Feasibility Study for Compton Computed Tomography (CT) for Radioactive Waste Drum Monitoring

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Introduction

Decommissioning of nuclear facilities

900-1300 MW(e)
PWR

Item*	Drums
Activation metal	500
Activation concrete	900
Pollution finishing metal	100
Contaminate metal	3,000
Contaminate concrete	1,800
Dry active solid waste	7,400
Total	**13,700**

Disposal cost for radioactive waste: ~300 billion won

*ref: International Atomic Energy Agency, Managing Low Radioactivity Material from the Decommissioning of Nuclear Facilities, Technical report series No.462, Vienna, (2008).

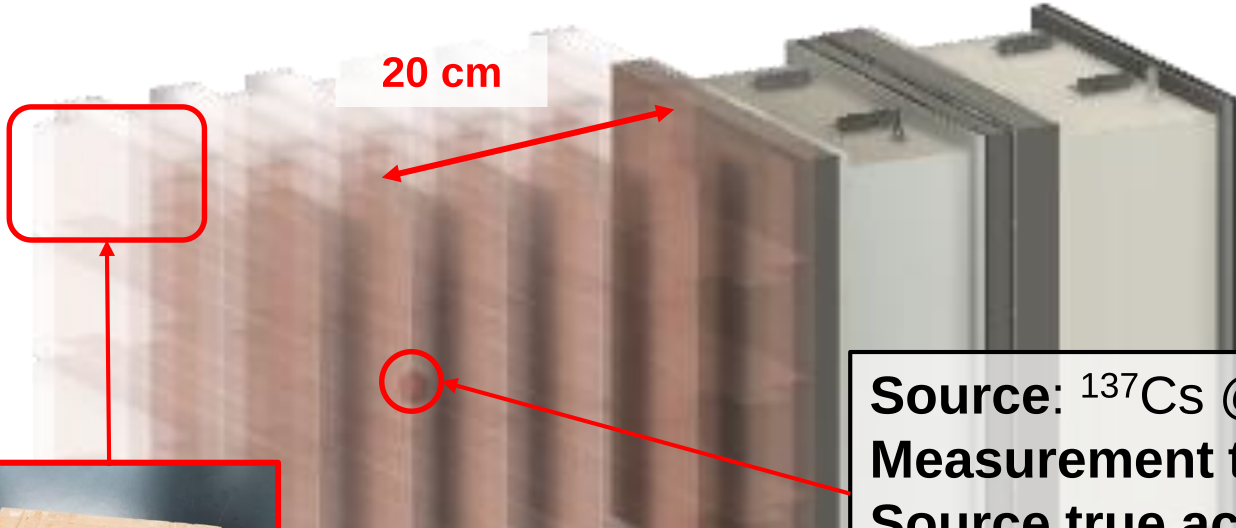
Necessity of hot-spot contamination imaging

- **Hot spot contamination**
  → tend to increase average activity of radioactive waste
  → increase of the volume and disposal cost of radioactive waste

Identifying and removing hot-spot contamination

*ref: International Atomic Energy Agency, Locating and Characterizing Disused Sealed Radioactive Sources in Historical Waste , IAEA Nuclear Energy Series No. NW-T-1.17, Vienna, (2008).

3D Compton imaging for internal contamination

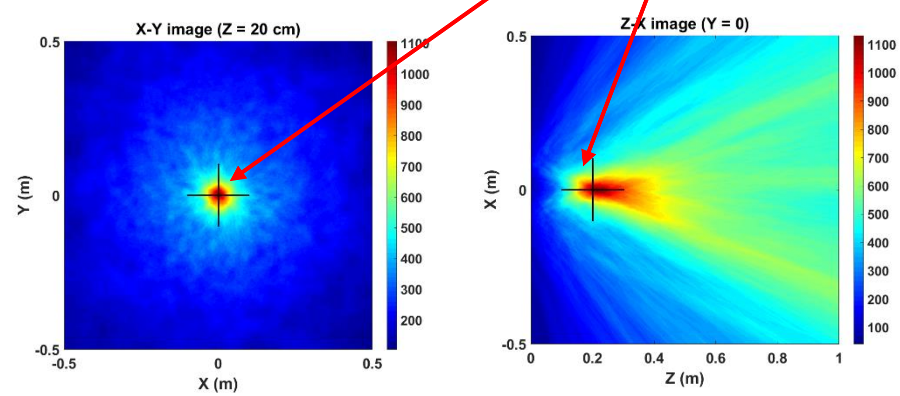


Source: ^{137}Cs @(0, 0, 20 cm)
Measurement time: 10 min.
Source true activity: 7.39 µCi
Estimated activity: **7.05 ± 0.68 µCi**

Brick: 5.0×11.4×23.0 cm^3, 2.5 kg (ρ=1.91 g/cm^3)

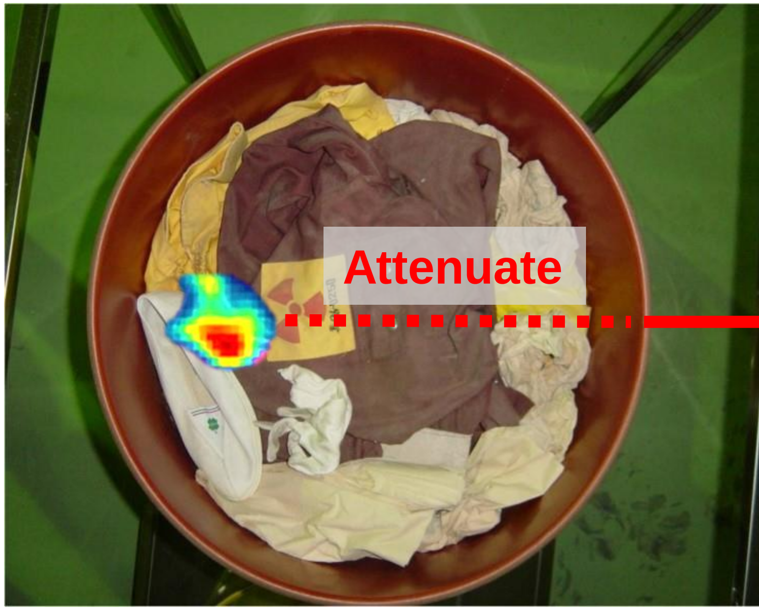
Large-Area Compton Camera (LACC)

- Uses large detectors (a few tens cm)
  → high imaging sensitivity
  (a few tens of times higher)
  → **3-D imaging capability**
  & **Estimation activity capability**

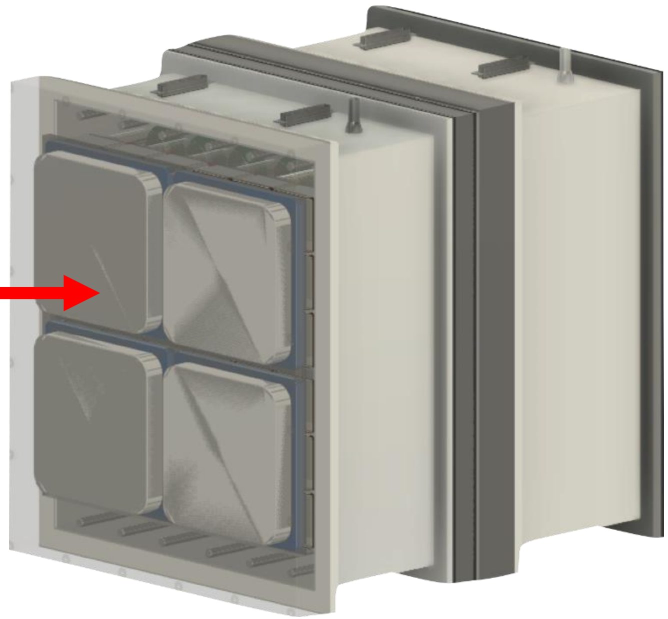


Ref: Y. Kim et al, "Large-Area Compton Camera for High-Speed and 3-D Imaging," IEEE Transactions on Nuclear Science, vol. 65(11), pp. 2817-2822, (2018).

Necessity of attenuation map for hot-spot analysis



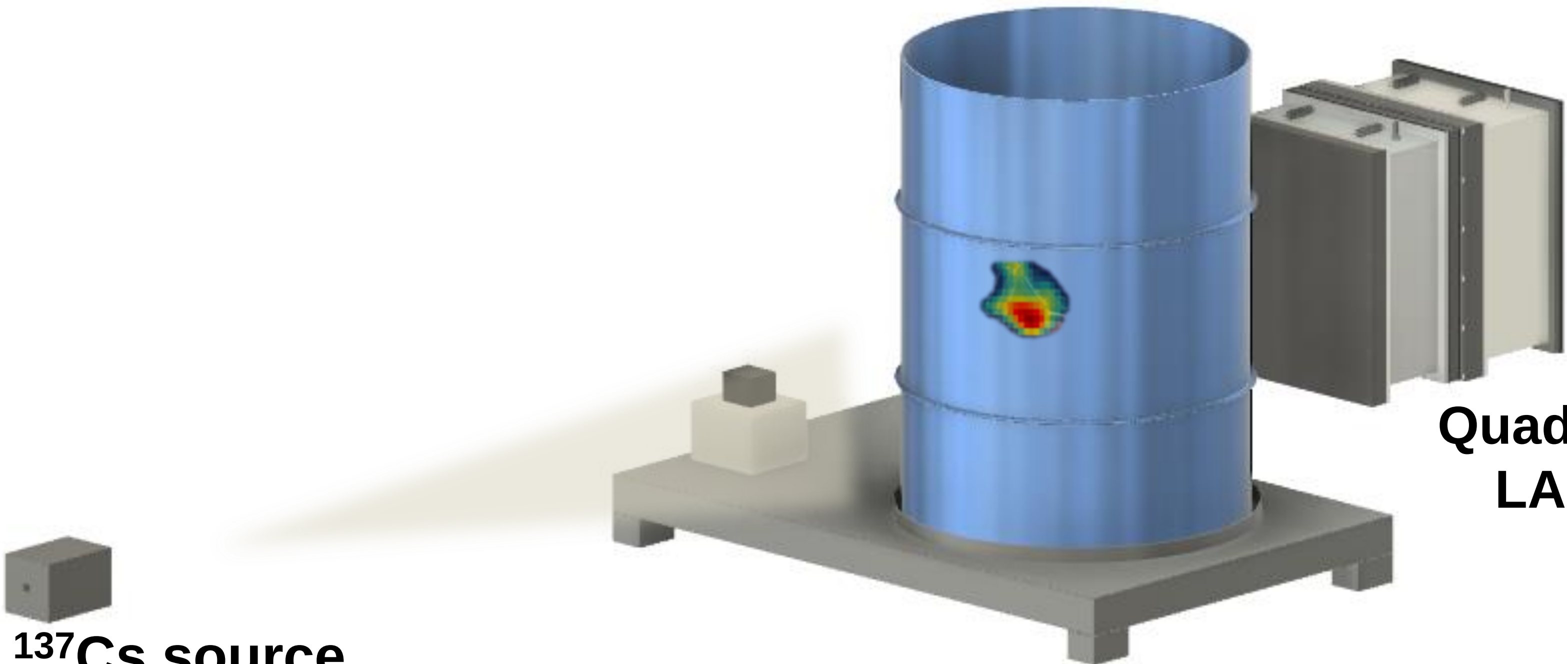
Large-Area Compton Camera



- **Accuracy enhancement of radioactive waste sorting process**
  - → 3-D image of hot-spot & Structural image of waste drum
  - → Quantitative analysis of hot-spot contamination

➡ **Distribution of linear attenuation coefficient inside radioactive waste drum**

Objective of this study



Compton CT
(Transmission imaging)

