# Conceptual Design of a Compact Accelerator-Based Neutron Generator for Multi-BNCT System

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**Osaka University**

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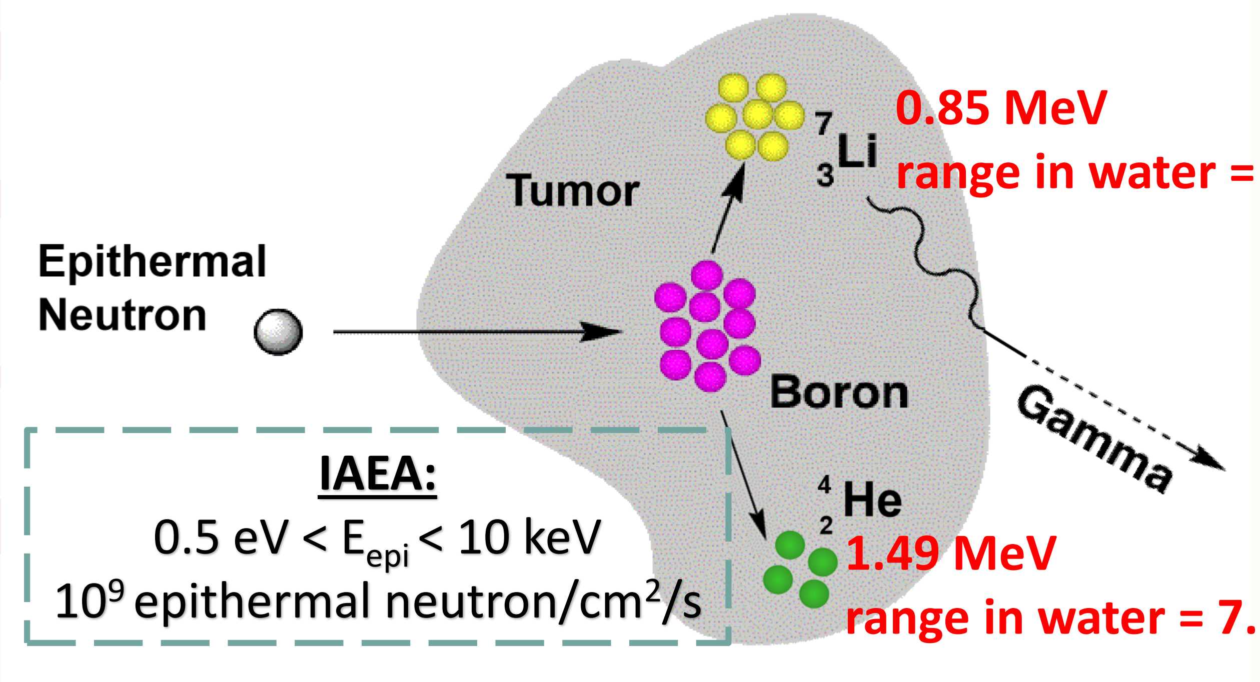
# 1.0 Introduction

**BNCT ➡ Boron Neutron Capture Therapy**

$$^{10}\mathrm{B}\,(n,\alpha)\,^{7}\mathrm{Li}$$

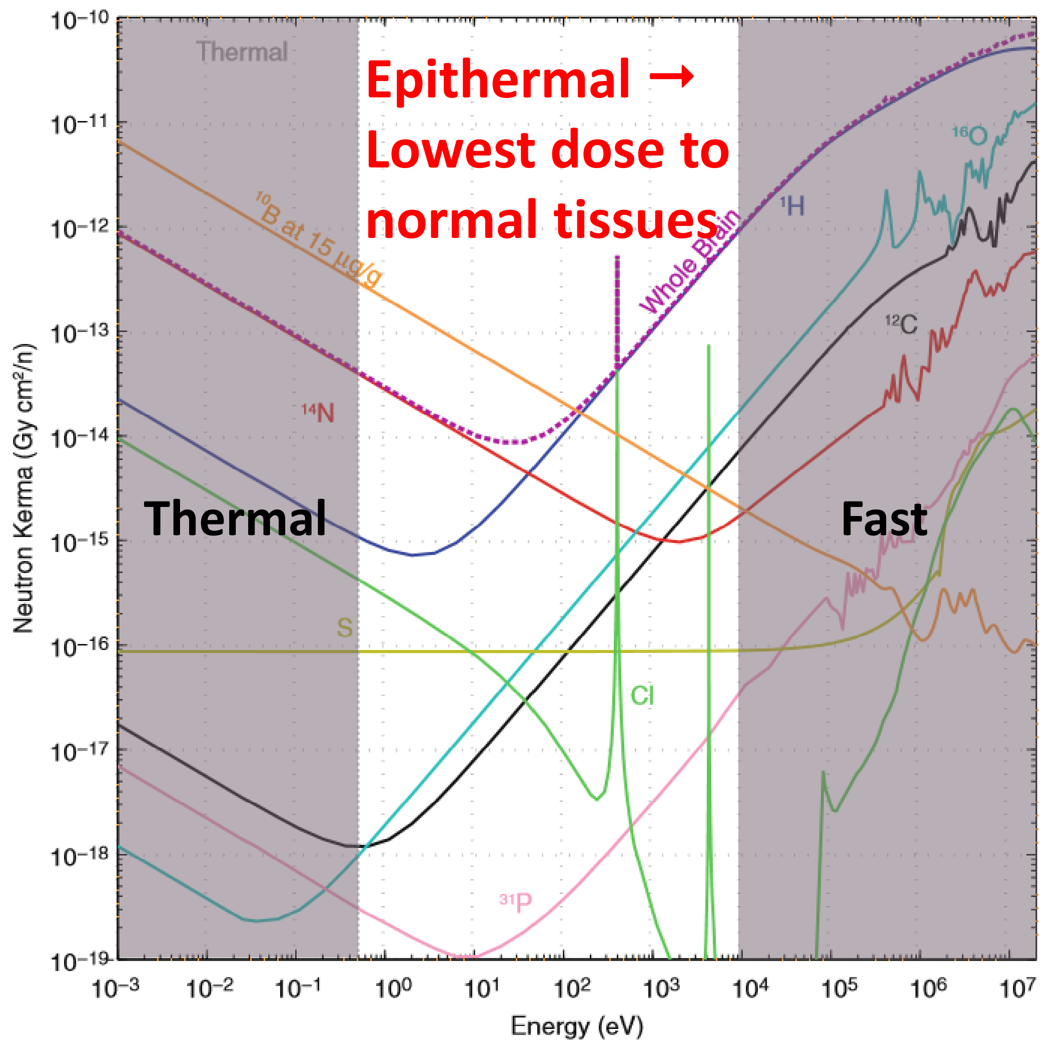


**0.85 MeV**
**range in water = 4.55 µm**

**1.49 MeV**
**range in water = 7.91 µm**

**IAEA:**
0.5 eV < $E_{epi}$ < 10 keV
$10^9$ epithermal neutron/cm$^2$/s

**Typical human cell size ranges from 2 to 150 µm**



**Epithermal → Lowest dose to normal tissues**

**Thermal**

**Fast**

10.1118/1.1428758

# Challenges

## Accelerator-based BNCT (AB-BNCT)

| | Facility | $E_p$ (MeV) | I (mA) | Target | Blistering | Activation | Port | Neutron energy control |
|---|---|---|---|---|---|---|---|---|
| High I<br>Low $E_p$ | National Cancer Center, Japan (NCC) | 2.5 | 20 | Li | Yes | Low | Single | Fixed spectrum |
| | Nagoya Univ. | 2.8 | 15 | Li | Yes | Low | Single | Fixed spectrum |
| | iBNCT | 8 | 5 | Be | Yes | Low | Single | Fixed spectrum |
| High $E_p$<br>Low I | CBENS | 30 | 1 | Be | No | High | Single | Fixed spectrum |

Limits the beam current, which further limits the neutron yield

Long irradiation time limits the number of treatment available daily

Different therapeutic efficacies of cancers at various depths

# Aim

**To propose a compact accelerator-based neutron generator for multi-BNCT**

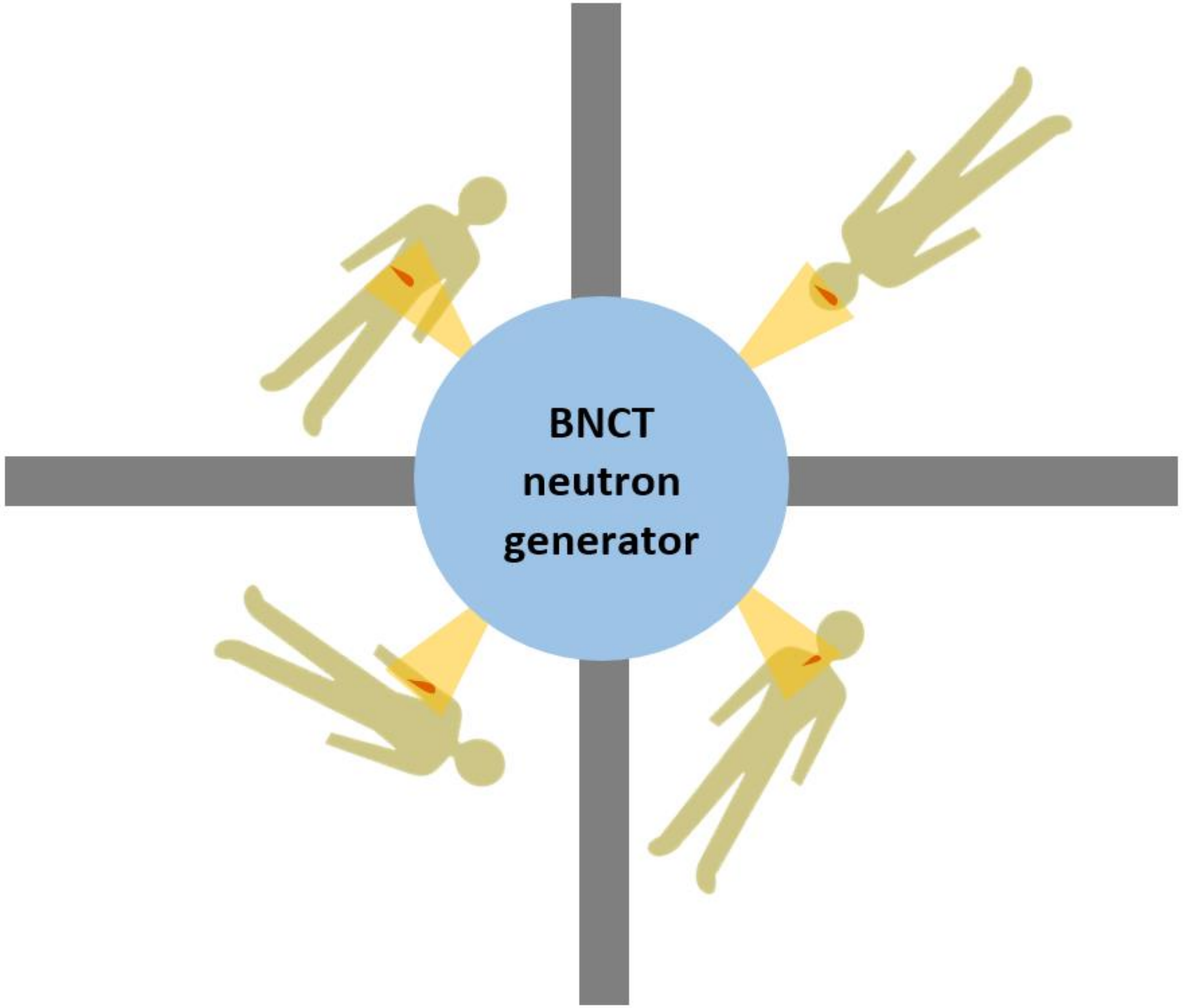
| | Facility | $E_p$ (MeV) | I (mA) | Target | Blistering | Activation | Port | Neutron energy control |
|---|---|---|---|---|---|---|---|---|
| **High I<br>Low $E_p$** | National Cancer Center, Japan (NCC) | 2.5 | 20 | Li | Yes | Low | Single | Fixed spectrum |
| | Nagoya Univ. | 2.8 | 15 | Li | Yes | Low | Single | Fixed spectrum |
| | iBNCT | 8 | 5 | Be | Yes | Low | Single | Fixed spectrum |
| **High $E_p$<br>Low I** | CBENS | 30 | 1 | Be | No | High | Single | Fixed spectrum |
| | This study | 50 | 0.5 | W | No | High | **Multiple** | **Controllable** |

**Current**

Future insight

# Aim

**Schematic of accelerator-based neutron generator for <u>multi-BNCT</u>**



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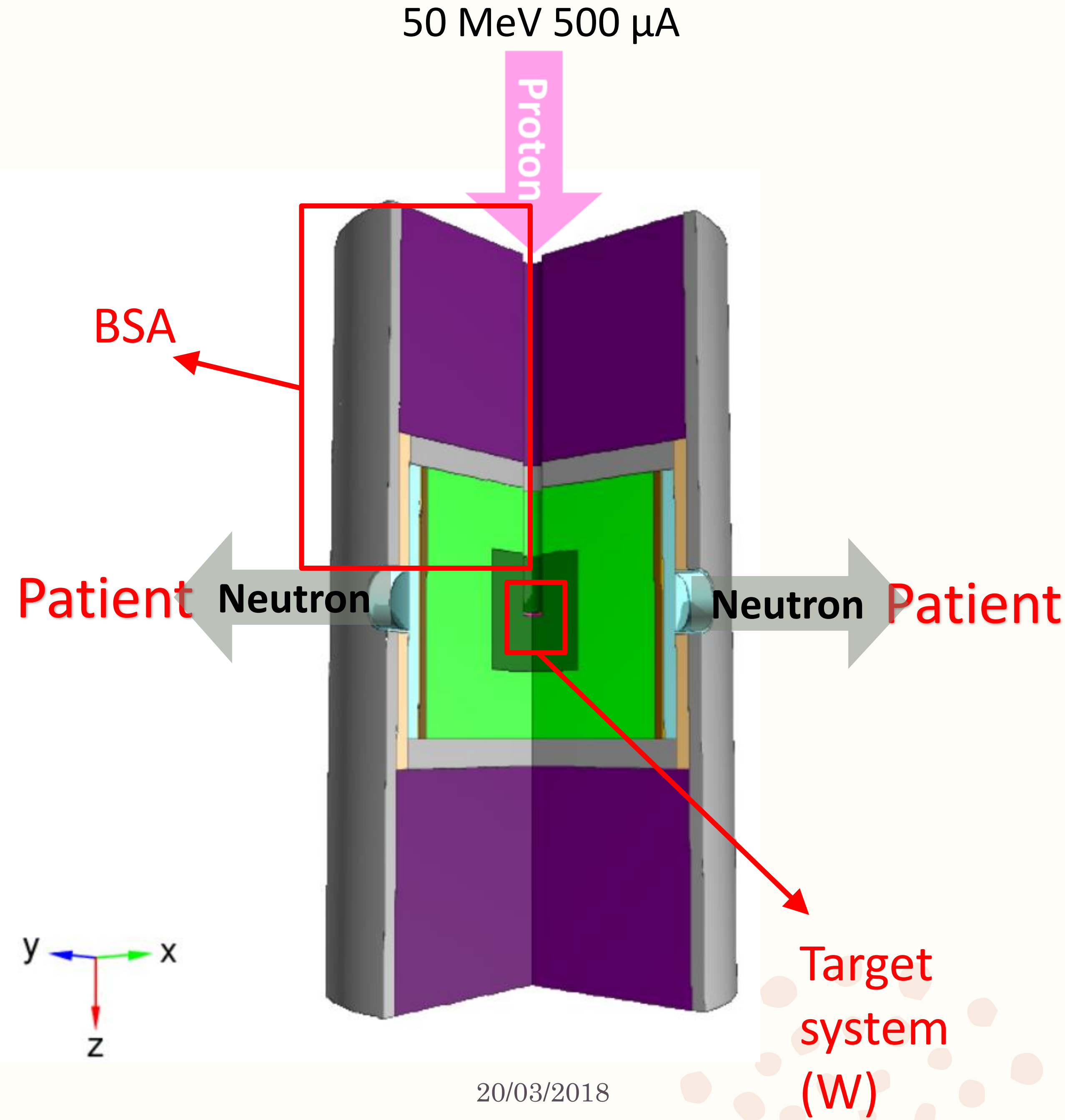
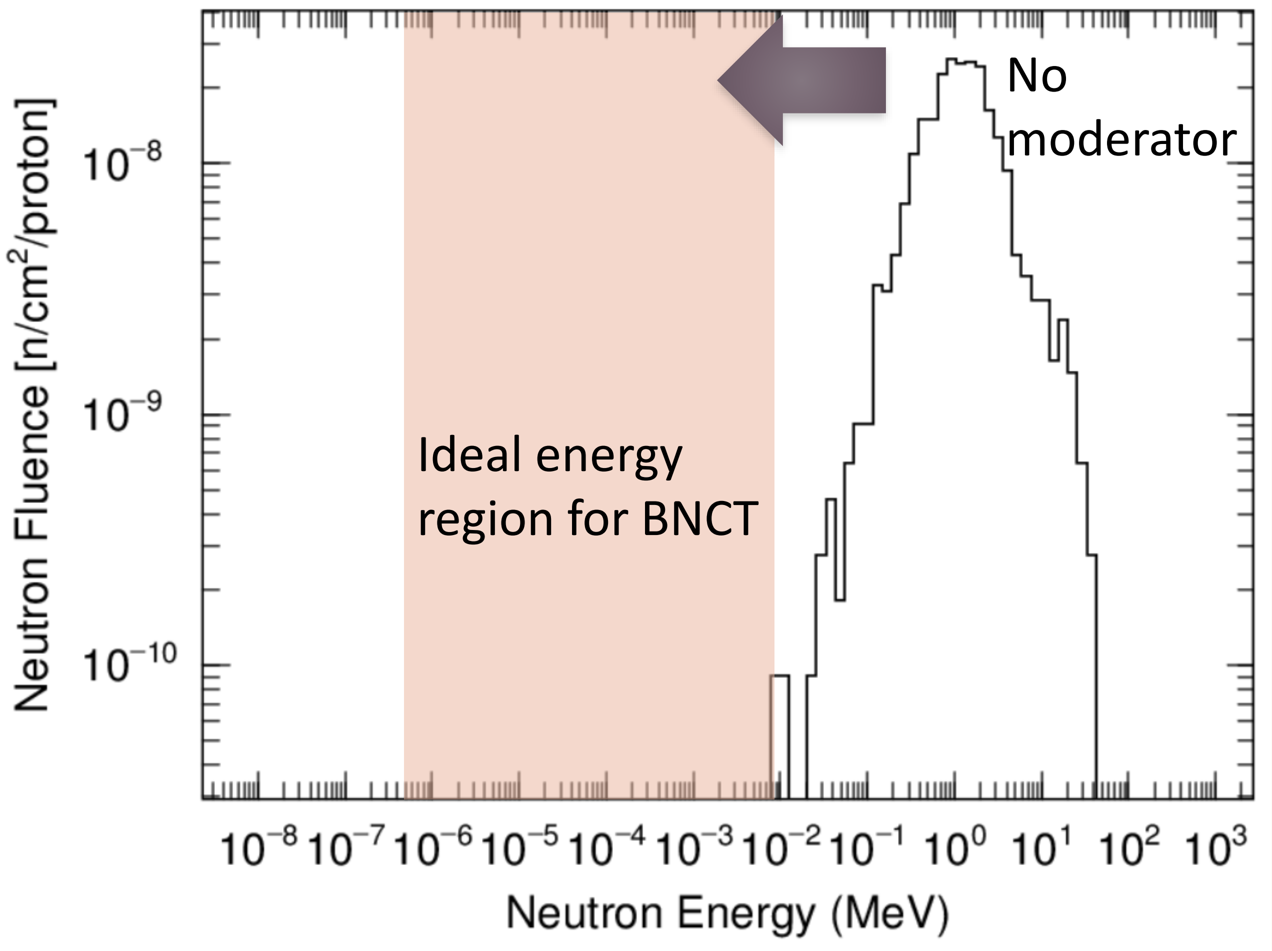


