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Application of a neutron-polarizing device based on a quadrupole magnet to a focusing SANS instrument with a magnetic neutron lens

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Abstract
A magnetic neutron lens based on a sextupole magnet is considered an ideal neutron-focusing device for focusing-geometry small-angle neutron scattering (FSANS) instruments using polarized neutrons. However, the magnetic neutron lens functions both as focusing and defocusing lens for positive and negative polarity neutrons, respectively. Negative polarity neutrons are defocused by the lens and spread over the detector of the instrument, resulting in an increase of the background level. Therefore, a neutron-polarizing device with a very high polarizing efficiency $P \gtrsim 0.99$ is required to be employed together with the magnetic neutron lens. A neutron-polarizing device based on a quadrupole magnet has a very high polarizing efficiency $P \gtrsim 0.99$, which is sufficient for the application to the FSANS instrument. In this study, we installed the quadrupole magnet in the FSANS instrument SANS-J-II and investigated its performance with respect to the conventional magnetic super-mirror polarizers of the FSANS instrument.

Keywords: polarized neutron, quadrupole magnet, neutron polarizer, magnetic neutron lens, beam focusing, sextupole magnet, small-angle neutron scattering

1. Introduction

A polarized neutron beam is a valuable probe to investigate structure of magnetic materials and materials composed of elements which have large incoherent scattering cross-section such as hydrogen atoms. However, in general, the intensity of a neutron beam created at accelerator and research reactor based facilities is incredibly lower than that of a photon beam created at synchrotron facilities. Furthermore, quantity of neutrons is reduced by more than 50% by polarizing neutrons using existing polarizing devices such as magnetic super-mirrors, magnetic crystals and ^{3}He spin filter due to neutron absorption and scattering by the materials. If the neutron beam is polarized and focused by only using the interaction between a magnetic field and magnetic moments of the neutrons, then we can use the polarized neutron beam with a high utilization efficiency. In this respect, a neutron-polarizing device based on a quadrupole magnet (Q-mag) and a magnetic neutron lens based on a sextupole magnet are considered to be an ideal neutron-polarizing device and a polarized neutron-focusing device, respectively [1–6], since no materials are required to be put on the beam axis so that the neutron beam is free from neutron scattering and absorption by materials.

As an application of such magnetic devices to practical neutron scattering experiments, the magnetic neutron lens is considered a suitable neutron-focusing device for focusing-

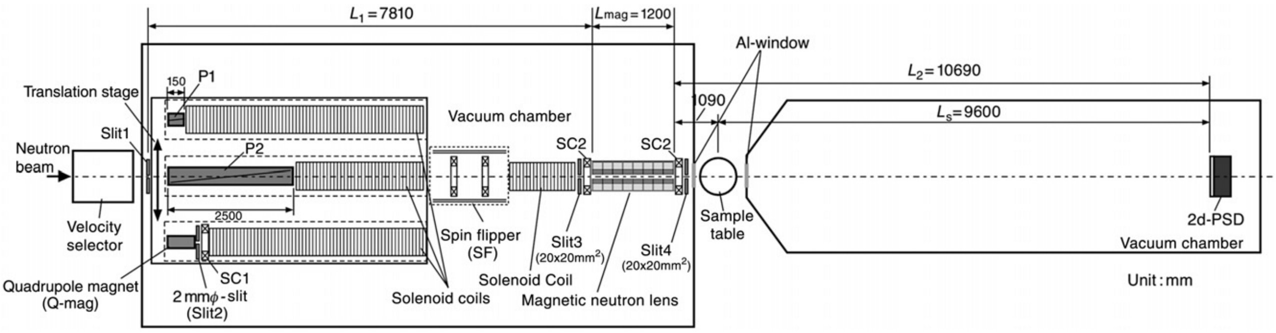

Figure 1. Experimental setup of SANS-J-II. P1 and P2 are the transmission-type Fe/Si super-mirror polarizers.The Q-mag was installed to study its performance as the neutron-polarizing device for the FSANS measurement. We can choose a polarizer to be used by translating a stage on which the polarizers are mounted. The magnetic neutron lens is a sextupole magnet which focuses the positive polarity neutrons on the surface of a 2d-position-sensitive detector (2d-PSD).

geometry small-angle neutron scattering (FSANS) instruments using polarized neutrons due to its above-mentioned focusing property for positive polarity neutrons whose spin is parallel to a magnetic field [1–5]. However, the magnetic lens functions as a defocusing lens for negative polarity neutrons whose spin is antiparallel to the magnetic field [1–5]. Therefore, if negative polarity neutrons are involved in the neutrons incident into the magnetic neutron lens, then they are defocused by the lens and spread over the detector of the instrument, resulting in an increase of the background level. In small-angle neutron scattering (SANS) experiments, information on material structure appears as scattering intensity changing by several orders of magnitude as a function of the modulus of the scattering vector $\boldsymbol{q}$. However, scattering intensity lower than the statistical and systematic errors of the background intensity is not measurable, so it is important to reduce the background level, which is a key parameter determining the performance of SANS instruments. A neutron-polarizing device with a very high polarizing efficiency $P \gtrsim 0.99$ is required to be employed as the neutron polarizer of the FSANS instrument using the magnetic neutron lens for the reduction of background intensity [7].

