High-brilliance and high-flux cold neutron source utilizing
high-aspect ratio rectangular para-hydrogen moderators

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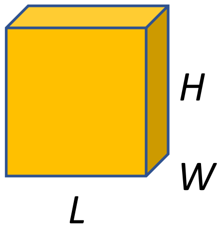
ICANS– XXIV

October 29 -November 3, 2023,

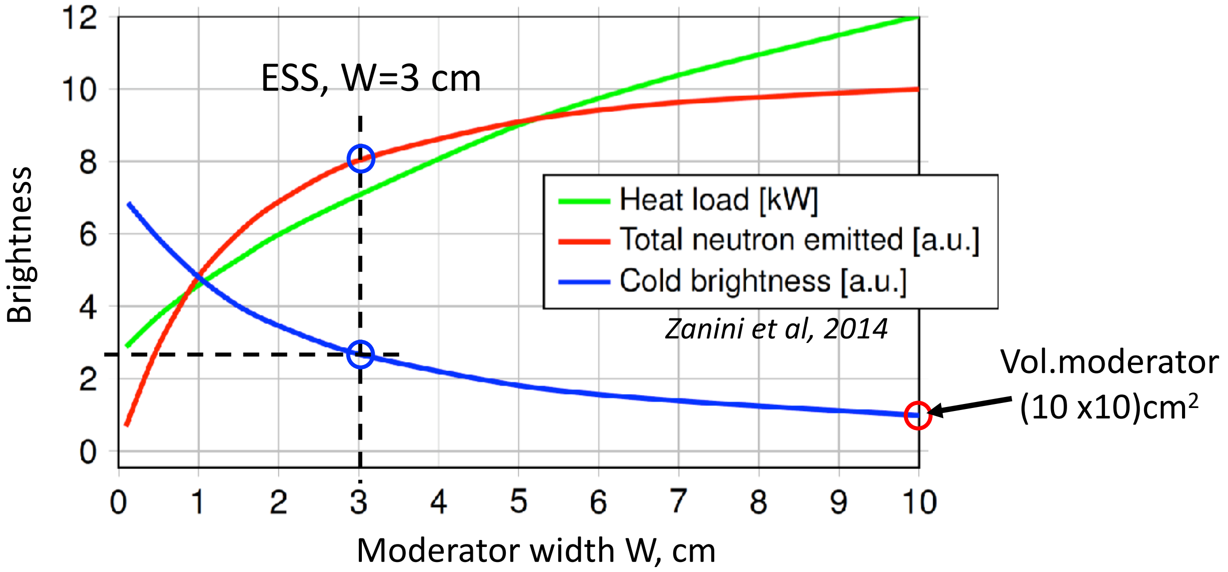
Dongguan (China)

Flat moderators vs. voluminous moderators

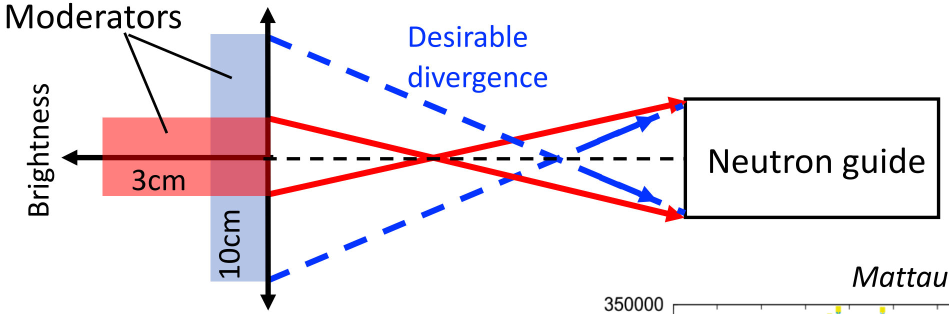


<u>Flat moderators developed at ESS (Mezei (2014), Zanini (2019)):</u>
=> brightness gain ≈ 3, intensity loss only about 20%
=> 2-2.5 times flux increase at high Q-resolution instruments

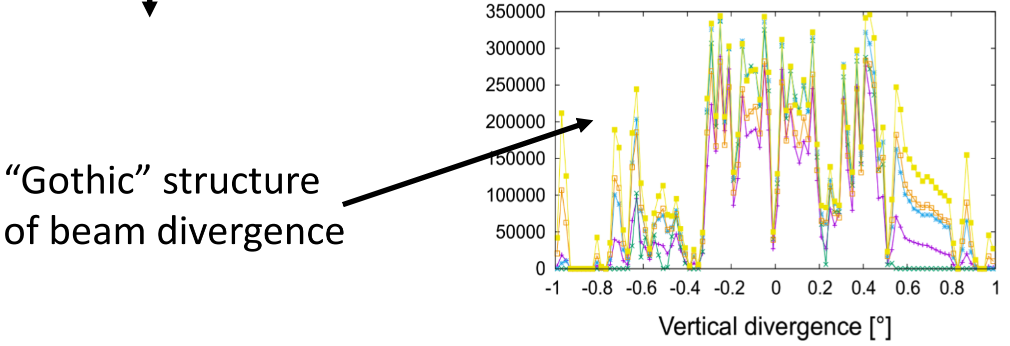
1. Gain in brightness by costs of intensity losses:



2. Under-illumination of neutron guide by small moderator

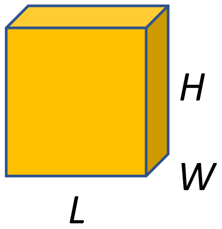


Mattauch et al, 2017



=> solution: multichannel guides (losses in intensity)

Flat moderators vs. voluminous moderators



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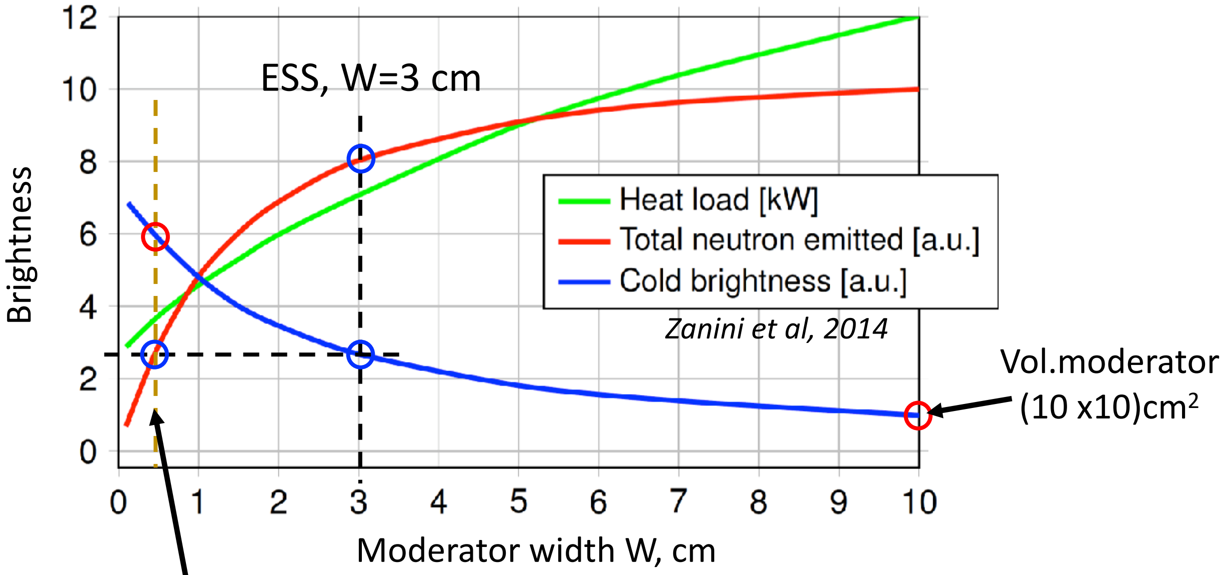

W=0.5 cm

(+) another gain in brightness,
(-) 5x intensity drop
(-) even worth divergence profile

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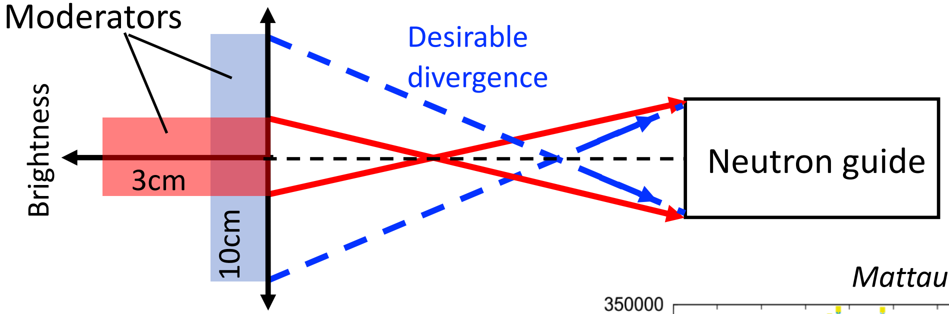

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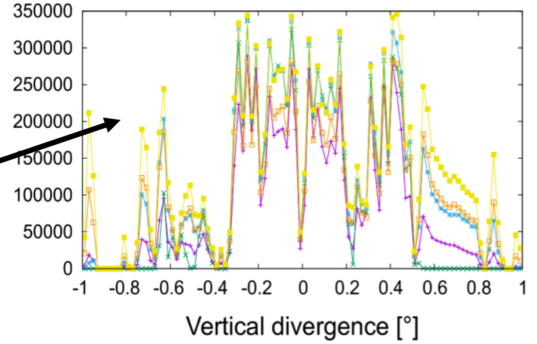

"Gothic" structure of beam divergence

=> solution: multichannel guides (losses in intensity)

Flat moderators vs. voluminous moderators

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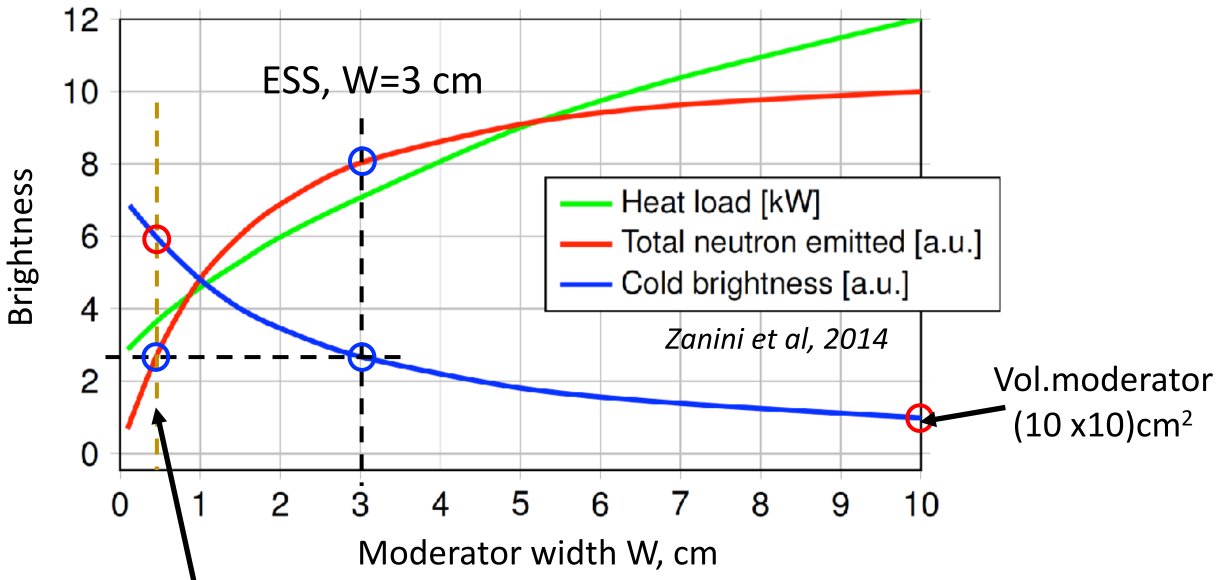