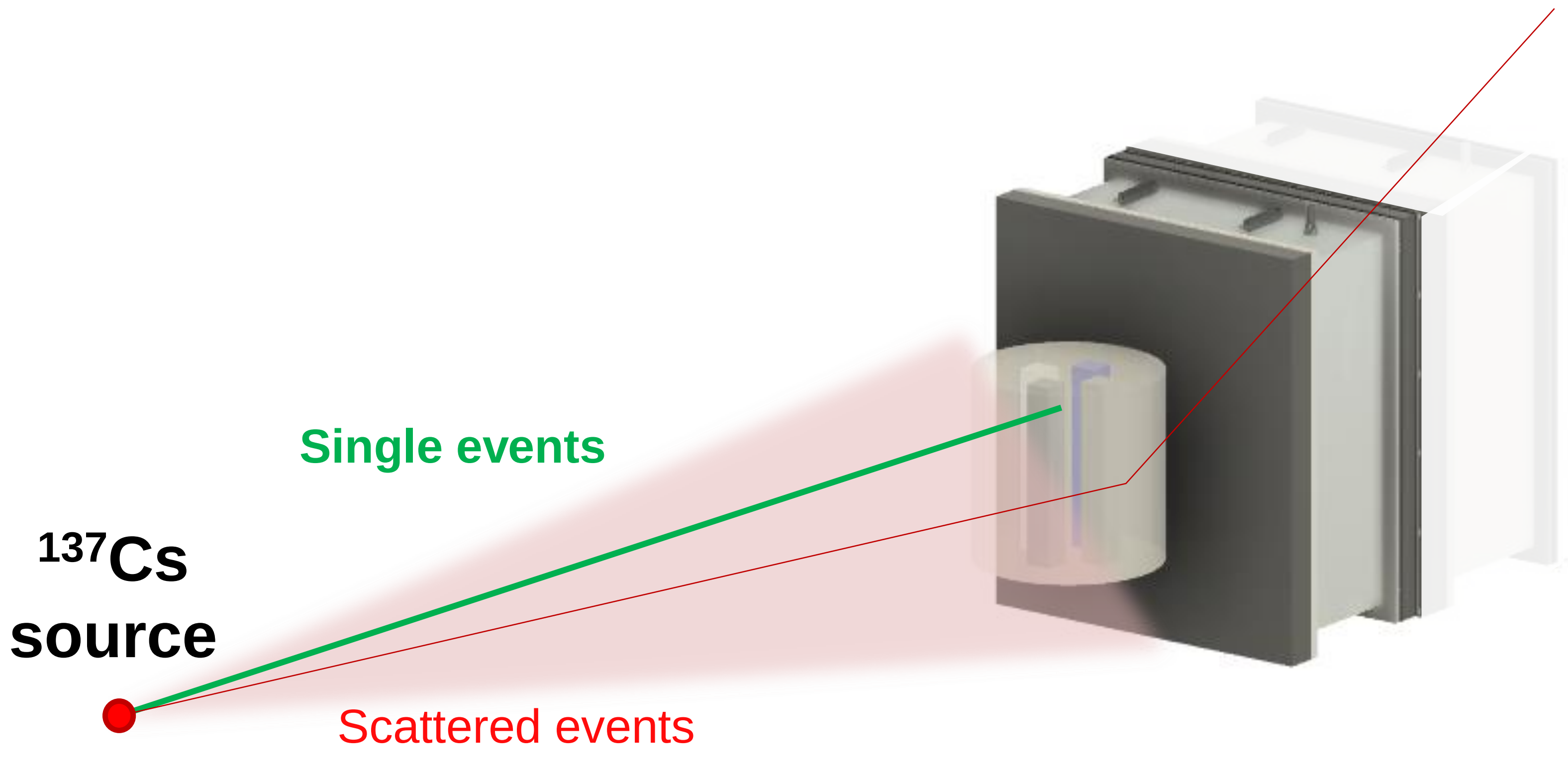
Compton imaging
(Emission imaging)

→

Activity estimation of hot spot in waste drum

Materials and Methods

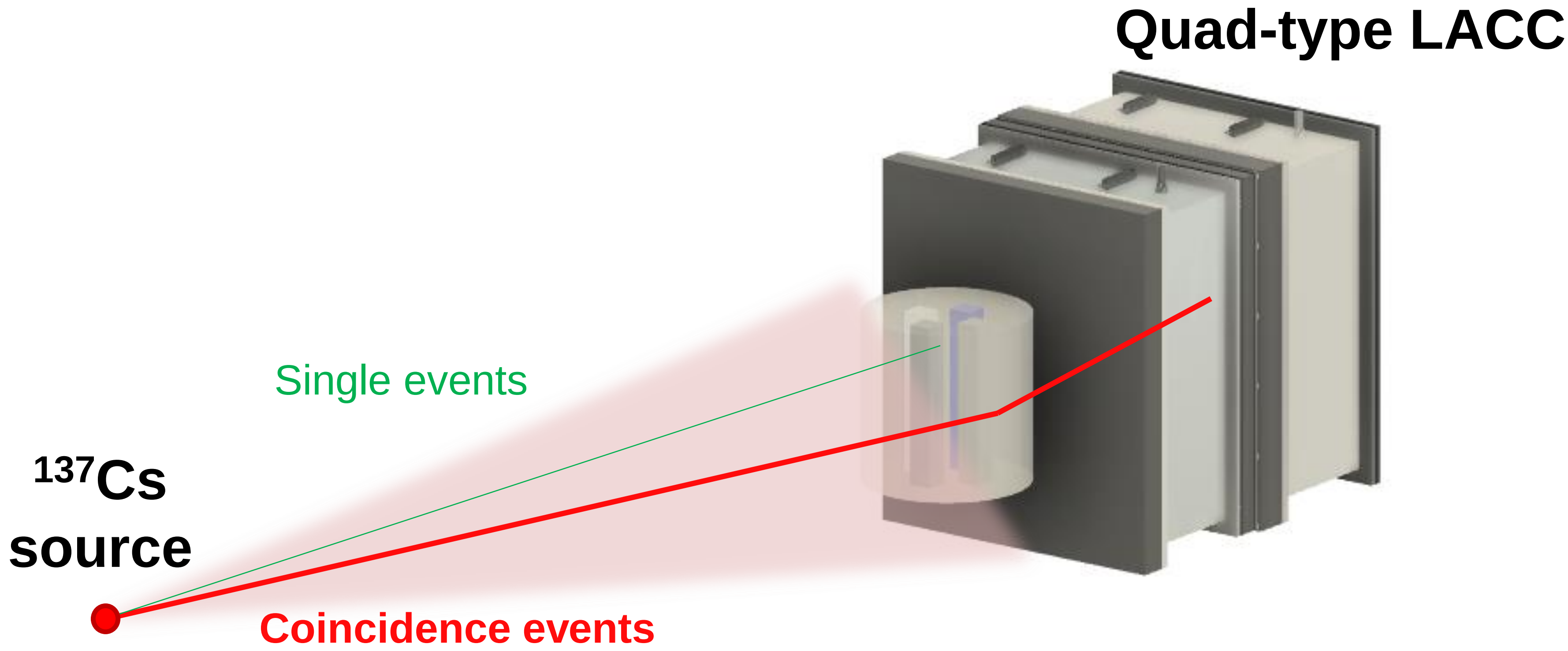
Principle of conventional gamma CT



<u>Single event</u>

- ➢ Using <u>energy window</u>
- ➢ Select an event in which the photon is fully absorbed in detector
- ➢ Loss of Compton scattered events

Principle of Compton CT

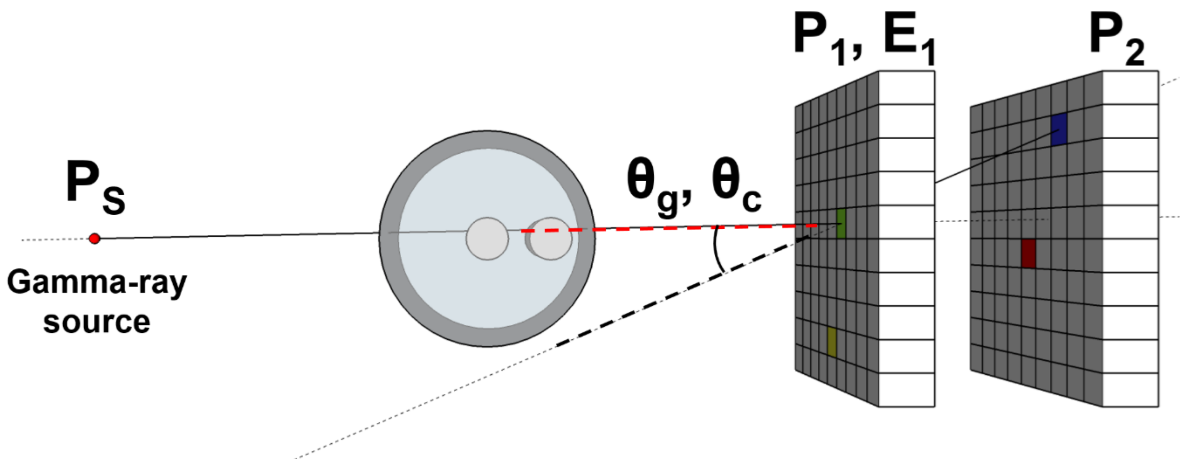


Coincidence event

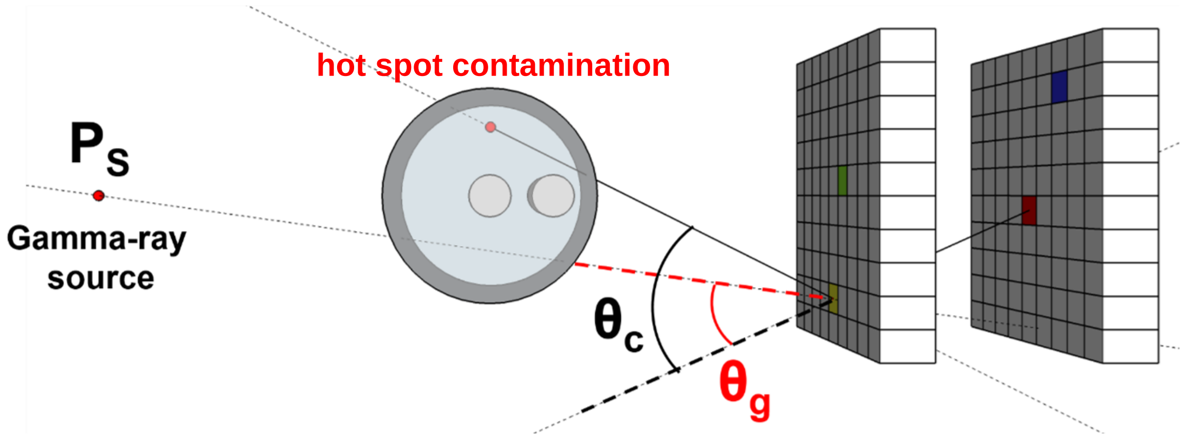
- **Using Compton kinematics**
- **Select an event in which the photon scatters in first detector and then interacts in second detector coincidentally**

