EFFECT OF SUPERCONDUCTING COMPONENTS ON IMAGING FIELD HOMOGENEITY IN ULTRA-LOW-FIELD MRI

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Introduction

In a classical MRI setup the MR signal scales as a square of imaging field B_0; thus most of the development of medical MRI scanners to date was focused on high-field magnetic resonance using magnetic fields of several tesla. Ultra-low-field (ULF) MRI adopts, on the other hand, a different approach to increasing SNR: instead of using high B_0 for achieving acceptable SNR, it relies on extremely sensitive superconducting quantum interference device (SQUID) detectors and employs separate prepolarizing field, making SNR independent of B_0 [2]. This approach allows MR imaging in microtesla fields, which provides a number of advantages over conventional high-field MRI: low cost, better patient safety, higher immunity to imaging field inhomogeneities, silent operation and enhanced T_1 contrast. Our ULF MRI experimental setup at Aalto University [4] contains superconducting components that are placed close to the imaging volume. These are superconducting niobium shields used for protecting SQUIDs from prepolarizing field [3] and two coils – prepolarizing and compensating – made of a composite material (superconducting niobium filaments in a copper matrix). We estimate the impact of these components on the homogeneity of B_0 for various geometric arrangements and, in case of SQUID shields, devise strategy for optimal placement.

Methods

We computationally model distortions introduced into an external homogeneous magnetic field by SQUID shields and the prepolarizing and compensating coils using finite elements methods. The modeling is done with COMSOL software. The impact of the coils is modeled by assigning them anisotropic effective magnetic permeability. The question of effective magnetic permeability of superconducting/normal composite materials has been previously investigated (e.g., see [1]), however analytical results derived are based on simplifying assumptions about the material geometry that do not strictly hold in our setup. For example, a formula for effective permeability of a multifilament superconductor derived in [1] is only strictly valid in a limit when the diameter of individual filaments goes to zero while keeping the total fraction of the superconducting material constant. Using a numerical simulation we investigate the applicability of theoretical results to the geometric configuration of our coils' filament structure. We then model the distortion introduced by the coils into the imaging field by modeling the coils as bulk solids with effective permeability computed above.

The plates are modeled as solid blocks of size 11x11x2 mm placed around SQUID sensors in pairs with 2 mm separation and posessing zero magnetic permeability.

Results

Numerical simulations have indicated that the analytical formula for effective permeability of multifilament composite superconductor is accurate enough over a wide range of different filament geometries (fig. 1) and can be used for modeling superconducting coils as solids, which greatly simplifies simulations. The distortion due to the coils alone was less than 0.5% anywhere inside the imaging volume (fig. 2). Image degradation due to such inhomogeneities is comparable to degradation due to other technical limitations of our current system, meaning that images can be acquired with this configuration. Imaging field distortion caused by SQUID shields depends considerably on SQUIDs' positions, with minimal distortion being achieved when the SQUIDs (and thus also shields) are parallel to the B_0 field lines (fig. 4).

Discussion

Since MRI experiment is sensitive to the absolute value of the imaging field inhomogeneity, ULF MRI is much more immune to relative field distortions (such as the distortions introduced by the presence of superconducting components), since in lower field the same relative inhomogeneity translates into lower absolute inhomogeneity. This allows the use of superconducting materials close to the imaging volume if their geometry is carefully optimized.

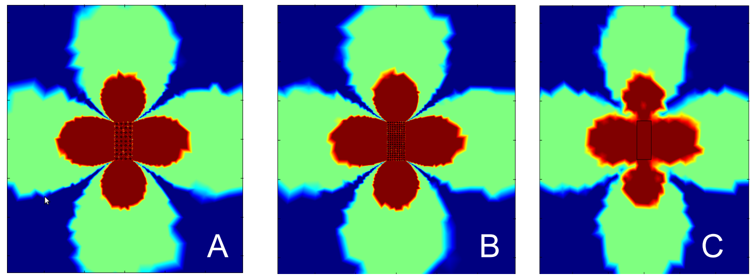

Figure 1: Distortion of the external magnetic field by infinite multifilament superconductor of a rectangular cross-section perpendicular to the image plane. The external magnetic field in the absence of the superconductor is homogeneous with field lines going from right to left. Green areas mark distortion of 0.5%, red – 1 %. **A.** Coarse filament structure. **B.** Fine filament structure. **C.** Theoretical limit of infinitesimally fine structure.

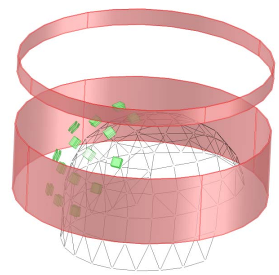

Figure 2: Geometry of our numerical simulations. The inner surface of the helmet (approximately patient's head's surface) is marked by the mesh. SQUID shields (green) are depicted here located above occipital areas. The pre-polarizing (lower) and compensating (upper) coils are colored red and are symmetrical with respect to the vertical axis. B_0 field lines are horizontal going from patient's right to left.

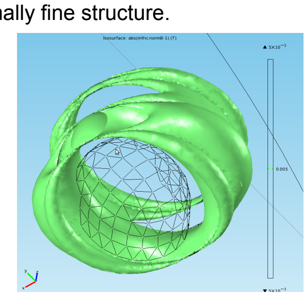

Figure 3: Imaging field distortion due to coils only. Green surface encloses the volume with distortion of more than 0.5%.

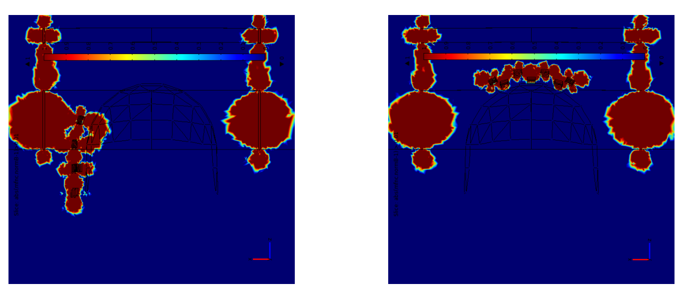

Figure 4: Distortion of the imaging field due to both, coils and SQUID shields (mid-sagittal cross-section). **A.** SQUIDs are located over right temporal area. **B.** SQUIDs are located over dorsal area. Red areas mark distortion of more than 1%. External magnetic field in the absence of any superconductors is homogeneous with field lines going from right to left.

References

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