Status of High Temperature Superconductor Development for Accelerator Magnets

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1) Abstract

High temperature superconductors are still under development for various applications. As far as conductors for magnets are concerned, the development has just been started. Small coils wound by silver sheathed Bi-2212 and Bi-2223 oxide conductors have been reported by a few authors.

Essential properties of high T_c superconductors like pinning force, coherent length, intergrain coupling, weak link, thermal property, AC loss and mechanical strength are still not sufficiently understandable.

In this talk, a review is given with comparison between the present achievement and the final requirement for high T_c superconductors, which could be particularly used in accelerator magnets.

Discussions on how to develop high T_c superconductors for accelerator magnets are included with key parameters of essential properties.

A proposal is also given how to make a prototype accelerator magnet with high T_c superconductors with prospect for future development.

2) Introduction

Since the discovery of superconductivity by K. Onnes in 1911, the record of critical temperature (T_c) had been updated slowly by the middle of 1980s. The speed of updating the record of T_c was remarkably increased after the discovery of the oxide superconductors in 1986, as shown in Figure 1. The highest record of T_c is approximately 134K for Hg-Ba-Ca-Cu-O1).

The oxide superconductors which have high critical temperatures are generally called high T_c superconductors. In recent years, enormous amounts of research concentrated on high T_c superconductors all over the world.

In addition to basic studies on superconductivity, various applications to films, tapes and wires have also been intensively studied. However, the high T_c materials are not well-understood in the viewpoints of solid-state physics and industrial production.

Characteristics of metallic and inter-metallic superconductors, which have low T_c, are also improved continuously. Copper stabilized Nb-Ti wires have become applicable for the magnets in the region of 10T with superfluid helium cooling. A15 compound as Nb_3Sn copper stabilized superconductor has become also applicable for magnets of 12T at 4.5K with liquid helium cooling.

The superconducting cables commonly used for accelerator dipole and quadrupole magnets in the range of several teslas are Nb-Ti Copper cables and practically operated at 4.5K with liquid helium cooling. Some magnets are wound with copper stabilized Nb_3Sn wires for actual operation around 12T at 4.5K. Nevertheless, it is difficult to use these wires and cables in the operation beyond 15T.

Recently, it was found that some oxide superconductors are applicable up to 30T at 4.2K2) as shown in Figure 2. This is quite attractive in application to generate a very high magnetic field.

Figure 3 shows the T_c of the metallic and the oxide superconductors. A15 intermetallic compound superconductor shows intermediate values between those of metallic and oxide superconductors in Tc and Hc.

3) Present status of high T_c superconducting wires and cables

There are three types of high T_c superconducting wires and cables, e.g., Bi-, Y- and Tl-based materials. Among these materials, Bi-based ones are considered as a main stream of development. Specially, Bi-2223 and Bi-2212 are studied by many researchers.

Bi-based silver sheathed Bi-2223 and Bi-2212 have been remarkably developed as the high T_c wires and cables for magnets.

G. J. Yurek has manufactured multi-core, tape-shaped wires using a combination of the metallic precursor method, and the silver-sheath method3) and the technique to produce about 300m long wires has been established. The wire J_c is reported to be around 50A/mm^2 at 20K in 5T for 3m long wires, and J_c=37A and 24A at 77K in 0T for 30m and 300m long cables, respectively.

P. Haldar *et al.*, reported the results of the test of short samples at 4.2K, 27K and 77K under magnetic fields up to 20T.4)

Quite recently, T. Hikata *et al.*, reported the result of 1km-class silver-sheathed Bi-based superconducting wires.5) They made monofilamentary and 61-multifilamentary wires. A J_c of 40A/mm^2 was achieved for 1,080m long wire. An anisotropy for the direction of external magnetic fields was found in J_c. They measured the parameter (J_c×length). The maximum value was (J_c×length)=9.91×10^{10}[A/m] for 623m long wire. Figure 4 shows the 1080m long high T_c tape wound in a coil.

Pancake coils wound with high T_c wires and cables were studied by S. Meguro.6) He studied the temperature dependence of J_c of Bi-2212 wire in magnetic fields and showed the possibility to operate the Jelly Rolled Bi-2212 silver sheathed superconductor below 20K.

Among high T_c superconductors available at present, it seems, only Bi-based silver sheathed conductors have suitable characteristics for accelerator magnet application. Bi-2212 silver sheathed tapes were significantly improved in J_c with the formation of the high c-axis orientation of laminated grains and reached $J_c \approx$ 350A/mm^2 at 77K with zero external magnetic field. However, J_c was lowered down to $\approx$ 4A/mm^2 at the same temperature with an external field of 1T. The large magnetic field dependence is not suitable for accelerator magnet application at 77K. Further study is necessary to find the method to satisfy both requirements of high J_c and I_c.