Principle of Compton CT

Selection of effective events for coincident events

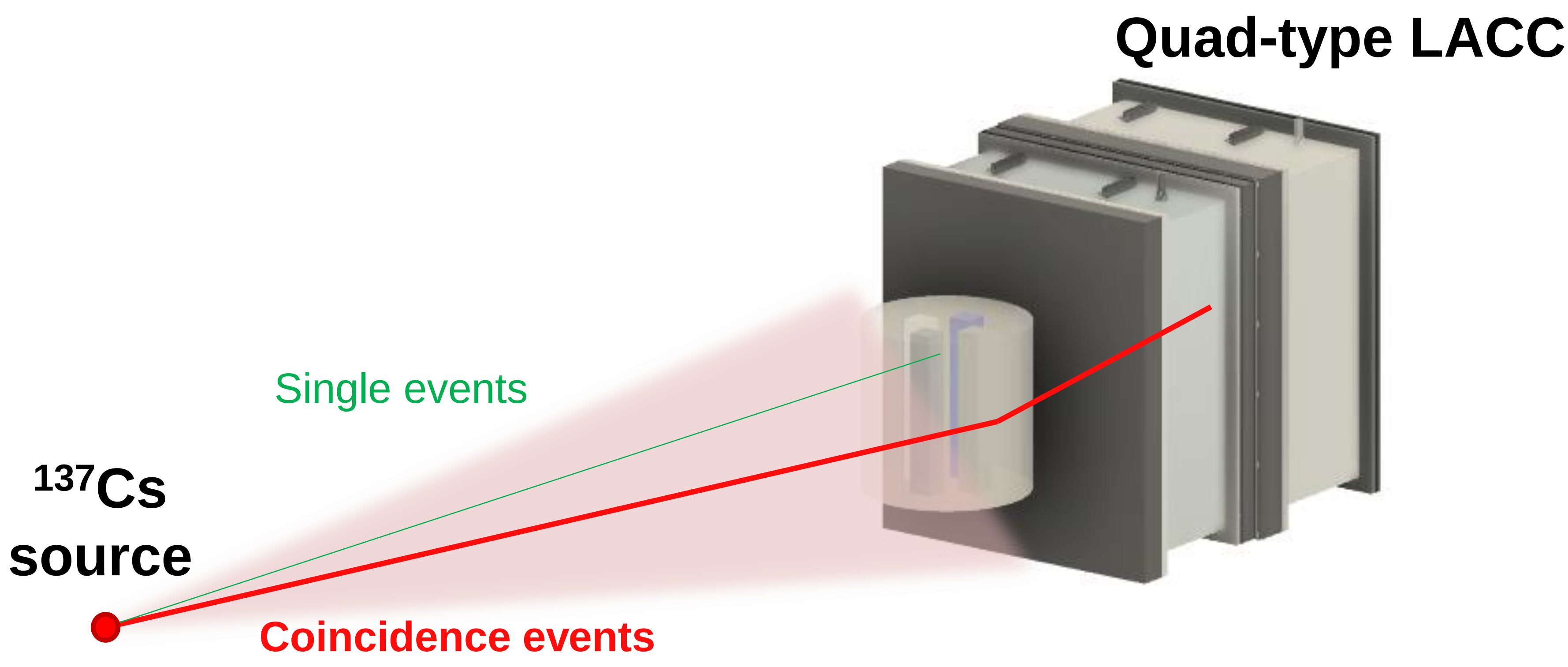


(a) Examples of effective events for coincident events



(b) Examples of non-effective events for coincident events

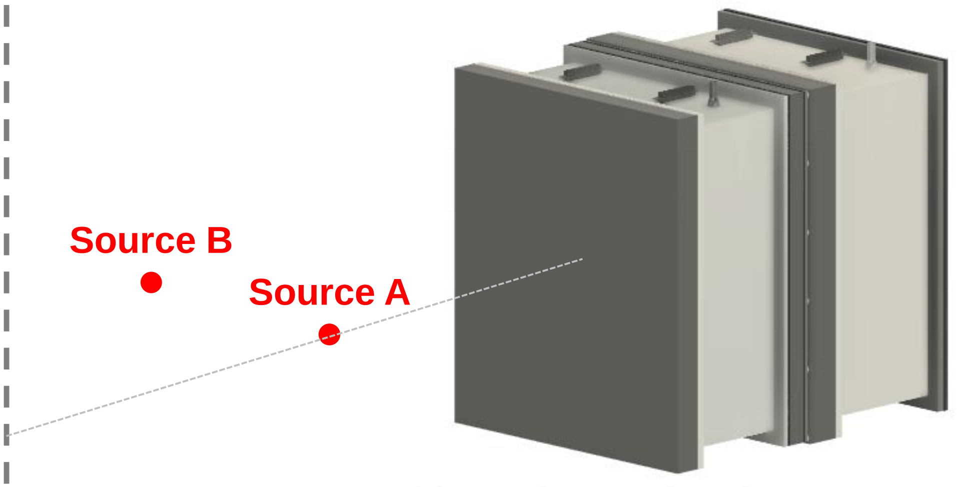
LACC-based Compton CT



<u>LACC-based Compton CT</u>

- Using two position-sensitive detectors
  - → making sinogram with both **single events** and **coincidence events**
  - → Increasing of efficiency and precision.
  - → **No need of extra equipment**

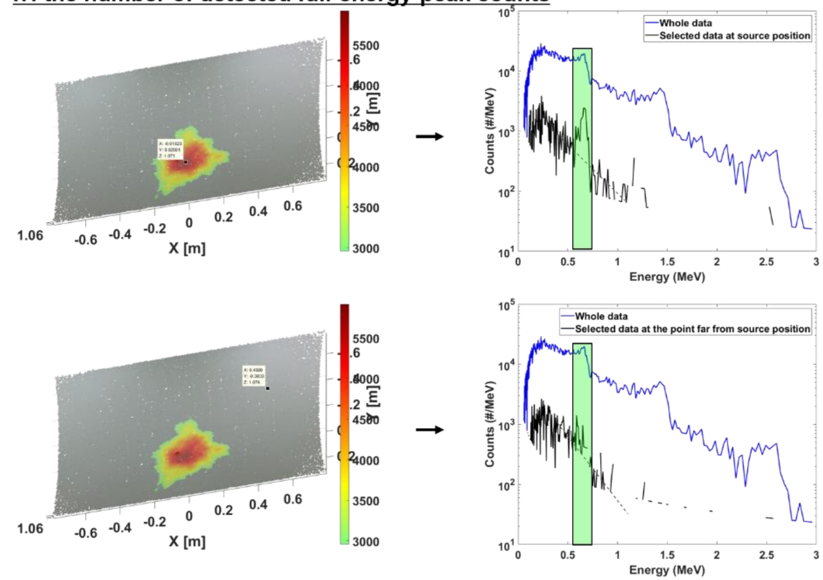
Activity quantification by Compton camera



Measurement with **undetermined** geometry

→ ***ε is UNKNOWN.***

N: the number of detected full-energy-peak counts



$$\boldsymbol{A = \frac{N}{tY\varepsilon}}$$

A: activity of the source

t: measurement time → easy to know

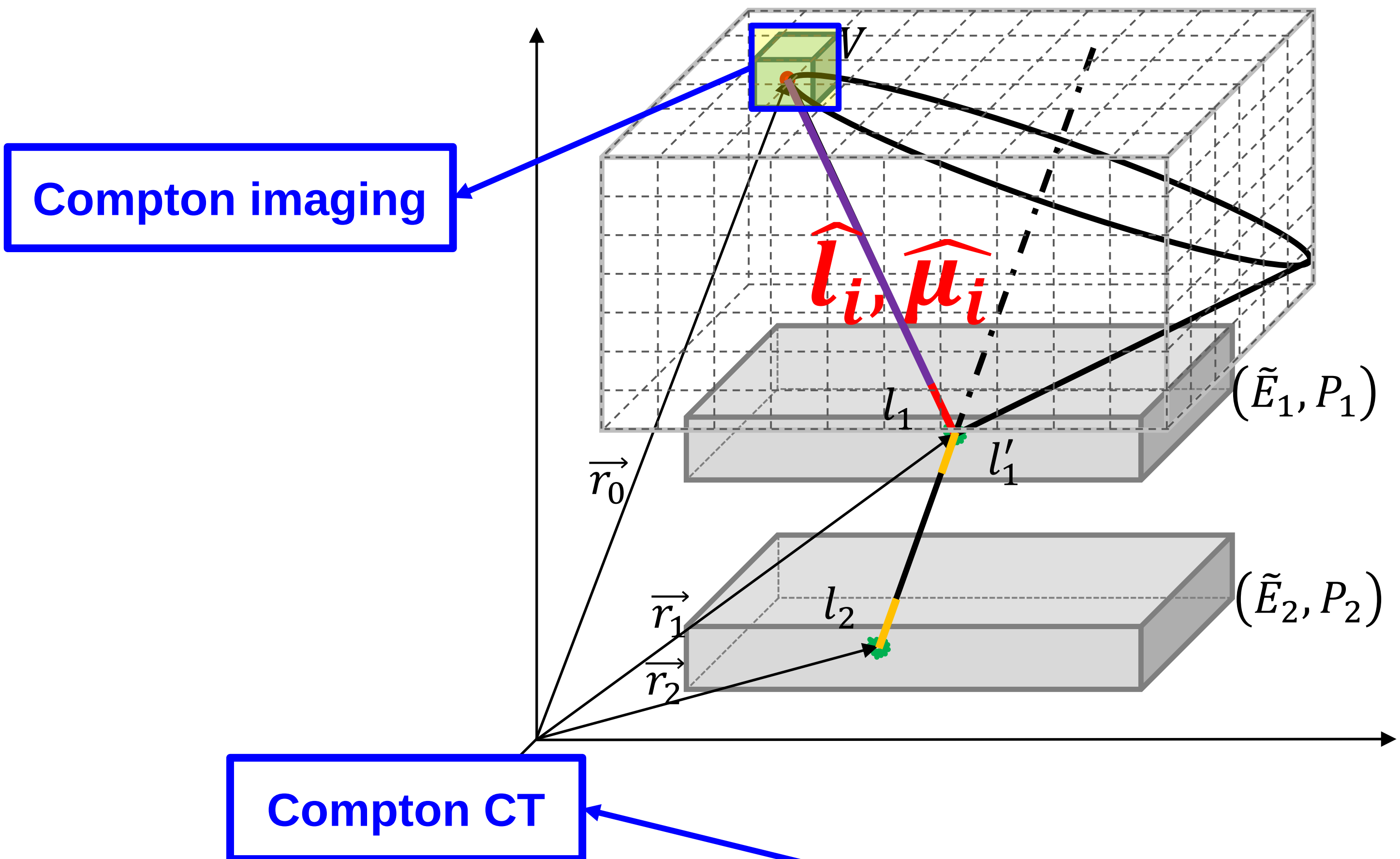
Y: gamma-ray emission yield → easy to know

N: the number of detected full-energy-peak counts → already studied

ε: full-energy-peak detection efficiency → complicated formula

Efficiency of Compton camera (internal)

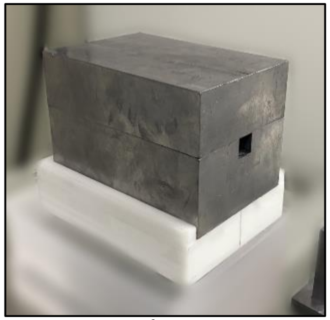
ε: full-energy-peak detection efficiency

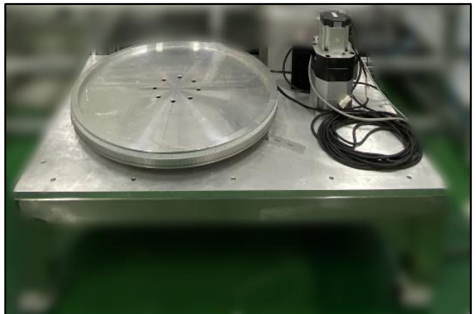


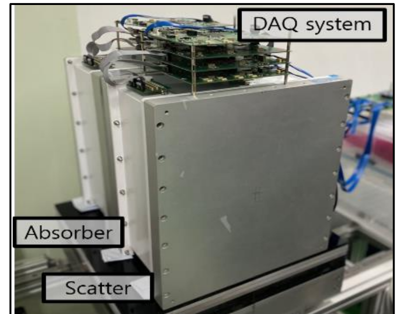
$$\varepsilon \propto \int_V d^3 r_0 \int_{P_1} d^3 r_1 \frac{e^{-(\sum \boxed{\widehat{\mu_i}} \widehat{l_i} + \mu_1 l_1)}}{|\vec{r}_1 - \vec{r}_0|^2} \int_{P_2} d^3 r_2 \frac{e^{-\mu_2 (l'_1 + l_2)}}{|\vec{r}_2 - \vec{r}_1|^2} \frac{d\sigma_0^C}{d\Omega_1} \mu_{2a}$$

Ref: E. Muñoz et al., Physics in Medicine & Biology., 63.13 (2018): pp 0–18.

