**PCB Coil Design Producing a Uniform Confined Magnetic Field**

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We present a magnetic field confining coil with a sub 10\(^{-3}\) field uniformity over a large fraction of the coil. The structure is entirely made out of printed circuit boards (PCB). The PCB design allows to tailor the path of wires to fit the required geometry. We measure the field uniformity with Cesium magnetometers in a field range from 1\(\mu\)T to 10\(\mu\)T. Our application uses such a coil for an atomic magnetometry based current controller.

**Index Terms**—Electromagnetics, Magnetic instruments, Magnetic measurements, Magnetic sensors

### I. INTRODUCTION

Many applications in modern research require a very uniform magnetic field over the experimental volume. Traditionally, a pair of Helmholtz coils or a solenoid would be used. They produce a reasonably uniform field for a coil geometry which has been known and used for many years [1], [2]. Extensions of the Helmholtz coils attempt to improve on the uniformity of the magnetic field by using more than just two coils [3]. Some applications have very stringent requirements on the field uniformity [4]. There one would prefer a \(\cos \theta\) or a spherical coil, which typically produces very uniform fields over a large volume of the coil [5]. All of these coils have large fringe fields. They may interact with environmental factors such as nearby high permeability materials, perturbing the actual uniform volume. One may then use either a return yoke or build a field confining coil to guide the stray field and reduce the influence of the environment [6], [7].

We present simulations and measurements of a PCB based field confining coil. The PCB design exploits the precision of modern PCB manufacturing. This allows for tailored wire paths as well as to choose the wire density, i.e. the coil constant. Furthermore, the wire width and thickness can be chosen. Thus, we can adapt the total resistivity of the coil to the used current source. Additionally, the use of PCB headers as connectors makes it easy to open and close this type of field confining coil.

#### A. Motivation

Our groups are involved in an international collaboration searching for the neutron electric dipole moment (nEDM) [8], [9]. The experiment uses Ramsey’s method of time-separated oscillating fields [10], where neutrons precess in a magnetic field \(\vec{H}\) and a parallel, or anti-parallel, electric field \(\vec{E}\). These types of measurements require a very stable and uniform magnetic field \(H_0\). The long-term stability for \(H_0\) is achieved with a mu-metal shield and active field stabilization [11]. We aim at improving the shielding factor in our experiment by at least a factor 10. Then, the stability will be fundamentally limited by the current source which feeds the \(H_0\)-coil. Thus, the present current source, 10\(^{-7}\) stability on 17 mA, must be improved. In order to improve on this stability, a current controller based on atomic magnetometry is presently being developed, see Fig.1 [12]. Modern atomic magnetometers easily reach sensitivities on the order of 10\(^{-8}\) for one second of integration time in the shot noise limit [13], [14]. These sensitivities can be exploited by converting drifts in currents into magnetic field changes [15]. The coil in Fig.1 is able to discriminate external field perturbations from a drift in current. The latter changes the field modulus in all quadrants by the same amount, while an external field will affect each quadrant in a different way.
II. COIL DESIGN

A. Method

The coil design, shown in Fig.1, confines the field by guiding it through all four quadrants. Each quadrant contains a scalar magnetometer, which measures the averaged field modulus over the sensor volume. A uniform field is required since field gradients broaden the magnetometer’s magnetic resonance lines, thus, causing a degradation in sensitivity [16]. The coil was designed using the magnetic scalar potential \( \Phi_M \) [17], [18]. In a currentless region, the magnetic field can be expressed as the gradient of a scalar potential \( \Phi_M \)

\[
\vec{H} = -\nabla \Phi_M. \tag{1}
\]

In this method, we first define a region representing the coil and then apply flux boundary conditions as demonstrated in Fig.2. The behavior of \( \Phi_M \) can be determined by solving the Laplace equation

\[
\nabla^2 \Phi_M = 0 \tag{2}
\]

for the appropriate set of boundary conditions. The solution is shown on the same figure in terms of isopotentials of \( \Phi_M \). Since \( \vec{H} \) is always perpendicular to the isopotentials of \( \Phi_M \), it can already be seen that the field will be quite uniform in each quadrant.

Next, we simulate the magnetic field produced by this coil. For this, each isopotential is interpreted as a single rectangular current loop. For the present case, this results in a cubic coil of which Fig.2 is the top view. To simulate the behavior of the magnetic field, the Biot-Savart law formulated for a straight wire segment was used [19]

\[
\vec{H} = \frac{I}{4\pi} \vec{R}_i \times \vec{R}_f \frac{R_i + R_f}{R_i R_f (\vec{R}_i \cdot \vec{R}_f + \vec{R}_i \cdot \vec{R}_f)}, \tag{3}
\]

where \( \vec{R}_i(f) = \vec{r}_i - \vec{r}_i(f) \) is the vector from the segment initial (final) point \( \vec{r}_i(f) \) to the observation point \( \vec{r} \). A current loop can then be simulated by composing it of four such wire segments. A Python program was written to simulate the field produced by the entire coil geometry.

B. Simulations

The following simulation results describe a cubic coil with dimensions \( a_o = 250 \) mm and \( a_i = 1 \) mm, as defined in Fig.2. The size of the coil was chosen to fit a 70 mm diameter magnetometer in each quadrant, as shown in Fig.1. Each quadrant consists of 50 current loops and the applied current is 100 mA.

