Task 3.1: Development of advanced high-brilliance cold neutron source in combination with bi-spectral extraction system

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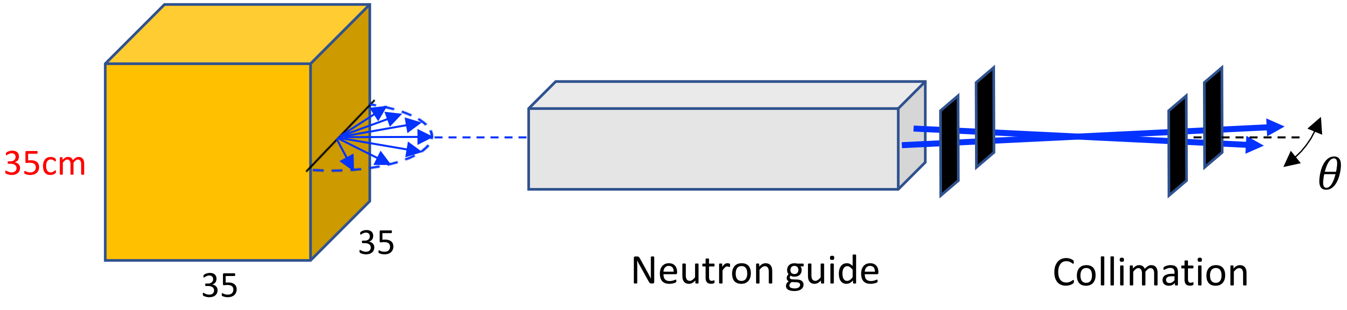
MLZ is a cooperation between:

Moderators are characterized by: *B* - brightness in *n/s/cm²/ster*

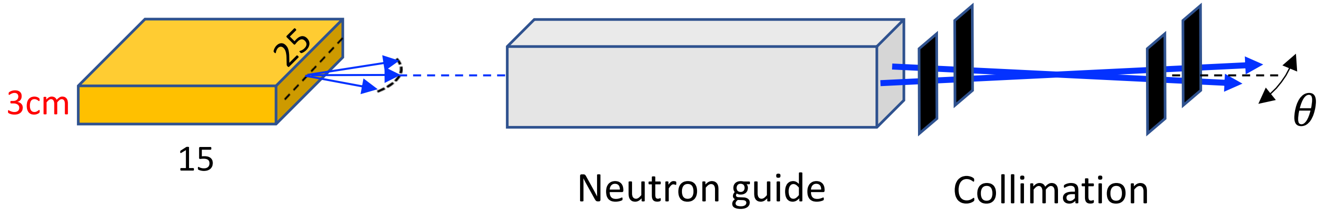
$$\text{Intensity} = \int_{\Omega} B d\theta$$

Volumed moderator (LD_2): low brightness, but high intensity in angle $\Omega = \pi$

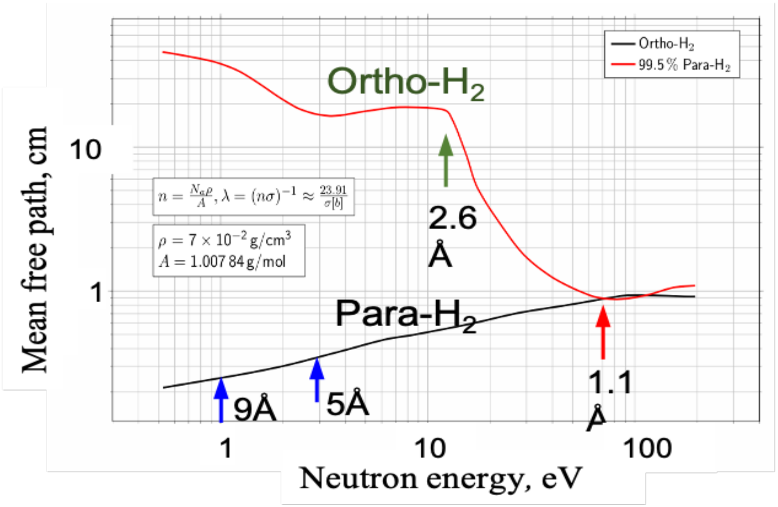


Low intensity at instruments requiring high angular resolution θ (SANS, reflectometers, imaging)

Flat moderators (p-H_2): high brightness, but low intensity in angle $\Omega = \pi$



Higher intensity at instruments requiring a high angular resolution θ
However, not so good for low resolution instruments



Para-H2:

- short mean free path for thermal neutrons
- long mean free path for thermal neutrons

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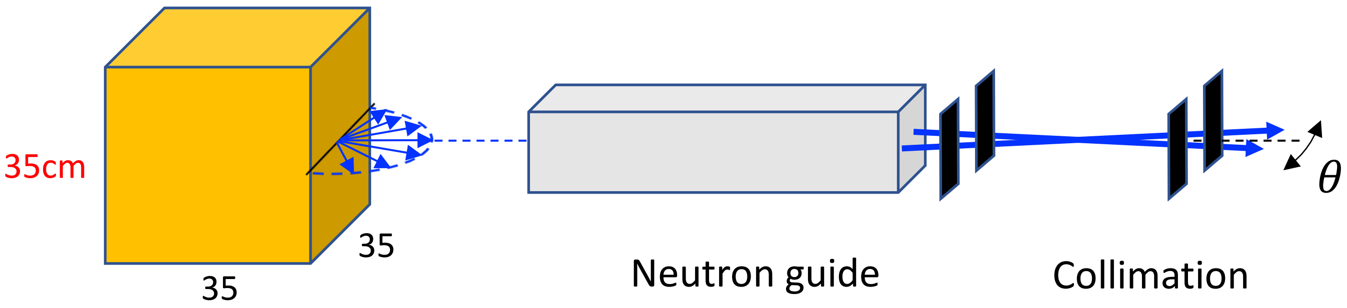

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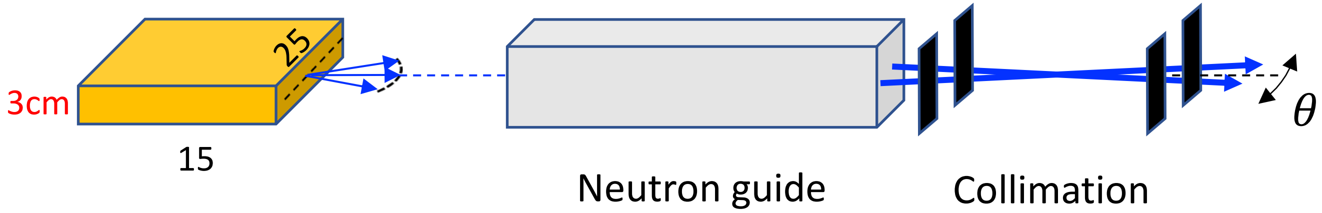

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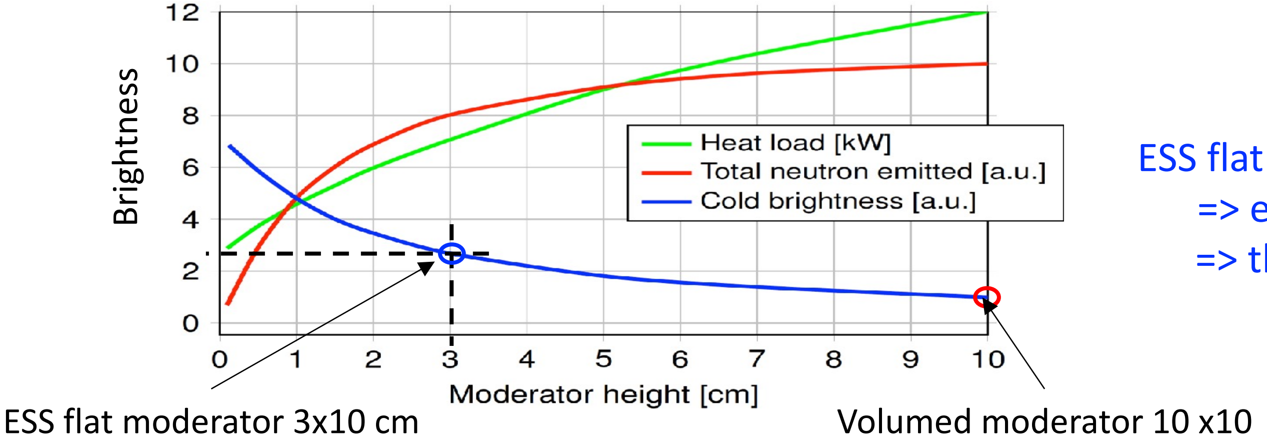
L. Zanini, et al., 2014.



ESS flat moderator: brightness gain ≈ 2.5
=> equivalent to 2.5 times decrease of power
=> the same flux at high resolution instruments at 2MW as at 5MW

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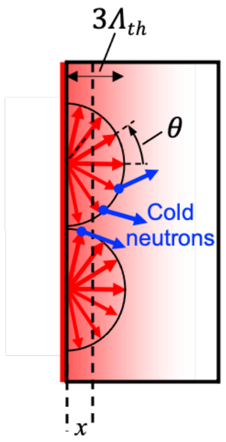
Further increase of moderator brightness?

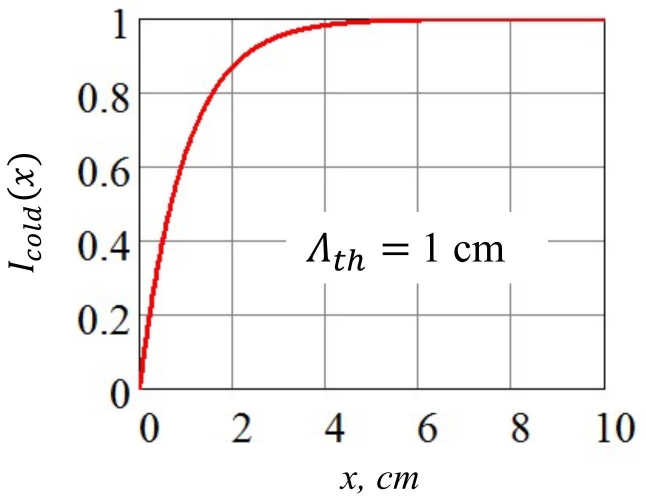
1. Theoretical approach to calculations of moderator brightness was developed.



