Conceptual design of a polarized $^3$He neutron spin filter for polarized neutron spectrometer POLANO at J-PARC

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Abstract. A $^3$He neutron spin filter (NSF) has been designed for a new polarized neutron chopper spectrometer called the Polarization Analysis Neutron Spectrometer with Correlation Method (POLANO) at the Materials and Life Science Experimental Facility of the Japan Proton Accelerator Research Complex. It is designed to fit in a limited space on the spectrometer as an initial neutron beam polarizer and is polarized in situ by spin exchange optical pumping. This will be the first generation $^3$He NSF on POLANO, and a polarized neutron beam up to 100 meV with a diameter of 50 mm will be available for research on magnetism, hydrogen materials, and strongly correlated electron systems.

1. Introduction
A Polarization Analysis Neutron Spectrometer with Correlation Method (POLANO) is in the final stage of construction at the Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). POLANO is a new inelastic neutron spectrometer, focusing on quasi-elastic and inelastic scattering techniques, for comprehensive material research with polarized neutrons [1]. Some of the basic instrumental parameters of POLANO are listed in Table 1.

| Parameter                      | Value                  |
|--------------------------------|------------------------|
| Incident neutron energy        | up to 200 meV          |
| Energy resolution ($\Delta E/E_i$) | 3 ~ 5% at elastic position |
| Momentum resolution ($\Delta Q/k_i$) | 1 ~ 2%      |
| Sample size                    | 20 mm × 20 mm          |
| Detector coverage              | $-30^\circ$ to $130^\circ$ (horizontal) |
|                                | $-10^\circ$ to $10^\circ$ (vertical) |

Table 1 Some basic instrumental parameters of POLANO.

A neutron polarizer as well as a neutron-spin analyzer is a key device for the successful operation of POLANO. A $^3$He neutron spin filter (NSF) will be installed on the spectrometer as an initial neutron...
beam polarizer, and polarizing supermirrors as neutron-spin analyzers. The $^3$He NSF will be continuously operated (in situ polarization) by spin exchange optical pumping (SEOP) [2] to provide a neutron beam with a constant polarization [3,4]. It will be placed at a distance of 16.5 m from the neutron source, between the collimators and the sample vacuum chamber, as illustrated in Fig. 1. The available space for the $^3$He NSF is limited, roughly 60 cm by 80 cm with the shorter side lying along the neutron beam axis. The other requirements for the first generation $^3$He NSF on POLANO are:
- a neutron polarization $P_n > 90\%$ at 100 meV
- a neutron beam diameter $> 50$ mm.

A converging guide mirror has been installed upstream, and the beam size at the $^3$He NSF position will be $50 \text{ mm} \times 50 \text{ mm}$ to $80 \text{ mm} \times 80 \text{ mm}$ depending on the neutron energy. Hence in the next generation $^3$He NSF, the $^3$He cell diameter will be increased to ~100 mm with the attainable neutron energies being as high as 200 meV.

Polarization of the $^3$He nuclei by SEOP requires a glass cell of $^3$He gas with a drop of alkali metal, a homogeneous magnetic field to hold the polarized $^3$He spins, heaters to vaporize the alkali metal in a $^3$He cell, and a high-power laser for optical pumping. An adiabatic fast passage nuclear magnetic resonance (AFP NMR) system is additionally required for POLANO to flip the $^3$He spins for reversing the neutron spin direction. In addition, real-time whole-system monitoring with a safety interlock is essential for long-term operation of an in situ $^3$He NSF. These components are discussed in detail in the following sections.

