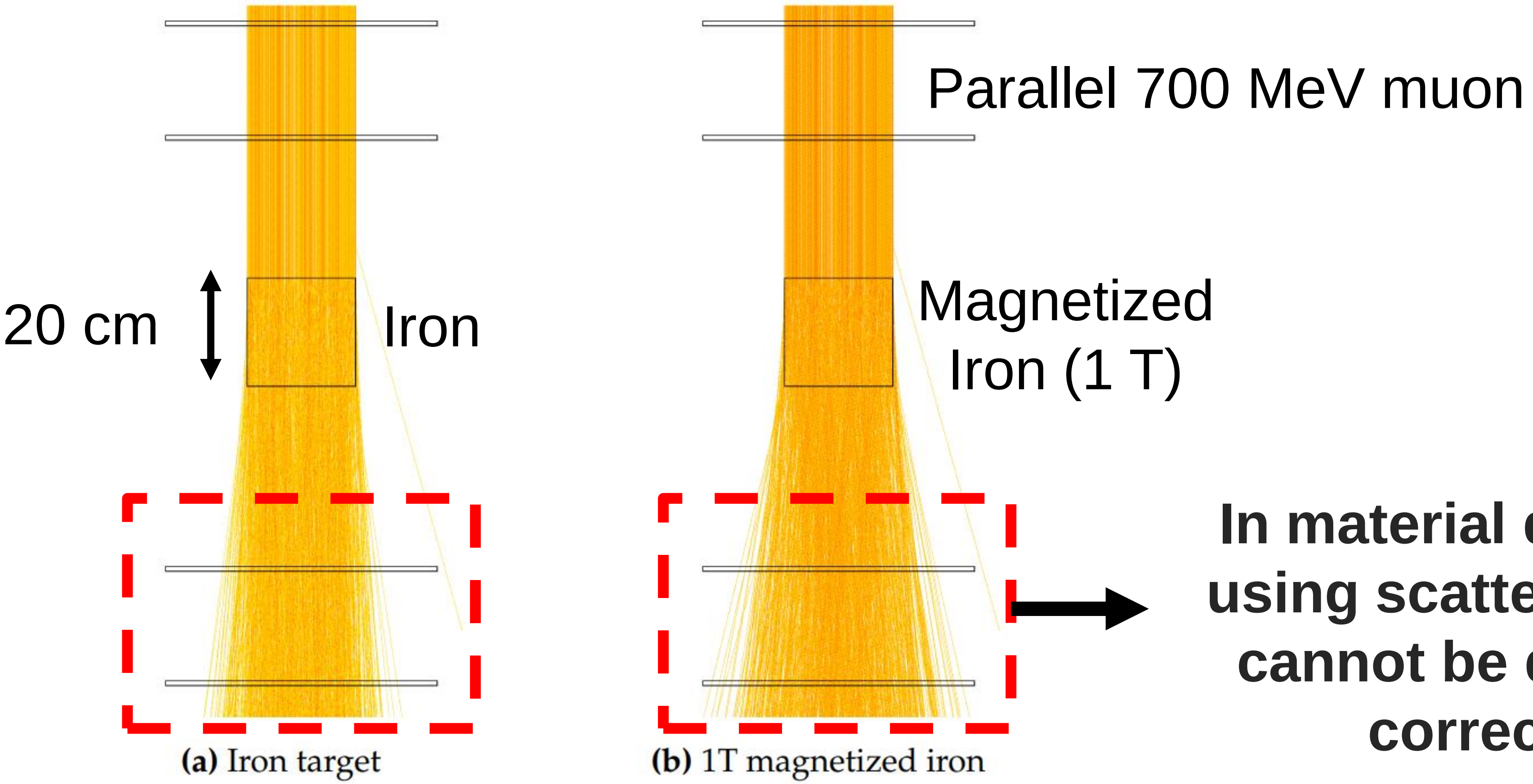
PHITS
Particle and Heavy Ion Transport code System

- **PARMA model** (An analytical model) has been implemented for simulation of cosmic-ray.

- Parameters such as **Altitude**, **latitude, date and the radius of hemisphere** can be inputted.



Effect of magnet on scattering angle distribution



In material detection using scattering, iron cannot be detected correctly!

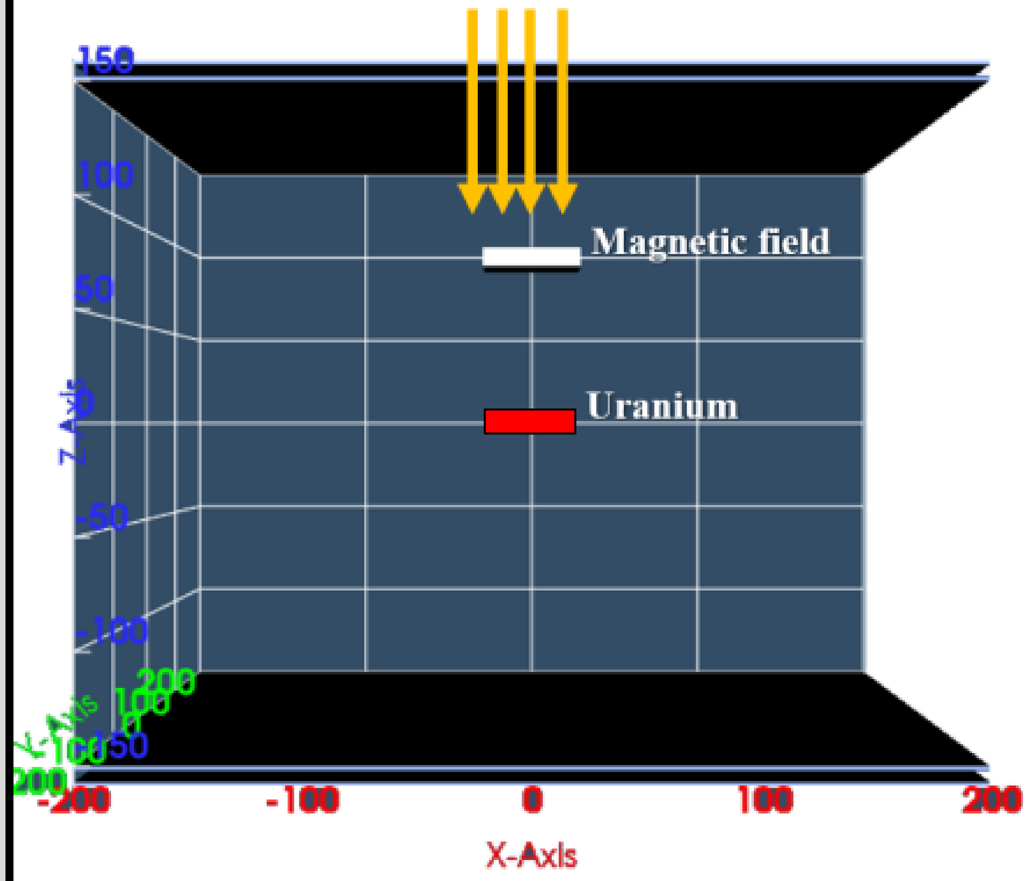
Scattering
(θ_{RMS} 4.55°)

Scattering & Deflection
(θ_{RMS} 6.14°)

Effect of magnet on PoCA points

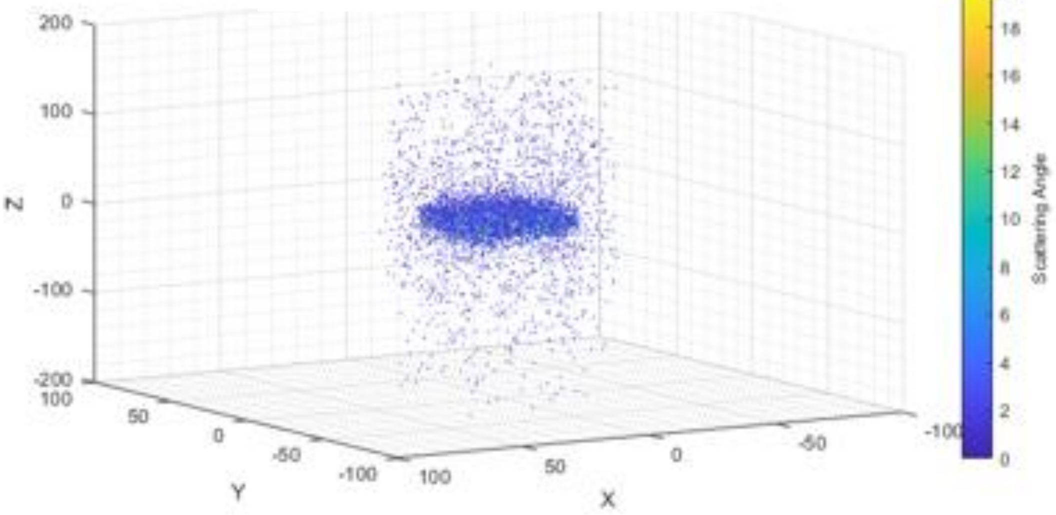
- A parallel beam of positive and negative muons was projected onto a uranium target.
- **Detectors:**
  - plastic scintillators of 2m x 2m x 2mm.
- **Magnetic field region:** 50cm x 50cm x 10cm.
- **Uranium target size:** 40cm x 40cm x 10cm.

10 cm of magnet in X-Y plane is not covered by uranium target!

