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OPTIMIZATION of the Transmission of a Double-Trumpet Neutron Beam Compressor

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ABSTRACT

With the aid of the Monte-Carlo method the transmission of a super-mirror coated double-trumpet beam compressor and its intensity distribution over the beam cross-section are studied numerically. The purpose of these calculations is the optimization of the geometrical dimensions of the neutron guide section before the sample,in order to obtain maximum neutron flux at the sample position. The transmission and the optimized parameter values are found to be wavelength-dependent. As a consequence we propose a variable compressor geometry.

I. INTRODUCTION

In a contribution to the ICANS-X conference, concerning neutron beam compressors for pulse widthreduction in a time-of-flight spectrometer, the use of a "double-trumpet" neutron guide arrangement was proposed as a useful component relevant for intensity and resolution optimization /1/. Such a "bottleneck" arrangement is a sequence of neutron guide sections, consisting of a conventional straight guide (with parallel walls) followed by a converging guide section (CGS) just before the last chopper of the spectrometer and a diverging guide section (DGS) just after this chopper. The latter two sections are supermirror (SM) coated, in order to compensate for the inclination of the double-trumpet side-walls.
The total transmission T of the double-trumpet (DT) is defined by the number of neutrons transmitted through its exit, divided by the number of neutrons entering into the DT. Even more important than T for practical purposes is the transmission T_s through a hypothetical window with dimensions corresponding to the sample size, located in a plane perpendicular to the incident neutron beam at the sample position. Both quantities depend on a number of parameters, such as mechanical dimensions of the double-trumpet, reflectivities, critical angle γ_c of the conventional guide section, maximum reflection angle γ_{cc} of the SM coated sections and neutron wavelength λ. The quantity T_s refers to a position in the neutron beam located after the double-trumpet exit at some finite distance from the latter. Therefore in addition to transmission it is also a measure of the DT's focusing properties and depends on the window (i.e.sample) size. The optimization of the double-trumpet leads to a certain choice of mechanical dimensions. This is necessarily a compromise, since beyond intensity and resolution considerations a number of

boundary conditions imposed by space and budget limitations have to be taken into account.

In the present paper we report on Monte-Carlo calculations of the transmission and focusing properties of double-trumpets. They were carried out, in order to optimize this component as a neutron beam compressor to be used in the multi-chopper time-of-flight spectrometer "NEAT" at the Hahn-Meitner-Institut in Berlin. The calculations are limited to the horizontal plane, since only a horizontal but no vertical beam compression is intended.

II. COMPARISON of CGS and DT Transmissions

An analytical result for the flux gain at the exit of a SM coated CGS, following a straight guide (see schematic drawing of Fig. 1a) was given by another author /2/. For our purpose this result is most conveniently discussed in terms of the total transmission T of the CGS, since we wish to obtain information on the intensity loss due to the use of this type of bottleneck in the neutron beam. Let us define the real-space reduction factor β = B/b (see Fig. 1a) and the divergence quotient m = γ_{cc}/γ_c (ratio of the SM limiting reflection angle γ_{cc} to the straight guide critical reflection angle γ_c).The transmission curve as a function of the neutron wavelength - according to ref. /2/ - displays oscillations which are periodic for β = m. Our Monte-Carlo calculations of the total transmission T of a CGS confirm this result: This is shown in Fig.2 where the open circles indicate calculated values; the full line is drawn to guide the eye. Here the realistic values β = m = 2 have been chosen. In order to make the results more transparent, the reflectivities have been set equal to 1 for reflection angles $\alpha \leq \gamma_c$ in the straight guide and for $\alpha \leq \gamma_{cc}$ in the CGS. Under these circumstances the transmission of the CGS shows periodic oscillations with maxima equal to 1 (i.e. all neutrons are transmitted) for values of k = Ψ/γ_c = 1,1/3,1/5,1/7,etc., where Ψ is the CGS inclination angle (see Fig. 1a). This angle was chosen equal to γ_c (at λ = 2Å) for the natural isotope mixture of Ni in this particular calculation. As a consequence the transmission maxima are obtained at wavelength values of λ = 2(2N-1)Å, N = 1,2,3,... .The maxima are necessarily separated by dips in T, but T is nowhere smaller than 0.92, except for $\lambda <$ 2Å. There, due to the particular choice of the inclination angle Ψ, the contribution to T of neutrons reflected within the CGS rapidly vanishes, so that T approaches its limiting value, which is 0.5 at λ = 0.

Although this result is encouraging, the simple CGS arrangement is not the best choice of a beam compressor for the present purpose. It has been suggested, that a CGS-DGS double-trumpet arrangement should be used instead because of its better focusing properties. This type of beam compressor has the same total transmission as the CGS alone, whether the DGS is truncated (Fig. 1c) or fully symmetrical (Fig. 1d), if both guide sections have the same inclination angle and the reflectivities are equal to 1 /1/. Therefore the calculated T values of Fig. 2 (circles) are valid for all four cases (a to d) of Fig. 1. This is quite evident. What we really are interested in, however, is the transmission through a window (representing the sample) at a certain distance from the exit of the neutron beam compressor. This is where the advantageous focusing properties of a double-trumpet become important. Infact the four cases of Fig. 1 are quite different from each-other in this respect. The Monte-Carlo calculation of T_s, carried out for a guide width of 2B = 30mm

