ENERGY-SENSITIVE PHOTON AND NEUTRON BIMODAL IMAGING SYSTEM: DESIGN AND PERFORMANCE VALIDATION

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Outline

1. The common issue of bimodal imaging system.

2. Design workflow of energy-sensitive bimodal target station.

3. Results.

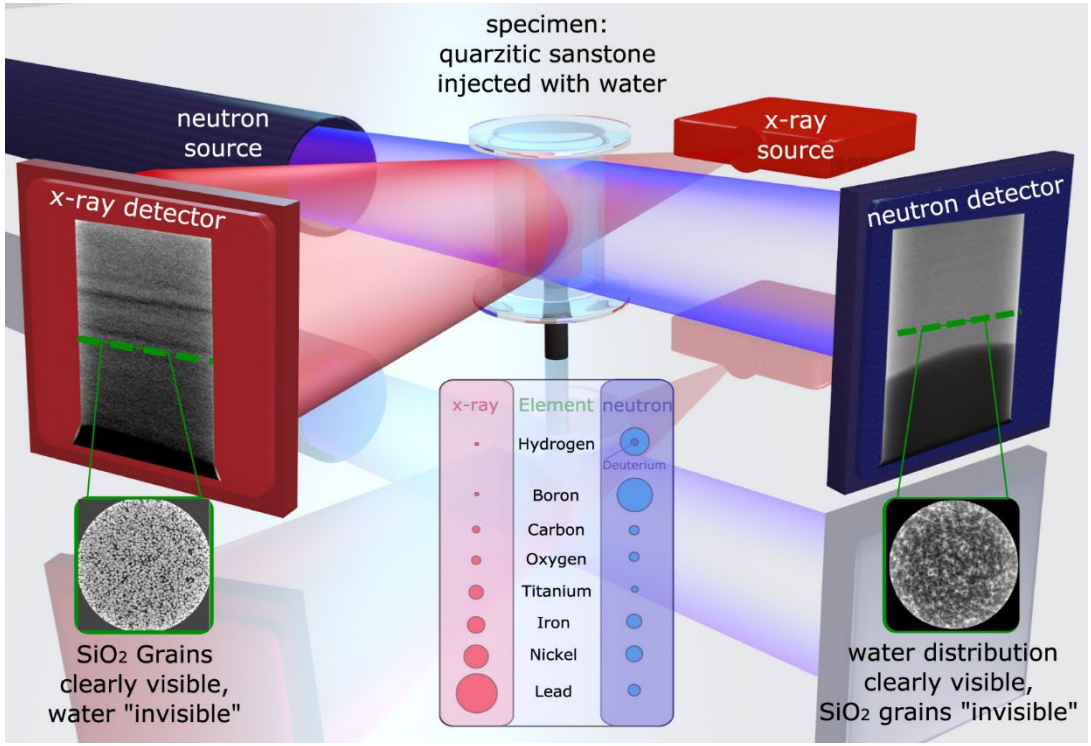
4. Summary.

Background-Limitation of conventional bimodal system

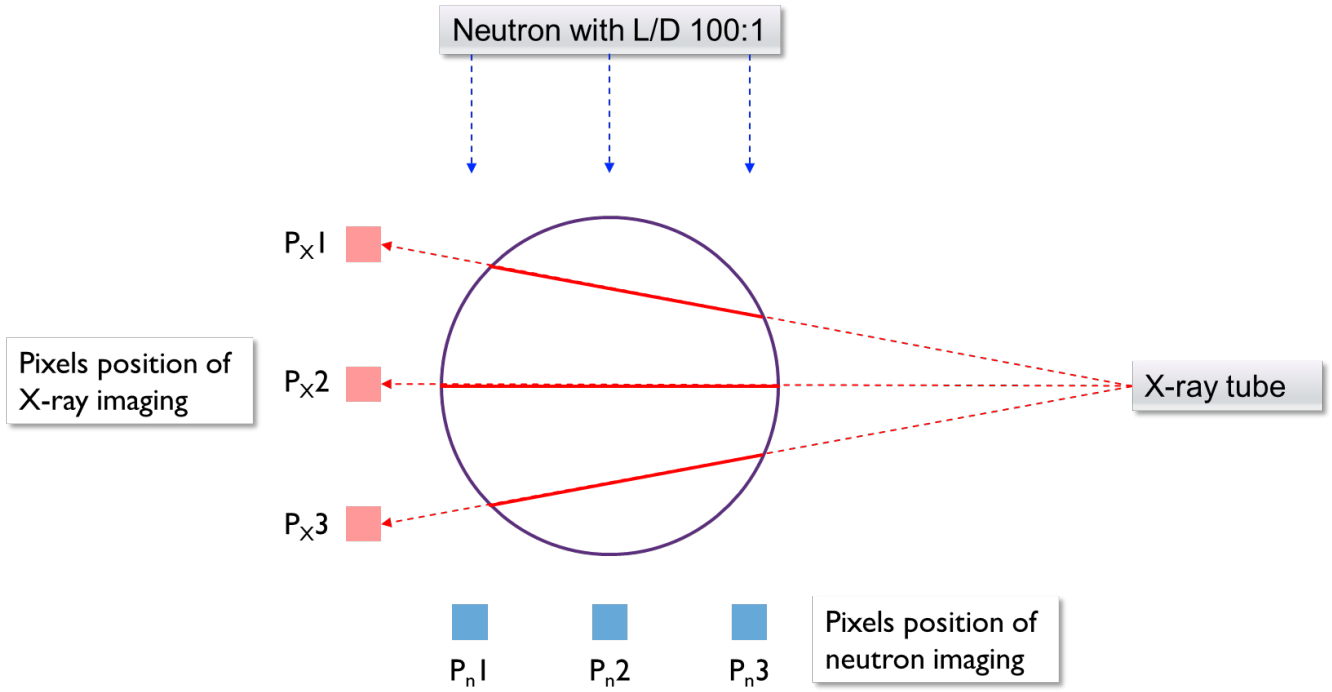
For monoenergetic neutron and photons

$$R = \frac{\mu_t}{\Sigma_t} = \frac{\ln\left(I_{E_\gamma} / I_{E_\gamma,0}\right)}{\ln\left(I_{E_n} / I_{E_n,0}\right)}$$

- The dual-source dual-detector mode leads to different beam path, resulting in slow CT imaging speed and increased difficulty in image fusion.



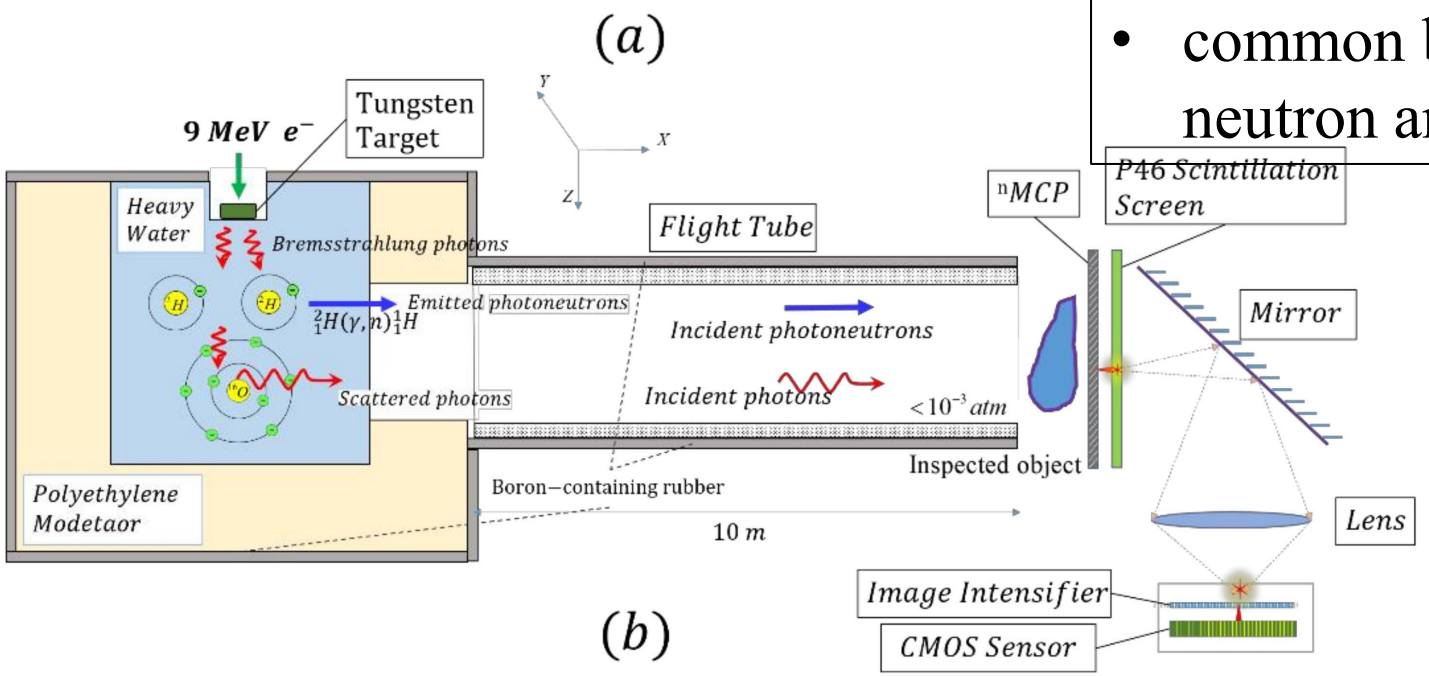
Tengattini, A., et al. (2020). "NeXT-Grenoble, the Neutron and X-ray tomograph in Grenoble." NIMA. 968: 163939.

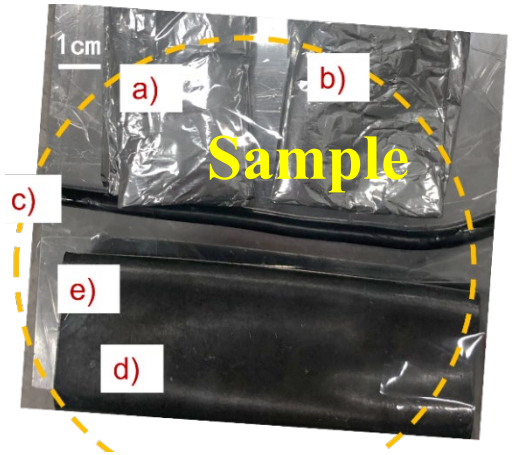


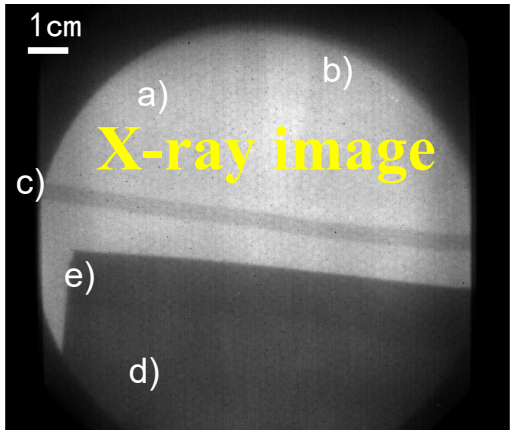
Transmission path is different. Tomography is necessary.