50 MeV 500 μA
Proton
BSA
Patient
Neutron
Neutron
Patient
y
x
z
Target system (W)

# 3.0 Moderator Assembly



**Ideal BNCT neutron beam:**

1. **High epithermal neutron**
   $(0.5\ \mathrm{eV} \leq \mathrm{E_n} \leq 10\ \mathrm{keV})$
2. **Low thermal neutron**
   $(\mathrm{E_n} < 0.5\ \mathrm{eV})$
3. **Low fast neutron**
   $(\mathrm{E_n} > 10\ \mathrm{keV})$
4. **Low gamma component**

# Moderator material estimation using ME

**Moderator Selection:**

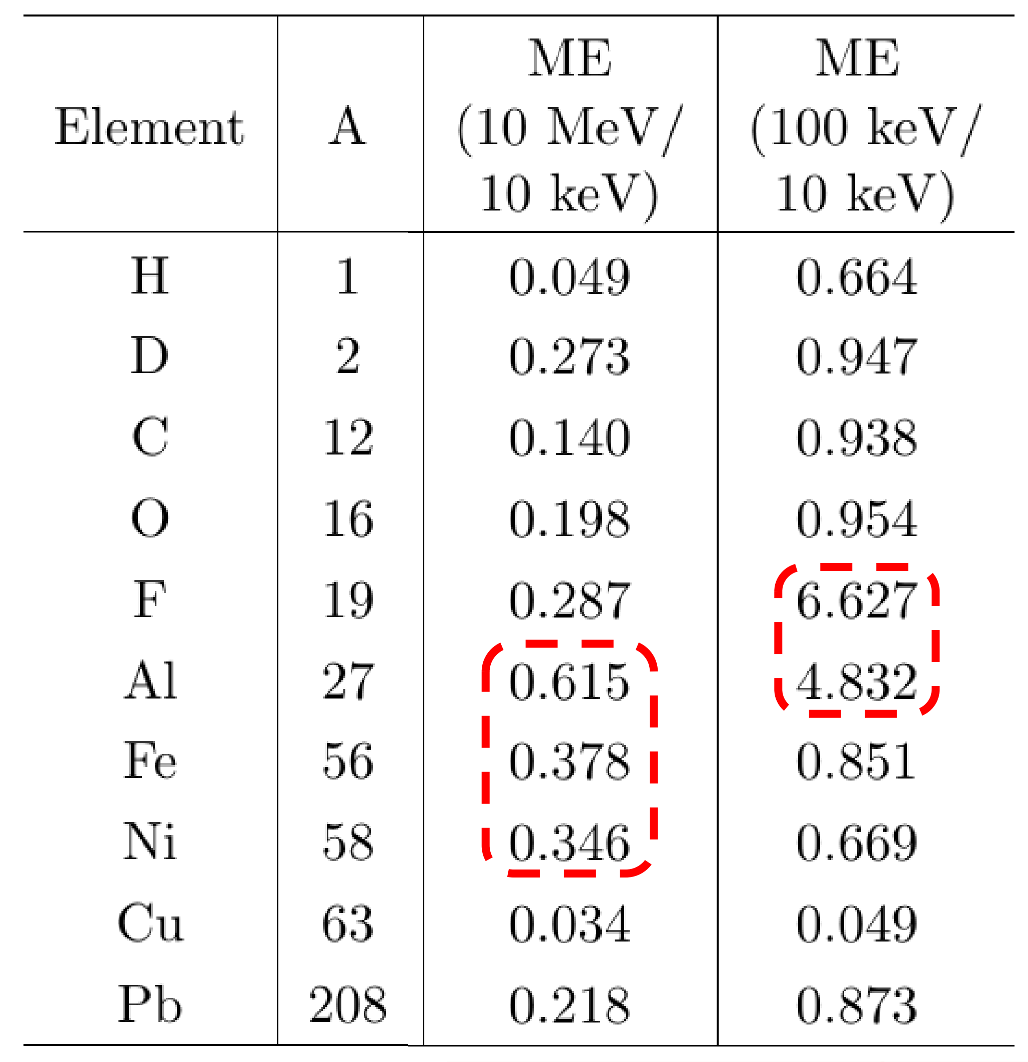
1. High epithermal neutron
2. Low thermal neutron
3. Low fast neutron
4. Low gamma component

HIGHER IS BETTER!

$$Moderating\ efficiency, ME\left(\frac{E_{fast}}{E_{epi}}\right) = \frac{\sigma_s(E_{fast})}{\sigma_s(E_{epi})}$$

$\sigma_s(E_{fast}) = \sigma$ of $(n, n')$ for $E_n > 10\ keV$

$\sigma_s(E_{epi}) = \sigma$ of $(n, n')$ for $0.5\ eV \leq E_n \leq 10\ keV$



| Element | A | ME (10 MeV/ 10 keV) | ME (100 keV/ 10 keV) |
|---|---|---|---|
| H | 1 | 0.049 | 0.664 |
| D | 2 | 0.273 | 0.947 |
| C | 12 | 0.140 | 0.938 |
| O | 16 | 0.198 | 0.954 |
| F | 19 | 0.287 | 6.627 |
| Al | 27 | 0.615 | 4.832 |
| Fe | 56 | 0.378 | 0.851 |
| Ni | 58 | 0.346 | 0.669 |
| Cu | 63 | 0.034 | 0.049 |
| Pb | 208 | 0.218 | 0.873 |

# Optimization of moderator assembly

① One material study by PHITS

② Multiple combinations study by PHITS

③ Sequential effect study by PHITS

④ Optimization of final configuration

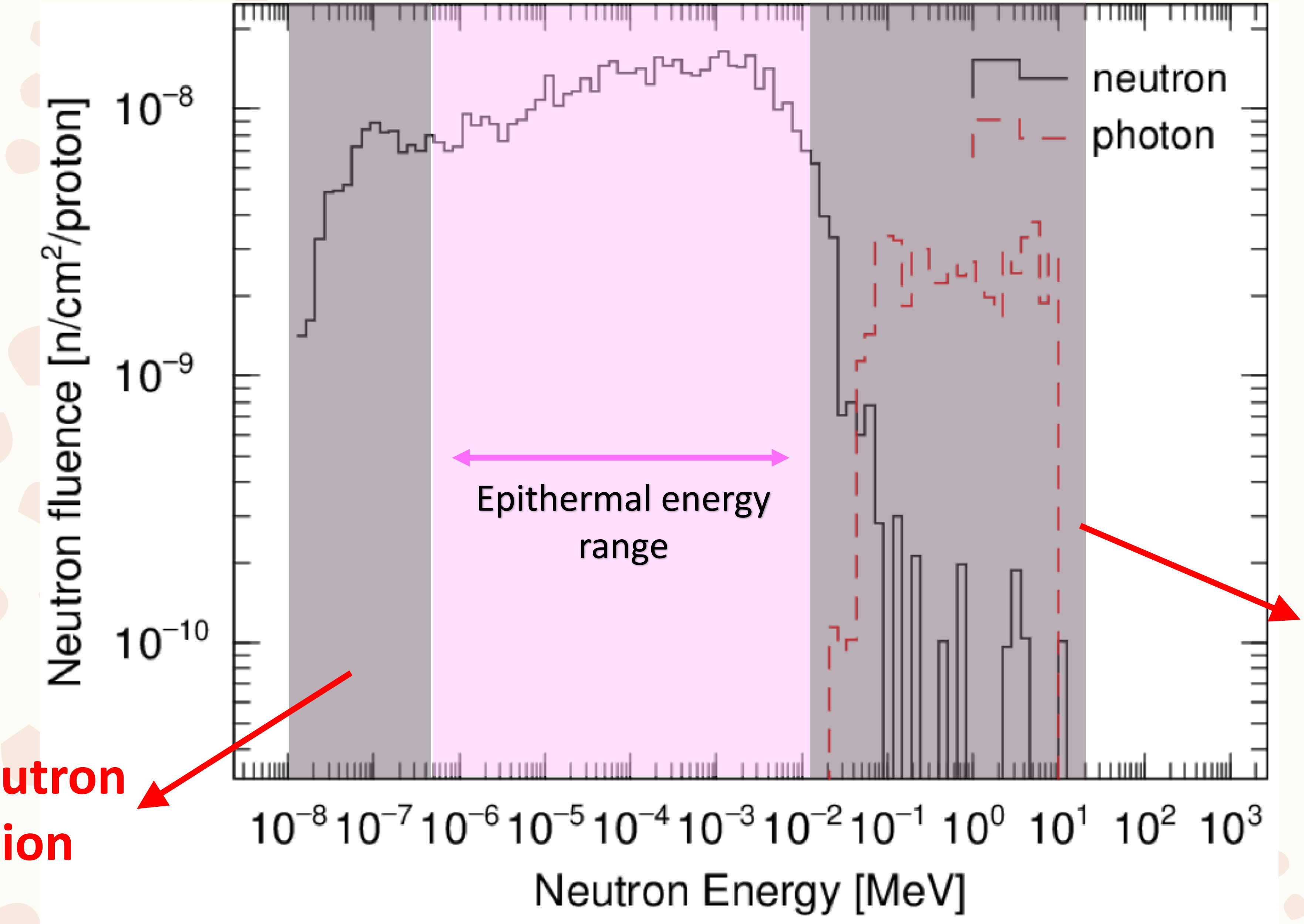
1. **High epithermal neutron flux**
2. **Low fast neutron flux**
3. **Low thermal neutron flux**

Inner most

**Fe** → **$AlF_3$** → **Teflon**

(22 cm) (34 cm) (3 cm)

# Neutron spectrum after moderation

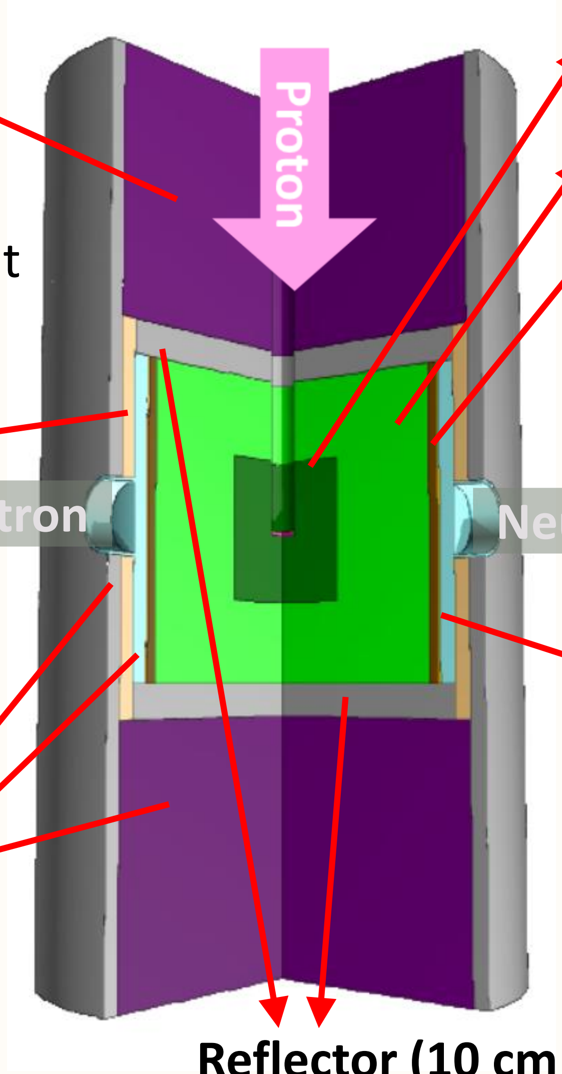


Epithermal energy range

Prompt Gamma from W target

Thermal neutron contamination

# 3.0 Beam Shaping Assembly (BSA)



**Final shield (magnetite concrete + Pb)**
- Shield photon and neutron leakage to surrounding environment

**Neutron shield / Collimator (5 cm of 5%-Borated polyethylene)**
- Direct the neutron beam to cancer region

**Gamma shield (Bi 5 cm)**

**Fe (22 cm)**

**$AlF_3$ (34 cm)**

**Teflon (3 cm)**

**Moderator assembly**

**4 Beam ports**

**Thermal neutron filter (0.7 cm of Li)**
- Absorb undesired thermal neutrons

**Reflector (10 cm of Pb)**
- Maximize epithermal neutron flux

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    - Target system
    - Beam Shaping Assembly (BSA)
4. Figure-of-Merit (FOM)
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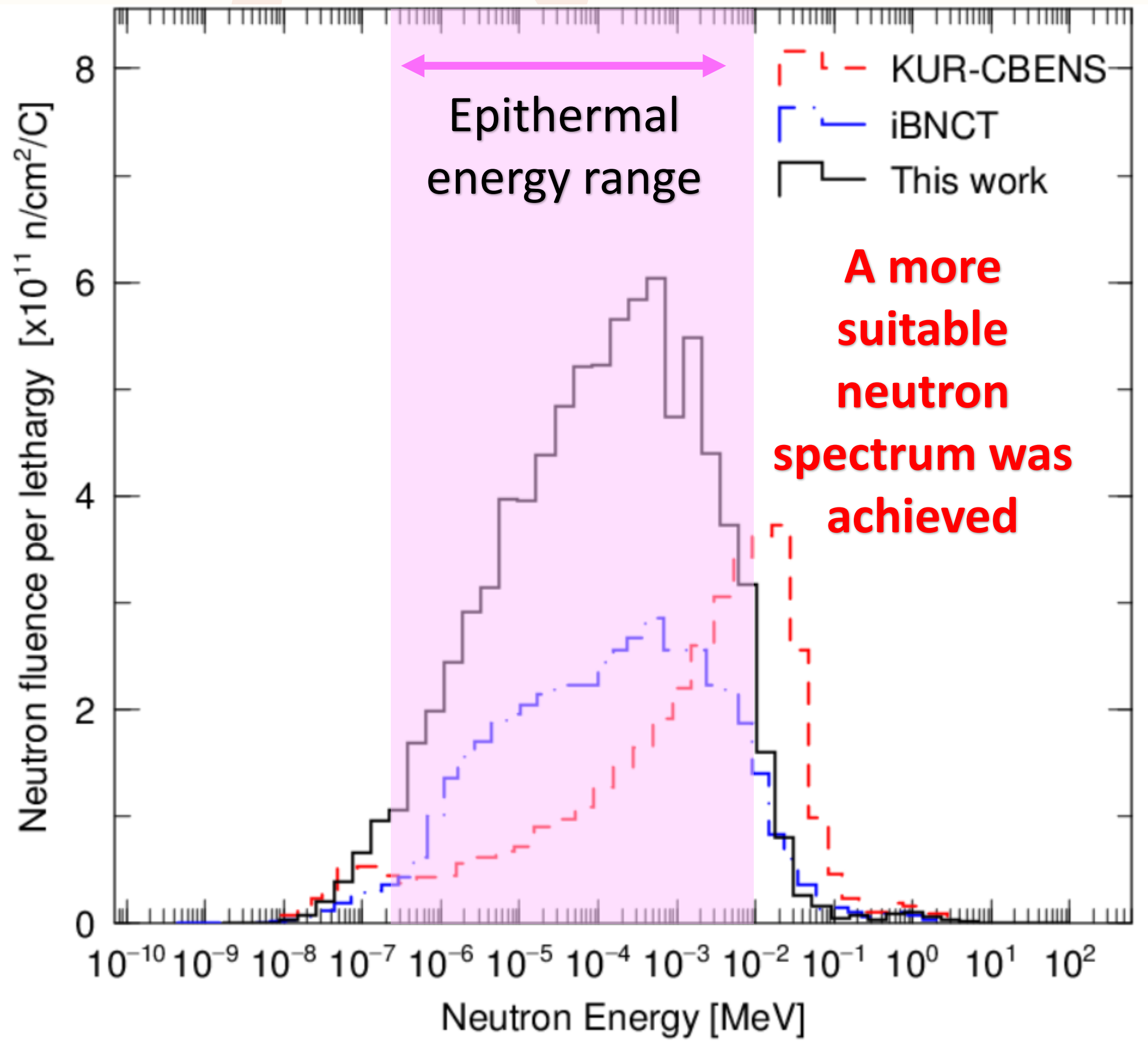
7. Future work

