

Polarization analysis for magnetic field imaging at RADEN in J-PARC/MLF

Takenao Shinohara^{1*}, Kosuke Hiroi¹, Yuhua Su¹, Tetsuya Kai¹, Takeshi Nakatani¹, Kenichi Oikawa¹, Mariko Segawa¹, Hirotoshi Hayashida², Joseph D. Parker², Yoshihiro Matsumoto², Shuoyuan Zhang², Yoshiaki Kiyanagi³

¹J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

²Comprehensive Research Organization for Science and Society, Tokai, Ibaraki 319-1106, Japan

³Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8601, Japan

E-mail: takenao.shinohara@j-parc.jp

Abstract. Polarized neutron imaging is an attractive method for visualizing magnetic fields in a bulk object or in free space. In this technique polarization of neutrons transmitted through a sample is analyzed position by position to produce an image of the polarization distribution. In particular, the combination of three-dimensional spin analysis and the use of a pulsed neutron beam is very effective for the quantitative evaluation of both field strength and direction by means of the analysis of the wavelength dependent polarization vector. Recently a new imaging instrument “RADEN” has been constructed at the beam line of BL22 of the Materials and Life Science Experimental Facility (MLF) at J-PARC, which is dedicated to energy-resolved neutron imaging experiments. We have designed a polarization analysis apparatus for magnetic field imaging at the RADEN instrument and have evaluated its performance.

1. Introduction

Neutron imaging is one of the fundamental techniques used to visualize the inner structure of objects nondestructively by using the neutron's unique characteristics such as high transmittance through massive objects and high sensitivity to light elements. As a neutron has a magnetic moment, it can also interact directly with magnetic fields. Hence the use of polarized neutrons enables us to visualize the distribution of magnetic fields by means of a change in neutron polarization [1, 2]. On the other hand, owing to improvements in the imaging devices and an increase of neutron beam intensity, a new neutron imaging technique, namely energy-resolved neutron imaging, has been developed. In this technique, analysis of the energy dependent neutron transmission has been performed position by position to produce quantitative distribution maps of physical quantities, for example, crystallographic structure information such as phase, texture, and strain, by Bragg-edge imaging [3], and elemental composition and temperature by Resonance absorption imaging [4, 5]. The neutron energy analysis technique using pulsed neutrons has also been applied to polarized neutron imaging, and we have developed a new magnetic field imaging technique, with which the magnetic field strength and direction can be treated quantitatively by analyzing the wavelength dependence of neutron polarization using the polarized pulsed neutron beam and the time-of-flight (TOF) method [6, 7].

In the MLF of J-PARC, a new instrument named "RADEN" has been constructed at the beam line BL22 [8, 9]. This is the first instrument dedicated to pulsed neutron imaging experiments. The main



purpose of RADEN is to conduct energy-resolved neutron imaging experiments efficiently by fully utilizing the nature of the neutron beam produced by the short pulsed neutron source i.e., fine energy or wavelength resolution by means of the TOF method and simultaneous availability of a wide energy range neutron beam from meV to keV. In addition, it has a role as the state-of-the-art neutron imaging facility in Japan, where it is possible to conduct experiments with sufficient neutron flux, selectable beam collimation and field of view, and monochromatic/white beam imaging capabilities. Because magnetic field imaging using polarized pulsed neutrons is regarded as one of the important applications of RADEN, a neutron polarization analysis apparatus has been prepared from the first stage of instrument operation. In this paper we report the design of the polarization analysis apparatus for polarized pulsed neutron imaging and its performance evaluated by commissioning studies using the neutron beam.

2. Design of the polarization analysis apparatus for magnetic field imaging

2.1. Magnetic field imaging using polarized pulsed neutrons

First, we explain the basis of the magnetic field imaging technique using polarized pulsed neutrons. As a neutron has a spin angular moment, it experiences torque in a magnetic field, causing the neutrons to precess around the magnetic field. The resulting precession angle ϕ of a neutron spin can be expressed by the following equation,

$$\phi = \gamma B t = \frac{\gamma m \lambda}{h} \int_{\text{path}} B \, ds \quad (1)$$

where γ is the gyromagnetic ratio of the neutron, t is the time for a neutron to traverse a magnetic field B , λ is the neutron wavelength, m is the neutron mass and h is Planck's constant. As is shown by equation (1), the precession angle ϕ depends on both the neutron wavelength and the accumulated magnetic field strength along the neutron beam path. Hence, when the absolute value of ϕ is measured, the path integral of the magnetic field strength can be evaluated using a monochromatic neutron beam with a given neutron wavelength. However, what we can measure is not ϕ but the neutron spin polarization P , which is defined as $P = (n_+ - n_-) / (n_+ + n_-)$ where n_+ and n_- are the number of neutrons with spin-up and spin-down states. According to the relation between ϕ and P that is discussed in reference [10], P undergoes a sinusoidal change against ϕ and wraps when ϕ increases above 2π . On the other hand, because ϕ is proportional to λ , P also shows a periodic oscillatory behavior against λ . Since the frequency of the neutron wavelength dependent P is equal to $\gamma m / h \int_{\text{path}} B \, ds$ from equation (1), we can evaluate the accumulated field strength without measuring ϕ . Thus performing polarization analysis position by position using a polarized pulsed neutron beam, whose wavelength can be easily determined by means of TOF analysis, it is possible to map the projection of the magnetic field strength distribution quantitatively for uniformly oriented fields.

