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Investigation of Bi-2223 high temperature superconducting tape as the material for gradient coil in MRI

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Abstract

The use of Bi-2223 high temperature superconducting (HTS) tape as a material for gradient coils in MRI is evaluated in this paper. Bi-2223 tapes have a very high critical current and a very low power loss. A HTS tape gradient coil is expected to provide much higher gradient strength and generate much lower heating than a copper coil. Measurements of the AC power loss of Bi-2223 tapes at typical operating frequencies for gradient coils are presented. The degradation of the critical current and its effect on the increase of AC power loss is analyzed. Practical technical issues such as resistance, gradient strength and mechanical performance are also discussed. A prototype Bi-2223 HTS tape gradient coil is evaluated to verify the concept.

Keywords: Bi-2223 HTS tapes; Critical current; Power loss; Gradient coil; MRI

1. Introduction

The gradient coil system is an important component of the hardware in MRI scanners. It establishes linearly varying magnetic fields which are superimposed on the homogeneous static main field and performs a number of important functions including slice selection, frequency encoding and phase encoding. Gradient coil technology is a relatively mature technology in the field of MRI. The early introduction of the Maxwell pair for an axial gradient coil and Golay pairs [1] for transverse gradient coils was followed by the use of target field methods to design coils with larger homogeneous regions [2]. However, some developments in gradient coil design have been made in the last decade. Gradient coils with novel geometries [3–6] were introduced for applications in specific tissues or samples. Designs for these novel geometric gradients usually depend on novel mathematical methods. For example, spherical harmonics expansion has been used for hemispherical gradient coil design [6] and the stream function method has been extended to cylindrical geometry [7] and arbitrary geometry [8] gradient coil designs. With the rapid development of micro-imaging and fast imaging methods, gradient coils with faster switching times and longer continuous ratings are needed. The continuous gradient rating depends on gradient coil conductor losses and on the efficiency of cooling system; therefore gradient heating and cooling has become another focus of research [9]. Other concerns include patient comfort and safety, reduction of the acoustic noise of the gradient coil [10], and the limitation of nerve stimulation caused by the gradient fields [11].

From a design perspective, performances of a gradient coil may be evaluated by parameters such as maximum gradient strength, gradient efficiency, gradient linearity, resistance (R), inductance (L), time constant L/R, cooling effectiveness and acoustic efficiency. But it is hard to say which parameter is the most important, because these parameters all rely on each other and thereby a change in one affects them all.

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Bi-2223 HTS tape is the first practical HTS conductor and has already reached a commercial stage. The Bi-2223 tape is usually produced by the "powder in tube" (PIT) method [12]. It consists of arrays of $(Bi_{2-x}Pb_x)Sr_2Ca_2Cu_3O_{10-y}$, the effective superconducting material in the tape, embedded in a silver or alloy-silver matrix. The tape is sheathed by silver to enhance its mechanical strength. Bi-2223 tapes with critical current higher than 100 A at 77 K are available in lengths of tens of kilometers. Because of its low cost, high critical current, and long length Bi-2223 HTS tape is considered to be a promising material for power applications.

We suggest that the use of Bi-2223 HTS tape as a material for gradient coils could improve performance in many areas. Modern gradient coils are often required to provide high gradient strength and long continuous gradient performance without producing excessive heating. Bi-2223 HTS tape is able to carry a large current and consequently is able to provide much higher gradient strengths than copper, due to its high critical current density j_c. In addition, Bi-2223 tape can greatly reduce coil heating because of its much lower power loss.

In this paper, the feasibility of using Bi-2223 HTS tape in gradient coils is studied. First, the AC power loss of Bi-2223 tape is measured for a range of normal operating frequencies for gradient coils, from 200 to 2000 Hz. Contributions of hysteresis loss, eddy current loss and resistive loss to the total power loss are discussed. The AC power losses of Bi-2223 tape and copper wire are compared. Because a gradient coil has to work in a strong main magnetic field, the additional AC power loss of Bi-2223 tape due to critical current degradation in a strong static magnetic field is discussed. Finally, a prototype Bi-2223 HTS tape gradient coil was fabricated and evaluated. The gradient performance and heating of this coil were measured. In Section 5 resistance, gradient strength, cryostat and the mechanical performance of the HTS gradient coil are discussed. Some engineering issues such as jointing in the coil fabrication and their effects on the coil performance are also addressed.

2. Theory

2.1. Self-field AC power loss in Bi-2223 tape

The AC power loss in Bi-2223 tape is a fundamental property of the tape that should be investigated before the tape is used as the material for gradient coils. Previously, measurement of the power loss in Bi-2223 HTS tapes has focused on low frequency applications below 600 Hz [13–15] instead of the typical 1–2 kHz at which gradient coils work.

There are three main sources of AC power loss in Bi-2223 tapes which are different from the AC power loss in copper, which is mostly due to its resistance. These are hysteresis loss (Q_h), eddy current loss (Q_e) and resistive loss (Q_r). Hysteresis loss is caused by magnetic hysteresis in the superconducting filaments that is caused by the changing self-field of the wire. Eddy current loss is the resistive power loss in the silver sheath of the HTS tape due to eddy currents, which is caused by the inductive coupling of the current in the superconducting filaments to the conductive sheath. Resistive loss is the normal AC transport loss in the superconducting filaments. Although HTS tape has a much smaller resistance than normal metals, its resistance is not strictly equal to zero. The total power loss is the sum of these three sources of losses. The standard unit of power loss for HTS materials is Joules per meter per cycle (Q). This unit is chosen because the largest contribution to the loss of the tape is the hysteresis loss that occurs during each cycle. At frequencies below 200 Hz, the major contribution to the power loss is from hysteresis loss [16].

