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Beam choppers for neutron reflectometers at steady flux reactors

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A B S T R A C T

Realizations of the TOF technique for neutron reflectometers at steady flux reactors are compared. Beam choppers for neutron reflectometers divide into choppers of type 1 ($\Delta\lambda$ = const) and 2 ($\Delta\lambda/\lambda$ = const). It follows from Monte-Carlo simulations that choppers of type 1 do not yield to more intricate choppers of type 2, widely used at neutron reflectometers. Because of a very fast drop of neutron reflectivities with the momentum transfer q, non-optimality of measurements with a chopper of type 1 is fully compensated by better statistics at large q, and is not so much essential at small q. To vary the TOF resolution with choppers of type 1, a phasing of two discs and a turning of the system of two discs are suggested. The fluxes of neutrons with wavelengths beyond the working range and the efficiencies of their elimination by means of a bandwidth limiting prechopper are evaluated.

1. Introduction

In the last decade, neutron reflectometry has become a powerful tool in the study of surfaces, thin films and multilayers [1–3]. It is used for detailed studies of physical and chemical processes at the interfaces, bio-processes with interaction and transfer of substances through interfaces, membranes, etc.

Measurements at reflectometers with white neutron beams are carried out by the TOF technique at a fixed glancing angle θ with the same divergence $\Delta\theta$ for all wavelengths λ. The role of monochromaticity of neutrons plays the TOF resolution $\Delta\lambda$. Double disc choppers [4,5] are widely believed (e.g., see [6]) to be more efficient than single disc choppers in measurements at neutron reflectometers. Therefore, of interest may be the reasoning [7] in favor of using single disc choppers instead of technically more complicated double isc chopper systems [8,9]. In the present paper this issue is considered in detail. To avoid details not essential for our considerations, only neutron reflectometry at steady flux reactors is analyzed.

Choppers of type 1 ($\Delta\lambda$ = const) and 2 ($\Delta\lambda/\lambda$ = const) for neutron reflectometry are represented in Section 2. Optimality of TOF measurements with these choppers is discussed in Section 3. The relations between the integral fluxes and between spectral flux densities of neutron beams prepared by the choppers of type 1 and 2 are given in Section 4. In Section 5 they are used to compare reflectometry with choppers of two types by means of Monte-Carlo simulations. Slow background neutron fluxes are calculated in Section 6. The possibility to eliminate them by means of a bandwidth limiting prechopper is considered in Section 7. The results obtained are summarized in Conclusion.

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2. TOF resolution for the choppers of two types

The TOF resolution is mainly determined by the neutron burst width τ:

$$\Delta\lambda_\tau = (h/m_n)\tau/L_b, \tag{1}$$

where L_b is the TOF base, h is the Planck constant, m_n is the neutron mass. The burst repetition period

$$T_p = (m_n/h)L_b\lambda_{max} \tag{2}$$

is related to the maximum wavelength λ_{max} of neutrons registered by the detector before the arrival of the next burst neutrons. On the other hand,

$$T_p = 2\pi/n\,\omega_{ch}, \tag{3}$$

where ω_{ch} is the rotation frequency and n is the number of slots in the chopper disc. Therefore,

$$\lambda_{max} = \frac{h}{m_n}\frac{2\pi}{n\,\omega_{ch}L_b}. \tag{4}$$

In the case of a single disc chopper with slots of width w_1 and for a beam width $w_b \ll w_1$, as usually in reflectometry, the burst duration is

