

Fabrication of a Working Bi-2223 Superconducting Magnet Cooled by Liquid Nitrogen

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Abstract

A practical Bi-2223 superconducting magnet, working in liquid nitrogen (L.N₂), was designed and fabricated. Bi-2223 tape with a critical current of 147 A was prepared by a controlled overpressure (CT-OP) process at 77.3 K in self-field. 10 double-pancake coils were resistively connected by copper terminals. The bore diameter was 54 mm ϕ , the magnet outer diameter was 122 mm ϕ , the height of the magnet was 124 mm, and the weight of the magnet was about 3 kg. The maximum magnetic field at the center of the bore was 0.48 T with an operating current of 50 A. The experimental results agree well with design predictions calculated by finite element method. AC operation was also performed, and no distortion of the voltage waveform was observed. Therefore, this Bi-2223 superconducting magnet is a suitable replacement for copper magnets designed for applications in science and technology.

Key words: superconducting magnet, Bi-2223 tape, overpressure sintering, critical current density

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1 Introduction

The critical current density of silver sheathed Bi-2223 superconducting tape has been drastically improved by the introduction of the controlled overpressure (CT-OP) process [1,2]. The critical current at 77.3 K self-field was over 200 A. In addition to the critical current density, the irreversibility field, n -value, and mechanical properties were also improved. These improvements were mainly attributed to the improved connectivity of superconducting grains due to better c -axis alignment resulting from elimination of voids. In addition, the enhancement of flux pinning strength also contributed to higher critical currents of over 150 A by development of the conditions of the CT-OP process. It has also been reported that the critical temperature of Bi-2223 tape was enhanced to over 110 K [3]. Therefore, further improvement of the superconducting characteristics of Bi-2223 is expected.

Many applications using Bi-2223 tape have been reported, such as a transformer[4–6], a power cable[7], and a superconducting motor[8]. We also fabricated a small superconducting transformer designed for AC transport loss measurements[5]. The maximum current obtained in the secondary winding was 500 A for an input primary current of 5 A. At that time, since the critical current of the tape was only 50 A, 10 tapes were parallel-wound. This concept was further developed into a 1,000 A transformer cooled by cryocoolers[6]. Hence, much higher performance is expected from the use of Bi-2223 tape prepared by CT-OP.

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The next logical development target would be a superconducting magnet made from Bi-2223 tape prepared by CT-OP, since the critical current would be much higher than that obtainable by standard fabrication, allowing a high-performance magnet to be designed and fabricated. For example, the maximum magnetic field of a typical copper magnet working in L.N₂ is 0.1 T at 10 A and 10 V. Much higher performance is expected from Bi-2223 tape prepared by CT-OP, as the overall size can be reduced while the maximum magnetic field is enhanced. There are many copper magnets designed for scientific measurement, such as bias magnets for magneto optical (MO) observation. The replacement of these copper magnets by Bi-2223 magnets, which are easily cooled by L.N₂, is expected. In the case of Rare Earth-123 coated conductor tape, it was reported that 0.48 T was obtained at 77.3 K with an operating current of 74.2 A for a Gd-123 coil in which the tape was fabricated by IBAD-PLD method[9]. However, since the tape length was only 60 m, the bore diameter was limited to 28 mm. In this work, we sought a more practical superconducting magnet. In the case of Bi-2223, 1.5 km long tape is readily available, so a practical superconducting magnet is possible.

In this study, Bi-2223 superconducting magnet was designed and fabricated, and its performance was measured and compared to design values. We conclude with discussion of possible enhancements to the maximum magnetic field at the center of the bore.

2 Experimental

2.1 Design

The specifications of the Bi-2223 superconducting tape fabricated by CT-OP are listed in Table 1. Results of detailed measurements of this tape are reported elsewhere[2]. Specimen #2 in ref. 2 was the same tape used in the present study. The inner diameter of the coil was determined by bending characteristics, and was 70 mm ϕ . Presently, the minimum diameter achievable using the Bi-2223 tape is 70 mm. The targeted maximum magnetic field at the center of the bore was 0.5 T. This is 5 times larger than a typical copper magnet of the same size working in L.N₂. The distribution of the magnetic field in the superconducting magnet was calculated by finite element method (FEM). A cross-section of the magnet is shown in Fig. 1. The total number of windings was 1040, and there are three important points in the magnet, as shown in Fig .1. (A) The maximum magnetic field at the center of the bore was 10.8 mT, and (B) the overall maximum magnetic field was 11.5 mT, and (C) the maximum magnetic field perpendicular to the tape surface ($B \parallel c$) was 4.84 mT at 1 A. The limitations of the magnet are determined when the tape reaches the critical current with the magnetic field applied perpendicular to the tape surface, since the critical current of a perpendicular magnetic field is far smaller than that of a parallel magnetic field. Therefore most of the tape in the magnet does not reach the critical current when the tape at the top of the magnet reaches the critical current in area (C) of Fig. 1.

