EUROPEAN
SPALLATION
SOURCE

Beam extraction and delivery at compact neutron sources

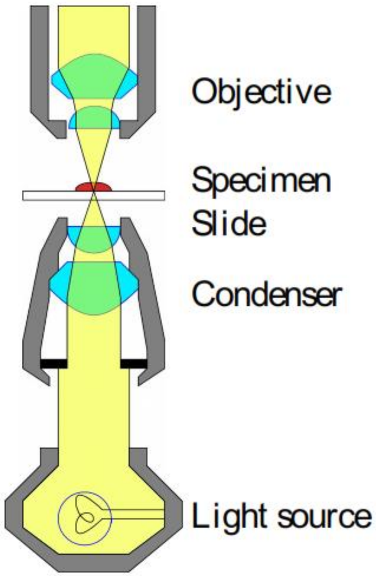
F. Mezei
Technical coordinator

www.europeanspallationsource.se
2014 October 21

Beam delivery

Delivering illumination for beam scattering studies

Microscope (XVI. c.):
(divergence **dΩ** prescribed)



$\Phi = \phi(r,\vartheta,\varphi,\lambda)\, d\Omega\, d\lambda$

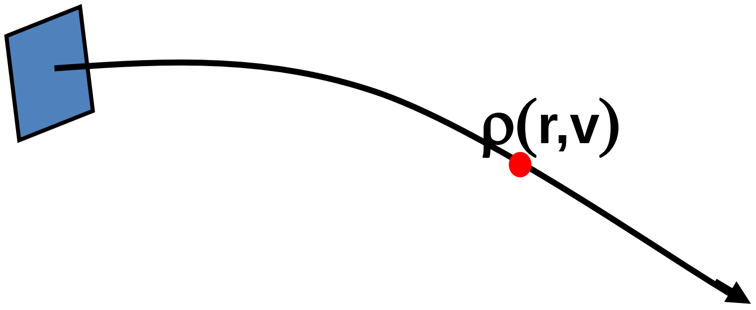
Brightness ϕ is a constant
of motion along trajectories
(if no beam loss, e.g. absorption)


J. Liouville

Liouville theorem and the brightness

Flux is governed by Liouville theorem:

Phase space density ρ is constant along particle trajectories in conservative force fields



No. of particles hitting in time dt a surface perpendicular to trajectory (local z axis):

$N = dx\, dy\, dz\, dv_x dv_y dv_z =$

$= \rho\, dx\, dy\, vdt\, v\alpha_x\, v\alpha_y\, v^2 d\lambda\, m/h \propto$

$\propto \phi(\lambda)\, dt\, dF\, d\Omega\, d\lambda$

where the **brightness**

$\phi(\lambda) = \rho\, mv^5/h$ **is a constant** if the neutron velocity is preserved (i.e. little acceleration)

Note: for Maxwellian tail ρ is independent of v.

Absolute flux determination:

at any point along the beam

$$\phi(\lambda) = \eta\, \phi(\lambda)_{source}$$

(absorption) loss factor ≤ 1

Practical Liouville theorem

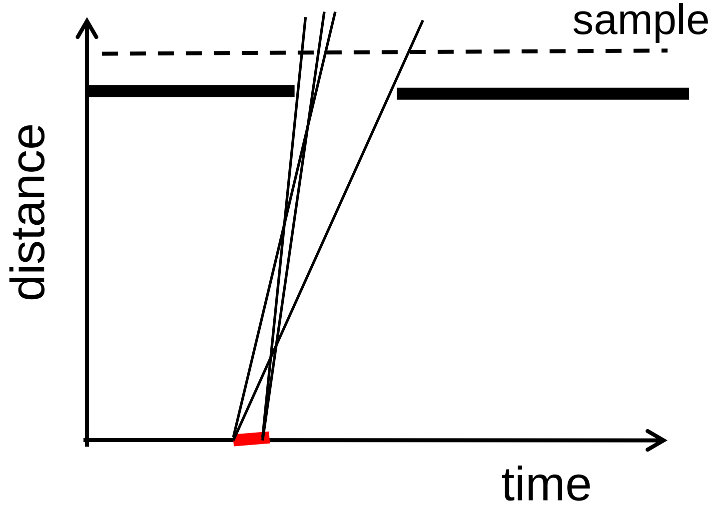
Neutrons on sample: $\mathbf{N = \eta\phi(\lambda)\ dt\ dF\ d\Omega\ d\lambda}$

↑

Source brightness (n/s/cm²/str/Å)

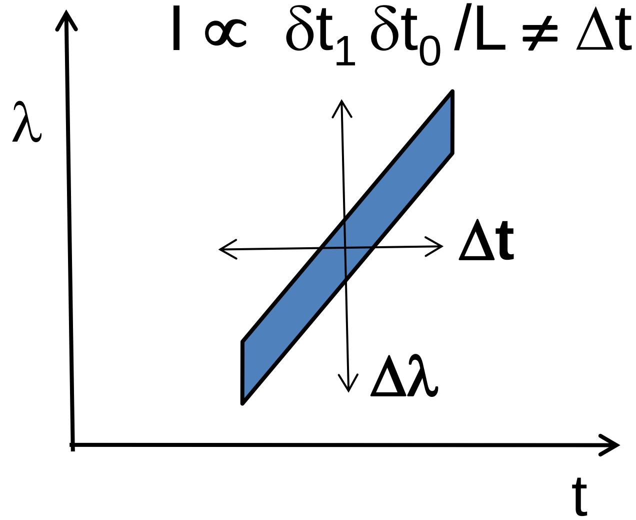
Example: TOF monochromator

TOF diagram



Phase space diagram

$I \propto \delta t_1\, \delta t_0 / L \neq \Delta t\ \Delta\lambda m/h$



Practical Liouville theorem

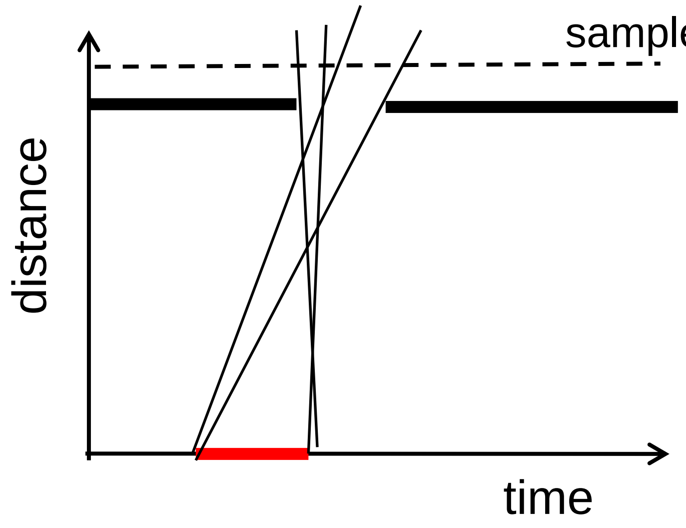
Neutrons on sample: $\mathbf{N = \eta\phi(\lambda)\ dt\ dF\ d\Omega\ d\lambda}$

↑

Source brightness (n/s/cm^2/str/Å)