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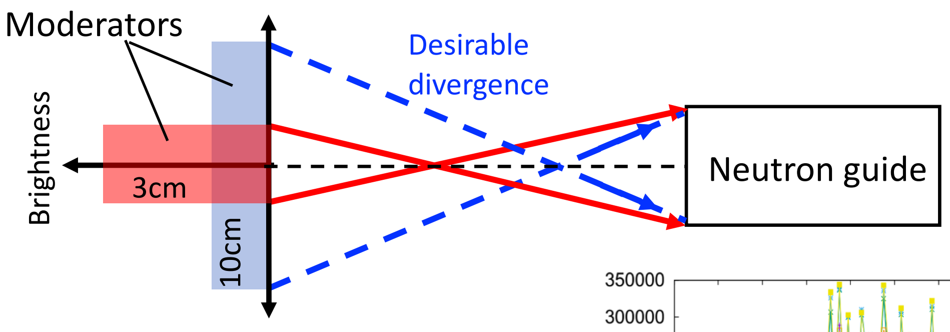
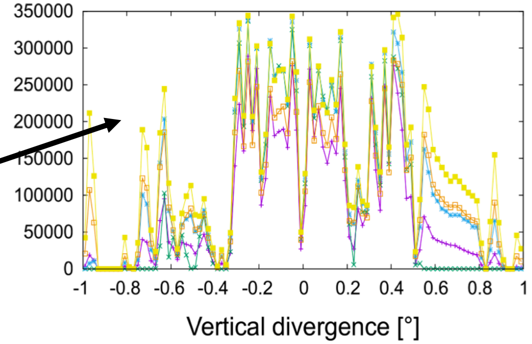
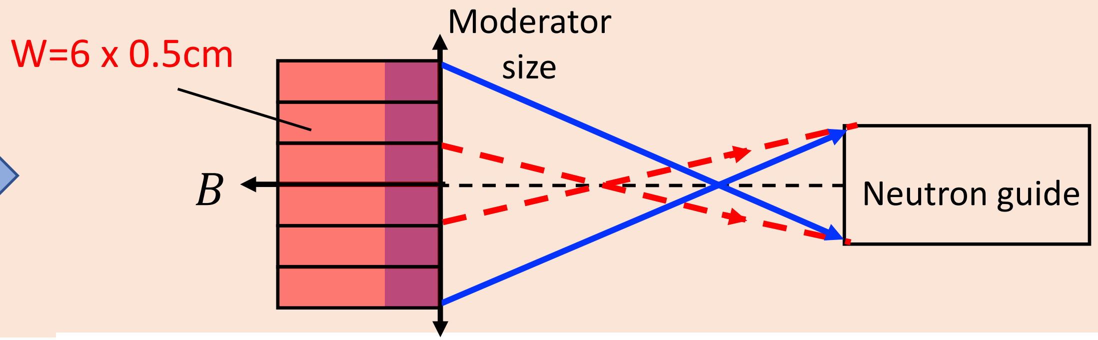


“Gothic” structure of beam divergence

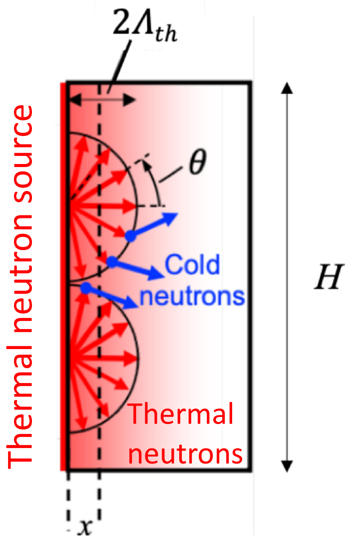


A dream: full illumination by wide moderator

⇒ Smooth divergence profile
⇒ High brightness AND high intensity



Brightness of high-aspect ratio moderators



Number of thermal neutrons penetrated through layer x :

$$exp\left(-\frac{x}{\Lambda_{th}\,cos(\theta)}\right)$$

Λ_{th} - mean free path for thermal neutrons

$\Rightarrow$ Number of thermal neutrons collided with H_2 atoms is equal to number of cold neutrons:

$$I_0(x)\left[1 - exp\left(-\frac{x}{\Lambda_{th}\,cos(\theta)}\right)\right]$$

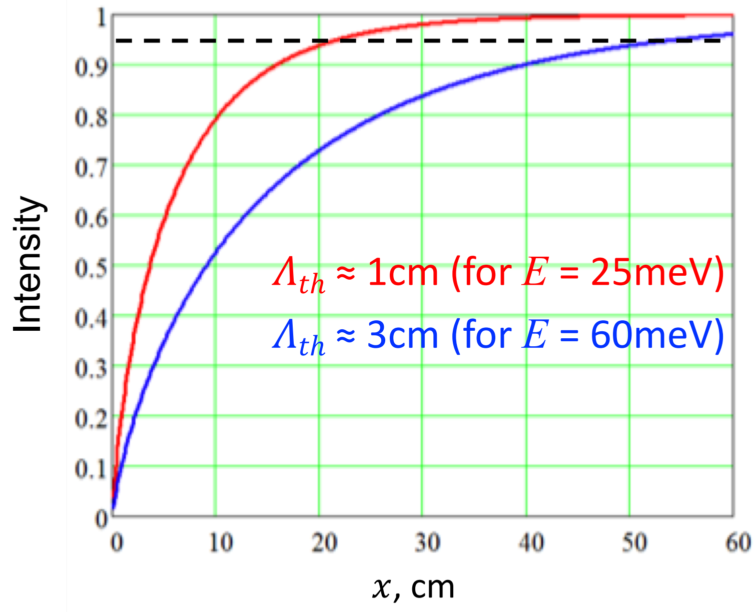
$\Lambda_{cold} > L$ (moderator length)

Thermal-to-cold neutron conversion in the single collision => Cold neutron beam intensity:

$$I_{cold}(x) = I_0\int_0^H\int_{-\pi/2}^{\pi/2}\left[1 - exp\left(-\frac{x}{\Lambda_{th}\,cos(\theta)}\right)\right]d\theta dh$$

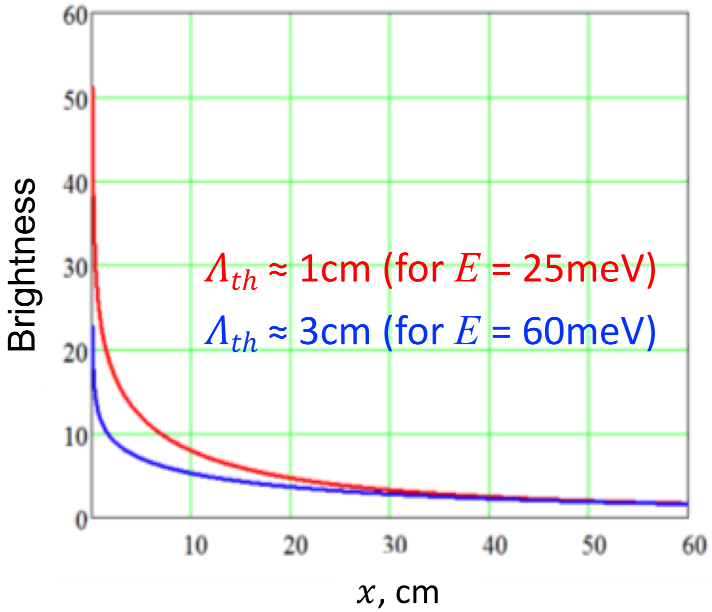
Brightness of the layer x:

$$B_c(x) = \frac{I_{cold}(x)}{x}$$

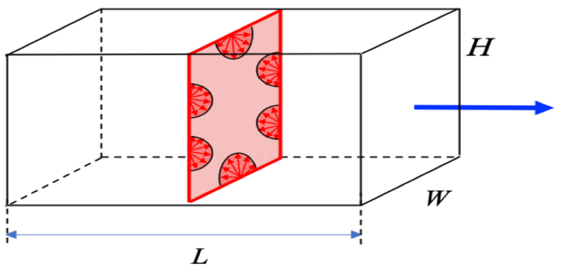


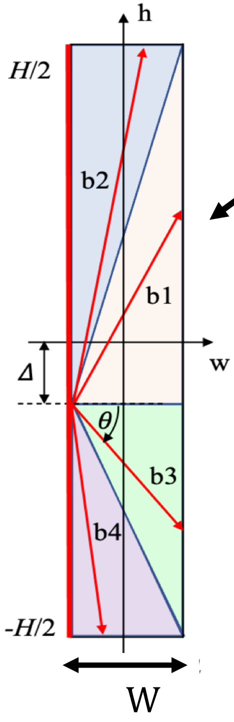
- ≈ 95% of thermal neutrons are converted to cold within layer $x = 2\Lambda_{th}$
- no significant increase in cold neutron intensity for $x > 2\Lambda_{th}$.

Sharp increase in brightness for $x \rightarrow 0$:



In-plane (infinitely thin) moderator: analytical calculations



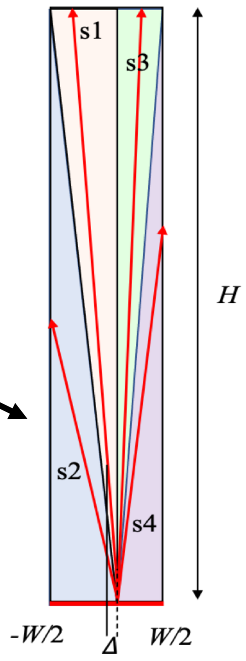


Side illumination (front view)

$$I_s(W,H) = I_0 \sum_{i=1}^{4} \int_{-\pi/2}^{\pi/2} \int_{-H/2}^{H/2} \left[1 - exp\left(-\frac{s_i(\Delta,\theta,W)}{\Lambda_{th}}\right)\right] d\theta dh$$

I_0 - intensity per unit length

$$I_B(W,H) = I_0 \sum_{i=1}^{4} \int_{-\pi/2}^{\pi/2} \int_{-W/2}^{W/2} \left[1 - exp\left(-\frac{b_i(\Delta,\theta,H)}{\Lambda_{th}}\right)\right] d\theta dw$$



Bottom illumination (front view)

Integration intervals are defined by geometry and different for each of s_i and b_i