On the other hand, this highly c-axis oriented Bi-2212 high T_c superconducting tape could survive since it shows high $J_c \approx$ 20A/mm^2 with the external magnetic field as high as 30T, if it is cooled down to 4.2K.

The J_c of high T_c superconductor around several tesla is still much lower than that of metallic superconductors which are presently used as accelerator magnets.

4) Requirements for superconducting wires and cables of accelerator magnets

The advantage of using high T_c materials for accelerator magnets is that the refrigeration system for high T_c magnets is much simpler than that for conventional metallic superconducting magnets. Quench protection from the heat load due to beam radiation is also expected to be easier.

The requirements for accelerator magnets are complicated since they must be determined after a delicate adjustment of various parameters which are not always compatible with one another. We discuss an overview of common requirements for 10T-class superconducting magnets which are desirable for a multi-TeV accelerator.

The beam size of the accelerator is preferred to be as small as reasonably achievable by optimizing the beam optics and improving a beam cooling technique, since the costs have risen remarkably for large scale magnets. A small magnet for a high field requires a high current density. The current density of 400A/mm^2 in the windings is a reasonable goal, which requires the current density of more than 1000A/mm^2 in the wires. This implies that the electric insulation must endure 100-150MPa at low temperatures. The choice of insulation materials and the manufacturing technique must be improved to achieve these conditions.

5) Proposed high T_c superconducting accelerator magnet cables

As mentioned in the previous section, requirements for superconducting wires and cables of accelerator magnets are remarkably severe. Further improvement is necessary for the production of high T_c superconductors for this application.

A possible solution to apply high T_c superconducting wires for accelerator magnets is to make a so-called superferric magnet as shown in Figure 5. In this configuration, the superconducting coil is cooled down together with the magnetic iron and enables us to assemble accelerator magnets below 2T. However, wires and cables are required to have much more mechanical strength and much better performance for the application to accelerator magnets which can be operated in the magnetic field larger than 2T, e.g. 5 to 10T.

One possible way to develop such wires and cables with high T_c superconductors is to combine the longitudinal *in-situ* and radial Jelly Rolled structures of the wire strands. The longitudinal *in-situ* structure within the coherent length of polycrystals in metallic wire will improve the J_c along the wire length and the Jelly Roll will also improve the J_c deterioration with external magnetic field. We believe that such a structure of high T_c superconducting wires should be created and tested for the future application to accelerator magnet.

6) Conclusions

Superconducting accelerator magnets require high T_c cables which show a high J_c and I_c with a strong magnetic field.

A proposed solution for these requirements is to develop the Jelly-Rolled Bi-2212 silver sheathed round wires. The multi-layer and round shape cross-sectional structure could be another solution for high J_c and I_c requirements. The J_c characteristics of this type of wires will be heavily deteriorated above 20K, therefore it is suitable for magnet operation at temperatures below 20K.

Another solution to develop accelerator magnet wire and cable would be found in a further study of the *in-situ* structure in high T_c polycrystal superconductors by adjusting their coherent length in appropriate metallic sheaths and/or stabilizers.

From the viewpoint of accelerator magnet application, we expect the development of high T_c superconducting wire with high J_c, I_c and lengths over 1 km in near future.

It is still very hard to see how high-T_c superconducting wires could be operated with high-J_c and high-I_c at the temperature around 70K. Further study of high T_c superconductors are strongly desired.

7)Acknowledgments

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8)References

1) A. Schilling et al., Nature **363**, 56(1993).
2) M. Mimura et al., Advances in Superconductivity V, eds. Y. Bando and H. Yamauchi, Springer-Verlag (ISS'92), p.693-696, and private communication.
3) G. J. Yurek, Advances in Superconductivity VI, eds. T. Fujita and Y. Shiohara, Springer-Verlag (ISS'93), p.3-8.
4) P. Haldar et al., Advances in Superconductivity VI, eds. T. Fujita and Y. Shiohara, Springer-Verlag (ISS'93), p.605-608.
5) T. Hikata et al., Proceedings of the 1994 International Workshop on Superconductivity, Jun. 6-9, 1994, Kyoto, Japan, p.69.
6) S. Meguro, private communication.

