Neutron beam compressors for pulse width reduction

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ABSTRACT: In the context of intensity and resolution optimization of a neutron time-of-flight spectrometer several methods of beam width reduction at the chopper are considered aiming at a reduction of the neutron pulse width at minimum loss of intensity. The most advantageous technique discussed uses a "double-trumpet" arrangement in which the chopper is placed in between converging and diverging neutron guide sections.

Introduction

It is one of the main tasks in optimizing a neutron spectrometer to strive for maximum intensity at any, and in particular at the best possible, resolution. For this reason every neutron optical device used in the spectrometer should have the highest possible transmission. In the present paper we shall consider part of this optimization problem with regard to a cold-neutron time-offlight spectrometer for inelastic scattering experiments. (We are referring here to the multi-disk chopper spectrometer under construction at HMI Berlin, which is an improved version of the IN5 instrument (Douchin et al., 1973) at ILL in Grenoble). The primary part of such an instrument essentially consists of several choppers.

One of the choppers is intended to create or taylor a pulsed neutron beam. Another one is used for the monochromatization of the latter. In addition to these two principal choppers, further choppers are needed for tail-cutting and for overlap prevention. However,these do not necessarily affect the spectrometer resolution. The present discussion will therefore be restricted to the two principal choppers.

Since the transmission of every chopper enters into the final intensity, we have chosen to use very thin disk choppers with open windows (transmission = 1) produced by cutting slits into the disk edges. These disks run in narrow slots (transmission better than 0.99) cut perpendicularly to the beam into the neutron guide. The energy resolution at the detector of a system of two single choppers is given as (Lechner, 1985):

$$\Delta E = g_0 \left(\tau_1^2 \, g_1^2 + \tau_2^2 \, g_2^2\right)^{1/2} \qquad (1)$$

if flight path length uncertainties are neglected. ΔE is governed by the chopper pulse widths in time, τ_1 and τ_2. Highest resolution {corresponding to minimum values of τ_1 and τ_2) is obtained at maximum chopper speed--at the limit of mechanical resistance of the disk material. An immediate improvement of the energy resolution by a factor of 2 is achieved, if one replaces each single chopper disk by a pair of identical, but counter-rotating disks (Hautecler et al., 1985) mounted at a small distance from each other and running at the same velocity. Formula (1) applies again. with τ_1 and τ_2 now being the effective chopper pulse widths of the first and the second pair, respectively. In the following, the term chopper will be used for such pairs of counter-rotating disks. Once the flight-path lengths (implicitly contained in the wavelength-dependent factors g_0, g_1 and g_2) are fixed, a further improvement of resolution for a given neutron wavelength λ is then possible only by a reduction of the widths of chopper windows and beam, in order to further reduce the neutron pulse widths. As concerns intensity and resolution optimization it is generally advantageous to have $\tau_2 < \tau_1$, especially if the secondary flight path (sample to detector) is shorter than the primary flight path (distance between the two choppers). This also applies when one is interested in good resolution in neutron energy gain scattering. In the following we shall therefore consider possibilities of a reduction of τ_2.

Neutron beam bottlenecks

Beam width reduction corresponds to the construction of some kind of a "bottleneck" in the neutron guide. Figure 1 (schematically) shows several different ways of reducing the beam width (in the horizontal plane) in order to fit it to reduced-width chopper windows. A reduction factor of 2 has been chosen as an example:

(a) normal neutron guide (parallel walls) with original width; a pair of counter-rotating disks, each of them spinning with a (tangential) velocity v, is placed at its end; effective pulse width: τ_2.

(b) the guide width has a step before the chopper; this method of guide width reduction was used in the case of IN5 at ILL: effective pulse width: $\tau_2/2$.

(c) a comb-like mask is used in front of the chopper with chopper windows matched to the mask. The widths of the two windows add up to half of the guide width. This corresponds to the simplest case of the multiple-slit chopper concept (Copley, 1988). I am using this example for the purpose of comparison, assuming that the two counter-rotating disks are spinning at velocity v/2, in order to obtain the same pulse width as in case b) i.e., $\tau_2/2$.

(d) a converging neutron guide section, placed at the end of a normal (parallel-walled) guide, reduces its width just before the chopper and thus leads to a pulse width of $\tau_2/2$ for a chopper velocity v.

