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OPTIMIZATION of a Multi-Disk Chopper Spectrometer for Cold Neutron Scattering Experiments

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ABSTRACT

The optimization with respect to intensity and resolution of the new multi-disk chopper time-of-flight spectrometer NEAT at the Hahn-Meitner-Institut (HMI) is discussed. In this discussion the following instrument variables and parameters are relevant :

- incident neutron wavelength and its range
- chopper revolution rate ("tangential" speed of disks)
- pulse widths of the two principal choppers and their ratio
- lengths of flight path between pricipal chopper disks and from sample to detectors
- total solid angle covered by the detectors
- transmissions of various spectrometer components.

It is shown, that a careful choice of parameter values, together with the minimization of neutron flux losses within the spectrometer, should allow to increase the intensity by at least an order of magnitude for given incident neutron flux and given energy resolution, as compared to existing spectrometers of the same type. The solution chosen for NEAT will provide a variable energy resolution at the detectors, which for elastic scattering is calculated to be in the range of $2\mu eV \leq \Delta(\hbar\omega) \leq 2meV$.

I. INTRODUCTION

In January 1985 the journal Physics Today presented on its frontpage a photograph of the Institut Laue-Langevin's neutron guide hall showing at its center the blue-coloured neutron shielding of the multi-chopper time-of-flight spectrometer IN5. This instrument /1/ is known to be one of the most successful high-resolution cold-neutron spectrometers for the study of low-energy excitations in condensed matter. About one year earlier (in 1984) we had decided at the Hahn-Meitner-Institut (HMI) in Berlin to build a new instrument of this kind for the same class of neutron scattering experiments. Obviously in this context the question arose, in which way such a spectrometer could be further improved regarding energy resolution and intensity. An answer to this question will be given in the present paper, with reference to the multi-chopper time-of-flight spectrometer NEAT under construction at the HMI.

II. SPECTROMETER Principle and Optimization

Let us start by briefly discussing the spectrometer principle as illustrated in Fig. 1 for the case of IN5. The left-hand side of the figure schematically shows the geometrical arrangement: Four chopper disks rotating around a horizontal axis are aligned along a neutron guide. The first (Ch1) and the last chopper (Ch4) are used to define the desired incident-neutron wavelength λ_0 by an appropriate phasing of their windows with respect to each-other. The remaining two choppers (Ch2 and Ch3) have additional filter functions required to achieve the monochromatization of the pulsed neutron beam and to avoid overlap in time of scattered neutron spectra due to consecutive chopper pulses. The nickel-coated glass guide connecting the choppers permits a transport of the neutrons from the first chopper to the sample (S) with very little loss in solid angle. At the sample the neutrons are scattered and then counted by a large number of detectors (D), set up at a distance of about 4m from the sample and at scattering angles from close to 0° up to about 132°.

The right-hand side of Fig. 1 represents - again schematically - a time-of-flight/flight-path diagram of the spectrometer for $\lambda_0 = 6\text{Å}$ as an example. It illustrates the role of each chopper disk: Ch1 creates a "white" pulse which on its way quickly spreads in time, since it contains the rather large spectrum of neutron wavelengths ($1\text{Å} \lesssim \lambda_0 \lesssim 20\text{Å}$) provided by the combination of a cold source moderator and a slightly curved neutron guide. At the location of Ch4 consecutive pulses would largely overlap each-other, because the faster neutrons of each pulse would have overtaken the slower ones of the corresponding previous pulse, by the time they arrive there. Therefore a pre-selection, narrowing down the wavelength band, is performed at an earlier stage by Ch2, in order to make the final monochromatization by Ch4 possible. Thus nicely tailored monoenergetic neutron pulses are leaving periodically Ch4 to be scattered at S. Scattering however transforms the pulses back into wide wavelength distributions reflecting the dynamics of the scattering system. The corresponding time distributions are generally so broad, that a new overlap problem arises at the detectors for spectra belonging to consecutive pulses. This problem can be circumvented by reducing the chopper pulse frequency with the aid of Ch3, running at a lower revolution rate. The corresponding time-of-flight period P3 is an integer multiple of the original value P.

The brief description of the IN5 lay-out given above represents a possible (and successful) solution for a multi-disk chopper t.o.f. spectrometer. The question, how the performance of such an instrument can be further improved, is answered by optimizing the spectrometer with respect to intensity and resolution. For this purpose three basically different, but to some extent interrelated problems must be considered:

i) Determination of optimum instrument parameter values on the basis of the fundamental relations between intensity and resolution on the one hand and spectrometer variables and parameters on the other.

ii) Effect of boundary conditions (mainly due to space and budget restrictions) on the possible choice of parameter values.

iii) Technical feasibility and optimization of spectrometer components, especially regarding their transmission.