# 4.0 Figure-of-Merit (FOM)

Neutron spectrum at the center of aperture



**A more suitable neutron spectrum was achieved**

Free beam parameters at aperture

| Parameter | IAEA | This work | KUR-CBENS [$^9$Be(p,n)$^9$B at 30 MeV 1mA] |
|---|---|---|---|
| Epithermal neutron flux ($10^9$ n/cm$^2$/s) | >1 | 1.98±0.08 | 1.88 |
| Fast neutron dose ($10^{-13}$ Gy cm$^2$/epi-n) | <2 | 2.13±0.35 | 5.84 |
| Gamma dose ($10^{-13}$ Gy cm$^2$/epi-n) | <2 | 2.31±0.25 | 0.78 |
| Thermal-to-epithermal ratio | <0.05 | 0.056±0.04 | - |
| Neutron forward-current-to-flux ratio | >0.7 | 0.72±0.08 | - |

**2 times more for 4 ports**

**Close to IAEA**

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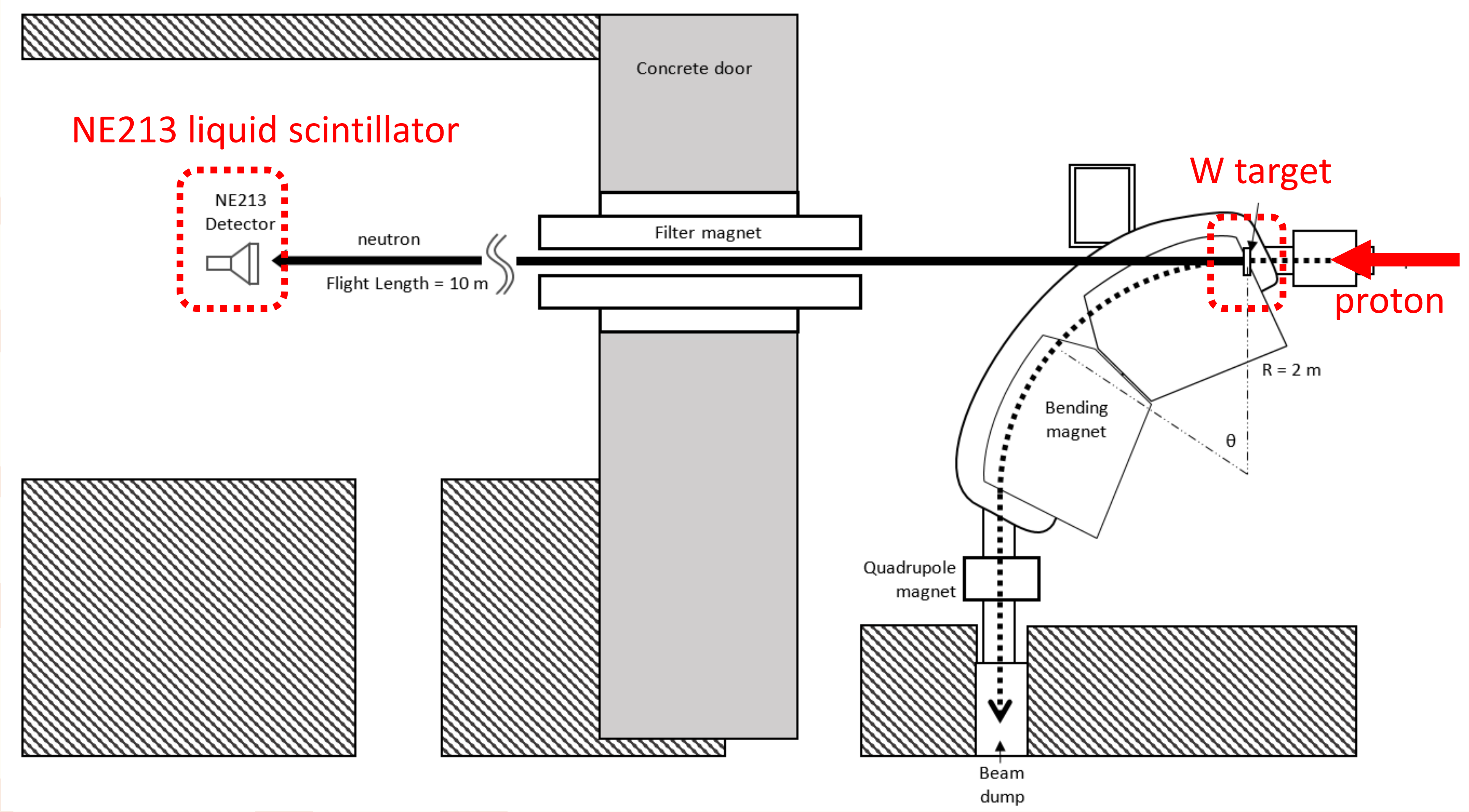
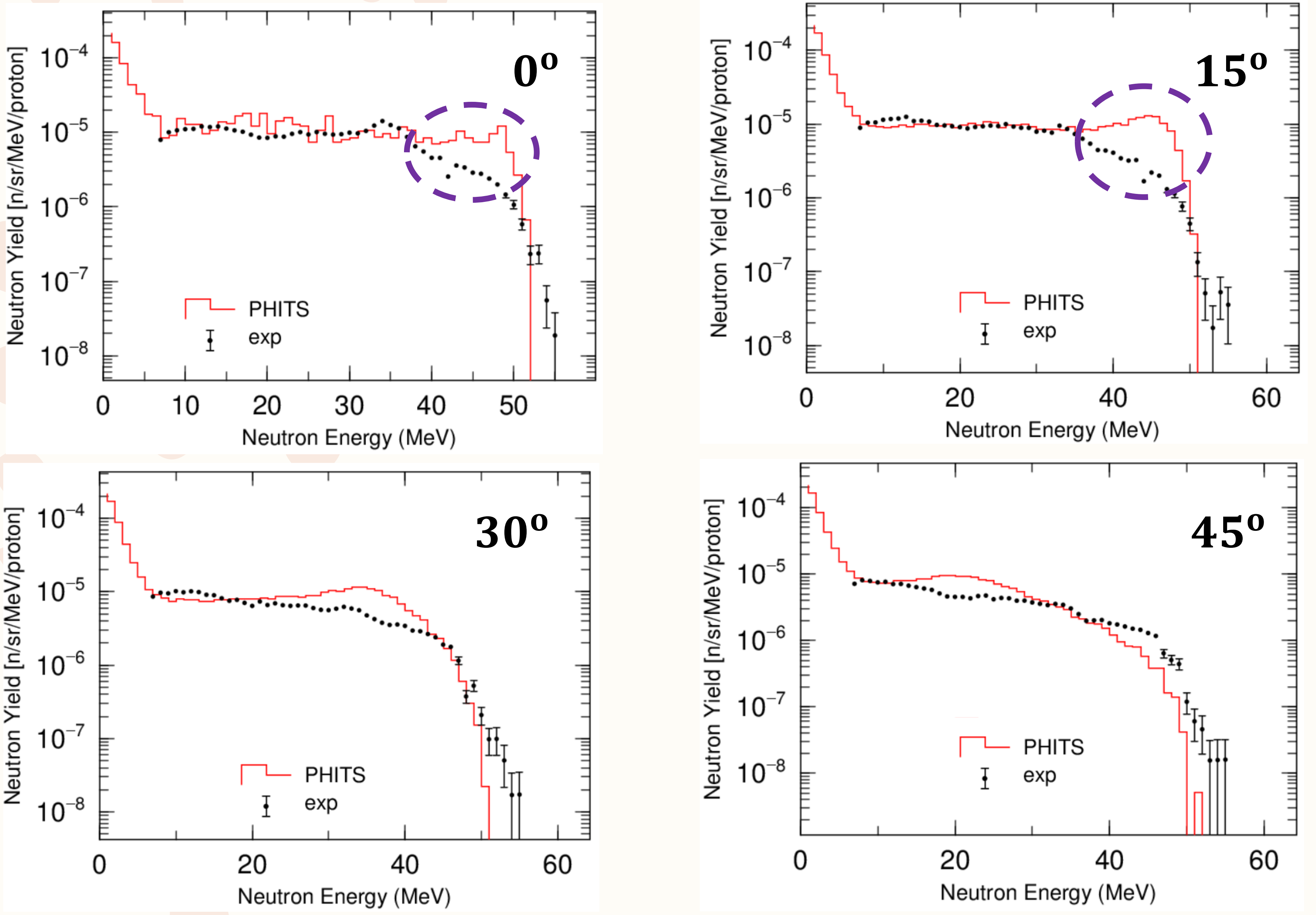
# 5.0 Experimental verification of angular distribution of fast neutron emitted from W target

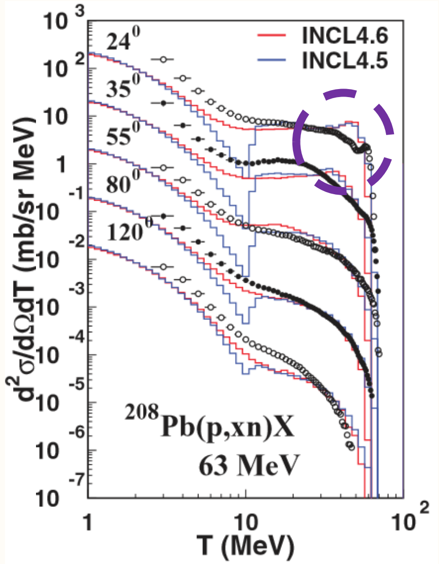


- Energy: 53 MeV
- Particle: Proton
- Target: W (0.2x20x20) mm$^3$
- Experiment hall: Neutron experimental hall (N0 course)
- Aim: Verify the angular neutron yield from W target calculated by PHITS
- Method: Neutron Time-of-flight (TOF) (10 m length)
- Detector: NE213 liquid scintillator

# Comparison of PHITS and Experiments



*10.1140/epja/i2004-10073-1



Comparison of INCL4.6 used by PHITS with other works of Pb(p,xn) at 63 MeV.

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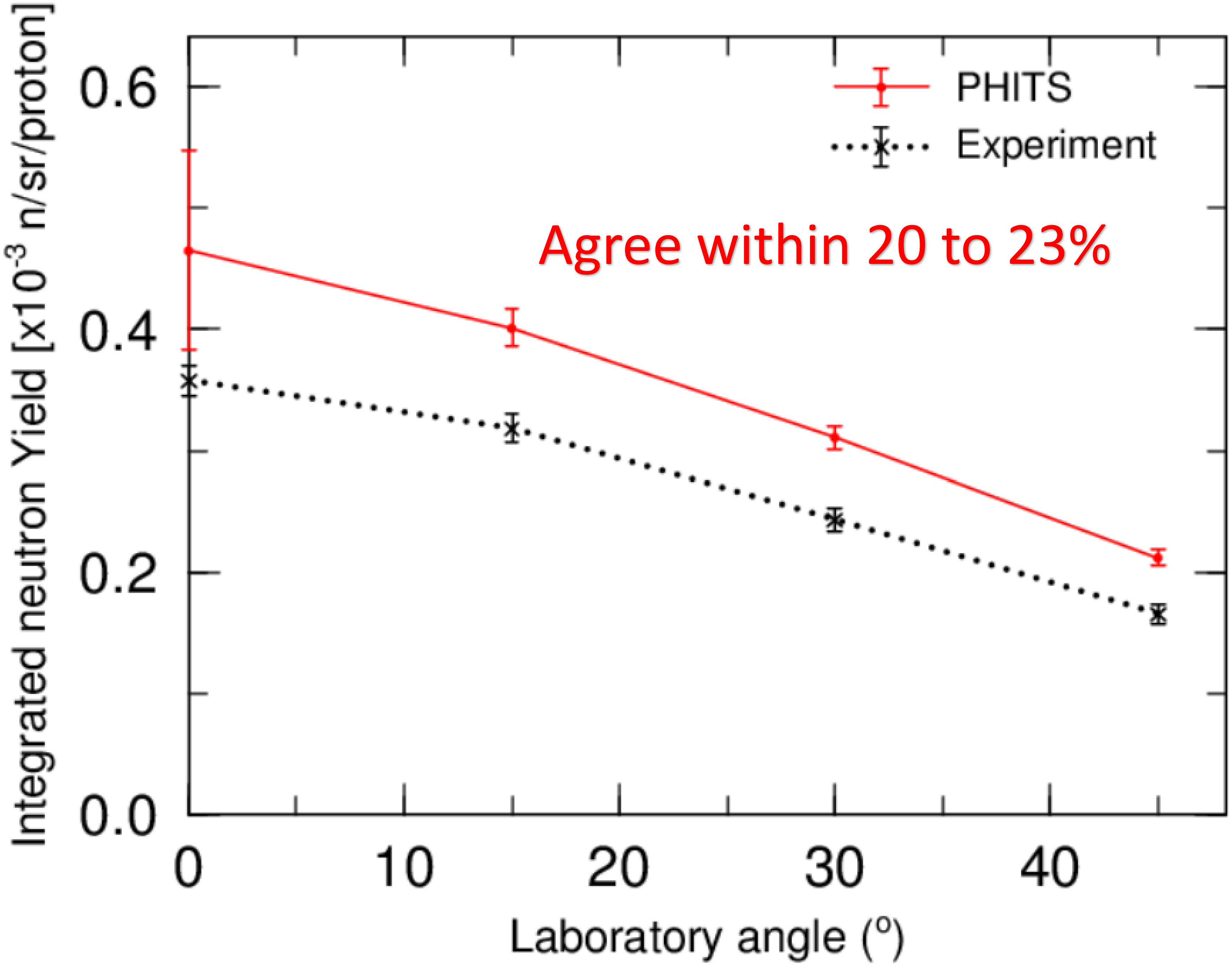
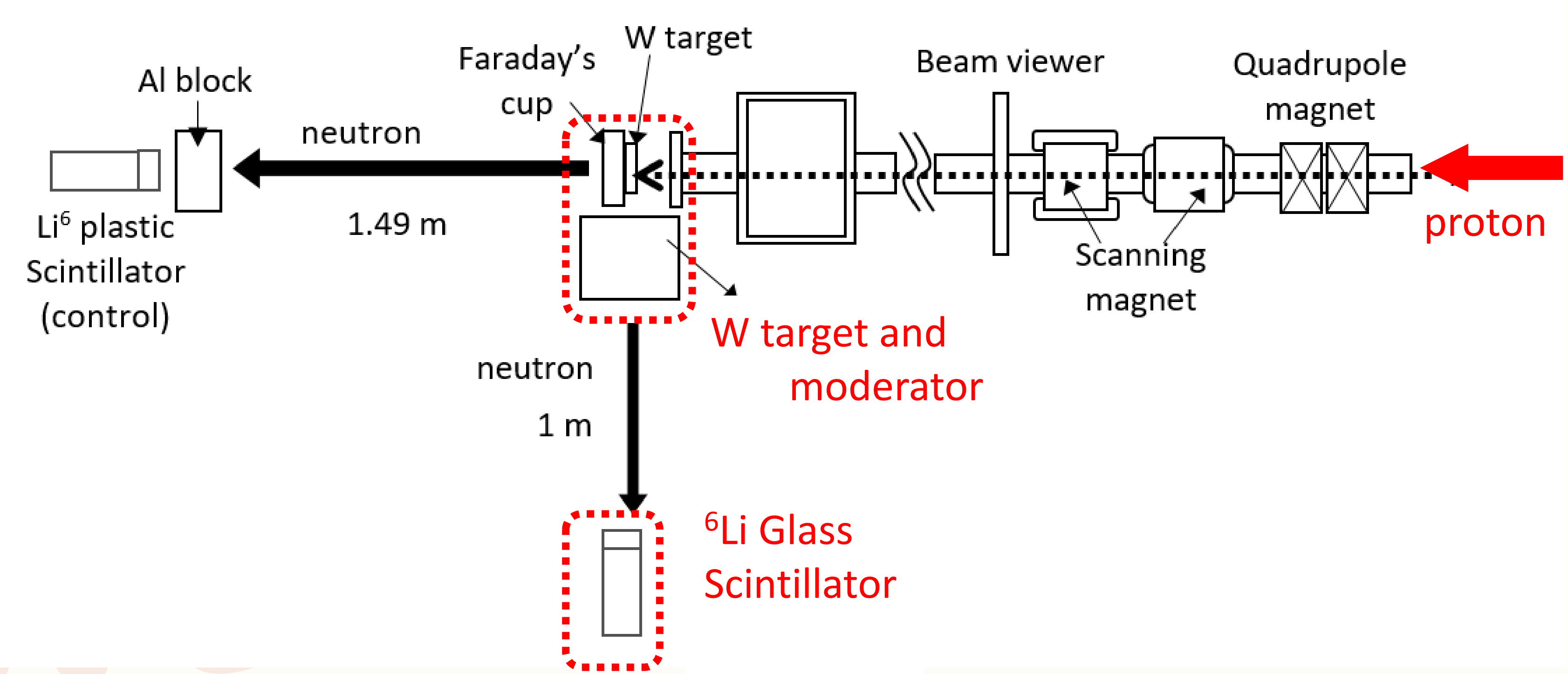