The load line of the magnet at 77.3 K is shown in Fig. 2. The maximum magnetic field perpendicular to the tape surface was 0.195 T, obtained at 40.3 A, and at the same time the maximum magnetic field at the center of

the bore was 0.435 T, about 2.2 times larger. This was close to the target magnetic field of 0.5 T. The calculated magnetic field at the center of the bore for various temperatures was also obtained from the magnetic field dependence of the critical current at various temperatures, and is shown in Fig. 3. It follows that approximately 1 T was attained by the magnet at 65 K, since the critical current was about two times larger than at 77.3 K.

It is important to estimate the electromagnetic hoop stress, σ , which is given by

$$\sigma = BJR, \tag{1}$$

where B is the magnetic field, J is the current density, and R is the radius of the coil. In the present magnet, the electromagnetic hoop stress was calculated to be 1.3 MPa for 0.5 T at an operating current of 50 A, far below the limit of 200 MPa. Therefore, operation at 500 A may be possible at lower temperatures, since the hoop stress is estimated to be 130 MPa at 5 T.

Although the irreversibility field is about 0.7 T in the magnetic field perpendicular to the tape surface, the magnetic field at the center of the present magnet is about 2.2 times larger. Therefore, a larger magnet could be designed and fabricated using the present superconducting tape. Additional improvement of the magnet is expected with the use of high-performance Bi-2223 tape with a high critical current.

2.2 Fabrication

The specifications of the Bi-2223 superconducting magnet are listed in Table 2. The magnet was built from 10 double-pancake coils. For simplicity, these pan-

cake coils were resistively connected by copper terminals. Fig. 4 shows an overview of the magnet.

It is also possible to fabricate a solenoid coil using the present technique [6]. In this study, however, pancake coils were selected for their high cost performance and high reliability. It is possible to achieve a higher performance magnet by replacing the pancake coils at the top and bottom portions of the magnet with a tape having a higher critical current. The cost of such a magnet can be reduced by the use of low critical current tape in the central portion of the magnet. In addition, if the superconducting magnet is damaged, it can be repaired by replacing only the damaged pancake coil, as opposed to requiring an entirely new coil.

3 Results and discussion

Fig. 5 shows the voltage-current characteristics of the magnet at 77.3 K. The total critical current, determined by 10^{-4} V/m ($= 1 \mu\text{V}/\text{cm}$), was 45.2 A when 0.43 T was measured at the center of the bore. This was higher than the design value of 40.3 A, since only the tape in region (C) of Fig. 1 reaches the critical current. Therefore, the magnet can be operated at a current higher than the design value. The magnetic field at the center of the bore stably reached 0.48 T at 50 A, with a loss of about 5 W. The voltage was gradually increased at $I < 40$ A, and the resistivity was estimated to be $0.16 \text{ m}\Omega$, due to the resistive connection between the pancake coils. Therefore, currents below 170 A are suitable for achievement voltages less than 10^{-4} V/m at 77.3 K. This value of 170 A increases with decreasing temperature.

The high-temperature operation of this superconducting magnet differs from

that of a metal superconducting magnet. A current source with a constant sweep rate is required for a metal superconducting magnet to prevent quenching of the magnet. On the other hand, since the high-temperature superconducting magnet is relatively stable in L.N₂ if the operating current is below the critical current, a constant sweep of current is unnecessary. Therefore, operation is as easy as it would be for a comparable copper magnet.

The magnetic field distributions inside the bore in the longitudinal and radial directions are shown in Fig. 6(a) and 6(b), respectively. The measured results agree well with the calculated results from FEM analysis. The uniformity of the magnetic field was 5%, obtained within a sphere of about 30 mm radius.

AC transport current tests were also performed. Current and voltage waveforms are shown in Fig. 7 for the case of peak-to-peak amplitude of 10 A at 10 Hz. No distortions were found in either waveform. Fig. 8 shows the waveforms of current and voltage for the case of 15.2 A DC superimposed on a peak-to-peak amplitude of 0.2 A at 300 Hz. It was found that the voltage waveform was not distorted. The AC transport current testing was insufficient, due to limitations of the AC current source used in the present study. Further study is necessary to evaluate potential usage as an AC magnet.

We now discuss the possibility of enhancing the maximum magnetic field of the Bi-2223 superconducting magnet. Since the magnet was built from pancake coils, we expect that replacement of the top and bottom portions of the magnet by higher-performance tape would result in improved performance. For example, double-winding the tape in the pancake coils should increase performance. Another possibility is the use of an iron yoke, to reduce the component of the magnetic field perpendicular to the tape surface. Operation at low temperatures is another promising method of enhancing the performance of the

magnet, such as the use of subcooled L.N₂.

4 Summary

A practical Bi-2223 superconducting magnet which can operate in L.N₂ was designed and fabricated, and several tests were performed. The magnetic field at the center of the bore was 0.43 T, determined by the electric field of 10^{-4} V/m ($= 1 \mu\text{V}/\text{cm}$), which agreed with the design value. The maximum magnetic field at the center of the bore stably reached 0.48 T at 50 A, with a loss of about 5 W. This was 5 times larger than the field in a typical copper magnet of the same size. Therefore, the present Bi-2223 superconducting magnet is a suitable replacement for copper magnets designed for various applications in science and technology. We expect that the performance of the magnet will be improved by replacement of the currently-used pancake coils at the top and bottom of the device with Bi-2223 superconducting tape, which can support a much higher critical current.

