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Abstract. A Bi-2223 superconducting magnet for practical use in liquid nitrogen is designed and fabricated. Bi-2223 tapes prepared by ConTrolled Over Pressure (CT-OP) process are used for the winding, and the critical current at 77.3 K and self-field is in the range of 174–185 A. 28 double-pancake coils are resistively connected in series by copper terminals. High critical current tape is used for top and bottom double-pancake coils, since the magnetic field normal to the tape surface is highest at the top and bottom of the magnet. Two iron plates at top and bottom of the magnet are used for reduction of the normal component of magnetic field to the Bi-2223 tape, since the total performance of the magnet is determined by the minimum critical current at maximum normal magnetic field component to the tape. The inner bore diameter of the magnet is 92 mm. And the homogeneity of magnetic field of long-axis direction in 50 mmϕ $\times$ 100 mm length is within 3%. The maximum magnetic field at the center of the bore is over 1.0 T at 77.3 K.

Keywords: Bi-2223 tapes, superconducting magnet, double-pancake coil, critical current, anisotropy of critical current
PACS: 84.71.Ba, 74.25.Sv, 74.72.-h

INTRODUCTION

The critical current density of $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) silver sheathed tape has been increased after introduction of the ConTrolled Over Pressure (CT-OP) process [1–3]. The critical current of Bi-2223 tape reaches over 250 A for 4 mm width in short sample. The critical current of commercially available tape is about 200 A. There are several types of Bi-2223 tape are available for suitable applications.

Superconducting magnet is one of the promising applications using superconducting technology, since it is impossible to obtain high magnetic field by other technologies. For example, Cu magnet is mainly used for MO (Magneto Optical) observation, and it is desired to replace it by a superconducting magnet to obtain much higher magnetic field. Several Bi-2223 superconducting magnets worked in liquid nitrogen (LN2) were designed and fabricated for practical usage by using double-pancake coils [4–6]. In conclusion, the maximum magnetic fields at 77.3 K and 65 K are 0.70 T (65.0 A) and 1.30 T (120 A), respectively. It is known that the critical current density in the normal magnetic field to the tape surface rapidly decreases compared with that in the parallel magnetic field to the tape surface due to the large anisotropy of the Bi-2223 tape. Therefore it is necessary to reduce the normal component of magnetic field to the tape. In the magnet, the normal component of magnetic field to the Bi-2223 tape of double-pancake coils is reduced using iron plates at top and bottom of the magnet.

Solenoid type of Bi-2223 magnet is also reported for insert magnet at high magnetic field at low temperatures [7, 8]. On the other hand, $REBa_2Cu_3O_x$ (RE-123; RE:rare earth) coated conductor tape is used and insert magnet for high magnetic field generation is fabricated [9]. Degradation of the performance of RE-123 double-pancake coil due to epoxy impregnation is investigated and it is found that dry winding and paraffin impregnation suppress degradation [10]. Therefore, superconducting magnets by cuprate oxide superconducting materials become more and more common.

In this study, 28 Bi-2223 double-pancake coils are stacked and superconducting magnet worked in LN2 is fabricated. The maximum magnetic field at the center of the magnet is over 1.0 T at 77.3 K. The bore size is 92 mm and the homogeneity of magnetic field of long-axis direction in 50 mmϕ $\times$ 100 mm length is within 3%.

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TABLE 1. Specifications of Bi-2223 superconducting magnet.

bore diameter	92 mmϕ
diameter	180 mmϕ
length	316 mm
weight	23.5 kg
total number of turn	4444
total length of tape	1742 m
magnetic field	1.00 T at 52.6 A
coil constant	19.0 mT/A
inductance	0.86 H
stored energy at 1.0 T	1.2 kJ
homogeneity of magnetic field of long-axis direction	3% within 50 mmϕ $\times$ 100 mm length
number of double-pancake coils	28

DESIGN AND FABRICATION

The main usage of the present Bi-2223 superconducting magnet is a measurement for newly designed superconducting DC power transmission cable by using longitudinal magnetic field effect [11]. Therefore, relatively large area with homogeneous magnetic field distribution is necessary such as 3% within 50 mmϕ $\times$ 100 mm length in long-axis direction. The bore size of the magnet is determined as 92 mm so as to insert a large model of DC power transmission cable. The maximum magnetic field at the center of the magnet is designed to be over 1.0 T at 77.3 K in LN2, since the maximum magnetic field of the previous magnet was 0.7 T at 77.3 K and 1.3 T at 65 K in subcooled LN2 [6]. The specifications of Bi-2223 superconducting magnet are listed in Table 1. The total length of the magnet is 316 mm for the large homogeneous magnetic field distribution. The number of double-pancake coils is 28. These double-pancake coils are resistively connected by Cu terminals. The Bi-2223 tapes were wrapped in half-lap fashion by 12.5 μm Kapton tape for insulation. Therefore, the thickness of insulation between tapes was 25 μm. The double-pancake coils were fabricated by dry wound, then they were vacuum epoxy impregnated. A GFRP sheet with 0.2 mm thickness was used for insulation between double-pancake coils.