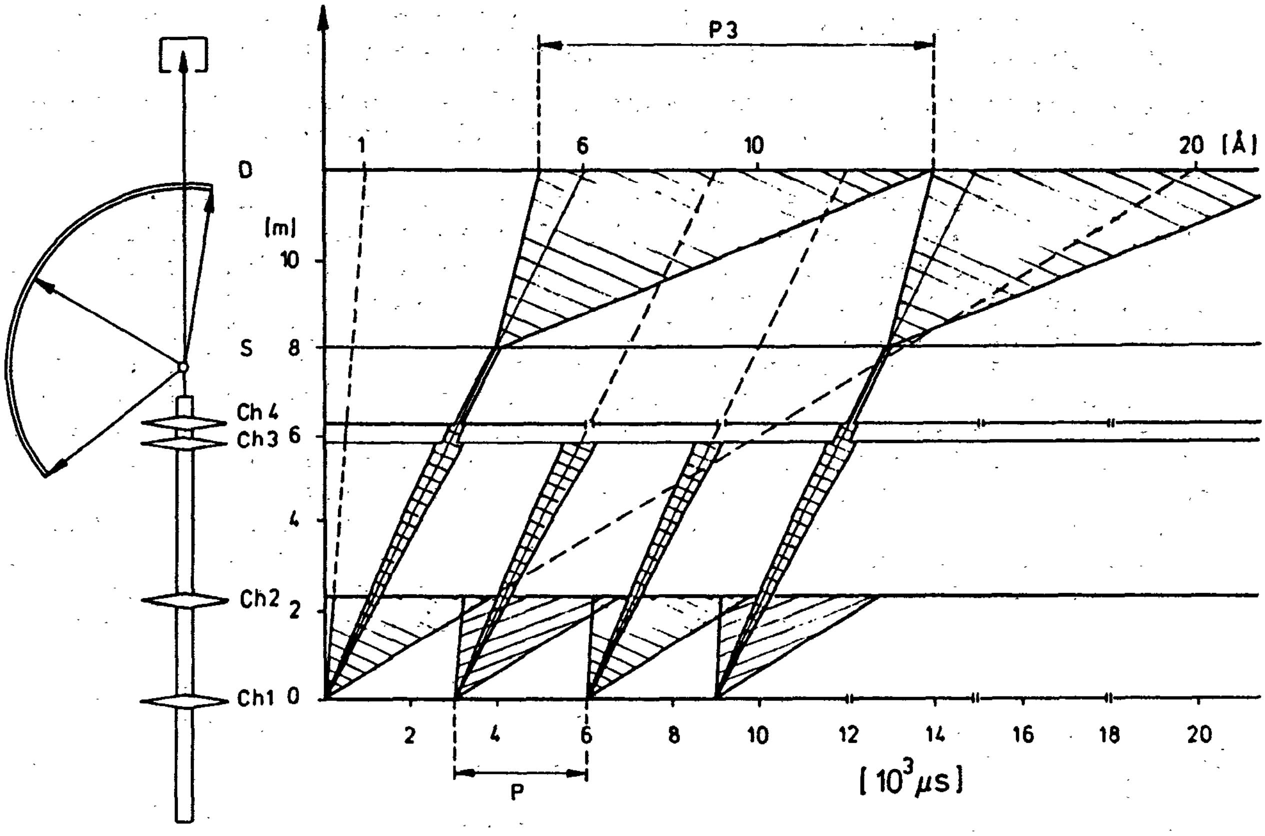

Fig. 1
Schematic drawing of the principle of a multi-chopper time-of-flight spectrometer (example: IN5). Left-hand side: four chopper disks (Ch1 to Ch4) aligned along a neutron guide directing the beam to the sample S in the center of a large detector array D. Right-hand side: time-of-flight/flight-path diagram for λ_0= 6Å. The positions on the flight-path axis corresponding to the different chopper disks, to the sample and to the detectors are indicated by horizontal lines. P is the period defined by the time elapsing between consecutive neutron bursts of Ch1. P3 is the period of the frequency reduction chopper Ch3. The hatched areas indicate the regions covered by neutron pulses, as they spread in time during their flight.

III. FUNDAMENTAL Spectrometer Relations

For the discussion of the basic formulae governing the relation between intensity, energy resolution and spectrometer parameters /2/, it is sufficient essentially to consider the two principal choppers which define the monochromatic neutron pulse. In the example of Fig. 1 these are the disks Ch1 and Ch4. Ch2 has no influence on intensity and resolution, because its pulse frequency, phasing and opening time are chosen such, that they do not prevent any neutrons of the wavelength band, to be selected by Ch4, to pass by the latter. For similar reasons Ch3 does not affect the resolution; it merely reduces the intensity by the same factor, by which it divides the pulse frequency. This reduction factor can however be expressed by an approximation in terms of the selected neutron wavelength λ_0 and the distance L_{SD} between sample and detectors. Thus no parameter directly related with Ch2 and Ch3 will appear in the spectrometer relations.

In deriving the formulae a number of assumptions and approximations were made. It was assumed that the mean width of each chopper window is equal to the inner width of the neutron guide, at the location where the disk is rotating. This is exactly true in the case of IN5 and also for one set of windows of the NEAT choppers. Since the border lines of the windows are oriented in radial directions, all windows have trapezoidal shape, deviating slightly from the rectangular cross-section of the neutron guide. As a consequence all neutron pulses created by single chopper disks have close to (but not exactly) triangular shape in time. These distributions have been approximated by Gaussians, in order to simplify their convolutions and the determination of the resulting widths in the resolution calculation. In fact, even if the single chopper pulses had exactly triangular shape, this would be a very good approximation.

The duration of the time-of-flight period, P3 = N·P, is equal to the flight time of neutrons with the maximum wavelength λ_{max}, that is to be observed. P3 is therefore proportional to λ_{max} and to L_{SD}. λ_{max} is usually chosen roughly proportional to λ_0; exact proportionality is not possible, since for given P only discrete values of P3 are allowed, N being an integer. The choice of N is dictated by the necessity to reduce the frame-overlap of scattered neutron spectra; nevertheless the value of N is not unique, since it depends to some extent on experiment-specific requirements. Therefore, in order to simplify the study of the general behaviour of intensities as a function of instrument parameters, P3 was replaced by a continuous function proportional to the product $\lambda_{max} L_{SD}$.

Further approximations concern the neglection of attenuation factors due to losses in the neutron guide (imperfections of alignment and reflectivity, gaps in the reflecting guide walls) and losses by absorption and scattering in the material encountered along the neutron flight path (rest gas, windows, sample holder and detector walls). This is justified, because such attenuation factors have relatively little effect on the optimum choice of instrument parameter values; they are minimized independently by the available technical means (see below). For the same reason finally the effect of sample geometry (e.g. orientation) on the resolution has been neglected.

On the basis of the above assumptions and approximations the relations for the intensity and the energy resolution were obtained /2/. The intensity I at the sample position, i.e. the number of neutrons hitting the sample per cm^2 and second, is given by

$$I = \emptyset(\lambda_0) \cdot F \cdot h^2/(m^2 \cdot \lambda_{max}) \qquad (1)$$

where $\emptyset(\lambda_0)$ is the differential neutron flux at the "monochromatic" wavelength λ_0 to be selected by the last chopper. We define $\emptyset(\lambda_0)$ as the number of neutrons arriving at the first chopper per unit of beam area, time and wavelength. This differential flux is already integrated over the beam divergence allowed for by the guide. The factor F contains those spectrometer parameters, which are relevant for the intensity :

$$F = \tau_1 \cdot \tau_2 \;/\; (L_{12} \cdot L_{SD}) \qquad (2)$$

Here τ_1 and τ_2 are the "opening times" of the first and the last chopper, respectively, i.e. the full-width-at-half-maximum (FWHM) of the neutron pulses at the locations of these choppers. L_{12} and L_{SD} are the lengths of the neutron flight paths between the two principal choppers and from the sample to the detector, respectively; h is Planck's constant and m is the neutron mass.