Acknowledgments

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Table 1: Specifications of Bi-2223 tape.

critical current (77.3 K self field)	147 A
width	4.4 mm
thickness	0.22 mm
tape length	~270 m

Table 2: Specifications of Bi-2223 superconducting magnet.

magnet outer diameter (flange diameter)	122 mm
magnet inner diameter (bore diameter)	54 mm
pancake coil outer diameter	98 mm
pancake coil inner diameter	70 mm
height of magnet	124 mm
weight of magnet	~ 3 kg
turn of coil	1040
total length of tape	~ 270 m
number of pancake	20
maximum magnetic field at center	0.5 T
coil constant	0.010 T/A
inductance	32 mH
stored energy at 0.5 T	400J

Figure captions

Figure 1 Cross section of the magnet for calculation of magnetic field distribution.

Figure 2 Load line of the magnet at 77.3 K. The limitation of the magnet is determined by the magnetic field perpendicular to the tape surface. At the same time, the maximum magnetic field at the center of the bore reached 0.435 T.

Figure 3 Calculated magnetic field at the center of the bore for various temperatures.

Figure 4 Overview of the Bi-2223 superconducting magnet. It is built from 10 double-pancake coils connected by copper terminals.

Figure 5 Voltage-current characteristics of the magnet at 77.3 K.

Figure 6 The magnetic field distribution inside the bore for (a) longitudinal and (b) radial directions. Symbols are measured results and the solid line is the result calculated by FEM.

Figure 7 The waveforms of current and voltage for a peak-to-peak amplitude of 10 A at 10 Hz.

Figure 8 The waveforms of current and voltage for 15.2 A DC superimposed on AC of peak-to-peak amplitude of 0.2 A at 300 Hz.

