POTENTIAL FOR USE OF HIGH-TEMPERATURE SUPERCONDUCTORS IN FUSION REACTORS*

by

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POTENTIAL FOR USE OF HIGH-TEMPERATURE SUPERCONDUCTORS IN FUSION REACTORS

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Abstract

The present rate of development of high-temperature superconductors (HTSs) is sufficiently rapid that there may be opportunities for their use in contemporary fusion devices such as the International Thermonuclear Experimental Reactor (ITER). The most likely application is for delivering power to the superconducting magnets, especially in substituting for the current leads between the temperatures of 4 K and 77K. A second possible application of HTSs is as a liquid-nitrogen-cooled power bus, connecting the power supplies to the magnets, thus reducing the ohmic heating losses over these relatively long cables. A third potential application of HTSs is as an inner high-field winding of the toroidal field coils that would operate at ≈ 20 K. While the use of higher temperature magnets offers significant advantages to the reactor system, it is unlikely that tested conductors of this type will be available within the ITER time frame.

Introduction

Since the 1987 announcement by Wu et al. [1] of a superconductor with a critical temperature (T_c) above the boiling point of nitrogen, additional high-temperature superconductors (HTSs) have been found and considerable progress has been made in developing these materials into wires and other forms that can be used in practical applications, as reviewed by Rowell et al. [2]. The present rate of development of HTSs has been sufficiently rapid that there may be opportunities for their use in contemporary fusion devices such as the International Thermonuclear Experimental Reactor (ITER). In this paper, after briefly reviewing the present state of HTS development, I discuss three potential HTS applications for fusion devices. The first two, magnet current leads and power bus bars, seem feasible with present or near-term materials because only moderate current densities are required. The third, toroidal field (TF) coil windings, could have significant benefit to a fusion reactor, but the availability of HTS conductors capable of producing high magnetic field strengths for the TF coils is more uncertain within the ITER time frame.

All of the HTSs presently under investigation for practical magnet applications are copper oxide ceramics. Holczer et al. [3] and Rosseinsky et al. [4] first showed that the fullerene compound C_{60} , when properly doped, can exhibit high T_c values. While there is considerable enthusiasm for their potential in applications as newer dopings with higher T_c s are discovered, these superconducting organics are too new for this to be quantified, and these compounds are not discussed further in this paper.

High-temperature superconductor families

There are three major families of ceramic HTSs. While the nomenclature is not totally consistent from researcher to researcher, a common abbreviation scheme denotes the families as YBCO, BSCCO, and TBCCO. For all HTSs, the oxygen content may vary somewhat, and this variation usually plays a minor role in determining some of the details of the physical properties. In addition, other elements are often substituted for the basic constituents in each family, occasionally resulting in significant improvements in one of the superconducting properties.

Wu et al. [1] discovered the first HTS discovered, $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$, where the subscript x denotes an amount less than unity. Others soon discovered that this YBCO compound could take the form $\text{REBa}_2\text{Cu}_3\text{O}_{7-x}$, where RE denotes "rare earth". The T_c of these compounds varies by several degrees around 92 K, depending on which RE is used. Most REs will form a superconducting compound in the YBCO family, however, Pr does not. $\text{REBa}_2\text{Cu}_3\text{O}_{7-x}$ is often called the 123 compound after the subscripts for the first three elements. There is also a 124 YBCO compound with a T_c of about 80 K that is more thermodynamically stable than the 123 phase. There is also a 247 phase.

The second family, discovered by Maeda et al. [5], has a basic constituent of Bi-Sr-Ca-Cu-O, hence BSCCO. Sometimes Pb is partially substituted for the Bi, which seems to simplify the formation of pure phases. There are two important phases of BSCCO, the 2212 compound with a T_c of about 80 K and the 2223 compound, with a T_c of about 105 K.