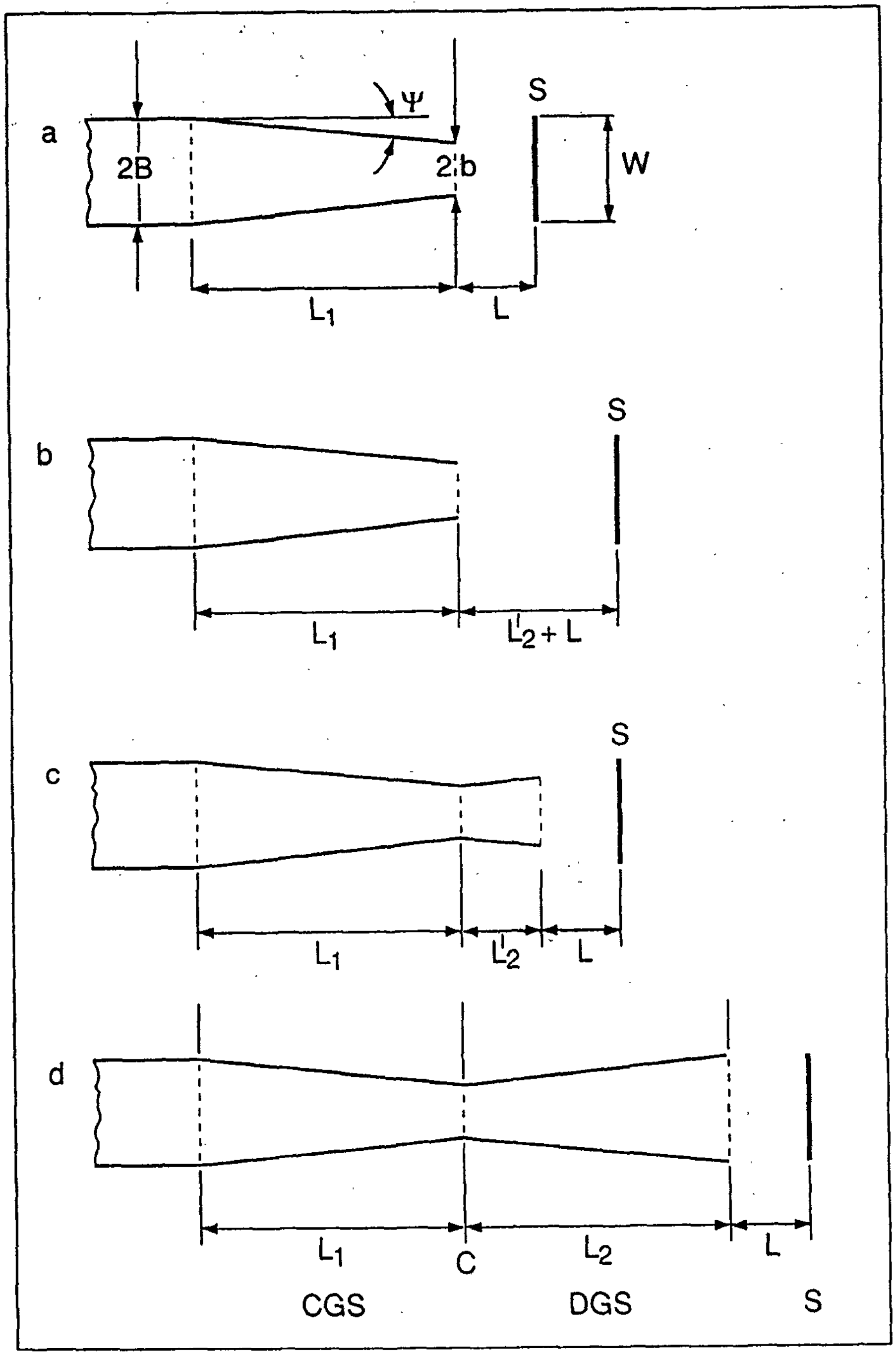

Fig. 1

Neutron beam compressor arrangements (shown schematically) in the neighbourhood of the chopper (chopper location indicated by C), following a straight neutron guide (G): G is followed by an "anti-trumpet" type converging guide section (CGS) of length L_1, width 2B at its entrance, width 2b at its exit.

a) sample S is placed at distance L from CGS exit.
b) sample at distance $(L_2'+L)$ from CGS exit.
c) a "trumpet" type diverging guide section (DGS) of length L_2' is added after the CGS, thus forming an asymmetric double-trumpet; sample is at same location as in b), i.e. at distance L from exit.
d) symmetric double-trumpet arrangement, S at distance L from exit.

