EUROPEAN SPALLATION SOURCE

Machine Directorate

Aug 6, 2013
Sep. 29, 2013

ESS Design Optimization: New moderator concept

I. Background

The master schedule for the ESS target station design envisaged a) the delivery by the end of 2012 of a design concept for the purposes of the TDR, realistic facility planning and cost estimate and based on best state-of-the-art practices and b) performing an in depth design optimization with the goal of freezing the design by Q3 2014. The first major results of this optimizations effort are:

a) Novel target-moderator-reflector layout concept for spallation sources

We have developed a new approach to moderator performance optimization based on the notion of the "unperturbed neutron brightness" (K. Batkov, A. Takibayev, L. Zanini, F. Mezei, NIMA, 2013). The results of the application of this method for the target design allowed us to discover a by now unsuspected moderator geometry to enhance the neutron beam production efficiency of a spallation facility in terms of source brightness by about a factor of 3 for the neutron scattering applications where the flux really matters. The approach is based on using pancake shaped, "flat" moderators of about 1.5 cm thickness (in the vertical dimension at ESS, ISIS, SNS, J-PARC,…) as opposed to the conventional box or volume moderators used by now, which are 12 – 14 cm high (e.g. ISIS, SNS, J-PARC, Lujan Center). It is to be expected that this discovery will redefine spallation source design / refurbishment for the future.

The feasibility of the use of such reduced height moderators depends on the conception of neutron optical beam transport systems that are capable to deliver with moderate losses the enhanced source brightness to the samples. This requires the redefinition of the current beam extraction paradigm, which essentially assumed that the moderators must have larger size than the entrance of the guide. Our simulations prove that with proper optical design this is not required. We have demonstrated that neutron optical systems based on existing supermirror guide technology are capable of delivering most of the 3 fold gain in moderator brightness for small samples (2 – 4 mm high) both for thermal and cold neutrons to all neutron scattering instruments and for all sample sizes in high angular resolution work (such as reflectometry, small angle scattering, neutron imaging). For large samples (2 – 4 cm) the flux gains on the instruments still range between 10 – 100 %, thus the novel "flat" moderators perform better than the conventional ones in all neutron scattering applications.

A less common feature in the conception of beam delivery systems for the vertically "flat" moderators is its sensitivity for the curvature of the neutron trajectories due to gravity for long neutron wavelengths (λ) and long flight paths (L), actually becoming important if λ*L > 400 Åm. We have established corrective measures that make gravity remain a moderate perturbation for the first 3 possible data collection frames at ESS (i.e. up to λ*L ~ 850 Åm, with $\Delta\lambda$*L = 286 Åm per frame). For completeness, we have also demonstrated the potentially good efficiency of the purported neutron nano-prism technology for the purpose of gravity effect compensation, but technically this method is not satisfactorily developed yet.

II. Impact on costs, schedule and interfaces

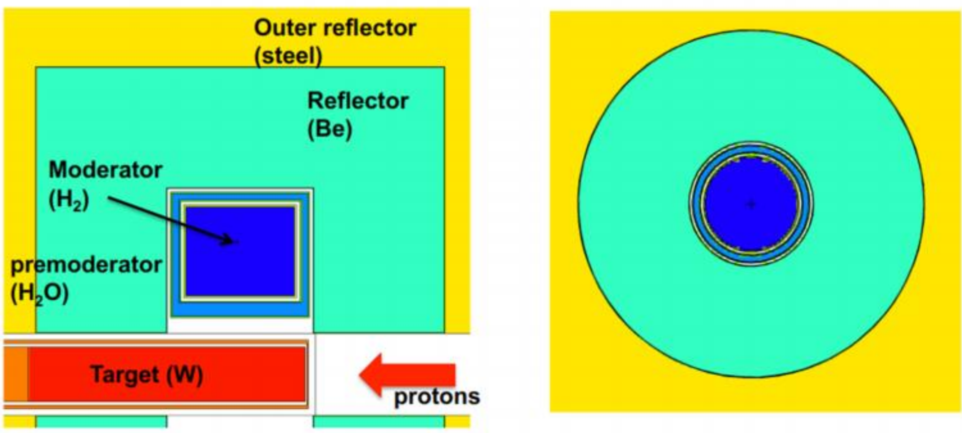
The novel "flat moderator" beam extraction concept we have developed opens up the way for substantially enhancing the performance of spallation sources. The implementation of this approach at ESS will radically enhance scientific opportunities and the facility mission within the framework of the sensibly planned target station optimization phase, Q1 2003 – Q3 2014. The adoption of the new moderator paradigm will not increase construction and operational costs (actually savings are more likely), will have no delaying effect on the project schedule (exploring unconventional vistas after the best available practice based TDR work was carefully worked into the timeline from the beginning), will not change the interfaces with Accelerator and Conventional Facilities and offers potentially significant reductions of the safety risks in operation (reduction of hydrogen gas inventory, eventually removal of the most critical water circuit from the moderator-reflector assembly).

