# Magnetic field shaping for quantum devices

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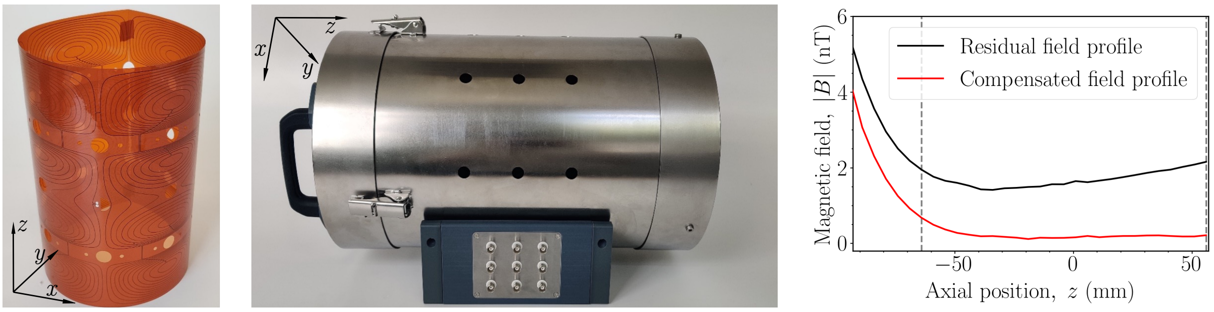

(a)

(b)

(c)

Figure 1: Nine cylindrical flexible printed circuit boards [flex-PCBs; a single board is presented in (a)] are arranged co-axially inside a four-layer mu-metal magnetic shield, as presented in (b). (c) The currents applied to the flex-PCBs are tuned to null residual magnetic variations inside the shield, reducing the mean magnetic field norm, $|B|$, from 1.68 nT to 0.23 nT (effective shielding efficiency, $SE = 2 \times 10^5$) along the $z$-axis of the shield between $z = [-64, 56]$ mm [grey dashed lines]. The field profile as measured using a three-axis QuSpin QZFM atomic magnetometer with [red line] and without [black line] flex-PCB nulling [1].

Advances in the understanding and control of atoms and ions have facilitated the development of quantum devices, from quantum computers and clocks to miniaturised atomic magnetometers for healthcare and atom interferometers for gravity sensing. These devices operate with unprecedented accuracy, speed, and precision, but their real-world performance may be limited by magnetic field noise. Traditionally, this is mitigated by enclosing magnetically-sensitive components with sheets of passive magnetic shielding. However, this shielding adds weight and size, may magnetise under applied fields, and distorts the fields generated by internal active current-carrying structures which are required to confine atoms and generate a quantisation axis.

To overcome this, here we present theoretical techniques [2–4] to shape magnetic fields specifically for quantum devices. We include the electromagnetic coupling to passive shields directly into the design of active current-carrying networks, creating *hybrid* shields. Using advanced manufacturing methods like 3D-printing and flexible printed circuits, we design, build, and demonstrate small hybrid shields for benchmarking atomic magnetometers [1], minimising the quadratic Zeeman effect in atom interferometers [5], and for housing superconducting qubits. We utilise this technology in a commercially-available, laboratory bench-sized, hybrid shield, as displayed in Fig. 1, which actively nulls the geomagnetic field by a factor of $2 \times 10^5$ along its axis. We also provide new theoretical techniques on future magnetic field shaping systems, prioritising size, weight, power, cost, and durability requirements whilst operating such systems in less magnetically ideal settings outside laboratory environments.

[1] P. J. Hobson, N. Holmes, P. Patel, et al., “Benchtop magnetic shielding for benchmarking atomic magnetometers”, IEEE Transactions on Instrumentation and Measurement **72**, 1–9 (2023).

[2] M. Packer, P. J. Hobson, N. Holmes, et al., “Optimal inverse design of magnetic field profiles in a magnetically shielded cylinder”, Physical Review Applied **14**, 054004 (2020).

[3] M. Packer, P. J. Hobson, N. Holmes, et al., “Planar coil optimization in a magnetically shielded cylinder”, Physical Review Applied **15**, 064006 (2021).

[4] M. Packer, P. J. Hobson, A. Davis, et al., “Magnetic field design in a cylindrical high-permeability shield: the combination of simple building blocks and a genetic algorithm”, Journal of Applied Physics **131**, 093902 (2022).

[5] P. J. Hobson, J. Vovrosh, B. Stray, et al., “Bespoke magnetic field design for a magnetically shielded cold atom interferometer”, Scientific Reports **12** (2022).