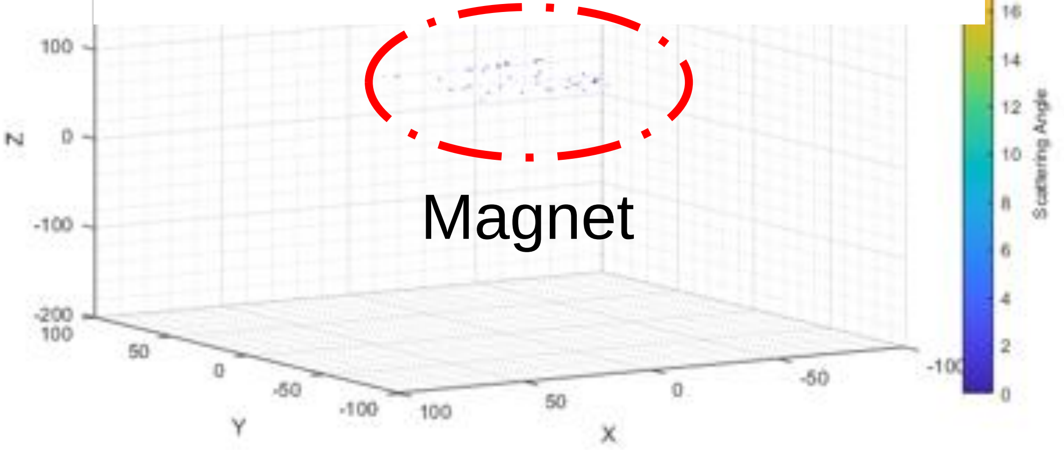


Magnet OFF

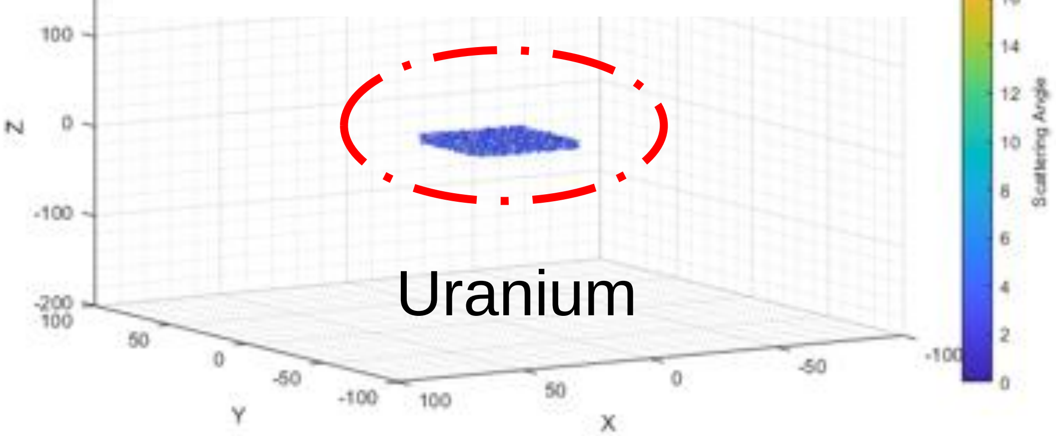
All PoCA Points



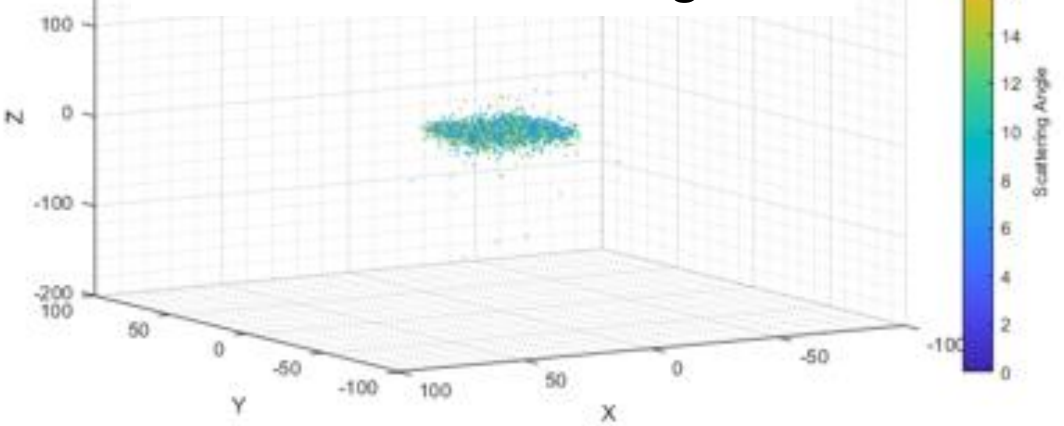
Ratio of points inside magnet: 0.002



Ratio of points inside target: 0.56

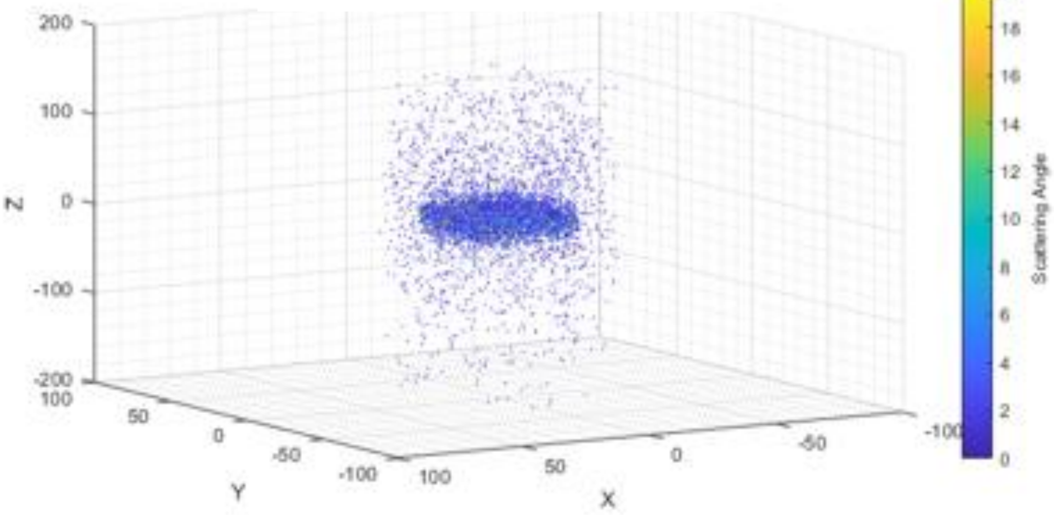


PoCA Points limited by scattering angle threshold of 5 degree

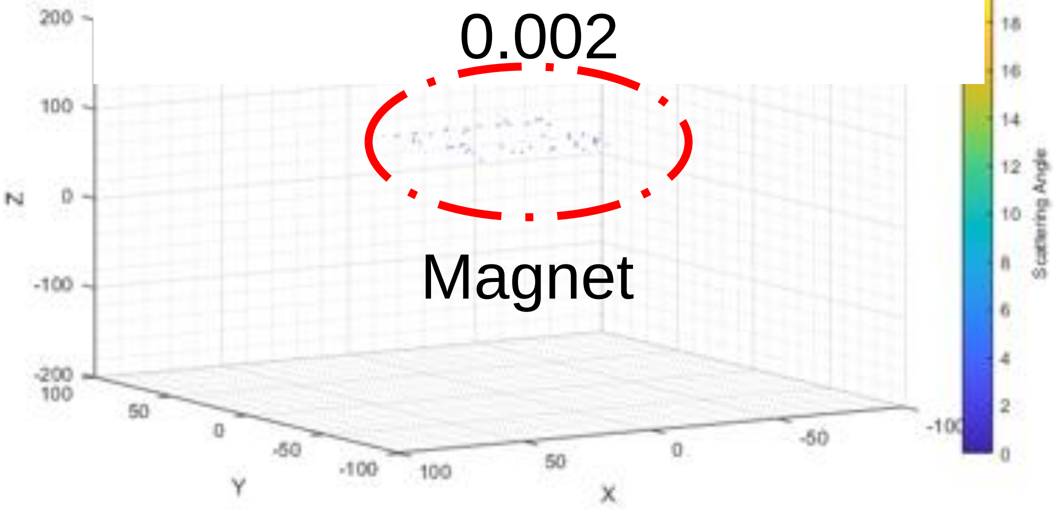


100 mT

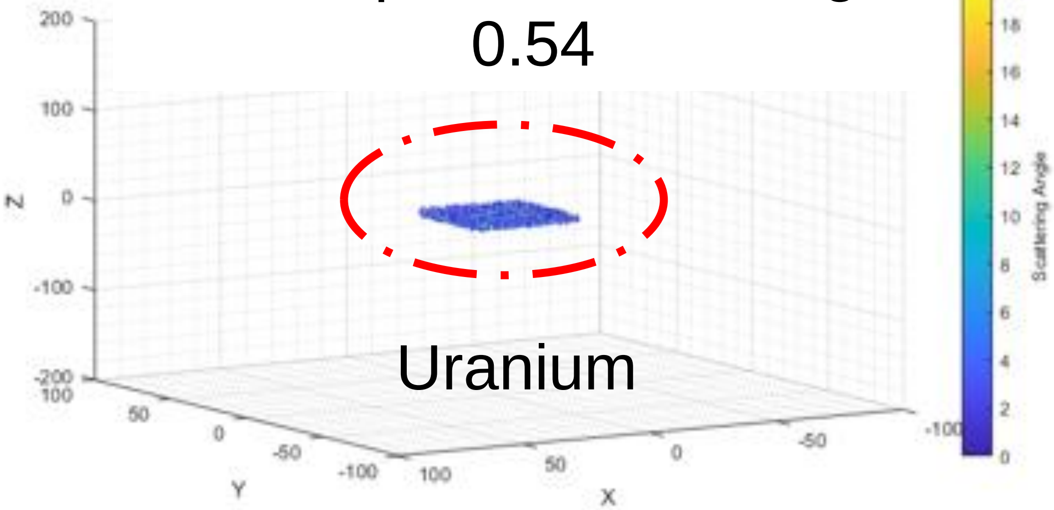
All PoCA Points



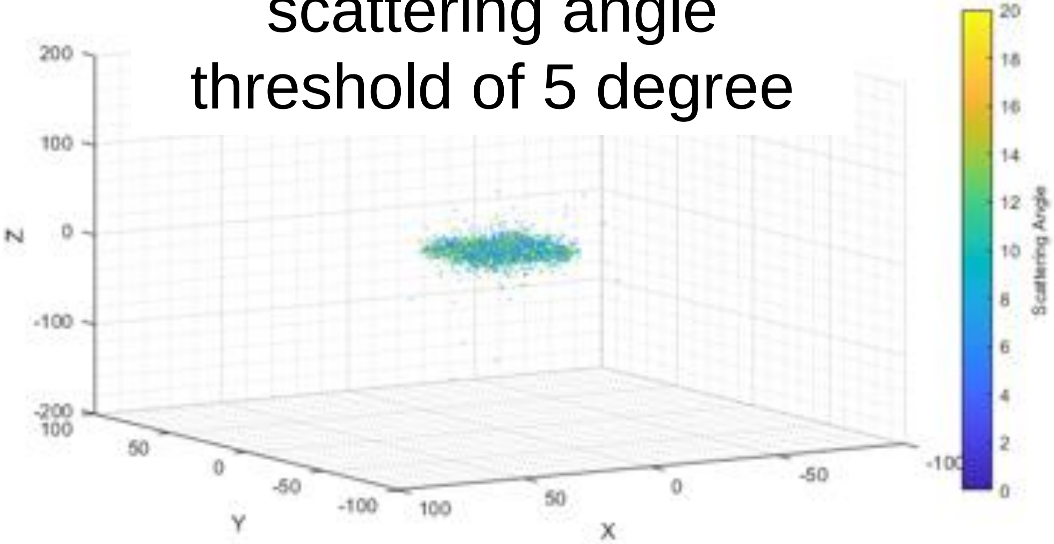
Ratio of points inside magnet: 0.002



Ratio of points inside target: 0.54

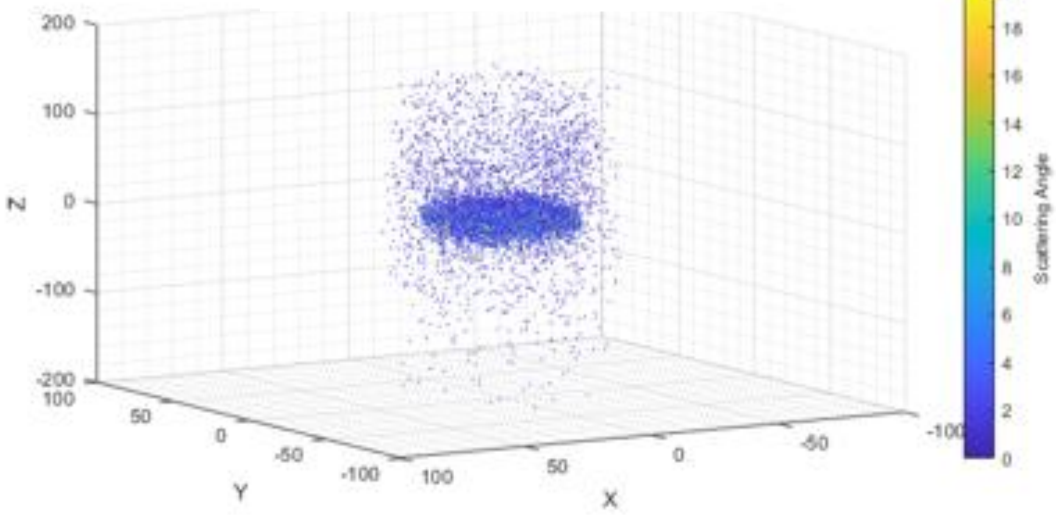


PoCA Points limited by scattering angle threshold of 5 degree

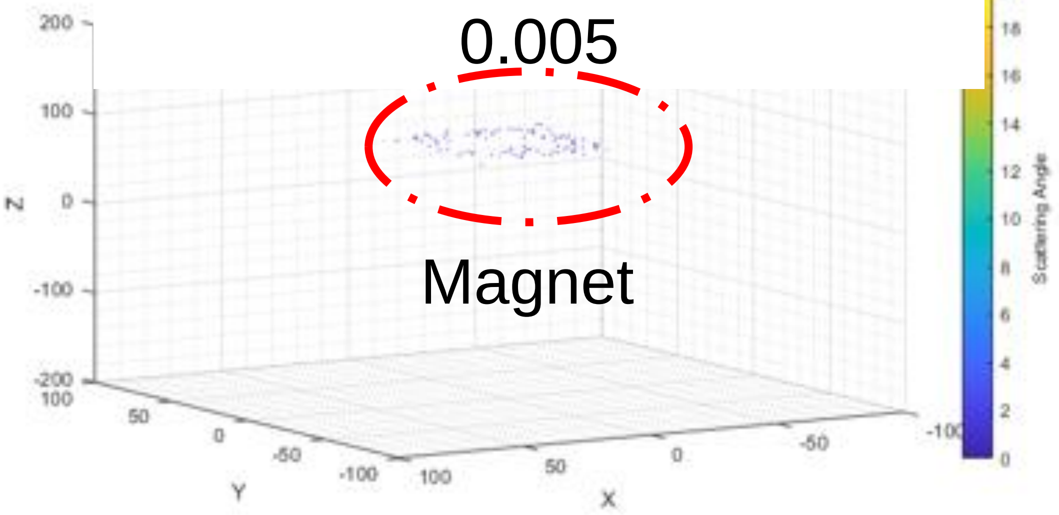


200 mT

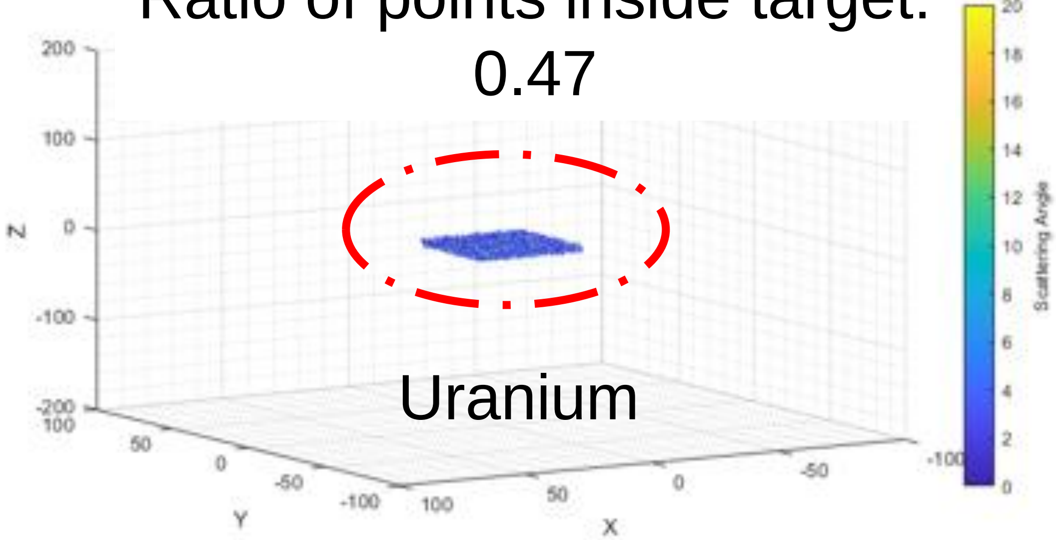
All PoCA Points



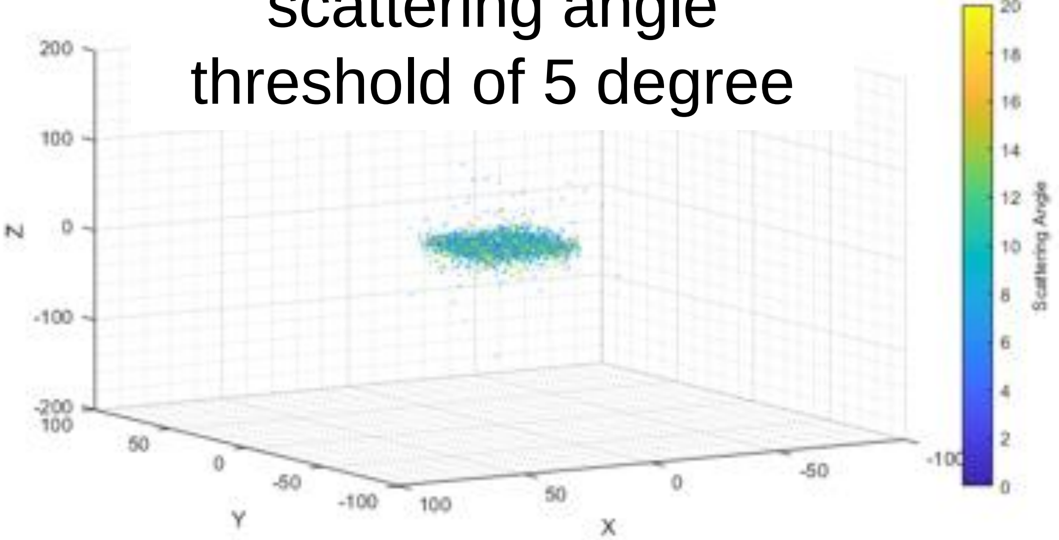
Ratio of points inside magnet: 0.005



Ratio of points inside target: 0.47

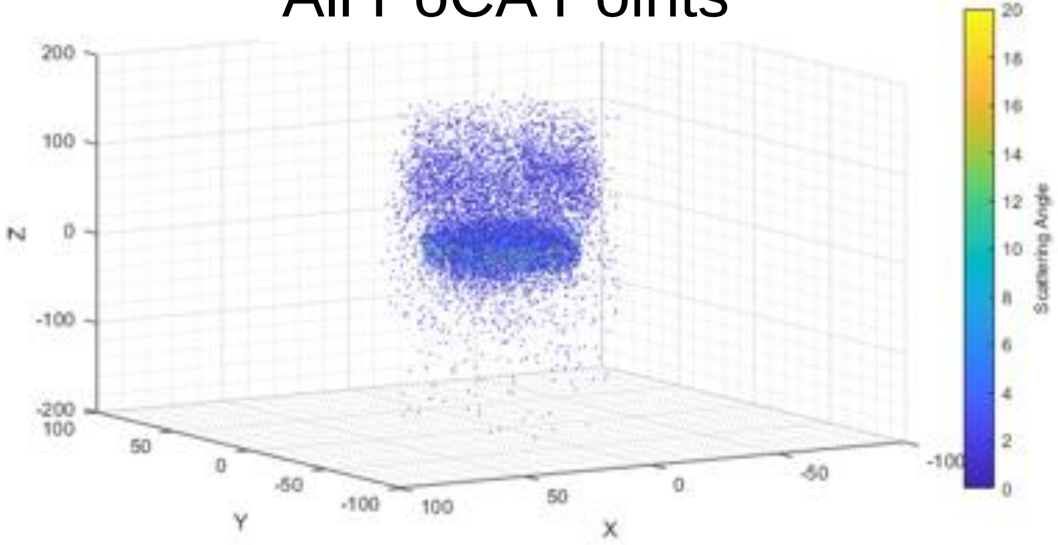


PoCA Points limited by scattering angle threshold of 5 degree

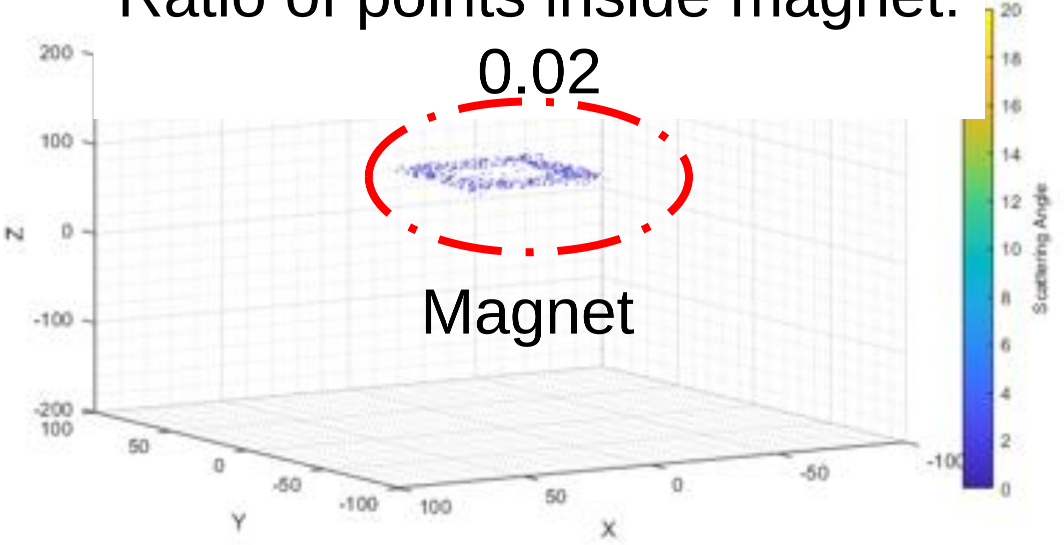


500 mT

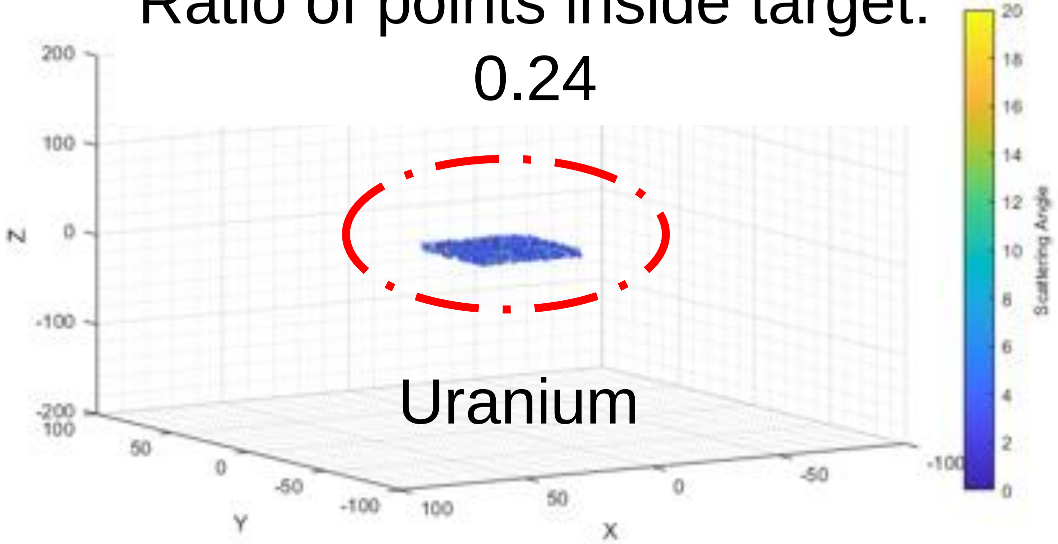
All PoCA Points



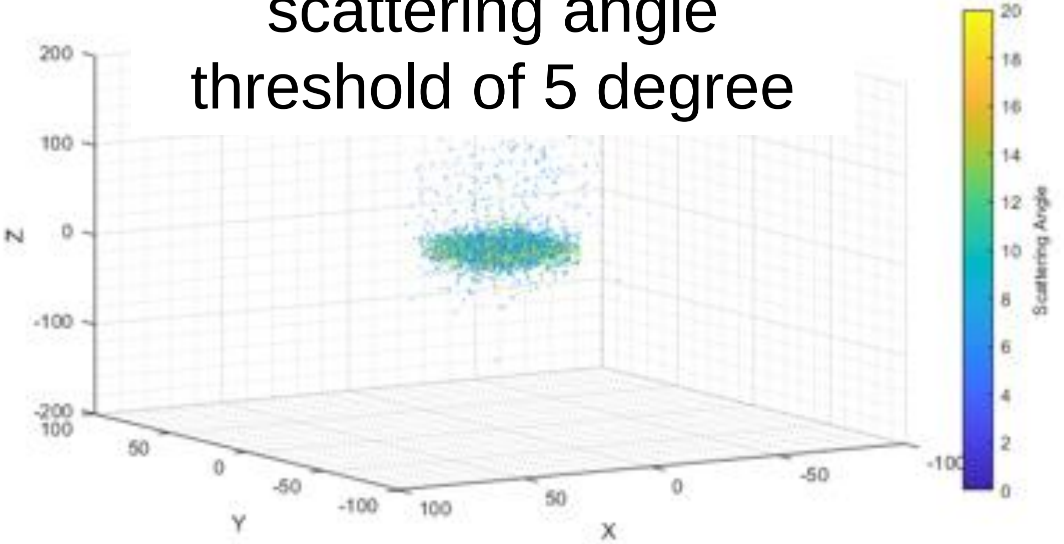
Ratio of points inside magnet: 0.02



Ratio of points inside target: 0.24

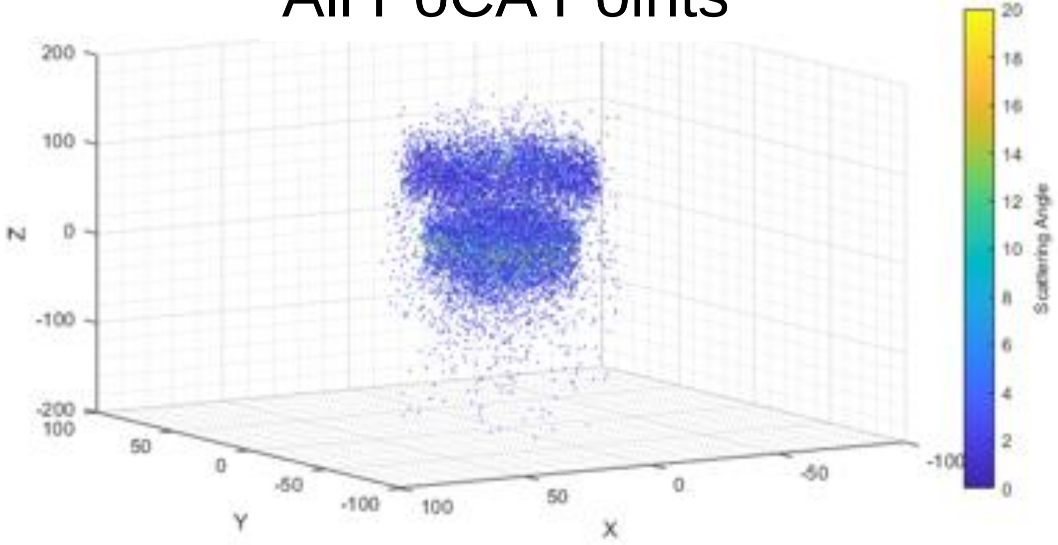


PoCA Points limited by scattering angle threshold of 5 degree

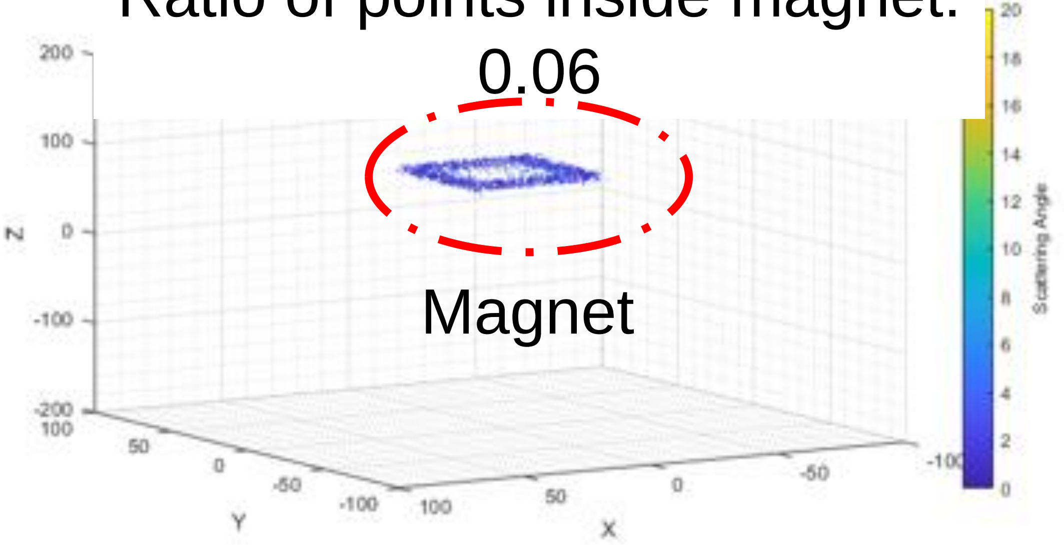


1 T

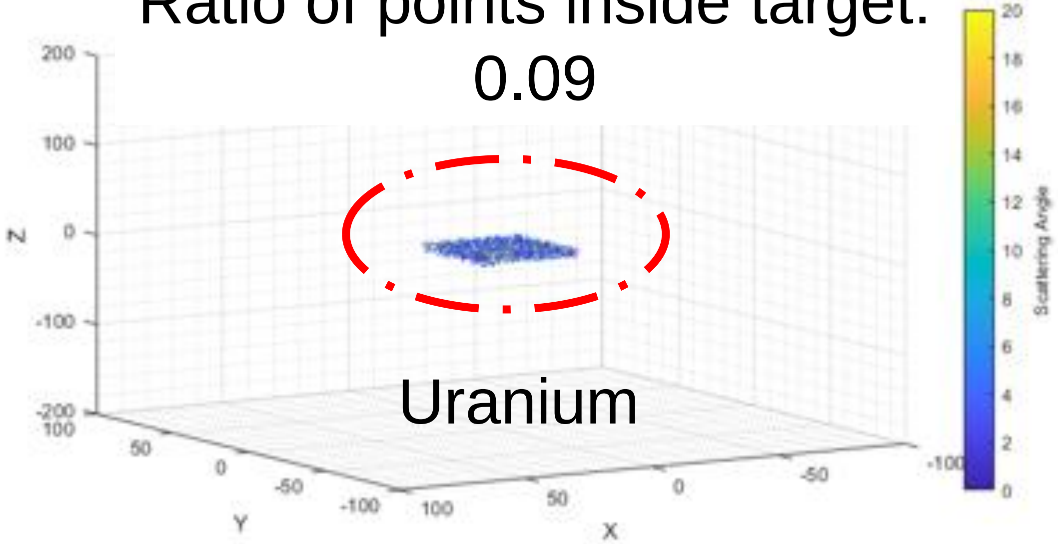
All PoCA Points



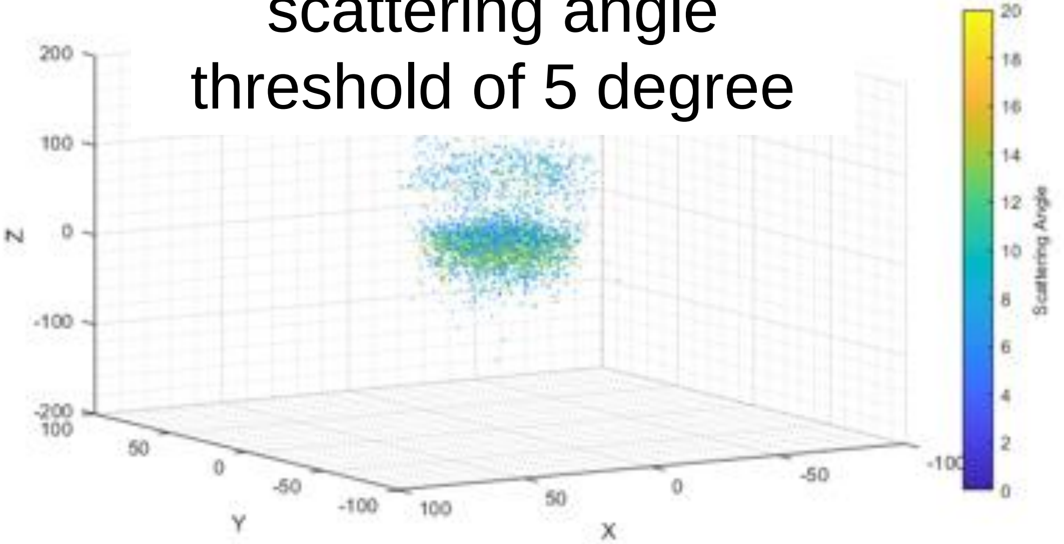
Ratio of points inside magnet: 0.06



Ratio of points inside target: 0.09



PoCA Points limited by scattering angle threshold of 5 degree



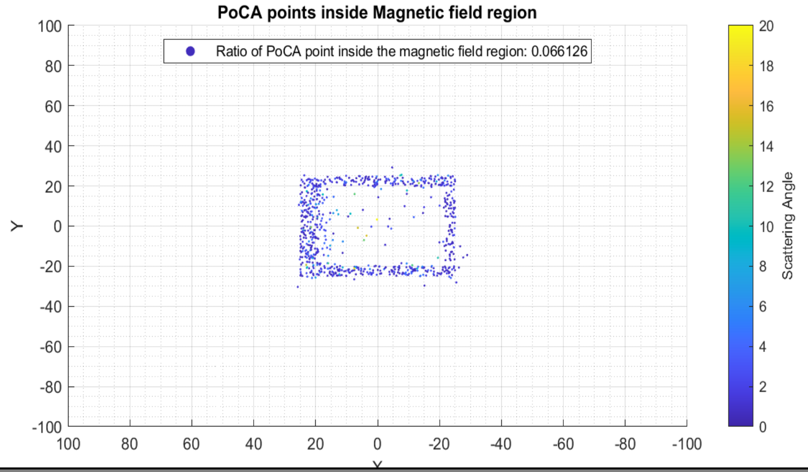
Muon Charge Identification

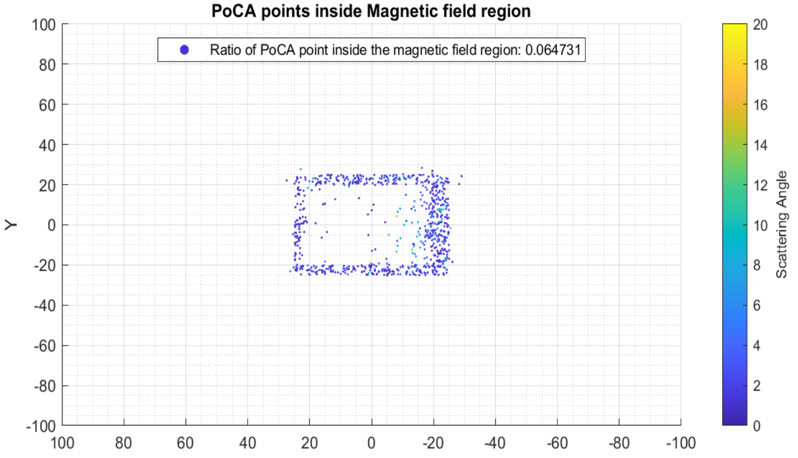
If we use the charge identification feature in our detector, we can find direction of magnetic field:

Mu+

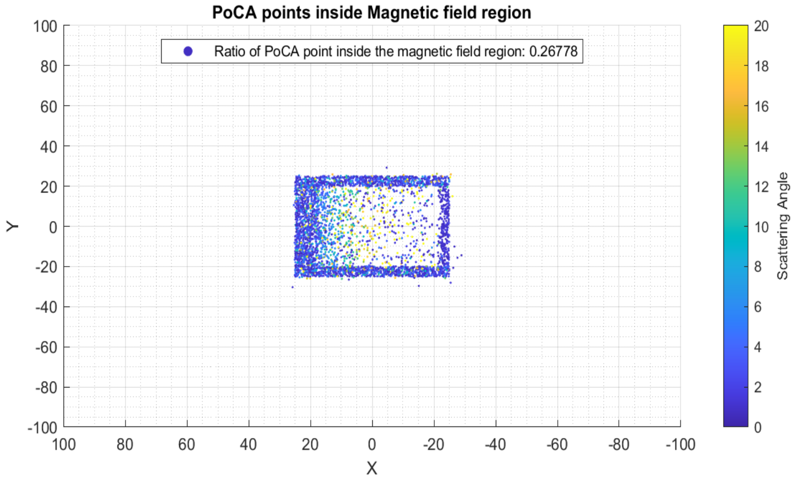
Mu-

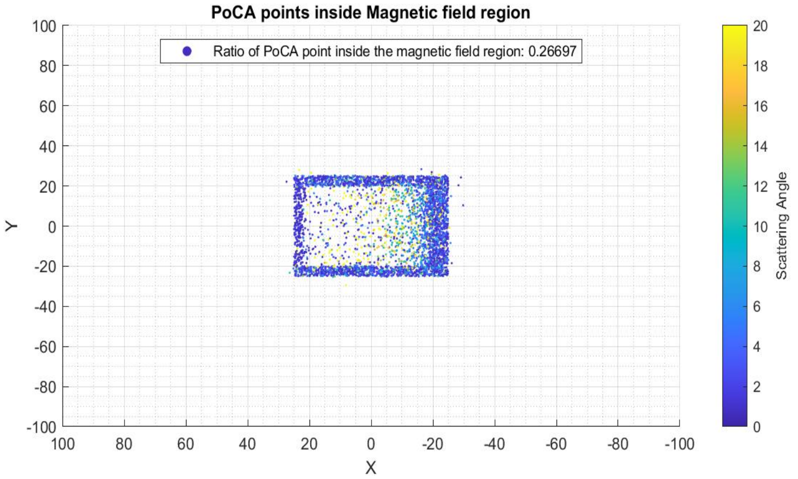
1 T



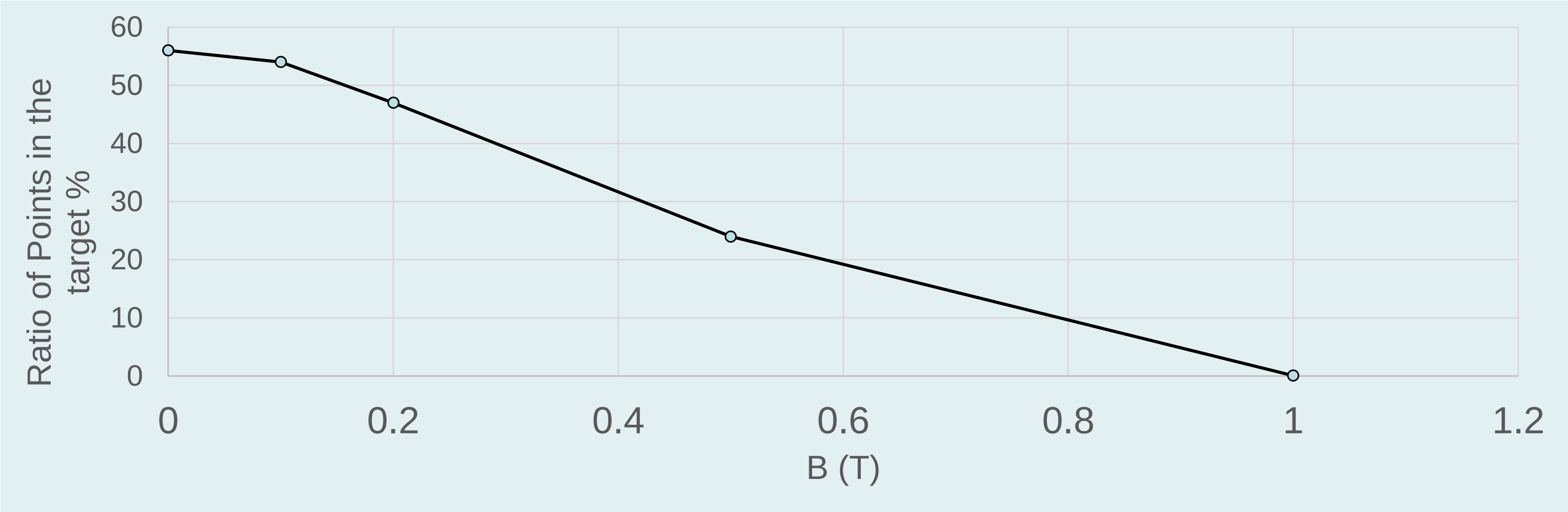


3 T





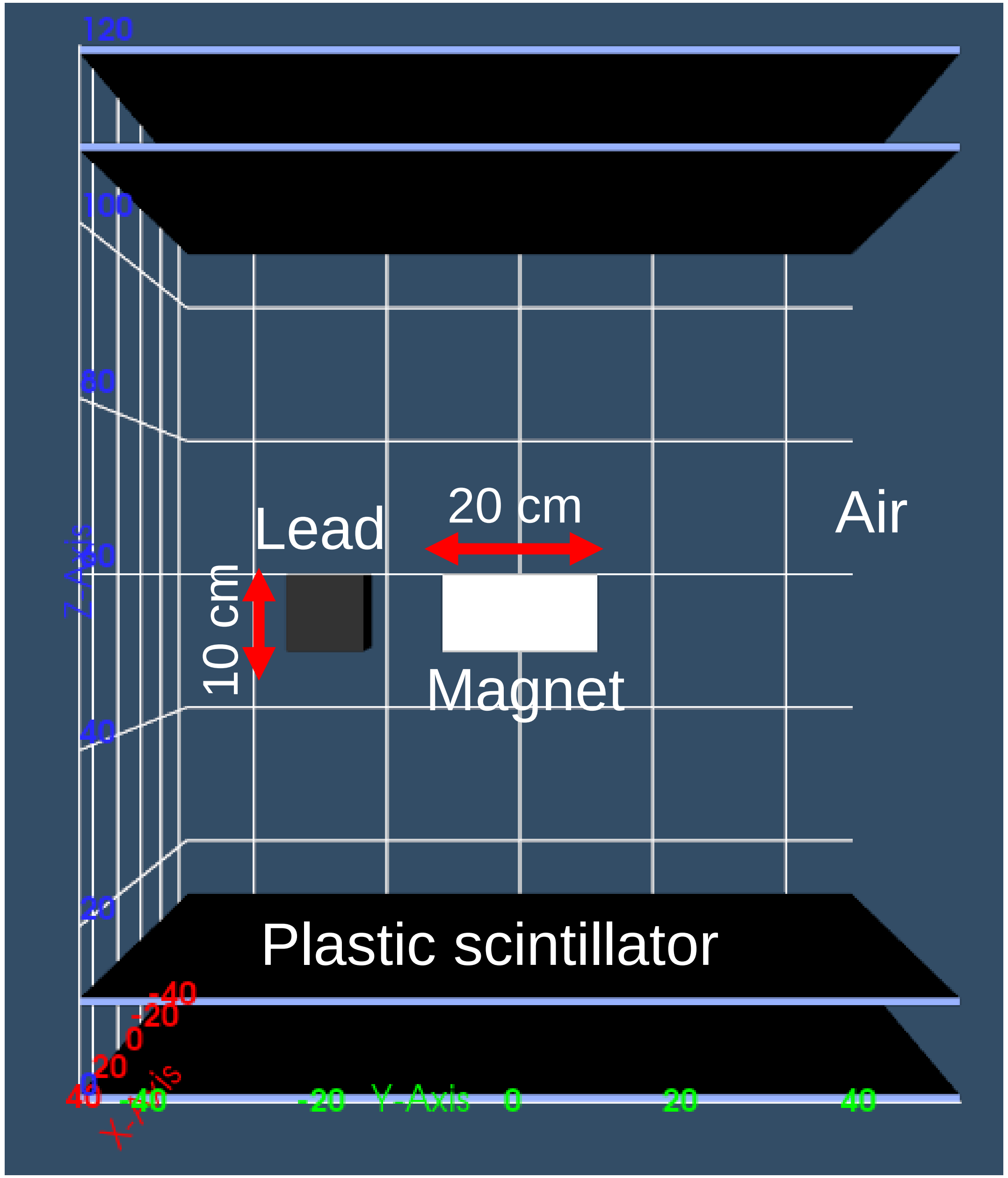
PoCA analysis can be used to estimate the magnetic field flux density.