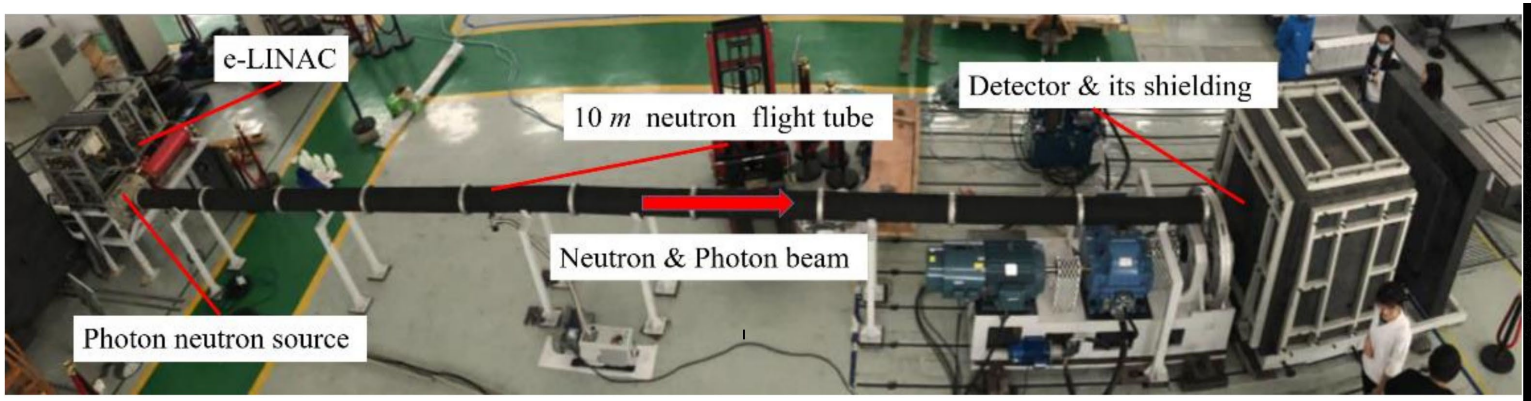
Background-one-source-one-detector bimodal system

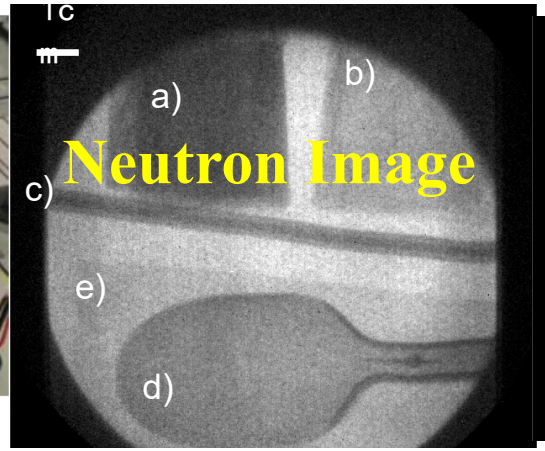
- common beam path, allowing direct fusion of neutron and photon transmission images.

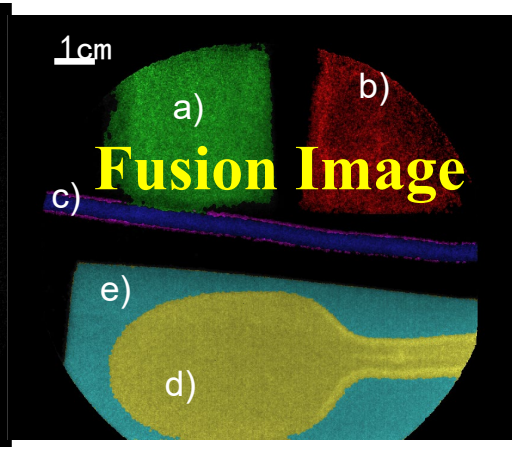












Yu, Y., et al. (2021). "The Bimodal Neutron and X-ray Imaging Driven by a Single Electron Linear Accelerator." Applied Sciences 11(13): 6050.

Common issue: beam hardening effect

For monoenergetic neutrons and photons

$$R=\frac{\log\left(I_n\left(E_{\mathrm{n}}\right)/I_{n0}\left(E_{\mathrm{n}}\right)\right)}{\log\left(I_p\left(E_{\mathrm{p}}\right)/I_{p0}\left(E_{\mathrm{p}}\right)\right)}=\frac{\mu_n\left(E_{\mathrm{n}}\right)t_m}{\mu_p\left(E_{\mathrm{p}}\right)t_m}=\frac{\mu_n\left(E_{\mathrm{n}}\right)}{\mu_p\left(E_{\mathrm{p}}\right)}$$

A continuous energy distribution is assumed for neutrons or photons

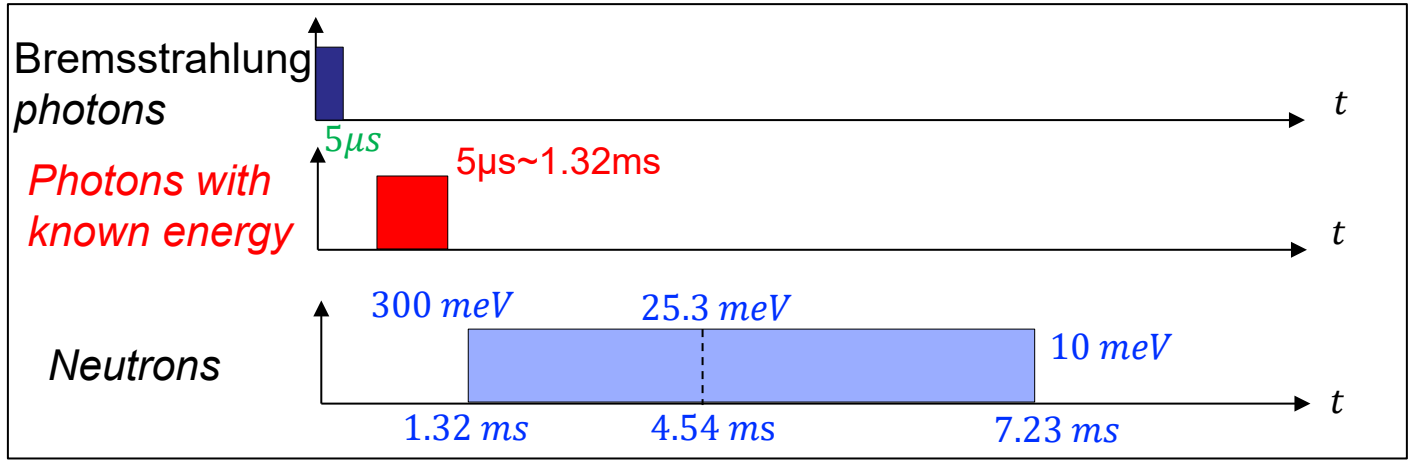
$$\overline{\mu_{\mathrm{m}}\left(t_m\right)}=\ln\left(\frac{\int_{E_{\min}}^{E_{\max}}\phi(E)\eta(E)dE}{\int_{E_{\min}}^{E_{\max}}\phi(E)\eta(E)e^{-\mu_m(E)t_m}dE}\right)\cdot\frac{1}{t_m}$$

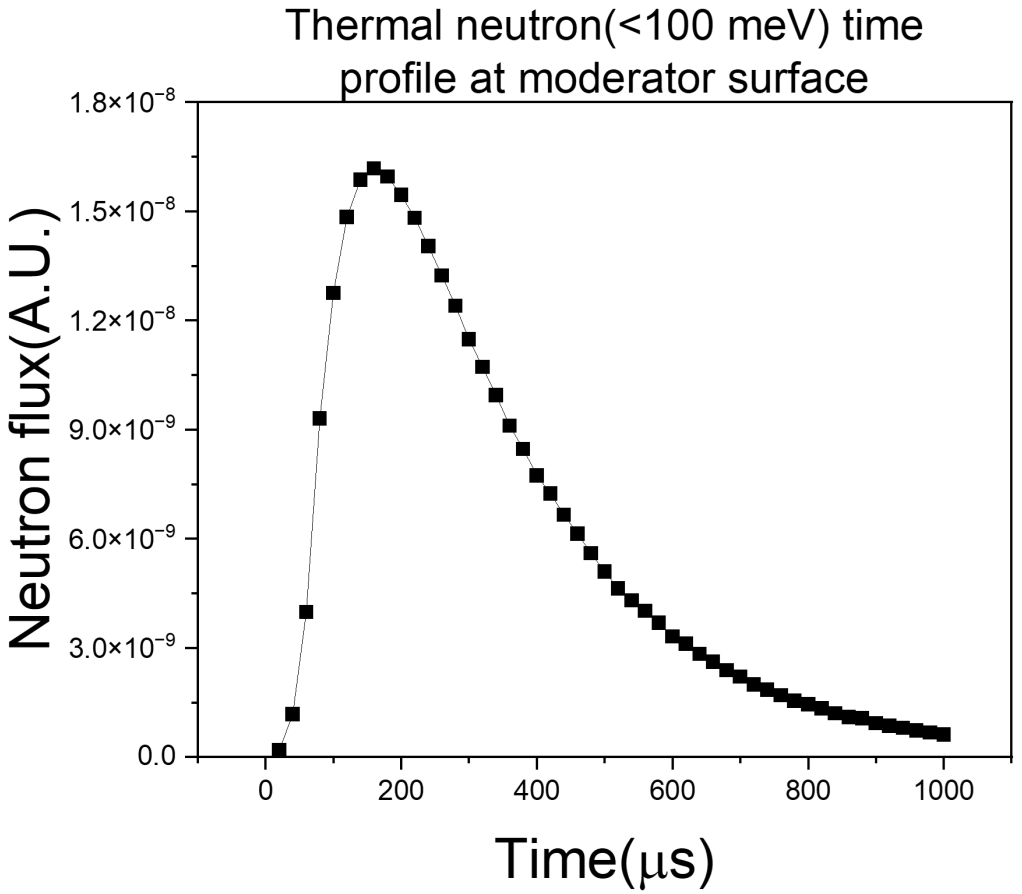
The material identification factor R depends on the mass thickness of the sample.

Φ(E): Neutron flux;
η(E): Detection efficiency
μ_m(E):mass attenuation coefficient
t_m: mass thickness of sample

Solution I: using radiative capture photons instead of Bremsstrahlung photons

Time of flight spectrum for bimodal system at 10m



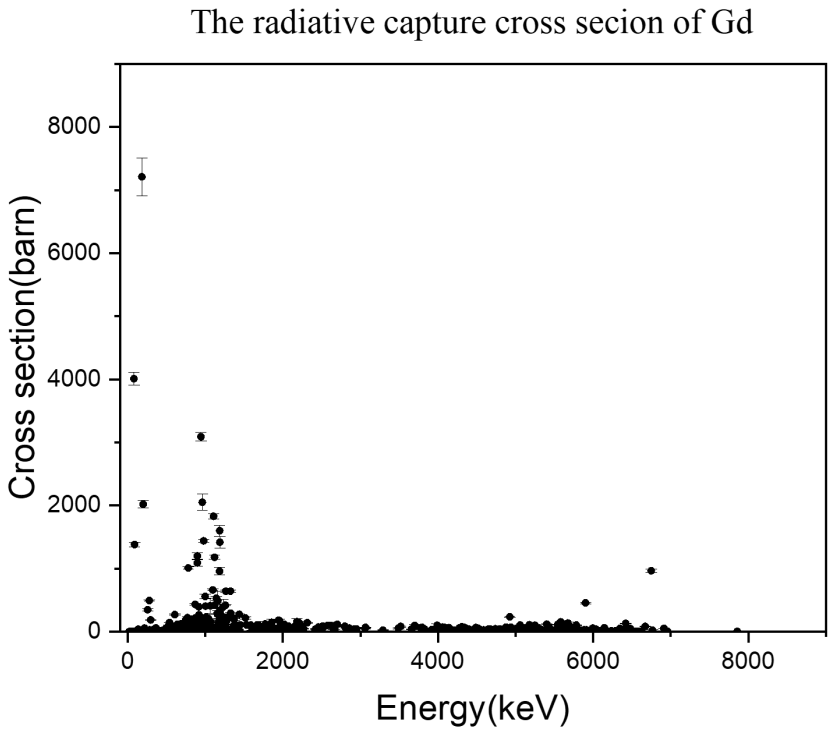


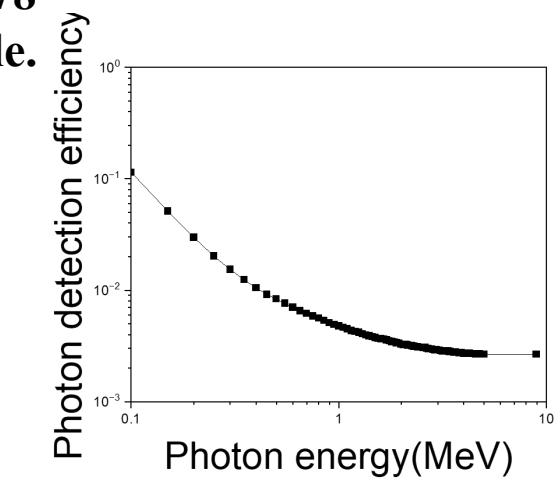
How to achieve?

