A High-Temperature Superconducting Volume Coil for Magnetic Resonance Microscopy at 9.4T

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Introduction

In magnetic resonance microscopy where the radiofrequency coil is an important source of noise, superconducting coils are of particular interest as their zero resistance increases the amount of signal recorded, while their low temperature decreases the noise contribution from the coil. Signal-to-noise ratio improvements as large as a factor of 10 have been reported using superconducting coils as compared to copper coils of similar dimensions [1]. We present here an Yttrium Barium Copper Oxide (YBCO) superconducting volume coil designed for magnetic resonance microscopy of the mouse brain at 9.4T. The probe consists of two spiral coils in Helmholtz pair configuration.

Method

The superconducting receiver meets the following requirements: (a) the imaging volume is 10mm x 10mm x 20 mm, (b) the quality factor of the coil is larger than 2000, (c) the coil resonance frequency can be manually adjusted and is stable over periods of several hours to less than 10% of the imaging bandwidth, (d) the match can be adjusted, (e) 60% of the radiofrequency excitation is preserved over 80% of the imaging volume, and (f) the superconducting coil is flat.

The coil configuration presents several advantages. The length of the spiral conducting trace can be shortened to increase the coil resonance frequency, by manually isolating a segment of the trace from the trace supporting the resonant mode (Fig. 2). The spacing between the Helmholtz coils can be adjusted to tune the resonance frequency of the probe. The spiral has been modeled using HFSS (Ansoft, Pittsburgh, PA), a finite-element radiofrequency simulation software. Electrical field lines predominantly link adjacent traces and minimize travel through the sample, limiting dielectric losses.

The two superconducting coils, tuned individually to 410 MHz, are attached to ceramic heat-exchangers containing recirculating helium. The temperature of helium for cooling is tightly controlled upstream to 57+-0.2 K to prevent drastic changes in coil quality factor and resonance frequency [2] by a custom-built cryogenic cooling system (Creare Inc., Hanover, NH). Vacuum is maintained inside the probe housing to limit heat conduction towards the cold coils. The spacing of the coils can be adjusted manually to tune the probe in-situ during operation. The position of the coupling loop and the probe match can be adjusted between experiments. A room-temperature shield is wrapped around the ceramic housing of the probe to limit radiofrequency noise.

The probe quality factor Q was recorded through the matched coupling loop circuit from the reflected power S_{11} on a 4195A network analyzer (HP, Palo Alto, CA).

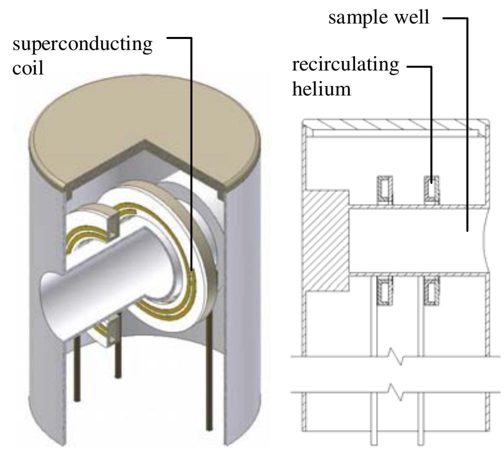

Figure 1: schematic of the superconducting volume coil.

Results and Discussion

The resonance frequency of an individual coil shows excellent agreement between model and experiment (Fig. 2). The sample-loaded probe resonance frequency can be precisely controlled between 398.2 MHz and 400.9 MHz inside our 9T magnet by adjusting the coil spacing from 11 mm to 13 mm.

Experimental field intensity profiles (Fig. 3) were recorded using a phantom containing a 1:500 solution of distilled water and ProHance (Bracco S.p.A., Milano, Italy).

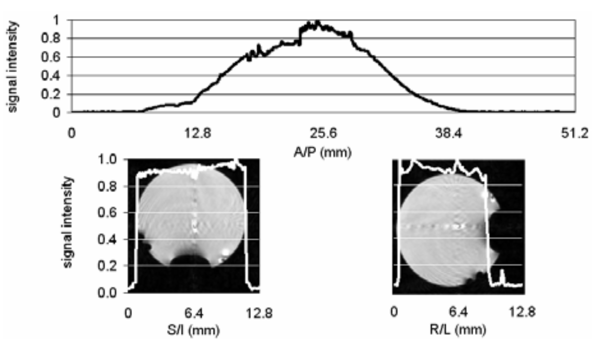

Figure 3: Intensity profile across a water phantom. 60% of the maximal radiofrequency excitation is preserved over at least 10 mm in the three orthogonal directions.

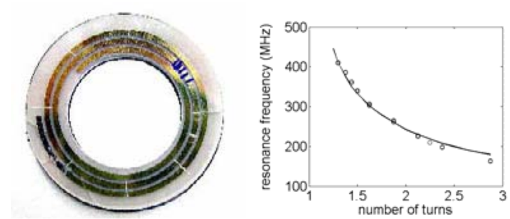

Figure 2: Segments of the superconducting spiral coil are manually isolated during tuning (left). The resonance frequency increases as the untrimmed segment becomes shorter (right). The measurements (dots) correspond well to our finite-element radiofrequency simulation (line).

The superconducting probe demonstrated a factor of 8 improvement in loaded Q compared to a copper solenoid coil of similar dimensions. Under the assumption that the sample is an important source of noise, an improvement in signal-to-noise ratio of square root of 8 can be expected, whereas a direct factor of 8 can be expected if the coil is the dominant source of noise. In addition, an increased coil quality factor translates itself into a signal-to-noise ratio improvement depending on the coil filling factor, the excitation homogeneity, and the noise temperature of the imager radiofrequency chain.

Table 1: Quality factors and extent of the area where 80% of the radiofrequency excitation is preserved, for a copper solenoid coil and the superconducting probe.

	Copper Solenoid Coil	Superconducting Helmholtz Pair
Q	380	3000
60% B_1 homogeneity	40 mm	10 mm

Conclusion

Superconducting spiral coils in Helmholtz configuration can be easily tuned and offer good radiofrequency excitation homogeneity. A large improvement in quality factor was recorded, as compared to a copper solenoid coil. The improvement in signal-to-noise ratio is currently being investigated.

References

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