

In-situ compact ^3He neutron spin polarizer based on a magneto-static cavity with built-in NMR coils

S Lee¹, M K Moon², J Kim², S J Cho², J H Lee³, C-H Lee³, S W Lee⁴, T Ino⁵

¹Quantum Optics Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Korea

²Neutron Instrument Development and Maintenance Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Korea

³Neutron Science Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Korea

⁴School of Mechanical Engineering, Pusan National University, Busan 609-735, Korea

⁵Neutron Science Laboratory, KEK, Tsukuba, Ibaraki 305-0801, Japan

E-mail: smlee3@kaeri.re.kr

Abstract. A polarized ^3He neutron polarizer for in-situ neutron beam line operation was developed based on a compact magneto-static cavity with a dimension of $280 \times 270 \times 300 \text{ mm}^3$ and a fiber-coupled VBG (Volume Bragg Grating) diode laser with a narrow spectral bandwidth of 25 GHz. Built-in NMR coils of the neutron spin polarizer designed for NMR signal measurements were described in detail and their performances were tested for monitoring the progress of in-situ ^3He polarization.

1. Introduction

Unlike neutron guides or neutron benders, which change the neutron beam alignment and/or neutron spatial beam uniformity owing to their characteristic multiple reflections, polarized ^3He neutron polarizers are free from such beam misalignment and beam interference [1]. In addition, a ^3He polarizer has a wide acceptance angle and creates a smaller amount of background gamma radiation owing to its low neutron activation [2]. Such merits enable the ^3He polarizer to be widely used for neutron experiments in fundamental particle physics or material researches involving neutron radiography, neutron diffraction, neutron reflectometry, neutron interferometry, and small-angle neutron scattering [3,4].

At KAERI, two programs were recently funded to develop a ^3He polarizer and a polarizing supermirror for a deployment of polarized neutrons in the neutron beam lines of the HANARO (High-flux Advanced Neutron Application ReactOr). A neutron guide test station G-TS will be utilized to test both types of polarizers. Currently, one of the top priorities is to apply the developed neutron polarizers for a neutron reflectometer (REF-V). In addition, the ^3He polarizer will be deployed for



neutron imaging applications. For such applications, a polarizer and an analyzer will be needed and we are developing ^3He polarizers based on a compact solenoid coil or a compact magneto-static cavity.

In this paper, we report a ^3He -cell fabrication station and a magneto-static cavity based ^3He polarizer. In particular, the design of an in-situ polarizer including a NMR signal measurement technique and an optical pumping method is described in detail.

2. ^3He -cell Fabrication

A rectangular shape quartz cell was made for uses in magneto-static cavity based ^3He polarizer and a wide angle cell for a multi-axis spectrometer has been planned. In addition, for applications with a solenoid based ^3He polarizer in a neutron reflectometer, neutron imaging, SANS, TAS, etc., cylindrical high purity Ge-180 glass cells were fabricated with various sizes and gas pressures.

2.1. A high purity ^3He -cell

A high purity cylindrical Ge-180 glass cell with a length of 50 mm and a diameter greater than 50 mm was fabricated, as shown in figure 1(a) and 1(b), for uses in a solenoid-based ^3He neutron spin polarizer. The GE-180 glass cells were prepared at a glass shop in the nuclear chemistry division of KAERI, and then filled with ^3He gas by using a ^3He -gas filling station constructed in the quantum optics division of KAERI.

Figures 1(c) and 1(d) show a wide-angle quartz cell and a rectangular quartz cell made from a local glass shop. The wide-angle cell has a cross-section of $50 \times 50 \text{ mm}^2$ and an angle of 120° . The size of the rectangular cell was $50 \times 50 \times 50 \text{ mm}^3$. After distilling rubidium metal vapor into the cell, the cell was filled with ^3He gas and nitrogen gas with a pressure ratio of 9:1. The cell was sealed off at a gas pressure of 0.9 atm, which can be obtained by immersing the cells in liquid nitrogen.

