HIGH-EFFICIENCY NEUTRON TRANSPORT USING MAGNETIC GRADIENT WITH PERMANENT MAGNETS*

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Abstract

Neutron guide tubes, which utilize reflection at material surfaces, are used for neutron transport. In many cases, neutron guide tubes with small divergence angles are sufficient. By arranging thin guide tubes radially according to the size of the sample, the overall efficiency of the system can be improved. We are developing a new type of neutron mirror that utilizes the orbital refraction of neutrons in a gradient magnetic field. Six prototype magnet plates were fabricated and tested at BL16. We report on the current status of research and development regarding this mirror.

INTRODUCTION

Slow neutron beams are widely used not only in fundamental physics and materials research but also in industrial applications. The cost of generating neutron beams is high compared to other imaging methods, such as X-rays. Because experimental areas are located far from the source due to radiation shielding, it is important to establish a mechanism for efficiently transporting neutrons between these areas. To address this issue, neutron guide tubes are used to reflect neutrons off the surface of materials. By employing multilayer mirror coatings for neutrons within the guide tube, it is possible to transport neutron beams with a wide range of divergence angles downstream (see Fig. 1).

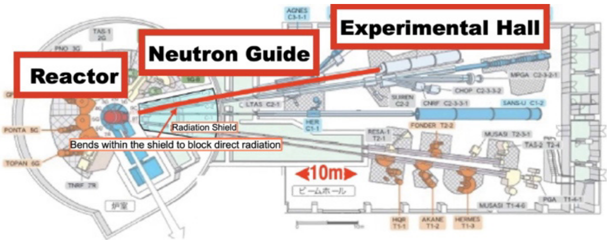

Figure 1: Layout of JRR3. The experimental area is far from the source due to radiation shielding. Neutron guide tubes that utilize reflections at the surface of materials are used to transport neutrons.

However, in many experiments, such as small-angle neutron scattering, the divergence angle of the incident beam must be sufficiently small to obtain measurements with good q-resolution. Although guide tubes transport beams with large divergence angles, most of the neutrons are removed by collimators. This can lead to an increase in radioactive waste and background radiation. In fact, in many small-angle scattering measurements, only beams with a divergence angle corresponding to m=1 in a supermirror, are used. Furthermore, in modern neutron facilities, a single experimental apparatus is installed directly at the end of a single guide tube. The beam does not branch during transport. In such cases, guide tubes capable of accommodating large divergence angles are unnecessary. Arranging thin guide tubes radially to match the size of the sample would likely improve the overall efficiency of the facility. (see Fig.2).

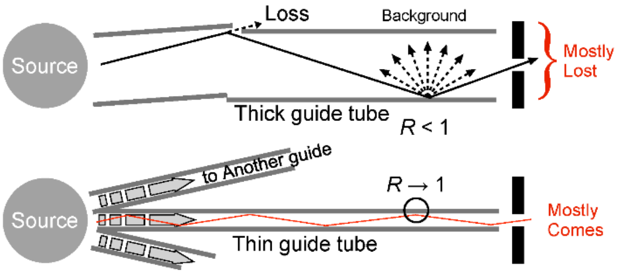

Figure 2: Top: Conventional guide tube with loss and background. Bottom: New concept of guide tube for modern neutron facilities. This will increase the number of beamlines. Fuzzy mirror surface eases alignment tolerances and reduce collisions with tiny dust particles on the mirror surface. Most transported neutrons will be used.

MAGNETIC NEUTRON DEFLECTION

We are developing a new type of neutron mirror that utilizes the orbital refraction of neutrons in a gradient magnetic field (see Figure 3). In a magnetic field, the neutron orbits are deflected according to the following equation:

$$\frac{d^2\boldsymbol{r}}{dt^2} = \pm\left|\frac{\mu_n}{m_n}\right| \cdot \nabla|\boldsymbol{B}|$$

where $\boldsymbol{r}$ and t are position of a neutron and time, μ_n and m_n are the magnetic dipole moment and mass of the neutron, respectively [1]. $\nabla|\boldsymbol{B}|$ is gradient of magnetic field

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* Work supported by partially supported by JSPS KAKENHI Grant Number JP23H03659. The neutron experiment at the Materials and Life Science Experimental Facility of the J-PARC was performed under a user program 2024B0198.
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strength. The sign on the right side depends on the direction of the neutron spin (magnetic dipole moment): positive if the spin and the magnetic field are parallel, and negative if they are anti-parallel. For unpolarized incident neutrons, this magnetic field initially reflects only one spin component, but thereafter, it behaves as a mirror with 100% reflectivity, if the spin is kept. We call this as a '<u>magnetic gradient mirror</u>'. In a conventional mirror, neutrons penetrate the material for about a wavelength because they are reflected through the pseudo-potential in the material. In this mirror, neutrons are gradually bent in space with the magnetic field and do not contact the surface of the material. Since the magnetic fields boundary is <u>fuzzy</u>, it is no longer affected by roughness of the material surface or gaps in the assembly. Furthermore, since neutrons do not interact with matter, no background events are generated as a result. This could be a key factor in ultra-low-background experiments.