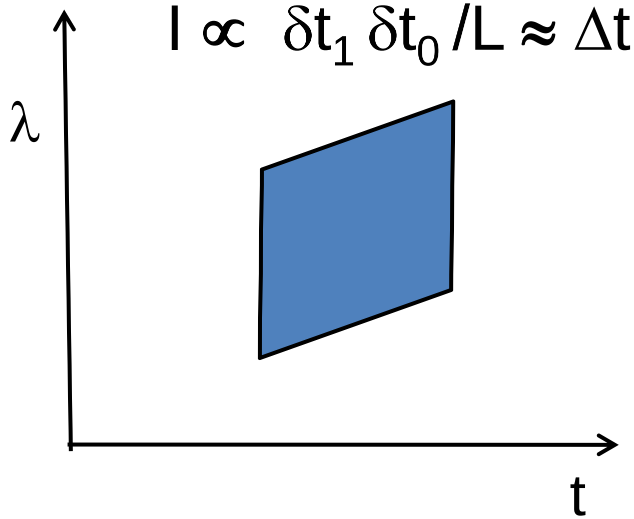
Example: TOF monochromator

TOF diagram



Phase space diagram

$I \propto \delta t_1\, \delta t_0 / L \approx \Delta t\, \Delta\lambda m/h$



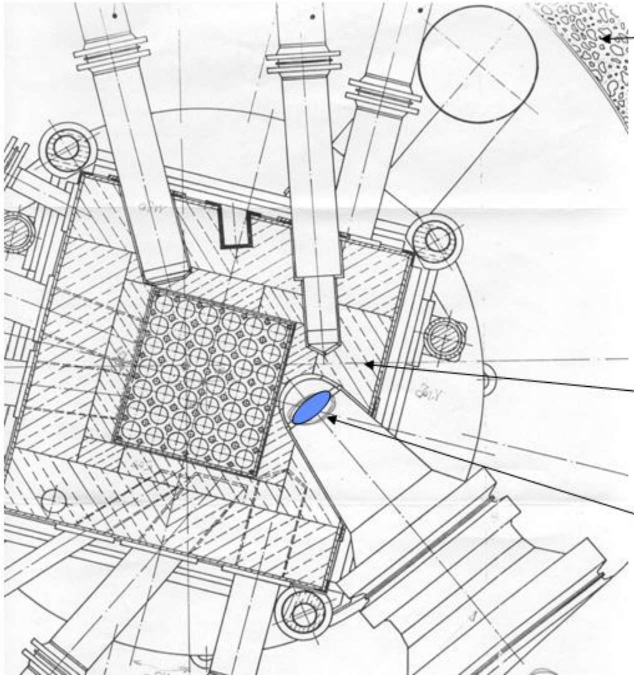
Beam delivery: direct view

Early reactors, spallation sources:
direct view of:

- **of reflector or**
- **of moderator / cold source**

$$\Phi_{sample} \propto \eta\phi_{mod}\, d\Omega_{sample}$$

$$= \eta\phi_{mod}\, F_{mod}/d^2$$



Shielding: ø 10 - 12 m

Example of a fission reactor (HMI)

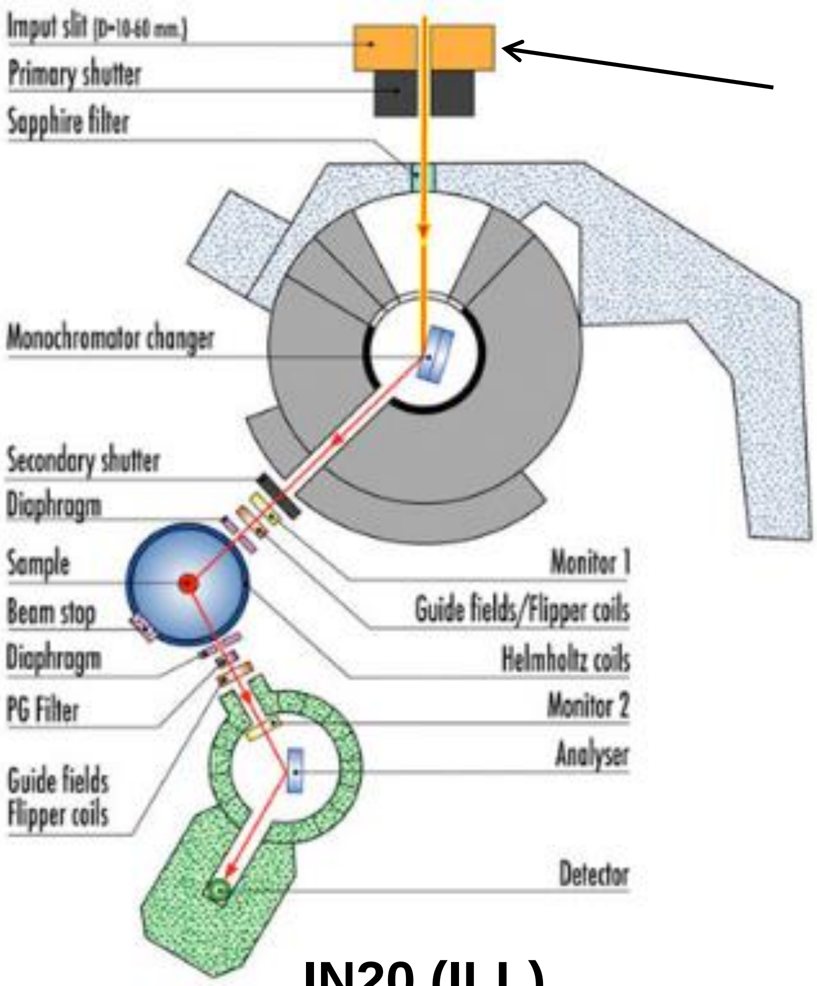
Thermal neutron source (Be reflector)

Cold neutron source (liquid H_2 bottle)

Figure of merit (for large enough d) : **brightness ∗ surface**

Moderator / beam tube sizes: 12 – 35 cm, “the bigger the better”

Beam delivery including optics



IN20 (ILL)

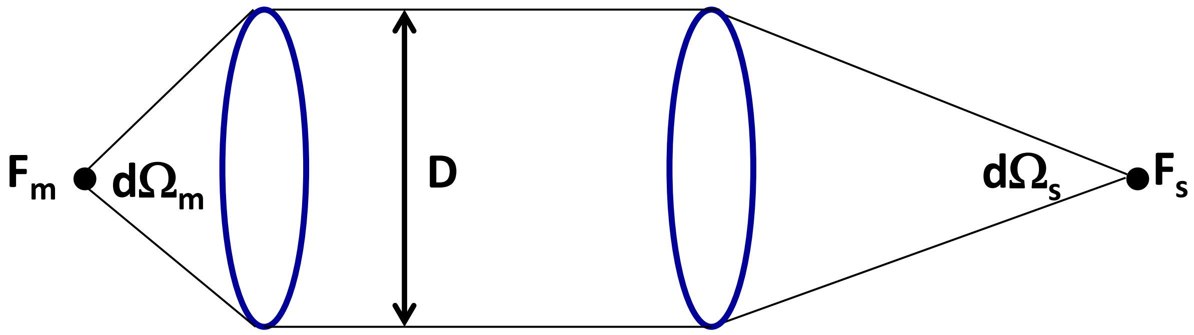
"Virtual source"
for focusing monochromator

→ minimizes extracted neutrons
to reduce background:
not bigger than needed

dΩ ~ determined by focusing
Xtal monochromator

Figure of merit: brightness
(above a minimum size)

Beam delivery including optics



Available neutrons ("phase space")

Neutrons available: $\phi F_m d\Omega_m$ On sample: $\eta\phi F_s d\Omega_s$, $\eta < 1$

$F_m d\Omega_m$ **should be >** $F_s d\Omega_s$

Beam losses:

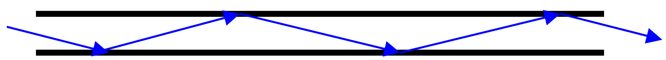
- < 100 % reflectivity of (super)mirrors, crystals
- impact angle above the (super)mirror cut-off angle
- gaps in the guide
- absorption in air, windows, imaging errors,…

……

Beam delivery by neutron guides

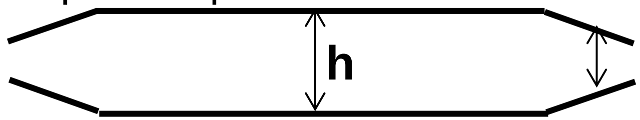
Neutron guide: $d\Omega$ is limited, but ~ independent of distance,

Beam losses by many reflections: can be reduced by guide shape (ballistic, elliptic,…)



$d\Omega \propto 1/h$:

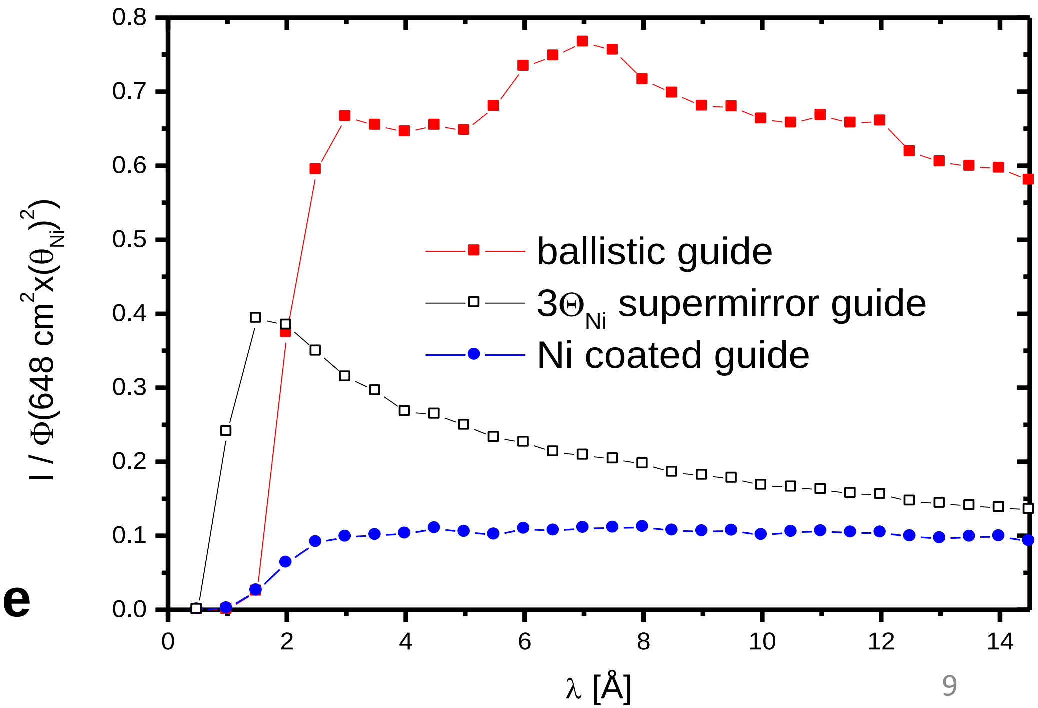
phase space transformation



Guide dimensions:

- **comparable to samples**
- **η > 0.5 commonly achievable**

$\Phi_{sample} \sim \phi_{mod}\, d\Omega_{sample}$



Bi-spectral beam extraction

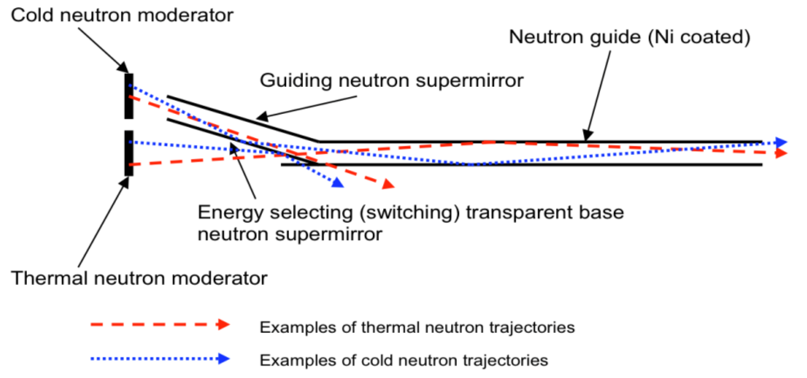
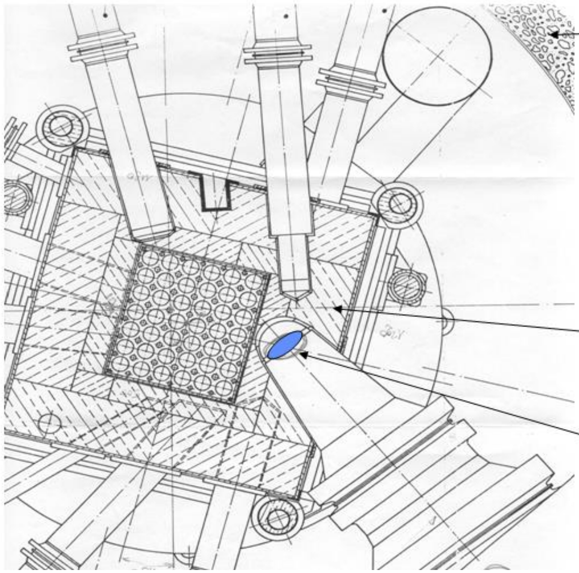


Fig.1. Example of realization of multi-spectral beam extraction



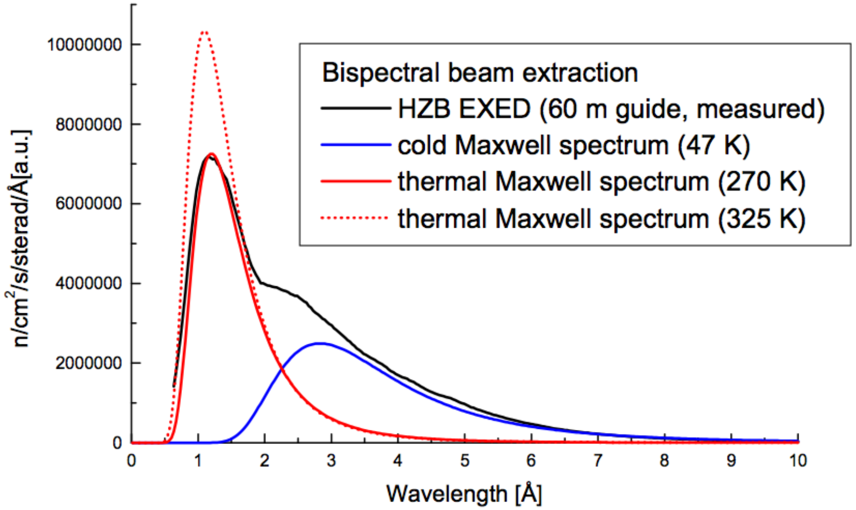
Shielding: ø 10 12 m

Example of a fission reactor (HMI)

Thermal neutron source (B reflector)

Cold neutron source (liquid H_2 bottle)

Combination of cold and thermal neutron spectra in one guide: experimentally established