➢The moderation time of slow neutrons reaches hundreds of microseconds scale, and radiative capture prompt photons can be generated using a converter.

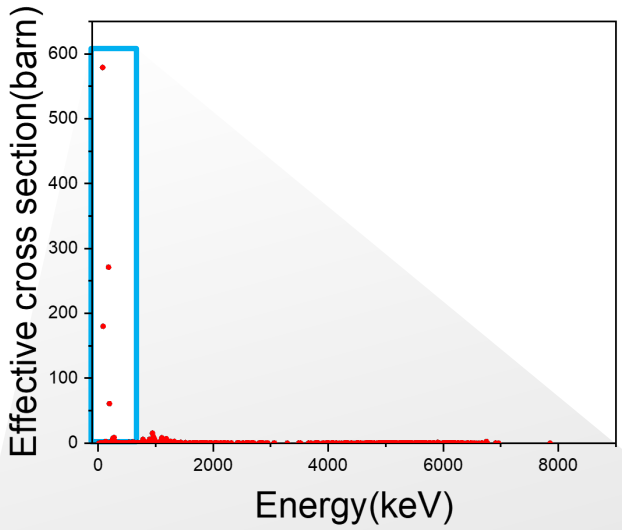
Solution I: using radiative capture photons instead of Bremsstrahlung photons

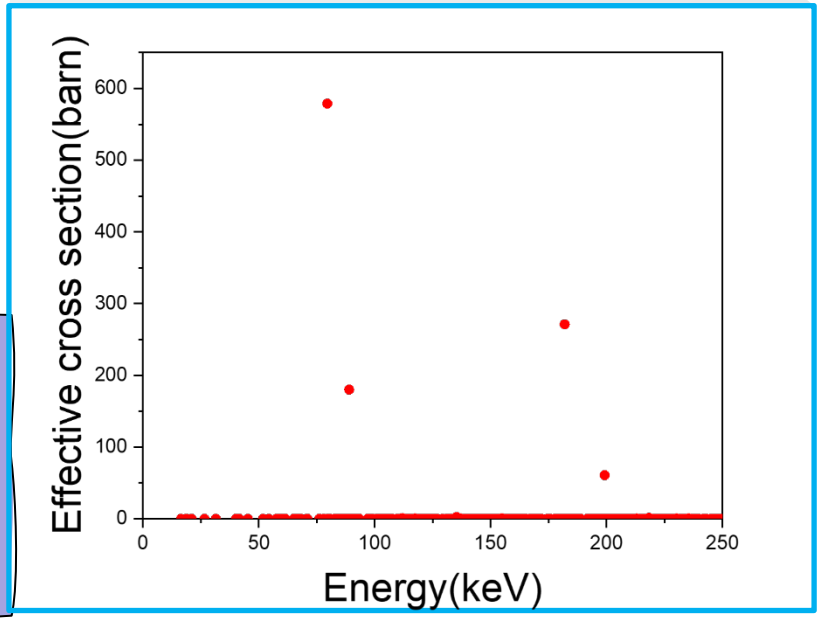
Boron's gamma rays are monoenergetic（~0.478 MeV), but other nuclides may also be applicable.





Multiplied by detection efficiency



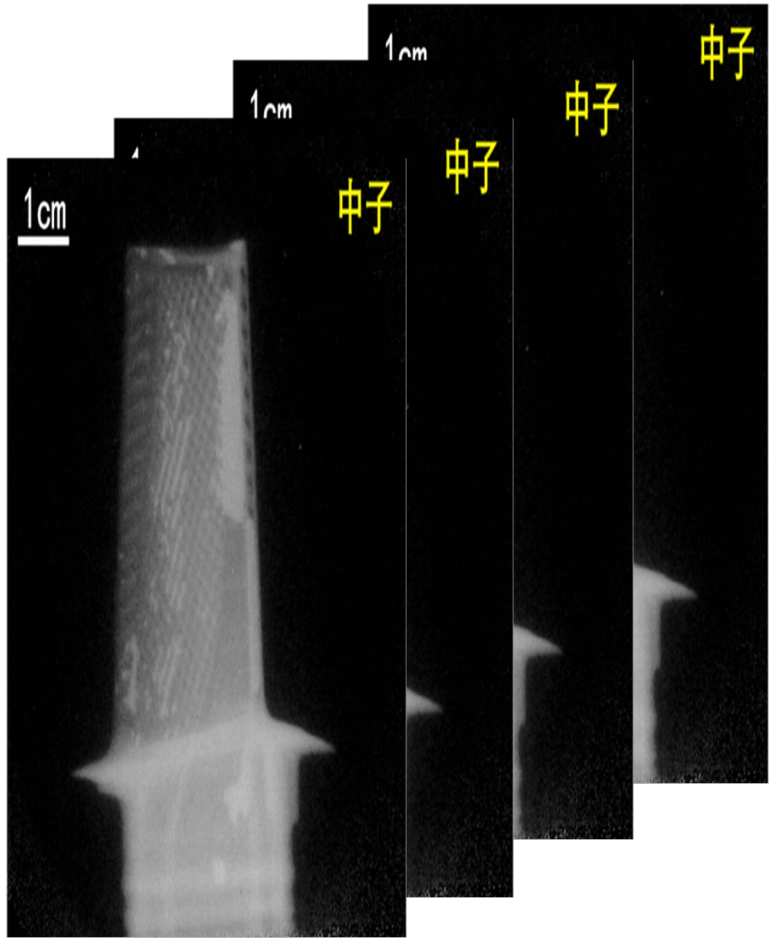


After applying detection efficiency corrections, the non-quasi-monoenergetic gamma rays exhibit characteristics of quasi-monoenergetic gamma rays.

Solution II：using event-based detector instead of frame-based detector

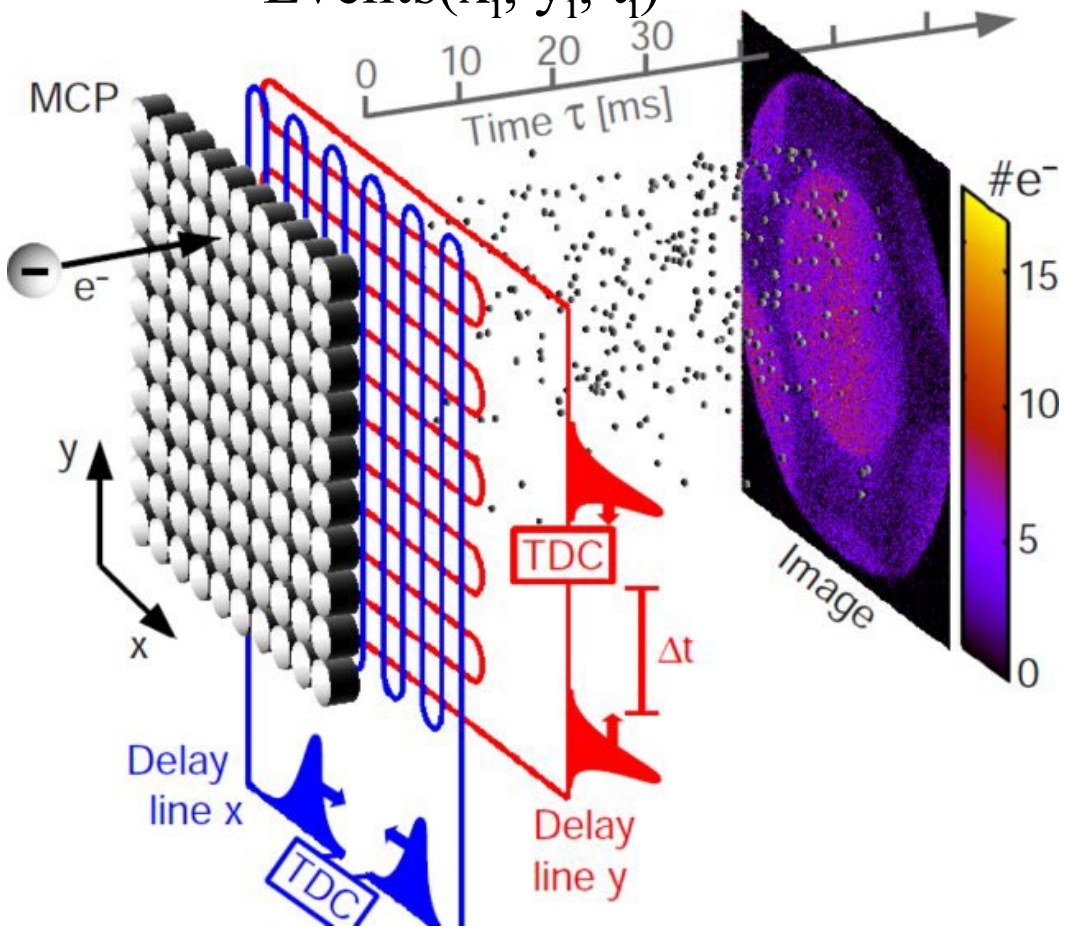
- Scintillation screen readout neutron-sensitive MCP

Frames per second



- Delay line readout neutron-sensitive MCP

Events(x_i, y_i, t_i)



Müller-Caspary, et al. STEM Strain Measurement From a Stream of Diffraction Patterns Recorded on a Pixel-Free Delay-Line Detector(2016).

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1. The common issue of bimodal imaging system.

