Power Applications of High-Temperature Superconductors

High-T_c superconductors show promise for bulk applications from transmission cables to high-field magnets.

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Ten years after Georg Bednorz and Alex Müller discovered the first high-temperature superconductors, and nine years after superconductivity was found with a transition temperature higher than that of liquid nitrogen, considerable progress is being made in bulk applications of high-temperature superconductors. Electronics applications and thin-film technology are even more advanced. (See PHYSICS TODAY, March 1995, page 20.) Among the first bulk applications are: current leads, fault current limiters, and wire for power transmission cables.

The Department of Energy program on superconductivity for electric systems has a FY 1996 budget of $19 million; the program supports work at national labs, universities and private industry to develop enabling technology and supports industry teams designing generators, transformers, transmission cables and current limiters. In addition superconductivity research is supported by DOE's basic energy sciences program and by the National Science Foundation. The Department of Defense power applications program is jointly led by the Navy and the Advanced Research Projects Agency with about $3 million in funding per year. The Electric Power Research Institute is spending $3 million in calendar 1996.

Japan is putting much more money into bulk applications than the US. Japan has a major effort in superconductor power applications that involves the Ministry of International Trade and Industry (MITI) and many companies and national labs. The country's annual budget for bulk material development and power-related projects is estimated by Paul Grant of EPRI to be about $100 million. In addition, Japan is doing high-T_c R&D on magnetically levitated trains and flywheels.

Materials of choice

Over fifty distinct copper oxide compounds have been found since Bednorz and Müller's discovery. At present, high-T_c materials research is concentrating on optimizing materials for applications through processing, according to Paul Chu of the Texas Center for Superconductivity at the University of Houston.

At present, bulk applications primarily use bismuth strontium calcium copper oxide, known as BSCCO; it's made in two popular versions—$Bi_2Sr_2CaCu_2O_{8+\delta}$, known as Bi-2212, and $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$, known as Bi-2223. The other leading high-T_c material for bulk applications is yttrium barium copper oxide, $YBa_2Cu_3O_7$, known as YBCO. Both YBCO and BSCCO have transition temperatures higher than the 77 K of liquid nitrogen, YBCO with 92 K and BSCCO up to 110 K.

Two major factors influence the amount of current density, J_c, that can be transported. The most important is that if the material is polycrystalline it tends to subdivide into regions of strong superconductivity separated by weak superconducting interfaces, known as weak links. The principal way of avoiding weak links is to align the grains so that grain boundaries are at a low angle with respect to the copper–oxygen planes, as was first demonstrated eight years ago by an IBM group.[1] High-angle grain boundaries tend to act as barriers to supercurrent and have electromagnetic properties that behave like Josephson junctions. So high-angle grain boundaries in the microstructure produce a network of weak links that reduce the bulk J_c. Many R&D efforts are aimed at reducing these weak links: One can improve the J_c characteristics of individual grain boundaries or one can align or "texture" the grains to improve the links in the current path.

At any given point in a polycrystalline BSCCO conductor, the current is weaving its way through the superconductor, percolating through the polycrystalline array and occupying as little as 10 percent of the cross section at any given place, according to David Larbalestier of the University of Wisconsin in Madison. The J_c for both BSCCO and YBCO is strongly correlated with the distribution of grain boundary misorientations, he said, consistent with earlier IBM work on thin-film YBCO bicrystal experiments.

Larbalestier and his Wisconsin colleagues have used magneto-optical imaging (in collaboration with Anatoly Polyanskii of the Institute of Solid State Physics in Chernogolovka, Russia) to reconstruct these current paths. Such images directly show the barriers to current flow, revealing both the influence of cracks and of the dislocations that form in low-angle grain boundaries. Larbalestier feels that by minimizing the size of the effective dislocation barrier, one can delay the onset of percolation.

