Multi-Layer Transverse Gradient Coils

R. Bowtell1, S. Crozier2, B. Beck1 and S. Blackband3

1University of Nottingham, Nottingham, UK, 2University of Queensland, Brisbane, Queensland, Australia
3University of Florida, Gainesville, Florida, USA

Introduction

Very large magnetic field gradients are required in a variety of NMR experiments. NMR microscopy and pulsed gradient spin echo (PGSE) experiments can particularly benefit from the availability of switchable gradients of more than 10 Tm⁻¹ strength. Access to such gradients is usually limited by the rapid increase in gradient coil resistance (R) with efficiency (η), which results from the reduction in usable wire diameter as the number of turns in a single layer cylindrical gradient coil increases (R ∝ η³). Similar effects occur in coils constructed by cutting wire patterns in conducting layers, because of the loss of conducting material with increasing numbers of cuts. Adopting a multi-layer approach to coil design, in which the coil windings are allowed to spread out in the radial direction, gives a more favourable scaling law, which allows larger gradients to be achieved at a given resistance and power dissipation. Previously we have applied this approach to the generation of axial magnetic field gradients. Here we extend this work to the design and construction of transverse field gradient coils.

Theory

A multi-layer cylindrical coil confined between radii a and b (a < b) can be described by a current distribution j(φ, z). If j has only azimuthal and axial components the magnetic field in the region ρ < a is given by

\[ B_z(ρ, φ, z) = \frac{μ_0}{2π} \int_a^b \int_0^{∞} \frac{ρ'}{ρ} \sum_{m=-∞}^{∞} \int_0^{∞} \frac{dk}{\sigma} j_m^w(ρ', k) e^{i(kz - \phi)} e^{im\phi} \times K_m(kρ') J_m(kρ') \]

where \( j_m^w(ρ, k) \) is the Fourier transform of the azimuthal component of j, with respect to φ and z. The power, P, dissipated by this current distribution is

\[ P = \int_a^b \int_0^{∞} \int_0^{∞} \frac{dk}{\sigma} |j_m^w(ρ, k)|^2 (1 + m^2) k^2 \]

where σ is the electrical conductivity. A similar expression for the inductance, L, has been previously derived. In transverse coils only the terms with m = ± 1 are important.

To design a coil, the current distribution is divided into a number of equally spaced layers and is composed from a number of axial varying harmonics in each layer. An optimal coil can be designed using the above equations by calculating the harmonic weightings in each layer, which together minimise a weighted combination of P, L and the field deviation from linearity, calculated over a grid of points defining the desired homogeneous region. Wire paths for a final coil design can then be calculated from the integral of the current distribution in each layer in the usual manner.

Results

The above methods have been used to design an unscreened transverse gradient coil with 10 mm inner diameter, which gives an internal region within which the field deviates from linearity by less than 5% consisting of a right cylinder of 6.5 mm diameter. The first coil layer was located at a radius of 5.65 mm, and subsequent layers were placed at 0.6 mm intervals in the radius. The desired coil resistance was 1.5 Ω.

Figure 1 shows the calculated variation of the optimum coil efficiency with the number of layers for two different types of coil. The lower curve corresponds to wire wound coils (incorporating a maximum wire diameter of 300 μm). The upper curve corresponds to coils composed of “fingerprint” patterns cut into 300 μm thickness copper, with a 100 μm cut thickness. In both cases it can be seen that significant gains in coil efficiency at fixed resistance can be achieved by increasing the number of layers. The “cut” based coils have higher efficiency than those composed of discrete wires. For both types of coil the inductance increases with the number of layers.

A two-layer, wire-wound, coil has been built to test the feasibility of constructing and operating multi-layer transverse gradient coils. The wire paths for one symmetry-unit of each coil layer are shown overlaid upon one another (1st layer = continuous, 2nd layer = dashed line). The first and second layers carry a total of 56 and 44 turns respectively, of 290 μm diameter copper wire. The first layer was hand-wound onto a guide pattern glued onto a cylindrical surface, which was viewed under a dissection microscope. Wires were tacked in place using cyanoacrylate adhesive and then set in epoxy resin under vacuum. The epoxy was then cured, thus forming the appropriate diameter cylindrical surface for the next layer, which was then wound in the same way as described above. The two layers were then connected together by soldering at the “eye” of each fingerprint, so that no radial space was required for axially running coil connections. The two units thus formed, were connected together in series. The final coil has a resistance of 1.7 Ω and an inductance of 22 μH, both numbers being in good agreement with the calculated values. The efficiency is calculated to be 0.42 Tm⁻¹ A⁻¹.

Conclusion

Multi-layer transverse gradient coils offer improvements in achievable gradient strengths in the regime where performance is limited by the coil resistance. A two-layer prototype coil has been constructed by hand winding. At 30 A current it will generate a gradient of 12 Tm⁻¹, over a homogeneous volume consisting of a 6.5 mm diameter right cylinder. A second, more robust, coil produced by micro-machining grooves is now under construction. Future work will be directed towards using larger numbers of layers and to constructing coils by cutting wirepaths in thin copper layers, both potentially offering a route to higher performance. The latter will also speed up the construction process.

References