The energy resolution $\Delta(\hbar\omega)$ of the spectrometer is the apparent FWHM in energy (at the detectors) of the spectrometer's response to a δ-function peak in the double-differential neutron scattering cross-section :

$$\Delta(\hbar\omega) = \Delta t_d \cdot h^3 \;/\; (L_{SD} \cdot m^2 \cdot \lambda^3) \qquad (3)$$

Here λ is the wavelength of scattered neutrons; Δt_d, the time spread (FWHM) of the resolution-broadened δ-function, is given by:

$$\Delta t_d = (A^2 + B^2 + C^2)^{1/2} \;/\; L_{12} \qquad (4)$$

with

$$A = \delta L \cdot \lambda \cdot L_{12} \cdot m \;/\; h \qquad (5)$$

$$B = b \cdot \tau_1, \text{ where } b = (L_{2S} + L_{SD} \cdot \lambda^3 \;/\; \lambda_0^{\,3}) \qquad (6)$$

$$C = c \cdot \tau_2, \text{ where } c = (L_{12} + L_{2S} + L_{SD}\, \lambda^3 \;/\; \lambda_0^{\,3}) \qquad (7)$$

The term A is due to the uncertainty δL in the length of the flight path, caused by beam divergence, finite sample size and detector thickness; the terms B and C represent the contributions of the chopper system, where L_{2S} is the distance from the second of the two principal choppers (Ch4 in Fig.1) to the sample; the other parameters have already been defined above.
We note, that calculations related to the same subject have been published earlier in a theoretical treatment of the resolution function of a two-rotor neutron velocity selector /3/. The resulting formulae for intensity and resolution differ however from ours.

IV. OPTIMIZATION of Intensity and Resolution

We wish to maximize the intensity I for any desired value of $\Delta(\hbar\omega)$ within the accessible range of energy resolutions, for a given pair (λ_0, λ) of neutron wavelengths. At a cold neutron guide neutron flux is available within the approximate limits $1Å \leq \lambda_0 \leq 20Å$ and scattered neutrons are then observable roughly in $1Å \leq \lambda \leq 24Å$. Intensity and resolution, given by expressions (1) to (7), are theoretically amenable to optimization via the variation of the spec-

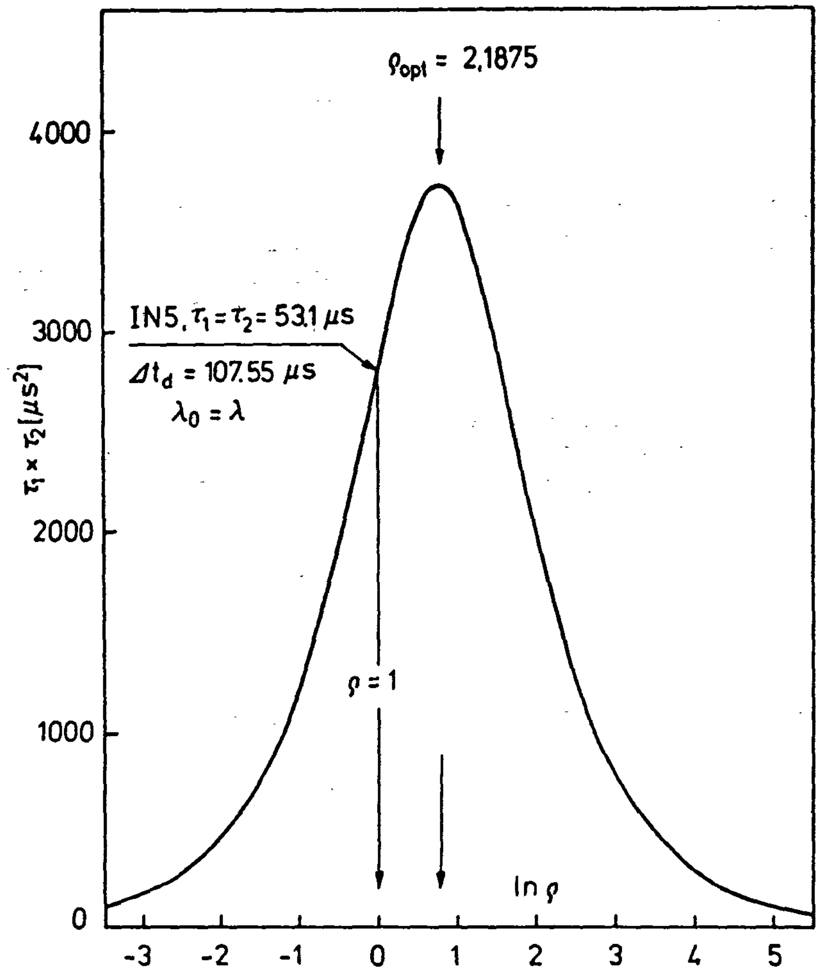

Fig. 2
The product of the chopper burst times $\tau_1 \cdot \tau_2$ as a function of $\ln\rho$, where $\rho = \tau_1/\tau_2$, is peaked at $\ln\rho_{opt}$; $\tau_1 \cdot \tau_2$ is proportional to the intensity at the sample. Example: spectrometer IN5 for elastic scattering ($\lambda_0 = \lambda$), for fixed time resolution at the detectors, $\Delta t_d = 107.55\ \mu s$.

trometer parameters L_{12}, L_{2S}, L_{SD}, δL, τ_1 and τ_2. In practice there are of course some restrictions due to (sometimes trivial) boundary conditions. It is immediately evident, that the flight-path uncertainty δL and the distance L_{2S} from the last chopper to the sample should be minimized. This improves the resolution without any loss in intensity. To decrease δL one has to reduce the sizes of sample and detectors. In the case of L_{2S} the possibility of minimization depends on the required range of scattering angles and on the space needed for sample environment and shielding. Values of the order of 1cm for δL and 1m for L_{2S} (1.2m in the case of NEAT) have been realized.
In choosing values of the parameters L_{12}, L_{SD}, τ_1 and τ_2 we have to keep in mind, that the highest possible resolutions generally require long distances and short pulse widths (see eqs. (3) to (7)). Furthermore it is desirable to have access to a large range of

energy resolutions, which means that at least some of these parameters must be variable. In the case of the spectrometer NEAT L_{12} has been fixed for theoretical and for practical reasons at the value of 12.1m, whereas L_{SD} is variable within certain limits (L_{SD} = 2.5m for about 400 He-3 detectors and 4m $\leq L_{SD} \leq$ 7.5m for a two-dimensional multidetector); τ_1 and τ_2 can be varied by factors of up to 80. Some technical details concerning the choppers will be given in the next Section.

