The Optimization of Uniform Magnetic Field for an Experimental Search for Axion-mediated Spin-Dependent Interaction

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Possible interaction between unpolarized and polarized nuclei in long range may provide a new source for PT-violation. Moody and Wilczek proposed that such force might be mediated by the axion. A new idea of tabletop experiment searching for such interaction has been proposed from ARIADNE collaboration including SQUID NMR with polarized ^{3}He nuclei using the metastability-exchange optical pumping (MEOP) method. In this method, uniform magnetic field is required to produce the polarized ^{3}He gas with a laser at 1083 nm. We describe the finite element method (FEM) as well as the semi-analytical approach to generate uniform field to preserve polarization with a number of Helmholtz Coils compared with each other.

1 Introduction

Axion is a pseudo-scalar boson that explains the strong CP problem [1] and may mediate a new macroscopic force between nuclei [2]. Such interaction can be tested in laboratory experiments by employing polarized and unpolarized masses [3]. The nuclear spin of ^{3}He gas can be polarized with MEOP method and used to search for the spin-dependent interaction. In the experiment, the unpolarized mass affects the polarized ^{3}He gas in the presence of the PT-odd monopole-dipole interaction depending on the distance between them. The distance will be modulated by controlling the position of unpolarized mass. The nuclear spin of the polarized ^{3}He will precess off from the original polarization axis resonantly by the modulation. This signal can be detected with SQUID. The schematic design of experimental setup (a), (b) and polarization unit (c) for ^{3}He are shown in the Figure 1.

However, the polarized ^{3}He gas would be depolarized if they experience a magnetic field gradient. Therefore, it is necessary to have a uniform guide field to preserve the polarization while transporting the polarized ^{3}He gas from the polarization unit to the measurement cell as in the Figure 1 (c). In this paper, we present the magnetic field distribution optimized with the FEM software called the OPERA 3D [4]. The result was compared with analytically calculated field distribution from the Biot-Savart law to design guiding coils.

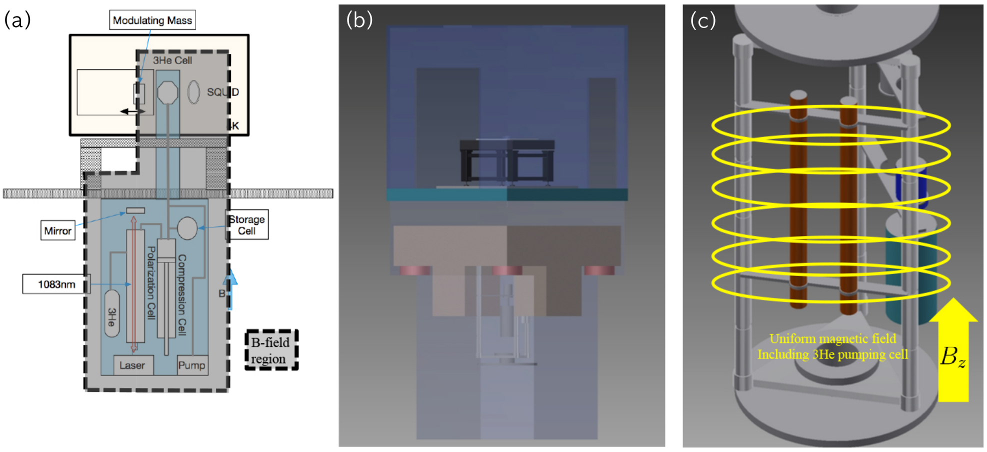

Figure 1: A conceptual design of the spin-dependent interaction experiment. The conceptual configuration (a), entire setup (b), and the polarization unit inside the magnetic field (c).

2 Optimization of the Field Distribution

Large enough square-shaped conducting coils were employed to generate guiding field, which allow better space utilization than circular-shaped or solenoid coils. It is necessary to optimize those conductors to generate guiding field uniformly distributed over wide range.

The variables for the uniform field generation are size, width, thickness, position, number of turns of the coil, and current. The size, width, and thickness of the coil were fixed at 1500 mm, 50 mm, and 1 mm respectively. The position and current density of conductor would be remaining parameters for the optimization. Each pair of opposite coils from the center should have the same parameters to generate symmetric field from the center.

2.1 Finite Element Method

The square-shaped conductor has 1500 mm length on each side with 1 mm thickness. The width of each coil was 50 mm. This geometry can be regarded as 50 turns of 1 mm^2 coil on the 1.5 m long square support.

The OPERA 3D [4] solver, TOSCA for a static magnetic field simulation, expands coefficients of the Legendre polynomial to calculate the variation level of the induced magnetic field in the spherical region. In this optimization, the radius was chosen 500 mm.