Moreover in general a magnetic field is treated as a vector and hence the neutron polarization P is also expanded to a vector quantity $\mathbf{P}$. The change in $\mathbf{P}$ after transmission through a magnetic field region $\mathbf{B}$ can be written as

$$\mathbf{P} = D(\mathbf{n}, t) \mathbf{P}_0. \quad (2)$$

Here $D(\mathbf{n}, t)$ is a rotation matrix depending on a unit vector along the magnetic field direction $\mathbf{n} = \mathbf{B}/|\mathbf{B}|$ and t [8], and $\mathbf{P}_0$ is the initial polarization. Since the diagonal and off-diagonal terms of $D(\mathbf{n}, t)$ can be expressed using vector elements of $\mathbf{n}$, namely (n_x, n_y, n_z) , as in the following equations,

$$D_{ii} = 1 - (1 - \cos \phi) \cdot (1 - n_i^2) \quad (3)$$

$$D_{ij} = 1 - (1 - \cos \phi) n_i n_j - n_k \sin \phi, \quad i \neq j \neq k \quad (4)$$

where $i, j, k = x, y, z$, it is obvious that the magnetic field direction can be derived from the analysis of the wavelength dependence of these terms when the field direction does not change along the beam trajectory. To obtain every matrix element it is necessary to control the incoming neutron spin direction in three-dimensions and to analyze the spin direction of the outgoing neutron after traversing the magnetic field region in three-dimensions as well. This means that the three-dimensional neutron

polarization analysis similar to spherical polarimetry [11] is required. While introducing a tomographic approach is strictly necessary to fully reconstruct the three-dimensional magnetic field distribution [12], such a technique enables us to produce maps quantitatively visualizing the distributions of both the magnetic field strength and direction. A pilot experimental study for the quantification of a magnetic field by means of 3D polarization analysis with pulsed neutrons has demonstrated that the magnetic field strength and direction in a solenoid coil was successfully deduced within an accuracy of less than 3% [13]. Building on this previous work, we have constructed an improved polarization analysis system for the RADEN beam line.

2.2. Design of the polarization analysis apparatus

For the neutron polarization analysis we have designed an apparatus as shown in Figure 1. Here the x , y , and z directions were taken along the horizontal, vertical, and neutron beam directions, respectively. The apparatus consists of three main components, i.e., neutron polarization devices, spin-controlling devices, and guide fields. We describe the details of each component below.

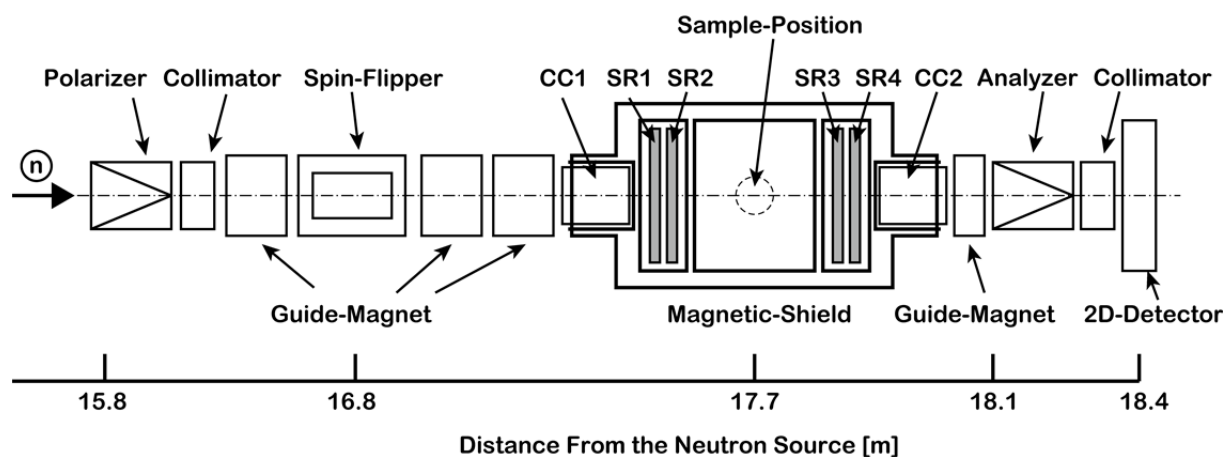


Figure 1. Schematic illustration of the polarization analysis apparatus for RADEN. The neutron beam comes from the left side of this illustration. SR1 to SR4 refer to spin rotators, and CC1 and CC2 are coupling coils.

2.2.1. Polarization devices. The polarizer and analyser are the most important devices for the polarization analysis. For magnetic field imaging, a large beam size and a short distance between the sample and the detector, which affects the accessible smallest spatial resolution, are desired. In addition, the capability to use a wide wavelength range neutron beam is required. Because the dynamic range of the magnetic field strength that can be evaluated by means of polarization analysis depends on the range of frequencies that can be analyzed from the wavelength dependent neutron polarization, a broader available wavelength range is better. Based on these requirements, we have designed a magnetic super mirror polarizer, and the same device has been used as an analyzer. The drawing of the polarizer (analyzer) and its photograph are shown in Figure 2. By means of a multi-V-shape arrangement of magnetic mirrors, it covers a cross section of 60 mm x 60 mm with a length shorter than 180 mm. The coating material is Fe/Si, and the substrate material is single crystal Si wafer with a thickness of 0.3 mm. The m value is 4.5. The tilt angle of each mirror was set at ± 12.0 mrad so as to achieve the critical neutron wavelength of 1.5 Å. This critical wavelength was determined so as to cover the peak of the neutron flux spectrum provided by the J-PARC/MLF's liquid hydrogen moderator, which is located at a neutron wavelength around 2.5 Å, to allow efficient measurements using polarized neutrons at the MLF. The magnetic mirrors are aligned vertically and spin-up neutrons are reflected in the horizontal plane.

