A method for designing gradient coils with minimum maximum temperature: theoretical considerations

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Introduction: Typically the problem of Ohmic heating during gradient coil operation is addressed by incorporating forced water cooling into the system. However, recently several methods have been proposed for redesigning gradient coils for optimal thermal performance and reduced hot spot temperature [1-3]. Generally this is achieved by spreading the coil windings in the dense portions of the coil. One such method by While et al. [2,4] models analytically the spatial temperature distribution and uses the total square of the gradient of this distribution as a design constraint in a relaxed fixed point iteration routine. This method has been shown to produce symmetric and asymmetric gradient coils that operate at up to 20% and 10% lower peak temperatures, respectively, at little or no cost to coil performance [2,5]. In the present work, the optimisation problem was reworked by considering maximum temperature directly as a design constraint to produce genuine minimum maximum temperature gradient coils. A variety of symmetric and asymmetric coil types were considered and results display considerable improvements over previous designs.

Method: The theoretical design of a cylindrical 50mT/m *x*-gradient coil of radius $r_c = 0.25$ m and length $2L = 1$ m was considered. Two target field arrangements were investigated by placing a spherical target region of radius 0.15 m at the origin for a symmetric example and displaced by 0.15 m from coil centre along the *z*-axis for an asymmetric example. The analytic model of While et al. [4,5] was used to predict the spatial temperature distribution over the coil surface assuming it carries a surface current density $\boldsymbol{j}$ (A/m), represented here using Fourier series. This model incorporates Ohmic heating by the current density, heat conduction throughout the copper layer, radial conduction through an epoxy former, and radial convection and radiation to a lossy environment, and has been validated experimentally [6]. Minimising the maximum temperature is a highly non-linear optimisation problem and must be solved iteratively by modifying some initial guess. A standard minimum power coil was chosen for this purpose and the problem was solved using the *fminimax* function from MATLAB's Optimisation Toolbox and 128 Fourier modes as free parameters. A constraint on the average volumetric field error was used to preserve field linearity within the target region for each coil. Coils were designed for a range of assumed material properties and cooling mechanisms.

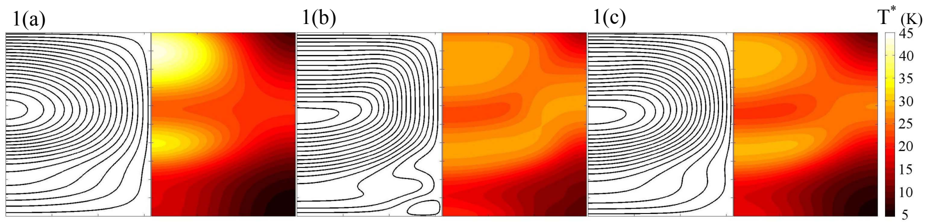

Fig. 1: Coil windings (one octant) and spatial temperature distribution (above ambient) for a symmetric: (a) minimum power coil, (b) extreme *minimaxT* coil, (c) *minimaxT* coil with additional power constraint.

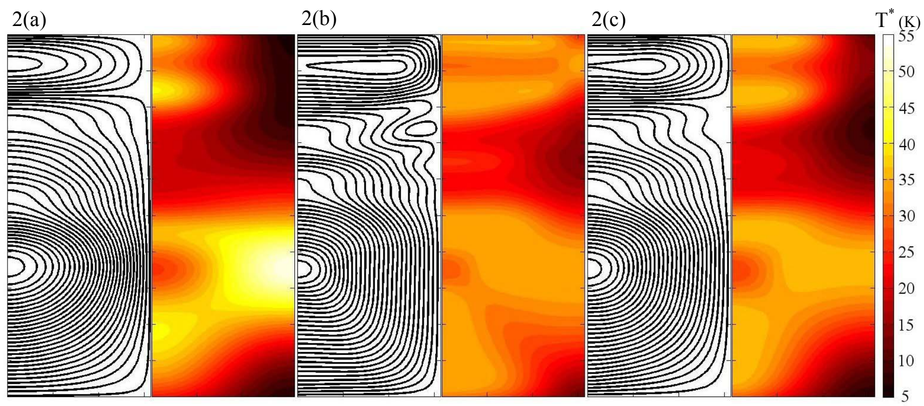

Fig. 2: Coil windings (one quadrant) and temperature distribution (above ambient) for an asymmetric: (a) minimum power coil, (b) extreme *minimaxT* coil, (c) *minimaxT* coil with additional power constraint.

Results and discussion: Fig. 1(a) displays coil windings for one quadrant of the symmetric minimum power coil with average field error $\delta^{1/2} = 1.0000\%$ and coil performance $\eta^2/L = 58.1$ μT/A/m^4. The corresponding spatial temperature distribution is also shown in Fig. 1(a) assuming a single copper sheet of thickness 2 mm embedded within two layers of 2 mm epoxy with forced air cooling, and the predicted hot spot temperature is max(T^*) = 44.5 K (above ambient). Generating a *minimaxT* coil for this arrangement took 4852 iterations with a total run-time of 79 min on a 2 GHz Intel Core2 CPU with 2 GB of RAM. Fig. 1(b) displays the convergent solution in which the dense portions of windings from Fig. 1(a) have been spread out and other portions have redistributed to preserve the field linearity. Most interestingly, the coil windings have not spread out evenly but have adopted a "fish-eye" characteristic in which the windings in the central region of the dense portion have spread out more than the windings surrounding the central region. This result is perhaps intuitive for a genuine minimum maximum temperature coil and demonstrates that the optimum solution will not be obtained simply by spreading coil windings evenly. The corresponding temperature distribution is also shown in Fig. 1(b), in which the peak temperature is smoothed over a large region of the coil surface with a much lower max(T^*) = 28.6 K (above ambient). This represents a 35.7% reduction in maximum temperature, which is a considerable improvement over previous work [2]. Importantly, this result is obtained at no cost to the coil performance measure $\eta^2/L = 58.5$ μT/A/m^4, although there is an 8.6% increase in dissipated power. Note that when using this extreme *minimaxT* optimisation it is common to generate coil winding solutions with troublesome reverse winding portions due to a mild ill-conditioning of the problem. However, it can be demonstrated that these windings are avoided by including an additional constraint to maintain the dissipated power at the same level as the minimum power coil and nevertheless achieve a drastic reduction in peak temperature (eg 32.3% in the present case), as shown in Fig. 1(c). Fig. 2 displays an equivalent set of results to Fig. 1 for an asymmetrically located target region. Once again the *minimaxT* algorithm generates coil windings that are spread-out and characterised by a "fish-eye" effect to minimise maximum temperature. For this example, the peak temperature drops from 54.8 K to 36.2 K (above ambient), a very considerable improvement over previous work [5], with no loss to η^2/L (actually this increases from 36.1 μT/A/m^4 to 38.0 μT/A/m^4). Note that the final coil solution is dependent heavily on the assumed thermal material properties and cooling mechanism used in the temperature model. This is particularly evident for the asymmetric case in which there is one region of very high current density of small extent and a second region of moderately high current density of large extent. For different thermal properties the hot spot location shifts between these regions and hence the *minimaxT* algorithm redistributes coil windings differently for each case. This highlights the importance of modelling the thermal behaviour of gradient coils accurately in the pursuit of optimum thermal performance, rather than necessarily defaulting to spreading the windings evenly. Note that for cases with lower effective thermal conductivity in the coil layer, reductions of up to 50% in peak temperature were obtained at no cost to coil performance.

References:

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