Ultra-efficient shielded dome gradient coils

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1. Purpose

Insert gradient coils built specifically for head imaging are useful for many purposes such as fMRI, diffusion imaging, and high-resolution anatomical imaging. Such coils inherently produce strong gradient fields because they are smaller and have wires closer to the region of uniformity (ROU). The geometry of the coil described here exploits this property by placing the conducting surface as close to the head as possible. A boundary element method after Lemdiasov and Ludwig [1] was used to design shielded coils on this surface.

2. Methods and Materials

The boundary element method [1] allows gradient coils to be designed on conducting surfaces with arbitrary geometry. It works by discretising the stream-function of the current density on the surface into a weighted set of divergence-free basis-functions. The inductance, resistance, and torque of the coil as well as the magnetic flux density at any point can be derived in terms of these basis functions, allowing a functional reflecting the coil characteristics to be optimised. Surface meshes were created in 3D Studio MAX® (Autodesk® Inc., San Rafael, CA, USA) and imported into Matlab® (Mathworks® Inc., Natick, MA, USA) for calculation of the basis-function weights. A 3D-contouring algorithm was written to generate the wire-paths from these weights. A Biot-Savart calculation was performed on the wire-paths to obtain the magnetic flux density distributions, and multipole expansion analysis was used to calculate the inductances and resistances using FastHenry© [2]. Fig. 1 shows the geometry of the coil, the inner surface is designed to be separated by roughly 50 mm from the head to allow space for the RF coil. Shielding points (not shown in Fig. 1), at which the flux leakage was minimised, are distributed on the surface of a 550 mm long cylindrical surface with a diameter of 640 mm. A prototype X-gradient coil has been constructed on a rapid-prototyped former, and tested electrically and with a field mapping sequence.

see: [Figure 1.]

3. Results

Figs. 2, 4, and 6 show the wire-paths of the X, Y, and Z gradient coils, and Figs. 3, 5, and 7 show contour maps of the magnetic flux density distributions produced when unit current is passed through the X, Y, and Z gradient coils. Table 1 shows the properties of the gradient coils. Fig. 8 is the half-scale prototype of the X gradient shown in Fig. 2. The measured inductance of the half-scale prototype was measured to be 34.3 μH and the resistance was 0.52 Ω compared with the 33.3 μH and 0.42 Ω as modelled in FastHenry© [2]. The field mapping sequence revealed an efficiency (scaled to full size) of 0.34 $mTm^{-1}A^{-1}$.

see: [Figure 2.] see: [Figure 3.]

see: [Figure 4.] see: [Figure 5.]

see: [Figure 6.] see: [Figure 7.]

Table 1.

Gradient	Efficiency, η (mTm-1A-1)	Inductance,L (μH)	Resistance,R (m Ω)	Figure of Merit, η2/L (T2m-2A-2H-1)
X	0.33	58.0 (63.3)	75.7	1.84 x 10-3
Y	0.29	50.3 (56.1)	73.6	1.64 x 10-3
Z	0.46	79.7 (86.2)	71.9	2.68 x 10-3

see: [Figure 8.]

4. Conclusion

A shielded gradient coil set has been designed to have very high efficiency using a boundary element method [1]. The gradient fields produced by these coils are 2.0, 1.8, and 2.4 times stronger than previous X, Y, and Z gradients of equal inductance, have superior homogeneity and are also shielded [3]. The results have been corroborated using Biot-Savart calculation and multipole expansion impedance extraction calculation with FastHenry© [2], as well as direct measurement of a half-scale prototype X gradient electrically and with a field mapping sequence. The measured values of inductance, resistance and efficiency are 3%, 18% and 4% different to their theoretical values.