The second major factor influencing the current density is the need to develop strong flux pinning so that vortices can resist the Lorentz force that dissipates energy and causes losses. Recent work in several labs has concentrated on chemical substitution to modify the crystal structure and thereby improve flux pinning. One approach cited by James Jorgensen of Argonne National Laboratory is to improve the behavior of the critical current by clever materials design. Flux pinning can be improved by irradiation, but according to Jorgensen this approach isn't practical for large-scale applications.

YBCO has much better intrinsic flux pinning than BSCCO, but it has poor intergranular current flow because of weak links. Despite its inadequate flux pinning, BSCCO has been preferred for making wire because the grains align and form good grain boundaries for conduction when they are drawn, rolled into a tape shape and then fired.

Two other cuprates show promise. Thallium barium calcium copper oxide, known as TBCCO, also has two varieties—Tl-2223 and Tl-1223, which appears more prom-

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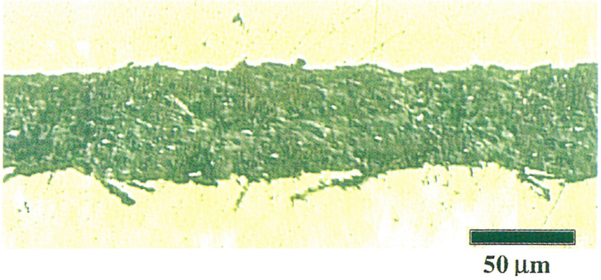

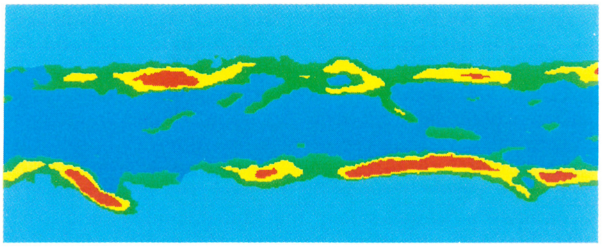

PERFORMANCE OF Bi-2223 TAPE. Top: Polarized light micrograph of a transverse section. BSCCO is the greenish central section and the yellow surrounding it is the silver sheath. Some 2223 grains have grown into the sheath. **Bottom:** Two-dimensional contour maps of the local current density extracted from a magneto-optical image. The dark blue central region, where J_c is less than 1.6×10^5 A/cm^2, is much less effective in carrying current than in regions near the silver interface, where the large grains occur. The red regions are J_c greater than 3.6×10^5; yellow is $2.6–3.6 \times 10^5$; green is $1.6–2.6 \times 10^5$ A/cm^2, and turquoise is zero. (Images by A. Polyanskii, A. Pashitski, at the University of Wisconsin.)

ising for wire applications. TBCCO, with a T_c ranging from 110 to 128 K, has properties that fall between the other two materials. It has links that are stronger than YBCO, but its flux pinning isn't as good as YBCO's. Mercury barium calcium copper oxide, known as HBCCO, has a T_c of 135 K but has only recently been discussed as a candidate for wire because it is difficult to form a single-phase material. Both TBCCO and HBCCO have caused some concern about toxicity, but Grant believes that they will be used if they prove to have good performance and price.

BSCCO

"Essentially every application of superconductivity to electric power technology depends on the successful development of suitable wire," said Grant. For almost all important electric power applications, a J_c of at least 10^4 A/cm^2 is needed. At present the most popular wire being considered for electric power applications is made by the powder-in-tube method, which helps overcome the brittleness, granularity and limited ductility of BSCCO. In this process, the high-T_c ingredients are mixed and reacted to produce BSCCO powder. Then the powder is tightly packed into a cylindrical silver billet. The filled billet is then subjected to repeated drawing and swaging, until an overall diameter of about 1 mm is produced. Then a bunch of these filaments are rolled together and deformed again to form a tape roughly 4 mm wide and less than 0.2 mm thick. As Alex Malozemoff of American Superconductor Corp (Westborough, Massachusetts) explained, the multifilamentary tape "is more resistant to crack formation—much like fiber-optic cables. Thus this step is vital to solve the brittleness challenge." The final step involves one or more heat treatments. Several companies, including American Superconductor, Intermagnetics General Corp (Latham, New York), and Sumitomo Electric in Osaka, Japan, are routinely making kilometer-length tapes containing large numbers of filaments.