The third family, discovered by Zheng and Hermann [6], is Tl-Ba-Ca-Cu-O (TBCCO) and has many phases with high T_c 's, with the highest, found by

Parkin et al. [7], at 125 K. Initially, the TBCCO family did not receive as much attention as the other two families, mainly because of the difficulty of isolating pure phases and in working with the volatile and somewhat toxic thallium. More recently, interest in the TBCCO family is increasing because of its potential for large current density at high temperatures and magnetic fields.

Present status of HTS technology

An approximation of the present status of HTSs in current-carrying applications relevant to fusion reactors is shown in Fig. 1. Wire making techniques such as plastic extrusion, oxidation of metallic precursors and electrochemical deposition on a metallic substrate are capable of producing arbitrarily long lengths of HTS. However, typical state-of-the-art J_c values for long lengths of these wires are several thousand A/cm² in zero magnetic field and hundreds of A/cm² in magnetic fields greater than 1 T, e.g., as reported by Shi et al. [8]. Mankiewicz et al. [9] demonstrated that high J_c values at high field strengths could be obtained in thin films of HTS, proving that such performance is theoretically possible. However, despite continuing advances (e.g. by Busch et al. [10]), the production of long lengths of wire by thin-film processes is not yet known to be feasible. Several directional solidification techniques, e.g. by Salama et al [11], have produced small samples of bulk HTS that approach the J_c and magnetic field requirements of fusion magnets. However, it is not clear that these methods can be used to make long lengths of wire in a reasonable period of time.

One of the most promising developments in HTS wire making has been the powder-in-tube fabrication using the BSCCO family, where Heine et al.

[12] demonstrated J_c values superior to that of low-temperature superconductor (LTS) wire in very high magnetic fields at 4 K. More recently, Sato et al. [13] have measured J_c s of over 50 kA/cm² in fields greater than 19 T in these materials at temperatures as high as 20 K. The performance of these wires degrades substantially at temperatures above 20 to 30 K. So far, the high J_c values have only been obtained in short lengths of wire, but most researchers feel confident that long lengths of practical HTS wire with satisfactory performance at temperatures up to about 20 or 30 K can be developed using the powder-in-tube method.

Critical current density

The major technical challenge for HTSs is to increase the J_c . Each of the different materials have different technical problems. For example, YBCO has difficulty passing current from one superconducting grain to the next. The BSCCO family does not have this problem, but instead seems to experience an intrinsic weakness in preventing the flow of magnetic flux through it for temperatures much above 30 K. Most of the TBCCO phases also seem to suffer from this flux-flow problem.

Ceramic materials consist of individual grains stuck together. For any superconductor, the grain boundaries of the material are in the normal state, and the superconducting current must quantum-mechanically tunnel through the boundary from one grain to the next. In NbTi, this is not a problem, because the superconducting coherence length is several orders of magnitude greater than the grain boundary thickness, and the attenuation at each boundary is negligible. For HTSs, the coherence length is about 3 nm, approximately the same length as the grain boundary thickness. In the

ceramic composite, the result is a network of good superconducting grains connected by these barriers, known as "weak links." Any sort of contamination or improper processing produces thicker grain boundaries and even weaker links, and one of the goals of the materials development of HTSs is to make exceptionally clean and thin grain boundaries.

One way to minimize the problem of weak links is to align the individual grains, and a number of processes have been investigated to achieve this end. Alignment is important because of the anisotropic nature of HTSs. With all of the copper oxide planes aligned, it is easier to pass current from one grain to the next. The BSCCO material is a micaceous compound and shears readily along certain planes, making it relatively easy to align when the material is rolled. This has been most readily achieved in a powder-in-tube making process, in which the HTS powder is sealed inside of a silver tube, and then the tube undergoes a series of reduction steps, either by drawing, swaging, or rolling, accompanied by heat treatment according to different schedules. In the YBCO compound, the only method that has yielded substantial alignment is various forms of melt texturing, in which the material is solidified in a temperature gradient. Because the rate at which the grains grow is limited, this method is very slow and probably not appropriate for making long lengths of wire.

