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Quality factor of Bi(2223) high-temperature superconductor tape coils at radio frequency

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Abstract
Bi(2223) high-temperature superconductor (HTS) tapes have been chosen for radio-frequency (rf) coils in magnetic resonance imaging (MRI) applications recently. This is because they are easier to fabricate and adjust, and have lower costs compared to HTS films. We study the quality factor (Q) of Bi(2223) HTS rf coils in the rf range. Several rf coils with different sizes and resonant frequencies have been fabricated and the values of Q measured at 77 K. A theoretical model is developed to investigate the relationship of Q with coil size, solder joint and resonant frequency. The model shows that Q increases with larger size and higher frequency. The value of Q of a five-inch HTS tape coil is about six times higher than a copper coil with the same size, and is expected to have 2.5 times signal-to-noise ratio improvement in MRI.

1. Introduction

In recent years, high-temperature superconductor (HTS) materials used for radio-frequency (rf) coils in magnetic resonance imaging (MRI) have been reported [1–3] due to their advantages of much lower resistance and much better signal-to-noise ratio (SNR) compared to normal copper coils. So far, most HTS rf coils in MRI are fabricated into films. However, HTS films are generally very expensive, and require delicate design and precise fabrication to obtain the accurate resonant frequency. In many cases, for example, the conditions of tuning, matching or loading of coils need to be adjusted based on different applications, therefore the resonant frequency of HTS film coils is very difficult to adjust after fabrication.

As a different form of HTS material, Bi- and Y-based HTS wires and tapes have been increasingly developed in the past few years, while they are often focused towards applications in alternating-current (ac) power transportation, transformation and energy storage. So far, in only a few experiments [4] have there been attempts to study the characteristics of HTS tapes applied at rf or even higher frequency. Using HTS tapes for rf coils can be a good alternative for HTS films. The cost of HTS tapes is much lower than that of films, and they are expected to obtain high SNR gain in MRI as well. Several rf coils with different sizes and resonated at different frequencies have been fabricated. Their quality factor (Q) at liquid nitrogen temperature (77 K) is measured and a theoretical model to determine Q by coil size and resonant frequency is presented. The comparison shows that the theoretical model fits the experiment data very well.

2. Experiments and results

The Bi(2223) tape used for the experiments, provided by Australian Superconductors Company, consists of arrays of $(Bi_{2-x}Pb_x)Sr_2Ca_2Cu_3O_{10-y}$ using the powder-in-tube process, which is embedded in a pure Ag or alloy Ag matrix. The specifications are listed in table 1.

To build the rf surface coil, the tape has to be bent into a circle with a diameter larger than the critical diameter of the tape, as shown in table 1, otherwise its critical current will decrease significantly. A non-magnetic capacitor (American Technical Ceramics, US) with high Q (>2000) is soldered directly at both ends of the tape to form an LC resonant loop. The resonant frequency of the surface coil can be determined by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

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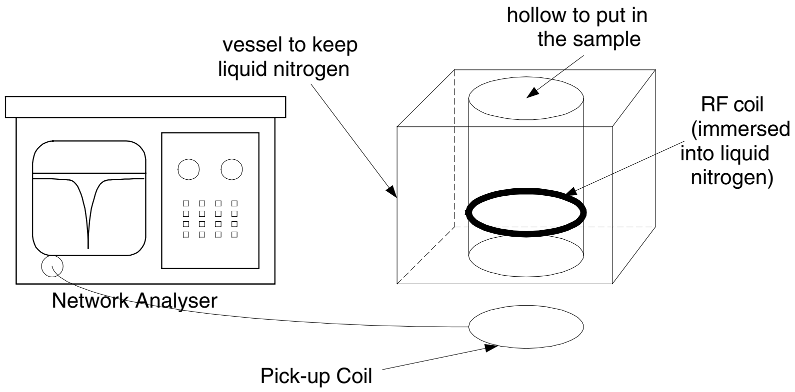

Figure 1. Experiment arrangement to measure the quality factor.

Table 1. General specification of Bi(2223) tapes.