Thermal-to-cold conversion in the single collision:

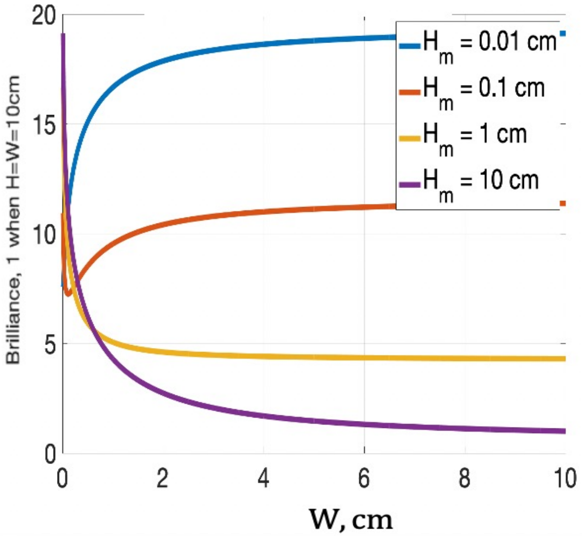
$$I_{cold}(x) = I_{th}\left(1 - e^{-\frac{x}{\Lambda}}\right)$$

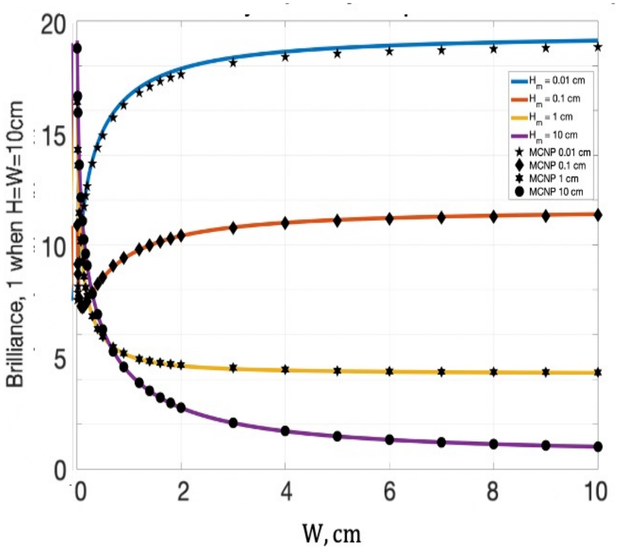
$$B_{cold}(x) = \frac{I_{th}}{x^2}\int_0^x \int_{-\pi/2}^{\pi/2} \left[1 - exp\left(-\frac{x}{\Lambda_{th}\, cos(\theta)}\right)\right] d\theta dx$$



95% of thermal neutrons are converted to cold ones within layer $x = 3\Lambda_{th}$ $\Rightarrow$ no further increase in cold neutron intensity for $x > 3\Lambda_{th}$.

2. Analytic calculations are benchmarked with MCNP calculations





- Low-dimensional (mm wide moderators) provide much higher brightness.
- The low dimensionality of moderators is determined not only by their asymmetric shape, but also by ratio x/Λ_{th} .

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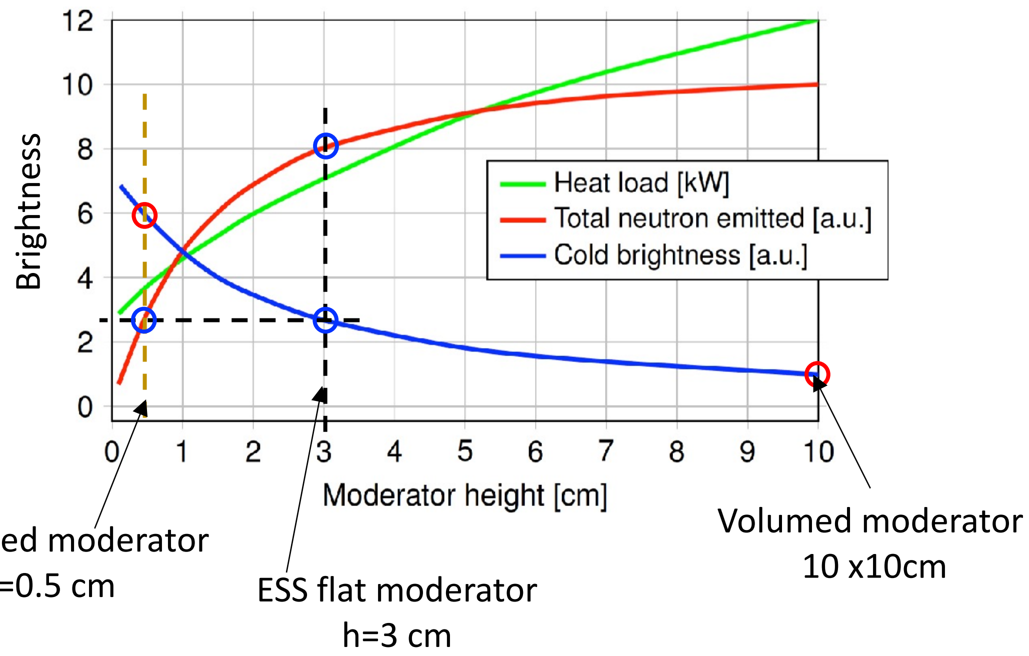
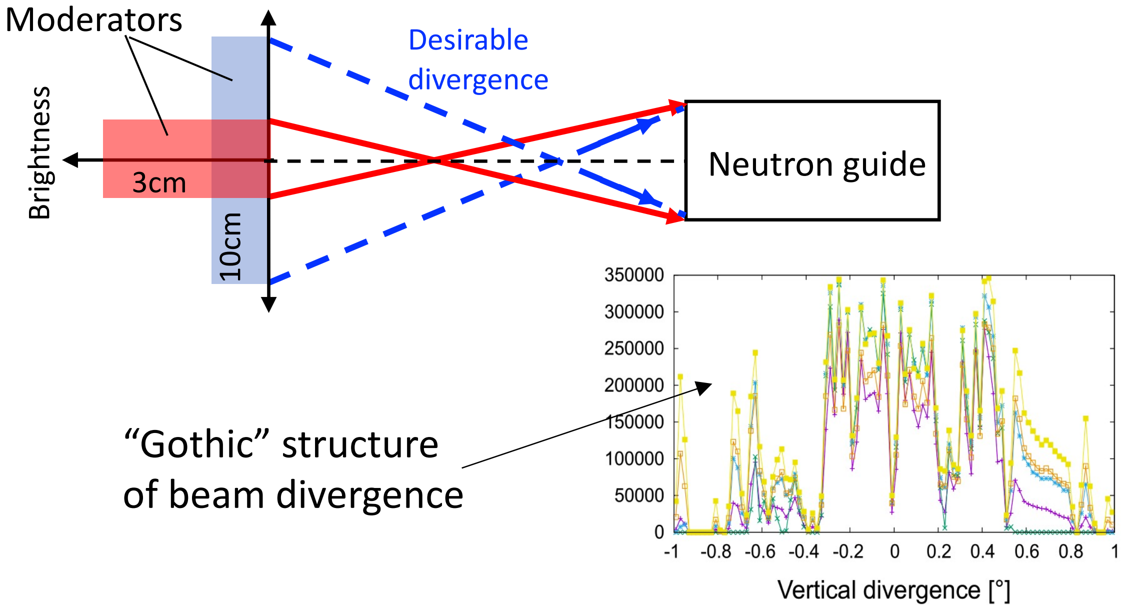
However, …

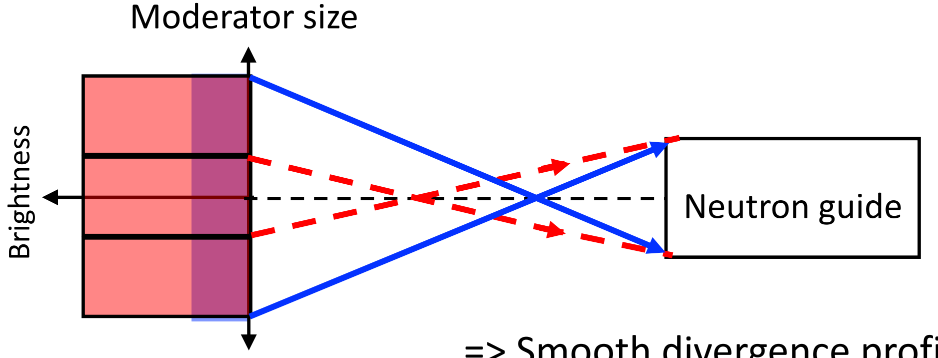
1. Gain in the moderator brightness comes by price of intensity losses:



2. Under-illumination of neutron guide by small moderator



Full illumination by tall moderator



=> Smooth divergence profile

A dream…

Could this dream be true?

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

$d = 0$

$2W$

$I_1' < I_1$

$I_1' < I_1$

Reduction of intensity I_1:

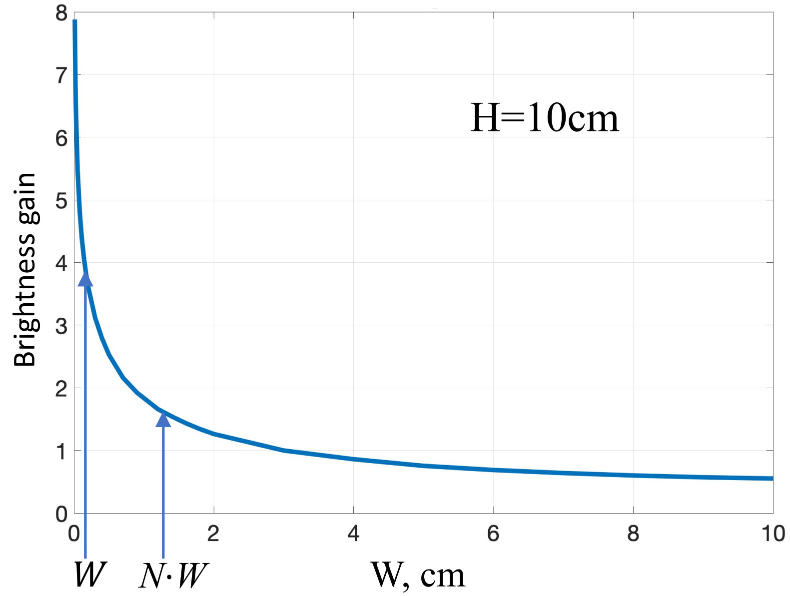
$$\Rightarrow B_{tot} \neq \frac{2I_1'}{2W} < B_1$$

W $\quad I_1 \quad B_1 = I_1/W$

d

W $\quad I_1 \quad B_1 = I_1/W$

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



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

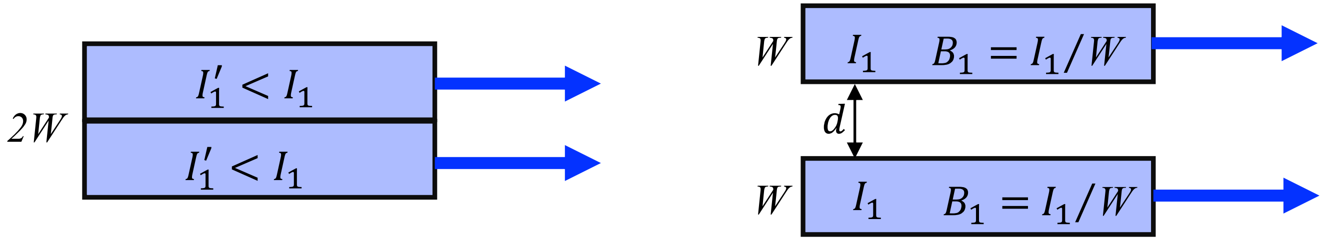
<u>Reason for reduction of I_1 in stack:</u>

- 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

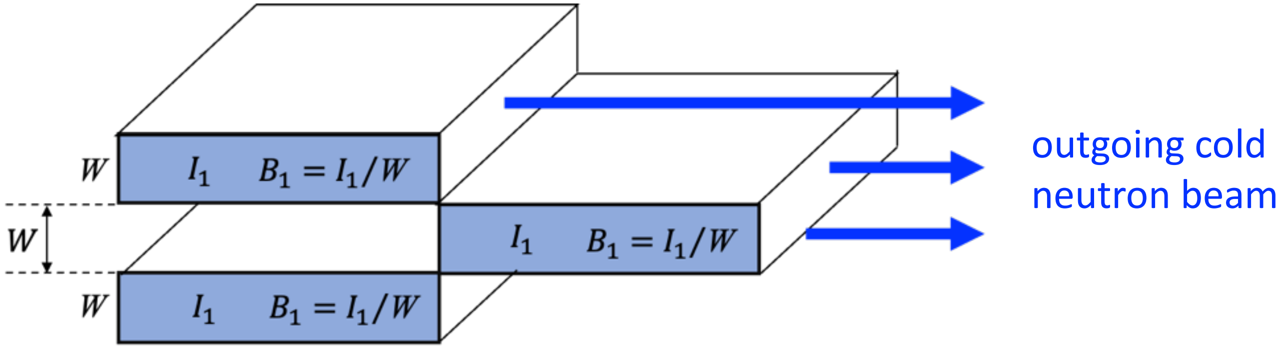
well developed and well-illuminated moderator surface.