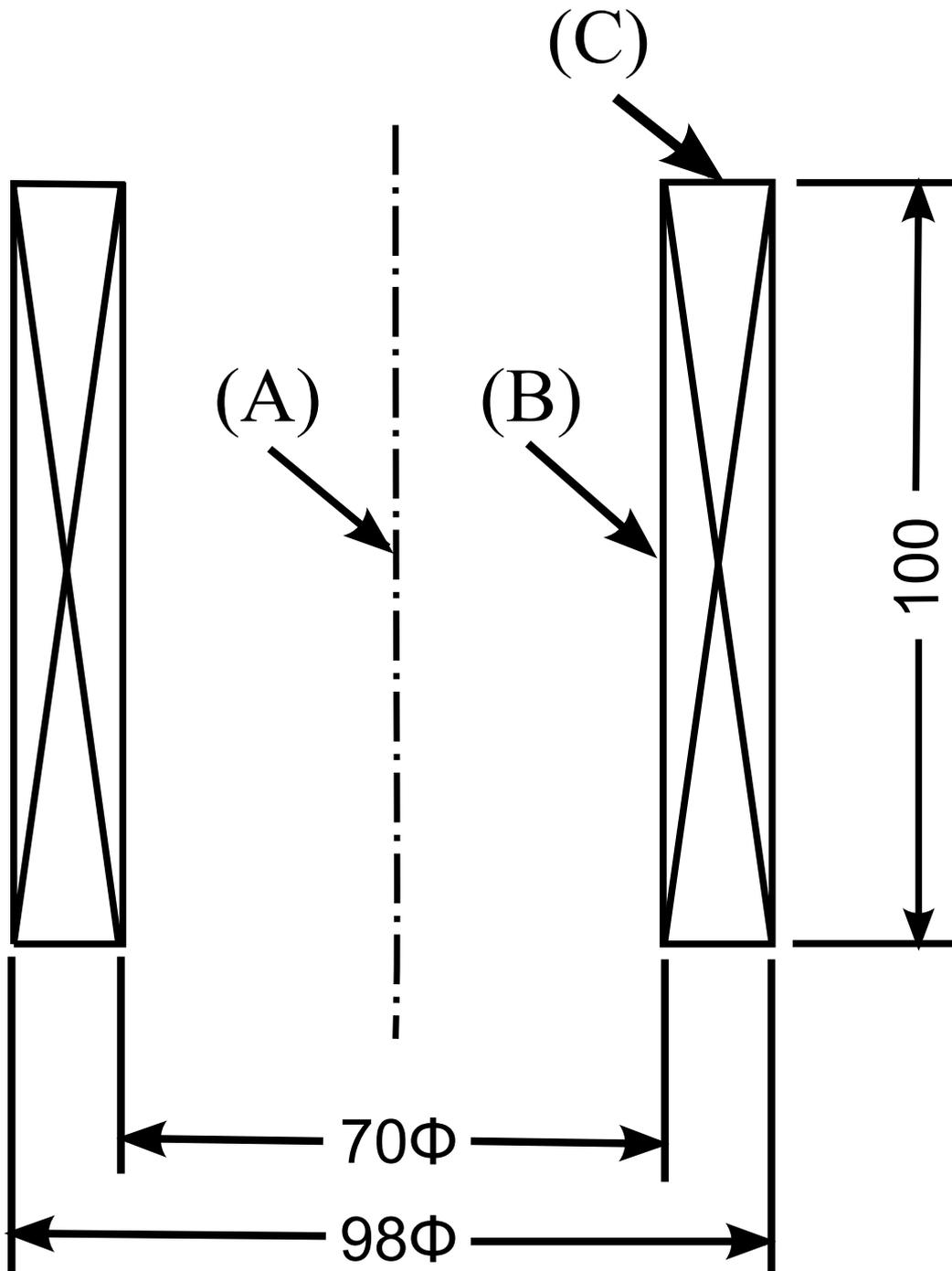


Fig. 1: E.S. Otabe *et al.*

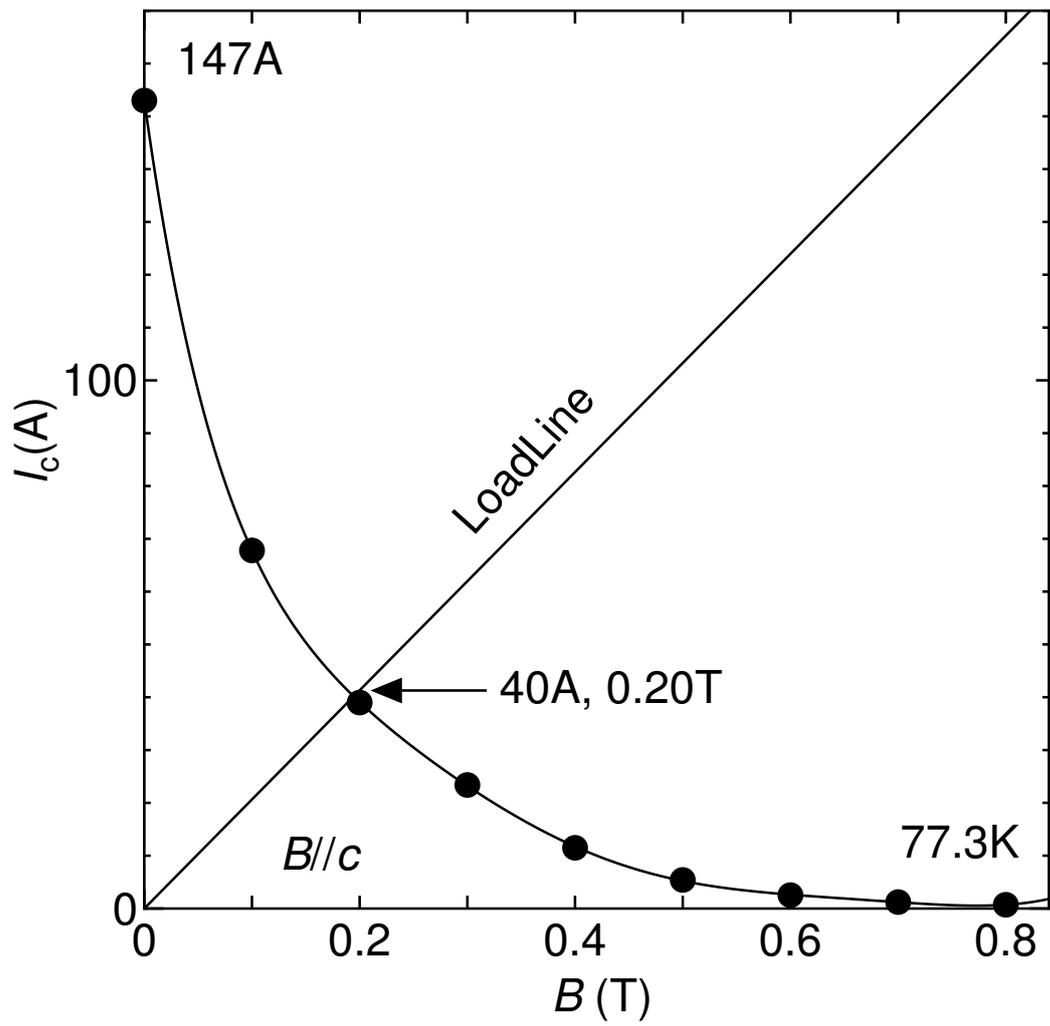


