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Magnetic Shields for QT in Space

Executive Summary Report

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This executive summary report describes the activity results of a novel hybrid magnetic shielding system that uses both passive and active cancelation. The design and simulations used, along with the characterisation and measurements taken on the optimised system, are summarised in this document, and described in more detail in the Final Report.

This activity was divided in two main work packages: study of optimisation and magnetic shield prototype. The study of optimisation work package looked at the current limitations, simulating the already existing magnetic shield system and exploring ways of improving this system. The magnetic shield prototype work package exploited the outcomes of the previous work package and converted it into a new magnetic shielding design ready for manufacture. At the end of this, both systems were experimentally characterised and the SWaP improvements quantified.

1 BACKGROUND

The continuous improvement in the sensitivity of devices, specifically sensing devices, is constantly reaching limits due to signal-to-noise ratio. In the case of magnetic field sensing, this is due to background magnetic fields. Current state-of-the-art technology offers a residual field of < 130 pT [RD01]. However, this work is based on an ideal shield with no SWaP restrictions. The geometry pattern greatly affects the shielding efficiency. For long baseline atom interferometry, the current state-of-the-art worsens, with residual fields below 4 nT and longitudinal inhomogeneities below 2.5 nT/m over 8 m distance [RD02]. Inside a space mission, the MAIUS-1 mission achieved a factor 1,000 reduction in magnetic field with a relatively heavy three-layer shield [RD03]. On a smaller scale, shields have been developed for atomic clocks in atom chips, achieving only a shielding factor of 10 in one of the directions [RD04]. Recently, several groups have started developing hybrid shields, combining passive and active magnetic field cancellation, paving the way to lighter shield [RD05].

2 STUDY OF OPTIMISATION

When designing passive magnetic field cancellation systems, materials are crucial to the shielding performance. Changes in the material affect its magnetic permeability. However, not only the permeability matters, as every material has a saturation intensity that, if reached, will make the material transparent to magnetic field and alter its permeability. Mu-metal is an alloy that is commonly used for magnetic shielding. It is made of 77% nickel, 16% iron, 5% copper and 2% molybdenum. This material is a good balance of permeability versus saturation intensity for most applications. If a larger saturation intensity is required, the alloy would contain a larger percentage of iron, for example for Supra50™, which is approximately 48% nickel and 52% iron. Iron has higher saturation intensity and so it is the preferred choice to shield larger fields. Depending on the application, different alloys could be used for different layers of the system, with the outer layer having a higher saturation intensity, and inner layers a larger permeability. It is important to remember that the vacuum chamber itself already acts as a magnetic shield.

It is also important to note that, for maximum performance, annealing in a hydrogen atmosphere is required, as this process ensures that the magnetic field domains are randomised, effectively de-magnetising the material.

Another very important aspect of magnetic shielding is the geometry. Minor changes in geometry can affect the way the field lines are re-directed by the material. The ideal magnetic shield would be a sphere, and any changes to this ideal, such as sharp edges, would result in a decrease in performance. It is essential to remember that gaps and holes are more relevant than minor geometrical details, as these break continuity in the shielding material.

A downside of passive shielding systems is that the permeability degrades over time, and this degradation dramatically accelerates with other factors, such as vibrations, shock, temperature changes, etcetera. These external factors are especially present in space applications, given the environment during launch and orbit.

All simulations' results agreed with the extensive literature available.

3 MAGNETIC SHIELD PROTOTYPE

Active cancellation could help solve some of the issues presented in this report. The basic principle is to create a system that generates a field that is identical to the one that we want to cancel, but in opposite direction. Conventional coils do a relatively good job at this, however, the field generated is not homogenous. New techniques [RD07] are now aiming at improving this homogeneity. Coil designs can be optimised to maximise power efficiency, field fidelity and/or size, with promising weight reductions, as well as the capability of increasing the cancellation region when compared to passive shielding. Holes or gaps in the system can be taken into account during the design process to minimise the effect these may have on shielding performance.

Additionally, changes in external magnetic field can be accounted for to maintain a constant internal field, rather than the constant shielding factor given by passive shielding. This system can also be used to generate any bias field necessary, such as the one used for defining the quantisation axis of the atoms in atom interferometry. There is also no need for degaussing of metal structures, which results in lower power consumption overall, as there are no long-term drifts in the magnetic properties or magnetization of shield after ECSS testing. These active cancellation structures are designed such that they can be mounted before assembly, as they can withstand bake out temperatures of 200°C.

The aim on this project was to replace the outer, and heavier, layer of the passive system with an active cancellation coil pattern. Coil patterns were designed using the theoretical model presented in [RD07].

The active coil part of the system was procured from the University of Nottingham. It was designed and manufactured following the requirements from RAL Space, utilizing copper wires wound around grooves in a custom 3D-printed cylinder. The objective of this system is to minimize uniform magnetic fields in the passive mu-metal magnetic shield of a candidate space CAI-based gravity gradiometer. The integrated coil system (see Figure 3-1) enables the external shielding layer of the shield to be removed to reduce weight and volume while maintaining magnetic shielding performance. The experimental setup employed for this characterization is shown in Figure 3-2.

Figure 3-1: The wound coil former is positioned within the first section of the internal passive shield (below), which is subsequently sealed with the second section of the shield (above) prior to testing.