2. **Design workflow of energy-sensitive bimodal target station.**

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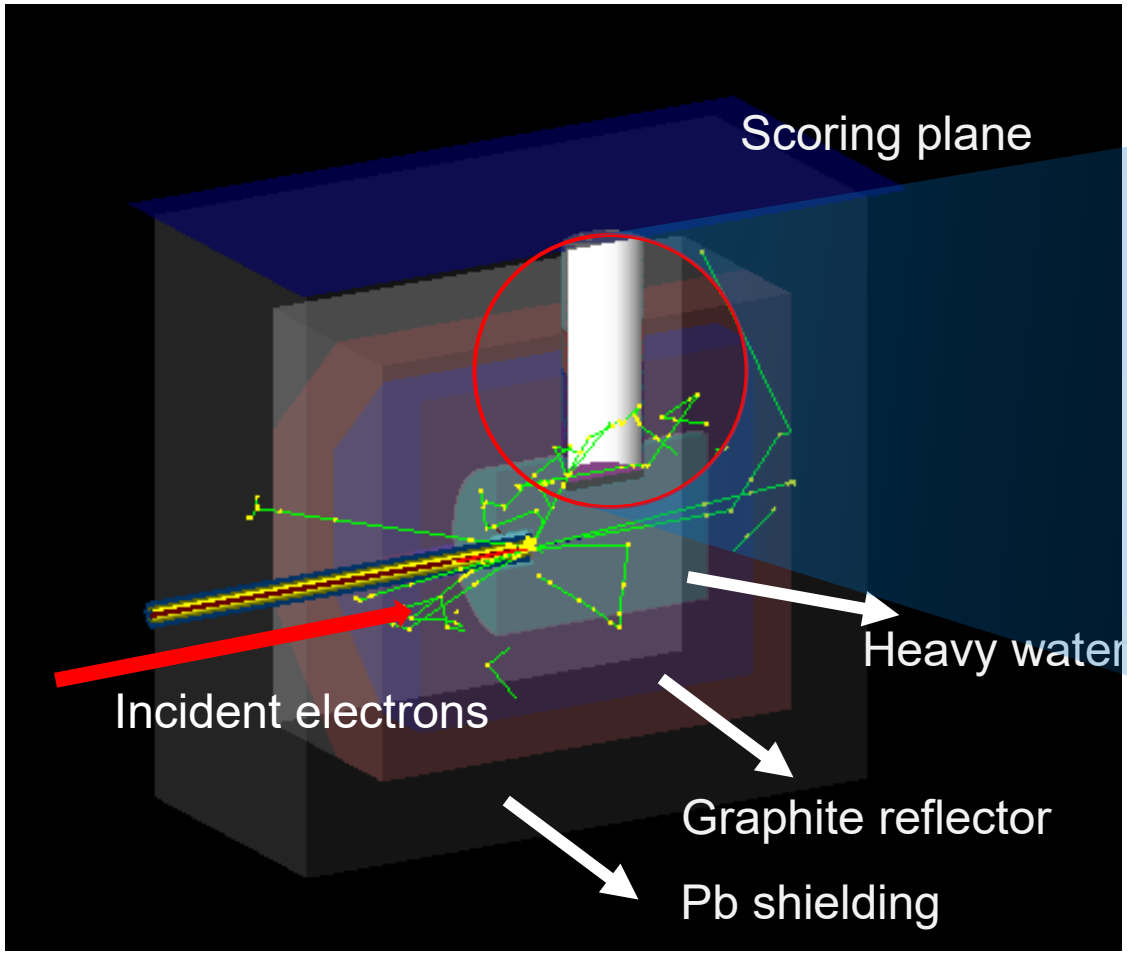
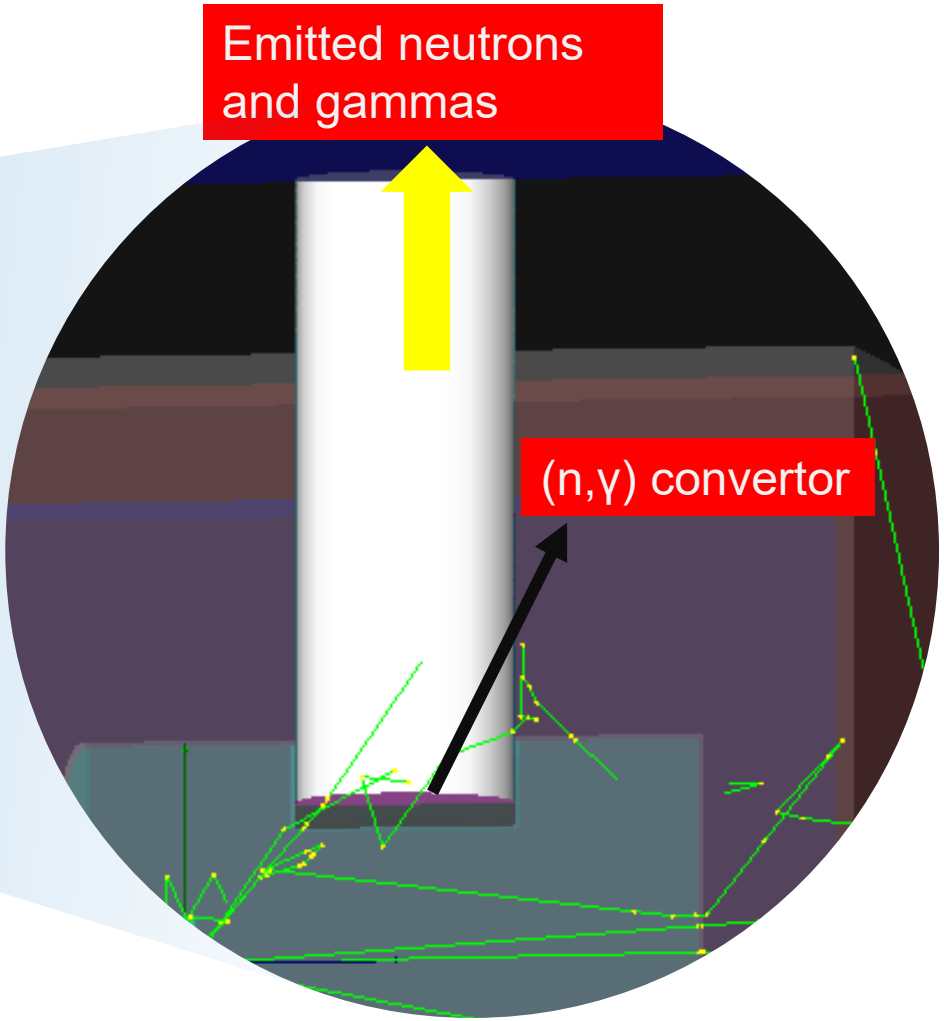
Simulation process for energy-sensitive target station

1) Record emitted neutrons and photons using GEANT4(Version 11.3.0)

- Using NuDEX deexcitation model(newly implemented)



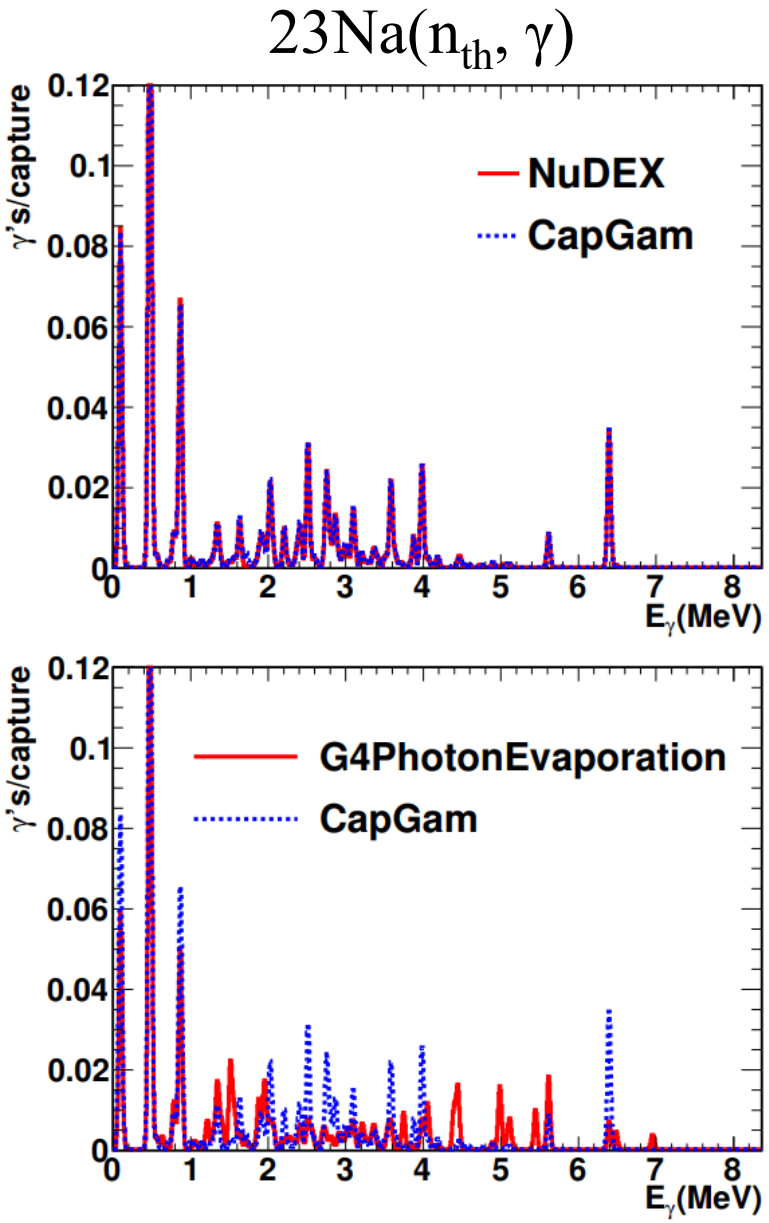


Simulation process for energy-sensitive target station

- The relative neutron capture gamma ray intensity has large difference with experimental data using default model.
  - Wrong absolute intensity.
  - The energy is not conserved.
  - Can't generate the γ-ray cascades in a correlated way.

- NuDEX generates the complete level scheme and branching ratios of the nucleus.

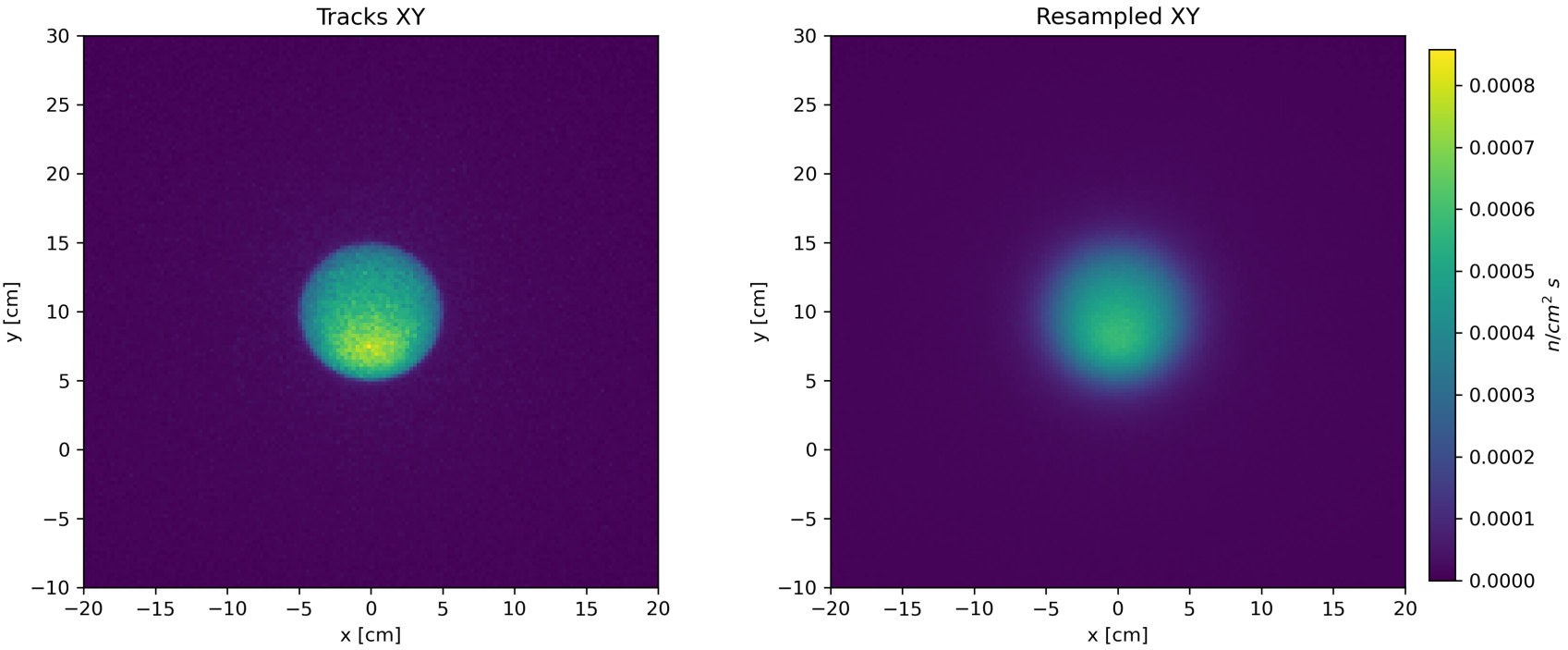
Mendoza, E., et al. (2020). "NuDEX: A new nuclear γ-ray cascades generator." EPJ Web Conf. **239.**