The question of optimization can now be asked in two ways :
i) which set of spectrometer parameter values will maximize the intensity I for a given value of the resolution $\Delta(\hbar\omega)$?
ii)which set of spectrometer parameter values will minimize the resolution width $\Delta(\hbar\omega)$ for a given intensity I ?
Both questions have the same answer, namely the following simple condition for the optimum of the ratio $\rho = \tau_1/\tau_2$ of the two chopper opening times /4/ :

$$\rho_{opt} = (L_{12} + L_{2S} + L_{SD}\lambda^3/\lambda_0^{\,3})/(L_{2S} + L_{SD}\lambda^3/\lambda_0^{\,3}) \qquad (8)$$

This relation covers all elastic and inelastic scattering experiments. We note, that it is independent of the flight-path uncertainty δL and of the pulse widths, τ_1 and τ_2. An analogous expression, but for the special case of elastic scattering only ($\lambda = \lambda_0$), has been mentioned previously by another author /5/.

Let us now study the intensity according to eq. (1) and see, how this behaves as a function of ρ, when the resolution is kept constant. Since the intensity does not depend on the flight-path uncertainty δL, we will neglect the term A in the expression (4) for Δt_d. As an example we will first consider the spectrometer IN5 for $\lambda \cong \lambda_0$ (L_{12} = 6.25m, L_{2S} = 1.286m, L_{SD} = 3.977m). Assuming a chopper velocity of 15000 revolutions/minute, the chopper opening times are $\tau_1 = \tau_2 =$ 53.1μs for $\rho = 1$. The time spread Δt_d at the detectors, obtained from eqs. (4) to (7) (with A=0) is then 107.55μs. (This corresponds to a possible conventional mode of operation of the chopper system). We will keep Δt_d fixed at this value, while ρ is varied. Since all parameters in the expressions (1) and (2), except for τ_1 and τ_2, have been fixed, it suffices to consider the product $\tau_1 \cdot \tau_2$, which is proportional to the intensity I at the sample. Starting from eqs. (4) to (7), the function $\tau_1 \cdot \tau_2$ can be expressed in terms of ρ :

$$\tau_1 \cdot \tau_2 = L_{12}^{\,2} \cdot \Delta t_d^{\,2} \,/\, (b^2 \rho + c^2 \rho^{-1}) \qquad (9)$$

Plotted as a function of lnρ, the intensity represented by ($\tau_1 \cdot \tau_2$) is peaked at the optimum opening time ratio $\rho = \rho_{opt}$, given in eq. (8), as can be seen in Fig. 2. Furthermore $\tau_1 \tau_2$ is perfectly symmetric about this value which is ρ_{opt} = 2.1875 in our example. In the case of the chopper system considered (with equal beam widths and windows for both principal choppers) the phasing requirement only permits the use of integer ρ values. It is therefore more interesting to examine ($\tau_1 \cdot \tau_2$) at ρ=2. This is so close

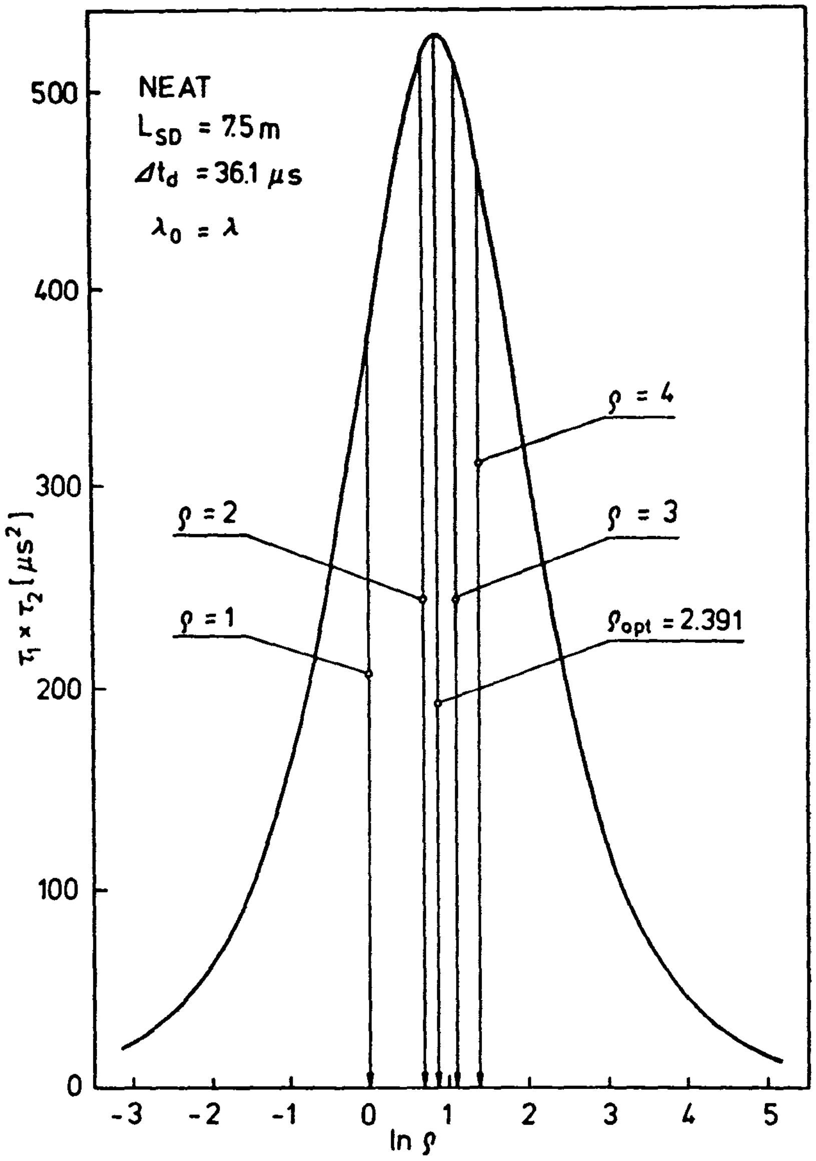

Fig. 3
Product of the chopper burst times $\tau_1 \cdot \tau_2$ as a function of lnρ for the spectrometer NEAT with $\lambda_0 = \lambda$, sample-detector distance L_{SD}= 7.5m and time resolution Δt_d = 36.1 μs.