Hysteresis loss is described by the Norris model [17]. In this model the alternating current penetrates the superconducting wire with a concentric elliptical contour that is dependent on the position, current density and eccentricity of the wire but does not depend on the size of the wire. If a rectangular wire is very elongated, so that the superconductor approximates a thin strip, then at peak current the magnetic field is very close to perpendicular to the strip in those parts where current occupies the full thickness, and is very small and parallel to the strip in the other parts. Therefore, the hysteresis loss in a HTS tape with an elliptical cross-section is different from that with a rectangular cross-section. The hysteresis loss for these two geometries is described by the Norris elliptical curve and Norris strip curve in Eqs. (1) and (2), respectively:

$$\text{Elliptical curve}: Q_{te} = (\mu_0 I_c^2/\pi)[(1-i)\ln(1-i) + (2-i)i/2], \quad (1)$$

$$\text{Strip curve}: Q_{te} = (\mu_0 I_c^2/\pi)[(1-i)\ln(1-i) + (1+i)\ln(1+i) - i^2], \quad (2)$$

where I_c is the critical current of the tape, μ_0 is the permeability in free space and i is the current amplitude ratio normalized to the critical current. Note that the hysteresis losses in both the elliptical curve and in the strip curve are independent of the aspect ratio of the wire. These two models are valid when the current amplitude ratio i is less than 1.

The estimation of eddy current loss, Q_e, presented by Ishii *et al.* [18], is shown in Eq. (3):

$$Q_e \approx \frac{2\mu_0^2 I_p^2 \pi^2 f d^3}{\rho L}, \quad (3)$$

in which I_p is the peak current, f is frequency, d is the silver sheath thickness of the tape, ρ is the resistivity of the inner silver matrix at operating temperature and L is the perimeter of the outer filament layer.

The resistive loss in Bi-2223 tape is so small due to the almost zero resistance that it can be considered to be negligible except when the carrying current exceeds the critical current [16].

2.2. Critical current degradation of Bi-2223 tape

When Bi-2223 tape is used for gradient coils in MRI, we have to consider the AC power loss of the Bi-2223 tape in the static magnetic field produced by MRI main magnet. Unfortunately, Bi-2223 tapes have critical current degradation in a magnetic field. The physical mechanism for this degradation can be discussed either in terms of a vortex glass–liquid transition [19] or as a consequence of enhanced flux creep [20]. In addition, critical current degradation caused by a magnetic field is dependent on the orientation of the HTS grain with respect to the magnetic field.

In addition to the critical current degradation caused by a magnetic field, Bi-2223 tape also suffers critical current degradation due to tensile stress from bending. Bending stress usually results in fractures in some of the superconducting filaments in the tape. These fractures irreversibly reduce the critical current of the tape. Many studies have reported on the bending properties of Bi-2223 tapes [21–23]. This degradation is an intrinsic property of the superconductor and is related to the material properties of different tapes.

3. Methods

3.1. Bi-2223 tape and copper wire characteristics

The Bi-2223 multi-filamentary tape sample used in this study was provided by Applied Superconductivity Research Center, Tsinghua University, Beijing. Its specifications are listed in Table 1. The original critical current value of 80 A was measured using the DC transport method [24] with an electric field criterion of 1 μV/cm at the liquid nitrogen temperature of 77 K. This is a 61-filament tape.

Throughout this paper reference is made to the characteristics of single-strand copper wire at room temperature, in particular AWG 3 and AWG 17 sizes. AGW 3 wire is discussed because it has a current carrying capacity similar to the HTS tape, and AWG 17 wire is discussed because it has a similar cross-sectional area to the HTS tape. The characteristics of these two wire sizes are presented below for reference.

Table 1
Specifications of the sample Bi-2223 HTS tape

Tape thickness	0.24 mm
Tape width	4.10 mm
Number of filaments	61
Filamentary filling factor	∼25%
Critical current I_{co} (77 K, self-field)	80 A

AWG 3 wire has a diameter of 0.233 in. (5.827 mm) and a cross-sectional area of 26.7 mm^2. Its linear resistivity is 0.647 mΩ/m, and its power loss is $Q = 3.24 \times 10^{-4}/f$ J/m/s/A^2 for sinusoidal current with a frequency of "f".

AWG 17 wire has a diameter of 0.045 in. (1.15 mm) and a cross-sectional area of 1.04 mm^2. Its linear resistivity is 16.6 mΩ/m, and its power loss is $Q = 8.3 \times 10^{-3}$ J/m/s/A^2 for sinusoidal current with a frequency of "f".

At 1 kHz the skin depth of copper is about 2 mm, and so AC loss increases for copper wire of these sizes are very modest, about an 8% increase for AWG 3, and less than 1% increase for AWG 17.

3.2. Self-field AC power loss measurement

The total AC power loss in the Bi-2223 tape was measured in its self-field for several test currents and test frequencies. The experimental setup for total AC loss measurement is shown schematically in Fig. 1 [25].