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



Crucial requirement: to provide the well-developed and fully illuminated moderator surface in moderator assembly with minimized shadowing of single moderators and absence of non-emitting areas (holes) .

Chessboard-like assembly of narrow moderators.



When illuminating a neutron guide:

- large effective width ($3W$)
- mutual shadowing for all-side illumination is about 5% .

Thus, the brightness of each single moderator in the chessboard will be almost kept, but intensities from each of moderators will add up.

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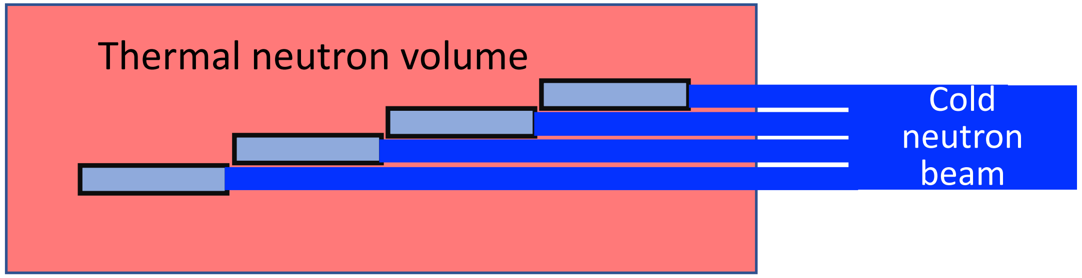
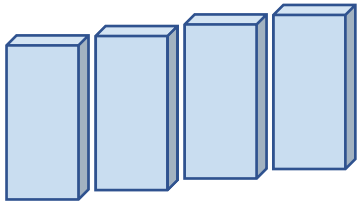
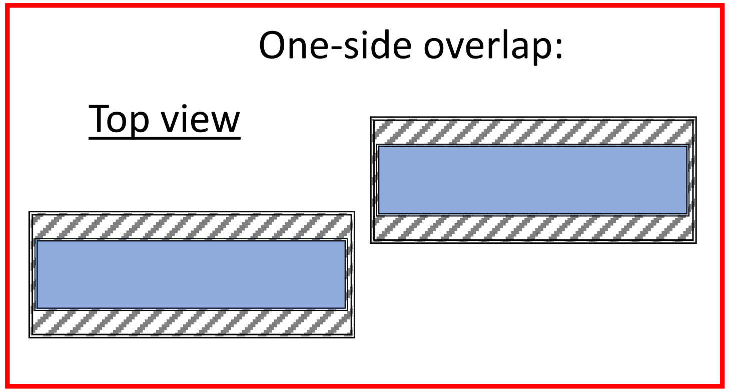
Staircase arrangement of rectangular moderators

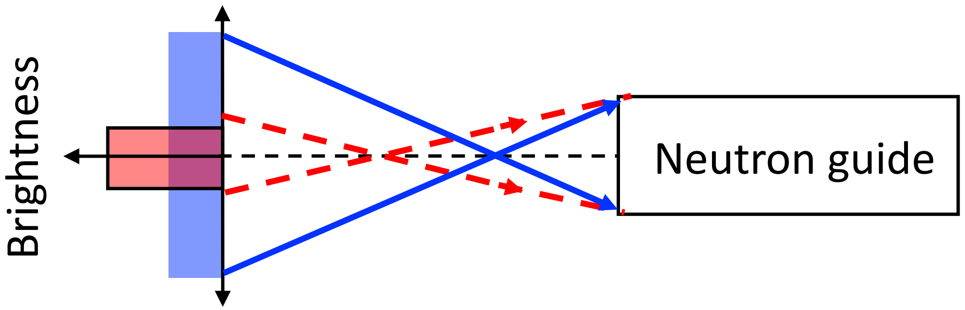




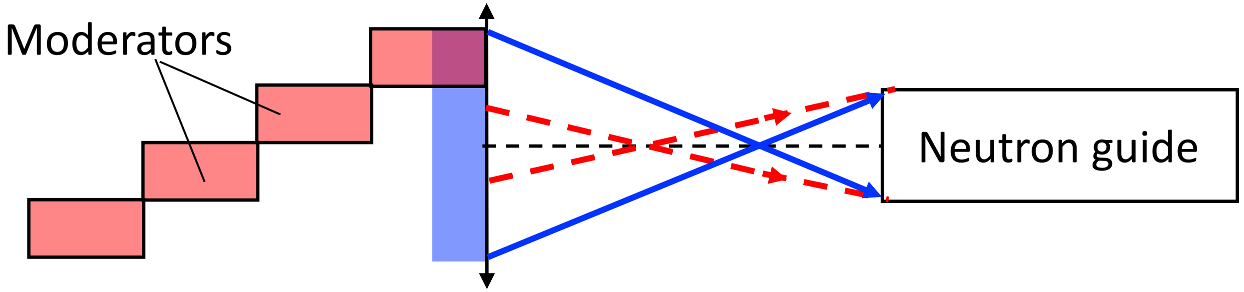


4x larger moderator surface and only slightly compromised illumination

Under-illumination



Full illumination



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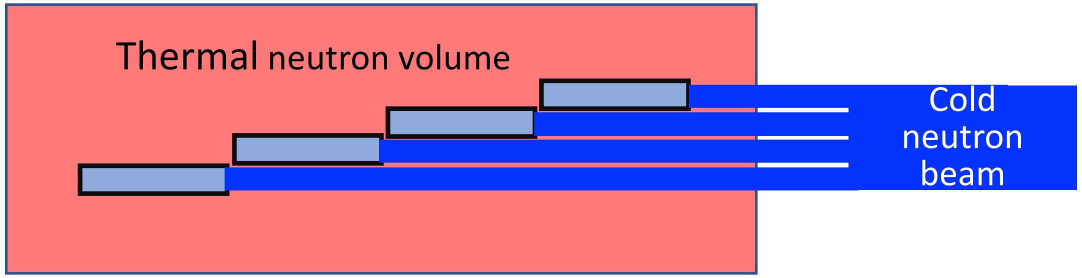
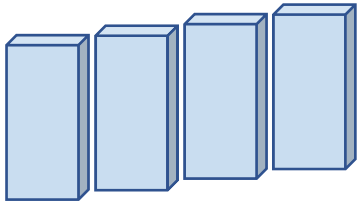
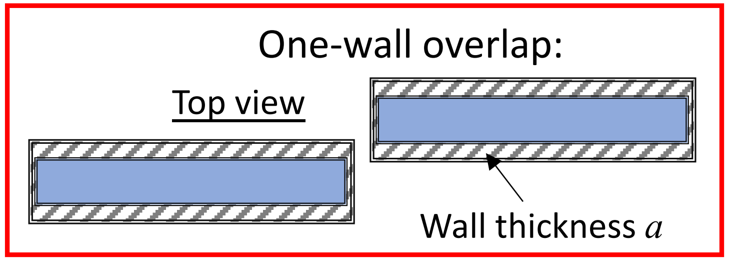
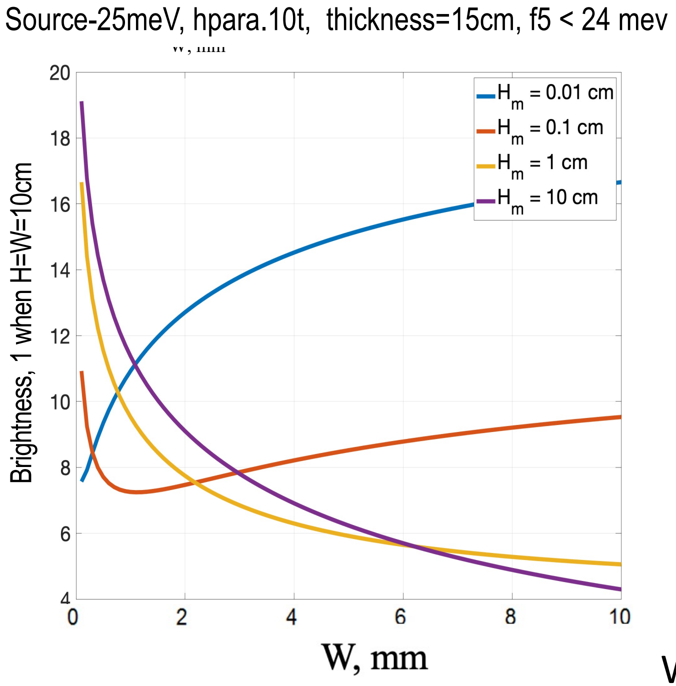
Staircase arrangement of rectangular moderators







Shadowed solid angle ≈ 2-3% of total => large moderator surface and small losses in thermal neutron illumination

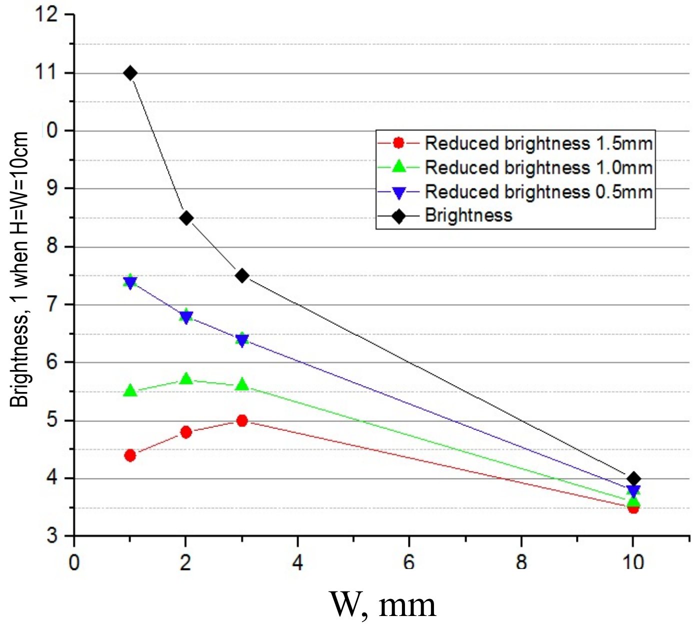


x

Losses caused by wall (thickness a)

