Tunable magnetostatic cavity for housing a $^3$He neutron spin filter

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Abstract. A new design of a magnetostatic cavity for housing a neutron spin filter with spin-polarized $^3$He gas at a neutron instrument is proposed. Movable components made of soft magnetic materials allow for an accurate tuning of the homogeneity of the holding magnetic field within the cavity and, thus, ensure a long $^3$He spin relaxation time. In addition, this design enables to correct the holding field in the presence of an external magnetic source near the cavity, which is usually the case in neutron experiments with polarization analysis.

1. Introduction

Recent years have seen significant progress in the application of neutron spin filters (NSF) utilizing polarized $^3$He gas for neutron polarization analysis [1-10]. The straight-line passage of a neutron beam through a NSF with no change of neutron trajectory enables one to measure a neutron polarization for nearly any divergent scattered beam. Furthermore, the NSFs offer homogeneous analyzing efficiency with a predictable value, predictable transmission, a negligible small angle scattering from the $^3$He cell and produce only a low gamma-ray background. Taken together these features make the NSF technique extremely useful in applications such as neutron imaging with polarization analysis, small-angle neutron scattering, off-specular reflectometry and large solid angle polarization analysis.

The successful application of $^3$He NSFs in neutron experiments is based on the considerable improvements in the large-scale production of hyperpolarized $^3$He gas in both Metastability Exchange Optical Pumping (MEOP) and Spin Exchange Optical Pumping (SEOP) methods. In the MEOP method, direct optical pumping of metastable $^3$He atoms occurs in a weakly ionized $^3$He plasma at about 1 mbar gas pressure [11-13] and hence a subsequent compression is required to produce a dense polarized gas. The gas at a pressure of a few bars may be then collected in a detachable cell (glass container) of a given size and shape and transported to a neutron instrument. The high production rate allows for several neutron experiments to be served in parallel. The limitation of this approach, however, is the necessity of the cell replacement in the course of a long running experiment since the polarization of the $^3$He gas in the cell decays exponentially with time according to the equation

$$P(t) = P(0) \cdot \exp \left( - \frac{t}{T_1} \right)$$

$$T_1$$

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Here $P(0)$ – the initial $^3$He gas polarization and $T_I$ – the longitudinal spin-relaxation time which will be discussed later.

Unlike MEOP, in the SEOP method $^3$He gas can be polarized directly at high pressure and there is no need for an additional compression. Here, a production of a highly polarized $^3$He gas is realized through the optical pumping of alkali-atoms (pure Rb, pure K or Rb-K mixture) in a high-pressure alkali-$^3$He gas mixture [14-17]. The polarized alkali-atoms then transfer polarization to the $^3$He-nuclei in a spin-exchange process thus obtaining a dense spin-polarized $^3$He gas. Although the polarization build-up time in SEOP is longer compared to MEOP, the SEOP method is of particular interest in neutron instrumentation since it allows for a $^3$He gas to be polarized steadily on a neutron beam in the course of a running experiment and, thus, there is no requirement for cell replacement. This means, on the other hand, that the SEOP setup has a limited capability to serve several experiments in parallel.

In spite of a difference between these methods, there is one common requirement which is valid in both cases: a cell with $^3$He gas has to be housed in a very homogeneous holding magnetic field during both the optical pumping and the neutron experiment. In the case of a detachable cell (e.g., MEOP cell), the inhomogeneity of the magnetic field sets an upper limit for the relaxation time of the gas polarization in the cell and, hence, can lead to either the necessity of a very frequent replacement of the cell or even to unacceptable conditions to perform the experiment. In the case of the on-line gas polarization (e.g., SEOP), the shortening of the relaxation time due to the inhomogeneity of the magnetic field results in lowering of the maximal achievable gas polarization in the cell. Therefore, the homogeneity of the holding magnetic field is of critical importance in production and implementation of the polarized $^3$He gas. With the aim to provide such a homogeneous field, different magnetostatic cavities were developed.

