Practical design of a high-power, high-homogeneous, actively-shielded, Bo insert coil, capable of +/- 1.0 T field-shifts and stand-alone, low-field imaging

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Introduction: There are several applications in which active control and modulation of the main magnetic field is necessary, including: prepolarized MRI [1, 2], combined field-cycled MRI and PET systems [3], and delta relaxation enhanced MR ("dreMR") [4]. In some of these cases (i.e. for prepolarized MRI and for dreMR), the modulation field is not used during signal acquisition, and therefore does not need to be of high uniformity. For a stand-alone imaging system, the field homogeneity is generally a limiting factor. In this work, we present the development of a resistive, actively-shielded, variable-field MR system for small animals which can temporarily pulse magnetic fields up to +/-1.0 T, yet has sufficient homogeneity that it can be used during signal detection for fields up to 0.25 T. Such a system could be used as a high-power dreMR coil insert within superconducting systems, or as a stand-alone low-field imaging system for mice and other small animals. Gradient and shim axes are included in the design, and allowance for the RF system has been made. The design details are based on our practical experiences in designing and constructing systems for the individual applications listed above.

Methods: The primary field coil was a uniform current density solenoid with inner diameter of 14.0 cm, outer diameter of 25.4 cm, and total length 19.2 cm. These dimensions correspond to 11 radial layers consisting of 37 windings per layer when wound with commercially available square hollow wire (5 mm outer width, 3 mm hole diameter). The hollow-wire construction is critical to allow sufficient cooling to manage the large dissipated power. Two shielding layers were designed (diameters 41cm and 43 cm, total allowable length 50 cm) using the minimum energy method [5]. Five layers of shim coils were designed to correct for the deviation in field produced by the primary/shield solenoid combination with respect to the field produced at the origin at 101 target points along the z-axis extending +/- 2.5 cm. Three of the shim layers were placed inside the primary coil (diameters: 9.02 cm, 9.86 cm, and 10.70 cm) with two shim layers located outside the primary solenoid (diameters: 26.00 cm and 27.04 cm). The inner and outer shim layers were constrained to have 4.2 mm and 5.2 mm wire-separation so as to be wound with commercially available hollow wire 4 mm width/2 mm hole diameter and 5 mm width/3 mm hole diameter respectively. All five shim layers were designed to be connected in series with the primary and shield coils

The x- y- and z-axis gradient coils were designed using the boundary element (BE) method [6] on cylinders of diameter 30.1 cm, 34.1 cm, and 32.1 cm respectively. The gradient coils were designed using 382 target points distributed over a prolate spheroid 5 cm in diameter (xy), 10 cm in length (z-axis), to have high efficiency while maintaining at least 5 % gradient uniformity over the field of view (FOV). The BE method was modified to constrain the wire spacing of the gradient coils to 3.1 mm, 3.1 mm, and 5.2 mm for the x-, y-, and z-axes respectively using an iterative approach similar to [7].

Results: Figure 1 displays the cross-section of the proposed insert coil. The radial gaps between the inner shim layer and primary, as well as the outer shim layer and gradient coils, allow for 1cm diameter cooling lines to parallelize the water flow. The field efficiency, inductance, and total resistance of the dreMR primary/shim/shield combination are 1.67 mTA^{-1}, 16.2 mH, and 453 mΩ respectively. The x-, y-, and z-gradient coils have efficiency, maximum resistance, and inductance of: 0.91 $mTm^{-1}A^{-1}$, 0.71 $mTm^{-1}A^{-1}$, 0.91 $mTm^{-1}A^{-1}$; 101 mΩ, 115 mΩ, 77 mΩ; and 749 μH, 861 μH, 660 μH, respectively. The maximum gradient inhomogeneity over a 5 cm x 5 cm x 10 cm field of view is: 6.0 %, 5.9 %, and 5.5 % for the x-, y-, and z-axes.

