DESIGN OF BESPOKE MERRITT-BRAUNBECK COILS WITH IMPROVED OPTICAL ACCESS FOR QUANTUM SENSING

Introduction

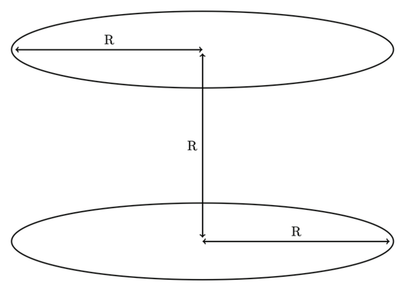
Magnetic fields play an indispensable role in quantum mechanics.[1] However, generating homogenous fields requires stable environments, and stray signals can greatly skew results.[2]

Most geometries are constrained by its range of optical access due to bulky objects, hence spatially restricting potential measurements.[3]

Main objective: to develop a bespoke coil system to generate homogenous magnetic fields, mitigate background noise and improve the range of optical access for experiments.

Preliminary Analysis

First, we analyse magnetic flux densities of existing coil systems using the Biot-Savart law, alongside field homogeneity through computational simulations. We simulate each system using the Magpylib library equipped with a filamentary wire of 1A, and find the proportion of length that falls within 99% of the magnetic flux at the origin.

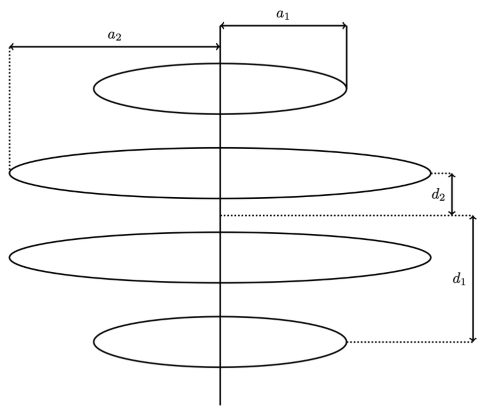


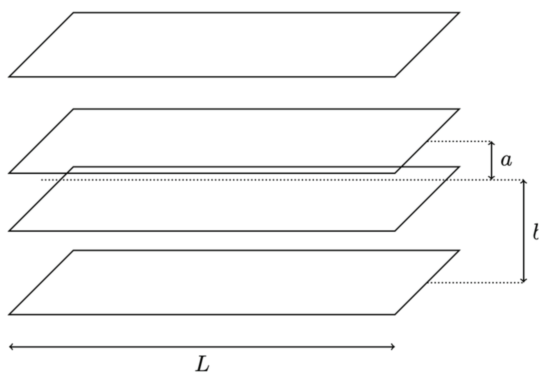
Helmholtz coils

- one pair of circular coils carrying equal ampere-turns (nI)
- coil radius (R) equal to coil separation
- magnetic flux of $0.7155\mu_0 nI/R$ at the origin
- radial homogeneity of 37.78%
- axial homogeneity of 31.38%

Braunbeck coils

- two differently-sized pairs of circular coils carrying equal ampere-turns (nI)
- specific ratios defining radii and separation[4]
- magnetic flux of **$1.28860\mu_0 nI/a_2$** at the origin
- radial homogeneity of 61.10%
- axial homogeneity of 213.74%





Merritt coils

- two pairs of equal-length (L) square coils carrying different ampere-turns
- specific ratios define separation and ampere-turns[5]
- magnetic flux of $0.71428\mu_0 nI/(L/2)$ at the origin
- radial homogeneity of **64.53%**
- axial homogeneity of **281.42%**

Methodology

We investigate a combination between Braunbeck and Merritt systems (**Merritt-Braunbeck system**) due to the Braunbeck's high magnetic flux and the Merritt's extensive homogenous and large range of optical access. We use Scipy's optimisation library equipped with the Nelder-Mead algorithm[6] to numerically determine the Merritt-Braunbeck system's dimensions, choosing to maximise radial homogeneity. The following ratios are obtained.

$$\frac{a_2}{a_1} = 1.40, \quad \frac{d_1}{a_1} = 0.67889, \quad \frac{d_2}{a_1} = 0.19856$$

