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Magnetic Field and Critical Current of a BSCCO HTS Magnet at Various Aspect Ratios

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***Abstract*—When the length of wire used to make an HTS magnet is fixed, the magnetic properties of the HTS magnet including the central magnetic field and stored energy mostly depend on the aspect ratio of the HTS magnet. This paper presents calculations of the magnetic properties of a BSCCO HTS magnet at various aspect ratios. The HTS magnet was assumed to be made by pancake windings. The total length of the BSCCO wire was varied from 2 to 10 km. For a specific length of the BSCCO wire, the number of pancake windings was varied up to 70. The inner diameter of the HTS magnet was fixed to be 50 mm and 77 K. When the length of the BSCCO wire was 2 km, the central magnetic field was maximum when 34 pancake windings were used. The maximum central magnetic field and the current of the HTS magnet were 859.3 mT and 21.8 A, respectively. The number of turns of a single pancake winding and the aspect ratio of the HTS magnet were 171 turns and 2.54, respectively.**

***Index Terms*—Aspect ratio, BSCCO magnet, magnetic field.**

I. INTRODUCTION

IN recent years, high field magnets have been developed for many different advanced technologies such as magnetic separation systems, NMR, MRI, etc., In particular, high field magnets have been used very extensively in the fields of life science, medical care, chemistry, and others for analyzing the characteristics of substances. The performance of a high field magnet in these applications generally improves with both the magnitude and uniformity of the field. Low temperature superconducting (LTS) wires with high current capacity have replaced conventional copper wire in high field magnets, making it possible to make small volume magnets [1], [2]. However, there is a limitation in producing high magnetic fields due to the $I_c - B$ characteristics of the LTS wire. In order to overcome the magnetic field limitation of LTS magnets, HTS wires have substituted LTS wires in some high field magnet applications [3], [4].

The magnetic field generated by a magnet shows different magnitudes and directions in all positions. Due to the non-uniform distribution of the magnetic field of a magnet, the magnetic field applied to an HTS wire is also different at all points in an HTS wire. In addition, because the HTS wire is fabricated as a flat tape shape, it presents an anisotropy in which the critical current varies according to the direction of the external magnetic field applied to the wire. All of these factors have to be taken into account in the design and construction of HTS magnets.

This paper describes the properties of an HTS magnet including the critical current and the central magnetic field, according to the change in the shape of the magnet, taking into account changes in the aspect ratio of the magnet, the inner radius of the magnet, total length of the HTS wire, and the number of pancake coils. The critical current that generates the maximum central magnetic field for each magnet shape was calculated using an $E - J$ relation through consideration of the magnitude and direction of the magnetic field applied to the HTS wire.

II. PROPERTIES OF THE HTS WIRE AND MAGNET

Unlike LTS wire, the HTS wire is fabricated as a flat tape shape and that leads to an anisotropy in the wire characteristics according to the magnitude and direction of the applied magnetic field. If the magnetic field is applied perpendicularly to the wide face of the HTS wire, the critical current decreases significantly and the degree of the decrease varies according to the angle of the applied magnetic field, unlike the case when the field is applied parallel to the wide face of the wire. The n-value characteristic also varies with the applied magnetic field in a manner similar to the behavior of the critical current.

The magnitude and direction of the magnetic field generated by a magnet vary for each position in which the magnitude and direction of the magnetic field are determined, in a way that depends on the shape of the magnet. In addition, although the direction of the magnetic field is the same for magnets of a given shape, the magnitude of the magnetic field varies according to the magnitude of the transport currents. The factors that determine the shape of a magnet are the inner radius, outer radius, and height of the magnet. In general, as the required inner radius of a magnet is determined, the outer radius and height of the magnet vary in accordance with the length of the HTS wires.

Fig. 1 shows the patterns of the magnetic field generated by a magnet with the 25 mm inner radius and a 2 km length of HTS wire. As shown in Fig. 1, the outmost pancake coil is enlarged to verify the direction of the magnetic field applied to the outmost pancake coil. As presented in Fig. 1, the patterns of the magnetic field vary according to the shape of the magnet, and the magnitude and direction of the magnetic field vary according to the position of the superconducting wire. Also, the magnitude and

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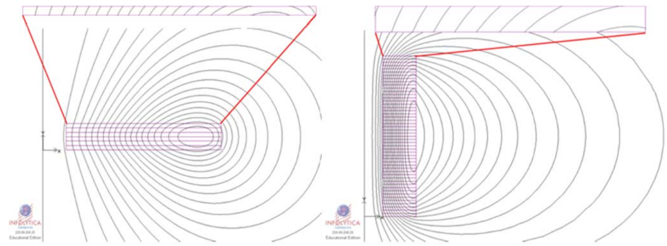

Fig. 1. Patterns of the magnetic field for different magnet shapes (a) thick shape and (b) thin shape.

direction of the applied magnetic field can vary in the cross-section of the superconducting wire and it is necessary to consider this anisotropy in the design of the magnet.