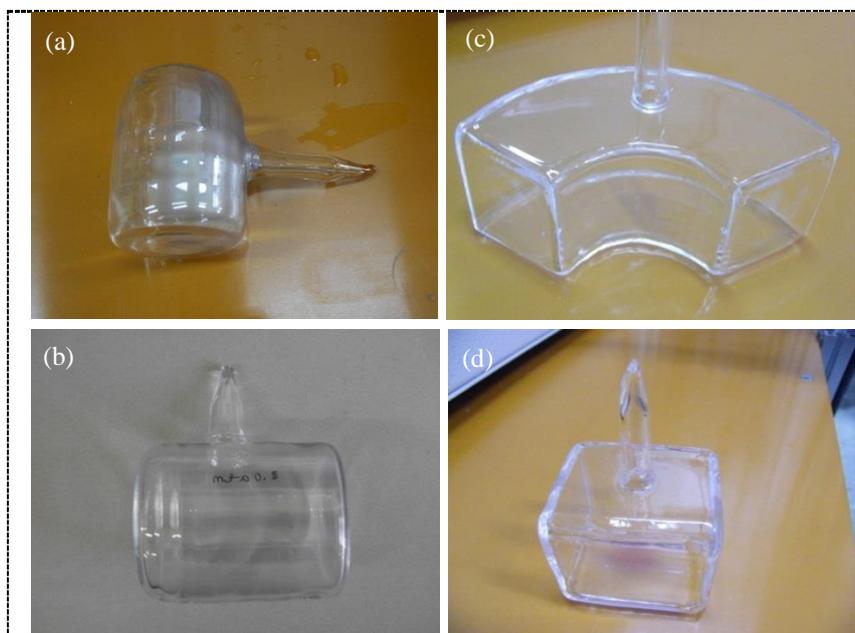


Figure 1. (a) Cylindrical ^3He gas cell made of Ge-180 glass (gas pressure: 1.5 atm), (b) cylindrical ^3He gas cell made of Ge-180 glass (gas pressure: 1.0 atm), (c) wide angle quartz cell (gas pressure: 1.2 atm), and (d) rectangular quartz cell (gas pressure: 1.0 atm).

2.2. Gas filling station

Figure 2 shows the constructed gas filling station system. The system was equipped with a high vacuum system including dry pump, turbo pump and ion pump, a high temperature cell-baking oven, a gas purification and inlet system, a residual gas analyzer, a manometer, and a liquid-nitrogen-cooling cell seal-off system, and band heaters for gas-pipe heating.

To obtain a high vacuum, all vacuum gas pipes made of stainless steel were heated using band heaters at a temperature of 100 °C, and a glass cell and a glass manifold near the cell were baked using a high temperature oven operating at a temperature of 400 °C. The remaining portion of the glass manifold made for rubidium metal vapor inlet into the cell was flame-baked with a hand torch until no vacuum pressure was changed during the flame heating. A small ion pump (VIPC1000, VMT) was used in combination with a dry and a turbo vacuum pump to obtain the desired high vacuum. With the vacuum system and flame heating, a high vacuum of 5×10^{-9} Torr was obtained within several days of operation.

Under high vacuum, a rubidium ampule was broken by a hammer. The rubidium was vaporized by a flame torch, and then chased into the cell by using a torch and a heat gun. After chasing a small portion of rubidium into the cell, the cell was filled with nitrogen gas and then vacuumed for cleaning of the gas filling tubes. The ^3He gas had a purity of 99.995% (9.1 bar); and the N_2 gas, 99.9999%, and these gases were purified by gas purifiers before filling. The filling gas pressures of the cell were controlled using a needle valve and a baratron manometer (mks, 629D) which can measure the gas pressure from 20 mTorr to 5000 Torr. After obtaining the desired mixed gas pressures of the cell, the cell was immersed in a liquid nitrogen bath and cooled to a desired sealed-off gas pressure of 0.9 atm. During the sealed-off process of the cell, the gas pressure was maintained close to the sealed-off pressure by adjusting how deep the cell was immersed in liquid nitrogen.