![Figure 1. Schematic of a part of POLANO. An in situ polarized $^3$He neutron spin filter will be located between the collimators and the sample vacuum chamber, 16.5 m from the neutron source. The available space for the $^3$He NSF is about 60 cm by 80 cm.](image)

2. $^3$He cells
Cylindrical $^3$He cells with diameters of 60 mm, that fully cover the required beam diameter of 50 mm, are to be used. They are made of aluminosilicate glass GE-180, which is now commonly used for $^3$He NSFs [4]. The $^3$He gas thickness $d_{^3\text{He}}$ necessary to achieve a certain neutron beam polarization $P_n$ can be formulated as

$^1$ We refer to the product of the $^3$He gas density at 0 °C and the length along the neutron beam direction as the $^3$He gas thickness.
\[ P_n = \tanh(P_{He}\sigma d_{He}) \quad \text{or} \quad d_{He} = \frac{\tan^{-1} P_n}{\sigma P_{He}}, \] 

where \( P_{He} \) is the \(^3\)He polarization, and \( \sigma \) is the spin-averaged neutron absorption cross-section of \(^3\)He. Figure 2 shows the relations between the \(^3\)He gas thickness and the neutron energy for \( P_n = 0.8 \), \( 0.9 \), and \( 0.95 \) with \( P_{He} = 0.7 \). To achieve a neutron polarization of 90% at 100 meV with a \(^3\)He polarization of 70%, a \(^3\)He thickness of \(~30\) atm-cm is required, which may be realized with a cell \( 10 \) cm long filled with \(^3\)He gas at \( 3 \) atm (\( 0 \) °C) or \( 3 \) amagat. Shorter and longer cells could be used with higher and lower \(^3\)He densities, respectively. However, both shorter and longer cells have drawbacks; longer cells require larger space and shorter cells with higher gas densities (pressures) portend structural difficulties in the fabrication of \(^3\)He cells and limit the \(^3\)He polarization owing to the magnetic-dipole interaction of \(^3\)He. The \(^3\)He spin relaxation by the magnetic-dipolar interaction between the \(^3\)He nuclear spins is proportional to the \(^3\)He gas density [5]. At \( 23 \) °C, the relaxation rate becomes

\[ \frac{1}{T_{\text{dipole}}} = \frac{\eta_{He}}{744} \quad \text{[hour]}, \] 

where \( T_{\text{dipole}} \) is the relaxation time by the magnetic-dipole interaction and \( \eta_{He} \) is the \(^3\)He density in amagat. In a \(^3\)He cell filled at 3 amagat, the magnetic-dipole relaxation time drops to \(~250\) h at room temperature, and higher gas densities further shorten the relaxation time.

The windows of a \(^3\)He cell should be as thin as possible to minimize the background neutrons scattered by the glass windows, but thick enough to withstand the gas pressure. Studies to develop \(^3\)He cells that can sustain higher pressures are underway [6].

**Figure 2.** The required \(^3\)He gas thickness is plotted against the neutron energy for neutron polarizations of 0.8, 0.9, and 0.95. The \(^3\)He polarization is assumed to be 70%.

\(^2\) An amagat is a unit of gas density corresponding to 1 atm at 0 °C.
3. Magnetically shielded solenoid

A homogeneous magnetic field is essential for polarized $^3$He nuclei since the $^3$He nuclear spin is quite sensitive to field gradients perpendicular to the principal axis of the magnetic field, and the polarization easily degrades in the presence of small field gradients [7]. The $^3$He spin relaxation by radial (transverse) field gradients $T_{\text{mag}}$ can be written as

$$\frac{1}{T_{\text{mag}}} = \frac{6400}{\eta_{^3\text{He}}} \left( \frac{1}{B_0} \frac{\partial B_r}{\partial r} \right)^2 \text{[/hour]}. \quad (3)$$

Here, $\left( \frac{\partial B_r}{\partial r} / B_0 \right)$ is the radial field gradient in $[/\text{cm}]$ normalized by the primary field $B_0$. At $\eta_{^3\text{He}} = 3$ amagat, a radial field gradient of 0.001 $/\text{cm}$ corresponds to $T_{\text{mag}} \approx 500$ h, which is twice as long as that by magnetic-dipole interaction, and therefore we have designed a magnetically shielded solenoid that yields radial field gradients less than 0.001 $/\text{cm}$ in the cell location.