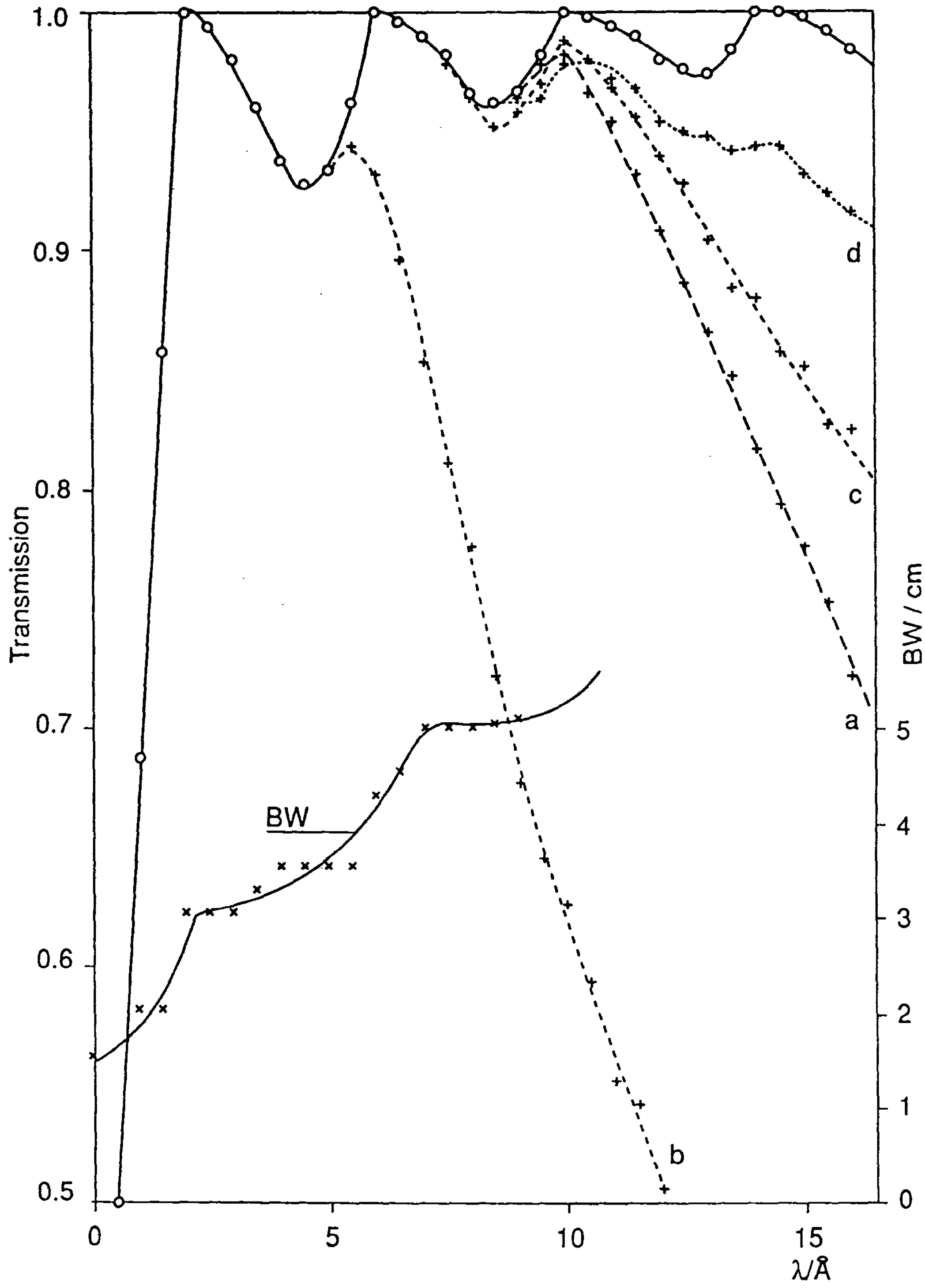

Fig. 2

Neutron beam compressor transmissions from Monte-Carlo calculations as a function of the neutron wavelength λ for the four different arrangements, a to d, of Fig. 1. Circles: total transmission (same for all four arrangements). Crosses (+): transmission through a window (width w = 50mm) at the sample location. Also shown is the calculated "focal" beam width (BW) at the sample position for case a); lines are drawn to guide the eye. Total reflection and supermirror reflectivities have been set equal to 1. Parameter values: $L_1=L_2=2143$, $L_2'=550$, $L=615$, $2B=30$, $2b=15$ (units: mm). The parallel-walled neutron guide is coated with the natural Ni isotope mixture (critical angle of total reflection γ_c), the CGS-DGS element is supermirror coated (cut-off reflection angle $\gamma_{cc} = 2\gamma_c$).

and a sample width of w = 50mm, confirms this. It shows that the symmetrical double-trumpet clearly has the best focusing properties: T_s only starts to deviate slightly from the total transmission curve above $\lambda \sim 9$Å; but even at λ = 16Å the loss in transmission is only about 7% (Fig.2, curve d; crosses indicate calculated values, dashed lines are drawn to guide the eye). If the DGS is truncated, T_s decreases somewhat faster with increasing λ. But even for an appreciable truncation, e.g. reducing the DGS to about 25% of its original length, the loss in transmission does not rise to more than about 17% at λ = 16Å (Fig.2, curve c). This is certainly much better than the case, where the DGS is completely omitted, while the sample is kept at the same position. In this case T_s starts to deviate from T appreciably already at $\lambda \sim 6$Å and decreases very rapidly with increasing wavelength (Fig.2, curve b). In summary the curves of Fig. 2 suggest, that the distance from the guide exit to the sample roughly determines the λ- limit where T_s starts to deviate from T, while the slope of the decreasing T_s curve is governed by the length of the DGS.