Good grain alignment is crucial to high J_c, said Larbalestier. Two factors contribute: The tape deformation process tends to shear the Bi-2212 precursor along the double Bi–O layer, which is like mica, and the grains tend to self-align during the subsequent heat treatment that forms the Bi-2223 phase. "Whatever the exact contributions of these two processes," said Larbalestier, "high J_c is very strongly correlated with good crystallographic alignment."

Industry can now manufacture lengths of 100 to 1000 meters with a J_c above 10^4 A/cm^2 at 77 K, so significant coils and cables can be fabricated from high-T_c wire, said Malozemoff. When the same wires are operated at 20 K, values of 10^5 A/cm^2 can be reached in a field of several tesla.

Although much of the work just described uses Bi-2223, according to Pradeep Haldar of Intermagnetics, Bi-2212 is easier to fabricate in wire and has a better J_c in high magnetic fields and low temperature (less than 20 K). Larbalestier noted that Bi-2212 can't be used at 77 K, but at 4 K it's superior because it's less prone to weak links, again confirming that J_c is controlled by percolation, not flux pinning. Hitachi in Japan has recently reported Bi-2212 wires with a J_c of 1.71×10^5 A/cm^2 in a 30-T field at 4.2 K, far beyond the reach of low-T_c wires.

YBCO

For operation at liquid nitrogen temperature, YBCO is preferable to BSCCO because it retains J_c under strong magnetic fields either as an epitaxial film or a single crystal. YBCO retains high critical currents in strong fields because there is stronger coupling between its copper–oxygen planes than that in BSCCO. But, as EPRI's Grant pointed out, YBCO lacks the micaceous layer of BSCCO, which has prevented attempts to use powder-in-tube processing to make wire out of YBCO.

Instead, experimenters tried to deposit thick films of YBCO onto nickel alloy tapes chosen to match the thermal expansion coefficient of YBCO. A thin buffer layer (such as yttria-stabilized cubic zirconia) was added between the tape and the superconductor to prevent the nickel from diffusing into the YBCO film. In 1991 Y. Iijima and his collaborators at Fujikura Ltd in Tokyo successfully used ion-beam-assisted deposition to texture the buffer layer, forming biaxial texture. They used two ion beams, one for sputtering and the second striking the surface at an angle of 55 degrees to assist in texturing.[2] This work was soon replicated in short samples at Lawrence Berkeley Laboratory by Paul Berdahl and his collaborators. The textured buffer layer acts like a template for the YBCO, which is deposited on the buffer layer by laser ablation. In 1991 the Fujikura group achieved a critical current density of 2.5×10^5 A/cm^2 at 77 K and zero field, and even when they applied 8.0 T at 77 K, they achieved 2.2×10^4 A/cm^2. By now the Fujikura group has made 1-cm-wide tape with 1.1×10^6 A/cm^2 at 77 K and zero field and 1.1×10^5 A/cm^2 at 5.0 T and 77 K. The group has also made tape that is 0.8 meters long with silver cryogenic stabilizer on the YBCO surface that yielded 1.2×10^5 A/cm^2 at 77 K and zero field, by moving the buffered tape during deposition.

Last April, at the Materials Research Society meeting in San Francisco, S.R. Foltyn of Los Alamos National Laboratory reported using ion-beam-assisted deposition to make tapes on polycrystalline, metallic substrates that are 1–2 microns thick and have currents up to 200 A. Malozemoff pointed out that in the past, it wasn't possible to make films thicker than about 0.5 microns. The Fujikura tape reported at conferences in Japan last October was 0.37 microns thick. Los Alamos's Dean Peterson said that the group has applied up to 19 T with little drop in J_c when the field is parallel to the plane of the tape. Applying a 5-T field normal to the tape plane, J_c was 10^5 A/cm^2 at 77 K. EPRI's Grant noted that sustaining such high critical current densities in a 5-T field opens the way for practical magnet wire cooled by liquid nitrogen.