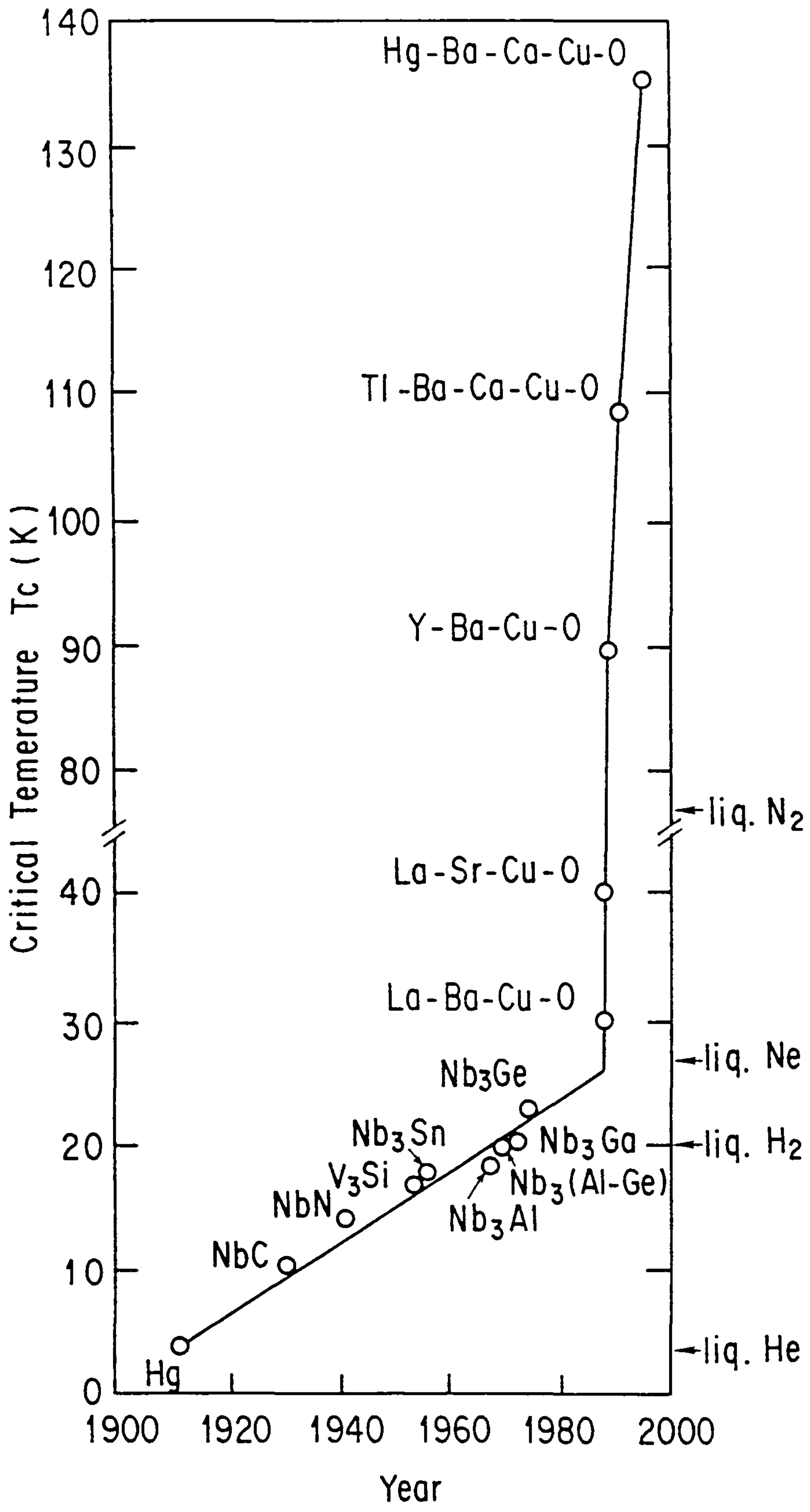


Figure 1.- History of updating the record of critical temperature of Superconductors.

