Suppressing local hot spots in RF coils and shields due to gradient eddy currents

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Introduction: A good RF shield in MRI should be transparent to the gradient field and opaque to the RF transmit field. Typically, the RF shield is a copper cylinder positioned between the RF and the gradient coils, with slits designed to suppress the generation of gradient eddy currents. A particular goal is to avoid eddy current heating of the RF shield; a recent patent, for instance, describes a global system of discontinuous axial slots [1]. Less is published, however, as far as localized shield temperature studies are concerned. Generally, it is important to avoid hot spots near the patient as well as in the vicinity of soldering joints, especially for novel gradient designs. In the present paper, we simulate the eddy current and corresponding temperature distributions resulting from gradient magnetic flux, and make successful comparisons to experimental measurements. Specific patterns of cuts for reducing particularly troublesome heating locations are studied.

Methods and Modeling: Consider a copper rectangular strip, 400mm × 80mm × 0.03mm, which is a mock-up of the end ring segments of an RF shield., and located under the highest current density area of an XY gradient. The thickness $d = 0.03mm$ of the strip is seen to be much smaller than the skin depth, which is approximately 1.6mm for a gradient waveform frequency chosen to be 1500Hz. With a gap between the shield and gradient coils of 1cm, the normal component of the gradient field dominates the heating, which can be understood by two limiting cases, a relatively homogeneous field normal and parallel to the strip surface, respectively, and is confirmed by simulation. For fields perpendicular to the strip, the total eddy current power loss $P_{loss} \propto d$, while for parallel fields, the total power loss $P_{loss} \propto d^3$. The heat equation is $\rho_c c \partial T / \partial t = k_c \nabla^2 T + J^2 / \sigma - h_t T / d$ where T is the shield temperature relative to a fixed (by cooling) ambient temperature, $\rho_c, c, k_c, \sigma, J$, and h_t are the mass density, specific heat, thermal conductivity, electrical conductivity, eddy current density (A/m^2), and total heat transfer (surface) coefficient, respectively. h_t is about 20 W/m^2/K for convective free air cooling on both sides. Heat radiation is neglected for the temperatures generated and the polished copper utilized in the study, and the heat transfer term is changed in the presence of a fiberglass former to $h_f = k_f / D$ for thickness D and k_f approximately 0.04 W/m/K. Maximum (saturated) temperatures are achieved upon balance between the EM power input and the heat flow out the copper surface. The numerical thermal solver is a finite-element FlexPDE™ program. The behavior of the heating results can also be understood by an analytic result [2] for rectangular ($a \times b$) thin plate power loss: $P \propto a^3 b^3 / \left(a^2 + b^2\right)$. Experiments were performed with an optical thermometer (Neoptix OMNIFLEX™ OFX-8S) to monitor temperature evolution with time, at a single mid-point on the copper strip.

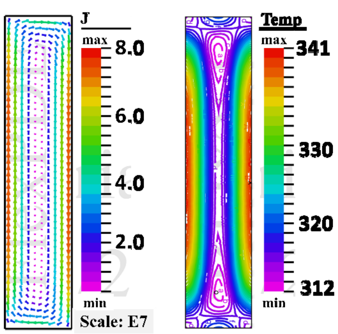

Fig. 1: Eddy current and temperature distributions

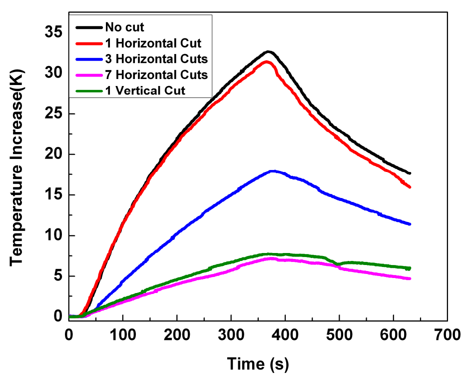

Fig. 2: Experimental temperature increase

Number and Kind of Cuts	Temperature Increase (measured)	Normalized Ratio (to Zero Cuts)	Simulated Ratio
0	32.7 K	1	1
1 horizontal	31.4 K	0.96	0.85
3 horizontal	17.9K	0.55	0.58
7 horizontal	7.2 K	0.22	0.26
1 vertical	7.8 K	0.24	0.26

Table 1: "Cutting" Peak Temperatures

Theoretical and Experimental Results: Fig. 1 displays the simulated results for both the eddy current and the saturated temperature distributions over the strip, which is shown vertically. Fig. 2 displays an example of measurements of the temperature at the edge near the middle of the strip as a function of time where the gradient currents were turned off just before saturation temperatures were achieved. Comparisons of the heating for different cuts made through the strip are found in Fig. 2 and Table 1. All cuts are symmetric and equidistant relative to the vertical illustration in Fig. 1 and have small gaps to allow orthogonal current flow past the cut. The peak temperatures shown in Table 1 lead to ratios within 10% of those for saturation temperatures, which is also the level of the simulation errors (conservatively estimated from the theoretical approximations made). With experimental errors also estimated to be less than 10%, we see excellent agreement for the ratios of the temperatures for all the different cuts studied. We also find good agreement for the shape and the scale of the temperature-time curves, which are found to be relaxation-like in their exponential approach to equilibrium. Note that the time scale is quite sensitive to the thickness of the fiberglass layer underneath the copper.

Conclusion: We find excellent qualitative understanding and quantitative agreement with measurements. For example, cutting along the long "vertical" edge reduces the heat (for the whole strip) much more than cutting along the short edge. The analytic formula for $a >> b$ yields $P \propto ab^3$, and, if we make one cut parallel to the short edge there is little change. However, if we make one cut parallel to the long edge then $P \propto ab^3 / 4$, or four times less power generated. In addition to the familiar meandering cuts, fan cooling, adding surface area through fins, and changing the thickness, judicious cuts in the locale of particular hot spots can be most helpful. As also seen in a study of a body coil [3], localized cuts and cutouts have been found to have little effect on the RF coil-shield performance (Q, SNR, and efficiency).

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References:

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