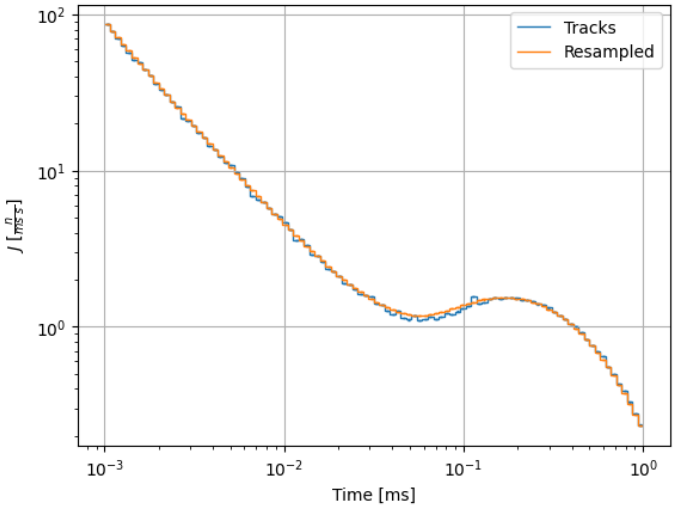


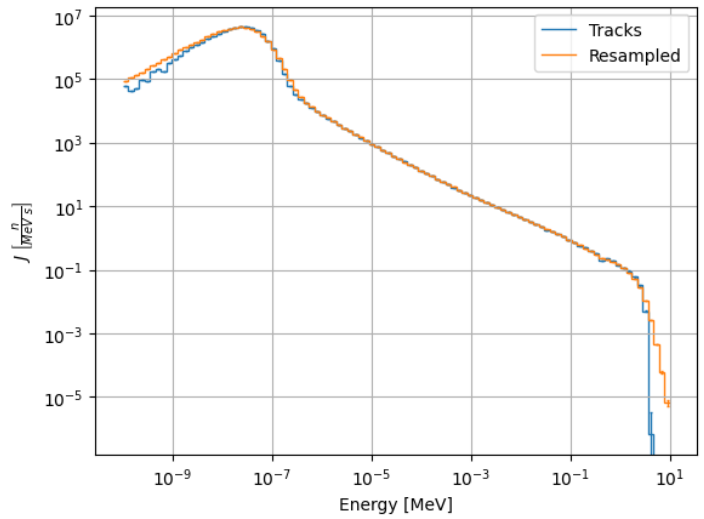
Simulation process for energy-sensitive target station

2)Using kernel density estimation algorithm to fit the source distribution.
Then resample.

$$P = \left(E, t, x, y, z, d_x, d_y, d_z \right)$$







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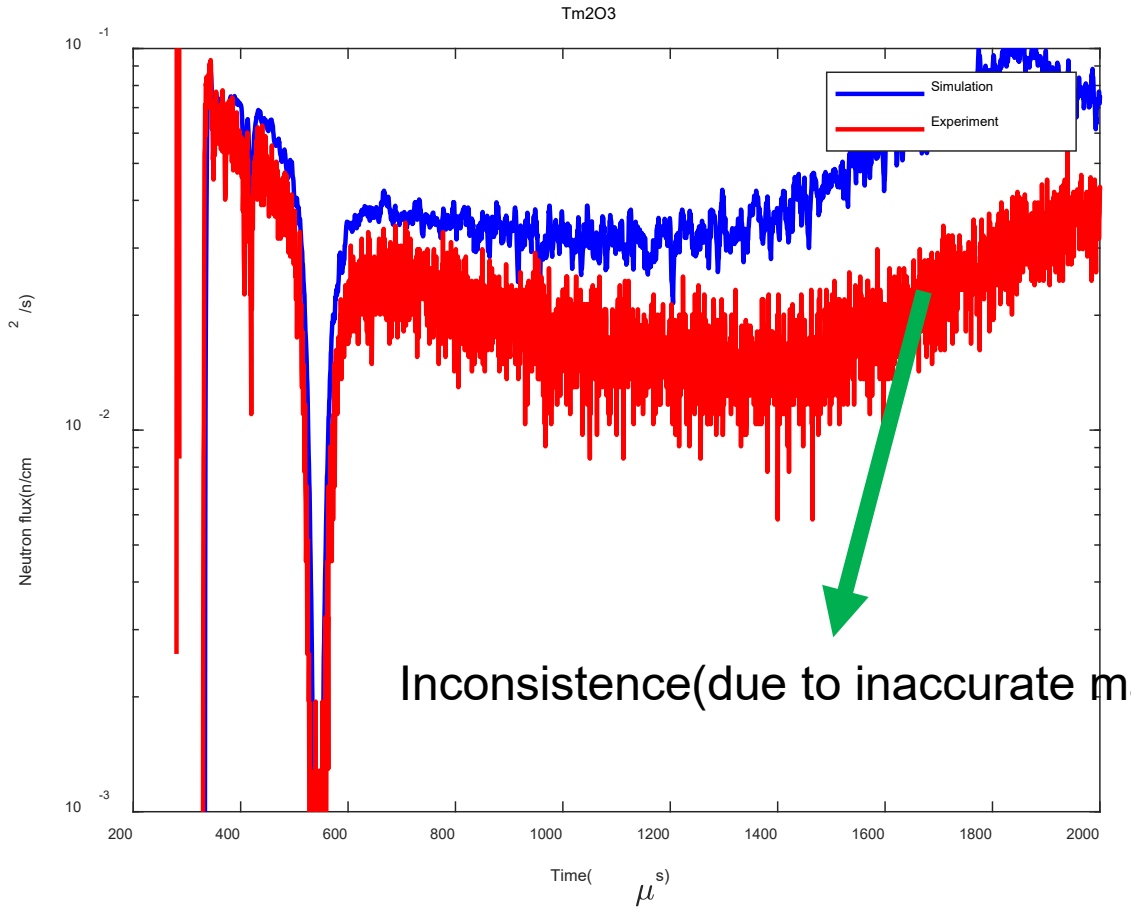
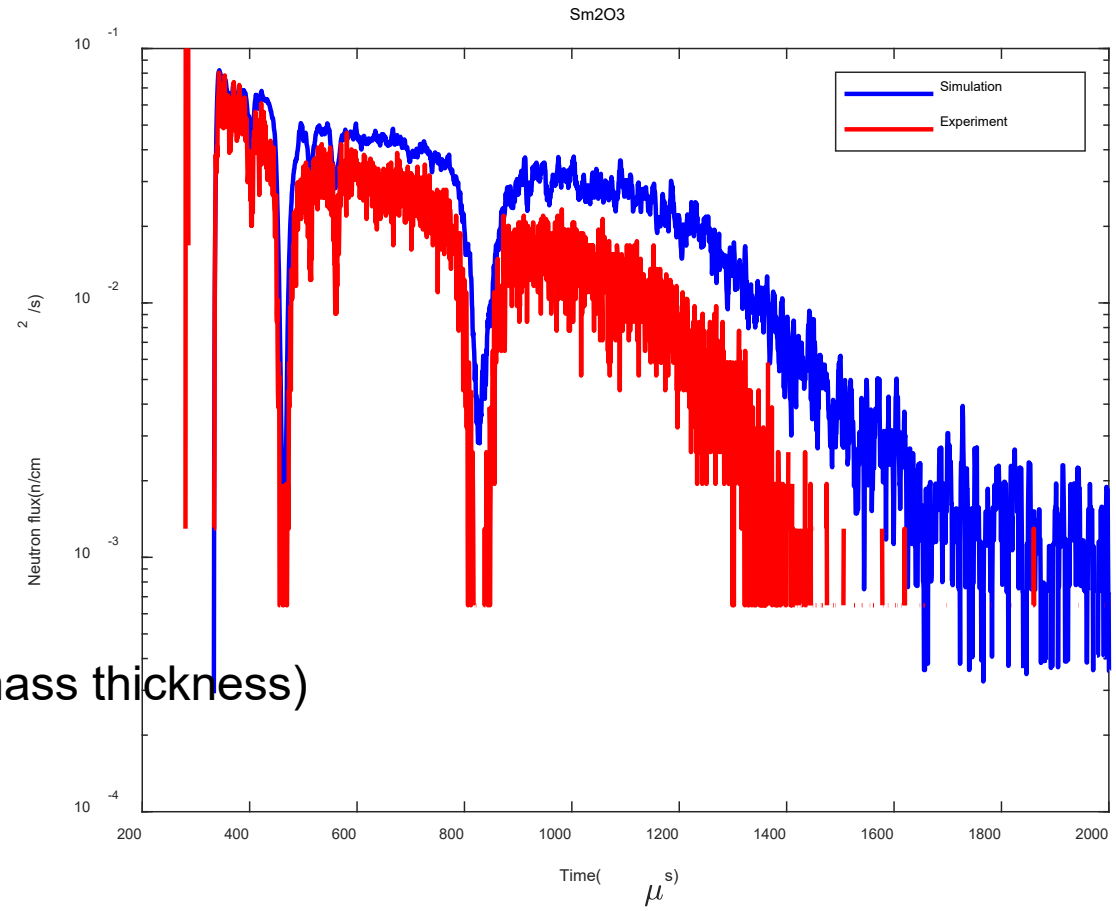
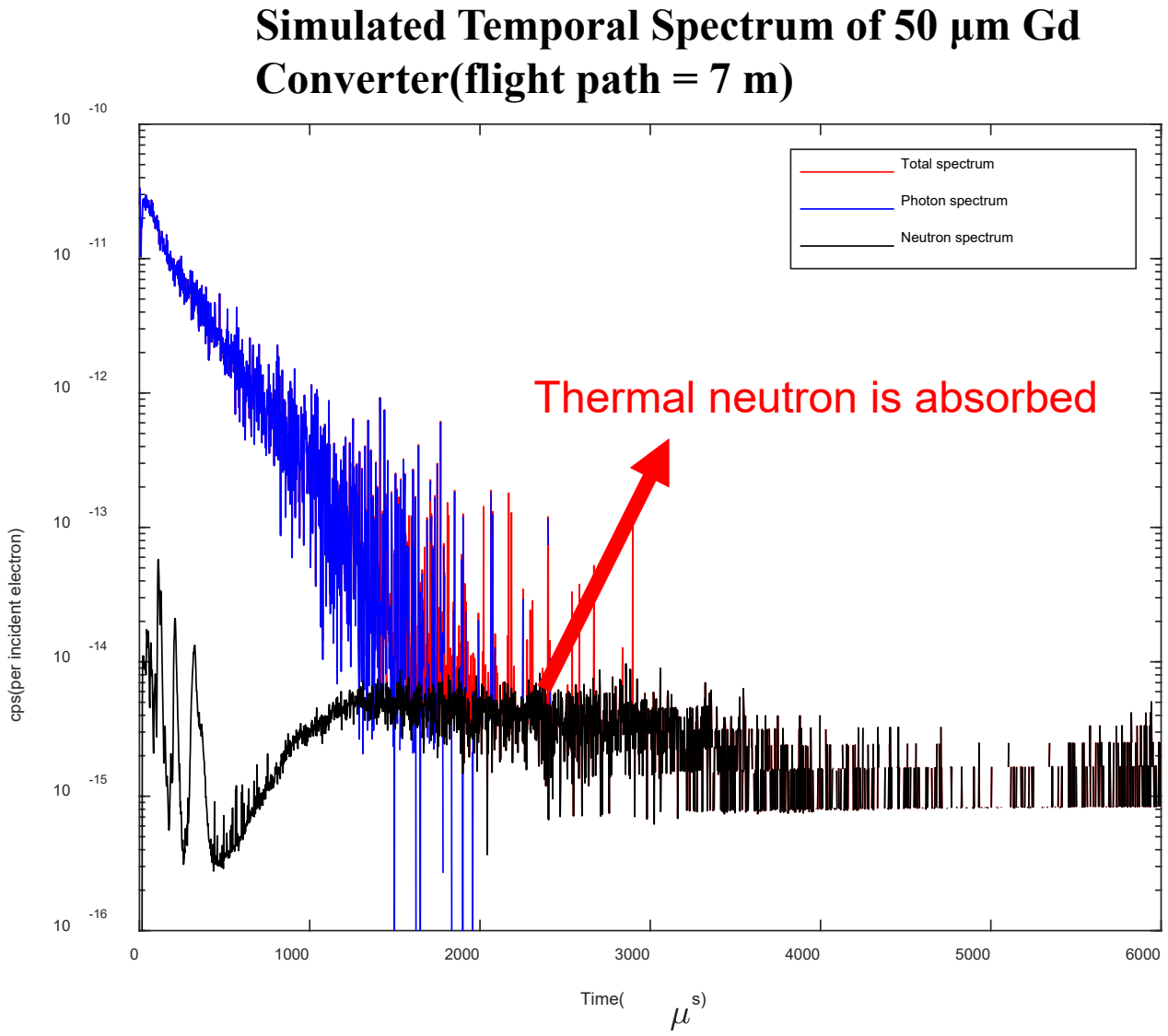
Simulation Results: benchmark for TOF calculation

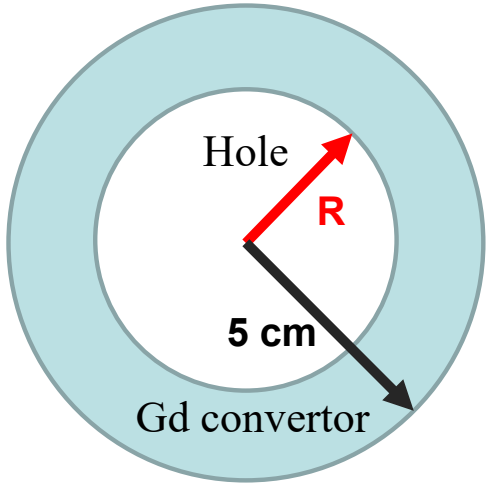
- Although the mass thickness of the rare earth oxide sample is inaccurate due to operational errors in the sample powder preparation process, the resonance peak positions exhibited excellent correspondence(Relative error < 0.5%).