At this point we should like to mention, that the final geometrical parameter values (lengths, widths, angles) which we have actually chosen for the construction of the double-trumpet to be used in the spectrometer NEAT, were not only influenced by the results of the Monte-Carlo calculations but to a large extent also by instrument "boundary conditions". These final values are very close to the following numbers used in the calculations which resulted in curve c of Fig.2 :

L_1 = 2143mm; length of CGS.
L_2' = 550mm; maximum possible DGS length (it has to end before the wall of the sample chamber).
L = 615mm; remaining distance to the sample position.
$L_2' + L$ = 1165mm; distance from the CGS exit (location of the chopper) to the sample.

It should be noted, that the cases a) and d) of Fig.1 (corresponding to curves a) and d) of Fig.2) can not be realized in the spectrometer NEAT because of the boundary conditions (due to resolution considerations and space requirements) which essentially determine the distance from the CGS exit to the sample. The curves a) and d) were merely calculated for the purpose of comparison.

Another result is seen in Fig.2. As an example the numbers calculated for case a) of Fig.1 were used here. This concerns the reason for the decrease of the transmission T_s, as the wavelength increases beyond $\lambda \sim 9$Å. This is elucidated by the calculation of the width of the "illuminated" surface on the plane perpendicular to the neutron beam at the sample position. This width starts to be larger than the selected sample "window" near $\lambda \sim 9$Å (curve BW in Fig.2).

III. DEPENDENCE of the Transmissions on the Length of the CGS and on the Reflectivities

While the instrument boundary conditions are rather stringent regarding the choice of the values of B, b, L and L'_2, the range of possible values of the length L_1 of the CGS is fairly large in the case of NEAT. Therefore the transmissions of a double-trumpet were studied numerically as a function of L_1. In these calculations all other parameters, including the reflectivities and guide coatings were the same as in the case of curve c in Fig.2 (see Section II). The results are shown in Fig.3a, b and c for L_1 = 4286mm, 2143mm

