Active-Passive Gradient Shielding for MRI Acoustic Noise Reduction

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Abstract. An important source of MRI acoustic noise--magnet cryostat warm bore vibrations caused by eddy-current-induced forces--can be mitigated by a passive metal shield on the outside of a vibration-isolated, vacuum-enclosed shielded gradient set. Finite element calculations for a z-gradient indicate that a 2 mm thick Cu layer wrapped on the gradient assembly would decrease energy deposition in the warm bore and reduce warm bore acoustic noise production by 25 dB. Eliminating the warm bore and other magnet parts as significant acoustic noise sources could lead to truly quiet, fully functioning MRI systems with noise levels below 70 dB.

Introduction. Acoustic noise has long been a problem for MRI subjects and operators [1] with sound levels approaching or exceeding 100 dB. Noise is further increasing as more powerful gradient amplifiers are deployed and the static field gets higher [2].

Recent work on acoustic noise reduction in MRI systems used vibration-isolated gradients contained in a vacuum enclosure and a magnet with a non-conducting inner cryostat bore [3, 4]. The results of these investigations indicate that Lorentz forces on the inner cryostat bore, created by eddy currents caused by shielded gradient leakage fields, contribute a significant level of acoustic noise.

Thus, in addition to vacuum and vibration isolation of the gradient assembly, it is necessary to provide *electromagnetic* isolation.

It might seem desirable, then, to manufacture magnets with nonconducting cryostat warm bores. Indeed, many early Oxford 1.5 T magnets were made this way. However, it is simpler and cheaper to make magnets with conducting warm bores, so it is important to achieve noise reduction using such magnets. Further, it is desirable to prevent gradient stray fields from reaching other metallic parts of the MRI system where resultant eddy currents could also contribute to acoustic noise.

We propose installing passive copper shielding on the outside of the shielded gradient assembly to increase the shielding efficacy. We believe that this active-passive shielding, in combination with vacuum enclosure and vibration isolation of the gradients, could lead to a dramatic decrease in MRI acoustic noise.

Shielding Calculations. Several workers have described the use of multiple active gradient shields (e.g. [5-7]). Mulder *et al.* suggest applying a copper shield to the circumference of an actively shielded gradient assembly [8]. We have calculated the shielding efficacy for that arrangement and for an extension of the idea in which the copper is wrapped down around the ends of the cylinder. Figure 1 shows an actively shield gradient assembly with different forms of additional passive shielding.

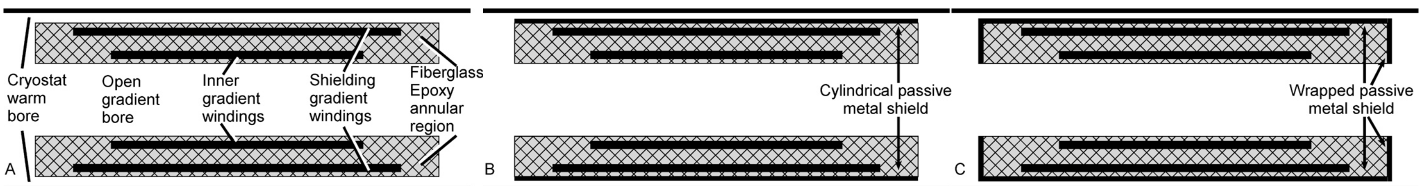

Fig. 1. Cross-section of shielded gradient configurations (not to scale). A) Actively shielded gradient. B) Actively shielded gradient with additional cylindrical passive metal shield. C) Actively shielded gradient with passive metal shield applied to circumference of gradient and wrapped around end of gradient.

We report here calculations involving the z-gradient, which has azimuthal symmetry. On the stainless steel bore, the Lorentz forces $F \propto I \cdot B$ and the deposited mechanical energy $E \sim F^2 \propto I^2 \propto I^2 R$. So the ratio of the ohmic power dissipation in the stainless bore without and with copper shield will be approximately the ratio of the mechanical energies imparted to the warm bore and, hence, the ratio of the acoustic noise powers produced by the warm bore.

Results. The calculations were carried out using Ansoft Maxwell 2D SV finite element (FE) electromagnetics program [9]. Approximate dimensions: inner gradient winding radius = 330 mm, length = 990 mm; outer winding radius = 420 mm, length = 1258 mm; gradient assembly length = 1600 mm; Cu shield radius = 442 mm; warm bore radius = 450 mm, length = 1700 mm. Table 1 shows the FE results for various Cu shield configurations.

Table 1. Power deposition in stainless steel bore. “1 kHz” refers to a sinusoidal gradient excitation current of 100 A at 1 kHz. “Rect Pulse” refers to a series of 100 A max gradient current pulses repeated at 10 ms intervals. (These have rise and fall times ~ 200 μs, flat top 600 μs.)

	1 kHz Power deposit in ss bore (W), no Cu shield	1 kHz power deposit in ss bore with Cu shield (dB decrease)	Rect. Pulse Power deposit in ss bore (W), no Cu shield	Rect Pulse Power dep. in bore with Cu shield (dB decrease)
No Cu Shield	4.05		0.976	
1 mm Cu shield, no wrap	0.131	14.9	0.0327	14.7
1 mm Cu shield, wrap around end	0.02513	22.0	0.00992	19.9
2 mm Cu shield, wrap around end	0.00723	27.4	0.00316	24.9

Discussion and Conclusions. Wrapping the Cu around the end of the gradient significantly enhances shielding of the warm bore. For a 1 kHz sine wave applied to the z-gradient, the 1 mm wrapped Cu shield deposits 22 dB less energy than does the bare gradient coil; the 2 mm Cu shield deposits 27.4 dB less energy. The corresponding figures for the rectangular pulse train are 19.9 dB and 24.9 dB. Examining Fig. 2 in reference [3], decreasing noise by 25 dB from the level of “conducting WB mechanical path” could lower noise to 65-75 dB inside the bore, depending on the source of acoustic noise designated “everything else.” Further, as “everything else” could include mechanical excitation of other parts of the cryostat or magnet, it is possible that the Cu shielding could save more than 25 dB.

We are presently calculating the shielding efficacy of the Cu wrap on warm bore eddy currents caused by transverse gradient leakage fields.

Once vacuum and electromagnetic isolation are in place, it will be possible to further investigate gradient assembly vibration isolation to see whether passive or, perhaps, active vibration isolation may be needed to drive acoustic noise lower without sacrificing image quality because of gradient coil motion. Ultimately, the goal should be to achieve a noise level of 60-70 dB near the magnet and in the bore to enhance working conditions for operators and physicians and for patient comfort.

References

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