A magnetic housing, which consists of NdFeB permanent magnets and pure iron plates producing a vertical magnetic field of more than 60 mT, was used to apply a magnetic field on magnetic super

mirrors to magnetize them. This housing was designed not to produce strong stray fields around it, since devices used in our system, described later, are sensitive to the environmental fields and respond in an undesirable way. The polarizer and the analyzer were used in combination with collimators consisting of stacked Gd coated Si wafers, which were placed behind the polarizer and the analyzer to remove the reflected neutrons. The acceptable horizontal beam divergence was designed to be ± 19 mrad by taking the natural beam divergence, which was determined by the size of aperture located at about 8 m upstream from the collimators, into account.

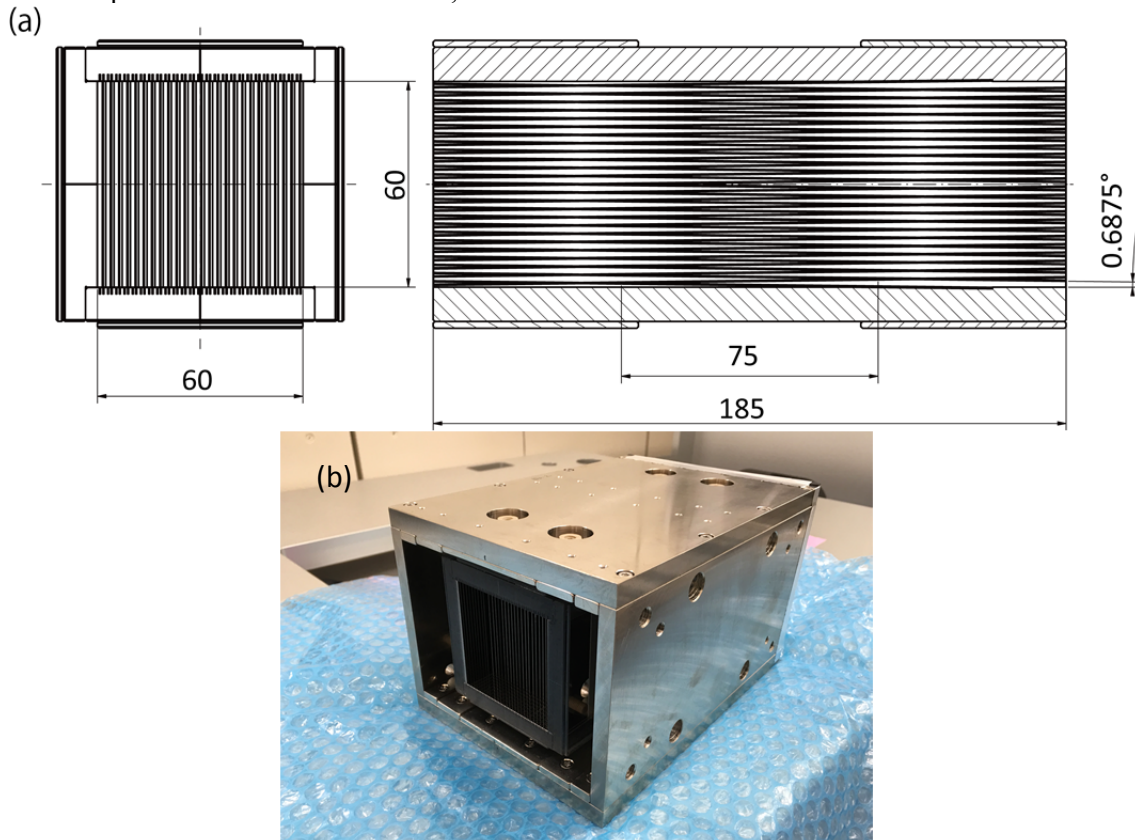


Figure 2. Drawing of the polarization device (a) and a photograph after the cavity is fixed in a magnetic housing (b). N-BK7 plates manufactured by SCHOTT are used for the body of the cavity.

2.2.2. Spin controlling devices. To control the neutron spin direction, we installed a spin flipper and a 3D spin rotation system with magnetic shielding. An adiabatic fast passage (AFP) type flipper [14] was adopted as a spin flipper because it works effectively for a broad wavelength range of neutrons. In this device a static field is generated along the y direction by a pair of pure iron plates that are magnetized by electromagnets. The strength of this field decreases along the z direction to produce a spatial magnetic field gradient. A solenoid coil is placed between the magnetized iron plates to provide an RF field along the z axis orthogonal to the static field by applying an alternating current of around 100 kHz (Figure 3). The static field is tuned by changing the applied current to the electromagnets so that a resonance occurs around the middle of the spin flipper.

The 3D spin rotation system consists of two pairs of spin rotators (SR1 to SR4 in Figure 1) and a magnetic shielding box. This system looks like the MuPAD device developed for spherical neutron polarimetry [15]. A spin rotator is a planar precession coil wound by 1 mm- ϕ Al wire and is used to turn a neutron spin by $\pi/2$ (Figure 4). The outer field of the coil is absorbed by a permalloy yoke and a surrounding permalloy shield. Then two coils with permalloy shields are arranged orthogonally and again placed together in another permalloy shield. Finally two pairs of spin rotators are mounted inside an outer permalloy shield. The first pair of spin rotators is located upstream of sample to turn the

incident neutron spin direction, and the second pair is located downstream of the sample to turn the transmitted neutron spin. The reason why we have constructed such a strict magnetic shielding is that the spin rotators are very sensitive to the environmental field and it is important to ensure a zero field environment for spherical polarimetry by eliminating magnetic fields not only from outside but also from the precession coils themselves. To apply this system to the pulsed neutron beam, a dumping current proportional to $1/t$ is applied to the spin rotators synchronized with the generation time of pulsed neutrons. Then we can get a constant neutron spin rotation angle of $\pi/2$ for a wide neutron wavelength range.