The experimental procedure for this measurement is as follows. The tape was fixed onto a plastic plate and its ends were connected to the current leads with screws. An EG&G 7265 lock-in amplifier was used to set the measurement frequency and voltage. The two voltage taps on the HTS tape were placed $l = 4.1$ cm apart. The output voltage of the lock-in amplifier was used as input to the LAX MA2400 amplifier, to which a toroidal output transformer was connected to drive current. All measurements were carried out at liquid nitrogen temperature of 77 K. The frequencies

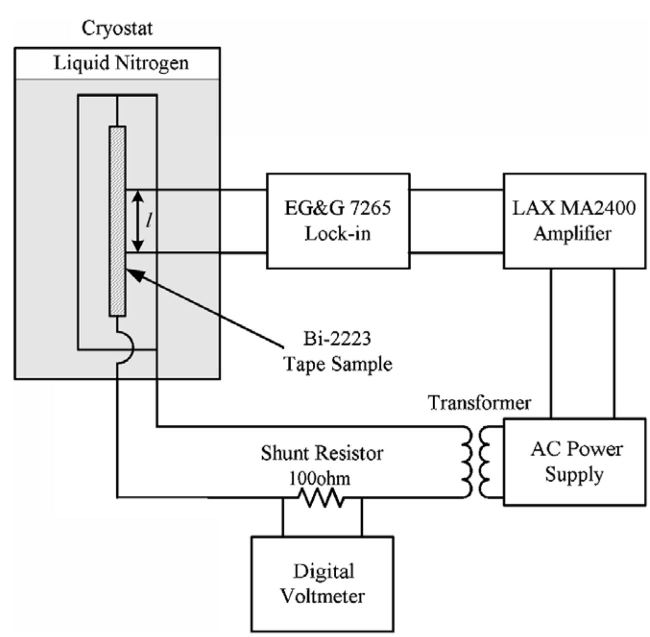


Fig. 1. A schematic block diagram of the Power loss measurement setup. The tape is fixed onto a plastic plate and placed in a cryostat filled with liquid nitrogen, with its ends connected to the current leads by screws. The two voltage taps are $l = 4.1$ cm apart. An EG&G 7265 lock-in is used for setting frequency and measuring voltage on the tape. Its output voltage is fed to the input of LAXMA 2400 amplifier, to which a toroidal output transformer is connected to drive current.

investigated ranged from 200 to 2000 Hz, in order to cover the typical operating frequencies of gradient coils. There were 29 test current values used, ranging from 1 A to the critical current of 80 A. Different test current values were used for each test frequency due to hardware limitations. The voltages were measured from the test tape with different transport currents I_t at each operating frequency f.

Measured voltages (U_t) were converted to standard AC power loss units (Q_t, J/m/cycle) using the following conversion Eq. (4) [26]:

$$Q_t = I_t U_t / lf. \tag{4}$$

3.3. Evaluation of a prototype Bi-2223 tape HTS gradient coil

A prototype HTS gradient coil was designed and fabricated using the same tape that was used in the power loss experiments. A PVC cylinder with inner radius a of 50 mm and thickness of 3 mm was used as the gradient form. Fiberglass material was used for insulation layers between the x, y, and z gradients. To simplify the fabrication, a conventional Maxwell pair was used for the z-gradient and Golay pairs were used for the transverse gradients [27]. Single turn coils were used. Due to the mechanical inflexibility of the tape, the tapes had to be jointed together with solder at every connection. There were four solder joints for the z-gradient and 16 solder joints for each transverse (X or Y) gradient.

The HTS gradient coil was fabricated as follows. First, HTS tapes were jointed together with stannous solder to match the 2-D coil patterns, and were then fixed onto a fiberglass layer. After that, the fiberglass layer was wrapped onto the cylinder to obtain the 3-D coil pattern. A homemade polyfoam cryostat was used with liquid nitrogen as the cryogen. The resistance and inductance of the gradient coil were measured with an Agilent 4263B LCR meter. To verify the gradient strength and the slew rate of the gradient field, a Sorensen DCS8-125E power supply was used as DC current source and a Bell 620 gauss meter was used to measure the magnetic field. Gradient fields produced by the prototype HTS coil at applied current of 50 A in liquid nitrogen along the directions of (0, 0, Z), (X, 0, 0) and (0, Y, 0) were measured. The applied current of 50 A used was lower than the critical current in order to ensure that the coil resistance was low enough.

4. Results

4.1. Self-field AC power loss—measurement

The measured AC power losses are plotted against the applied current amplitude ratio i ($i = I_p/I_c$, where I_p is the peak current and I_c is the critical current of the tape) in Fig. 2 with theoretical comparison curves as explained below.

4.2. Self-field AC power loss—predictions

The three AC power loss terms described in Section 2 were estimated for the Bi-2223 sample, using the expressions in Section 2.

