

# CRITICAL CURRENTS AND MAGNET APPLICATIONS OF HIGH- $T_c$ SUPERCONDUCTORS

What has become of the great expectations of 1987? Achieving critical currents high enough for practical magnet applications is no easy matter with materials as complex as the high-temperature superconducting compounds. But prospects are now very bright.

David Larbalestier

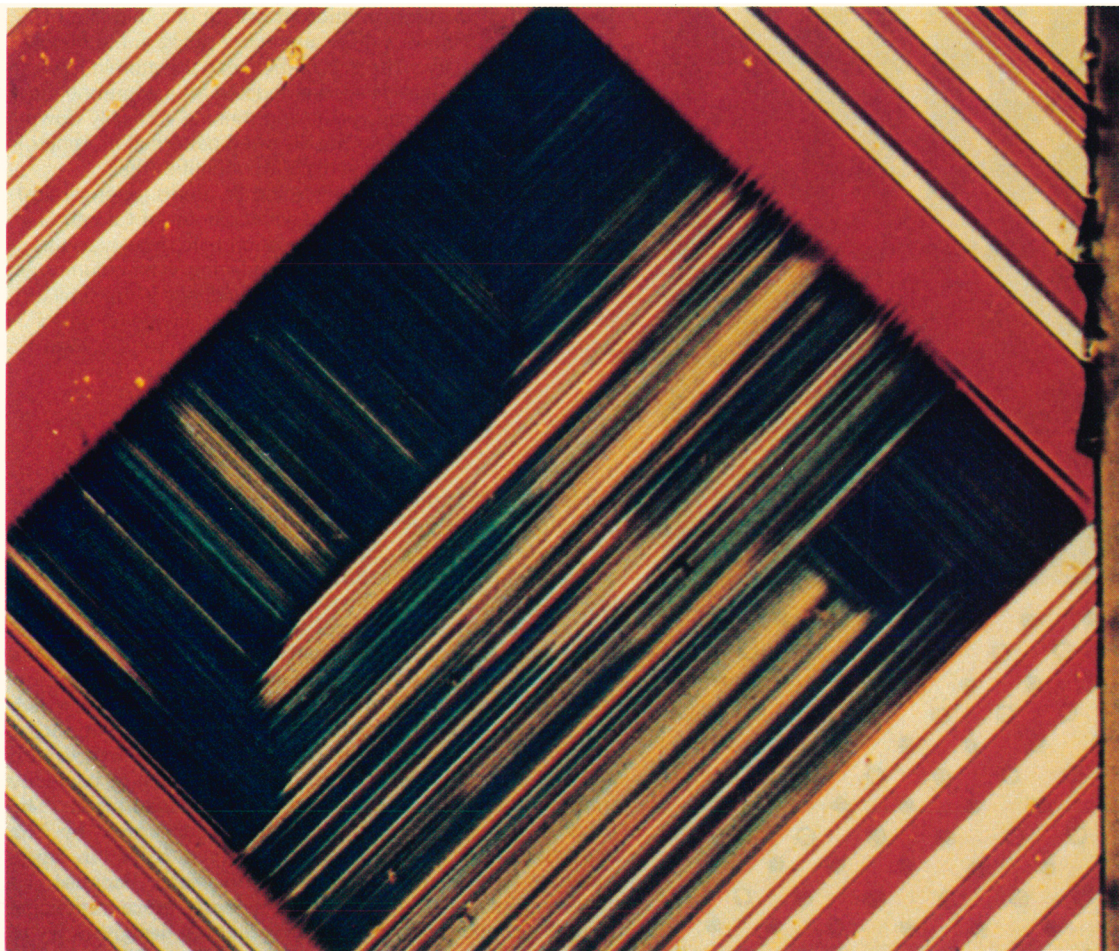
David Larbalestier is L. V. Shubnikov Professor in the department of materials science and engineering, the physics department and the Applied Superconductivity Center at the University of Wisconsin, Madison.

The discovery of a 92 K superconductor in early 1987 by M. K. Wu, Paul Chu and their coworkers at the Universities of Alabama and Houston produced widespread euphoria. Newspapers and magazines of every conceivable political and social persuasion speculated on the applications of superconductivity. Some even foretold a new age; after the stone, bronze, iron, steel and semiconductor ages would come the superconductor age. Most of the applications envisaged for this new age depended on the generation of strong magnetic fields, frequently in large volumes. Thus the vanishing of resistance in the superconducting state was the key property for these applications, and it is this ability to carry very large current densities without ohmic loss that forms the essential thread of this article.

## Present technology

Current transport with zero resistance forms the basis of most present applications of low-temperature superconductivity: The enormous particle accelerators at Fermilab and DESY, the 60-mile-long string of magnets to be built for the Superconducting Super Collider, the kiloton fusion magnets of the Mirror Fusion Test Facility, the thousands of clinical magnetic-resonance-imaging magnets and tens of thousands of laboratory superconducting magnets all depend on this zero-resistance property. They all have been realized with just two materials: a ductile Nb-Ti alloy and a brittle intermetallic compound having the nominal composition Nb<sub>3</sub>Sn. (See the article by Gene Fisk, Bruce Montgomery, David Hawksworth and me in *PHYSICS TODAY*, March 1986, page 24.)