$$\tau_1 = w_1/\omega_{ch}R_{ch}, \tag{5}$$

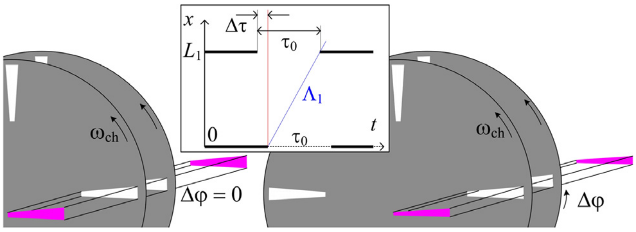

Fig. 1. A tuned-phase chopper made as a couple of closely spaced coaxial discs rotating with the same frequency ω_{ch}. The effective slot width depends on the phase shift $\Delta\varphi$ of one of the rotating discs with respect to the other. In the inset: the time-beampath diagram for the chopper (x is the beampath coordinate, L_1 is the distance between the rotating discs, τ_0 is the duration of bursts after the first disc, $\Delta\tau = \Delta\varphi/\omega_{ch}$ is an advance of the second disc in rotation, Λ_1 is the maximum wavelength of neutrons traversing the two slots).

where R_{ch} is the disc radius. It follows from (1)–(5) that the respective TOF resolution is

$$\Delta\lambda_1 = \frac{nw_1}{2\pi R_{ch}}\lambda_{max}. \tag{6}$$

Therefore, a single disc chopper ensures the same TOF resolution for all wavelengths. When the distance L_b from the chopper to the detector is changed, the chopper disc rotation frequency should be changed so that the product $\omega_{ch}L_b$ be the same. Then λ_{max} will be the same, and $\Delta\lambda_1$ will depend only on the slot width w_1.

The value of w_1 can be changed, e.g., by using two coaxially rotating, closely spaced discs with slots of the same width w_0 (tuned-phase chopper [10]). Overlap of the slots is changed by small phase shifts $\Delta\varphi$ (see Fig. 1) so that the second disc rotates with an advance $\Delta\tau = \Delta\varphi/\omega_{ch}$. The time-beampath diagram is in the inset in Fig. 1. The burst duration now depends on the neutron wavelength λ, since the effective slot width is ($\Delta w = R_{ch}\Delta\varphi$).

$$w_1 = (w_0 - \Delta w)(1 - \lambda/\Lambda_1). \tag{7}$$

The effective slot width w_1 weakly depends on λ in the entire range of the working wavelengths, if

$$\frac{\lambda_{max}}{\Lambda_1} = \frac{L_1}{L_b}\frac{T_p}{\tau_0 - \Delta\tau} = \frac{L_1}{L_b}\frac{1}{\rho_1} \ll 1, \tag{8}$$

$$\rho_1 = (w_0 - \Delta w)/2\pi R_{ch}, \tag{9}$$

i.e. when the distance between the discs

$$L_1 \ll \min(\rho_1)L_b. \tag{10}$$

Then the duration of neutron bursts will be almost the same as with a single disc, in which the width of slots is $w_1 = w_0 - \Delta w$. Neutrons with wavelengths above

$$\Lambda_1 = \rho_1\lambda_{max}\frac{L_b}{L_1} \tag{11}$$

do not pass the two slots of the chopper.

Another possibility to vary the effective slot width is to turn two discs rigidly fixed at a shaft about an axis passing in the middle between the discs and parallel to the diaphragm slits of the beam collimator (Fig. 2):

$$w_1 = L_1\sin(\alpha_0 - \alpha)/\cos\alpha_0 \tag{12}$$

where α is the angle of turning about the additional axis and $\alpha_0 = \mathrm{atan}(w_0/L_1)$. The chopper turned by an angle α_0 completely blocks the beam. In particular, when $w_0 = 5$ mm and $L_1 = 10$ (5) mm, one has $\alpha_0 = 27°$ (45°). E.g., with $\lambda_{max} = 2$ nm, $L_b = 2$ m and $\rho_1 = 0.01$ we find from (8) that $\Lambda_1 = 4$ (8) nm; the factor $1 - \lambda/\Lambda_1$ in Eq. (7) is minimum at $\lambda = \lambda_{max}$, where it amounts to 0.5 (0.75).

