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Design and demonstration of a neutron spin flipper for a new neutron reflectometer SHARAKU at J-PARC

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Abstract

A new neutron reflectometer SHARAKU with vertical sample-plane geometry was installed on the beam line 17 (BL17) at Materials and Life science experiment Facility (MLF) at J-PARC. Magnetism in a thin magnetic film is one of the main targets on SHARAKU and polarizing devices and neutron spin flippers are required. Since polarized neutrons of wavelength from 0.24 nm to 0.64 nm can be used on SHARAKU, a neutron spin flipper has to control white neutron beam. A two-coil neutron spin flipper (Drabkin spin flipper) is one of the powerful devices to control neutron spin with white beam. In this study, the two-coil flipper was designed and installed in SHARAKU. Demonstration of the two-coil flipper was also performed and polarization of more than 0.95 with wavelengths ranging from 0.24 nm to 0.64 nm was obtained.

Selection and peer-review under responsibility of the Organizing Committee of the 9th International Workshop on Polarised Neutrons in Condensed Matter Investigations

Keywords: Neutron spin flipper; Neutron reflectometer; Polarized neutrons

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1. Introduction

Polarized neutron reflectometry is a very effective method to investigate a layer structure of magnetic thin films and this is expected to lead to development of high-density magnetic recording devices. For this development, measurement of a very weak magnetism less than 1 μ_B is required. Hence a polarized neutron beam with high polarization of more than 0.95 is necessary for such investigations.

A new neutron reflectometer SHARAKU with a vertical sample plane geometry was constructed at beam-line (BL) 17 at MLF. SHARAKU provides polarized neutrons and enables us to analyze a magnetic structure in a magnetic thin film. Hence polarizing devices and neutron spin flippers have to be installed to SHARAKU. In this paper, the topic is focused to the development and demonstration of neutron spin flipper on SHARAKU.

A two-coil spin flipper, so called Drabkin flipper, is one of the effective flippers for white beams. Design study of the two-coil flipper was performed to achieve a high polarization more than 0.95 and demonstration was performed at SHARAKU. The details of the design study and demonstration are described in section 2 and 3, respectively.

2. Design of the two-coil flipper

Here the principles of the two-coil flipper are briefly explained [1]. Figure 1 (a) and (b) show schematic principles of the typical two-coil flipper with OFF and ON, respectively. The two-coil flipper consists of two coils, Coil-in and Coil-out, set coaxially about the neutron beam path direction (z direction). The thin arrows in fig. 1 indicate the direction of the magnetic field generated by the two coils. The spin of incident polarized neutron beam follows the guide magnetic field generated by the Coil-in adiabatically. When both of the currents are applied to same direction as shown in fig. 1 (a), the magnetic field in the two-coil flipper does not change direction from Coil-in to Coil-out. The neutron spin also does not change the direction and remains parallel to the magnetic field. Hence the spin component parallel to the guide field is obtained. On the other hand, when an opposing current is applied to the Coil-in as shown in fig. 1 (b), magnetic field is cancelled at the center of the two coils. The spin of incident polarized neutron beam follows the guide magnetic field generated by the Coil-in adiabatically. When no radial direction of magnetic field (B_x or B_y) exist at the center of the two coils, neutron spin is conserved because the spin does not change direction without a magnetic field perpendicular to the neutron spin. Thus the neutron spin becomes antiparallel to the guide field non-adiabatically, and the spin component antiparallel to the guide field is obtained.

