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Critical Current Density and Best Transport Current of an Ag-Sheathed Bi-2223 Tape Conductor

Hiroyasu Ogiwara,[a] Yutaka Yamada,[b] Masako Satou,[b] Tasuku Kitamura[c] & Takayo Hasegawa[c]

[a]Shonan Institute of Technolgy, 1-1-25 Tsujido-nishikaigan, Fujisawa 251, Japan
[b]Toshiba Research and Development Centre, 4-1 Ukishima, Kawasaki 210, Japan
[c]Showa Wire and Cable Co. Ltd, 2-1-1 Oda-sakae, Kawasaki 210, Japan

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Abstract: A critical current density of as high as 66,000 A/cm^2 has been achieved in an Ag-sheathed Bi-2223 superconductor. Also a coil wound with the same kind of wires has generated a magnetic field of 1.5 T. The conductors of this coil consisted of six elemental conductors connected in parallel.The reason why the parallel conductors were used was that it was difficult to fabricate a single conductor which had the capability of passing a large amount of current at a high critical current density. In an Ag-sheathed Bi-2223 superconductor, one limiting factor prevents a single conductor from having a large current-passing capability and the highest critical current density, at the same time. A larger amount of current passes through a conductor with a larger cross-section. However, we can only realize a higher critical current density with a conductor of a smaller cross-section. This core size limitation (CSL) gives rise to many problems that need to be solved when considering large scale applications in the electrical engineering field with Ag-sheathed Bi-2223 superconductors.

1 INTRODUCTION

In the area of electrical engineering, superconductors in the shape of a wire or a tape are wound to a coil and produce a high magnetic field without any joulean loss. A wire or a tape is a thin and long continuum. It should stand up against mechanical deforming and electromagnetic stress and should also have excellent superconductivity. Processibility has high priority in superconductors when we consider their applications. We readily recall a niobium–zirconium alloy superconductor which disappeared from the engineering superconductor list a long time ago because of its poor processibility. Today's widely used niobium–titanate alloy superconductor owes its usefulness largely to the material itself, to its co-processibility with a stabilizing material, and to processability of fabricated wires. Though the niobium–titanate superconducting wires used in accelerators and MRIs (Magnetic Resonance Imaging medical diagnostic systems) fulfill all the above mentioned conditions, they need R & D for future applications.

High temperature superconductors, like bismuth-system cuprate superconductors, also need much R & D in order to become really usable engineering materials for the electrical industry.

We have two kinds of bismuth-system cuprate superconductors: a tape-shape conductor with a Bi-2212 film on an Ag-tape base, and an Ag-sheathed Bi-2223 superconductor which has better electromagnetic properties than the 2212-phase bismuth–cuprate tape conductor. The latter also has the shape of a tape, which presently gives us a problem to be discussed. Hopefully, this provides the freedom to choose the aspect ratio of the cross-section of a conductor. In this report, we are doing R & D on an Ag-sheathed 2223-phase bismuth superconductor.

We have already reported the world's highest critical current density of as high as 66,000 A/cm^2,[1] and the magnetic fields of 0.2 T (at liquid nitrogen temperature) and 1.5 T (at liquid helium temperature) generated by a coil of inner diameter 15 mm and a height of 48mm, wound with 60 pieces of 3.8 metre-long Ag-sheathed Bi-2223 superconductors.[2]

2 CRITICAL CURRENT DENSITY

Arranging the crystalline axes of Bi-2223 crystals along the longitudinal direction by uniaxial pressing and elongating in an Ag sheath results in an increase in critical current density and an improvement of magnetic properties. We reported the best critical current density of as high as 66,000 A/cm^2 so far. This record was the result of pressing an Ag-sheathed Bi-2223 conductor uniaxially, by keeping the interface between the sheath material and the Bi-2223 core (hereafter core for simplicity) smooth and flat, while bringing the core material density as close as possible to the theoretical packing density level, and by making the core thickness thinner.[3]