Hysteresis power losses were predicted. The solid and the dash line in Fig. 2 are the Norris elliptical curve and the Norris strip curve, expressed by Eqs. (1) and (2), respectively. As can be seen in Fig. 2, most of the AC losses fall between the Norris elliptical curve and strip curve, but closer to the Norris elliptical curve. This indicates that the sample tape has approximate elliptical cross-section. Because the inductive impedance of the tape becomes comparable

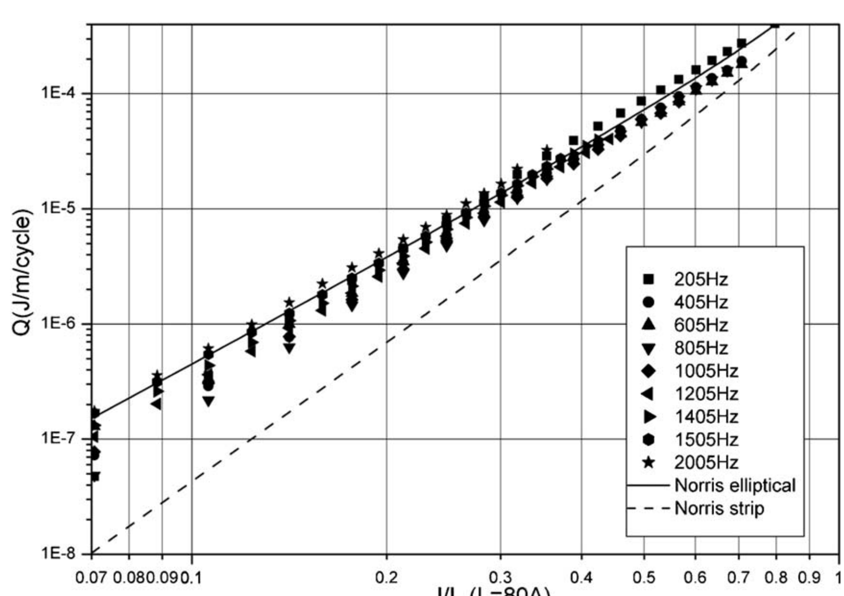


Fig. 2. Measured AC power losses per cycle per meter as a function of the current amplitude ratio i ($i = I_p/I_c$).

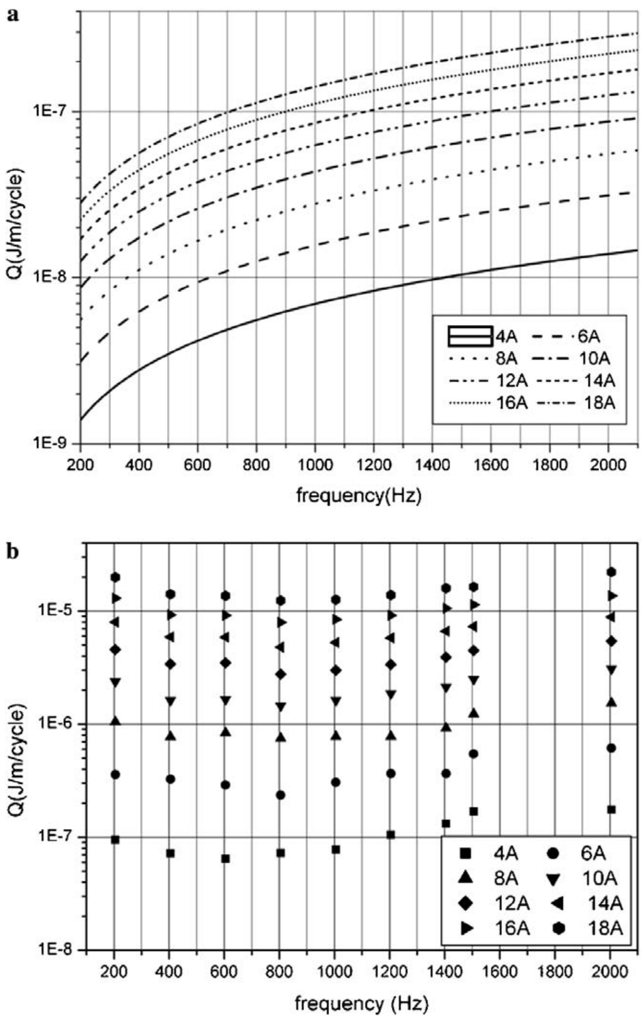


Fig. 3. Comparison of (a) estimated theoretical eddy current loss vs. frequency with (b) measured AC loss vs. frequency, for different transport currents.

to its resistance at high frequency, the tape shows an attenuated response at high frequency and the test equipment could not support current higher than 28 A at 2000 Hz. Therefore, only AC power losses for low i values at high frequencies could be measured with the available driving voltage.

The estimated eddy current loss according to Eq. (3) is plotted in Fig. 3(a), and the measured AC losses for different transport currents at different frequencies are plotted in Fig. 3(b). The estimated eddy current loss is one to three orders of magnitude lower than the estimated hysteresis loss. Since the resistive loss can be often negligible, it can be concluded that the hysteresis loss dominates the total power loss for Bi-2223 tape.

4.3. AC power loss in copper wire—prediction

Comparison can be made between the measured AC power loss in the HTS tape and a comparable copper wire. For a fair power loss comparison between Bi-2223 tape and copper the copper wire should have a similar current carrying capability to Bi-2223 tape without a significant temperature rise in the conductor. Therefore, the copper wire comparison is based on AWG 3 copper wire, whose characteristics are listed in Section 3. A comparison of the measured power loss of HTS tape with estimated AWG 3 copper wire loss at 200 and 2000 Hz is illustrated in Fig. 4. At 200 Hz, the HTS tape shows a three-order lower loss than copper for low $i < 0.1$, and an about two-order lower loss at $i < 0.5$. At 2000 Hz, the HTS tape still demonstrates a much lower power loss than copper, which is two orders lower at low $i < 0.1$ and about one-order lower at $i = 0.3$.

