A compact magnet design to create low-gradient magnetic field in the presence of magnetic shielding

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Abstract

Magnetically induced Faraday rotation or so called gyromagnetic Faraday effect is significantly weaker, up to leading order, than its electric counterpart, thus requires extremely uniform magnetic field ($\nabla_z B_z < 0.08\% B_z$, $B_z \simeq 25\ G$). With the help of COMSOL simulations and the method of magnetic scalar potential, we were able to produce such uniform magnetic field in the presence of magnetic shielding in a very compact way, and hence exploring future applications for precision measurements.

The Faraday Effect

- The Faraday effect (FE) describes a **rotation of linearly polarized light** through a medium in a magnetic field along the direction of light propagation.

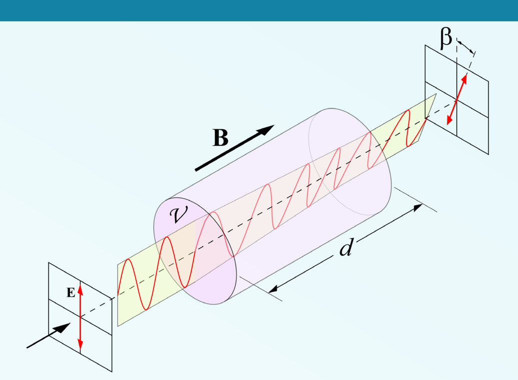

Figure 1:Polarization rotation due to the Faraday effect.

- The gyromagnetic Faraday effect is an optical rotation that is generated solely from a magnetic interaction with an electromagnetic wave.
- FE offers a unique method to monitor spin polarized targets that unlike electric Faraday effect, it's independent of the frequency of electromagnetic wave.

The Experiment

- In 2017, our group conducted several detailed experiments aimed on measuring the small magnetic Faraday effect from polarized ^3He targets using a triple modulation technique with a spin exchange optical pumping scheme.
- Losses of polarization per flip through constant spin flips via NMR caused by large field gradients.
- Though the ^3He spins are flipped via NMR Adiabatic Fast Passage (AFP) with an oscillating transverse $\vec{B}$-field, cell dependent AFP losses also partially contributed from static magnetic field gradients.