Fig. 2: E.S. Otabe *et al.*

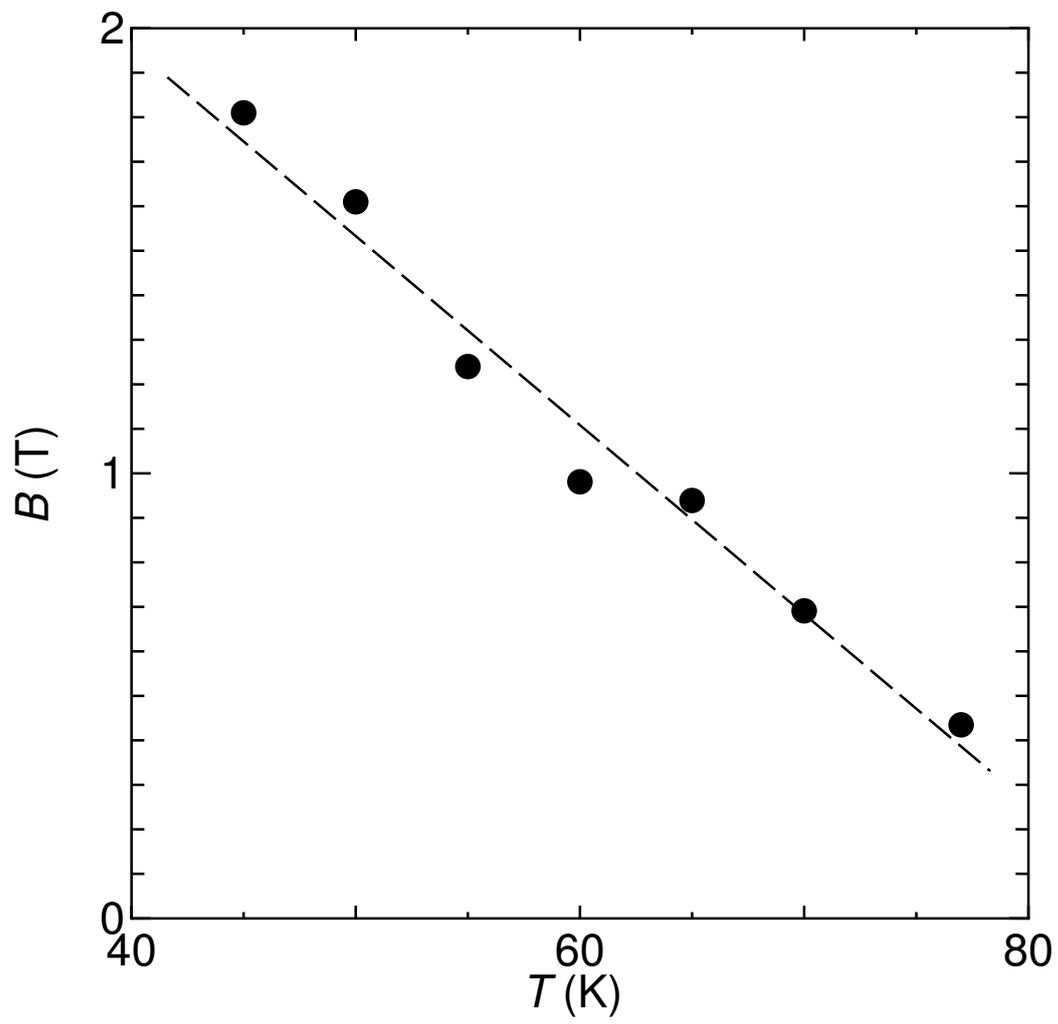


Fig. 3: E.S. Otabe *et al.*



Fig. 4: E.S. Otabe *et al.*

