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Peculiarities of the construction and application of a broadband adiabatic flipper of cold neutrons

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Abstract

An available mathematical model for calculation of a broadband adiabatic flipper for cold polarized neutrons is suggested. This model of the sine–cosine modulation of an effective field enables one to optimize and to simplify the calculation for constructing the flipper. A functional relation between spin flip probability and the main parameters of the device such as the length of the flipper, the neutron wavelength and both form and size of the magnetic fields have been found. Tests of flippers constructed on the base of this model has been successfully carried out.

1. Introduction

The application of broadband adiabatic spin-flippers (BASF) of neutrons started at the beginning of the seventies by the experimental groups of the Nuclear Physics Institute in St.-Petersburg (PNPI) [1-3]. At present these flippers are being exploited successfully at a few places in the world. Lately, at least two articles have been devoted to the flipper [4,5]. A total account of the principles and a detailed technical description including a sketch of a RF generator for the flipper are presented in Ref. [4]. New variants of the magnetic field modulation for the spin flipper are proposed and a comparison between them is carried out in Ref. [5]. There is a great interest for application of the flipper. For this reason it is necessary for users to have a detailed description of the construction and tuning possibility of the flipper with respect to the special conditions of an installation.

The main characteristics and advantages of a flipper of this type are well-known but we will give them here again. Firstly, the range of high efficiency (spin flip probability practically equal to unity) is limited only by the minimum wavelength λ_{min} of the neutron spectrum. The theoretical background of this most familiar property of the flipper will be given in Section 2. Secondly, the flipper has a high flipping stability with respect to external influences. This property will be considered in detail in Section 3. Thirdly, there is the possibility of working with neutron beams with a lareg cross section. And last but not least, there is not any absorbing and scattering matter for the neutron passing through the flipper.

In order to make use of all these advantages in the construction of the adiabatic flipper one should find out the exact relation between flipping probability and spatial parameters of the device, neutron wavelength, form and size of magnetic fields. It is especially important when the required wavelength λ_{min} is small or the constructed flipper should be short. For this reason, sometimes ago a mathematical model for calculation of BASF of cold polarized neutrons was suggested [6]. This model of the sine–cosine modulation of an effective field enables one to optimize and to simplify the calculation for constructing the flipper.

2. The model of sine–cosine modulation

The adiabatic spin flipper consists of two mutually perpendicular magnetic fields. One of them is a guiding magnetic field with a gradient, stationary in time. The other one is oscillating. Let us consider the problem of the behavior of a neutron spin in the magnetic system of the flipper and determine the spin flip probability of a neutron passing through the device.

As Fig. 1 shows, we consider the entry of an initially polarized neutron beam ($\boldsymbol{P} = \boldsymbol{P}_x$) with velocity v into the region of magnetic fields. We assume that the particle trajectory is parallel to the z-axis and the magnetic configuration consists of a guiding field with a gradient along the z-axis, $H_0(0,0,z)$, collinear to the x-axis and perpendicular to it an oscillating field, $\boldsymbol{H}_1(z,t) = H_1(z)\sin(\omega_0 t)\boldsymbol{e}_z$, where ω_0 is the frequency and $H_1(z)$ is the amplitude of the field. We propose the model of the so-called sine–cosine modu-

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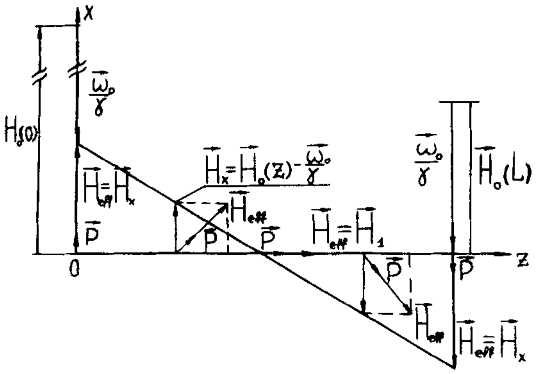

Fig. 1. Flipping of the neutron spin in the frame rotating with a frequency ω_0. Scheme of the magnetic fields in the effective frame.

lation of the effective field for the resonance spin flipping. Thus we assume that the amplitude of the oscillating field, $H_1(z)$, distributed along the neutron path is described by the sine function:

$$H_1(z) = A\sin\left(\pi\frac{z}{L}\right), \quad z = [0, L]. \tag{1}$$

In addition, the coordinate dependence of the guiding field $H_0(z)$ can be expressed by the cosine function:

$$H_0(z) = H_0 + A\cos\left(\pi\frac{z}{L}\right), \tag{2}$$

where H_0 is the magnitude of the field at the point $z_0 = L/2$, L is the length of the flipper, and $A = H_0(0) - H_0(z_0)$ is the amplitude of the modulation.