There will be significant changes in the optical conception of the neutron beam delivery systems for the instruments, but this is far from being time critical, since established neutron guide technology is sufficient. The baseline vertical dimension of the in-pile guide plugs (> 30 cm) allows for the flexible adjustment of the elevation of the beam axis over the lifetime of the facility. There is no need to extend the guides closer to the target than planned by now. Since the optimal width of the moderator is the same as specified by now, there will be no direct effect to the chopper system lay-out. The integration of the new beam extraction concept into the instrument lay-out plan will not lead to significant change of schedule: the instrument selection and design process was poised to reshape the straw-man instrument layout in any case.

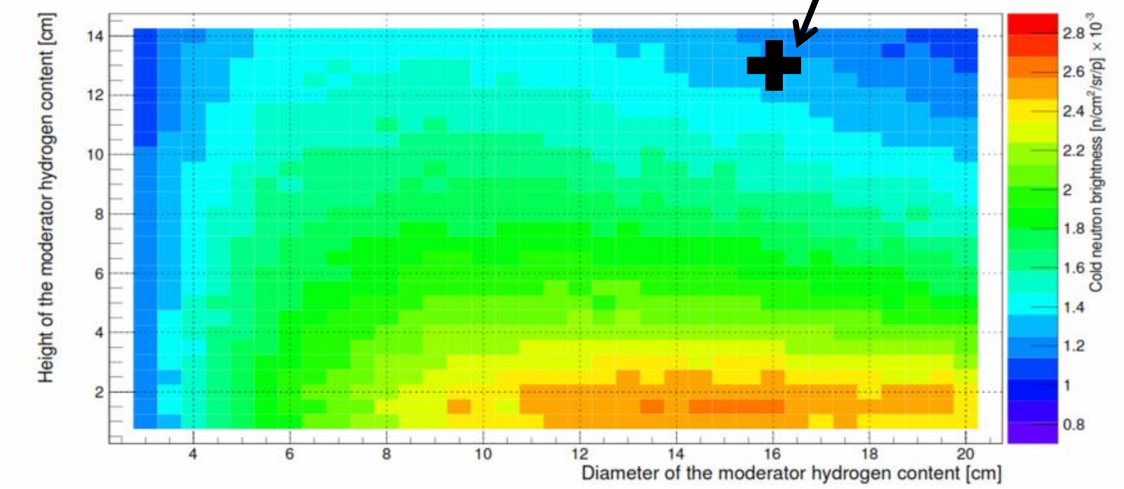
III. Summary of a few technical details and available evidence

a) Concept and optimization of "unperturbed cold moderator brightness".
(K. Batkov, A. Takibayev, L. Zanini, F. Mezei, NIMA, 2013).

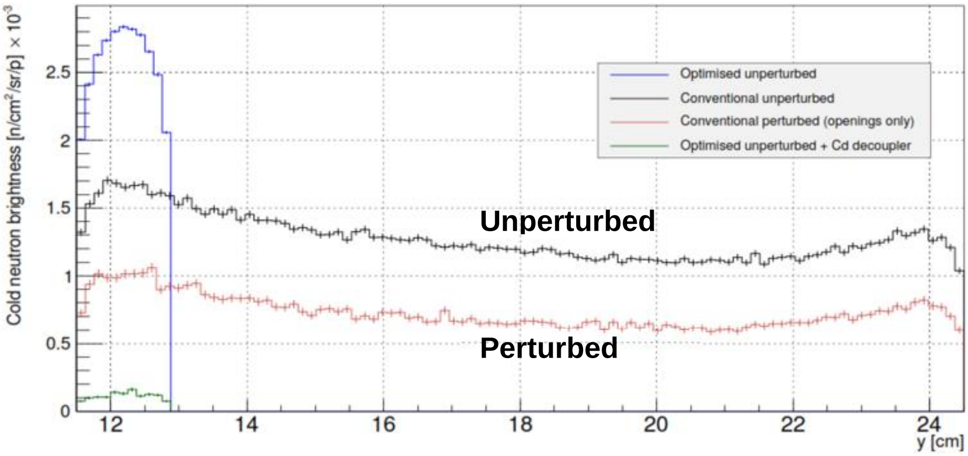
Definition of geometry:
Beam extraction openings disturb the moderator brightness, complicate optimization boundary conditions, add extra parameters. Unperturbed brightness: no reflector removed for beam extraction



Results:

