


NEW PARA-HYDROGEN COLD NEUTRON SOURCE AT THE BUDAPEST RESEARCH REACTOR: MONTE CARLO SIMULATIONS

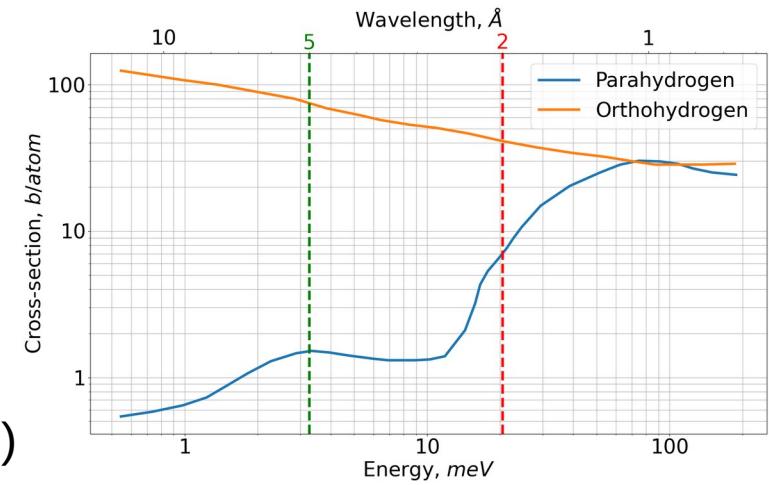
13.04.26 | DMITRII SHAPIRO, MINA AKHYANI, ALEXANDER IOFFE (JCNS)
PETER KONIK, MÁRTON MARKÓ, LÁSZLÓ ROSTA (BNC)
FERENC MEZEI (MIRROTRON)

INTRODUCTION

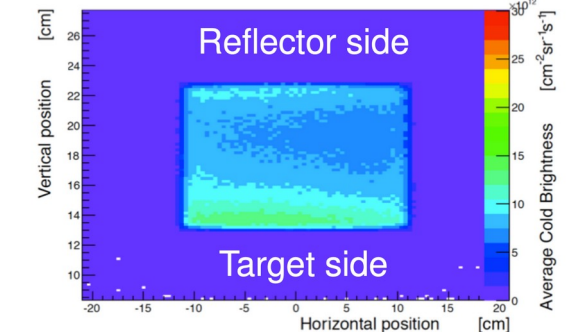
- Budapest Research Reactor (BRR): Light water 10MW reactor with Be reflector
- Neutron guide system upgrade => Cold source exchange
- Former hydrogen disk moderator is suggested to be replaced by a new pH one:
 - Box
 - Assemblies of flat moderators
- Optimization:
 - Individual instruments
 - Common solution
- Methodology:
 - Curve of Optimal and Full Sample Illumination (COFSI)
 - Monte-Carlo simulations with  PHITS
Particle and Heavy Ion Transport code System

PARA-HYDROGEN MODERATORS

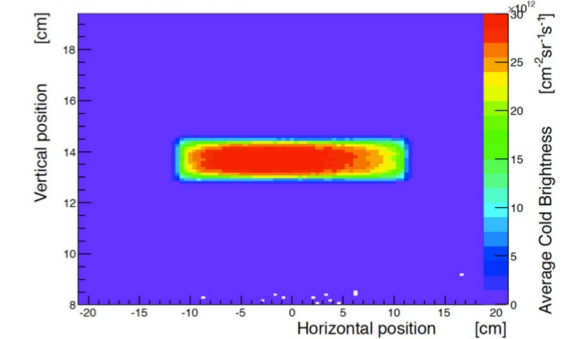
- Thermalisation => voluminous moderator
- Para – ortho conversion + pH cross-section => flat moderator
- Flat moderator => enhanced brightness (e.g. pancake cold moderator at ESS)
 - Brightness enhancement => intensity reduction
 - Small moderator size => under-illumination of a neutron guide entrance
- Solution: assemblies of flat moderators
 - Moderator aperture doesn't change => Brightness gain = Flux gain



