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Beam extraction and delivery at compact neutron sources

F. MEZEI[1][2]

[1] *European Spallation Source ESS AB - PO BOX 176, SE-22100, Lund, Sweden*
[2] *Wigner Research Centre of H.A.S - PO BOX 49, H-1525 Budapest, Hungary*

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Summary. — The beam performance of a source of radiation is primarily characterized by its brightness, which remains constant in a conservative force field along the propagation of the beam. The neutron flux at an area with direct view to a homogenous radiation emitting moderator surface will just depend on the solid angle of beam divergence as determined by the moderator size. Recently it was found that by reducing the size of neutron moderators their brightness can be enhanced by a factor in the range of up to 3–6. In direct view of such moderators from sizable distances often required in neutron scattering applications the beam divergence will become reduced. Supermirror based neutron optical guide systems allow us to deliver neutron beam divergences independently of distance from the source. Due to the low radiation fields at compact sources such systems can be placed close to the neutron emitting moderators, a specific advantage and a new design feature. Focusing type neutron guides with phase space acceptance properly matched to the phase space to be delivered over distance can provide for beam delivery with small losses of brightness within a convenient and flexible range of beam parameters.

PACS `61.05.F-` – Neutron diffraction and scattering.
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1. – Introduction

The beam performance of a source of radiation is primarily characterized by its brightness ϕ, *i.e.* the number particles emitted in unit time by surface area δF into solid angle $\delta\Omega$ within the fraction of the spectrum $\delta\omega$. Here the product $\delta F\, \delta\Omega\, \delta\omega$ represents the particle phase space volume. By Liouville theorem in a conservative force field the phase space density of particles remains constant along beam propagation. This means that if we could have good optical systems for delivering the neutron beam to the sample area F to be illuminated with neutrons with well-defined beam divergence of solid angle $\Delta\Omega$ and spectral window $\Delta\omega$, the total number of neutrons delivered in unit time would be $\phi\, F\, \Delta\Omega\, \Delta\omega$. Here ϕ is the brightness of the neutron emitting moderator (for simplicity assumed to be approximately constant over the moderator surface and isotropic within the angular range of beam extraction), which converts the high energy neutrons originally created in the neutron source by some type nuclear reaction to slow neutrons. Optical lenses with visible light, for example condenser lenses in microscopes (which have a very similar function of delivering best beam intensity to a given area) are examples for "good" optical systems with little beam losses. For neutrons, the direct view of the moderator through vacuum is de facto the only available "good" optics, *i.e.* loss free optical system for which the above intensity formula applies in good approximation. With direct view of the moderator the beam divergence will be $\Delta\Omega = F_M/R^2$, where F_M is the neutron emitting area of the moderator and R the distance from the moderator. The beam divergence, and hence intensity per unit area (*i.e.* flux), diminishes rapidly with the distance. Direct view of the slow neutron emitting moderator was the most common neutron delivery "optics" for a long time. In the past few decades neutron guides gradually became the standard, basically since they are more efficient in transporting neutrons over large distances. Here neutrons are transported in wave guides like tubes with (supermirror) coated reflective inside surfaces. Such systems are optically rather poor compared to lenses: the reflectivity of the walls is less than 100%, there can be gaps between guide pieces or between guide and the moderator, fluctuation in the angular orientation of the reflecting mirrors and —most significantly— the domain of high reflectivity of neutron mirrors is limited to small grazing angles in the range 0.2–2. Consequently, the flux (neutrons per unit surface) at the sample area will be given as