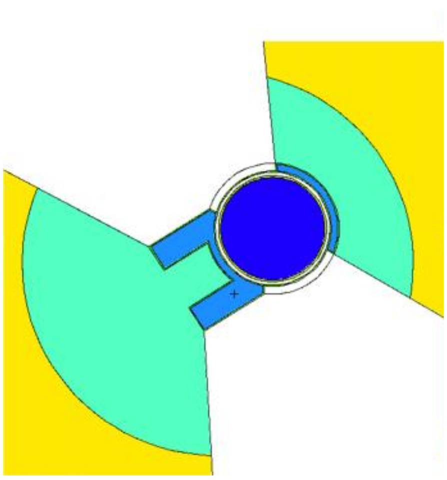


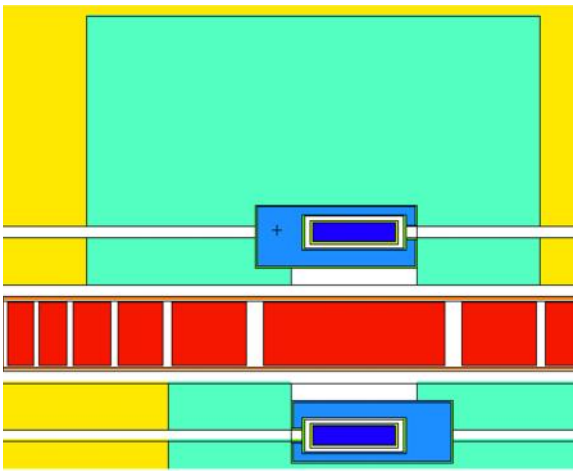
Average moderator brightness as a function of the size of the cold moderator cylinder
Optimum: 16 cm diameter, 1.4 cm height

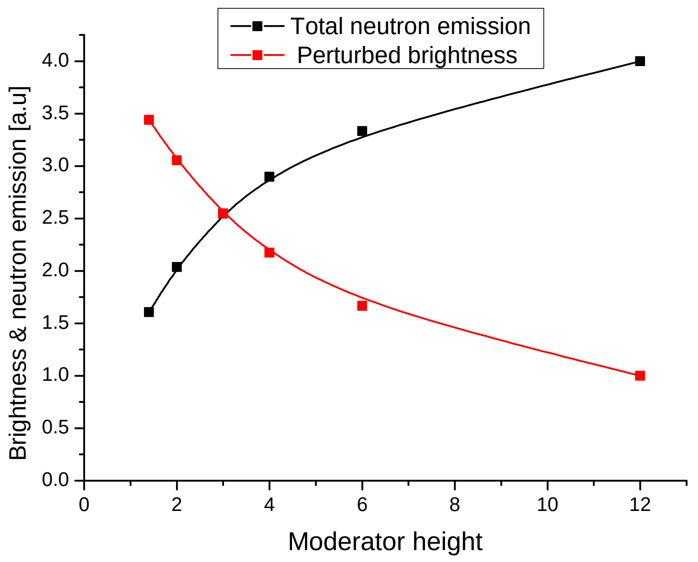


Distribution of moderator brightness as a function of distance from the center of the target

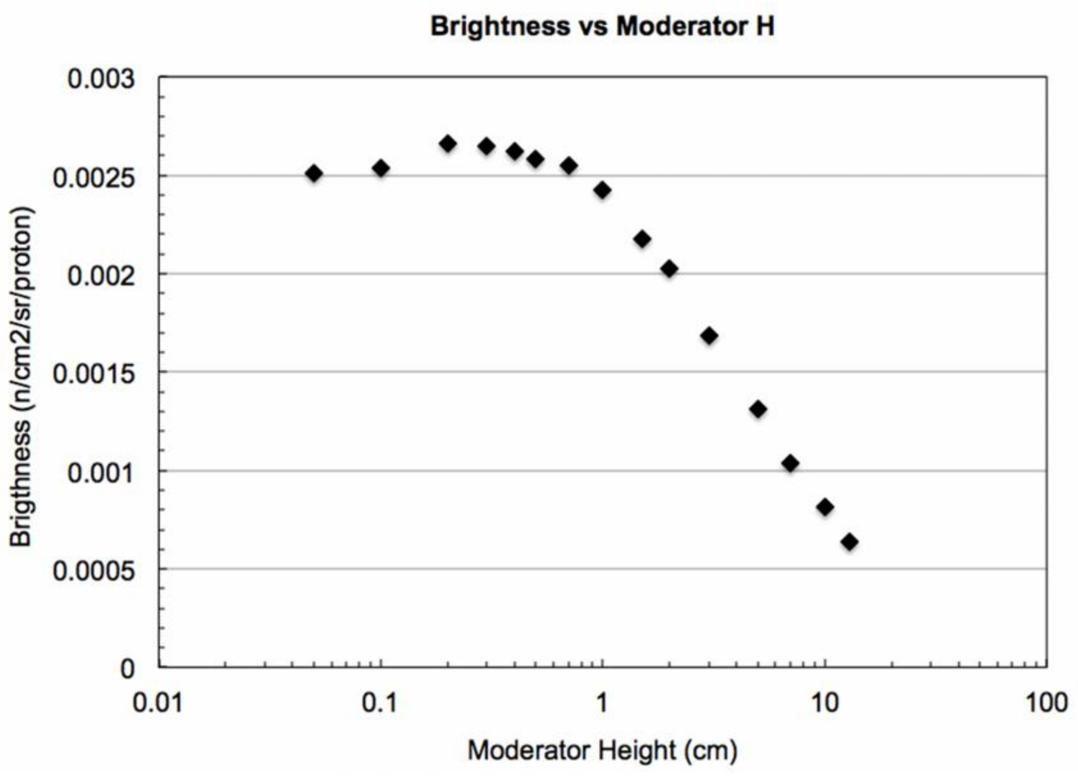
b) Determination of the perturbed brightness, including thermal moderator