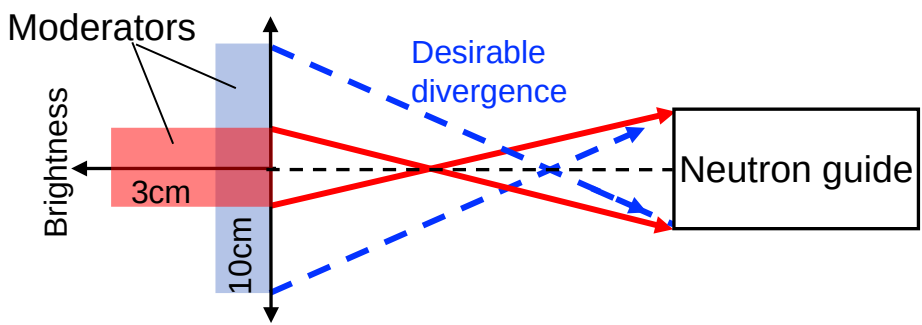
Volume moderator



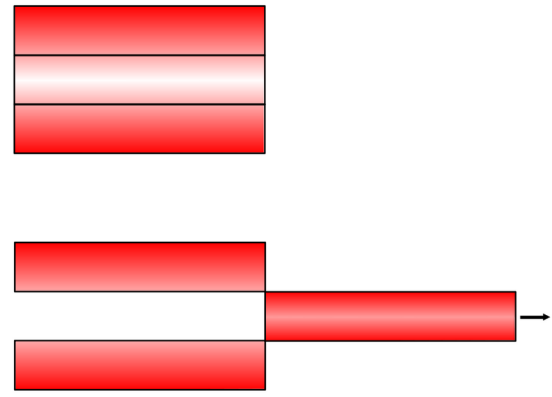
Flat moderator



F. Mezei et.al, JNR 17(2), 101-105 (2014)



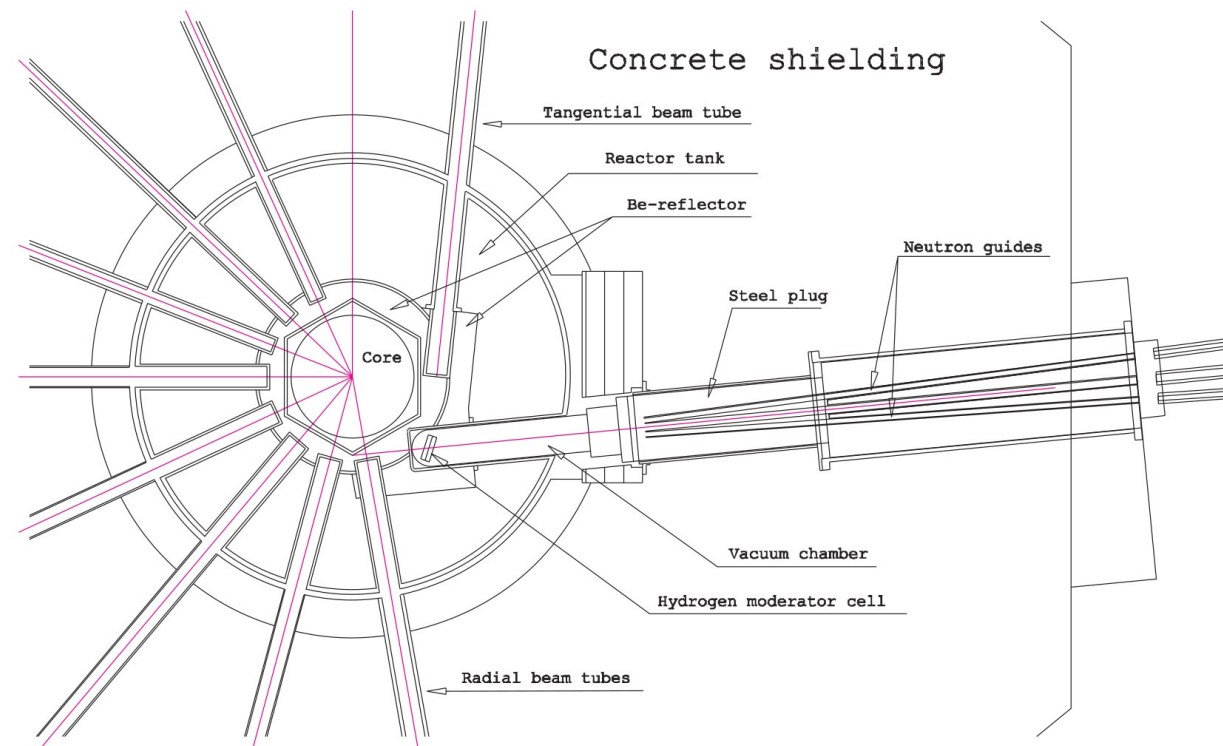
A. Ioffe, P. Konik, K. Batkov, JNE 6, 3 (2025)



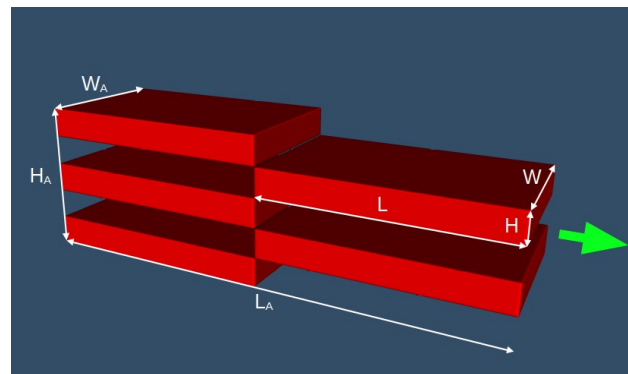
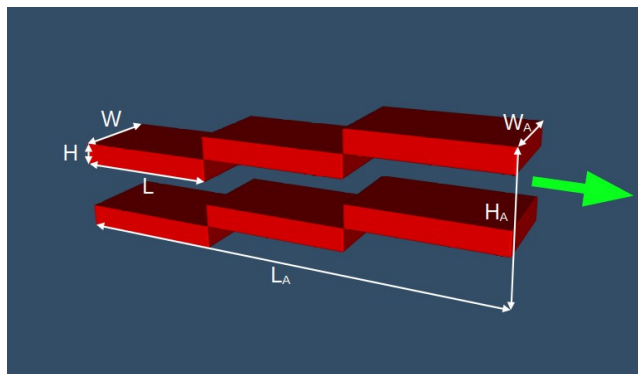
K. Batkov, A. Takibayev, L. Zanini, F. Mezei., NIM A729, 500 (2013)

MODERATOR EXCHANGE

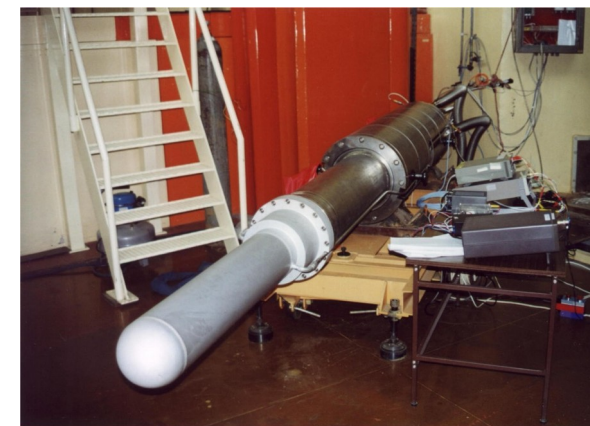
- Current moderator:
 - $L = 4$ cm, $R = 6$ cm, rotated 23°
 - nH filled, 2.5 mm Al walls
 - He cooling
- New pH moderator options:
 - Box
 - Assemblies of flat moderators



L. Rosta, T. Grósz, T. Hargitai, *Applied Physics A* 74 (Suppl3761), s240–s242 (2002)



D. Shapiro et al., *J. Appl. Cryst.* 59, 392–403 (2026)



Rosta, L., Fuzi, J. & Koroknai, B. *BrightnESS Deliverable Report: D4.15.* (2018)

NEW MODERATOR OPTIMIZATION

- Optimization:

- Instrument requirements
 - Wavelength
 - Phase space (COFSI)
- Moderator brightness (PHITS)

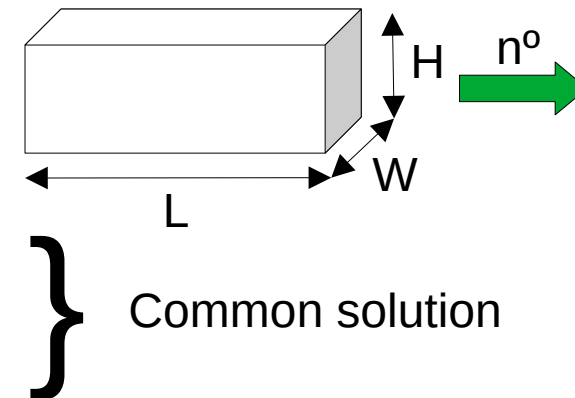
- COFSI – Curve of Optimal and Full Sample Illumination

- Instrument's phase space requirements (cross-section and divergency) => moderator size vs guide entrance size

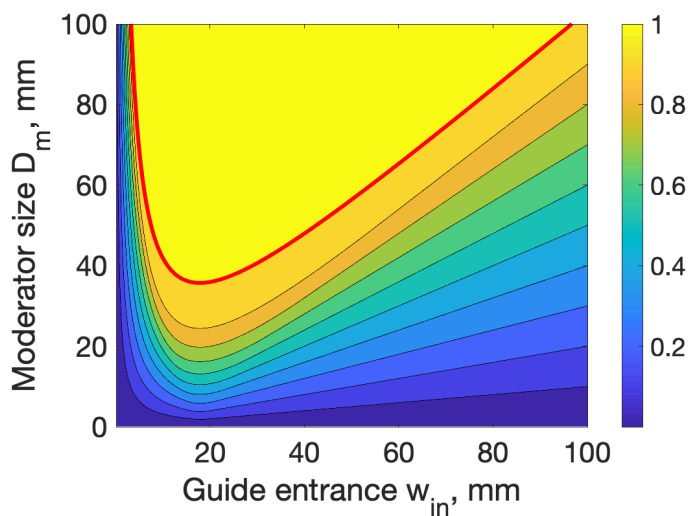
- Moderator's brightness depends on its size => compression curve / map

- Instruments :