To easily seal off the cell from the glass manifold, a GE-180 cell was fused with a GE-180 glass tube, which has a thin bottle neck. In addition, the cell was mounted in the liquid nitrogen bath on a lab jack. The height of the lab jack was adjusted according to the melting degree of the bottle neck. Then, the melted bottle neck was closed off due to the pressure difference between the cell and the atmosphere and the seal-off of the cell is completed. Using the seal-off procedure above, various high pressure cells can easily be manufactured.

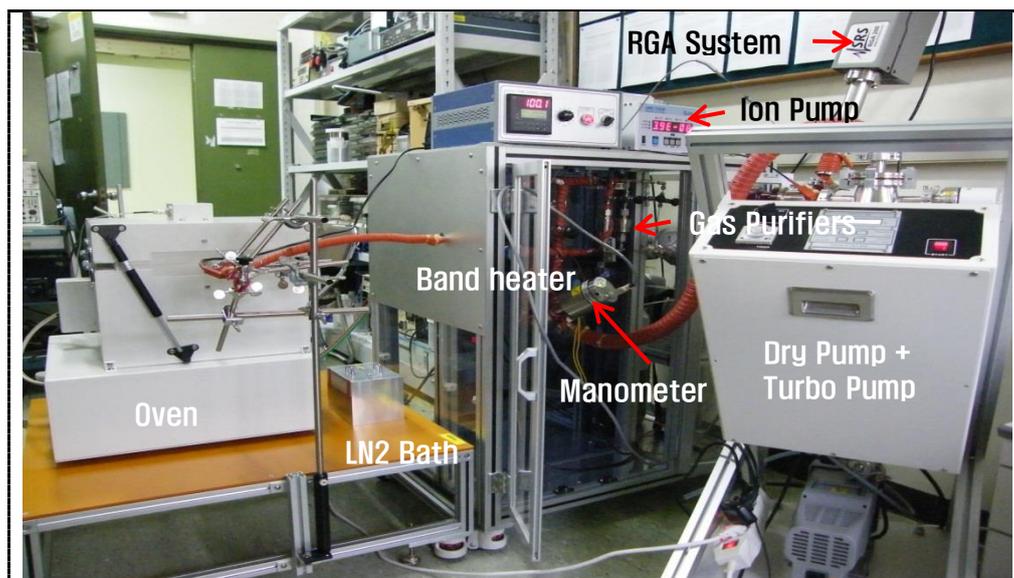


Figure 2. A ^3He -cell fabrication station constructed for sealing a high purity ^3He cell.

3. Novel Magneto-static Cavity Based In-situ ^3He Polarizer

A unique in-situ ^3He polarizer based on a novel magneto-static cavity was developed. The magnetic field profile of the magneto-static cavity was analyzed using a commercial magnetic field calculation code, Vizimag 3.19. In addition, a NMR system was designed and installed inside the cavity to measure the polarization of the ^3He cell in real time.

3.1. Magneto-static Cavity

A ^3He polarizer takes at least 1 day to be polarized through the Spin Exchange Optical Pumping process. It is often cumbersome to then transport the polarizer to neutron beam lines and the polarization ratio decays with time. Therefore, an in-situ neutron polarizer is preferred to utilize the polarizer more efficiently.

For use as an in-situ neutron polarizer, a magneto-static cavity was designed based on the analysis of magnetic field profiles depending on the magnet's size and strength, cavity's size and structure, and magnetic material properties. Figure 3 shows the magneto-static cavity with a small Helmholtz coil inside the cavity. The cavity consists of symmetric magnetic side-structures and symmetric top and bottom magnetic plates. The side-structure consists of a mild steel plate with a thickness of 3 mm and two arrays of a permanent magnet (N35) as shown in figure 3(right). The mild steel was magnetized by the strong permanent magnets. The magnetized mild steel was held by an inside aluminum frame, which was also maintained by top and bottom aluminum plates. On the top and bottom aluminum plates several permalloy magnetic sheets with high permeability are attached and connected with the magnetized mild steel of the side-structure. The top and bottom permalloy sheets are then magnetized and a uniform magnetic field is formed along the top-to-bottom direction at the central part of the cavity. The other mild steel plates are placed at the outside of side-structure with a gap from the magnetized mild-steel plates. By adjusting the gap distance, the inside magnetic field distribution and the strength of the cavity can be varied. The magnetic field strength can also be changed by the Helmholtz coil located in the vertical direction.