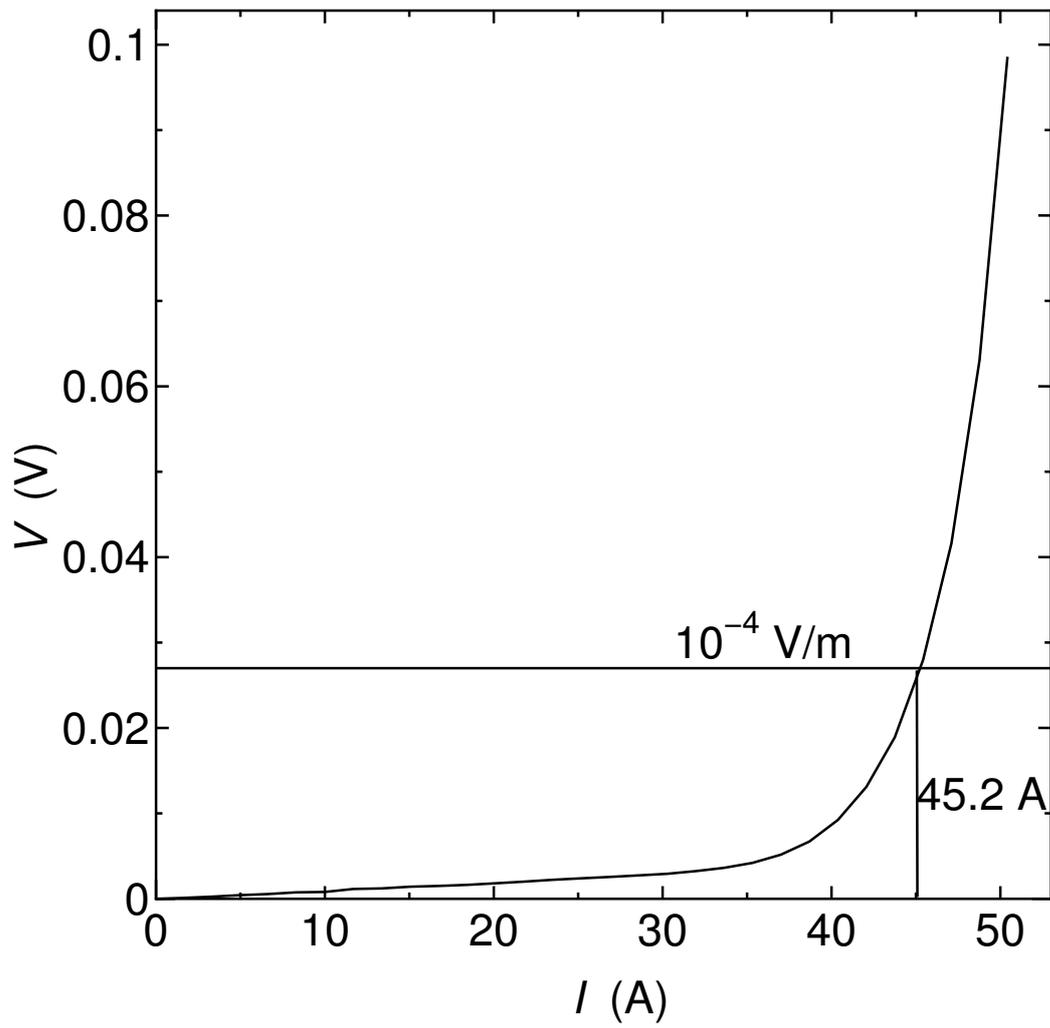


Fig. 5: E.S. Otabe *et al.*

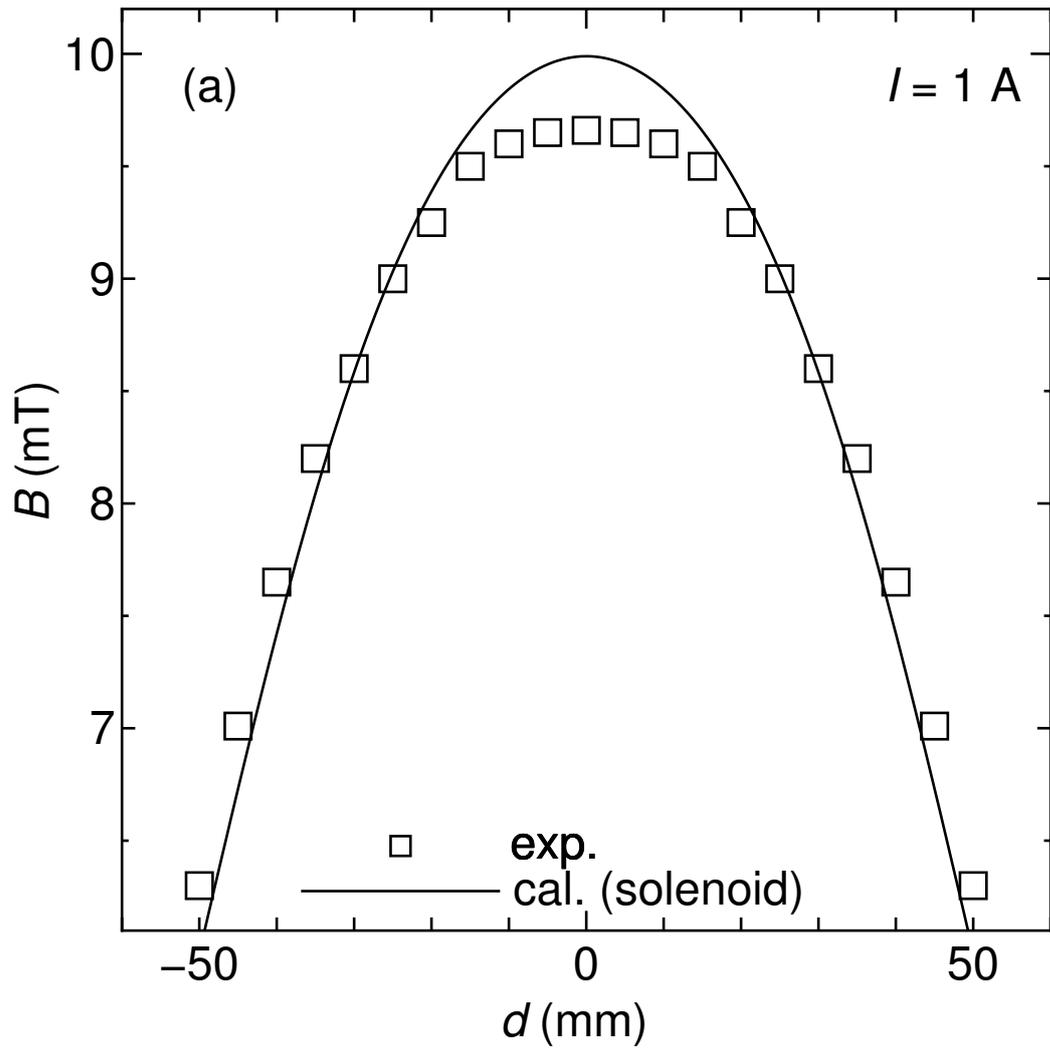