W, mm	a, mm	g =W/(W+a)	B	B·g
1	1.5	0.4	8.5	3.4
2	1.5	0.57	6.5	3.7
3	1.5	0.67	5.5	3.7
1	1	0.5	8.5	4.2
2	1	0.67	6.5	4.4
3	1	0.75	5.5	4.1
1	0.5	0.67	8.5	5.7
2	0.5	0.8	6.5	5.2
3	0.5	0.85	5.5	4.7

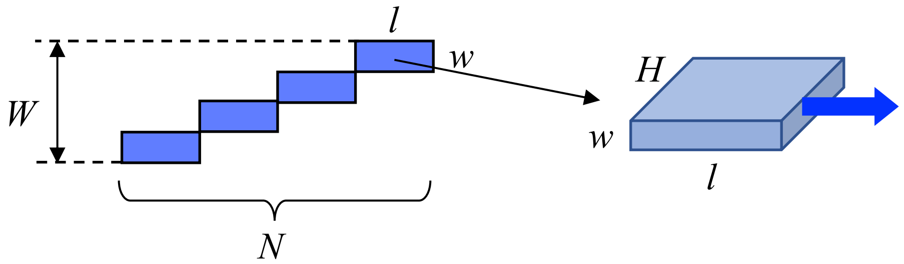
=

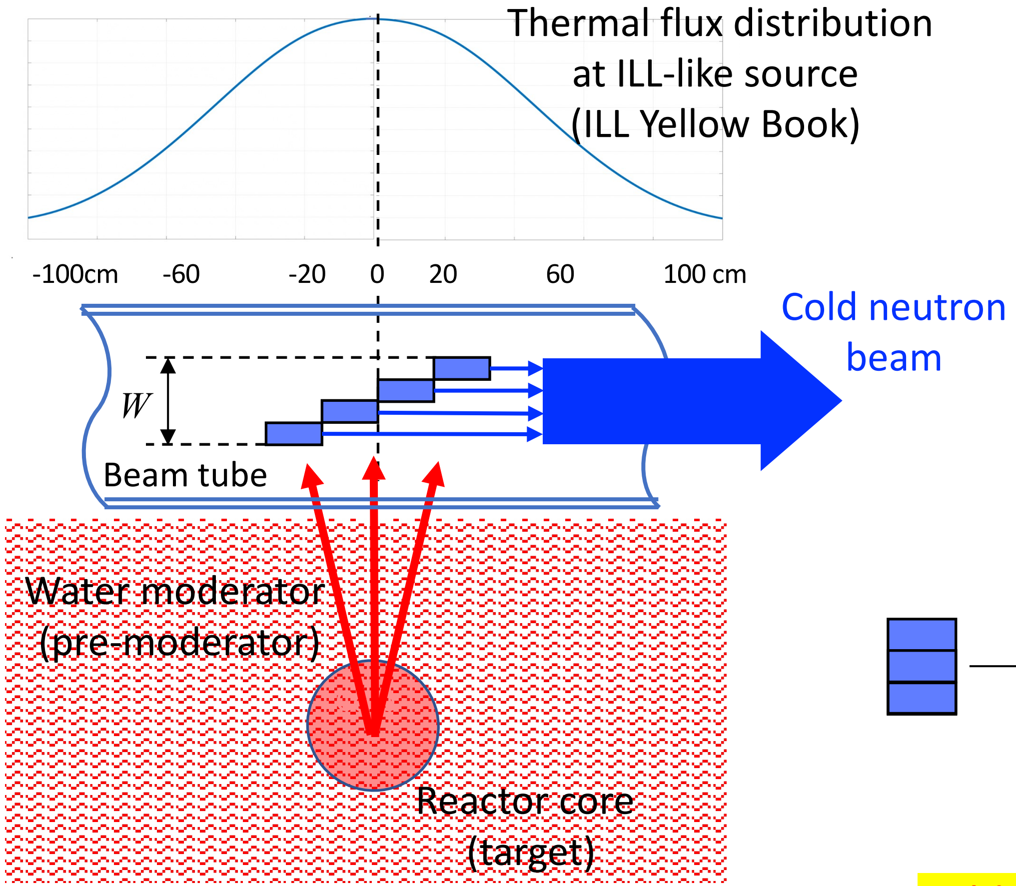


Wall thickness a is comparable to moderator width => reduction of achievable brightness

- Maximal gain for thin moderators of (1-3) mm
- Homogeneous illumination of all steps

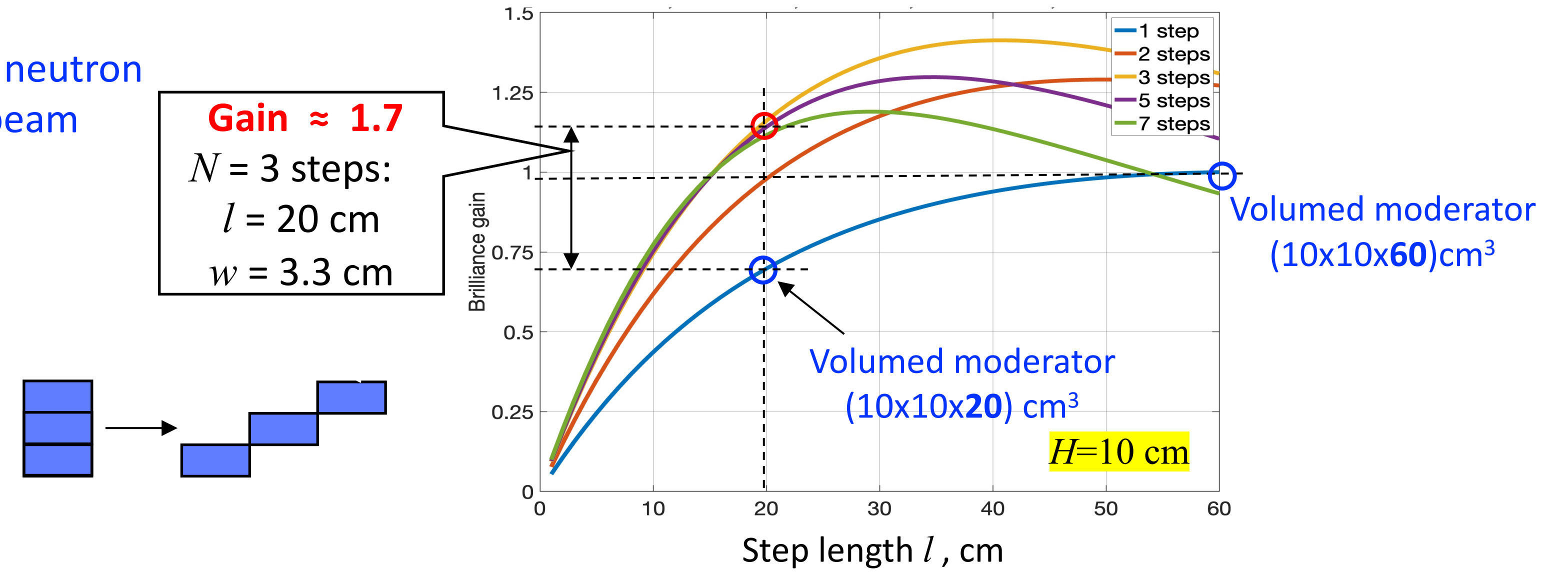
Staircase moderator in beam tube: 10cm beam





Reduction of flux along moderator
reduces potential brightness gain.

Beam width W=10 cm, moderator wall thickness d=1 mm

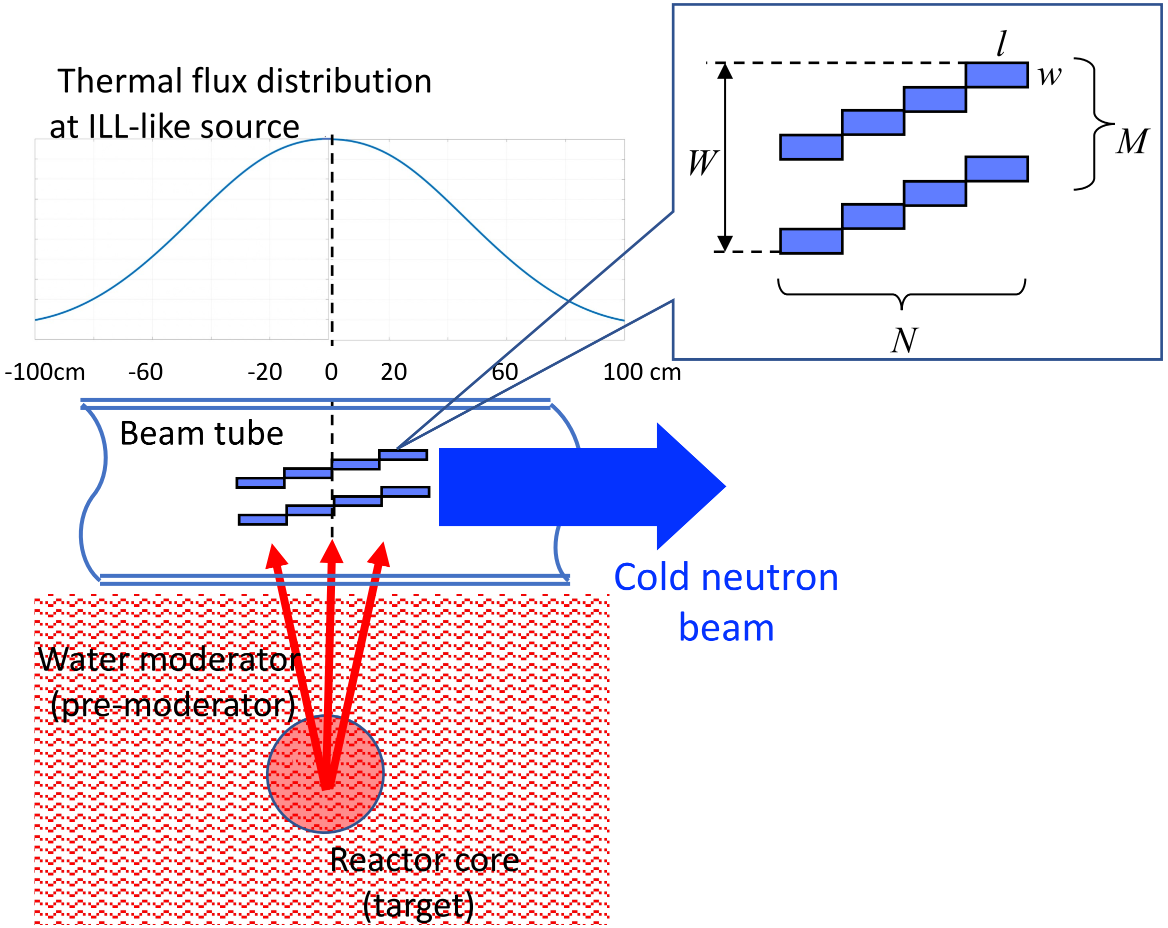


Cold neutrons with λ>2.6Å: gains 1.7 relative to 20cm long moderators.

