A compact SEOP $^3$He neutron spin filter with AFP NMR

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Abstract. We developed AFP NMR in an aluminum container for polarized noble gas nuclei. The radio frequency magnetic field inside the aluminum container was designed from computer simulations. The polarization loss by the AFP spin flip of $^3$He was measured to be as low as $3.8 \times 10^{-4}$. With this technique, a compact in-situ polarizing $^3$He neutron spin filter with AFP NMR is demonstrated.

1. $^3$He neutron spin filter and AFP NMR

The $^3$He neutron spin filter (NSF) attracts wide attention in neutron scattering because of its broad energy range and wide solid angle coverage. Some of such $^3$He neutron spin filters are equipped with adiabatic fast-passage (AFP) NMR [1] that allows one to measure the $^3$He nuclear polarization as well as to flip the spin of $^3$He nuclei and, in consequence, the neutron spin direction is reversed [2-6]. An AFP NMR system consists of static and radio-frequency (RF) magnetic fields. Both fields are perpendicularly aligned, and by slowly sweeping either the strength of the static field or the frequency of the RF field through the Larmor resonance, the $^3$He spin direction can be reversed. During the sweep, the $^3$He nuclear spin adiabatically follows the vector sum of the static and the RF magnetic fields in the rotating frame at the Larmor frequency, and the NMR signal from the processing nuclei can be detected by a pick-up coil. It is required to keep the AFP condition in the following equations [1] to minimize the polarization losses during the spin flip process:

$$\frac{1}{T_2} \frac{B_1}{2} \ll \left| \frac{dB_o}{dt} \right| \ll \gamma \left( \frac{B_1}{2} \right)^2$$

or

$$\frac{1}{T_2} \frac{B_1}{2} \ll \left| \frac{d\omega}{dt} \right| \ll \gamma \left( \frac{B_1}{2} \right)^2,$$

where $\gamma$ is the gyromagnetic ratio of $^3$He nuclei, $T_2$ is the transverse relaxation time, and $B_o$ is the flux density of the static magnetic field. The amplitude and the angular frequency of the RF magnetic

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field are $B_1$ and $\omega$, respectively. Large inhomogeneity of $B_1$ does not fulfill the AFP condition and will increase depolarization in the AFP spin flip for a given sweeping rate.

2. Designing a compact $^3$He spin filter with AFP NMR

Many compact $^3$He neutron spin filters with solenoid magnetic cavities have already been developed successfully [2, 5, 6]. A solenoid magnetostatic cavity may reduce radiation shielding void space compared with those using permanent magnets [7], and it is essential to minimize such void spaces especially at a spallation neutron source since high energy neutrons and gammas will increase the background level at instruments without proper shielding.

![Figure 1](image1.png)

**Figure 1.** Cross sectional views of the oven, the RF coil, the pick-up coil, and the $^3$He cell. The lengths are in mm.

An additional demand is the in-situ polarization of $^3$He nuclei at neutron instruments or on neutron beamlines in the caves. It will provide a neutron beam with a steady polarization, otherwise the beam polarization decreases with time as $^3$He nuclei depolarize. Previously, we demonstrated such an in-situ polarizing compact NSF but without AFP NMR [8]. In the process of polarizing $^3$He nuclei by the spin-exchange optical pumping (SEOP), the $^3$He cell has to be kept at an elevated temperature of 150°C to 200°C in an oven, and the choice of materials for the oven always becomes an issue when one designs the in-situ polarizing NSF with AFP NMR because the RF magnetic field interferes with conductive materials. In the case of Ref. 5, the authors used Ultem (polyetherimide) for the oven, Teflon in Ref. 6, and calcium silicate in Ref. 4. Unlike these insulating materials, the oven of our previous in-situ polarizing NSF was made of aluminum for easy and cheap fabrication. It did not seem to allow AFP NMR at a first sight, but we tried RF electromagnetic field simulations to introduce a uniform RF magnetic field over a $^3$He cell inside the aluminum oven for AFP NMR. A special RF coil was finally designed to be installed inside the aluminum oven. The cross sectional views of the aluminum oven and the RF coil inside are shown in Fig. 1. A cosine winding is employed to produce a uniform RF magnetic field in the horizontal direction of the cylindrical oven. A circular pick-up coil is aligned perpendicular to the RF magnetic field under the $^3$He cell. Polyimide insulated copper wires are used for both the RF and pick-up coils for better thermal properties. The oven is placed in a homogeneous static magnetic field produced by a solenoid with a diameter of 200 mm and a length of 300 mm, additional compensation coils, and permalloy magnetic shielding (Figs. 2 and 3). A picture of the modified $^3$He NSF is shown in Fig. 4.
3. Radio-frequency electromagnetic field simulation for the $^3$He AFP NMR

There are many methods developed for computational calculations of the radio frequency (RF) electromagnetic field. We used the finite-difference time-domain (FDTD) method to simulate the RF field for the $^3$He AFP NMR. The FDTD method consists in computing the finite-differences of electromagnetic field in a meshed space with time according to the Maxwell's equations [9]. In the FDTD, the simulated space is segmented into small unit cells, and the electric and magnetic field components are calculated in every cell from those in the adjacent cells using the Maxwell's partial differential equations. The time evolution of the electromagnetic field can easily be computed by the leapfrog scheme in this simulation method.
Three dimensional FDTD simulations were performed for the $^3$He AFP NMR. The volume was segmented into cubic cells of 1 mm side, and approximate representations of the 1/8 parts of the RF coil, the oven, the window flange, and the solenoid frame were configured by considering the symmetry (Fig. 5). Aluminum parts (the oven, the window flange, the solenoid frame) were simulated as perfect conductors, which have no resistivity or magnetization. The outer edges of the simulated space were filled with electromagnetic field absorber (perfectly matched layers or PML) [10]. The FDTD calculations were performed for the following five configurations to see the effects of the solenoid frame, the window flange, and the end of the winding of the RF coil:

1 : The oven and only the linear parts of the RF coil wires were configured; no solenoid frame, no window flange, no end of the winding of the RF coil wires (the RF coil wires were omitted at the edges and outside of the oven).
2 : The oven, the solenoid frame, only the linear parts of the RF coil wires.
3 : The oven, no solenoid frame, the linear parts and end of the winding of the RF coil wires.
4 : The oven, the solenoid frame, the linear parts and end of the winding of the RF coil wires.
5 : The oven, the solenoid frame, the linear parts and end of the winding of the RF coil wires, the window flanges (a 3 mm thick aluminum disc with a circular hole at the center approximated the window flange; the real flange has two holes that are not at the center).