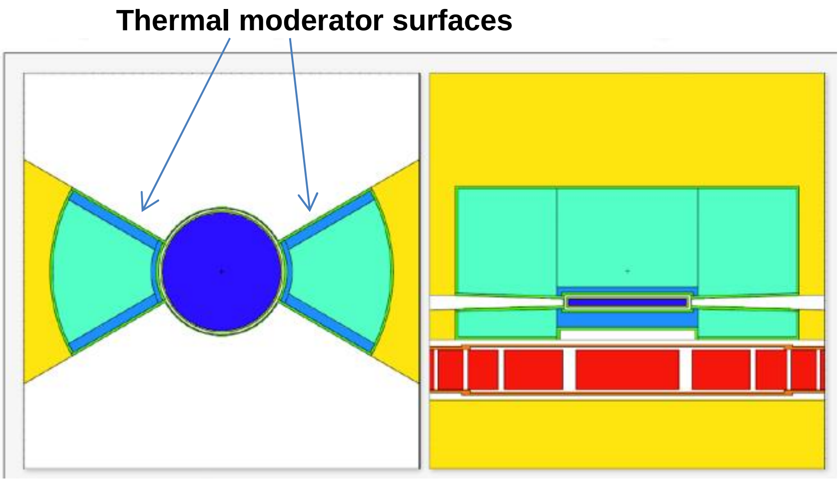


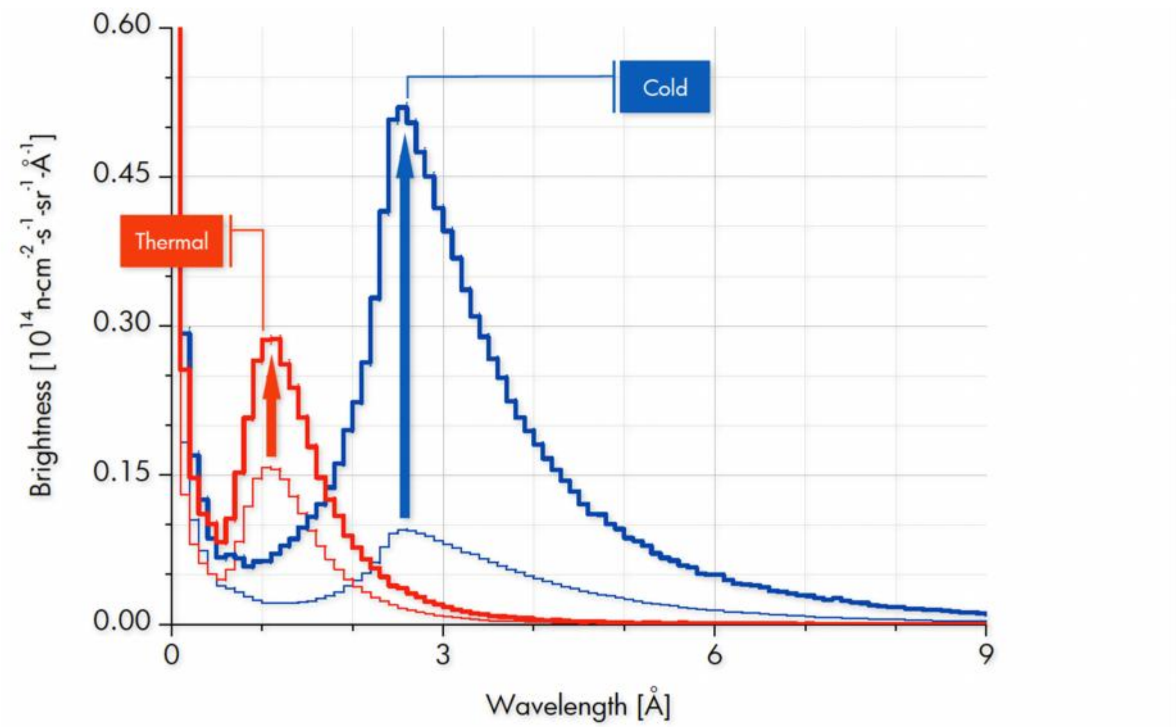
Removed reflector volume small: perturbed brightness ~ unperturbed
Bi-spectral thermal neutron moderator brightness: ~ comparable gains to the cold moderator