MCNP simulations are in progress to take into
account shadowing effect: estimation ~3%.

Multiple staircase moderators in beam tube: 3 cm beam

- Reduction of flux along moderator reduces potential gain
- Staircase moderators of smaller total length are preferable
  - ⇒ **Multiple staircases**



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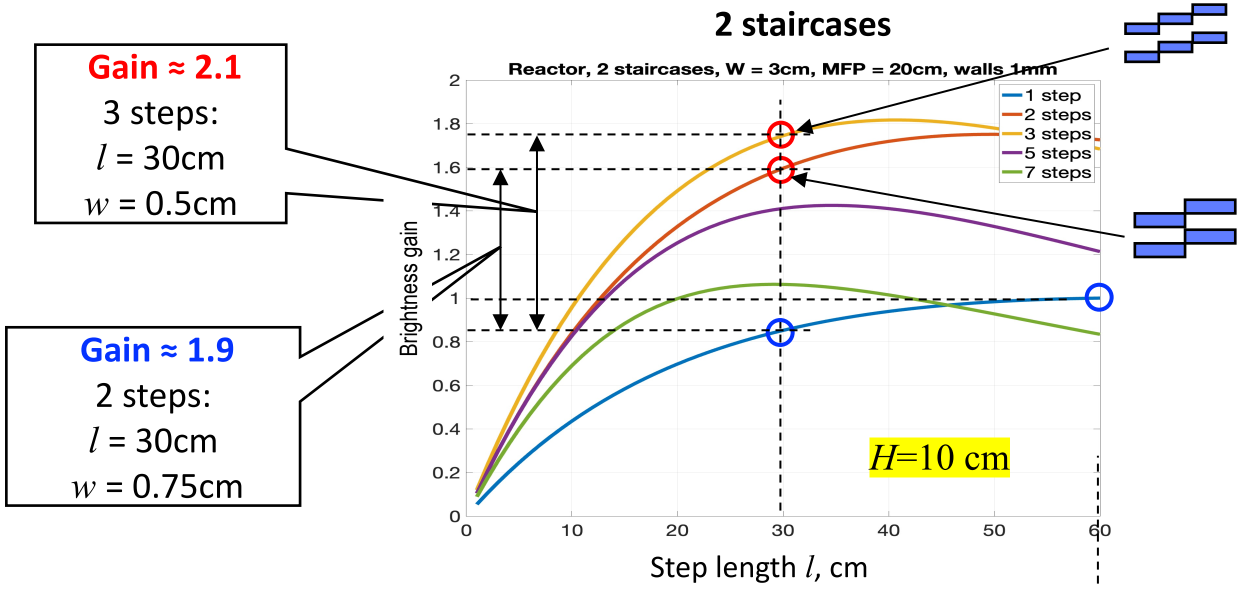

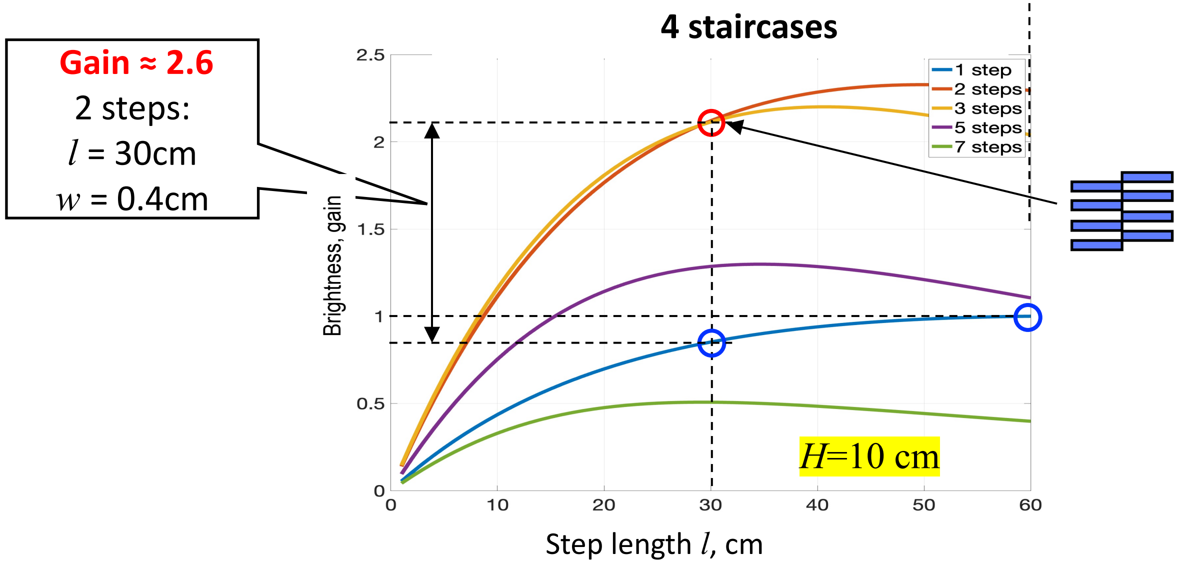

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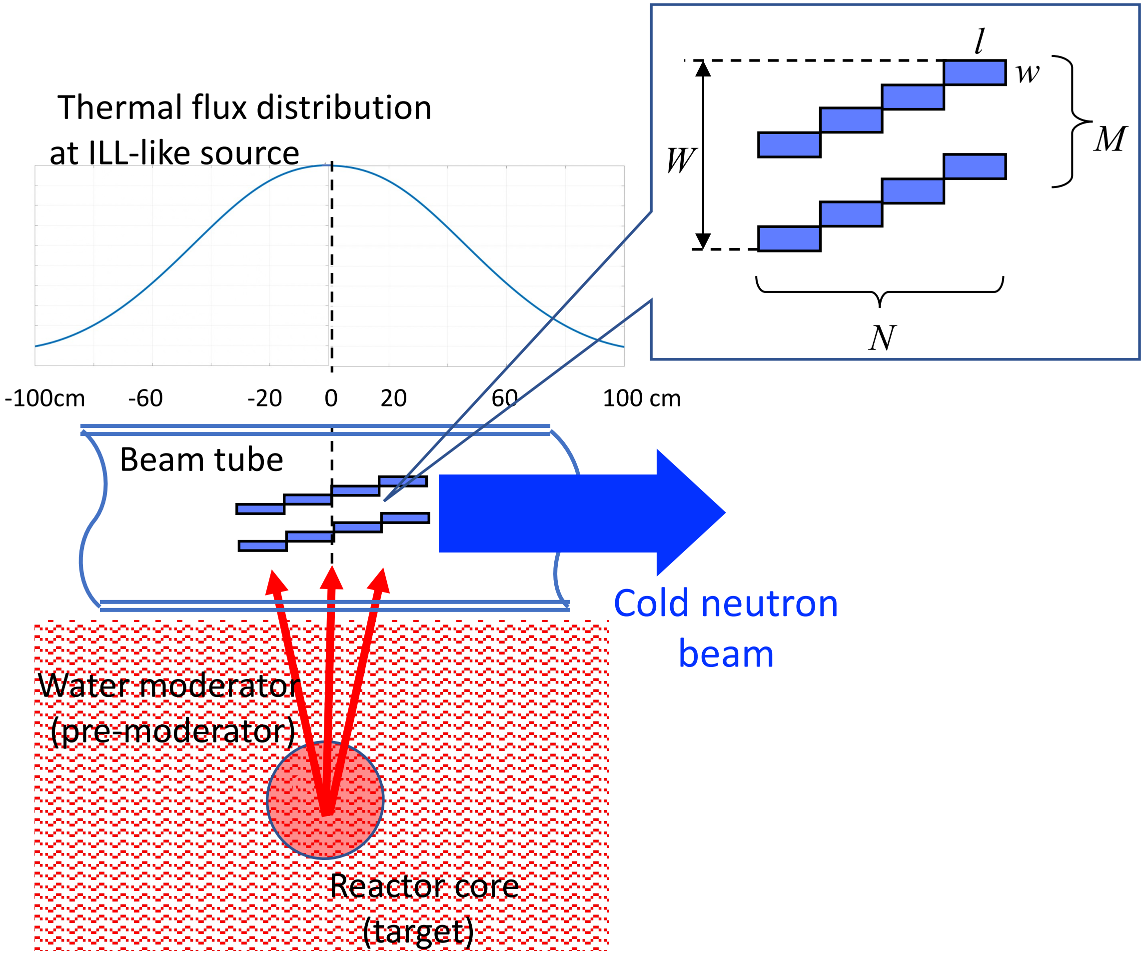