Components of Compton CT system





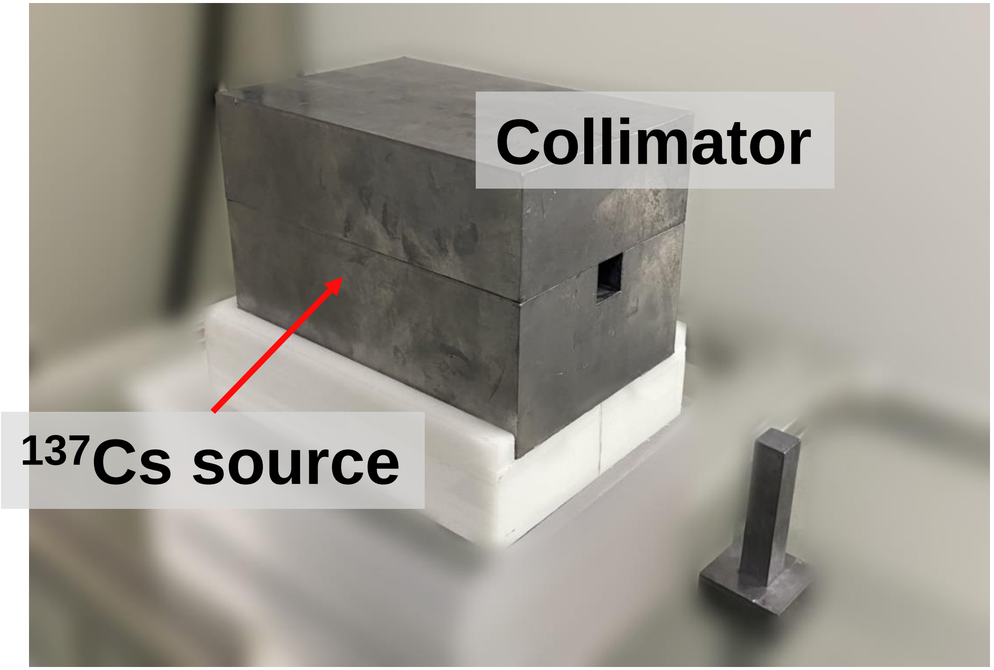


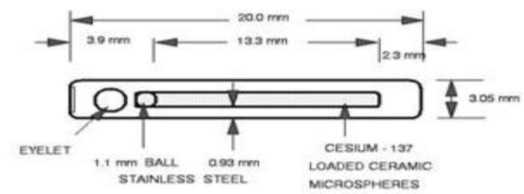
^{137}Cs Source & collimator

Rotation system

Detector module

Gamma-ray source for CT

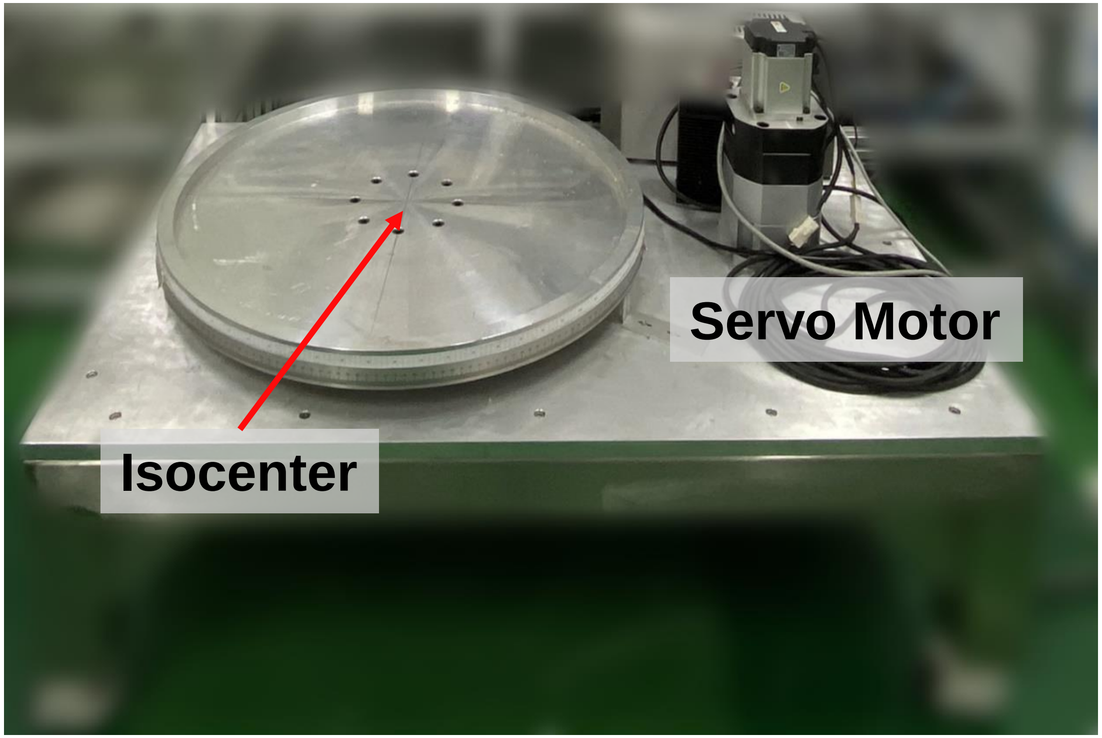




Cs - 137 Intracavitary tube source for manual afterloading, 3 M, series 6500 .

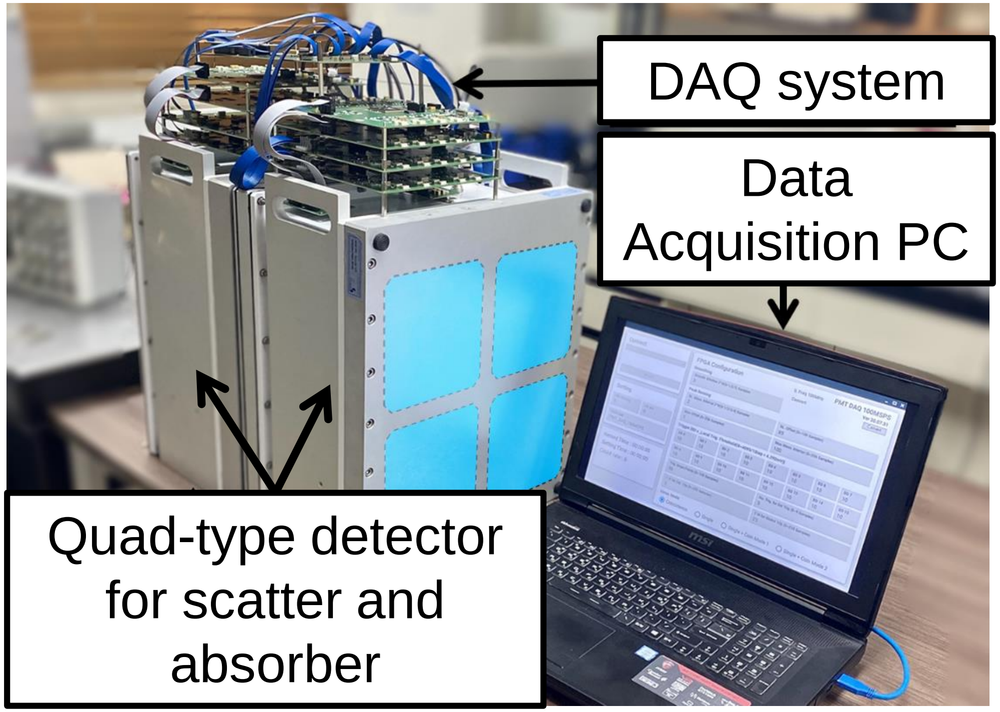
- **Gamma-ray source for CT**
  - <u>Source: 32 mCi ^{137}Cs tube source (KIRAMS)</u>
  - Collimator: lead collimator (10×10×15 cm^3)
    → Generate cone-beam-shaped gamma-rays
    → Opening hole size: 1.5×1.5 cm^2
  - <u>Source-to-detector distance: 4 m</u>

Rotation system



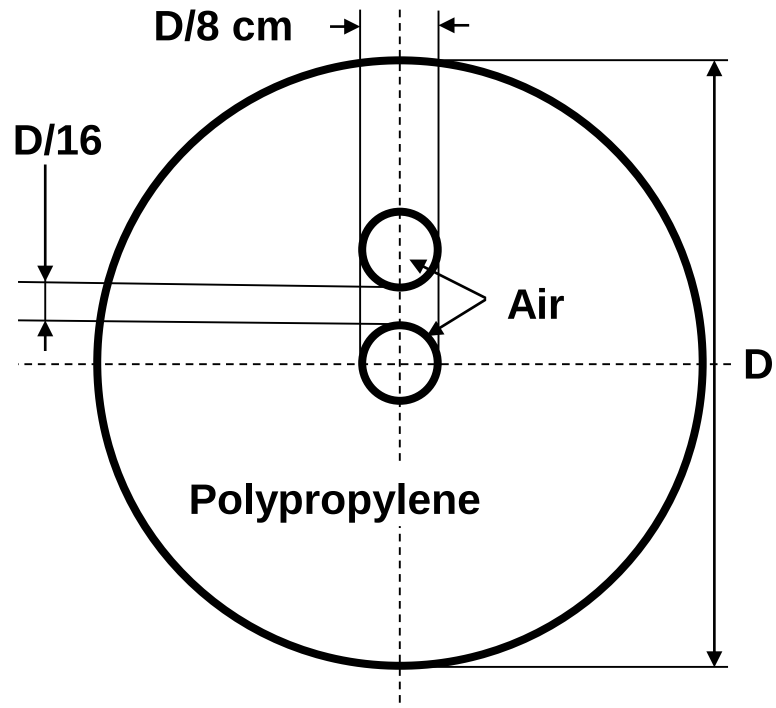
- **Rotation system**
  - Servo motor: MINAS A5B (Panasonic, Japapn)
  - Power range: 50 W – 1500 W
  - Data transmission: EtherCAT
  - <u>Supportable weight: ~800 kg</u>

Large-Area Compton Camera (LACC)



- **Large-area Compton Camera (LACC)**
  - Crystal: 2×2 NaI(Tl) (14.6×14.6 cm^2)
  - PMT: XP3290; Photonis, France
  - High imaging sensitivity
  - **3D Compton imaging**
  - <u>**Energy resolution**: 6.9% (@ 662 keV, ^{137}Cs)</u>
  - <u>**Position resolution**: 5 mm</u>

Compton CT experiment: IAEA phantom

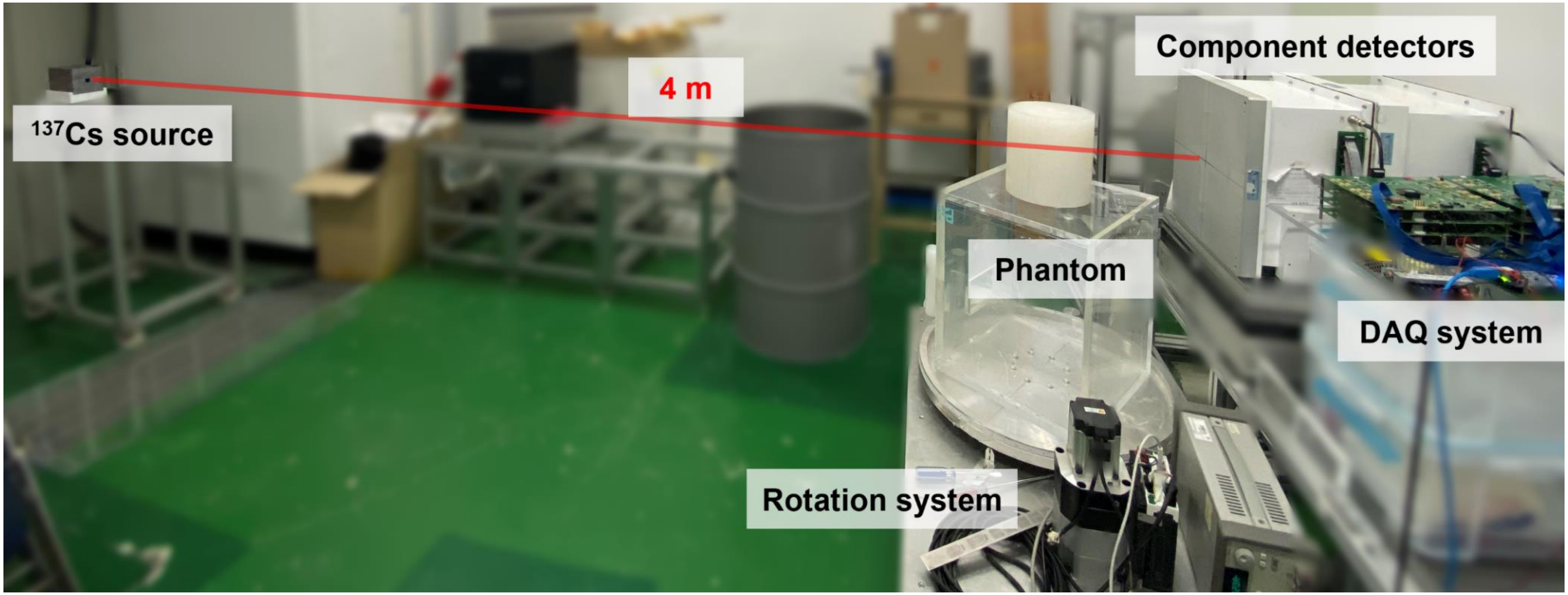


- **Imaging object**
  - <u>IAEA standard phantom for industrial gamma CT</u>
  - Diameter: 20.32 cm (USA) / 40 cm (Korea)
  - Height: 22 cm
  - Material: PP (ρ = 0.91 g/cm^3)
  - Two holes were filled with air

Object for experiments: 200 L drum

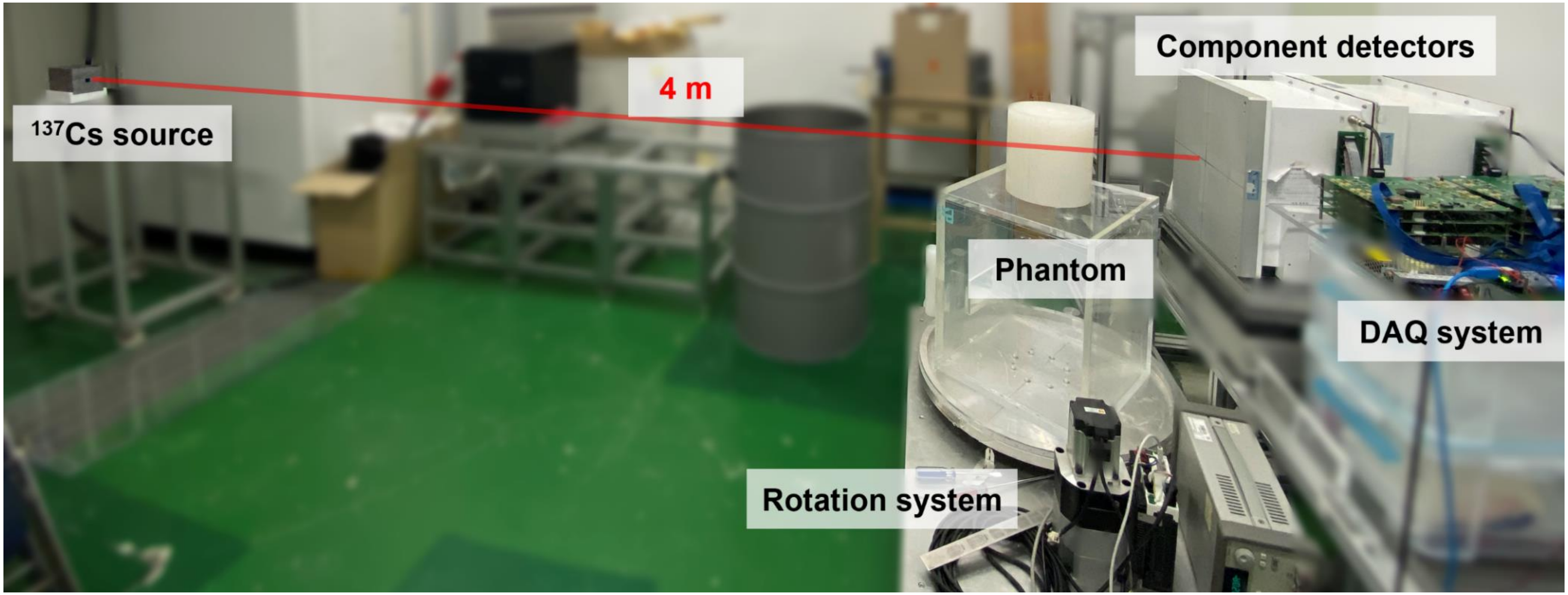
- **200 L Drum**
  - Dimension: Φ57 cm × 85 cm (10T)
  - Material: iron
  - Various object inside a drum