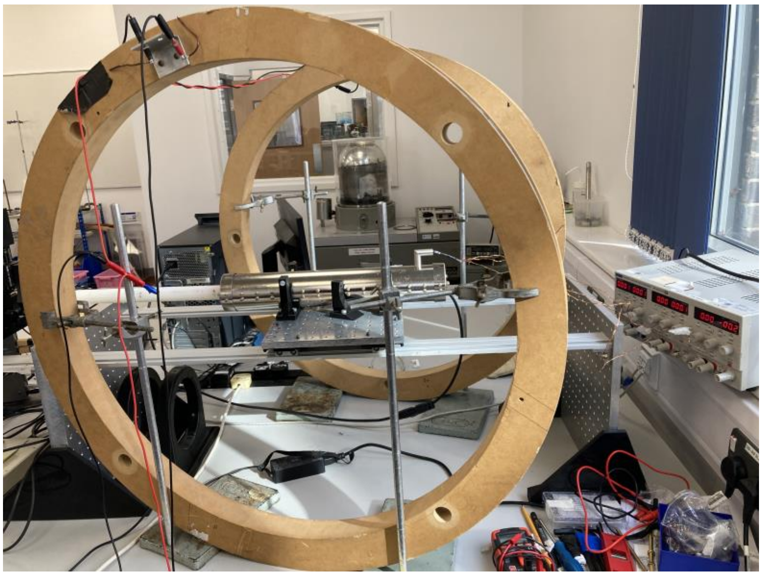

Figure 3-2: The magnetic field along the axis of the shield (grey) is measured under different conditions. These conditions include the application of currents to the coils inside the shield, the application of currents to the large circular external coils (brown), and the absence of any currents.

4 CONCLUSION

The experimental results show that the one-layer passive shield and integrated coil system effectively reduces applied fields by a factor of 18000 over the central region of the inner shield axis. This represents a 120% greater reduction compared to the passive two-layer shield. Additionally, the one-layer passive shield and integrated coil system is 57% lighter and requires a

4.8 times smaller volume than the passive two-layer shield. The power consumption of this system is extremely low, less than 1 mW, and it also provides the opportunity of a design that generates the bias field necessary for interferometry within the same coil system, potentially resulting in no power consumption increase when compared to traditional systems.

Although the results exhibit substantial promise, it is crucial to consider the necessity of control systems, comprising of miniaturised and robust current drivers and reference magnetometers, for active coil systems to function dynamically. However, as the size of the shield increases, it is expected that the weight of control systems would not increase proportionally. Thus, these systems may be suitable for larger missions. Furthermore, if the magnetic shielding system is utilized for atomic experiments, it may be feasible to directly map the magnetic field utilizing the atomic system, eliminating the requirement for a reference magnetometer, e.g. by measuring Zeeman splitting [RD10].

Additionally, further experiments may scrutinize the shielding system in other contexts. For instance, the shielding effectiveness may alter as a result of the applied field magnitude [RD11] and must be evaluated in environments that are similar to the background field profile that a system is expected to encounter in space [RD12]. The potential of the system to generate highly uniform bias fields for atomic experiments should also be examined further.

Reference documents

The following documents, although not a part of this document, amplify or classify its contents.

IR No	Title
RD01	Sun, Z., Fierlinger, P., Han, J., Li, L., Liu, T., Schnabel, A., ... & Voigt, J. (2020). Limits of low magnetic field environments in magnetic shields. *IEEE Transactions on Industrial Electronics*, *68*(6), 5385-5395.
RD02	Wodey, E., Tell, D., Rasel, E. M., Schlippert, D., Baur, R., Kissling, U., ... & Fierlinger, P. (2020). A scalable high-performance magnetic shield for very long baseline atom interferometry. *Review of Scientific Instruments*, *91*(3), 035117.
RD03	Kubelka-Lange, A., Herrmann, S., Grosse, J., Lämmerzahl, C., Rasel, E. M., & Braxmaier, C. (2016). A three-layer magnetic shielding for the MAIUS-1 mission on a sounding rocket. *Review of Scientific Instruments*, *87*(6), 063101.
RD04	Hong, H. G., Park, J., Kim, T. H., Kim, H. Y., Park, S. E., Lee, S. B., ... & Kwon, T. Y. (2020). Magnetic shield integration for a chip-scale atomic clock. *Applied Physics Express*, *13*(10), 106504.
RD05	Packer, M., Hobson, P. J., Holmes, N., Leggett, J., Glover, P., Brookes, M. J., ... & Fromhold, T. M. (2021). Planar Coil Optimization in a Magnetically Shielded Cylinder. *arXiv preprint arXiv:2101.01275*.
RD06	O. Carraz, C. Siemes, L. Massotti, R. Haagmans, P. Silvestrin, "A spaceborne gravity gradiometer concept based on cold atom interferometers for measuring Earth's gravity field", Microgravity Sci. Technol. (2014), 26: 139-145
RD07	M. Packer et al. "Optimal Inverse Design of Magnetic Field Profiles in a Magnetically Shielded Cylinder". In: Physical Review Applied 14 (5 Nov. 2020), p. 054004.
RD08	P. J. Hobson et al. "Bespoke magnetic field design for a magnetically shielded cold atom interferometer". In: Scientific Reports 12.10520 (2022).
RD09	P. J. Hobson et al. "Benchtop magnetic shielding for benchmarking atomic magnetometers". In: arXiv (2022).
RD10	Q.-Q. Hu et al. "Mapping the absolute magnetic field and evaluating the quadratic Zeeman-effect-induced systematic error in an atom interferometer gravimeter". In: Physical Review A 96 (3 Sept. 2017), p. 033414.
RD11	N. Holmes et al. "A lightweight magnetically shielded room with active shielding". In: Scientific Reports 12 (Aug. 2022).
RD12	S. Washburn et al. "Active magnetic radiation shielding system analysis and key technologies". In: Life Sciences in Space Research 4 (2015), pp. 22–34.