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Investigation of timing and positioning of T_0 choppers at long pulse neutron sources

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Abstract. We examine the prerequisites for the operation of T_0 choppers at a long pulse spallation source using the parameters of the European Spallation Source (ESS). We discuss the constraints imposed to the chopper position and the operation parameters by the long pulse nature and the low repetition rate of the ESS. For an instrument having a moderator-to-detector distance $L_D = 155$ m with a double elliptic neutron guide shape we analyze possible solutions for chopper rotational frequencies of 7 and 28 Hz, that are acceptable for a cold instrument, while for a bi-spectral or a thermal instrument the lower frequency requires the chopper to be placed at a large distance from the moderator.

1. Introduction

At spallation neutron sources a proton beam is injected into the neutron production target causing the emission of high-energy particles that can hardly be shielded, as the energy, e.g. for fast neutrons, is limited by the proton beam energy to several GeV. The high-energy particles, which can leave the monolith shielding, are potentially scattered and/or moderated within the instruments beam-lines. This source of background has to be kept as low as possible, since the key figure describing the performance of any neutron instrument is the signal to noise ratio. Several measures are currently in use at existing facilities and various options exist to assure that the experimental area is out of the direct line-of-sight of the neutron source. Geometrically the line-of-sight can be avoided by curved neutron guides[1] also including more involved design such as the *Selene* concept [2]. In time the use of T_0 choppers mitigates the intensity of high energy neutrons by blocking off the beam-line around the time of neutron production. It consists of a rotor with blades that block the beam-line and the rotor is synchronized with the injection of the proton beam and therefore with the emission of the prompt neutron pulse. The use of T_0 choppers is a common practice at spallation sources [3, 4]. T_0 choppers rotating at comparably high frequencies of 100 Hz are in use at the Japan Proton Accelerator Research Complex (J-PARC), where the tests performed on High Resolution Chopper Spectrometer (HRC) [5] show a reduction of two orders of magnitude in the background noise detected for monochromatic beams of energy above 100 meV [6].

The long pulse of the ESS requires different design parameters and also further technical development. The crucial difference between short and long pulse spallation sources is the interaction time of the proton beam with the target: the short pulse requires a fully opaque chopper only for μs, while in the long pulse this time amount to several ms, which is a substantial fraction of the periodicity of the source.

Here we describe how the long pulse nature and the low repetition rate (14 Hz) of the ESS affect the layout of T_0 choppers, but we do not cover any aspects of the engineering design of a T_0 chopper and we especially keep the search for appropriate materials and thickness open. Our considerations apply to the different layouts that are used today, with a rotation axis parallel to the main neutron flight direction. We assume that the choppers are symmetric with respect to the rotation axis, i.e. they close the neutron beam twice during a full revolution.

2. Timing and positioning

We describe in figure 1 the absorption of a T_0 chopper as a function of time with respect to the pulse structure at the ESS, assuming that the chopper is placed at a distance L_{ST_0} from the moderator surface. First, the T_0 chopper has to confirm that the neutron beam is fully closed when high-energy particles are produced. We assume that this time range is given by the ESS neutron pulse length of τ_s =2.86 ms plus an additional arbitrary time after the pulse τ_{ag}, referred to as after glow, therefore having $T_0 = \tau_s + \tau_{ag}$. Furthermore the chopper reduces