III. Analysis Method and Model

The magnetic field generated by a magnet shows different magnitudes and directions in all positions, and the magnitude and direction of the magnetic field vary according to the shape of the magnet. In addition, as the characteristics of the critical current and n-value of the HTS wire vary according to the magnitude and direction of the applied magnetic field, the accuracy of the calculation is improved by calculating the superconducting wire as m elements in order to consider the non-uniformity of the magnetic field applied to the HTS wire. Details of the estimation of the applied magnetic field to the tape are described in [5].

The analysis of the characteristics of a magnet can be performed in the following steps. A numerical calculation for arbitrary currents is applied to a specific single shape of the magnet. Then, the electric field generated at the nth turn is calculated using the characteristics of $I_\mathrm{c} - B$ dependence, the n-value in the superconducting wire and the $E - J$ relation as presented in (1).

$$E_n = E_c \left(\frac{I}{I_c(B_n, \theta_n)} \right)^{n(B_n, \theta_n)} \tag{1}$$

where E_c is the critical electric field, which is determined as $1\ \mu\mathrm{V/cm}$, and B_n and θ_n give the magnitude and angle of the magnetic field applied to the nth turn, respectively. $I_\mathrm{c}(B_\mathrm{n}, \theta_\mathrm{n})$ is obtained from the measured one [6].

Whilst the sum of the voltage generated at each turn does not exceed the reference voltage, the current that makes the central magnetic field of the magnet as maximum is defined as the critical current. Then, this process is repeated by varying the shape of the magnet.

BSCCO wire with a critical current of 126 A at 77 K, from its self field, was used. $1\ \mu\mathrm{V/cm}$ was selected as the criterion for the critical current. Table I shows the detailed specification of the wire. Also, the basic shape of the magnet is a layered structure of pancake coils. Fig. 2 shows the shape of the magnet. The inner radius (a_1) of the magnet, the length of the HTS wire, and the number of pancake coils were selected as the design factors that change the shape of the magnet. Therefore, as the inner radius is determined, the height $(2b)$ of the magnet is also determined by number of pancake coils used, whilst the number

TABLE I
Specifications of the BSCCO HTS Wire

Type of wire	BSCCO-2223 reinforced wire
Width	4.4 mm
Thickness	0.285 mm
Critical current	126 A @ 77 K, 0 T
Min. bending diameter	38 mm

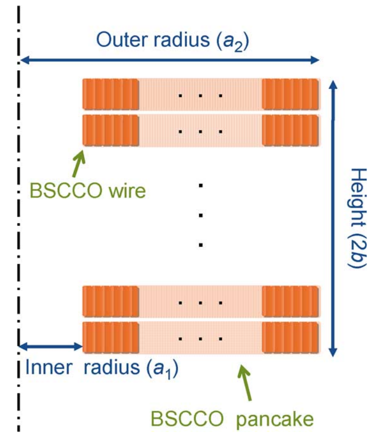

Fig. 2. Cross-section of the HTS magnet.

of turns in these coils determines the outer radius (a_2) of the magnet.

In this paper, the total length of the HTS wire was changed from 2 km to 10 km with intervals of 2 km in order to vary the shape of the magnet. Also, the number of pancake coils was increased from 6 to 70 with intervals of 2. In addition, the inner radius of the magnet was changed from 20 mm, which took into account the minimum bending diameter of the HTS wire, to 50 mm, with intervals of 5 mm [7].

IV. Calculation Results

The variables of α and β that represent the aspect ratio of the magnet were defined as

$$\alpha = \frac{a_2}{a_1}, \qquad \beta = \frac{b}{a_1} \tag{2}$$

where a_1, a_2, and b show the inner radius, the outer radius, and the half the height of the magnet, respectively, as illustrated in Fig. 2.

These definitions are made in order to investigate the characteristics of the central magnetic field and critical current as a function of the aspect ratio. Because α is determined by the inner and outer radii, it determines the area of the magnet. Also, it can be seen that the variable β determines the height of the magnet as a function of the number of pancake coils.

