Actively Shielded Multi-layer Gradient Coils Optimised for Cooling

J. Leggett1, S. Crozier2, R. Bowtell1

1University of Nottingham, Nottingham, Nottinghamshire, United Kingdom, 2University of Queensland, Brisbane, Queensland, Australia

Very large magnetic field gradients are required in a variety of NMR experiments. Access to such gradients is often limited by the rapid increase in gradient coil resistance with efficiency, resulting from the reduction in conductor cross-section as the number of wires increases. Adopting a multi-layer approach to coil design gives a more favourable scaling. The three-dimensional nature of the resulting current distribution, however, could cause difficulties in cooling the coil’s underlying layers. Here we describe a new method for designing screened multi-layer coils optimised for cooling, which is based on a model of heat flow in the coil.

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 gradients of more than a few Tm⁻¹ strength. Access to such gradients is often limited by the rapid increase in gradient coil resistance with efficiency, resulting from the reduction in conductor cross-section as the number of wires increases. A multi-layer approach to coil design [1], in which the coil windings are allowed to spread out in the radial direction, gives a more favourable scaling law [1], which allows larger gradients to be achieved at a given resistance and power dissipation. However, it is possible that the overlying layers may hinder heat-flow through the coil and give rise to higher localised temperatures than would be encountered in a single-layer coil. Previously we have applied the multi-layer approach to the design of unscreened axial and transverse gradient coils [3] due to we extend this work to the design of actively screened, multi-layer gradient coils optimised for cooling. We have also modelled the coil temperature as a function of current.

Method

The design method that was used is an extension of Turner’s “Target Field Approach” [4]. A current distribution was defined over a number of equally spaced layers, and in each layer was composed of a weighted set of axial Fourier harmonics [5], which are only non-zero over the extent of the coil. A region of interest (ROI) within which a linear field gradient is desired was defined. In previous work [3], a functional composed of a weighted combination of the power dissipation, inductance, deviation of the field from linearity over a set of points within the ROI, and the average deviation of the field from zero over a second set of points located outside the outer layer, was minimised in order to determine the amplitude of each harmonic in each layer. Here, the contribution to the functional by the power dissipated in each layer is given a weighting dictated by its position in the coil, and also by the cooling coefficients of the inner and outer coil surfaces. The weighting function, wᵣ, favours power dissipation in coil layers close to the coil surface and further favours those close to the surface with higher heat transfer coefficient:

\[ wᵣ = \frac{D(r-r_i)\ln(A/A_i)}{(A-A_i)} + \frac{D(r-r_i)\ln(A/A_i)}{(A-A_i)} \],

where \( D(r) \) is the radius of the layer, \( r_i \) and \( r_o \) are the radii of the inner and outer coil surfaces respectively, and \( A \) and \( h \) are the corresponding areas and heat transfer coefficients of the surfaces. The values used for \( h \) represent the total potential to remove heat from the coil surface, and as such include contributions from both convection and radiation. From the temperature dependence of the two mechanisms, \( h \) will not be constant with temperature of the coil. In the operational temperature range, convection will be by far the dominant process, particularly if forced convection or water cooling are used. Having thus calculated the optimum continuous current distribution, a set of wire paths that approximate the current density must be derived. This was achieved in the usual manner using the stream-function of the current density in each layer [4].

This approach was used to design 4-layer x- and z-gradient coils, with 2.3 mm layer spacing and the first layer radius of 9.7 mm. Coils were designed both without and with (C=3, 10) cooling optimisation. For all coils, the internal ROI within which the field deviation from a perfect gradient was less than 5% was defined to be a right-cylinder whose radius and half-length was 0.55 times the first layer radius. The z-coil half-length was constrained to be twice the inner layer radius, while that of the x-coil was four times the inner layer radius. The number of wires for the C=3 weighted z-coil was chosen to give the maximum possible number of turns using 0.32 mm diameter wire. For all other coils the number of wires was adjusted to give the same resistance as the C=3 z-coil, using a wire size such that the wires were just touching in the layer with most turns. An iterative model was then used to predict the coil temperatures. Heat input to each layer of the coil was provided through the ohmic heating effect of the current. This was balanced by conduction of heat through the coil along with heat convection and radiation from the inner and outer coil surfaces. Iterations continued until a steady state was reached. The C=3 z-coil was constructed and temperature sensors were embedded above each layer.

Results and Discussion

Table 1 summarises the performance of the resulting multi-layer coil designs. The average shielding values were calculated by evaluating the ratio of the fields of the screened and unscreened coils over an array of points. Inspection of the distribution of wires across the layers indicates that addition of the screening condition leads to a re-distribution of the relative number of turns in the middle layers of the coil. Adding in the cooling weighting with a higher coefficient at the outer surface can be seen to move even more of the current distribution away from the inner layers, and the effect is more pronounced at higher coefficient ratios. At the same time, the efficiencies are similar, and the inductances rise slightly. However, the shielding is markedly improved. This is due to a higher proportion of the current being moved to the outer layers which provide the screening, hence a more accurate representation of the shielding current is yielded upon discretisation. Fig. 1 shows the variation of the temperature of the innermost (hottest) layer of the z-coil as a function of current under identical cooling conditions, operating with 100% duty cycle. The upper line represents the coil designed without cooling, the middle line is that with C=3, and the lower line is for C=10. Increasing C, which results in more current being placed towards the coil’s more strongly cooled outer surface, leads to a reduction in the coil temperature. The crosses represent experimental measurements made on the real coil operating with naturally convected air-cooling only, and can be seen to agree quite well with the model. If a temperature limit of 80°C is set, then the unweighted coil can be used at a gradient of 0.128 Tm⁻¹, for a 100% duty cycle. In comparison, the C=3 and C=10 weighted coils can be run with progressively higher gradients of 0.130 and 0.146 Tm⁻¹ respectively.

Conclusion

A multi-layer approach allows the design of screened coils exhibiting higher gradient strengths than conventional coils. Cooling is an important parameter for multi-layer coils, and a new method for design of coils with optimal cooling characteristics has been outlined here. A clear benefit of this method is that considerably higher gradient strengths can be used before a given temperature is reached within the coil. A shielded multi-layer coil has been built to verify both its performance and that of the model. We now aim to develop an integrated multi-layer, screened three-axis coil incorporating cooling optimisation.

References


Table 1: Summary of key parameters for shielded (sh) and unshielded (u/sh) coil axial (Z) and transverse (X) multi-layer gradient coils.

<table>
<thead>
<tr>
<th>Method</th>
<th>Average Shielding (T/m/A)</th>
<th>Efficiency (T/m/A)</th>
<th>Inductance (mH)</th>
<th>Resistance (Ω)</th>
<th>No. of wires/layers</th>
<th>Wire dia. (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=1 top line</td>
<td>N/A</td>
<td>4.869%</td>
<td>2.287%</td>
<td>0.576%</td>
<td>N/A</td>
<td>1.980%</td>
</tr>
<tr>
<td>C=3 middle line</td>
<td>0.319</td>
<td>0.175</td>
<td>0.175</td>
<td>0.185</td>
<td>0.217</td>
<td>0.131</td>
</tr>
<tr>
<td>C=10 bottom line</td>
<td>2.166</td>
<td>2.243</td>
<td>2.228</td>
<td>2.060</td>
<td>2.338</td>
<td>2.142</td>
</tr>
</tbody>
</table>

Figure 1: Temperature of inner layer of 4-layer z-coil as a function of current, designed for cooling coefficient ratios of C=1 top line, C=3 middle line, C=10 bottom line.