The configuration #1 is ideal and the simplest; #4 and #5 are rather realistic. The current in the RF coil was powered at a frequency of 100 kHz. The results of the FDTD simulations are presented in Figs. 6 and 7 for the root mean square (RMS) amplitudes of the RF magnetic fields. The two dimensional RF magnetic field maps are shown for the configuration #5, and the RF fields along the x, y, and z axes for all the configurations. The contribution of the end of the winding of the RF coil is rather significant while the reflection effect by the solenoid frame is almost negligible. The static magnetic field produced by the RF coil (the linear parts only) was also calculated by the Biot-Savart equation. It was found that the static field was roughly three times larger than that by the alternating current of 100 kHz because of the reflected RF wave from the oven. The RF magnetic field simulated for the configuration #5 was found almost uniform in the area for the $^3$He cell, a cylindrical area with a diameter of 40 mm and a length of 100 mm, and the polarization loss by the AFP spin flip is expected to be quite limited.
Figure 6. Two dimensional images of the RF magnetic field by the FDTD simulation for the configuration #5. The cross sectional mappings are at z = 0, y = 0, and x = 0, respectively. The cylindrical oven is shown in dark blue. The scale is in Gauss.

Figure 7. RF magnetic field along the x, y, and z axes by the FDTD simulations.

4. RF magnetic field measurement
The RF field strength inside the oven was measured with a small search coil magnetometer. A small circular coil with a diameter of 5 mm was wound with a fine insulated copper wire. The voltage induced in the coil is proportional to the RF field strength. The positions of the coil were scanned, and the RF field mapping was measured without the window flanges. The RF magnetic field strength along the x, y, and z axes as well as the FDTD calculation for the configuration #4 are represented in Fig. 8. A slight difference is observed in the field strength between the measurement and the simulation especially around the edges of the cylindrical oven (z = ±50 mm in the right plot). It may be due to the fact that the structural arrangement in the FDTD simulation is limited to the size of the meshed cell while the real oven and the RF coil are more complex arrangements. Nevertheless, the simulations show excellent agreements with the measurements.

Figure 8. RF magnetic field strength along the x, y, and z axes deduced from the measurements and the FDTD simulations for the configuration #4 (without the window flanges).
Let us compare the RF magnetic field with the AFP condition mentioned in Section 1. The RF magnetic field $B_1$ was measured to be $\sim 0.17$ G near the center of the oven. The RF frequency was 100 kHz, and the corresponding static magnetic field $B_0$ was 30.8 G for the $^3$He nuclei ($\gamma = -2.038 \times 10^8$ /s). In the AFP spin flip process, $B_0$ was swept at a speed of 11 G/s. Thus,

$$\frac{1}{T_2} \frac{B_1}{2} \approx 0.85 \text{ G/s}, \quad \left| \frac{dB_0}{dt} \right| \approx 11 \text{ G/s}, \quad \text{and} \quad \gamma \left( \frac{B_1}{2} \right)^2 \approx 1.5 \times 10^6 \text{ G/s}.$$ 

Here, the transverse relaxation time $T_2$ is assumed $\sim 0.1$ s [11]. The above numbers satisfy the AFP condition in Section 1, and the polarization losses in the AFP spin flip process is expected to be minimal.

5. AFP NMR test
The polarization loss by the AFP spin flip was measured for a cylindrical $^3$He cell with a diameter of 3 cm and a length of 5 cm. The $^3$He cell was polarized in a different laser pumping station and moved into the in-situ AFP NMR system. In this test, the static magnetic field was swept over the Larmor resonance while the frequency and the amplitude of the RF magnetic field were fixed. One AFP sweep took 0.5 second, and the AFP NMR measurement was repeated 60 times (Fig. 9). The polarization loss in one AFP spin flip was found only to be $4 \times 10^{-4}$. Note that the RF coil was operated by a common function synthesizer with an output power of $\sim 0.3$ W in this measurement; no RF power amplifier was used.

![Image of NMR signal](image)

**Figure 9.** The AFP NMR signals (raw data and the peak heights) are plotted for 60 continuous measurements. The loss of $^3$He polarization in one AFP spin flip was calculated from the exponential fit to the data. Note that the spin relaxation of $^3$He ($T_1$) was 187 hours and enough long compared to the time duration of the measurements.
6. Conclusions
We have developed an in-situ compact $^3$He neutron spin filter with AFP NMR. The oven was made of aluminum for easy and low-cost fabrication. The RF magnetic field inside the aluminum oven was designed with the FDTD simulation. The FDTD calculation of the RF field was in good agreement with the measurement, and one may be able to rely on the FDTD simulation to design this kind of AFP devices. The polarization loss of $^3$He in one AFP spin flip was measured to be very little, and it will further be reduced with the amplitude modulation AFP technique [12]. A neutron beam test of this $^3$He NSF was performed at J-PARC just before the disastrous earthquake in Japan, and the results are presented in a separate article [13].

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