Brightness (left+right)

$$B_s(W,H) = \frac{2 \cdot I_s(W,H)}{W \cdot H}$$

Brightness (top+bottom)

$$B_B(W,H) = \frac{2 \cdot I_b(W,H)}{W \cdot H}$$

Brightness for full illumination (top-bottom and left-right):

$$B(W,H) = B_s(W,H) + B_B(W,H)$$

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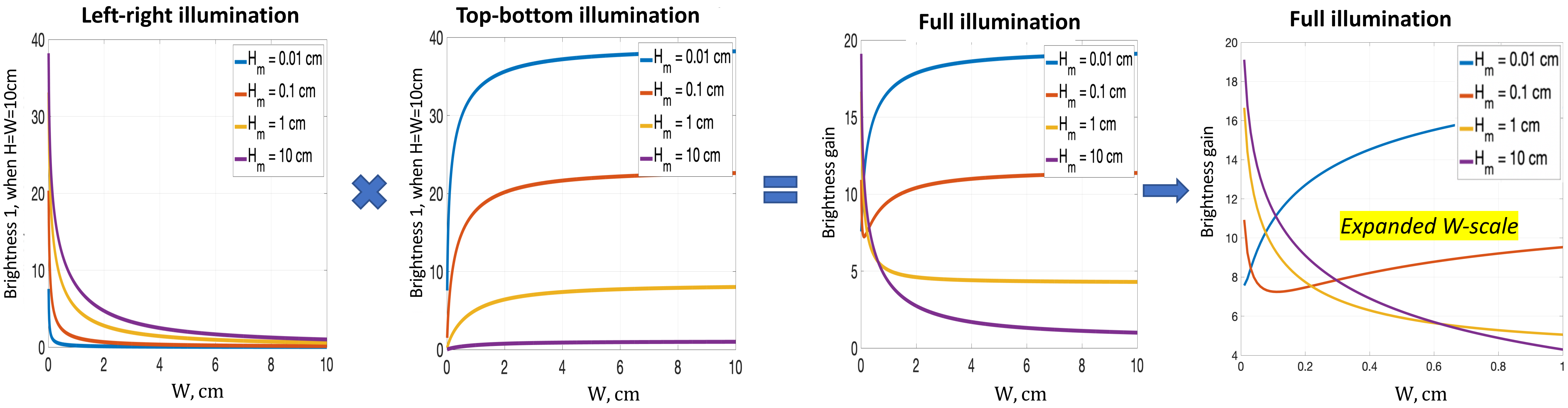
Full illumination of in-plane moderator: results

Brightness normalized to brightness of voluminous moderator (10x10) cm^2
=> **brightness gain relative to voluminous moderator**

$$\text{Brightness gain}\,(W,H) = \frac{B_s(W,H) + Bb(W,H)}{2 \cdot B(10,10)}$$

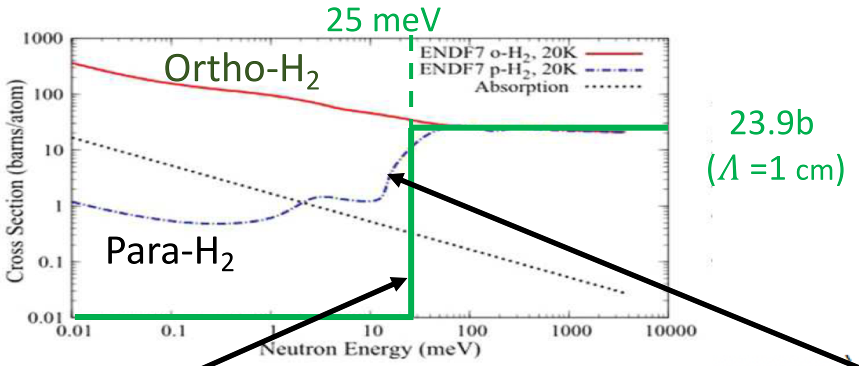


- High gains for (0.1-0.3) x 10 cm^2 moderators
- Non-monotonic behaviour
- To be confirmed by MNCP simulations

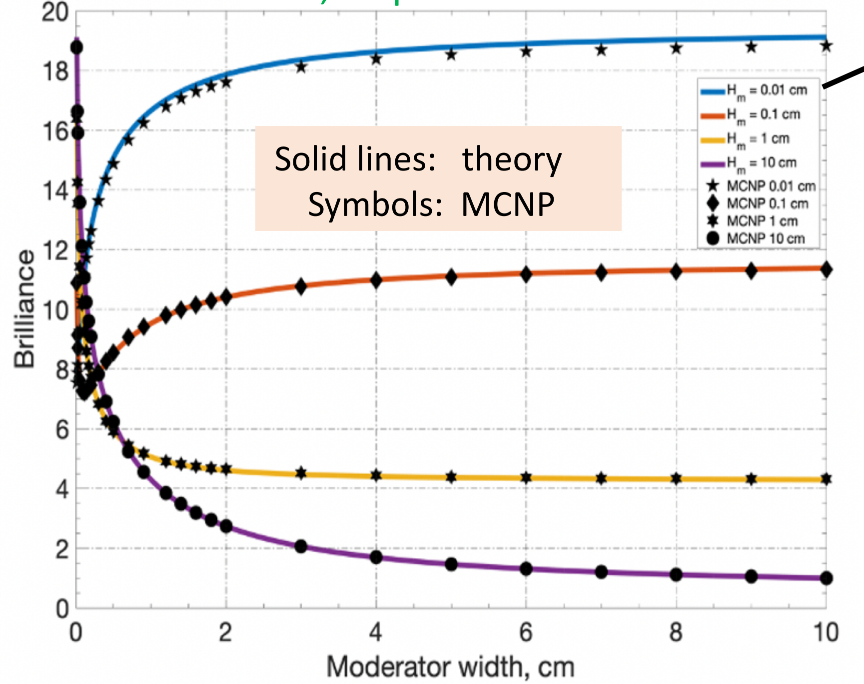
As brightness both of flat and reference moderators are calculated for the same illumination conditions, **brightness gain is invariant to illumination**

Brightness of high-aspect ratio moderators: theory and MCNP

Comparison between analytic calculations and MCNP: simulations are limited to single collisions.



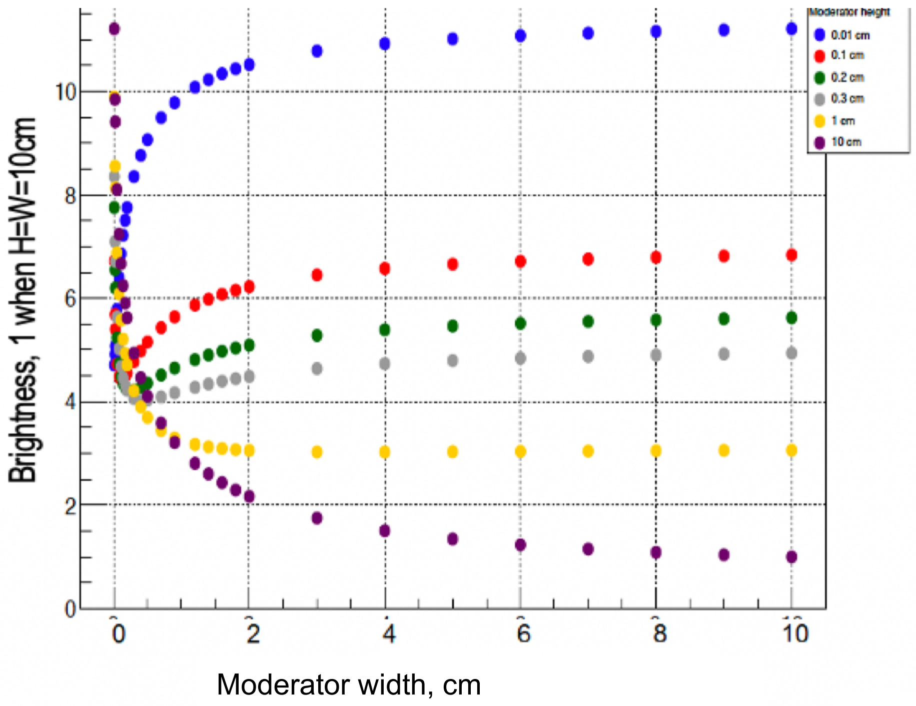
E= 25 meV, step-like cross-section



Transition to reality:

- Spectrum
- Cross-section

Maxwellian spectrum illumination, real cross-section

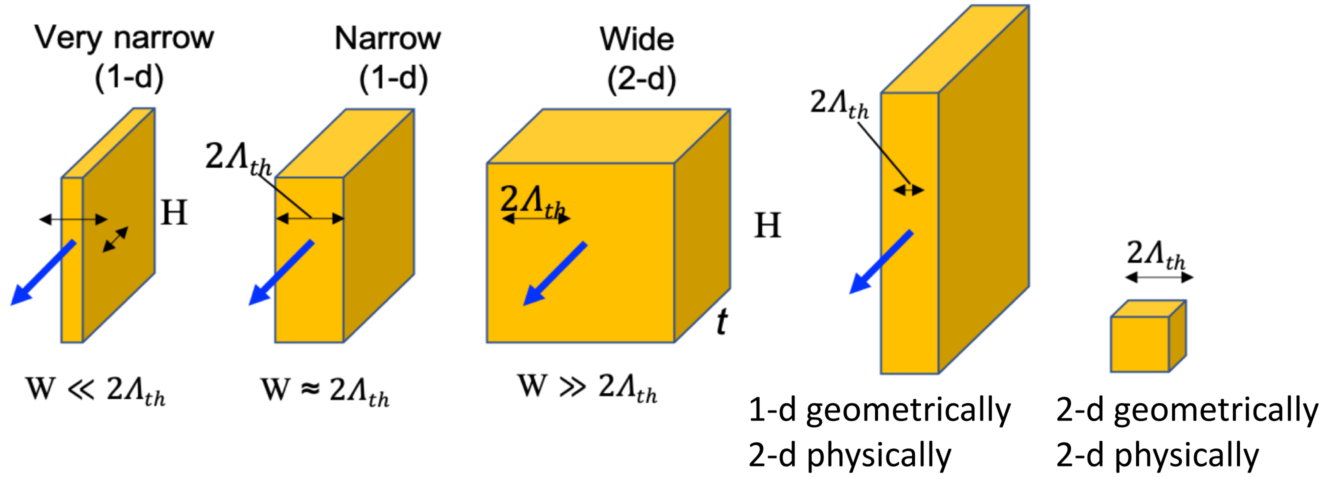


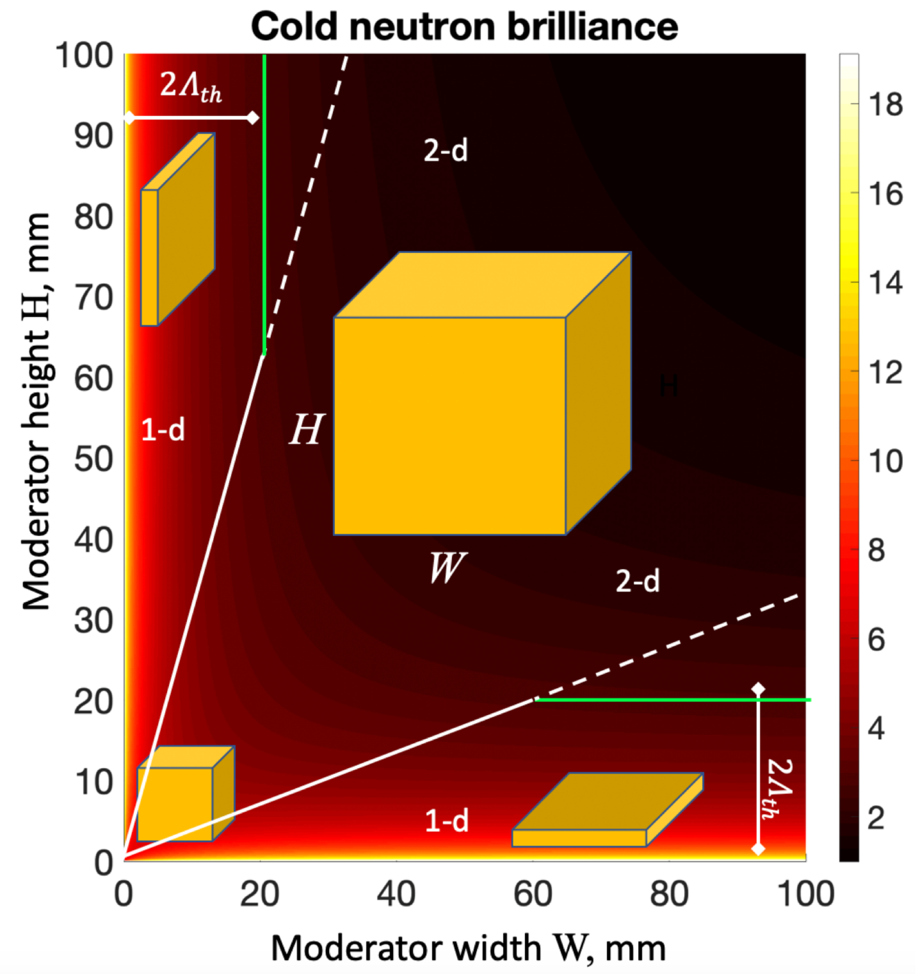
Excellent agreement demonstrates accuracy and reliability of both analytic calculations and MCNP simulations.