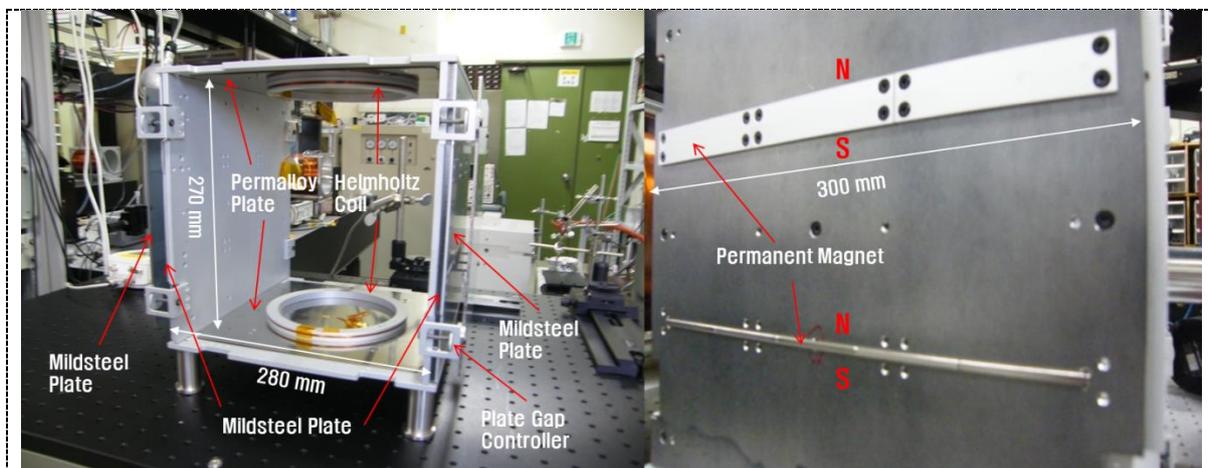
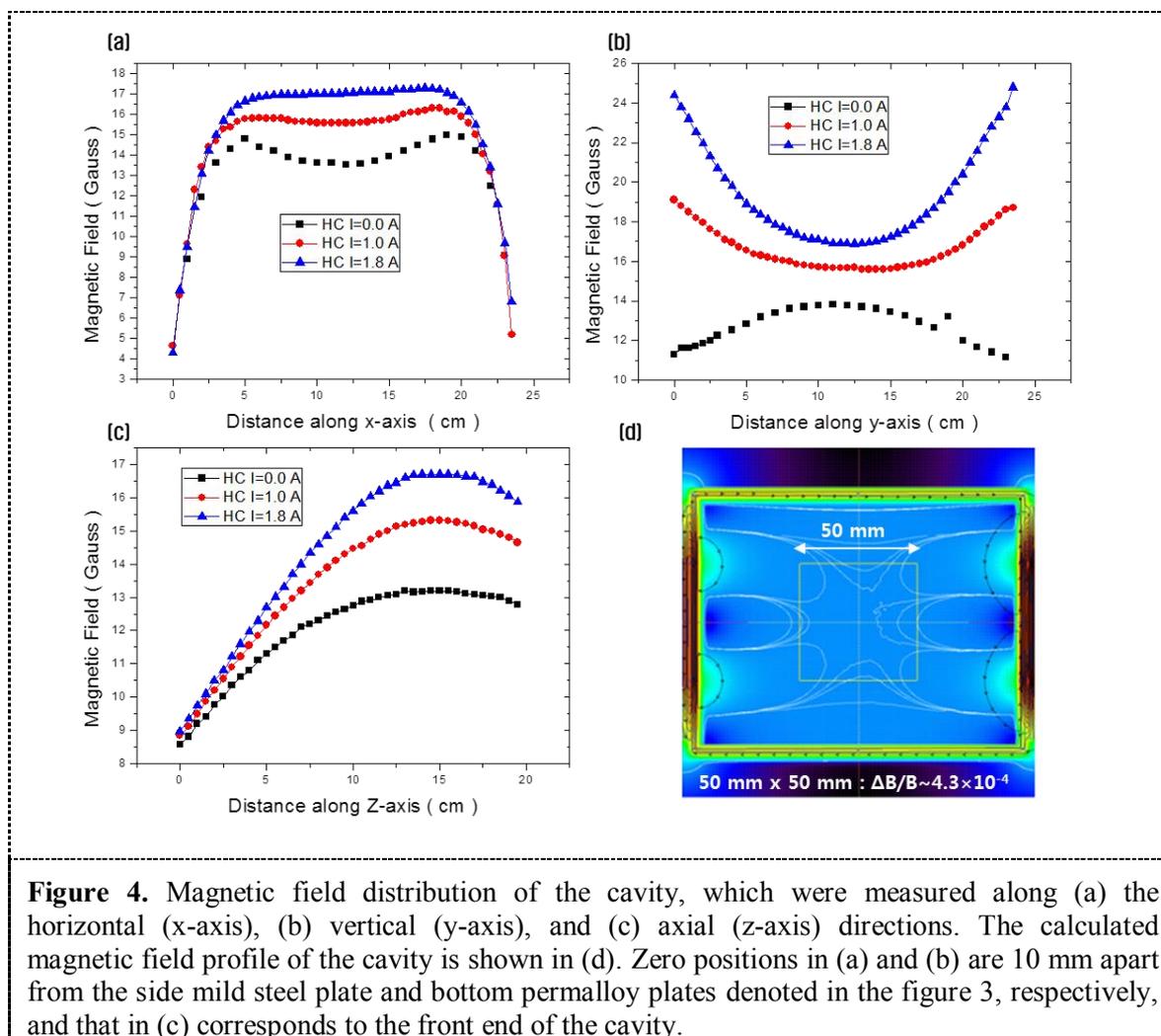


