Impact of High-Temperature Superconductors on the Superconducting Maglev

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ABSTRACT: This paper reviews briefly the development status of Bi2223 and YBCO high-temperature superconductors, and discusses the impact of the high-temperature superconductors on the superconducting maglev. The present superconducting maglev uses NbTi low-temperature superconductor for the on-board magnets. To replace the NbTi magnets with high-temperature superconducting magnets, both technical advantages and economic feasibility are obviously important. YBCO superconductor is expected as a promising candidate for such an application for the future.

1 INTRODUCTION

More than twenty years have passed since the discovery of high temperature superconductor. Bi2223 superconducting wire is now widely used for developing superconducting coils, cables and equipment in various fields. YBCO superconducting wire, which is called the second generation superconducting wire or coated conductor, has been intensively developed especially in the USA and Japan in recent years, and its performance is approaching to a practical application level (Shiohara et al. 2008a,b).

The superconducting maglev developed and tested in Japan uses NbTi superconductor in on-board magnets. The present NbTi superconducting magnet is almost on the technology level of practical application. However, if high-temperature superconductor with higher performance and reduced cost is available, the superconducting coils would have improved performance such as better stability and higher current density or smaller cross section, and they would need simpler cooling systems. In particular, YBCO superconductor is expected to bring higher coil performance, easier coil winding and higher cost performance. Fundamental levitation and propulsion characteristics of the maglev could be also improved.

This paper gives a brief summary of the development status of Bi2223 and YBCO superconductors, shows design study of high-temperature superconducting coils, and discusses the impact of high-temperature superconductors on the superconducting maglev.

Although maglev systems using bulk superconductors have been also studied in China, Germany, Brazil, etc., this paper deals only with application of high-temperature superconducting wires and makes no reference to the bulk superconductor. In addition, more emphasis is put on the YBCO superconductor.

2 HIGH-TEMPERAUTRE SUPERCONDUCTORS

2.1 Overview

Dependence of J_C-B characteristics of YBCO and Bi2223 superconductors on the temperature T is shown in Figure 1, where J_C is the critical current density and B is the magnetic field. The J_C-B characteristics of Nb_3Sn low-temperature superconductor at higher magnetic fields is also shown in Figure 1 for reference. Bi2223 superconductor is now available in the market and used in the research and development of magnets and electric machines. However, the critical current density J_C decreases with increasing magnetic field as shown in Figure 1, and the application of Bi2223 superconductor for magnets is rather difficult at liquid nitrogen temperature (77 K). When Bi2223 superconductor is used for producing magnetic fields or used in higher magnetic fields, it should be cooled down to about 20-30 K. On the other hand, YBCO superconductor has good J_C-B characteristics. Especially in the temperature range between 20 K and 50 K the influence of magnetic field on the critical current density is relatively small and the YBCO superconductor can be applied to high field magnets or compact magnets. Development status and fundamental characteristics of Bi2223 and YBCO superconductors will be reviewed in more detail below.

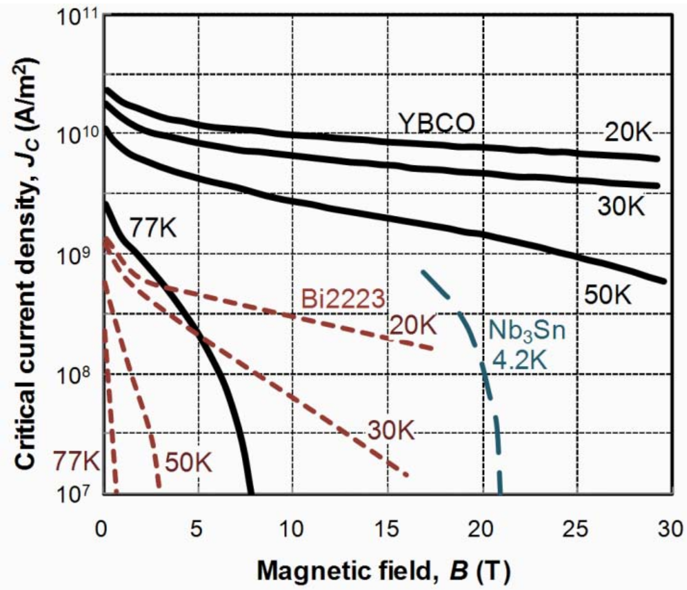


Figure 1. Performance of high-temperature superconductors (J_C-B-T characteristics).