High-aspect ratio moderators provide a high brightness.

What is actually low-dimensionality of moderators?

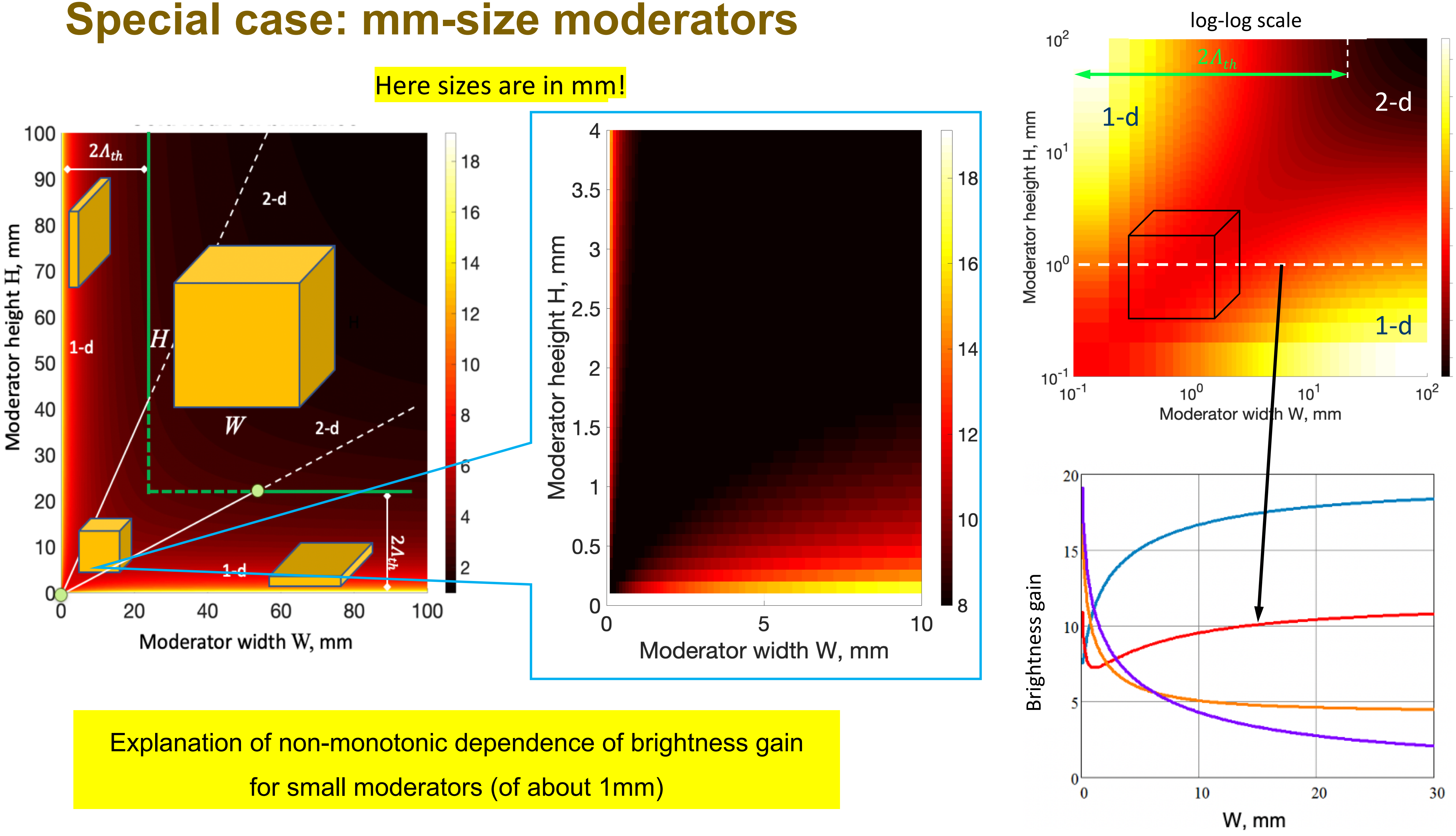
- Dimensionality of moderator is related only to its front face, depth is free parameter.
- Only moderators of 1-d shape provide essential gain (factors) in brightness.
- However, to be 1-d "geometrically" => high-aspect ratio W/H <<1 or H/W<<1 is **necessary**, **however not sufficient** to be 1-d moderator!
- The scale in moderator physics is the mean free path Λ_{th}:
  "*narrow*" means W < $2\Lambda_{th}$, "*wide*" means W > $2\Lambda_{th}$.
- Indeed, to be 1-d moderator, it should be:
  a) "1-d geometrically" **AND**
  b) at least W or H should be "*narrow*" (i.e. less than $2\Lambda_{th}$).





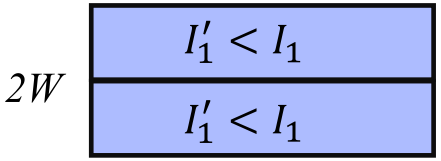
Special case: mm-size moderators

Here sizes are in mm!



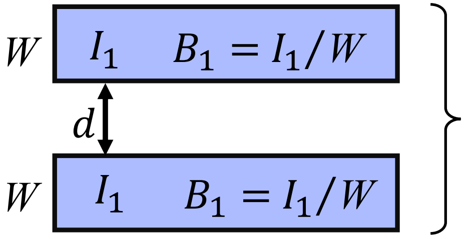
Explanation of non-monotonic dependence of brightness gain for small moderators (of about 1mm)

Increasing the moderator width while keeping brightness of narrow moderator: multiple moderators

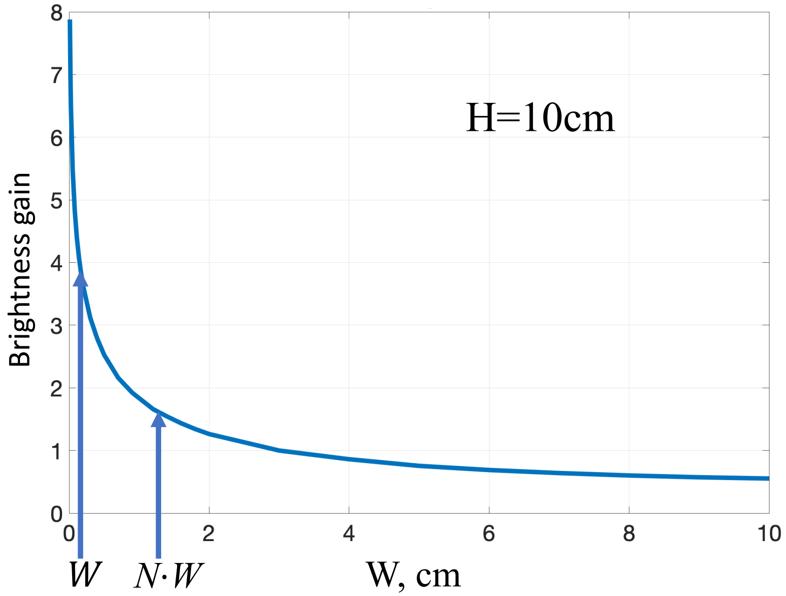


Reduction of intensity I_1:

$$\Rightarrow B_{tot} \neq \frac{2I_1'}{2W} < B_1$$



$$B_{tot} = \frac{2I_1}{(2w+d)} < B_1$$



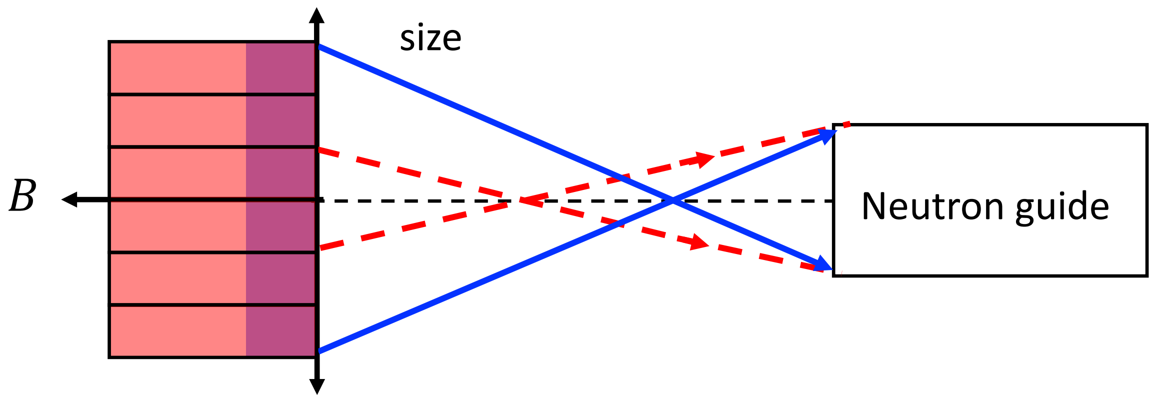
Vertical stack of N moderators is equivalent to thick moderator ($N{\cdot}W$)

Reason for reduction of I_1 in stack:

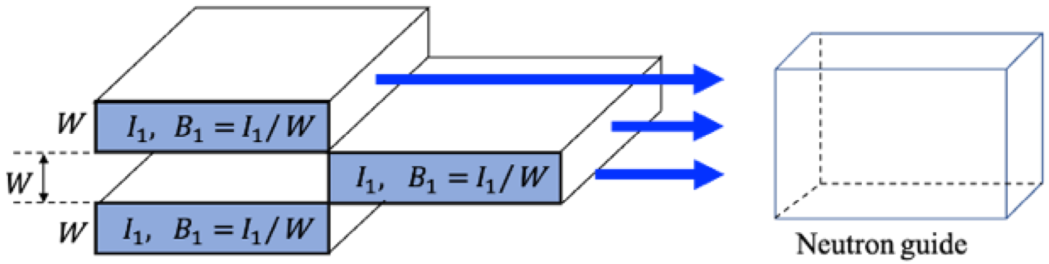
- high intensity comes from next-to-the-surface area of moderator, which is now shadowed by neighbouring moderators at small d (reduction of illumination).
- for $d \gg w$ shadowing is small, $I_1' \approx I_1$, however $B_{tot} \ll B_1$

For good moderator performance one needs
well developed and well-illuminated moderator surface.

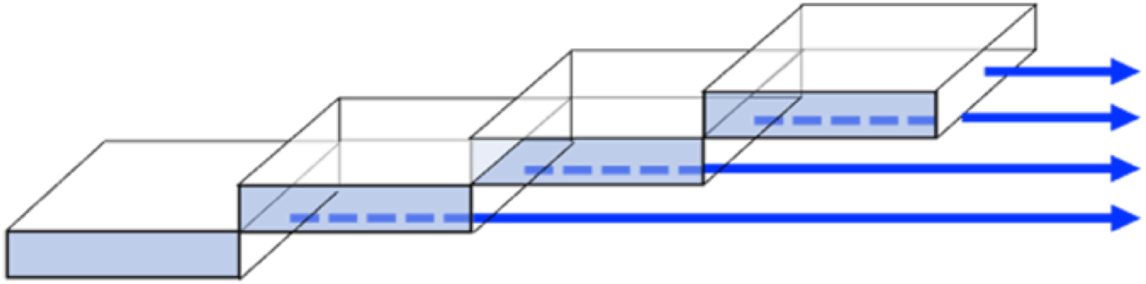
Increasing the moderator width while keeping brightness of narrow moderator: multiple moderators



Chessboard-like assembly of narrow moderators.