to the peak, that the intensity gain is almost the same as for ρ_{opt}, namely about 32% (gain factor: 1.32), as compared to the conventional example of operation mentioned above, with $\tau_1 = \tau_2$ at 15000 revolutions/minute. This means that in our example about 32% can be gained in intensity at the sample, with no loss in energy resolution at the detectors, if the first chopper is rotated at 9242 rev./min and the last chopper at 18484 rev./min rather than both at 15000 rev./min. It is interesting to note, that this gain is independent of the wavelength λ_0 and of the flight-path uncertainty δL. If the latter is also taken into account, the

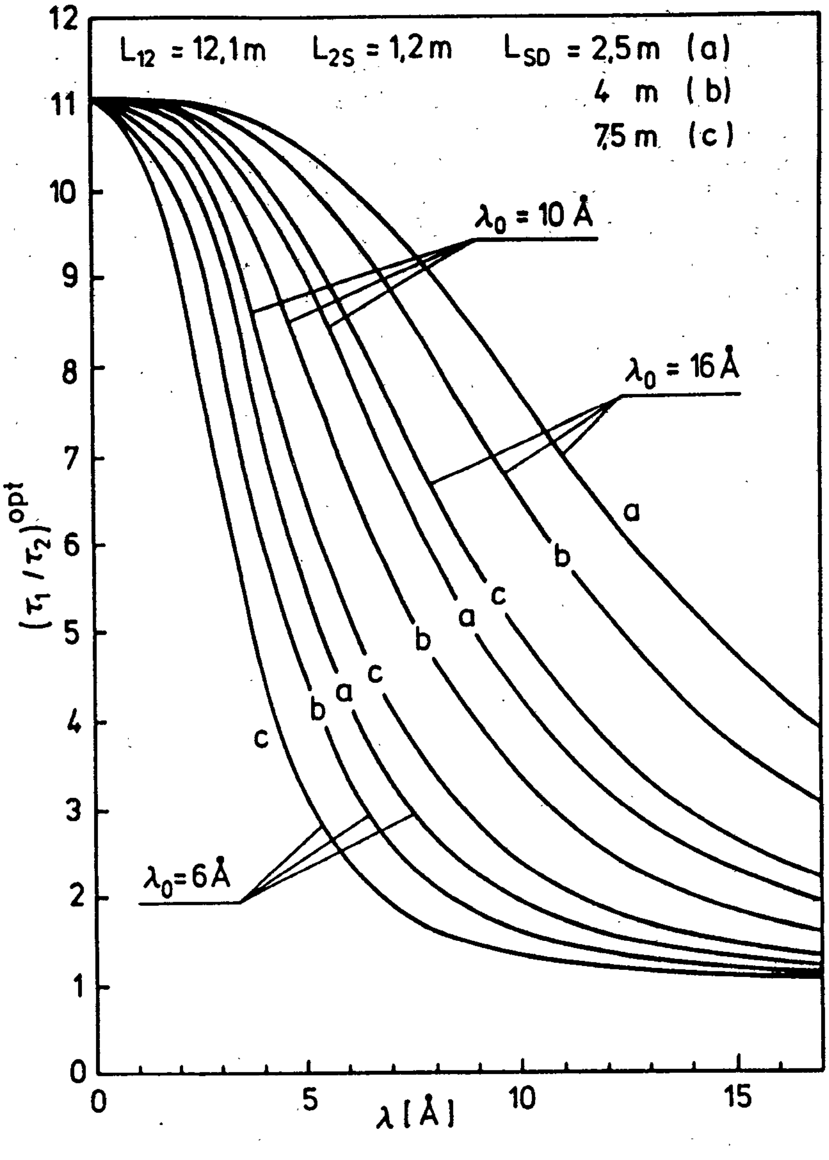

Fig. 4
Optimum burst-time ratio $\rho_{opt} = (\tau_1/\tau_2)^{opt}$ of the spectrometer NEAT as a function of scattered neutron wavelength λ, with incident neutron wavelength λ_0 and sample-detector distance L_{SD} as parameters. L_{12} = distance between the two principal choppers, L_{2S} = distance from the last chopper to the sample.

intensity curve shown in Fig. 2 is only renormalized, but neither changes shape nor peak position.

A similar calculation carried out for the spectrometer NEAT (L_{12}= 12.1m, L_{2S}= 1.2m, largest sample-detector distance L_{SD}= 7.5m) in the case of elastic scattering yields the curve of Fig.3. Here the best possible time resolution at the detector - when, as before, the term A is neglected - corresponds to Δt_d = 36.1μs. The integer value closest to ρ_{opt}=2.391 is ρ=2. In this case the intensity gain relative to the case $\rho=1$ is about 38% (gain factor: 1.38), at the same energy resolution.

The behaviour of the optimum opening time ratio ρ_{opt} in the general case of inelastic neutron scattering is illustrated for NEAT in Fig. 4. Here ρ_{opt} is plotted for three different sample-detector distances (L_{SD}= 2.5m, 4m and 7.5m) as a function of the scattered neutron wavelength λ, with λ_0 as a parameter. It is easily seen, that the limiting value of ρ_{opt} at $\lambda=0$ is $(L_{12}+L_{2S})/L_{2S}$, which is independent of L_{SD} and λ_0. For $\lambda \rightarrow \infty$ ρ_{opt} tends towards 1, independently of all parameters.