Figure 1(a) and 1(b) show the magnetic field distribution of the cross section of the middle half of the Bi-2223 superconducting magnet for long-axis and radial directions, respectively. In the figures, small white rectangles represent 28 double-pancake coils. In the calculation, finite element method (FEM) is used and the current is 52.6 A. The magnitude of magnetic field at the center is 1.00 T. The top and bottom parts of the magnet in the figures are iron plates (SS400) which is used for diverters. The iron plate has ledge in inner part. It is known that this ledge

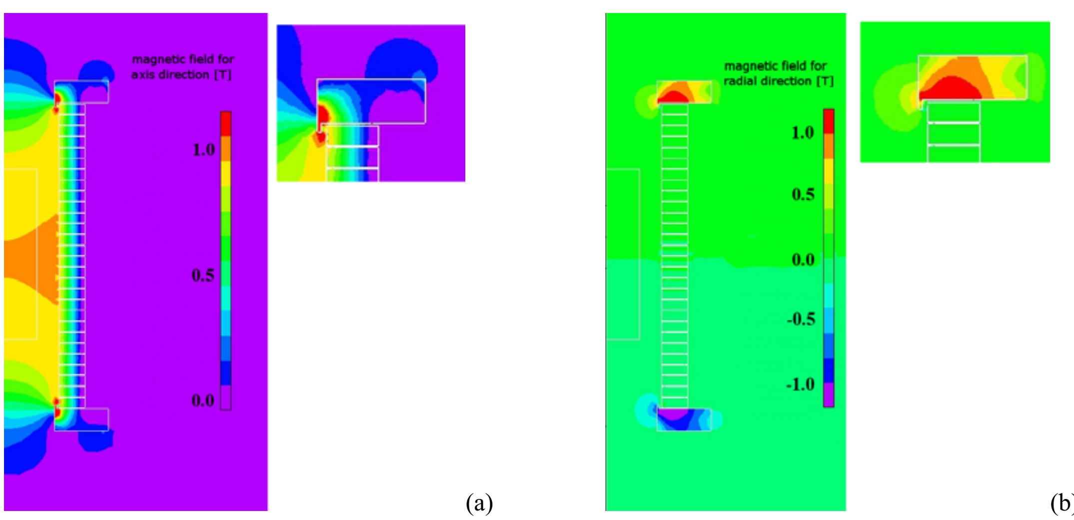

FIGURE 1. Magnetic field distribution for (a) long-axis and (b) radial directions by using finite element method. Insets are the enlarged images around the top flanges.

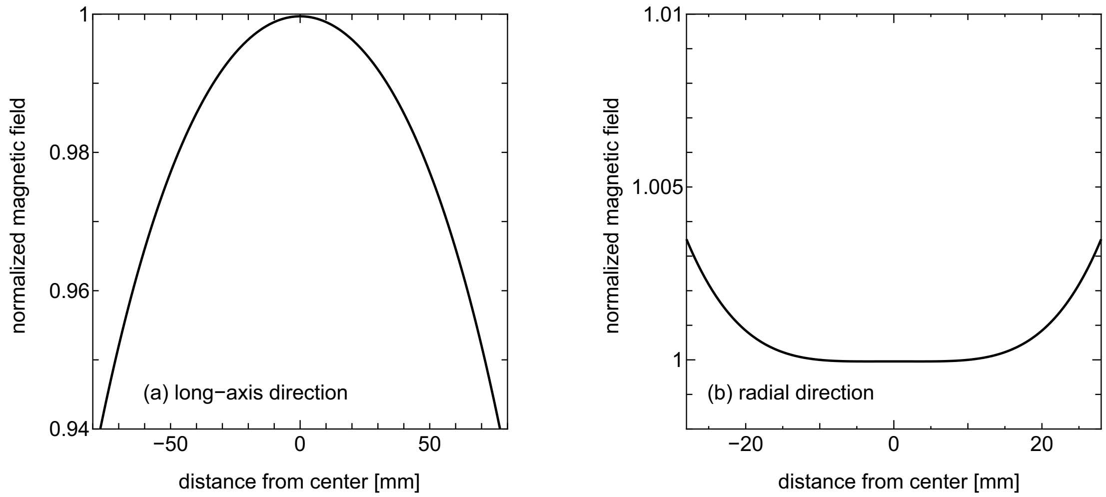

FIGURE 2. Numerically calculated magnetic field distribution for (a) long-axis and (b) radial directions with iron plates for each edges.