4.4. Critical current degradation due to magnetic field—measurement

The critical current in the HTS tape degrades in the presence of an ambient magnetic field. The amount of degradation is dependent on whether the tape surface is parallel to or perpendicular to the magnetic field. Measurements of the changes in critical current for these two magnetic field orientations at different operating temperatures are shown in Fig. 5. These data were provided by the tape manufacturer.

It can be seen from Fig. 5 that the critical current decreases with magnetic field strength, and that the critical current degrades more rapidly when the tape surface is perpendicular to the field than parallel to the field at the same temperature. When it is parallel to a 1.5 T magnetic field the critical current of the tape decreases to about 20% of I_{c0}, the critical current without magnetic field at 77 K. When the tape surface is perpendicular to a 1.5 T magnetic field the critical current decreases to almost zero. Fortunately, the tape surface is always parallel to the main magnetic field for gradient coils that are wound on a cylindrical form.

When Bi-2223 tapes are used in a high field MRI system, decreasing the operating temperature would seem to be a very effective method for compensating for the reduction of critical current due to the magnetic field. At a temperature of 64 K the critical current is only reduced to about 80% of I_{c0} when the tape is parallel to the field at 1.5 T.

4.5. Critical current degradation due to bending—measurement

When Bi-2223 tape is used in MRI gradient coils, it has to be bent and wound on the gradient form. The critical current degradation due to bending must also be taken into account, especially when the gradient coils involved have small diameters.

As an illustration we measured the critical current degradation of the tape after it was bent to the surface of a 4 cm diameter cylinder. After being bent onto this small cylinder, the tape was flattened and mounted in the measurement setup shown in Fig. 1, and its critical current

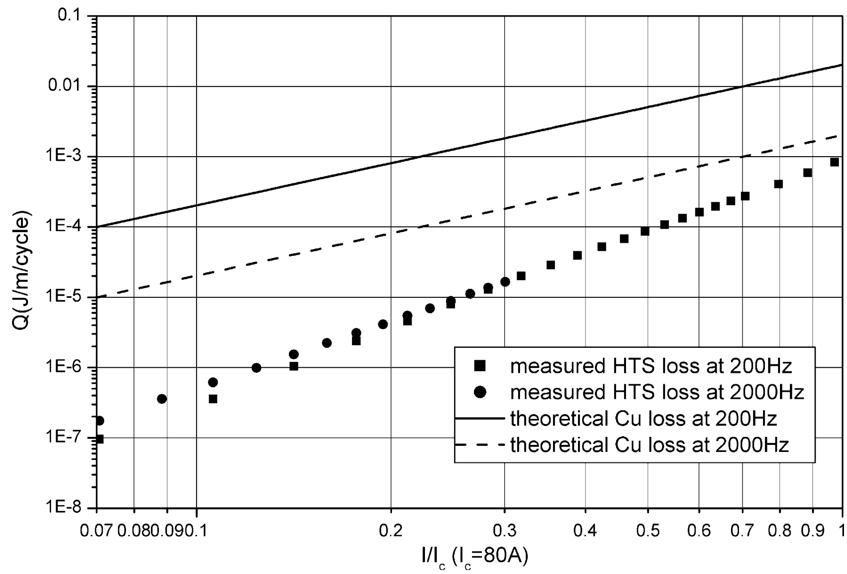


Fig. 4. Power loss comparison of Bi-2223 tape and AWG 3 copper wire.

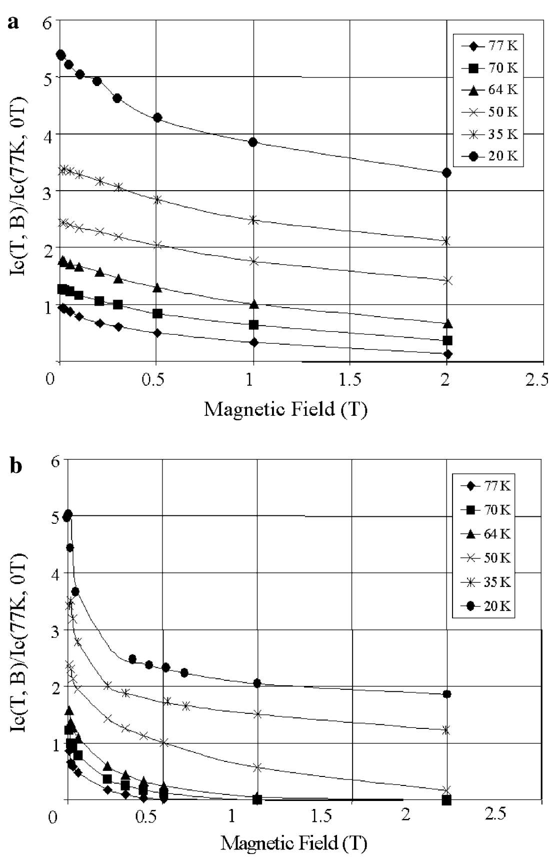


Fig. 5. Critical current degradation of the test Bi-2223 tape at different operating temperature when (a) parallel to the field, and (b) perpendicular to the field. The critical current is normalized to the original value of the critical current at 77 K without magnetic field.

was determined. Its critical current decreased from the original value I_{c0} of 80 to 68 A, a change of 15%. This result indicates that most of the filaments in the tape were not damaged under the bending stress, and the effect of bending the tape in gradients of this size is not a primary concern.