MAGNETIC GRADIENT MIRROR

Since the number of reflections increases within a narrow waveguide, it is important to maintain the reflectivity as high as possible. In the case of multilayer mirrors, the reflectivity decreases depending on the condition of the material surface, such as surface roughness. Additionally, gaps and steps created during the assembly process also contribute to a decrease in effective reflectivity. Extremely high-precision installation is costly and makes the system vulnerable to shocks caused by earthquakes or other accidents. Therefore, we are developing a new type of neutron mirror that utilizes the orbital refraction of neutrons in a gradient magnetic field (Fig. 3).

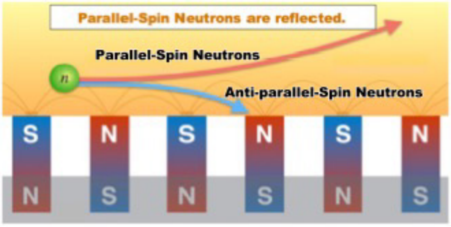

Figure 3: Schematic image of reflected neutron by magnetic repulsive wall. Field gradient produces repulsive force to spin parallel neutrons. Anti-parallel neutron is stopped in magnets or substrate.

MAGNETS

To generate the largest possible magnetic field gradient on the surface of the plate, 1 mm × 2 mm × 50 mm rod-shaped permanent magnets were arranged and secured to the substrate with adhesive, as shown on the left in Fig. 4. Their easy axes are perpendicular to the 50 mm axis. By arranging 50 permanent magnet bars on the plate while rotating the easy axes of adjacent magnets by 90° increments, we formed a 50 × 50 mm plate-shaped magnet with a strong magnetic field gradient on its surface. This is known as the Halbach configuration. Figure 4 (left) also shows the magnetic flux lines obtained from magnetic field calculations. Figure 4 (right) shows the magnetic field strength along a straight line 0.1 mm above the top surface of the magnet set. The dependence of the magnetic field strength on distance from the surface changes exponentially as the distance from the surface increases slightly.

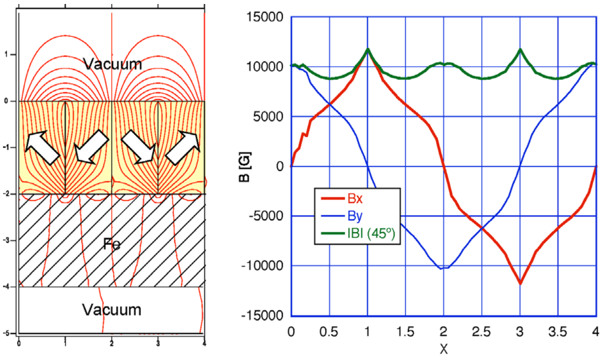

Figure 4: Magnet configuration (left) and its magnetic field distribution at 0.1mm above the magnet (right).

During the evaluation experiments, neutrons are introduced at a highly oblique angle relative to the magnet surface. Since each magnet assembly plate is only 50 mm long, the neutrons may encounter a sudden drop in the magnetic field at the edge of the magnet, which could complicate the analysis of the experimental results. Therefore, three sets of magnet plates were arranged as shown in Fig. 5 to prevent the neutrons from encountering such abrupt changes in the magnetic field. Figure 6 shows a top-down view of the magnetic viewer sheet placed on top of three magnetic plates. The magnets are slightly misaligned between the plates.

In order to prevent neutrons from scattering off the non-polished surface of the magnet assembly, a 10-µm-thick polished Ni foil was applied over the Kapton tape as shown in Fig.7. This reduced the number of background events that are difficult to analyze.

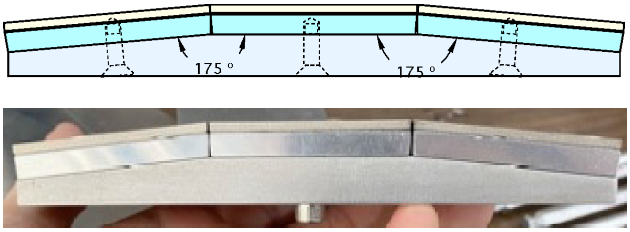

Figure 5: Three 50×50 mm magnet plates are arranged at a 5-degree angle to prevent neutrons from suddenly encountering the edges of the magnets.

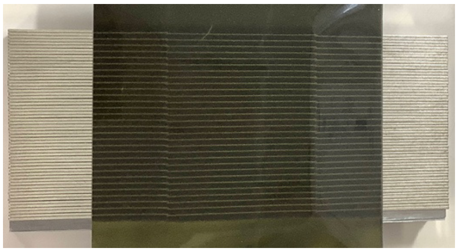

Figure 6: Top view of a set of three magnet plates.