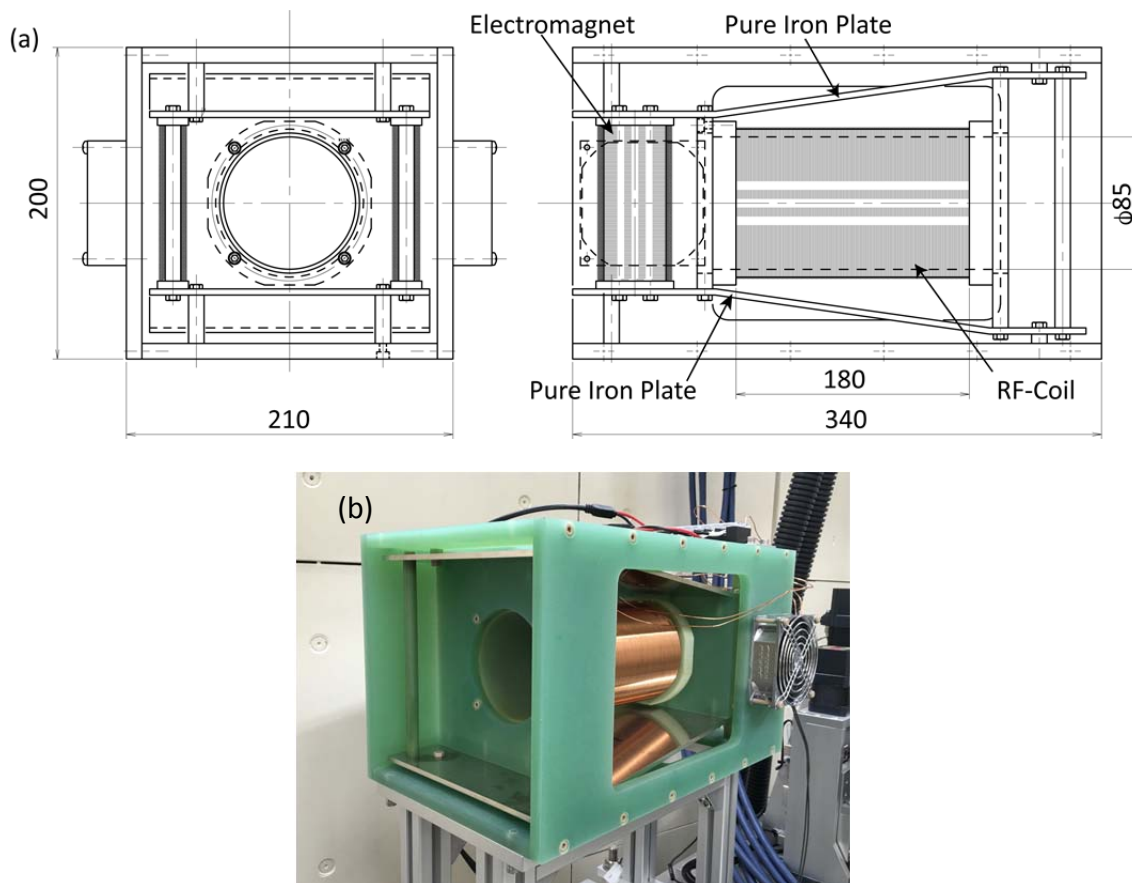


Figure 3. Drawing of the AFP spin flipper (a) and its photograph (b).

In addition, since the polarized neutron beam has to enter the zero field area inside the magnetic shield, it is necessary to avoid possible depolarization by a sudden decrease of the guide magnetic field and stray fields around the apertures of the beam pass. In this system, two coupling coils (CC1 and CC2 in Figure 1) made by Al-wire are placed at the entry and exit of the outer magnetic shield to preserve the neutron spin along the y direction (Figure 5). The magnetic field of the coupling coil is connected to the outer guide field by splitting the Al-wire at one side. The opposite side of the coupling coil, i.e., that facing the inside of the magnetic shield, is closed to create a screen of Al-wire that acts as a boundary for the magnetic field, like a current sheet. The neutrons come into the field of the coupling coil from the outer magnetic field adiabatically and then go through the field of the coupling coil to zero field non-adiabatically at the entrance of the outer magnetic shield. At the exit of the magnetic shield, this process occurs in reverse. Similar to the precession coil of the spin rotator, the coupling coil was surrounded by a permalloy yoke and a shield to absorb stray fields.

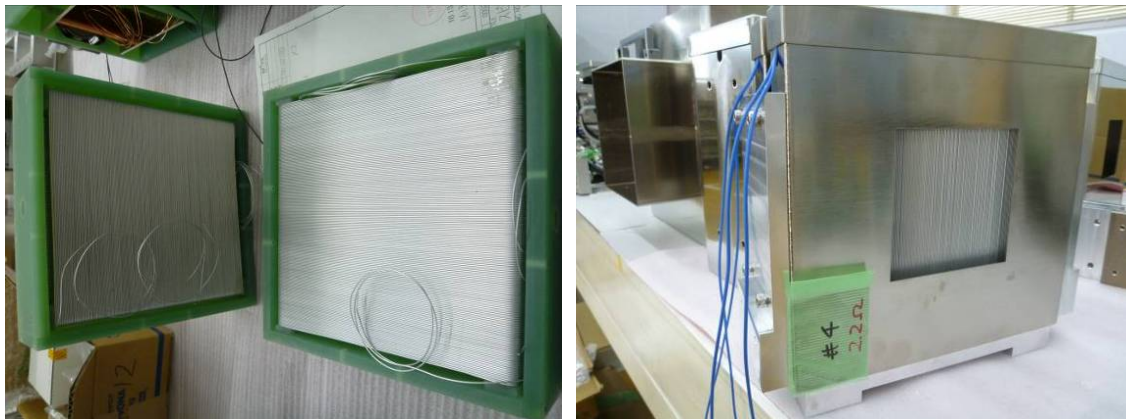


Figure 4. Photographs of the spin rotator. Left side is a photograph of the precession coils, and right is that of the assembled spin rotators inside a permalloy magnetic shield. The surface of the Al-wire was coated by an aluminum oxide layer for insulation.