Figure 3. A magneto-static cavity: front view (left) and side view (right).

The magnetic field distribution of the cavity was measured as a function of the current of the Helmholtz coil using a magnetic field strength meter (FH 54, Magnet-Physik). Figure 4 shows the resulting magnetic field strength measured along the horizontal, vertical, and axial directions. A static magnetic field of 14 Gauss generated from the permanent magnet was increased to approximately 17 Gauss for an applied current of 1.8 A. These magnetic field distributions correspond to the results measured before a field adjustment using the outside mild plate gap controller, and a slight asymmetry in magnetic field profile can be compensated.



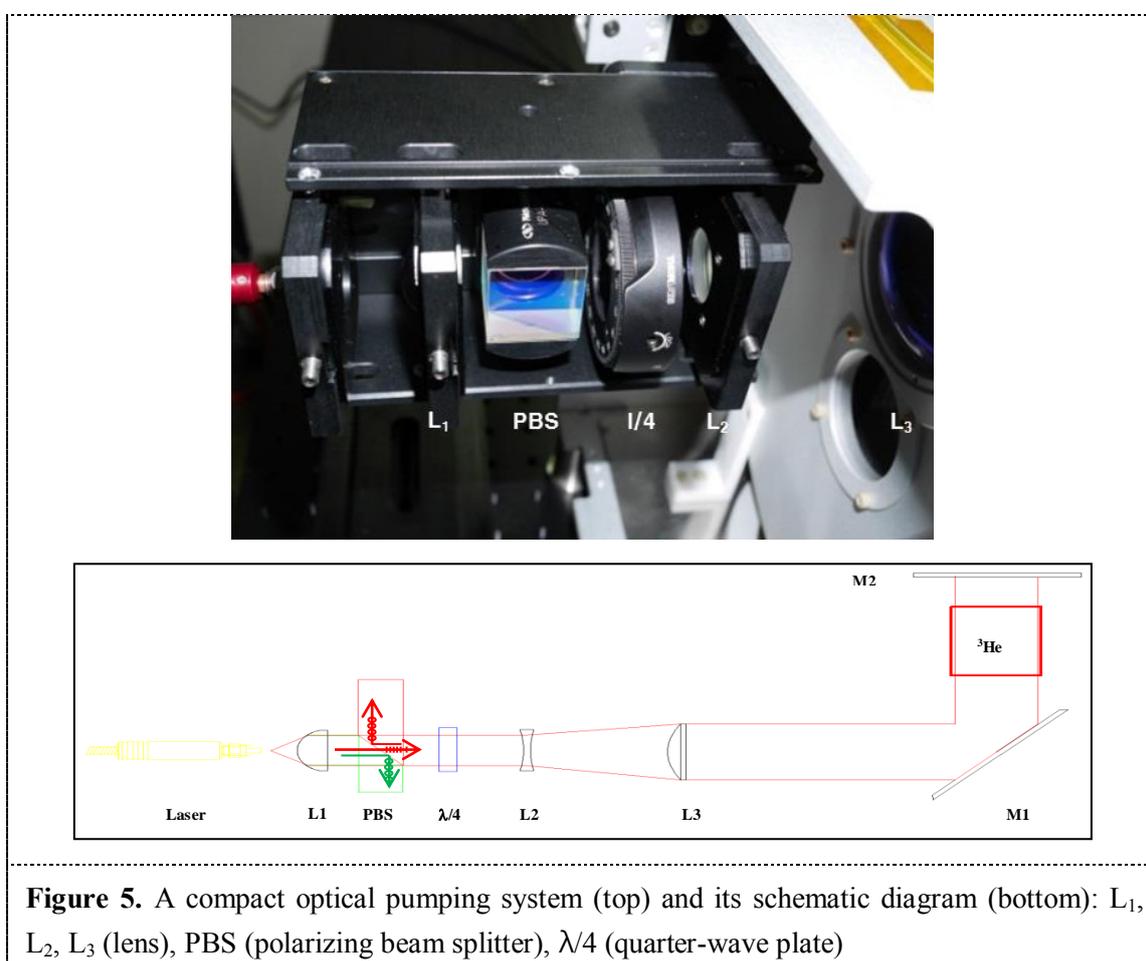
In the figure 4(a), 4(b), and 4(c), the measured magnetic fields are the summed magnetics originated from the cavity and the Helmholtz coil. These magnetic fields are only used during a sweeping period for NMR signal measurements. To maintain the He-3 polarization, only the uniform magnetic field of the cavity can be used. The uniformity of the cavity's magnetic field, $\Delta B/B$ is calculated as $\sim 4.3 \times 10^{-4}$ within a cell size of 5 cm \times 5 cm. The uniformity can be improved by using a larger size cavity.

3.2. In-situ neutron spin filter based on magneto-static cavity

An in-situ ^3He neutron spin filter based on the novel magneto-static cavity was developed for use as an in-situ neutron polarizer or a neutron analyzer in the neutron beam lines of a HANARO research reactor. The in-situ neutron spin filter consists of the magneto-static cavity, a laser beam transport system, a ^3He cell, a nuclear magnetic resonance (NMR) signal measurement system, and a hot air supply system.