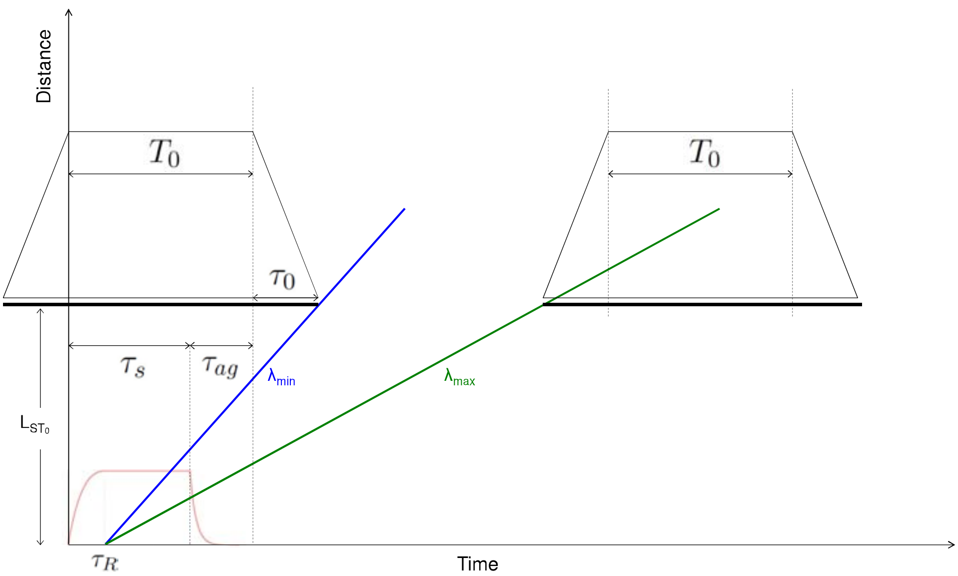

Figure 1. Schematic representation of the T_0 chopper time operation within a tof-diagram snapshot taken from the moderator to the chopper position L_{ST_0}. τ_0 is the opening and closing time, T_0 is the time interval in which the chopper is fully closed. Thus the horizontal black lines represent the chopper closing. The ESS pulse shape as a function of time is also represented (red curve). The blue and the green lines represent neutrons starting from the moderator at the rise time τ_R, with the desired minimal and maximal wavelength $\lambda_{\min}$ and $\lambda_{\max}$ respectively.

the transmission during the additional time necessary for the hammer to be removed from the neutron guide cross section

$$\tau_0 = \frac{2\arctan\frac{w}{2R}}{2\pi f} = \frac{\alpha}{2\pi f}, \tag{1}$$

where f is the chopper rotational frequency, w is the guide width and α the angular width of the neutron guide at the chopper position. The latter depends basically on the radius of the chopper blade and the guide cross section at the position of the chopper The radius R in equation (1) is taken from the bottom of the neutron window to the axle of the chopper. The width of the chopper hammer has to be larger than the guide width in order to allow complete closing. Therefore the reduced transmission might be relevant for complex guide designs with variable cross section along the neutron flight path.

As a consequence of the long neutron pulse structure, the total angular width of the hammer, which is given by

$$\beta = T_0 \times 2\pi f + \alpha, \tag{2}$$

increases linearly with the frequency, as can be seen from table 1.

As it is seen in figure 1, fixing the position of the T_0 chopper reduces the transmission for any wavelength shorter than

$$\lambda_{\min} = \frac{h}{m_n}\frac{T_0 + \tau_0 - \tau_R}{L_{ST_0}}, \tag{3}$$

which depends on the starting time at the moderator of the neutrons reaching the chopper when it is fully open. When the chopper closes again, it determines the upper limit of the wavelength band, which is transmitted without gaps due to the chopper operation,

$$\lambda_{\max} = \frac{h}{m_n}\frac{(2f)^{-1} - \tau_0 - \tau_R}{L_{ST_0}}, \tag{4}$$

where it is assumed that the chopper closes the beam twice during a full revolution. However, the repetition rate of the T_0 chopper has to fulfill the more relaxed condition to be an integer multiple of the source frequency to block the background from every source pulse. The resolution defining chopper system selects the neutrons released during a portion of the pulse, whose length depends on the required energy resolution. For a chopper system as proposed in [7] the effective extraction time $\tau_R \pm \tau_{\text{eff}}/2$ can be centered at any time during the neutron pulse, independent of the incoming wavelength. In particular it can be moved towards the end of the pulse to maximize $\lambda_{\min}$ giving $\tau_R = \tau_s - \tau_{\text{eff}}/2$. The requested effective pulse length τ_{eff} constraints the position of the T_0 chopper L_{ST_0}, depending on the minimum wavelength required,

$$L_{ST_0}^{\min} = \frac{h}{m_n}\frac{T_0 + \tau_0 - (\tau_s - \tau_{\text{eff}})}{\lambda_{min}}, \tag{5}$$

while the upper limit for the position depends also on the requested bandwidth $\Delta\lambda$:

$$L_{ST_0}^{\max} = \frac{h}{m_n}\frac{(2f)^{-1} - \tau_0 - (\tau_R + \tau_{\text{eff}})}{\lambda_{\min} + \Delta\lambda}. \tag{6}$$

In figure 2 we present potential positions for the T_0 chopper to transmit at least the natural bandwidth ($\Delta\lambda = 1.88$Å) of a 155 m long instrument, which is a typical length for the long ESS instruments, as a function of the lowest wavelength λ_{min} to be transmitted for different chopper frequencies. The panel *b*) represents the neutron guide width assumed for the calculation of

Table 1. Hammer width of the T_0 chopper calculated from equation (2) for different rotational frequencies commensurate with the ESS source frequency. The neutron guide cross section used for the calculation is $8.5 \times 8.5\text{cm}^2$.