Right now, Peterson said, the YBCO samples are 1 cm wide and 5 cm long, and it takes several hours to deposit them. The next goal is 10 cm, then 1 meter. To get these longer lengths, the Los Alamos team will move the tape substrate during the longer-length deposition. And, of course, the team would like to speed up the deposition.

At the same MRS meeting last April, A. Goyal of Oak Ridge National Laboratory reported on a new method called rolling-assisted biaxial textured substrates. Oak Ridge workers have reported that their process results in near-perfect substrate biaxial texture, aligned within 2°, in silver, other metals and oxides. Robert Hawsey said that Oak Ridge has obtained a "modest" current density in zero field, 8.5×10^4 A/cm^2, an order of magnitude lower than that reported by Los Alamos, but the Oak Ridge material exhibits the same field dependence of the J_c as the Los Alamos material out to 8 T, "demonstrating that at least a small fraction of the YBCO is strongly linked," said Hawsey. At the DOE annual workshop on wires held 31 January, the Oak Ridge experimenters presented recent data showing that their process can produce substrates as thin as 25 microns.

Comparing the effectiveness of ion-beam-assisted deposition of YBCO and powder-in-tube BSCCO wires, Malozemoff said the YBCO technology promises to extend the range of application of high-T_c wires, particularly at high fields and temperatures, especially if the substrate thickness can be reduced and the film thickness increased. He thinks that the ion-beam-assisted YBCO would be very useful in dc applications at higher fields and temperatures. (But he feels that the ac losses will be high in the ion-beam assisted flat-tape arrangement, whereas the twisted composite multifilament arrangement of BSCCO has more flexibility in cutting ac losses.)

TBCCO technology appears to be less advanced than BSCCO, although General Electric, Intermagnetics and six national labs have worked on thallium-based superconductors. GE and Oak Ridge have used spray pyrolysis on ceramic to make short samples (about 1 cm) of TBCCO with current densities of 3×10^5 A/cm^2 at 77 K and zero field.

Kohji Kishio and his collaborators at the University of Tokyo and Paul Chu and his collaborators at the Texas Center for Superconductivity have been using chemical substitution and new processing techniques to overcome the problems associated with HBCCO—it's chemically unstable and loses mercury when high-temperature processing is used to make cable or tape.

High-current power transmission cables

Projects to build prototype power transmission cables are under way. Because of the excellent performance of BSCCO conductors, electrical utilities in the US, Japan and Europe are evaluating their capability to retrofit existing underground cable. At present, high-performance underground cable consists of copper conductor cooled by oil. It would be replaced with BSCCO cooled by liquid nitrogen.

Tokyo Electric Power is planning to develop compact high-T_c power cable with a transmission capacity of 0.5–1.0 GW to replace existing lines that deliver power to the city of Tokyo, doubling the power capability without construction of new underground tunnels. TEPCO is heading two separate collaborations, one with Sumitomo and one with Furukawa Electric in Chiba, to develop such cables using BSCCO wires. In these projects a coaxial structure is used. Recently TEPCO and Sumitomo built a 7-meter full-cable prototype and did a 7-hour transmission test with 1 kA rms, according to Hideo Ishii of TEPCO. And he said that Tokyo Electric and Furukawa have built a 5-meter, single-phase model with a real-scale termination box at both ends. A 15-minute continuous load test was conducted, with 2000 A and a line voltage of 66 kV.

A consortium consisting of EPRI, Pirelli Cable Corp (Lexington, South Carolina), American Superconductor and DOE is developing a three-phase circuit enclosed in an 8-inch steel tube instead of the coaxial structure used by TEPCO. A 4200-A prototype conductor, 1 meter long, has been demonstrated, and American Superconductor's Malozemoff said that the consortium plans to build and test a 30-meter prototype cable operating with ac at 115 kV rms by 1997. Meanwhile, he said, the group expects to complete a 30-meter-long machine-stranded conductor early this year. Roughly speaking, Malozemoff said, the target length for cable is 1 km; he envisions each 1-km segment having its own liquid nitrogen circulation system.