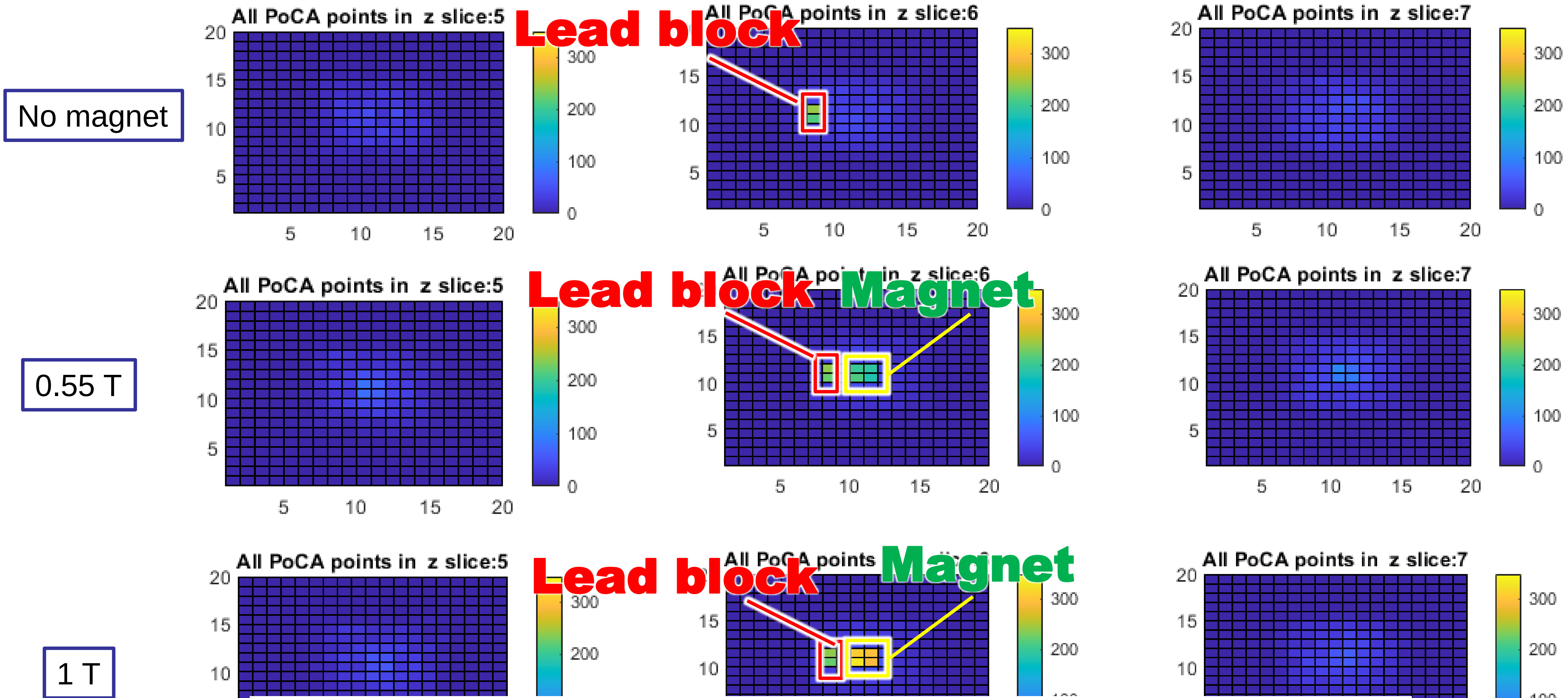
- 1T magnetic field of 10 cm thick cause the ratio of PoCA points inside the **target change from 56% to 9%.**

Magnetic field imaging and magnetic flux estimation using PoCA points

- PARMA Source
- Measurement time: one hour
- Voxel size: 10 cm x 10 cm x 10 cm



Simulation of Magnetic Flux Density Estimation Through PoCA Point Analysis

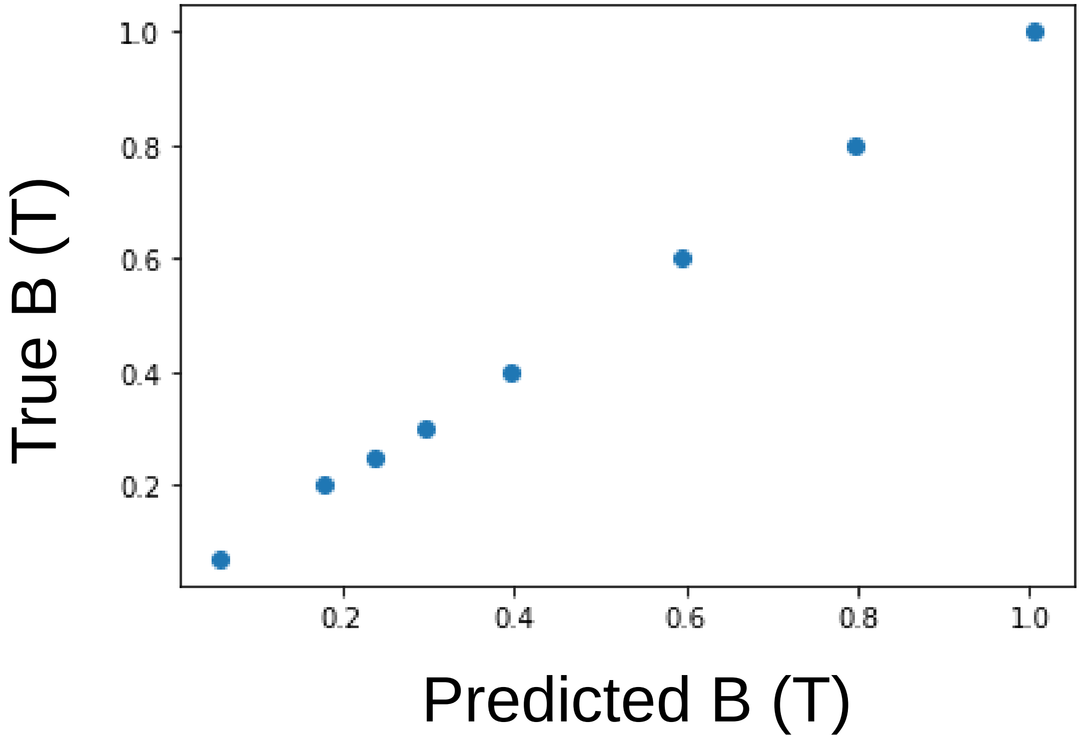


Color represent number of PoCA points per voxel and it can show the strength of magnetic field

Magnetic field estimation using POCA points

We repeat the simulations with many magnetic field flux densities and extracted some features of PoCA points based on the position of points.

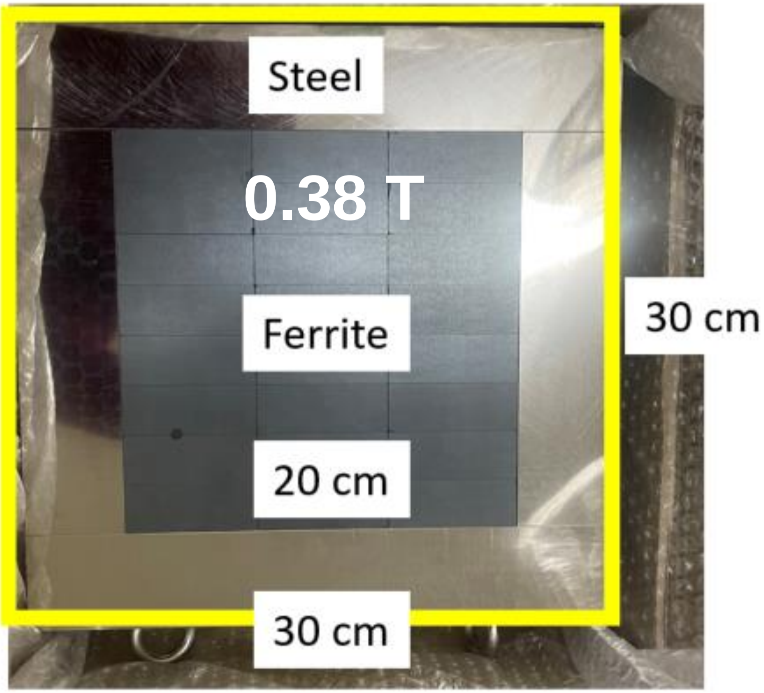
Results showed that using ***linear regression*** (ordinary least squares) magnetic field can be estimated with a Mean absolute percentage error of 4.1% for magnetic fields within (0.1 T to 1 T).



Future work

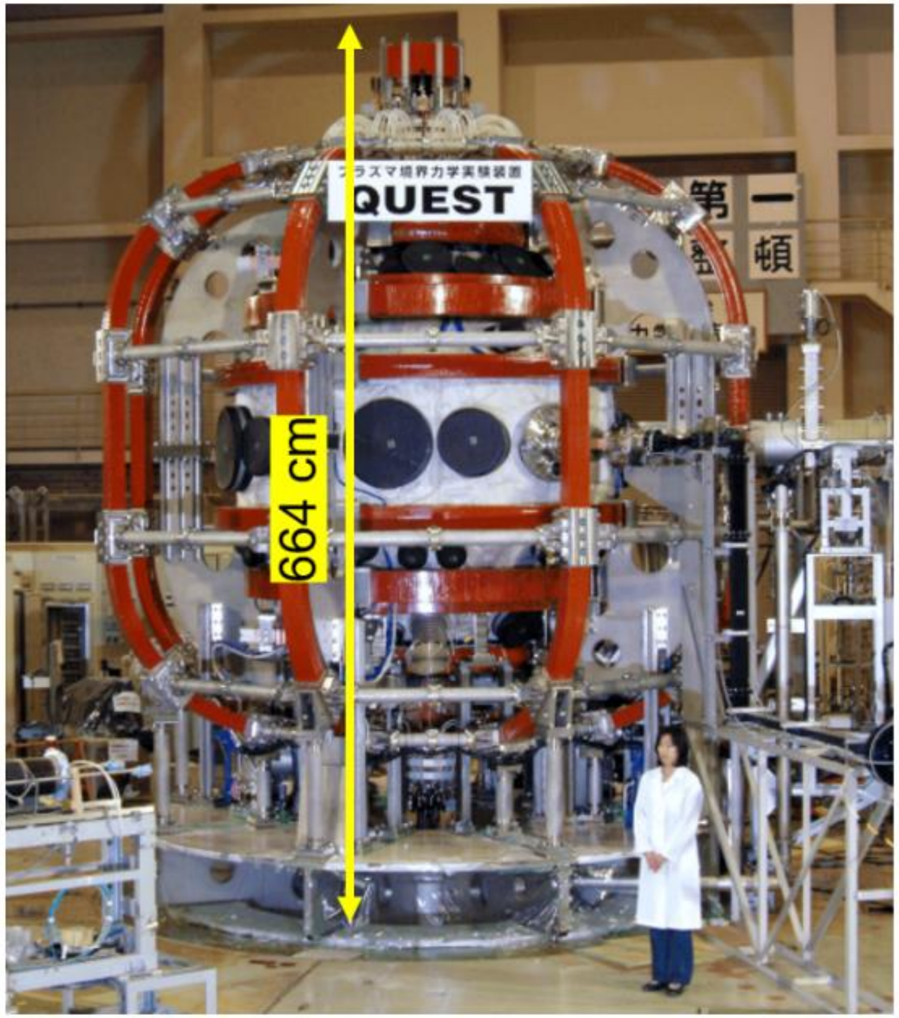
Targets to be measured

For scattering muography



Magnetized ferrite
vs.
Non-magnetized ferrite

For absorption muography



Spherical Tokamak (QUEST)

Summary

1. Preliminary simulation results showed that cosmic-ray muons have a **potential** to be used for magnetic field imaging.

2. Magnetic fields may have an impact on the **scattering angle distribution** and **imaging** using cosmic-ray muons and this may cause difficulties in material detection!

Thank you for your attention!

Any feedback, comments, or questions are welcomed!

Please feel free to reach us at:

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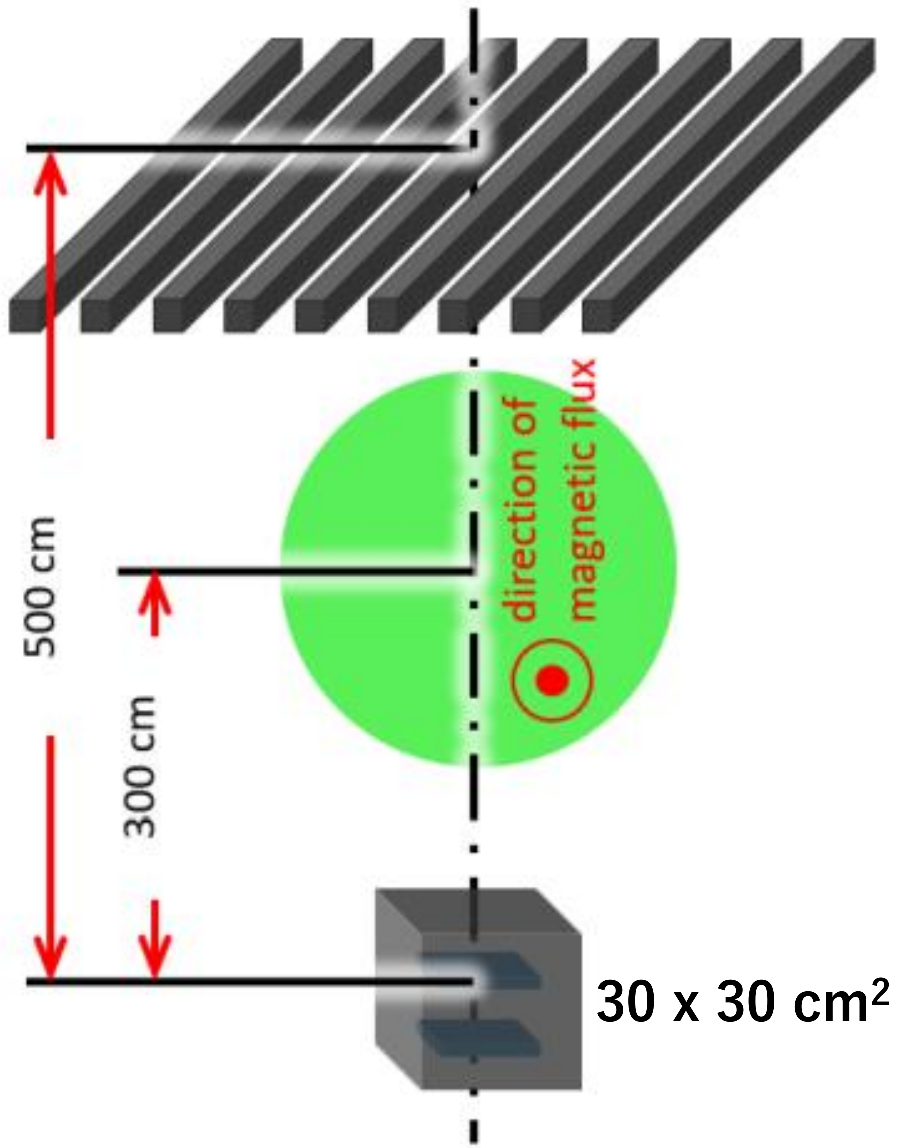
Simulations for Practical Approaches

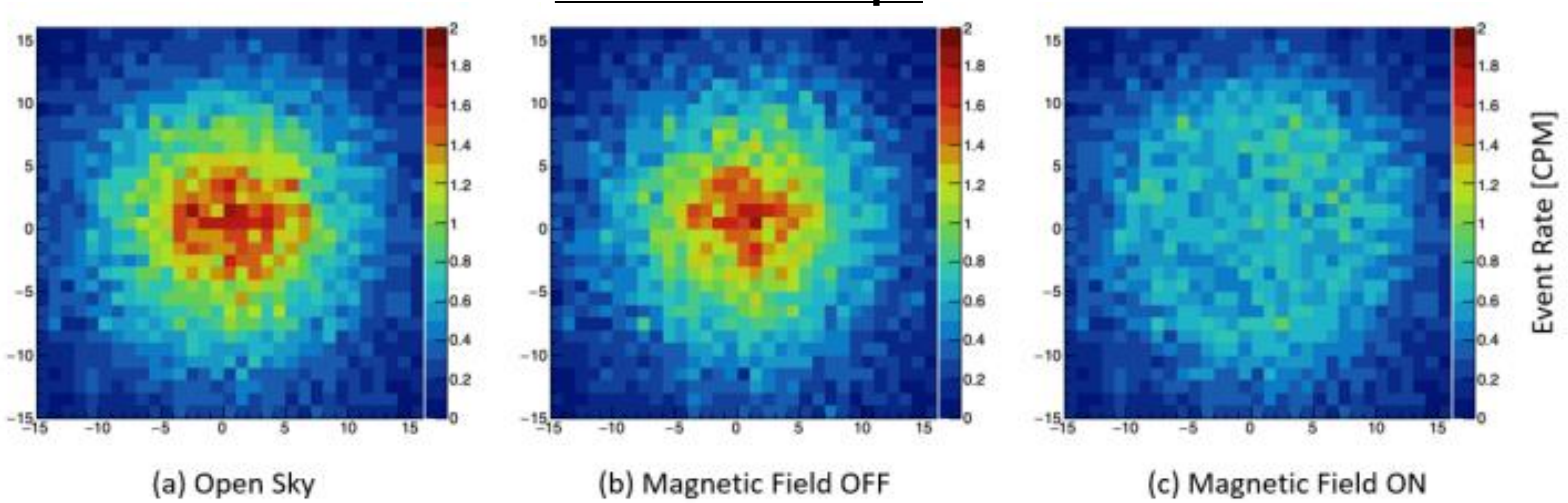
One-hour cosmic-ray muons by PARMA source at Tokyo on Jan. 1, 2020

- **Lead bars: 30 x 30 x 700 cm^3**
- Lead bars placed before the magnetic field to make the background muography image.
- Magnetic field applied is a dipole magnetic field (2T) with a radius of 130 cm spherical shape.

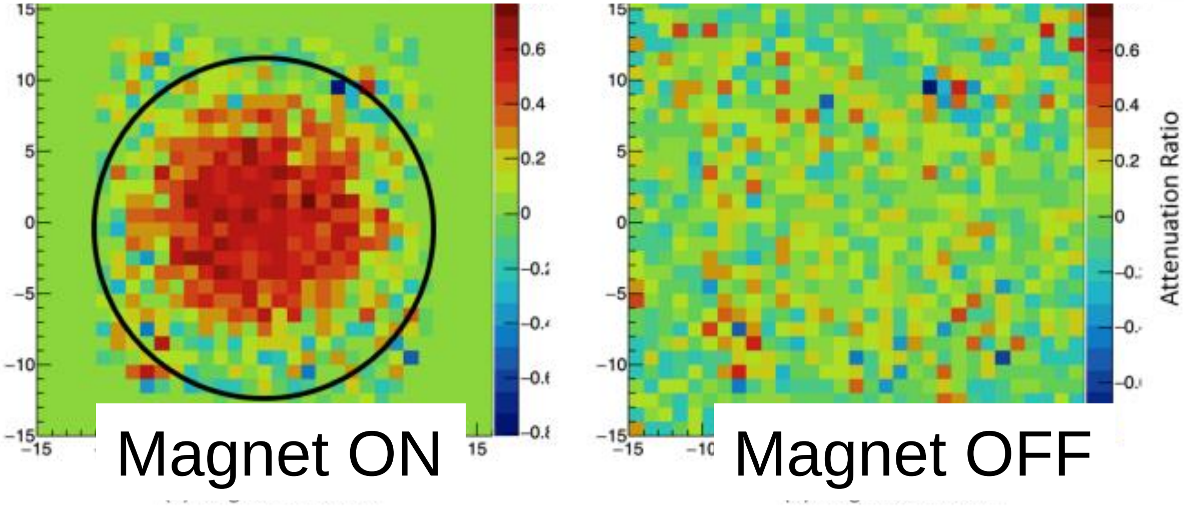


Simulations for Practical Approaches

Count Rate Maps



Attenuation Ratio Maps



Simulations for Practical Approaches

Muons Deflected back estimation using PARMA model and analytical equations

- Using the derived equations and PARMA model, the threshold energy of muons that cannot penetrate a magnetic field of 2T and a thickness of 1.3m is **556 MeV.**

- This threshold corresponds to **13.5% of the total muons**, a significant value given that an absorption of a few percent can provide a muography image using the absorption method.

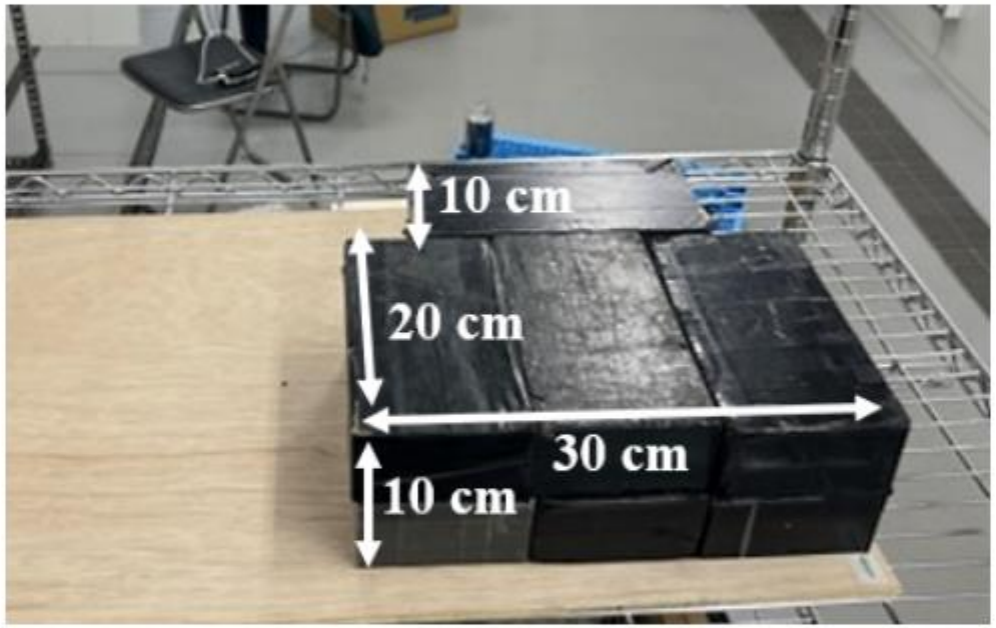
What is the solution?? → Charge identification!

- The key point is that the deflection due to the magnet is not random while multiple scattering is random!
- If images obtained by mu+ and mu- are different there is a magnetic field.

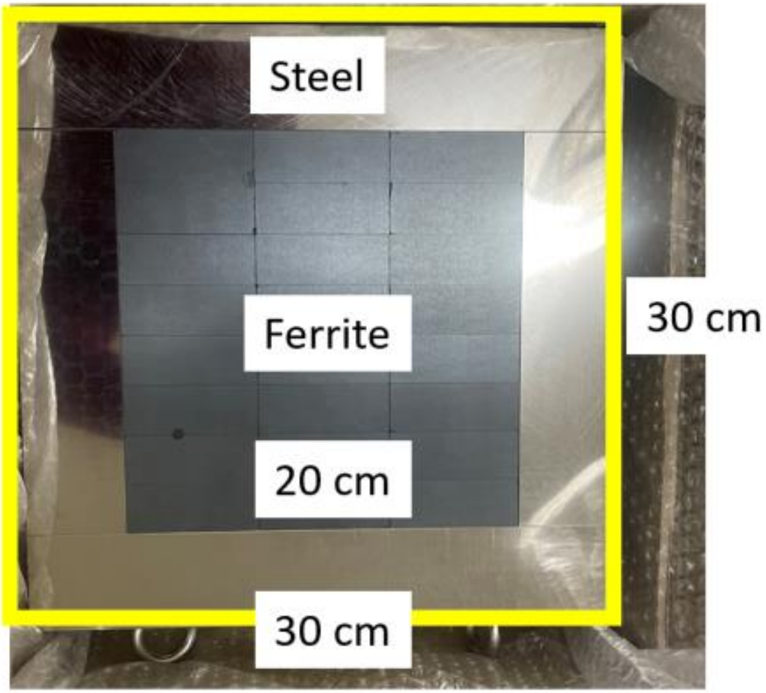
Simulation of Permanent Magnet Measurement

- Experiment designed to validate the magnetic field measurement using cosmic-ray muons considering targets such as electric car motor

- **Ferrite-based magnet**, **non-magnetized ferrite** for comparison and lead blocks to provide background muography image



Lead blocks

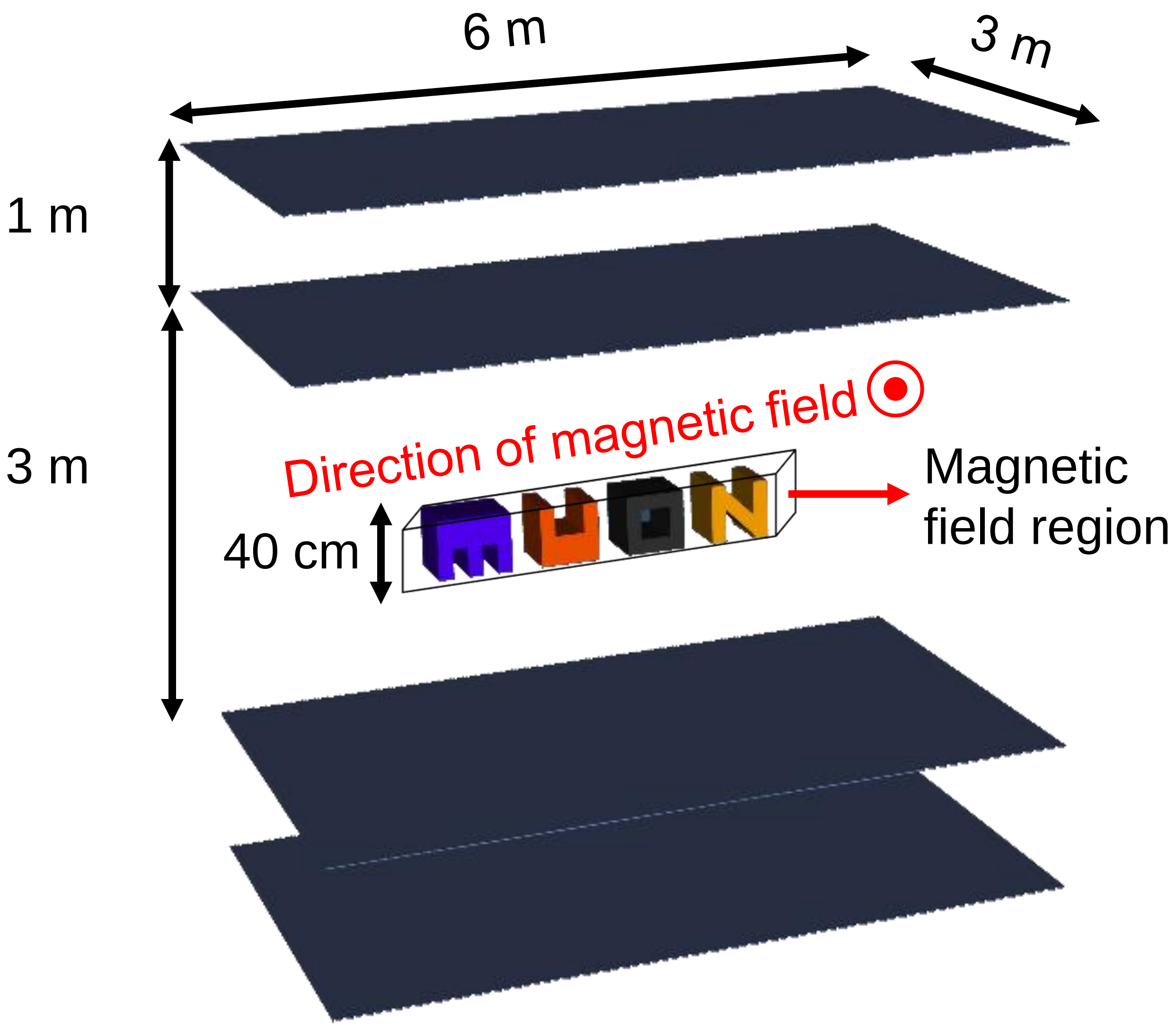


Permanent magnet

Simulation of Muon-based Inspection System for Cargo Investigations

20' Container DC/GP/HD

Image from https://rabinmarine.com/



- **Measurement time:** 13 minutes
- **Source:** PARMA model at Kyushu University Chikushi Campus, January 2020
- Materials:

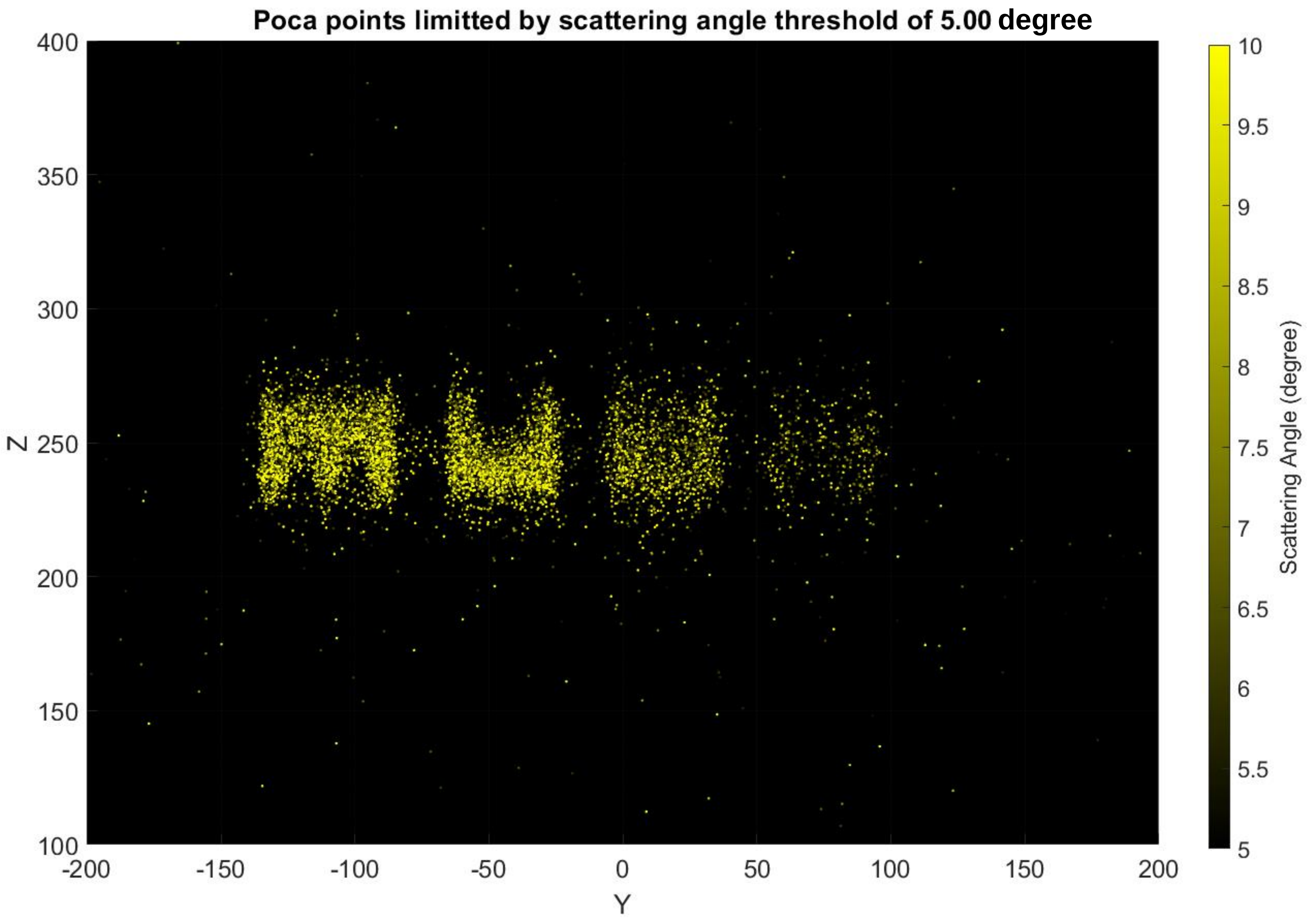
M : *Uranium* **U :** *Lead* **O :** *Iron* **N :** *Aluminum*

Density of the materials are decreasing from left to right!