To conclude this Section, we consider an example of inelastic scattering on the spectrometer NEAT, with λ_0=10Å, λ=6Å, L_{SD}=7.5m. This corresponds to E_0~0.8meV, E~2.2meV, $\hbar\omega$ = E-E_0~1.4meV, where E_0 and E are the energies of incident and scattered neutrons and $\hbar\omega$ is the energy gain of the latter. In this case ρ_{opt}=5.291 and at the closest integer value, ρ=5, the intensity gain factor is ~2.74.

V. CHOPPERS, Neutron Guide and Detectors

One of the origins of the limitation in energy resolution of a chopper time-of-flight spectrometer is the limit of mechanical resistance of the disk material, since highest resolution (corresponding to minimum values of τ_1 and τ_2) is obtained at maximum chopper velocity. The latter is effectively doubled, if the first and last (single disk) choppers (Ch1 and Ch4 in Fig. 1) are replaced by counter-rotating pairs of disks /6/. NEAT has therefore been provided with this feature. The disks are made of a high-strength aluminium alloy and magnetic bearings are used, in order to achieve high phasing stability and reliability in operation.

In addition, in order to further improve the resolution, we have foreseen the possibility to use a built-in opening time ratio of ρ=2, especially at the highest velocity of both principal choppers (20000 rev./min), since this value of ρ is an excellent choice for low-energy-transfer experiments, where the highest resolution is needed (see Sec. IV). The (ρ=2)-operation at highest resolution is achieved using a double-trumpet beam compressor /7/ at the last chopper (pair). This reduces the beam width at this location by a factor 2, while the flux integral over the beam cross-section is essentially conserved. On the other hand, in the lower-resolution regime, ρ can also be varied by changing the chopper velocities and/or by using different chopper windows. Fig. 5 shows a schematic illustration of the last pair of chopper disks; each disk has three different pairs of windows, the narrowest ones of which have the same width as the guide; in the lower part of the figure the disks are shown, looking at their faces opposite to the respective chopper drives. A particular pair of windows is selected by an appropriate choice of the phase relationship between the members of the chopper pair. If windows larger than the guide are used, the eqs. related to the resolution given above have to be modified slightly, since the Gaussian convolution approximation mentioned in Sec. III is then not applicable. This subject will however not be treated here.

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

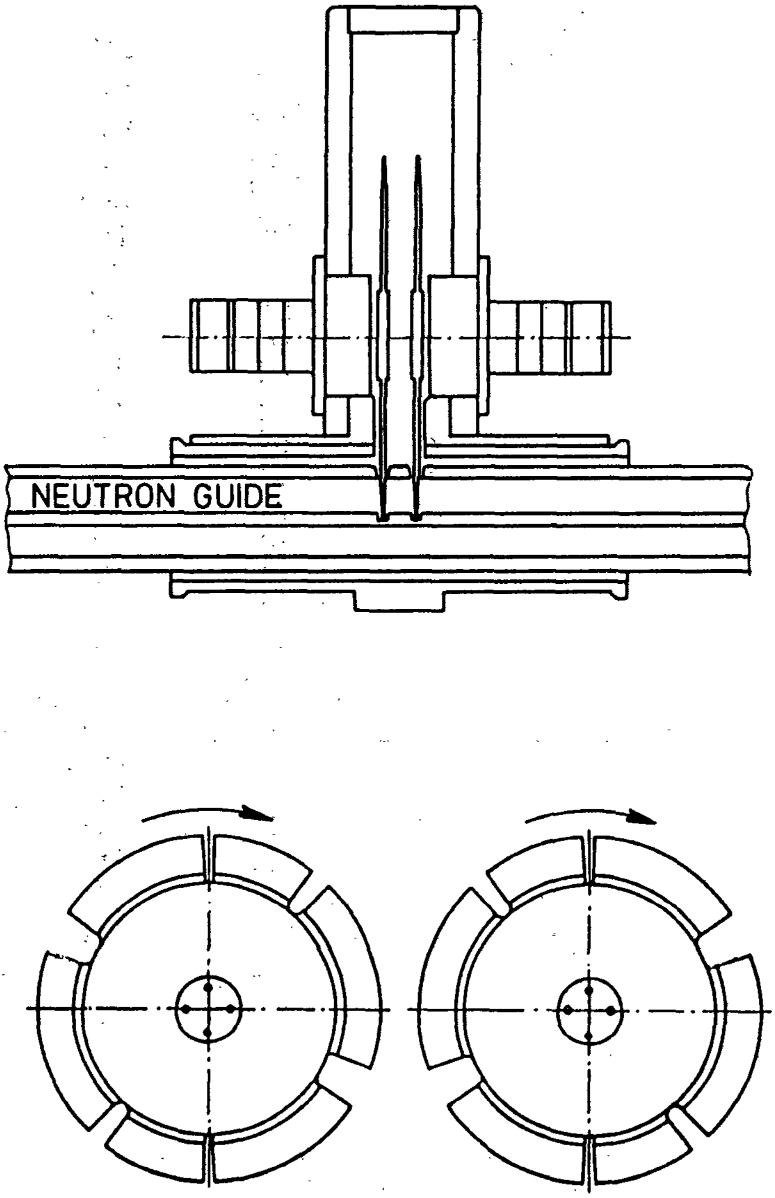

Fig. 5
Schematic drawing of the last pair of chopper disks of the spectrometer NEAT. Above: vertical cut showing, how the disks are placed in slots within the upper part of a divided neutron guide. Below: each disk has 3 different pairs of windows; arrows indicate the sense of rotation; the face opposite to the chopper drive is shown for each disk.

edges. These disks run in narrow slots (transmission better than 0.99) cut perpendicularly to the beam into the neutron guide (Fig. 6). In order to avoid unnecessary losses, it is important to minimize gaps (i.e. interruptions) in the neutron guide, which are needed for inserting chopper disks and other components, such as vacuum windows, shutters and monitors. The intensity loss V due to