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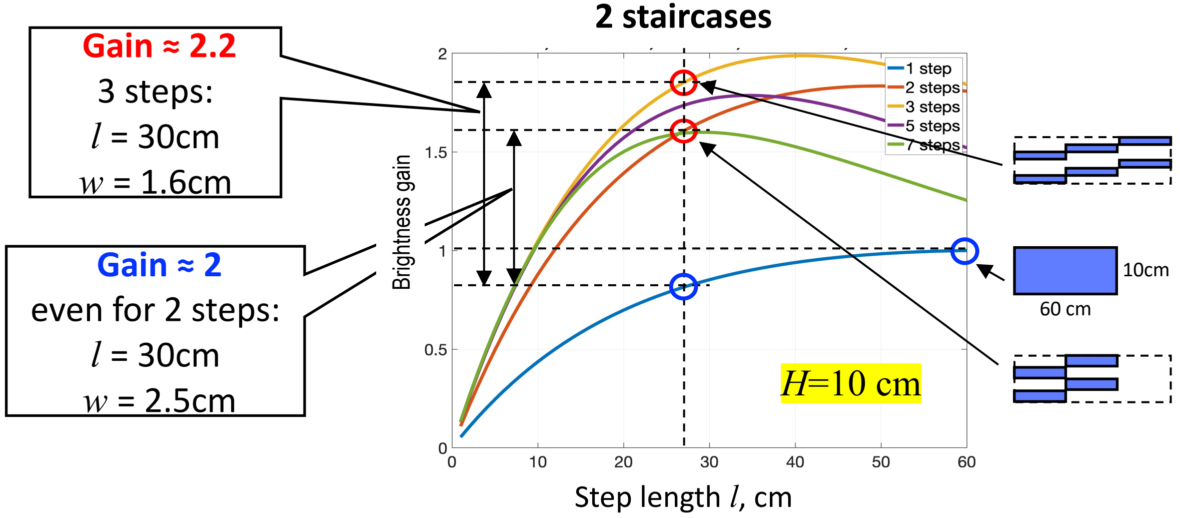
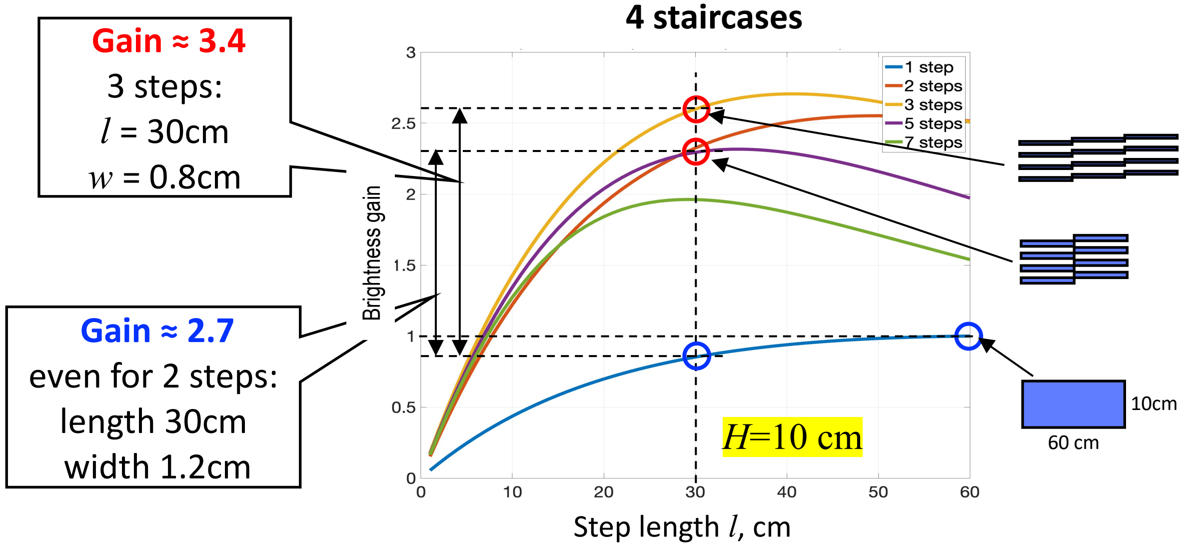
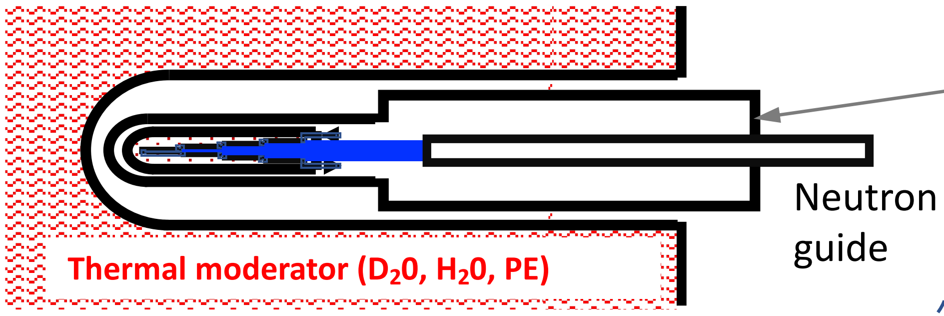
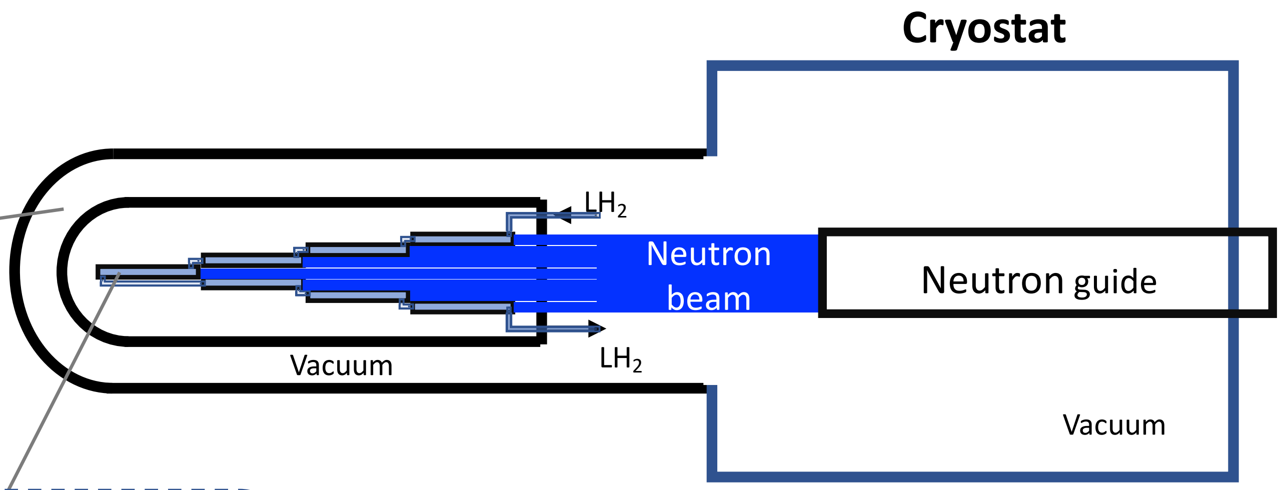




Staircase moderators: realization

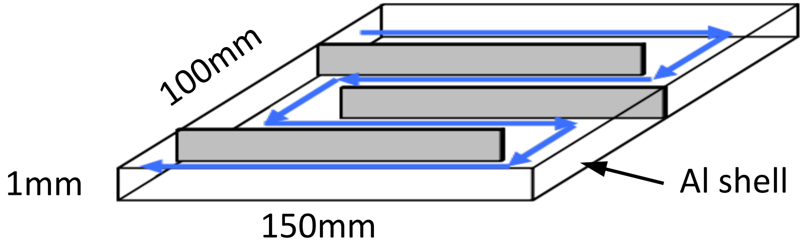
Beam tube in a neutron source

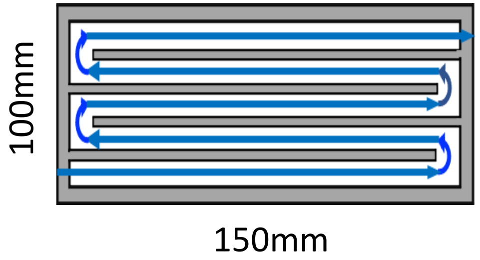




Single cold moderator

Can be made of a single Al piece: inner walls connect large surfaces and direct LH_2 flow





Y.Bessler (FZJ)

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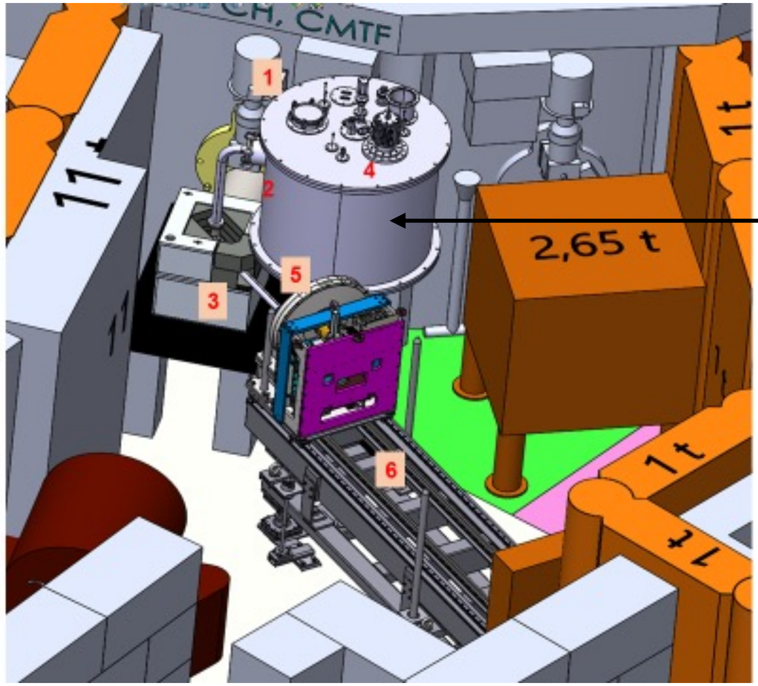
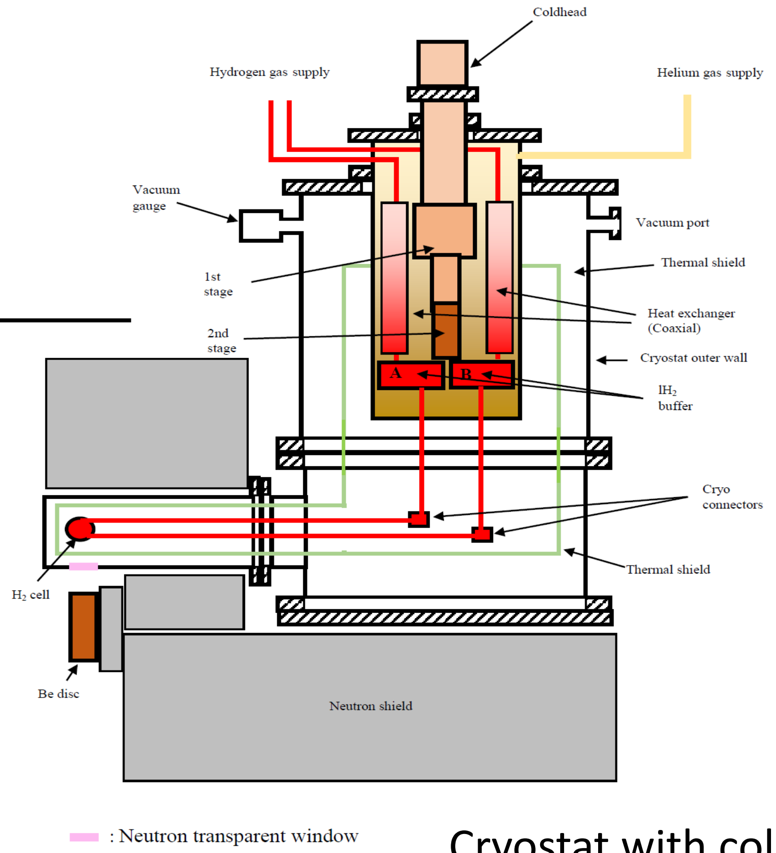
Plan for the next year:

- manufacturing of the moderator in FZJ
- test measurements at dedicated test facility at BNC using the pin-hole camera device (6) (details in the talk of L.Rosta)



Test facility at BNC



Cryostat with cold moderator

Now we know how to increase moderator brilliance when its total size is fixed.

Actually, such multiple-moderator assembly can be of any desirable total size.