The thinner the thickness of an oxide-core in a uniaxially pressed and elongated Ag-sheathed Bi-2223 conductor, the higher the current density we obtain. This fact has already been reported by Neumuller *et al.*[4] They reported that along the interface there was a thin layer of several tenths of micrometres, where Bi-2223 crystals were highly orientated and had a high critical current density, and that the highest value of the critical current density should be about 10^6 A/cm^2 when the core thickness attains a value of about 1 μm (the thickness of a thin single crystal). Therefore, we investigated the distribution of the hardness in the core (using a Vicker's hardness meter) and the relation between critical current density and Vicker's hardness.[3]

We divided the core into three parts, depending on local density distributions, in accordance with the results of Vicker's hardness measurements. They were: (1) two layers, each adjacent to the Ag sheath (2) the central part of the core, and (3) the edges as shown in Fig. 1. The critical current density was highest at the layers adjacent to the sheaths and lowest at the central core.[3] So, we could obtain the highest critical currrent density with a thin sample which had no central part, so that the core thickness was below the core size limit. Core size limitation (CSL) was reported in the superconducting oxide layer of an Ag tape base Bi-2212 film conductor, where the highest critical current density was found at the tape surface and at the layer adjacent to the base silver metal tape.[5]

Larbalestier and his colleagues reported 76,000 A/cm^2 as the critical current density of the highest density part of a core which was cut out from a

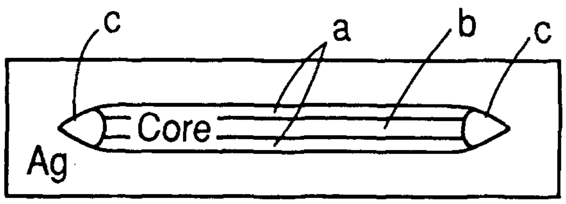

Fig. 1. Density distribution in the oxide core of an Ag-sheathed Bi-2223 conductor.

best processed Ag-sheath Bi-2223 conductor by uniaxial pressing.[6]

We have already pointed out this limited effect on core size as the CSL effect, which means that the part of a core with high critical current density is limited to thin regions in the core, and prevents us from fabricating a large size conductor which can pass a large amount of transport current.[7]

However, to make a core with higher density means that the mechanical properties of the conductor become weaker against deformation, which is necessary when building a coil with it. One of the countermeasures against this problem is to divide a core into many fine filaments, like today's widely used ultra-fine filamentary metallic superconducting wires. This has surely improved the mechanical properties against bending.[8] However, there was no increase in critical current density. These various efforts resulted in obtaining higher tolerance against deformation at the expense of critical current density.

For all practical purposes, where long length and large scale superconducting wires are needed for fabricating large coils, tolerance against bending is more important than the best critical current density. For application in the electrical engineering field, a length, a critical current (an amount of transport current), and a critical current density should be balanced out against each other.

3 TEST FABRICATION OF AN Ag-SHEATHED Bi-2223 COIL

In order to make an R & D policy of an Ag-sheathed Bi-2223 conductor for a superconducting magnet and to obtain higher critical current density, even better than the best one of today with a short sample, we have made a coil which generated a high magnetic field (as high as possible) with coils fabricated in our laboratory, and discussed how to make a larger conductor.[2] As a starting point of this research, we used 60 pieces of Ag-sheathed Bi-2223 conductors, each one being 4.0 mm wide, 0.11 mm thick and 3.8 m long. With a tape of these dimensions we could easily pass a current of from 30 to 50 A, with a critical current