Compton CT set up



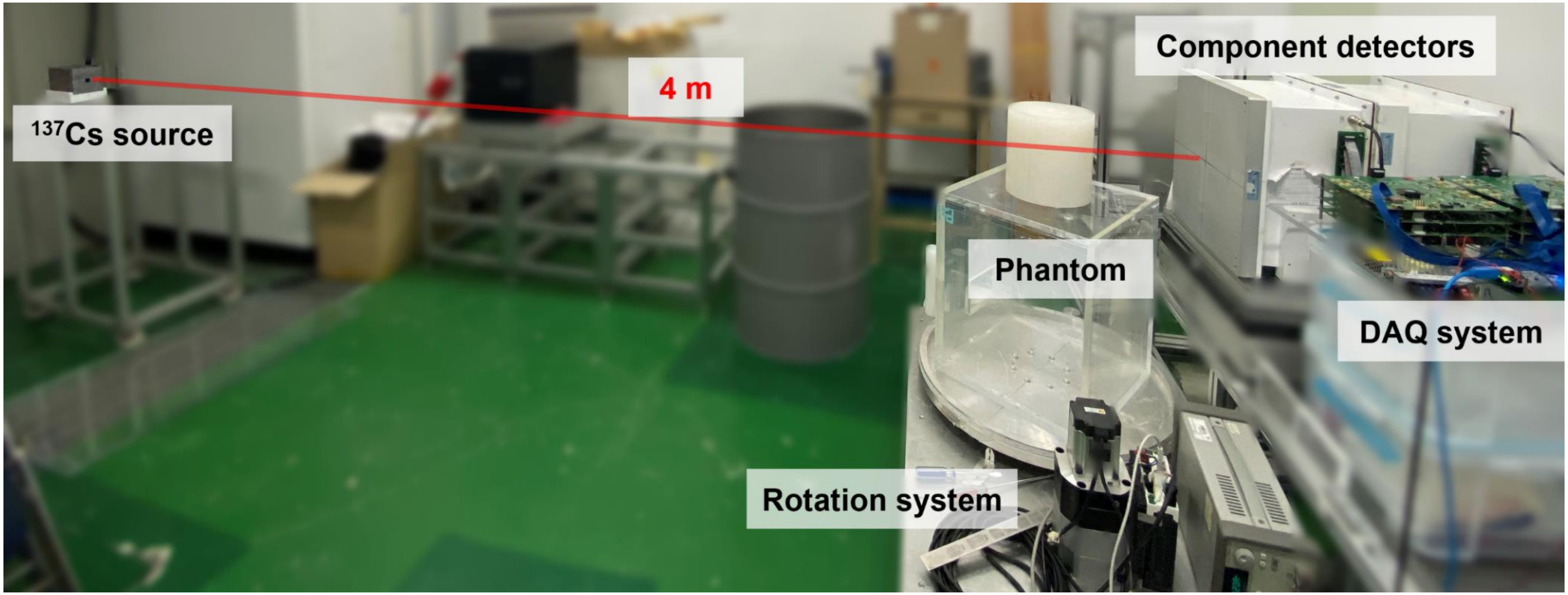
- **Compton CT set up**
  - Source-to-detector distance: **4 m**
  - Isocenter-to-detector distance: **35 cm**
  - Supportable weight of drum: **~800 kg**
  - Supporting dimension: Φ60 cm

Compton CT set up



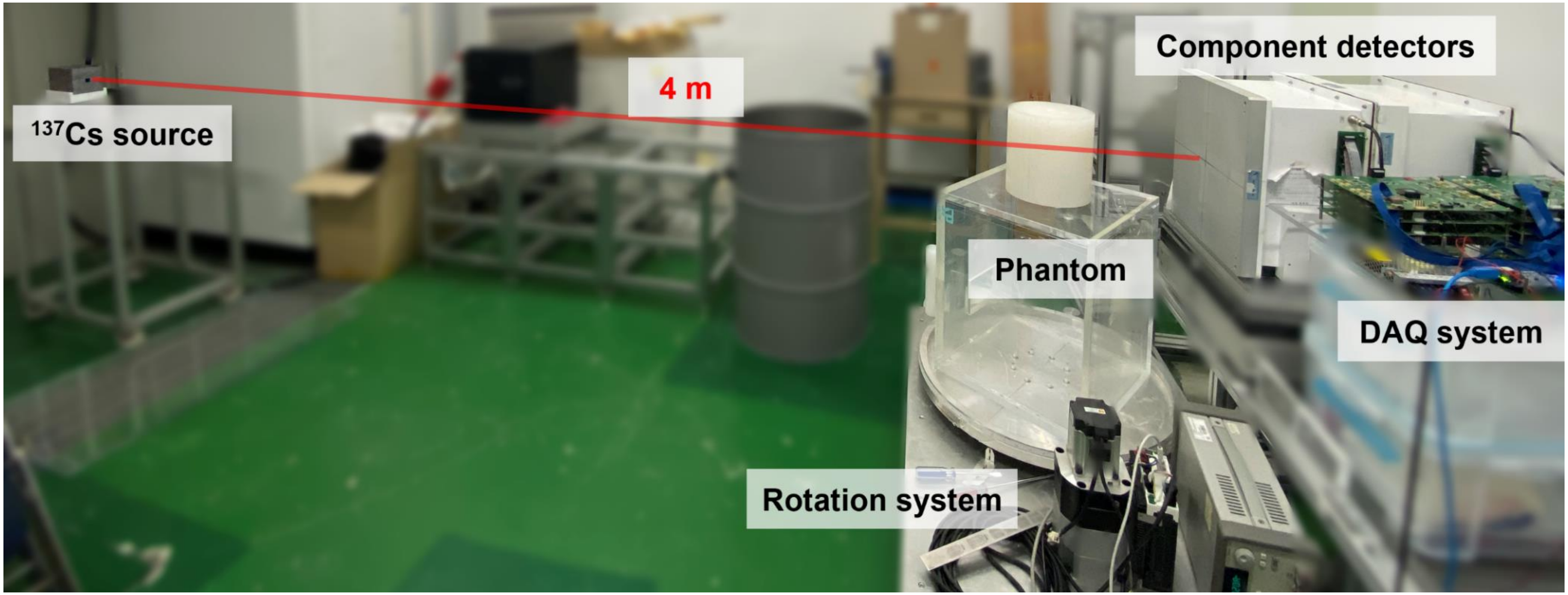
- **Compton CT set up**
  - Rotation interval: **5 degree**
  - Number of projections: **72 projections**
  - Measurement time: **20 sec / projection**
  - Sinogram pixel size is **5 mm**, CBCT reconstructed voxel size is **5 mm**

Compton CT set up



- **Selection of effective events by Compton CT**
  - Energy window of **662±45 keV**
  - Scatter angle difference window of **± 15°**
- **Cone beam CT Image reconstruction**
  - Cone beam filtered back projection (CBCT-FBP)
  - with the Hann filter (cutoff frequency 0.75)

Root Mean Square Error (RMSE) estimation



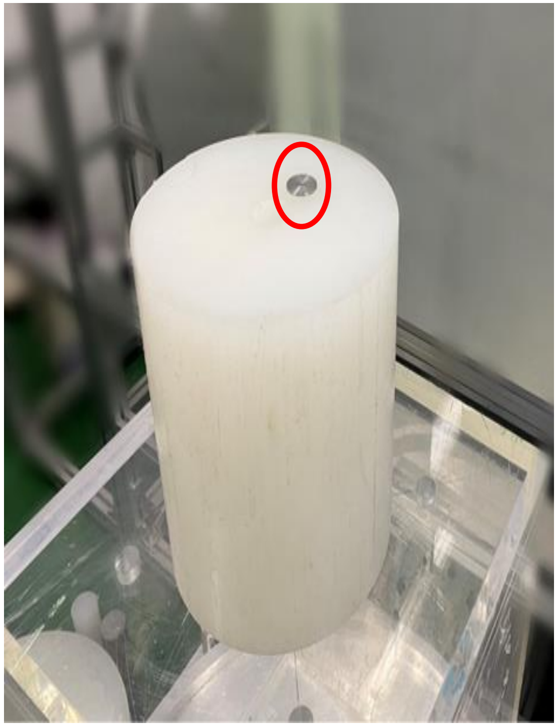
➢ To estimate the reconstruction error in the attenuation maps, **Root Mean Square Error (RMSE)*** was calculated for selected cases.

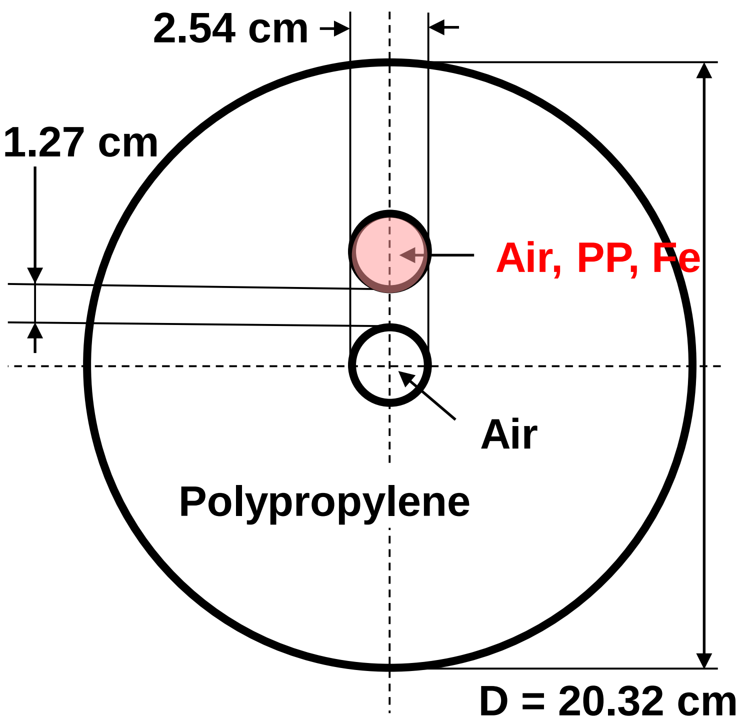
$$RMSE = \frac{\sqrt{\sum_{i=1}^{N} (\mu_i^{recon} - \mu_i^{true})^2}}{N}$$

*ref: TECDOC, IAEA. "1589, Industrial Process Gamma Tomography, Final Report of a Coordinated Research Project 2003–2007." *International Atomic Energy Agency, Austria* (2008).