The Q-mag has a very high polarizing efficiency, which is considered sufficient for the application to the FSANS instrument [6]. Thus, by using the magnetic neutron lens together with the Q-mag, it is expected that a highly polarized and well-focused neutron beam can be created with high efficiency. In this study, we installed the Q-mag in the FSANS instrument with the magnetic neutron lens, and investigated the instrument's performance. By comparing the obtained results with those obtained with conventional magnetic super-mirror polarizers, we discussed the performance of the Q-mag based polarizer for the FSANS instrument with the magnetic neutron lens.

2. Experimental setup

To study the effect of the Q-mag as a neutron-polarizing device for the FSANS instrument with the magnetic neutron lens, we installed the Q-mag in the FSANS instrument SANS-J-II at JRR-3 of Japan Atomic Energy Agency. The instrumental setup is shown in figure 1. The neutron beam was monochromated by using a mechanical velocity selector, and we used neutrons with wavelength $\lambda = 6.5$ Å and $\Delta\lambda/\lambda = 0.113$ in FWHM. SANS-J-II is equipped with a magnetic neutron lens based on an extended Halbach-type permanent magnet together with magnetic Fe/Si super-mirror polarizers P1 and P2 [7, 8]. Since P1 and P2 are transmission-type polarizers, the transmitted neutrons have negative spin polarity. Thus, they are spin flipped by π using the spin flipper (SF) with the flipping efficiency $f \gtrsim 0.99$ to satisfy the focusing condition of the magnetic neutron lens. P1 has a length of 150 mm and is effective for an incoming beam with a cross section of 1 mm (W) × 1 mm (H) [7, 8]. On the other hand, P2, which is 2500 mm long, has Ni-side walls for efficient neutron transfer and has an effective cross section of 20 mm (W) × 50 mm (H) [7, 8]. The polarization efficiencies of P1 and P2 are ∼0.96 and ∼0.99, respectively [7].

The Q-mag is a Halbach-type permanent quadrupole magnet with an aperture size of 5 mm in diameter and a length of 600 mm. The Q-mag consists of 12 segments of a strong permanent magnet NdFeB, and the direction of the magnetization vector of each NdFeB segment is assigned as shown in figure 2. According to a magnetic field measurement, the magnetic field gradient $\partial|\boldsymbol{B}|/\partial r = 791.9 \pm 8.3$ T m^{-1} was observed inside the Q-mag aperture. In the aperture of the Q-mag, positive polarity neutrons are confined around the magnet center axis, but negative polarity neutrons are accelerated away from the magnet center axis due to the magnetic field gradient in the Q-mag. Accordingly, neutron-absorbing cadmium (Cd) cylinders with an inner diameter of 3.5 mm were inserted into the Q-mag aperture to suppress neutron reflection on the inner surface of the Q-mag. Moreover, a Cd slit with a 2 mm ∅ pinhole (Slit2) is attached at the end of the Q-mag. Under this experimental condition, only the positive polarity neutrons pass through the Q-mag aperture.

Inside the Q-mag, neutrons are polarized along the direction of the local field in the Q-mag. By applying a dipole field around the end of the Q-mag using a solenoid coil (SC1), the neutrons are transferred from the quadrupole field to dipole field regions adiabatically. The neutrons are focused on the surface of the 2d-position-sensitive scintillation detector (2d-PSD) [9], and the neutron intensity distributions are measured by the 2d-PSD with the position resolution 0.8 mm in FWHM.

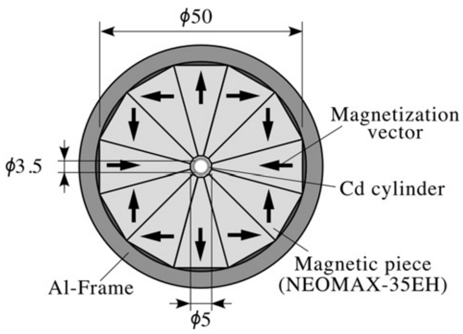

Figure 2. Halbach-type quadrupole magnetic circuit.