More precise recent data show that the perturbed brightness has its maximum at ~ 0.5 cm moderator height

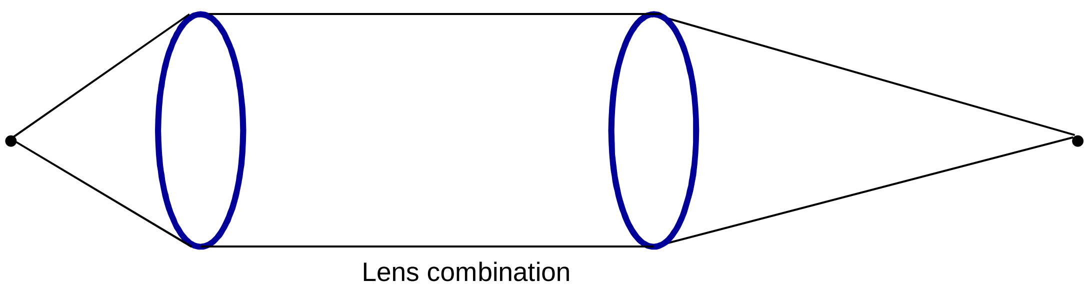
Example of a moderator with 240° opening: the little volume of removed Be reflector results in little intensity penalty for more opening angle:





There are significant modifications in the neutron spectrum: the peak of the cold moderator perturbed brightness gains exceeds a factor of 5 between 2 and 3 Å. The thermal moderator has received less effort for optimization: gain factor ranges from 1.5 to 3, depending on geometry.

c) Liouville theorem



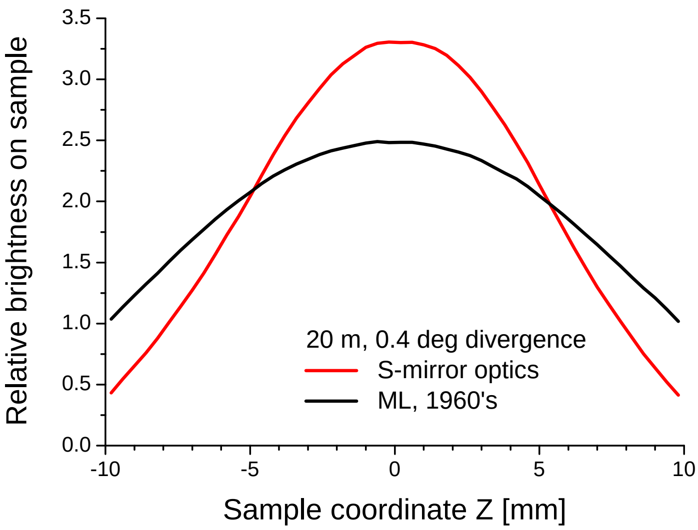
Brightness is constant of motion, can be imaged / transported to the sample, with efficiency η≤ 100 %, if we have proper optics (exists for light, restricted approximations for neutrons).

d) Neutron optics for flat moderators 12 cm x 1.4 cm:

Demonstrative, proof of principle examples: brightness gain small phase flat space moderator can be largely delivered to the samples in experiments / instruments with reduced beam phase space needs at the sample in the vertical dimension. Beam delivery in the horizontal direction remains unchanged: small phase space related losses are limited to 1 dimension.

i. Direct view, η ~ 100 % (reflectometry, small angle scattering, imaging)

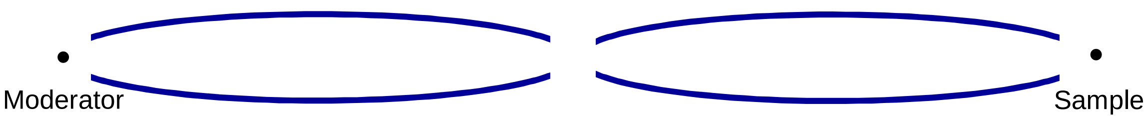
ii. For low vertical beam divergence on sample (0.2° – 0.4° FWHM): small height (guide entrance ≤ moderator) simple Ni guide (Maier-Leibniz, 1960's) or small height supermirror focusing optics transmit > 75 – 95 % for any distance < 200 m, and λ < 10 Å. Guide staring at ~2 m from moderator.