Results

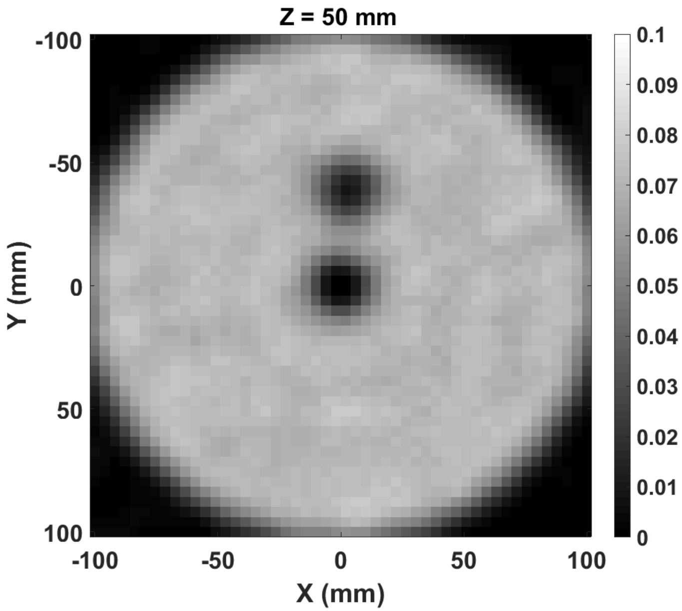
Compton CT experiment: IAEA phantom

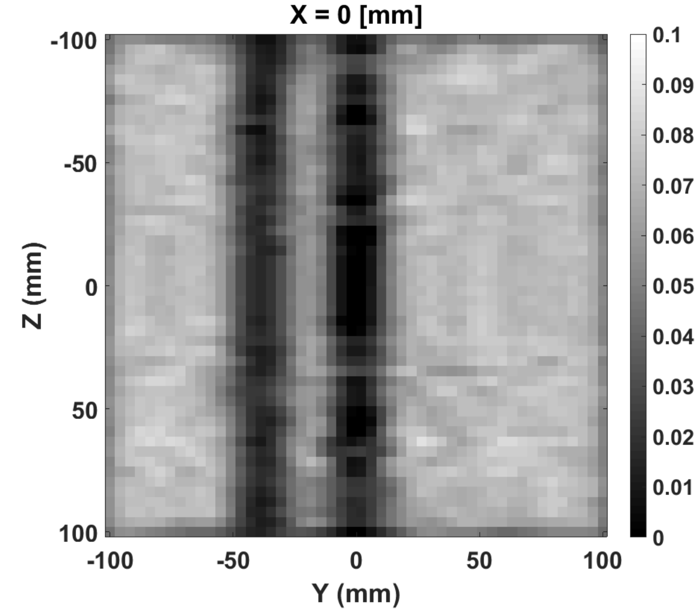


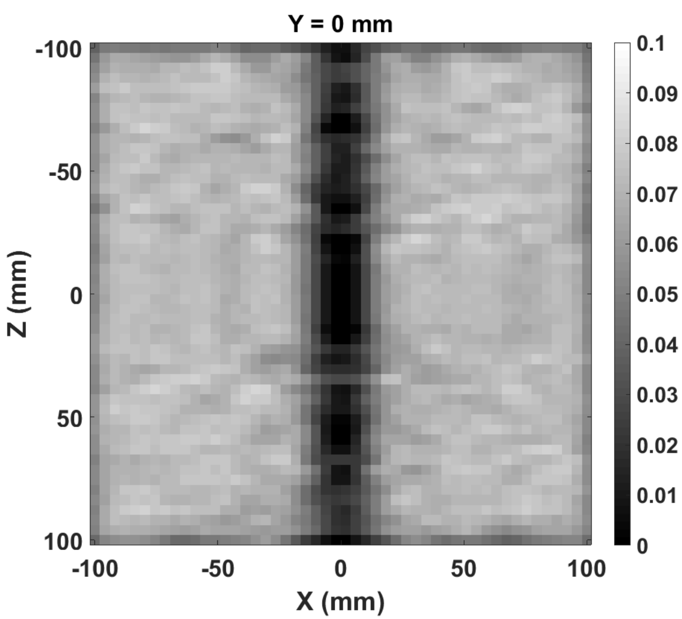


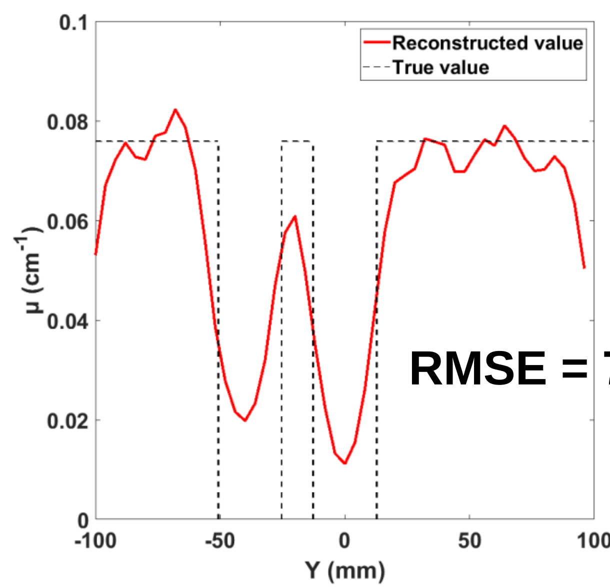
- **Imaging object**
  - IAEA standard phantom (USA)
  - Diameter: 20.32 cm
  - Height: 22 cm
  - Material: PP (ρ = 0.91 g/cm^3)
  - The one holes were filled with air
  - The another was filled with **air**, **PP**, and **Fe pillar**, respectively.