When a superconducting wire is operated in a magnet, magnetic flux will penetrate the superconductor. The combination of current through the wire and magnetic field perpendicular to the current produces a Lorentz force that tries to push the magnetic flux lines through the superconductor. For there to be no resistance in the superconductor, it is necessary that these flux lines be immobile, i.e., pinned in place. If the flux lines move,

dissipation and heating occurs, and high-current density magnets can experience severe heating, often leading to destruction.

Flux pinning is one of the least understood aspects of HTSs. However, it is believed that thermal noise in the superconductor can depin flux lines, and the higher the operating temperature the more thermal noise is present. For LTSs, flux flow was a minor irritation, because the thermal noise was so low. At 77 K, the thermal noise is about 20 times higher than at 4 K, and the problem is more severe. The different HTS materials appear to suffer from this problem to different extents. A summary of the magnetic field versus temperature at which flux flow becomes a problem is shown in Fig. 2. Practically speaking, for a fixed temperature, it is unlikely that large current densities can be obtained for magnetic fields above that shown in the figure. As seen in Fig. 2, YBCO suffers almost no flux-flow problems until the critical temperature or critical magnetic field is reached. From a flux-flow viewpoint, YBCO is an ideal material. If the weak-link problem could be solved in YBCO, it would be the material of choice.

Of all the other HTS materials, only the 2201 phase of the TBCCO family appears to have the potential, from a flux-flow viewpoint, to achieve useful magnetic field strengths at temperatures in the vicinity of 77 K.

Unfortunately, the TBCCO seems to react with Ag, and the powder-in-tube methods that were successful with BSSCO will need to be modified for TBCCO. In addition, it is not yet known whether TBCCO will suffer from weak links, however, there is some suggestive evidence that it will not.

Mechanical strength

For a conductor to be useful in practice, it must withstand appreciable mechanical stress. Normal use may require thermal cycling, repeated strain (during fabrication and operation), and consistent behavior over long lengths.

Ceramic materials are well known for their brittleness. Clearly, if a crack develops in a HTS wire, the current will no longer be able to flow. Singh et al. [14] found that the addition of Ag to the HTS powder at the early stages of fabrication improves tensile strength and fracture toughness. Singh [15] has produced sintered YBCO with flexural strength over 200 MPa and with fracture toughness as high as $4.5 \text{ MPam}^{1/2}$, which gives the HTS about the same toughness as a ceramic spark plug. Even with these high numbers, one cannot take the HTS and bend it into a magnet form after it is fired. Considerable improvements must occur before this can happen.

One solution to the brittleness problem is to wind the magnet in the green state and then react it in the heat treatment stage. This was done with Nb_3Sn , one of the two most commonly used low- T_c compounds, which is also brittle like a ceramic.

A second solution is to form the superconductor in the form of fine filaments. With a small enough diameter, the fibers can be bent to a considerably small radius after they are fired. So far, those processes that have produced fine filaments of HTS have not produced very high critical current densities, however, the powder-in-tube method is capable of producing thin tapes. This is clearly an area where more development is needed.

Magnet Leads

Hull [16] has suggested that vapor-cooled leads employing HTSs can be used to reduce helium boiloff from superconducting magnets. A typical arrangement consists of a copper lead joined in series with a HTS lead, the copper part operating between 300 K and 77 K, and the HTS part operating between 77 K and 4 K. Hull [16] calculated that fully stabilized leads should be able to reduce by a factor of about 2 (compared with the best nonsuperconducting leads) the fraction of heat leaking into the helium cryogen because of the power leads. The leads are stabilized in the sense that even if the entire HTS part becomes normal, the temperature throughout the HTS remains low enough for operation to continue indefinitely (although at a higher boiloff rate). Such performance is only attainable with a heat sink such as liquid nitrogen at the hot end of the HTS to intercept all heat flow at the cold end of the copper part. If full stability is sacrificed, then the helium boiloff can be reduced even further.