The conductors and induced field map are shown in the Figure 2. By the symmetric condition, we need only one octant instead of whole space to reduce calculation time as in the Figure 2.

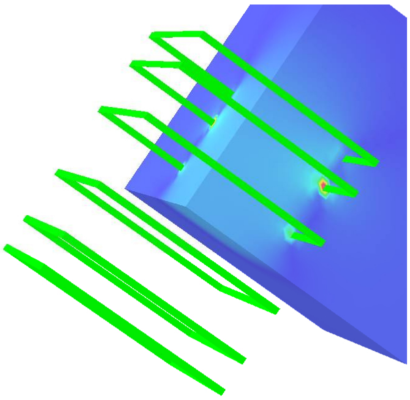

Figure 2: Simulation scheme for six conductors with OPERA 3D (TOSCA solver)

2.2 Analytic Calculation

The Biot-Savart law allows us to evaluate the magnetic field by integration. The induced field from square-shaped conductor is

$$B_z(z) = \frac{4\mu I}{\pi} \frac{d^2}{(d^2 + 4z^2)\sqrt{2d^2 + 4z^2}}. \tag{1}$$

The optimized parameters from the OPERA 3D will be assigned to this formula. The fields generated by the analytic calculation and finite element method will be compared with each other.

3 Result and Discussion

The optimization result of the positions and current densities from the OPERA 3D is as below Table 1:

Conductor	Position (mm)	Current density (A/mm^2)
1st pair	180	0.93
2nd pair	720	1.35
3rd pair	945	0.90

Table 1: The simulation output. The positions are distances from the center.

To produce uniform field along the central region, the second pair of coils plays a dominant role. They have the highest current density among three pairs of coils as 1.35 A/mm^2 at 720 mm distance from the center. The first pair makes the central part of the magnetic field more uniform. The third pair revises the field around the edge of the optimized range, 500 mm from the center. The superpositioned field distribution is shown in the Figure 3.

3.1 Field Distribution

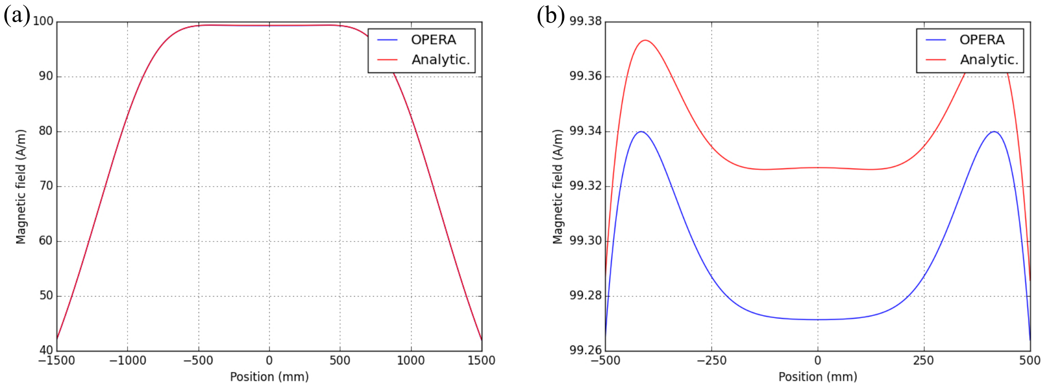

Figure 3: Field distribution along the z-axis (a) and magnified one for optimized range (b).

The difference between maximum and minimum values of uniform field distribution is order of 0.01 %. Also, the results from two approaches agree with each other.

3.2 Uniformity

The uniformity of the field can be tested by a rate of field value change, which is defined by the homogeneity

$$H(z) = \frac{B_z(z) - B_{\text{avg.}}}{B_{\text{avg.}}}. \tag{2}$$

The homogeneity is less than 0.1 % on the whole optimized range as in the Figure 4.

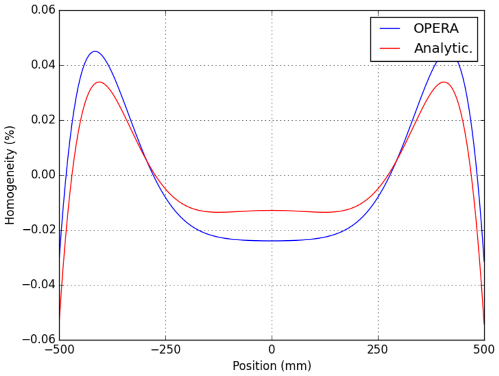

Figure 4: The homogeneity in the optimized range.

4 Summary

We designed and simulated the uniform guiding field of six square-shaped conductors to produce polarized ^{3}He gas in our setup. They are very useful to design optical polarization system of ^{3}He over large volume. We plan to build a proto-type coil system and integrate it into the ^{3}He gas optical pumping system.

Acknowledgement

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