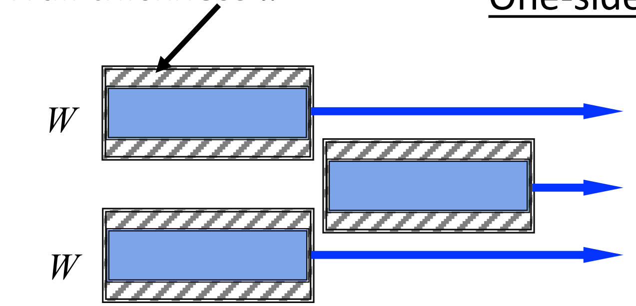


Staircase -like assembly of narrow moderators.



Brightness of each single moderator in chessboard is almost kept, but intensities from each of moderators will add up.

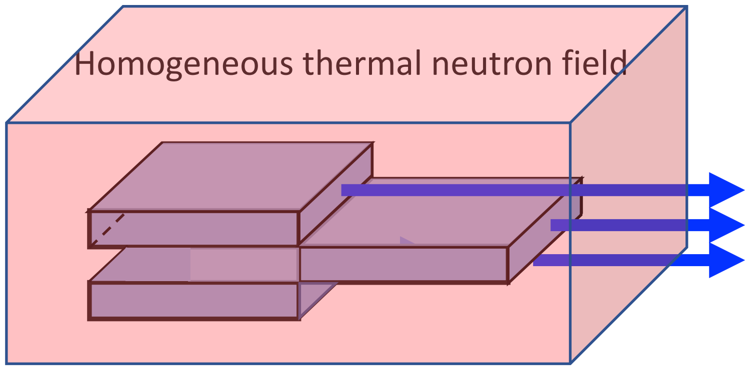
Effect of finite wall thickness



One-side overlap

Open area:

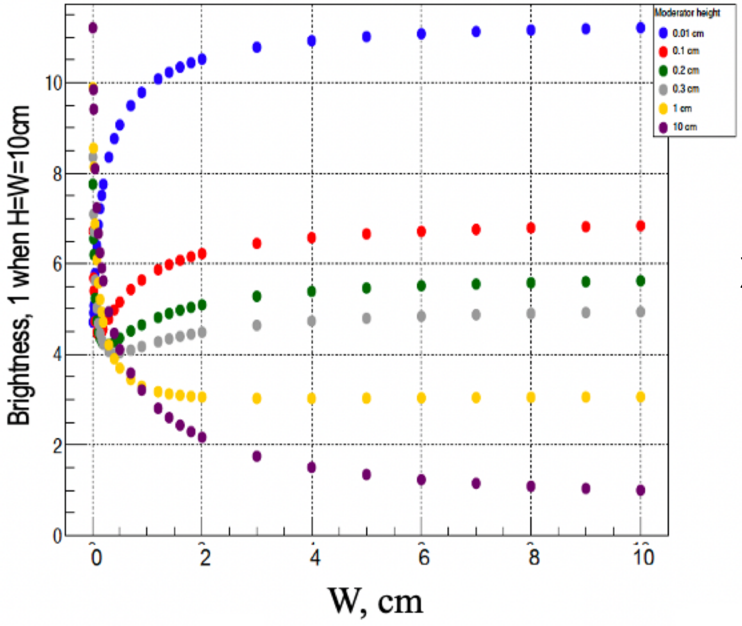
$$g = W/(W+a)$$



$I_{tot} \approx 3I_1$ (zero walls)

$B_{tot} \approx B_1$

Brightness gain for cold neutrons

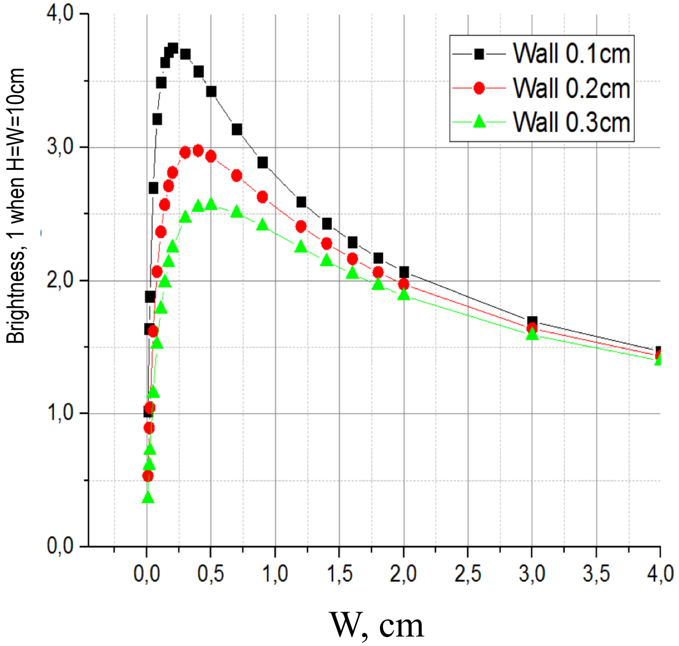


X

Losses caused by wall (thickness a)

W, mm	a, mm	g =W/(W+a)	B	B·g
1	1.5	0.4	6.8	2.7
2	1.5	0.57	5.6	3,.2
3	1.5	0.67	4.9	3.9
1	1	0.5	6.8	3.4
2	1	0.67	5.6	3.8
3	1	0.75	4.9	3.7
1	0.5	0.67	6.8	4.6
2	0.5	0.8	5.6	4.5
3	0.5	0.85	4.9	4.2

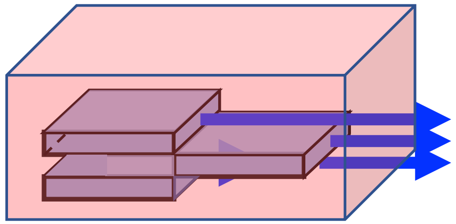
=



Wall thickness a is comparable to moderator width
=> reduction of achievable brightness

- Maximal gain for thin moderators of (3-4)mm
- Homogeneous illumination of all steps

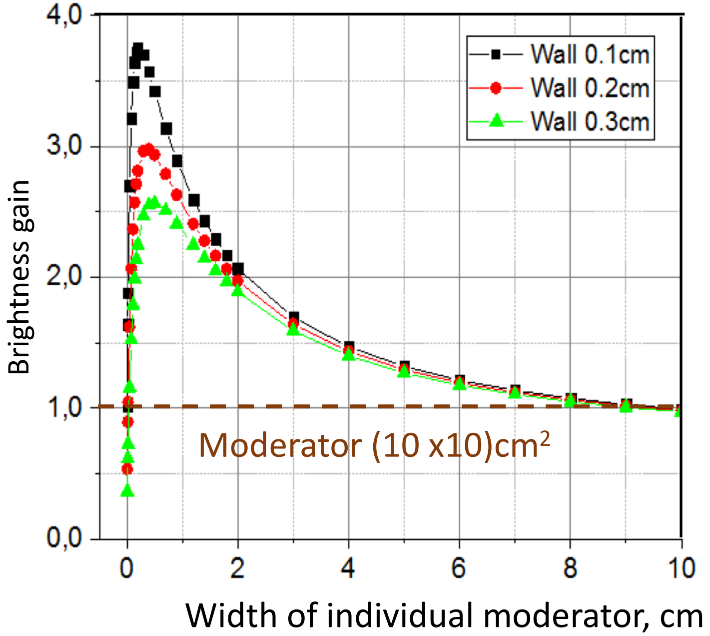
Brightness and intensity gains of assembly (all relative voluminous 10cm moderator)



Number of individual moderators in assembly: $N_{ind} = W_A / W$

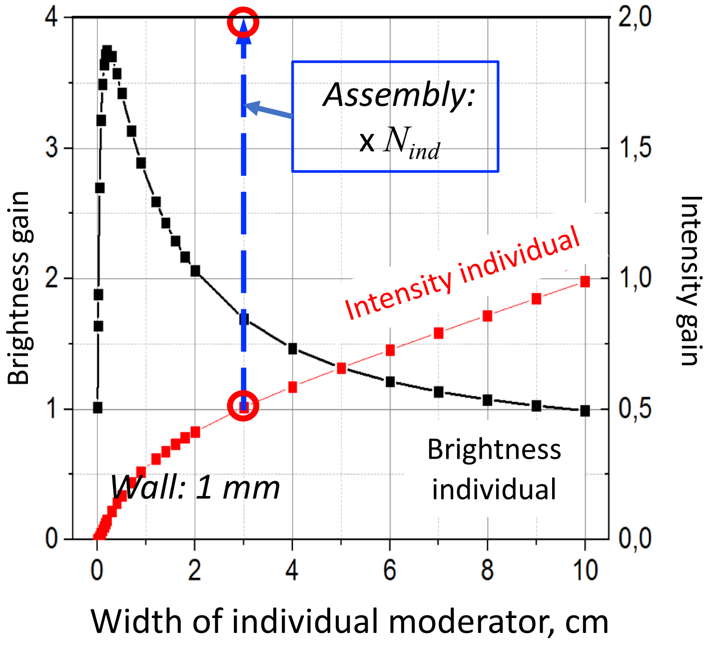
Brightness gain of individual moderator

(relative 10cm moderator)



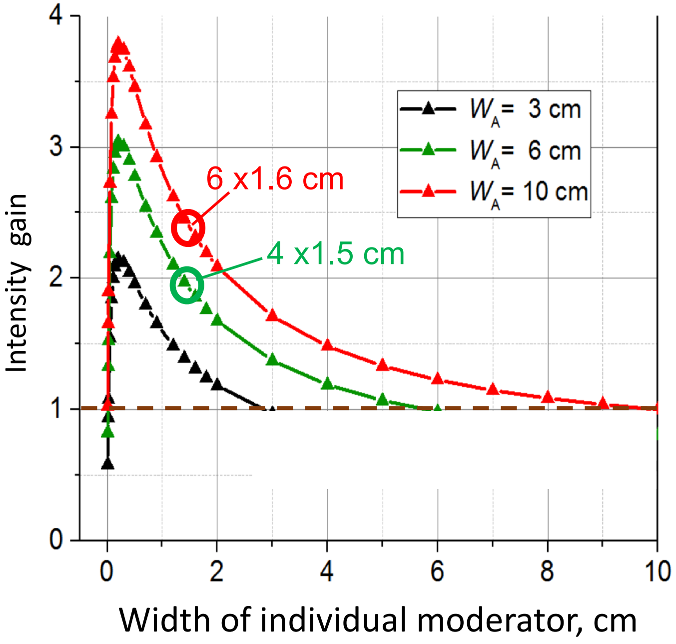
Intensity of individual moderator

Intensity_Gain = Intensity_Ind x N_{ind}



Intensity gain of moderator assembly

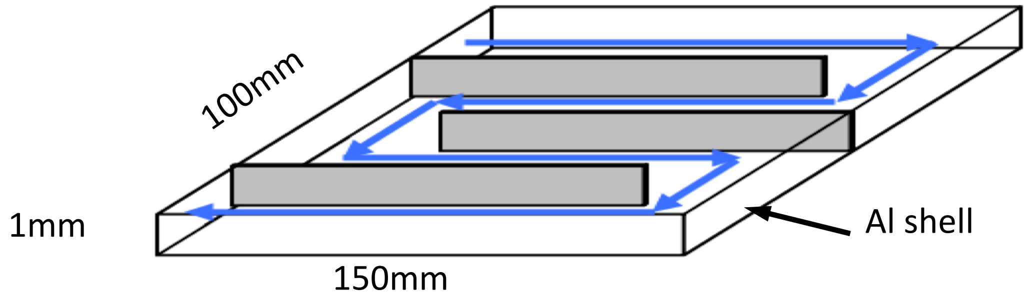
(relative 10cm moderator)

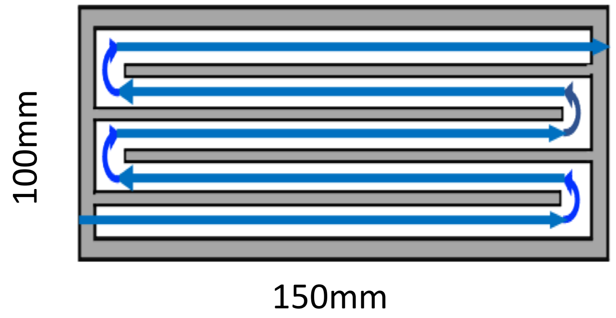


- Such moderator assemblies can provide a significant gain **both** in brightness **and** in intensity.
- Significant brightness and intensity gains for the assembly of 4 and 6 individual moderators (H/W = 6-7).