Fig. 3 shows the contour plot of the change in the central magnetic field according to the values of α and β where graphs (a), (b), (c), and (d) show the 2, 4, 6, and 10 km length HTS wires, respectively. In Fig. 3, the β is a shape variable that is the height of the magnet and can be determined by the number of pancake coils. Because the number of pancake coils used in

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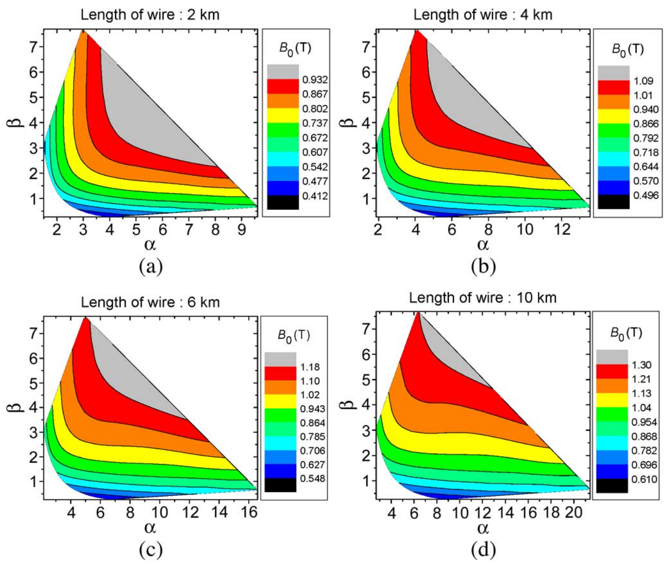

Fig. 3. Central magnetic field of the HTS magnet as a function of the variables of α and β.

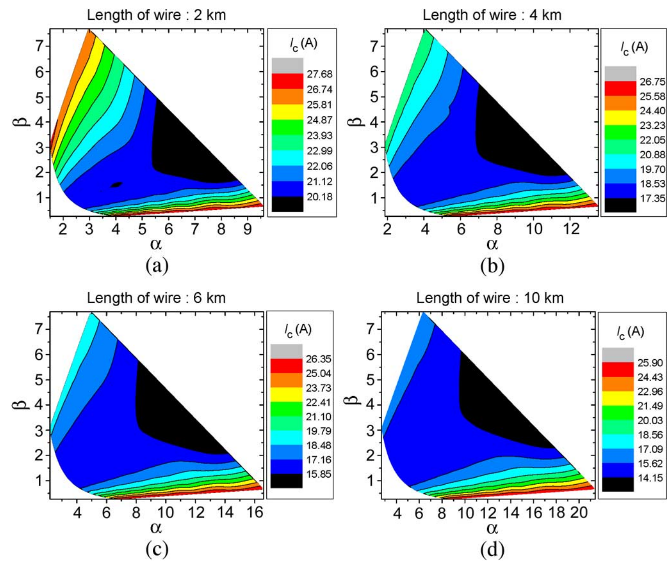

Fig. 4. Critical currents of the HTS magnet as a function of the variables of α and β.

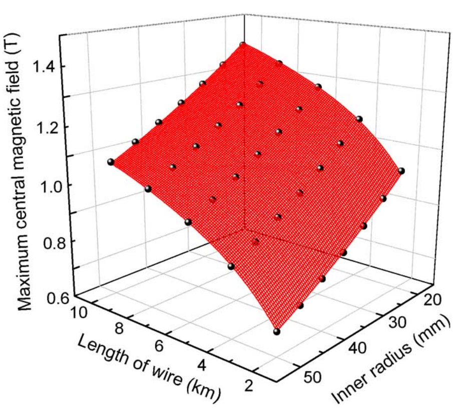

Fig. 5. Central magnetic fields as a function of the length of the high temperature superconducting wire and the internal radius of the magnet.

this study is varied from 6 to 70, β is a fixed value ranging from a minimum of 0.2 to the maximum of 7.7 regardless of the length of the wire. However, α is determined by the inner and outer radii of the magnet. In this study, the outer radius varies according the length of the wire and the number of pancake coils, so that it can be determined according to the change in the length of the superconducting wire. For the case that shows no data for the large values of α and β in Fig. 3, the area cannot be represented by the length of the superconducting wire, and the other section of the area, which has no data, is not to be calculated.

As illustrated in Fig. 3, according to the increase in the length of the HTS wire from 2 km to 10 km, the maximum central magnetic field generated by the magnet increased from about 0.9 T to 1.3 T. Also, it is verified that the central magnetic field of the magnet can be varied according to the shape of the magnet even though the same wire length is used, and there is an optimal aspect ratio that generates the maximum central magnetic field. For example, in the case of the 10 km length wire, the central magnetic field increased by a factor of 2 from 0.61 T to 1.30 T depending on the aspect ratio.

