Temperature Characteristics of Gradient Coils with Minimax Current Density

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Introduction Recently, we have developed a method by which coils can be designed with minimum maximum current density, minimax|*j*|. This approach spreads the wires out evenly on the coil surface and can be employed instead of or in conjunction with stored energy or power minimisation [1]. Minimax|*j*| coils are expected to be useful in gradient and shim coils where the minimum buildable wire spacing limits the strength of the coil. Here we study the temperature behaviour of the coils since lower current density means lower local power dissipation and infers lower peak temperature in the coil. Gradient coils are routinely water cooled in order to remove as much heat energy as possible whilst permitting very high currents to be used with duty cycles that are required for demanding MRI sequences such as EPI. For short gradient coils in particular, there exists regions of the coils where current density is high, where wires have small cross-sectional area that produces high localised temperatures or "hot spots" [2]. By reducing the temperature of these hot spots it is hoped that gradient strength or duty cycle may be increased with reduced risk of damage to the gradient coil and safety risks to the subject. Small scale prototypes were used to demonstrate the temperature behaviour of minimax|*j*| X-gradient coils in the present study.

Methods Two X-gradient coils were designed to test their temperature behaviour. Both were designed on 1200 mm long cylinders with 760 mm diameters to generate an X-gradient field in a cylindrical region of interest (ROI) of 400 mm length and 400 mm diameter with 5% max field error. The current density was parameterised by its stream-function, $\psi(\varphi,z)$, that was a weighted sum of truncated sinusoidal functions [3,4] of the form

$$\psi(\varphi,z)=\sum_{m=1}^{M}\sum_{n=1}^{N}\lambda_{mn}\hat{\psi}_{mn}(\varphi,z), \quad \text{where} \quad \hat{\psi}_{mn}(\varphi,z)=\sin\left(\frac{2\pi n}{l}z\right)\cos\left((2m-1)\varphi\right) \quad \text{if} \quad |z|\le\frac{l}{2} \quad \text{or} \quad \hat{\psi}(\varphi,z)=0 \quad \text{if} \quad |z|>\frac{l}{2} \tag{1}$$

where λ_{mn} are the weights, *m* and *n* dictate the degree and order of the sinusoid and *l* is the coil length. *M* and *N* are the maximum number of sinusoids available and were set to 10 and 20 respectively in this work. One coil was designed with purely power minimisation and the other was designed with minimax current density (combined with a small amount of power minimisation to ensure some degree of smoothness).

The coils were scaled down in size to fit on the outside of a 111 mm diameter plastic pipe and CAD drawings were made for each coil respecting 4 mm maximum track width and 0.5 mm wire spacing. The coils were micro-milled with 0.35 mm thick flexible PCB with 18 μm thick copper. Return path were soldered, and the coil was attached to the plastic pipe with electrical insulation tape. Electric current was passed through the coils in series at 100 Hz and varying amplitudes. Temperature measurements were made using two thermocouples and a Fluke Ti25 infrared thermal imaging camera under heating and thermal equilibrium conditions with natural convective cooling mechanism assuming a surface emissivity of 0.94.

Results Figure 1 shows the results of a 1 hour transient heating test performed on both coils from room temperature (22 °C) as measured by thermocouples and Figure 2 shows the thermal images of the two coils at thermal equilibrium when conducting 2.48 Amps (rms). Figure 3 gives the peak temperature, obtained from the thermal images, as a function of drive current amplitude with quadratic fits superimposed.

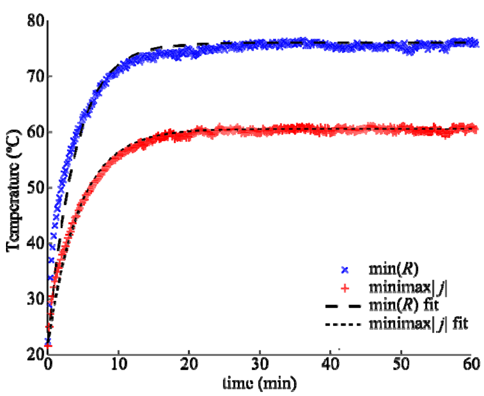

Figure 1. Time variation of the temperature for both coils measured with thermocouples and exponential fits.

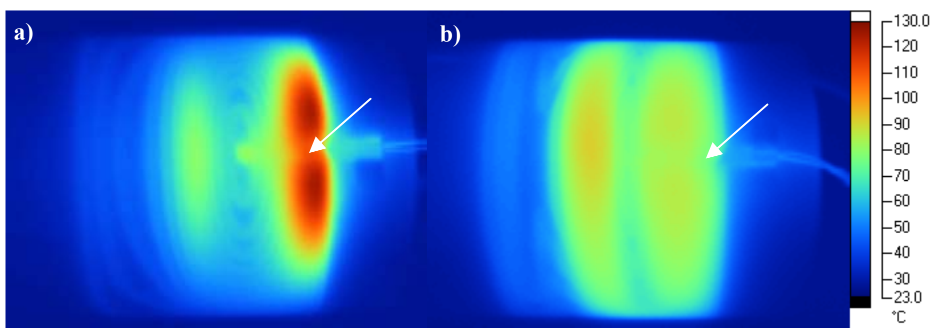

Figure 2. Thermal images of a) the standard power minimised coil and b) the minimax|*j*| coil when conducting 2.48 Amps (rms). Colour scale is the same for both images and is shown on the right. Arrows indicate the approximate positions of the thermocouple tips for the transient heating measurement shown in Fig. 1.

Discussion and Conclusions All data recorded shows that the peak temperature in the minimax|*j*| coil is considerably lower than the min(*P*) coil as expected. Figure 1 shows that thermal equilibrium temperatures of 76 and 60.5 °C were achieved in 30 mins and that simple exponential fits only approximately predict the transient behaviour of the temperatures. It can be seen from the thermal images in Fig. 2 that the hot spot is significantly cooled by the presence of the return path underneath the coil which is a thicker copper strip that conducts heat away. The difference in peak coil temperature may actually be greater without this cooling effect. It also shows how the hot spot is reduced in the minimax|j| coil whilst the heat is spread to other parts of the coil. Figure 3 shows that the peak temperature is approximately quadratic with respect to the drive current, which means that the difference between the peak temperature of both coils will be greater for higher temperatures. The small scale model cannot predict the temperatures of a real, full-sized, water-cooled gradient made with appropriate materials, but this study does demonstrate that the minimax|*j*| coil exhibits lower peak temperature than standard min(*P*) coils.

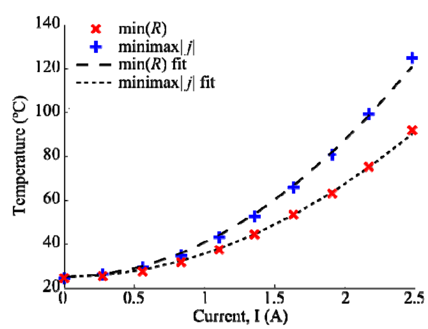

Figure 3. Peak temperature variation for different (rms) drive currents from thermal image data and their respective quadratic fits.

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