5. References

[1] R. A. Lemdiasov, R. Ludwig. A Stream Function Method for Gradient Coil Design. *Concepts Magn. Reson. B.* **26B** , 67-80 (2005)
[2] M. Kamon, M. J. Tsuk, J. K. White FASTHENRY: A Multipole-Accelerated 3-D Inductance Extraction Program. *IEEE Trans. on MTT.* **42** , 1750-1758 (1994)
[3] D. C. Alsop, T. J. Connick. Optimisation of Torque-Balanced Asymmetric Head Gradient Coils. *Magn. Reson. Med.* **35** , 875-886 (1996)

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Figure 1.

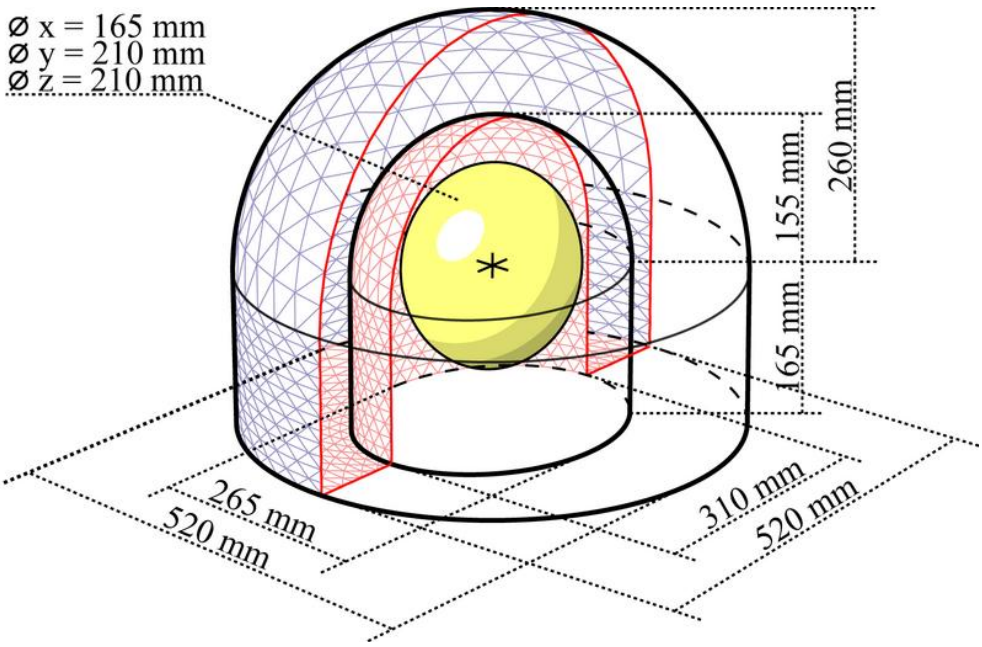

Figure 1. The geometry of the gradient coil. The spheroid is the region of uniformity (ROU), and the triangles show half of the discretised surface of the primary (red), secondary (blue) surfaces. The ROU contains 587 evenly distributed points, and the surface is discretised into 2162 basis-functions.

Figure 2.

