# Improved active gradient shield design with endcap windings

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## Introduction

Actively shielded gradient coil sets are intended to minimize gradient-generated eddy currents on the magnet cryostat and surrounding metal structures, as such eddy currents interfere with image quality and produce acoustic noise [1]. Problems worsen as fields increase to 3 T and higher. Conventional designs have generally confined the windings to cylindrical surfaces, where it is difficult to suppress the fringe field leakage near the ends. Use of the SUSHI [2] shielding-function equation can lead to a remarkable decrease in such leakage, but at the expense of increasing the peak current and inductance of the coil.

We consider here the use of shielding current distributions in the radial direction. In particular, we have studied a shielded z-gradient coil assembly with annular windings included at both ends of the coil geometry. This configuration reduces fringe fields by 76% compared to a traditional design with similar dimensions. In addition, the new design reduces eddy current power dissipation in the cryostat inner bore by 16.2 dB. The electrical energy deposition is proportional to acoustic power generated by eddy current induced vibrations.

## Theory

Our proposed shielded gradient coil assembly is shown in Fig. 1, with primary and secondary coil radii $\mathrm{R_p}$ and $\mathrm{R_s}$, lengths $2\mathrm{L_p}$ and $2\mathrm{L_s}$. For the annular end winding caps, the inner radius is $\mathrm{R_s}$ and the radial height is $\mathrm{L_c}$. The current densities for the primary (P), secondary (S), and annular caps(C) have the form:

$$\mathbf{J}^{(P,S,C)}(\mathbf{r}) = \sum_n b_n^{(P,S,C)} \bullet \mathbf{f}_n^{(P,S,C)}(\mathbf{r}) \tag{1}$$

where $b_n^{(P,S,C)}$ are the expansion coefficients, and $\mathbf{f}_n^{(P,S,C)}(\mathbf{r})$ refers to a cosine or sine basis that is nonzero only inside the assumed length of the primary and secondary structure. Our method is based on an iterative approach [3] to a design functional constructed out of a series of quadratic terms, each of which has a minimum corresponding to a given constraint. The minimizing functional *W* is given by

$$W = a_1 E + a_2 \sum_{i=1}^{N_{dsv}} \left[ B_z(\mathbf{r}_i) - B_{z_i} \right]^2 + a_3 \sum_{j=1}^{N_{shield}} \left[ \mathbf{B}(\mathbf{r}_j) \right]^2 \tag{2}$$

The terms on the right represent, respectively, system energy, variance of the field minus target field inside the DSV, and variance of the field from its desired zero value at the inner cryostat bore. Weighting parameters $a_1$, $a_2$ and $a_3$ are used to change the relative importance of those terms. The DSV predetermined points are $\mathbf{r}_i$ corresponding to the desired field values $B_{z_i}$. The field leakage is minimized at $N_{shield}$ points on the cryostat inner bore.

The iterated solution searches for extrema of Eq.2 through variations in the coefficients $b_n$ of the harmonic functions in Eq.1. The resulting linear equations are solved by inverting a matrix that depends on the original $b_n$. This creates new values of $b_n$, and the process is repeated. The accuracy with which the constraints are met improves with each iteration. Finally, a discrete version of the resulting continuous current densities is derived.

## Results and Discussion

We have designed a shielded axial gradient coil with annular end winding caps as an example of this approach. The gradient strength is 30mT/m. The primary and secondary coil radii are $\mathrm{R_P}$=0.36m, $\mathrm{R_S}$ =0.44m with total lengths $2\mathrm{L_S}$ =1.0m and $2\mathrm{L_P}$=1.22m. The annular width of the cap is $\mathrm{L_C}$= 0.076m. The constraint points assume a 30 mT/m gradient field with 10% linearity and 20% uniformity variations inside the 45cm DSV. Figure 2 shows the continuous current densities of the primary, secondary and cap distributions. Figure 3 compares the fringe field for this design with that of a traditional capless design, along the cryostat inner bore at 0.475 m radius. The end cap design achieves a fringe field of less than 78μT, a 76% reduction with respect to the traditional design. The maximum residual eddy current was estimated to be 5A for the traditional design [4], but only 0.76A for the capped design. This translates into a 16.2dB reduction in the power deposited to the magnet's metallic structure.

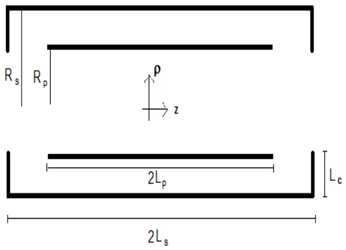

Figure 1

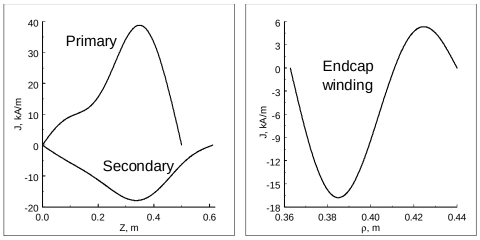

Figure 2

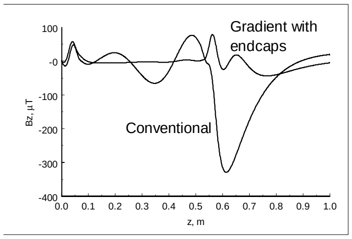

Figure 3

## References

[1] Edelstein, W.A., et al. in *ISMRM Twelfth Scientific Meeting*. 2004. Kyoto, Japan
[2] Brown, RW,Shvartsman S, Phys Rev Lett 1999;83:1946-9
[3] Brown RW et al, MAGMA 2002; 13:186-192
[4] Kidane TK et al, ISMRM Twelfth Scientific Meeting and Exhibition, Kyoto, Japan, May 15-21, 2004:480