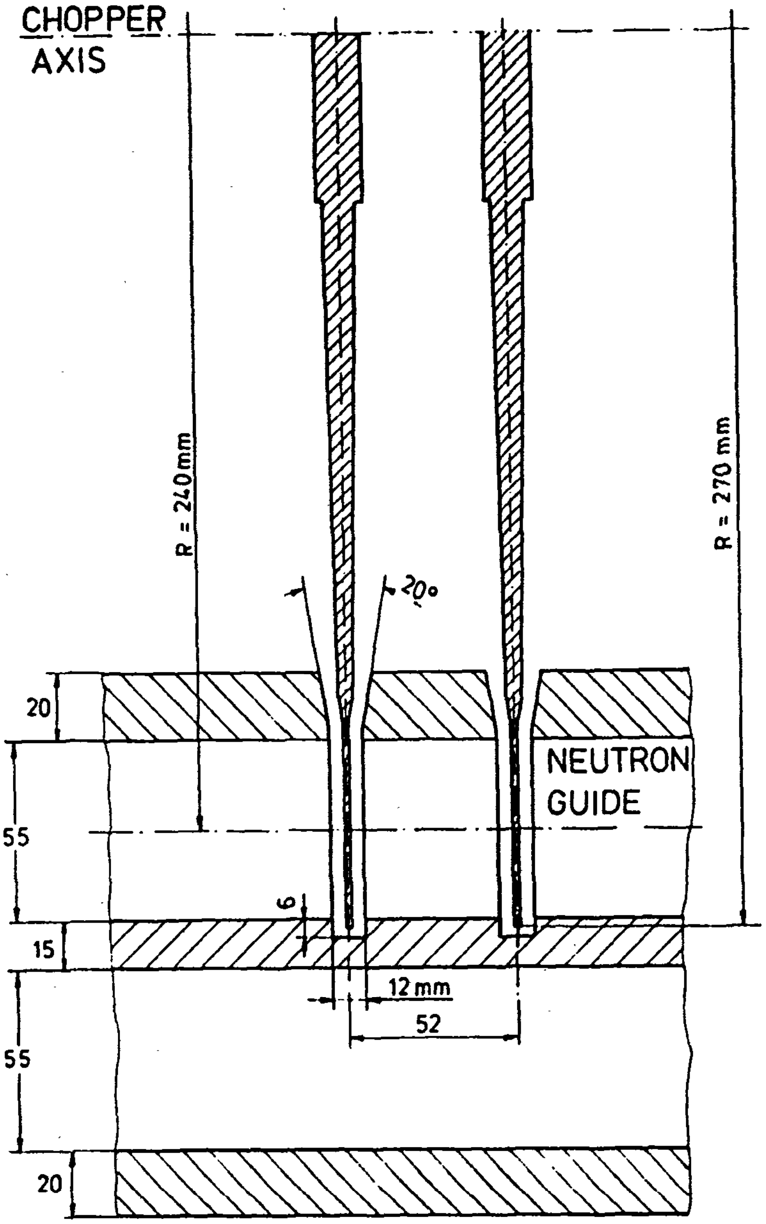

Fig. 6
Vertical cut of neutron guide, drawn to scale, with slots in which the chopper disks are running. The widths of the slots in beam direction, as wellas the thickness of the disks are made as small as possible, in order to minimize intensity losses.

a guide gap is related to the beam divergence and is therefore wavelength dependent. It can easily be shown that V, expressed as a percentage of the neutron flux, is given by

$$V = 100 \cdot G \cdot tg\gamma_c (W+H-G \cdot tg\gamma_c/2) \;/\; (2WH) \qquad (10)$$

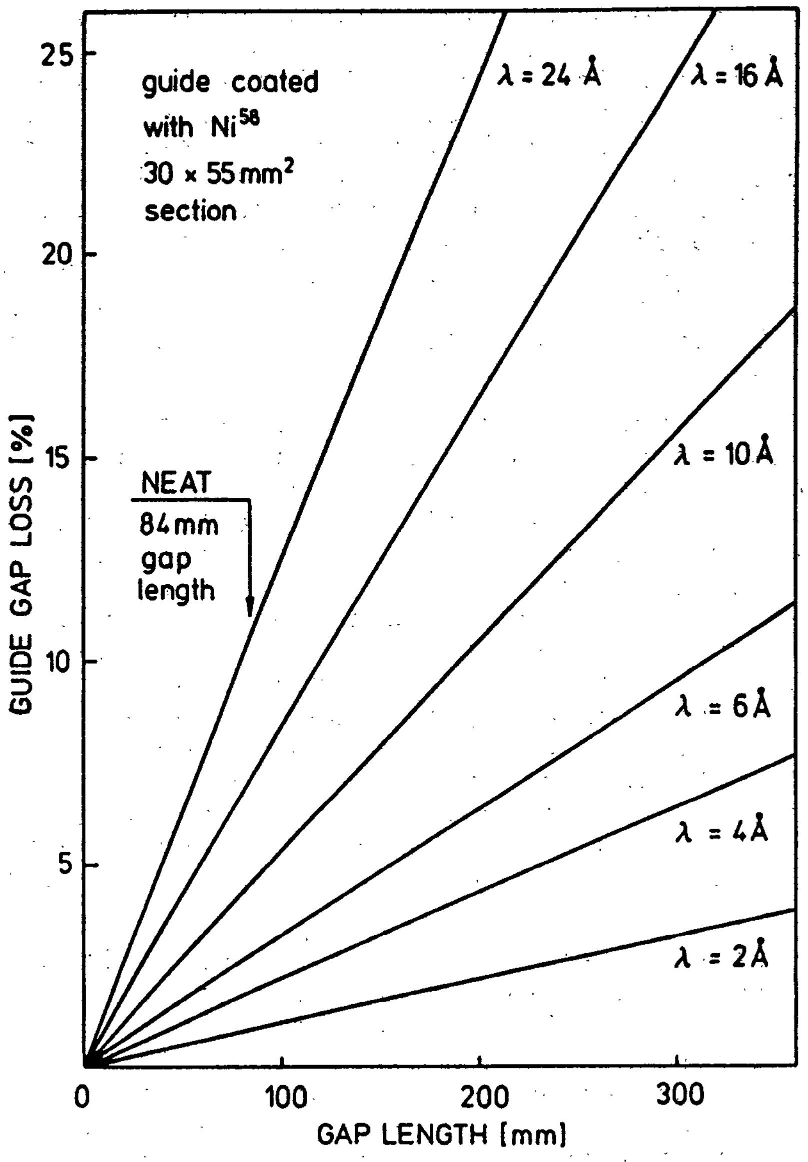

Fig. 7
Percentage of intensity loss due to interruptions in the neutron guide (guide gaps) as a function of the gap length, with the neutron wavelength λ as a parameter. The curves apply to the Ni-58 coated neutron guide section (with parallel walls) of the spectrometer NEAT (beam cross-section: 30 X 55 mm^2).