Fig. 6(a): E.S. Otabe *et al.*

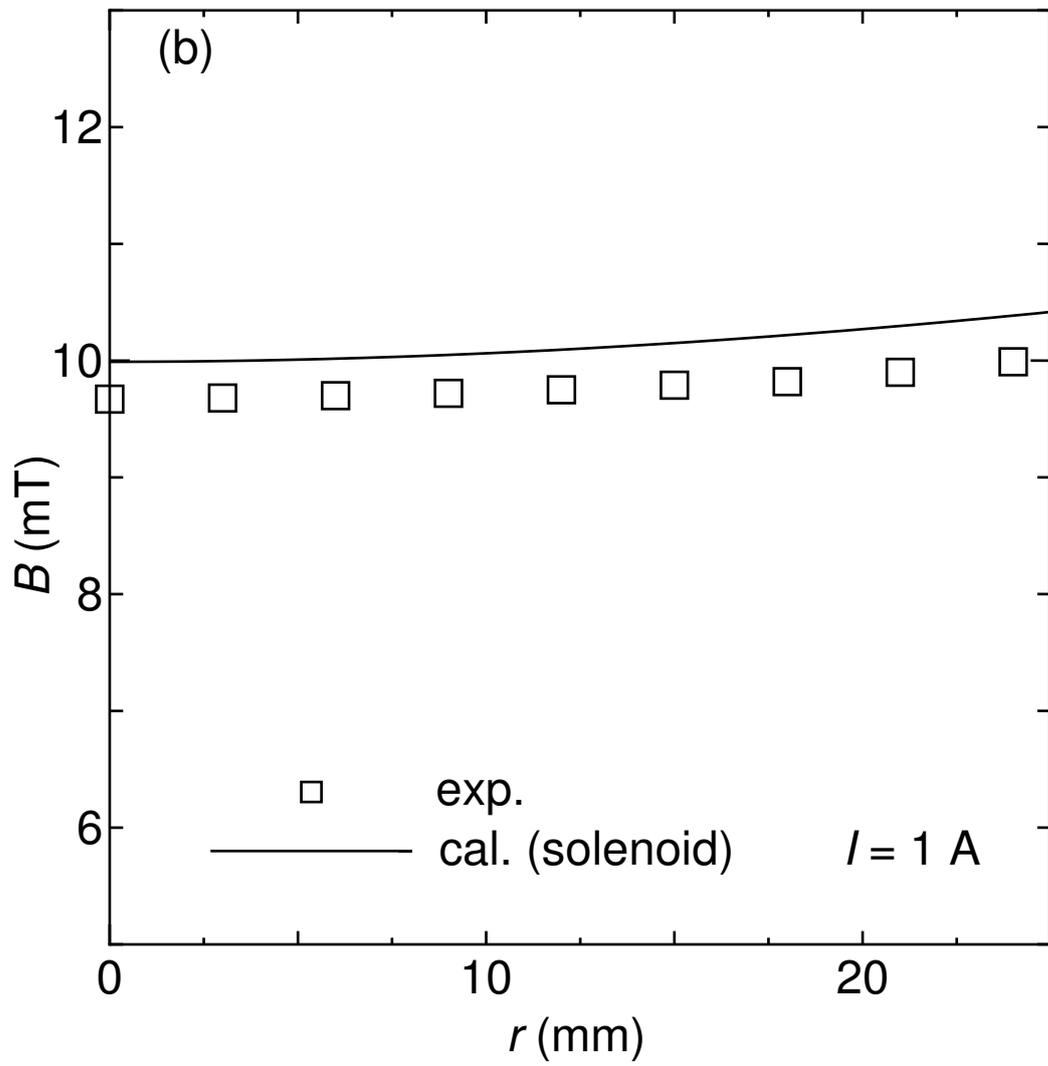


Fig. 6(b): E.S. Otabe *et al.*

