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Non-periodic multi-slit masking for a single counter rotating 2-disc chopper and channeling guides for high resolution and high intensity neutron TOF spectroscopy

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ABSTRACT

Energy resolution is an important design goal for time-of-flight instruments and neutron spectroscopy. For high-resolution applications, it is required that the burst times of choppers be short, going down to the μs-range. To produce short pulses while maintaining high neutron flux, we propose beam masks with more than two slits on a counter-rotating 2-disc chopper, behind specially adapted focusing multi-channel guides. A novel non-regular arrangement of the slits ensures that the beam opens only once per chopper cycle, when the masks are congruently aligned. Additionally, beam splitting and intensity focusing by guides before and after the chopper position provide high intensities even for small samples. Phase-space analysis and Monte Carlo simulations on examples of four-slit masks with adapted guide geometries show the potential of the proposed setup.

1. Introduction

In time-of-flight (TOF) instruments in direct geometry, the incoming-beam energy is selected by a combination of the pulsing and monochromatizing choppers. Having been scattered by the sample, the neutrons are counted by a detector. The energy transfer that occurred in the scattering process is determined based on the time difference between the chopper pulse and the detection of the neutron. The energy resolution of inelastic measurements is governed by the burst times of the two choppers, sample dimensions and the detector's counting depth, as well as the distances of all these components along the beam with respect to each other [1]. Short pulses in the microsecond range have to be generated by the monochromatizing chopper in order to achieve a high energy-resolution of a few μeV. Short burst times are produced by small-sized slits on counter-rotating discs (CRD) at high speeds. State of the art are identical double-slit masks on the disc pair combined with a two-channel guide in front of and behind the chopper [2–4]. In this approach the beam is first split into two channels, and the partial beams are then recombined at the sample position. As the energy resolution depends on the width of the chopper window, which is typically the same as the width of the neutron guide, it is possible to increase the guide transmittance by increasing the number of channels, without affecting the resolution. Besides the dual-beam configuration, periodic multi-slit arrangements were suggested and it has been pointed out that additional discs are needed to avoid satellite pulses in the case of more than two slits [5].

The objective of this publication is to design masks that allow to operate a TOF spectrometer with multiple guide channels, and still produce a monochromatic beam using just a double-disc counter-rotating chopper. Quintessential to our novel idea is the non-regular arrangement of equally wide slits, which makes the distances between nearest-neighbor pairs of slits different. Only one pulse will be generated if the two disc-masks, moving in opposite directions, meet at the same position as the identical fixed beam mask defined by the supermirror guide systems before and after the chopper. These systems offer very short burst times due to narrow slits and promise high intensity by using guide systems performing beam splitting and focusing intensity first to the slits and thereafter to the sample. Burst times of a few microseconds become feasible without significantly diminishing the intensity. Alternately, for instruments where the chopper speed is limited, it becomes possible to improve the resolution by increasing the number of channels while keeping the sum of the channels' width constant. This way the size of the chopper window decreases, while the guide cross-section open to neutrons remains constant, so that the beam intensity is reduced only due to an increase in the total number of reflections from the supermirrors.

Different non-regular multi-slit masks are proposed and we give examples for focusing multi-channel guides designed to maximize neutron transmission. The guide design between the chopper and sample continues the analysis considering flux enhancement within small spots. Special care is devoted to maintaining beam homogeneity at the sample position by applying phase space volume transformations

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[6,7]. A four-slit mask is studied by Monte Carlo ray-tracing simulations, in order to optimize the corresponding guide geometry.

2. Multi-slit arrangement

We propose a time-of-flight setup that monochromatizes the beam using a double-disc chopper. This is sufficient to achieve high energy-resolution, given that the chopper slits are narrow enough. For a disc chopper with a radius r, window width s and frequency ω, the burst time is close to $t=s(2\pi r\omega)^{-1}$, scaling linearly with the window width, if we neglect the variation of the window width due to the finite height of the window. Therefore, from the point of view of the chopper burst time alone, reducing the window width has the same effect as increasing the chopper frequency.

In an example instrument, where the distances between the pulse chopper (1), monochromatizing chopper (2), sample (3) and detector (4) are $L_{1,2}$=50 m, $L_{2,3}$=1 m and $L_{3,4}$=3 m, the chopper-disc radius is 500 mm, and the maximum chopper frequency is 330 Hz, the burst time at (2) would become 2.4 µs for a 5 mm wide slit. Following the recommendations for the design given in [1], the burst time of the pulsing chopper should be set to 32.4 µs resulting in a high energy resolution for elastic scattering of $2.2/\lambda^3$ meV where λ is the neutron wavelength. This satisfies the requirements for the high TOF-resolution; contributions to the resolution from spread in the flight-path length by divergence, sample size and detection depth are not considered. In order to achieve a high flux at the sample for these parameters it is now necessary to increase the number of slits. In the following section we will derive beam masks starting with two slits and then adding more slits.

The neutron guides and the two counter-rotating chopper discs define three identical multi-slit masks, allowing neutron transmission only if all the masks are congruently aligned (one-pulse-condition), rendering additional discs obsolete. Each mask shall consist of exactly N slits of the same width D. The slits are not regularly spaced on the mask. The mask segments between adjacent slits block the beam and their widths are, by definition, multiples of the slit width D.