- SANS Yellow Submarine
- PGAA
- ToF spectrometer NEAT

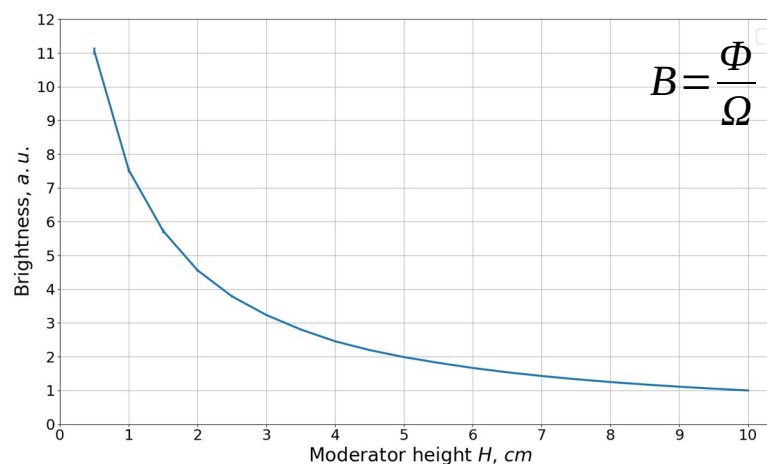


Size-independent flux (sample illumination)



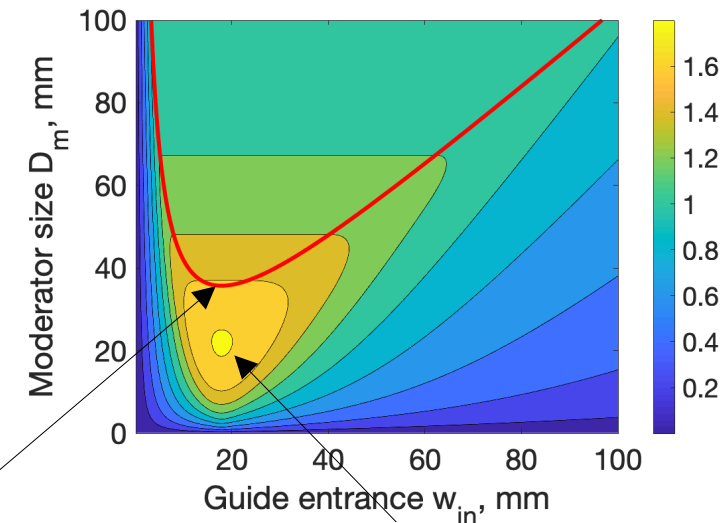
Konik, P., Ioffe, A. (2023) NIM A 1056, 168643

Size dependence (compression curve)



High flux + ideal sample illumination

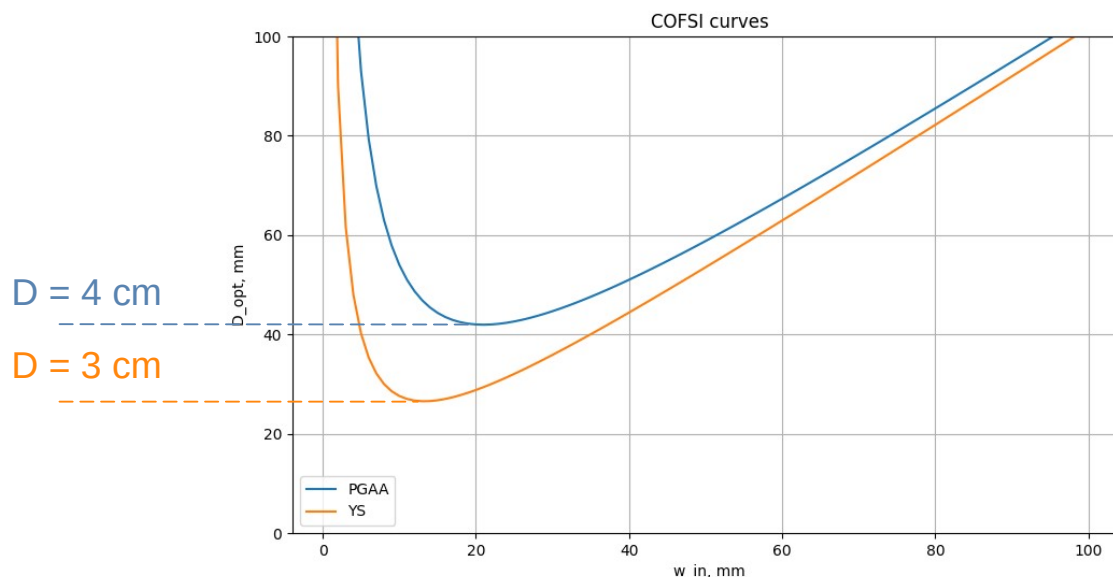
Size dependent flux (sample flux)



Higher flux + under-illumination

INSTRUMENT REQUIREMENTS

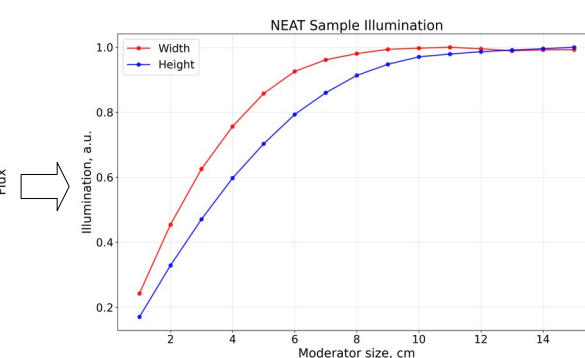
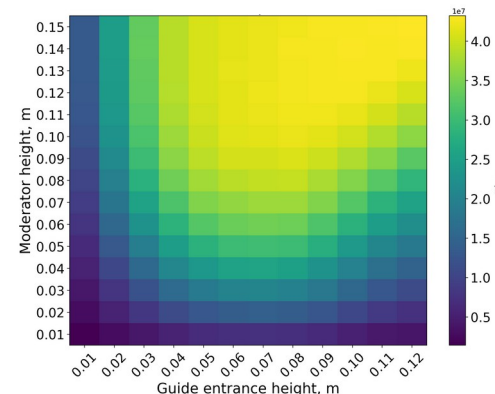
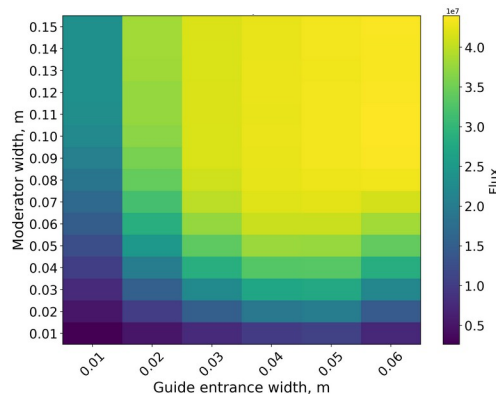
- Yellow Submarine:
 - 5 Å
 - COFSI: $D \geq 3$ cm
- PGAA:
 - λ -weighted flux (capture flux)
 - COFSI: $D \geq 4$ cm
- NEAT:
 - 5 Å
 - McStas simulation: Illumination curve