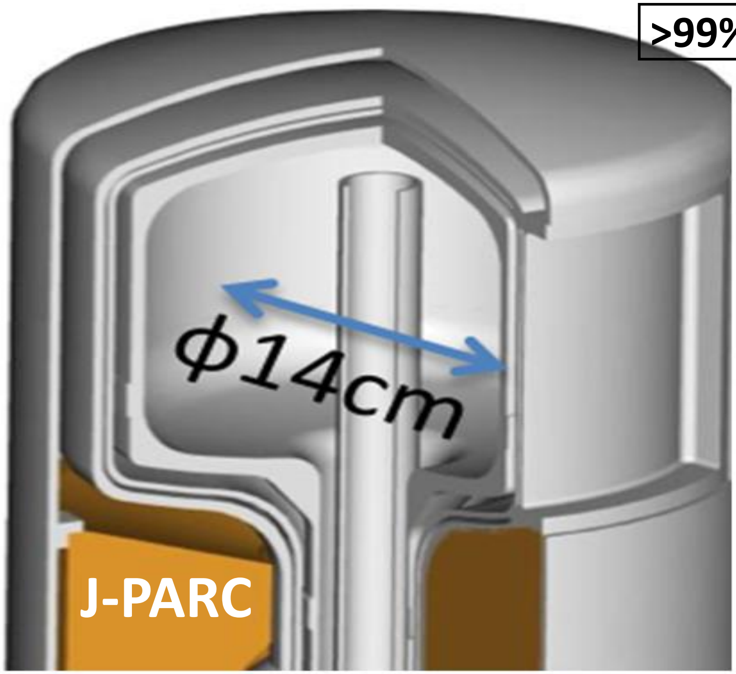
Measured and calculations for comparison

Recent best practice / developments at spallation sources

Conventional "box" moderators: 2 – 6 cm thick, ~12x12 cm^2 area

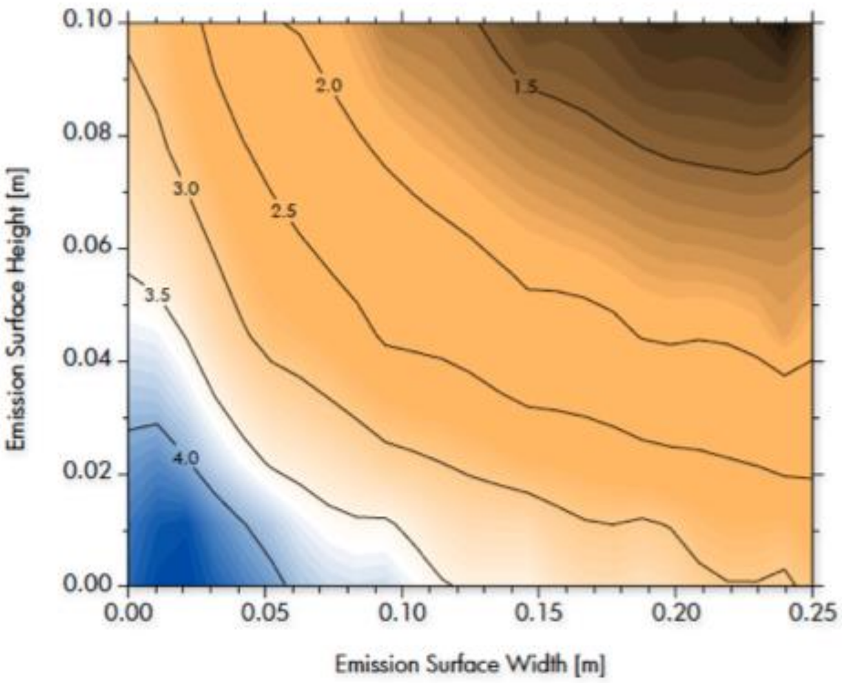
→ Re-entrant / grooved moderators: flux higher in depth

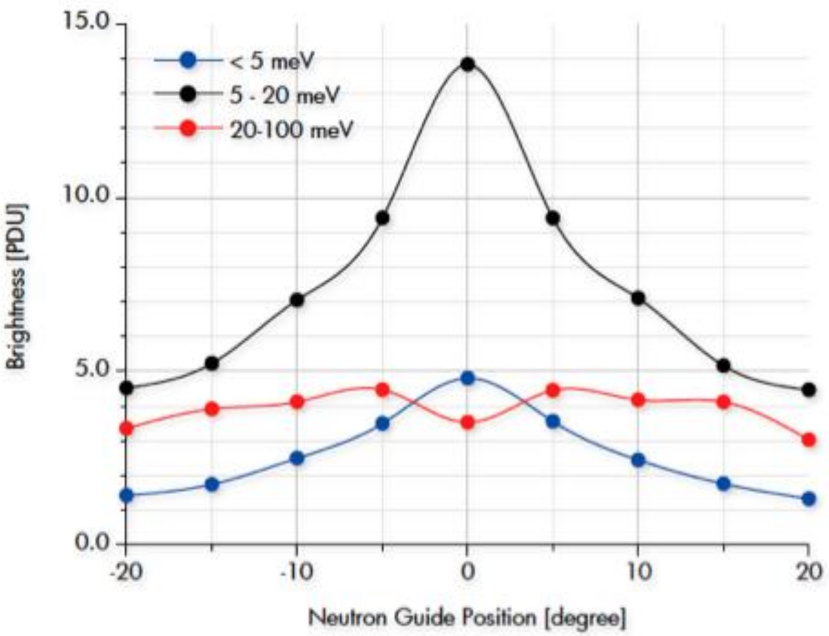
→ Volume moderators: para-H_2 ($\phi \sim 15$ cm), liquid D_2 ($\phi \sim 30$ cm)