4.6. Effect of critical current degradation on the AC power loss—prediction

The increase in hysteresis loss due to critical current degradation can be estimated by using the Norris elliptical curve expression Eq. (1). Fig. 6 shows the predicted change in hysteresis loss when the critical current is reduced from the original I_{c0} of 80 to 40, 20 and 10 A, respectively. Note that a reduction of critical current from 80 to 10 A causes an increase in hysteresis loss by two orders of magnitude. The power losses of AWG 17 copper, whose cross-section is similar to the tape, at 2000 Hz at 77 and 300 K, are also plotted in Fig. 6 for comparison. It is found that the Bi-2223 tape still shows a nearly two-order lower power loss at $i = 0.1$, and a one-order lower power loss at $i = 0.4$, when its critical current is reduced to 40 A. The power losses of the tape shown in Fig. 6 indicate that the critical current degradation results in the greatest increase of power loss, and that critical current degradation reduces the power loss advantage of HTS tape over copper wire.

4.7. Evaluation of a prototype Bi-2223 gradient coil

Gradient fields produced by the prototype HTS coil at a current of 50 A along the directions of (0, 0, Z), (X, 0, 0) and (0, Y, 0) in liquid nitrogen were measured and the results are shown in Fig. 7. The measurement results agree with the theoretical values [27] well. The differences may be caused by the coil pattern deviation in winding. The specifications of the prototype HTS gradient coil are illustrated in Table 2. Comparing the HTS gradient coil to a copper gradient coil with the same size and patterns, the total resistance of the HTS gradient coil should be much lower. The

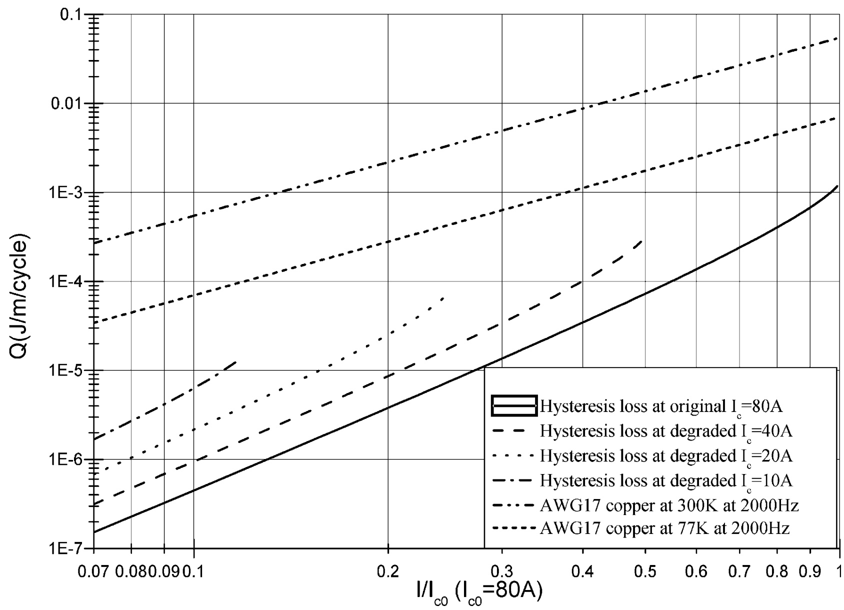


Fig. 6. Norris elliptical curves of the tape when critical current degrades due to the magnetic field. Critical currents are normalized to original value I_{c0} of 80 A. The four curves end at the degraded critical current value. The power losses of AWG 17 copper in a cycle of 2000 Hz at 77 and 300 K are also plotted for comparison.

resistance of an X gradient coil made of AWG17 copper wire at room temperature, which has a similar cross-section area to the Bi-2223 tape, with a length of 2.2 m is about 36 mΩ. The heat generated by a 50 A current with a duty cycle of 100% is 90 W. This is much higher than the resistance and heating of the HTS tape gradient coil. For such a AWG 17 copper coil at 77 K, the corresponding resistance and the heat with 100% duty cycle are 4.6 mΩ and 11.5 W, respectively.