- Geometry is similar to **"La Rocca, Paola, et al. Journal of Instrumentation 9.01 (2014): C01056"**

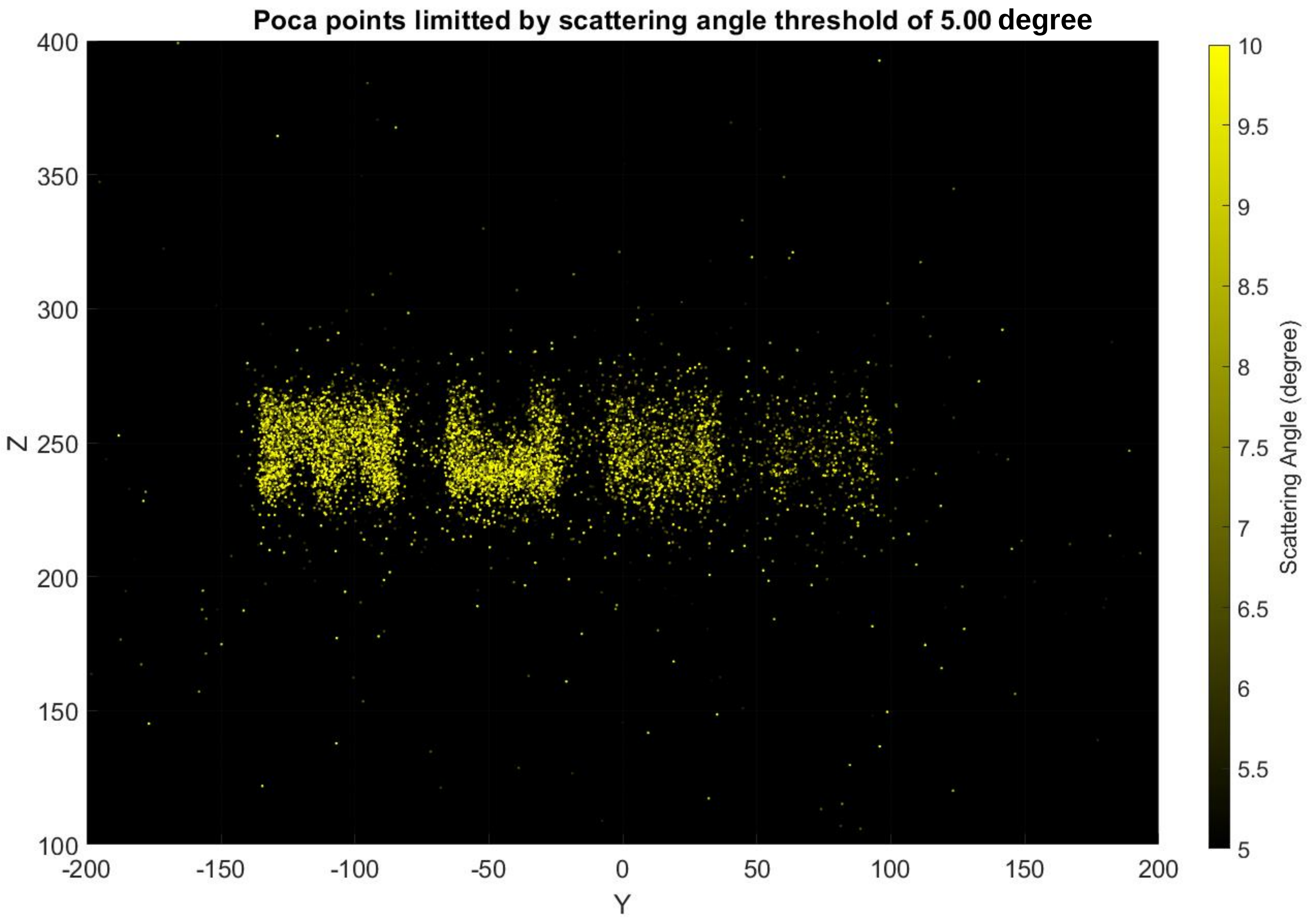
Results of Muon-based Inspection System for Cargo Investigations

No Magnet



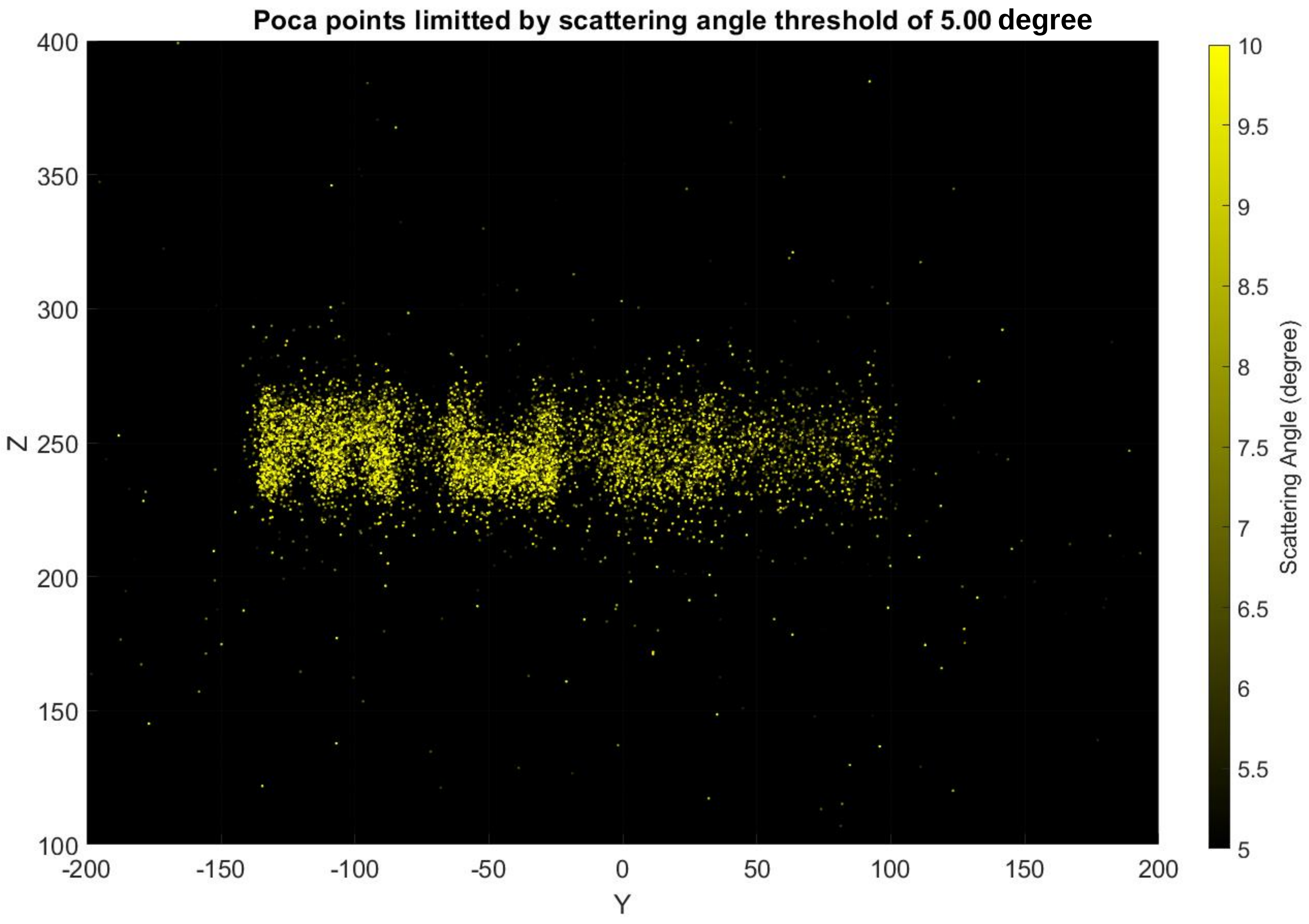
Results of Muon-based Inspection System for Cargo Investigations

100 mT



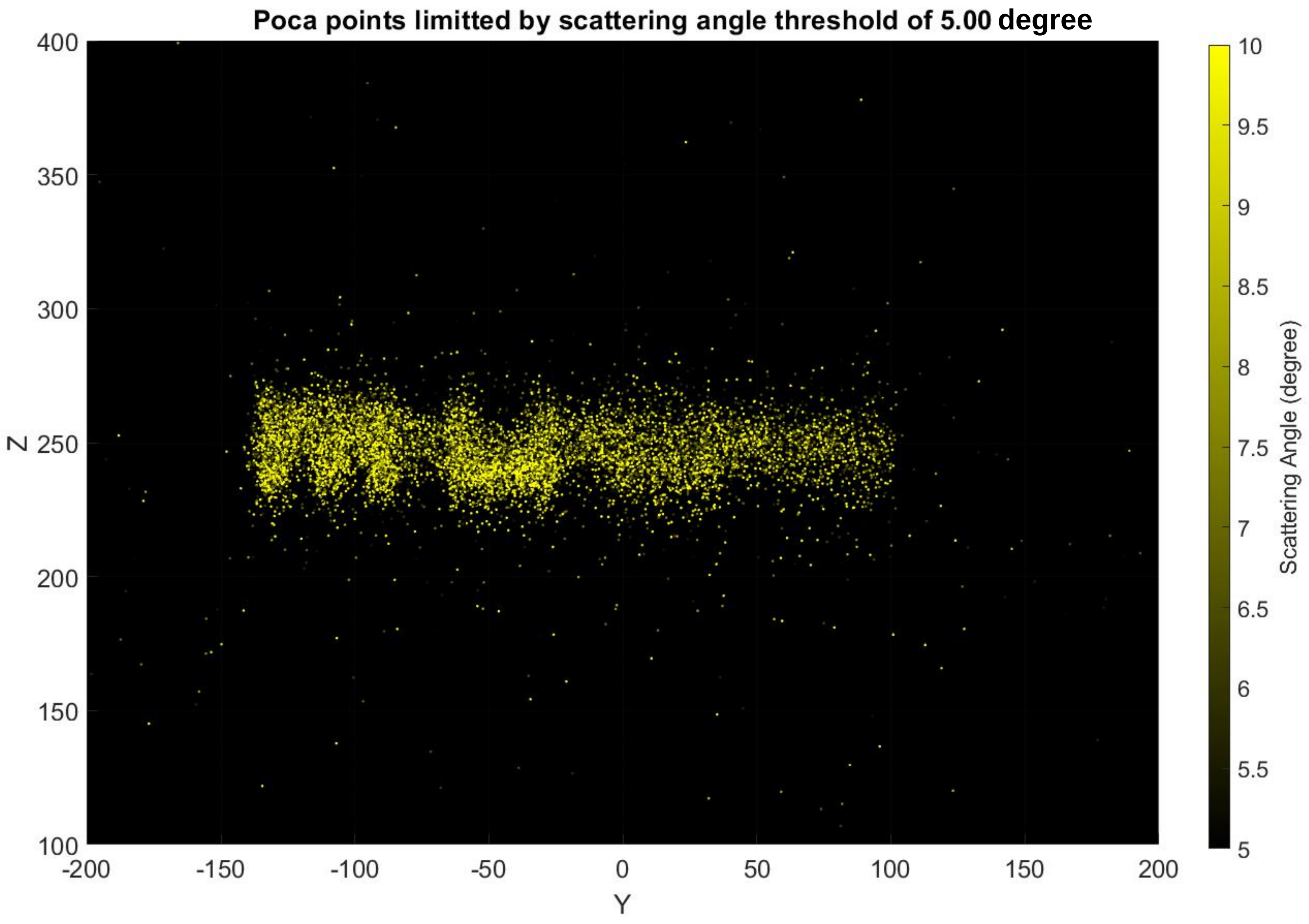
Results of Muon-based Inspection System for Cargo Investigations

200 mT



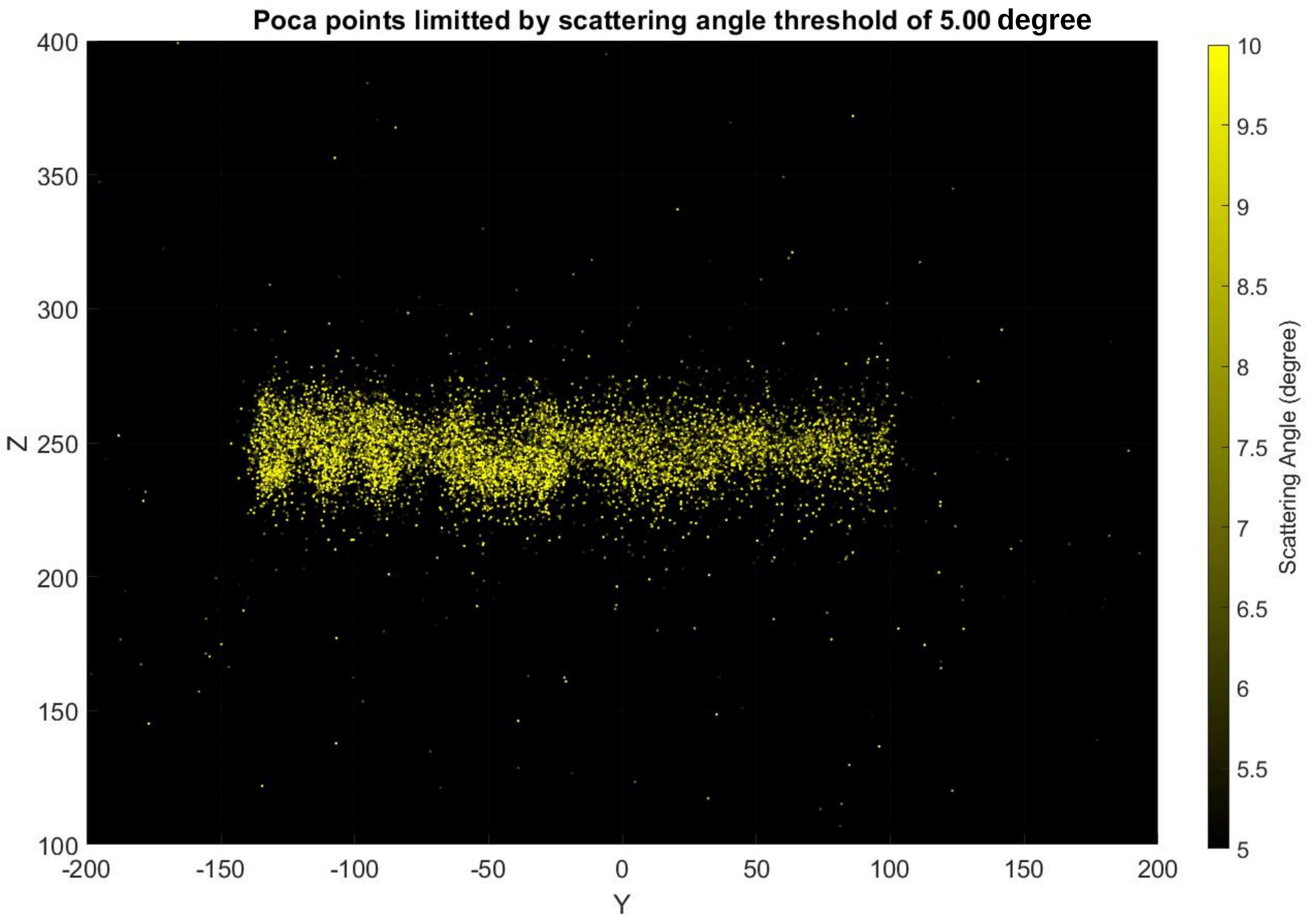
Results of Muon-based Inspection System for Cargo Investigations

300 mT



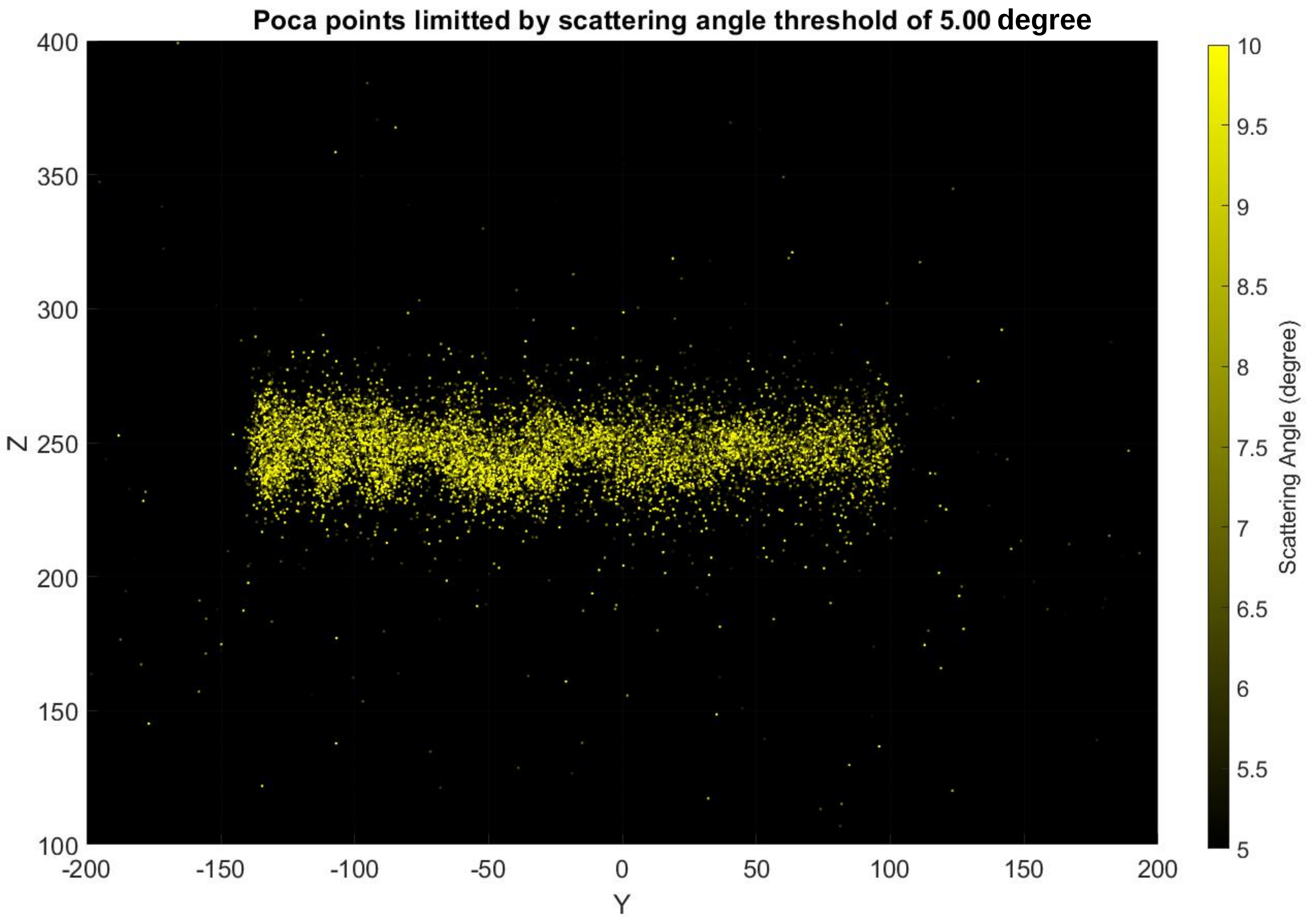
Results of Muon-based Inspection System for Cargo Investigations

400 mT



Results of Muon-based Inspection System for Cargo Investigations

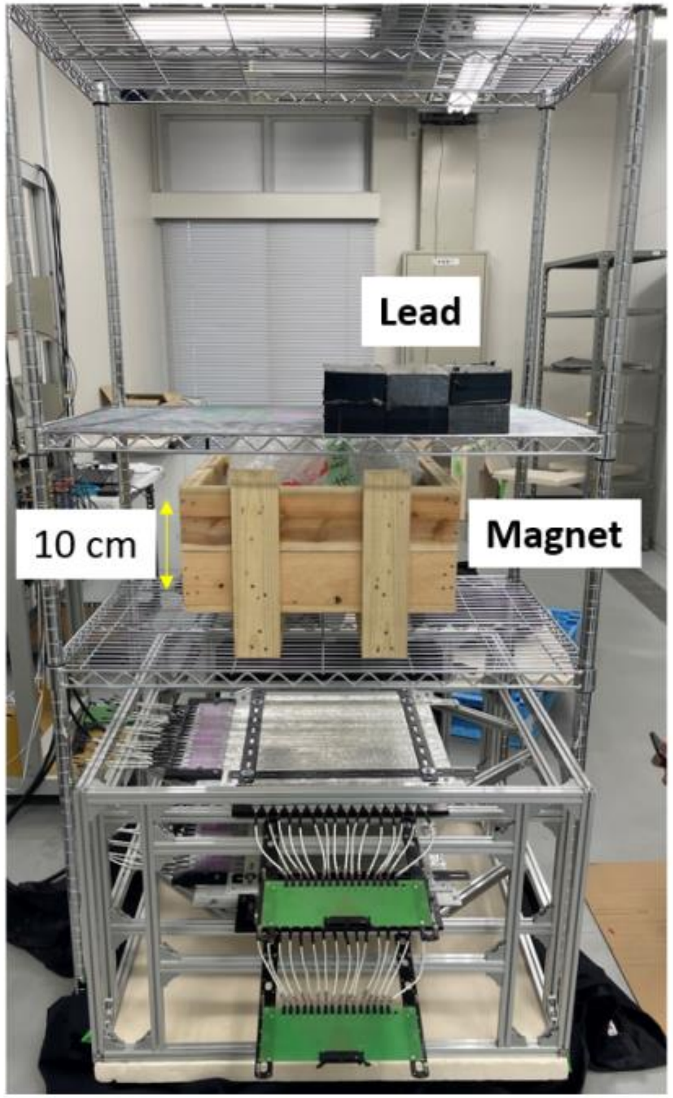
500 mT



Simulation of Permanent Magnet Measurement

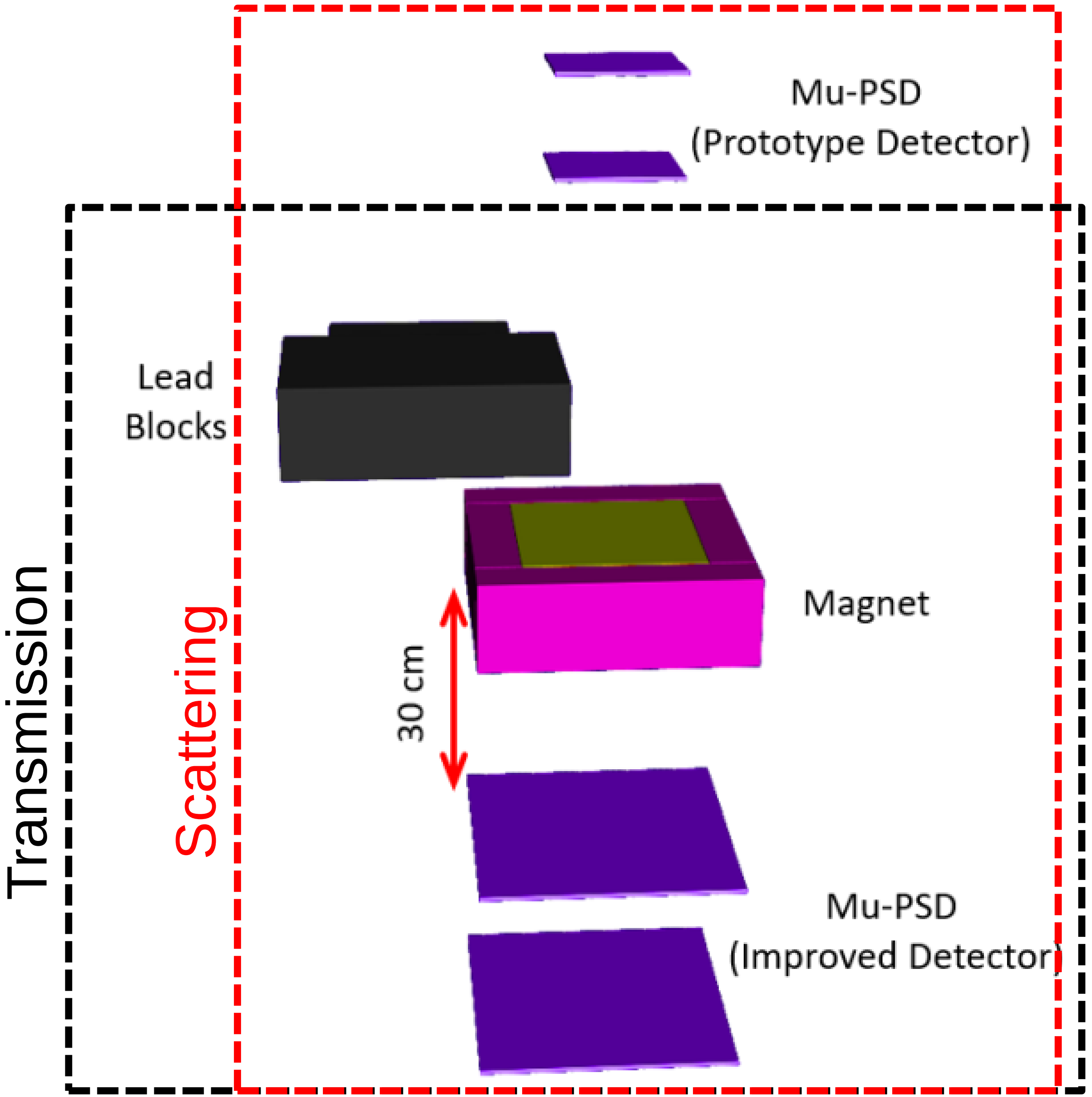
- Two-mode experiment to gather data on muon trajectories through targets.