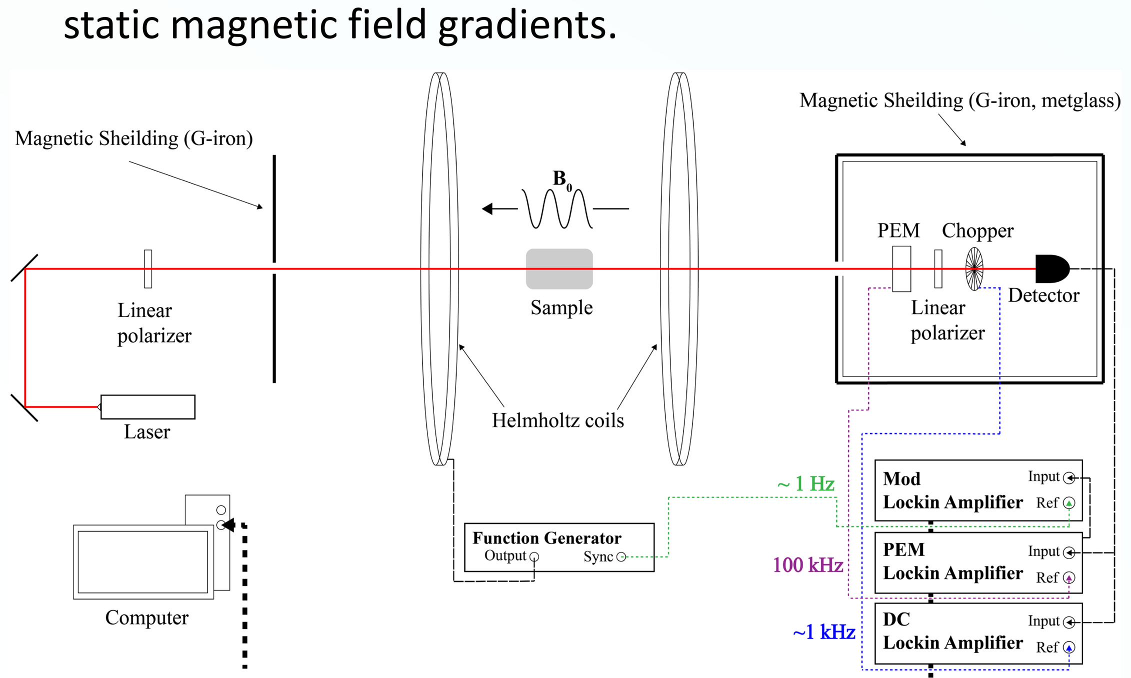

Figure 2: Schematic diagram of the triple modulation setup. Magnetic shielding prevents the field from affecting the polarizing optics or the analyzing optics. The analyzing optical elements consist of the PEM, analyzer(final linear polarizer), optical chopper, and the photo-detector.

Prototype Design: The Method of Magnetic Scalar Potential

- Suppose we want **a uniform magnetic field ($B_z \simeq 25\ G$, $\nabla_z B_z < 20\ \mathrm{mG/cm}$) within a target volume ($15\ cm \times 15\ cm \times 32\ cm$), and we add a layer of soft iron (low-carbon steel) with open ends** along z-axis outside the target volume to shield the static magnetic field from ambient field such as earth magnetic field.
- The method utilizes **surface current distributions** that enclose our current-free target region, thus a magnetic scalar potential U can be constructed through

$$\vec{H}(\vec{r}) = -\vec{\nabla} U(\vec{r})$$

- With the help of **COMSOL Multiphysics** (FEA software), we were able to construct physics environment with well defined boundary conditions to simulate our physics environment.
- The simulation consists of two parts: 1) The target region inside the shielding with boundary condition **$B_z = 25\ G$ normal to the two end surfaces**; 2) The outside region where most **magnetic flux is confined within the shielding** sheets. (see below left)

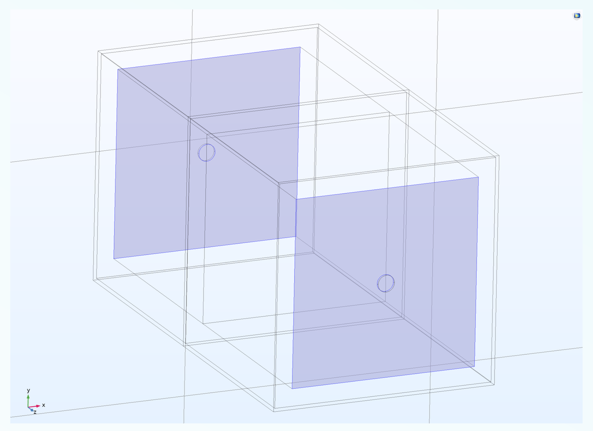

Figure 3: Transparent 3D model with two blue faces defining the boundary conditions.

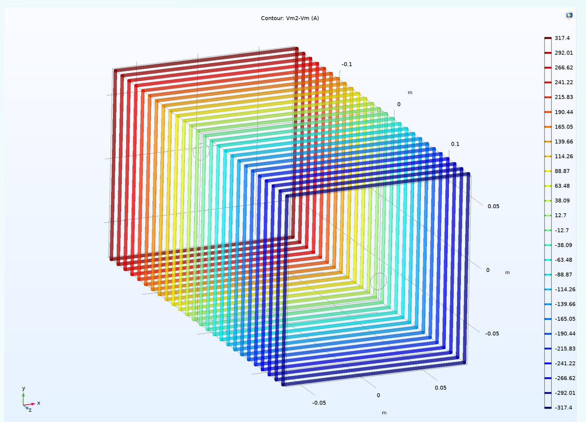

Figure 4: Plot of isocontours represent the physical locations of the coils.

- A set of discrete isocontours of closed loops represent multiples of **equipotential surfaces** that differs by a constant amount ΔU.
- Combining continuity conditions and surface current density we obtain the expression for actual carried current

$$\oint (\hat{n} \times \vec{K}) \cdot d\vec{r} = -\oint \vec{\nabla}(\Delta U) \cdot d\vec{r} = I$$

i.e.

$$I = -\Delta U$$

- The physical significance of ΔU is of the greatest importance, once **the number of isocontours is fixed**, for each value of ΔU there corresponds a **unique configuration of isocontours over the surface of target region.**
- **There always exists a certain value of ΔU such that the length where $\nabla_z B_z = 0$ along z-axis is maximized.**
- **Rebuilding the coils at the exact locations of those isocontours with constant current I**, this guarantees the distribution of the extracted contours lines is always linear.
- **The image field** generated by the magnetic shielding sheets reduces the change of rate of gradients in the central region while smoothen out the overall field distribution and increases stability.