3. Experimental results and discussion

Figures 3(*a*) and (*b*) show the radial distributions of the averaged intensity normalized by the measuring time and the peak-height intensities, I_{peak}, respectively. It is considered that the difference in the peak height of the intensity normalized by time mainly results from the difference in the neutron transmission property of the polarizing devices (figure 3(*a*)). Since P2 has a neutron transmission $T_{unpol} \sim 0.22$ for unpolarized neutrons with $\lambda = 6.5$ Å [7], the neutron transmissions of the Q-mag and P1 are estimated to be $T_{unpol} \sim 0.44$ and $T_{unpol} \sim 0.16$, respectively. Since the Q-mag has a very high polarization efficiency $P \gtrsim 0.99$ and there is no material to absorb and scatter neutrons on the beam axis of the Q-mag, much higher neutron transmission close to $T_{unpol} = 0.5$ is expected for the Q-mag. The experimentally obtained lower neutron transmission for the Q-mag is considered to result from the fact that a small amount of the positive polarity divergent neutron beam is absorbed by the Cd cylinders in the Q-mag and/or the Cd-slit (Slit2) in this setup. In the case of P1 used, a flat background intensity region was observed as indicated in figure 3(*b*). This background intensity is created by the negative polarity neutrons, because they are defocused by the magnetic neutron lens and spread over the detector homogeneously [1, 4, 5]. On the other hand, such a flat background region was not observed in the cases of P2 and Q-mag due to their higher polarizing efficiencies. In figure 3(*b*), relatively large peak broadening of the intensity peak profiles was observed for P1 and P2 when compared with the case of the Q-mag. The peak broadenings are considered to be the result of the neutron scattering from the mirror materials of the P1 and P2 and/or neutron reflection on the Ni-side walls of the P2 [6]. In the case of Q-mag, there are no materials to scatter neutrons on the beam axis, so that the well-sharpened intensity profile is considered to be obtained.

As the results of this study, the excellent performance of the Q-mag as a neutron-polarizing device based on its characteristics such as high neutron transmission and high polarization efficiency was demonstrated in the application to the FSANS instrument using the magnetic neutron lens. The weak aspect of the Q-mag-based polarizer is its small opening aperture, which is required to realize a sufficiently strong magnetic field gradient for the application. However, in the application to the FSANS instrument, a large cross section of the neutron beam is not required at the polarizer position for the high angular-resolution measurement [10, 11], so that the small aperture of the Q-mag does not matter in this case. If the effective aperture of the Q-mag is enlarged while keeping its polarizing power by employing an extended-Halbach circuit [12] or a superconducting magnet, the performance of the FSANS instrument would be further improved and another kind of application such as a highly efficient polarized-neutron transporting guide would be expected.

4. Summary

In order to study the performance of the neutron-polarizing device based on the Q-mag in the application to the FSANS instrument using the magnetic neutron lens, we installed the

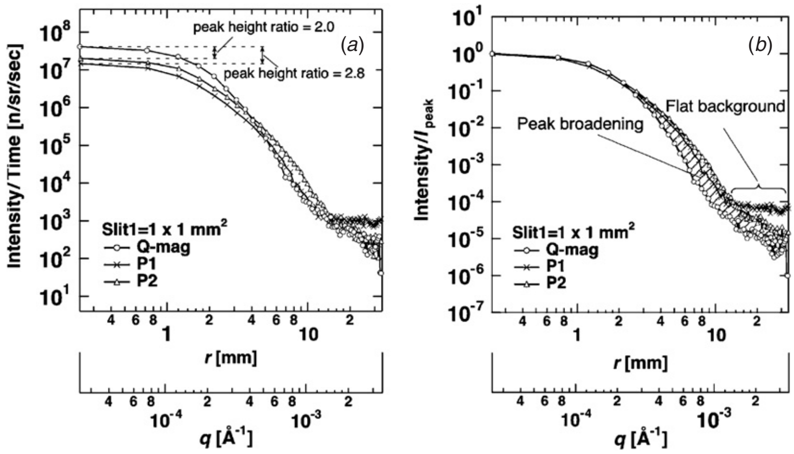

Figure 3. The radial averages of the intensity distributions when the size of Slit1 is 1×1 mm^2. (*a*) The intensities are normalized by the measuring time. (*b*) The intensities are normalized by the peak-height intensities I_{peak}. r is the distance from the peak center and q is the corresponding modulus of the scattering vector defined as $q = (4\pi/\lambda)\sin(\theta/2)$, where θ is the scattering angle.

Q-mag in the FSANS instrument with the magnetic neutron lens, and measured the intensity distribution of the neutrons focused on the detector. By comparing the obtained results with those obtained by using the conventional magnetic super-mirror polarizers, it was found that an intensity distribution with higher peak height and sharper peak profile could be obtained by using the Q-mag. Therefore, we conclude that the FSANS setup that is composed of the magnetic neutron lens and the neutron-polarizing device based on the Q-mag is considered a suitable setup of the FSANS instrument using polarized neutrons for high angular-resolution measurements.

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