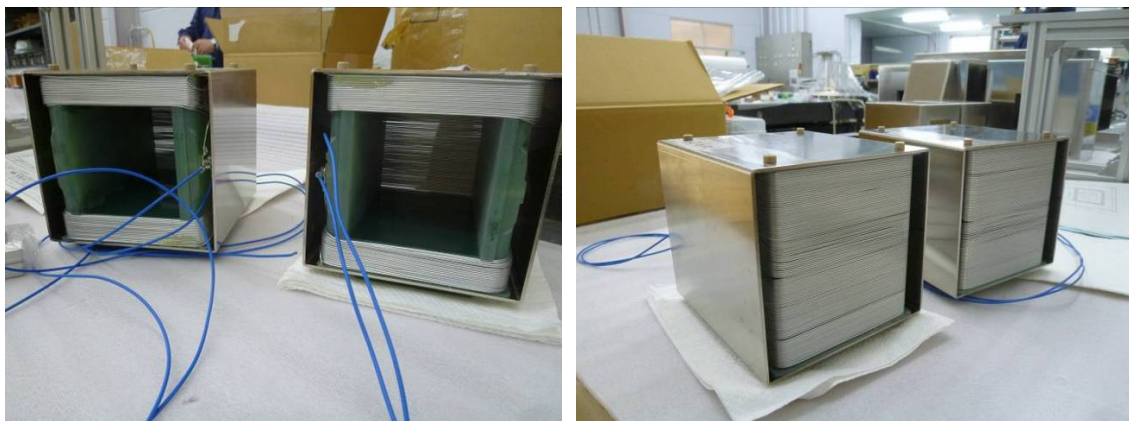


Figure 5. Photographs of coupling coils. The left photograph shows the coils' open side facing outside of the magnetic shield box and right displays the screen side facing inside. The coils are tightly surrounded by a permalloy yoke.

2.2.3. Guide fields. The guide field plays an important role to preserve neutron spin direction and to avoid possible depolarization. We placed several magnetic field guides to fill the gap between devices as shown in Figure 1. A magnetic field guide is composed of two opposing pure iron plates and Al-Ni-Co permanent magnet pillars placed between plates. The distance between the iron plates is 120 mm and their width is 120 mm. The size of the cross section of this guide was determined to make a uniform magnetic field in the central 60 mm x 60 mm area, which corresponds to the maximum beam size, by means of magnetic field calculation. The field strength is about 6 mT in the middle of the guide.

2.3. Magnetic field simulations

Magnetic field simulation has been performed to confirm the magnetic field connection along the neutron beam passage and the uniformity of the field in the vertical plane perpendicular to the beam propagation. A commercial magnetic field calculation software ELF/MAGIC, which has the capability to perform electromagnetic field analysis using the boundary element method, was used. The calculation model is shown in Figure 6(a). In this calculation we omitted the RF coil of the spin flipper, spin rotators and non-magnetic components since they don't affect the characteristics of the static magnetic field in the system related to transportation of the polarized neutron beam. The magnetic field simulation results, shown in Figure 6(b), clearly indicated that the magnetic field is

smoothly connected along the beam direction except inside the magnetic shield box and that the difference along the vertical direction is small. On the other hand, to guarantee that the neutron spin follows the guide magnetic field, the adiabaticity condition indicating the relation between the Larmor frequency ω_L and the frequency of rotation of the magnetic field ω_B , which is expressed as equation (5), should be fulfilled.

$$\Gamma = \frac{\omega_L}{\omega_B} \gg 1, \quad \omega_B = \frac{ds}{dt} \left| \frac{\partial \mathbf{n}}{\partial s} \right|, \quad (5)$$

where $\mathbf{n}$ is the magnetic field direction and s is the neutron beam path. The ratio Γ is called the adiabaticity parameter. We calculated Γ from the magnetic field simulation results along the entire neutron beam path and found that it exceeded 10 over the whole system except inside the magnetic shield. This Γ value is large enough to effectively hold the neutron spin direction along the guide field. According to the results of these simulation studies, we concluded that the designed polarization analysis apparatus possesses enough capability to preserve the spin direction of the polarized neutron beam with a large beam size homogeneously over the whole system.

