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Bi-2223 Superconducting Magnet Generating over 1T in Liquid Nitrogen

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Abstract. Performance of a Bi-2223 superconducting magnet consisted by ten double-pancake coils was improved by using iron plates (SS400) for top and bottom flanges. The magnetic field dependence of the critical current density of Bi-2223 tape for magnetic field normal to the tape was determined the maximum magnetic field of the magnet. Hence, a reduction of the normal component of the magnetic field to the tape was achieved by using the iron plates. The magnetic field distribution in the magnet was calculated by a finite element method, and the reduction of the normal magnetic field component was confirmed. The maximum magnetic field at the center of the magnet bore reached 1.30 T at 65.0 K of subcooled liquid nitrogen and 0.70 T at 77.3 K. These values were about 1.6 times higher than the previous magnet and agreed well with the calculated result.

1. Introduction
One of the leading application using superconducting technology is a superconducting magnet. High static field over 20 T can only be induced by a superconducting magnet. Recent development in fabrication of long length REBa₂Cu₃O₇ (RE denotes rare earth) coated tape demonstrated the ability for an insert coil[1, 2]. It was reported that the demonstration insert coil generated central field in excess of 26.8 T[3]. On the other hand, Bi₂Sr₂Ca₂Cu₃O₉ (Bi-2223) silver sheathed tape has been developed by the introduction of the controlled overpressure (CT-OP) process[4]. The critical current at 77.3 K self-field was over 200 A. The length of the Bi-2223 tape exceeds 1 km. An insert solenoid coil was fabricated and the 13.42 T total magnetic field in 12 T external field was achieved at 4.2 K[5].

Another type of superconducting magnet is not an insert type magnet but a standalone superconducting magnet. A practical Bi-2223 superconducting magnet, working in liquid nitrogen (L.N₂), was designed and fabricated[6]. Ten double-pancake coils were resistively connected by copper terminals. The advantages of using double-pancake coils compared with usual solenoid coil are the improvement of the performance by the replacement of the coil, the repair of the damaged coil and so on. These futures can not be expected in the solenoid coil. Hence, 0.84 T at 65 K in subcooled L.N₂ and 0.44 T at 77.3 K were attained by improvement of double-pancake coils at top and bottom portions of the superconducting magnet[7]. Further
improvement was discussed that the reduction of normal magnetic field component to the Bi-2223 tape was promising, since the total performance of the magnet was determined by the minimum critical current at maximum normal magnetic field component to the tape. It is well known that the magnetic field dependence of the critical current at magnetic field normal to the tape is worse than that at magnetic field parallel to the tape due to the large anisotropy in the Bi-2223 tape.

In this study, the maximum magnetic field of the Bi-2223 superconducting magnet is improved by using iron plates for the top and bottom flanges for reducing the normal magnetic field component to the tape and increasing the total critical current of the magnet from previous work[7]. Discussion is given for further enhancements of the maximum magnetic field of the Bi-2223 superconducting magnet.

2. Experimental
The Bi-2223 superconducting magnet working in L.N₂ was designed and fabricated[6, 7]. The inner bore diameter of the magnet is 54 mm, the outer diameter is 122 mm, the height is 124 mm, and the weight is about 3 kg. The maximum magnetic field at the center of the bore is 0.44 T at 77.3 K and 0.84 T at 65 K.

Figure 1 shows the cross-section views of the several plans for improving the magnet performance. Case 1-1 in the figure is the simple improvement by replacing the FRP flanges at top and bottom of the magnet by iron plates (SS400). The magnetic field is attracted to magnetic material of the iron flanges and the magnetic field is almost parallel to the tape surface, i.e., the normal magnetic field component to the tape is drastically reduced. A dip is introduced for case 1-2 in the figure to enhance the effect of reducing the normal component to the tape.

A finite element method (FEM) was used for estimation of the magnetic field distribution in the magnet. There are three important points of magnetic field for current of 1 A in the calculation, i.e., the maximum magnetic field at the center of the bore, B₁, the maximum magnetic field parallel to the tape, B₂, and maximum magnetic field normal to the tape, B₃. The value of B₁ is $1.11 \times 10^{-2}$ T/A for case 1-1 and is increased from $9.6 \times 10^{-3}$ T/A of previous

Figure 1. Cross-section views of proposed Bi-2223 magnets based on previous magnet[7]. Top and bottom flanges are made of iron (SS400).
Figure 2. Calculation result by finite element method of normalized magnetic field as a function of axial distance from the center of the magnet bore.

Figure 3. Load lines of magnet for maximum magnetic field parallel to the tape ($B_2$) and maximum magnetic field normal to the tape ($B_3$) for case 1-1.

case[7].

Figure 2 shows the calculated result of normalized magnetic field as a function of axial distance from the center of the bore by FEM. The better uniformity of the magnetic field distribution is obtained by the all plans for improvement.

The load lines of the magnet for $B_2$ and $B_3$ in case 1-1 are plotted in figure 3. It is found that the maximum magnetic field of the magnet is determined by $B_2$ for parallel magnetic field component rather than $B_3$ for normal magnetic field component. On the contrary, it was determined by $B_3$ in previous case of the magnet. It means that the normal component to the tape is drastically reduced by the replacement of the flanges from FRP to the iron plates. The critical current of the magnet and the maximum magnetic field are estimated as 62.0 A and 0.69 T, respectively from the load line.

Figure 4 shows the experimental result of current-voltage characteristics of the magnet in L.N$_2$ for ambient pressure (77.3 K) and subcooled L.N$_2$ (65 K). The reason for a gradual increase of voltage at low currents is the resistivity of the copper terminals between the double-pancake coils. Hence, the resistivity becomes low at lower temperature, the voltage is lower at 65 K. These voltages are enough lower than the electric field criterion of $10^{-4}$ V/m ($1 \mu$V/cm), where the total length of the tape is 267 m. The maximum magnetic field at 77.3 K is 0.70 T and agrees well with the prediction result of 0.69 T. Therefore, the design of the magnet by FEM is effective for the present case.

Finally, discussion is given for the further improvements of the magnet performance as shown in figure 1. The calculated results of parameters of the proposed magnets by FEM are listed in Table 1. The dips for the flanges except of case 1-1 are effective resulting in the enhancement of the maximum magnetic field at the center of the bore, $B_{1\text{max}}$. In case 2-1 and 2-2, the number of winding for every coil has grading for the purpose of the reduction of the total normalized length of the tape ($l$) or the enhancement of $B_{1\text{max}}$ and the uniformity. The uniformity is determined from the axial length of 5% decrease from $B_{1\text{max}}$. It is found that the efficiency defined by $B_{1\text{max}}/l$ is maximum in case 2-2. For case 3, the number of the double-pancake coils is 12 to
enhance $B_{1\text{max}}$. Although the tape length is 137% of case 1-1 of the present study, $B_{1\text{max}}/l$ is 1.18 times larger than case 1-1. There are many possibilities for the design of the magnet. Hence, it is desired to optimize the design of the magnet for several usages and aim of the magnet.

3. Conclusions
In this study, the maximum magnetic field of the Bi-2223 superconducting magnet consisted from ten double-pancake coils was tried to enhanced by replacing FRP flanges to the iron flanges for reducing the magnetic field normal to the Bi-2223 tape in the magnet. The maximum magnetic field at center of the bore was 0.70 T at 77.3 K and 1.30 T at 65 K in subcooled L.N$_2$. These values were about 1.6 times higher than the previous magnet. The uniformity of the magnetic field in the bore was also improved. Several plans for further improvement of the magnet performance were proposed. It is necessary for further investigation for the optimum design of the magnet.

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