Fig. 4 shows the critical current of the magnet as a function of the length of the superconducting wire, α and β. Here graphs (a), (b), (c), and (d) represent the 2, 4, 6, and 10 km length HTS wires, respectively. In the case of the 2 km length HTS wire, although it shows large changes in the critical current according to the shape of the magnet, it gave no significant change in the critical current according to the shape of the magnet as the length increased to 10 km. However, in the case of variation with β below about 1.5, the critical current varies rapidly with β for all lengths.

Fig. 5 shows the maximum central magnetic field generated by the magnet according to the length of the HTS wire and the inner radius of the magnet in which the circular symbol shows the actual data, and the surface is fitted by using the actual data. The maximum central magnetic field varies with the length of the HTS wire and the inner radius of the magnet. For a specific length of HTS wire, the central magnetic field becomes higher as the inner radius decreases. For a specific inner radius, the central magnetic field becomes higher as the length of HTS wire increase. Therefore, the 20 mm inner radius of the magnet and the 10 km length of the wire provided the highest central magnetic field, 1.30 T, and the 50 mm inner radius of the magnet and the 2 km length of the wire showed the lowest central magnetic field, 0.58 T.

Fig. 6 shows the aspect ratio that generates the maximum central magnetic field. Here the aspect ratio can be obtained by dividing the height $(2b)$ of the magnet by the width $(a_2 - a_1)$ of the magnet. In Fig. 4, the circular symbol shows the actual data, and the surface is fitted by using the actual data. For instance, the 50 mm inner radius of the magnet and the 2 km length of the HTS wire generated the maximum central magnetic field, about 0.58 T, while the aspect ratio was about 4.01 and the number of pancake coils was 38.

As shown in Fig. 6, although the small inner radius (20 mm) of the magnet shows no significant changes in the aspect ratio (about 2.5) according to changes in the length, the increase in

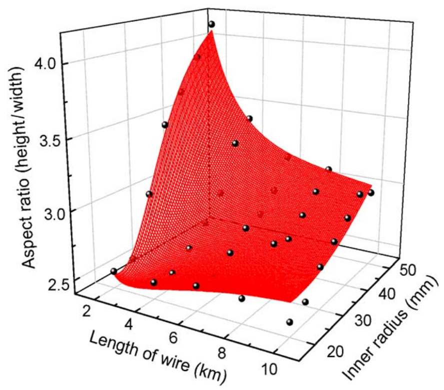

Fig. 6. Aspect ratios that generate the maximum central magnetic field as a function of the length of the high temperature superconducting wire and the internal radius of the magnet.

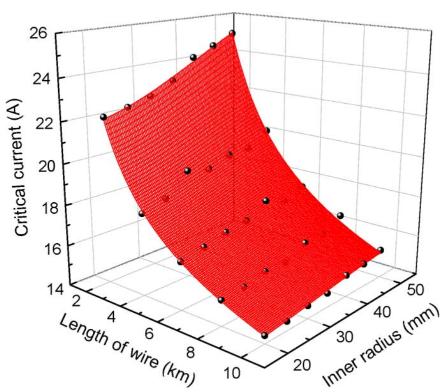

Fig. 7. Critical currents that generate the maximum magnetic field as a function of the length of the high temperature superconducting wire and the internal radius of the magnet.

the inner radius (50 mm) decreases the aspect ratio from about 4.1 to 2.9. However, in the case that shows an invariance in the length and a variance in the inner radius, the aspect ratio increases according to the increase in the inner radius, and the rate of increase is larger for the shorter length.

Fig. 7 shows the critical current that generates the maximum central magnet field as a function of the length and inner radius of the magnet. The critical current that generates the maximum central magnet field decreases with increasing length of the HTS wire as the inner radius of the magnet is kept constant. Also, for constant length the critical current decreases with increasing inner radius. This is due to the fact that the magnetic field increases with decreasing inner radius and increasing length of the HTS wire. These effects lead to a low rate of decrease of the critical current with increasing magnetic field and also an increase in the external magnetic fields applied to the HTS wire.

V. Conclusion

This paper showed the effect of the magnet shape on the central magnetic field and the critical current. Three parameters, the inner diameter of the magnet, length of the superconducting wire and the number of pancake windings, were varied to examine the effect. Based on the calculation results, the optimum aspect ratio which maximizes the central magnetic field varies as the length of wire varies. When the length of the superconducting wire was 10 km, the central magnetic field was maximum at $\alpha = 6.6$ and $\beta = 7.0$. As the length of the wire increased and the inner diameter decreased, the optimum aspect ratio decreased. The optimum aspect ratio varied from 4.1 to 2.5 at this calculation.

The critical current was also function of the aspect ratio. When the number of pancake windings increases, the critical current decreases and then increases. The results of this paper can provide the relation between the basic parameters of the magnet (length of the superconducting wire, number of pancake windings and the inner diameter) and the central magnetic field.

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