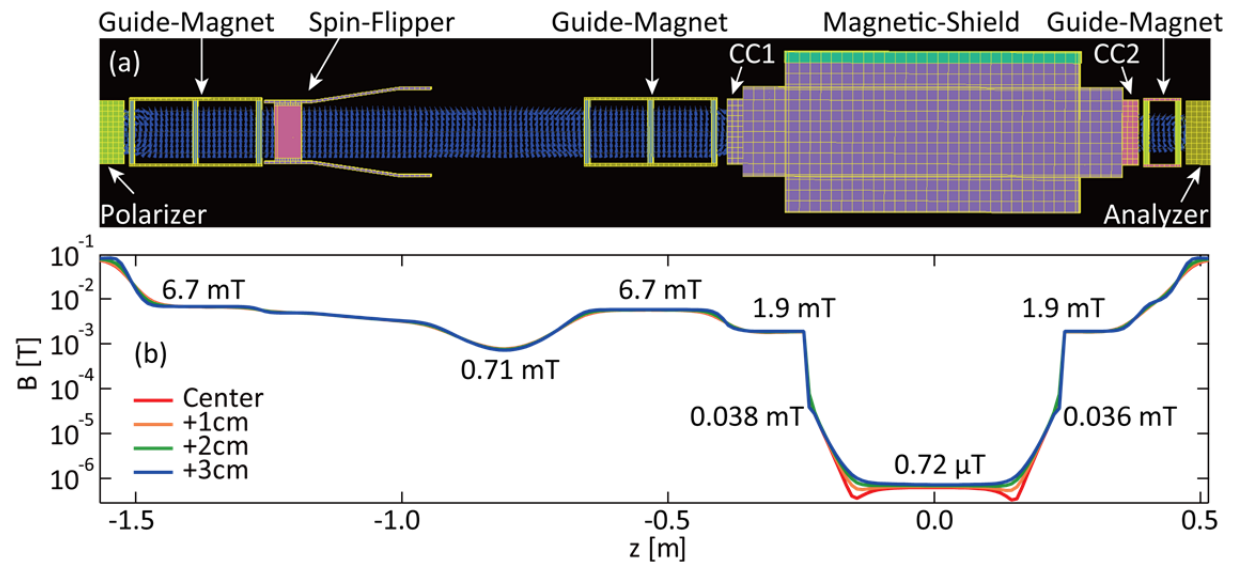


Figure 6. Schematic drawing of magnetic field calculation model (a) and the obtained magnetic field distributions along the beam direction at several beam height (b).

3. Polarization analysis performance

Performance of the polarization analysis apparatus has been studied at the RADEN instrument using the nGEM detector [16] as a two-dimensional neutron detector. The spatial resolution was 0.8 mm, and the active area was 100 mm x 100 mm. Distance between the source and the detector was 19 m. The available wavelength range was defined using a double disk chopper installed in the up-stream beam line shield. In addition, high energy neutrons and prompt gamma-rays generated at the time of neutron production were eliminated using a T_0 chopper [9]. The beam was shaped to the size of 45 mm x 45 mm by a B_4C slit located in front of the polarizer. The beam power at that time was 200 kW.

First, we measured the polarization distribution without turning on the spin rotators. Here the polarization P was replaced by $P = (I_{\text{off}} - I_{\text{on}}) / (I_{\text{off}} + I_{\text{on}})$ where I_{off} and I_{on} are the measured neutron intensity with the spin flipper switched off and that with the spin flipper on, respectively [17]. Since the efficiency of our spin flipper was very close to 1, as confirmed from the experimental results of the flipping ratio and the polarization data provided by the polarizer manufacturer, the measured P can properly describe the performance of our apparatus. Figure 7(a) is an image of the two-dimensional polarization distribution obtained at the wavelength of 3.5 Å and clearly demonstrates a flat distribution in the xy plane. We evaluated the standard deviation of the polarization along the x

direction to be 2.0% and that along the y direction to be 0.3% within the beam area. The small deviation along the y direction is evidence that vertically homogeneous guide magnetic fields are smoothly connected along the beam path. On the other hand, the larger deviation along the x direction can be attributed to the difference in performance of individual magnetic mirrors. The wavelength dependence of the polarization is shown in Figure 7(b). The polarization rises from around 1 Å and quickly increases up to 80% at a wavelength of about 2 Å. Then it exceeds 90% for wavelengths longer than 3 Å. This behavior agrees with the original design, and this system is deduced to possess adequate polarization analysis performance.

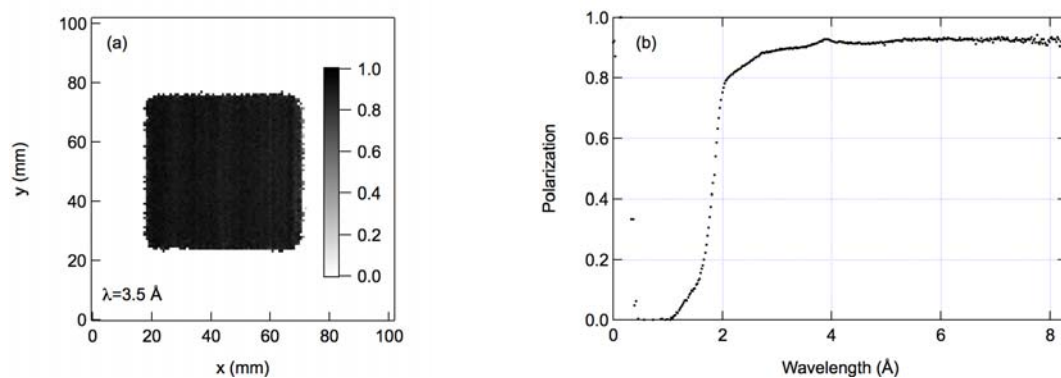


Figure 7. (a) Polarization distribution map ($\lambda = 3.5$ Å) and (b) wavelength dependence of neutron polarization.