$$\Phi_S = \eta\,\phi\,\Delta\Omega_S\,\Delta\omega, \tag{1}$$

where the efficiency factor $\eta < 1$ characterizes the beam transmission losses. These losses in principle can only include neutron absorption while going through materials (such as beam windows, air) and imperfect mirror reflectivity. In practice the effectively measured brightness at the sample area can be inhomogeneous on the short scale in space and in angular distribution. By Liouvilles theorem the peaks cannot exceed the source brightness ϕ. Therefore inhomogeneity implies holes in the distribution and it reduces the average brightness. In practice the brightness is determined as an average over the sample area and some angular distribution; the efficiency factor η primarily characterizes the homogeneity of the delivered beam. If η is close to the value expected in view of neutron absorption and mirror reflectivity losses, this implies that the beam must be close to homogeneous. Figure 1 shows the angular distribution in the vertical direction of the neutron beam transported to the sample area by a rather commonly used, conventional guide configuration: a straight guide with $8\,\mathrm{cm}\times 8\,\mathrm{cm}$ cross section, facing a $10\,\mathrm{cm}\times 10\,\mathrm{cm}$ moderator and delivering a focused beam to $3\,\mathrm{cm}\times 3\,\mathrm{cm}$ sample area with the help of a converging ("focusing") guide section at its end. The large fluctuations in the angular distribution are due to the 2 m gap in the transport system between the moderator and the guide entrance, which is a typical distance for reducing the radiation damage on the guide (most commonly coated glass) to levels that allow for years of operation at high power neutron sources. The transport efficiency factor η is still 90%, with most of the loss due to the inhomogeneity. Note that the sample area F_s is defined exactly (*e.g.* by an absorbing diaphragm) and the beam divergence solid angle by the collimation provided by the cross section of the exit window of the guide A_f and the distance to the sample area L_f as $\Delta\Omega_S = A_f/L_f^2$. The angular distribution in one direction averaged over the whole rectangular sample area thus ideally becomes a trapeze. The product $V_S = F_S\,\Delta\Omega_S\,\Delta\omega$ is called the beam phase space volume at the sample. In view of eq. (1) the total number of particles arriving in unit time is proportional to V_S. We can

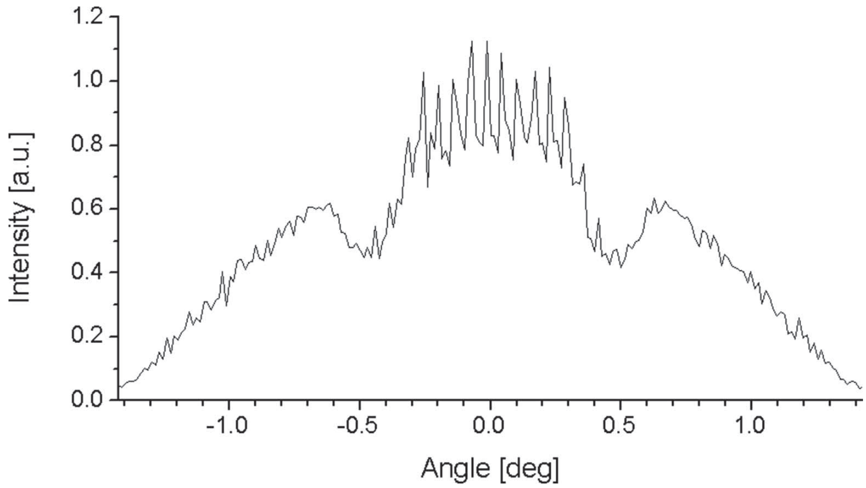

Fig. 1. – Angular distribution of the neutron beam divergence in the vertical direction at the exit of a conventional neutron guide of 8 cm height at its entrance, facing a 10 cm high conventional size neutron moderator. The fine structure in the distribution is inherent to common guide construction routine and in practice only impacts as inhomogeneity the transmission efficiency η of the guide system, without visible effect on the angular resolution.

define in the same way the phase space volume for the entrance of the optical guide system in terms of the optical system entrance window cross section A_i, its distance from the moderator L_i and the area of the moderator F_M. The spectral width $\Delta\omega$ will correspond to the beam mono-chromaticity defined by some monochromator system (*e.g.* reflection on crystal, time-of-flight, etc.) and can be considered as unchanged for a beam lay-out during beam transport. For simplicity in what follows we will replace this common constant by 1. With the basic notion of phase space volume V the number of particles crossing a surface (*e.g.* moderator, sample area) in unit time can be expressed as $N = \eta\,\phi\,V$.