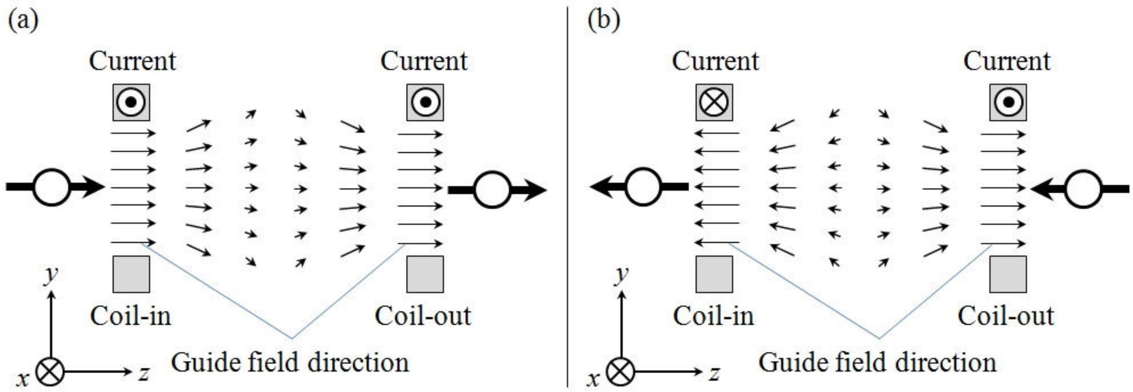

Fig. 1. Schematic principles of the typical two-coil flipper. (a) and (b) show the flipper OFF and ON mode, respectively. In the flipper OFF mode, the current directions of the two coils are same and neutron spin component parallel to the guide field is obtained. On the other hand, in the flipper ON mode, opposing currents are applied to the Coil-in and neutron spin antiparallel to the guide field is obtained.

Figure 2 shows a schematic view of SHARAKU. The *x*, *y*, *z* directions are horizontal, vertical and beam path directions, respectively. Effective size of the moderator is 100 mm in height and typical sample size is 30 mm in height. Since the center position of the two-coil flipper is placed at z = 11500 mm, the typical beam size at the center of the two-coil flipper is about 50 mm in height. Moreover, wavelength of polarized neutron range is between 0.24 nm to 0.64 nm in SHARAKU [2]. Thus the two-coil flipper has to cover a 50 mm of beam size and wavelength from 0.24 nm to 0.64 nm.

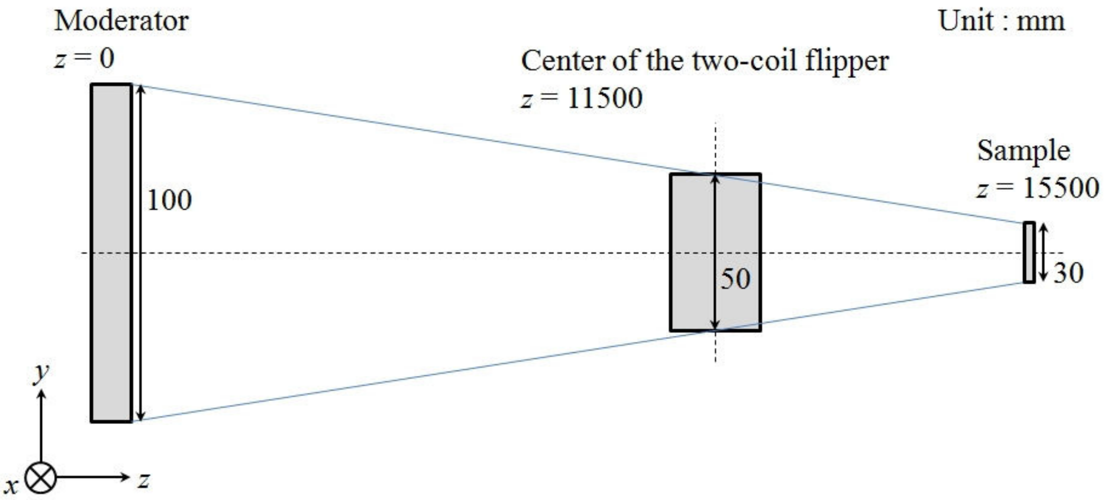

Fig. 2. Schematic view of SHARAKU. The center of the two-coils flipper is placed at z = 11500 mm. Since the effective size of the moderator is 100 mm and the typical sample size is 30 mm, the size of neutron beam at the center of the two-coil flipper is 50 mm.

