Forces and Torques on Small Animal Insert Gradient Coils

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Introduction: There are a growing number of facilities worldwide using insertable gradient coils within otherwise normal whole-body MRI systems. In some cases these gradient inserts are used for preclinical imaging of small animals, and in others they are used for human imaging of specific anatomical areas such as the head or extremities. Gradient inserts are typically only temporarily used within a scanner, and are therefore portable and designed to slide easily into the magnet bore. There has always been a question of potential dangers due to possible unbalanced Lorentz forces and torques exerted on the insert gradient coil by the main magnet. Under normal imaging conditions and symmetric gradient designs placed centrally within the magnet, the force and torque are typically approximately zero; however, there exists the potential for large net forces and torques when: (a) coils experience a failure; (b) coils are positioned somewhere other than the centre of the magnet during operation; or (c) some combination of these two circumstances. To the authors' knowledge, there is no existing literature in which these failure modes are systematically studied for small insertable gradient coils. The goal of this study is to identify a "Safe Region" for coil operation, representing a spatial region within the bore of a realistic magnet within which any given rotation, position or failure mode of the coil results in net forces and torques sufficiently small as to not result in significant coil motion.

Method: The magnetic field of a realistic actively shielded superconducting magnet was simulated for this study [1]. This magnet has a one-meter bore and produces a field of 1 T, which allows for easy scaling. Transverse gradient coils with a length-to-diameter ratio of two and a constant inductance of 200 μH were simulated for radii of 5, 10, 15 and 20 cm. The wires of the gradient coils and main magnet were approximated by a series of short current-carrying elements for calculations of magnetic field etc. To quantify the effects of positioning errors of the inserted coil, a series of geometries was considered where the centre of mass of each gradient coil was placed at different positions relative to the isocentre of the main magnet. Additionally, at these positions the gradient coil was also rotated by -23, -11.5, 11.5 and 23 degrees about the x-axis from its position of symmetry. Since only the magnitude of force or torque was of importance only rotations about the x-axis were performed at each position. The "Safe Region" of operation is mapped out by considering all positions where the net force on the gradient insert is less then 10% the force of gravity, for a Gy coil, and the torque on the coils is less then 10% the force of gravity in Nm for any combinations of angular mis-alignments up to 23 degrees and any failure mode. For transverse coils that had four fingerprint quadrants 16 possible modes (15 of which are "failure modes") of operation exist. Considering that only the magnitude of force or torque was important, symmetry was used to reduce the number of operation modes investigated to 6 possible shorts: one quadrant, opposite quadrants, upper quadrants, one sides quadrants, three quadrants and working normally. The masses of all 4 quadrants was approximated based on the density of a commonly used epoxy. The mass of each coil was approximated as 12.5 kg, 25 kg, 50 kg and 100 kg for the 5 cm, 10cm, 15cm and 20 cm coils respectively. When the locations of centre of mass to position the coil were chosen, the geometry of the gradient coil relative to the main magnet was considered so that only physical placements were considered.

Results/Discussion: The "Safe Region" in figure 3 displays a region where the net force on a 5cm radius gradient insert, carrying 300 A and in a main field of 3.0 T, is less then 10% the force of gravity in N and the torque is less then 10% the force of gravity in Nm. So if the centre of mass of the 5cm coil is located at any location in the "Safe Region" the forces and torques will not be large enough to cause the coil to move, and its operation can be considered safe. The " Safe Region" for the coils of radii 10 cm, 15 cm and 20 cm showed a similar geometry but the volume of the " Safe Region" decreased as the radius of the coil increased. The volume of the " Safe Region" for the 5 cm coil, carrying 300 A and in a 3.0 T main field, was approximately 1.4 e-1 m^3 and this decreased to approximately 2 e-3 m^3 for the 20 cm coil, carrying 300 A and in a 3.0 T main field.

References:

[1] Cheng, Yu Chung N. et al. IEEE transactions on Applied Superconductivity vol14.No3. Sept 04 pgs 2008-2014

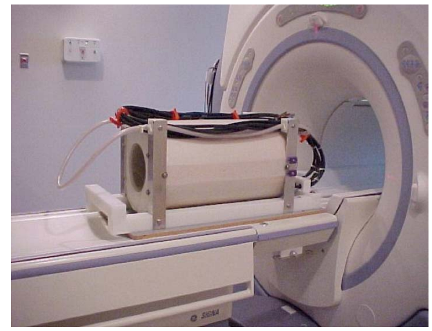

Figure 1: A small animal insert gradient coil before implementation in a MR main magnet

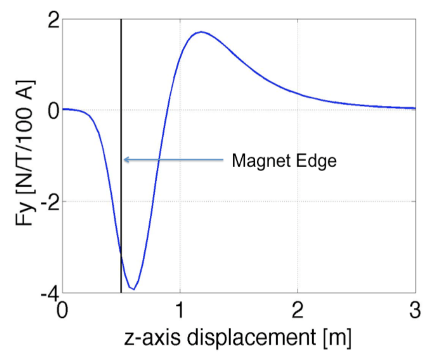

Figure 2: Fy forces on a 5 cm Gy transverse coil carrying 100 A and in a 1.0 T main magnetic field for varying centre of mass locations along the z-axis

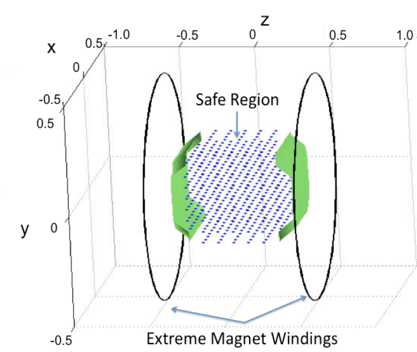

Figure 3: The Safe Region, representing where the net force is less than 12.25 N and the torque is less than 12.25 Nm, for a 5 cm Gy transverse gradient coil carrying 300 A and in 3.0 T main field