ESS: scheduled target optimization beyond best practice: 2013 - fall 2014

Low dimensional para-H_2 moderator for reactors

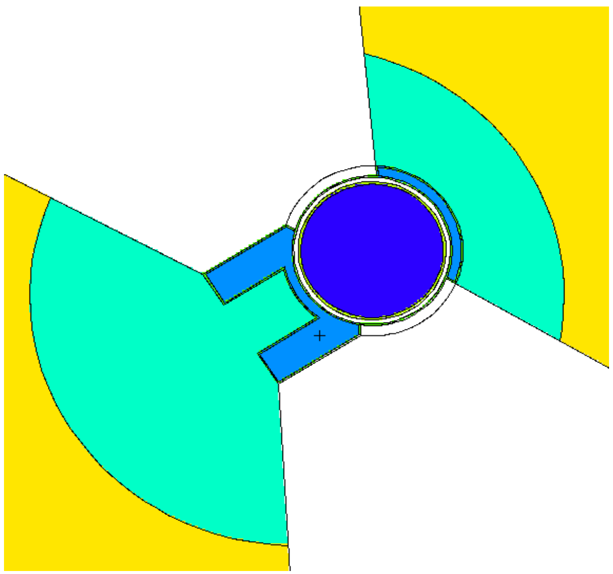


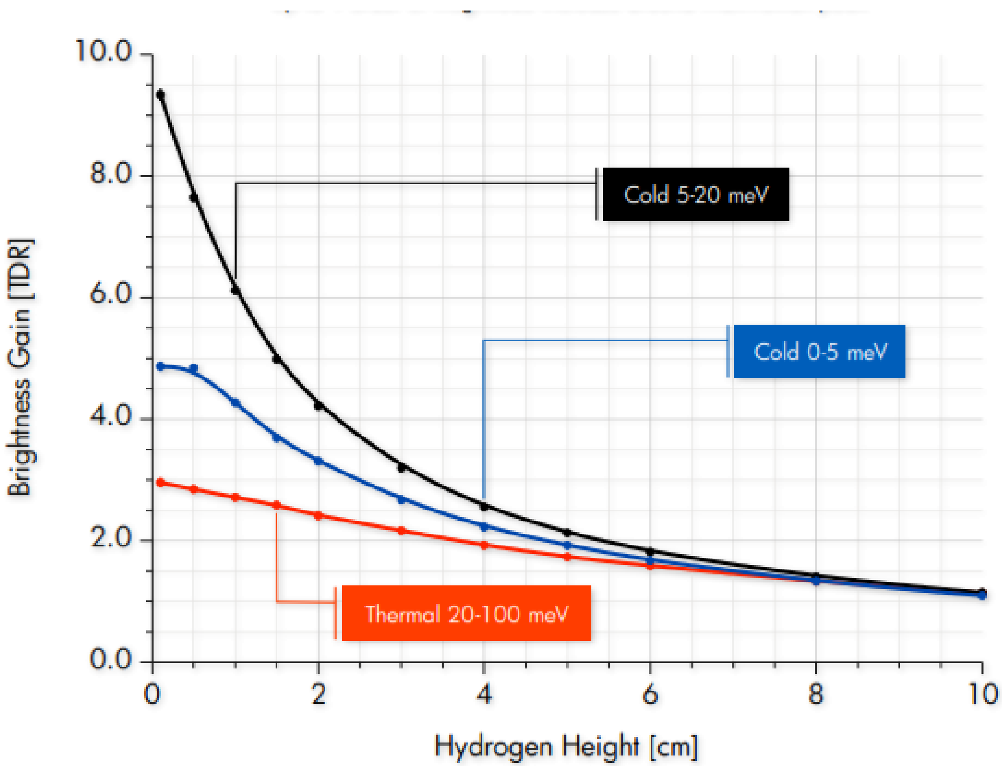


Low-D xyz moderator brightness
(z = 15 cm)

Directionality of 1.5 cm x 1.5 cm tube moderator:
- slow neutron creation still isotropic

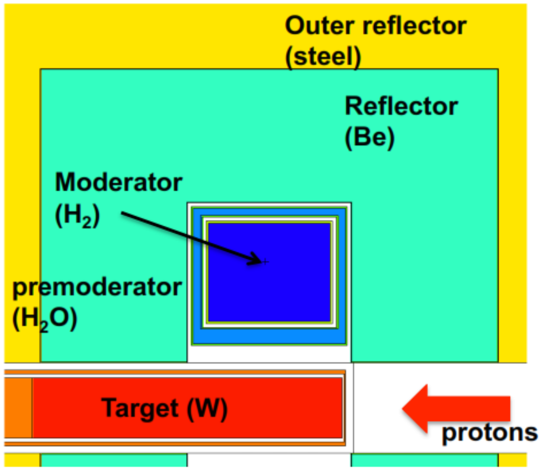
Perturbed flux increase vs. wavelength

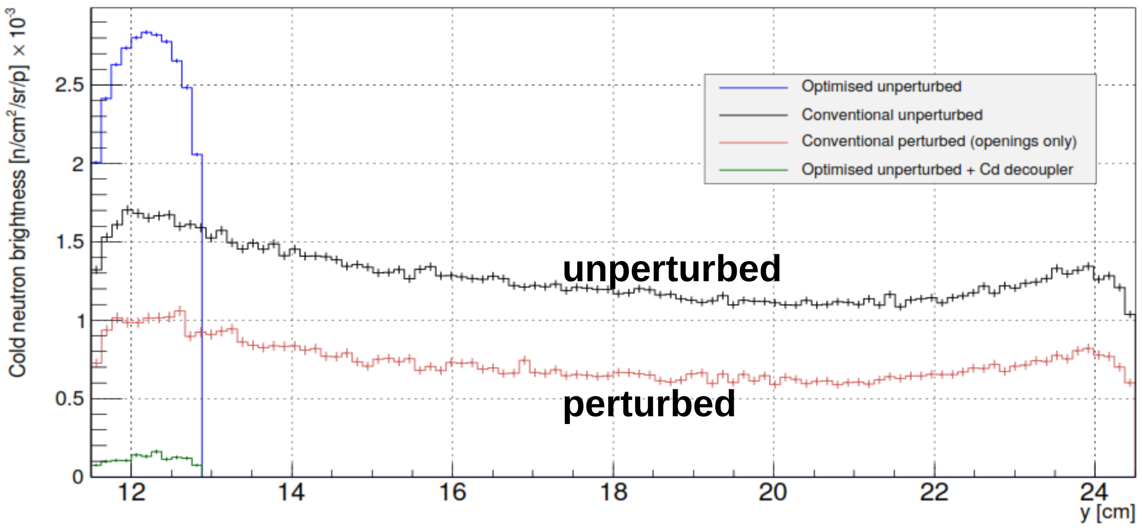


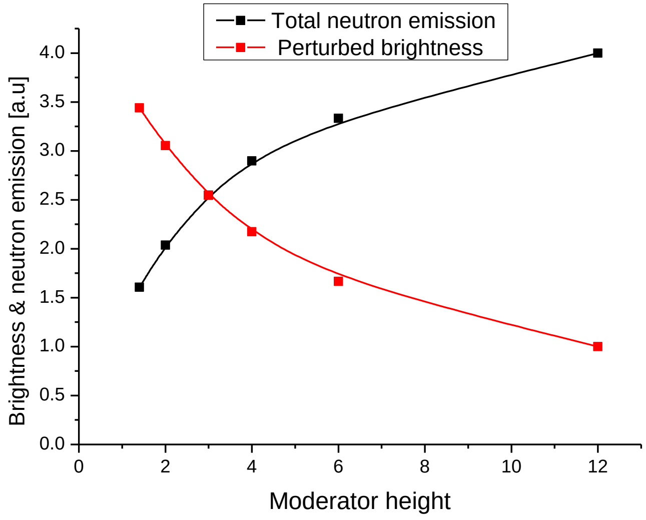


Thermal flux: also enhanced
- **less moderator removed**
- **center closer to target**
- **…?**