2. – Low-dimensional neutron moderators

As pointed out above, with the direct view of the moderators as beam extraction and delivery system, the size of the neutron emitting moderator surface had to be substantial in order to avoid intensity loss by limiting the delivered phase space volume V_S by too low beam divergence. The typical dimensions exceeded 10–12 cm in both directions of the emitting moderator surface. It has been recently discovered [1] that by reducing certain dimensions of the moderators the emitted neutron brightness goes up to nearly by an order of magnitude compared to the traditional design. This is illustrated in fig. 2 for cylinder shape cold neutron moderators filled with pure liquid para-H_2. The plot in the figure applies to the unperturbed brightness in the absence of removal of reflector around the moderator for the opening of beam lines for neutron extraction. It turned out that one of the several physical mechanisms driving this phenomenon [2] is the loss in neutron slowing down efficiency by the removal of reflector material for both the large volume of the moderator and the large cross section of the beam hole openings. The variation is even bigger than shown in fig. 2, if we take into account the matching size of the beam openings.

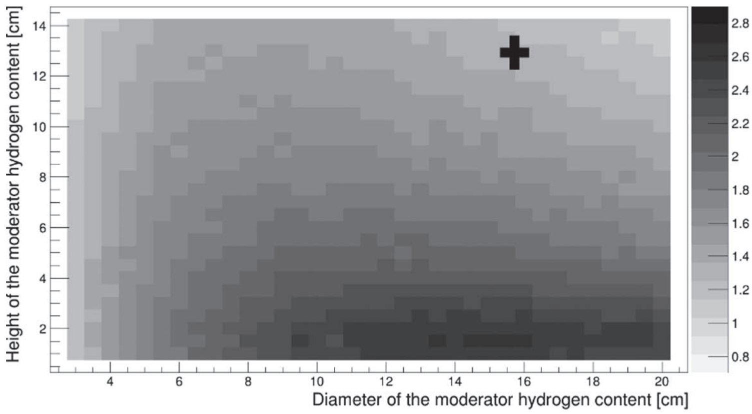

Fig. 2. – Unperturbed cold neutron emission brightness on the side surface of a cylinder shaped liquid para-H_2 moderator as function of its height and diameter. The highest brightness corresponds to a flat "pancake" like shape. The black cross indicates a size and shape corresponding to traditional practice.

3. – Neutron optical beam delivery

We can schematically represent a neutron optical system by entrance and exit windows and some structure in-between, with the ensemble conceptually corresponding to a familiar light optical system *e.g.* of two lenses, fig. 3. Ballistic neutron guides with smoothly varying cross section in the form of tapered or elliptical portions can be a practical example [3]. In modern guide systems a sequence of sections with different shapes is often chosen, after extensive optimization calculations by ray tracing simulations. Two fundamental boundary conditions are particularly important to determine performance:

a) The number of particles entering of the optical systems has to be larger than what we expect to deliver. Taking into account losses by absorption or imperfect reflectivity and Liouville theorem on the preservation of beam brightness, this requires that the phase space volume $V_M = F_M\,\Delta\Omega_M$ entering the system is larger than $V_S = F_S\,\Delta\Omega_S$, the one we expect to deliver to the sample area. This can be formulated as an additional upper limit for the beam transmission efficiency η, even in the absence of any other losses in the beam delivery system (*e.g.* absorption type, optical type...). Namely

$$\eta_y < \left(\frac{V_M}{V_S}\right)_y \equiv \left(\frac{F_M \Delta\Omega_M}{F_S \Delta\Omega_S}\right)_y \text{ and } \eta_y < 1, \tag{2}$$

$$\eta_z < \left(\frac{V_M}{V_S}\right)_z \equiv \left(\frac{F_M \Delta\Omega_M}{F_S \Delta\Omega_S}\right)_z \text{ and } \eta_z < 1. \tag{3}$$

If the optical system does not couple motions in two coordinate directions perpendicular to the mean beam propagation direction x, Liouville theorem also applies for each coordinate of the particle motions separately. This condition is fulfilled for the common, straight rectangular cross section guide systems; therefore here we had to consider the ratios of the horizontal (y direction) and vertical (z direction) of the phase space volumes separately. The upper limit for the transmission efficiency η in this context will be the product of the smaller upper limits given in each of eqs. (2) and (3).