Agree within 20 to 23%

# 5.0 Experimental verification of moderated neutron energy spectra

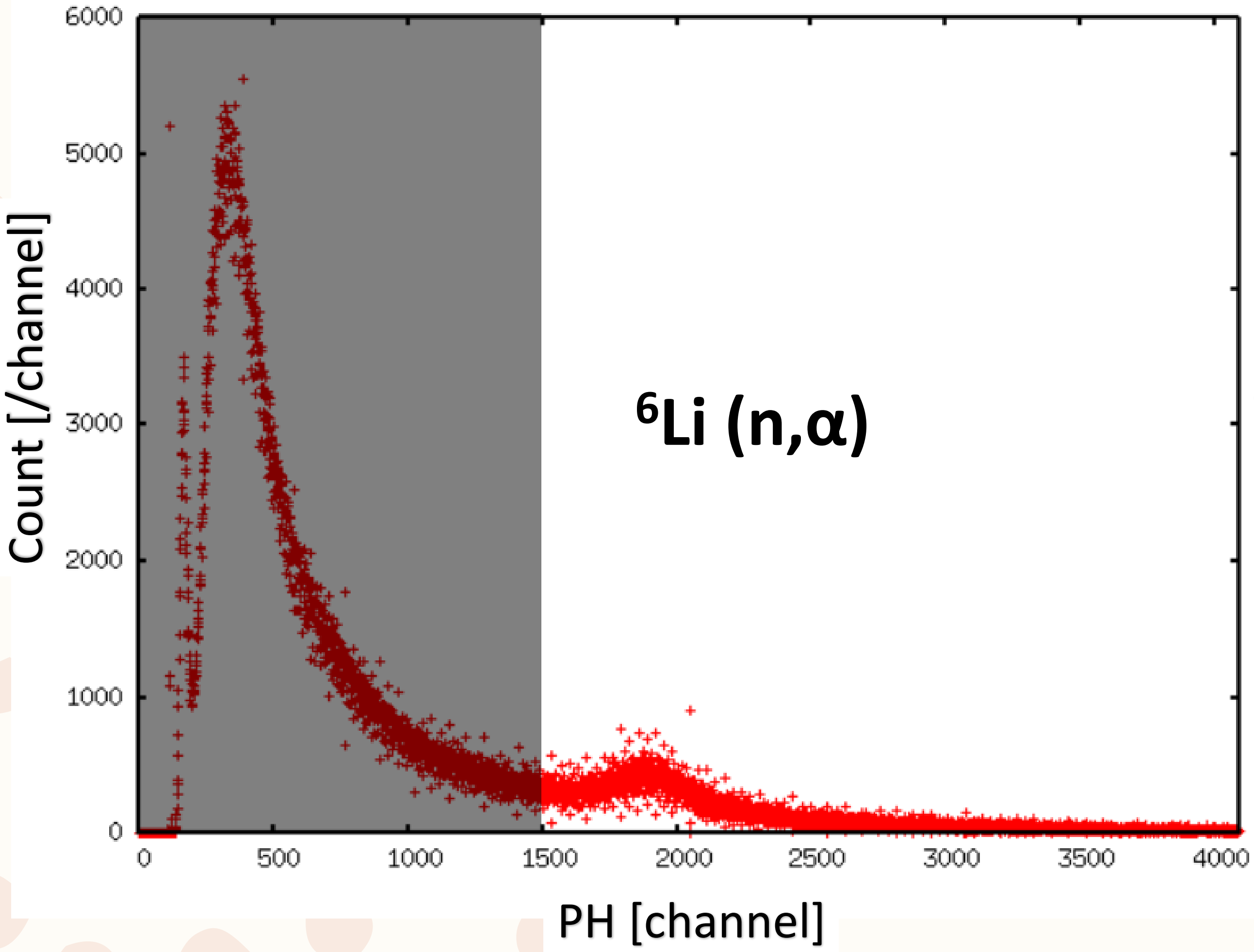


- Energy: 53 MeV
- Particle: Proton
- Target: W (0.2x20x20) $mm^3$
- Experiment hall: East experimental hall (ES course)

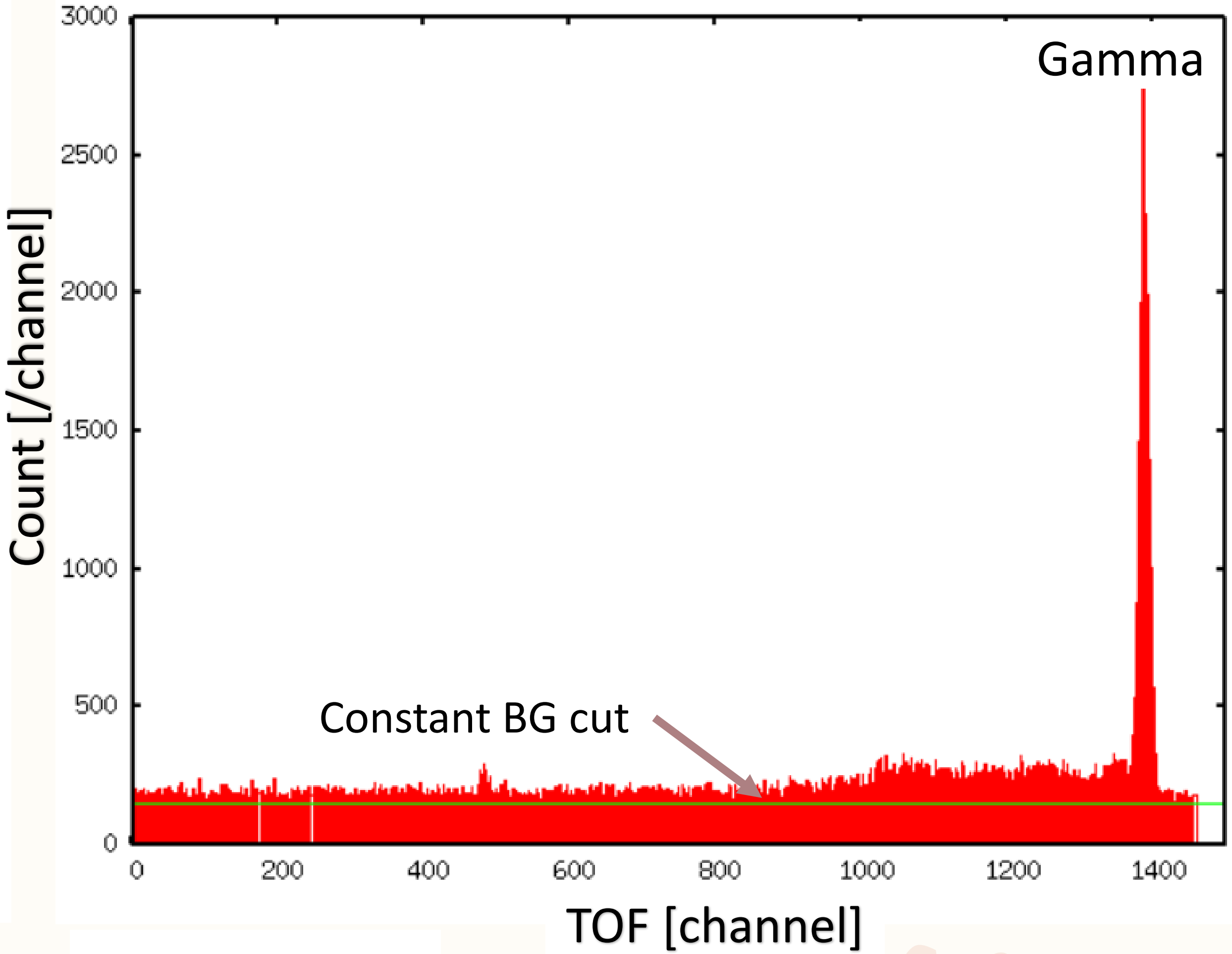
- Aim: Verify the moderated neutron yield from a test moderator
- Method: Neutron Time-of-flight (TOF) (1 m length)
- Detector: $^6$Li glass scintillator

# PHS Discrimination and TOF background cut

PHS of $^6$Li glass scintillator (90° no moderator)



TOF spectrum (90° no moderator)



*Increasing time* ←

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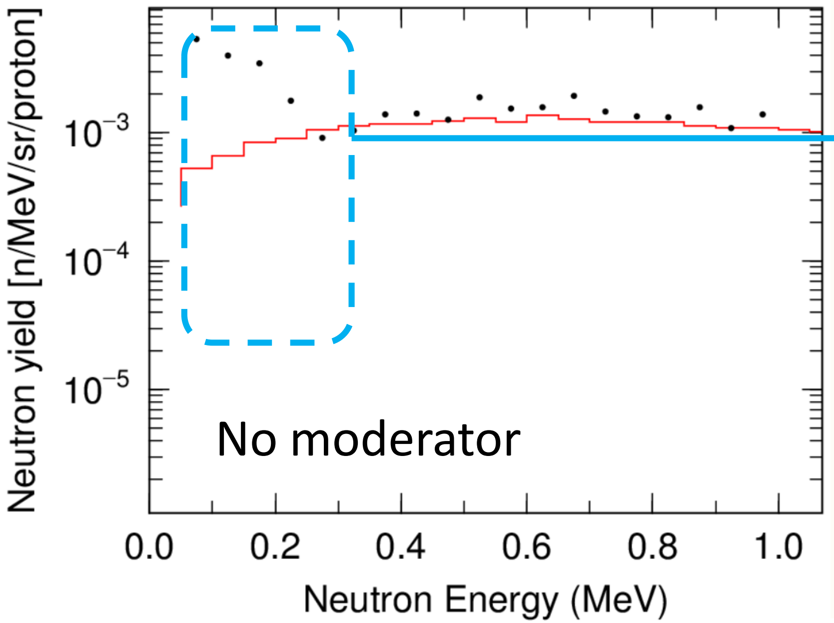
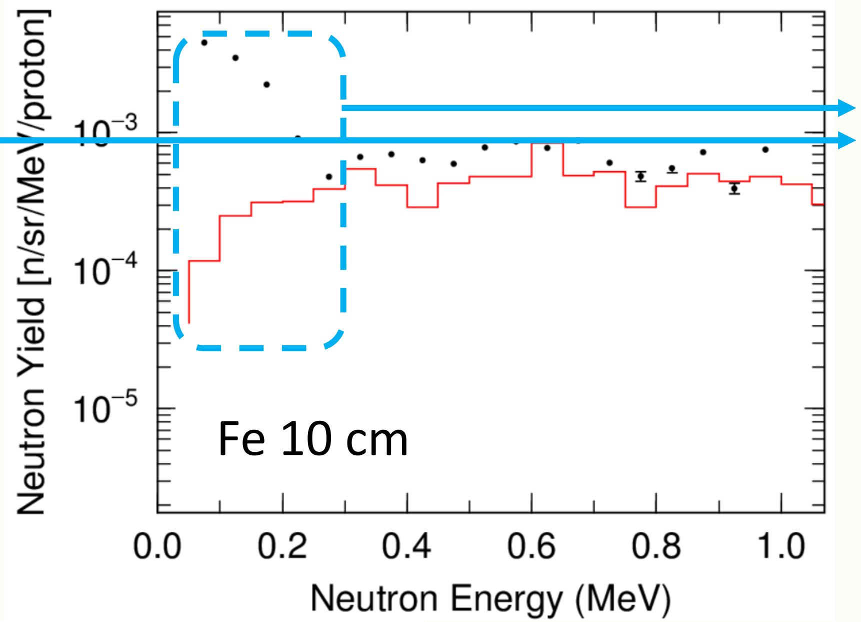
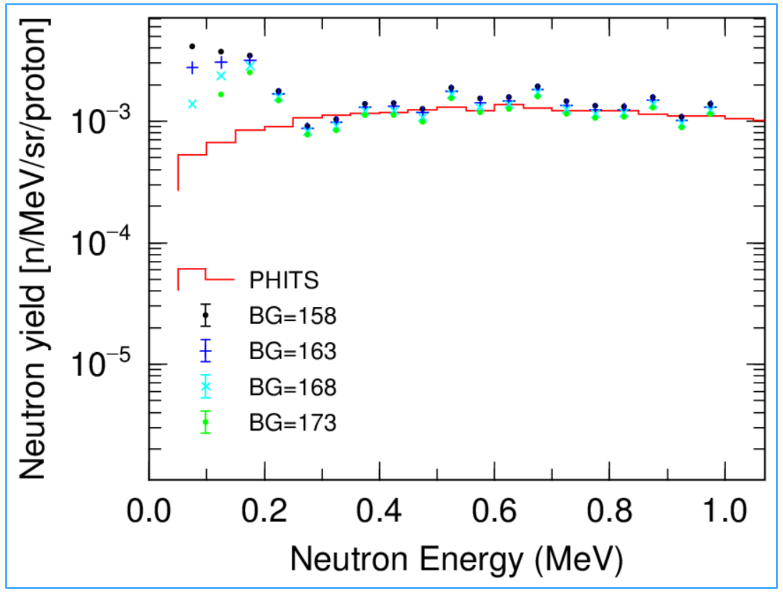
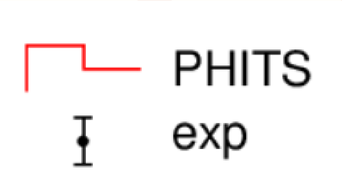
# Results



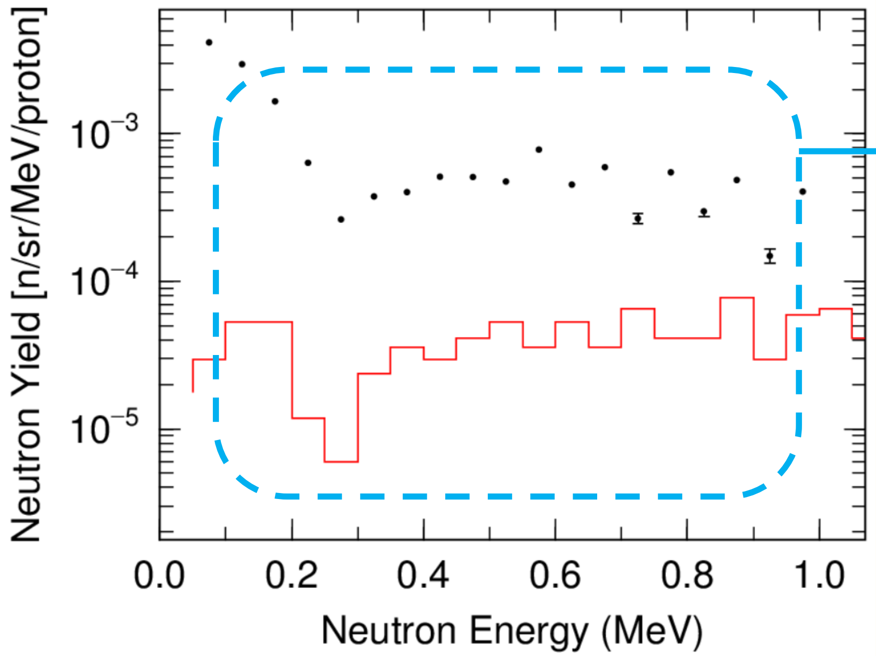


**Possible reasons for discrepancies:**





Fe 10 cm + $AlF_3$ 10 cm + Teflon 10 cm + LiF 1.5 cm



**Possible reasons for discrepancies:**

1. More absorption caused by (n,γ) reaction by materials in the experiment hall, causing a higher noise.
2. Higher ambiguity in the origin of TOF when the moderator thickness (about 30 cm) is comparable to the neutron flight length (1 m).

# 6.0 Conclusion

1. Neutron generator by using W target at 50 MeV can provide sufficient epithermal neutron flux of $2x10^9 n/cm^2/s$ at 4 ports with a SATISFACTORY beam quality.
2. The integrated angular neutron yield of W target agrees with experiment. This suggests that PHITS is reliable in predicting the primary neutron production from W.
3. Experiment with a test moderator shows discrepancy with calculations. It should be repeated to confirm all the neutron transport calculations done.

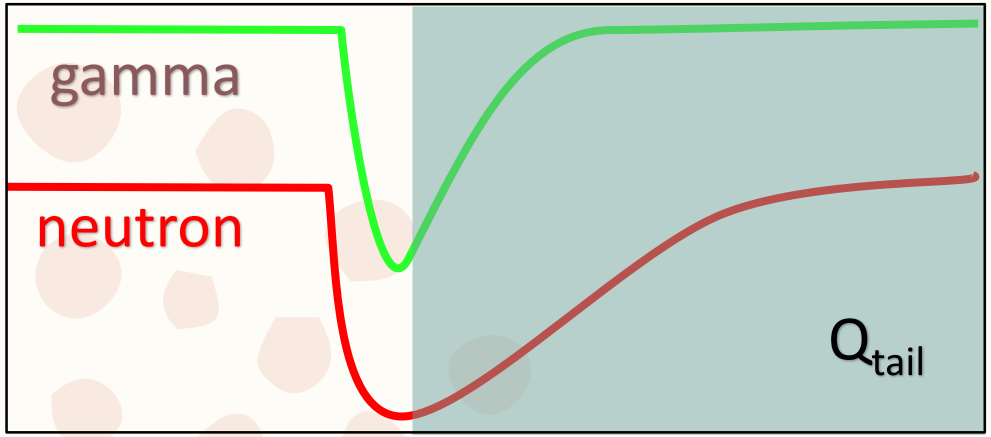
# Thank you!!!

# 7.0 Future work

1. Perform an experiment with the real configuration to verify the performance of this neutron generator using in-phantom dose measurement.
2. Development of variable neutron spectra at multiple neutron ports.
3. For clinical implementations, the following conditions should be fulfilled:
   - W target should be replaced at least monthly to reduce the accumulated activation and radiation damage.
   - The activated W target shall be replaced remotely by a robot and kept in a fully sealed room or container to avoid any leakage of activated dose.
   - The use of a special beam irradiation system such as beam scanning, broadening and target rotating system to ensure an even heat deposition onto target
   - A proper shutter system or shield when it is in off-line mode to shield activated radiation in the treatment room.