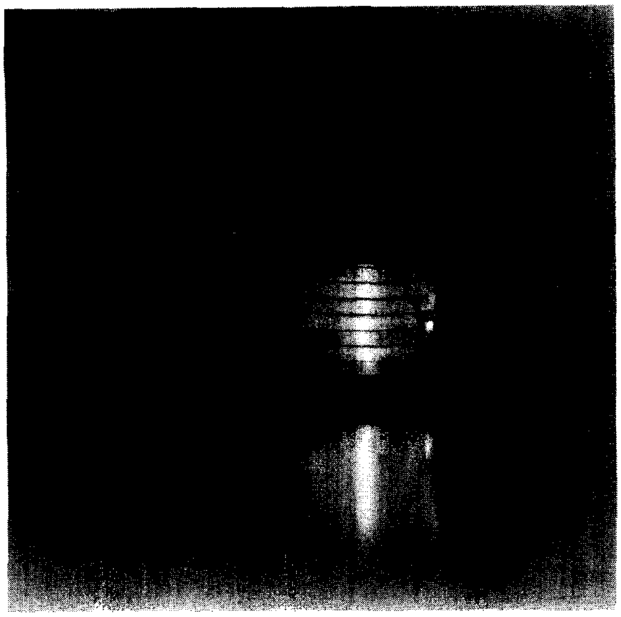

Fig. 2. The birth of the HiTc SC magnet, CP-10.

density of 10,000 A/cm^2 level. After investigating the tolerance against bending of a single tape and after we made sure that bending of a radius of 7.5 mm gave but a small decrease in the current passing capability of the tape, we built a small, so-called fist-size, coil with a bore diameter of 15 mm. At first, using a conductor with six parallel pieces of tape, we fabricated a one-layered pancake coil. The stacking of ten pancake coils made up a fist-sized coil. The coil, CP-10 shown in Fig. 2, had an inner diameter of 15 mm, an outer diameter of 68 mm, and a height of 43 mm, and generated 1.42 T with a transport current of 221 A in liquid helium, and 0.16 T with 25 A in liquid nitrogen temperature. Another coil of the same dimension generated 1.48 T in liquid hydrogen and zero external magnetic field, and 0.8 T in liquid helium with an external magnetic field of 14 T. Recently, a magnetic field of 2.6 T was reported with this fist-sized coil.[9]

A magnetic field between 1.5 and 2.8 T is not high enough for magnetic field generated with a superconducting magnet. However, the important thing is the fact that we have already come to the point where we can make a coil which generates a magnetic field of higher than 1 T with a high-temperature superconductor, like a Bi-2223 conductor, and that we can start thinking of true applications of high-temperature superconductors. A conductor which can pass a transport current of $\geq$300 A at liquid nitrogen temperature has already been reported.[10]

Considering the current status of R & D of the conductors mentioned above, we think that it is important to step into the test fabrication of various superconducting apparatuses, even in the limited areas of low magnetic field of from 0.1 to 1 T. The American Superconductors' marine acoustic sensor system is a good example of this sort.[11]

Fig. 3. 6T-compact SC magnet.

4 NEEDS FOR LARGE SCALE CONDUCTORS

There are many varieties of superconducting coil/magnets, from gigantic ones for fusion reactors to small ones of fist-size, and various generated magnetic fields from the 20 T of a laboratory magnet to the 0.5 T of an MRI magnet. Conductors also have varying amounts of current, from several tens of thousands to 10 A. For example, Fig. 3 shows the 6 T-compact superconducting magnet built with niobium–titanium superconducting wires and with a pair of the Bi-2223 current-lead rods. Both were cooled at liquid helium temperature by a newly developed G-M refrigerator. Figure 4 shows the cross-section of the magnet which had a room-temperature bore of diameter 18 cm and depth 45 cm. The cross-sectional area of the winding was 32 mm $\times$ 240 mm (76.8 mm^2). The amount of current used for generating a magnetic field of 6 T was 128 A. The total number of windings was about 12,000 turns, so the magnetomotive force was 1.54×10^6 Ampere–turns. The total length of the conductors was about 10 km. The superconducting wire used had a diameter of 0.7 mm, and the ratio of copper to superconductor was 1, so the current density of