Unperturbed moderator flux

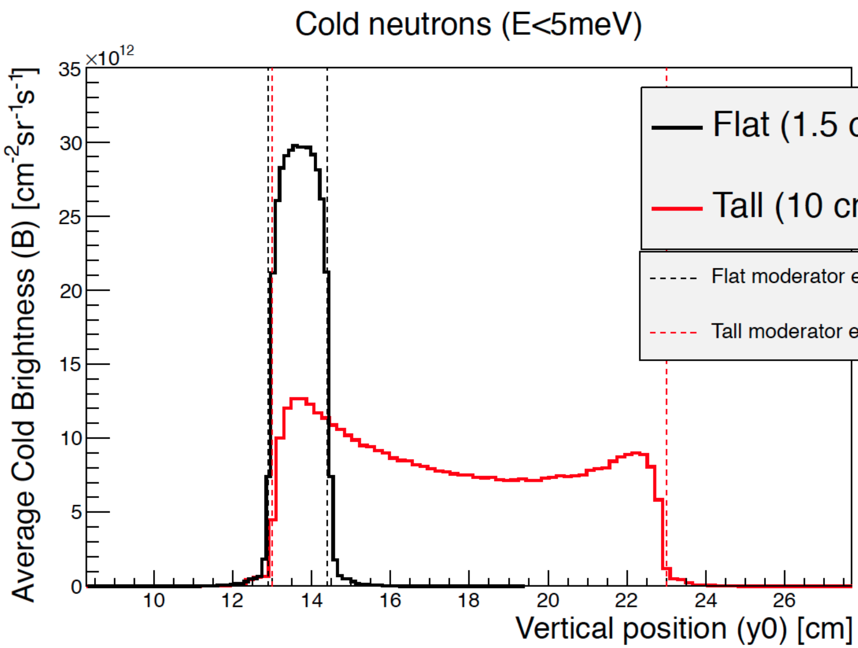


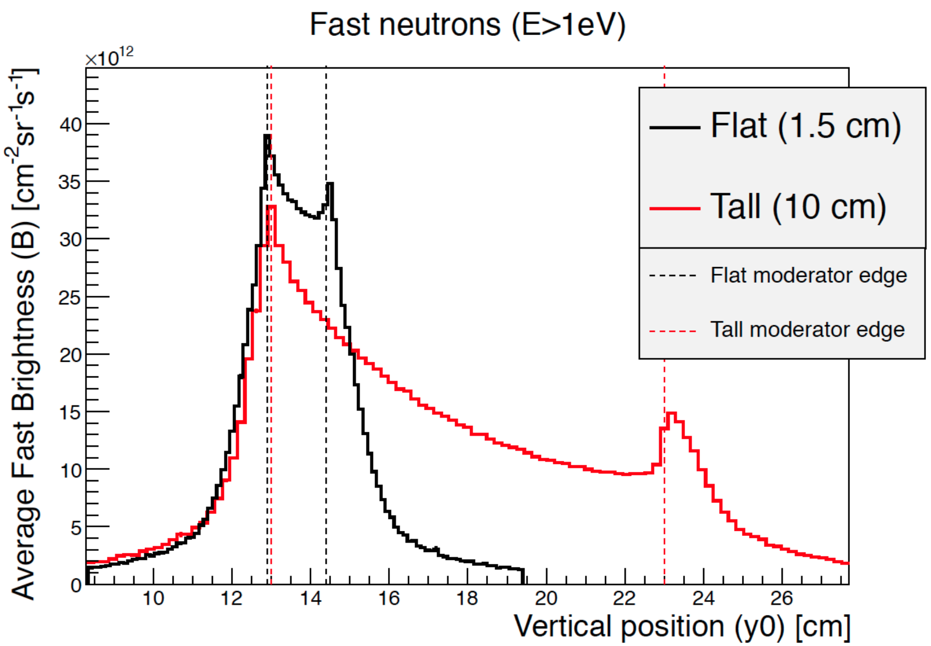




- Trend **even stronger for the perturbed flux**
- **Also gains in the thermal flux from water moderator / Be reflector**

Higher brightness, better signal vs. noise

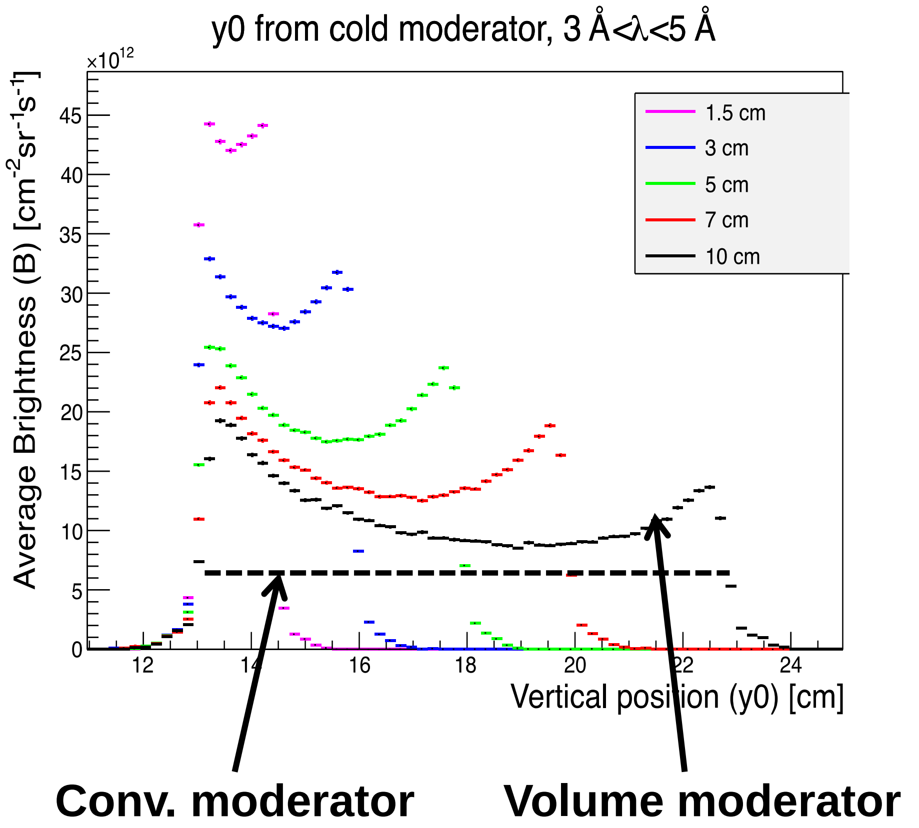




Less diffuse fast neutron background with the flat moderators: smaller opening for beams, more shielding up front.

Conventional vs. flat cold moderators

Moderator brightness and homogeneity: actual gains > average brightness



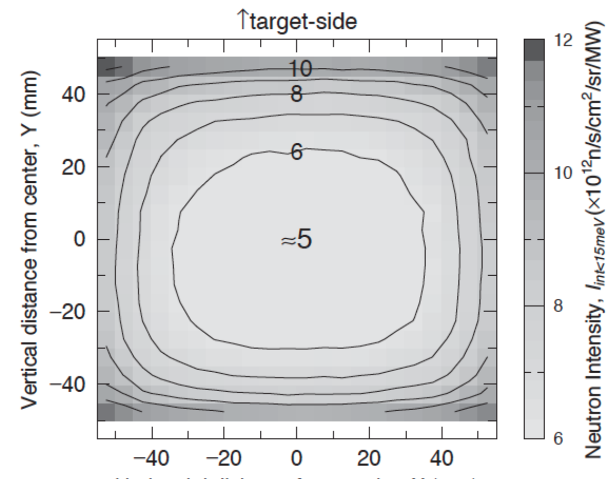
Low dimensional moderator shapes

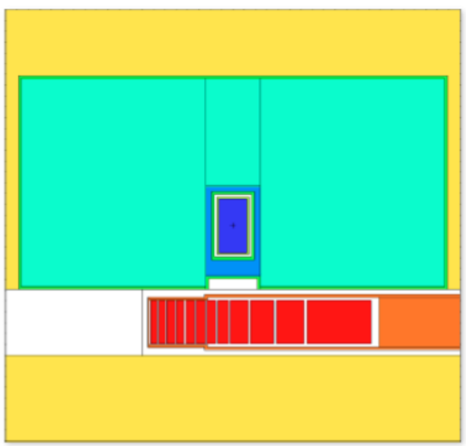
In para-H_2:

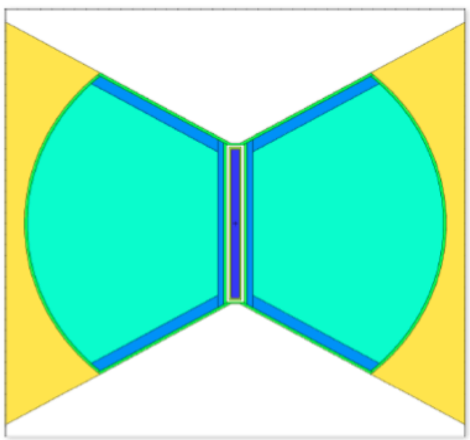
high brightness along flat walls > 10 cm