part is effective for the attraction of the magnetic field resulting in the parallel magnetic field to the Bi-2223 tape. As the result, it is found that the magnetic field is almost parallel to the Bi-2223 tape even at top and bottom parts of the magnet, i.e. the normal magnetic field component to the tape is drastically reduced. That is, the magnetic field is attracted to the ledges of the top and bottom iron plates, and the magnetic field takes maximum value at the points. As shown in Fig. 1(b), the magnetic field for radial direction is almost constant through the Bi-2223 superconducting magnet. The peak field in the iron plate is found to be 1.2 T from Fig. 1(a), when the central field of the magnet is 1.0 T.

Figure 2(a) and 2(b) show the plotted magnetic field distribution calculated from Fig. 1(a) and 1(b) for long-axis and radial directions, respectively. In the figures, the normalized magnetic field is plotted as a function of distance from the center of the magnet. It is found that the homogeneous of the magnetic field is satisfied for the demanded values of within 3% in the range of 50 mmϕ $\times$ 100 mm length.

The properties of critical current and *n*-value at 77.3 K of the Bi-2223 tape before winding which is used in the magnet are shown as a function of coil ID in Fig. 3(a). *n*-value is determined by the slope in the electric field range of 0.1–1 μV/cm. The coil ID 1 is the top. One of the advantages using several double-pancake coils compared with single solenoid coil is a grading of superconducting tapes. That is, the critical current is small in the center part of the Bi-2223 superconducting magnet. On the other hand, the critical current at the top and bottom parts of the magnet are larger than those at center part, since the maximum normal component of the magnetic field is applied to top and bottom part of the magnet. It is possible to reduce the total cost of fabrication of the magnet by the grading.

The electromagnetic hoop stress σ which is estimated from $\sigma = BJR$, where B is the magnetic field, J is the current density, and R is the radius of the coil, is estimated to be 3.4 MPa. This value is far below than the limit value of 160 MPa of the Bi-2223 silver sheathed tape [1].

RESULTS AND DISCUSSION

The critical current and *n*-value of the double-pancake coils as a function of coil ID is shown in Fig. 3(b). The measurement of the critical current is performed for each individual double-pancake coils. It is found that the critical current and the *n*-value are smaller than those of bare tape as shown in Fig. 3(a). This is due to the self-field of the double-pancake coil.

Figure 4 shows the picture of the Bi-2223 superconducting magnet made by 28 double-pancake coils. The outside is covered by a perforated tube for protection, and it is easy to cool down by LN2 through holes in the tube.

The voltage-current characteristics of Bi-2223 superconducting magnet at 77.3 K are shown in Fig. 5. It is found that the maximum magnetic field reaches 1.29 T at 68 A at the electric field criterion of 1 μV/cm. Therefore 1.00 T

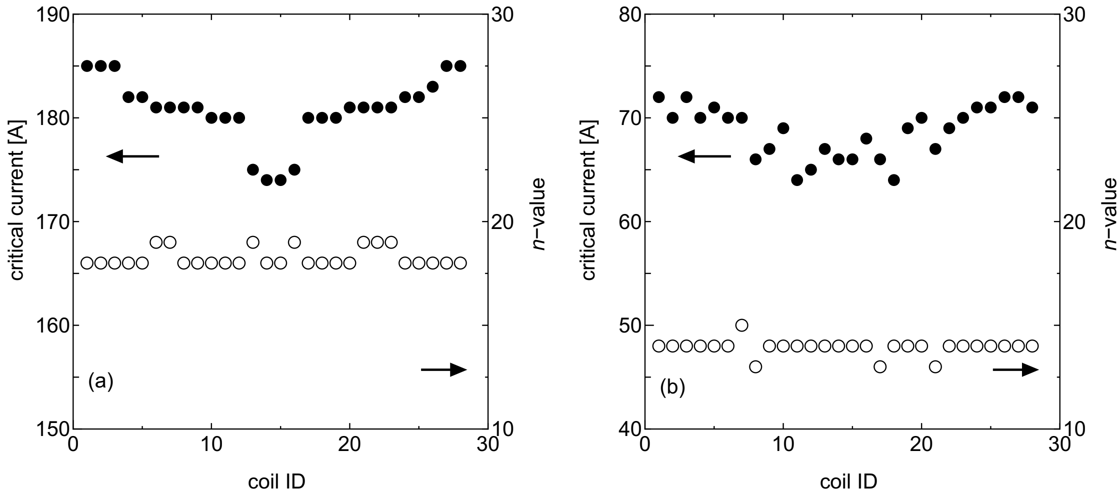

FIGURE 3. Critical current and *n*-value at 77.3 K as a function of coil ID for (a) before winding and (b) after winding. Coil ID 1 is the top and Coil ID 28 is the bottom.

is safely obtained by the present Bi-2223 superconducting magnet, since the electric field is less than 0.1 μV/cm at 52.6 A.