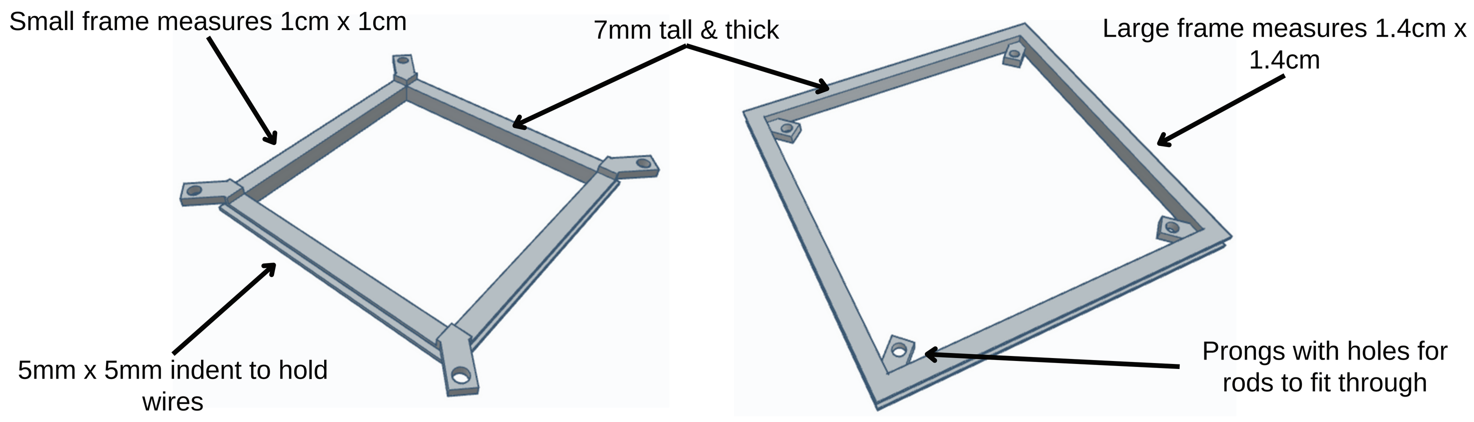


Figure 1. *3D models of the* ***(a)*** *smaller frame and* ***(b)*** *the larger frame.*

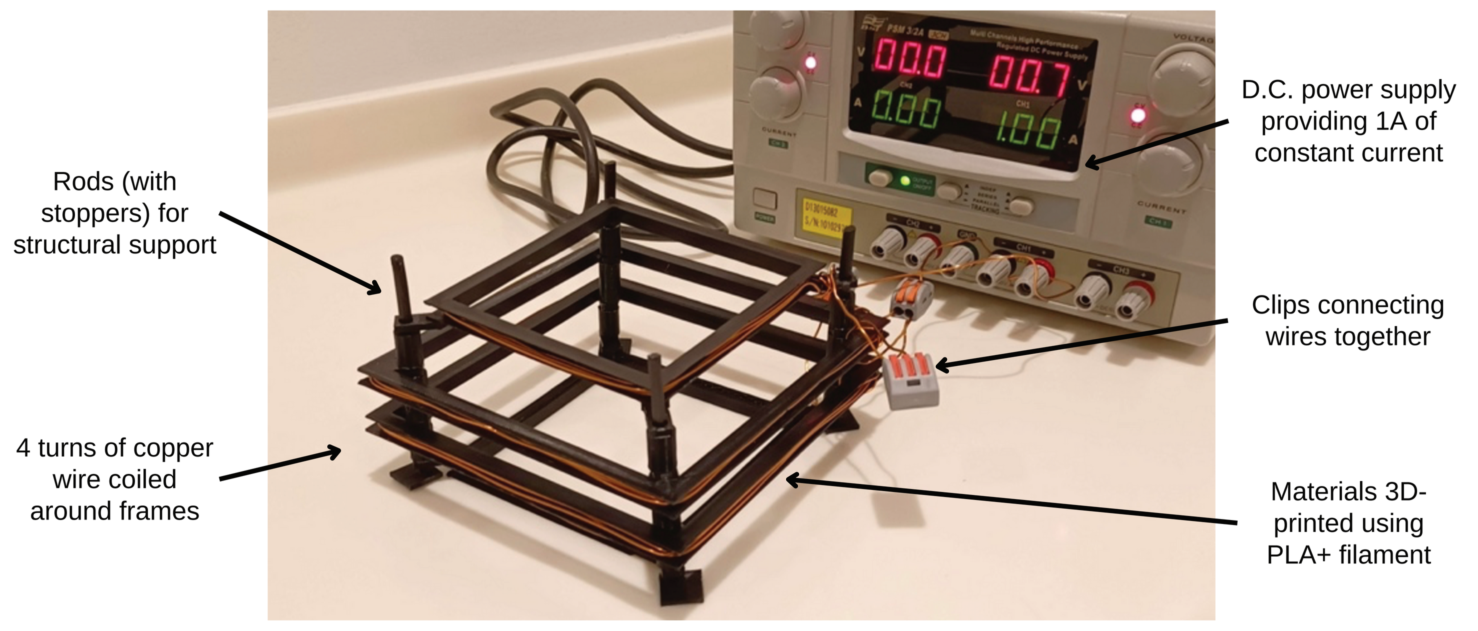


Figure 2. *The physical coiled frames, complete with rods, stoppers, and clips, connected to a D.C. supply.*