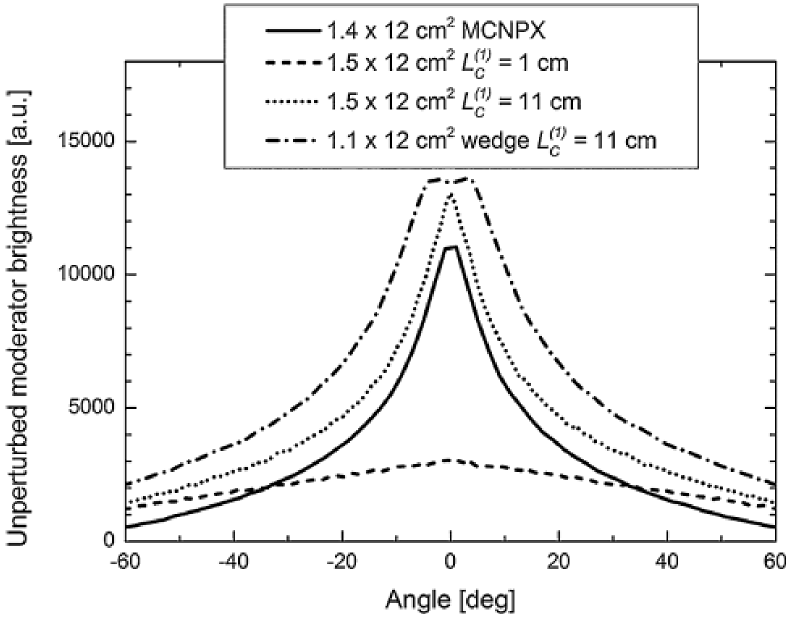
Flat moderator: quasi 2D

Tube moderator: quasi 1D









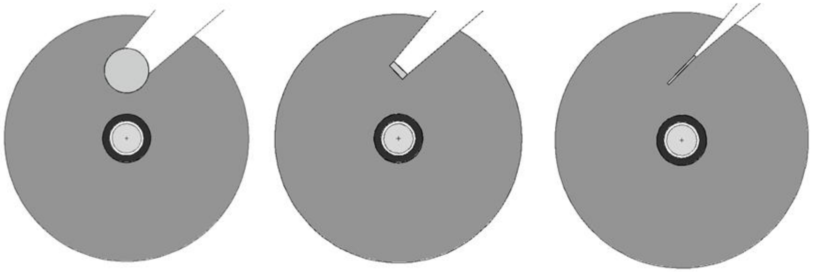
Low dimensional para-H_2 moderator for reactors

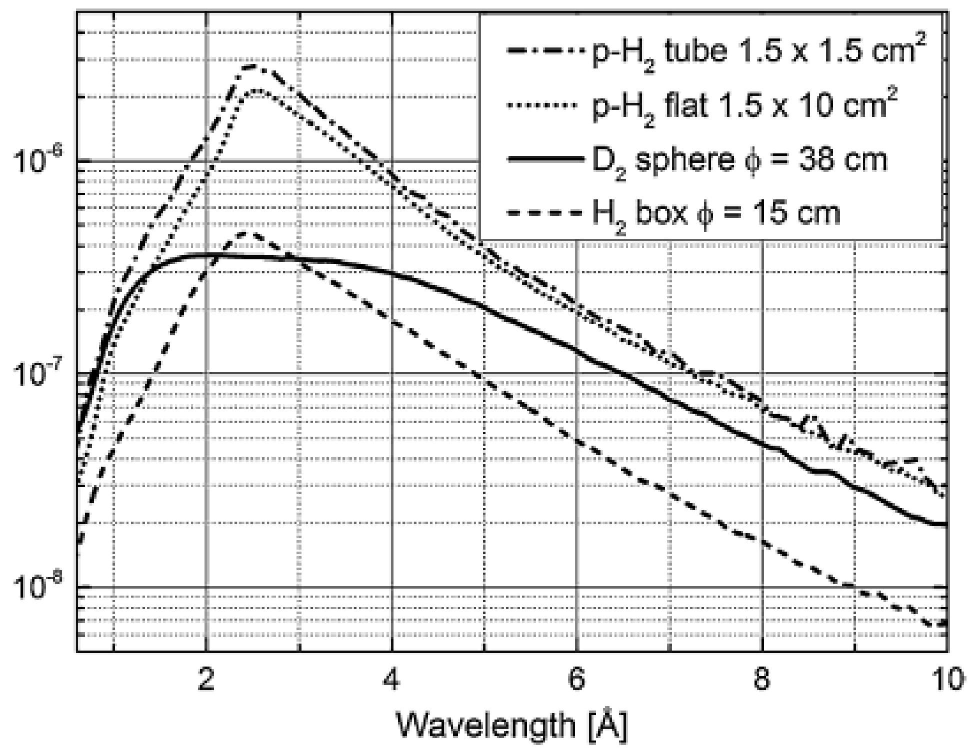
The same cold moderator concept also works well at reactor sources too:

compared with. optimal D_2 or conventional H_2 moderators

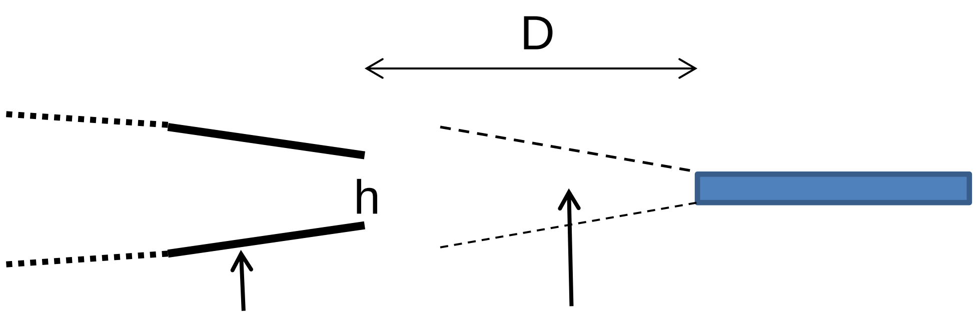
Lower volume / compact source
- → reduced heat deposition
- → can be closer to core
- → additional flux gain

Opportunity for BRR, PIK, etc





Efficient beam delivery to sample



$$V_m = (\mathbf{d}\alpha)^2\ \mathbf{F_m} \quad \textit{or} \quad (\mathbf{h/D})^2\ \mathbf{F_m}$$

supermirror optics

dα: acceptance angle of optics

High power sources:

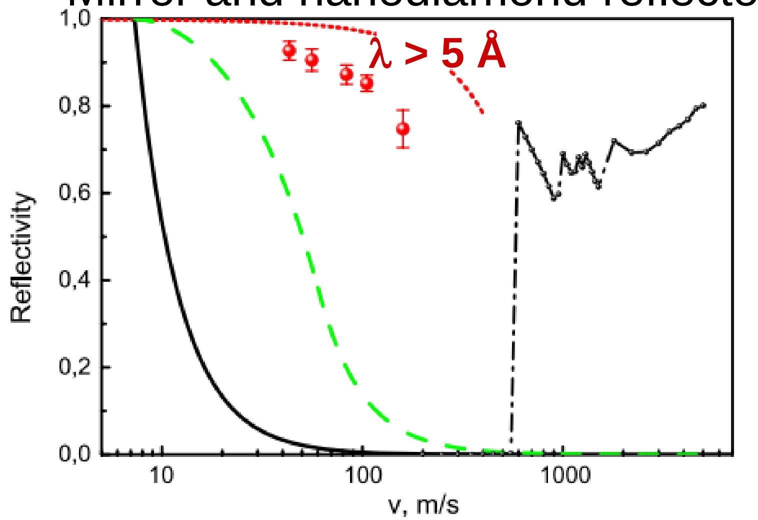
D ~ 150 – 200 cm (damage)