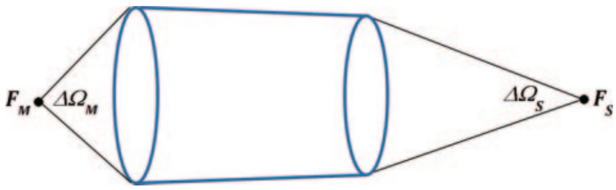

Fig. 3. – Schematic lay-out of an optical condenser lens system, which is actually the functional model of neutron beam extraction and transport systems. The beam parameters for the determination of the Liouville phase space are indicated.

b) The beam divergence neutron guides can accept or deliver depends on the cut-off grazing angle of the coating used. With modern supermirror coatings this cut-off angle can achieve 0.7 λ in degree units if the neutron wavelength λ is expressed in Å units (although the average reflectivity will not exceed about 70%, in contrast to more than 90% for mirrors with the half of this cut-off angle.) Quantitatively this restriction strongly depends on the details of the design, and it tends to disappear as the neutron wavelength gets longer. Roughly speaking, for the example of 2° full beam divergence set by the collimation geometry for every point of the moderator or the sample (*i.e.* 2° FWHM for the integral over the whole beam surfaces) at 2 Å neutron wavelength the 1.4° grazing incidence cut-off angle of the mirrors —which can be used in both directions on both sides of the guide system— only leads to modest reflectivity losses. At $\lambda = 1$ Å these losses are much more serious and actually the beam divergence will be reduced by the guide coating.

Practical examples of simulated neutron beam delivery to a large distance (150 m) using supermirror based neutron guide optics illustrate these points. Figure 4 displays three different fundamental cases. The top (red) curve shows the scientifically most

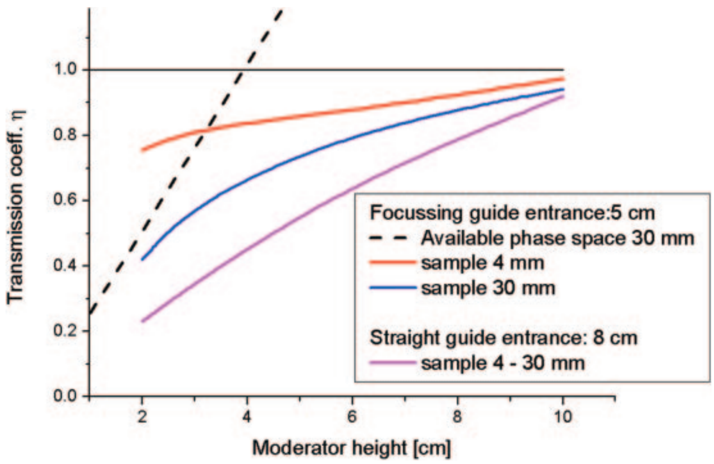

Fig. 4. – Simulated beam transport efficiency $\eta < 1$ for various neutron guide systems with various sample area dimensions. The dashed line represents an additional theoretical upper limit to the blue curve, derived from phase space volume considerations, as explained in more detail in the text.

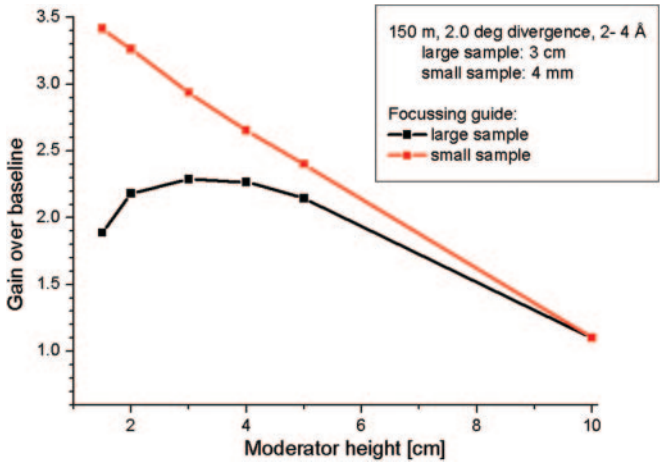

Fig. 5. – Gain in neutron flux on the sample as a function of the height of a cylindrical para-H_2 moderator, illuminating a 150 m long focusing neutron guide for beam delivery. The gain factor is given compared to the conventional height of 12 cm. The difference between the two curves is due to the variation of the beam delivery efficiency η with the vertical dimension of the sample.

