# A Superconducting Probe for High-Throughput Magnetic Resonance Histology at the Diffusion Limit

**J. C. Nouls[1], and G. A. Johnson[1]**

[1]Center for In Vivo Microscopy, Duke University Medical Center, Durham, NC, United States

## Introduction

The fundamental resolution limit in biological magnetic resonance microscopy is defined by motion –macroscopic motion for live animal studies [1] and microscopic diffusion for tissue specimens [2]. In studies of inanimate objects a number of authors have acquired images at the diffusion-imposed limit, usually with specialized phantoms or over a very limited field-of-view where microscopic radiofrequency coils can achieve the required sensitivity [3].

We present here a second generation yttrium barium copper oxide superconducting volume coil for high-throughput, high-resolution magnetic resonance histology of the entire mouse brain at 9.4T. A custom-built cryocooler maintains the probe at 60K for several days, while sample replacement and probe retuning can be carried out promptly and repeatedly. The very high quality factor of 5000 increases signal-to-noise ratio, which is used to reduce acquisition time at a spatial resolution unreachable with copper coils. We demonstrate 10x10x20 micron resolution images of the mouse brain and a resolved mesh with opening size of 20 micron.

## Method

The probe consists of two superconducting spiral coils in Helmholtz pair configuration. The distance separating the coils can be adjusted after specimen loading to retune the probe, which is inductively coupled and matched to the radiofrequency chain.

Finite-element simulations (HFSS, Ansoft, Pittsburgh, PA) validated by copper mimic coils were used to optimize: i) the physical dimensions of the receiver and the desired Larmor frequency, ii) the geometry that realizes a power match with the radiofrequency chain, iii) the impact of lossy materials on the quality factor, iv) the probe tuning capability. Agreement between simulations and experiment was excellent allowing iterative optimization of all of the elements (figure 1).

All work was performed on a vertical bore 9.4 T magnet interfaced to a General Electric EXCITE (EPIC 12.0) imaging console. The radiofrequency chain was modified to accommodate the high output power levels from the superconducting coils by extending the linear range of the amplifiers. A custom 3D encoding scheme was implemented with accompanying reconstruction software to accommodate image arrays up to $4096^3$. The effective dynamic range of the digitizer was extended by systematically increasing the receiver gain as Fourier space is sampled from the center to the periphery. Acquisition time was reduced by the use of an asymmetric partial Fourier sampling algorithm and actively stained specimens [4] allowing use of short repetition time (TR≤100ms).

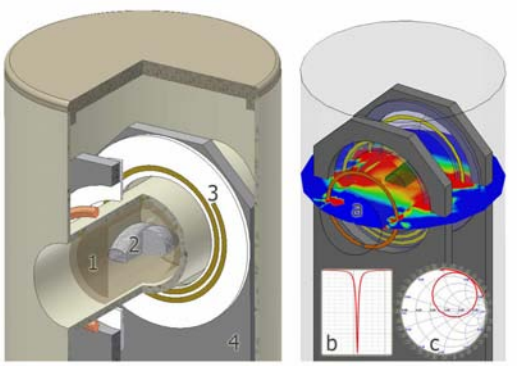


**Figure 1**: (right) Radiofrequency simulations typically predict resonance frequency and quality factor (b), power transfer (c) and field homogeneity (a). In the implemented design (left), the cartridge (1) containing the mouse brain (2) sits between superconducting coils (3) on low loss beryllium oxide heat exchangers (4).

## Results

A three-dimensional gradient-recalled array of a mouse brain was acquired in 17 hrs at a 10x10x20 micron resolution using the superconducting probe. An identical sequence was used to image a resolution phantom containing a polyester mesh (Small Parts, Miami Lakes, FL) with an opening size of 20 microns. Representative images are shown in Figure 2.

The performance of the superconducting probe was compared to a copper mimic probe. The unloaded quality factor is 5000 for the superconducting probe and 250 for the copper probe. Two 256x256x32 three-dimensional gradient-recalled arrays of a mouse brain slab were acquired in 14min at a 40x40x160 micron resolution with the superconducting probe and a copper mimic (TR=100ms, TE=4.0ms, BW=62.5kHz, NEX=1, full k-space sampled). Signal-to-noise ratio improved from 35 with copper to 76 with the superconducting probe, by a factor 2.2.

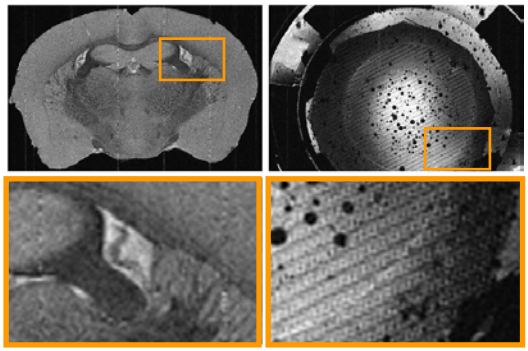

**Figure 2**: cross-sections through a mouse hippocampus and a mesh with opening size of 20 micron with respective SNR of 21 and 19 (GRE, RES 10x10x20micron, TR 100ms, TE 5.5ms, DIM 1024x1024x1024, FOV 10.64x10.64x21.28mm, BW 62.5kHz, NEX 1, asymmetric 75% k-space sampling).

## Discussion

An image at 10-micron in-plane sampling reveals anatomical details in the mouse brain unseen at lower resolution. The 20 micron mesh is clearly resolved with the 10x10 micron in plane sampling.

The implementation of the following steps is scheduled to resolve current limitations so that signal-to-noise ratio increases further, enabling higher throughput and resolution:

- Increase the cooling capability of our 850 mT/m gradients to allow shorter TR;
- Replace the coils with the next generation of superconducting films exhibiting lower AC surface resistance to increase signal further. Simulations indicate that the probe quality factor should reach 10'000 with non-degraded films (figure 3);
- Cool resistive components before and possibly including the preamplifier to decrease noise.

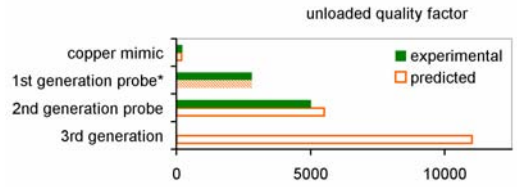


**Figure 3**: for different probes, experimental quality factor (full bar) and predictions from simulations (hollow bar).

*the equivalent surface resistance of the superconducting film was chosen so that quality factors are identical. The 2nd generation validated quality factor predictions.

## Conclusions

While the promise of superconducting probes has been tantalizing, realization of that promise has been hindered by practical engineering challenges and optimization of the entire imaging chain. The use of simulations has allowed us to systematically understand the most critical limitations. The construction of a robust mechanical system with cryocooler has provided an experimental platform to test the simulations. Routine imaging of tissue specimens at the diffusion limit is finally a reality.

## References

[1] Mai, W, Magnetic Resonance in Medicine, 2005. 53(4): p. 858-865
[2] Callaghan, PT, Journal of Magnetic Resonance, 1988. 78: p. 1-8
[3] Cho ZH, Philosophical Trans. of the Royal Society of London, 1990. 333(1632): p. 469-475
[4] Johnson, GA, Radiology, 2002. 222(3): p. 789-793