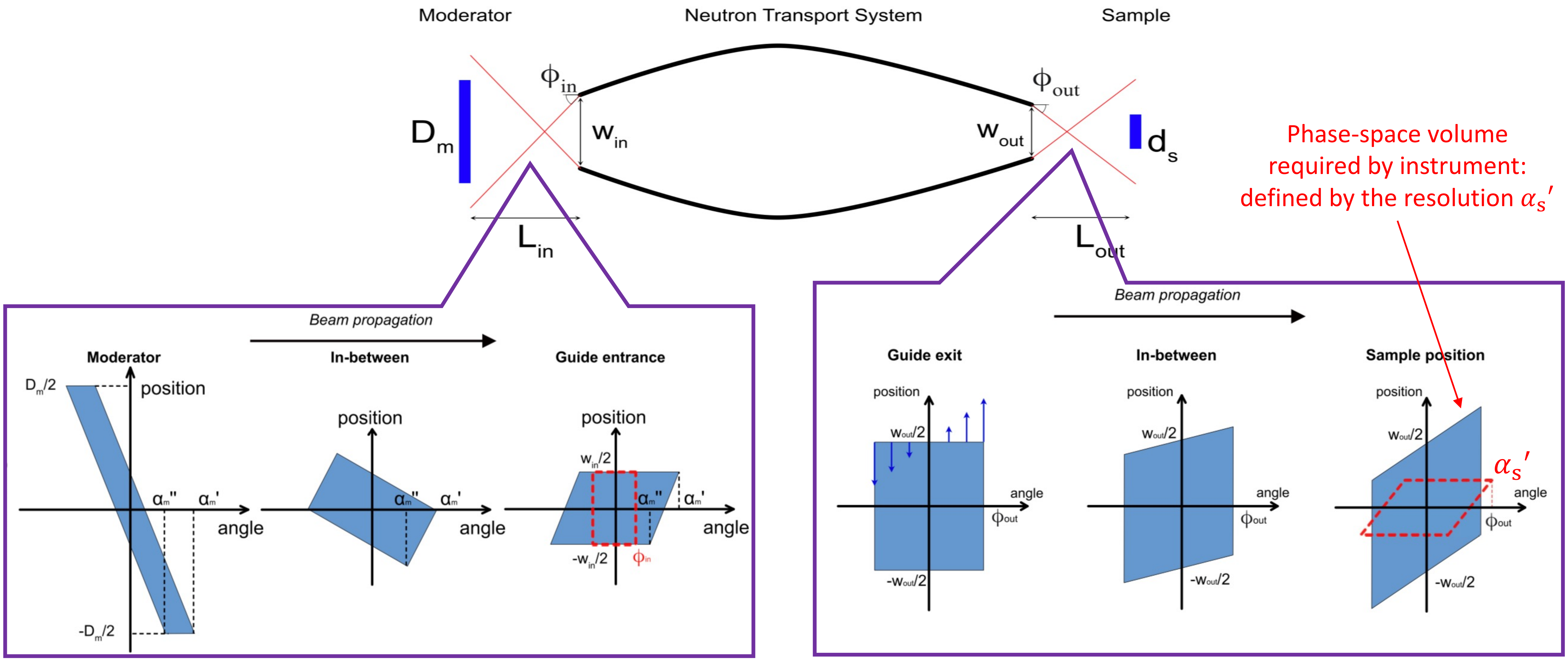
=> What is the right combination of moderator and guide entrnace sizes?

To answer this question we developed a new optimization method to determine the optimal neutron moderator size based on instrument parameters.

Simple and fast analytic method to find out optimal combinations of sizes of neutron moderator and optical system entrance, which allow for the full sample illumination with minimum to none background.

P. Konik, A. Ioffe, https://arxiv.org/abs/2302.00581

General layout of neutron instrument



Phase-space approach: each point corresponds to the unique state of the system - single neutron trajectory in neutron beam

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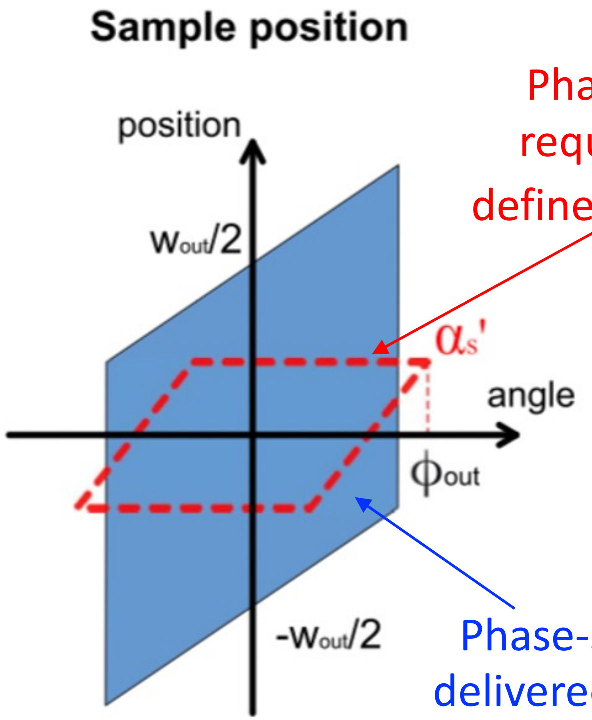


Phase-space volume V_S required by instrument: defined by the resolution $\alpha_s{}'$

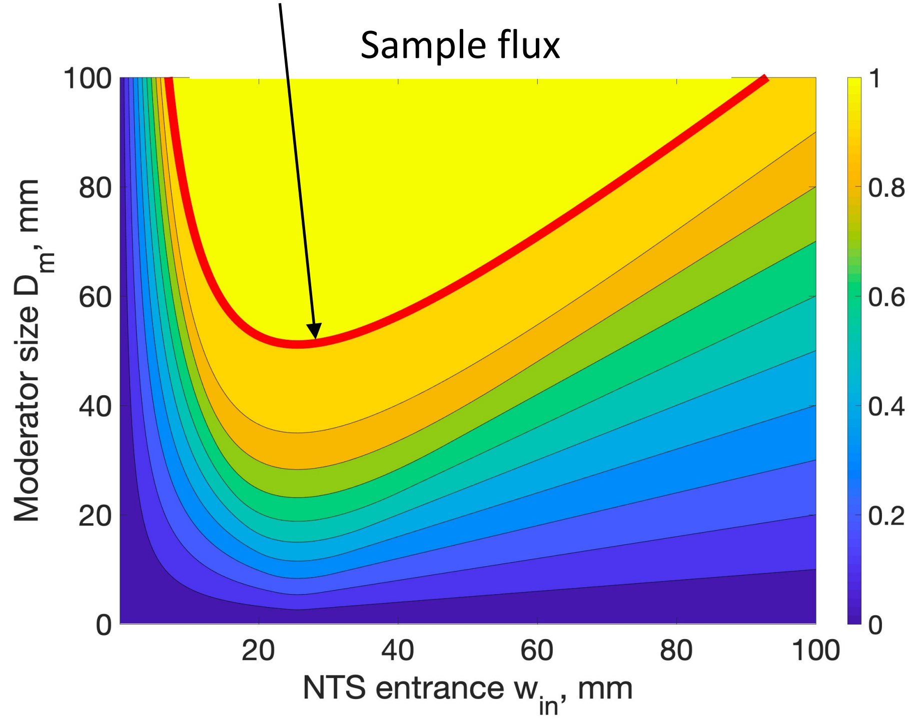
Phase-space volume V_{NG} delivered by neutron guide

Optimal instrument performance is reached when:

- V_S is fully inscribed in V_{NG},
- the excess volume (V_{NG} - V_S) is minimal

$$D_{opt}(w_{in}) = \frac{2L_{in}\alpha_s(2L_{out}\alpha_s - d_s)}{w_{in}} + w_{in}$$

- Curve of Optimal and Full Sample Illumination (COFSI)

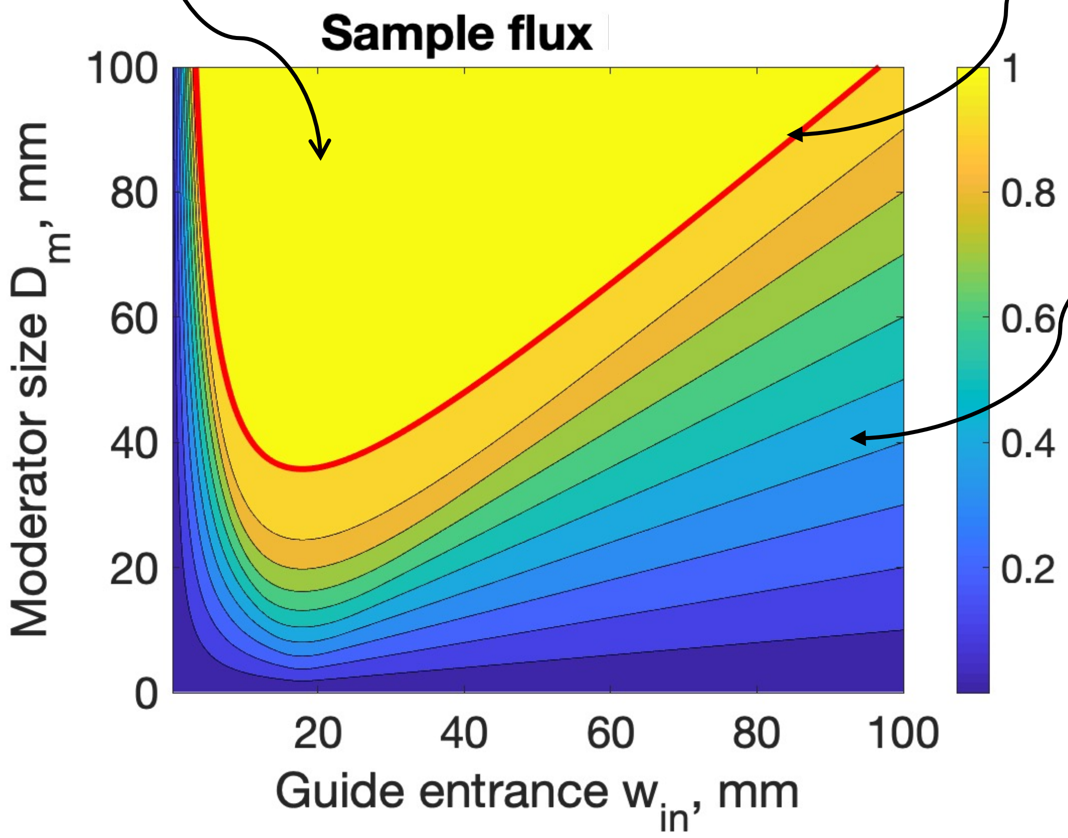


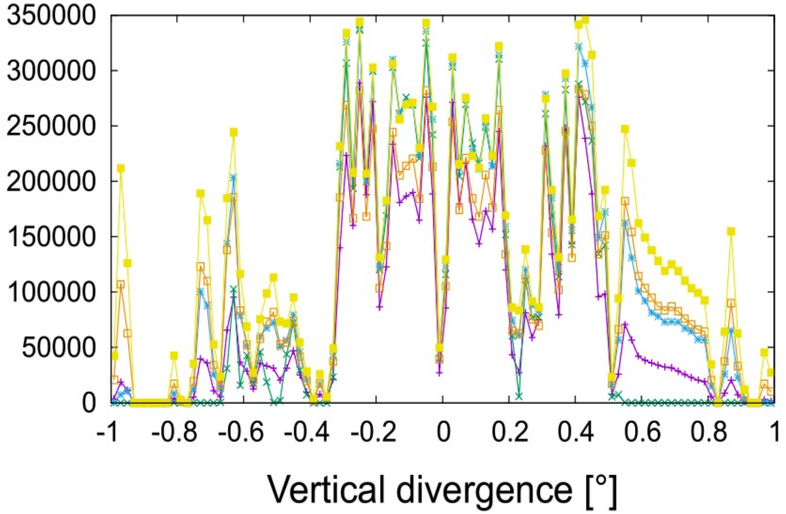
What happens when one deviates from COFSI?