2. Magnetostatic cavity

A magnetostatic cavity is an important unit intended to produce a homogeneous magnetic field for holding a polarized $^3$He NSF and to screen the polarized gas against environmental stray magnetic fields at a neutron instrument. Generally, the relaxation rate of the gas polarization in a NSF cell may be represented as a sum (see, for example, [18]):

$$\frac{1}{T_1} = \frac{1}{T_{cell}} + \frac{1}{T_{mag}}$$  \hspace{1cm} (2)

Here $T_{cell}$ – the relaxation time related to the cell (relaxation due to interactions of the gas atoms with the cell walls [19-23] and due to dipole-dipole interactions of helium atoms [24]) and $T_{mag}$ – the relaxation time related to the gradient of the magnetic field over the cell volume [25-27]. The last term in equation (2) can be written as [18]

$$\frac{1}{T_{mag}[hour]} = 1.7 \cdot 10^2 \left( \left| \frac{\nabla B_\perp}{B_0} \right| [cm^{-1}] \right)^2 \cdot \frac{1}{p[bar]}$$  \hspace{1cm} (3)

where $p$ is the gas pressure, $B_0$ refers to the value of the holding magnetic field and $B_\perp$ - to the component of the magnetic field normal to $B_0$. From hereon the ratio $|\nabla B_\perp|/B_0$ is referred to as a field gradient. It follows from equation (3) that a field gradient less than $3 \cdot 10^{-4}$ cm$^{-1}$ is required to ensure $T_{mag} > 500$ h in a 1 bar pressure cell.

Magnetostatic cavities aimed at providing a homogeneous magnetic field have been developed in all groups working with polarized gas (see, for example, [15, 28-33]). Generally, if we consider only non-cryogenic cavities, they can be classified as current based or permanent magnet based cavities depending on the source chosen to produce a holding magnetic field. Soft magnetic materials such as iron or mu-metal are used to redistribute the
field over the desired volume and/or to screen against environmental fields. Typically, all these systems are based on an accurate design of a cavity with a fixed geometry and with an assumption made about the value and space distribution of the environmental magnetic field at a neutron instrument. This final assumption requires some free parameters to be added to the design. In many instances, however, these parameters cannot be evaluated in advance. As a result, the real field gradients over the cell volume may differ significantly at different instruments.

The simple method to solve this problem would be to build a magnetostatic cavity with an excessive screening factor and, hence, to make it heavy and/or large. One may expect this method to be extremely useful for a fixed cavity integrated to a neutron instrument or for a portable cavity designed to hold small cells (of size of a few centimeters). However, as it was mentioned earlier, the special benefit of using a polarized $^3$He NSF is expected in such areas as neutron imaging with polarization analysis, small-angle neutron scattering, off-specular reflectometry and large solid angle polarization analysis. In all these cases the use of large area NSF cells would be advantageous. Obviously, for relatively large cells the restrictions on the size and weight of the portable cavity make the method of excessive screening of limited usefulness.

In this paper we present a new approach to the design of a compact magnetostatic cavity which allows one to build a portable magnetostatic cavity for relatively large NSF cells.

3. Tunable magnetostatic cavity

With the aim of simplifying the use of NSF's at neutron instruments, a robust compact magnetostatic cavity was developed at the FRM II (Garching, Germany) (figure 1). It is comprised of plain steel plates assembled in a box as shown in figure 2. Two rows of permanent magnets are sandwiched between steel plates on the sides. Each row consists of many pieces of permanent magnets assembled along the direction normal to the plane of the picture. The polarities of the magnets in both rows are identical and aligned in the vertical direction. The magnetic field is guided to the top and bottom parallel steel plates (5 and 6 in figure 2) and from there through the empty cavity, creating a holding field inside the box. In addition to this desired field, a strong stray field occurs in the vicinity of the permanent magnets resulting in an inhomogeneous field distribution. This is illustrated in figure 3 where the magnetic flux lines distribution was calculated for a cavity without inner mu-metal plates.

![Figure1](image_url)  
**Figure1.** TUnable Magnetostatic cavity (TUM box) at the FRM II. A neutron spin filter holder is located in the centre of the box.
Figure 2. Front view of the TUM box. 1-6 – the plain steel plates, 7 and 8 – two rows of permanent magnets, 9-12 – the adjustable mu-metal plates.

Figure 3. Magnetic field flux lines distributed over the box without mu-metal plates.

To correct the field distribution and build up a uniform field inside the box, four mu-metal plates (9-12) were installed as shown in figure 2. The thickness of these plates and the distance to the walls was chosen to affect the stray field in such a way that the resulting field inside the box becomes uniform. Figure 4 shows the distribution of the field inside the box calculated for the adjusted distances between the mu-metal plates and the walls. It can clearly be seen from this figure that some of the magnetic flux lines are closed by the mu-metal plates 9 and 10 and do not penetrate into the interior part of the cavity; this depends on both the thickness of the plates and the distances to the magnets. Optimizing the positioning of the mu-metal plates results in a very homogeneous field in the central area where a NSF cell is supposed to be located. The small shift of the mu-metal plates 9 and 10 in the direction of the sidewalls or in the opposite direction leads to the variation of the number of the closed lines and to deterioration of the field homogeneity.