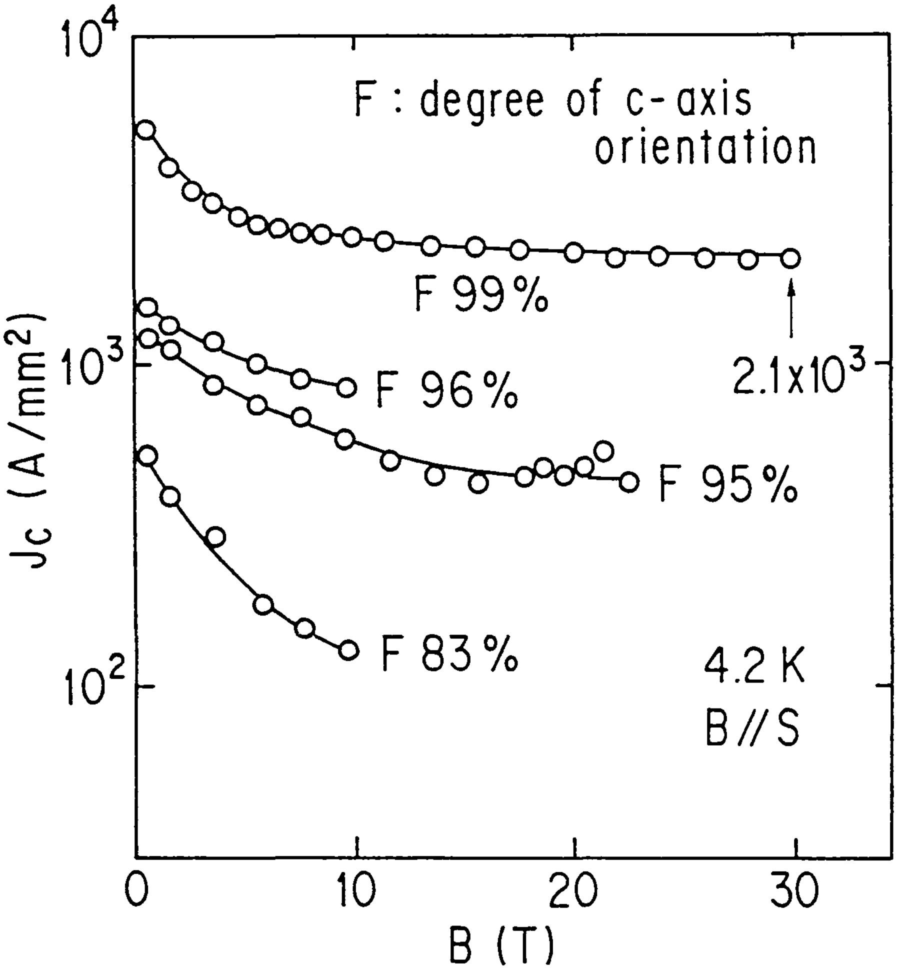


Figure 2.- Dependence of J_c of Bi-2212 on magnetic field at 4.2K.