- Moderator over-illuminates guide entrance
- Excessive neutrons are absorbed along the guide

COFSI:
- sample is fully illuminated.
- minimal number of useless neutrons at sample

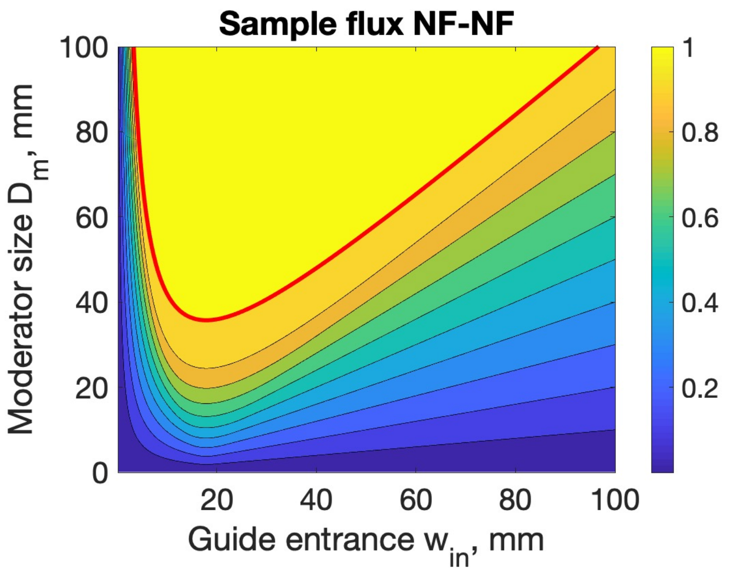
- Moderator under-illuminates guide entrance
- Useful sample flux reduced
- “Gothic-like structure” of divergence



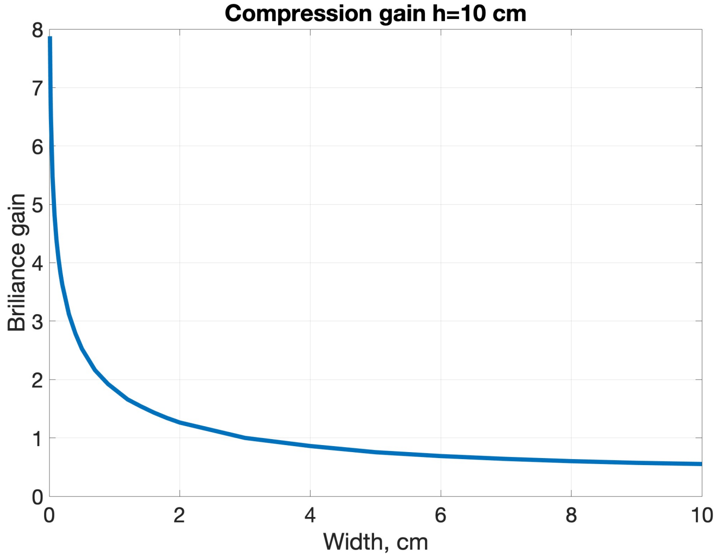


Illumination with low-dimensional para-H_2 moderator

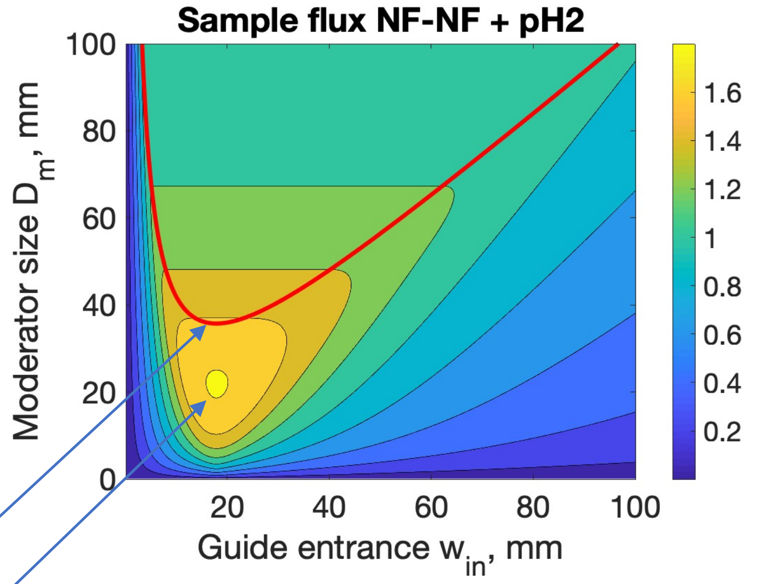
Size-independent brilliance



Size dependence for pH_2 flat moderator



Size-dependent brilliance



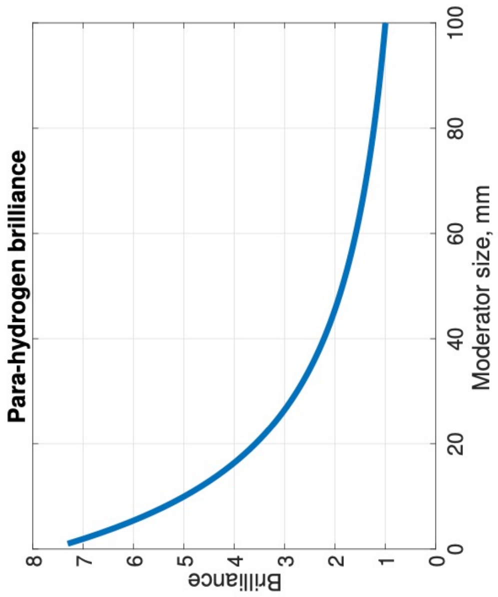
High flux + ideal sample illumination

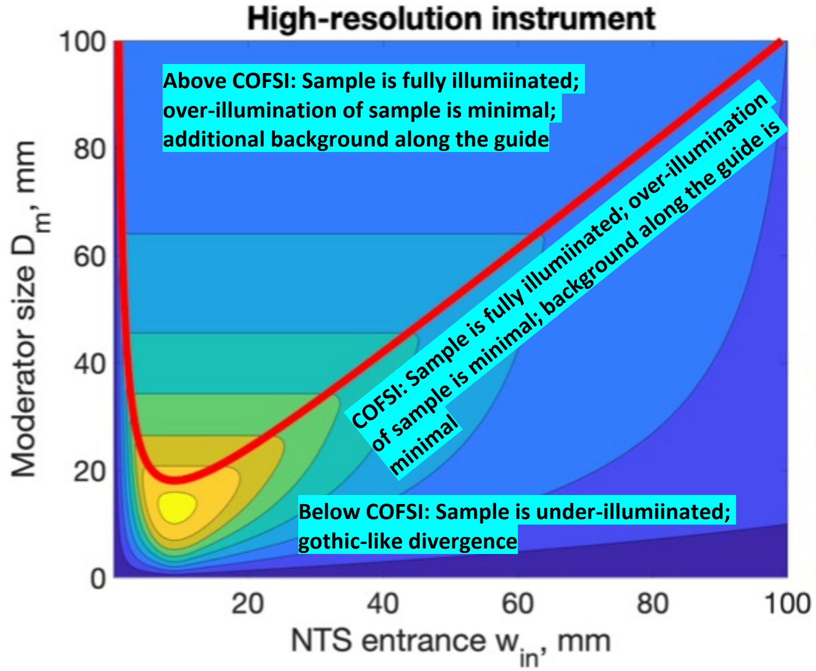
Higher flux + “gothic” divergence profile

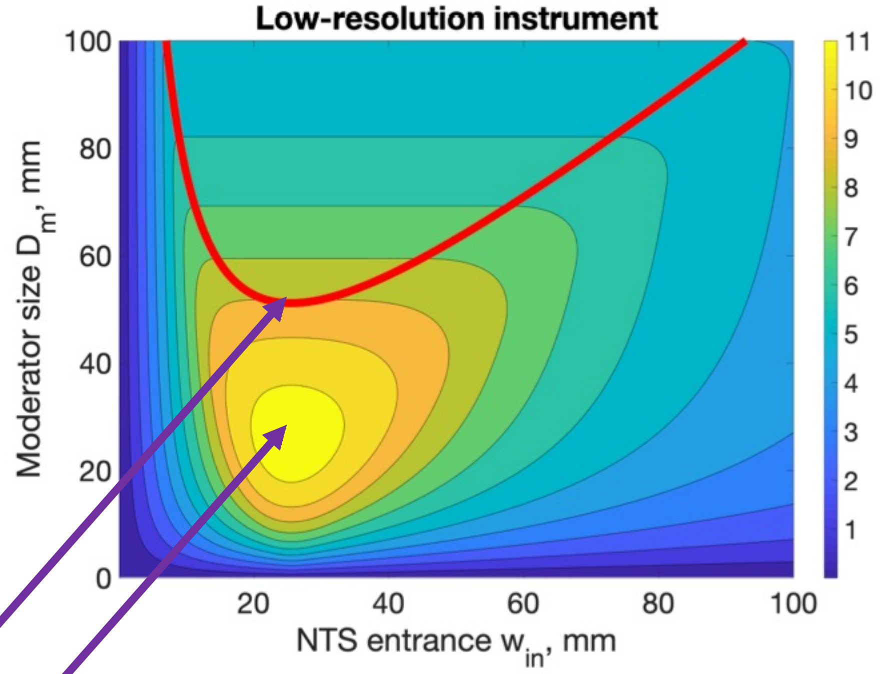
This is a recipe how to find the optimal combination of moderator size and neutron guide size.

One moderator serving two instruments

(flux scales are different!)







	HR instrument	LR instrument
Optimally and fully illuminated sample	$D_{opt} = 18$ mm $\Phi_s = 3.8$	$D_{opt} = 51$ mm $\Phi_s = 9$
Under-illuminated sample; maximal sample flux	$D_{opt} = 13$ mm $\Phi_s = 4.1$	$D_{opt} = 25$ mm $\Phi_s = 11.5$

Best solution is close to D_{opt}=18 mm:

- HR instrument reaches best performance
- LR instrument gets very high (not maximum) flux
- LR instrument sample under-illumination does not compromise its operation

Conclusions

Staircase moderator geometry

Choice of the moderator size
(not compromising on brightness and intensity)

Combination of moderator-neutron guide sizes
for optimal and full sample illumination

Choice of neutron guide size
for the given moderator

Manufacturing high-brilliance cold moderator of optimal size
for existing neutron guides with brightness gain of about (2-3)

Thank you for attention!