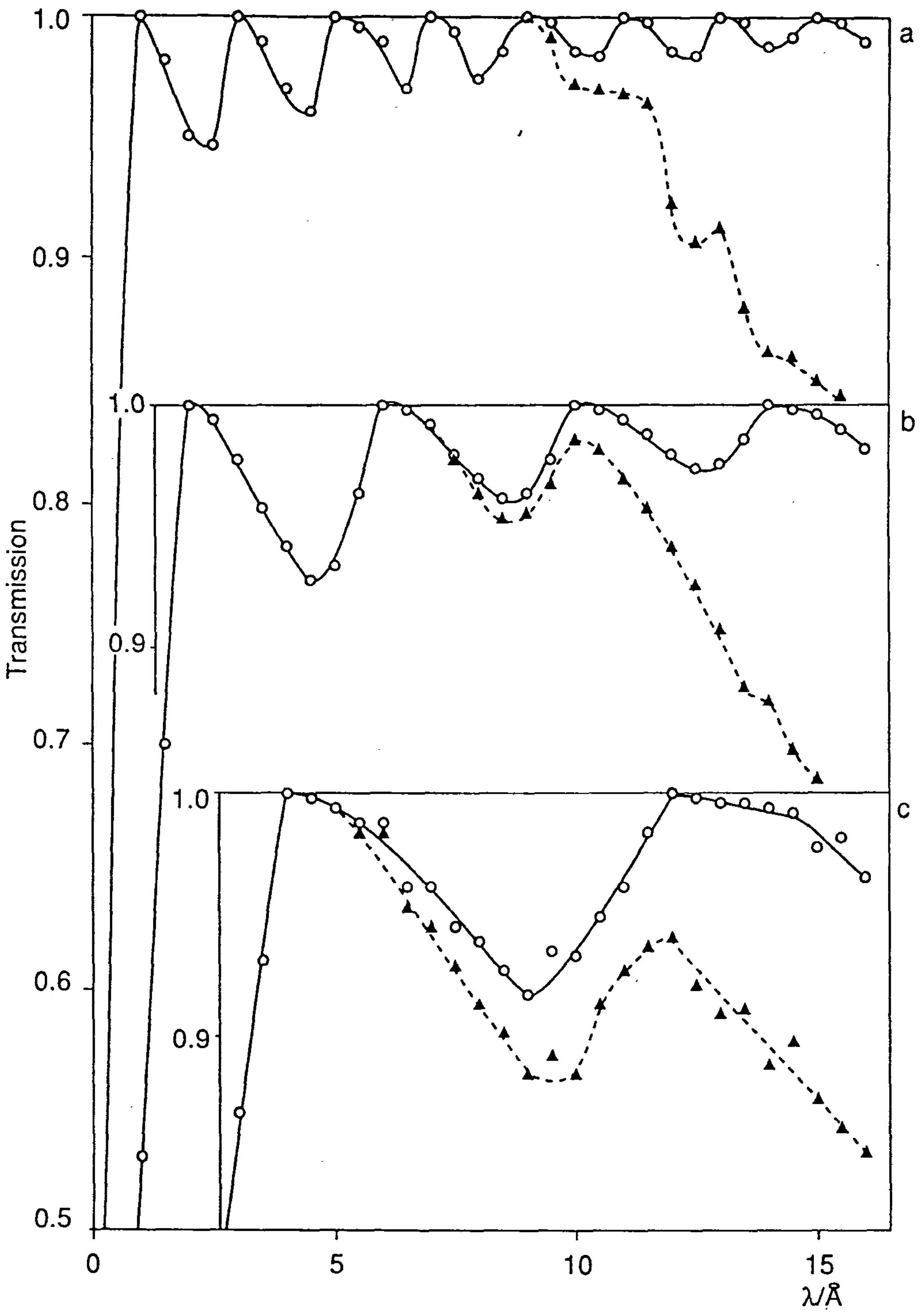

Fig. 3

Total transmissions (circles) and transmissions through a window at the sample position (triangles) for three double-trumpet arrangements differring in the length L_1 of the CGS: a) L_1 = 4286mm, b) L_1 = 2143mm, c) L_1 = 1071.5mm. All other parameters are the same in the three cases: L'_2= 550mm, L = 615mm, 2B = 30mm, 2b = 15mm, w = 50mm; reflectivities and guide coatings are the same as in Fig.2.

and 1071.5mm, respectively. The values of T are indicated by circles, those of T_s by triangles. The following observations are made: i) the period of oscillation of T as a function of the neutron wavelength λ is inversely proportional to the length L_1 of the CGS.

The transmission maxima are obtained at wavelength values of λ = (2N-1)Å, 2(2N-1)Å and 4(2N-1)Å in Fig.3a, b and c, respectively. This is, because the CGS (and DGS) inclination angles ψ were chosen such, that $\psi = \gamma_c$(at λ = 1Å, 2Å and 4Å, respectively).

ii) the amplitude of the oscillation increases with decreasing L_1.

iii) the λ-limit, where T_s starts to deviate from T, decreases with L_1.

iv) the transmission "gap" at low wavelengths increases, as L_1 decreases.

All these features would favour a maximization of the length L_1. A conclusion can however only be drawn, when the ideal reflectivity values (so far set equal to 1) are replaced by realistic ones. Therefore the next step in this study was a calculation of the transmissions for various combinations of reflectivity values in the straight neutron guide and in the SM coated double-trumpet. The following assumptions concerning the reflectivities were made in these calculations: Firstly, the reflectivity in the total reflection region (RTR) was assumed to be constant in the whole region. Secondly, in the supermirror region, $\gamma_c \leq \alpha \leq \gamma_{cc}$, the reflectivity was assumed to be linearly decreasing towards a minimum value at γ_{cc}, the "reflectivity at maximum angle" (RMA). Finally, for $\alpha > \gamma_{cc}$ the reflectivity was set equal to zero.

In Fig.4 we compare as an example the calculated total transmission values (curve a) for a double-trumpet with the same specifications as used in Fig.3a (L_1 = 4286mm, L'_2= 550mm, 2B = 30mm, 2b = 15mm, RTR = 1, RMA = 1) to three curves corresponding to different combinations of the RTR and the RMA. In the case of the curves b and d a realistic value of 0.98 was chosen for the RTR, whereas for the curve c this was set equal to 1. The RMA was set equal to 0.98 in the case of curve b, whereas for the curves c and d somewhat pessimistic values (0.75 and 0.735, respectively) were used. As expected the total transmission decreases with increasing wavelength, when the reflectivities are smaller than 1. This is due to the fact, that the number of reflections increases with λ. In addition it is observed, that the oscillations of T with λ appear to be damped in the cases, where the RMA is appreciably smaller than 1 (curves c and d).

We wish to conclude this discussion by comparing the transmissions, T and T_s, of the double-trumpet with those of a "normal" parallel-walled neutron guide. So far in all our calculations a natural Ni isotope mixture coating was assumed for the parallel guide section. For the SM coated DT-part of the arrangement $\gamma_{cc} = 2\gamma_c$(Ni-nat.) was used. In the actual case of the NEAT spectrometer it was however decided, that neutrons will be supplied by a parallel-walled guide coated with the isotope Ni-58, which has a γ_c-value larger by 20% than that of Ni-nat. The CGS-DGS sections will be coated such, that the γ_{cc}-value is the same as mentioned above (i.e. twice the γ_c-value of Ni-nat.). Thus $\gamma_c > \gamma_{cc}/2$ and the divergence quotient m is then smaller than 2. As a consequence the transmissions T and T_s are expected to be generally somewhat lower, than they would be for m = 2, if otherwise identical parameter values are used. In Fig.5 we show the T (open circles) and T_s (full circles) values calculated under such conditions for a double-trumpet with L_1 = 2143mm and L'_2= 550mm. The values of B, b, w and L are the same as the ones used for the calculations of Fig.2. Realistic numbers were chosen for the reflectivities: RTR = 0.98 and RMA = 0.833. For comparison T and T_s were also calculated for a straight parallel-walled guide of the same total length ($L_1+L'_2$= 2693mm) and with the same coating as