Figure 3 illustrates the structure of a magnetically shielded solenoid. The diameter and length of the solenoid are 20 cm and 30 cm, respectively. Two additional coils are wound around the solenoid at both ends; the solenoid and the two correction coils, for which insulated wires with a diameter of 1.0 mm are used, are connected in series so that they can be driven by a single power supply. Permalloy sheets wrap the coils for magnetic shielding with two openings at both the ends of the solenoid for the neutron and laser beams. The magnetic field distribution around the center of the solenoid and the radial field gradients have been calculated for a coil current of 1 A, as shown in Fig. 4. From the calculation, the transverse field gradients are much smaller than 0.001 $/\text{cm}$ and satisfy our requirement in the volume of the cylindrical cell with a diameter of 60 mm and a length of 100 mm.

**Figure 3.** The structure of the magnetically shielded solenoid with correction coils for the $^3$He NSF on POLANO. An insulated wire with a diameter of 1 mm is used for the solenoid (300 turns $\times$ 2 layers) and two correction coils (11 turns $\times$ 2 layers each).
4. Oven with AFP NMR

During the optical pumping of a $^3$He cell by SEOP, the temperature in the oven is kept at around 200 °C to evaporate the alkali metal. An aluminum oven is used for the $^3$He NSF on POLANO with AFP NMR to enable flipping the $^3$He spins instantaneously [8]. A uniform radio-frequency (RF) magnetic field is essential to avoid polarization loss in AFP NMR. The AFP conditions can be written as

$$D \left| \frac{\nabla B_z}{B_1} \right|^2 \ll \frac{dB_z}{dt} \ll \gamma B_1^2$$

or

$$D \left| \frac{\nabla B_z}{B_1} \right|^2 \ll \gamma \frac{d\omega}{dt} \ll \gamma B_1^2,$$  \hspace{1cm} (4)$$

where $\omega$ is the RF magnetic field frequency, $B_1$ the magnitude of the RF field, $\nabla B_z$ the gradient of the holding field $B_z$, $\gamma$ the gyromagnetic ratio of $^3$He, and $D$ is the $^3$He diffusion constant [9]. To fulfill the AFP conditions, a cosine-theta coil has been designed to produce a uniform RF magnetic field inside the oven (Fig. 5), and the calculated RF magnetic field is presented in Fig. 6. The variation of the RF field strength is less than +/-10% inside the $^3$He cell location, and should be uniform enough to satisfy the AFP conditions. It is to be noted that the RF magnetic fields yielded by the coil wire leads outside the oven, extracted at both ends, do not affect the inside of the oven because the
aluminum body of the oven is much thicker (5 mm) than the skin depth of aluminum at the RF frequency of AFP NMR and shields RF interference from the outside.

Figure 5. A sketch of the aluminum oven with a cosine-theta RF coil for AFP NMR. Wires are arranged at 20 degree intervals with a cosine-theta current distribution inside the oven.

Figure 6. Calculated RF magnetic field distributions are shown on the xz plane at z = 0 mm and 50 mm inside the aluminum oven (Fig. 5). The relative field strengths normalized at the oven center and the field directions are plotted together with the $^3$He cell (dashed line). Owing to the inlet pipe for the $^3$He cell, the cylindrical body of the cell is off the center of the oven.

5. Oven heater

Hot air is commonly used to keep $^3$He cells at elevated temperatures during optical pumping because conventional heating wires produce magnetic fields that interfere with the spin-holding magnetic field, causing additional depolarization. We, however, plan to use heating wires for the $^3$He NSF on POLANO to keep the system compact and for safety reasons. Flexible sheet heaters, which are made of resistive strips sandwiched between thin polyimide films, are widely available. The strip patterns of the heater element can be customized, and we have studied these strip patterns to obtain ones that minimize the magnetic interference to the $^3$He cell. Two patterns of the heater element are shown in

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3. The skin depth of aluminium is ~0.3 mm at 80 kHz, which corresponds to the Larmor frequency of $^3$He in a static magnetic field of ~2.5 mT.
Fig. 7. The magnetic fields resulting from them have been calculated for a heater current of 1 A and are plotted in Fig. 8. Assuming the primary magnetic field is ~2.5 mT, the additional field gradients due to the presence of the sheet heater current will not exceed 0.0003 /cm in the ³He cell position in either strip pattern. Note that the required heating capacity expected from preliminary tests of similar heaters is 100 W or less, much lower than that of a hot air heater used in Ref. 10.