2.2 *Bi2223 Wire*

Bi2223 superconductor is the first generation high-temperature superconductor, and has been widely used for developing power cables, coils, magnets, electrical machines, etc. Although it seems that more effort for superconducting wire development has been put on the YBCO superconductor in recent years, Bi2223 superconductor still stands at the forefront of practical applications. DI-BSCCO wire of Sumitomo Electric Industries, Ltd. is taken as an example, and its major characteristics are introduced below.

Sumitomo Electric Industries, Ltd. has developed Bi2223 superconducting wires for long since the discovery of this superconductor. After the introduction of the Controlled Over Pressure (CT-OP) sintering furnace in 2004, they succeeded in producing higher performance Bi2223 wire (DI-BSCCO) with higher critical current and mechanical properties (Kikuchi et al. 2008, Sato 2008).

Fundamental specifications of typical DI-BSCCO wires are summarized in Table 1. A typical conductor width is 4.3-4.5 mm and the critical current is as high as 180 A. Type H has the maximum permissible tensile stress of about 130 MPa, which may not be sufficient for high magnetic field application. However, Type HT, which is reinforced with stainless steel tapes, has higher mechanical strength, and the maximum permissible tensile stress of it has been improved to about 270 MPa. In 2007, the critical current has reached 218 A. A mass production technology for producing 2 km class DI-BSCCO wires has been established.

Although it is undeniable that most of the properties of Bi2223 superconductor are essentially lower than YBCO superconductor, Bi2223 is the only practical superconducting wire at this moment. Further development for higher critical current (density) and mechanical properties is strongly expected.

Table 1. Typical specifications of DI-BSCCO wire (SEI).

	Type H	Type HT
Width	4.3 mm	4.5 mm
Thickness	0.23 mm	0.30 mm
Length	< 1500 m	< 500 m
Critical current (77 K, self-field)	< 180 A	< 180 A
Maximum permissible tensile stress (77 K)	130 MPa	270 MPa
Minimum permissible bend diameter (RT)	70 mm	60 mm
Remarks		Reinforced with stainless steel tapes

2.3 *YBCO Wire (Coated Conductor)*

YBCO superconducting wires have been intensively developed in the USA, EU and Japan in recent years. SuperPower, Inc. and American Superconductor, Inc. have started supplying YBCO superconducting wires to the market and are used for development of power cables, magnets and electrical machines. SuperPower, Inc. has succeeded in producing YBCO wires of I_C = 153 A/cm and 1311 m in length (200,580 Am), 227 A/cm and 1030 m (233,810 Am), 200 A/cm and 945 m (189,000 Am), and 302 A/cm and 630 m (190,260 Am) (Hazelton et al. 2008, Selvamanickam, et al. 2008).

Examples of specifications of SuperPower YBCO superconducting wires are shown in Table 2. The superconducting wires using Hastelloy substrate are as thin as 0.095 mm and have I_C = 80-110 A (Width: 4 mm). The critical tensile stress is higher than 500 MPa and the yield strength is as high as 1200 MPa. The critical bend diameter is as small as 11 mm. Such nice mechanical properties enable the application to high magnetic field coils. Therefore, if the economic feasibility of the YBCO wires is improved and the wire supply increases, then YBCO wire could be used for a variety of applications.

In Japan YBCO superconducting wires have been developed in a national project, where a wire of I_C = 350 A/cm and 504 m in length (176,400 m) was fabricated. A project for application of YBCO superconducting wires to electric power apparatuses such as power cables, SMES and power transformers and the performance improvement of YBCO wires is now going on.

YBCO superconducting wire has the following features:

- Better J_C-B-T characteristics
- Future possibility of lower cost than Bi2223 wires
- Higher mechanical properties
- Relatively lower AC losses
- Possible reduction of anisotropic J_C-B characteristics

Table 2. Examples of specifications of SuperPower coated conductors.

Width	4 mm
Thickness	0.095 mm
Critical tensile stress	> 550 MPa
Yield strength	1200 MPa
Critical bend diameter	11 mm
Critical current	80-110 A

Better J_C-B-T characteristics

As shown in Figure 1, YBCO superconductor has much better J_C-B characteristics than Bi2223 superconductor, and, in particular, there is a large difference between them in performance in higher magnetic fields at relatively higher temperatures. Although YBCO superconducting film is as thin as less than 1 μm, the substrate is also thin and the total thickness is 100-300 μm. So the engineering critical current density J_e, which takes into account the substrate, etc., is high enough for application.