  - Absorption muography
  - Scattering muography



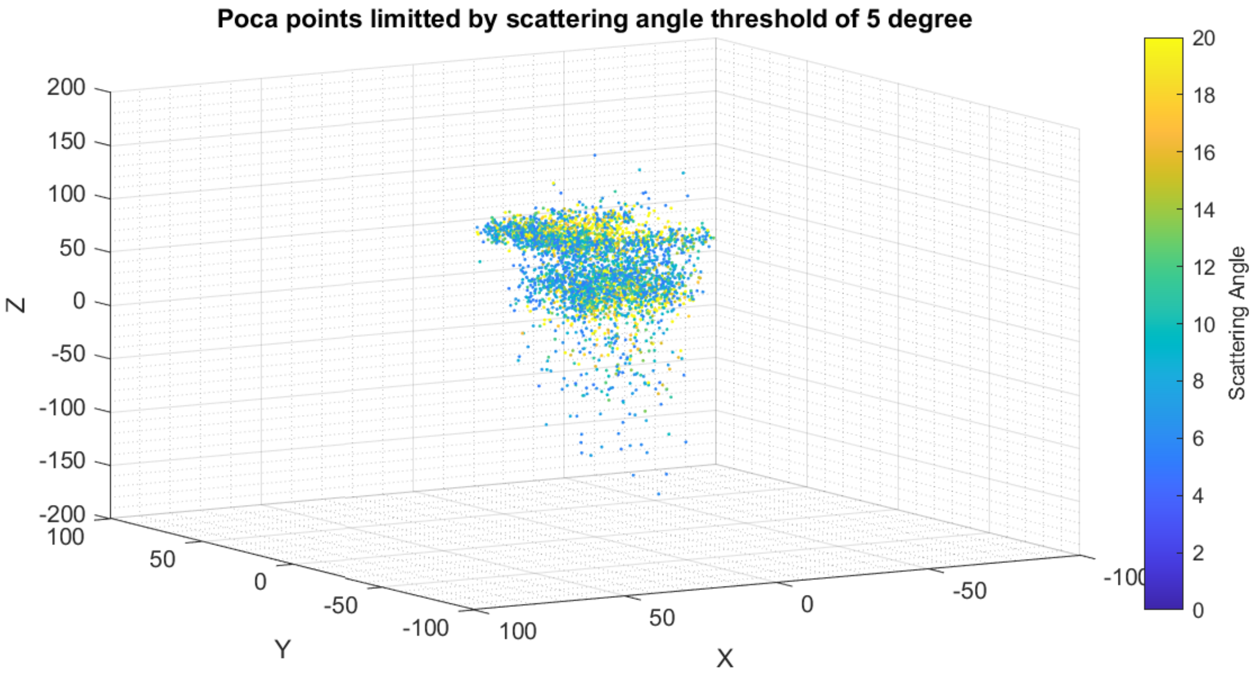
Simulation of Permanent Magnet Measurement

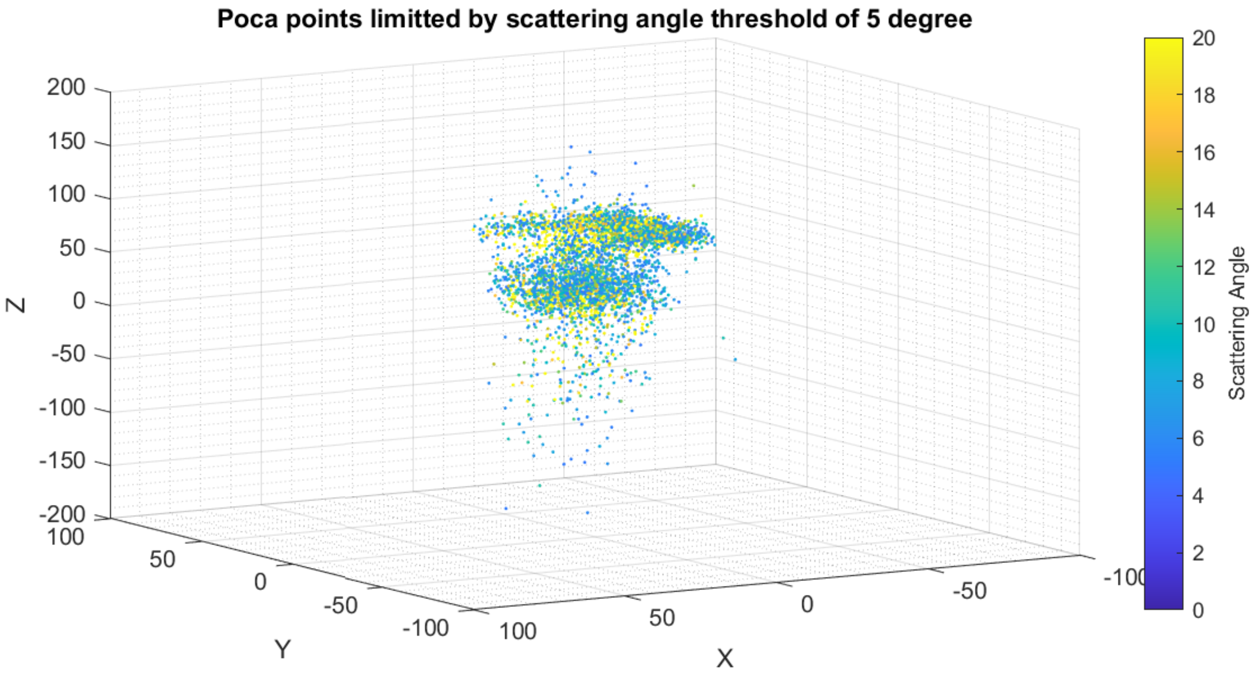
- Simulation for one-week real-time measurement.
- Different detector sizes used on top and bottom. Prototype detector on top and our improved detector in bottom.
- Conditions adjusted to match experiment frame and space limitations



Muon Charge Identification

All PoCA points that has scattering angle more than 5 degree while the magnet is 3T





POCA and Magnetic Field Simulations

Simulations using four different materials (uranium, lead, aluminum, and iron)

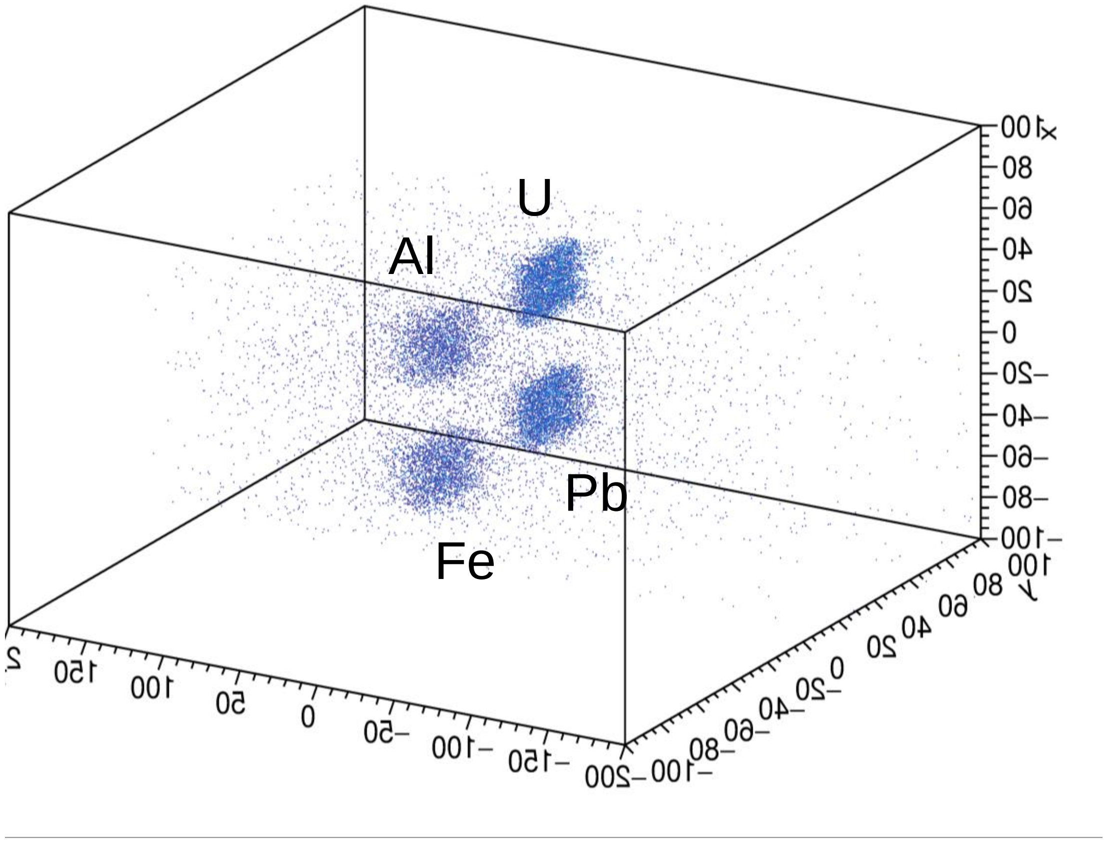
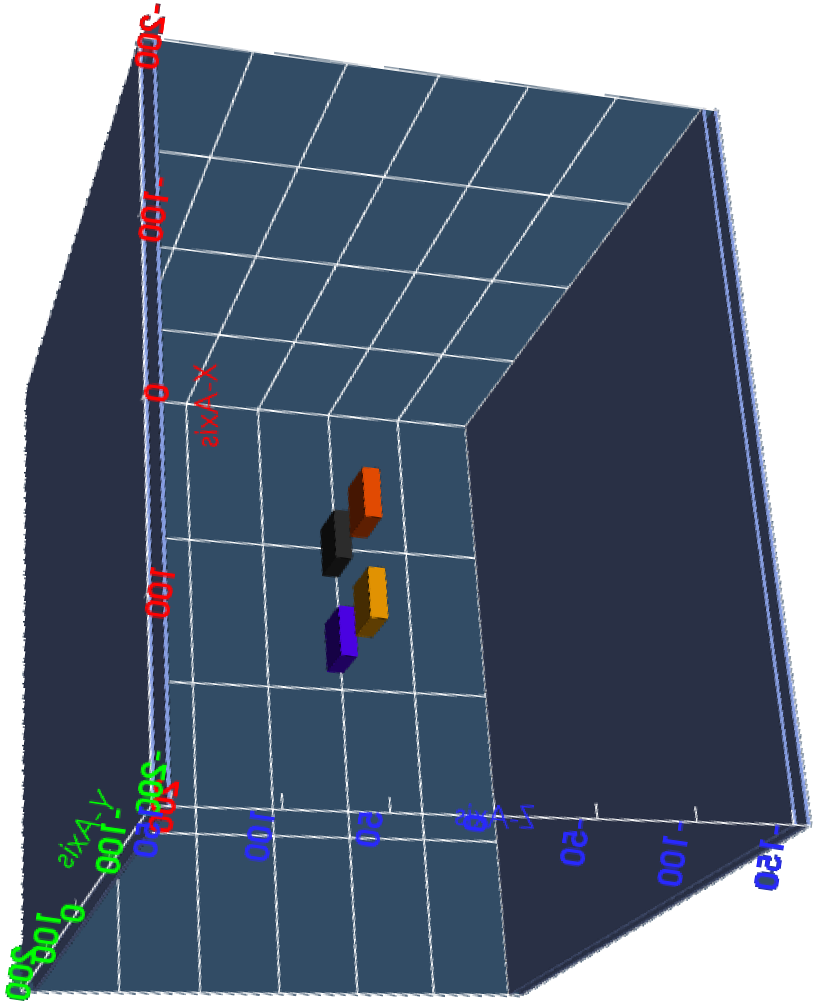
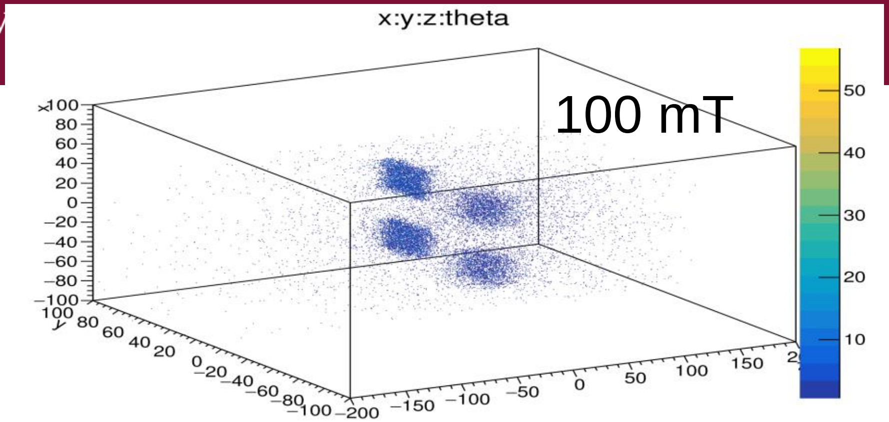
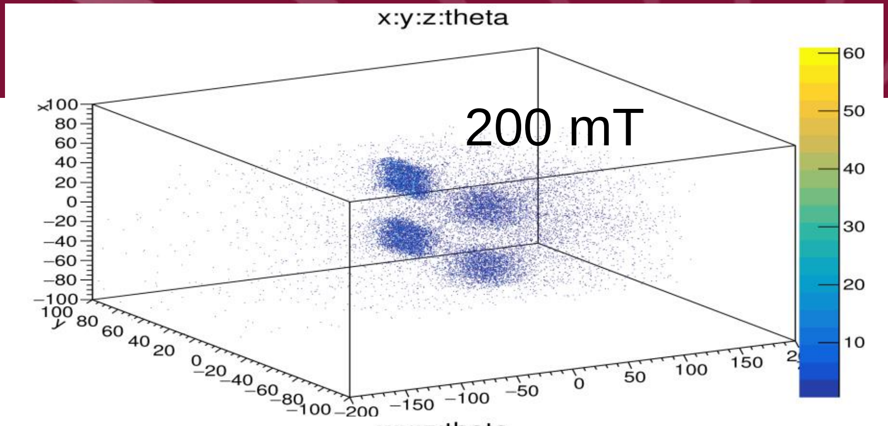


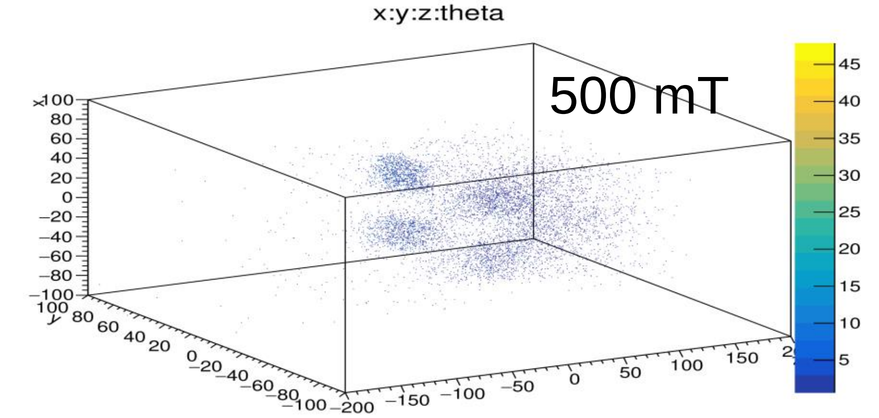
Image without magnetic field

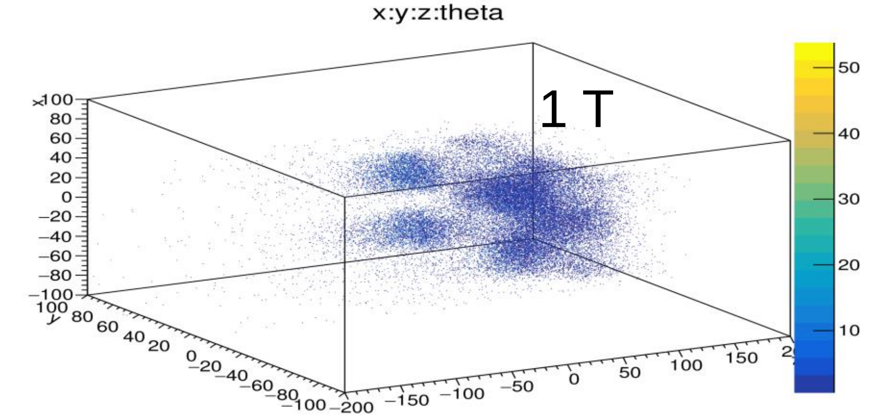


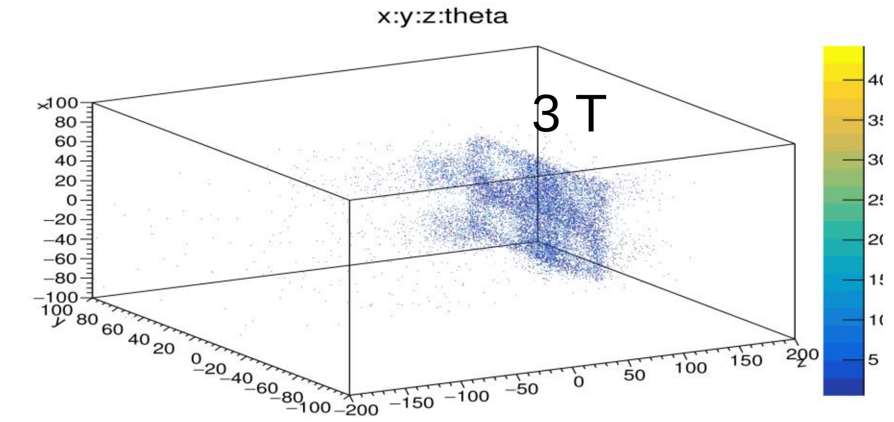
Simulation geometry in PHITS

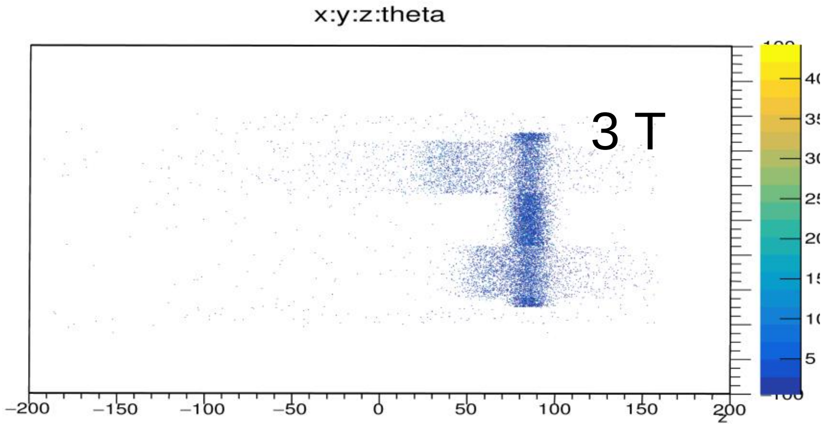

x:y:z:theta
100 mT


x:y:z:theta
200 mT


x:y:z:theta
500 mT


x:y:z:theta
1 T


x:y:z:theta
3 T

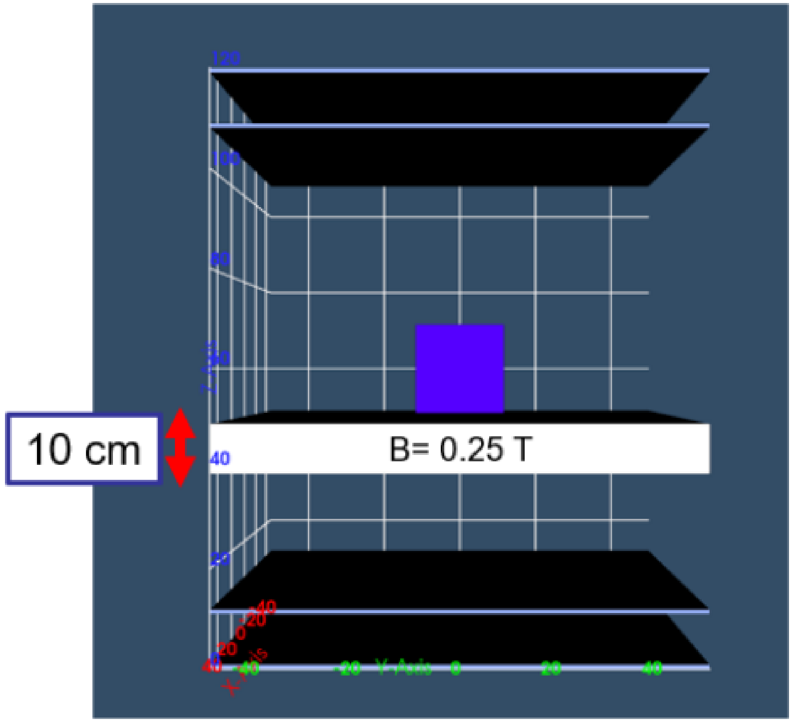

x:y:z:theta
3 T

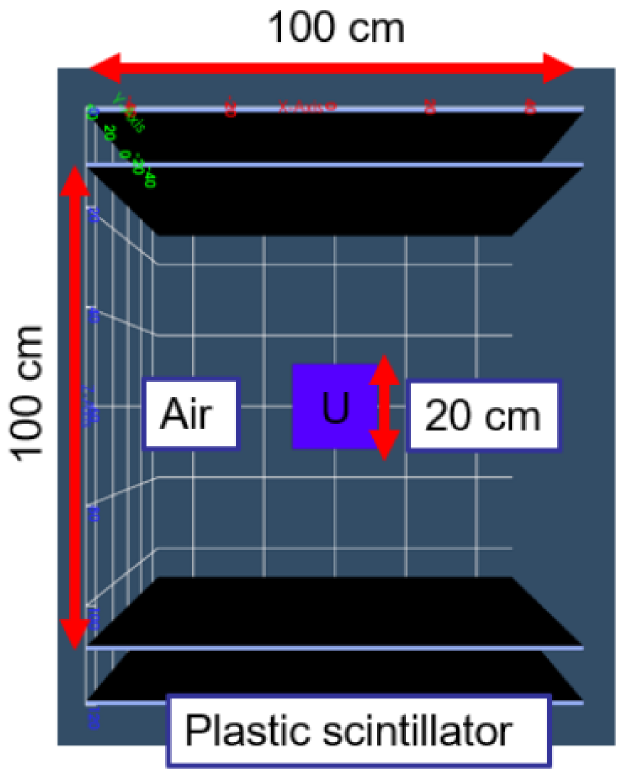
Simulation of Magnetic Field Effect in Material Detection

- **One-hour real-time measurement** muons source based on PARMA model.
- The simulation was conducted in two steps, obtaining the muography image of a uranium target and the distribution of PoCA points in a **voxelized** region of interest.

Voxel dimension:
10 cm * 10 cm * 10 cm

Uranium is made of 8 voxels.
(20 cm x 20 cm x 20 cm)

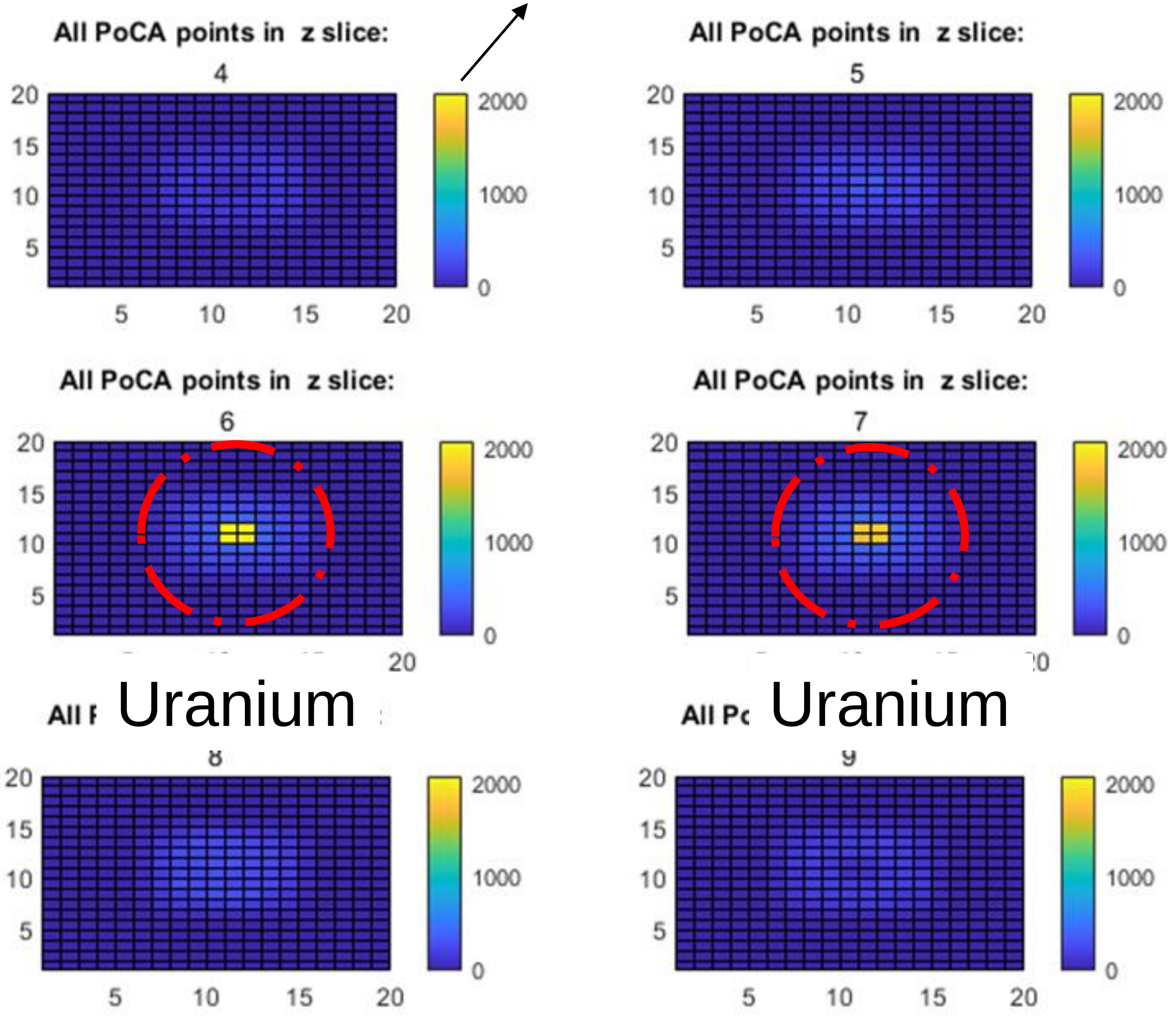




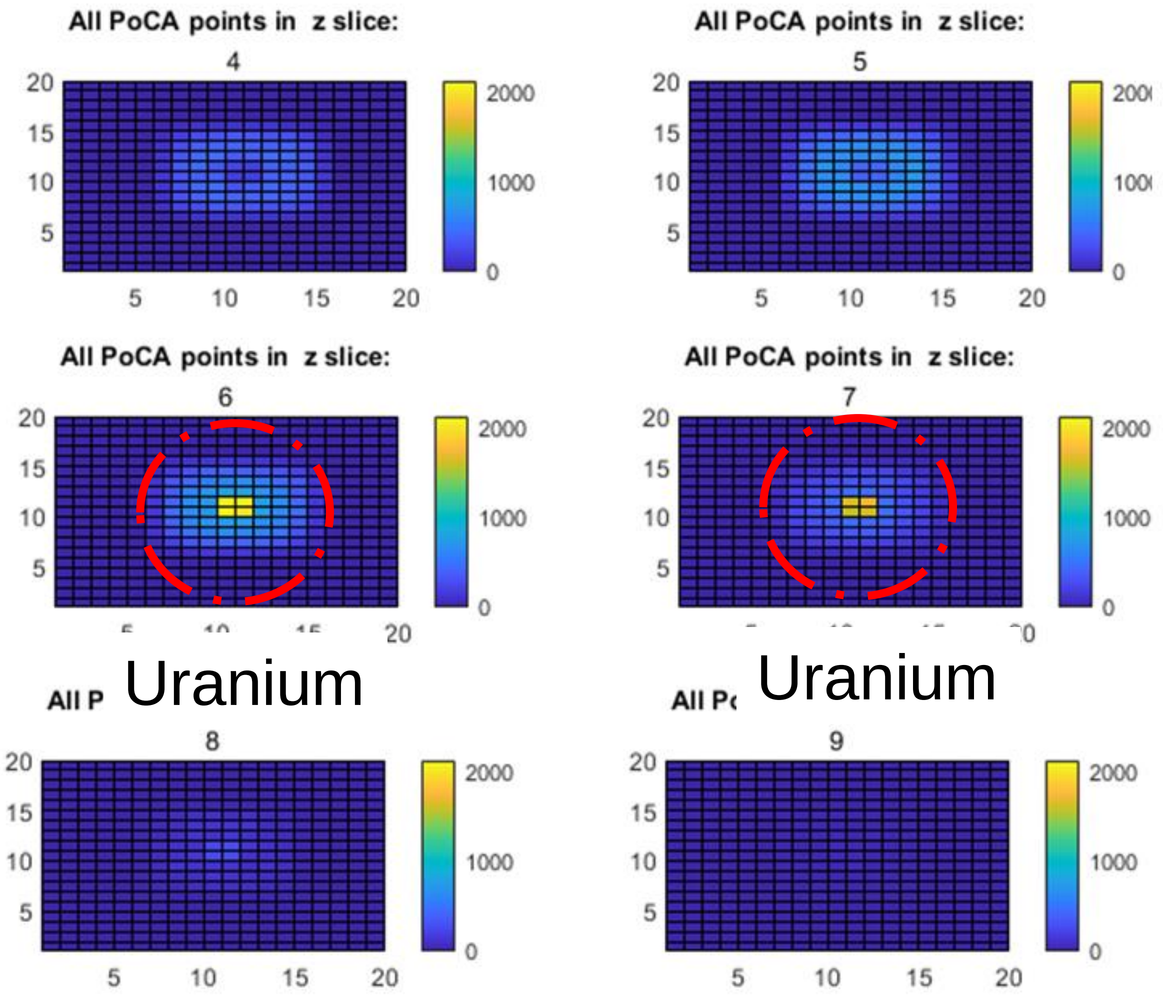
Results of Magnetic Field Effect in Material Detection