Results & Discussion

By the Biot-Savart law, the Merritt-Braunbeck system gives an origin magnetic flux of **$1.65597\mu_0 nI/a_2$.**

Computational and simulated results using the Magpylib library illustrating the field distribution (86.07% for radial and 127.02% for axial) show that the Merritt-Braunbeck configuration possesses two-fold rotational symmetry.

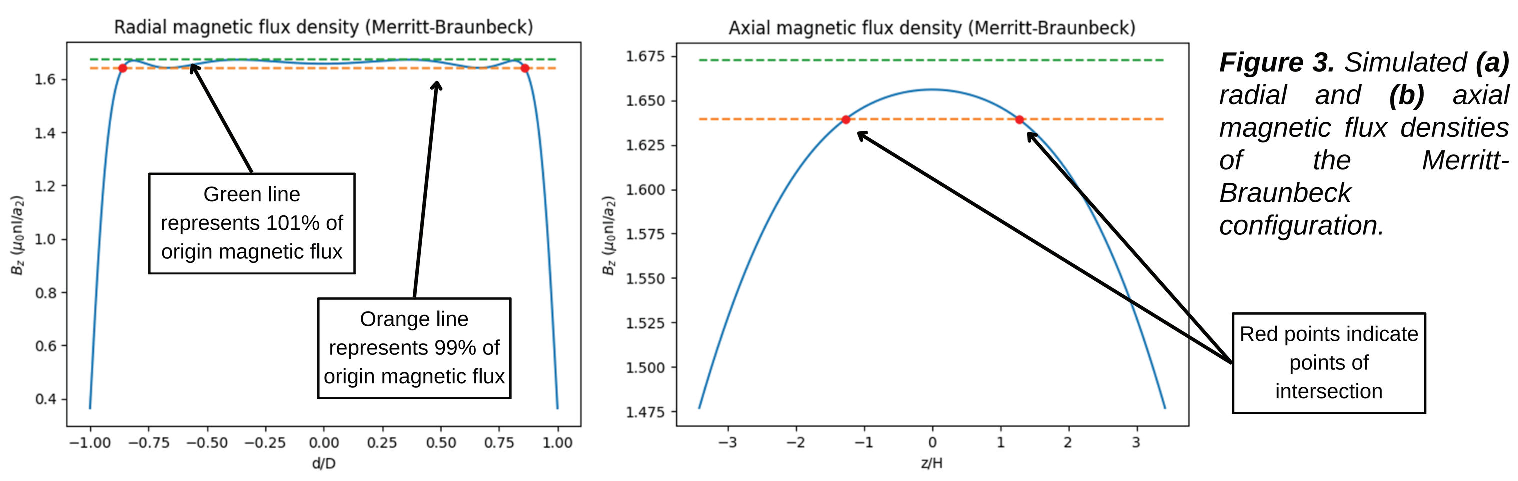


Figure 3. *Simulated* ***(a)*** *radial and* ***(b)*** *axial magnetic flux densities of the Merritt-Braunbeck configuration.*