Figure 2a,b shows the B_0 field homogeneity in the xy- and xz-planes respectively over a 5 cm FOV. The maximum local B_0 gradient with respect to the x-axis is 6.5 $\mu Tm^{-1}A^{-1}$ and 4.1 $\mu Tm^{-1}A^{-1}$ over a (3 cm x 3 cm x 5 cm) FOV and (3 cm x 3 cm x 3 cm) FOV respectively. Assuming a 10 kHz read-out bandwidth and an order of magnitude requirement for the ratio of read-out gradient to B_0 gradient strength [1], this design would be capable of imaging over a (3 cm x 3 cm x 5 cm) FOV at 0.2 T and a (3 cm x 3 cm x 3 cm) FOV at 0.32 T. The required field stability, assuming a 1 mm voxel and a 10 kHz bandwidth, is approximately 7.8 μT. This corresponds to a required current stability of better than 4.7 mA. Table 1 summarizes the power requirements for the insert coil at 0.1 T, 0.2 T, 0.5 T, and 1 T.

Discussion: The design of a practical small-animal field modulating imaging system with the combined capability of prepolarized MRI, dreMR (which requires excellent active shielding), and stand-alone low-field MRI (which requires modest strength but high uniformity and temporal stability) is obviously a challenging task. The design presented is adequate for imaging over a small FOV at reasonable read-out field magnitudes. This design is quite similar in construction to the dreMR insert coils our group has designed and built several times over the past few years. The main differences here are: (1) the focus on drastic improvement in the field uniformity (achieved through the use of the shimming layers), and (2) on the integration of the gradient layers into the main coil construction. Practical current densities and water-cooling topologies have been included in all stages of the design. If a maximum steady-state cooling system could sink 20 kW (a very reasonable value with existing commercial chiller systems), note that 0.5T fields could be maintained at 50% duty cycle, and 1.0T for slightly more than 10% duty cycle. It should be noted that with modern implementation of pulse-width-modulated amplifiers, active current modulation can be achieved even with steady-state rms current values of 400 A or more. We believe this design to be practical, and we are currently pursuing the construction of this system in our laboratories.

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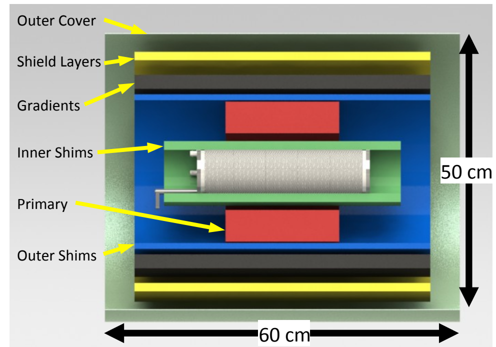

Figure 1. Cross-section of complete insert coil. The inner diameter is 8 cm, with outer diameter (including G10 casing) 50 cm; the total length (outer casing) is 60 cm.

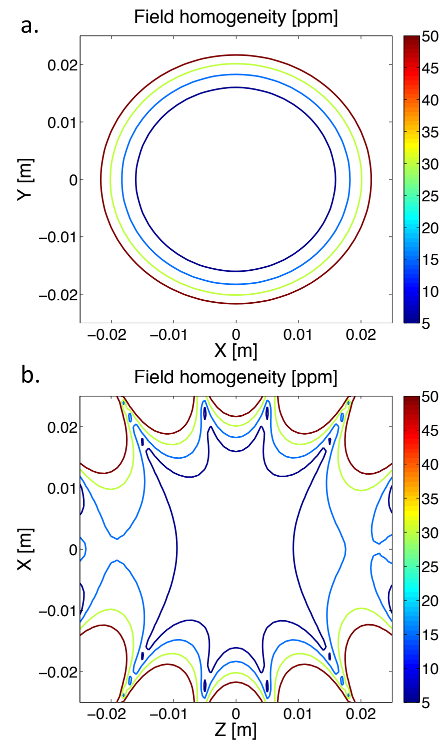

Figure 2. (a) B_0 field homogeneity in ppm over a 5 cm by 5 cm region in the xy-plane. (b) B_0 field homogeneity in ppm over a 5 cm by 5 cm region in the xz-plane. For both figures, contour lines are at 5, 15, 30, and 50 ppm.

Table 1. Current and power requirements for the B_0 insert coil at various field strengths and duty cycles.

Field Strength (T)	Required Current (A)	Power (kW) 10% Duty Cycle	50% Duty Cycle	100% Duty Cycle
0.1	60	0.16	0.81	1.62
0.2	120	0.65	3.25	6.50
0.5	300	4.06	20.30	40.61
1.0	600	16.24	81.21	162.43