We should like to choose the solution corresponding to a minimum loss in intensity at a given improvement in resolution. In order to make this choice let us now compare the intensities for each of these different cases.

The intensity I of an experiment is governed by the number of neutrons leaving the second chopper per unit of time. This is proportional

(i) to the "duty cycle", τ_1/P, i.e., to the fraction of time for which chopper 1 is open,

(ii) to the incident neutron flux per unit of energy integrated over the beam

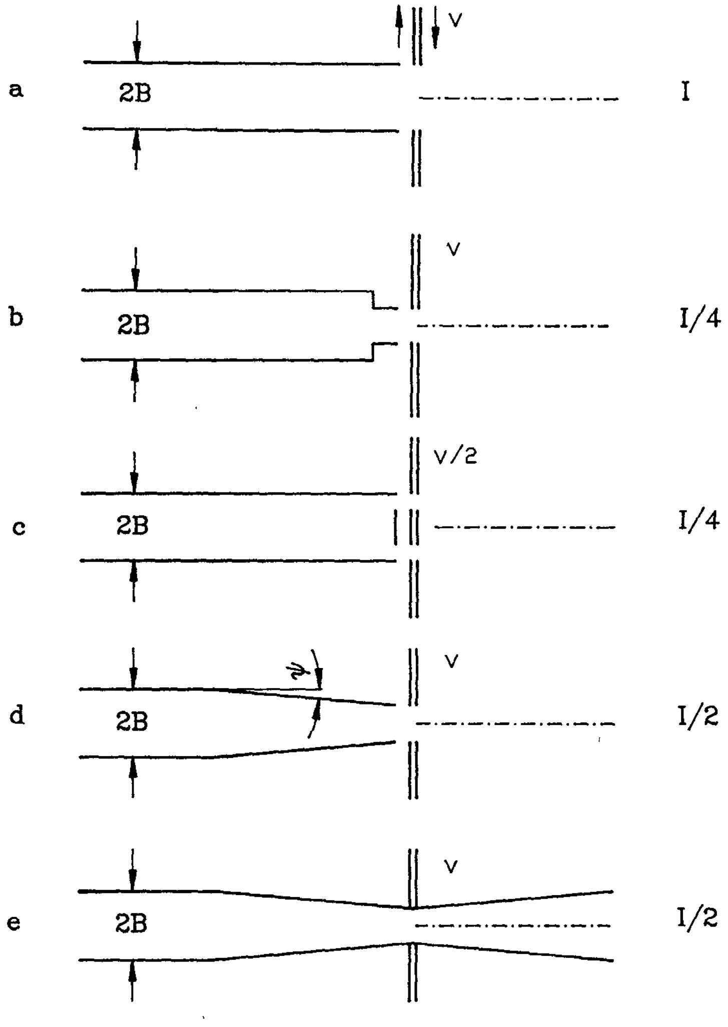

Fig. 1 Schematic drawing of a chopper consisting of a pair of counter-rotating identical disks placed at the end of a neutron guide. (a) mirror-coated guide with parallel walls, width 2B, chopper velocity v. (b) to (d) three different ways of producing a bottleneck in the neutron beam, reducing the total beam width by a factor of 2 in order to decrease the chopper pulse width: (b) guide width reduced by a step to the value B before its exit; chopper velocity v. (c) the guide exit is reduced to two slits of width B/2 each, using a mask; the chopper windows are matched to this mask, chopper velocity v/2. (d) a guide width reduction to the value B is achieved using a supermirror-coated converging guide section before the chopper; chopper velocity v. (e) as in case (d) the neutron guide has a converging section just before the chopper; however, in addition, a diverging neutron guide section is added just after the chopper in order to focus on the sample position.guide section is entirely supermirror coated.

cross-section A, A $d\phi/dE_0$, and

(iii) to the energy band width, ΔE_0, selected during the chopper burst time τ_2:

$$I \propto (\tau_1/P)\ A\ (d\phi/dE_0)\ \Delta E_0 \qquad (2)$$

It is obvious that for the chopper velocities given above the energy band width factor is equally reduced in the cases b), c) and d) as compared to a) of Fig. 1, whereas the flux factor is affected only in cases b) and c). Thus, for the same improvement in resolution, the intensity I of case a) is reduced to I/4 in b) and c). but only to I/2 in case d). This is assuming that a converging guide section can be made with a transmission of 1, which is true to a good approximation (see below). We note that the result of case d) would also be obtained with a normal guide (case a), if it was possible to double the chopper speed. Furthermore, it should be noted that a pulse width reduction by another factor of 2 is possible in case c) if the maximum chopper velocity v is used. This leads to a pulse width of $\tau_2/4$ and reduces the intensity by another factor of 2 (thus giving I/8). Precisely the same result (within the present approximations), i.e., pulse width $\tau_2/4$ and intensity I/8, is also obtained in case d) if the horizontal dimensions of the parallel and converging guide sections as well as that of the chopper window are reduced by a factor of 2. The latter case has the advantage of an intensity spatially concentrated within a single slit rather than in two.