Minimization of wall thickness

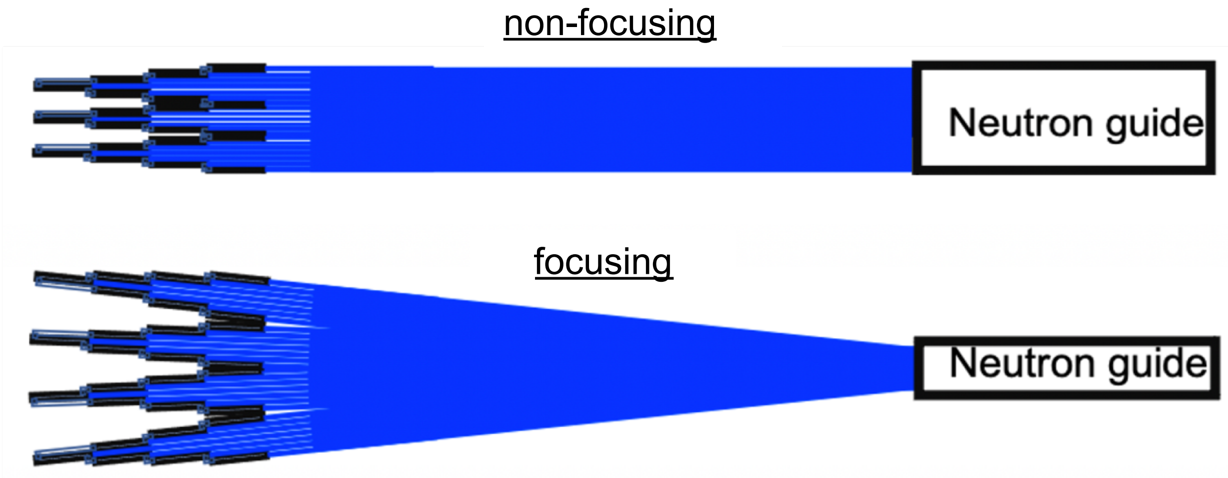
Single moderator can be made of a single Al piece: inner ribs connect large surfaces and direct LH_2 flow



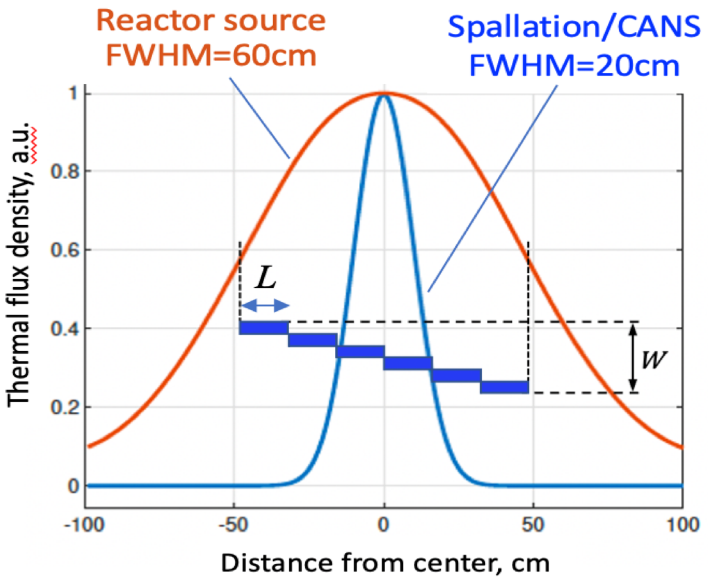


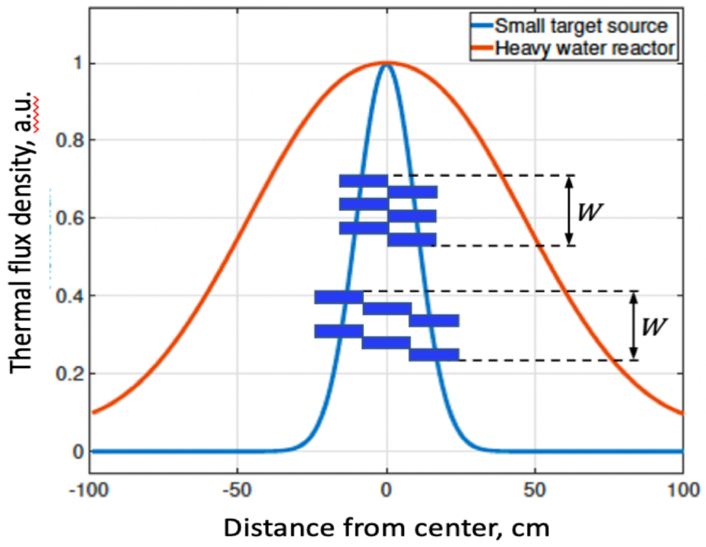
Y.Bessler (FZJ)

W-arrangements of single high-brilliance moderators:



Inhomogeneous thermal neutron illumination



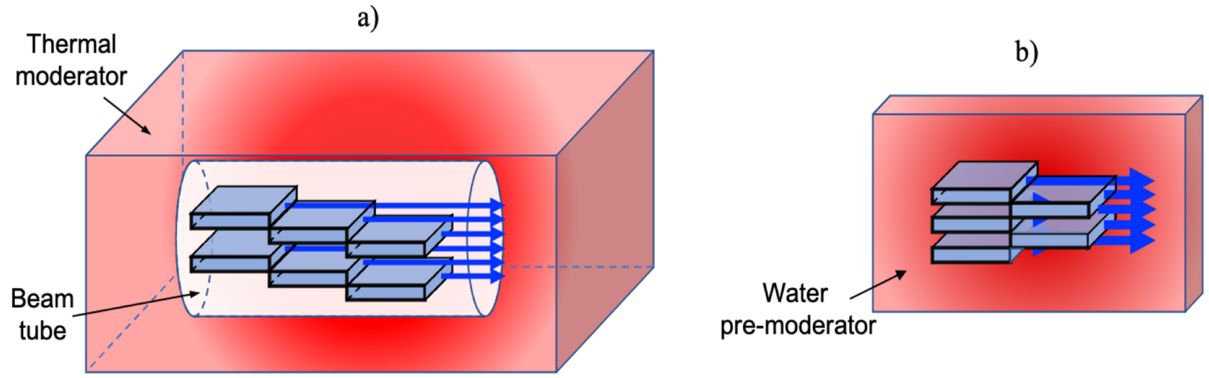


Lower illumination at the periphery:

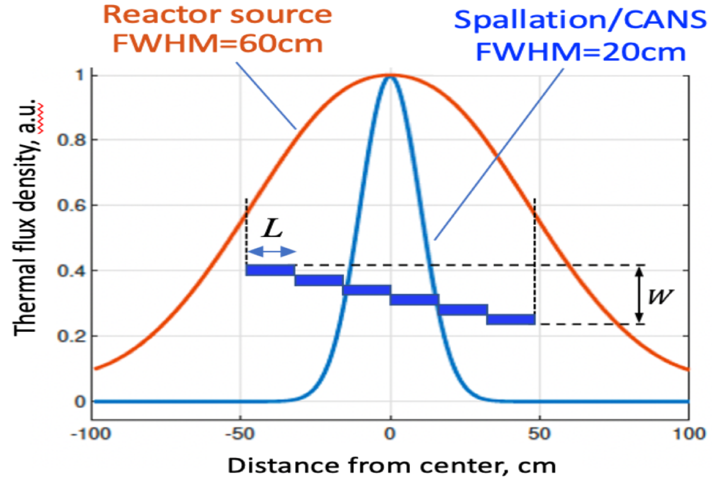
⇒ restricted overall length

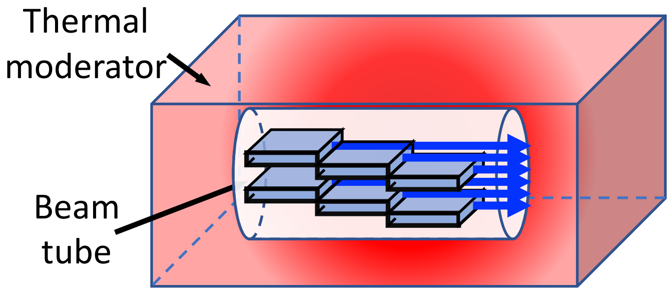
⇒ restricted number of individual moderators (L=15 cm)

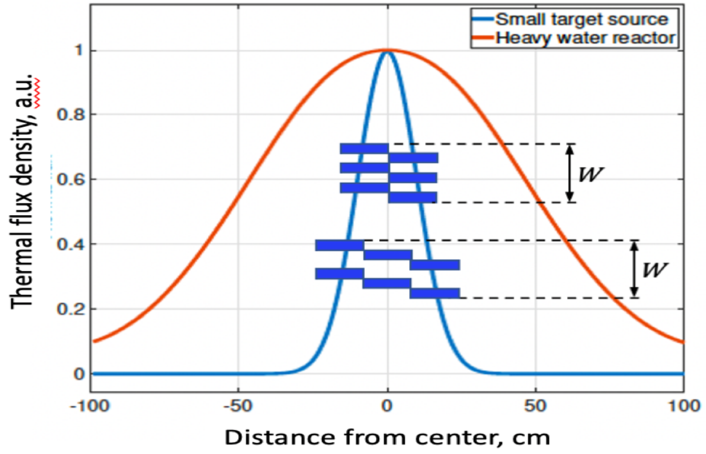
'Zigzag' or parallel staircase assemblies with smaller overall length



Inhomogeneous thermal neutron illumination: reactor sources







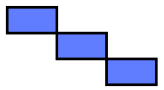
Beam width **W=10 cm**, wall thickness = 1 mm