Last October DOE, Oak Ridge and Southwire Cable (Carrollton, Georgia) announced a different cable project. Intermagnetics will supply the wire. The collaboration has fabricated and tested a 1-meter cable carrying 2000 A of ac.

Last summer, BICC Cables in the UK, its Italian subsidiary, CEAT CAVI, and Ansaldo Richerche announced the construction of a dc cable prototype, 1 meter long, which used Intermagnetics wire. The cable carried 11 000 A at 20 K. In the next phase of the project, the team plans to build a prototype working at operational voltages with joints, terminations and cryogenic systems for a cable cooled with pressurized helium gas at about 40 K.

Coils, motors and generators

Last September the Naval Research Laboratory and the Naval Surface Warfare Center set a world record in high-T_c motor performance—167 hp. The field magnet for the motor consisted of two sets of coils made of Bi-2223, one made by American Superconductor and the other by Intermagnetics. NRL's Donald Gubser convinced the Navy that an old 400-hp homopolar motor that had run with NbTi coils could be used as a testbed. The NbTi coils were removed and replaced with BSCCO coils. In the first demonstration, the motor was only half loaded with high-T_c coils; they generated 1 T. The motor operated at 4.2 K to reach 167 hp; when the coils were operated at liquid-neon temperature, 28 K, the motor produced 112 hp. Gubser speculates that the next application for the Navy might be a minesweeping magnet, where the field needed is 5–6 T.

Reliance Electric Co (Cleveland, Ohio) and American Superconductor are building a demonstration motor based on high-T_c rotor coils, with the goal of making a 5000-hp motor by 2000. In early 1996, Malozemoff said, the partnership expects to test a 125-hp ac synchronous motor with BSCCO windings that operates at 20–30 K.

General Electric Co has been developing a high-T_c coil to be used on the rotor for a generator. The racetrack-shaped coil contains about 2 km of Bi-2223 wire made by Intermagnetics. It will be operated at 35 K and 20–50 A. GE has completed the prototype, which was cooled by cryorefrigeration at 10–20 K.

In the early 1980s General Electric had built a low-temperature superconducting generator, made with NbTi coils and operated at liquid-helium temperature. The company's James Bray said that the GE group was the only one to load test such a machine, which operated at 20 MVA.

In Japan, MITI and a group of major manufacturers have organized a big superconducting generator project, called Super GM, which is slated to get \$250–300 million over an 11-year period, ending about 1998. The project has almost finished a prototype generator of 70 MVA in the Osaka power station of Kansai Electric Power Co, and tests in the actual network are to start this year. It would also operate at liquid-helium temperatures with NbTi coils. A fully commercial generator is in the 200-MVA range.

Transformers, magnets and more

Late this year the world's first high-T_c prototype transformer is scheduled to be installed in the power grid for Geneva, Switzerland. ASEA Brown Boveri, SIG (Geneva's electric utility), and Electricité de France (an electric utility) are partners in the project; American Superconductor began shipping wire to ABB in 1994. The transformer is to produce 630 kVA and will operate at 77 K. To be economically feasible, transformers for power grids will need to be in the range of tens of MVA, Malozemoff said.

Intermagnetics and Waukesha Electric Systems (a Waukesha, Wisconsin, transformer manufacturer) have teamed with Rochester Gas & Electric and Oak Ridge to build a demonstration single-phase transformer rated at 1 MVA and operating at 20–50 K with a cryocooler. The windings are to be surface-coated Bi-2212; the rest of the transformer is to be iron core. The prototype is scheduled to be ready early in 1997.

FABRICATION OF A DOUBLE-PANCAKE COIL. It is made of three strands of silver-sheathed Bi-2223 tape (heat treated before winding) and has 37 filaments. (Courtesy of Intermagnetics General Corp.)