The simulations used a planar region of interest (ROI) in one of the quadrants of the coil, see Fig.2, where field values were evaluated on a grid of 100 by 100 points. Only values of the main field component, hereafter \( H \), were used for uniformity characterizations. The transverse components are several orders of magnitude smaller than the longitudinal component. The values for \( H \) were then normalized to the field value at the center of the ROI, \( H_c \)

\[
\eta = \frac{H - H_c}{H_c}. \tag{4}
\]

The result is shown as a contour plot in Fig.3. Most of the points are distributed narrowly around \( \eta = 0 \). In order to characterize the uniformity of the field in the ROI, the interquartile range (IQR) of the \( 10^4 \) values for \( \eta \) was calculated. The IQR is more robust to outliers, which allows it to cope with the edge effects in Fig.3. The value \( \eta_{IQR} \) will be used to characterize the field uniformity in the ROI.

The most important technique for high field uniformity is to properly connect individual current loops. The most uniform field is reached with disconnected individual loops. A simple but realistic case would be to connect the loops at the outer boundary of the coil, the solid black line in Fig.2. This leads to a residual current loop, which follows the mentioned boundary. This can be avoided by connecting the current loops along the dashed boundary in Fig.2. There, the current of one quadrant flows outwards, whereas the current of the neighboring quadrant flows inward. This leads to a compensation of both...
perturbations and the net effect is reduced. We extended the simulations by calculating $\eta_{QR}$ as a function of the height $h$ of the ROI in the coil. The values of $H_c$, used to calculate $\eta$, have a very uniform dependence on the height $h$. Thus, Fig.4 shows the field uniformity in each quadrant. One clearly sees that a residual current loop ruins the performance of the coil. Connecting current loops along the inner boundaries of the quadrants leads to no residual current loop, resulting in an order of magnitude better uniformity.

III. Prototype

In order to verify the uniformity of this coil design, a prototype was built, see Fig.5. Three different types of PCB panels were used to build it. A total of eight triangular “top panels” form the top and bottom planes of the coil. Four “center panels” were placed between the quadrants. These panels implement the connections between the current loops, see Fig.5b. Finally four “front panels” were connected to the rest of the coil via non-magnetic PCB headers (Molex KK4455 Series). The equidistant wires are 3 mm wide and 35 $\mu$m thick, yielding a total resistivity of 50 $\Omega$ for the entire coil. Each quadrant has 50 current loops, which yields a coil constant $c_B = 249.4\frac{\mu\text{T}}{\text{mA}}$. We shall from here on refer to the magnetic flux density $B$, which is the quantity that our magnetometers measure.

This coil was tested in a 4-layer mu-metal shield, which is the quantity that our magnetometers measure. This is the author’s version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication. The final version of record is available at http://dx.doi.org/10.1109/LMAG.2017.2701771.
Fig. 6. Gradiometer locations. For a horizontal gradiometer, the dashed circles represent sensor 1, reading $B_1$, and the solid circles represent sensor 2, reading $B_2$. For a vertical gradiometer, the thick circles at the bottom represent sensor 1 and the thin circles on top represent sensor 2. Thus measurements were made for 3 horizontal and 2 vertical configurations.

The reproducibility of the measurements was estimated via the standard deviation of the 8 values for $s_{xy}$, given in parenthesis in Fig.7. All $s_{xy}$ are at the sub $10^{-3}$ level of uniformity over the central volume of the $\alpha$ quadrant. Alternatively, these measurements may be represented in terms of the coil constant, in nT/mA, for each individual sensor. In order to better compare the values, we set the current such that the average reading of all six sensors is 1000 nT, i.e. for I = 4.010 mA. Each sensor records a magnetic flux density value, which is slightly different from the 1000 nT, see Fig.8. The variations are on the sub-nT level for a flux density of 1000 nT. This can again be interpreted as a sub $10^{-3}$ uniformity over the central volume of the $\alpha$ quadrant. These results, as well as the understanding of the working principle of the coil, make it reasonable to assume a similar uniformity in all four quadrants.

The simulation case, which is closest to the measurements, is the “oblique connections” case shown in Fig.4 with the wire paths shown in Fig.5b. However, building the prototype has left some small misalignments between the PCBs, which lead to an imperfect wire pattern compared to Fig.2. This could explain the worse uniformity and the flux density variations are on the sub-nT level for a flux density of 1000 nT. The coil constant of each individual sensor differs by the amount of the coil constant for that sensor. In Fig.7 and 8, the left side represents the $s_{x}$, and the right side the $s_{y}$. These results, as well as the understanding of the working principle of the coil, make it reasonable to assume a similar uniformity in all four quadrants.

The fringes outside of our prototype were measured with fluxgate sensors. A total of four fluxgate sensors were mounted outside the coil. This makes it a viable solution for many applications which require uniform magnetic fields at sub $10^{-3}$ level.

Fig. 8. Coil constant uniformity. Set the average reading of all six sensors to be 1000 nT. The coil constant of each individual sensor differs by the amount shown in each circle, representing a CsM. The values in parenthesis are the standard deviation of the coil constant for that sensor.

IV. CONCLUSION

The presented field confining coil is a simple PCB structure, which uses PCB headers as connectors to open and close the coil. This makes it a viable solution for many applications which require uniform magnetic fields at sub $10^{-3}$ level.

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