Next, we operated the spin rotators to measure the spatial distribution of each spin rotation matrix element. The neutron spin direction of the incident beam was aligned with the y direction at first. Then it was rotated from the y to the z direction by switching on SR1, and from the y to the x direction by SR1 and SR2. The z element of the neutron spin polarization vector of the transmitted beam was then analyzed by switching on SR4, and the x element by SR3 and SR4. With SR3 and SR4 switched off, the y element of the polarization vector could be analyzed. In this way, every element of the spin rotation matrix of equation (2) was measured by switching on and off the appropriate combination spin rotators. The obtained images for all spin rotation matrix elements and their wavelength dependences are shown in Figure 8, 9 and Figure 10. From these results, it was found that the diagonal terms demonstrated similar behavior as the original one shown in Figure 7(b), and that the off-diagonal terms were almost constant with a value close to 0. Accordingly, the spin rotators were clearly verified to rotate the neutron spin direction into the proper direction and to cause no significant deterioration of the polarization. However when looking in detail at the profiles along the horizontal axis (x direction) and the vertical axis (y direction) for the off-diagonal terms shown in Figure 9 and their wavelength dependences shown in Figure 10, we can recognize that a small but nonzero polarization of less than 10% remains. Since this small deviation of the polarization from 0 is attributed to an insufficient tuning of the spin rotators, a precise adjustment of the applied current to the spin precession coil is needed to improve the accuracy of the spin rotation angle. Moreover, the uniformity along the vertical direction was slightly worse for the off-diagonal terms as compared to the diagonal terms. This spatial variation originates from a small magnetic field difference between the central region and top and bottom parts of the coupling coils. To improve the uniformity of the polarization distribution, a more careful connection of the outer guide field and the coupling coil field is required by placing additional guides or by overlapping both fields more deeply.

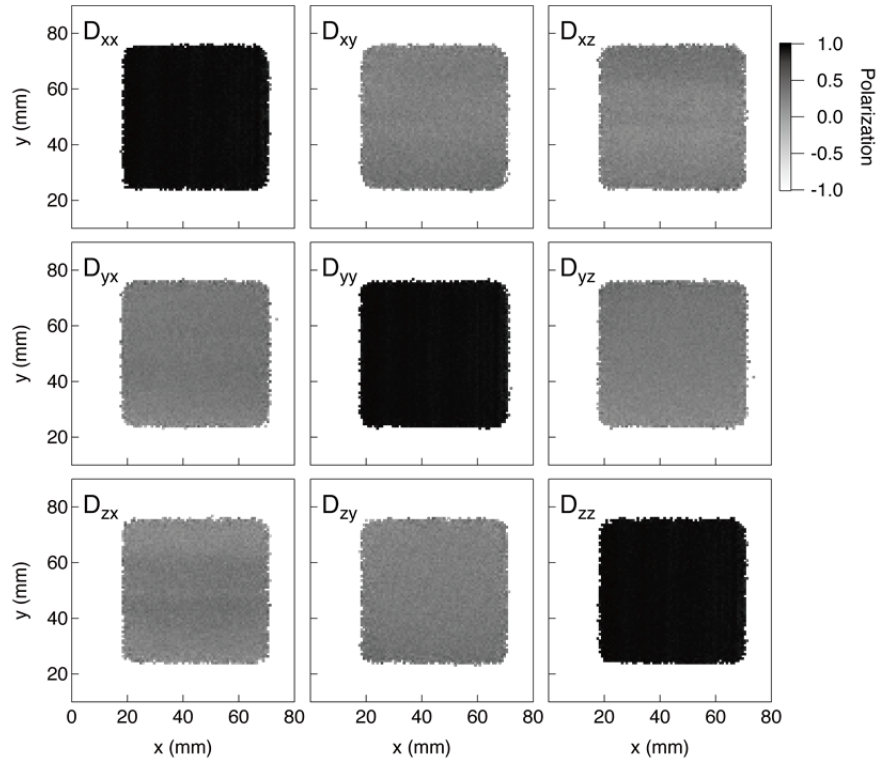


Figure 8. Distribution maps of spin rotation matrix elements ($\lambda = 3.5 \text{ \AA}$).

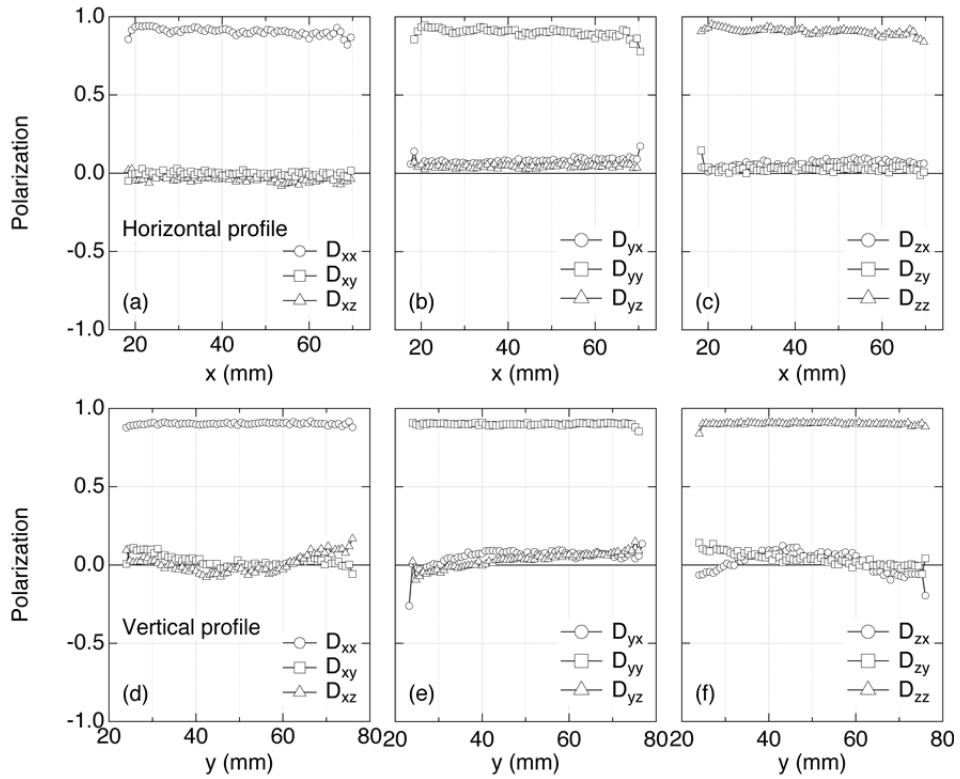


Figure 9. Polarization profiles along the horizontal ((a) to (c)) and vertical axes ((d) to (f)) for the spin rotation matrix elements ($\lambda = 3.5 \text{ \AA}$).