The oscillating field can be decomposed into two opposite rotating fields with frequencies $\pm\omega(v)$. Only one component of these fields produces the spin flipping and its rotating direction coincides with the direction of the precession of the polarization vector in the field $\boldsymbol{H}_0$. The influence of the other component is neglected for the condition $|H_1| \ll |H_0|$ [7].

In the reference frame of a neutron rotating with frequency ω_0 one can obtain the effective field $\boldsymbol{H}_{\text{eff}}$ described by the expression for the components:

$$\boldsymbol{H}_{\text{eff}} = \{H_x = H_0(z) - \omega_0/\gamma,\ H_y = H_1(z),\ H_z = 0\}. \tag{3}$$

Substituting the Eqs. (1) and (2) into Eq. (3) one can rewrite the components of the effective field as follows:

$$H_x = H_0 - \frac{\omega_0}{\gamma} + A\cos\frac{\pi z}{L},\ H_y = A\sin\frac{\pi z}{L},\ H_z = 0. \tag{4}$$

On the condition $\gamma H_0 = \omega_0$ we arrive at the problem of spin behavior in the magnetic harmonic configuration:

$$H_x = A\cos\frac{\pi z}{L},\ H_y = A\sin\frac{\pi z}{L},\ H_z = 0. \tag{5}$$

Considering the neutron spin as a classical vector, one can describe the spin movement by the precession equation [7]:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \gamma[s\,\boldsymbol{H}_{\text{eff}}]. \tag{6}$$

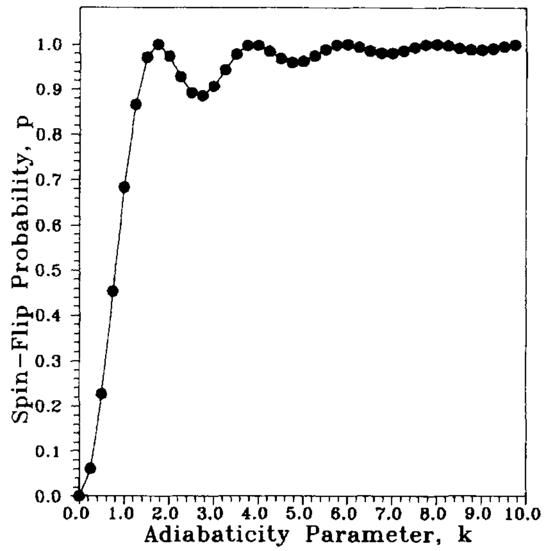

Fig. 2. Dependence of the spin flip probability p on the adiabatic parameter k.

The configuration (5) permits an accurate solution of Eq. (6) (see for example Ref. [8,9]). In this case the spin flip probability at $T = L/v$ is given by:

$$p = 1 - \frac{\sin^2((\pi/2)\sqrt{1+k^2})}{k^2+1}, \tag{7}$$

where k is the adiabaticity parameter of the rotating frame

$$k(v, z) = \omega_1/\omega_f. \tag{8}$$

Here ω_1 is the Larmor precession rate in the rotating frame $\omega_1 = \gamma|H_{\text{eff}}| \approx \gamma A$, and ω_f is the the field turning rate with respect to z-axis. According to $z = vt$ the field turning rate, ω_f, is equal to $\pi v/L$ (see Eq. (5)). As a result, the value of the adiabatic parameter equals $k \approx \gamma AL/\pi v$.