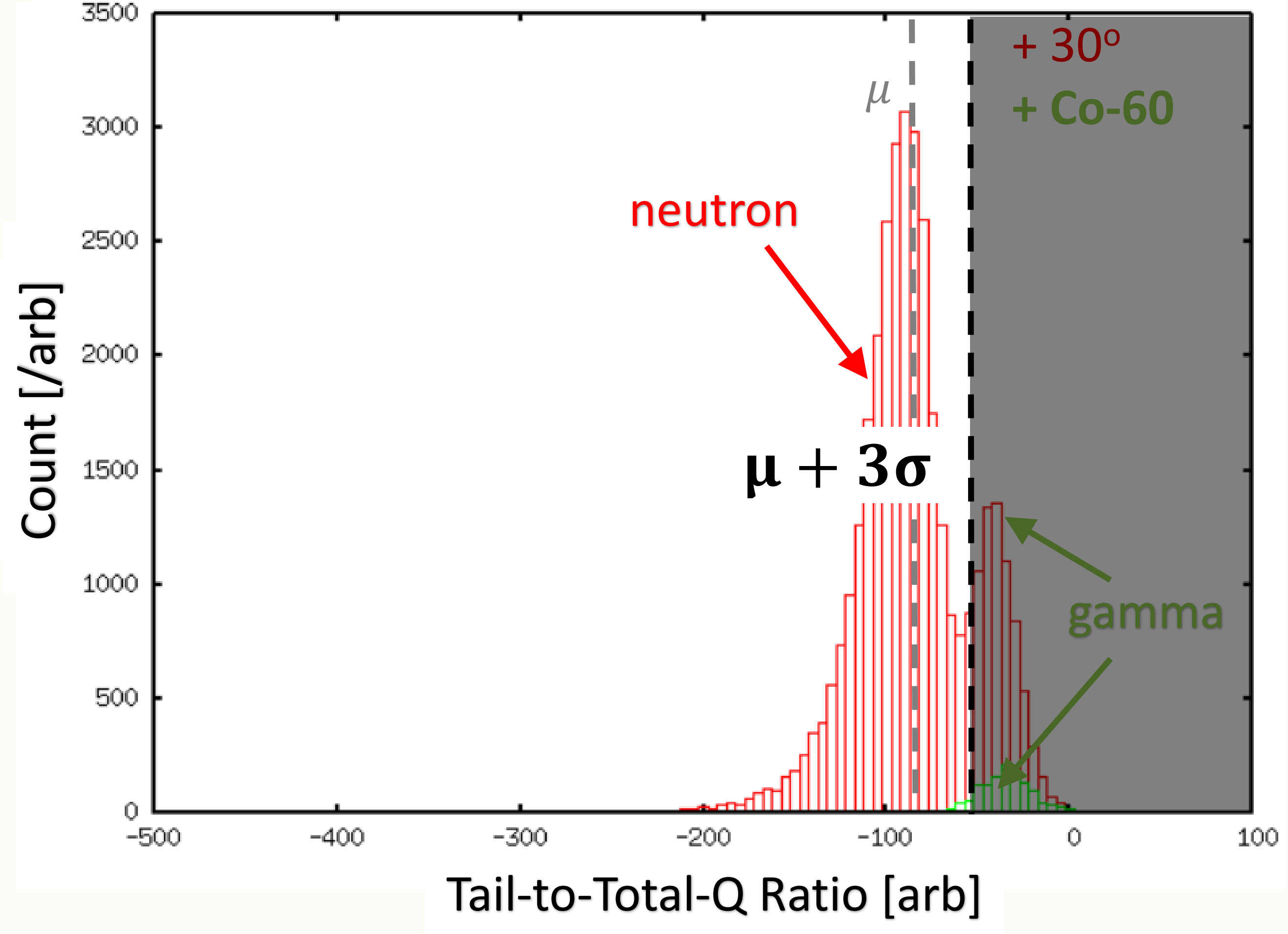
# Pulse Shape Discrimination

Typical pulse shape of a gamma and neutron signal from NE213 liquid scintillator



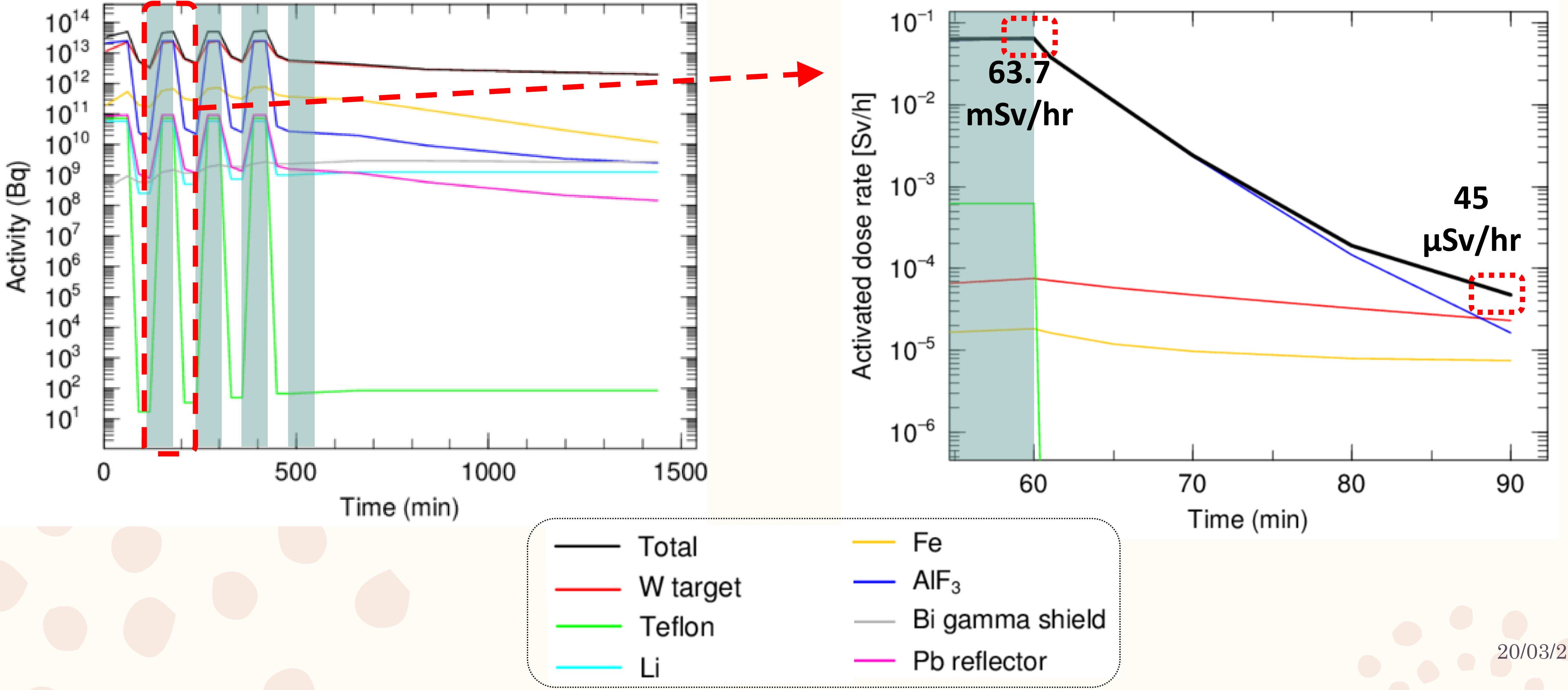
$$Neutron's\ \frac{Q_{tail}}{Q_{total}} > gamma's$$

*Tail-Q to Total-Q spectrum*



# Target and BSA Activation

🟩 Irradiation of 1 hour ☐ Off-line mode

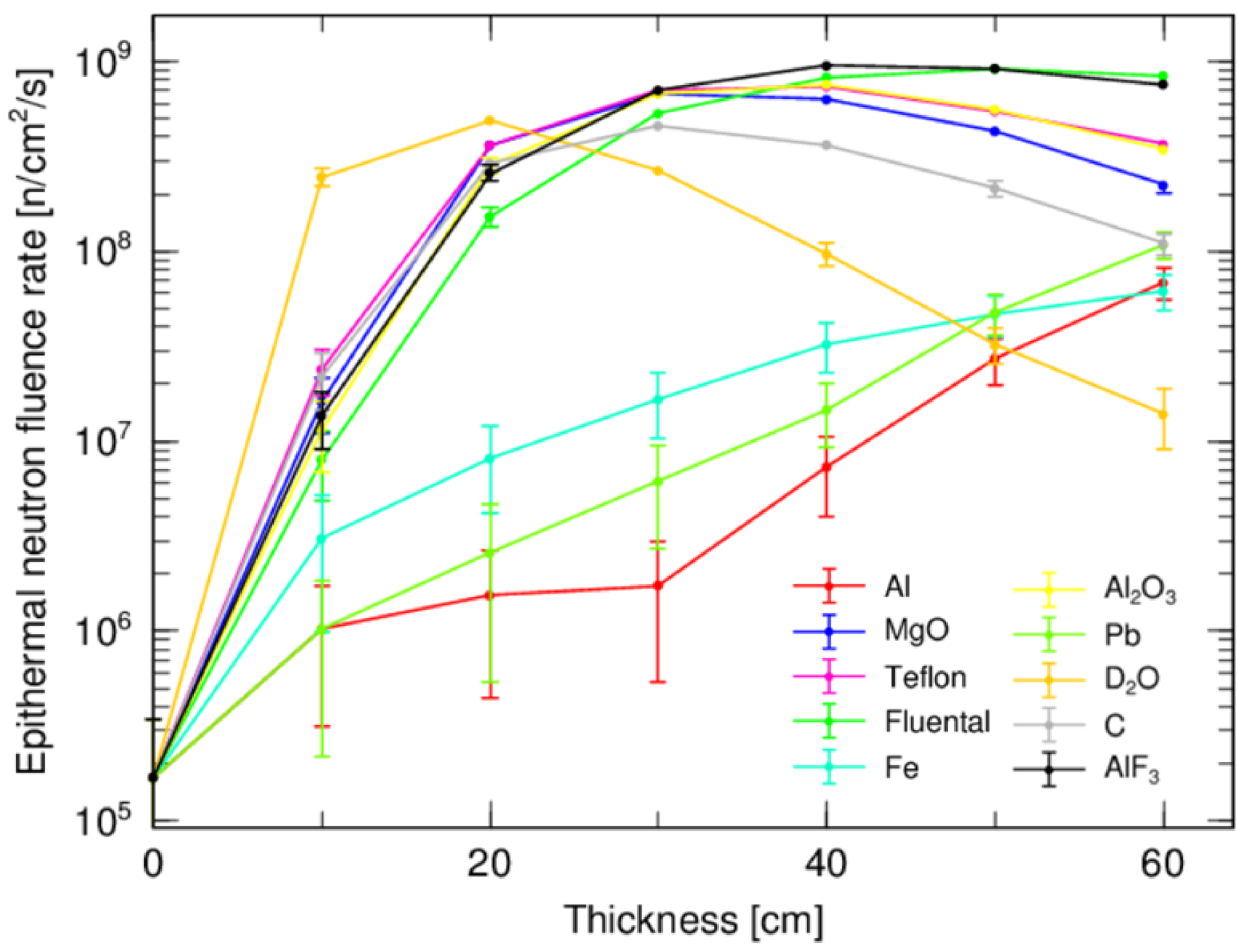


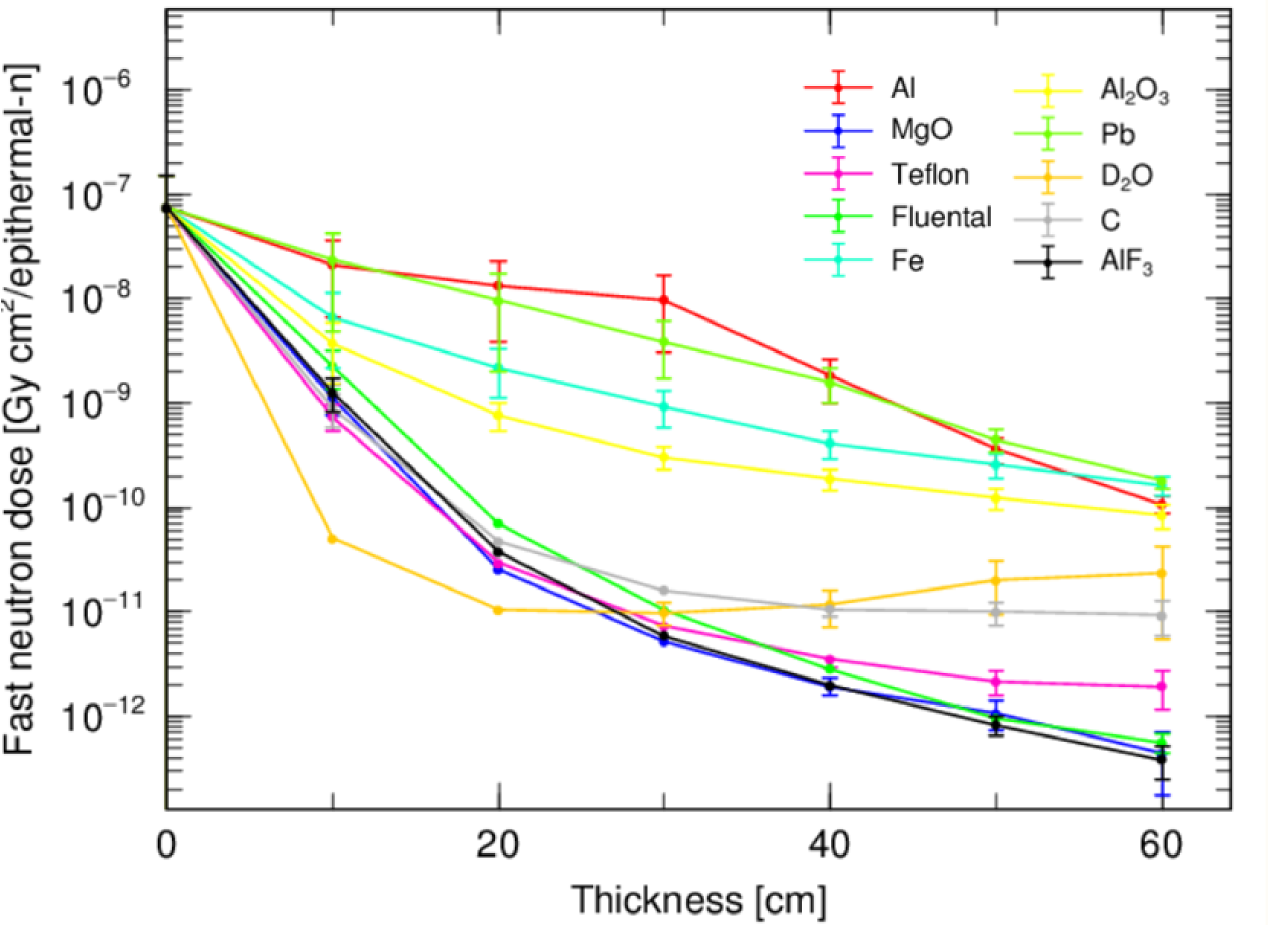
The activated dose rate at patient position (5 cm from aperture)