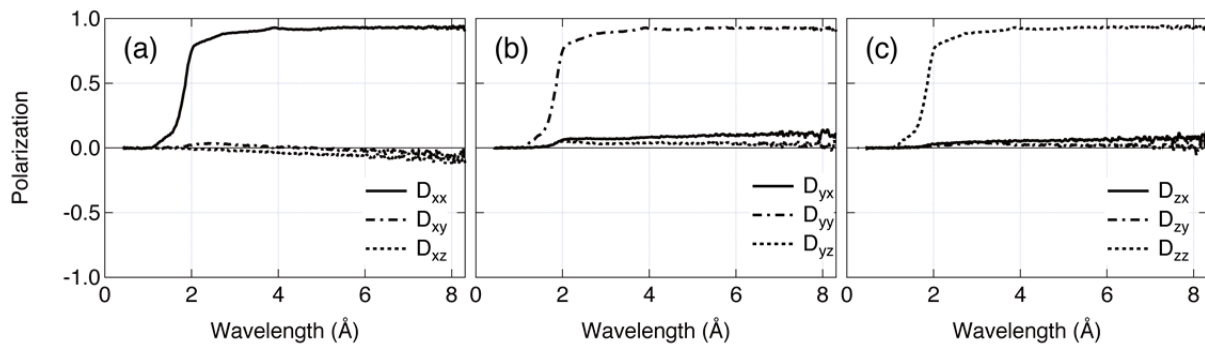


Figure 10. Wavelength dependences of spin rotation matrix elements. The spin direction of the incident beam is parallel to (a) x direction, (b) y direction, and (c) z direction.

4. Conclusion

We have constructed a three-dimensional polarization analysis apparatus for magnetic field imaging experiments using a polarized pulsed neutron beam at the RADEN instrument at J-PARC/MLF. We decided the arrangement of the devices based on the magnetic field calculation and on the evaluation of the adiabaticity parameter along the neutron beam trajectory. From the test experiment, it was confirmed that a good polarization over 90% over a wide wavelength range with a flat spatial distribution could be obtained and that the neutron spin direction was properly controlled by the spin rotators. Therefore, we conclude that our polarization analysis apparatus can be effectively used for quantitative magnetic field imaging.

Acknowledgement

This work was partially supported by the Grant-in-Aid for Science Research (S) 23226018 from the Japan Society for the Promotion of Science and by the Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan. The performance evaluation experiments have been performed under a user program (Proposal No. 2015I0022).

References

- [1] Kardjilov N, Manke I, Strobl M, Hilger A, Treimer W, Meissner M, Krist T and Banhart J 2008 *Nat. Phys.* **4** 399
- [2] Kardjilov N, Manke I, Hilger A, Strobl M, Banhart J, 2011 *Materials Today* **14** 248256
- [3] Sato H, Takada O, Iwase K, Kamiyama T, Kiyanagi Y, 2010 *J. Phys.: Conf. Ser.* **251** 012070
- [4] Kaneko K, Kamiyama T, Kiyanagi Y, Sakuma T, Ikeda S 1999 *J. Phys. Chem. Solids* **60** 1499
- [5] Kai T, Maekawa F, Oshita H, Sato H, Shinohara T, Ooi M, Harada M, Uno S, Otomo T, Kamiyama T, Kiyanagi Y 2013 *Phys. Proc.* **43** 111
- [6] Shinohara T, Sakai K, Ohi M, Kai T, Harada M, Oikawa K, Maekawa F, Suzuki J, Oku T, Takata S, Aizawa K, Arai M and Kiyanagi Y 2011 *Nucl. Instr. and Meth. A* **651** 121
- [7] Strobl M, Kardjilov N, Hilger A, Jericha E, Badurek G, Manke I, 2009 *Phys. B* **404** 26112614
- [8] Shinohara T, Kai T 2015 *Neutron News* **26** 11
- [9] Shinohara T, Kai T, Oikawa K, Segawa M, Harada M, Nakatani T, Ooi M, Aizawa K, Sato H, Kamiyama T, Yokota H, Sera T, Mochiki K, Kiyanagi Y 2016 *J. Phys: Conf. Series* **746** 012007
- [10] Rekveldt M T 1941 *Z. Phys.* **259** 391
- [11] Tasset F 1989 *Physica B* **156–157** 627
- [12] Hochhold M, Leeb H, Badurek G 1996 *J. Magn. Mang. Mater.* **157/158** 575
- [13] Wada N, Shinohara T, Sato H, Hasemi H, Kamiyama T and Kiyanagi Y 2015 *Phys. Proc.* **69** 427
- [14] Weinfurter H and Badurek G 1989 *Nucl. Instr. and Meth. A* **275** 233

- [15] Janoschek M, Klimko S, Gähler R, Roessli B, and Böni P 2007 *Phys. B* **397** 125
- [16] Shoji M, Uno S, Uchida T, Murakami T, Sekimoto M, Koike T, Nakano E, Yamamoto K, Hoshi Y, Nagashima F, 2012 *J. Inst.* **7** C05003
- [17] Mitsuda S, Endoh Y 1985 *J. Phys. Soc. Jpn.* **54** 1570