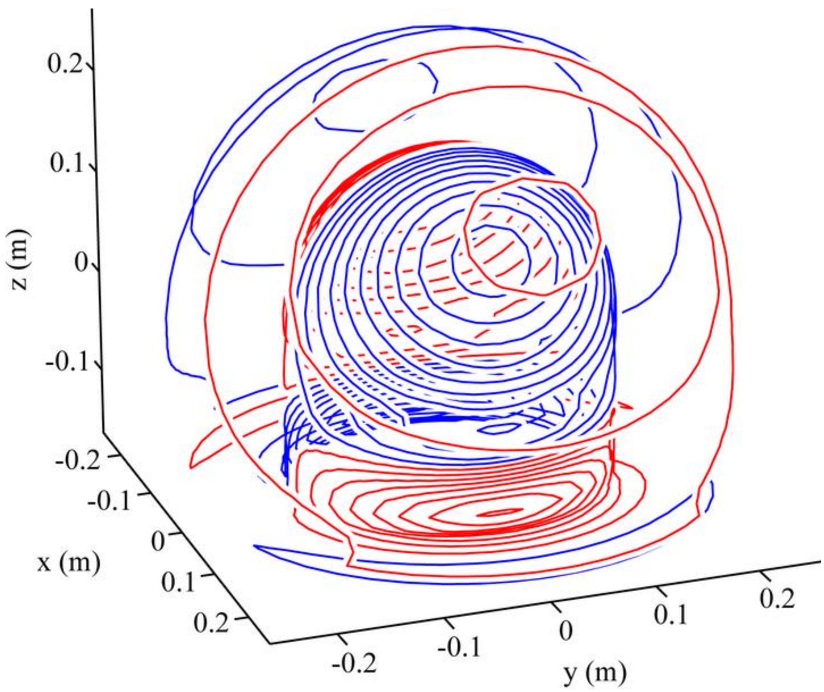

Figure 2. The wire-paths for the X-gradient coil. Red wires indicate reversed current flow with respect to blue.

Figure 3.

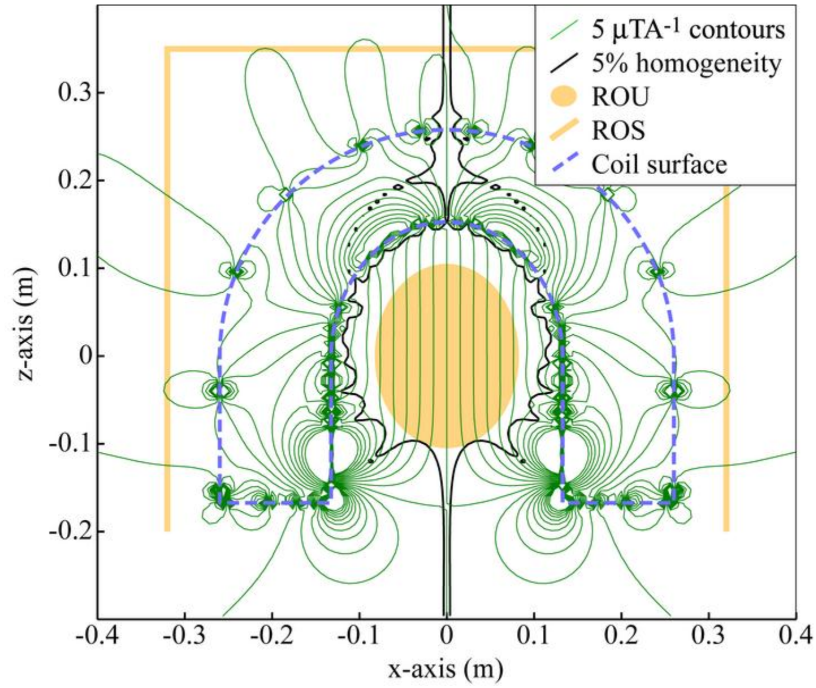

Figure 3. Contour map in the y=0 plane of the longitudinal magnetic field generated by the ultra-efficient X gradient coil with unit current. Each field line corresponds to a 5μTA-1 contour. The solid black line shows the region inside which the field error is less than 5%. The ROU, ROS, and coil surface are also shown.

Figure 4.