Because the superconducting transition temperatures of Nb-Ti and Nb<sub>3</sub>Sn are 9 K and 18 K, respectively, one has to cool these materials down to about 4 K with liquid helium. Liquid nitrogen, by contrast, is a much less expensive cryogen with a much higher heat capacity. Its use requires less care than does liquid helium. The discovery of superconductors with transition temperatures well above the 77 K boiling point of nitrogen



**A single crystal** of the high-temperature superconducting compound  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ , mounted on a black background. The almost perfectly square crystal, grown by Debra Kaiser at the National Institute of Standards and Technology, is about 200 microns on a side. The diagonal striations that show up in this polarized-light micrograph indicate complex twin-domain structure within the single crystal. **Figure 1**

immediately held out the promise of superconducting technology with much simpler and cheaper cryogenics.

All the devices of electrotechnology that depend on strong magnetic fields or low-loss current transport could, it was hoped, be made to work economically in liquid nitrogen: Not just motors, generators, transmission lines and other such everyday things, but also more speculative possibilities such as levitated trains, electromagnetically propelled ships and superconducting magnetic energy storage devices. But as we survey the field in the spring of 1991, these heady prospects for magnetic-field applications of high-temperature superconductors have not yet come to pass. What has been holding us up?

### Properties of useful superconductors

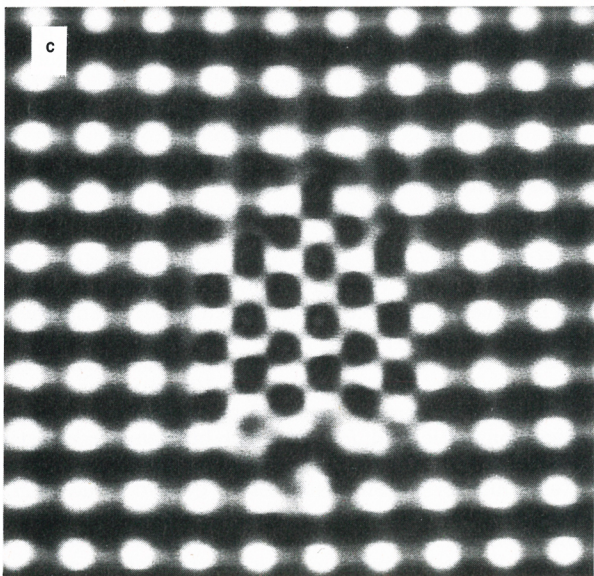
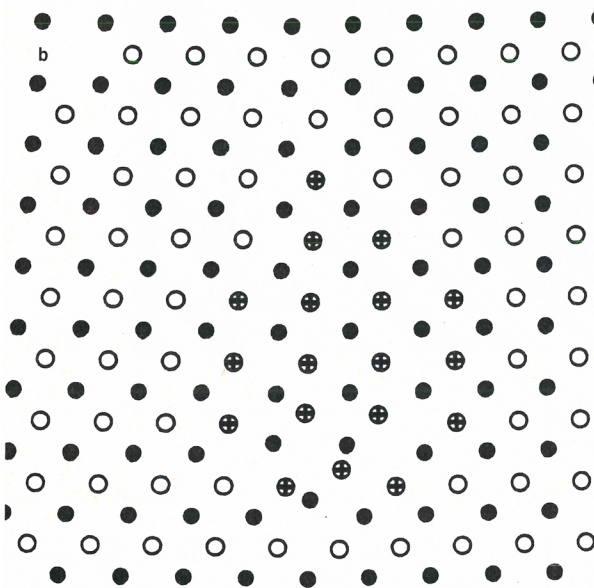
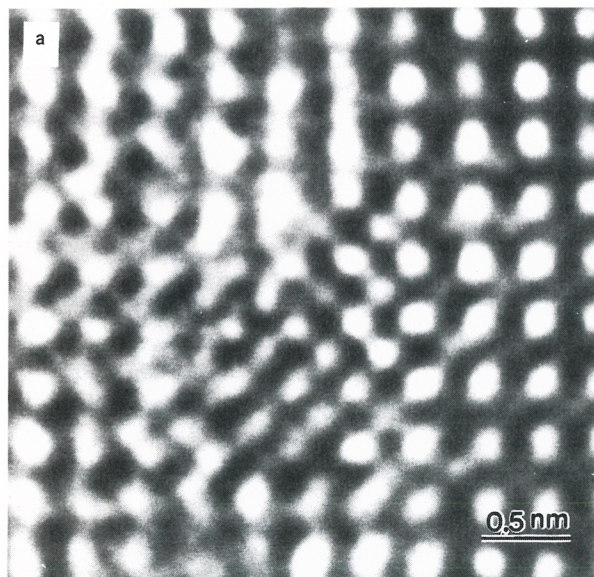
One of the most useful ways of assessing the prospects of a magnetic-field technology with *high-temperature* superconductors is to understand what properties of the *low-temperature* superconductors have been crucial to their success. Both Nb-Ti and  $\text{Nb}_3\text{Sn}$  can be fabricated economically as multifilamentary conductors incorporating as many as 6000 filaments, each as thin as 5 microns. Fine filaments are electromagnetically stable, with low ac losses. They resist fracture, even though  $\text{Nb}_3\text{Sn}$  is as brittle as a typical ceramic.