Further we may neglect a weak dependence of $\Delta\lambda_1$ on λ. Then the choppers in Figs. 1 and 2 are practically equivalent to a single disc chopper. Name them as choppers of type 1 to distinguish from choppers of type 2, in which the role of two discs is quite different. The drum chopper suggested for the TOF measurements of specular reflection with a fan beam [7] is a chopper of type 1. A couple of coaxial drums can work as a chopper of type 1 with a phase tuning. The two drums severed by the same distance as the discs in the van Well design [4] will work as a chopper of type 2. Later on, only disc choppers are discussed, the drum choppers can be considered in the same manner.

The van Well chopper includes two discs with slots of width w_2, which produce neutron bursts of duration

$$\tau_2 = (m_n/h)L_2\lambda \quad (\lambda < \lambda_0), \tag{13}$$

where L_2 is the separation of the two discs, and

$$\lambda_0 = \frac{h}{m_n}\frac{w_2}{L_2\,\omega_{ch}R_{ch}}. \tag{14}$$

The proportionality of τ_2 to λ, when $\lambda < \lambda_0$, follows from the diagram in Fig. 3. The closing of the beam by the first disc coincides with the opening of a slot in the second disc. The location of the edges in a slot in the second moving disc at the instant of crossing it by neutrons with different velocities (wavelengths) is different. A maximum duration of the burst is $\tau_2 = \tau_0 = w_2/(\omega_{ch}R_{ch})$ for neutrons with $\lambda = \lambda_0$. When $\lambda > \lambda_0$, the edge of the second slot blocks the path of the neutrons crossing the first disc slot too late, and restricts the burst duration growth with λ.

To avoid any ambiguities, note that λ_{max} is a quantity defined in (4) (not the maximum wavelength of neutrons that pass the opposite slots in the chopper discs), and L_b is the distance from the second disc of the chopper to the detector. As a rule, $R_{ch} \ll L_b$, and the condition $\lambda < \lambda_0$ will be assumed to be fulfilled for all working wavelengths, i.e. $\lambda_{max} < \lambda_0$, which is equivalent to the inequality

$$\frac{nw_2}{2\pi R_{ch}} > \frac{L_2}{L_b}, \tag{15}$$

so the TOF resolution with a double disc van Well chopper is

$$\Delta\lambda_2 = (m_n/h)\tau_2/L_b = \lambda L_2/L_b. \tag{16}$$

Choppers of type 2 ensure a TOF resolution proportional to λ in the working wavelength range. The relative TOF resolution in this case is a constant designated further as $(\Delta\lambda_2/\lambda)$. Again, to retain λ_{max}, a change in the distance L_b to the detector requires such a change in the rotation frequency of the chopper discs that conserves the product $\omega_{ch}L_b$. Then $(\Delta\lambda_2/\lambda)$ is set by choosing L_2. The quantity $(\Delta\lambda_2/\lambda)$ will be the same, if one retains the ratio L_2/L_b. The width w_2 of the disc slots is not a strictly defined quantity and may be chosen according to (15) and (16) for a maximum designed value of $(\Delta\lambda_2/\lambda)$.

3. Optimality of TOF measurements

In the approximation of small glancing angles θ (usually they do not exceed several degrees) the momentum transfer is

$$q = (4\pi\sin\theta)/\lambda \cong 4\pi\theta/\lambda. \tag{17}$$

Therefore, for the Gaussian distributions of the glancing angles and the wavelengths with the respective deviations $\Delta\theta$ and $\Delta\lambda$ (FWHM), the relative resolution of neutron reflectometry is

$$\Delta q/q = \sqrt{(\Delta\theta/\theta)^2 + (\Delta\lambda/\lambda)^2}. \tag{18}$$

When the beam is collimated with two slits of widths d_1 and d_2 at a distance L, the distribution of neutrons over the glancing angles is a trapezium with the bases $(d_1 + d_2)/L$ and $|d_1 - d_2|/L$. The respective root-mean-square deviation is

$$\sigma_\theta = (2L)^{-1}\sqrt{(d_1^2 + d_2^2)/3}. \tag{19}$$