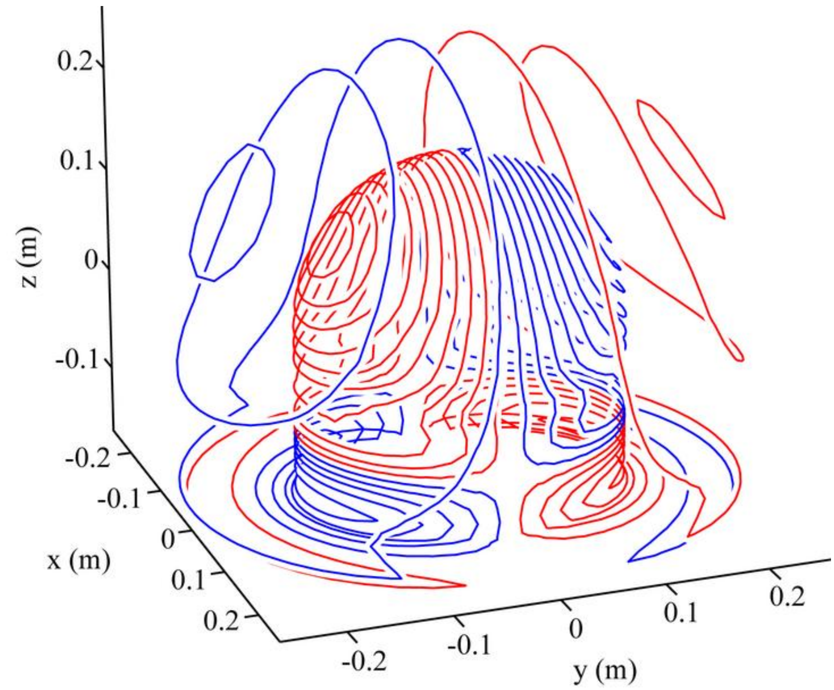

Figure 4. The wire-paths for the Y-gradient coil. Red wires indicate reversed current flow with respect to blue.

Figure 5.

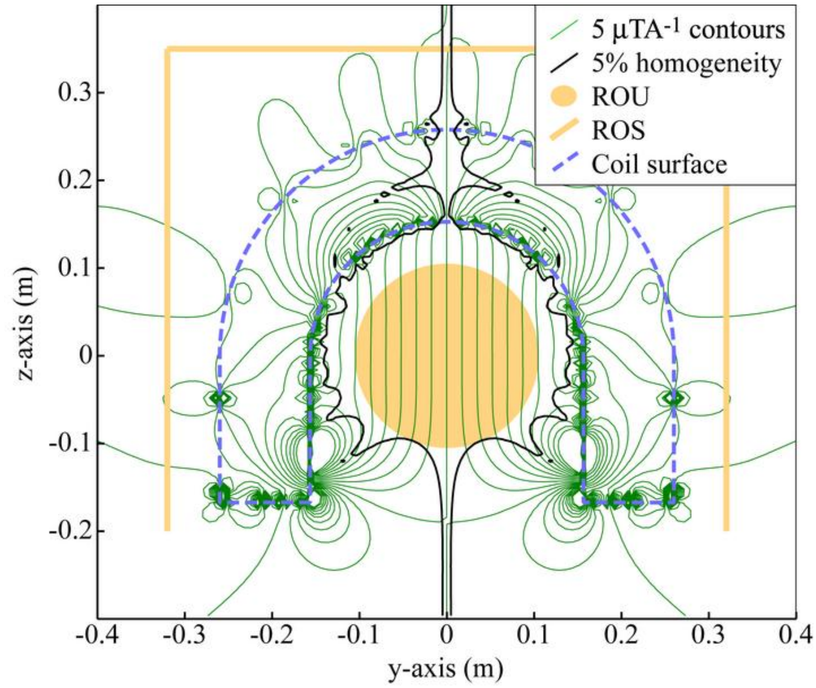

Figure 5. Contour map in the x=0 plane of the longitudinal magnetic field generated by the ultra-efficient Y gradient coil with unit current. Each field line corresponds to a 5μTA-1 contour. The solid black line shows the region inside which the field error is less than 5%. The ROU, ROS, and coil surface are also shown.

Figure 6.