63.7 mSv/hr

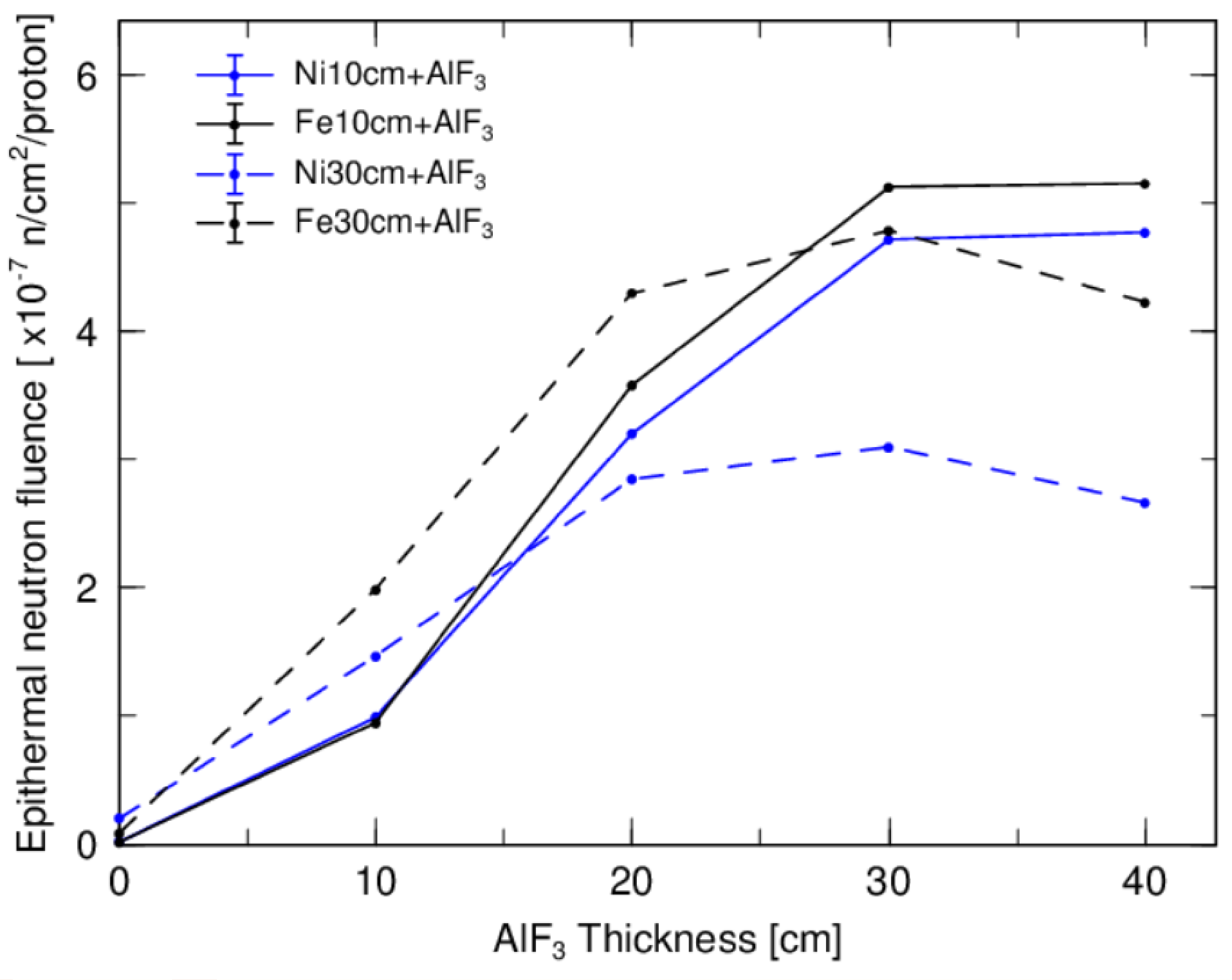
45 µSv/hr

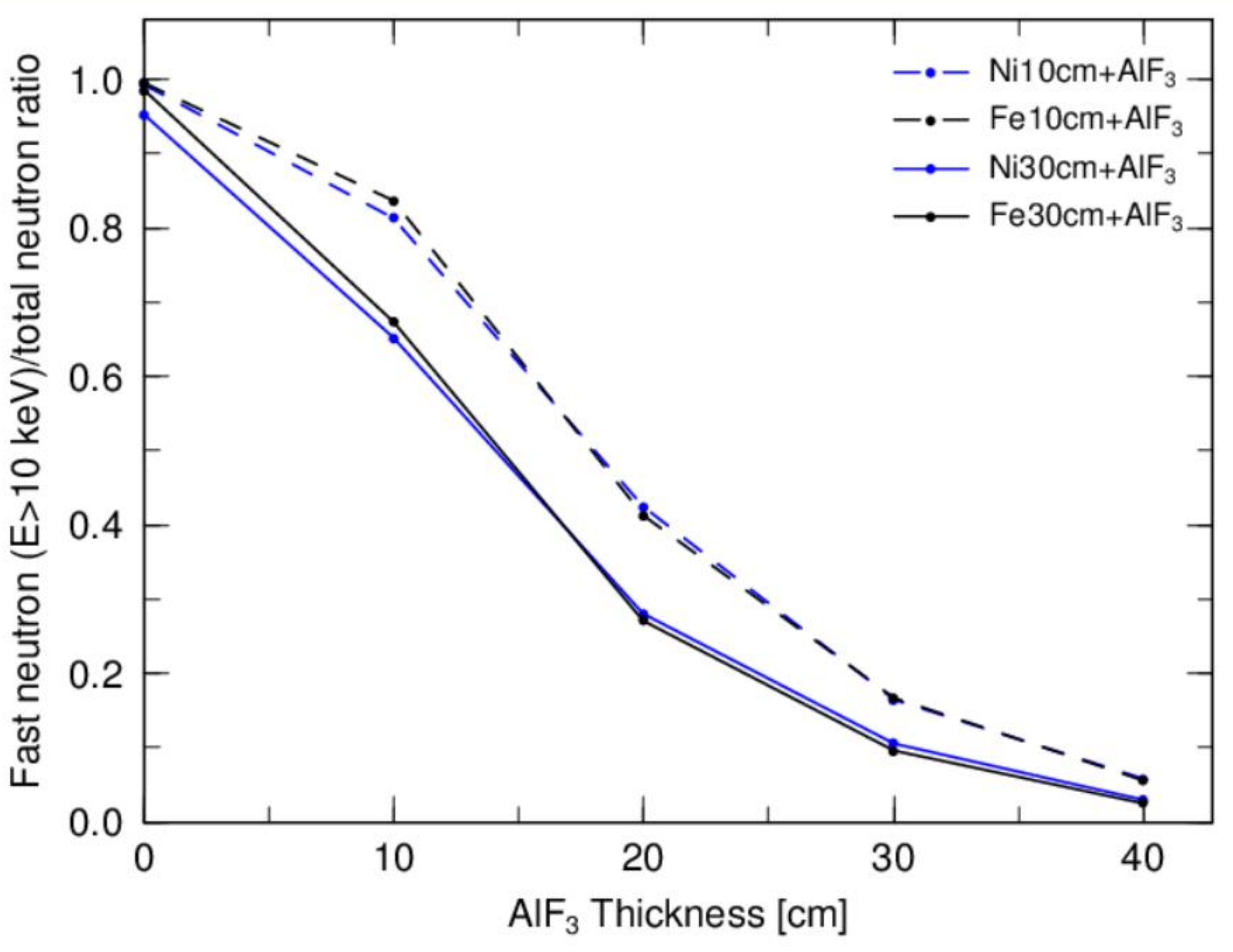
# One material study by PHITS



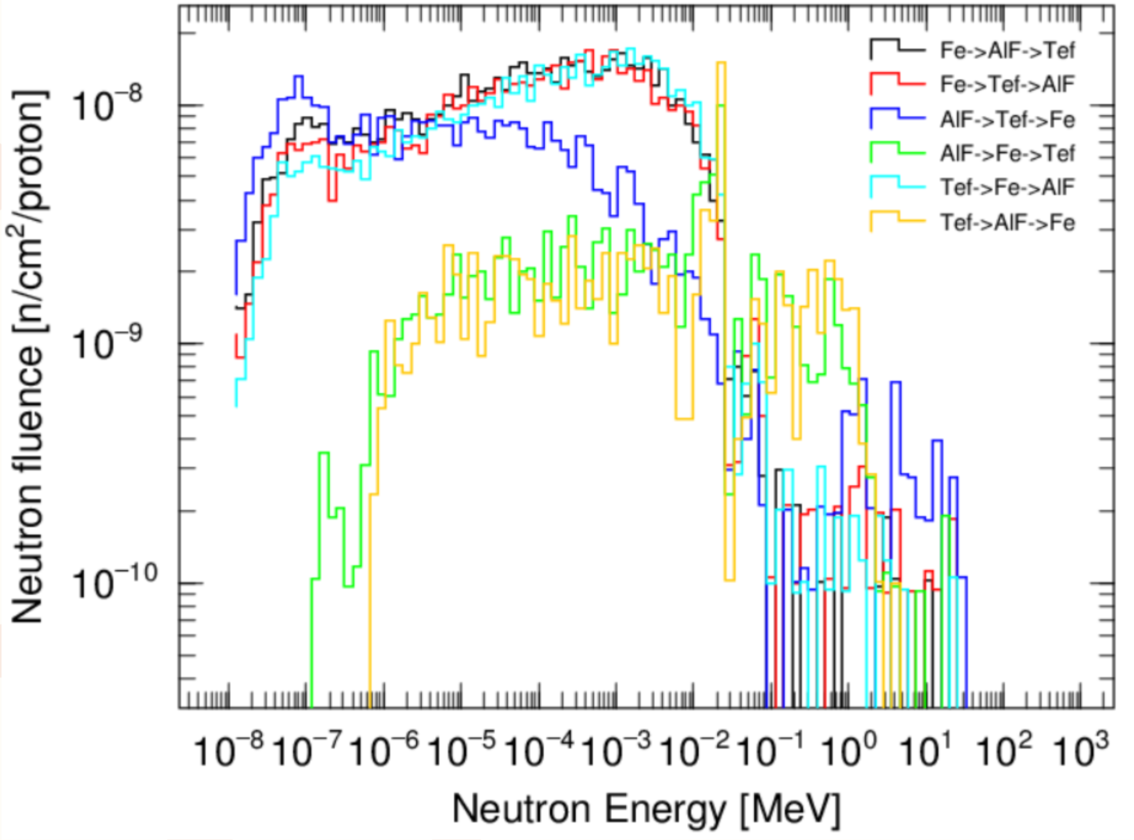


# Two materials study by PHITS



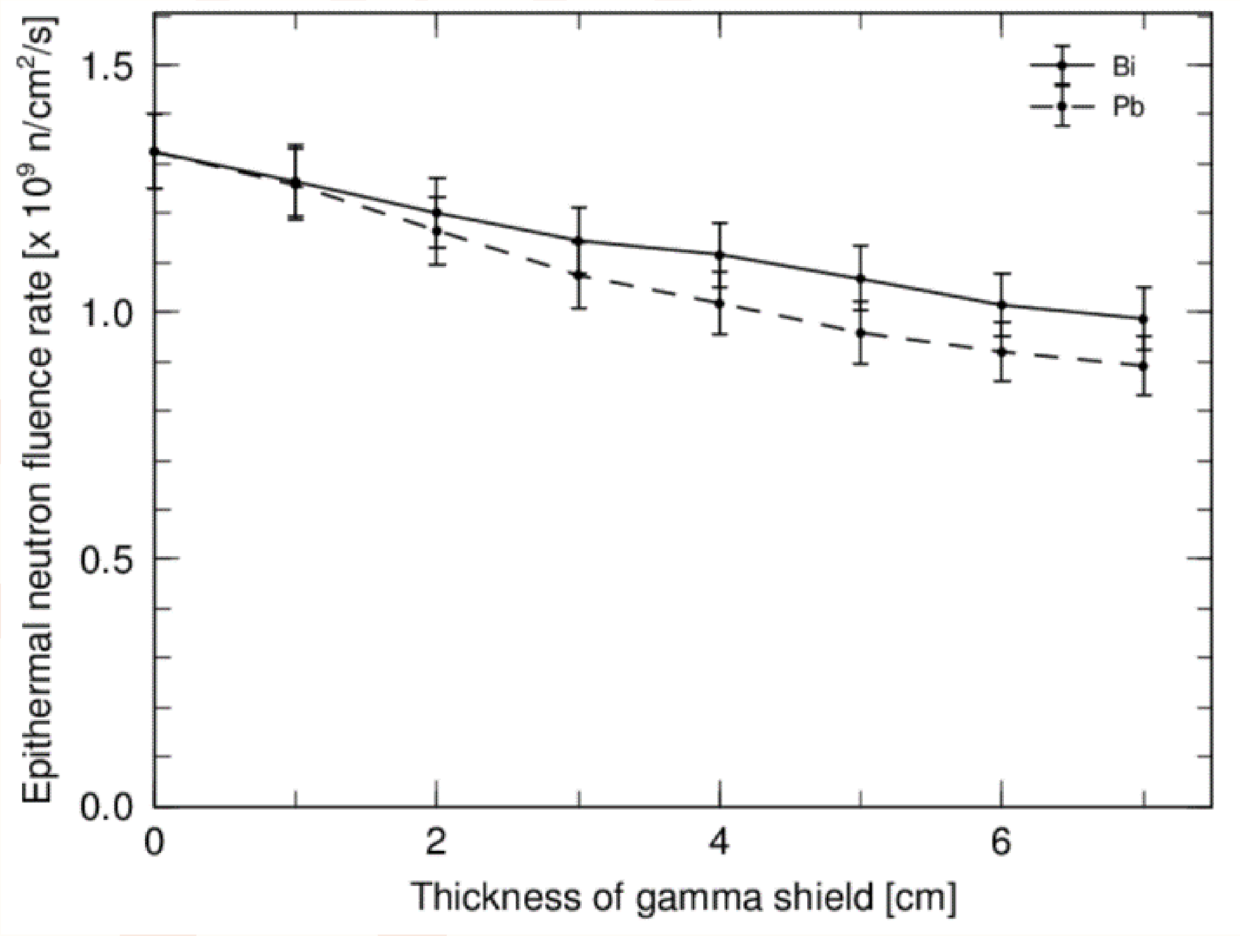


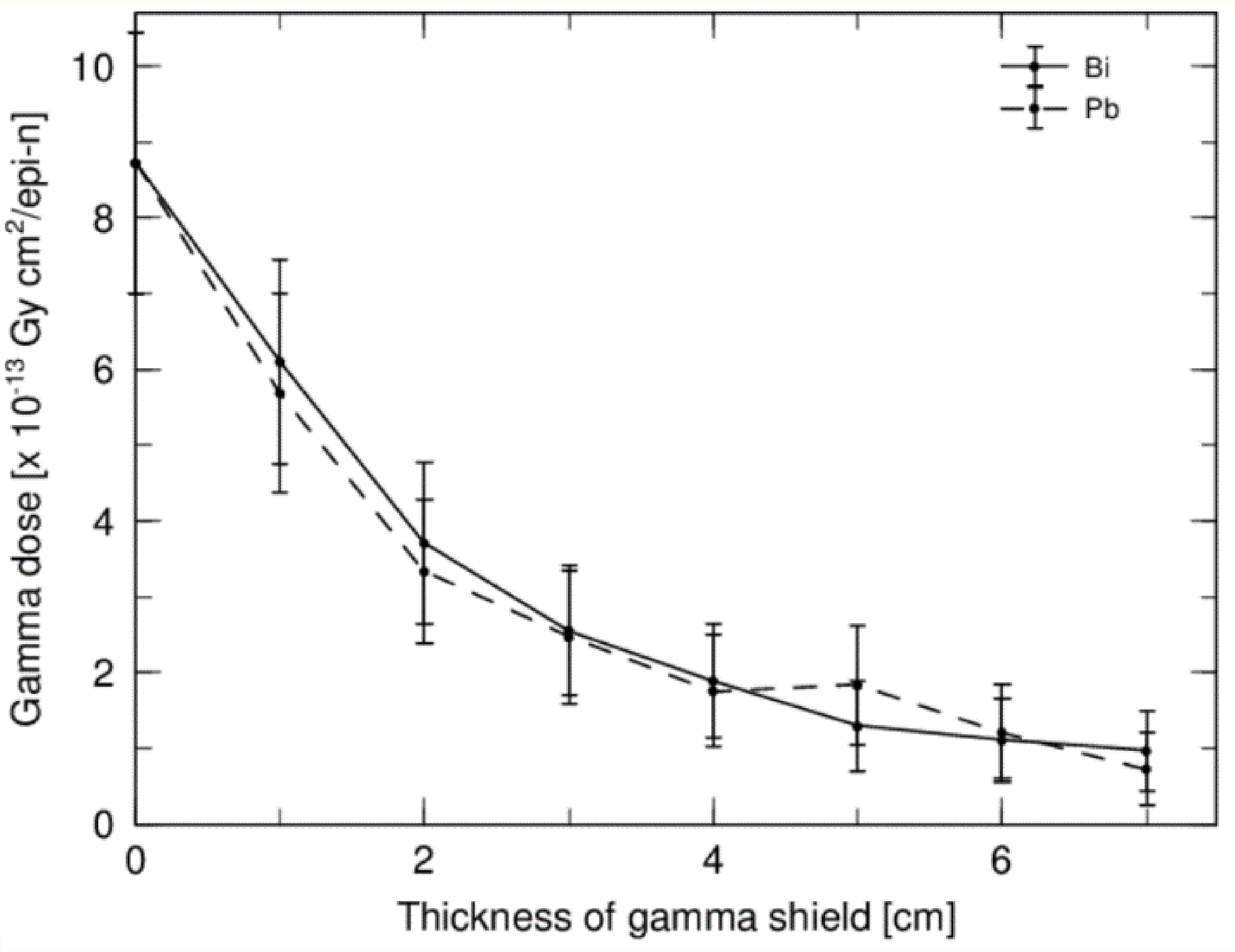
# Sequential study by PHITS



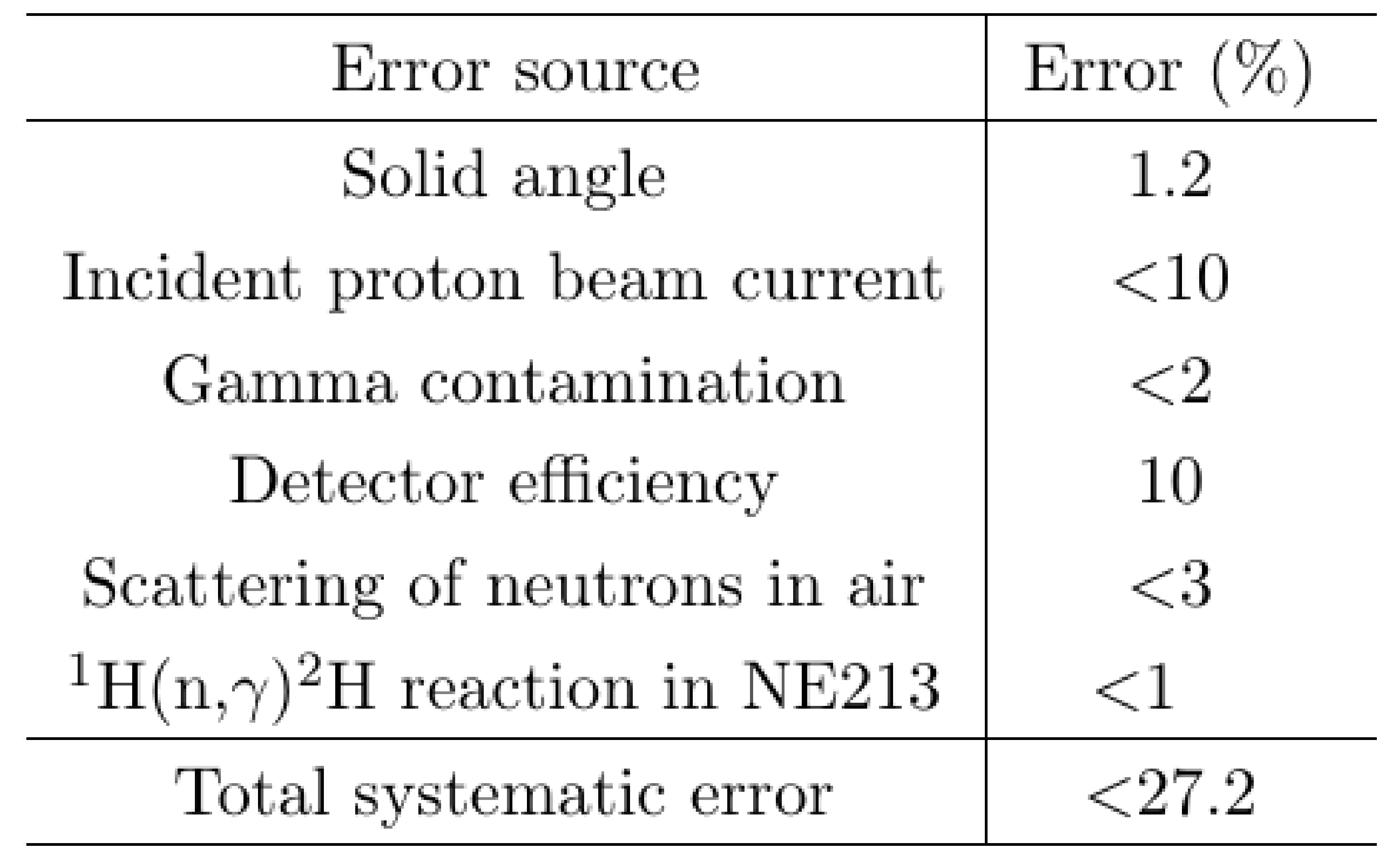
| Sequence | Epithermal fluence ($\times 10^{-7}$ n/cm$^2$/proton) | Fast neutron dose ($\times 10^{-13}$ Gy cm$^2$/epi-n) | Thermal-to-total-neutron ratio |
|---|---|---|---|
| Fe → $AlF_3$ → Tef | 4.78±0.25 | 1.80±0.34 | 0.157±0.012 |
| Fe → Tef → $AlF_3$ | 4.52±0.24 | 3.63±0.69 | 0.139±0.012 |
| $AlF_3$ → Fe → Tef | 0.75±0.10 | 42.8±10.0 | 0.009±0.003 |
| $AlF_3$ → Tef → Fe | 2.57±0.16 | 8.90±3.77 | 0.317±0.026 |
| Tef → Fe → $AlF_3$ | 4.52±0.25 | 2.68±0.49 | 0.119±0.010 |
| Tef → $AlF_3$ → Fe | 0.62±0.09 | 58.4±13.6 | 0 |