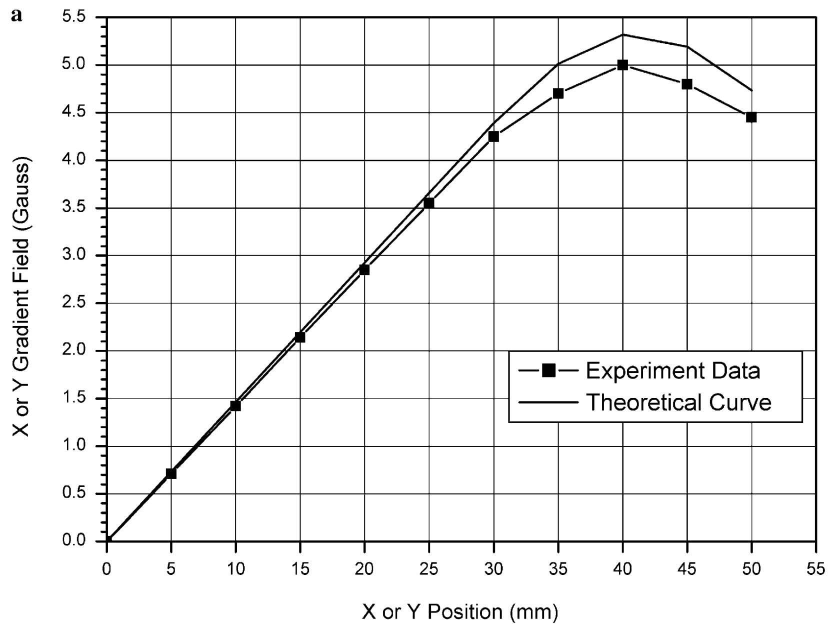
5. Discussion

Although a Bi-2223 HTS gradient coil should have many advantages over a copper coil, especially with respect to power loss and maximum gradient field, there are still many possible technical issues to be addressed. HTS tape offers significant advantages over copper coils in terms of resistance, heating generation and in peak gradient strengths. The first two of these aspects directly affect the continuous gradient rating, or duty cycle, of the gradient system; the second of these is a primary system performance parameter. Technical issues that remain to be solved include degradation of the critical current in a magnetic field as well as the more technical issues of superconducting tape jointing and the need for gradient coil cryostats. Finally, there are mechanical considerations in the use of HTS tapes that need to be resolved.

5.1. Resistance

Resistance is one basic parameter used for evaluating gradient coil performance, and it directly limits continuous gradient rating for the MRI system. For normal copper gradient coils resistance is often determined by the thickness of the layers, the cross-sectional area of the conductors, the number of layer, and the parallel or series interconnection of the four quadrants. However, due to the intrinsic resistivity of copper, the resistance of a normal gradient coil will always have a minimum limit set by the volume in the gradient coil that is available for a conductor. Copper coils usually require embedded water cooling systems in order to remove the generated heat, otherwise the temperature rise in the copper will result in an increase in resistivity. This heating problem can become severe in microscopy due to the small conductor cross-sections. Bi-2223 HTS tapes show an advantage over copper in terms of resistance, which is several orders of magnitude lower in HTS tape than in copper. In particular, the low power loss in the HTS coil for a given conductor volume will directly improve heat generation limitations, and will increase the continuous gradient rating.

In practice, it is difficult so far to fabricate an HTS gradient coil with resistance orders lower than a copper one. The reason is that HTS tapes have to been jointed together to obtain the required coil pattern. An easy method to joint Bi-2223 tapes is by soldering. Normal resin cored stannous solder can be used, but there can be poor ohmic contact between the solder and the tape silver sheath which causes a significant increase in the overall coil resistance. This problem is revealed in the resistance of the prototype Bi-2223 gradient coil. Its resistance is just 3.1 mΩ, about 8% of an AWG 17 copper coil. Specific joint methods for superconductors have been developed to solve this problem [28,29] but the process is still time-consuming and complicated.



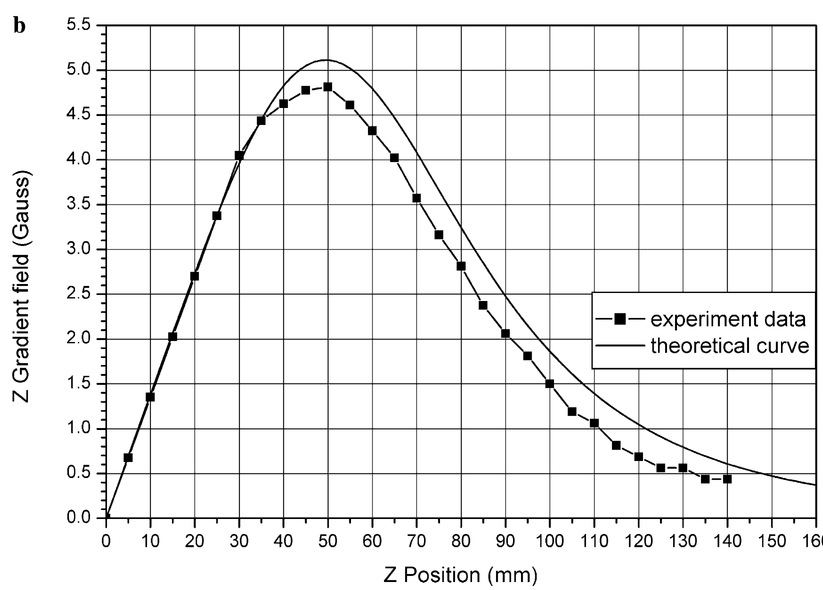


Fig. 7. (a) Plottings of X or Y gradient field distribution produced by the Bi-2223 HTS gradient coil. The current in the coil is 50 A, $z = 0$, x or $y = 0$. (b) Plottings of Z gradient field distribution produced by the Bi-2223 HTS gradient coil. The current in the coil is 50 A, $x = 0$, $y = 0$.