Sumitomo recently produced a record 4-T field magnet at 4.2 K and 3 T field at 20 K, with a 60-mm bore, according to Kenichi Sato of Sumitomo. American Superconductor has operated a 0.6-T magnet at 77 K and 3.4 T at 4.2 K. Earlier, Intermagnetics had made a 2.6-T magnet, and more recently a 3.2-T magnet, both operating at 4.2 K. Oxford Instruments has produced several 2-T magnets using Bi-2212 tape.

High-field magnets with low-T_c coils (which can reach 20–21 T), could be enhanced by adding a high-T_c coil insert, boosting the field to 25 T or above, said Jack Crow, director of the National High Magnetic Field Laboratory at Florida State University. There is hope of developing a 1-GHz high-resolution nmr spectrometer with such a field. The very high J_c in Bi-2212 reported by Hitachi in a 30-T field offers hope for a super-high-field high-T_c magnet for a 1-GHz nmr spectrometer in a few years, said Koichi Kitazawa of the University of Tokyo.

A fault-current limiter is a device that protects a power transmission and distribution system from surges, such as those resulting from a lightning strike. A limiter that can reduce the fault current to a fraction of its peak value in less than a cycle (8 ms) can bring about significant cost savings and operation benefits to power utilities, said Eddie Leung of Lockheed Martin in San Diego, California. A team led by Lockheed Martin, in collaboration with Southern California Edison and supported by DOE, recently completed testing of a 2.4-kV, 2.2 kA, fault-current limiter, whose coil is made out of BSCCO. The need for low J_c in a low magnetic field (less than 0.2 T) for this application makes fault-current limiters an excellent near-term application for high-T_c, said Leung. High-T_c fault-current limiters are also being developed by teams elsewhere, including GEC-Alstholm and Electricité de France, Toshiba and TEPCO, and Siemens and Hydro Quebec.

To connect a cryogenic machine electrically to the outside produces a heat leak. Because high-T_c materials have low thermal conductivity, a current lead can be installed to reduce the heat loss. Sumitomo has been using a pair of high-T_c current leads carrying 2000 A in NbTi synchrotron radiation magnets for the last two years. Oxford Instruments is equipping its low-T_c magnets that are operated with a mechanical cryocooler for gaseous helium with high-T_c current leads. And, in collaboration with materials companies, Oxford is building experimental current leads operating at 1.2×10^4 A. GE is now using a pair of high-T_c current leads in advanced mri devices with Nb_3Sn magnets operated at 10 K. The high-T_c material replaces the yttrium in YBCO with dysprosium. According to Bray, "These leads carry 200 A, the full load in these advanced mri machines, which allow surgeons to do surgery inside the machine."

At the Texas Center for Superconductivity, Wei-kan Chu and his collaborators are working on magnetic bearings, which would use melt-textured YBCO and permanent magnets. The superconducting magnetic bearings would be used with large flywheels, which would be spun up during the evening hours to store energy. The new bearings would be simpler and cheaper than conventional, active magnetic bearings, according to Chu. The Texas team is collaborating with Argonne and Commonwealth Research in the Chicago area. Also at the Texas Center, Roy Weinstein is proposing to use YBCO tiles in conjunction with electromagnets in a prototype bumper-tether system for spacecraft docking.

In Japan magnetically levitated model train cars were built and transported to a test site last fall; when tracks are completed, a running test will begin. By the end of 1999 the JR Tokai Co is expected to decide whether to introduce maglev or continue to rely on the conventional Shinkansen bullet train. Although the magnet installed in the model cars is made of low-T_c wires, according to Kitazawa there is a wide belief the magnet will be replaced by a high-T_c magnet in the actual line.

At the Superconductivity Research Laboratory in Tokyo, a YBCO-related material has been found with a J_c three times higher than YBCO's. According to Kitazawa, the lab is planning to make a single piece of this material into a disk and soon expects to use it to levitate a popular Sumo wrestler.

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