Lower cost

YBCO superconducting wires do not need expensive material like Ag for the matrix of Bi2223 superconducting wire. So the production cost may be reduced more than Bi2223 wire in the future. Figure 2 shows a trial calculation result of the production cost for Bi2223 and YBCO wires. In the Japanese wire development project the target cost of YBCO wire is three yen/Am. To achieve the cost target, the production processes such as the IBAD-PLD method (IBAD: ion beam assisted deposition, PLD: pulsed laser deposition) for high-performance wire production and the TFA-MOD method (TFA: trifluoro acetate, MOD: metal organic deposition, MOCVD: metal organic chemical vapor deposition) for lower cost production have been investigated.

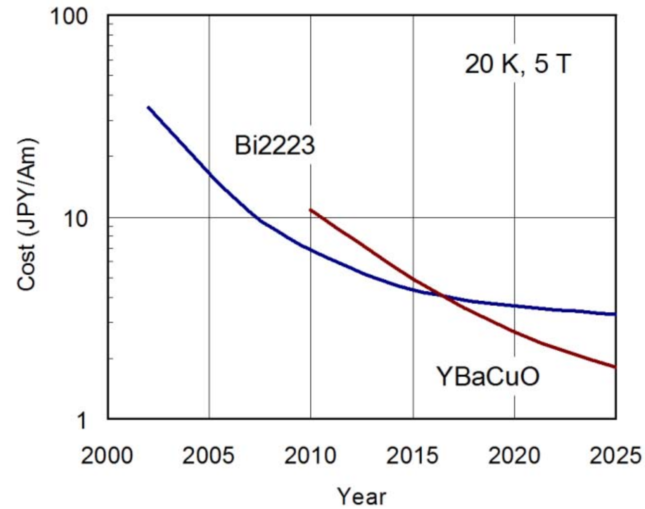


Figure 2. Cost projection of Bi2223 and YBCO wires.

Higher mechanical properties

YBCO superconducting wire uses mechanically strong materials such as Hastelloy for the substrate, and the thickness of the substrate is quite thin. Therefore, the wire has excellent mechanical properties. As shown in Tables 1 and 2, the critical tensile stress of YBCO superconducting wire is a few times as high as that of Bi2223 wire. Experimental data were reported which show J_C does not change under the tensile stress up to about 700 MPa (Figure 3). A smaller minimum bend diameter is also an important parameter for coil winding.

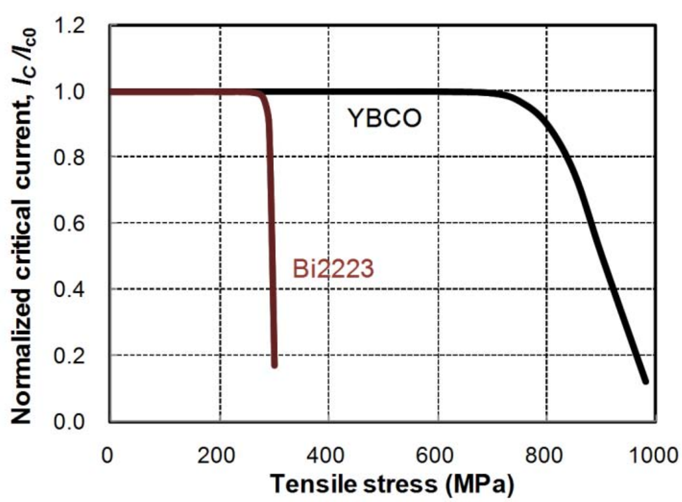


Figure 3. Tensile stress dependence of normalized I_C (Example data).

Lower AC losses

A superconducting film on the substrate is very thin and, therefore, the AC loss under the AC magnetic field parallel to the conductor surface is very low. To reduce the AC loss for the AC magnetic field perpendicular to the surface, the scribing technique to cut the wire into several narrower wires is developed. Superconducting magnets of the superconducting maglev are DC magnets and no AC loss problem exists except during the processes of increasing or decreasing coil currents.

Anisotropy

Both YBCO and Bi2223 superconducting wires have a large anisotropy in critical current characteristics, which are influenced by the direction of the applied magnetic field. When a magnetic field is given perpendicular to the tape surface, the critical current becomes lower than when it is parallel to the surface (Figure 4). Introduction of artificial pinning centers would enhance the critical current density of the wire and reduce the anisotropy. Such research and development are important for designing and fabricating high-performance high-field coils.