Critical temperature	110 K
Critical current (77 K, self-field)	35 A
Critical diameter	60 mm
Thickness	0.25 mm
Width	3.50 mm
Number of filaments	61

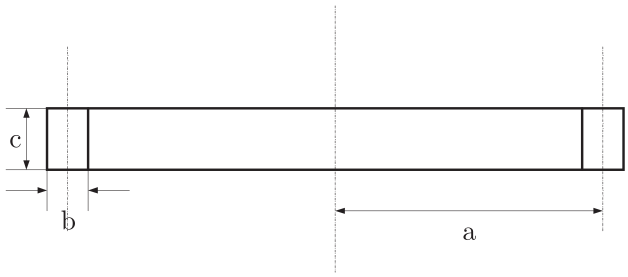

Figure 2. Cross-section of a HTS tape surface coil.

where f_0 is the resonant frequency of the surface coil, L is the inductance of the loop, and C is the capacitance of the capacitor, which can be chosen to obtain the specific resonant frequency required. Normally, an HTS tape has a silver sheath (Ag or Ag alloy) to increase its flexibility and strength for ac power applications. However, for the rf signal, the skin effect can be a serious issue, because the rf signal may only flow through the sheath, and the HTS actually does not play a superconducting role. To avoid the complete screening of the superconducting phase from the rf signal, it is necessary to dissolve the outer Ag or Ag alloy sheath of the tape. The skin depth of Ag at the rf region varies from about 6 μm at 100 MHz to about 60 μm at 1 MHz, which is usually smaller than the sheath thickness of the tape. The removal of the outer sheath is carried out by the chemical wet etching method [4]. The etching solution is based on ammonium hydroxide and hydrogen peroxide mixed in an equal amount of distilled water. Because the reaction is very intense, the coil should be fixed by a supporter to keep its original shape while having an etching bath.

The set-up of the experiment to measure Q is shown in figure 1 (the wave shape should be modified). The HTS tape is wound around the supporter to fix its position and then is immersed into the liquid nitrogen. The interior of the supporter is made hollow to insulate the sample from liquid nitrogen. A two-inch pick-up coil connected to an HP 8735C network analyser (Hewlett-Packard, Pole Alto, CA) is used to couple the rf signal to the HTS coil. This mutual inductive coupling is also used to match the HTS coil impedance with the source impedance by adjusting the relative positions between the pick-up coil and the HTS coil. The value of Q can be read from the network analyser using $S11$ (the reflection coefficient) directly.

The unloaded Q values for the HTS coils with different sizes and resonant frequencies at 77 K are listed in table 2.

3. Theoretical analysis

A theoretical model has been developed to deal with the relationship betweeen Q, coil dimension and resonant frequency. Q is normally defined by the ratio of the average energy to the energy loss per rf cycle, as shown in equation (2) [5]:

$$Q = \omega \left. \frac{\text{average stored energy}}{\text{energy loss per cycle}} \right|_{\omega=\omega_0}. \tag{2}$$

For an LC resonant loop (surface coil), its Q is often given by

$$Q = \frac{f_0}{\Delta f} = \frac{\omega_0}{\Delta\omega} = 2\pi f_0 \frac{L}{R} = \omega_0 \frac{L}{R} = \frac{1}{2\pi f_0 C R} \tag{3}$$

where f_0 and ω_0 are resonant frequency and resonant angular frequency of the loop, respectively, Δf or $\Delta\omega$ are the bandwidth of the resonant frequency at –3 dB, L is the inductance of the loop, C is the capacitance, and R is the total resistance given by the sum of the resistance of the coil itself and the equivalent resistance caused by the loaded sample.

In practice, the coil size and its resonant frequency are most important. Therefore, in our theoretical model for Q, the coil size and its resonant frequency are defined as basic parameters instead of the capacitance and the inductance.

The inductance of the coil is determined by its geometry, dimension and the magnetic medium around it. The geometry of the rf coil is circular with a rectangular cross-section, which is shown in figure 2. Here, a is the radius of the coil (if it is a multi-turn loop, a is the mean radius of the turns), b is the width of the tape, c is the thickness of the tape, and N is the total number of turns for a multi-turn coil.

Table 2. Coils characteristics and Q values at 77 K.

HTS coil	Diameter (mm)	Capacitance (pF)	Inductance (μH)	Resonant frequency (MHz)	Quality factor, Q (at 77 K)
Coil 1	56	39	0.125	72.08	809
Coil 2	65	10	0.160	125.82	1270
Coil 3	65	1000	0.152	12.91	396
Coil 4	127	1000	0.318	8.92	861

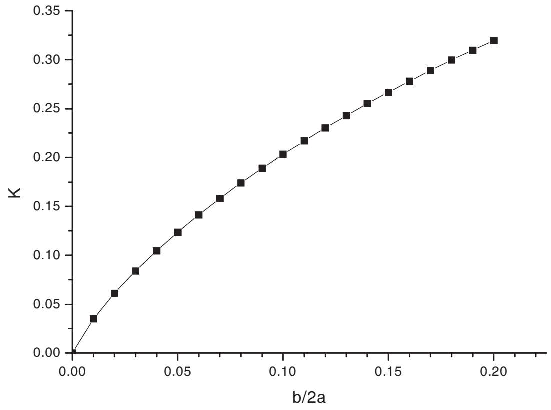

Figure 3. The K function.