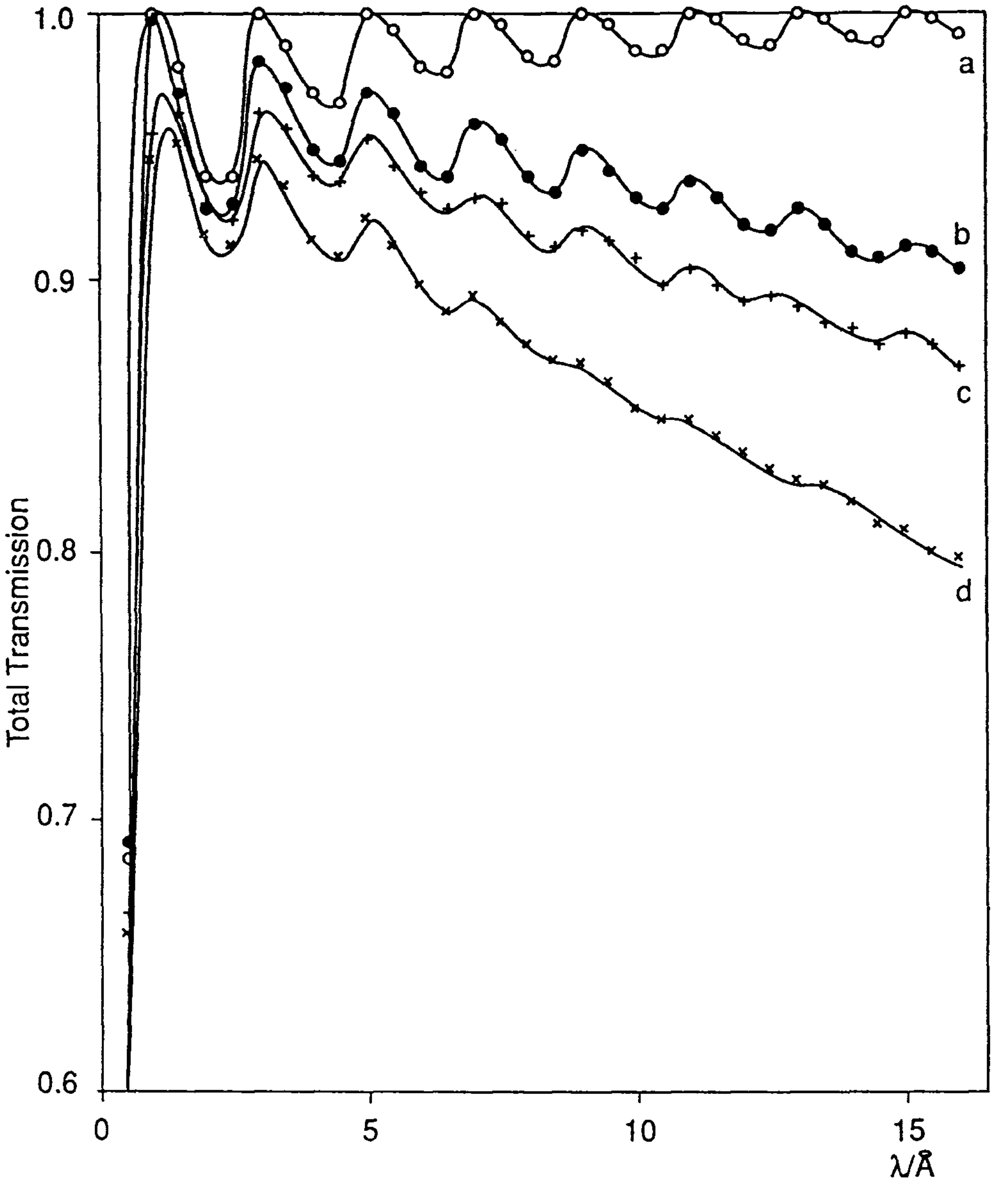

Fig. 4

Total transmission for various combinations of reflectivity values in a double-trumpet arrangement with the following dimensions: L_1 = 4286mm, L'_2 = 550mm, 2B = 30mm, 2b = 15mm. The reflectivity is assumed to be constant for reflection angles $\alpha \leq \gamma_c$, but to decrease linearly in the region $\gamma_c < \alpha \leq \gamma_{cc}$ down to a minimum value at γ_{cc}. The definitions of γ_c and γ_{cc} and the guide coatings are the same as in the calculations for Fig.2.

a) Reflectivity in the total reflection region (RTR) = 1.
   Reflectivity at the maximum angle γ_{cc} (RMA) = 1.
b) RTR = 0.98, RMA = 0.98
c) RTR = 1, RMA = 0.75
d) RTR = 0.98, RMA = 0.735

the DT: curves a and b, respectively, in Fig.5. It is seen that the transmissions of the DT are generally lower by roughly 10 to 20%, in the λ-range from 2.5 to 16Å, than the corresponding transmissions of the parallel-walled guide. Nevertheless - because of the beam compressor action - the flux gain factor of the double-trumpet