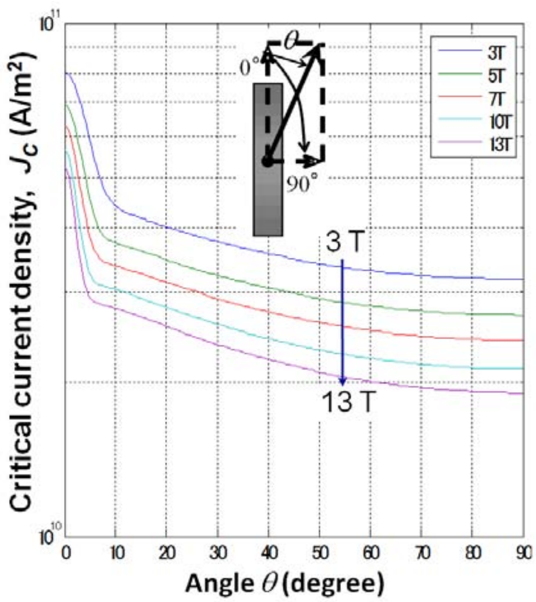


Figure 4. Anisotropic nature of J_C characteristics.

3 SUPERCONDUCTING MAGNET DESIGN FOR A SUPERCONDUCTING MAGLEV

3.1 *Superconducting Magnets using Bi2223 Wire*

The New Energy and Industrial Technology Development Organization (NEDO) in Japan entrusted the project for developing Bi2223 coils for the superconducting Maglev to the International Superconductivity Technology Center (ISTEC) in 2001. Central Japan Railway Company actually performed the research and development (recommissioned by NEDO), which was also reported in Maglev 2006. Although it was a very hard development, with great efforts of the people involved an almost full-scale Bi2223 superconducting coil of 750 kA was finally fabricated (Nakao et al. 2006). It was operated at about 20 K. A persistent current mode operation of the coil was successfully demonstrated and the resultant current decay rate was as small as about 0.44 %/day.

Then a superconducting magnet containing four Bi2223 superconducting coils was fabricated and the test of the vehicle carrying this Bi2223 magnet was carried out at Yamanashi Test Line from the end of November 2005 to the beginning of December 2005. Without any serious problems the speed of 550 km/h was achieved (Nishikawa et al. 2006).

A high-temperature superconducting magnet could not compete with NbTi magnets due to its higher cost at this moment. The test results indicated that, however, cost reduction by the future research and development could make the high-temperature superconducting magnet more practical.

3.2 *Design Concept of Superconducting Magnets using YBCO Wire*

Design concepts of superconducting maglev magnets using YBCO and Bi2223 wires have a lot in common. Fundamental concepts can be organized below mainly for YBCO superconducting wires.

YBCO superconducting wire has the following features:

- Simplified magnet and thermal insulation structures
- Reduced coil cross section by higher J_e
- Performance improvement by decreasing the distance between the superconducting coil and the ground coils
- Double pancake coils
- Coil design with the anisotropy taken into account
- Persistent current mode

Simplified magnet and thermal insulation structures

In the present Maglev vehicles, four NbTi superconducting coils are installed in the magnet and cooled in liquid helium (4.2 K). It can be considered that high-temperature superconducting magnets use cryocoolers and conduction cooling technology, like Bi2223 magnet described in 3.1. An operational temperature would be 20-30 K and will be finally determined from comprehensive examination of wire and cooling performance, and total cost. In this temperature range, the thermal conductivity and specific heat of materials are quite different from those at liquid helium temperature (4.2 K). The magnet structure including thermal insulation can be simplified. The use of cryocoolers and conduction cooling technology will bring easier operation and maintenance of the magnets.

High-temperature superconducting current leads have been developed also for the present NbTi superconducting coils. It will be naturally used in high-temperature superconducting magnets because it will be useful to reduce the thermal conduction through the current leads. Verification of mechanical strength of the high-temperature superconducting current leads will be needed for practical application of them.

Reduced coil cross section by higher J_e

YBCO superconducting wires available now have high J_e likes 20-30 kA/cm^2. Namely, the overall current density in the cross section including the substrate, etc. is fairly high. As a result, the cross section of the superconducting coil can be reduced and the distance between the center of the superconducting wire cross section and the ground coil can be reduced. In addition, it will reduce the coil weight and volume. A superconducting wire development leading to J_e improvement is still expected in the future.

Performance improvement by decreasing the distance between the superconducting coil and the ground coils

Simplified thermal structure will enable to omit the radiation shield and/or to reduce the thermal insulation distance. As a result, the distance between the magnet outer surface on the ground coil side and the center of conductor cross section of superconducting coil (Figure 5). The reduction of cross section by improving J_e will also contribute to reducing the distance.