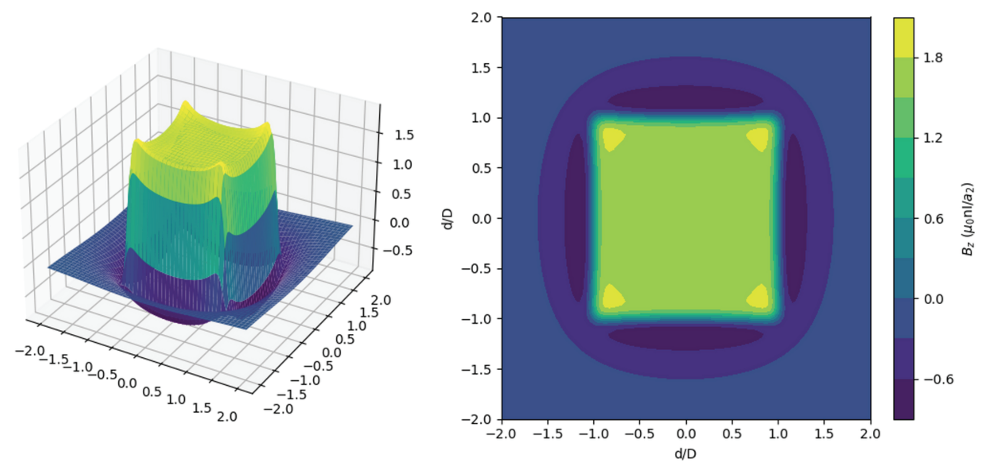
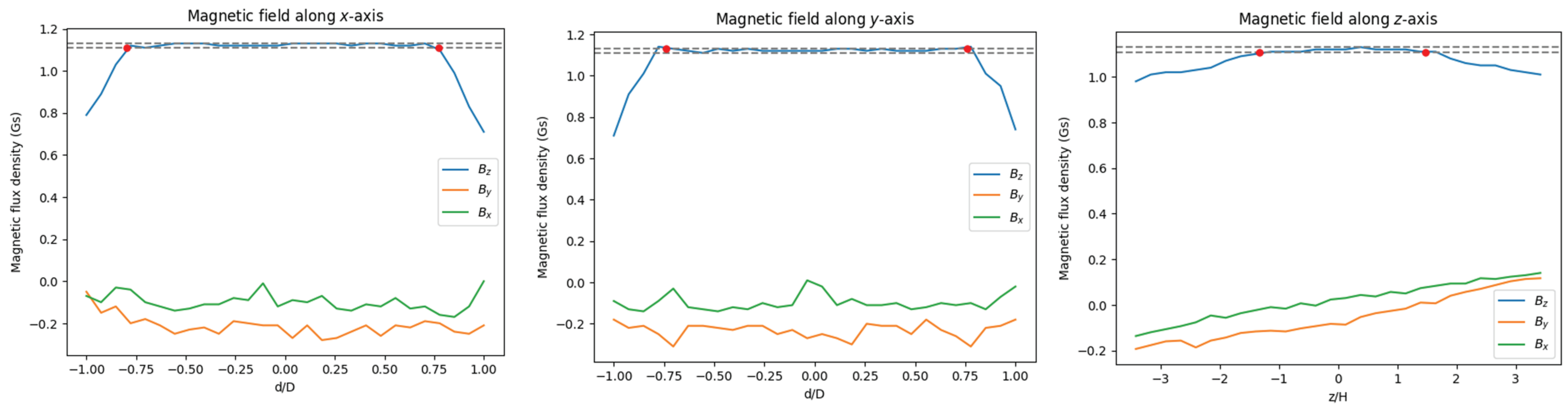


Figure 4. *Simulated* ***(a)*** *3D surface plot and* ***(b)*** *2D contour plot depicting magnetic flux densities along the radial plane.*



Measurements using a triple-axis gaussmeter taken at 5mm intervals show that the origin Bz value is approximately 1.12Gs. The Bx and By values fluctuate randomly throughout the radial plane, but increases along the axial plane. Homogenous lengths span 78.5%, 77.6%, and 150.3% of the x, y, and z axes respectively, indicating the Merritt-Braunbeck system's superiority in magnetic flux density and radial homogeneity.

Figure 5. *The magnetic flux densities generated by the Merritt-Braunbeck coils across* ***(a)*** *the x-axis,* ***(b)*** *the y-axis, and* ***(c)*** *the z-axis.*

Conclusion

We demonstrate that the Merritt-Braunbeck system offers a 231.4%, 128.5%, and 231.8% **increase in magnetic flux density** at the origin, and a 203.6%, 127.3% and 119.7% **increase in the radial homogeneity length** in comparison to the Helmholtz, Braunbeck, and Merritt coil systems respectively, **demonstrating superiority** in these aspects. However, axial homogeneity is compromised, possessing subpar 65.8% and 50.2% proportions of the Braunbeck and Merritt systems. Nonetheless, this holds **significant promise for a spectrum of quantum-related applications**, enabling the integration of quantum setups into compact systems.

Future research could

- explore alternative materials with sturdier mechanical properties for construction
- refine coiling processes via industrial means to achieve neater structures
- conduct extensive research on effects of different coiling methods with regards to field homogeneity and strength

References

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