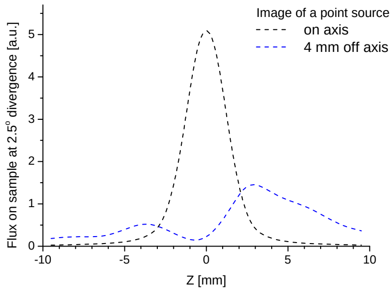


Relative brightness = 1: hypothetical loss free transmission of large moderator average brightness. (Realistic losses can be in the range of 5 – 15 % for well-designed guides.)
3.3 fold gain for small sample (2-4 mm), ~ 2 fold gain for 2 cm large sample

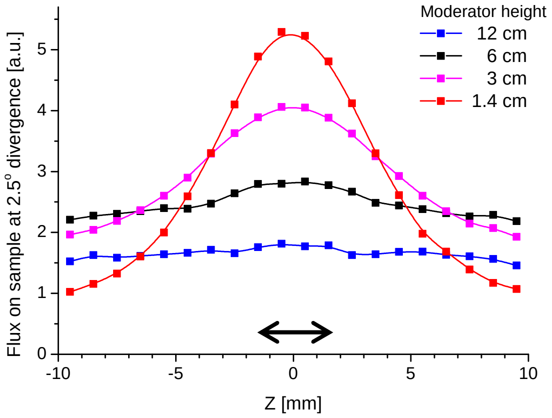
iii. Beam transport at larger distance and larger beam divergence

Tentative best optics (J. Stahn, PSI): provides > 70 – 80 % brightness transmission for small samples at any distance L < 200 m. Gravity effects important if λL. > 600 Åm



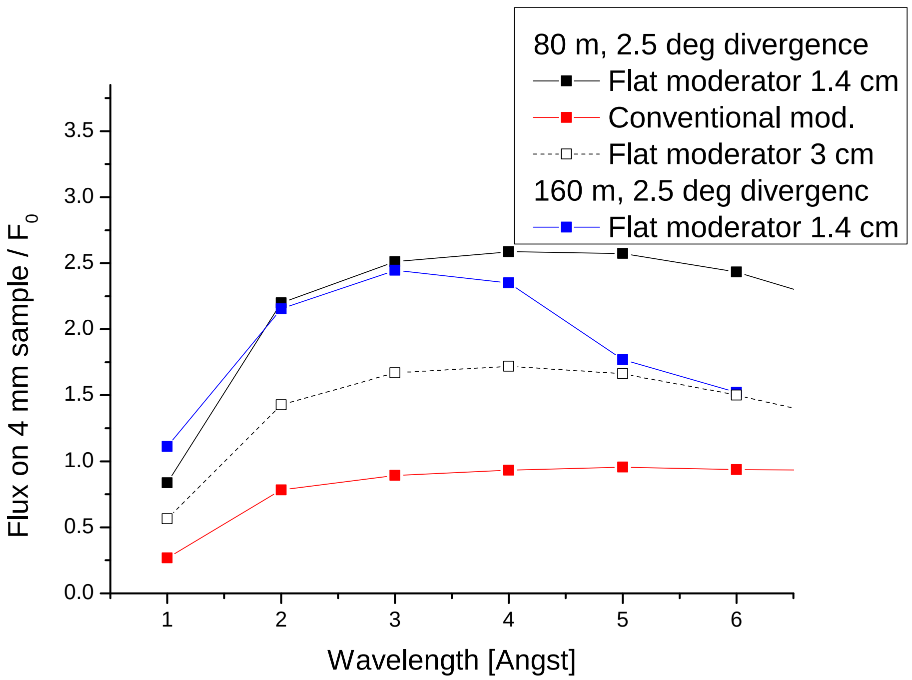


Poor imaging quality outside axis!!
Example: double ellipse for 80 m,
25 cm flat guide pieces