Results: IAEA phantom



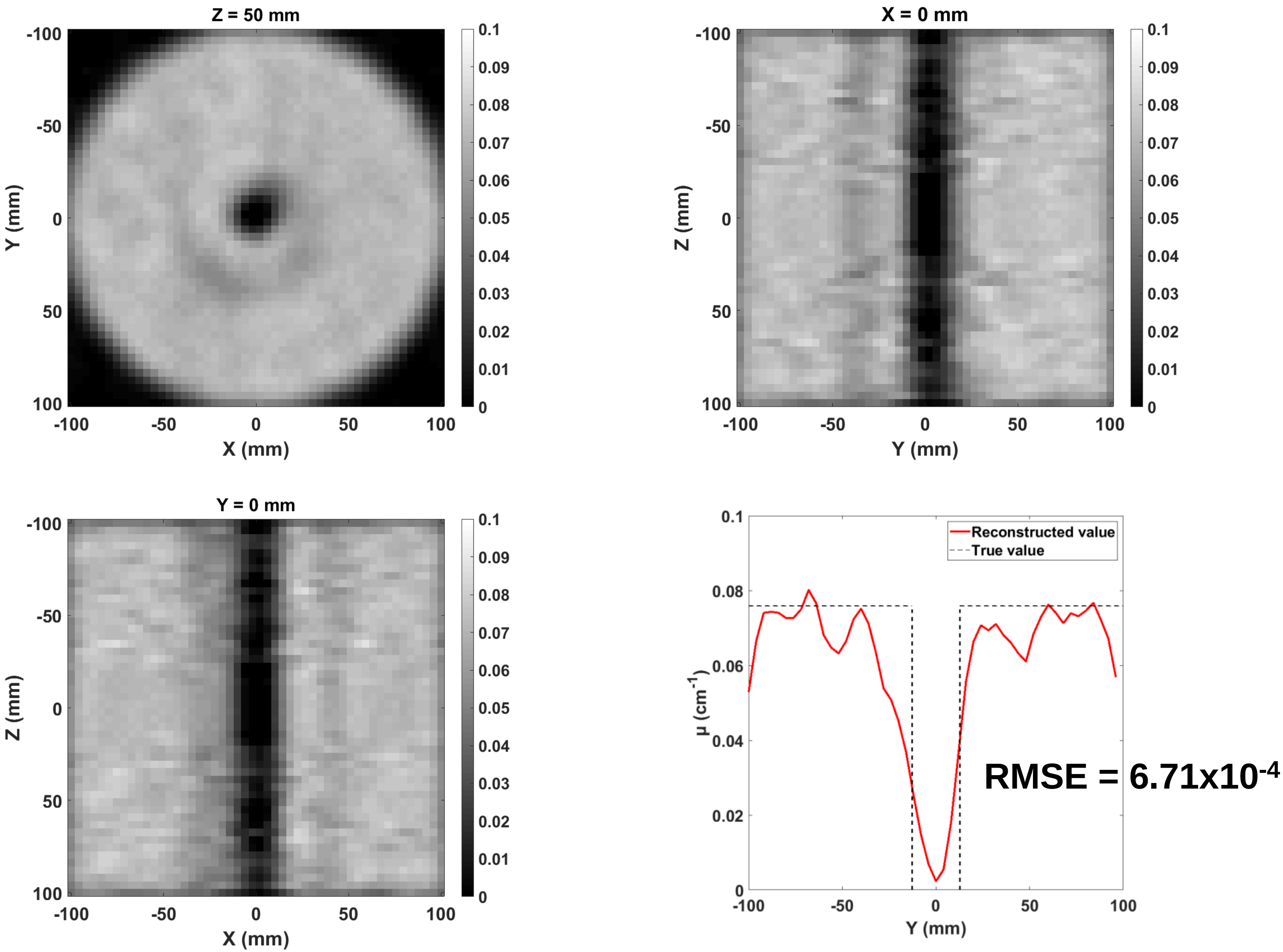




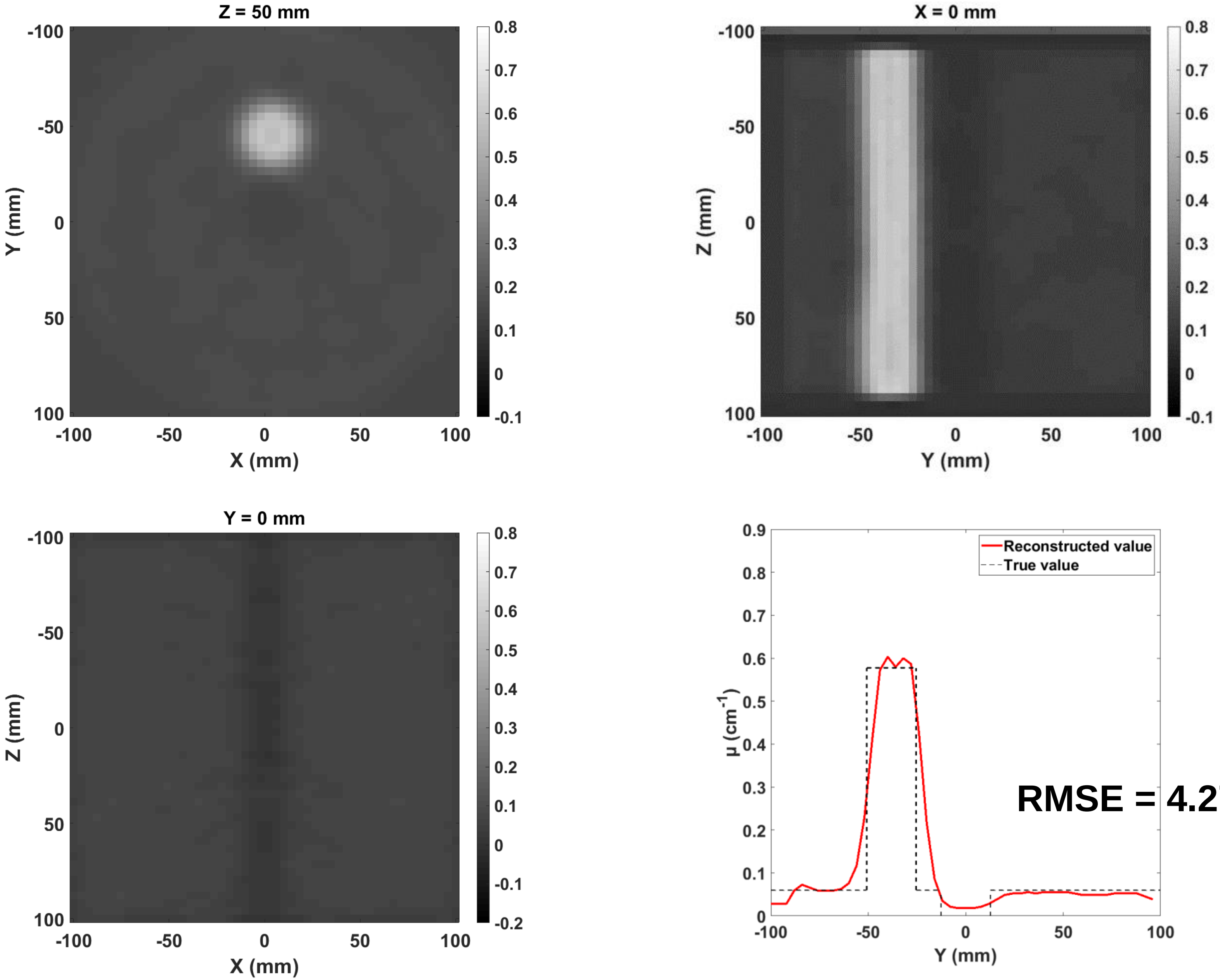


RMSE = 7.23×10^{-4}

Results: IAEA phantom with PP



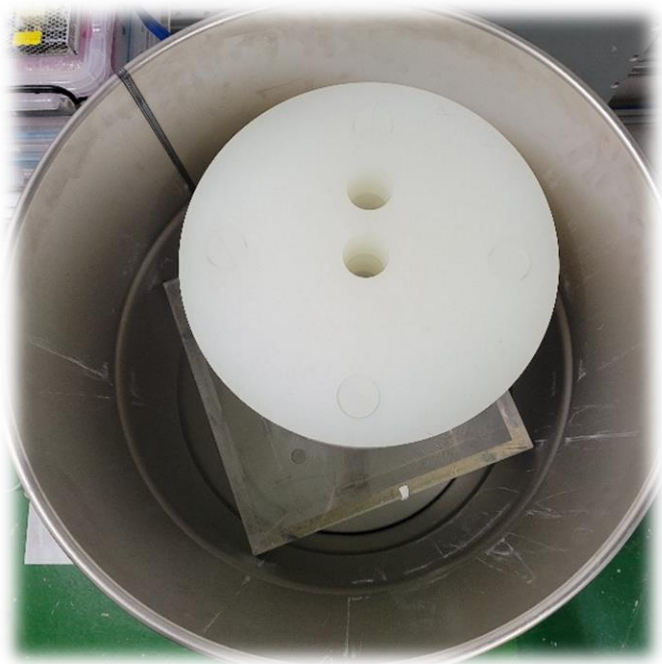
Results: IAEA phantom with Fe

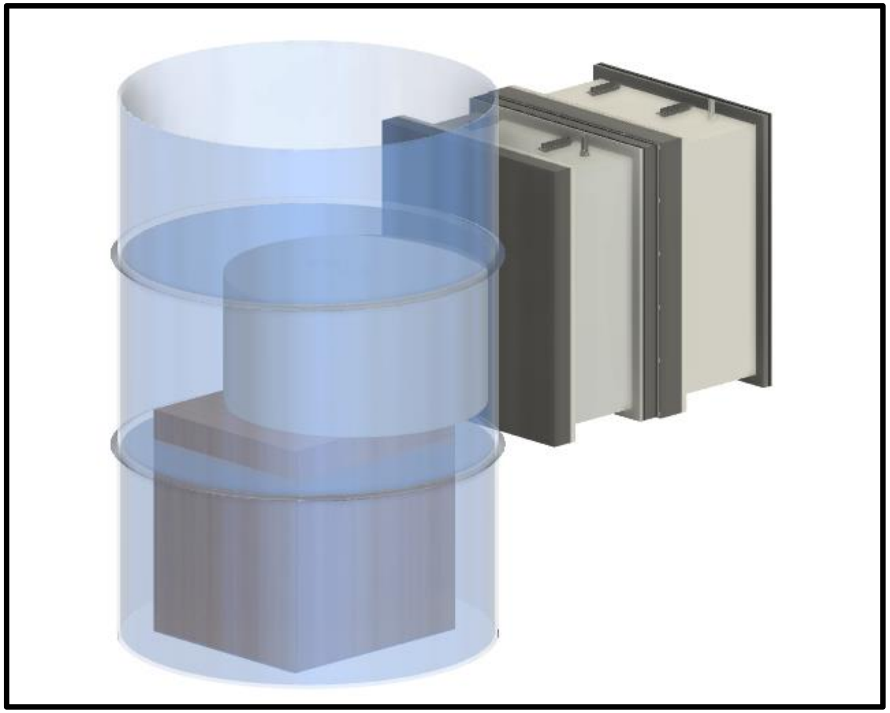


RMSE = 4.27×10^{-6}

Compton CT experiment: 200 L drum

200 L drum with IAEA phantom

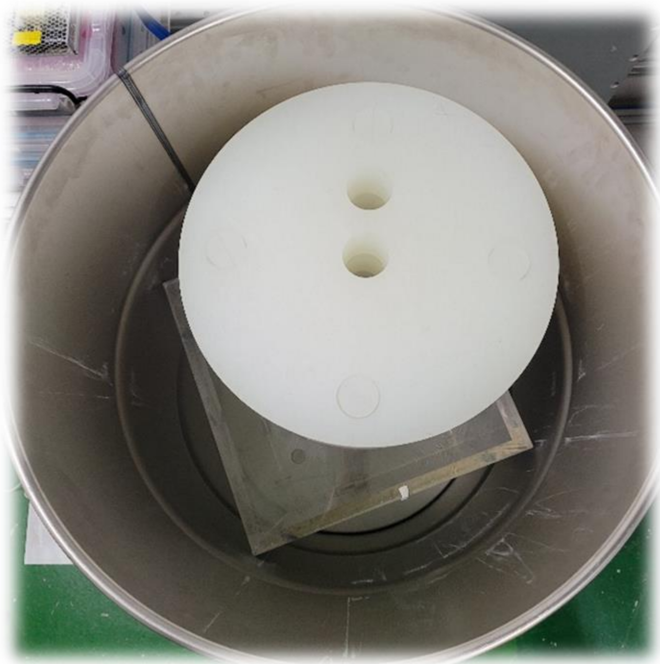


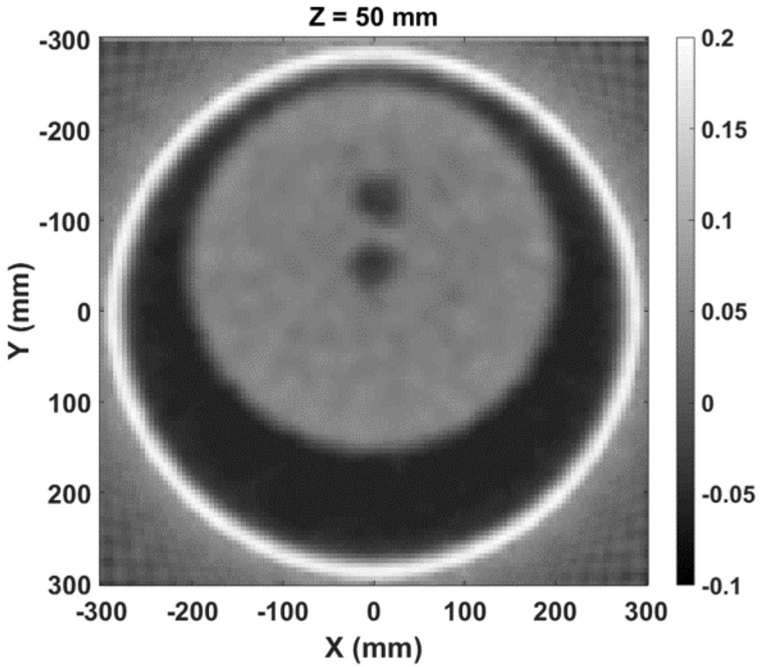


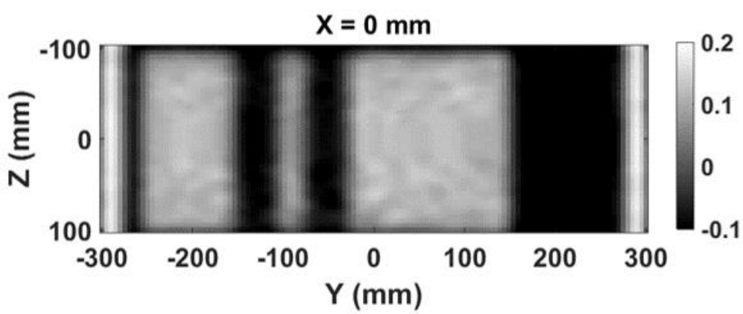
- **Imaging object**
  - 200 L drum with IAEA phantom (Korea, D = 40 cm)
  - IAEA phantom was shifted to 5 cm for isocenter.

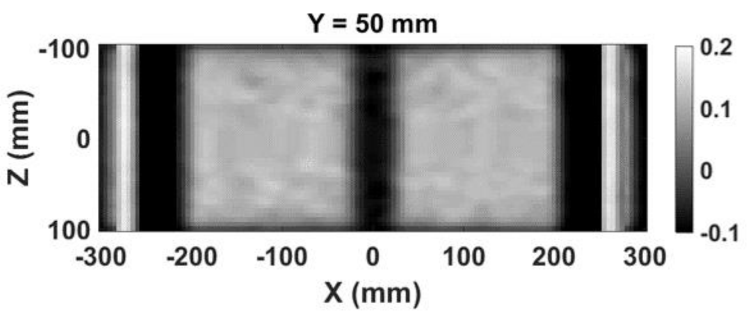
Result: 200 L drum with IAEA phantom

<u>200 L drum with IAEA phantom</u>



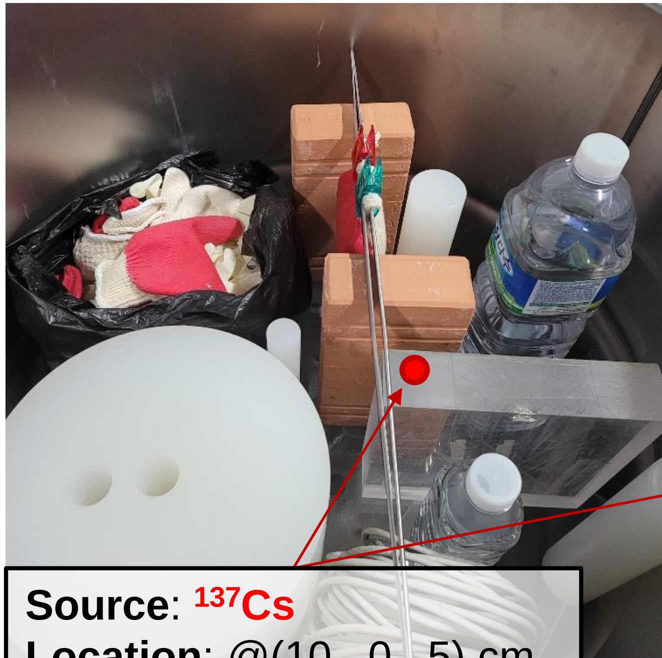




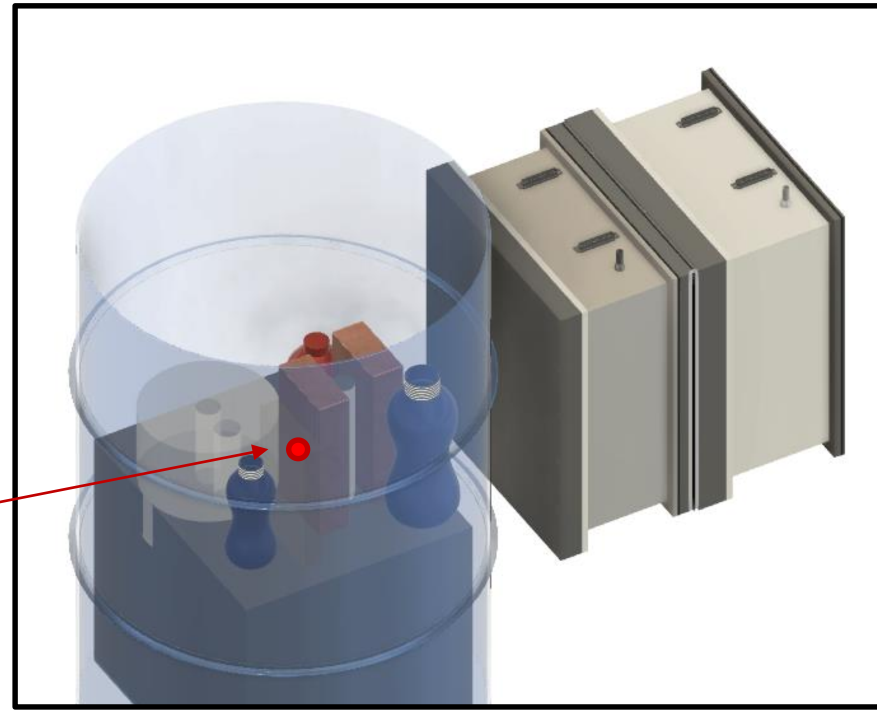


Compton CT experiment: 200 L drum

<u>200 L drum with heterogeneous objects & ^{137}Cs source</u>



Source: ^{137}**Cs**
Location: @(10, 0 , 5) cm
True activity: **7.04 μCi**
Measurement time: 1 min.

