Toward an integrated RF-shield-gradient coil design method

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Introduction: The radiofrequency (RF) shield aims to prevent electromagnetic interactions between the RF coil and the electromagnetic environment in which the coil is immersed. Usually a thin copper cylinder with slits is placed between the RF coil and the gradient coils [1]. The slits cut the path of the eddy current's flow, thus partially ameliorating deleterious effects such as imaging artifacts, mechanical vibration and power heating. This last mentioned undesired effect can cause significant deteriorate the RF coil performance if excessive heating is produced in the RF shield. Some initiatives have been presented to remedy the power heating problem in the RF shield [1]. Less effort however, has been devoted to integrating the design of the RF shield and the gradient coil. In this paper we present an integrated design RF-shield-gradient coil in which power loss in the RF shield due to eddy currents is reduced by more than 8 times than of a conventional design. We used the equivalent magnetization current method (EMC) [2] to design the coils and the RF shield. An efficient hybrid eddy current simulation method was used to evaluate the power loss [3]. We demonstrated that an integrated design that includes the conducting environment in the design process conduces toward novel gradient coil designs with controlled and fewer eddy currents.

Method: The EMC method is a "free-surface" gradient coil design method based on the equivalency between the conducting current and the magnetization of a thin vertically magnetized volume [2]. The hybrid eddy simulation method is a combination of the Fourier network method and a boundary element method (BEM) [3]. The Fourier network method assumes an analytical expression of current density expressed as sin and cos. In the BEM the current density is expressed as linear basis functions [3]. Two kinds of whole-body gradient coils were designed. The first coil was designed without considering the RF shield but including the cold shield of the magnet. The second was designed considering both the cold shield and the RF shields with 4, 8, 12, 16 and 20 axial slits along the azimuth. The primary and secondary coil radii were set to 344 mm and 435 mm, respectively, and the axial lengths were set to 1.07 m and 1.36 m, respectively. All the coils were constrained to produce a figure of merit $\eta^2/L = 4.7\cdot10^{-6}\ T^2/m^2\ A^2\ H$. The field linearity was 5% for all the coils and the maximum magnetic field produced by the eddy currents in a DSV of 40x40x40 cm was 2.7 µT for all the gradient coils. The number of contours was set to 18. The gradient strength was set to 20 mT/m. The total stored magnetic energy of the system was minimized and at the same time a uniform and small secondary gradient field was constrained within the DSV. The copper RF shield thickness was set to 12 µm, the radius 320 mm and the axial length 600 mm.

Table 1. *Average power loss for the conventional and integrated gradient coil design*

RF cuts	4	8	12	16	20
Conventional gradient coil (watts)	115.82	98.35	73.04	57.51	46.06
Optimized gradient coil (watts)	28.60	27.84	29.13	18.96	18.48

Table 2. *Possible coils - RF shield combinations. Power loss (watts)*

Shield cuts	Coil (A)	Coil (B)	Coil (C)	Coil (D)	Coil (E)
4	28.6	52.63	71.10	63.99	68.18
8	22.47	27.84	59.30	46.44	53.50
12	18.32	34.80	29.14	35.11	37.58
16	16.01	19.84	33.65	18.98	27.97
20	14.43	21.98	27.66	21.30	18.48

Results and Discussions: Figure 1 shows the novel gradient coils designed for each of the RF shield with 4 A), 8 B), 12 C), 16 D) and 20 E) slits. The primary coil shows a change in current pattern that minimizes the inductive coupling between the coil and the RF shield. Table 1 describes a significant reduction in power loss (1 kHz) in the RF shield when the gradient coil is designed including all possible conducting surfaces. When the number of slits is increased, a further reduction in power loss is obtained. However, this also produces an increased inductive interaction between the RF coil and the electromagnetic environment. The shield with 4 slits reduces the power by 4 times; however, the z-gradient coil induces a considerable amount of ohmic power. Moreover, an overlap may occur in the time decay constant between the cryostat and the shield (shield time decay range 0.8µs-52µs and cryostat 44µs-0.94s). This means that the 4-slits shield may produce a magnetic field for a short period of time at the same time as that produced by the cryostat. Table 2 shows the average power loss of optimized coils and shields. Power loss tends to increase when gradient coils designed for a shield with a larger number of slits are used in shields with small number of slits. Coil (A), when is combined with a shield with 20 slits produces a minimal power loss. Coil (B) produces 19.84 watts when 16 slits are used. In this case the RF shield does not produce overlap with the cryostat in terms of the time decay constant which becomes this combination in a possible optimal design. We have assumed that the *z*-gradient coil is not optimized hence the new gradient coil set can be manufactured in the conventional way.

Further research is necessary to choose the optimal number of cuts in terms of the RF coil performance.

Conclusions: In this paper we have proposed a new concept of integrating the design of gradient coils and the RF shield. We demonstrated that a significant reduction in power loss (up to 8 times) can be achieved if the gradient coil is designed including all conducting surfaces that contribute to the system performance.

References:
[1] D. Weyers and Q. Liu, US Patent 7102350, 2006. [2] H Sanchez-Lopez *et al. Journal of Magnetic Resonance*, 207, 251-261, (2010). [3] H Sanchez *et al.* Submitted to ISMRM 2012.

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