The magneto-static cavity had a width of 280 mm, a height of 270 mm, and a length of 300 mm. Two sets of permanent magnet are installed on each side. The ^3He cell is placed at the center of the cavity where a uniform magnetic field is formed. The ^3He cell was surrounded by a cosine theta NMR coil bobbin. The rubidium in the ^3He cell was vaporized by hot air at a temperature of approximately 150 $^\circ\text{C}$, which is supplied into the cosine theta coil by an external hot air supply system.

A VBG (Volume Bragg Grating) diode laser with a narrow spectral linewidth of 18 GHz was used for pumping vaporized rubidium D_1 absorption lines at a wavelength of 794.8 nm. The precise wavelength tuning ability was obtained by a temperature control of the VBG external cavity. As shown in figure 5, the fiber delivered laser beam was collimated to have a large proper diameter and circularly polarized by a combination of a Galilean telescope, a polarizing beam splitter (PBS), and a $\lambda/4$ -plate. The enlarged laser beam is reflected by an aluminum mirror (M_1) and then absorbed uniformly by the vaporized rubidium. The pumping laser beam was directed along a top-to-bottom direction of the cavity. Thus, the laser propagation direction was parallel to the direction of the magnetic field of the cavity and a selective σ^+ optical pumping of rubidium became possible. The transmitted laser beam can also be reabsorbed after being reflected back to the cell by the other aluminum mirror (M_2).