A mask is characterized by an array of integers (0 n_1 0 n_2 0 n_3 0 n_4 0....), if one represents slits of width D by zeros and the closing segments by their respective widths $n_i \cdot D$. In this framework, the counter-rotation of the discs readily translates into sliding of the masks in opposite directions (Fig. 1). Therefore, we will discuss the change of the chopper positions with time in terms of steps, where one step is defined as translation of the mask by a distance D equal to the slit width.

2.1. Two slits

At “zero”-position all masks are congruently aligned and the beam passes through both slits. For the closing segment with $n_1 \geq 1$, each slit on the fixed guide mask is simultaneously closed from both sides by the two sliding masks during step 1. During the following steps slit 1 and slit 2 will remain closed by disc-mask 1 and disc-mask 2, respectively.

2.2. Three slits

Next we focus on the (0 1 0 n_2 0) sequence in order to find the minimum of n_2 to fulfill the one-pulse condition. The regular sequence (0 1 0 1 0) closes all three slits at step 1, however at step 2 a satellite pulse is generated at the central slit 2. The outer slits 1 and 3 remain closed by disc 1 and 2, respectively. Even the sequence (0 1 0 2 0) is not suitable, as illustrated in Fig. 1(a). The disc-mask 2 opens the central slit from the right, before the disc-mask 1 has closed it again. A satellite occurs, indicated by the white triangle in the figure. The satellite is eliminated if the disc-mask 1 can close the central slit before it has been opened by the disc-mask 2. This is the case for (0 1 0 3 0) as shown in Fig. 1(b).

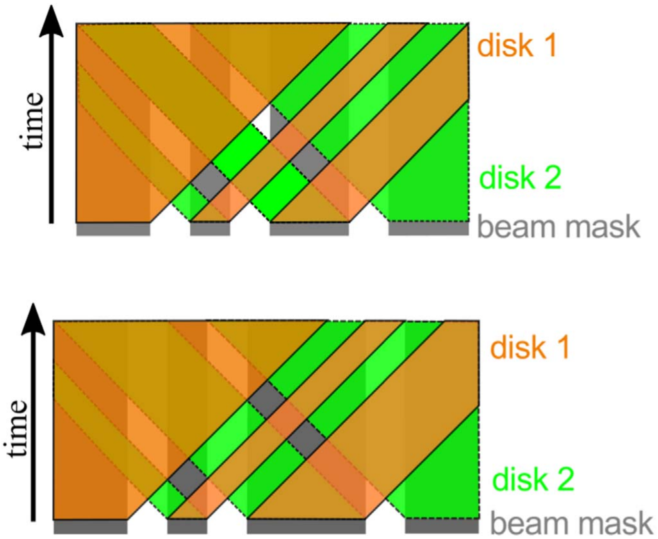

Fig. 1. a) Time evolution of disc-mask 1 (moving to the right) and 2 (moving the opposite way) starting with both masks congruently aligned to the beam mask (0 1 0 2 0). The occurrence of a satellite is visualized by the white triangle in the central part of the figure. b) Mask (0 1 0 3 0) suppresses the satellite from the previous case by enlarging the closing segment by one unit.

The latter sequence can be generalized to (0 n_1 0 n_1+2 0) with arbitrary n_1. From this we can derive a sufficient criterion for the one-pulse condition. Disc-mask 2 blocks the slit for n_1+2 steps. Simultaneously, the beam is blocked by disc 1 for n_1 steps, followed by an opening in the next step and a closing thereafter for the rest of the chopper cycle. Thus disc 2 blocks the beam until the disc-mask 1 is outside of the beam mask. This recipe can be extended for a general case of many slits, resulting in the condition $n_{i+1} \geq i+\sum n_i+1$. The index i counts the number of slits and the sum adds up all the closing segments on the left. The last unit step assures that the disc mask is positioned outside of the beam mask. An iterative form for the length of closing segments can be given for the case that minimizes the values of all the n_i's for $i > 1$. When a value of n_1 has been chosen, the next spacing $n_2=n_1+2$ and the recursive law becomes $n_{i+1}=2n_i+1$.

2.3. Symmetrized mask

Starting from a definition of an asymmetric mask like (0 n_1 0 n_2 0), it is possible to define a symmetric mask as (0 n_1 0 n_2 0 n_1 0). Same as in the previous example, the second slit is opened only at step “zero”. By mirror symmetry this is valid for the third slit as well and the defined symmetric sequence is valid. This type of sequence (referred to as M-I) is characterized by a continuous decrease of the slit distances from the center towards the outer side.

M-II sequences, with continuously increasing slit distances from the center to the outer side will have the form of (0 n_2 0 n_1 0 n_2 0), based on the asymmetric unit (0 n_1 0 n_2 0). It has to be checked whether these masks fulfill the one-pulse-condition. First one has to assure that all slits are closed by the disc masks from both sides during step 1. Then all the slits are allowed to be opened by only one disc-mask if the slit was closed by both disc masks in the preceding step. This is valid for (0 n_2 0 n_1 0 n_2 0) with $n_2 \geq n_1+2$, since the second slit on one disc mask moves out of the beam mask after n_1 +2 steps. The other disc mask blocks the slit continuously for $2n_1+1 \geq n_1+2$ steps.

3. Multi-slit chopper with incoming and outgoing guide systems

In this section we study systems composed of masks with four slits, together with guides before and after the chopper position. We present