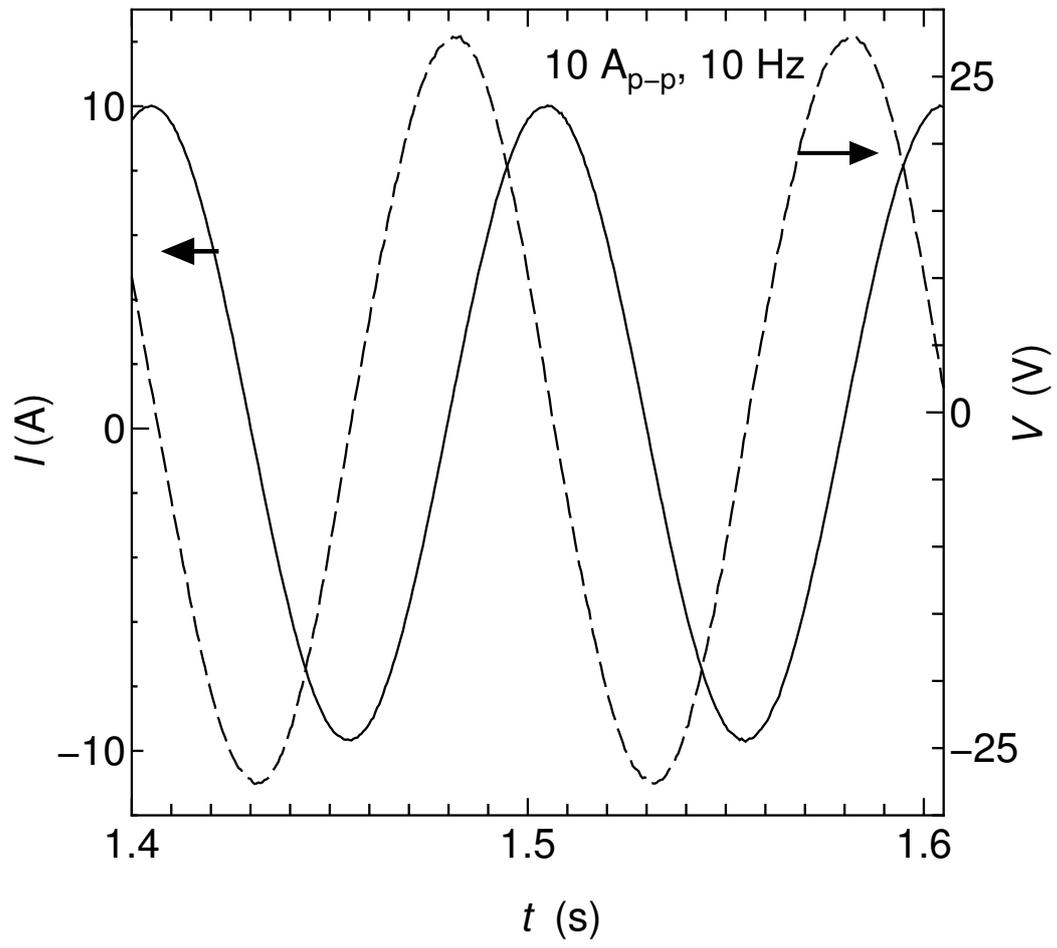


Fig. 7: E.S. Otabe *et al.*

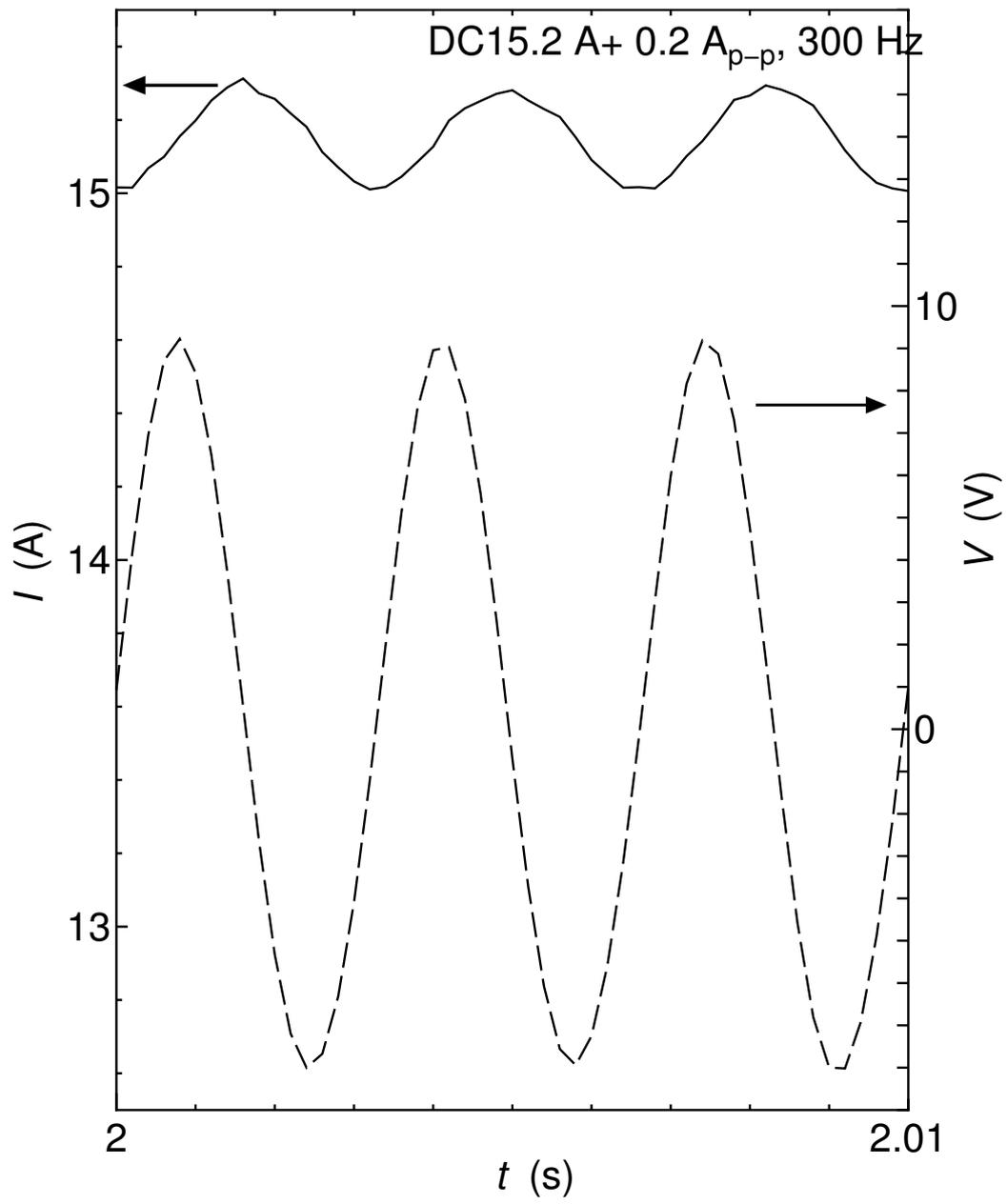


Fig. 8: E.S. Otabe *et al.*