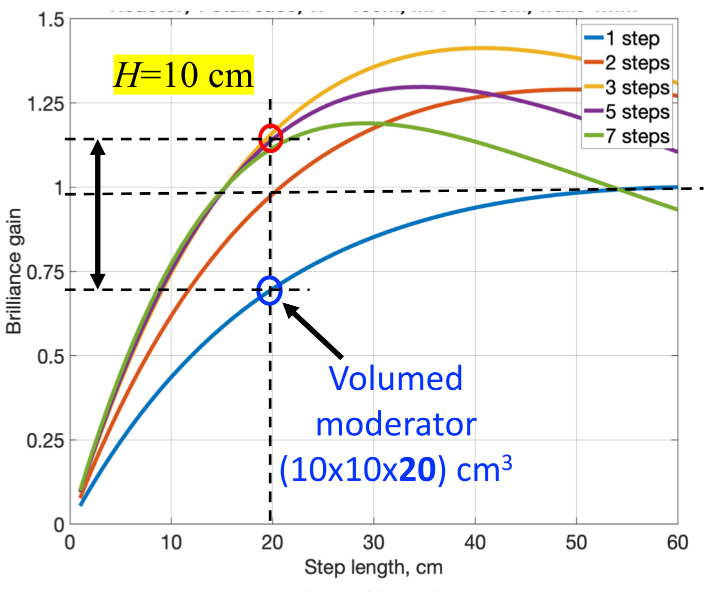
3 staircases

Gain ≈ 1.7

3 x 3.3cm

L = 20 cm





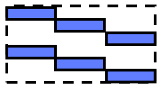
2 staircases

Gain ≈ 2.3

2 x 3 x 1.6cm

L = 20 cm

W = 1.6 cm

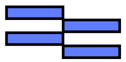


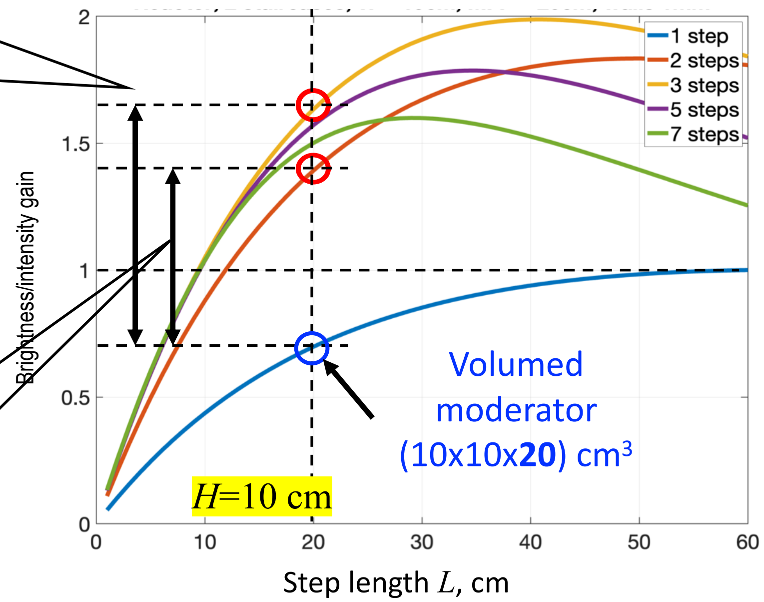
Gain ≈ 2

2 x 2 x 2.5cm

L = 20 cm

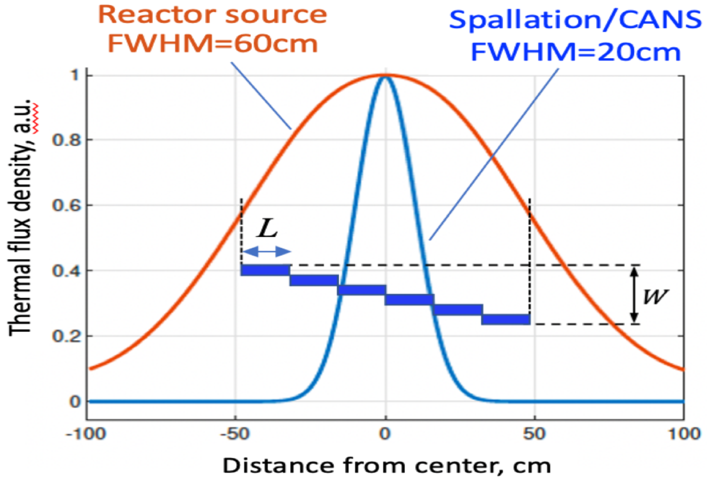
W = 2.5 cm

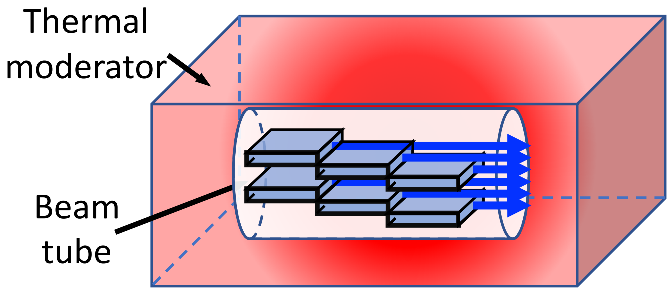


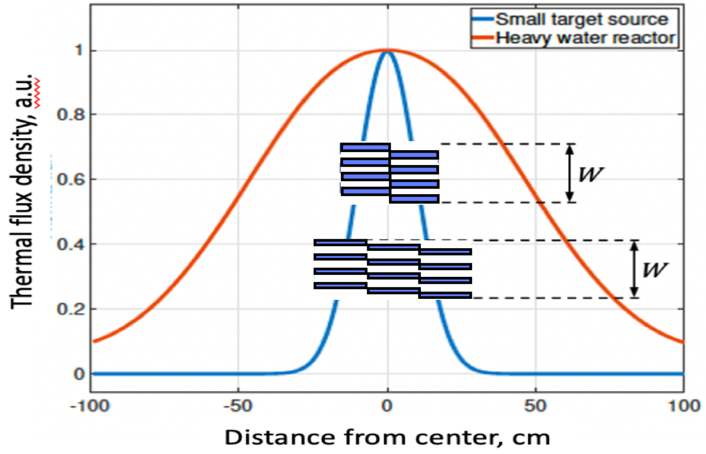


Gain even for 2 steps

Inhomogeneous thermal neutron illumination: reactor sources

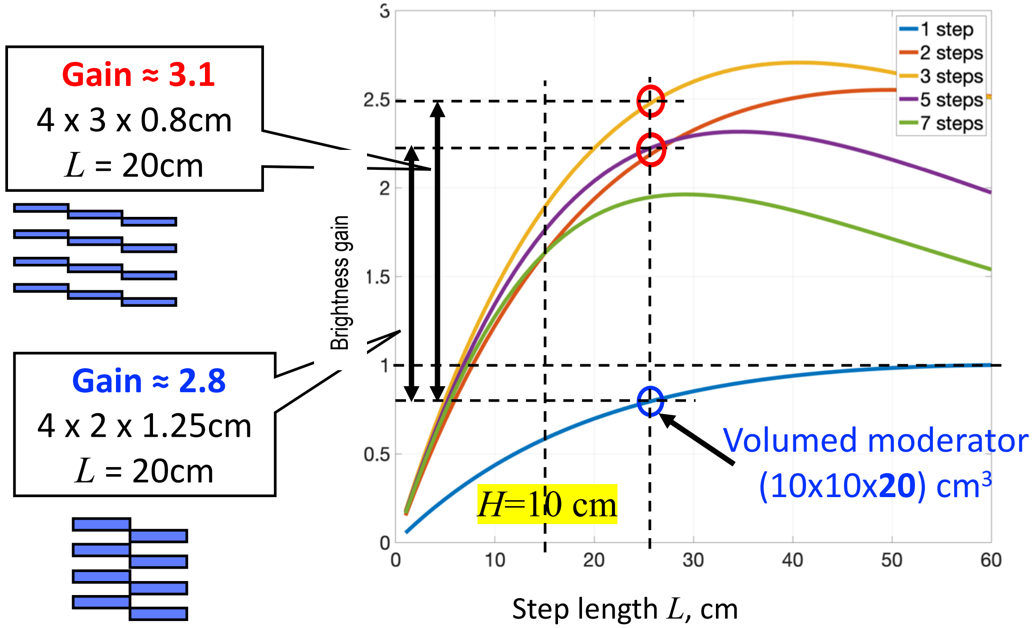




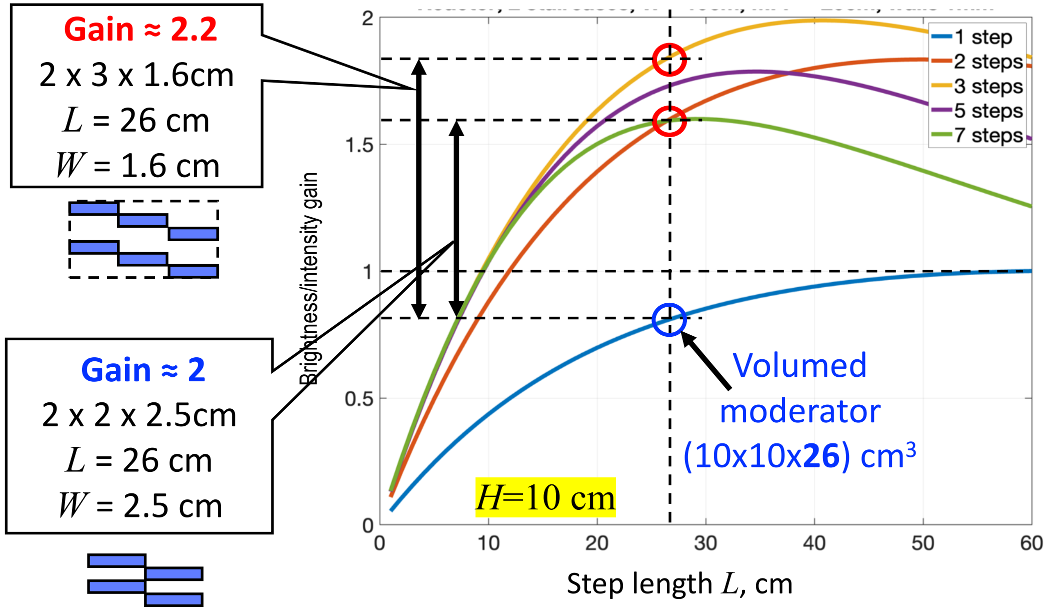


Beam width **W=10 cm**, wall thickness = 1 mm

4 staircases

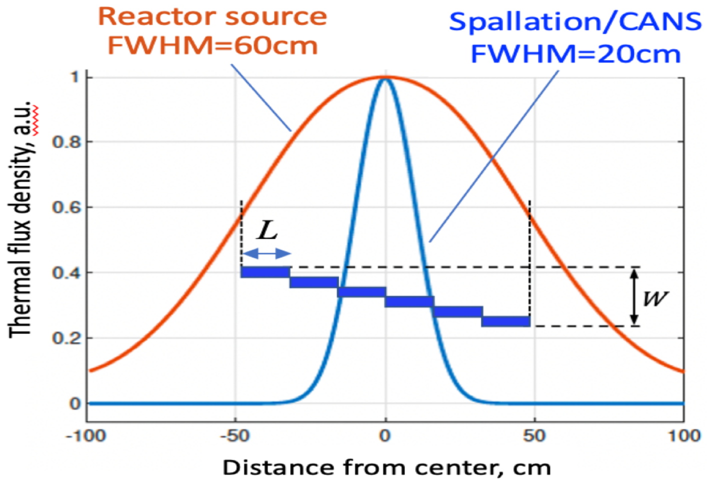


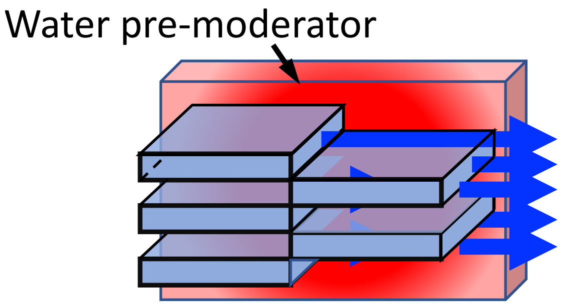
2 staircases

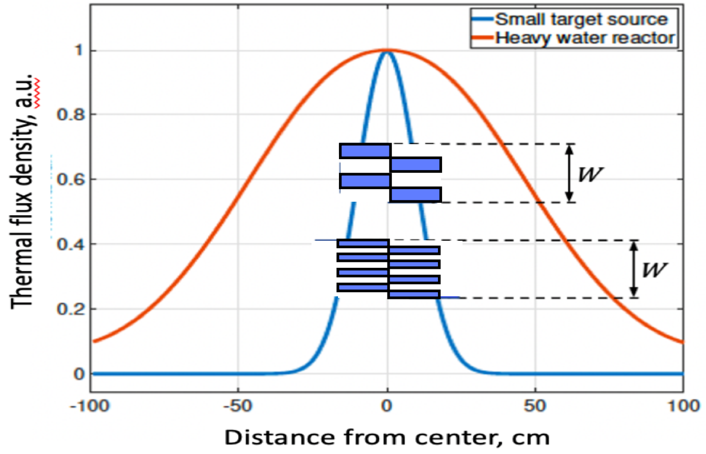


Gain even for 2 steps!