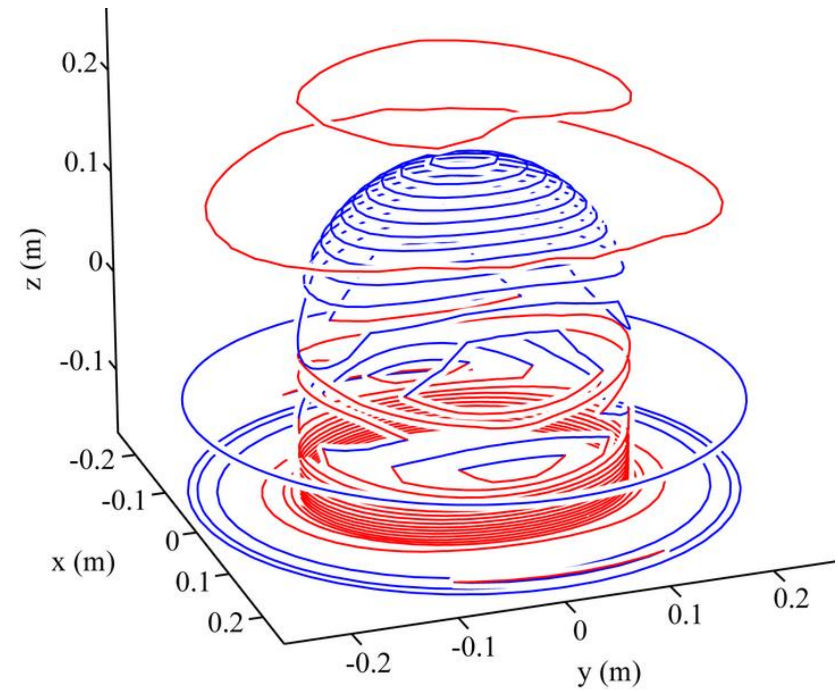

Figure 6. The wire-paths for the Z-gradient coil. Red wires indicate reversed current flow in the opposite azimuthal sense with respect to blue.

Figure 7.

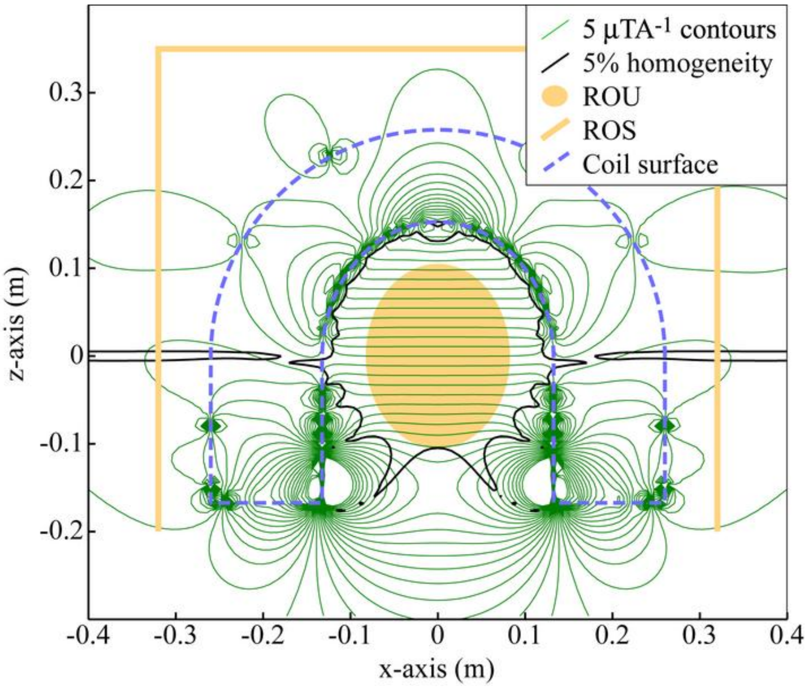

Figure 7. Contour map in the y=0 plane of the longitudinal magnetic field generated by the ultra-efficient Z gradient coil with unit current. Each field line corresponds to a 5μTA-1 contour. The solid black line shows the region inside which the field error is less than 5%. The ROU, ROS, and coil surface are also shown.

Figure 8.

Figure 8. The half-scale prototype shielded X gradient coil.