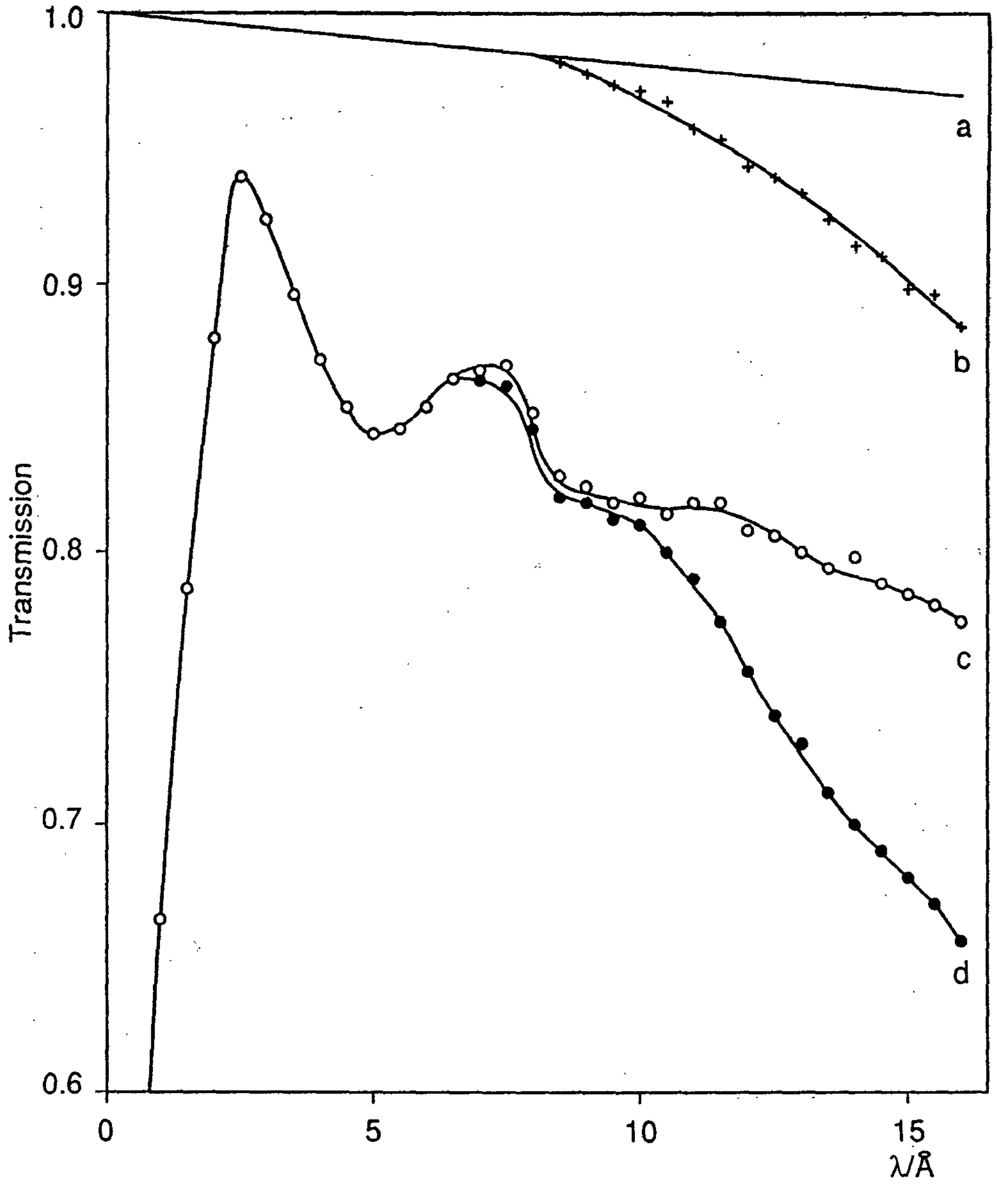

Fig. 5

Comparison of transmission properties of a straight guide (upper 2 curves) with those of a double-trumpet (lower 2 curves) of the same total length, $(L_1+L'_2) = (2143 + 550)$mm; the parameter values B, b, w and L are the same as in Fig.2. The arrangement is supermirror coated with $\gamma_{cc} = 2\gamma_c$(Ni-nat.) in both cases, whereas the incoming straight guide is coated with Ni-58. Note that γ_c(Ni-58)$\sim$ $1.2\gamma_c$(Ni-nat.). The curves a and c correspond to total transmission; the curves b and d show the transmissions through a window of width w at a distance L from the exit of the guide arrangement (sample position). Realistic values of the reflectivities were used: RTR = 0.98, RMA = 0.833 .

over the parallel guide (which is twice the transmission for B= 2) lies between 1.8 and 1.6 in the whole λ-range mentioned above, at the exit of the CGS.
The effect of changing the length of the CGS can be judged from Fig.6, where results of calculations analogous to those of Fig.5 are shown. Here L_1= 4286mm was chosen; all other parameter values were the same as in Fig.5. It is quite evident from these figures,