Magnetic field OFF

Number of points per voxel

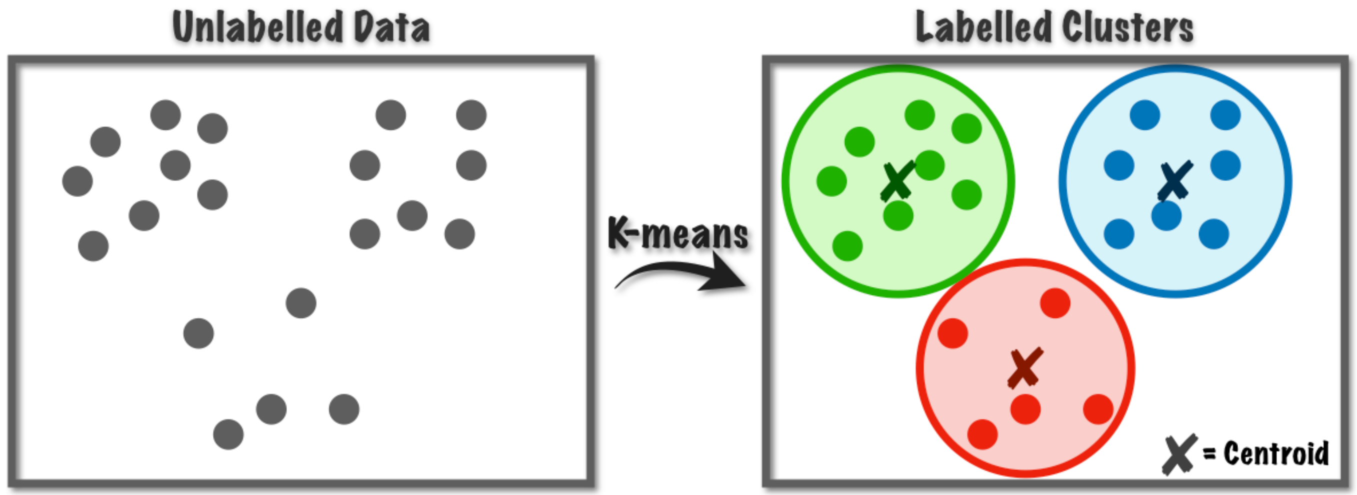


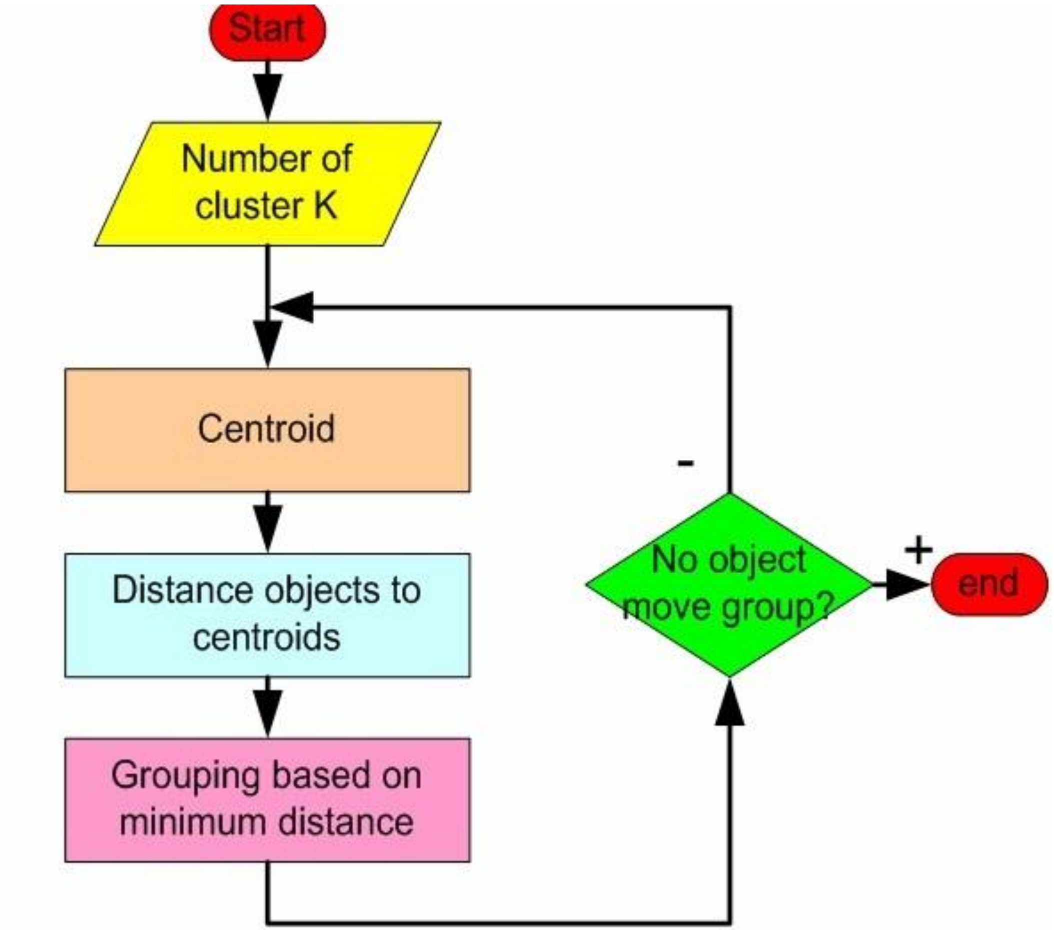
Magnetic field ON



One method to distinguish nuclear materials in this systems is ***clustering*** of voxels

K-means Clustering:

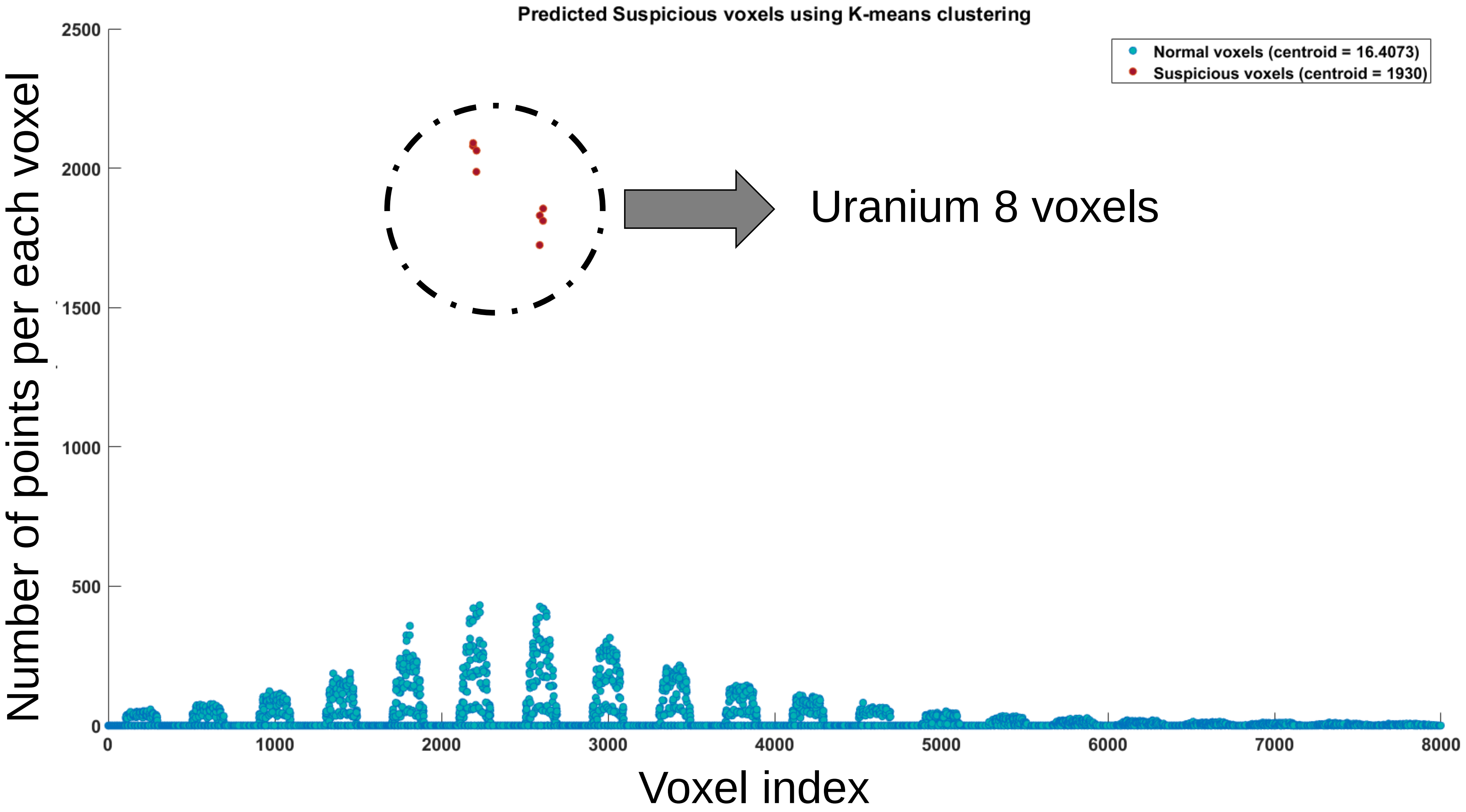




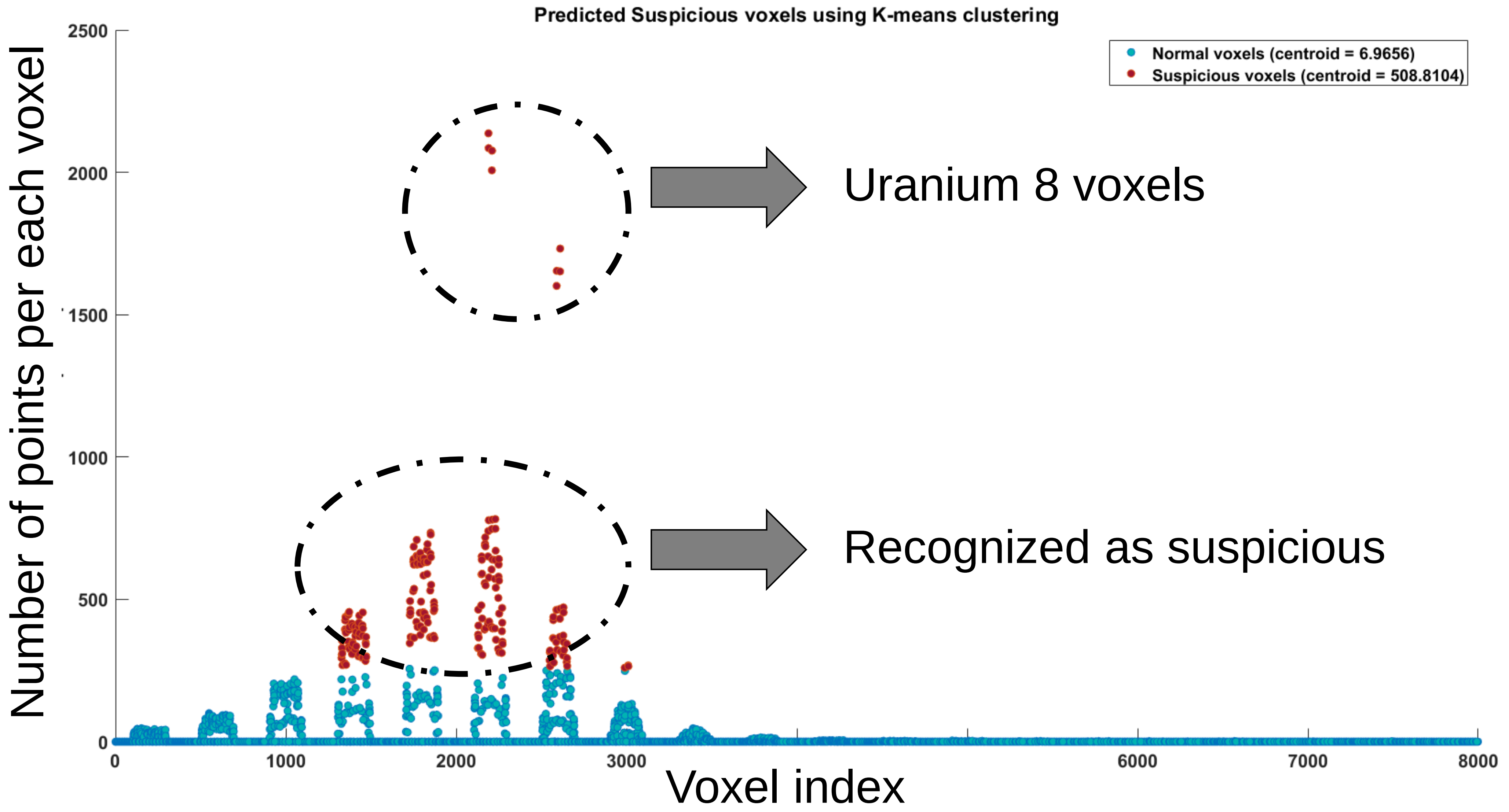
We used two clusters

- Suspicions to nuclear material voxels
- Normal voxels

Magnetic field OFF



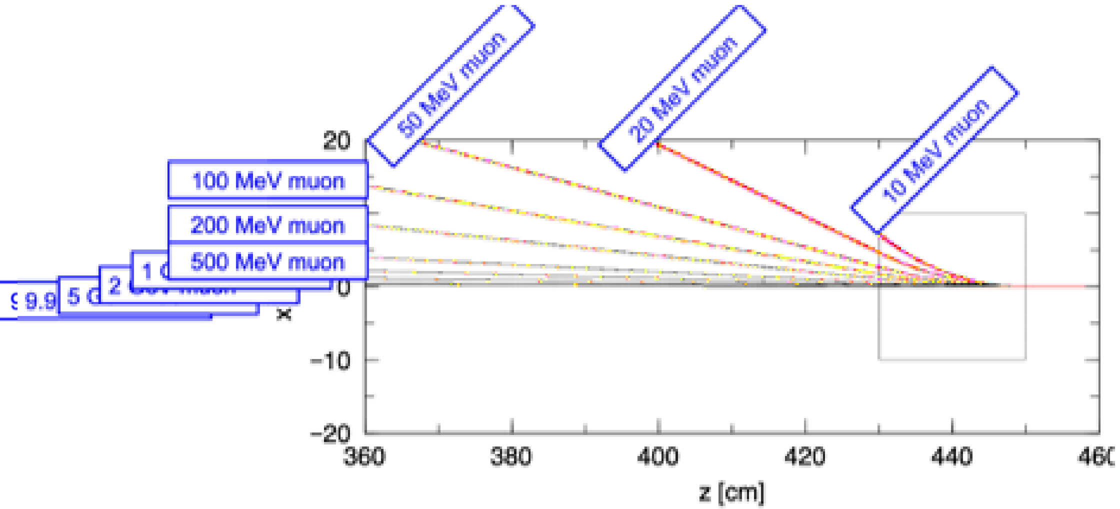
Magnetic field ON



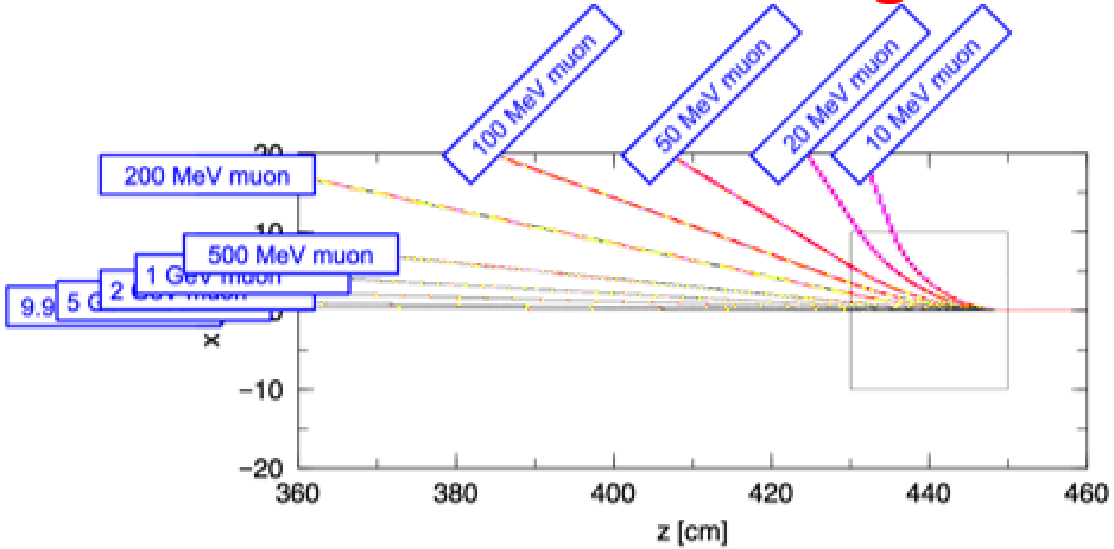
Cosmic-Ray Muons in Magnetic field

Cosmic-ray muon can be deflected by magnetic field.

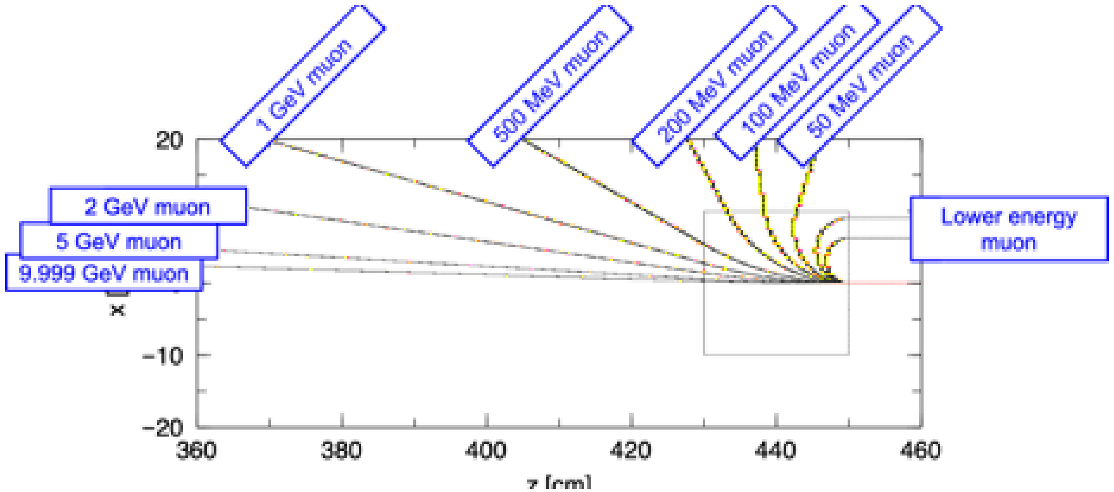
0.5 T and 20-cm thick magnetic field



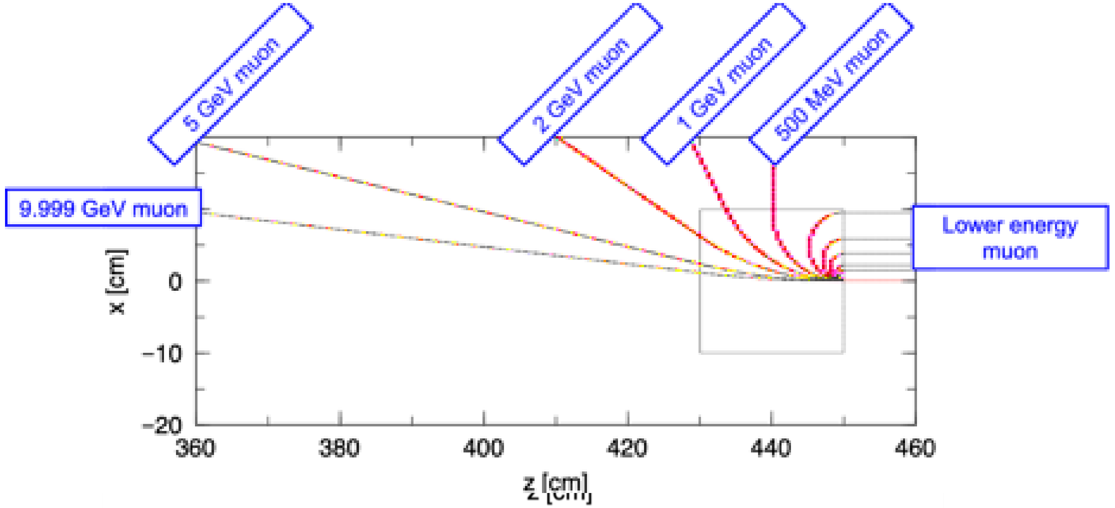
1.0 T and 20-cm thick magnetic field



5.0 T and 20-cm thick magnetic field



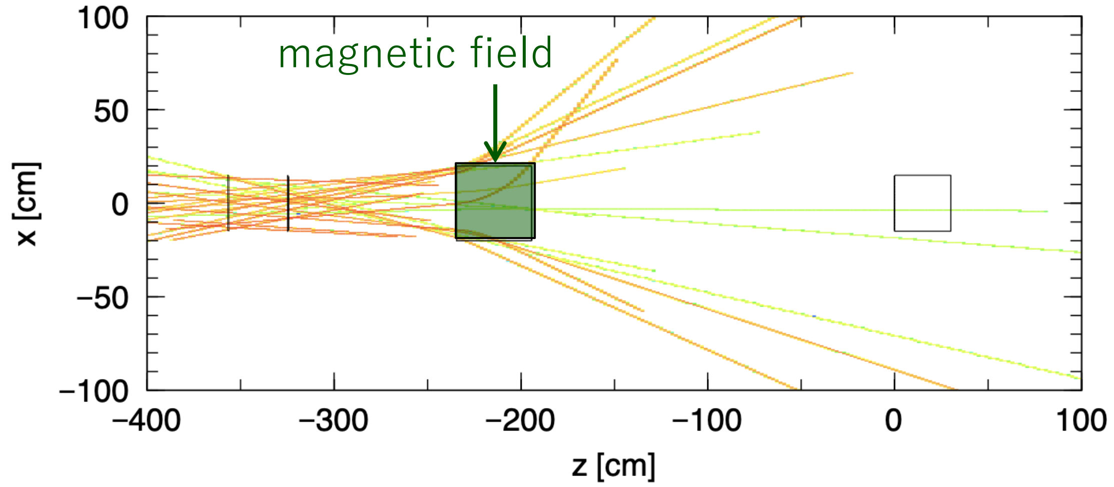
20 T and 20-cm thick magnetic field



Strong magnetic field acts as shielding of muon

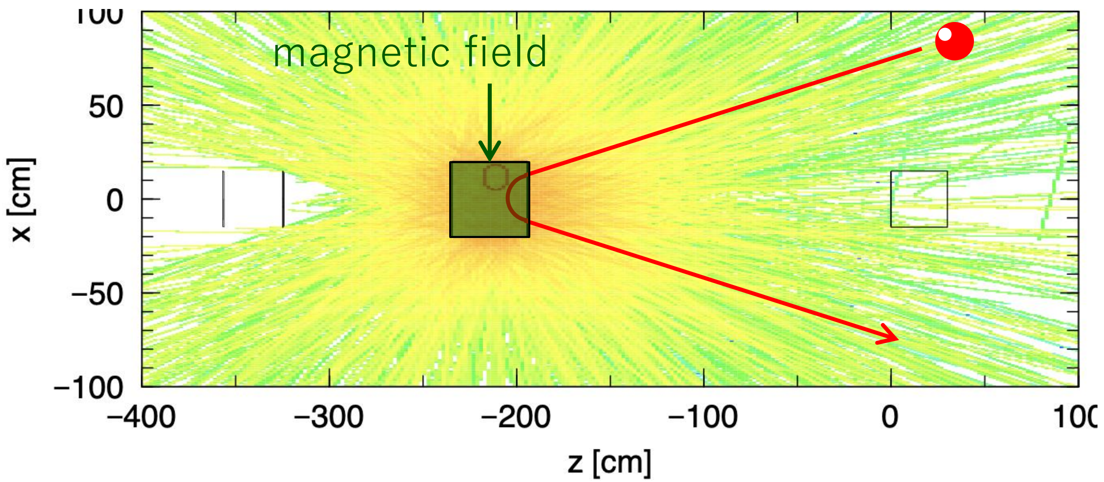
■20 T and 20-cm thick magnetic field simulation result with realistic cosmic-ray muon flux by PARMA

Detected muons' trajectories that pass through magnetic field.