The probability dependence $p(k)$ is shown in Fig. 2. The figure also demonstrates that resonance spin flipping occurs for large k

$$k = \gamma LA/\pi v \gg 1. \tag{9}$$

The inequality (9) is the real resonance condition imposed on the length of the flipper, L, the magnitude of the modulated field, A, and the value of velocity, v. In order to obtain the dependence of k on λ we should use the relation between velocity, v, and wavelength, λ, ($v = \beta/\lambda$, where $\beta = 3.958 \times 10^5$ [Å cm s^{-1}]). At given L and A it is immediately seen that the condition (9) is well satisfied for a range limited below by certain minimum wavelength only. The last conclusion forms a basis for designing the broadband adiabatical spin flipper. However the main advantage of the sine-cosine model as compared with other models is the extraction of the functional relation (7) between the spin flip probability and the main parameters of the device. The existence of the dependence (7) determines the property of the high flipping stability of the device with respect to external influences and changes of flipper parameters. This is easy to understand when taking the derivative of the expression (7) under condition (9):

$$\frac{\mathrm{d}p}{dk} \sim \frac{1}{k^2}. \tag{10}$$

The derivative is asymptotically approaching to zero without a limit in a large range of the parameter $k > k_0$. It means that no k-variation limited below by the only boundary of the stability region, k_0, has any effects on the spin flip probability, $p(k)$, which equals unity in this area. For instance, reasons for k-variation may be instabilities of the working frequency of the generator which changes the x-component of the effective field as well as the direct influence of the external magnetic field on flipper, and so on. In spite of these factors which vary the working conditions of the flipper, the flipping efficiency of the device is constant.

This property named by us as "high flipping stability" should be considered as a great advantage of this flipper as distinguished from other kinds of flippers.

3. Peculiarities of the construction and application of the adiabatic flipper

The special point of this paper is to consider the correspondence between the above assumed model (1), (2) and the forms of the fields created by the real flipper. If the fields of the real flipper do not satisfy the prior assumptions (1) and (2) then the Eq. (7), describing the flipping probability, can not be used as an explanation of the observed flipping actions.

Let us consider the standard design of the flipper (Fig. 3). The construction of the flipper is usually a combination of coils generating the magnetic configuration of the fields. The diagram is shown in Fig. 1. Firstly, a pair of coils 1) inclined to the z-axis creates the gradient of the guiding field $H_0(0,0,z)$ collinear to the x-axis. Secondly, the solenoidal coil 2) produces the oscillating field $H_1(z)$. The essential peculiarity of the construction is the fact that the RF coil must be shorter than the coils of the guiding field (Fig. 3). The reason for this is expressed even in the name of flipper – "adiabatic". It consists of the necessity to provide spin the adiabatic transmission through the flipper in the effective frame for the neutron. It means that the amplitude of the RF field must be close to zero at the entrance and exit of the flipper and must be maximum at the center. Such an amplitude of the field $H_1(z)$ is provided by a solenoidal coil which is shorter than the length of whole flipper. It is well-known that the solenoidal coil creates a field which can be described by the equation:

$$H_1(z) = \mathrm{const}\left[\frac{z-l_1}{\sqrt{b^2+(z-l_1)^2}} + \frac{z-(L-l_1)}{\sqrt{b^2+(z-(L-l_1))^2}}\right]. \tag{11}$$

Here b is the coil radius, l_0 is the coil length and $L = l_0 + 2l_1$ is the length of the whole flipper. In the case of $l_1 = L/4$ and $b = L/4$ the form of the oscillating field is presented in Fig. 4. One can see that the real curve is very close to a sine function. Simultaneously the linear coordinate dependence of the guiding field H_0 can be substituted by the cosine one (Fig. 5). The curves in Figs. 4 and 5 demonstrate the possibility to use the sine–cosine modulation in this system.

It should be noted that in any case in practice we try to attain the above mentioned sine–cosine modulation of the field in the flipper by additional corrections to both the guiding field and the oscillating one. While constructing the flipper we take in account the explicit conditions of each installation such as: bounded space, distributions of magnetic fields, and so on. Considering the high flipper stability we have applied the above mentioned calculating technique to different complex situations. Examples of applications of the method

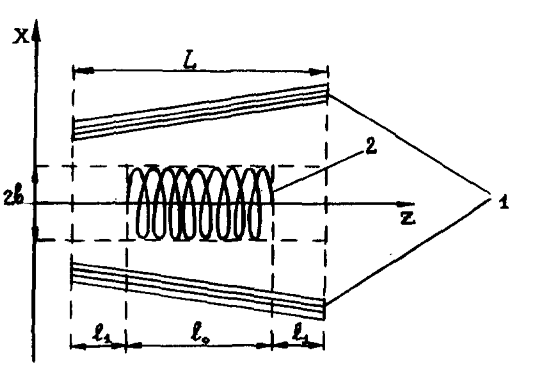

Fig. 3. Scheme of the adiabatic flipper. 1) – Coils creating the guiding field H_0. 2) – solenoidal coil creating the oscillating field H_1.