As mentioned in fig. 1 (b), we can obtain the neutron spin component antiparallel to the magnetic guide field without radial direction of magnetic field at the center of the two-coil flipper. This means that making zero magnetic fields at the center of the two-coil flipper is the most important factor to develop a high performance two-coil flipper. The diameters of two coils, the distance between the two coils and the magnetic shield between the two coils affect the magnetic field at the center. Although large diameter and distance are

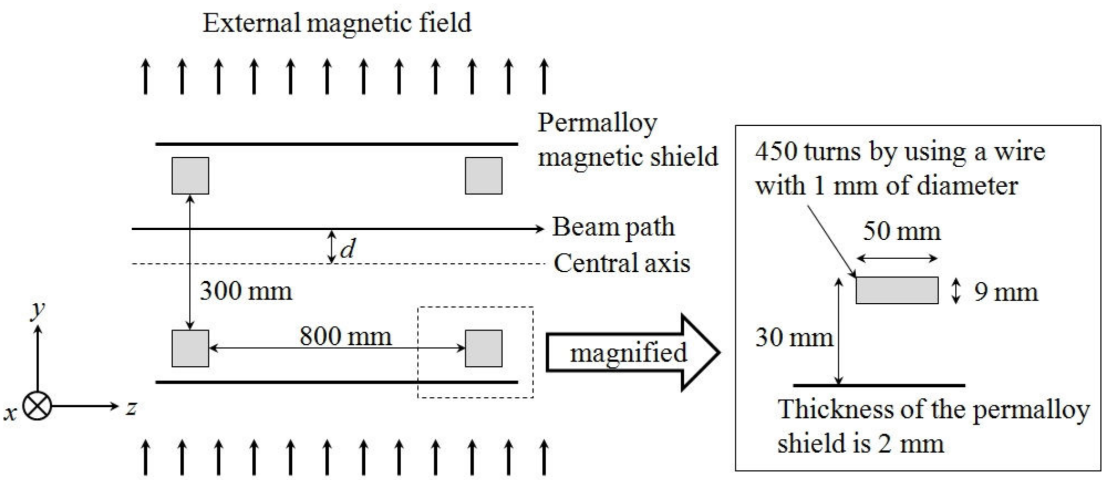

Fig. 3. Conceptual figure of simulated model. External magnetic field of 0.5 Oe is applied as an environmental magnetic field. Magnetic field along to a beam path distant by *d* mm from central axis is calculated by integral element method and Biot-Savart law.

effective to make zero magnetic fields at the center, a space to set the two-coil flipper on SHARAKU is about 400 mm in horizontal (x), 400 mm in vertical (y) and 900 mm in beam path direction (z). Thus, in this study, diameters of the two coils and the distance are fixed to 300 mm and 800 mm, respectively. A design study of the two-coil flipper on SHARAKU was focused to evaluate the performance of the permalloy magnetic shield.

Evaluation of the performance of the magnetic shield was performed by calculating the magnetic fields along the beam path. After that, simulation of neutron spin polarization along the calculated magnetic field was performed. Figure 3 shows a conceptual figure of simulated model. Permalloy magnetic shield is applied around the two-coils flipper. An external homogeneous magnetic field of 0.5 Oe is applied as an environmental magnetic field. Magnetic field along the beam path distant by d mm from the central axis is calculated with a 1 mm pitch by integral element method and Biot-Savart law. Two coils consist of a wire with 1 mm diameter and the number of turns of the two coils is 450. A current of 0.5 A is applied in both coils. Polarization of neutron spin is simulated by calculating an expectation value of neutron spin along the calculated magnetic field as follows [3],