Very rare events

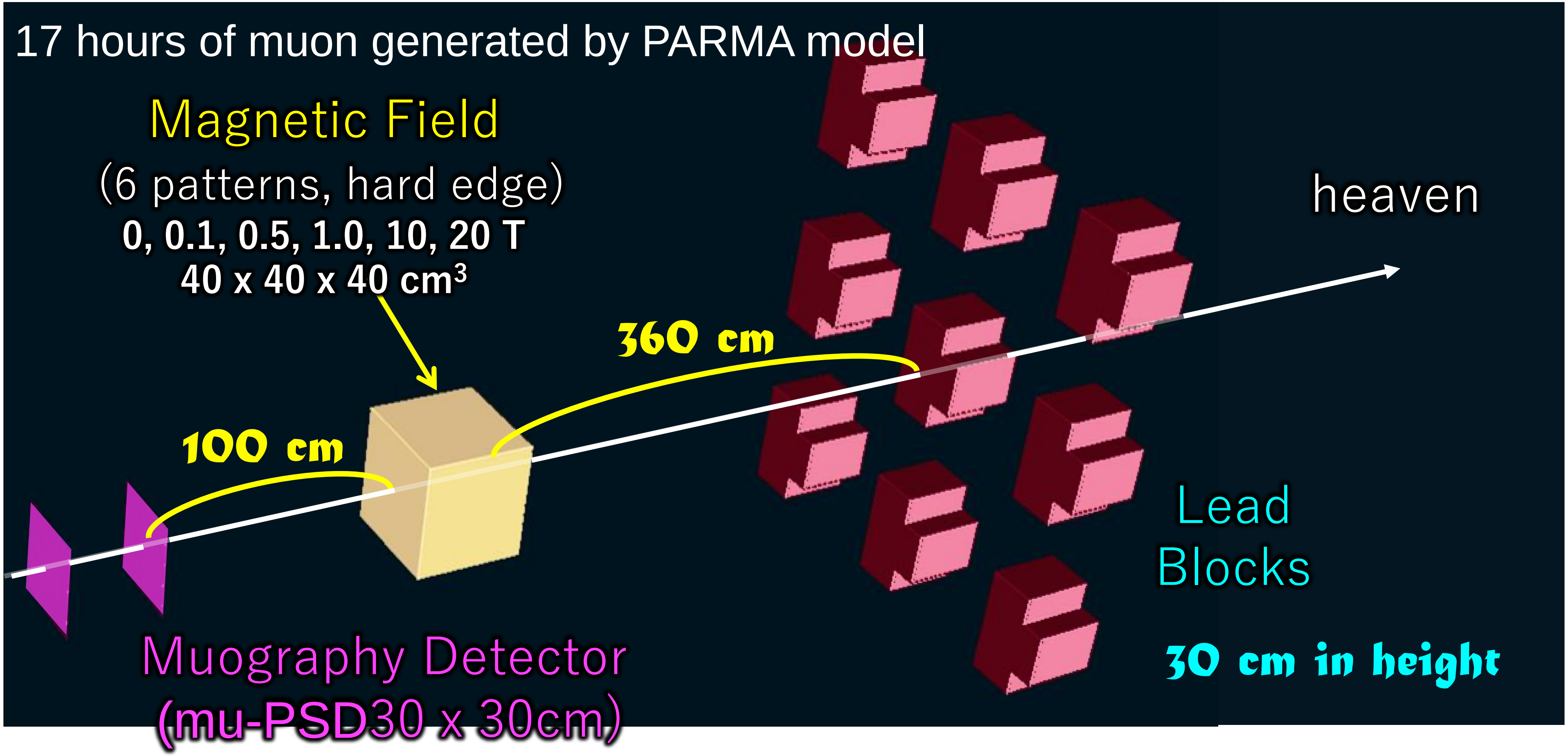
NOT Detected muons' trajectories that pass through magnetic field.



dominant

Low energy muons are kicked back to the universe.

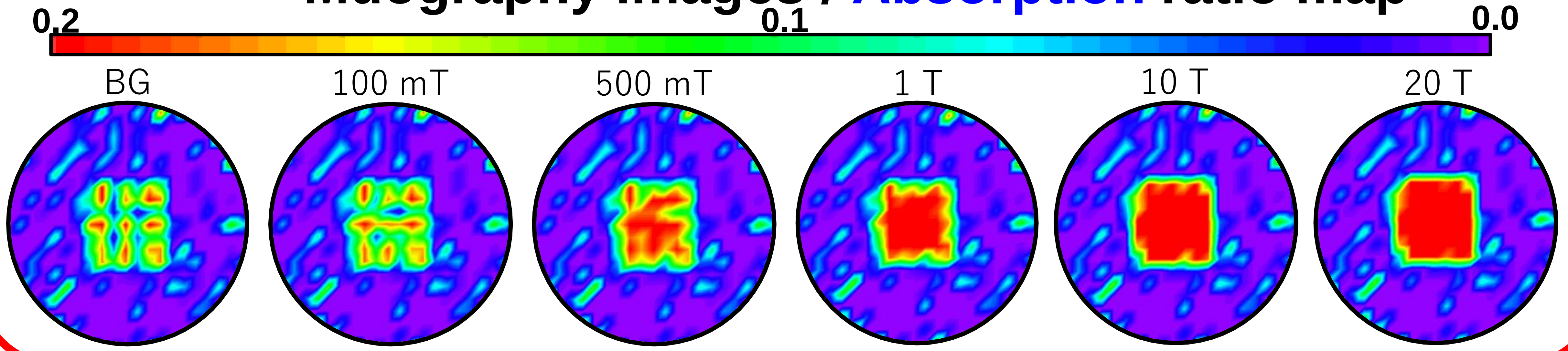
Simulations for Strong Magnetic Fields



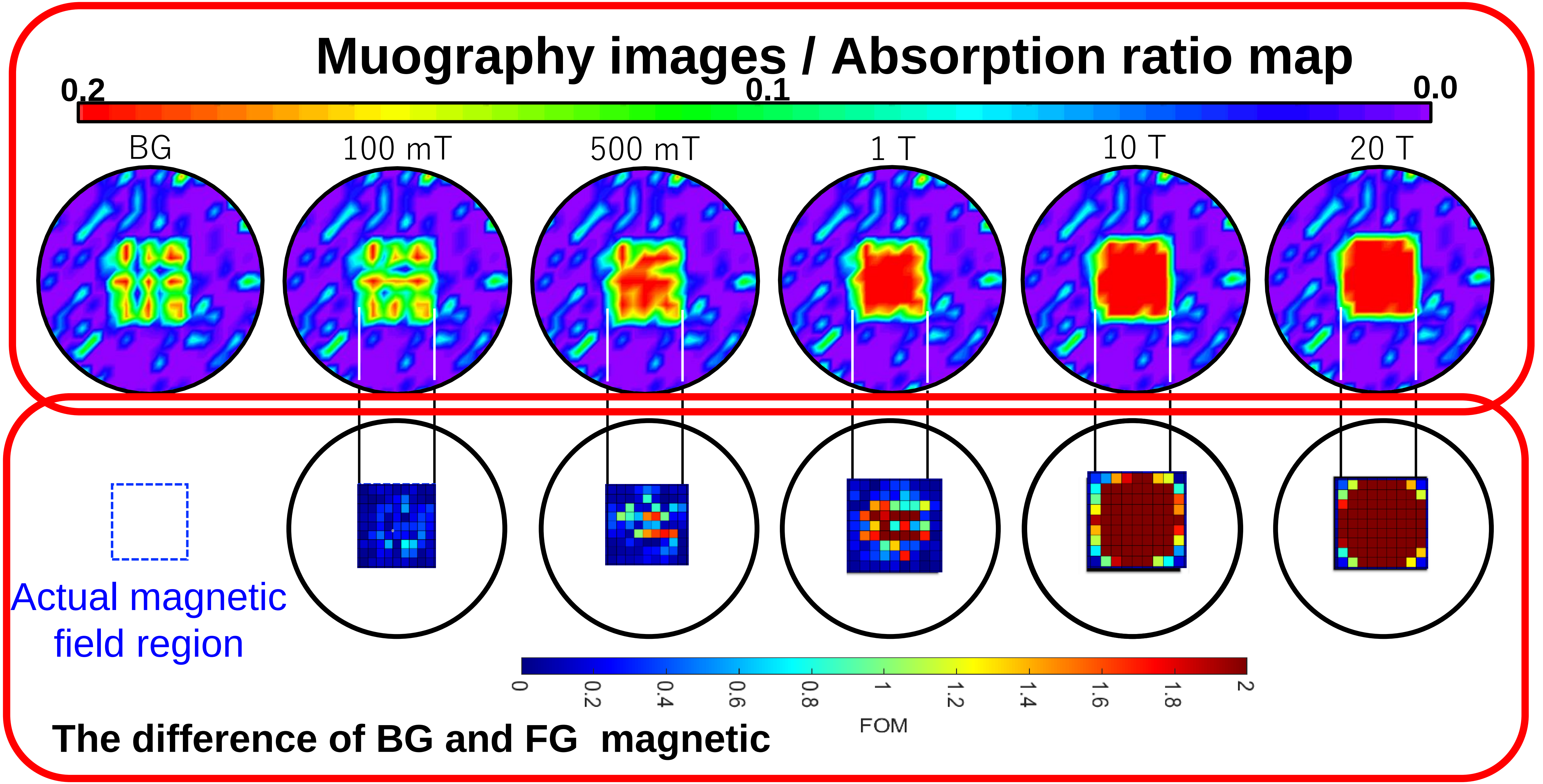
- Muography image calculated for the background (designed to be with in single pixel on muography image).
- Various magnetic flux density applied in the yellow box (have hard edge).

Results for Strong Magnetic Fields

Muography images / Absorption ratio map



Results for Strong Magnetic Fields

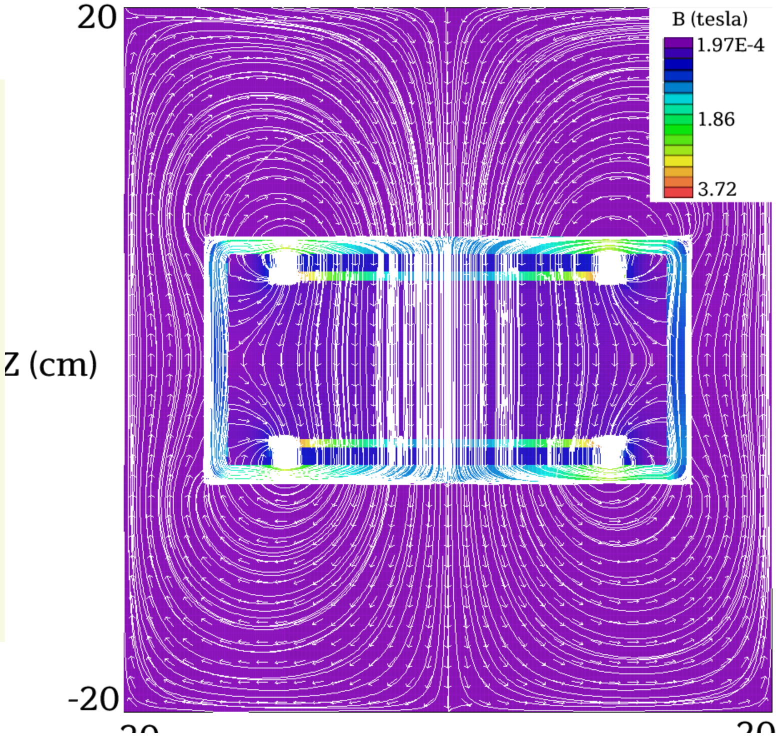


Simulations for a Real Magnet

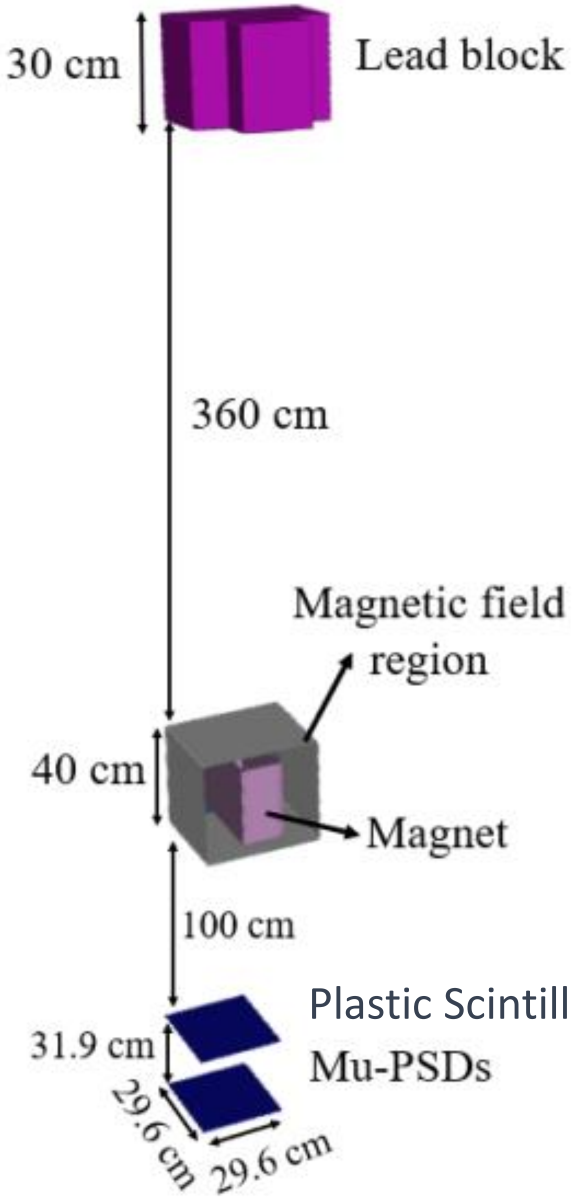
- The 3D distribution of magnetic flux densities calculated using finite element solution package **AMaze** software and implemented in PHITS.

- A lead block was placed above the magnet to represent **a single pixel in the center of the count rate map**, considering the detector resolution.

- **152 hours measurement**

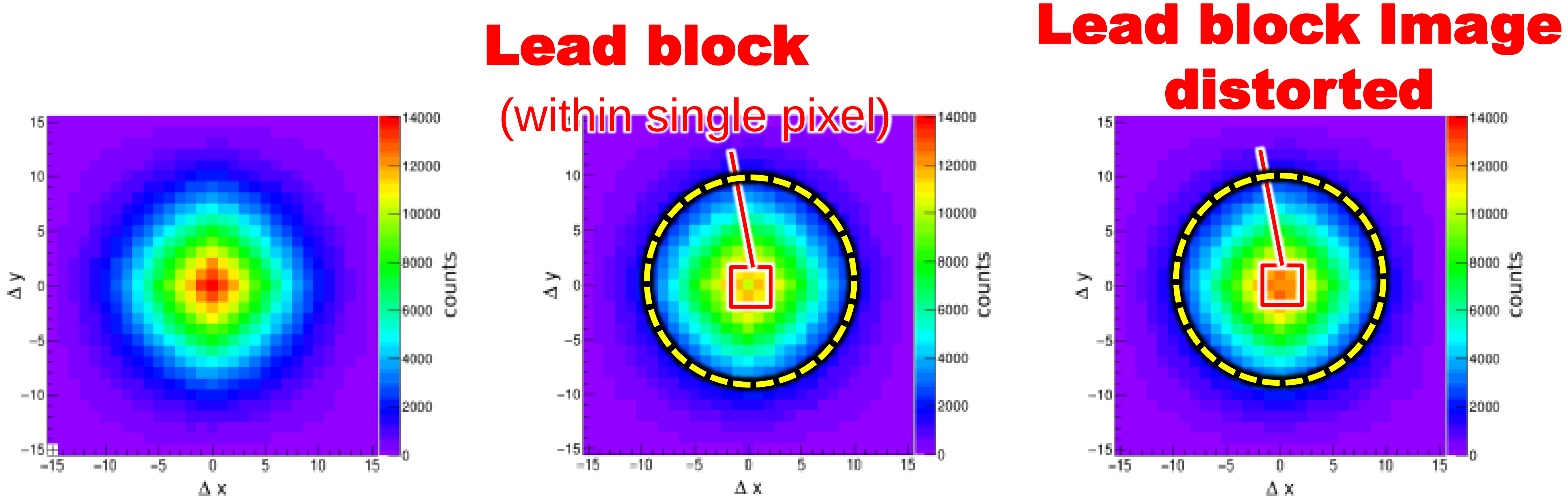


Magnet simulation in Amaze
Mean (0.2T)



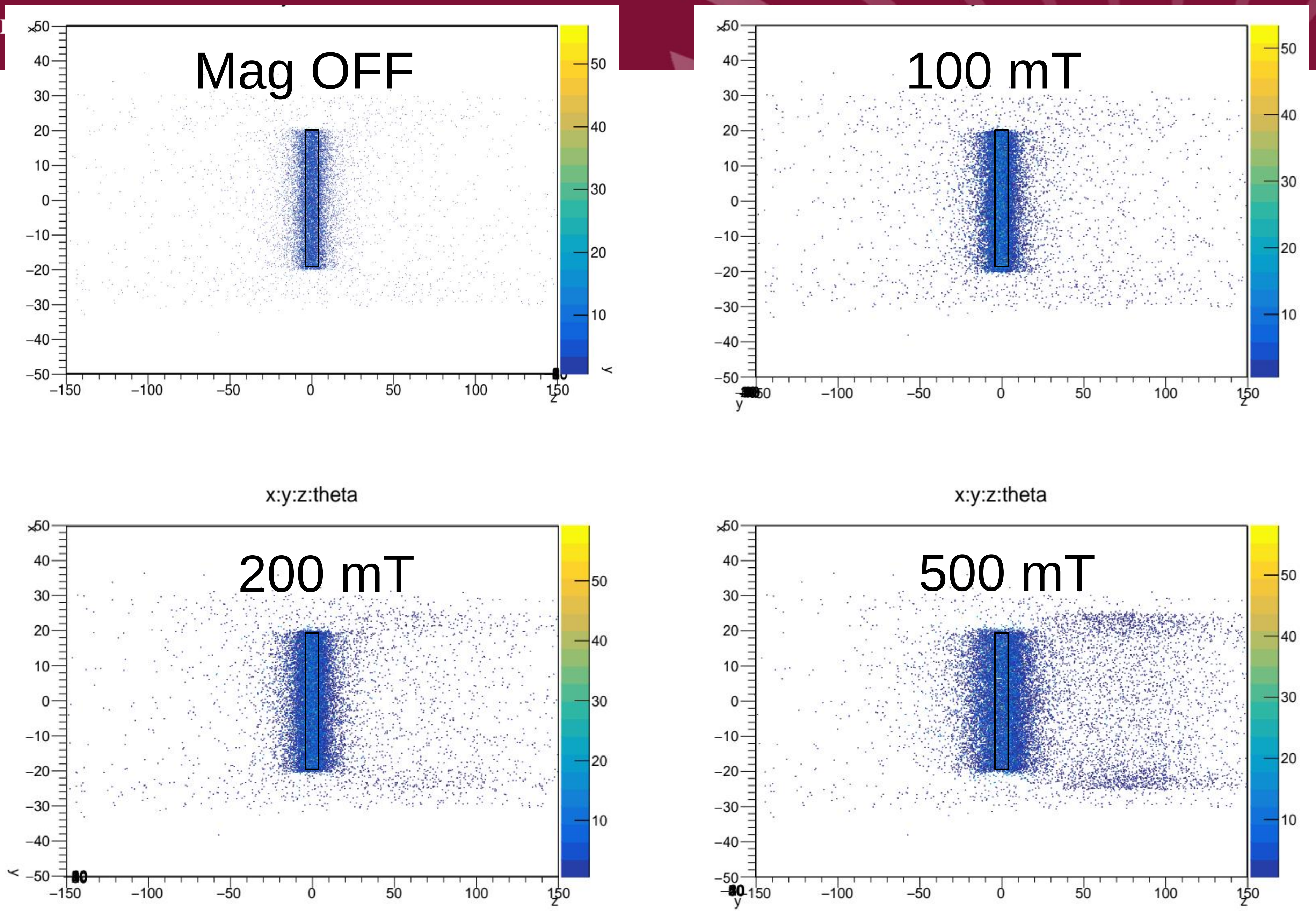
Results for a Real Magnet

- Three different conditions were simulated: open sky, background (magnet off), and foreground (magnet on).

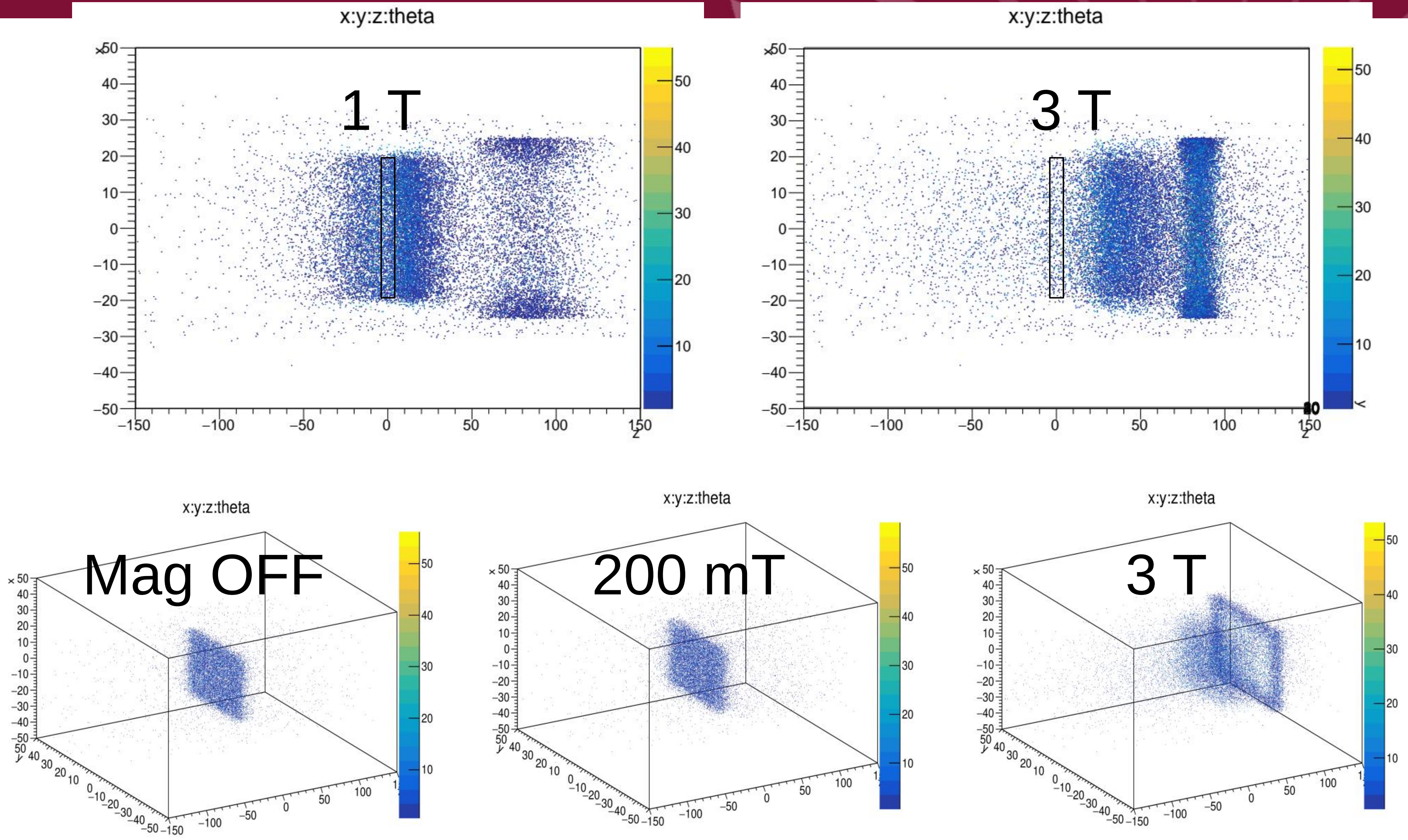


(a) Open sky (b) Background (c) Foreground

- The foreground simulation showed ***changes in the distribution of counts*** due to the magnetic field, with the central pixel blurred and the detection of some muons that would have been missed in the background condition.



Color Represents Scattering angle



Color Represents Scattering angle

Cosmic-Ray Muons in Magnetic field

■ Lorentz Force

Relativistic effect cannot be ignored for cosmic-ray muons

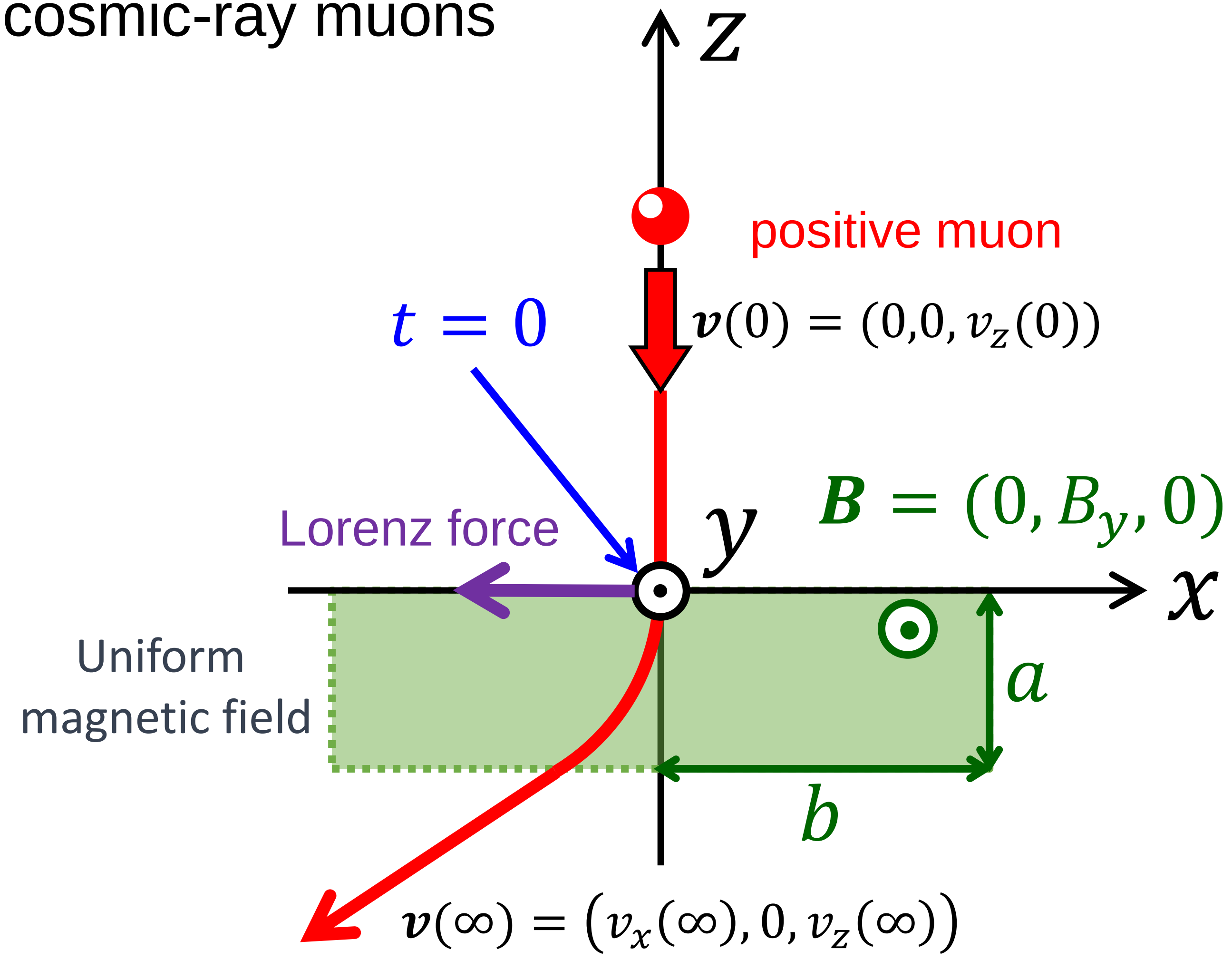
$$\frac{d}{dt}\left\{\frac{m\boldsymbol{v}}{\sqrt{1-\frac{v_z(0)^2}{c^2}}}\right\} = \boldsymbol{v} \times \boldsymbol{B}$$

The **circular motion** is derived as:

$$x(t) = -r\cos\omega t$$
$$z(t) = r\sin\omega t$$

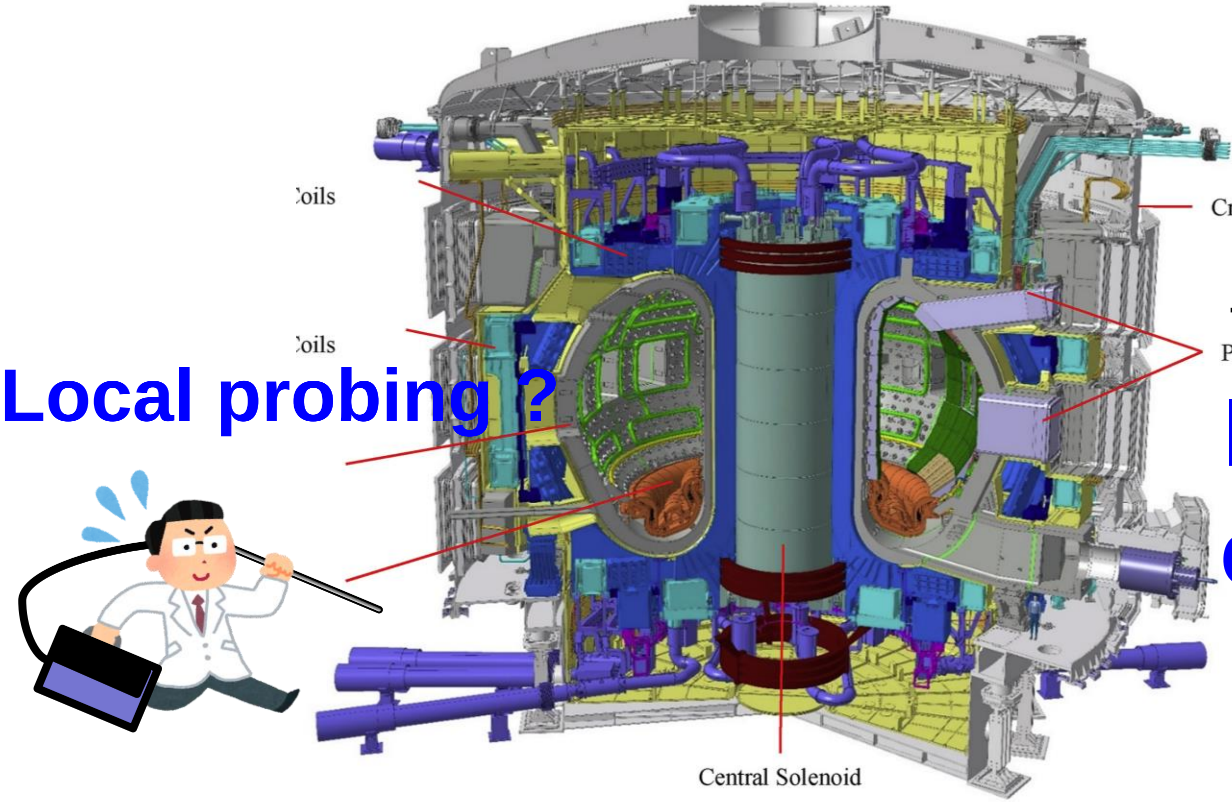
Lamor radius defined as:

$$r \equiv \frac{v_z(0)}{\omega} = \frac{m v_z(0)}{B_y\sqrt{1-\frac{v_z(0)^2}{c^2}}}$$



Huge & strong magnetic field

Neutron irradiation induces degradation of superconductive coil.
→ Many reports say, “it determines the life of fusion reactor.”