Frequency (Hz)	7	14	28	56
β (deg.)	29.57	36.78	51.19	80.02

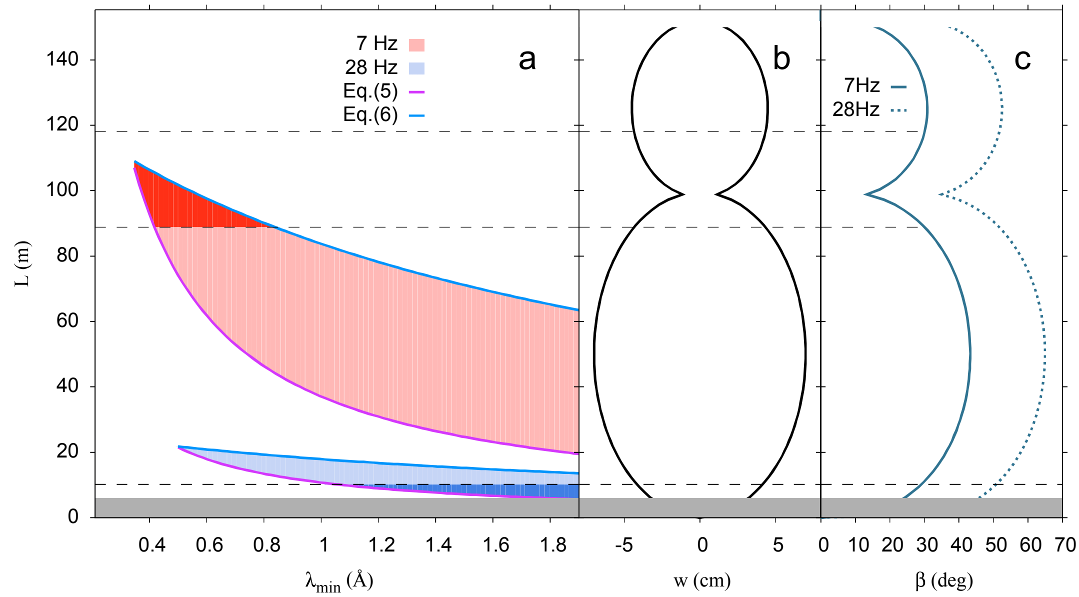

Figure 2. Possible positions for different frequencies of the T_0 chopper if the usable wavelength band starts at $\lambda_{\rm min}$ and extends over the natural bandwidth (here 1.88 Å for a total instrument length of 155m). The lower limit is defined by equation (5), the upper limit is set by the equation (6). The dark red and dark blue areas represent the regions where the guide width is smaller than 8.5cm. The pulse can be used for an effective pulse length $\tau_{\rm eff} = 500\mu$s from the end of the pulse for the lower limit and from the beginning of the plateau at the upper limit, respectively. The grey area represents the inaccessible area within the monolith.

the hammer size according to equation (2) that is shown in panel *c*). The double elliptic shape results in a smaller guide width close to the focal points of the ellipses than compared to the width in the ellipse center, which is manifest in the T_0 chopper hammer width shown in panel *c)*. In order to limit the size of the hammer to a reasonable value, we emphasized with darker color the regions where the guide is smaller than 8.5cm, a value that is similar to the one assumed in [6]. Therefore two working conditions for the chopper are identified: it can be operated in the region across the connection of the two ellipses with a rotational frequency of 7 Hz or close to the start of the first ellipse for $f = 28$ Hz. The latter is valid for an instrument using neutrons with $\lambda > 1.1$ Å, which is sufficient for any cold instrument, while any instrument using thermal to epithermal neutrons needs a larger distance to make use of short wavelength neutrons. One could envision a T_0 chopper at this position as the second line-of-sight breaker, once the line-of-sight is first broken by a curved or kinked guide section upstream the chopper position. In this case the T_0 chopper has to block the fast particles emitted from the first impact point, therefore its thickness might be reduced as compared to a chopper in the primary fast particle spectrum.

