Optimization of Low Frequency Litz-wire RF Coils

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INTRODUCTION

In MRI the patient or sample losses increase with the square of the resonance frequency. This makes coil losses significant at low field strengths.
It is well known (1) that for frequencies of several hundreds of kHz stranded or litz wires can have lower losses than conventional wires. Here we will investigate and present the optimization of copper solenoid coils for room temperature and for liquid nitrogen temperature.
For litz wire coils we distinguish three types of losses:
1. losses within each considered strand,
2. proximity losses in the surrounding strands and
3. eddy losses the environment of the coil (mainly determined by the sample losses). The losses within the considered strands are called skin losses. We will show that the maximum coil quality is achieved if the skin losses are equal to the proximity losses. The skin losses increase with increasing resistivity of the wire-material, while the proximity losses decrease with increasing resistivity. This means that the coil quality of an optimized coil for room temperature will decrease when the coil is cooled. For the lower resistivity an optimum coil can again be achieved by lowering the amount of winding material.
The low field RF coils presented in this paper have been developed for an 8.5 mT Overhauser imager. This imager is based on the Overhauser effect that is observable in free radical solutions (2,3). If electron resonance is induced before the nuclear resonance, a significant increase of the NMR signal can occur. In this way obtaining images of high quality at low magnetic fields is possible.

METHODS

The experiments and calculations are done at a solenoid coil. At low field strengths where the coil losses are larger than the sample losses the effective volume has a large impact on the SNR. The superior effective volume or filling factor of a solenoid makes this coil attractive for low field MRI. Given a sinusoidal current with rms amplitude I_{ac} the winding losses (skin and proximity) of a solenoidal coil are

$$P_{loss} = F_r I_{ac}^2 R_{dc} \qquad [1]$$

where F_r is a factor relating dc resistance (R_{dc}) to an ac resistance, which accounts for all winding losses. If the skin depth is much larger than the diameter of a single strand of the litz wire, we can ignore the increase of the resistance due to the skin effect. The approximate expression for F_r is than (4)

$$F_r = 1 + \frac{\pi\omega^2\mu_0^2 N^2 n^2 d^6 k}{192\rho^2 b^2} \qquad [2]$$

with ω the radial frequency of the sinusoidal current, n the number of strands, N the number of windings, d the diameter of the copper in each strand, ρ the resistivity of the copper conductor, b the diameter of the solenoidal coil, and k a factor accounting for field distribution in multi winding coils, normally equal to one.

The expression for the DC resistance (R_{dc}) is

$$R_{dc} = \frac{4\rho N b}{d^2 n} \qquad [3]$$

A substitution of the equations [2] and [3] in equation [1] gives:

$$P_{loss} = \left(\frac{4\rho N b}{d^2 n} + \frac{\pi\omega^2\mu_0^2 N^3 n d^4 k}{192\rho b} \right) I_{ac}^2 \qquad [4]$$

The first term of the right side of equation [4] specifies the skin resistance and will be replaced by an R_{skin} and the last term, that specifies the proximity resistance, is referred as R_{prox}. Equation 5 changes to

$$P_{loss} = (R_{skin} + R_{prox}) I_{ac}^2 \qquad [5]$$

Equations [4] and [5] show that the skin losses are proportional to the resistivity while the proximity losses are proportional to the conductivity. The total losses are minimized if the derivative of P_{loss} to ρ is zero.

$$\frac{dP_{loss}}{d\rho} = \frac{R_{skin}}{\rho} - \frac{R_{prox}}{\rho} = 0 \quad or \quad R_{skin} = R_{prox} \qquad [6]$$

Thus the maximum coil quality is achieved if the skin losses equal the proximity losses.

RESULTS

The results of table 1 concern solenoids with a single litz wire and with six parallel litz wires. The six parallel wires are placed above each other and twisted such that the losses in each parallel wire are the same. Both, the inner diameter and the length of the rat-coil are 70 mm. The single layer coil has 116 windings. The litz wire has a diameter of 0.6 mm, the number of strands is 100 and the diameter of each strand is 0.04 mm. Both coils have an inductance of ≈ 660 μH. The AC-experiments are done at a frequency of 356 kHz. In contrary with eq. [2] in our calculations we took the extra skin losses due to the limited skin depth also in account and used the method from Ferreira (1) of which [2] is an approximation. Eddy current losses of the environment, exclusive the sample, represent an experimentally checked Q of ≈5000. The values of table 1 are corrected for these environment losses.

Table 1: experimental and calculated results of a litz wire solenoid.

	77 K single wire		300K single wire		300K 6 wire
	experiment	calculation	experiment	calculation	calculation
R_{dc}	0.50	0.49	3.6	3.44	0.60
R_{skin}	0.52	0.49	3.62	3.44	0.60
R_{prox}	0.60	0.61	0.09	0.09	0.61
R_{tot}-R_{env}	1.12	1.10	3.70	3.53	1.21
Q	1318	1342	400	418	1220

At 77 K the single layer solenoid is almost optimised for maximum quality ($R_{skin} \approx R_{prox}$). For higher temperatures, optimisation can be achieved by using more winding material. Calculations show that for room temperature (300 K) a solenoid with ≈ six parallel wires has its maximum quality. If the windings are twisted in the best way the quality of a six-wire 300 K solenoid is approximately equal to the Q of a single layer 77 K coil. Thus, even for a "lossless" sample, the increase in MRI sensitivity is only due to the lower temperature of the coil resistance $(300/77)^{1/2}$. The increase in effective volume by the multi wire construction is largely compensated by the necessary isolation and cooling between sample and cooled coil.
Note that all the above applies only if the skin depth is large compared with the strand diameter. This is of course not so if super conductive wire is used. Then the conditions and equations are completely different.

CONCLUSION

The quality of litz wire coils are independent of the resistivity of the conductors' material if proximity losses can be made equal to the skin losses and the skin depth is small compared with the strand diameter. The advantages of cooling the coils are then limited to a lower noise temperature of the cooled coil resistance and a simpler coil construction.

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