![Flexible sheet heaters with the heater elements in radial (left) and axial (right) strip patterns are wrapped around the ovens. Each heating strip is 1 mm wide and is arranged at 3 mm intervals.](image1)

**Figure 7.** Flexible sheet heaters with the heater elements in radial (left) and axial (right) strip patterns are wrapped around the ovens. Each heating strip is 1 mm wide and is arranged at 3 mm intervals.

![Magnetic field gradients due to the flexible sheet heaters calculated for a heater current of 1 A. The uniform spin holding magnetic field is assumed to be 2.5 mT along the z direction.](image2)

**Figure 8.** Magnetic field gradients due to the flexible sheet heaters calculated for a heater current of 1 A. The uniform spin holding magnetic field is assumed to be 2.5 mT along the z direction.
6. Frequency narrowed diode laser optics

With the advances in high-power semiconductor diode lasers, the $^3$He polarization as well as the polarized gas volume has increased significantly. External cavity diode lasers have further improved the efficiency of optical pumping by reducing the linewidth of a diode laser [11,12].

We have tested and found a high-power laser diode array (LDA) with a chirped volume holographic grating (VHG) to be suitable for the $^3$He NSF on POLANO owing to the performance and compactness. The grating constant of a chirped VHG varies with its translation position, and its emission wavelength can be finely tuned to the $D_1$ resonance of an alkali metal [12]. Figure 9 shows our measurements of emission spectra from an LDA with and without a chirped VHG. The full width at half maximum (FWHM) was successfully narrowed to less than 0.2 nm by the use of a chirped VHG. The FWHM is comparable to that obtained from our previous external cavity optics with a diffraction grating [13] but is achieved with smaller and lesser number of optical components.

Circularly polarized light for optical pumping has to be reversed in helicity according to the $^3$He spin direction that can be flipped by AFP NMR. The helicity of the laser radiation can easily be reversed by rotating a quarter wave plate, thus converting the linearly polarized light from an LDA to circular. The quarter wave plate is mounted on a rotational holder, and the angle of rotation is remotely controlled synchronously with AFP spin flipping of the polarized $^3$He.

![Figure 9. Laser emission spectra from a high-power LDA with and without a chirped VHG. Output power from the LDA was ~85 W.](image)

7. Summary

We have designed an in situ operable $^3$He NSF for initial neutron beam polarization on POLANO. Neutron polarizations > 0.9 and energies up to 100 meV may be achieved for a neutron beam diameter > 50 mm. A schematic of the $^3$He NSF of dimensions 50 cm × 50 cm × 30 cm (length × width × height) is shown in Fig. 10. The laser illuminates a $^3$He cell from one side in the drawing, but the laser optics will be modified to illuminate both sides of a $^3$He cell with two lasers to improve the $^3$He polarization.

Safety is a priority in today’s scientific environments. High-power lasers, heaters, and electromagnets are possible hazards in SEOP. Various sensors will be installed in the $^3$He NSF to monitor temperatures, electrical currents, voltages, cooling water for LDAs, and vibrations owing to
earthquakes or accidental motion of the system. The sensor signals will be used for an interlock circuit to shut the system down automatically in case of an emergency. The $^3$He NSF may be continuously operated for several weeks without maintenance on POLANO. Safety and reliability are crucial aspects in ensuring the success of the spectrometer.

![Cross-sectional view of the $^3$He neutron spin filter on POLANO. The length is 500 mm along the beam direction, the width is 500 mm, and the height is 300 mm.](image)

**Figure 10.** Cross-sectional view of the $^3$He neutron spin filter on POLANO. The length is 500 mm along the beam direction, the width is 500 mm, and the height is 300 mm.

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