P. Konik, D. Shapiro, M. Akhyani, A. Ioffe, M. Markó, L. Rosta, F. Mezei.
 "How to optimize a cold neutron source: Budapest case study", to be published

$$Q = \int_0^{\text{inf}} \Phi'(\lambda) d\lambda$$

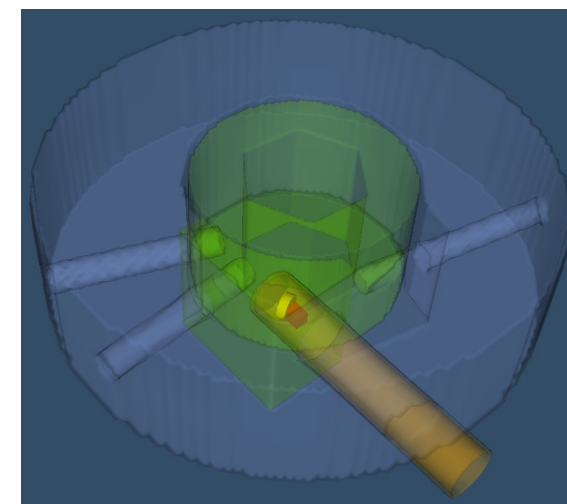
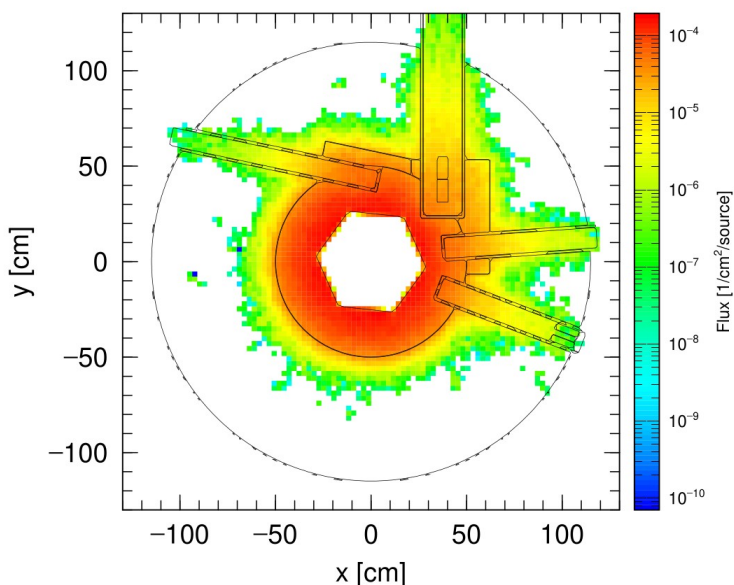
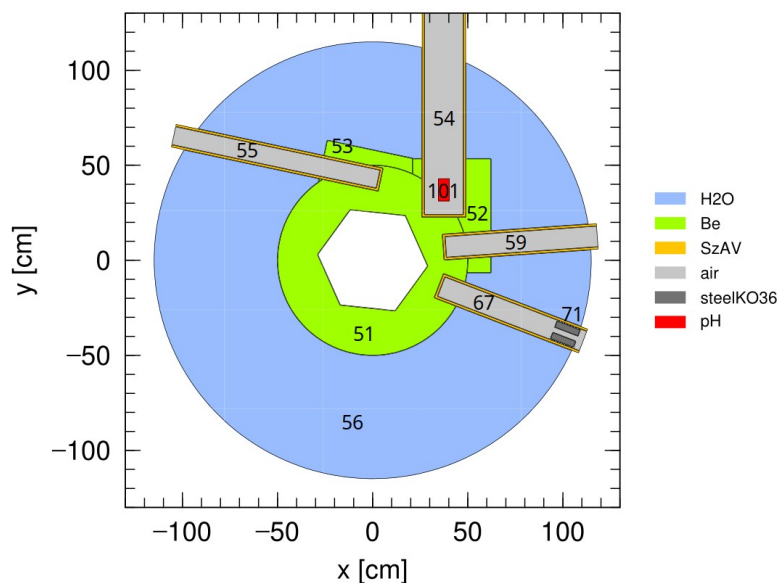
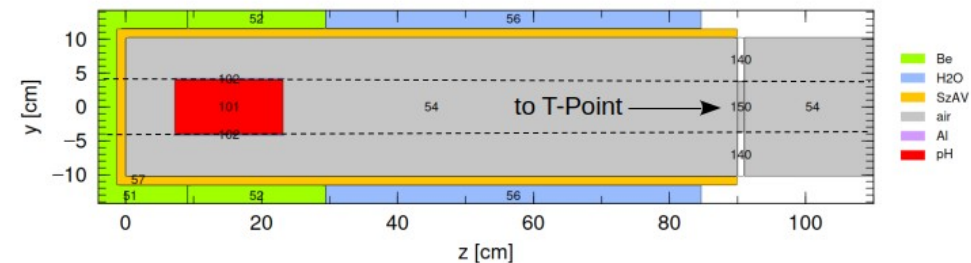
$$\Phi' = \begin{cases} 4\Phi(\lambda)\lambda^3, & \text{if } \lambda \leq 0.95 \\ \Phi(\lambda)\left(2 \times 0.95 + \frac{(\lambda - 0.95)^2}{2.87 - 0.95}\right)^2 \lambda, & \text{if } 0.95 < \lambda \leq 2.87 \\ \Phi(\lambda)(0.95 + 2.87)^2 \lambda, & \text{if } \lambda > 2.87 \end{cases}$$



D. Shapiro et al., J. Appl. Cryst. 59, 392–403 (2026)

MODERATOR BRIGHTNESS: BRR MODEL

- PHITS model of BRR (JENDL-5 library)
- Reactor core spectrum: $f(E, T) = f_w(E) + f_M(E, T)$
 - Fast neutrons from U fission (Watt): $f_w(E) = \sinh(\sqrt{2E}) e^{-E}$
 - Thermal neutrons from water (Maxwell): $f_M(E, T) = \sqrt{E} e^{-\frac{E}{kT}}$
- Collimator to look at the moderator exit surface



D. Shapiro et al., J. Appl. Cryst. 59, 392–403 (2026)

FIGURES OF MERIT: FLUX AND BRIGHTNESS

- Flux Φ : how many neutrons per m² arrive at a detector / sample
- Point detector in Monte Carlo codes measures neutron flux as

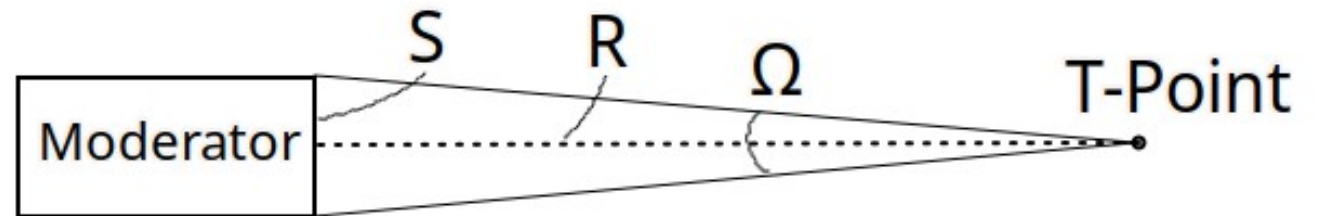
$$\Phi = \int dE \int dt \int d\Omega v\rho$$

where $\rho = \frac{N}{dVd\Omega dE}$ - number of neutrons N per unit volume dV, per solid angle d Ω , per energy dE, v – neutron velocity