$$\psi_{out} = \exp\left[-i\frac{\boldsymbol{S}\cdot\boldsymbol{n}}{\hbar}\cdot\frac{2\omega l}{v}\right]\psi_{in} = \exp\left[-i\left(\boldsymbol{\sigma}\cdot\boldsymbol{n}\right)\cdot\frac{\omega l}{v}\right]\psi_{in} \quad (1)$$

$$\left\langle S_x\right\rangle_{out} = \frac{1}{2}\psi^*_{out}\sigma_x\psi_{out},\ \left\langle S_y\right\rangle_{out} = \frac{1}{2}\psi^*_{out}\sigma_y\psi_{out},\ \left\langle S_z\right\rangle_{out} = \frac{1}{2}\psi^*_{out}\sigma_z\psi_{out} \quad (2)$$

$$P = \boldsymbol{S}\cdot\boldsymbol{B} = \frac{\left\langle S_x\right\rangle_{out}B_x + \left\langle S_y\right\rangle_{out}B_y + \left\langle S_z\right\rangle_{out}B_z}{|B|} \quad (3)$$

where $\boldsymbol{\sigma}$ is the Pauli matrix, $\boldsymbol{n}$ is the unit vector of magnetic field, ω/B is the Larmor frequency, l is the flight path of the neutron and v is the neutron velocity, respectively. The polarization P is calculated by the scalar product of spin vector $\boldsymbol{S}$ and magnetic field vector $\boldsymbol{B}$.

Figure 4 shows one of the results of calculating magnetic field and simulating the polarization along the neutron path distant by 1 mm (d = 1) from the central axis for a wavelength of 0.64 nm. Calculated magnetic fields B_x, B_y and B_z along the neutron path are shown in fig. 4 (a), and expectation values of $\langle S_x\rangle$, $\langle S_y\rangle$, $\langle S_z\rangle$ and polarization P of the neutron spin are shown in fig. 4 (b). Dots, dashed line and line indicate x, y and z components in fig. 4 (a) and (b). The thin line shown in fig. 4 (b) correspond to the polarization P. The $\langle S_z\rangle$ value is -1 for whole flight path on this simulation as shown in fig. 4 (b), and the directions of B_z before and after the center of the two coils are negative and positive. This means that the neutron spin is parallel and antiparallel to the magnetic field before and after the center of the two coils, respectively. Thus polarization P changes from +1 to -1 at the center of the two coils and neutron spin component with antiparallel to the magnetic field is obtained.

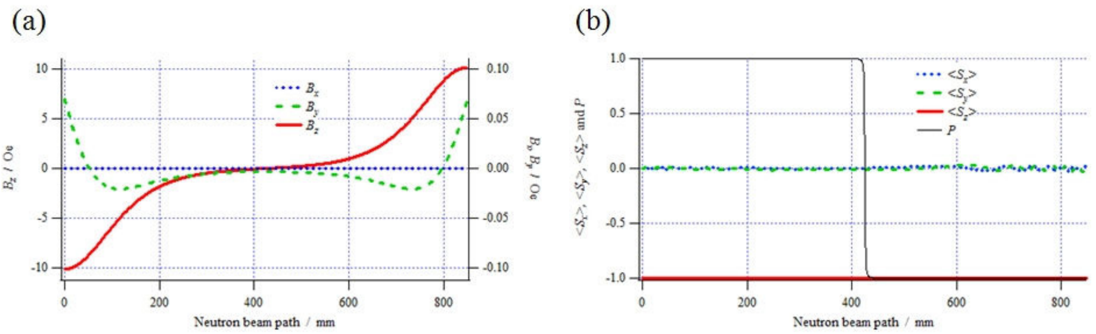

Fig. 4. One of the results of calculating magnetic field (a) and simulation of expectation values and polarization (b). Dots, dashed line and line indicate x, y and z components in fig. 4 (a) and (b). Thin line shown in fig. 4 (b) is polarization P.