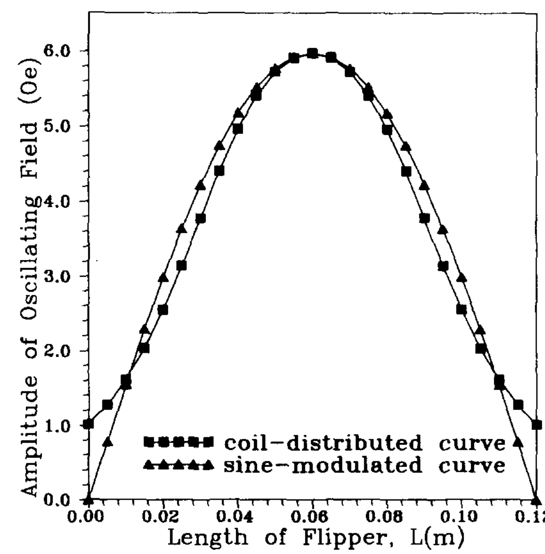

Fig. 4. Distribution of the oscillating field H_1.

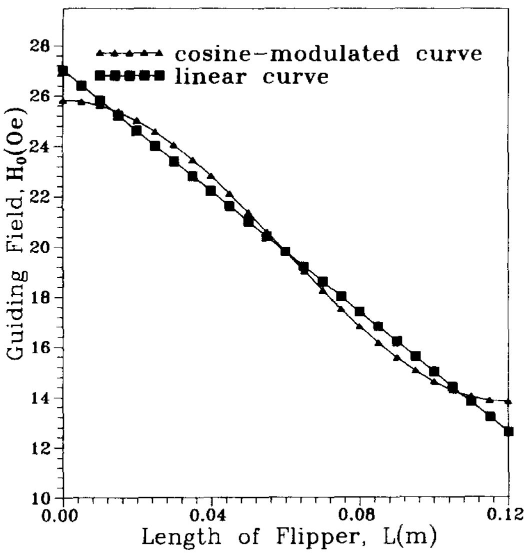

Fig. 5. Distribution of the guiding field H_0.

are given below.

After construction, each flipper was checked by measuring the efficiency of the unit. The spin flip efficiency can be determined using well-known methods. This technique is based on using two flippers and measuring the detector count rate for the four different states of the flipper system (both flippers switched off I_{00}, one or another flipper on I_{10}, I_{01}, both flippers switched on I_{11}). Using the measured rates I_{00}, I_{10}, I_{01}, I_{11} one can obtain the spin flip probabilities of both flippers:

$$f_1 = \frac{1}{2}\left(1 + \frac{I_{11} - I_{10}}{I_{00} - I_{01}}\right), \quad f_2 = \frac{1}{2}\left(1 + \frac{I_{11} - I_{01}}{I_{00} - I_{10}}\right).$$

3.1. Adiabatical flipper near a polarizer

The first flipper to be described was placed on the installation near a polarizer and it was located in a space bounded between other devices. However, as a rule, the polarizer incorporates strong magnets in its construction that create a strong magnetic field growing smaller as the distance of the magnet increases. This field is usually considered as parasitic and, consequently, an investigator seeks to suppress it in the region near the polarizer. In this case the weakness could be transformed into a strength, because such a field with a gradient (sometimes with a small correction) is convenient to use for constructing a flipper based on adiabatical RF flipping. In this case the flipper does not occupy additional place and both the flipper and the polarizer could be represented as one united system (Fig. 6).

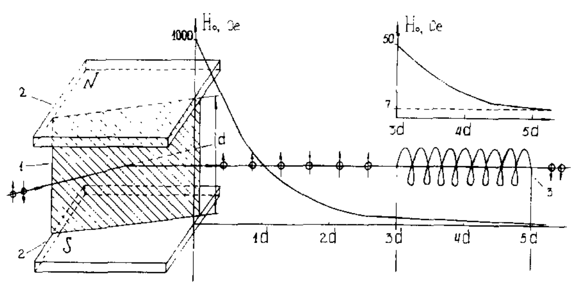

Fig. 6. Adiabatical flipper near a polarizer. 1) - Polarizing mirror, 2) - permanent magnets, 3) - solenoidal coil for producing RF field.