significant new capability of the new moderator concept [1, 2]: if the deliverable phase space volume V_S is small, the enhanced brightness of the moderator with reduced size can still be transmitted. with very high efficiency to the sample. In the horizontal direction 8 cm wide moderator, 1.5° beam divergence was considered on the side of guide entrance at 2 m from the moderator and 3 cm wide sample area with 2° beam divergence at the sample side. The vertical dimensions of samples considered are given in figs. 4 and 5. These provide in view of eq. (2) a moderator to sample phase space volume ratio of 2 in the horizontal dimension y. Thus the upper limit for η_y is 1, which can be very well approached with proper guide design. Thus eq. (3) is to be considered only from the point of view of the beam transmission efficiency η. Here the moderator side phase space volume at the entrance of the guide is $1.5° \times h$, where h is the height of the moderator. We consider a 4 mm high small sample illuminated with 2° beam divergence. The $(V_M V_S)_z$ phase space volume ratio will change from 3.75 to about 19 in the range $h = 2$ to 10 cm, *i.e.* we have 1 as upper limit for η over the whole range including unusually small moderator heights (flat or 2 dimensional moderator). The simulated values of η for an adequate (reasonably optimized) ballistic guide with focusing sections on both ends indeed are close to 100%.

For the middle (blue) line the only change is the 3 cm height of the sample area, *i.e.* it covers a phase space volume ratio range of 0.5 to 2.5. It is indicated by the dashed line, which thus shows the upper limit for efficiency η below 4 cm moderator height. The simulated values for the same ballistic guide as above approaches the upper theoretical limit everywhere to $> 60\%$. It is the empirical observation in a good number of guide optimization studies that the upper limit established by eq. (3) can in general be approached to this degree of $> 60\%$, if the neutron wavelength is sufficiently high to avoid reflectivity losses due to the guide coating, which was the case here for $\lambda \geq 2$ Å. The bottom (magenta) line illustrates the importance of a reasonable design optimization effort: it shows the efficiency behavior of a guide of commonly used configuration for 10 cm high moderators, starting with an 8 cm high straight section.

Finally, fig. 5 shows the achievable gain in flux on the sample taking into account the increase of the moderator brightness with decreasing moderator height [4] for the beam delivery cases shown in fig. 4 for the focusing guide. The results in fig. 5 show that by the use of low-dimensional moderators the neutron flux in the sample area can be enhanced by a significant factor, in particular for the delivery of low phase space volumes corresponding to small samples and/or small beam divergences.

4. – Conclusions

Novel, so-called low-dimensional moderators now allow us to enhance by a substantial factor the brightness of the slow neutron emitting moderators at several kinds of neutron sources, including spallation and reactor sources [2]. The same also applies to proton accelerator driven compact neutron sources, where the initially created fast neutrons cover the same several MeV energy range, as for fission or spallation. The efficient delivery of this enhanced neutron brightness as enhanced neutron flux to the sample for these reduced size moderators depends on the phase space volume that can be extracted from the moderators by supermirror based beam delivery guide systems. In contrast to higher power neutron sources, the lower radiation field in compact neutron sources makes possible to envisage neutron guides that start at a short distance in the range of 50 cm from the moderators. This allows for extracting neutron beams with higher divergence than by guides starting at larger distances (1.5–2 m) at high power sources. The corresponding increase of the extracted beam phase space volume compensates for the reduction due to the smaller moderator size, and thus offers more efficient beam delivery to the sample from small moderators than at high power sources. This advantage primarily applies for cold neutron wavelengths (> 2 Å) for which the cut-off grazing incidence angle for reflection on the supermirror coated structures in the beam extraction guide systems exceeds 1°. In sum, state-of-the-art beam extraction and delivery techniques can be applied particularly efficiently at compact sources for taking advantage of the novel possibility of increasing the neutron beam performance by the use of about 5 times smaller moderator dimensions.

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