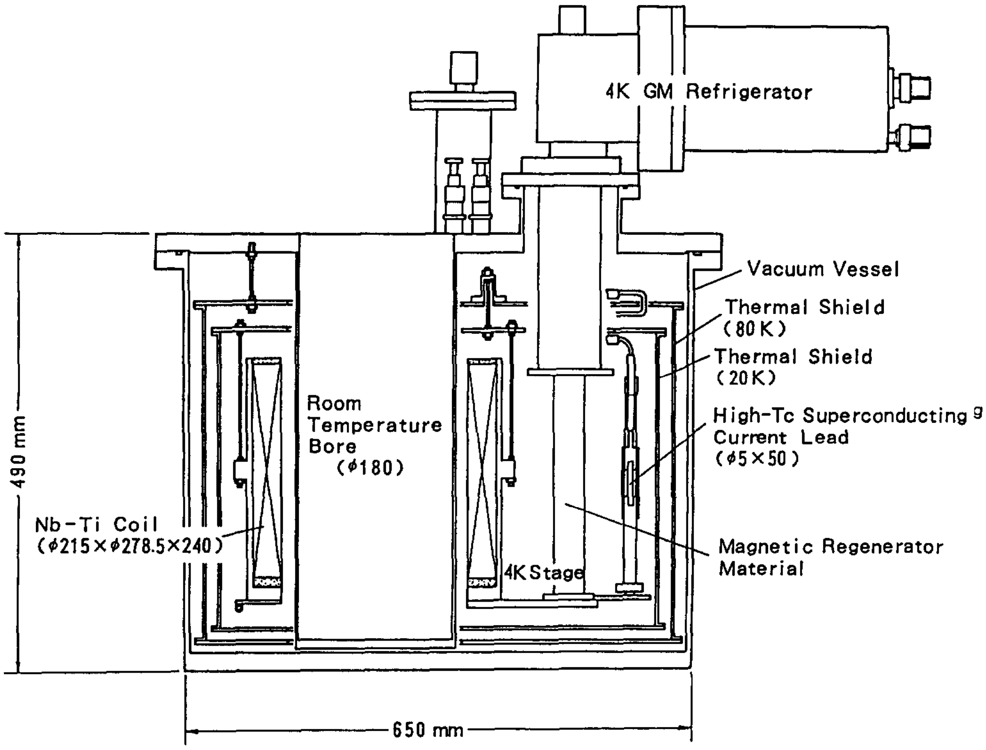

Fig. 4. Cross-sectional drawing of 6T-compact SC magnet.

the conductor was 6.7×10^4 A/cm^2 at 6 T. The interesting coincidence of this amount of critical current density to one which we had previously reported with the short sample of an Ag-sheathed Bi-2223, led us to plan the test fabrication of a large coil with Ag-sheathed Bi-2223 conductors, ignoring the difference of coolants.

An Ag-sheathed Bi-2223 conductor has several problems. These include: (1) critical temperature, (2) magnetic properties, (3) critical current density, (4) amount of transport current, (5) length, (6) tolerance against winding deformation, and (7) stability.

One of the reasons why applications of an Ag-sheathed Bi-2223 conductor at liquid helium temperature and at one below liquid neon temperature (43 K) are being considered is poor magnetic characteristics of Ag-sheathed Bi-2223 conductors because of flux-flow. However, it is important to recall that the fist-size coil generated 1.5 T in liquid helium temperature and about 0.2 T at liquid nitrogen temperature, and that a long conductor over 1 km has been produced.

5 NEAREST GOAL OF R & D OF Ag-SHEATHED Bi-2223 CONDUCTORS

In order to demonstrate the possibility of liquid nitrogen cooled Bi-2223 coils and to search for what are the key issues for building coils for use in electrical equipment applications, we discuss here a trial design for an MRI coil built with Ag-sheathed Bi-2223 conductors which work in a low magnetic field of below 0.1 T.

Up to now, magnetic resonance imaging systems for medical use put a patient in a deep and narrow channel. Some patients psychologically cannot stand being kept in a prone position in such a closed environment (claustrophobia) and the doctor cannot approach the patient during examination. An open configuration MRI system is proposed for avoiding these inconveniences and for providing space for a doctor to make an *in situ* operation while watching the patient being examined.

The ACCESS, proposed by Prof. L. Kauffman of the Radiologic Imaging Laboratory of the San Francisco School of the University of California, is one of these open MRIs.[12] Presently the ACCESS uses a magnetic field of 650 gauss generated with high performance permanent magnets. We are aiming at replacing the permanent magnet system with a pair of coils wound with Ag-sheathed Bi-2223 conductors cooled by liquid nitrogen.