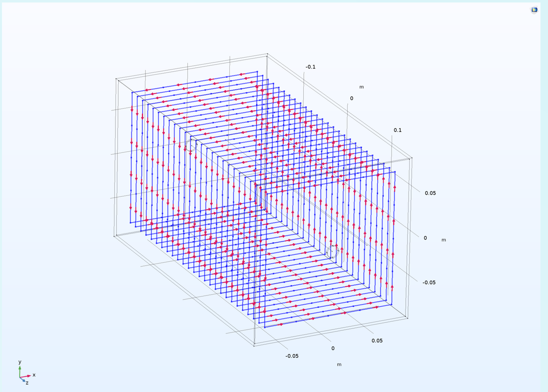

Figure 5: Reconstruction of the coils at the exact locations of isocontours.

- **The coil locations near the two end faces** play an essential role in determining the shape of field distribution in the central region.

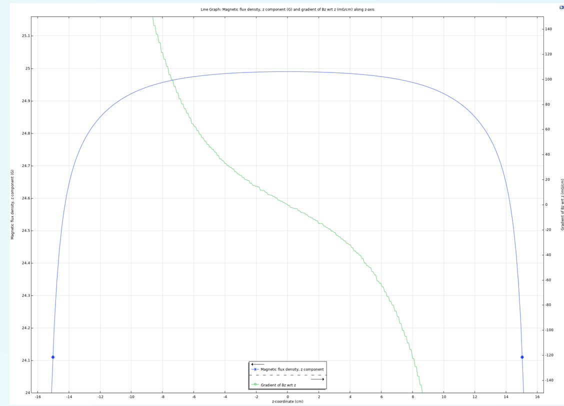

Figure 6: Simulated distribution of B_z and $\nabla_z B_z$ for ΔU=25.34 A

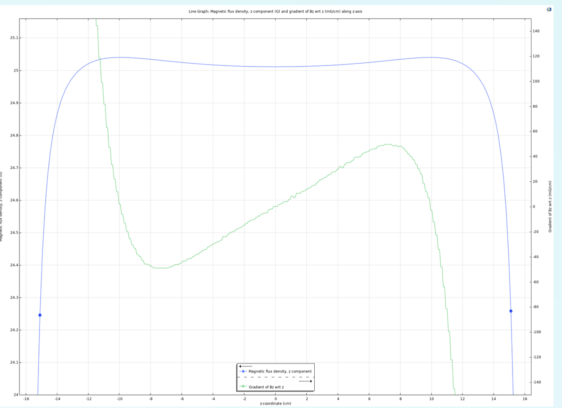

Figure 7: Simulated distribution of B_z and $\nabla_z B_z$ for ΔU=25.45 A

- After locating the exact value of ΔU we need for optimum field distribution, we carefully **designed the physical grooves on polycarbonate sheets to guide the coils.**