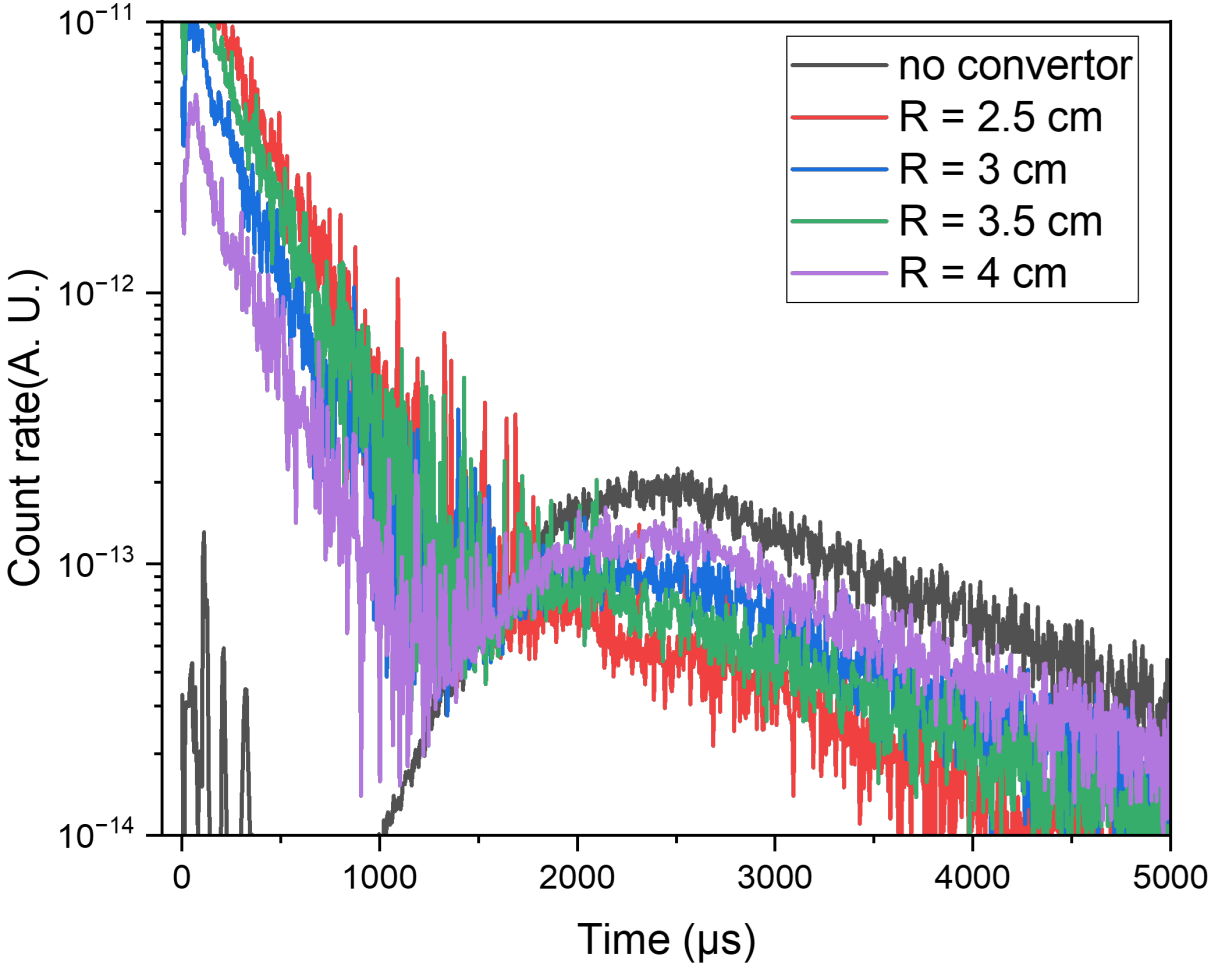
Simulation Results: Temporal Spectrum





Adjust the radius of the hole in the converter to modulate the ratio of neutrons to gamma rays

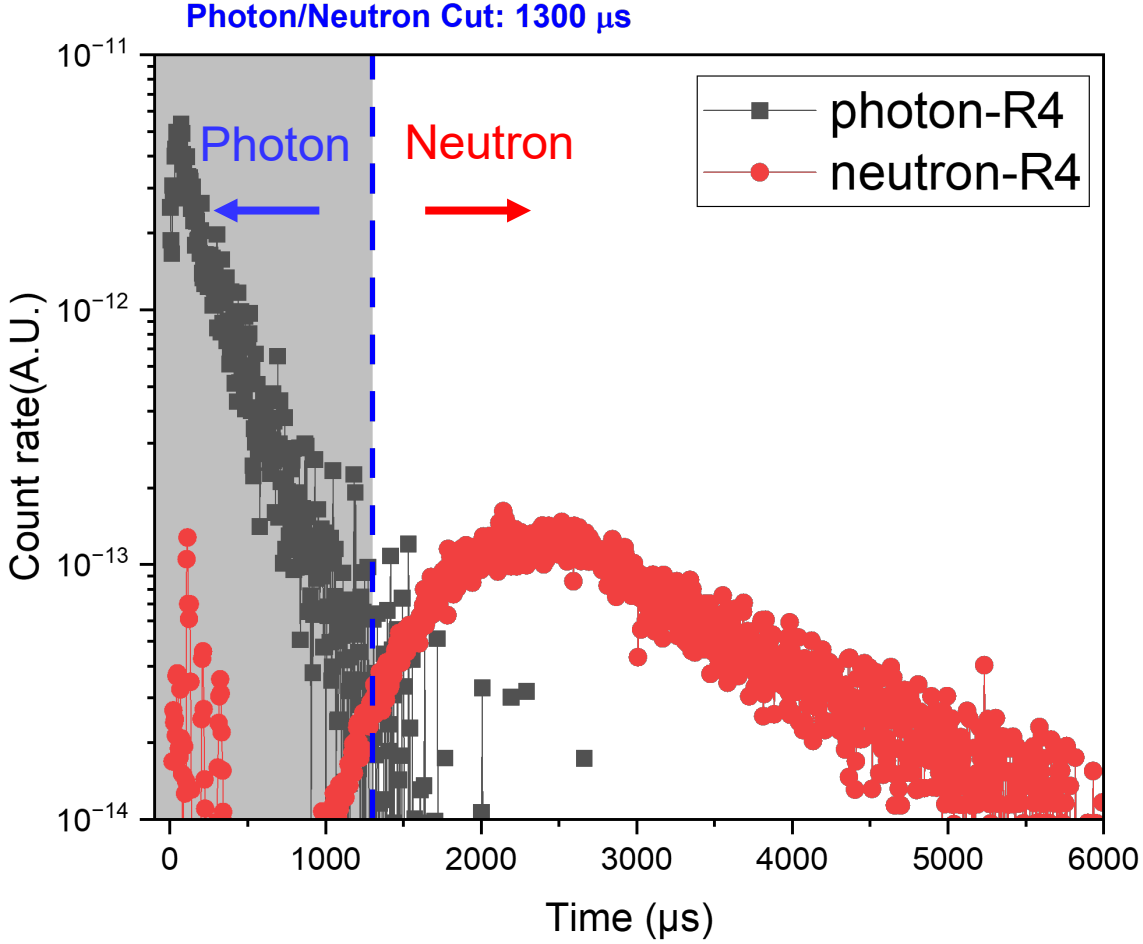
Simulation Results: Change the open ratio of Gd convertor



Temporal spectrum with different hole radius

R = 4 cm

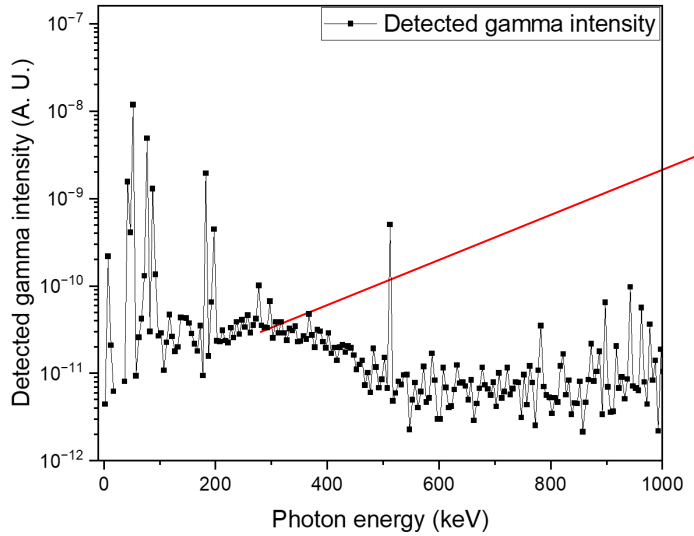
- <1300 μs：photon image（1.25% neutron mixed)
- >1300 μs：neutron image（3.04% photon mixed)
- Lost 33% thermal neutrons.