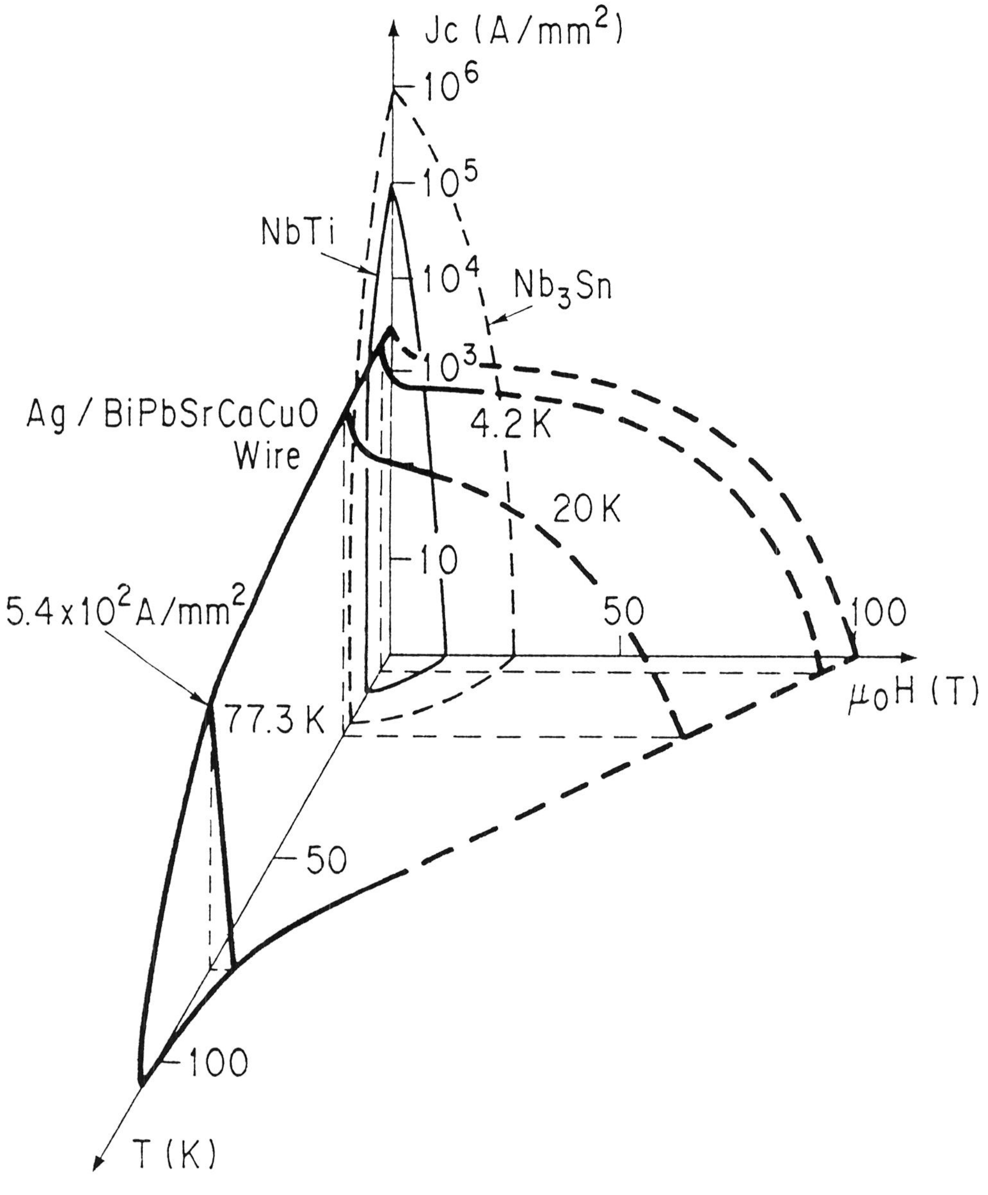
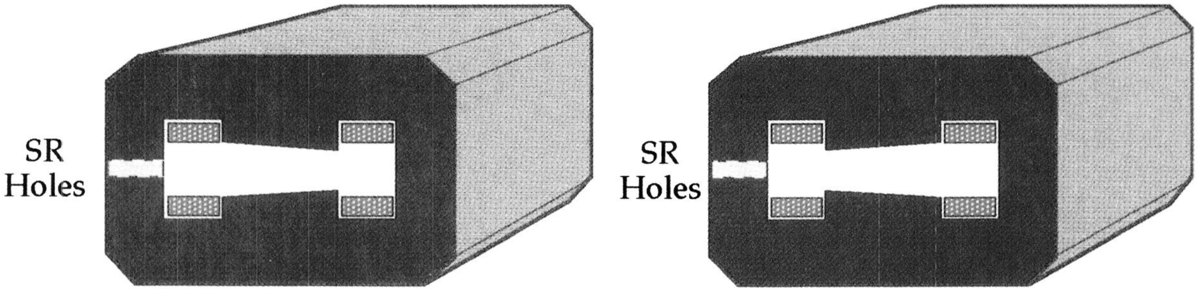


Figure 3.- Critical values of superconductors.

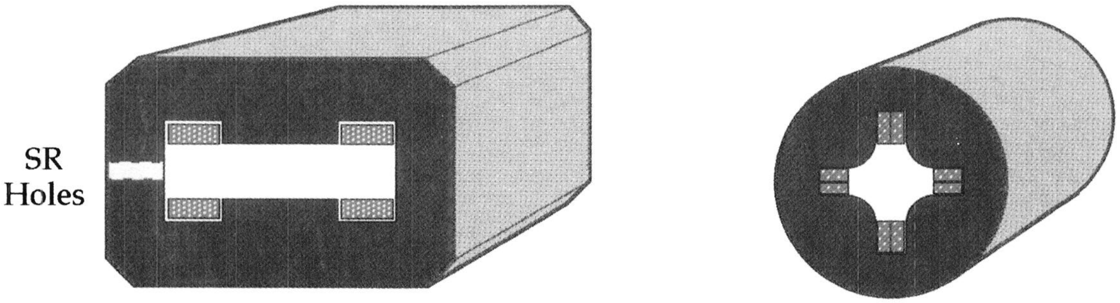
FABRICATION OF LONG LENGTH WIRES

61-MULTI FILAMENTARY WIRES		Jc	JcxL
		A/mm^2	10^{10} A/m
100 m-CLASS LONG WIRE	74 m	267	1.98
	100 m	261	2.61
1,000 m-CLASS LONG WIRE	623 m	159	9.91
	1,080 m	40.2	4.34

Figure 4.- 61-multifilamentary long high T_C superconducting wire.



**High Tc Superconducting
Alternating Gradient Synchrotron Magnets
with Cold Iron**



High Tc Superconducting Magnets with Cold Iron

Figure 5.- Superferric magnets with cold irons.