Here, we shall discuss the possibility to enhance of the maximum magnetic field of the Bi-2223 superconducting magnet. The main reason for the enhancement of the maximum magnetic field in present work from the previous works [5, 6] is the enhancement of the critical current of Bi-2223 tape from 135–165 A to 174–185 A. The critical current of short sample of CT-OP Bi-2223 tape is about 250 A, and the critical current of commercially available long length tape is about 200 A. Therefore, the maximum magnetic field will increase in near future. Since the performance of the Bi-2223 superconducting magnet is determined by the critical current at the maximum normal magnetic field component to the Bi-2223 tape at the edges of the magnet, the reduction of the anisotropy of Bi-2223 tape is effective. The reduction of the anisotropy of Bi-2223 tape was investigated by addition of lead to Bi-2223 tape [12]. The anisotropy of Bi-2223 tape is also related to the number of filaments, since the superconducting region near the interface with silver matrix increases with increasing the number of the filaments due to the less anisotropy in

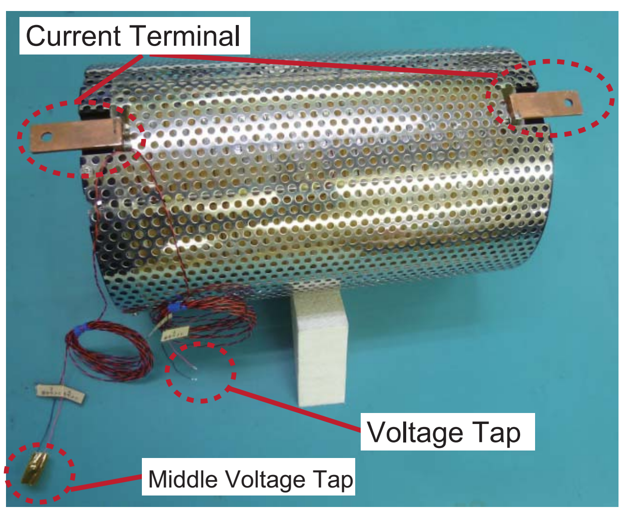

FIGURE 4. Bi-2223 superconducting magnet made from 28 double-pancake coils.

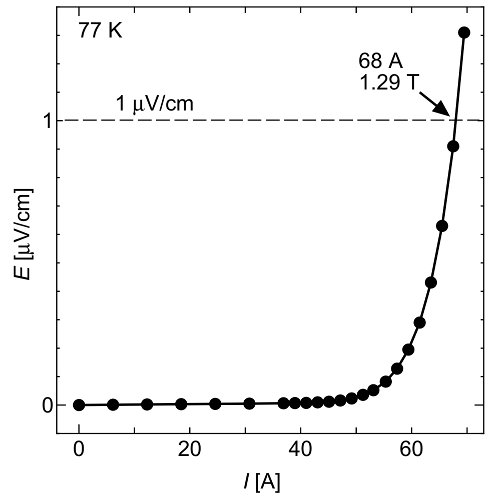

FIGURE 5. Electric field-current characteristics of Bi-2223 superconducting magnet at 77.3 K.

the critical current density [13]. Therefore, it is necessary to investigate the optimum condition of the Bi-2223 tape fabrication for designing the Bi-2223 superconducting magnet.

It is also expected to increase the maximum magnetic field by using subcooled LN2 and reduce the temperature to 65 K. In our previous works, the maximum magnetic field at 65 K is enhanced 1.9 times larger than that at 77.3 K [5, 6]. Therefore, if the present Bi-2223 superconducting magnet is cooled by subcooled LN2, the maximum magnetic field would be about 2 T, which is limited by the saturation of the iron plates.

SUMMARY

In this study, Bi-2223 superconducting magnet consisted by 28 double-pancake coils is designed and fabricated. The maximum magnetic field at the center is designed to be more than 1.0 T, and the bore size of the magnet is 92 mm. The homogeneous magnetic field area is obtained for 3% within 50 mmϕ $\times$ 100 mm length for a measurement of a new type of DC superconducting transmission cable using longitudinal magnetic field effect. As the result, the maximum magnetic field at the center of the magnet reaches 1.29 T at 68 A in LN2 by the criterion of 1 μV/cm. Since the electric field at 1.00 T (52.6 A) is less than 0.1 μV/cm, steady operation at 1.00 T is possible with the present Bi-2223 superconducting magnet. This practical superconducting magnet is suitable for replacement of conventional Cu magnet.

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