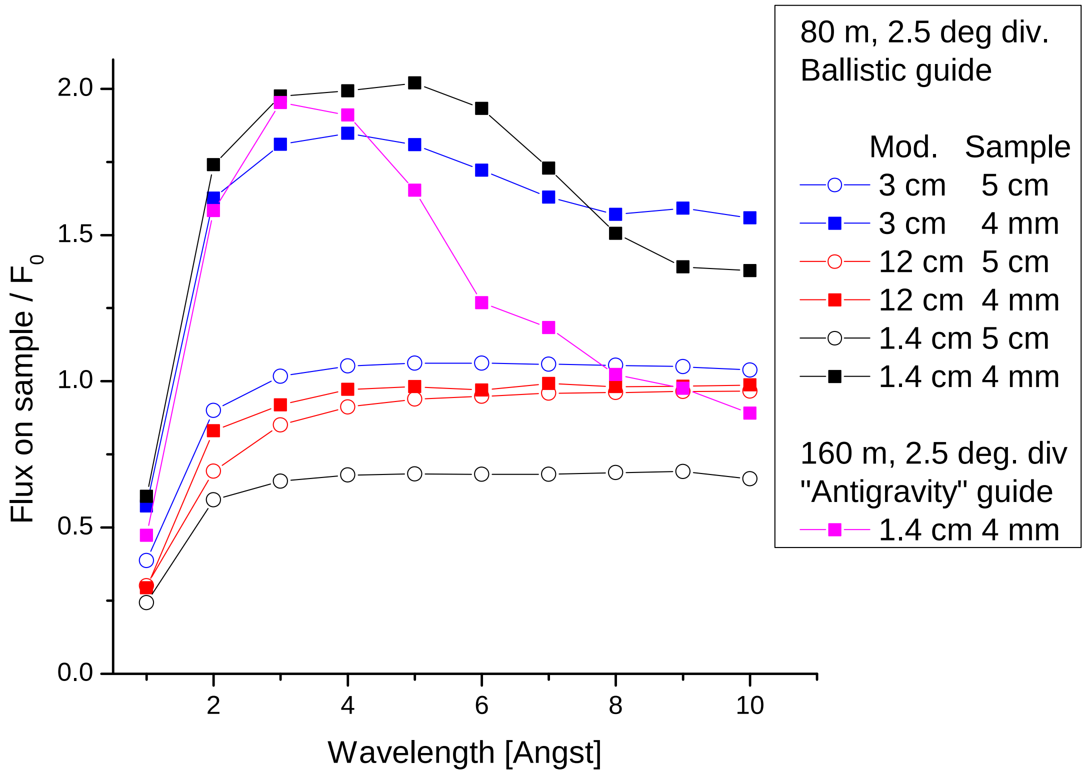


Flux on sample as a function of moderator size
Gain factor for 3 mm sample: 2.95
for 40 mm sample: 1.8
(L=80 m, 2.5° divergence, λ=4 Å)

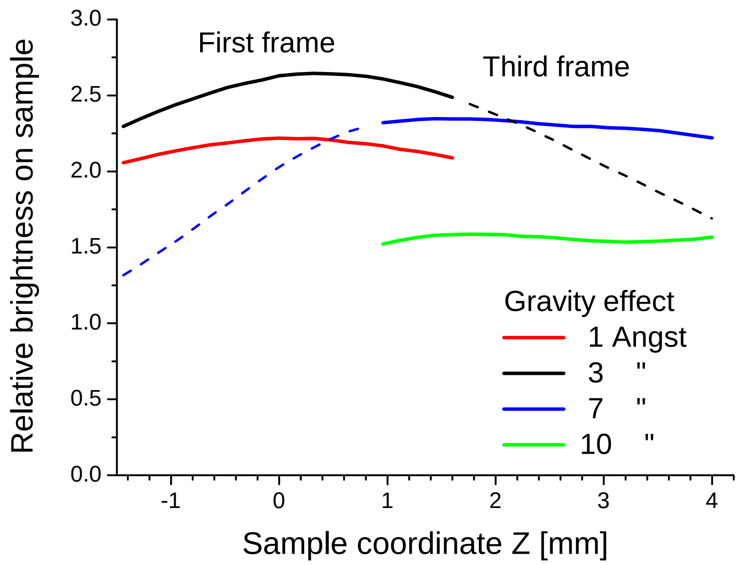
e) Longer wavelengths / distances: gravity distorts profile



Gravity effect for a small sample (4 mm height): reduced transmission efficiency with increasing wavelength as a function of moderator height and transport distance (guide: double ellipse, starting at 2 m from the moderator).



The combined effect of gravity, different moderator and sample height on the flux on the sample for a ballistic guides. (F_0 = Liouville limit for 12 cm high moderator)

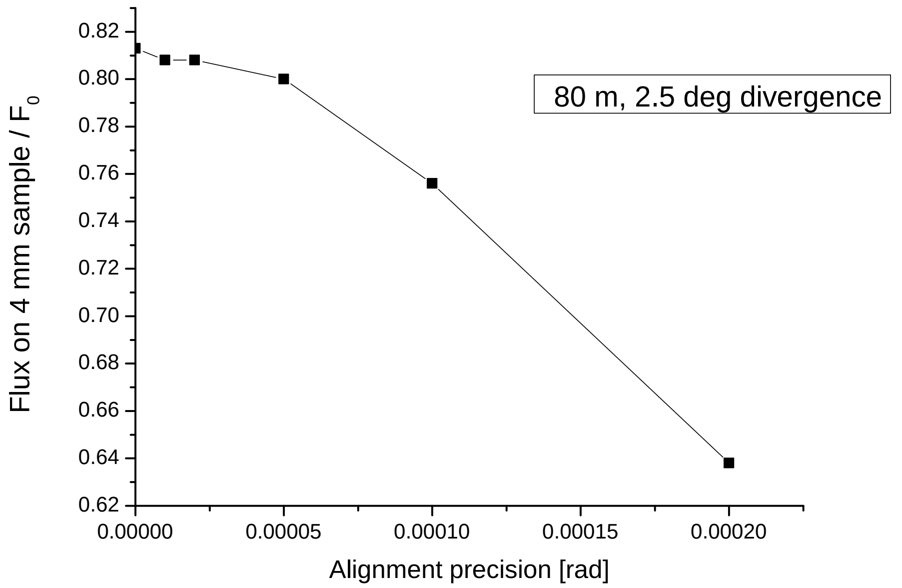


Corrective measure: position of the 3 mm sample window adjusted to the data collection frame used: at 80 m