- Brightness B: how many neutrons per m² per sr² are emitted from a moderator
- In our measurements neutrons are detected only within Ω => Brightness B is defined as:

$$B = \frac{\Phi}{\Omega}$$

where $\Omega = \frac{S}{R^2}$



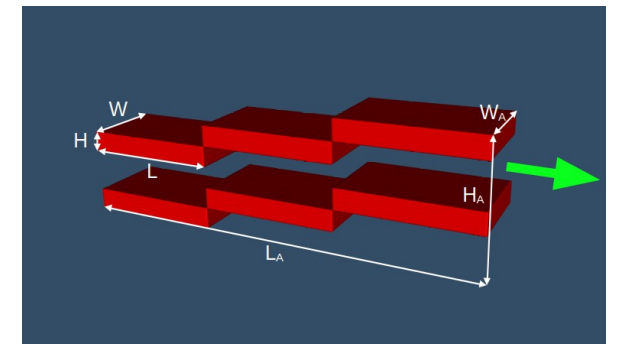
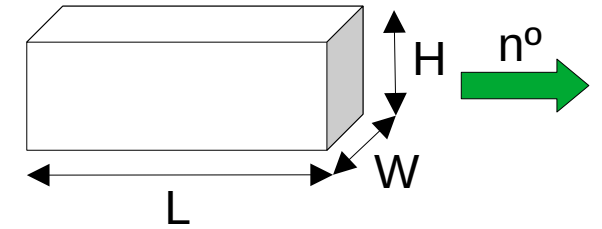
- Brightness gain g: the degree to which one moderator is brighter than another: $g = \frac{B_1}{B_2}$

MODERATOR BRIGHTNESS CALCULATION

- Algorithm of compression map calculation:

- Start with box configuration
 - Width from 1 cm to 13 cm
 - Height is adjusted to fit 14 cm diameter beam tube for each width
 - For each (W, H) length L is varied, using discrete ternary search algorithm
 - Flux at 5 Å / capture flux is calculated
 - Optimal L is found
- Proceed to the configuration with larger number of steps
 - If new flux is smaller => Stop
 - If new flux is larger => Proceed
- For each (W, H) with optimal L and geometry brightness is calculated $B = \frac{\Phi}{\Omega}$

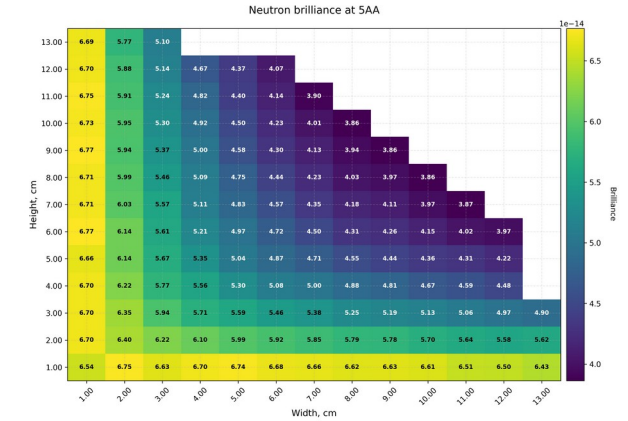
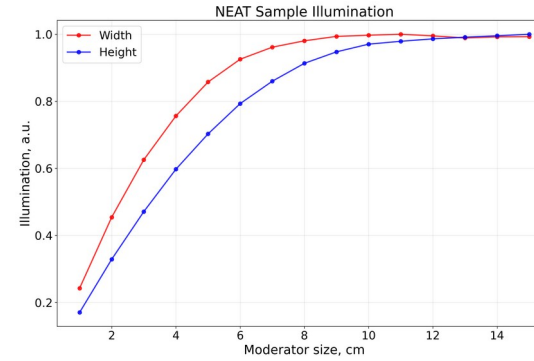
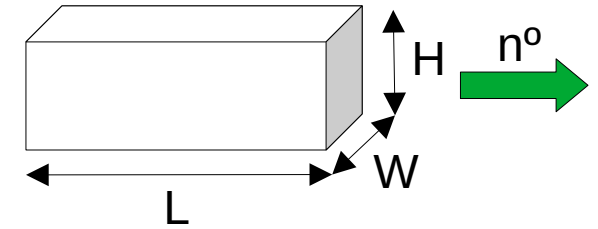
- Size limitations from COFSI × compression map = optimal moderator size



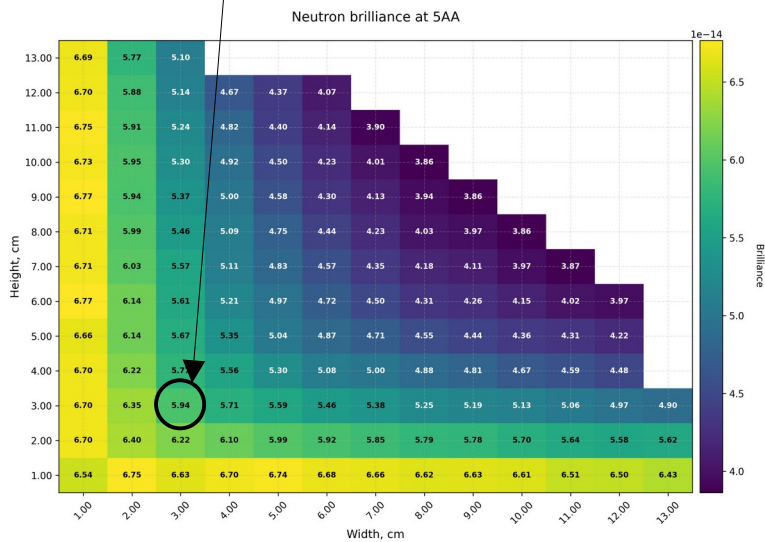
OPTIMAL MODERATOR

- Box geometry for all the cases
- Yellow Submarine: $D \geq 3 \text{ cm} \Rightarrow 3 \times 3 \text{ cm}^2$, ($L = 17 \text{ cm}$)
- PGAA: $D \geq 4 \text{ cm} \Rightarrow 4 \times 4 \text{ cm}^2$, ($L = 16 \text{ cm}$)
- NEAT: Illumination curve $\Rightarrow 6 \times 10 \text{ cm}^2$ ($L = 15 \text{ cm}$)

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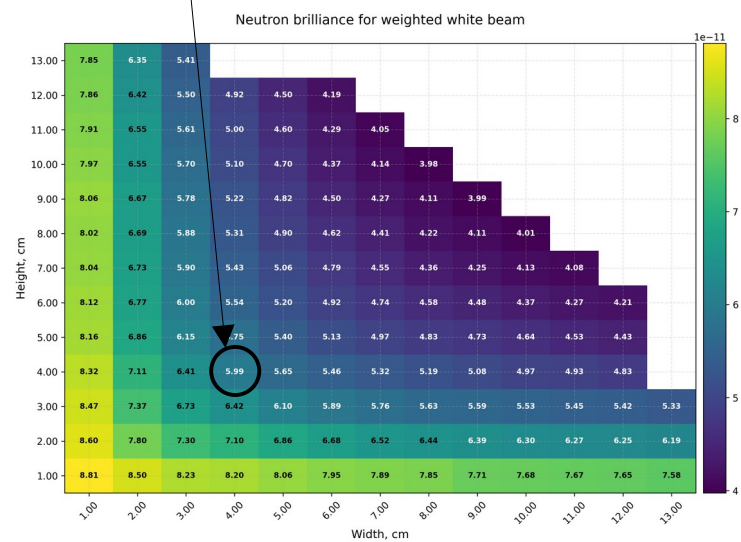