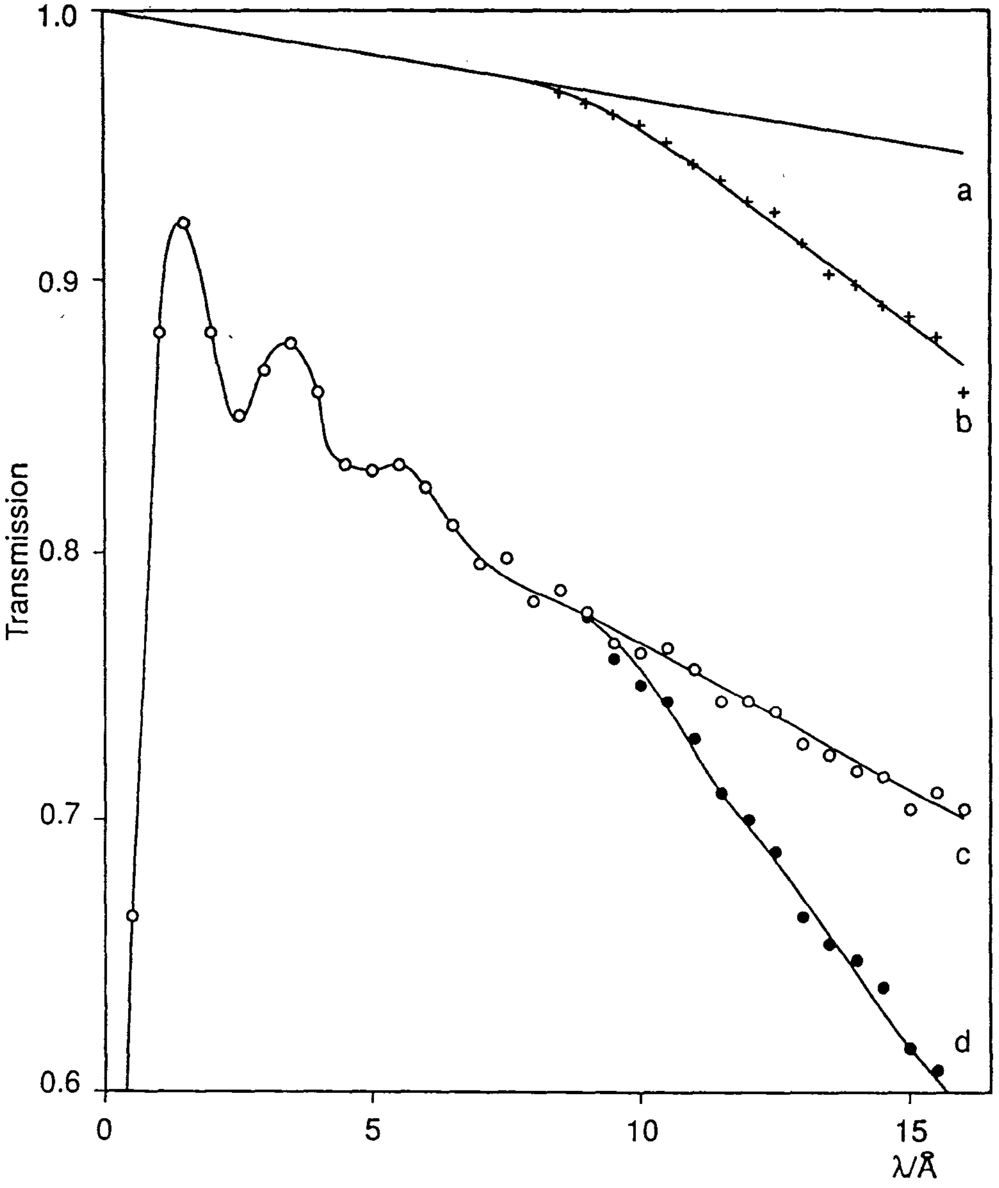

Fig. 6

Comparison of straight guide and double-trumpet as in Fig.5, except that L_1 was doubled: L_1= 4286mm.

that the transmission values of the longer DT are generally lower than those of the shorter one. It seems obvious, that this must be due to a larger number of reflections occurring within the longer flight path. In order to make this comparison completely fair, the attenuating effect of a parallel guide section before the shorter DT, which would compensate for the difference in length of the two DTs, should be added. Although this was not taken into account in Fig.5, it is easy to see by inspection of curves a and b, that the inclusion of this effect would not change the qualitative result of this comparison. Therefore we have chosen the shorter one of the two double-trumpets as a beam compressor to be built for the time-of-flight spectrometer NEAT.

Finally we would like to point out, that it is also possible - in principle - to optimize the construction of a double-trumpet with respect to the positions of oscillation maxima of the transmission as a function of λ. If the inclination angle ψ of the double-trumpet side-walls is made variable, in general one of the maxima of T (or T_s) may be shifted into the λ-value selected for the experiment, in order to maximize the intensity. A double-trumpet constructed in this way may also be transformed without difficulty into a parallel-walled guide for experiments, where this is an advantage.

References

/1/ R. E. Lechner, in "Advanced Neutron Sources 1988", ed. D. K. Hyer (Institute of Physics Conf. Series No.97, Institute of Physics, Bristol and New York), page 843(1989).

/2/ I. S. Anderson, in "Thin Film Neutron Optical Devices", Proc. SPIE 983 (1988).

Q(H.Tietze): What is the cross-section shape of the double trumpet used and what about an influence of a non-circular cross-section shape on the transmission and performance of the device with respect to an isotopic circular cross-section?

A(R.E.Lechner): The cross-section is rectangular. Because of the purpose of the double-trumpet (pulse-width reduction of a disk-chopper) it has to be rectangular. For other purposes (e.g. purely spatial focusing) a circular cross-section could be useful. The transmission could be calculated in an analogous way; the problem is two-dimensional, whereas my calculation is in one dimension only: the flux is calculated in a horizontal axis perpendicular to the beam.