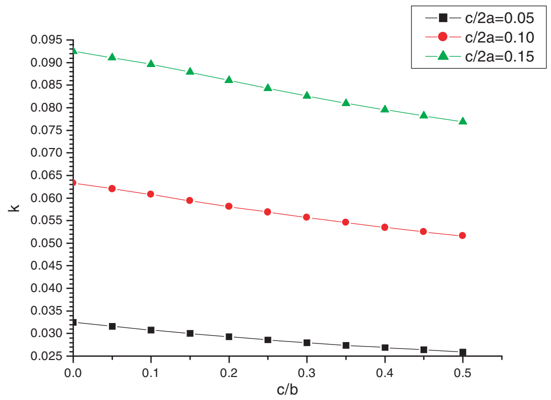

Figure 4. The k function.

For a thin coil ($c/2a < 0.5$, $b/c > 1$), its self-inductance can be obtained from [6]

$$L = 0.019\,739 \left(\frac{2a}{b}\right) N^2 a_{\mathrm{cm}} K' \tag{4}$$

where L is the self-inductance of the coil in microHenry (μH), a_{cm} is the radius of the coil in centimetres, and K' is the difference of $(K - k)$. The value of K is a function of $b/2a$, and k is a function of two parameters $c/2a$ and c/b. The parameters K and k are shown in figures 3 and 4.

The resistance of the coil includes two parts: the resistance of the HTS tape and the resistance contributed by the solder and the capacitor. The capacitors chosen should have much higher Q than the coils to minimize their effect on the measurements of coils' Q values. The resistance of a coil can be represented by

$$R_{\mathrm{total}} = R_t + R_s. \tag{5}$$

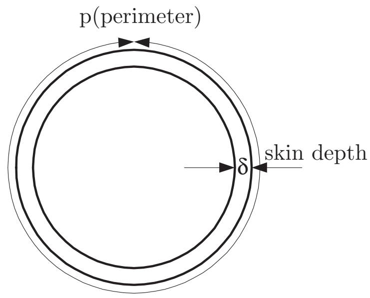

Figure 5. Calculation of cross-sectional skin area.

In equation (5), R_{total} is the total resistance of the coil, including R_t, the resistance of the tape, and R_s, the resistance of the solder. The skin effect should be taken into account while calculating the resistance of the solder at rf. The calculation can be represented by

$$R_s = \rho\frac{l}{S} = \rho\frac{l}{p\sqrt{\frac{2\rho}{\omega\mu_0}}} = \frac{l}{p}\sqrt{\frac{\rho\omega\mu_0}{2}}. \tag{6}$$

In equation (6), ρ is the resistivity of the solder material at the temperature of 77 K, l, p and S denote the length, cross-sectional perimeter and area of the solder respectively, and μ_0 denotes the permeability in free space. The item of $\sqrt{\frac{2\rho}{\omega\mu_0}}$ is the skin depth at the frequency of ω. Because the skin depth for common metals in rf is usually in the micrometre region, the cross-sectional area S can be calculated by multiplying the perimeter with the skin depth, which is demonstrated in figure 5. It is estimated that the resistance of the solder is about several to tens of milliohm.

At the temperature of liquid nitrogen, 77 K, the tape comes into the superconducting state. Its surface resistance R_t can be estimated by the two fluid models [7], which is expressed by

$$R_t = \tfrac{1}{2}\sigma_n\mu_0^2\omega^2\lambda^3 x \qquad \text{where} \quad x = (T/T_c)^4$$
$$\text{and} \quad \lambda = \lambda_0/[1-(T/T_c)^4]^{1/2}. \tag{7}$$

In equation (7), σ_n is the normal state conductivity of the material, λ and λ_0 denote the London penetration depth at the temperature T (K) and 0 K respectively. T_c is the critical temperature of the material. μ_0 and ω have the same meanings as in equation (6). Since the London penetration depth is usually of the order of 1 μm [8], it can be estimated that the surface resistance of the tape is several orders lower than that of the solder. Thus, it can be neglected in the total resistance safely in equation (5). Then the total resistance approximately equals the resistance of solder R_s.

Table 3. Experimental verification for equation (9).