Figure 4. Magnetic field flux lines distributed over the TUM box with mu-metal plates installed and adjusted.
So far we have considered a model where all components have been thought to be ideal, i.e., all magnets had the same strength and perfectly aligned and all soft magnetic materials (plain steel and mu-metal plates) had a uniform permeability to magnetic field. In practice, however, one usually has to deal with non-ideal components like non-uniform permanent magnets and soft magnetic materials. Therefore, the practical design of a magnetostatic cavity has to be adapted to these conditions. The cavity in figure 2 was designed to meet this requirement. For this purpose, the positions and inclinations of the mu-metal plates 9 and 10 with respect to the sidewalls can be adjusted in situ to minimize the field inhomogeneity caused by the imperfection of the materials. This allows for a fine tuning of the magnetic field homogeneity inside the box, which may be, thus, referred to as a TUM Magnetostatic box (TUM box).

Two additional mu-metal plates (11 and 12 in figure 2) are positioned near the bottom and the top of the box. Figure 5 illustrates the effect of these plates on the distribution of the holding field $B_0$ measured along the central line of the constructed box (along the neutron beam).

![Figure 5](image_url)

**Figure 5.** Effect of the horizontal mu-metal plates on the field homogeneity. Line “a” shows the field distribution measured without horizontal mu-metal plates and line “b” – after the horizontal plates were installed.

In this particular example the distribution of the vertical field component was measured first without mu-metal plates 11 and 12 (line “a”) and then with mu-metal plates installed (line “b”). As one can see, a significant field gradient occurs in the central area of the box without mu-metal plates. This most probably results from the non-uniformity of the permeability of the steel plates. The mounting of the horizontal mu-metal plates helps to redistribute the field leading to a decrease of the field gradient. The adjustment of these plates in situ provides a way of further decreasing the field gradient to an acceptable value.

The first tunable magnetostatic box at the FRM II had dimensions 50x50x22 cm (WxLxH) and was capable of holding a cell with a gas volume of size 10x10x10 cm. The optimal design of the box was found with the help of the computer simulation software FEMM (Finite Element Method Magnetics [34]). For this optimal design the magnetic field gradient was calculated to be around $1 \cdot 10^{-4}$ cm$^{-1}$. In practice, however, the cavity assembled in accordance with this design displayed extremely poor magnetic field homogeneity over the desirable cell volume. We ascribe this largely to the inhomogeneous permeability of the plain steel plates and, to a smaller degree, to the variation of the magnetization of the pieces of
permanent magnets since the latter were selected and distributed evenly in both rows of magnets. To reduce the field inhomogeneity (or, in other words, to tune the cavity), both the vertical and horizontal mu-metal plates were shifted and tilted against the calculated positions. This correction was performed by an iterative process with measuring the field gradient distribution after each step. Finally, for this particular cavity, the tuning was performed successfully with the resulting field gradient $4.4\times10^{-4}$ cm$^{-1}$. (Later we have constructed two more cavities with field gradients of $2.5\times10^{-4}$ cm$^{-1}$ over the volume 10x10x10 cm$^3$.) It should be mentioned that the gradients of the field components normal to the main component $B_\perp$ (see equation (3)) were measured only along the sides of the cubic volume 10x10x10 cm in the central area of the box. This is a useful approach to perform express analysis of the field homogeneity and it offers fast tuning if necessary. This approach is based on the fact that the points located inside the volume are at greater distances from the sources of the magnetic field and hence we may expect the gradients at these points to be less than the ones measured on the outer surface of the volume. Thus, the mean value of the field gradient measured along the sides can be considered as an upper limit of the mean value of the field gradient over the entire cubic volume. Indeed, for the considered cavity, the field gradient in a smaller volume (6x6cm cross-section) was measured to be $3.5\times10^{-4}$ cm$^{-1}$.

The final test of the performance of the TUM box was done by measuring the relaxation time of polarized $^3$He gas in a cell which was placed in the central area of the box. The polarization of the gas was performed at HELIOS, the facility for large-scale production of dense highly polarized $^3$He gas at the FRM II (Garching, Germany) [7]. With the aim to measure gas polarization in the cell a very small amount of the gas was taken from the cell back to the HELIOS facility. The polarization was then evaluated by measuring the degree of circular polarization of the 668nm spectral line [35-36] emitted by the polarized gas in a low-pressure discharge at HELIOS. For the purpose of measuring the relaxation time, the polarization of the gas in the cell was measured successively over the period of two-three days. Fitting the experimental data to the exponential decay function (equation (1)) yields the relaxation time.

