Improvements in magnetic shielding of a B_0 insert coil

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Introduction:

Delta relaxation enhanced magnetic resonance (dreMR) is a method that has been shown to drastically improve the specific detection of targeted contrast agents, theoretically producing signal only when the agent is in the bound state [1-3]. The technique requires modulation of the magnitude of the main magnetic field as a function of time during the magnetization recovery and evolution periods of a pulse sequence. This is typically achieved by driving a supplementary, actively shielded "B_0 insert coil" to modulate the main magnetic field within an otherwise unmodified, clinical, super-conducting MR system. Magnetic shielding (along with thermal management) is a major challenge in the design and construction of these B_0 insert coils, because of the inherent coupling (if unshielded) to the superconducting magnet itself. This coupling can result in field instability in the superconducting system. In this work, we investigate the possible improvements in practical shielding capability that can be achieved if the specific details of the primary coil construction are taken into account prior to the design of the shield.

There are three practical "errors" that we observe in the winding of the thick-solenoid primary current density comprising the dreMR coil. The first type is errors in the positioning and orientation of the individual windings themselves (see Figure 1). Despite taking care during the winding process, the windings were frequently twisted (~50% of the time) causing variances in both longitudinal and radial location. This effect is magnified because of the use of square cross-section wire. The second type of error is a net misplacement of an entire block of windings with respect to the rest of the coil (Fig. 2b). This occurs if small errors in individual winding placement accumulate coherently during winding, or if there is a significant error in the production of the winding former. The third type of error is really not an error at all, but a practical necessity in the construction: individual winding layers need to be connected, and in the case of hollow-wire construction (through which coolant must be flowed during operation), these connections must serve the needs of both the electrical and hydraulic systems. These connections, which can be seen in Figure 2a, result in deviations from the assumed primary current density. Our hypothesis was that if the above three sources of non-ideal primary current density were minimized (in the case of the individual winding errors) and measured (in the case of the second two errors) during the construction process, the design of a shield which specifically included these detailed effects would result in a significantly improved shielding result for the final coil.

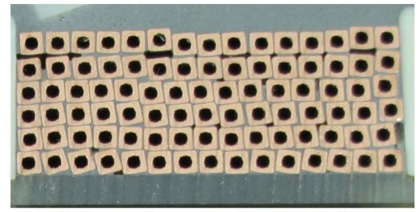

Figure 1. Cutaway of one quarter of previously built dreMR coil split power-solenoid that failed during operation. Note how the cross-section of the wire is frequently twisted (~50% of the time), causing wire displacement both radially and longitudinally.

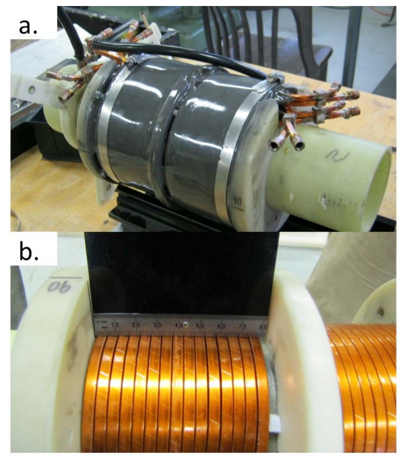

Figure 2. (a) Completed primary solenoid. Note the wire connections between radial layers at each end of the coil. (b) Example measurement of wire positions after completion of one layer of the primary coil.

Methods:

In order to minimize the individual winding errors, the construction protocol was adapted to make use of a customized wire straightener during winding. Square hollow wire (5-mm width, 3-mm-hole diameter) was wound onto a cylindrical G-10 former into a split solenoid pattern with 12.7-cm gap (6 radial layers, 30 wire turns per layer, 15 turns per half). After winding each radial layer, the individual wire positions were manually recorded at four equidistant azimuthal positions (Fig. 2b). In addition, the overall position of the individual winding blocks (error #2 above) was measured and included in the "realistic" primary coil model. Once the primary solenoid construction was completed, the connection wire segments (both between winding layers, as well as between the actual external connectors and the primary windings) were manually measured and added into the full realistic primary coil model. This realistic model was used to design the shield stream function distribution using the minimum energy method [4]. A modified 3D contouring algorithm was used to create the spiral-like shield wire pattern. The shield wire pattern was wound onto a G-10 cylindrical former at a diameter of 28.8 cm with a total length of 30.5 cm.

Eddy currents (over a period of 100 ms following application of a 0.3 T field shift with a rise time of 10 ms) were simulated for both the idealized and the realistic shield cases, assuming a conducting cylinder at a radius of 50 cm (approximate position of the cryostat bore of an MR scanner). The resulting eddy-current-induced magnetic fields were calculated at the center of the imaging region, and expressed as a percent of the applied 0.3 T field pulse. For confirmation of accurate shield construction, radial magnetic flux was experimentally measured for multiple longitudinal displacements of the constructed shield with respect to the actual primary solenoid using an AC Gaussmeter (Magnetic Sciences International MC20) positioned approximately 20 cm away (radially) from the shield wire pattern, centered +/- 1 cm (longitudinally) with respect to the primary coil. For these measurements, the primary and shield were driven in series by an AE Techron power amplifier (model 7796) programed to produce a 1.77 kHz sinusoidal current waveform. The relative position of the shield coil with respect to the primary was systematically varied along the longitudinal direction in order to identify the position yielding minimal radial flux. Once this optimal position was determined, the entire primary/shield system was vacuum potted with epoxy using an air cycling method [5].

Results and Discussion:

The shield designed for the realistic primary current density gave a theoretical improvement in shielding efficiency (field produced at center of imaging region/maximum fringe field at radius of 50 cm) of approximately 15%. Figure 3 compares the simulated eddy-current-induced fields for the realistic shield and the ideal shield. Figure 4 displays the experimental radial magnetic flux values plotted along with theoretical values, as a function of shield-primary longitudinal displacement. As expected, the minimum radial flux occurs when the shield is centered with respect to the primary solenoid. These results also provide a specification for primary-shield alignment, suggesting that an approximately 1 mm shift between the two would be the maximum allowable alignment error. These results indicate that if construction-specific details are included into the shield design, the eddy-current fields produced by a dreMR Bo coil can be maintained (prior to the application of any active eddy-current compensation) at under 0.01% of the applied field. This performance is critical for the successful implementation of robust dreMR systems going forward.

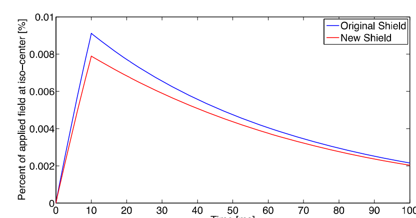

Figure 3. Induced field at iso-center caused by eddy-currents generated on a cylindrical copper surface (radius 0.5 m, length 1 m) due to driving the dreMR system at typical values (rise-time = 10 ms, field-shift = 0.3 T.) The induced field is expressed as a percentage of applied field shift.

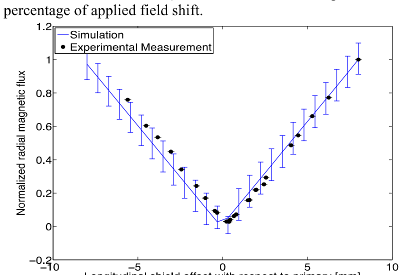

Figure 4. Normalized radial magnetic flux measurements for various longitudinal displacements of the shield coil with respect to the primary. The flux was calculated over a 4 cm (x-axis) by 2.5 cm (z-axis) region approximately 20 cm away from the shield, centered on the primary coil within 1 cm.

References and Acknowledgements:

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