The NMR coils were developed to measure the ^3He polarization and were installed within the magneto-static cavity. As shown in figure 3, the Helmholtz coil was installed to have the same vertical magnetic field with that of the magneto-static cavity. The summed magnetic fields were used as an external holding magnetic field for the polarized ^3He gas. A triangular shape current was applied to the Helmholtz coil to sweep the Larmor precession frequency, which is proportional to the magnitude of the holding magnetic field. A cosine theta coil was used as a RF coil for NMR signal measurement [5]. As shown in figure 6, the magnetic field \mathbf{B} of the RF coil was formed from left to right direction. The resonance frequency of the coil was tuned to a Larmor frequency ($f=50$ kHz) of ^3He gas for the given holding magnetic field.

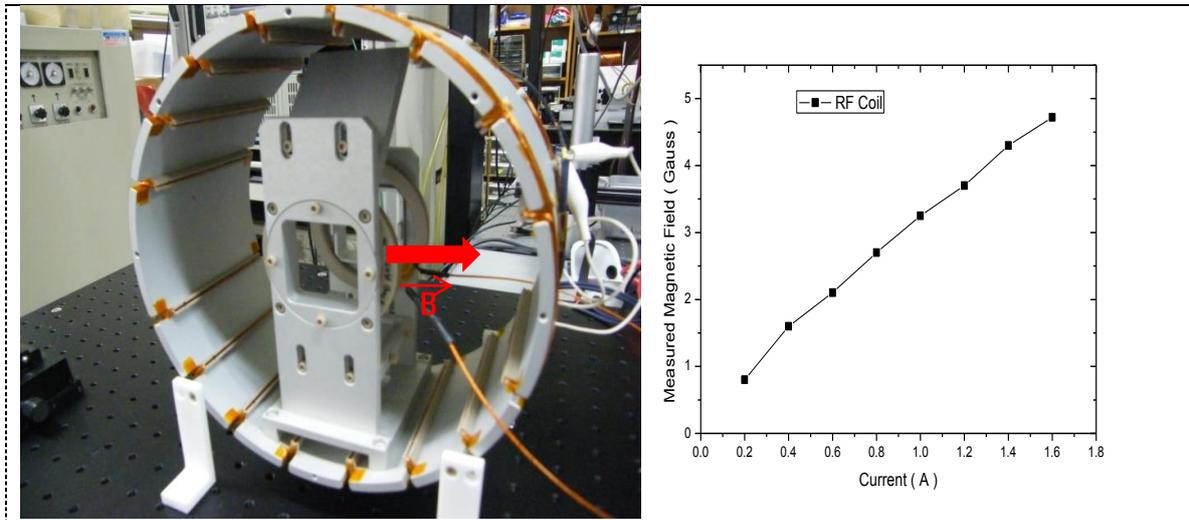


Figure 6. A $\cos\theta$ coil used for the NMR signal measurement (left), and the magnetic field B measured at the varied dc current of the $\cos\theta$ coil (right).

A ring-type pick-up coil has a magnetic field in the horizontal direction perpendicular to that of the cosine theta coil and was employed for NMR signal measurement. The resonance frequency of the pick-up coil was also adjusted to the Larmor frequency of the ^3He gas for the given holding magnetic field.