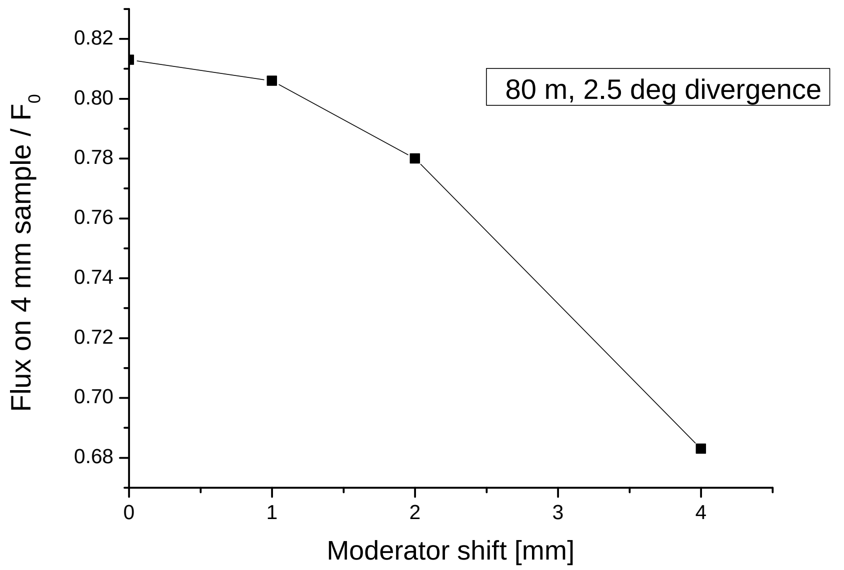
1st frame: 0 – 3.5 Å
2nd frame: 3.5 – 7 Å
3rd frame: 7 – 10.5 Å

Conclusion: The 1-D character of the moderator shape is a crucial, very lucky feature. For all sample sizes 0 – 4 cm the 1.4 cm flat moderator provide substantial gains (1.5 – 3.3 fold). The probable exceptions: working beyond 3rd frame, beam divergence > 5°.

f) Effect of precision of guide alignment:



Effect angular misalignment of the 25 cm long flat guide plates (half of peak-to-peak) for a double ellipse guide, starting at 2 m from the 1.4 cm high moderator.



Effect misalignment of the elevation of the 1.4 cm high moderator with respect of the axis of a double ellipse guide starting at 2 m from the moderator

e) Supporting evidence
(T. Kai, M. Harada, M. Teshigawara, N. Watanabe, Y. Ikeda, 2004)

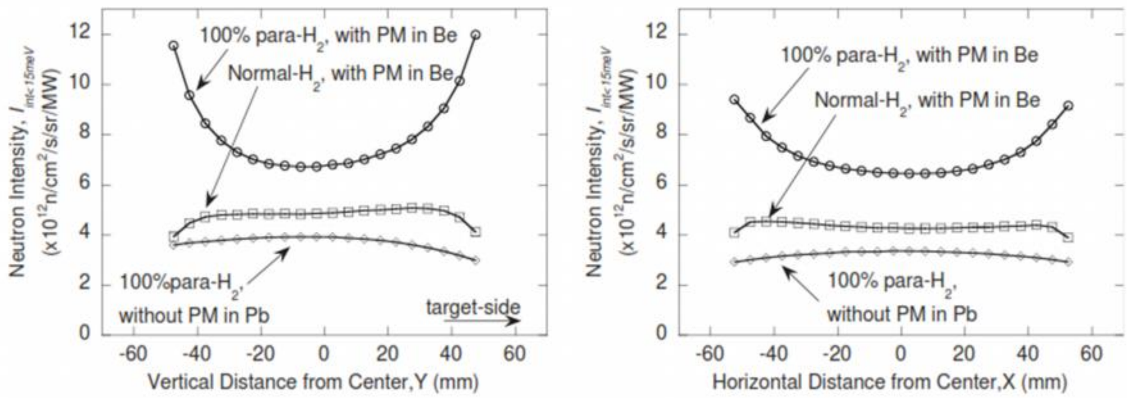


Fig. 16. One-dimensional projections of time-integrated neutron intensity below 15 meV ($I_{\mathrm{int}<15\ \mathrm{meV}}$) on moderators of 100% para-H_2 with PM in Be reflector, normal-H_2 with PM in Be reflector and 100% para-H_2 without PM in Pb reflector. The left is vertical projection and the right is horizontal. Center of viewed surface is defined as $X = Y = 0$.

Flux is maximum at the interfaces with reflector / premoderator (for para-H_2 only!)