It is actually this flipper that we use on the installation of the small-angle scattering of the polarized neutron "Vector" of the WWR-M reactor in Gatchina (PNPI). The flipper was arranged at the output of the polarizer in a magnetic field perpendicular to the beam with a distribution practically followed by the exponential law: $H(x) = H_m \exp(-x/d)$, where H_m is the field inside polarizer, d the distance between poles of magnet, and x the distance to polarizer. As is shown schematically in the Fig. 3, the field decreases drastically by a factor $1/e^n$ for a distance of $n\,d$ mm and then diminishes smoothly with a gradient of about 2-3 Oe/cm. It is namely this area of space that is used for constructing the flipper. In the given case, the parameters of the magnetic field are as follows: H_m = 1 kOe, d = 80 mm, $H(3d)$ = 50 Oe, $H(5d)$ = 7 Oe. The entry of the flipper was located at a distance of $3d$ (240 mm) from the polarizer, and its length equals $2d$ (160 mm). The magnitude of the guiding field at the center of the flipper ($x = 4d$) H_0 is about 20 0e. The RF field is produced by the solenoidal coil. The sizes of the holes of the solenoidal coil are hardly larger than the cross section of beam which covers the area of 10×60 mm^2. According to the guiding field at the center of the flipper, $\omega_0/2\pi$ = 60 kHz. The value of the modulation field A is about 10 Oe.

As a result, the flipper is highly stable and available for work with a spin flip probability better then 0.99 for the range, limited only by the minimum wavelength $\lambda_{min} \approx 5$ Å.

3.2. Adiabatical flipper with large cross section

The creation of an adiabatic resonance device for flipping an incident beam of polarized neutrons with an average cross section (10-50 cm^2) has no insuperable obstacles. Any installation of polarized neutrons at PNPI is equipped with such a kind of flipper.

The other complex situation arises when flipping spins of scattered neutrons on an installation of SAPNS (Small Angle Polarized Neutron Scattering) with an area detector. The reason for difficulties arising is the position where the flipper must be placed on the SAPNS installation (between the sample position and the analyzer). The disposition requires flipping spins in the whole range of small angles, respectively, for capturing the area of the detector. As a consequence of that, the flipper must interact with a scattered neutron beam with large cross section.

Such a flipper was created for the setup SANS 2 (GKSS - research center, Geesthacht, Germany) by joint efforts of PNPI and GKSS (Fig. 7) [10]. The outside dimensions

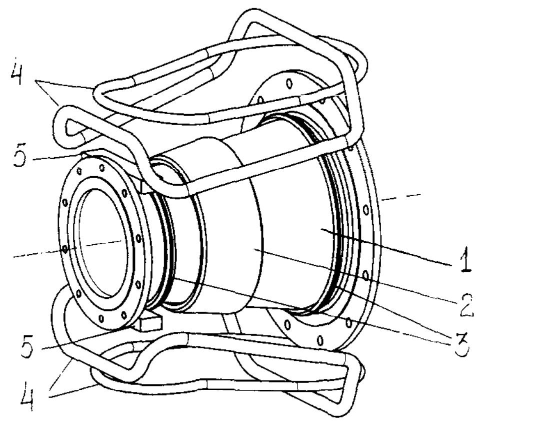

Fig. 7. Adiabatical flipper with a large cross section. 1) – Plastic conical corpus, 2) – solenoidal coil for producing RF field, 3) – metallic rings, 4) – coils for producing guiding field, 5) – additional magnets for correction of guiding field.