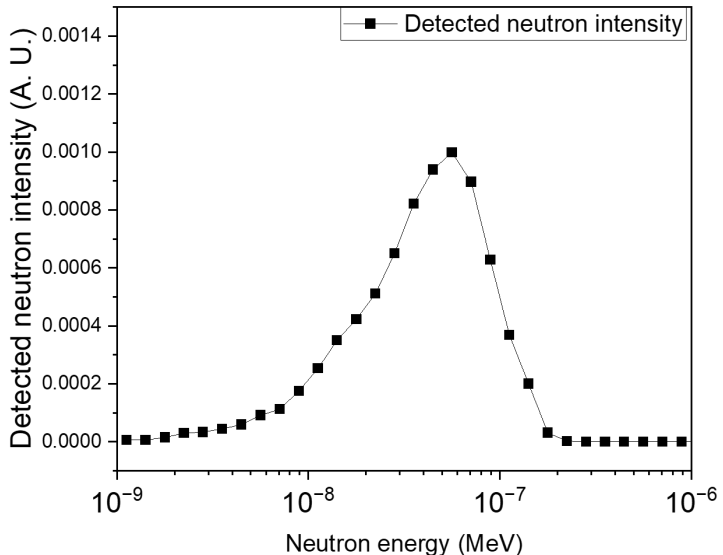
Temporal spectrum when R = 4 cm

Simulation Results: R factor of Gd convertor

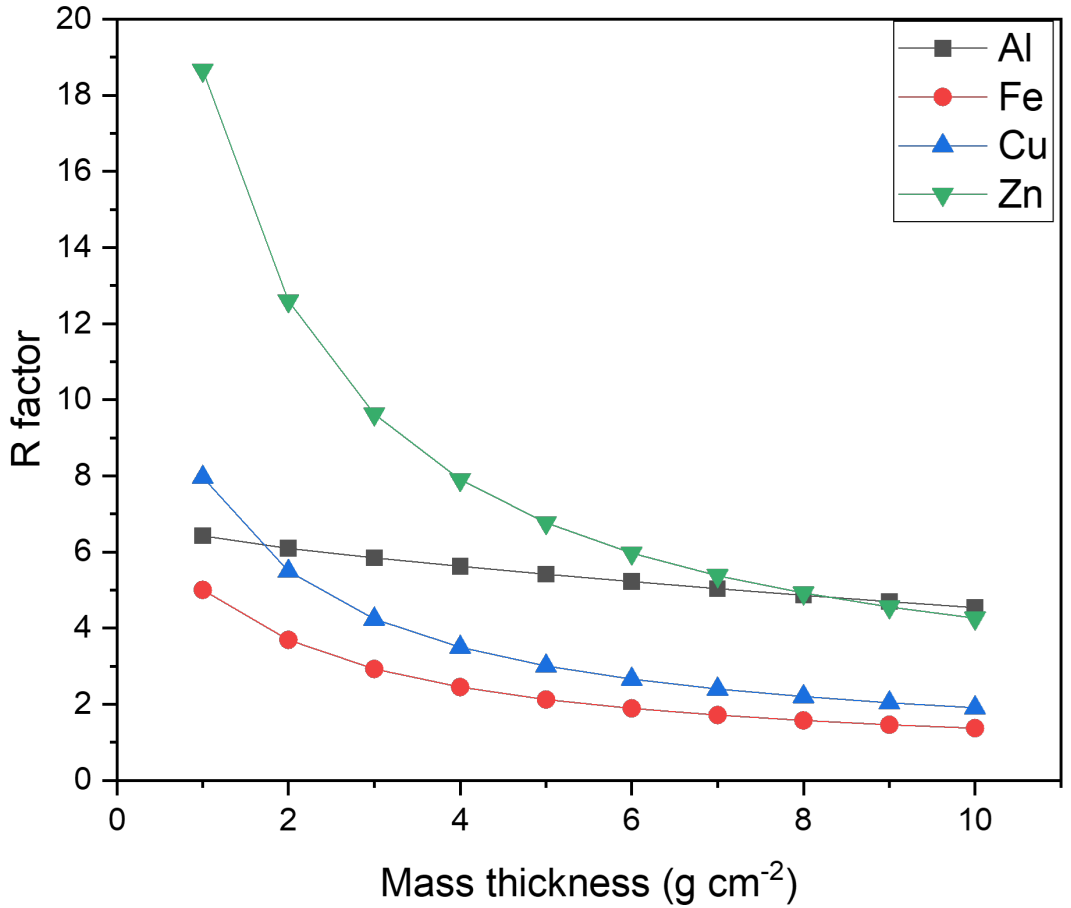
Photon Energy Spectrum under <1300 μs Time Window



Neutron Energy Spectrum under >1300 μs Time Window



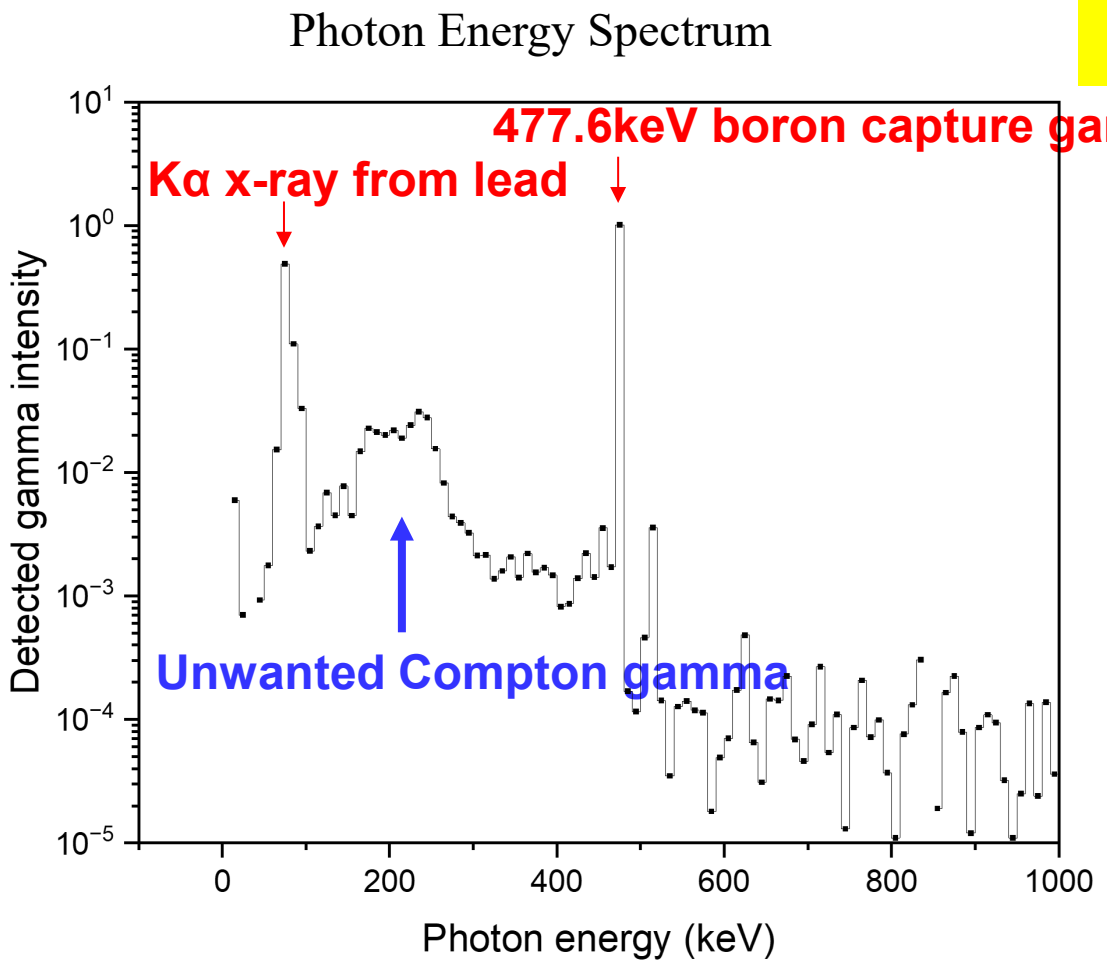
- **The unwanted Compton-scattered photons and annillation photons alter R factors with sample thickness.**

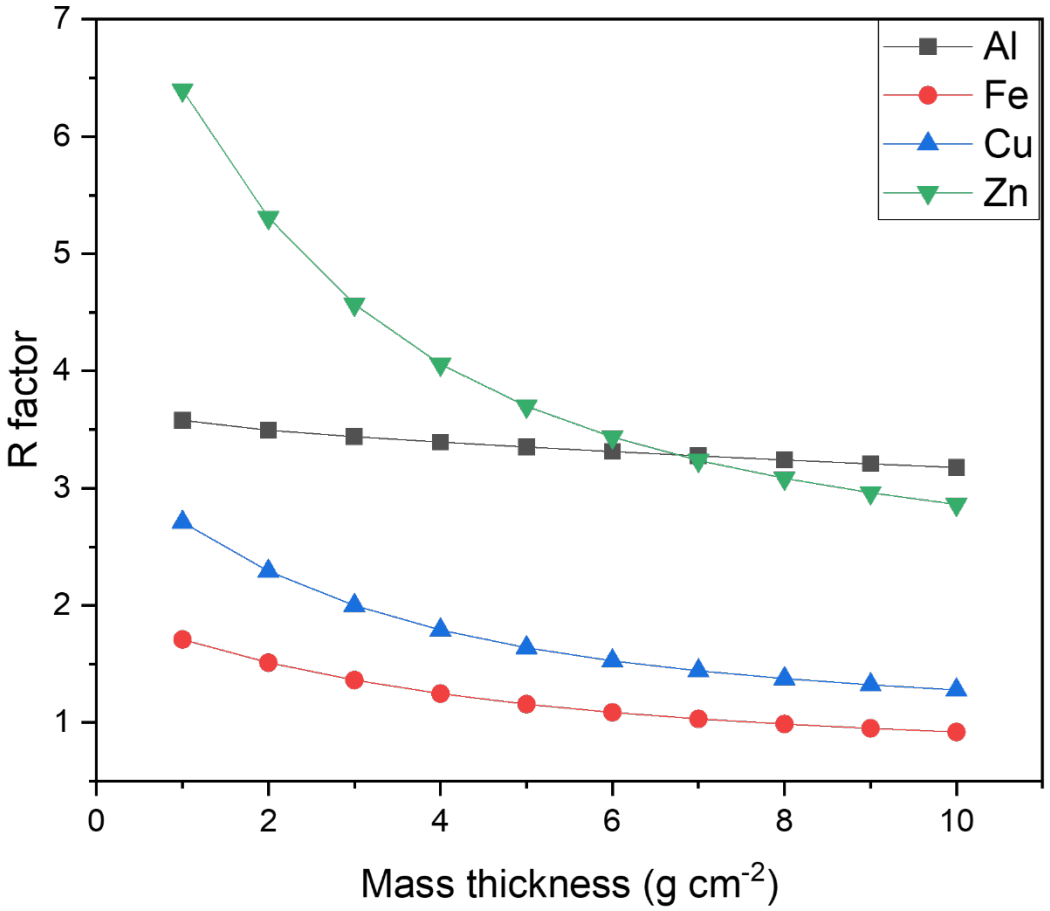


The ratio (R) of the logarithm of the simulated transmission of gamma-rays and neutrons from Gd convertor.

Simulation Results: R factor of BN convertor

- **The performance has improved significantly, but further enhancements are needed.**