W = H = 3 cm



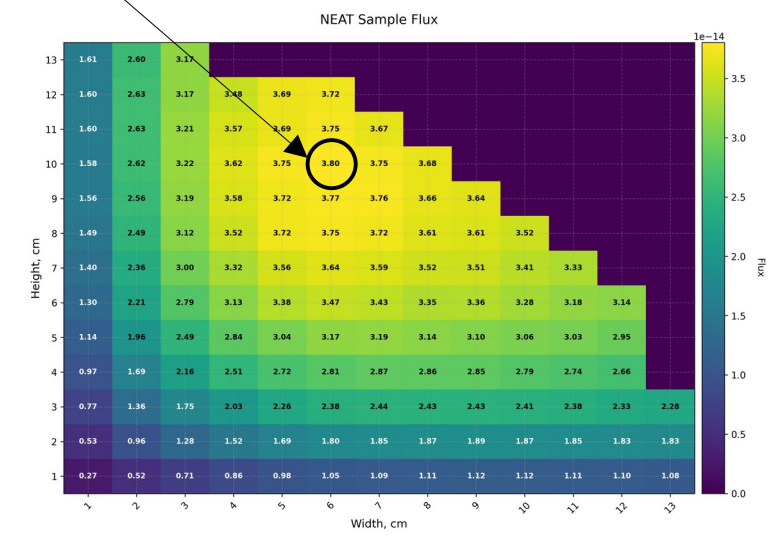
Yellow Submarine

W = H = 4 cm



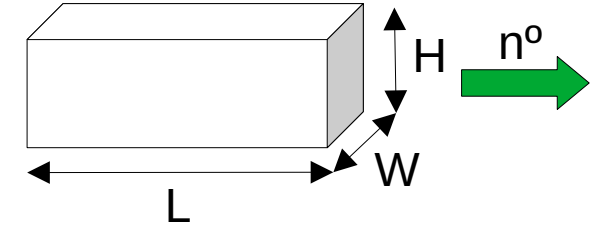
PGAA

W = 6 cm, H = 10 cm



NEAT

OPTIMAL MODERATOR: COMPROMISE



- Yellow Submarine: 3 x 3 x 17 cm³

- PGAA: 4 x 4 x 16 cm³

- NEAT: 6 x 10 x 15 cm³

- Compromise:

- L = 16 cm

- Sum of normalized sample fluxes

- Yellow Submarine:
sample flux = 0 for $D < 3$ cm

- PGAA:
sample flux = 0 for $D < 4$ cm

- Find the highest value

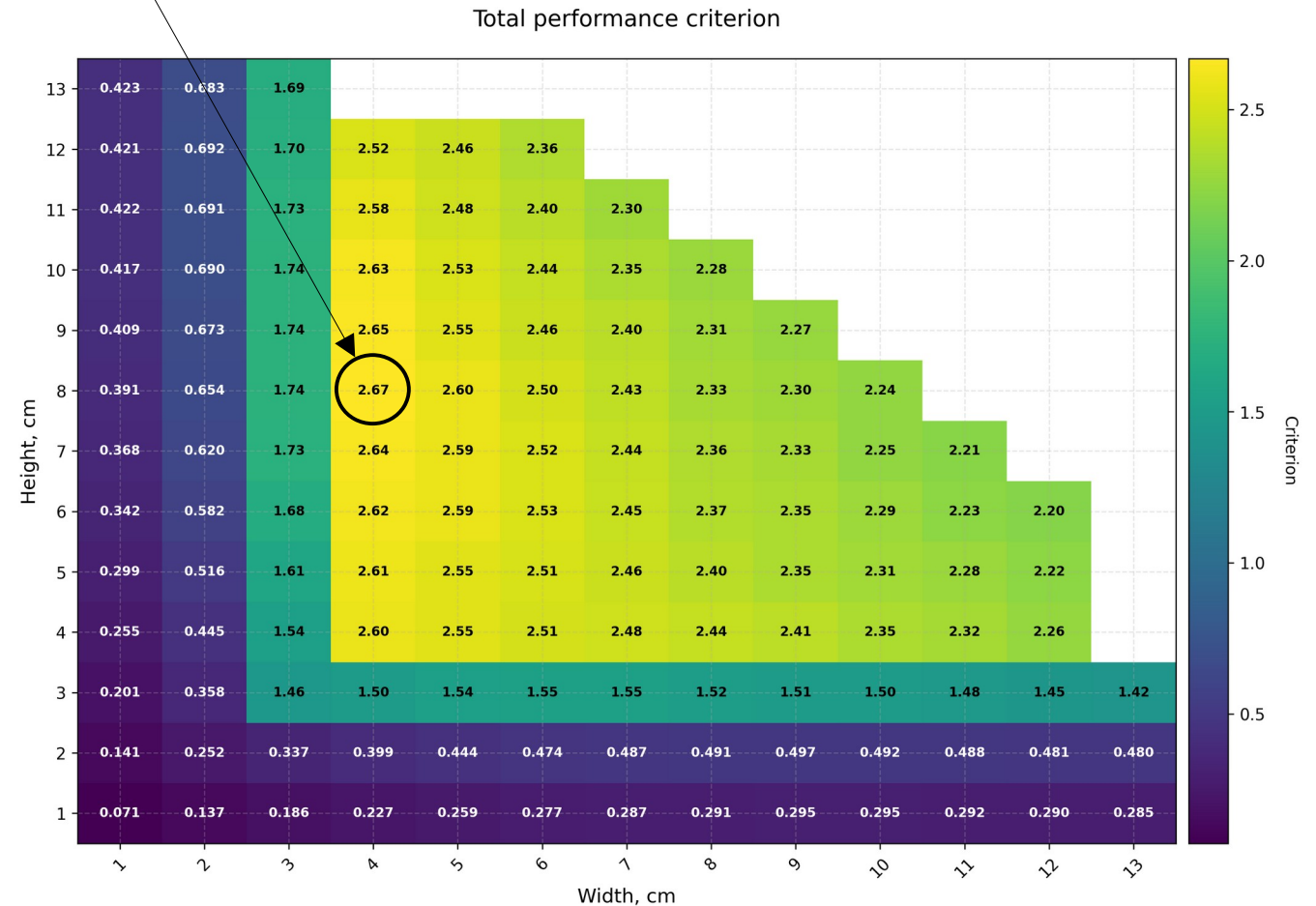
- Optimal moderator: 4 x 8 x 16 cm³

- Increase of brightness at 5 Å for NEAT & YS: ~2.2

- Increase of capture flux at PGAA: ~2.5

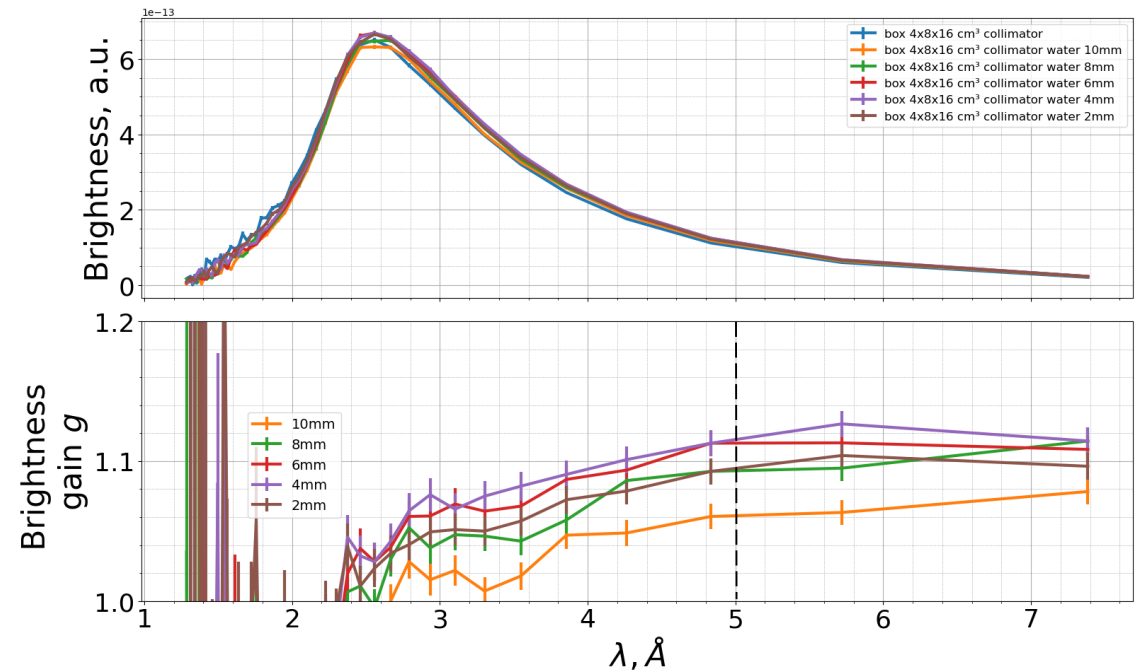
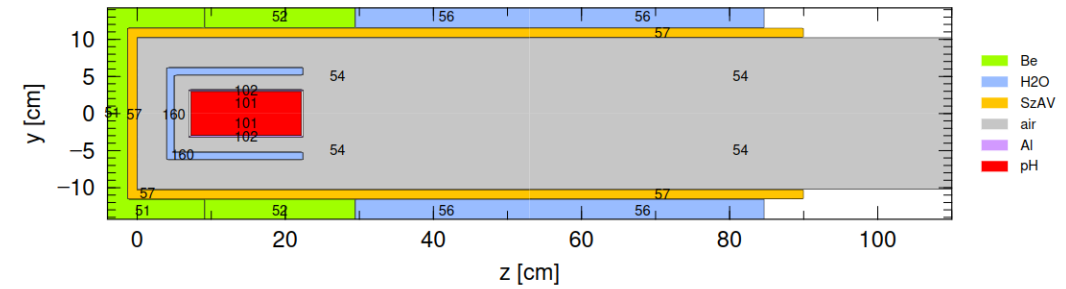
- Instruments' losses because of compromise solution: ~10%

W = 4 cm, H = 8 cm



ADDITIONAL WATER LAYER

- Water jacket around pH moderator
- Advantages:
 - Moderates fast neutrons in reactor spectrum
 - Places thermal neutron source closer to pH moderator
 - Allows bi-spectrality
- Disadvantages:
 - Absorbs already thermalized neutrons
- 4 mm thick at 5 mm from pH moderator: ~10% gain at 5 Å

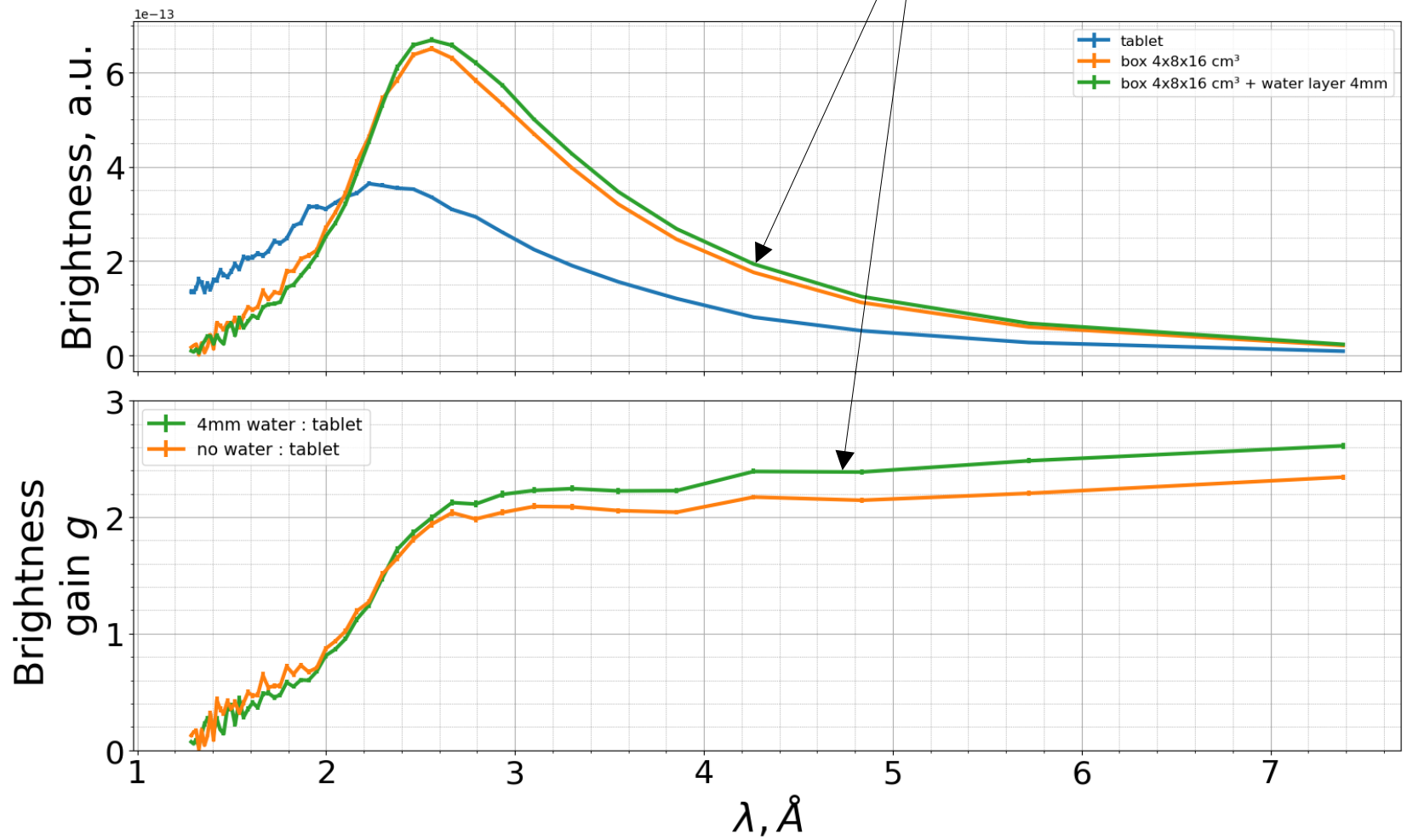


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SPECTRA COMPARISON

- Brightness gain (2 – 2.4) for $\lambda > 2.5 \text{ \AA}$
 - 2.2 for $\lambda = 5 \text{ \AA}$