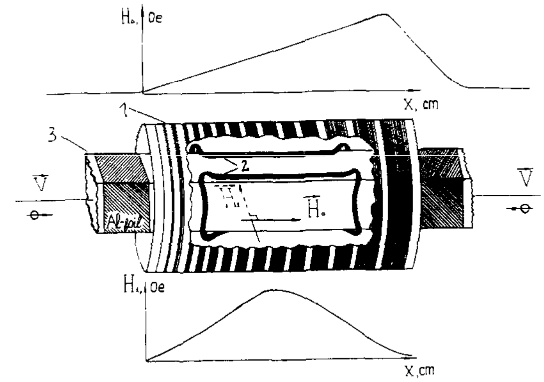

Fig. 8. Adiabatical flipper with guiding field parallel to the beam direction. 1) – Solenoidal coil for producing guiding field with a gradient $H_0(x)$, 2) – coils for producing RF field, $H_1(x)$, 3) – the neutron guide.

of this large flipping machine are 620 mm length, 700 mm height, and 530 mm width. The working space was conically shaped. Starting and finishing diameters were equal to about 200 mm and 350 mm, respectively, and the length equal to 450 mm. This plastic conical body is an element of the vacuum equipment of the installation. The solenoidal coil with length about 200 mm for creating the RF field has been wound directly on the conical body. The frequency of the RF field was set to 73 kHz. Owing to the large diameter, the coil causes a noticeable fringing field which was suppressed by two metallic rings at the entrance and exit of the flipper. The complex system consisted of two sets of coils and a few magnets created a guiding field with a gradient and provided a uniform field in the cross section of the flipper. According to the frequency, the field equals 25 Oe at the center of flipper and the decrease of the guiding field was about 40 Oe from maximum to minimum.

The test of the flipper has been carried on the neutron facility of GKSS, namely, at the reflectometer "TOREMA 2" and "SANS 2". The measurements of the spin flip probability are in agreement with the calculated dependence (7). The spin flip probability of the device, f, is better than 0.998 for neutrons with wavelength higher than 4 Å in the whole range of small angle scattering up to $\pm 9^0$.

3.3. *Adiabatical flipper with a guiding field parallel to the beam*

At present a new modification of the RF flipper is projected for the setup SANS 3 and the reflectometer PNR at GKSS. The feature of this flipper as compared to the common one is that a mutual exchange of magnetic field directions takes place (Fig. 8). Namely, the direction of the guiding field with the gradient is changed from perpendicular to parallel to the beam trajectory. Owing to this fact it is convenient to create the guiding field by a solenoidal coil. In order to reach a smooth growth of the guiding field along neutron path the number of wire turns per cm rises smoothly from 1 to 20 over the length of the coil (about 30 cm). Such a coil construction allows one to create the necessary parameters of the guiding field by a technically more easy way than the other flipper constructions, which create a field gradient by a pair of Helmholz coils inclined to the axis parallel to the beam. So in the considered case the change of current in the coil provides the gradient of the field and the tuning the device. In contrast with that, in order to tune the former construction we need to pay special attention to the agreement of several factors such as the distance between the coils, the coil inclined angle and current in coils as well.

In the case when the guiding field of the whole installation is parallel to the neutron trajectory, the present flipper design has some advantages, because no efforts are spent on arranging an additional adiabatical spin transition both before and after the flipper.

As to the RF field it is perpendicular to the guiding field and created by Helmholz coils located inside the solenoidal coil. In order to produce a field with a maximum at the center of the flipper which decreases as the distance from the center increases we have given a special form to these coils by bending them as shown on Fig. 8. It is clear that such an RF coil organization causes a noticeable fringing field in the whole space near the flipper. However one can use a metallic shield (for instance an aluminium foil) to cover that part of the neutron guide where the fringing field should be suppressed. As a result, the main parameters of the flipper are as follows: The diameter of the solenoidal coil was chosen to be 200 mm and its length 300 mm. The sizes of the RF coils are 250 mm in length and 100 mm in width and these coils are layed-out on a distance over 60 mm with respect to each other. The frequency $\omega_0/2\pi$ is set to 71.4 kHz and its amplitude equals 20 Oe. The magnitude of the guiding field H_0 at the center of the flipper according to the frequency is about 24 Oe. The modulation A should be equal to the amplitude of RF field (about 15 Oe).

The test of the flipper has been carried at the installations "Torema 2" at GKSS. The spin flip probability attained was

0.999 ± 0.004 for the wavelength 4 Å and is stable within the error interval. Additionally, it has been found that a real neutron guide with ^{58}Ni covering does not change the flipping efficiency. It means that it is possible to make a flipper without disturbing a neutron guide by making a gap.

In conclusion we note that tests of the flippers constructed on the basis of the sine–cosine model were successfully carried out. It showed the adequacy of the model for flipper construction. The opportunities of flipper application are not limited by the three modifications described above. One could construct flippers taking in account the specific conditions of each installation.

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