# 3.0 Gamma shield



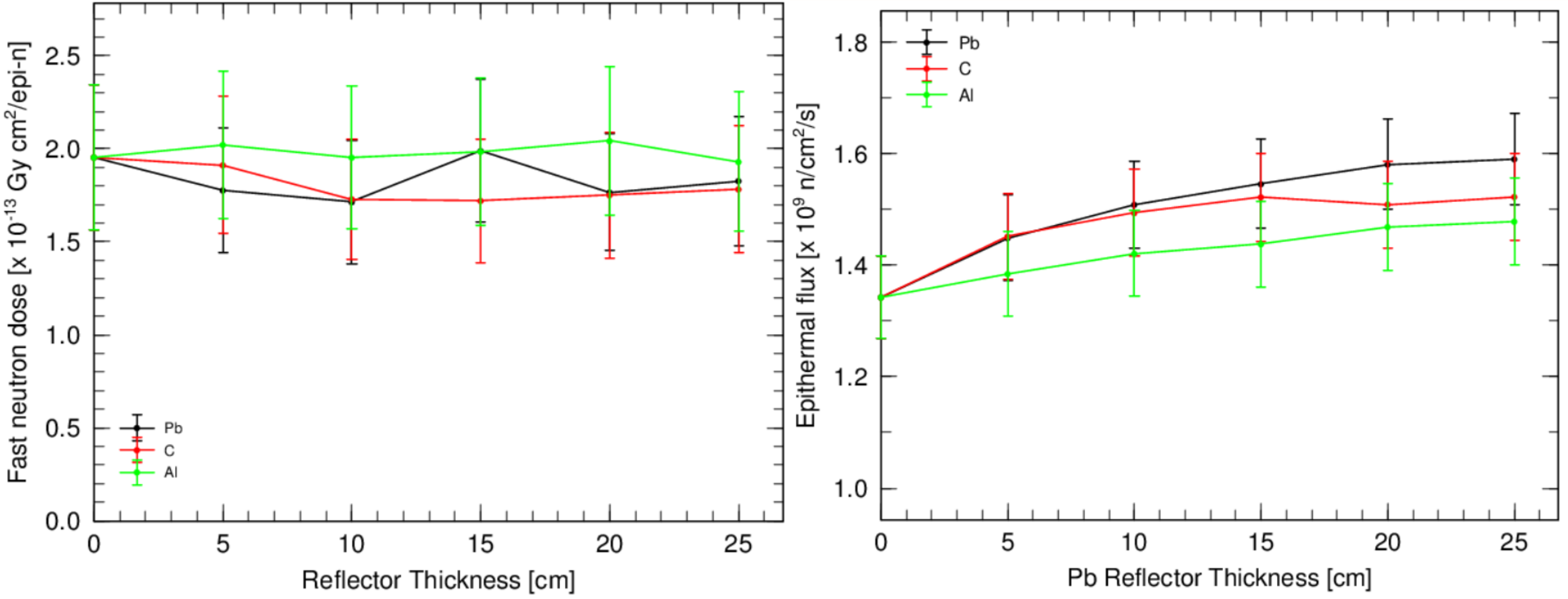


# Systematic Error Estimation

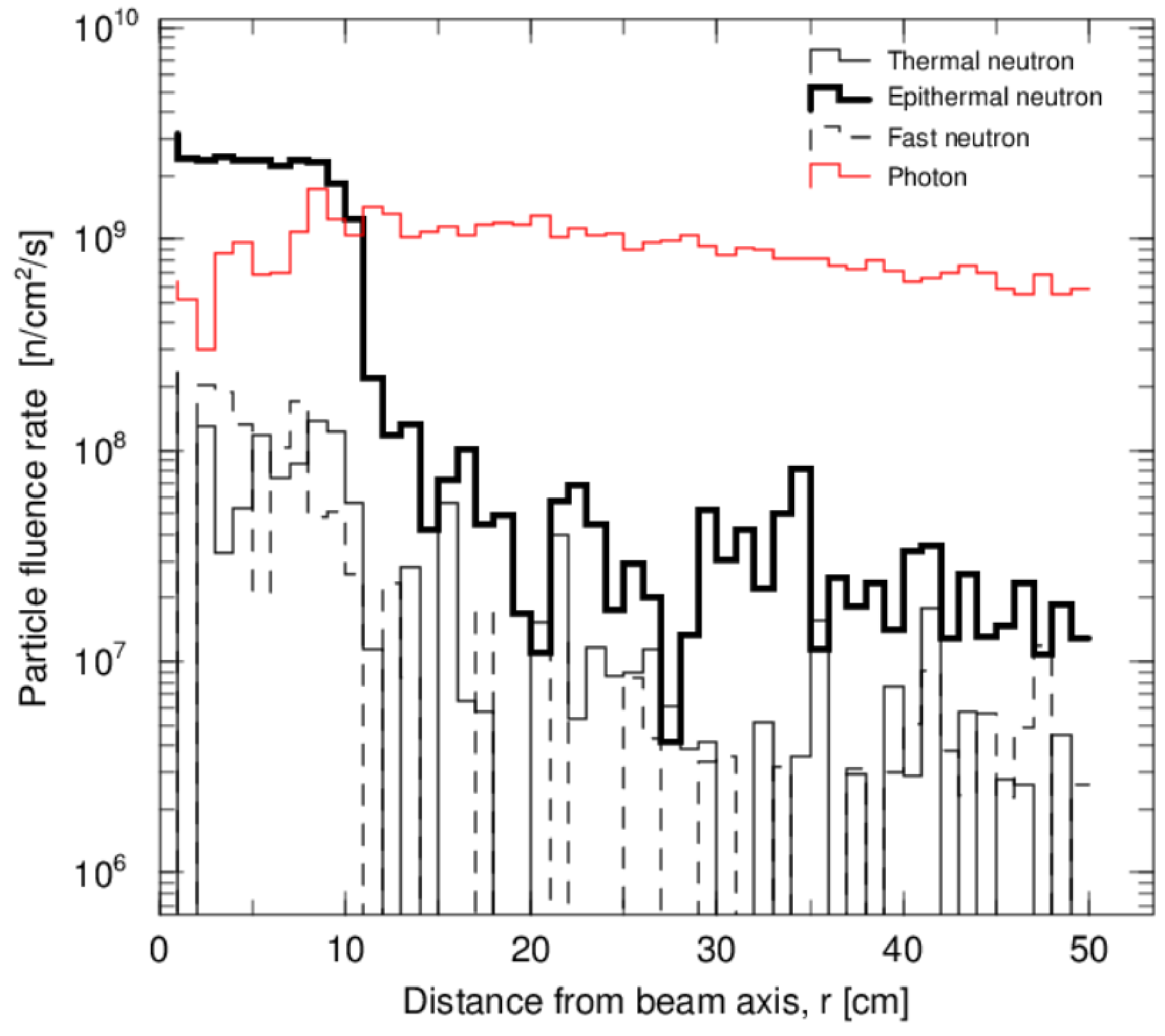


| Error source | Error (%) |
|---|---|
| Solid angle | 1.2 |
| Incident proton beam current | <10 |
| Gamma contamination | <2 |
| Detector efficiency | 10 |
| Scattering of neutrons in air | <3 |
| $^1$H(n,$\gamma$)$^2$H reaction in NE213 | <1 |
| Total systematic error | <27.2 |