Figure 5 shows the conceptual drawing of the the HiTc-ACCESS coil which uses the Helmholtz coil configuration. Its inner diameter is 0.8 m, its height 10 cm, and its width 5 cm. The distance between the two coils is 60 cm. This coil system generates 680 gauss at a magnetomotive force of 50 kA–turns. So, when the coil passes an operating current of 25 A, 2,000 turns of winding are required, which mean 20 pancakes with 100 turns or two solenoids with 50 layers of 20 turns. To build this coil 20 pieces of 500 m-long Bi-2223

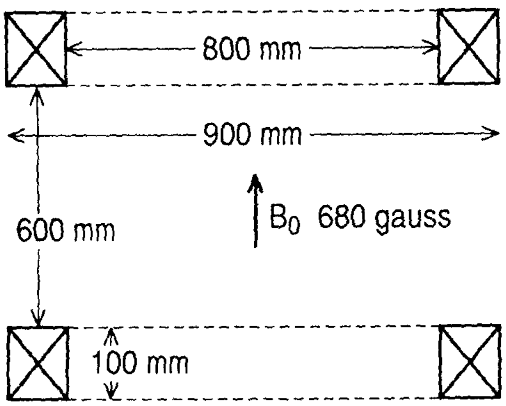

Fig. 5. Concept of HiTc-ACCESS.

tapes consisting of three element tapes of 5 mm width and 0.05 mm thickness are needed. The current density in the Bi-2223 core is 3,300 A/cm^2 when a current of 25 A passes through the conductor. The total length of the conductors is about 10.1 km.

In Table 1, three coils are compared: the 6T-compact superconducting magnet, the Helmholtz coil system for the ACCESS, and the CP-10 (the 1.5 T fist-size Bi-2223 coil). In the table we can see the differences and the similarities between the three coils. In this table we'd like to emphasize the differences between the total length of all the conductors used for the HiTc-ACCESS and the length of the CP-10. The production of a large number of long conductors of uniform quality — which, at present, can only be produced by scientists and engineers in the ceramics industry — should now become the aim of R & D, an aim which has yet to be achieved.

6 CONCLUDING REMARKS

As far as we can see, the short sample characteristics of an Ag-sheathed 2223-phase bismuth system superconductor are individually approaching the characteristics of currently used metal superconducting conductors. For example, we have already reported a critical current density of as high as 66,000 A/cm^2 in a short sample, and a magnetic field of 1.5 T generated with a fist-sized coil. Now, one coil has generated a magnetic field of as high as 2.6 T.

A detailed survey of the specifications of the 6T-compact superconducting coil made by using niobium–titanate alloy superconducting wires indicates that R & D should be focused on processing technology for a long-length conductor with large current carrying capability, and with a toughness against deformation exerted when the conductor is wound to a coil. These aren't problems that can be solved only by using a large size silver tube and enough quantity of oxide powder.

Table 1. Comparison of three coils

	6T-compact	HiTc-ACCESS	CP-10
Generated magnetic field B_0 (T)	6	0.068	0.16
Coil			
inner diameter (mm)	215	800	15
outer diameter (mm)	278.5	900	68
height (mm)	240	100 × 2	48
Magnetomotive force (kA–turns)	3.3×10^3	50	7.2
Operating current (A)	128	25	25
Core current density (A/cm^2)	67,000	3,300	5,200
Conductor cross-section (mm)	0.7ϕ	0.5 × 0.45	0.5 × 0.45
Total length (km)	10	11(20 p × 0.55 km)	0.664(20 p × 0.003 km)

Lastly, to define the R & D target of Ag-sheathed Bi-2223 conductors, we have discussed the specifications of a liquid nitrogen-cooled, low magnetic field MRI coil. In these specifications, the engineering aspects of conductors, such as the amount of operation current, the total length of a conductor, and toughness against winding, are important. Even after those specifications are achieved, two factors of reduction in the cost of conductors still remain to be solved.

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