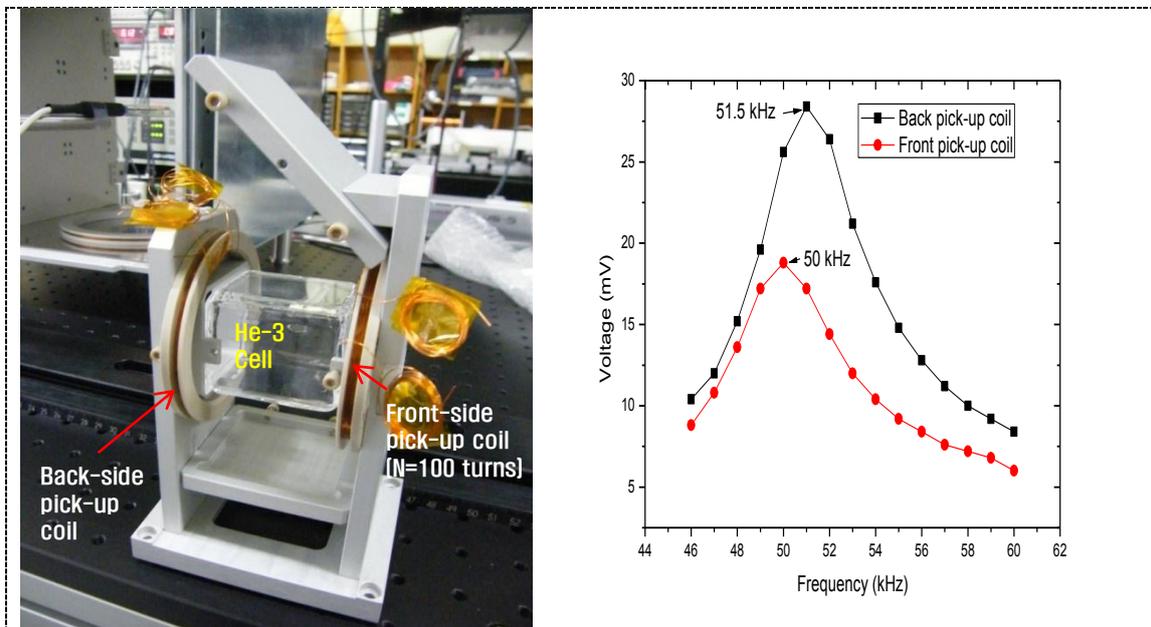


Figure 7. A ring-type pickup coil employed for the NMR signal measurement (left), and the measured resonance frequencies of the LRC circuits for the front- and the back-side pickup coils (right).

4. Conclusions

The characteristics of the magnetostatic cavity and the NMR coils were measured and analyzed experimentally. The developed magnetostatic cavity has a uniform magnetic field distribution and has the advanced capability to compensate a stray environmental magnetic field. These properties of the magnetostatic cavity can lead to successful development of a superior ^3He polarizer.

A high-purity-cell fabrication station was constructed and used to make a ^3He cell for the ^3He neutron spin polarizer. High purity ^3He cells with various shapes and pressures were fabricated successfully based on Ge-180 glass and fused quartz.

The novel in-situ ^3He neutron spin polarizer will be applied in the fields of polarized neutron imaging, TAS, SANS, Reflectometer, etc. Detailed characteristics of the neutron spin polarizer will be reported later.

References

- [1] M. Schulz, P. Böni, C. Franz, A. Neubauer, E. Calzada, M. Mühlbauer, B. Schillinger, C. Peiderer, A. Hilger, N. Kardjilov, *J. of Phys.: Conference Series* **251**, 012068 (2010).
- [2] S. Boag, E. Babcock, K. H. Andersen, M. Becker, T. R. Charlton, W. C. Chen, R. M. Dalgliesh, S. D. Elmore, C. D. Frost, T. R. Gentile, R. Lopez Anton, S. R. Parnell, A. K. Petoukhov, M. W. A. Skoda, T. Soldner, *Physica B* **404**, 2659 (2009).
- [3] W. C. Chen, R. Erwin, J. W. McIver III, S. Watson, C. B. Fu, T. R. Gentile, J. A. Borchers, J. W. Lynn, G. L. Jones, *Physica B* **404**, 2663 (2009).
- [4] E. Babcock, S. Mattauich, A. Ioffe, *Nucl. Instr. and Meth. A* **625**, 43 (2011).
- [5] T. Ino, Y. Arimoto, H. M. Shimizu, Y. Sakaguchi, K. Sakai, H. Kira, T. Shinohara, T. Oku, J.-I. Suzuki, K. Kakurai, and L.-J. Chang, *J. of Phys.: Conference Series* **340**, 012006 (2012).