Compact sources:

D ~ 30 – 50 cm

advantage for high **dα**

Mirror and nanodiamond reflectors



Efficient beam delivery to sample

Neutrons on sample: **N = η φ(λ) dt dF dΩ dλ**

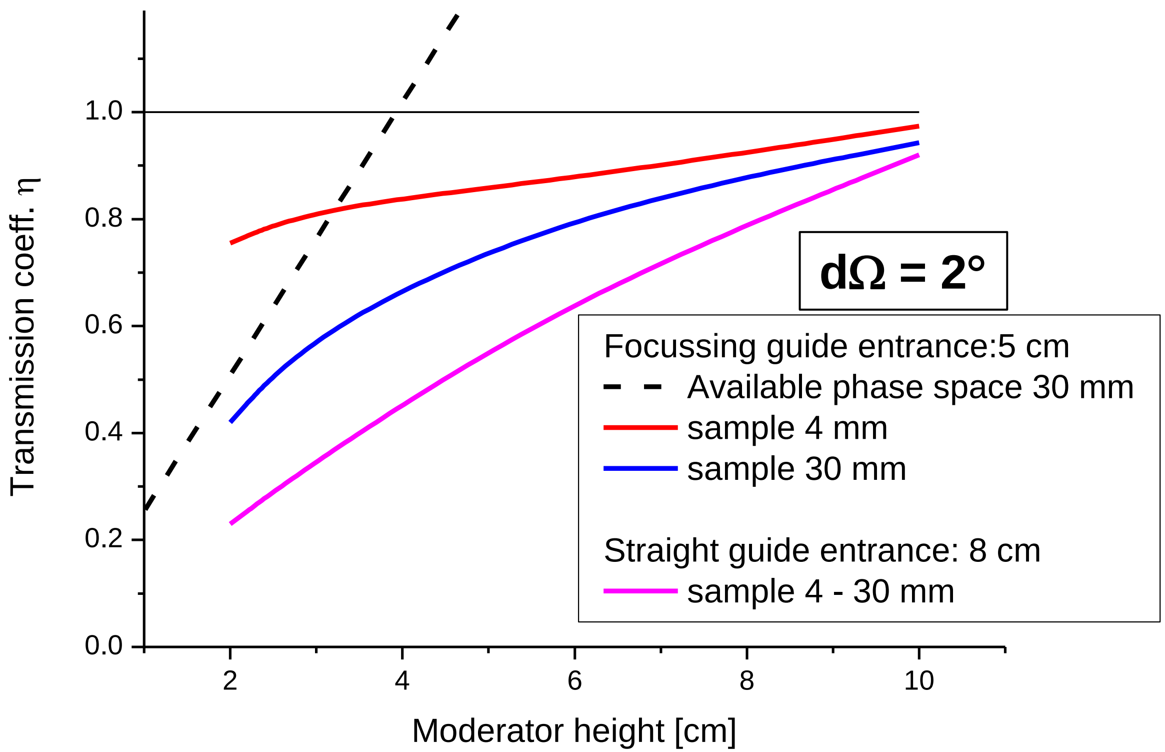
↑

Source brightness (n/s/cm²/str/Å)

η > 60 %, if

- **"good" optical design**
- **(super)mirror critical angle sufficient**
- **available phase space large enough**

Losses in horizontal and vertical dimensions combine: asymmetric shapes can be advantageous

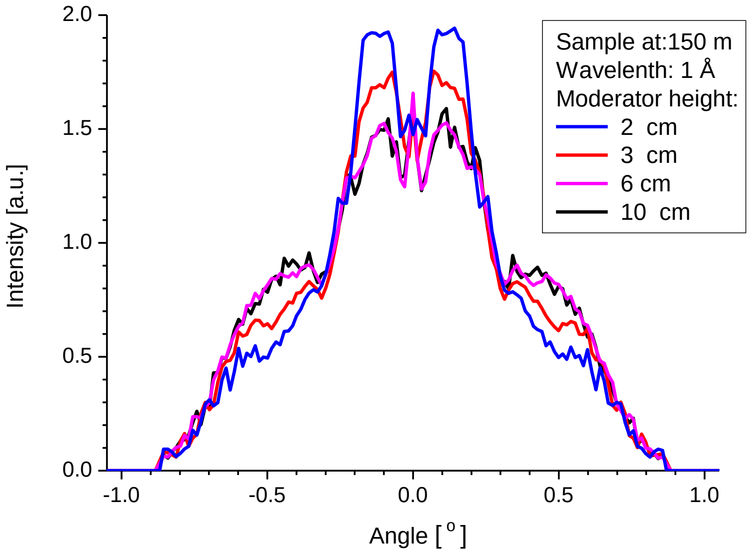


(for homogeneous moderator brightness)

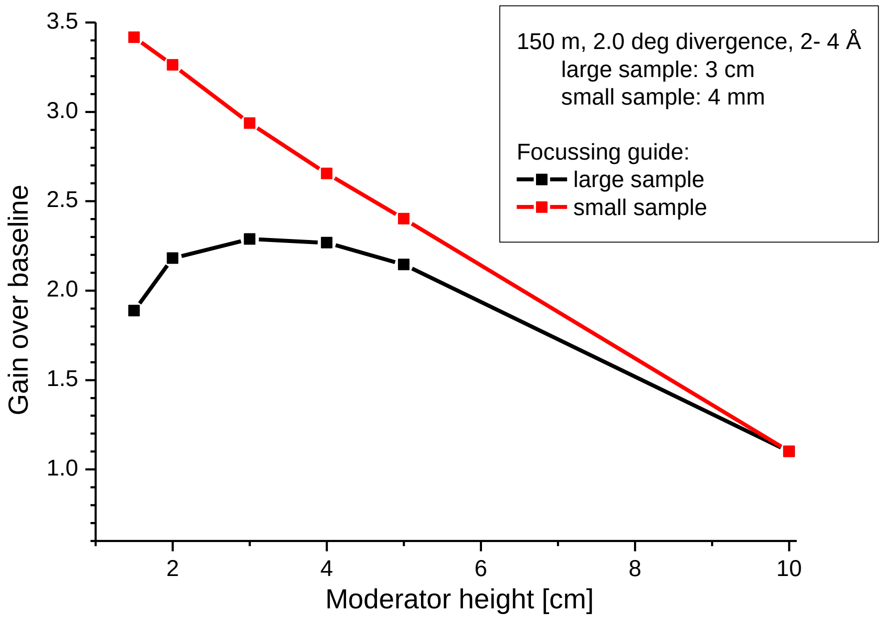
Efficient beam delivery to sample

The enhanced moderator brightness can always be delivered with little losses to the sample for moderate samples size (<2 cm) and moderate angular resolution (< 2°) or < 4 °cm phase space per direction.

Beam optics quality



Flux on sample



Summary

Low dimensional moderator concept: enhanced slow neutron generation capability for all neutron sources: reactors, spallation and compact neutron sources

Efficiency of use of enhanced brightness limited by current neutron supermirrors optics: development potentials

Full efficiency: for small samples and beam divergences
Main challenges: large samples and/or divergences (> 4 °cm)

Compact sources: smaller distance → higher divergence → smaller moderator → higher cold n. brightness efficiency

Future improvement potentials: (regular) exchange of moderators (~ 2-3 years at ESS), new sources