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Coil extensions improve line shapes by removing field distortions

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ABSTRACT

The static magnetic susceptibility of the rf coil can substantially distort the field B_0 and be a dominant source of line broadening. A scaling argument shows that this may be a particular problem in microcoil NMR. We propose coil extensions to reduce the distortion. The actual rf coil is extended to a much longer overall length by abutted coil segments that do not carry rf current. The result is a long and nearly uniform sheath of copper wire, in terms of the static susceptibility. The line shape improvement is demonstrated at 43.9 MHz and in simulation calculations.

1. Introduction

In NMR, the rf coil is generally as close as possible to the sample, to enhance signal-to-noise ratio. As a result, the magnetic field at the sample arising from the static susceptibility of the coil material can have large deleterious effects on the overall field uniformity and NMR line shape [1–3].

Consider a scaling argument, with two samples and their rf coils differing by a factor of ten in every linear dimension. Every corresponding piece of the smaller rf coil has 1/10 the linear size and 1/1000 the volume and mass of the larger coil. The magnetic moment m is $m = \chi B_0 V/\mu_o$, with χ the susceptibility, B_o the externally imposed static field, V the volume of the coil piece, and μ_o the permeability of free space (a constant, $\mu_o = 4\pi \cdot 10^{-7}$ in SI units) [4]. Thus, a corresponding piece of the small coil has 1/1000 the volume and magnetic moment as in the large coil. Hence one might think the field distortion in the small coil would be negligible. However, dipole fields vary as $1/\text{distance}^3$ [4] and the relevant distance from coil piece to sample is 1/10 as long for the small coil; thus the small coil with its 1/1000 moment produces the *same magnetic field* as in the large coil case. As a result, in this scaling example, the field shift and field distribution and nmr line shape would be the same for the two cases, large and small.

This result can be obtained more generally through dimensional analysis [5]. Consider a geometry with a *fixed* ratio of wire size, coil length, turns spacing, and coil radius R. The distortion field b arising at (say) the center of the coil from the magnetic susceptibility of the coil material must be in field units (Tesla) and must be a function only of the input parameters to the problem. The only possibilities for the parameters are the field B_0 (in Tesla), the dimensionless susceptibility χ, the radius R (in meters), and the constant μ_o (in Tesla∗meter/amp). Inspection reveals that there is no way to combine these input parameters to yield b (in units of Tesla) that involves the radius R. Thus R cannot be involved in the field distortion strength b. Of course, χB_o times any dimensionless number has the correct dimensions and is the correct answer.

In practical situations, the field distortion will generally be larger in microcoil nmr [6], because the coil wire size is typically a larger fraction of the sample diameter. At large sizes, rf skin depth effects lead to no improvement in rf performance when using excessively thick wire, so thin or flattened or plated-on rf coils [1] can reduce the field distortion from the coil, without penalty in the rf performance. But at small sizes, such as 150 μm diameter sample tubes, 50 AWG wire (25 μm diameter) will be useful and not much larger than a skin depth [7,8]. Further reduction in wire size would decrease the rf performance. This wire is a substantial fraction of the sample size; the proportionately larger wire in the microcoil case results in larger field distortions.

The scaling argument above implies that the magnitude of the field distortion for scaled coils (hypothetically having all linear dimensions scaled equally) would be the same at all scales. Then the second spatial derivatives (say) of the field scale as the inverse square of the length scale. Thus, to correct the higher derivatives

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arising from a microcoil's susceptibility would require very strong correction coils, which are often not available.

There are methods to reduce the effect of the rf coil's susceptibility. One method is to use a wire constructed with both positive and negative susceptibility materials (e.g., copper and aluminum) physically joined in the correct proportions in order to have zero net susceptibility [1]. This susceptibility matching solution is popular in the large nmr firms but hard to duplicate in a small shop ("build it yourself"), though at least one vendor can supply compensated wire of 0.5 mm diameter and larger [9]. For the very fine wire sizes used for microcoils [6–8], producing zero susceptibility wire seems difficult. One can use wire that is thinner (compared to optimum for rf) and endure the decrease in rf performance [10]. A successful method is to immerse the rf coil in a fluid whose susceptibility matches the rf coil. The U. of Illinois group used a Fluorinert liquid [11–14], avoiding hydrogen nmr signals from the fluid (Fluorinert is fully fluorinated). The difficulties in maintaining the fluid-filled chamber through sample changes are unattractive, however. We note that an elliptical volume of susceptibility-compensated epoxy surrounding the rf coil has been reported [15,16]; a long cylinder should be equally effective.

We report here the use of simple extensions of the rf coil to reduce the distortion of B_o.

2. Coil extensions

Fig. 1 presents a short rf coil with nearby extensions. In use, the two coil extensions are positioned to be in physical contact with the rf coil, eliminating the gaps or separations and creating a long, uniform winding along the sample tube axis, from the dc susceptibility viewpoint. The extensions are electrically insulated from the rf coil, so no rf current flows in the extensions; the nmr sensitive region is within and near to the central rf coil. The goal is to avoid rf current in the extensions; at modest nmr frequencies, this is ensured by the open-circuit ends of the extensions. Thus, the extensions could be electrically connected to the rf coil itself, if this were more convenient. At very high frequencies, stray capacitance could allow rf current to flow on the extensions; segmenting the extensions into multiple electrically disconnected pieces would help to reduce this current.