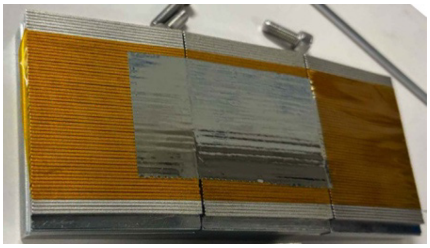

Figure 7: 10-µm-thick polished Ni foil applied over the Kapton tape (see text).

EXPERIMENT

To demonstrate that this magnet can bend the neutron beam as expected, we conducted an experiment using a prototype mirror and observed the wavelength dependence of the reflected neutrons. The experiment was performed at BL16 (SOFIA) of the J-PARC MLF. Fig. 8 shows the experimental setup. The neutron beam incident from upstream (the left side) is restricted in size and divergence angle by two slits before it is irradiated onto the sample, reducing its height to 0.1 mm. Neutrons reflected from the sample surface are measured by a position-sensitive detector. Since this detector has time resolution, we can observe the wavelength dependence of the reflection angle by utilizing the pulsed neutron characteristics of the J-PARC, based on the time-of-flight (ToF) of the detected neutrons and their position on the detector. As mentioned earlier, the sample consisted of three magnetic plates stacked together.

Since a large number of background events, believed to be caused by neutron scattering on the non-flat surface of the magnet, were observed, we have, as mentioned earlier, affixed a thin Kapton tape to the magnet surface and placed a 10-µm-thick, mirror-polished Ni foil on top of it. Ni is a ferromagnetic material, and because it is thin, once it is attracted to the magnet, it is difficult to peel off. The Kapton tape facilitates the peeling process.

After installing this 10-micron Ni foil, the number of random background events decreased, and we were able to obtain better data changing the magnet height and angle. Fig. 9 shows one of the measured data. The components of neutrons totally reflected at the Ni surface appear in the horizontal region, regardless of their wavelength (ToF). Since the component that is deflected by the magnetic field causes the deflection point (distance from the magnet) at which the sign of the vertical velocity reverses to vary depending on the wavelength, the detection position is wavelength dependent. Other noise is believed to be background noise caused by scattering off the nickel-plated surface of the unpolished magnet. Note that this experiment is highly sensitive to the relative alignment of magnets. Although the experimental data is recorded using the absolute values of the magnet angles and heights indicated by the apparatus, these values should be considered relative.

Fig. 10 shows a simulation result currently under investigation. The components of neutrons totally reflected at the Ni surface also appear in the horizontal region, regardless of their wavelength. The components that were deflected by the magnetic field also seen.

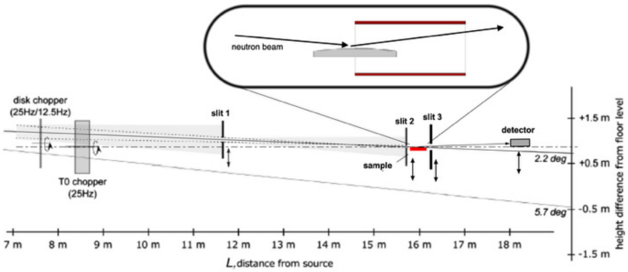

Figure 8: Setup at the BL16 at MLF, J-PARC.

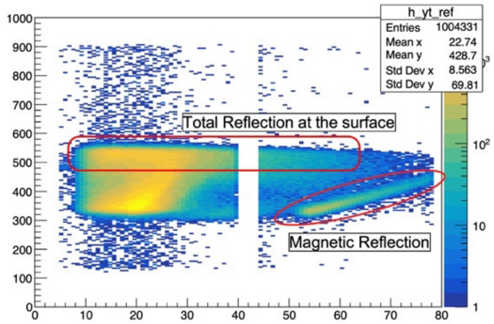

Figure 9: Example of Detected position of reflected neutron as a function of ToF.

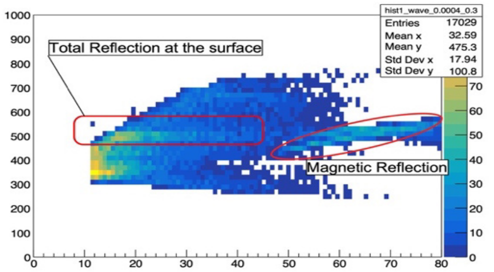

Figure 10: Simulation output.

CONCLUDING REMARKS

We fabricated a magnet capable of generating a magnetic field gradient and conducted neutron beam experiments. The results are under analysis.

As a next step, we plan to evaluate the effects of corner reflections, which are essential for neutron guide tubes.

ACKNOWLEDGMENT

This work is partially supported by JSPS KAKENHI Grant Number JP23H03659. The neutron experiment at the Materials and Life Science Experimental Facility of the J-PARC was performed under a user program 2024B0198 and 2025A0268.

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