where
G = gap length in beam direction
γ_c = critical angle of total reflection of the material used for coating the neutron guide (Ni-58 in the case of NEAT)
W = inner width of the guide (beam width)
H = inner height of the guide (beam height)
For geometries occurring in practice V is an almost linear function of G. In Fig. 7 this is shown for a number of different neutron

wavelengths for the parallel-walled guide of NEAT. An arrow points at the value of the total gap length (84mm) in the case of NEAT, which is due to the insertion of 7 chopper disks with minimized thickness; here the fact, that a beam compressor is used at the last chopper pair, was neglected. The corresponding flux loss is, for instance, about 2.7% at $\lambda = 6$Å and about 4.5% at $\lambda = 10$Å. For the same wavelengths the theoretical loss values in the case of IN5 (4 chopper disks, total gap length 80mm, but smaller beam cross-section) are 2.9% and 4.8%, respectively. Much larger loss percentages are expected in the case of the spectrometer MIBEMOL /6/, where the total gap length related to the use of 6 chopper disks amounts to 300mm.

Last, not least, the connection between resolution, intensity and detector budget needs some consideration. Roughly speaking the total efficiency of the spectrometer increases with the total solid angle Ω_t, that can be covered with detectors, the energy resolution improves with increasing sample-detector distance L_{SD}, whereas the total cost of the detectors is proportional to $(\Omega_t \cdot L_{SD}^2)$. Obviously some compromise has to be made. For the 400 Helium - 3 detectors of the spectrometer NEAT we have chosen a distance L_{SD} of 2.5m, which is fairly modest as compared to IN5 (where L_{SD} is about 4m). This was done, in order to increase the total solid angle by a factor of about 2.5 for the given number of detectors. Thus an intensity gainfactor of 2.5 is obtained at fixed resolution, since we have nevertheless conserved the energy resolution (for given chopper pulse widths) by choosing a relatively large distance of L_{12}=12.1m between the principal choppers (see eqs. (3) to (7).

Another interesting feature of NEAT is the addition of a large two-dimensional position-sensitive detector (surface 1m^2) with variable distance, $4m \leq L_{SD} \leq 7.5m$, in order to be able to reach larger distances for highest-resolution experiments. This multidetector can be used at all scattering angles from 0° (small-angle-scattering) up to 134°. It increases appreciably the accessible range of $\Delta(\hbar\omega)$ and thus the flexibility of the spectrometer; e.g. for elastic scattering energy resolutions over three orders of magnitude ($2\mu eV \lesssim \Delta\hbar\omega \lesssim 2000\mu eV$) will be available.

VI. CONCLUSION

In the present paper we have discussed the optimization of a multi-disk chopper time-of-flight spectrometer regarding intensity and resolution. Our considerations have led to the concept of an improved version of this type of instrument. It has been the basis for the development of the new spectrometer NEAT, which is being installed at the Hahn-Meitner-Institut in Berlin.

For the evaluation of the improvement achieved it is useful to consider intensity gain factors at constant energy resolution. Obviously it is not possible to define one single factor describing the total gain for all experiments, since gain factors depend on the incident and scattered neutron wavelengths and on a number of instrument parameters varying from case to case. One can however obtain some insight by summarizing the pertinent results discussed in Sections IV and V :

1. In an example of elastic scattering using $\varrho=2$ (rather than the conventional value $\varrho=1$) we obtained a typical gain factor 1.38,

whereas in an example of inelastic scattering the gain factor was 2.74.

2. Once a chopper disk runs at the highest possible velocity, a further reduction in the neutron pulse width - for instance by a factor 2 - is always possible by simply reducing the width of the (parallel-walled) neutron guide and that of the chopper window by the same factor. Obviously this method (used in the spectrometer IN5) causes a corresponding intensity loss. This kind of loss is avoided to a large extent in the spectrometer NEAT with the aid of a double-trumpet beam-compressor /7/ with real-space reduction factor $\beta=2$. The avoided loss corresponds to a gain factor of about 1.7; it is smaller than 2, because the transmission of the beam-compressor is somewhat short of 1.

3. In similar fashion we claim to introduce an additional intensity gain factor of 2, if the single disk chopper is replaced for the purpose of a further pulse-width reduction by a pair of counter-rotating disks /6/, turning at the same velocity (rather than employing the detrimental method of pulse-width reduction, which consists in throwing away half of the beam).

4. The minimization of neutron guide interruptions (total gap length of 84mm in the case of NEAT) also permits to decrease intensity losses; for instance at λ= 10Å a factor of 1.12 is gained as compared to a case with a gap length of 300mm (MIBEMOL).

5. As compared to IN5, where slots were cut into the absorber coating but not into the aluminium disk itself, we gain a factor of about 1.08 by the use of open chopper windows.

6. As compared to IN5 we have shortened the sample-detector distance for the 400 single detectors, but increased the distance between the principal choppers; by doing this we gain a factor 2.5 in intensity due to the corresponding increase in solid angle subtended by the detectors, while the resolution is kept (roughly) constant.

Combining the above gain factors, we achieve - at fixed energy resolution - a total intensity gain factor of about 13 in the example given for elastic scattering and about 26 in the inelastic scattering example. Thus we may conclude by stating, that the concept presented here represents an improvement by at least an order of magnitude over the design of the spectrometer we have realized almost twenty years ago.

As a final remark I should like to note, that the concept of NEAT described above was developed in 1984/85 at the Hahn-Meitner-Institut. Design work began in 1985. At the time of writing the present paper (end of 1990) most of the components are completed and the spectrometer is being installed at the BER-II reactor. In 1988 I have communicated the essential points of this concept to our colleagues at the N.I.S.T. Labs. in Gaithersburg (USA), who had expressed interest in building a similar instrument. We have been informed , that this is now under way /8/.

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Q(J.M.Carpenter): What range of wavelength do you expect to use?
A(R.E.Lechner): Between 1 and 16Å. Intensity goes to zero for $\lambda = 0.8$ Å.