For a uniformly magnetized, right cylindrical annulus that has length L much larger than its diameter d, $L \gg d$, the field inside the annulus is zero (except near the ends). This result from magnetostatics holds whether the magnetization is along or perpendicular to the cylinder axis. The result is put to use whenever nmr samples are held in long, uniform glass tubes (the glass has nonzero susceptibility). For the coil with extensions, the result says that field distortion from the coil plus extensions will be eliminated across the nmr-sensitive region provided (1) the extensions are long enough, (2) there are no gaps between the coil and extensions, (3) the discrete nature of the turns of wire can be neglected, (4) the wire material is uniform, and (5) the lead wires emanating from the rf coil can be ignored. This last item is approximately true, because there is only a short amount of lead wire *close* to the sample (we recall the inverse distance-cubed fall-off of dipolar fields). Item (1) above is similar to the routine use in high-resolution nmr of sample extending many diameters below and above the rf coil region [17]. Overall, the coil extensions function like susceptibility matching plugs for the short rf coil [1,18,19]. We note that a related method is in use for saddle-shaped rf coils [20], with the axial coil members extended well beyond the rf-active region. Item (3) above, the discrete nature of the turns of wire, represents a fundamental limitation to our approach. Further, such distortions, arising so close to the sample, are virtually impossible to remove with shimming; however, they can be reduced by using close-wound coils and extensions.

Fig. 1. Sketch of 4-turn rf coil with 8-turn coil extensions along the sample tube. The coil lead wires are represented as filled circles, with the leads oriented in/out of the page. The extensions' wires start and stop at the extensions (no leads). In use, the extensions are moved axially to be in contact with the rf coil. All segments are close-wound, in practice.

3. Simulations

The distortion magnetic field $\overrightarrow{\Delta B}$ arising from a point dipole magnetic moment $\vec{m}$ at vector displacement $\vec{r}$ is [4]

$$\overrightarrow{\Delta B} = \frac{\mu_o}{4\pi}\frac{1}{r^3}\left[3(\vec{m}\cdot\hat{r})\hat{r} - \vec{m}\right] \tag{1}$$

with $\hat{r} = \frac{\vec{r}}{r}$ We set $\vec{m}$ to

$$\vec{m} = \frac{\chi \overrightarrow{B_o} V}{\mu_o} \tag{2}$$

with external field $\overrightarrow{B_o}$ pointing in the $\hat{z}$ direction. Here $B_o = 1.03$ Tesla to match our experiments and $\chi = -9.6 \times 10^{-6}$ (dimensionless, in SI units) for copper.

A uniform winding of copper wire is situated around the sample tube, oriented along the $\hat{x}$ direction. This geometry is appropriate for iron-core electromagnets and permanent magnets [17]. Since we are only interested in the nmr frequency, $\omega = \gamma|B_o + \Delta B|$, and because $|\Delta B| \ll |B_o|$, we only keep the component of $\overrightarrow{\Delta B}$ parallel (or anti-parallel) to $\overrightarrow{B_o}$, namely ΔB_z [2,3].

We simulate with a 3 mm diameter sample and #26 AWG copper wire (wire diameter 0.4 mm). The rf coil itself is 4 turns (so 1.6 mm long); with both 13-turn extensions abutting the rf coil, the entire copper winding of 30 turns is 12 mm long. This ratio of wire diameter to sample diameter (0.13) is relevant to typical microcoils (recall the example above with 25 μm wire and a 150 μm sample diameter, a ratio of 0.17).

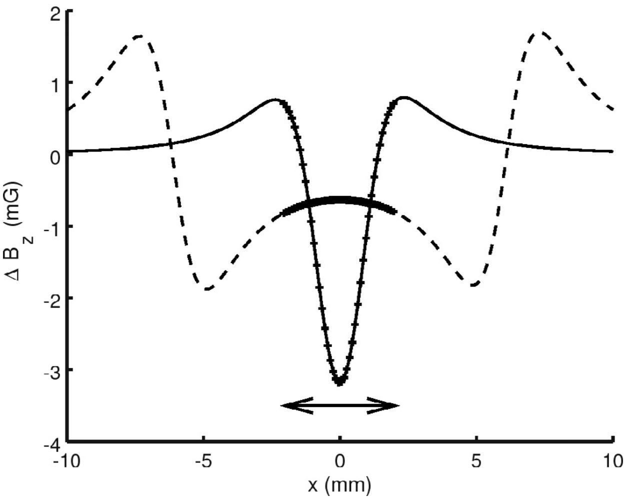

Fig. 2. Field simulation results for the field distortion ΔB_z due to the copper rf coil and the extensions (see sketch, Fig. 1), measured along the cylinder axis. The heavy arrow and crosses on the data curves show the 4 mm long rf sensitive region. Curves are shown without extensions (rf coil only, solid curve) and with extensions (dashed curve). The overall length of the coil with extensions is 12 mm.