Table 2
Specifications of the prototype Bi-2223 HTS tape gradient coil

	Conductor cross-section (mm^2)	Total length (m) (X, Y, Z)	Gradient at 50 A (mT/m) (X, Y, Z)	Inductance (μH) (X, Y, Z)	Resistance (mΩ) (X, Y, Z)	Heat 100% duty (W) (X, Y, Z)
HTS	0.984	2.2	14.2	7.0	3.12	7.8
		2.2	14.2	7.0	3.12	7.8
		0.8	13.5	4.1	0.91	2.3

5.2. Gradient strength

Modern gradient coils are often required to provide high gradient strength and thus they need to support a high current density. Compared with copper, the Bi-2223 tape has a critical current density of over 8000 A/cm^2, much higher than the typical value of 300 A/cm^2 for copper without forced cooling in AWG standard. Therefore, a HTS gradient coil is able to produce much higher gradient strengths than a copper coil purely on a "current density per conductor volume" basis. Because the behavior of the critical current for the HTS coil presents a much more difficult limit to performance than the resistance of copper (although a much higher limit), considerations of coil layout and parallel coil windings will have great significance in addressing maximum current issues in HTS gradients. For example, one scheme to address maximum current issues has been the use of tape stacks to divide the current in each tape. An additional benefit of using tape stacks is that the current amplitude ratio i decreases in each tape, so that the hysteresis loss can be significantly reduced compared to the situation in which the current flows through a single tape. Finally, if the critical current degradation of the tape in the magnetic field is taken into account, the maximum gradient field produced by a HTS tape gradient coil will deteriorate. Conversely, the performance of the gradient can be improved even more by decreasing the temperature.

5.3. Cryostat

A major complication of HTS gradient coils would be the need for a cryostat. Because a self-contained cryostat for a gradient coil would be inefficient, the need to integrate the gradient with the magnet will present a high entry barrier to this technology, however, efficient it may be afterwards. A laboratory Bi-2223 tape gradient coil can be immersed in a pool of liquid nitrogen for testing. But in a commercial system the use of cryocooler as the cooling method will be necessary. When a cryocooler is used a number of issues come into play including the vibration of the cryocooler, its reliability, and its cost. There must be tradeoffs between performance and cost for a specific HTS gradient coil for microscopy. However, for a normal body size MRI scanner, it may be possible to integrate the HTS gradient coil into the same cryostat for the main magnet to simplify construction and to reduce the cost. In particular, the best solution for critical current degradation is to lower the operating temperature of the coil—the cryostat efficiency and cost need serious study to find the best cost/performance tradeoff.

5.4. Mechanical properties

The mechanical properties of the tape are also very important in gradient coil fabrication. Localized deflections, vibration and acoustic noise are often caused by the large local forces and torques.

The mechanical properties of Bi-2223 tapes are quite different from those of copper and most low temperature superconductors, which behave like metals. The superconducting filaments inside the tape are very brittle so the tape mechanical properties have to be strengthened by sheath and matrix, often silver alloy materials. The inflexibility of the tape limits the possible winding, cutting and etching processes that are used in fabrication with copper. This may restrict the application of Bi-2223 tapes in some novel gradient designs.

Local forces and torques in the gradient coils are caused by the Lorentz force when the current flow direction is not parallel to the main magnetic field direction. The hoop stress σ_h caused by the Lorentz force can be easily calculated by the following equation:

$$\sigma_h = \frac{IB_0}{w}, \tag{5}$$

where I is the transport current in the tape, B_0 is the main magnetic field strength, and w is the width of the tape. It can be easily shown that the electromagnetic hoop stress due to Lorentz force for a gradient coil in the main magnetic field of 1.5 T at 77 K, carrying critical current of 80 A, is about 0.029 MPa. Recent work [23] has shown that the critical hoop stress under which the critical current of the tape would not degrade is about 80 MPa, large enough for an application in a 19 T magnet at liquid helium temperature of 4.2 K. Thus Lorentz forces do not place a barrier for the use of Bi-2223 tape in a gradient coil at 1.5 T, where the expected electromagnetic hoop stress is 0.029 MPa, or for even higher field strengths.

5.5. Future direction

Future developments for HTS gradient coils could involve the development of a tape suitable for distributed winding gradient coils that will model many of the winding and mechanical issues of a practical HTS gradient coil, and the testing of a full prototype in a MRI scanner.

6. Conclusion

Bi-2223 HTS tape will be a promising material for gradient coils in MRI, but work remains in developing it for this purpose. The high critical current of Bi-2223 HTS tapes permits much higher gradient strengths than copper wire for a given volume of conductor, driven by the same voltage, and the power loss from the HTS tape is orders of magnitude less than that of copper wire. Even though the degradation of critical current of HTS tape in the main magnetic field increases hysteresis loss, HTS tape still demonstrates an advantage in terms of power loss over copper wire with the same cross-section area. In order to make practical HTS gradient coils many technical issues remain. The degradation of critical current due to magnetic fields and bending will limit the maximum gradient strength; this can be compensated for by reducing the operating temperature or by using multiple layers of HTS tape. The additional resistance due to jointing cannot be completely avoided and remains an issue for future development. The poor mechanical performance of Bi-2223 tapes may restrict the fabrication methods available for achieving the coil patterns in some novel gradients. The much lower heat produced by the HTS tape will make a significant improvement in continuous gradient ratings and will eliminate the gradient water cooling systems currently in use. HTS tape will, of course, require a gradient cryostat and the integration of this with a MRI system will present an engineering challenge. The performance improvements possible with this material will make its further development an important part of future MRI programs.

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