Figure 5 shows a simulation result of polarization P comparing a performance of magnetic shield of single with that of triple layer of permalloy. In the simulation model of triple layered shield is same with the single one shown in fig. 3 except the number of layers of magnetic shield. In the triple shield model, the 2nd and 3rd shields were placed coaxially with the 1st one. The radius of the 2nd shield was larger by 30 mm than that of 1st one, and that of 3rd one was larger by 30 mm than that of 2nd one. The thickness of the 2nd and 3rd shield was same with that of 1st one (t = 2 mm). Simulation was performed for wavelength of 0.24 nm (fig. 5 (a)) and 0.64 nm (fig.5 (b)) and with 6 patterns of neutron paths of d = 1, 5, 10, 15, 20, 25 mm. This result shows that the polarization of the triple shield is better than that of the single one, especially in neutron path apart from the central axis and in longer wavelength.

(a) (b)

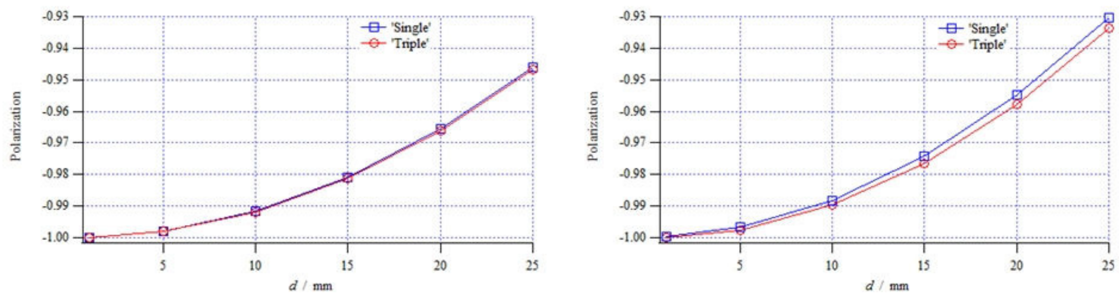

Fig. 5. Simulation result of polarization P comparing the performance of magnetic shield of a single layer with that of triple layer. (a) and (b) are the result with wavelength of 0.24 nm and 0.64 nm, respectively. Squared and circled symbols correspond to the polarization of the two-coil flipper with single and triple magnetic shield.

3. Demonstration and result

A two-coils flipper was fabricated according to the simulation results and has been installed to SHARAKU. Demonstration of the two-coils flipper was performed and the result of spin-flip probability is shown if fig. 6. Since a transmission type of polarizer and reflection type of analyzer are used on SHARAKU, the spin-flip probability can be defined by $P_n = (I_{ON} - I_{OFF}) / (I_{ON} + I_{OFF})$, where I_{ON} and I_{OFF} are number of neutrons with the flipper ON (spin up) and OFF (spin down), respectively. Although the spin-flip probability P_n includes polarization of polarizer and analyzer, extremely high spin-flip probability for wide wavelength band was obtained. All the required specifications for the two-coils flipper on SHARAKU, $P_n > 0.95$ for beam size of 50 mm with wavelength from 0.24 nm to 0.64 nm, was accomplished.

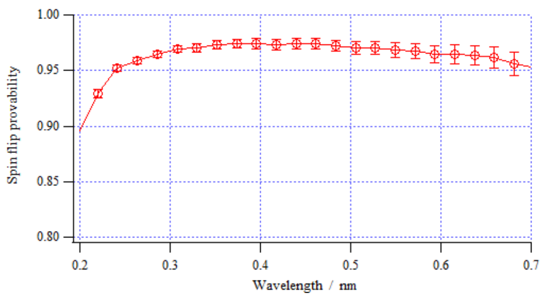

Fig. 6. The result of the demonstration of the two-coil flipper installed to SHARAKU. Although the spin-flip probability includes polarization of polarizer and analyzer, extremely high spin-flip probability for wide wavelength band was obtained.

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