# 3.0 Reflector

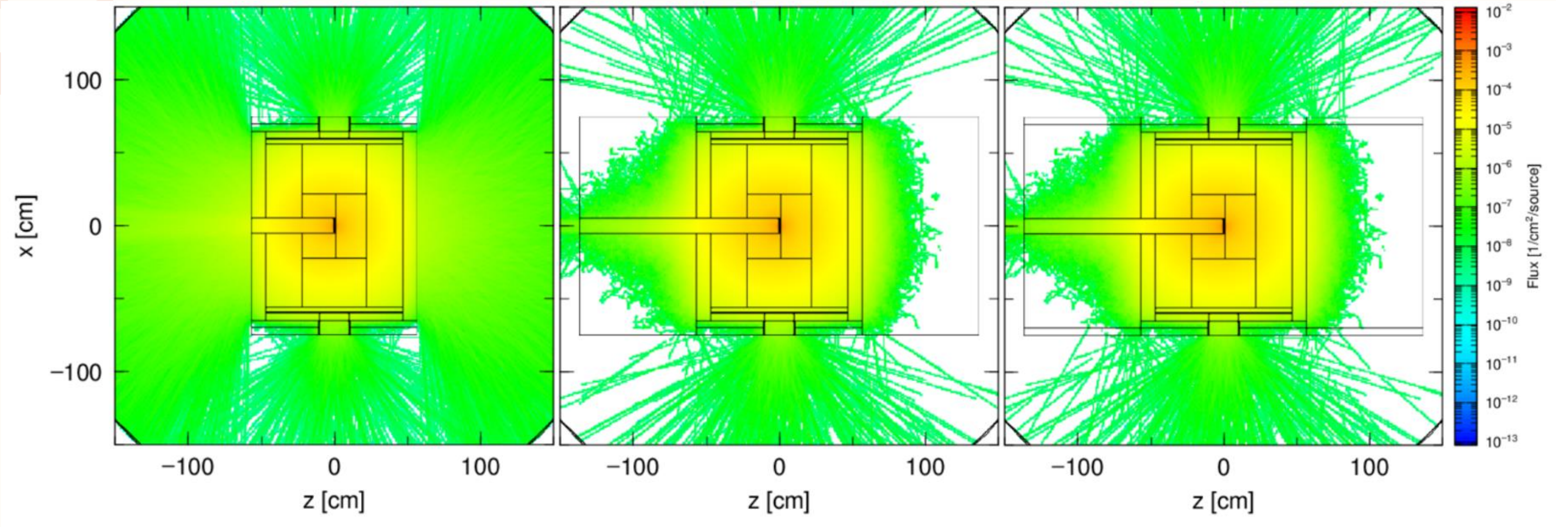


# 3.0 Collimator

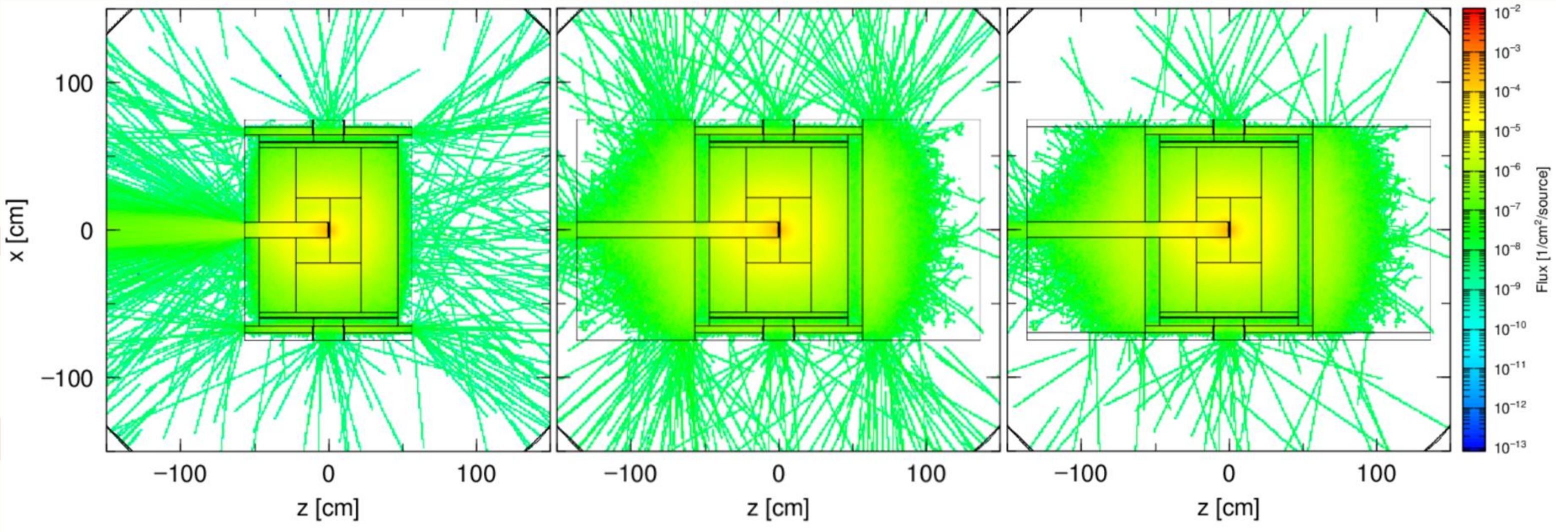


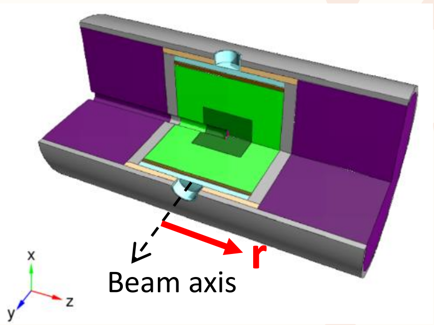
# Final shield

**Neutron:**



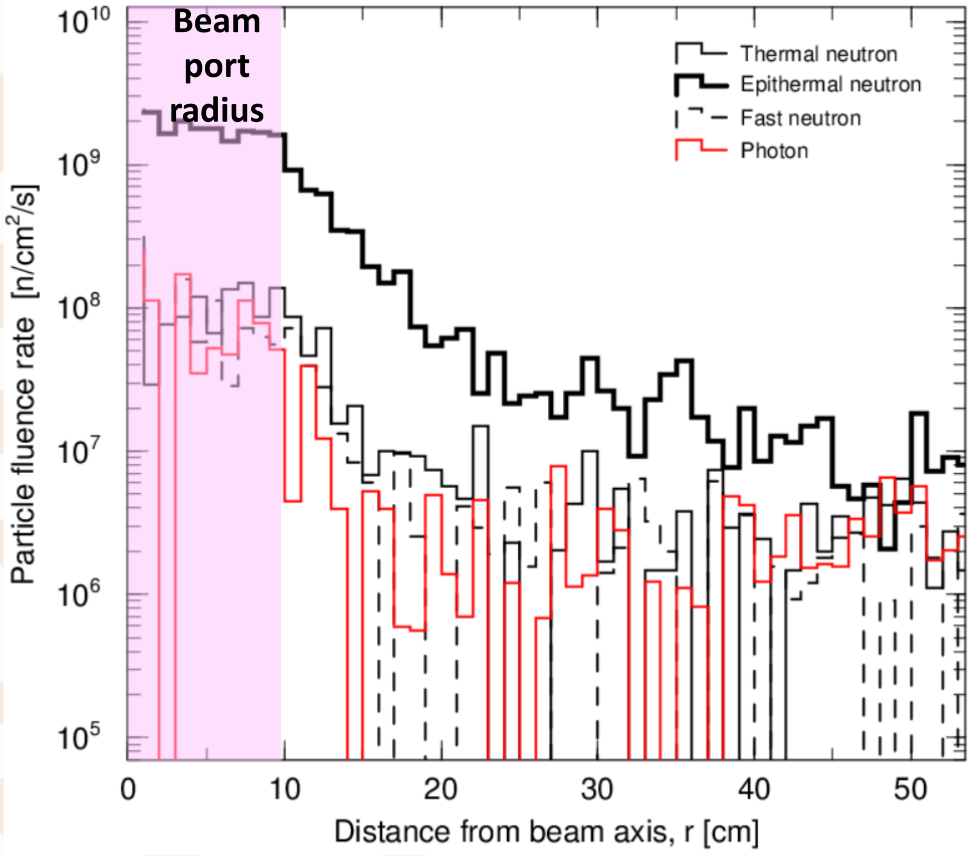
**Photon :**



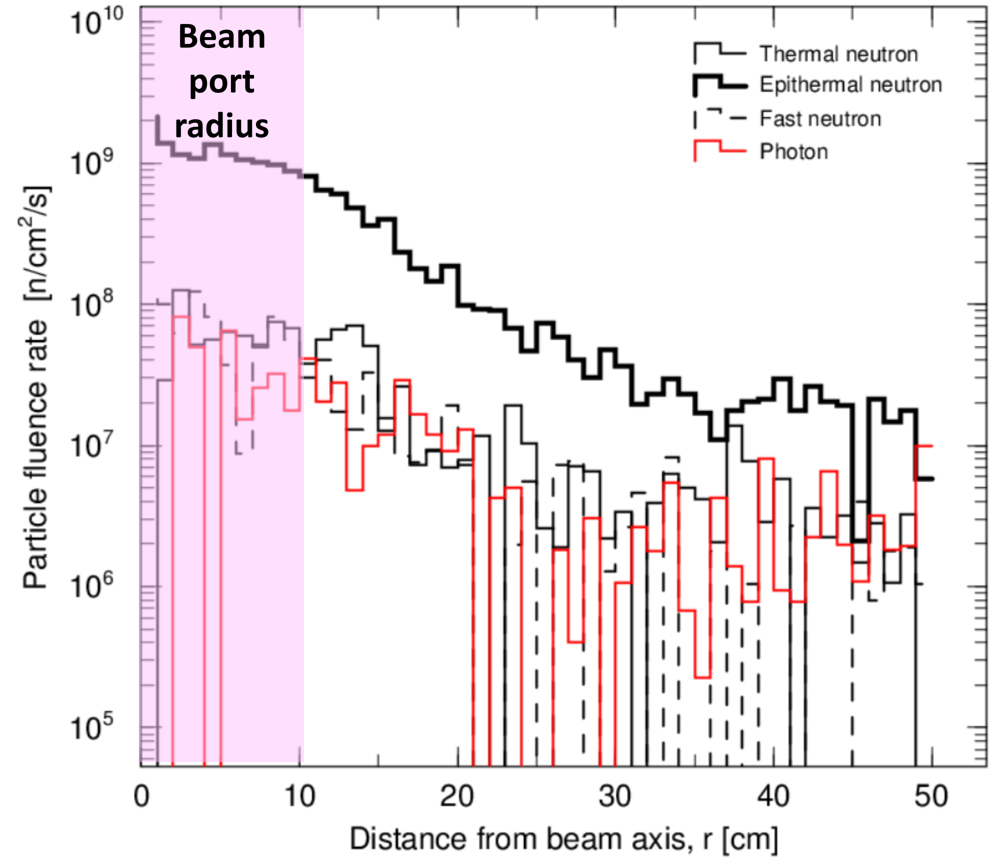


# Beam profile (port 1)

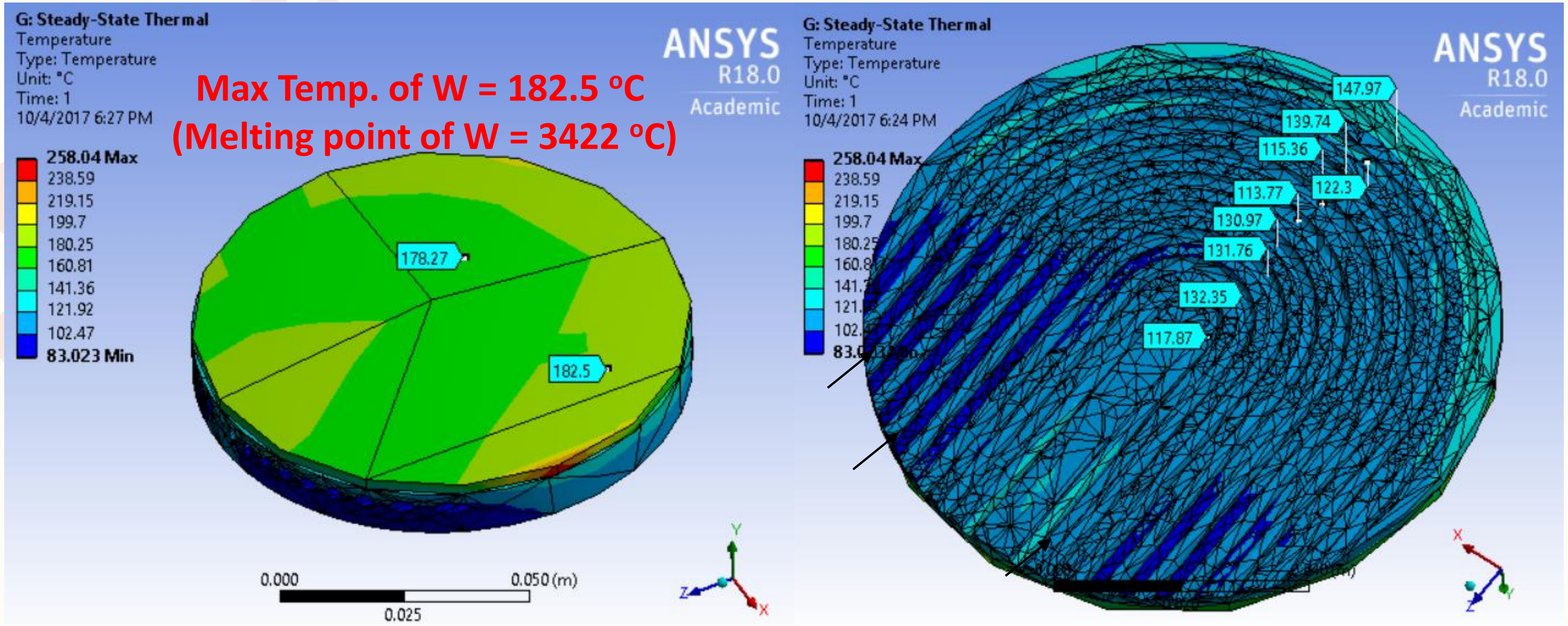
At the plane of aperture



At 5 cm from apertures [R = 10 cm]



# 3.0 Target Cooling - Thermal Analysis



Max Temp. of W = 182.5 °C
(Melting point of W = 3422 °C)

Max Temp. of Cu
inner wall = 148 °C
(Boiling point of
water = 178 °C)

Power: 25kW (50 MeV 500 μA)
W dimension: Φ 100 mm ; thickness 2.4 mm
Cu dimension: : Φ 100 mm ; thickness 10 mm
Tube dimension: Inner Φ 3 mm (9 tubes)

# 3.0 Target Material

①

**Advantages:**

1) Low activation

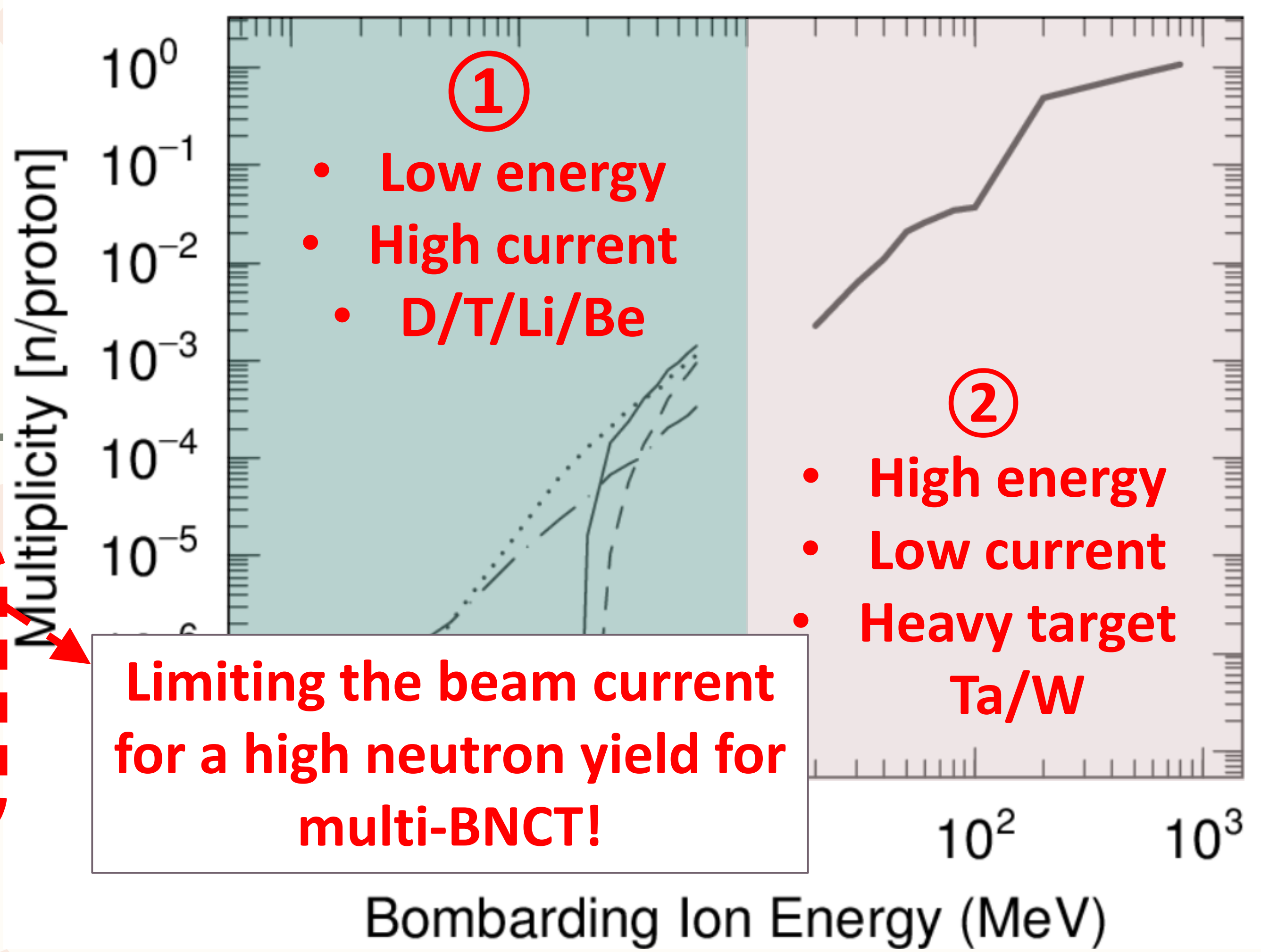
2) Low fast neutron contamination

**Disadvantages:**

1) High surface heat deposition leads to target blistering

2) Low melting point (Li)

3) Low neutron yield



①

- Low energy
- High current
- D/T/Li/Be

②

- High energy
- Low current
- Heavy target Ta/W

**Limiting the beam current for a high neutron yield for multi-BNCT!**

②

**Advantages:**

1) High melting point

2) No blistering

3) High neutron yield

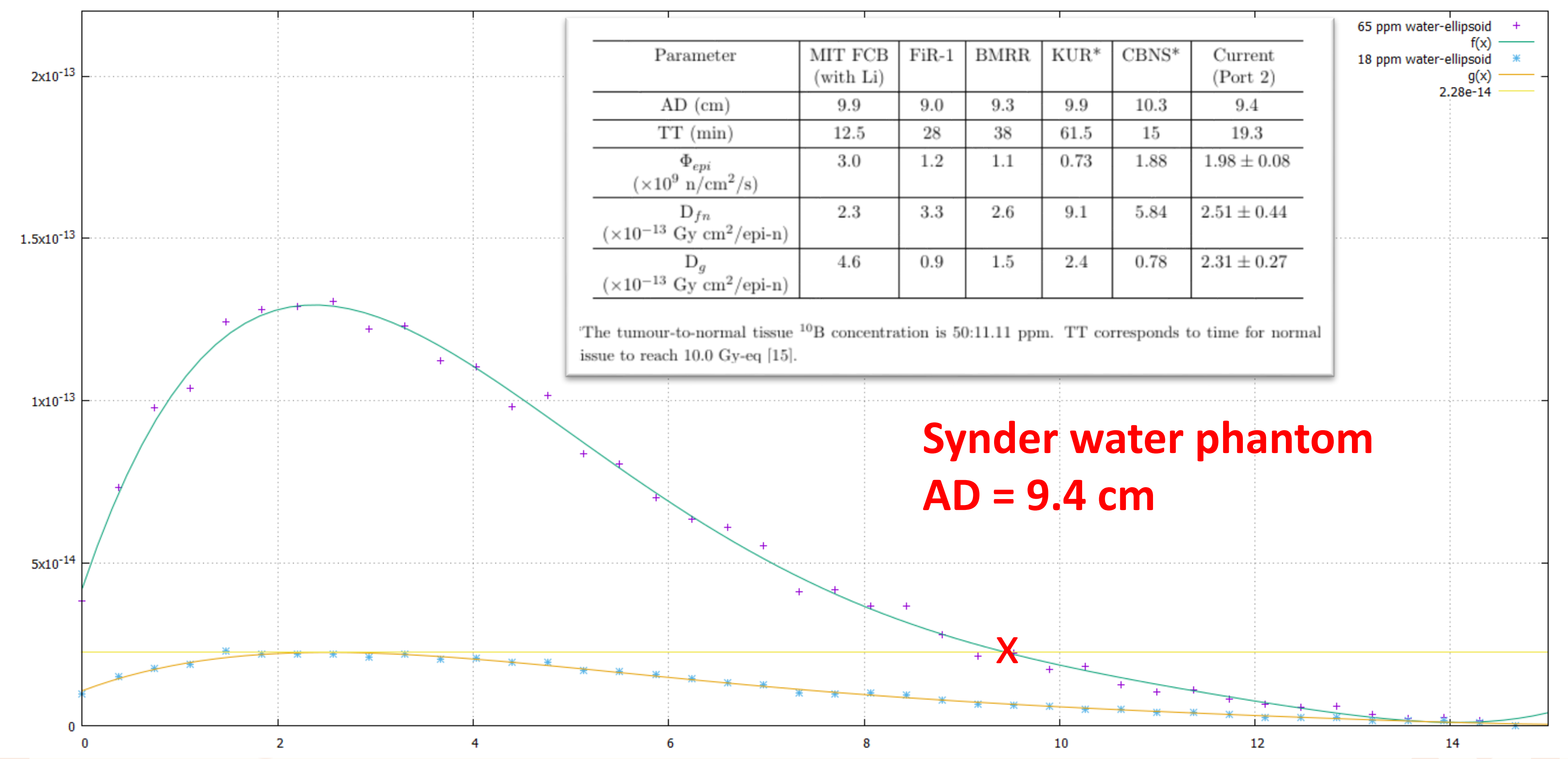
**Disadvantages:**

1) Target activation causes severe γ radiation

2) High fast neutron contamination

# 3.0 FOM – Dose calculations

(AD means depth in phantom where the tumour dose = maximum normal dose)



| Parameter | MIT FCB (with Li) | FiR-1 | BMRR | KUR* | CBNS* | Current (Port 2) |
|---|---|---|---|---|---|---|
| AD (cm) | 9.9 | 9.0 | 9.3 | 9.9 | 10.3 | 9.4 |
| TT (min) | 12.5 | 28 | 38 | 61.5 | 15 | 19.3 |
| $\Phi_{epi}$ ($\times 10^9$ n/cm$^2$/s) | 3.0 | 1.2 | 1.1 | 0.73 | 1.88 | $1.98 \pm 0.08$ |
| $D_{fn}$ ($\times 10^{-13}$ Gy cm$^2$/epi-n) | 2.3 | 3.3 | 2.6 | 9.1 | 5.84 | $2.51 \pm 0.44$ |
| $D_g$ ($\times 10^{-13}$ Gy cm$^2$/epi-n) | 4.6 | 0.9 | 1.5 | 2.4 | 0.78 | $2.31 \pm 0.27$ |

'The tumour-to-normal tissue $^{10}$B concentration is 50:11.11 ppm. TT corresponds to time for normal issue to reach 10.0 Gy-eq [15].

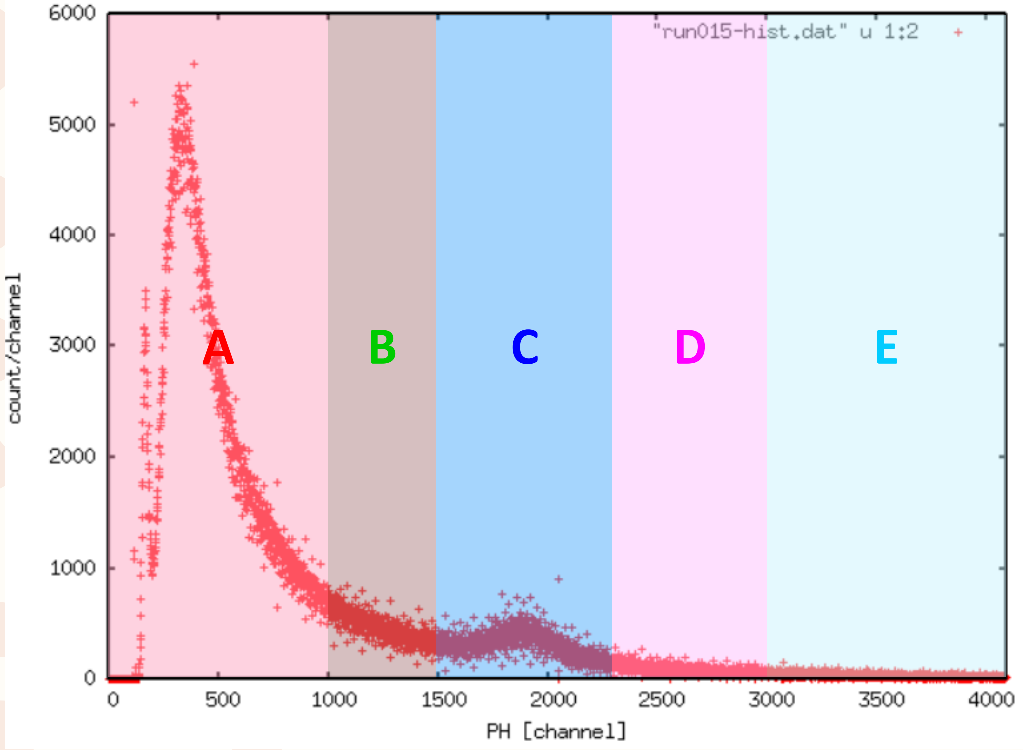
**Synder water phantom**

**AD = 9.4 cm**

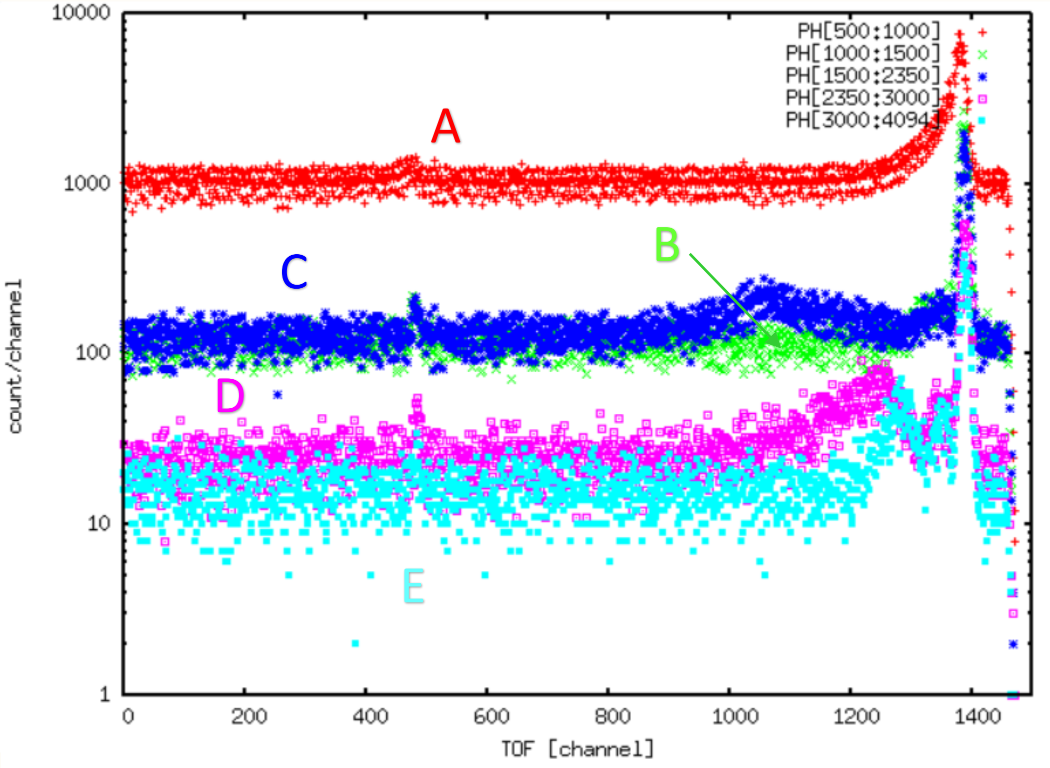
*Using neutron spectra at 5cm (saving computational time)

# $^{6}$Li (n,α) data discrimination

**Pulse Height Spectrum (PHS) from $^{6}$Li glass scintillator detector**



**Corresponding Time-of-flight Spectrum (TOF)**



**Only neutron data < 1 MeV is analyzed!**