Even if the same mechanical gap between the superconducting magnet and ground coils is kept, the distance between the superconducting coil and the ground coils can be reduced, and as a result, the mutual inductances between them increases and the levitation and propulsion characteristics will be improved.

Double pancake coils

Coils using high-temperature superconducting tapes should be multi-stacked double pancake coils, each of which is composed of two single-pancake coils wound with a single superconducting wire (Figure 6).

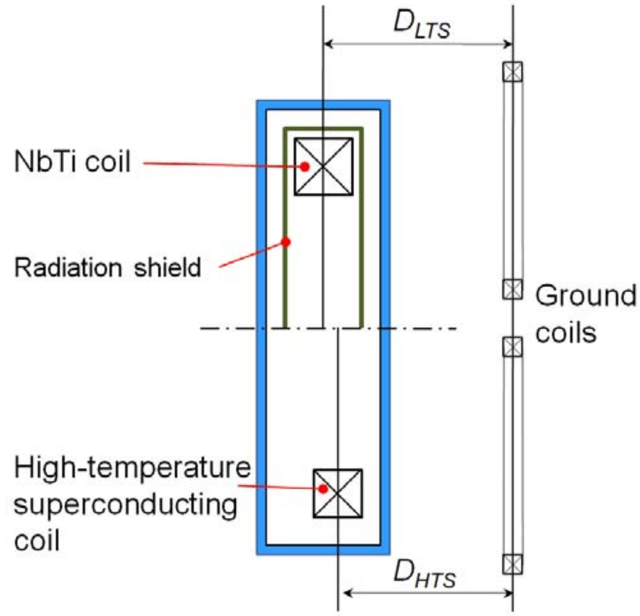


Figure 5. Reduced distance between a superconducting coil and a ground coil ($D_{HTS} < D_{LTS}$).

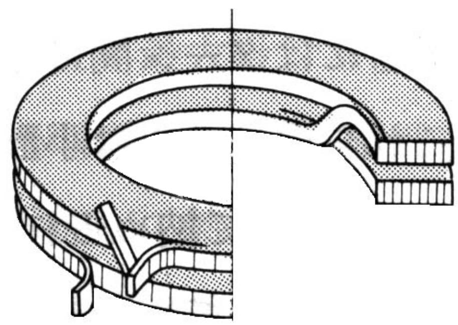


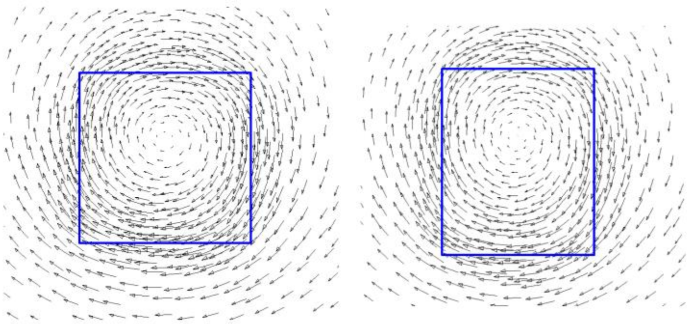
Figure 6. Double-pancake coil.

Coil design with the anisotropy taken into account

High-temperature superconductors have anisotropic J_C-B characteristics as shown in 2.3. Although some research is performed to reduce the anisotropy, it is important to design the coils with the influence of anisotropy well taken into account. As shown in Figure 7, magnetic field perpendicular to the tape surface depends on the shape of coil cross section, which should be therefore optimized. In actual situations, there are influences of other superconducting magnets and magnetic shielding material, which should be considered in designing the coils.

Persistent current mode

If the superconducting coils producing DC field are operated in the persistent current mode, they need no power supply for the coil or suffer no heat conduction through the current leads, which will make the system simpler. However, the current decay ratio of YBCO superconducting coils should be also verified in the future.



(a) square (b) rectangle

Figure 7. Dependence of magnetic fields on the shape of coil cross section.

4 SUMMARY

This paper reviewed the application of Bi2223 and YBCO superconducting wires to the superconducting maglev, which uses now NbTi superconducting wire. NbTi superconducting coils are technically completed at a high technical level. Therefore, to introduce high-temperature superconducting coils the economic feasibility of the total system is important as well as the technical advantages. YBCO superconducting wires are strongly expected on that point. Attention should be paid to further improvement of the performance and the economic feasibility of YBCO superconducting wires, which are intensively and competitively developed in the USA, EU and Japan.

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