Transmission of CGS and double-trumpet

Let us now consider the transmission of a converging guide section (CGS). Transmission and "gain factors" for such neutron guide elements have been calculated by several authors (Anderson, 1988; Mezei, 1988; Rossbach et al., 1988). We have also made such calculations (with a Monte Carlo program written by F. Mezei). Anderson has given analytical results. In the following I shall use his notation and consider the CGS of Fig. 1d as an example which, in one dimension, reduces the beam width from 2B to 2b, with a real space reduction factor $\beta = B/b = 2$. If the straight guide has a mirror coating with a critical angle γ_c, the CGS must be supermirror-coated with maximum reflection angle γ_{cc}, in order to achieve high transmission. In our example we may choose a critical angle ratio of $m = \gamma_{cc}/\gamma_c = 2$. Reflectivities of both neutron guide mirror and supermirror surfaces can be made close to 1 for reflection angles $\alpha < \gamma_c$. In the supermirror region, $\gamma_c < \alpha < \gamma_{cc}$, average values of about 0.8 can be achieved. For simplicity we shall assume here that the reflectivities are equal to 1 in both cases. Under these assumptions the transmission of the CGS shows periodic oscillations with maxima equal to 1 at values of $k = \Psi/\gamma_c = 1, 1/3, 1/5, 1/7$, etc. These maxima correspond to transmission of all neutrons which enter the CGS. If, for instance, the CGS inclination angle Ψ (Fig. 1) is chosen equal to γ_c(at $\lambda = 2$ Å) the transmission maxima are obtained at wavelength values of $\lambda = 2(2N-1)$Å, $N = 1, 2, 3,..$ The locations of the maxima can obviously be adapted to the experiment requirements by varying the above-mentioned CGS parameters.

We have thus shown that case d) of Fig. 1 is superior to b) and c) as regards neutron intensity just after the chopper for the given improvement in energy resolution. The use of more realistic reflectivity values would not change this qualitative result. However, it is a serious disadvantage of the simple CGS arrangement, that the sample to be studied in the experiment usually can not be placed very close to the last chopper. Because of shielding, sample environment and scattering angle requirements, a distance of at least 1 m is typical. At such distances the increase in flux density achieved by a CGS at the location of the chopper window, is lost due to the corresponding increase in divergence (cf. Louiville's theorem). This problem can easily be solved considering that we do not need to conserve the narrow beam width, once the neutron pulse has passed the chopper. It is quite evident that the addition of a supermirror-coated diverging guide section (DGS) just after the chopper will not only allow for a certain increase in beam width but also reduce the beam divergence. Thus, the beam will be focussed at distances from the chopper window which are convenient for applications. Such a CGS-DGS "double-trumpet" arrangement is shown in Fig. 1e for the symmetric case (equal inclination angles Ψ and equal lengths). It is seen by inspection that every neutron passing through the CGS will also be transmitted by the DGS. Therefore, the transmission of this double-trumpet is 1 if that of the CGS is 1. We note that the double-trumpet does not have to be symmetric. For instance the double-trumpet of the HMI time-of-flight spectrometer for reasons of space requirements will have a truncated DGS. This leads to different focussing properties at an equally high transmission. We may conclude that the double-trumpet arrangement described above is a good solution for the bottleneck problem initially stated. It is evident that the same method could be used for further improvements of the energy resolution with a minimum loss of intensity if the maximum supermirror reflection angle γ_{cc} could be increased beyond presently possible values. Detailed results of calculations of double-trumpet transmissions and focussed intensity distributions will be published elsewhere. Finally it should be mentioned that the multiple-slit chopper concept (Copley, 1988) in principle also permits still higher resolution if the number of slits per chopper is increased; however, this would require the use of a larger number of disks.

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