- 4 mm water jacket: further ~10% brightness gain



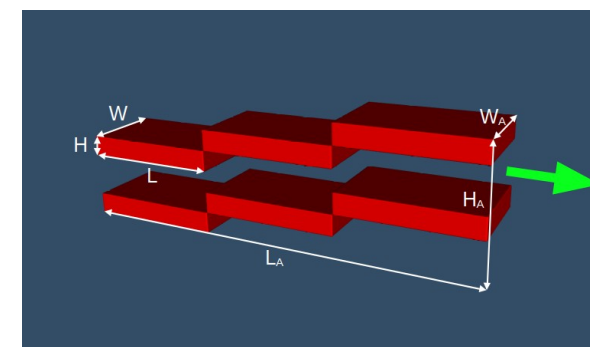
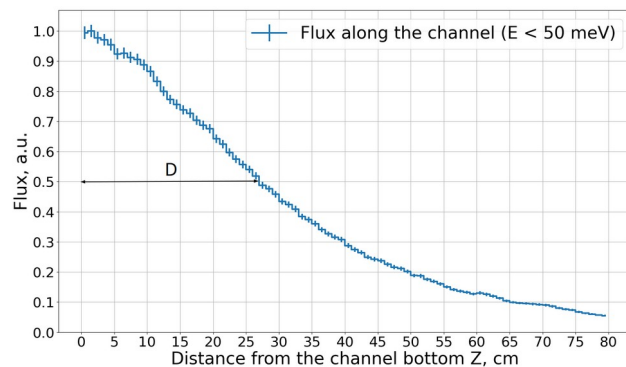
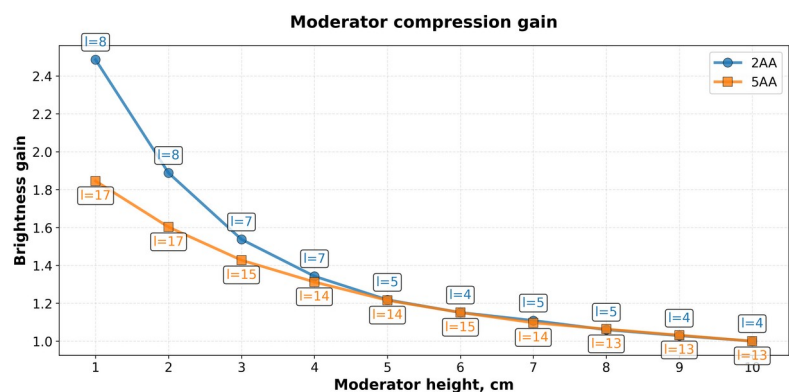
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ASSEMBLIES OF FLAT MODERATORS

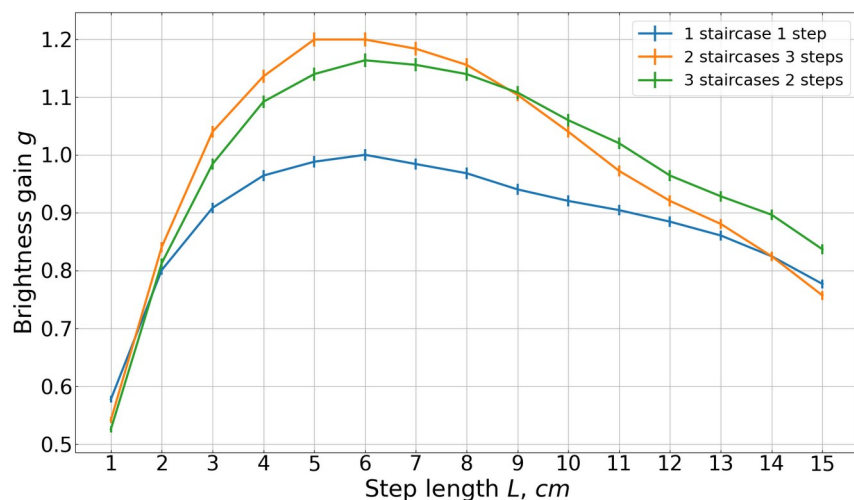
- Provide brightness gain $\sim 20\%$ at 2 AA
- No brightness gain at 5 AA

• Reasons:

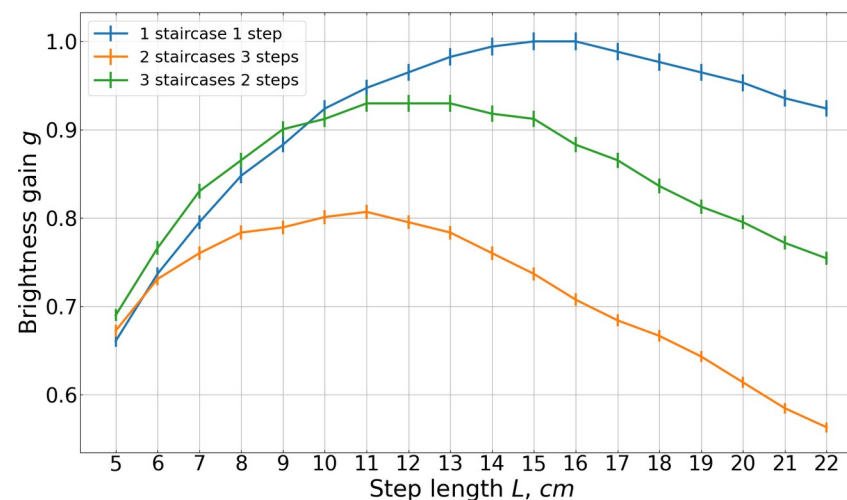
- Lower compression gain for 5 AA
- Rapidly decreasing thermal illumination along the channel



2 Å, staircase:
 $L = 6$ cm
 $g \sim 20\%$



5 Å, staircase:
 $L = 11$ cm
 No gain



CONCLUSIONS

- We suggest 4 x 8 x 16 cm³ pH moderator for BRR as best compromise for Yellow Submarine, PGAA and NEAT
 - Brightness gain (2 – 2.4) for $\lambda > 2.5 \text{ \AA}$
 - NEAT & Yellow Submarine at 5 \AA : brightness gain ~ 2.2 , comparing to disk moderator
 - PGAA: capture flux increases by ~ 2.5 times, comparing to disk moderator
 - Compromise moderator results in $\sim 10\%$ losses, comparing to individually optimized moderators
 - Additional 4 mm thick water layer provides a further $\sim 10\%$ brightness gain for $\lambda > 2.5 \text{ \AA}$
- Assemblies of flat moderators
 - Provide $\sim 20\%$ brightness gain for 2 \AA
 - No brightness gain for 5 \AA
 - Small compression factor
 - Rapidly decreasing thermal illumination along the channel
 - Experimental verification at the test station of BRR
- Moderator design strongly depends on instrument requirements



ACKNOWLEDGEMENTS

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- The speaker acknowledges support from the Global Neutron Science (GNeuS) fellowship, project number DEFB1354

THANK YOU FOR ATTENTION!