As mentioned above, the measured relaxation rate (inverse value of a relaxation time) represents the total effect of many parameters (see equation (2)). With the aim to evaluate the relaxation time related solely to the magnetic field gradient in the TUM box, we measured first the relaxation time in the cell positioned in the box and then the relaxation time in the same cell positioned in a very homogenous magnetic field at HELIOS. This second measurement was performed without repolarization of the gas. Since the magnetic field gradient at HELIOS is very low (about $1\times10^{-4}$ cm$^{-1}$), it results in a negligible contribution to the total relaxation rate. Thus, we may assume the relaxation rate measured at HELIOS is entirely related to the first term in equation (2). Thus, measuring $T_r$ in the TUM box and then $T_{cell}$ in the magnetic field at HELIOS one can extract $T_{mag}$, i.e., relaxation time related to the field gradient in the TUM box. Applying equation (3) to the evaluated value of $T_{mag}$, the field gradient over the cell volume can be calculated. The following results were obtained: $|\nabla B_\perp|/B_\perp \approx 5\times10^{-4}$ cm$^{-1}$ over a cell with 10x11 cm cross-section and 5.5 cm length and $|\nabla B_\perp|/B_\perp \approx 3.5\times10^{-4}$ cm$^{-1}$ over a cell with 6 cm diameter and 10 cm length. These values are in a good agreement with the direct measurement of the field gradients discussed earlier. Thus, the measurements of the relaxation time confirmed the ability to tune the magnetic field homogeneity in the cavity, which showed initially a very poor performance. It is worth noting that after all these measurements have been finished we performed further adjustments of the field that brought the gradient down to the value $3.5\times10^{-4}$ cm$^{-1}$ over the volume 10x10x10 cm$^3$.

4. Tuning in the presence of an external magnetic field

The approach with a tunable magnetic field can be readily applied to the magnetostatic cavity located in the vicinity of an external magnetic source, which is usually the case at a neutron instrument with polarization analysis. This external field usually originates from a
neutron spin guiding magnetic system and/or from a magnetic field applied to the sample under study. The external magnetic field may result in an additional field gradient over the NSF cell in the cavity and special care has to be taken to minimize this effect. We have mentioned earlier the problems that may arise while constructing a passive shielding for cells of a relatively large size. In this respect the tunable magnetostatic cavity offers an alternative solution, since it was specially designed to correct any inhomogeneity of the holding field regardless of the particular source of that inhomogeneity. Consequently, the field gradient resulting from the presence of an external magnetic field can also be corrected in this cavity. With the aim to check this possibility, the TUM box was exposed to an external magnetic field similar to the field used in neutron experiments. In figure 6 the local source of the field is located at a distance D from the TUM box. This source represents a model of a guiding field with the size 20 x 32 cm (W x H) and the strength of 28 G.

![Figure 6. Experimental setup for measuring the effect of the external source. 1 – external source (magnetic guiding field at a neutron instrument), 2 – TUM box with a NSF cell. Neutron beam is shown for the reference only.](image)

It is anticipated that the passive suppression of the external field within the TUM box can be performed only to some extent and the field gradient is expected to rise as an external source moves closer. Figure 7 presents the measured field gradient in the central area of the TUM box as a function of the distance D.

![Figure 7. Effect of tuning in the presence of an external magnetic source. Bold circles – the measured gradient of the holding field averaged over the cell volume (10x10x10 cm). The dashed curve is a guide to the eye.](image)
It is clearly seen that the field gradient over the cell volume increases as the distance between the TUM box and the external source decreases. At the distance of 22 cm the measured field gradient is twice as much as that without external source. The value of the magnetic field produced by the external source at the front of the box is 5 G. After the gradient has been doubled, the additional tuning with the help of the movable mu-metal plates in the TUM box was performed and the gradient was brought down to the required value (see the bold arrow in figure 7). This additional tuning was done with a simple tilting of the horizontal mu-metal plates at the top and bottom of the box. Finally, the obtained result proves the ability to tune a holding field at a neutron instrument.

5. Conclusion
The new design of a magnetostatic cavity with a homogeneous magnetic field is proposed and tested. The distinguishing feature of this design is the possibility for correcting the field gradient within the central area of the cavity in situ. This correction is performed with the help of special movable components, which are made of soft magnetic materials and integrated into the cavity. So, the design involves both passive and tunable shielding components. This fact is of special importance in the case when the cavity is exposed to an external magnetic field, which usually occurs at a neutron instrument with polarization analysis. The correction of the field gradient caused by an external source has been demonstrated in a special measurement performed with field geometry similar to one at a neutron instrument.

One may expect that replacing of the plain steel plates by mu-metal plates will result in even better performance of the tunable magnetic boxes and allows for more compact design for relatively large NSF cells.

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