Present fabrication methods are sufficient to produce the HTS part of the lead for most applications. Such leads do not require high current densities, experience low Lorentz forces, and can be shielded from external magnetic fields. Wu et al. [17] have operated a HTS lead in the superconducting state at 2 kA and have measured low helium boiloff. Arbitrarily high-amperage leads can be fabricated by modularizing leads into 1 or 2 kA units and using a thin shell of high permeability material to shield each module from the magnetic field generated by the other modules.

The technology seems scalable to the ≈ 40 kA that was estimated by Henning and Miller [18] for ITER magnets. The ensuing reduction of heat

leakage into the TF magnets would reduce the refrigeration requirements and possibly improve magnet stability.

Component reliability is an important part of any large facility, and current leads are no exception. Testing of large-amperage HTS power leads could be accomplished in the near term at the U.S. FENIX test facility, described by Slack et al [19]. Of particular note is that the power supply is a low voltage supply and that the system has low inductance. Together, these features allow leads to be designed for extremely low boiloff, and the leads will be automatically protected in the event of a quench.

Power Bus

A second possible application of HTSs to ITER is as a liquid-nitrogen-cooled power bus, connecting the power supplies to the magnets. With ohmic heating losses reduced over these relatively long cables, there is potential to reduce the size of the power supplies. As shown in Fig. 1, the current densities required for short transmission lines of this type are larger than those needed for current leads but much smaller than that needed for the magnets and will probably be within the capability of HTS fabricators within several years.

Toroidal Field Coil Windings

Analysis by Ehst et al. [20] of tokamak reactor designs that substitute HTS magnets, operating at the same current densities and magnetic fields but cooled by liquid nitrogen, for conventional magnets, cooled by liquid helium, has shown a modest reduction in reactor cost due to the difference in cooling. Because of the success of the powder-in-tube BSCCO, it seems possible that HTSs could be used as inner high-field winding of the TF coils

that would operate at ≈ 20 K. A number of synergistic advantages may occur if conductors of this type are available. Because the heat capacity of HTS and copper stabilizer is about 100 times higher at 20 K than at 4 K, the magnets should be considerably more stable and could possibly tolerate a higher heat flux than LTS magnets can. Hydrogen is also a better heat transfer fluid than helium. Analysis by Iwasa and Butt [21] has shown that normal-zone propagation velocities are sufficiently high at 20 K that traditional magnet quench methods are adequate, whereas, at 77 K these velocities are much too low and magnet protection on quenching may be difficult. While the effects of radiation on high-performance HTS wires must wait until longer lengths become available, a review by Parkin [22] indicates that the influence of different radiation on HTSs is similar to that for A-15 compounds, such as Nb_3Sn , however the total response of the HTSs is considerably more complex.

A further possibility of the BSSCO wire is to take advantage of its potential to produce very high magnetic fields. Schwartz et al. [23] have indicated that design constraints resulting from plasma physics are relaxed when toroidal magnetic field values are increased. Schwartz et al. [23] have also shown that structural materials capable of containing the greatly increased mechanical pressures on the magnets have the potential to be developed in the same time frame as the HTS wires.

Whereas development of high-performance BSCCO conductors is proceeding rapidly, it is uncertain whether these HTS conductors will be available for use in ITER. However, the probability that they will be available for a successor to ITER is reasonably high.

Conclusions

The present rate of development of HTSs is sufficiently rapid that there may be opportunities for its use in ITER. The most likely application is for delivering power to the superconducting magnets, where present technology appears scalable to the currents required by ITER magnets. The ability to produce liquid-nitrogen-cooled power buses in 10 to 50 m lengths also appears technically feasible in the near future. The ability to produce long lengths of wire for high-field TF coils appears technically feasible in the future, but probably not in the time frame of the ITER project. However, the probability that they will be available for a successor to ITER is reasonably high.

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Figure Captions

Fig. 1. Approximate critical current density versus ampere meters of conductor for present fabrication methods and fusion reactor requirements.

Fig. 2. Intrinsic irreversibility curves for major HTS materials. (courtesy K. Gray, Argonne National Laboratory)

fig. 1

Fig. 2

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