Inhomogeneous thermal neutron illumination: spallaltion/CANS



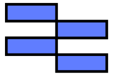


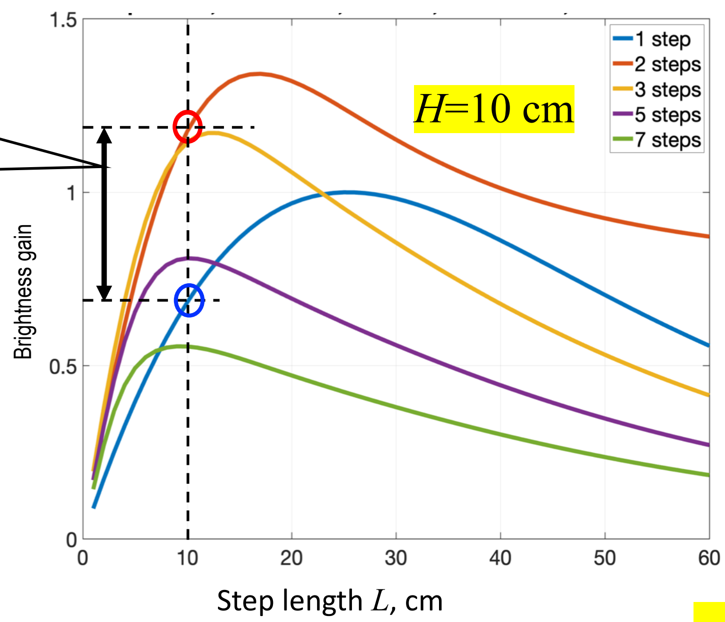


Beam width **W=3 cm**, wall thickness = 1 mm

2 staircases

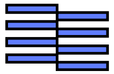
Gain ≈ 1.7
2 x 2 x 0.75cm
L = 10cm

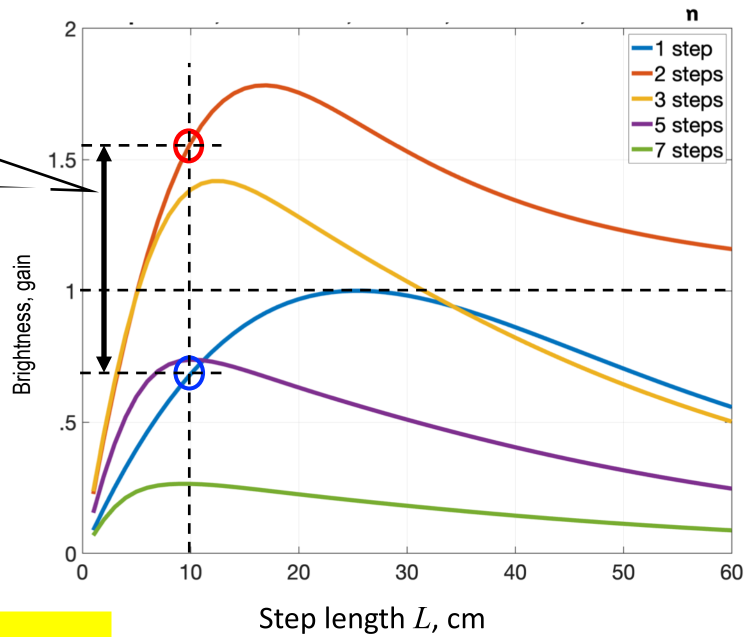




4 staircases

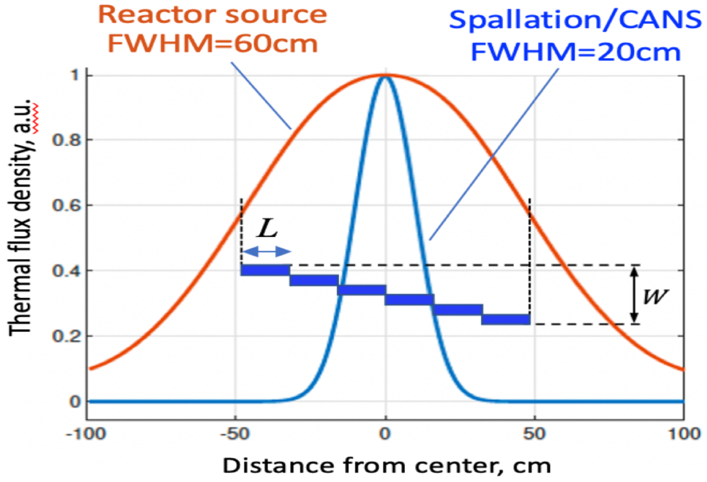
Gain ≈ 2.3
4 x 2 x 0.37cm
L = 10cm

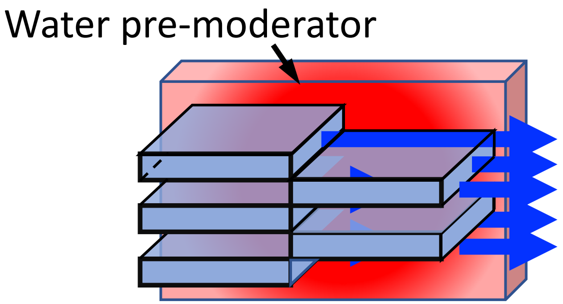


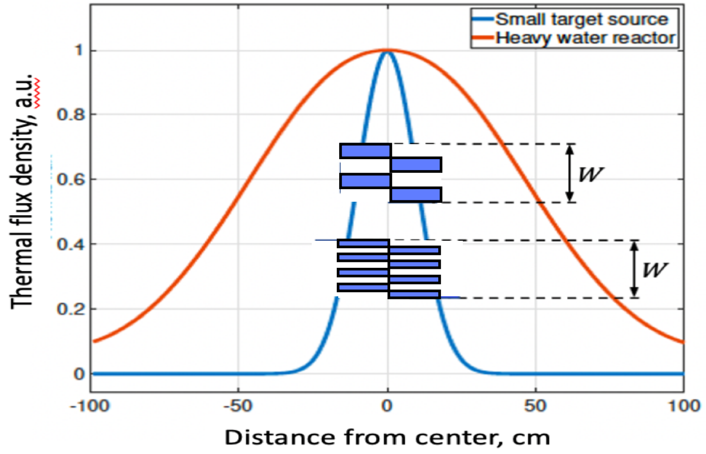


Note: not for short pulse source

Inhomogeneous thermal neutron illumination: spallaltion/CANS



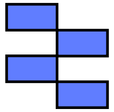


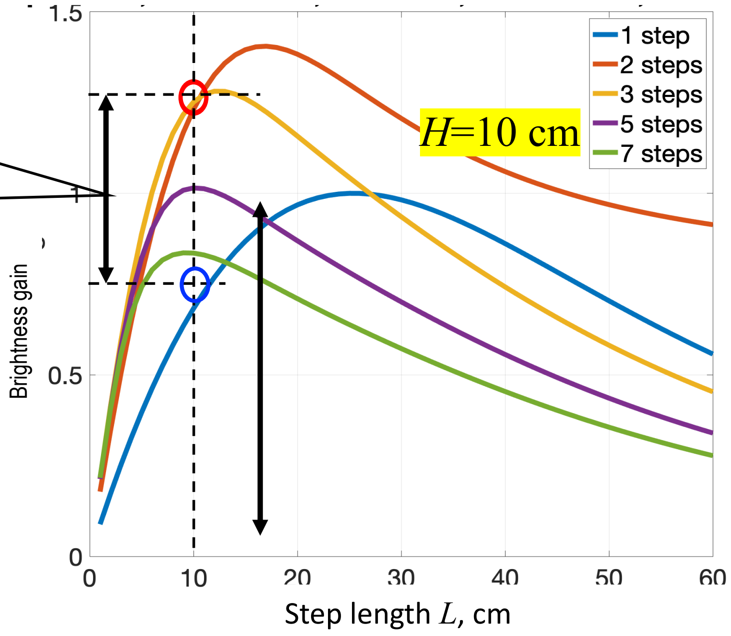


Beam width **W= 10 cm**, wall thickness = 1 mm

2 staircases

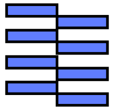
Gain ≈ 1.8
2 x 2 x 2.5cm
L = 10cm

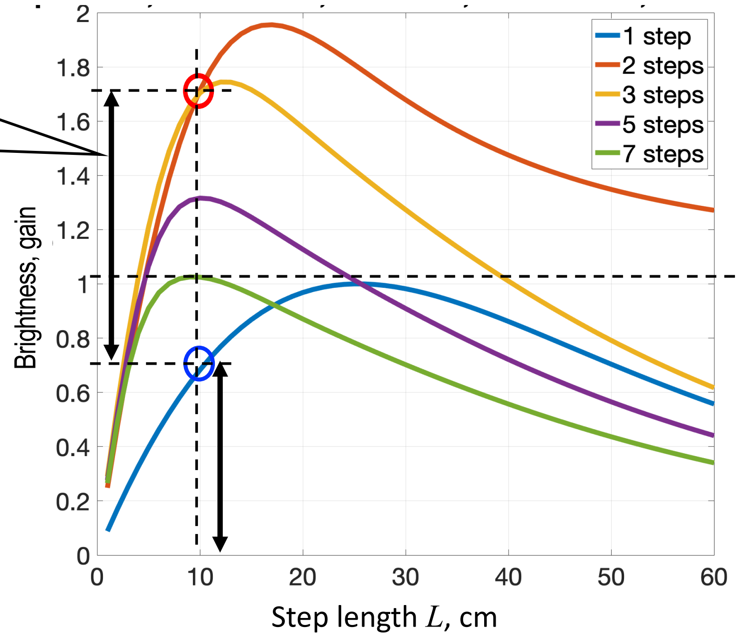




4 staircases

Gain ≈ 2.4
4 x 2 x 1.25cm
L = 10cm





Summary

- Cold neutrons are generated near the moderator's surface. Narrow 1-dimensional cold pH2 moderators offer higher brightness but come with significant intensity losses.
- We suggest to use chessboard-like and staircase-like arrangements of narrow moderators to create cold moderators with a larger cross-section, enhancing cold neutron intensity while maintaining high brightness.
- A Gaussian-like thermal flux distribution around the core/target limits brightness and intensity gains, which are still 2.5-3 times higher compared to a flat p-H_2 moderator of the same width.
- However, laterally shifted moderators broaden the cold neutron pulse by about 0.2 ms and are not suitable for short neutron pulses.

This project has received funding from the European Union‘s Horizon 2020 research and innovation programme under grant agreement No. 871072