Coil number	Diameter, $2a$ (cm)	K'	Resonant frequency (MHz)	Quality factor	$a^2 K' \omega^{1/2}/Q$ ($\text{cm}^2\ \mu\text{s}^{-1/2}$)
Coil 1	56	~0.1414	72.08	809	2.9162
Coil 2	65	~0.1236	125.82	1270	2.8903
Coil 3	65	~0.1236	12.91	396	2.9692
Coil 4	127	~0.0839	8.92	861	2.9416

Substituting equations (4) and (6) into equation (3), it is easy to obtain the following equation:

$$
\begin{aligned}
Q = \omega\frac{L}{R} &= \omega\frac{0.019\,739\left(\frac{2a^2}{b}\right)N^2K'}{\frac{l}{p}\sqrt{\frac{\rho\omega\mu_0}{2}}} \\
&= \frac{0.019\,739\cdot 2\sqrt{2}a^2N^2K'p\sqrt{\omega}}{lb\sqrt{\rho\mu_0}} \\
&= \left(\frac{0.019\,739\cdot 2\sqrt{2}}{\mu_0}\right)\left(\frac{a^2N^2K'}{b}\right)\left(\frac{p}{l\sqrt{\rho}}\right)\omega^{1/2}. \qquad (8)
\end{aligned}
$$

The length items in equation (8) should be represented in centimetres otherwise the constant 0.019739 should be adjusted. It can be seen from equation (8) that Q depends upon all the shape parameters of the tape coil, solder joints and resonant frequency. The item within the first brackets is a constant; the second reflects the influence on Q by the shape of the tape coil; the third item reflects the influence by solder joints; the last item reflects the influence by resonant frequency.

In our experiments, resin cored stannum solder is applied and soldering processes are operated by a machine to make the solder joints as uniform as possible to minimize the influence on Q. Therefore equation (8) can be simplified to

$$Q \propto \frac{a^2N^2K'}{b}\omega^{1/2}. \qquad (9)$$

The value of b corresponds to the width (3.5 mm) of the tape in table 1 and all coils fabricated are single-turn coils ($N = 1$). Table 3 gives the verification of the experimental data to equation (9).

Seen in table 3, the experimental data fit the linear relationship in equation (9) successfully. The errors are mainly due to the non-uniformity of the solder joints.

4. Conclusion and discussion

The rf coils using HTS tape have much higher Q values than copper rf coils, but their Q values are lower than HTS film because the coils using tapes have contact joints with the lumped capacitors. From equation (8), some methods can be applied to obtain higher Q. First, larger HTS tape coils have larger Q values. The radius of the coil is a major factor affecting its Q due to its square proportionality to Q. In addition, the Q value of a HTS tape coil is proportional to the square root of the resonant frequency. Due to these two reasons, HTS tape coils may be applied to large samples imaging at high-field MRI.

Equation (8) also shows that the solder joints can influence the Q value of the coil. The Q value can be further enhanced by using the solder with low resistivity or making the solder joints as thin as possible, to decrease their resistance.

The theoretical model indicates the relationship of Q to coil size and geometry, resonant frequency and solder joint. The model can be used to estimate the Q of the HTS coil before its fabrication.

A normal copper surface coil with a five-inch diameter is fabricated to compare with the HTS tape coil of the same size. The HTS tape shows an improvement of Q of over six times compared with the copper coil. Since the SNR is proportional to the square root of Q, the HTS tape coil is expected to have a SNR improvement of a factor of 2.5. The HTS tape coil has shown great advantages of easier fabrication and much lower cost than the HTS film rf coil, and its Q is much higher than that of copper coil. Therefore, it has a great potential to provide high SNR improvement for MRI applications.

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References

[1] Black R D, Early T A, Roemer P B, Mueller O M, Mogro-Campero A, Turner L G and Johnson G A 1993 *Science* **259** 793

[2] Miller J R, Hurlston S E, Ma Q Y, Face D W, Kountz D J, MacFall J R, Hedlund L W and Johnson G A 1999 *Magn. Reson. Med.* **41** 72–9

[3] Wosik J, Nesteruk K, Xie L-M, Strikovski M, Wang F, Miller J H Jr, Bilgen M and Narayana P A 2000 *Physica* C **341–348** 2561–4

[4] Grasso G, Malagoli A, Scati N, Guasconi P, Roncallo S and Siri A S 2000 *Supercond. Sci. Technol.* **13** L15–8

[5] Ludwig R and Bretchko P 2000 *RF Circuit Design: Theory and Application* (Englewood Cliffs, NJ: Prentice-Hall) p 205

[6] Grover F W 1962 *Inductance Calculations: Working Formulas and Tables* (New York: Dover) p 105

[7] Gorter C J and Casimir H B G 1934 *Physica* **1** 306

[8] Alford N McN, Button T W, Adams M J, Hedges S, Nicholson B and Phillips W A 1991 *Nature* **349** 680–3