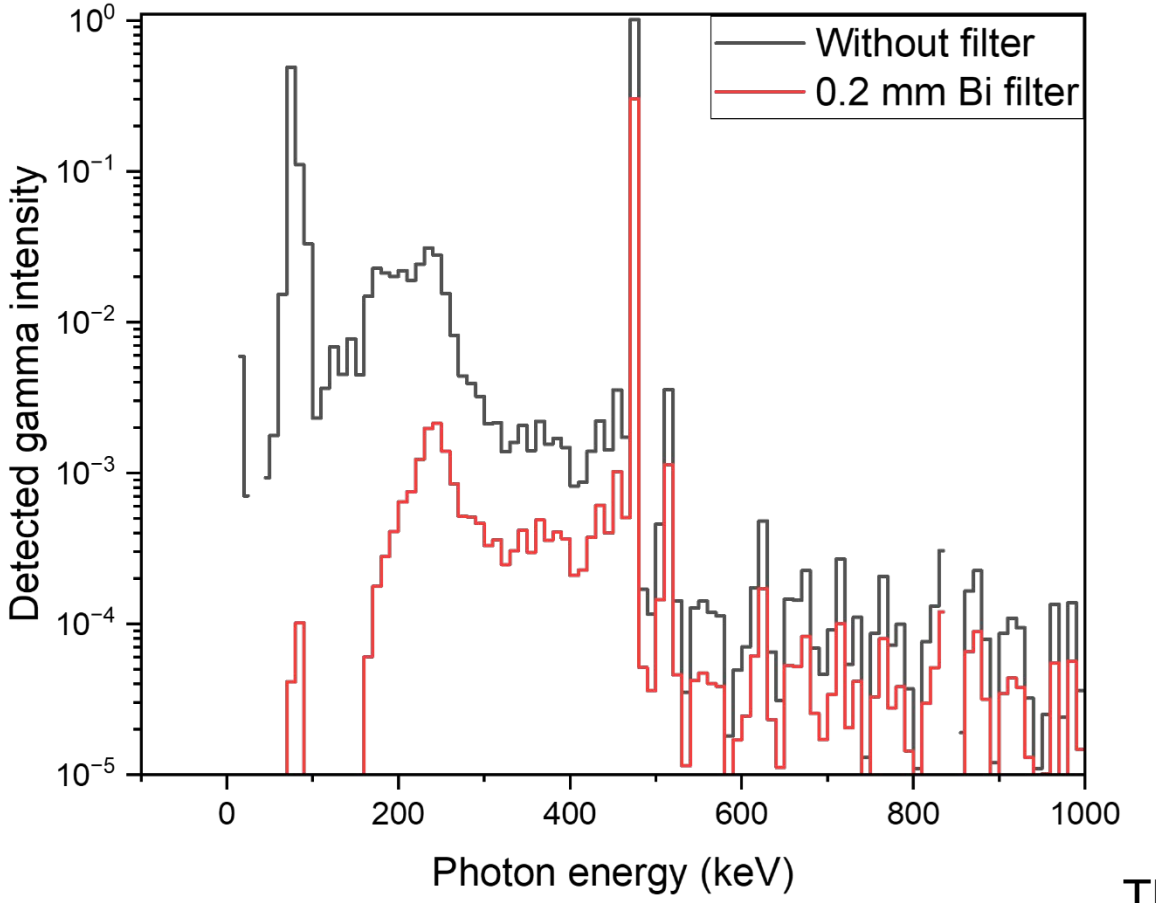




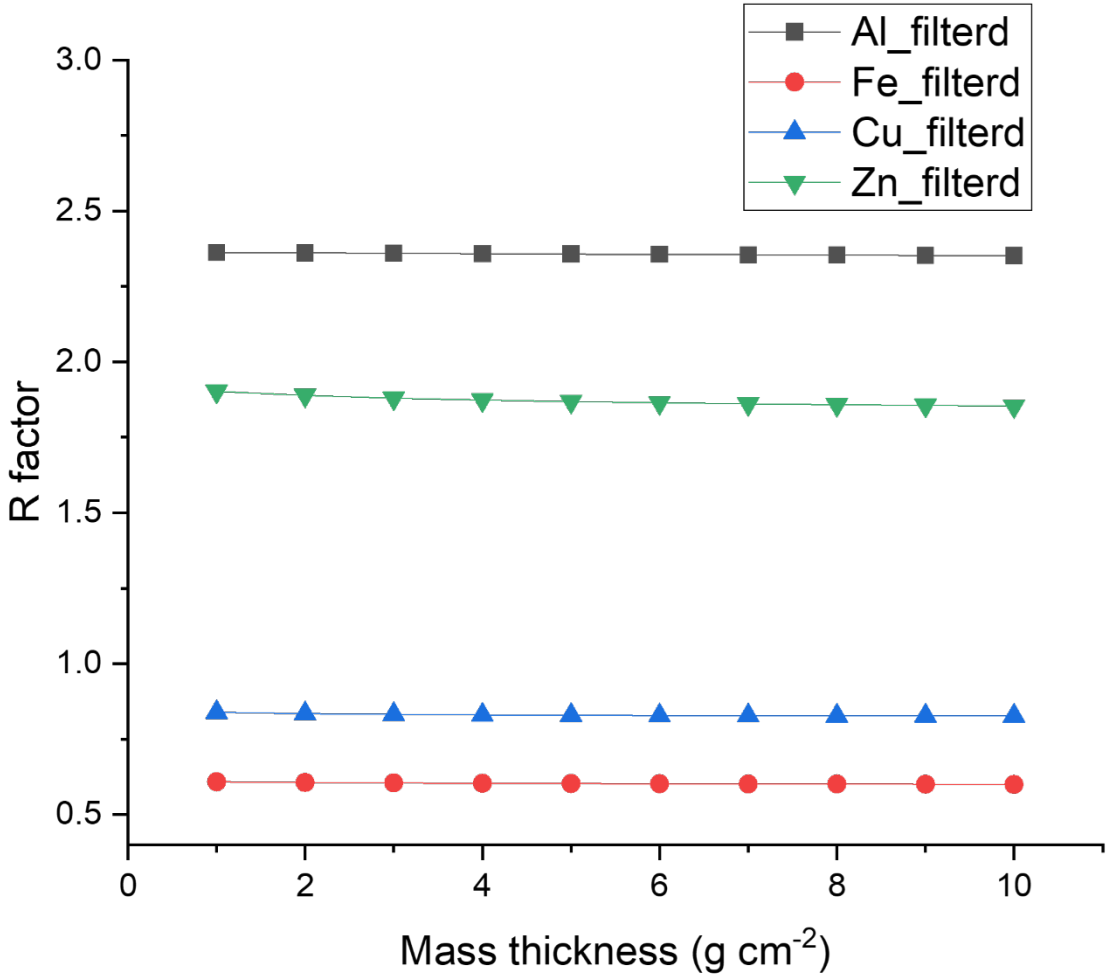
The ratio (R) of the logarithm of the simulated transmission of gamma-rays and neutrons from BN convertor.

Simulation Results: Add gamma energy filter

Photon energy spectrum of BN convertor when 2 mm Bi filter is added.



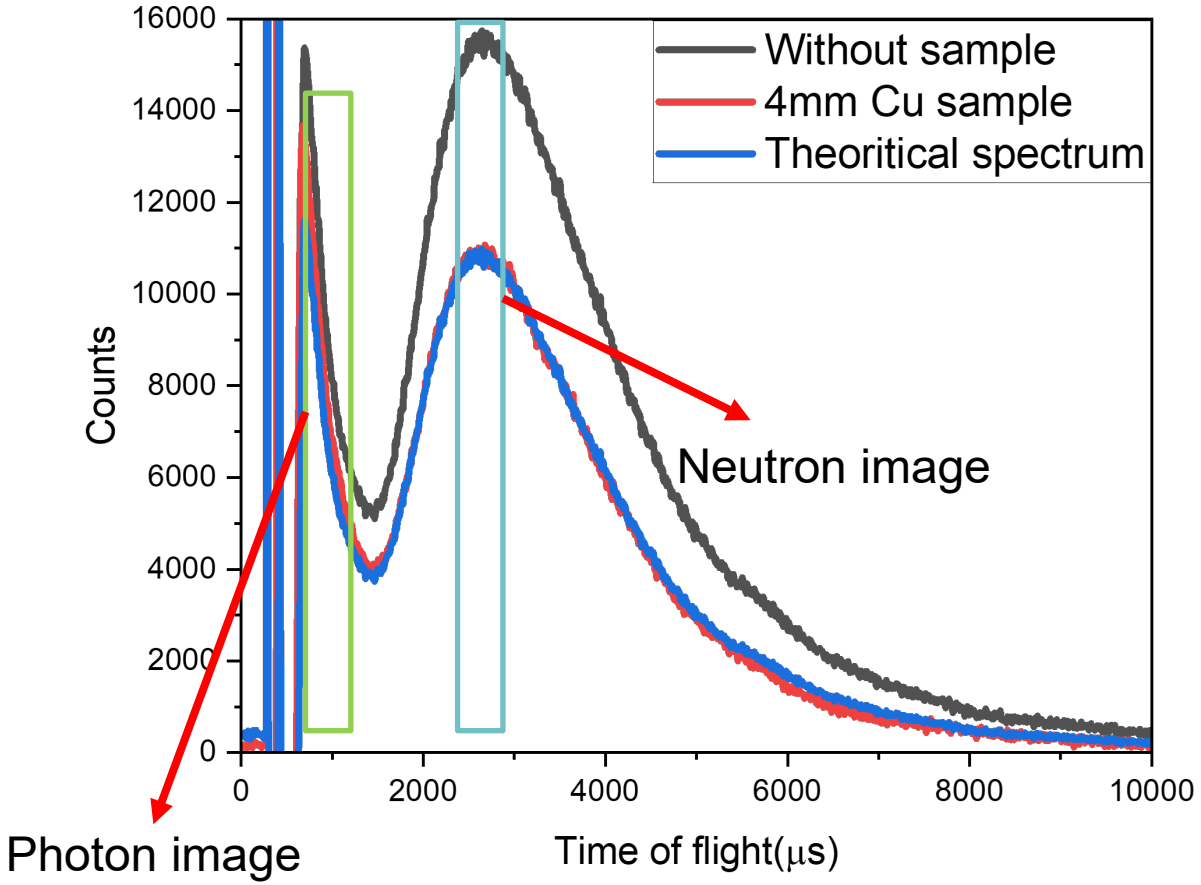
- **The beam hardening issue is solved**

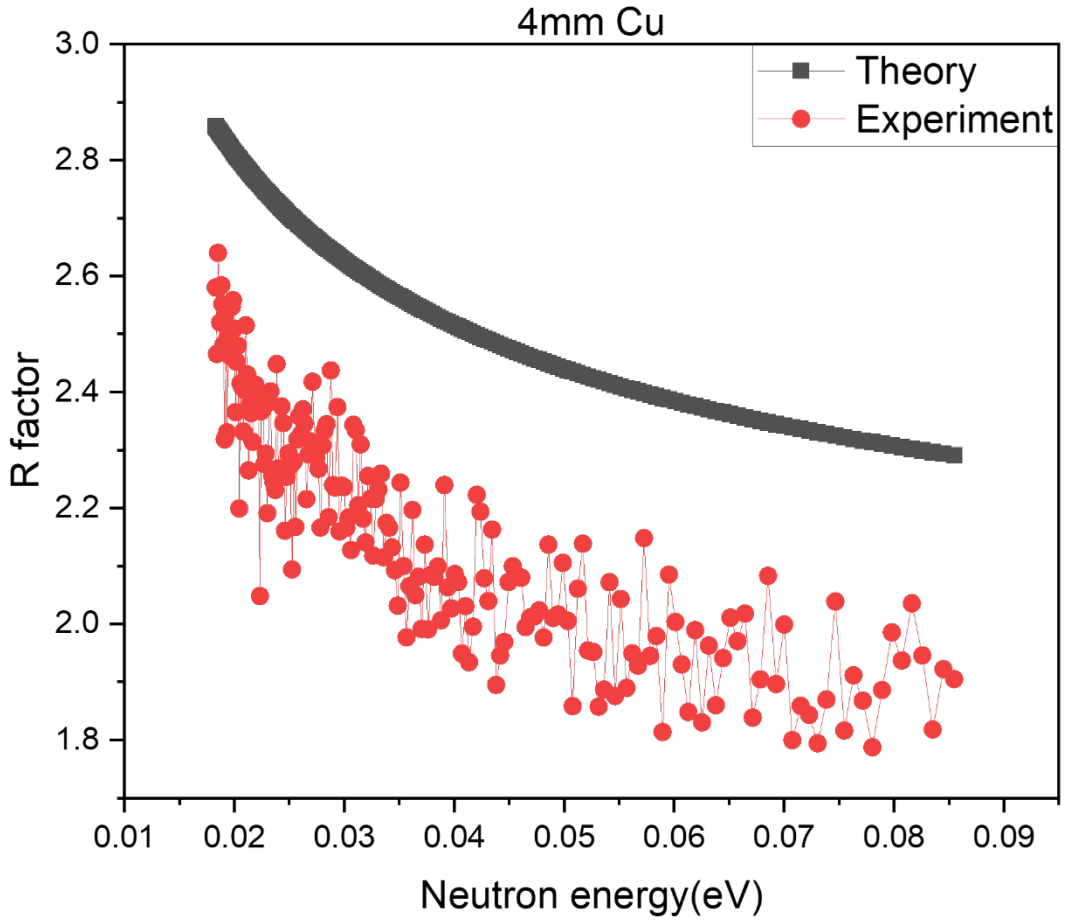


The ratio (R) of the logarithm of the simulated transmission of gamma-rays and neutrons from BN convertor(filtered).

Preliminary experimental results

- Using LaBr3 to simultaneously get photon and neutron signal.
- The experiment is conducted in old target station, which using polythene as moderator and BN as shielding, thus the radiative gamma spectrum is continuous.
- Assuming the energy of gamma is 2.2 MeV for the below two picture.





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Summary

- The proposed energy-sensitive bimodal system is designed.
  - has the potential to effectively corrects beam-hardening effects, significantly enhancing the reliability of material identification.
- The configuration and material of gamma convertor should be further investigated.
- Event-based detector enables neutron energy discrimination.
  - the energy-resolved dual-mode imaging is expected to provide more information compared to the integrated dual-mode imaging approach.