Making use of acceptance diagrams in figure 3, the transmission properties of the T_0 chopper are analyzed for the two situations, assuming the position of the chopper is close to the upper limit expressed by equation 6:

- When the chopper is placed close to the moderator, as shown in the bottom panel, the lower bandwidth limit is quite high and a higher frequency is needed to keep τ_0 short or alternatively one might employ a set of two counter-rotating T_0 choppers in series [7]. On

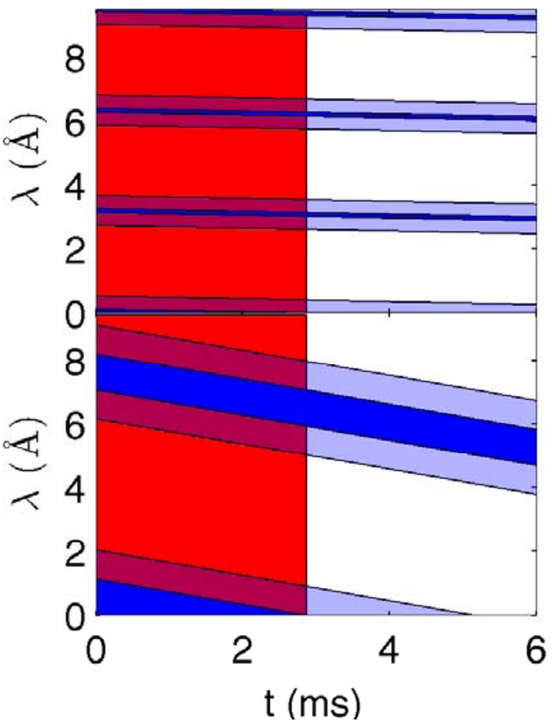

Figure 3. Acceptance diagrams for T_0 choppers spinning at different frequencies (top: 7 Hz, bottom: 28 Hz) and placed at different positions (top: $L_{ST_0} = 90$ m, bottom: $L_{ST_0} = 10$ m). The red areas indicates when the T_0 chopper transmits the neutrons originating from the source pulse, neglecting the after glow. The light blue area indicates regions where the chopper is opening and closing, in the dark blue regions the chopper is completely opaque. The T_0 chopper is fully closed for 2.86 ms. The chopper hammer size is calculated according to table 1. The repetition rate is twice the chopper frequency.

the other hand the transmitted bandwidth is twice wider than the natural bandwidth of an instrument with total length $L_D = 155$ m. An increase of the bandwidth by skipping a pulse can always be realized for this layout.

- Placing the chopper at a larger distance, as shown in the top panel, the lower wavelength limit is reduced for a lower frequency, despite the longer τ_0. The natural bandwidth starting from a lower limit of 0.7 Å is transmitted continuously, while higher order bands are separated by a wavelength gap that depends on the chopper position and speed. The gap in the spectrum is narrower, but the transmitted bandwidth is also reduced. Hence the choice of the T_0 chopper position can limit the opportunities for pulse skipping.

3. Conclusions

We discussed analytic considerations related to the use of T_0 choppers at a long pulse spallation source using ESS parameters. Due to the long pulse structure the T_0 chopper constraints the lower limit of the neutron wavelength spectrum. As the T_0 chopper and the source pulse act also as a band filter, the transmitted band must be at least as wide as the requested instrument band. We discussed in detail possible solutions for chopper frequencies of 7 and 28 Hz. Depending on the neutron wavelength band of interest these options are both acceptable for a cold instrument. For a bi-spectral or a thermal instrument, which uses neutron wavelengths down to 0.7Å the lower frequency requires the chopper to be placed at a large distance from the moderator. Considering the constraints and uncertainties attached to the T_0 chopper layout, additional means to prevent the effect on the instrument performance must be pursuit. Here we mention to avoid the direct line-of-sight sufficiently by the neutron guide layout, possibly for rather long instruments, or having the instrument so compact that the neutrons are always analyzed before the next source pulse begins. Our results show that the T_0 chopper design for a long pulse spallation source is a complex task and has severe implications for the instrument operation, not to mention the complexity of the engineering and radiological design. In particular the wavelength limits and gaps in the spectrum have to be considered to retain a large flexibility in terms of usable neutron wavelength. We hope that the present contribution can be of use for instrument designers, which need to use T_0 choppers in their instrument.

3.1. Acknowledgments
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