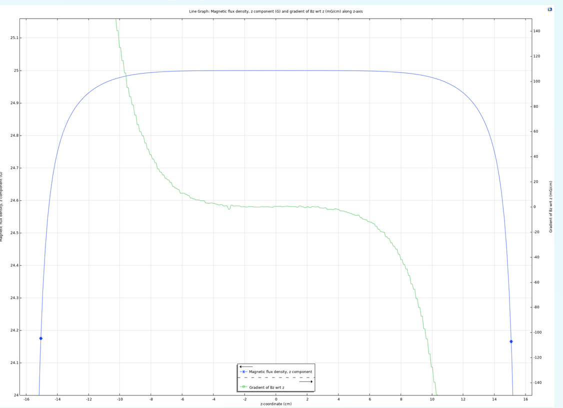

Figure 8: Simulated distribution of B_z and $\nabla_z B_z$ for ΔU=25.392 A

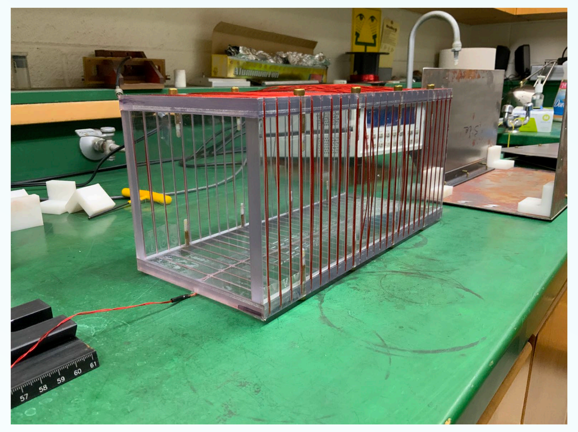

Figure 9: Prototype coils without shielding (after the test runs).

Figure 10: Prototype coils inside shielding ready to test.

Results

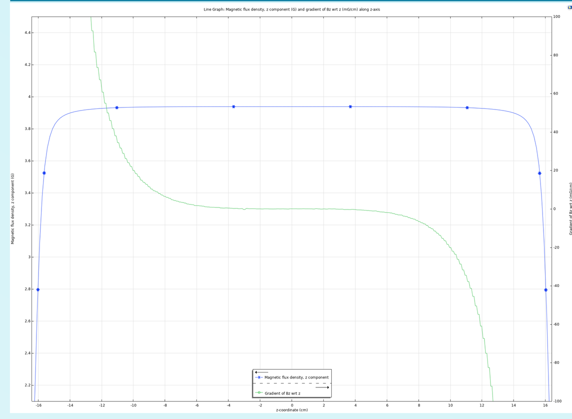

Figure 11: Simulated distribution of B_z with $I = 4\ A$.

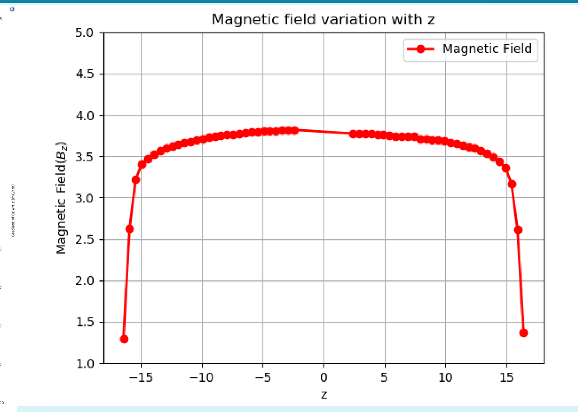

Figure 12: Measured distribution of B_z with $I = 4.\ A$.

- Static magnetic field was successfully measured along z-axis, however the **measurement was performed at $I = 4\ A$ because the box gets to $\sim 80°C$ inside** to reach $B_z = 25\ G$.
- The actual field distribution has a **$\sim 0.12\ G$ offset** in comparison to the simulated result.

Systematic Uncertainties

1. Error in fixing **axial probe angle** while mapping the field: the length of axial hall probe is too short and there is a difference in angle θ while mapping the field from two sides of the box ($\theta > 5°$).
2. Errors from the **temperature change** between the zero Gauss chamber and the prototype box: hall probes are extremely sensitive to temperature changes ($\sim \pm 20\ mG/0.1°C$).
3. **Position of hall probe** that mounted to a Dovetail optical rail: $\sim \pm 0.5\ mm$.

Summary

- The magnetic field measurement was successfully completed in August 3, 2021.
- The measured field gradient is less than $\sim 10\ mG/cm$ along z-axis at a $12\ cm$ long central region which satisfies our goal ($\nabla_z B_z < 20\ mG/cm$).
- According to simulated results, the uniform region is even longer when off-axis ($\sim 4\ cm$ below z-axis).

References & Acknowledgement

[1] Crawford, C. B. "The physical meaning of the magnetic scalar potential, and how to use it to design an electromagnet." *arXiv preprint arXiv:2012.00800* (2020).

[2] Abney, Joshua. "Studies of Magnetically Induced Faraday Rotation by Polarized Helium-3 Atoms." (2018).

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