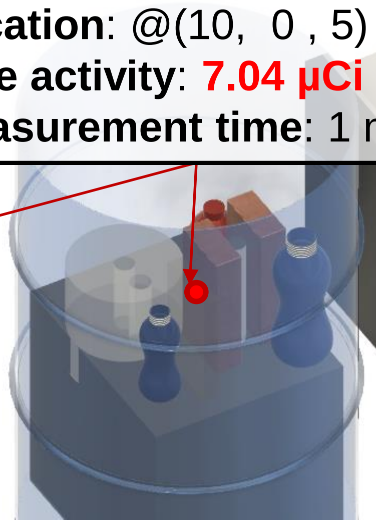


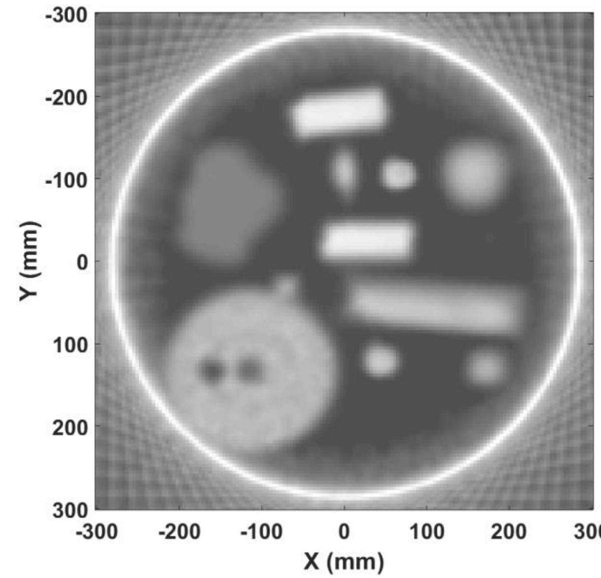
- **Imaging object**
  - <u>200 L drum with IAEA phantom (USA), water bottles, gloves, bricks, phantoms, etc.</u>
  - <u>The glove was filled with sand.</u>

Integrated image: 200 L drum with sources

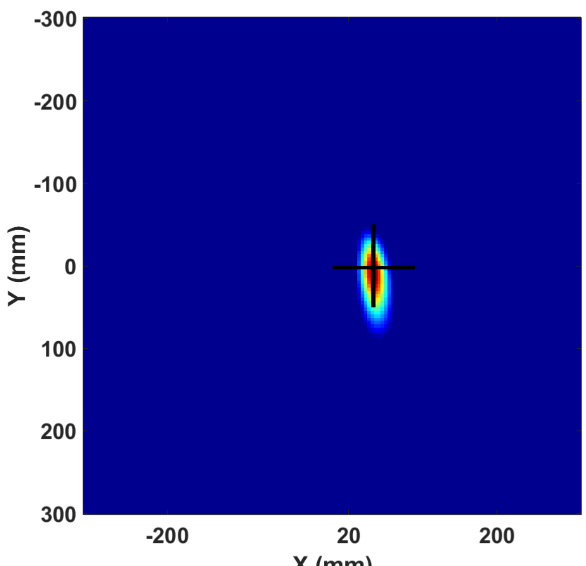
200 L drum with heterogeneous objects & ^{137}Cs source

Source: ^{137}**Cs**
Location: @(10, 0 , 5) cm
True activity: **7.04 μCi**
Measurement time: 1 min.

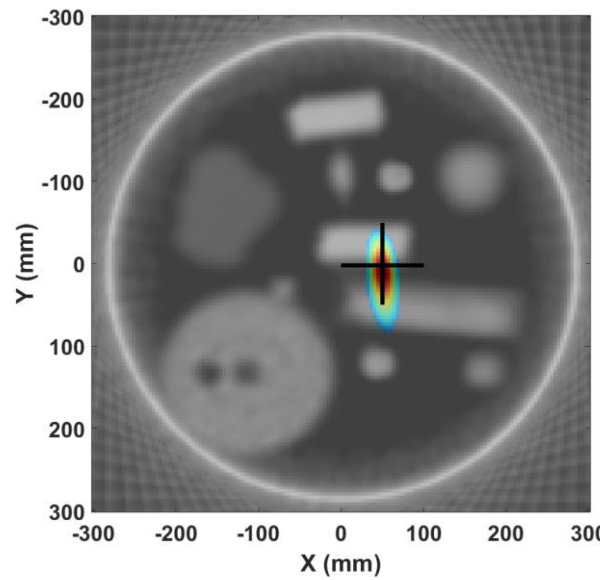




CT image

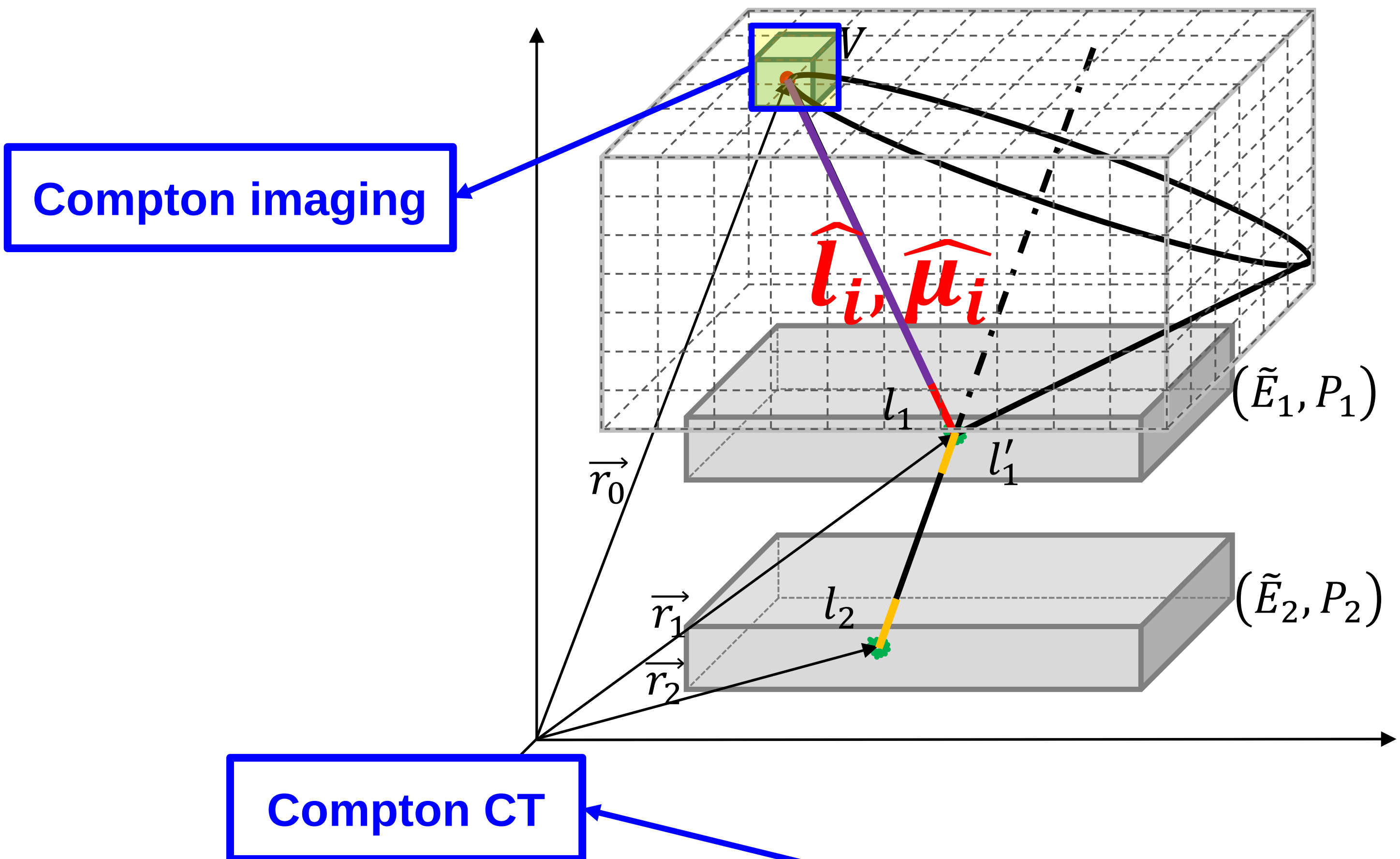


Compton image



Efficiency of Compton camera (internal)

ε: full-energy-peak detection efficiency

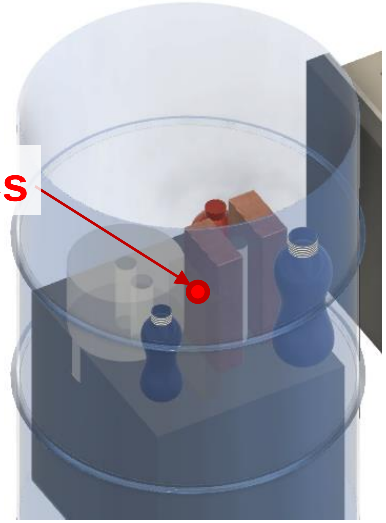


$$\varepsilon \propto \int_V d^3 r_0 \int_{P_1} d^3 r_1 \frac{e^{-(\sum \boxed{\widehat{\mu_i}} \widehat{l_i} + \mu_1 l_1)}}{|\vec{r}_1 - \vec{r}_0|^2} \int_{P_2} d^3 r_2 \frac{e^{-\mu_2 (l_1' + l_2)}}{|\vec{r}_2 - \vec{r}_1|^2} \frac{d\sigma_0^C}{d\Omega_1} \mu_{2a}$$

Ref: E. Muñoz et al., Physics in Medicine & Biology., 63.13 (2018): pp 0–18.

Quantitative analysis of internal hot spot

200 L drum with heterogeneous objects & ^{137}Cs source

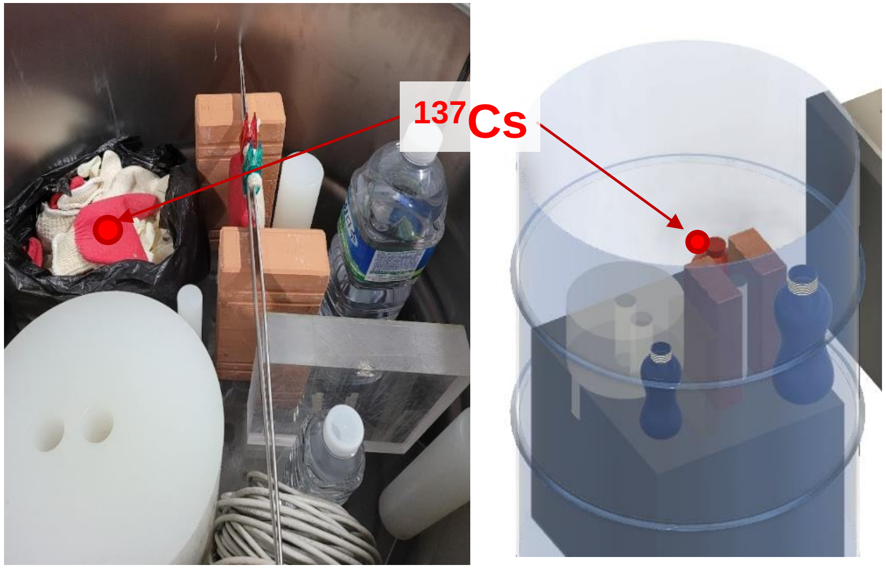


Object: drum with various materials
Source: ^{137}Cs
Location: @(10, 0 , 5) cm
True activity: 7.04 µCi
Measurement time (activity): 20 min.

Condition	True activity (µCi)	Estimated activity (µCi)	Difference
No attenuation map		8.4×10^{-3}	838 times
Avg. attenuation map	**7.04**	3.72	1.89 times
Attenuation map		**8.12**	**1.15 times**

Quantitative analysis of internal hot spot

200 L drum with heterogeneous objects & ^{137}Cs source

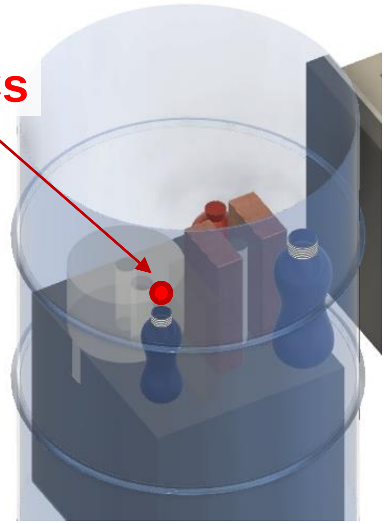


Object: drum with various materials
Source: ^{137}Cs
Location: @(-10, -10 , 5) cm
True activity: 7.04 μCi
Measurement time (activity): 20 min.

Condition	True activity (μCi)	Estimated activity (μCi)	Difference
No attenuation map		1.28	19.64 times
Avg. attenuation map	**7.04**	10.72	1.52 times
Attenuation map		**9.27**	**1.32 times**

Quantitative analysis of internal hot spot

200 L drum with heterogeneous objects & ^{137}Cs source



Object: drum with various materials
Source: ^{137}Cs
Location: @(0, 15 , 5) cm
True activity: 7.04 μCi
Measurement time (activity): 20 min.

Condition	True activity (μCi)	Estimated activity (μCi)	Difference
No attenuation map		1.1×10^{-2}	640 times
Avg. attenuation map	**7.04**	2.53	2.78 times
Attenuation map		**6.81**	**1.03 times**

Conclusion

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- In the present study, as a preliminary study, a LACC-based Compton CT was developed to estimate the activity of the spot inside the radioactive waste drum. To improve the reliability of activity estimation, the **3D attenuation map** was reconstructed by using two position-sensitive detectors without additional equipment.

- The experiments using IAEA phantoms, filled with air, polypropylene, and an iron pillar, respectively, were then performed to verify that the attenuation map was reconstructed properly. Furthermore, the additional experiment assuming the real radioactive waste drum was performed to demonstrate the feasibility of the developed Compton CT.

- As a result of the experiment with IAEA phantoms, it was confirmed that the 3D attenuation map was successfully reconstructed within the RMSE of 7.23×10^{-4} for the various filling materials. It was also confirmed that the activity of the source inside the drum was calculated in a **discrepancy of 1.32 times** compared with true activity, applying the 3D attenuation map.

- The LACC-based Compton CT is expected to be used to improve the economics of radioactive waste disposal.

Thank you