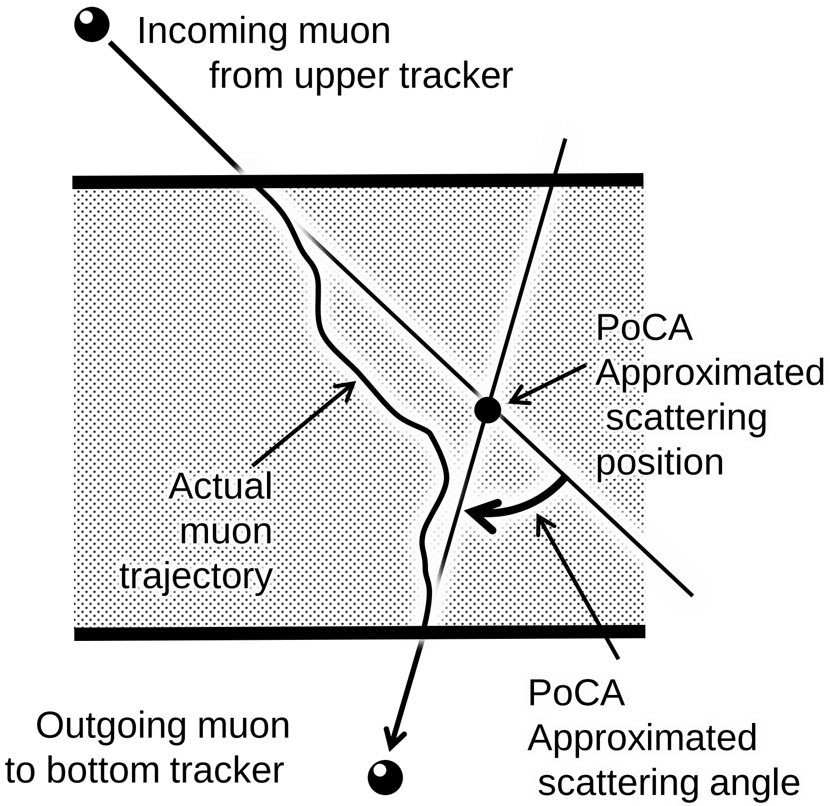
I found some reports to show the degradation by deviation of the electric current possible to flow to the superconductive coil.

It can predict when the degradation starts, but…

never say “how” and “where”.

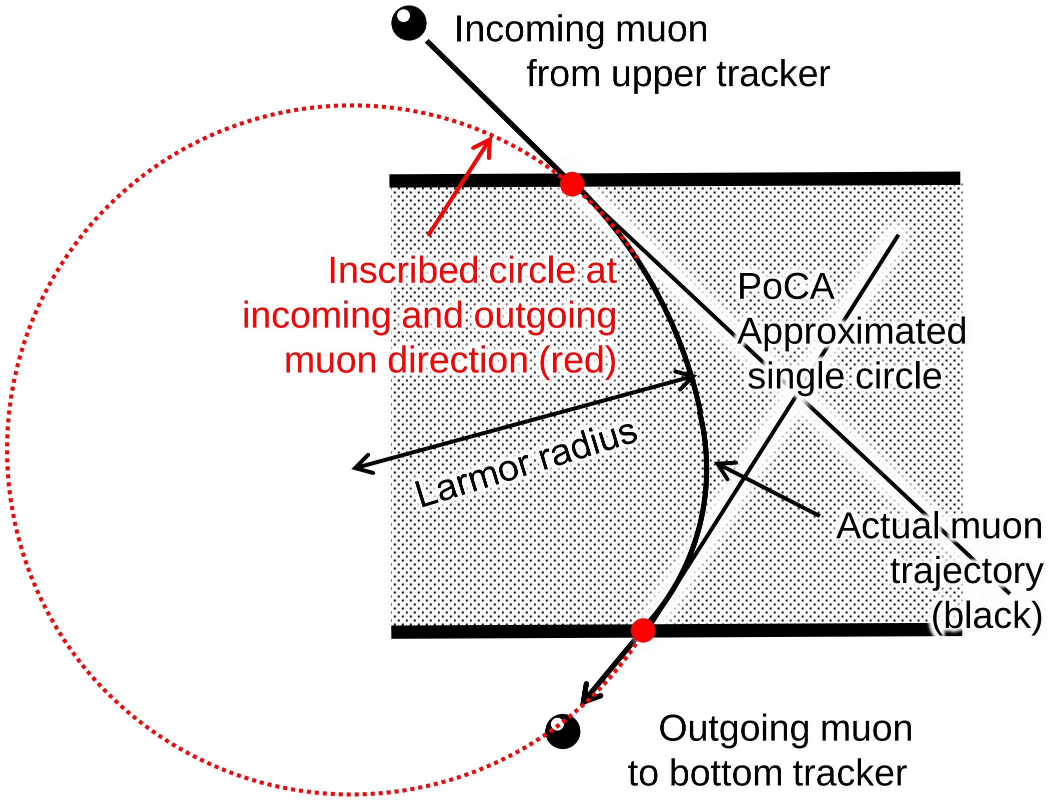
Magnetic field measurement by deflection method

■ Scattering Muography



$$\sigma \approx \frac{13.6\,\mathrm{MeV}}{pc}\sqrt{\frac{X}{X_0}}$$ +Model (Gaussian) + MLEM

■ Magnetic field measurement by deflection method



$$B_y^2\left(\frac{1}{v_z(0)^2}-\frac{1}{c^2}\right)=\frac{m^2}{r^2}$$ +Model (PARMA)
+ MLEM or such

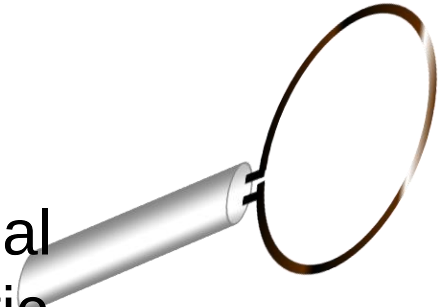
Currently used methods

- **Hall device probing**

Measure magnetic field intensity via the Hall effect.

Primary limitation: Sensitivity changes due to temperature fluctuations. Only local measurement is possible. Must touch the magnetic field.

- **Coil probing**



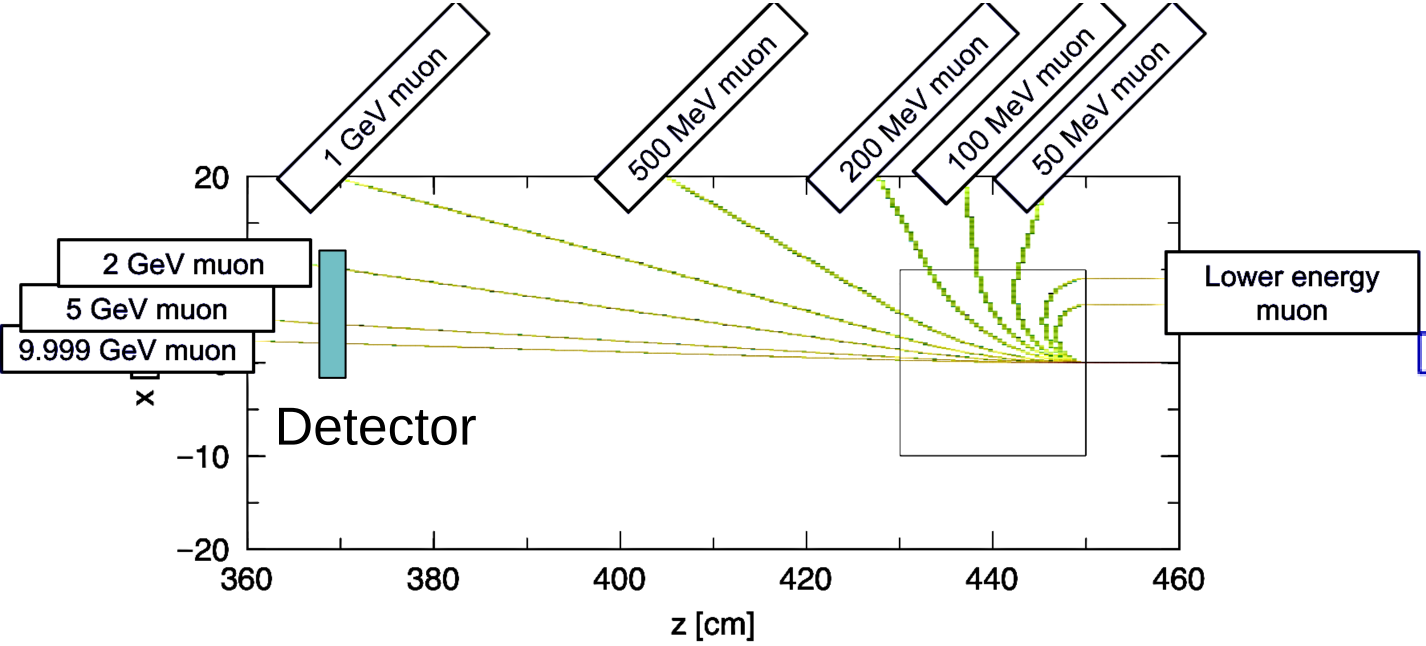
Operate based on Faraday's law of electromagnetic induction.

Primary limitation: Influenced by temperature variations and external electromagnetic interference. Only showing the difference of magnetic field flux densities **(time dependent one only)**

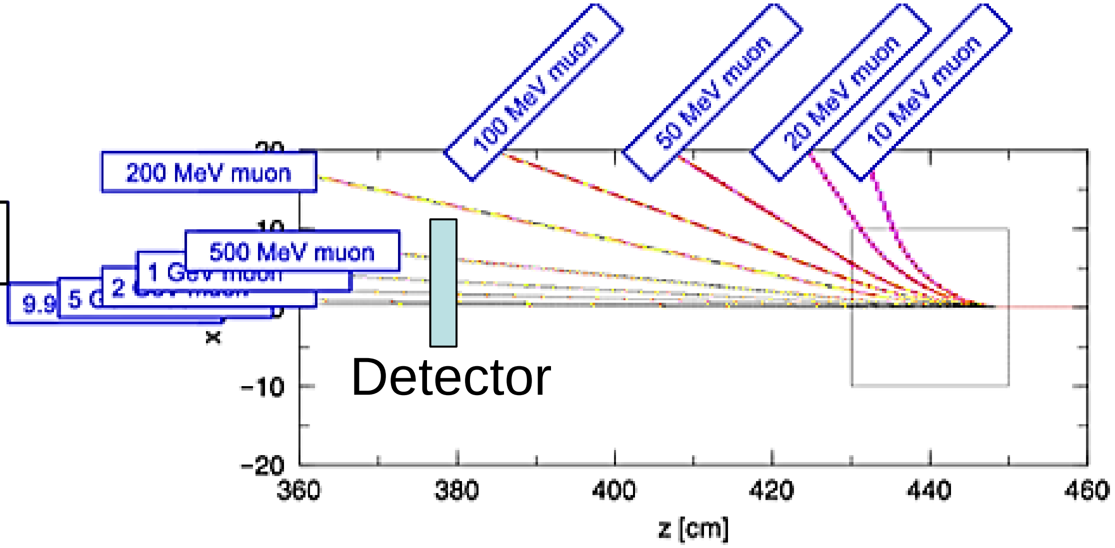
Cosmic-Ray Muons in Magnetic field

To have an idea of the effect of magnetic fields on various muon energies

■ 5 T and 20-cm thick magnetic field



■ 1 T and 20-cm thick magnetic field

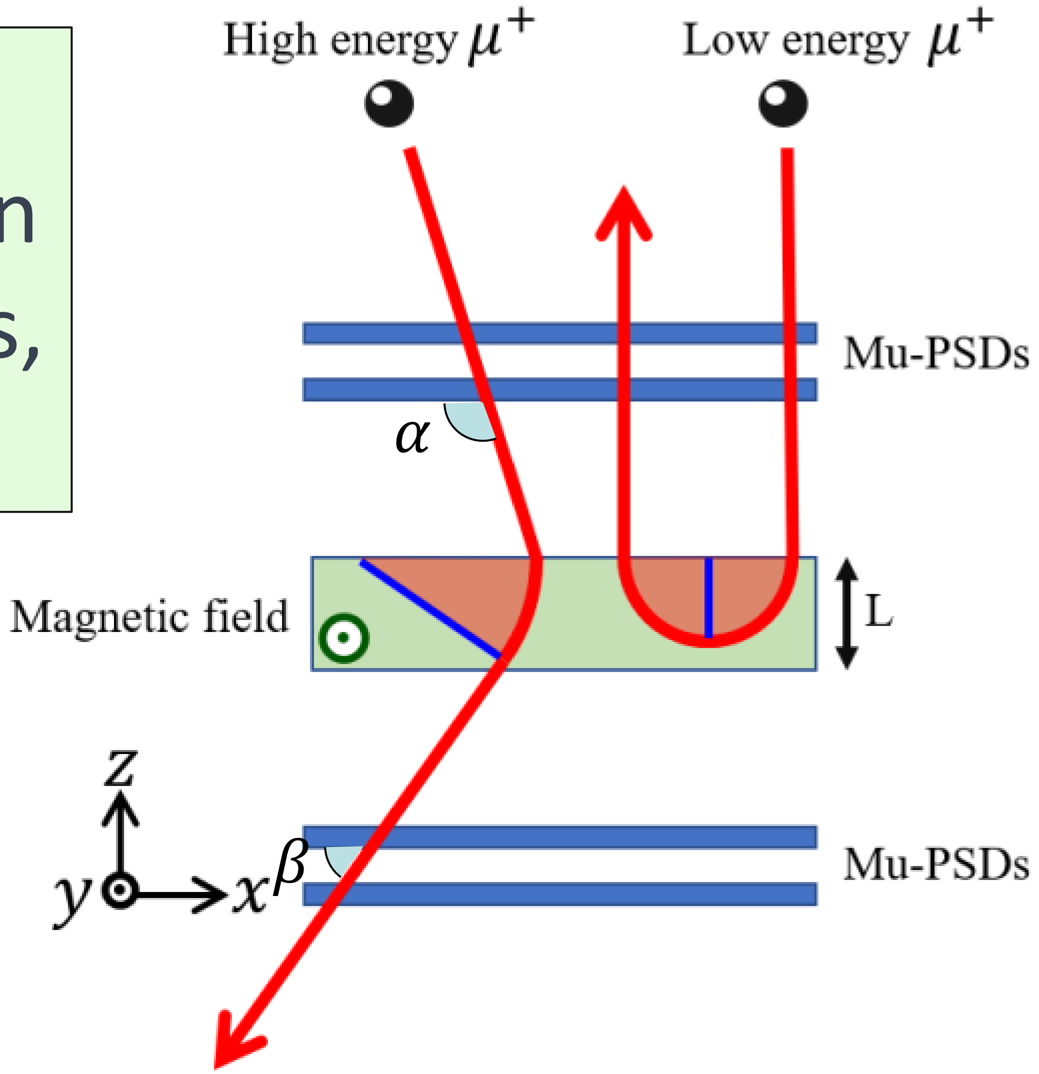


Muons that cannot reach the detector because of the magnet are important for us!

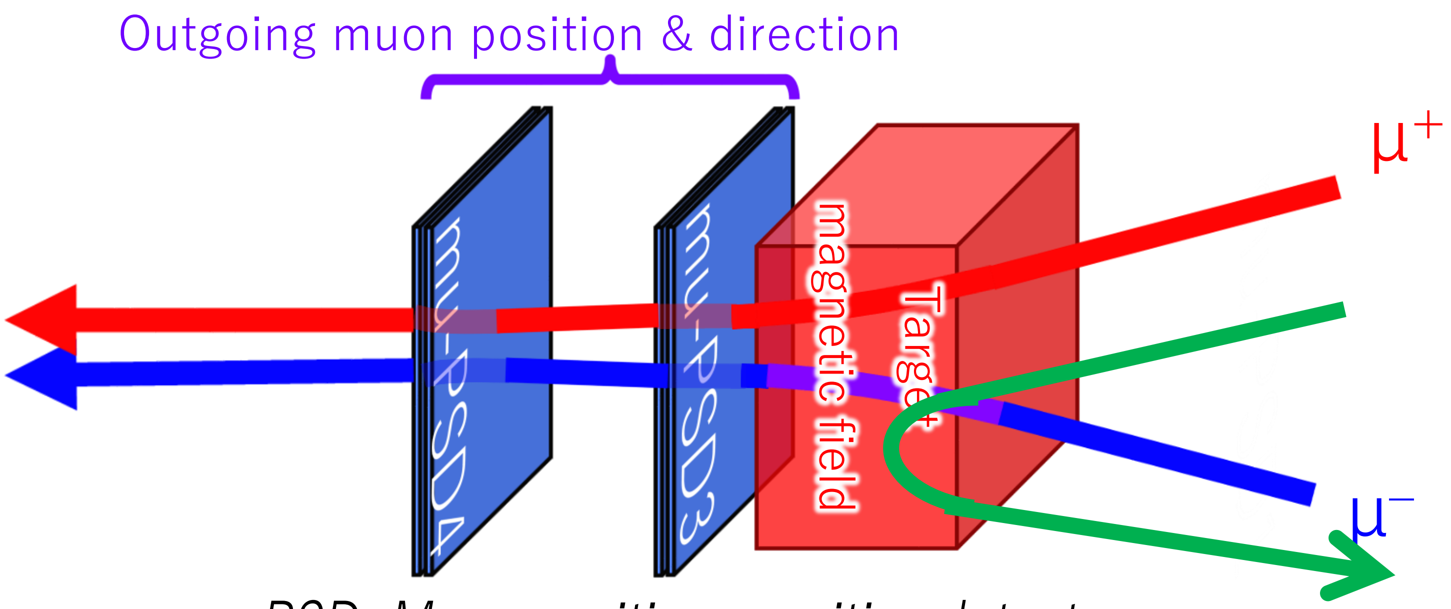
Deflection Angle

- The deflection angle of muons is defined as the difference between the outgoing and incoming angles, and it can be calculated as $\Delta\theta$:

$$\alpha - \beta = \Delta\theta = \frac{qBL}{p_{\perp}}$$



Magnetic Field Imaging by Transmission Muography



mu-PSD: Muon position sensitive detector

Completely the same setup with normal absorption muography detector.

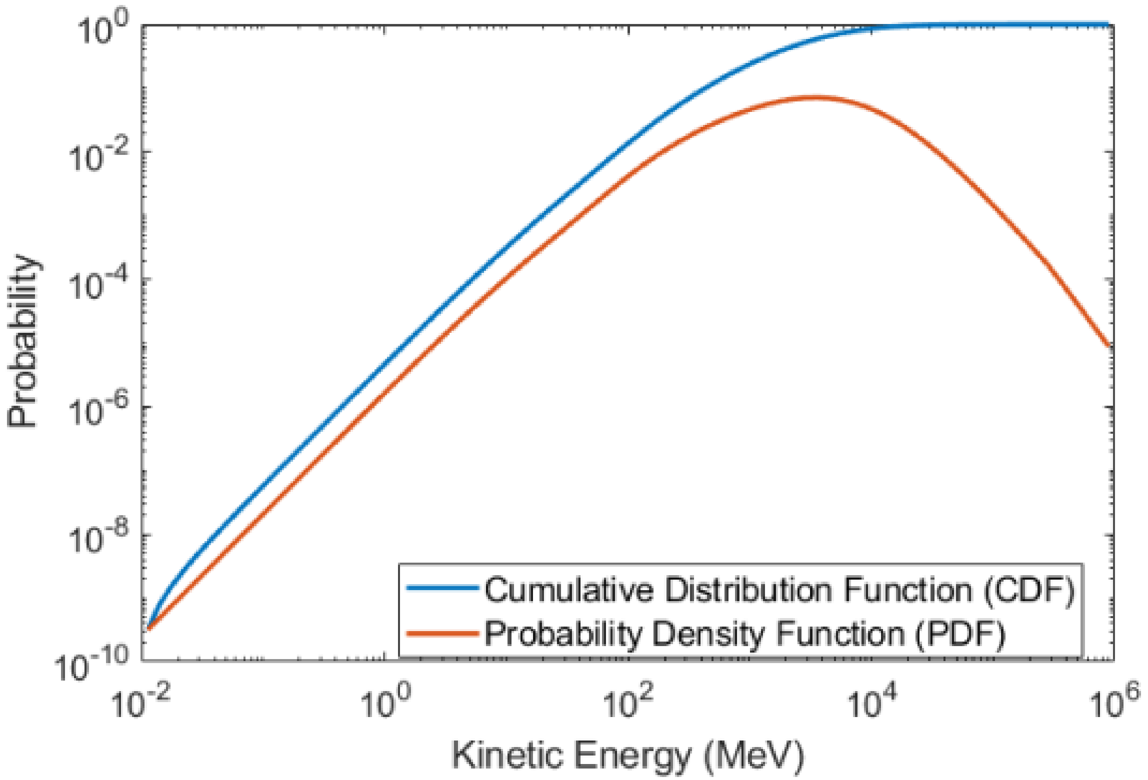
Applicable for:

- Huge and strong magnetic fields
- Background measurement or precise simulation must be possible.

Note: "Background" is NOT an open-sky, but a magnetic field off measurement.

Low-Energy muons are kicked back to the universe!

Are the low-energy muons important?



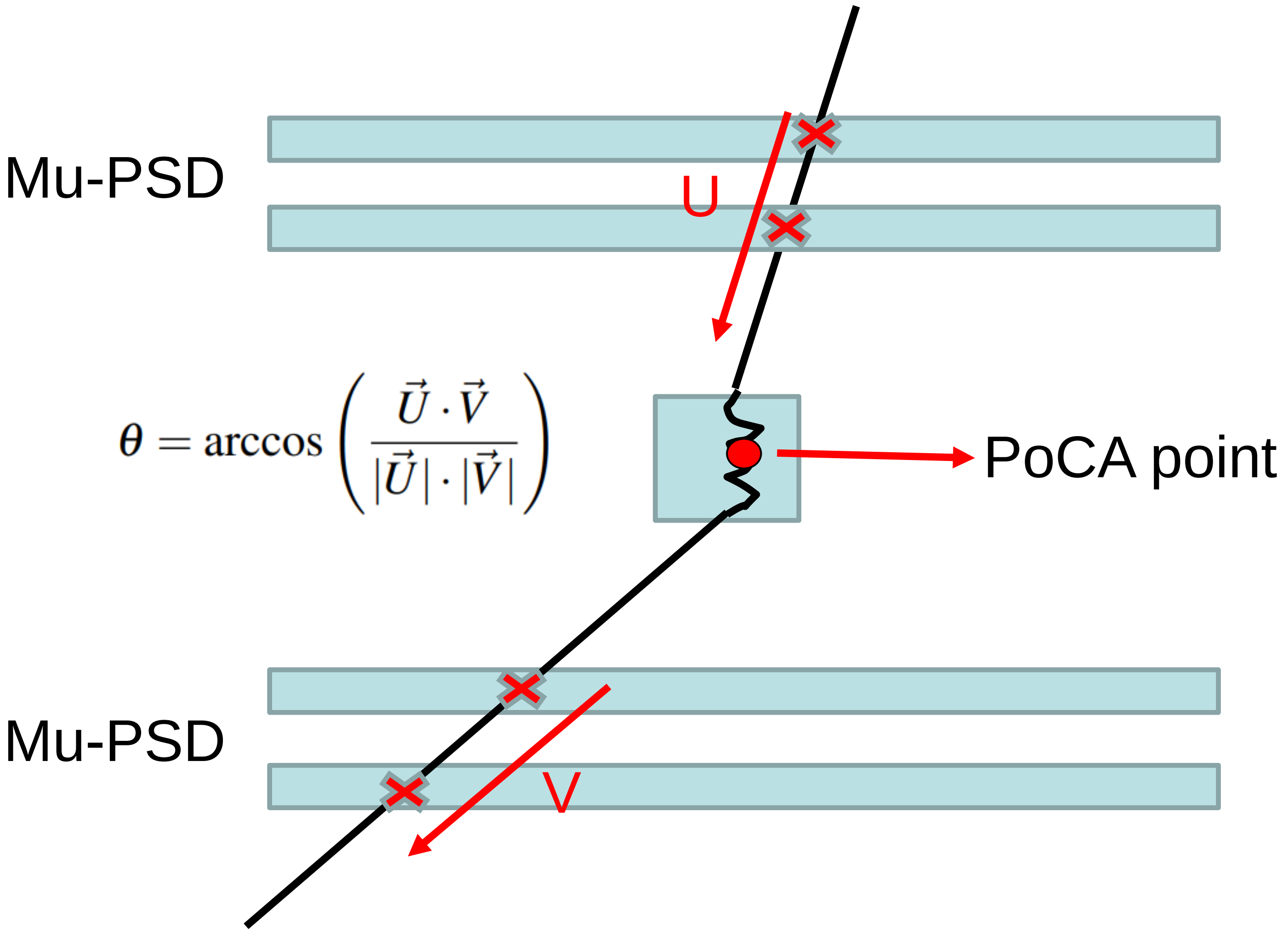
Location of Tokyo using PARMA model

Based on previous equations, in a **1 m** magnetic field of **1 T**, muons up to **180 MeV** will be **completely deflected back**. These constitute **3.5%** of the muon flux.

- **500 MeV** account for ~**12% of the CDF**

Lower-energy muons in **magnetic field imaging** could reveals the information of magnet mainly in strong magnetic field (tesla order)!

Point of Closest Approach (PoCA) algorithm



$$\theta = \arccos\left(\frac{\vec{U}\cdot\vec{V}}{|\vec{U}|\cdot|\vec{V}|}\right)$$

Using precise hit positions, the direction can be calculated

Using position of one point and the direction, PoCA point can be obtained.

By using directions, the scattering angle can be calculated.

- For each incoming muon one PoCA point is calculated