Two crucial virtues of both materials are that they are not granular and that they develop strong flux pinning. The tendency of granular superconductors to subdivide into regions of strong superconductivity separated by weak superconducting interfaces ("weak links") is bad for applications. The critical "transport" current density ( $J_{ct}$ ) for transmitting current over useful lengths is then very much less than the local critical current density ( $J_c$ ) in the strong superconducting regions with good flux pinning. In Nb-based superconductors  $J_c$  and  $J_{ct}$  are essentially the same. In the high-temperature materials they can be very different.

High  $J_{ct}$  is essential for widespread applications. For Nb-Ti at 4.2 K,  $J_{ct}$  can exceed  $10^5$  amp/cm<sup>2</sup> in magnetic field intensities up to 8.5 tesla. So can  $\text{Nb}_3\text{Sn}$ , in magnetic fields all the way up to 12 tesla. For useful applications one needs a  $J_{ct}$  of at least  $10^4$  amp/cm<sup>2</sup>, but the economics become much more favorable above  $10^5$  amp/cm<sup>2</sup>.

Another important material parameter is the upper critical magnetic field,  $H_{c2}$ , at which bulk superconductivity is destroyed. For Nb-Ti the upper critical field is about 11 tesla, and for  $\text{Nb}_3\text{Sn}$  it is 22 tesla. Typical values of  $H_{c2}$  for high-temperature superconductors are 15 tesla at 77 K, rising to more than 50 tesla as one reduces the temperature to 4 K. Most conventional electrotechnology only uses





**High-resolution electron micrograph (a)** of a thin film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  shows a dislocation core sitting in the middle of a grain boundary. The  $3.5^\circ$  tilt between the atomic rows at the left and right edges is accommodated by a grain-boundary layer normal to the image plane and running vertically down the middle of the picture. The distorted pattern at its center is a dislocation core. The schematic (b) identifies the micrograph dots as columns of Y and Ba atoms (open circles) normal to the image, alternating with columns of Cu and O atoms (solid circles). In the dislocation core, however, this pattern is upset by Cu-O columns replacing Y-Ba columns at sites marked by crossed circles. The evidence is the similarity between the micrograph and the simulated image (c) based on replacing the Y-Ba columns by Cu. (From ref. 5) **Figure 2**

fields of 1 or 2 tesla, because that is the limit of iron cores and copper windings. But superconductors, whether high- or low-temperature, can produce much higher fields. Indeed fields above 5 tesla would be optimal for a number of electrotechnical applications.

The design of a practical superconductor must consider the inevitable, abrupt transitions from superconducting to normal current flow. When such a "quench" happens, the current must flow in a parallel, resistive path in which the ohmic heat is dissipated. Thus the superconductor must be intimately bonded to a good conventional conductor like copper or silver, and space must be provided in the windings for coolant and electrical insulation. The fraction of space in the conductor occupied by the superconductor itself seldom reaches a third; in large magnets it is frequently less than a tenth. Because the superconducting component is generally more expensive than the copper or the insulation, magnet designers try to minimize the superconductor cross section. These considerations once again emphasize the desirability of the highest possible  $J_{ct}$ .

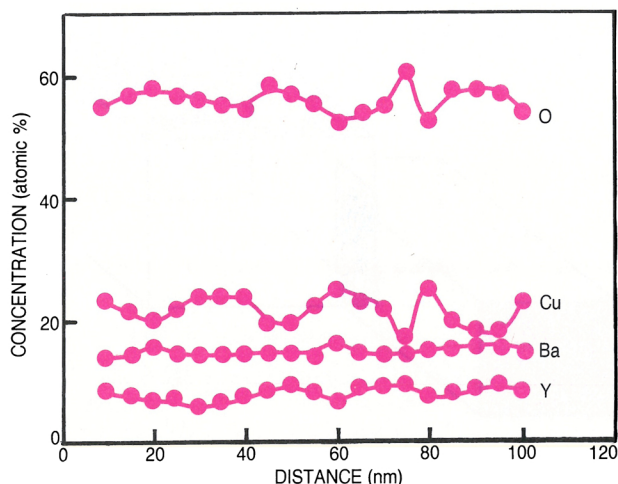
### Critical current density

Recognizing these issues helps us understand the sometimes confusing rhetoric used to describe applications of high-temperature superconductivity. For making high-field magnets the principal need is simple enough: to develop materials that can transport supercurrent densities in excess of  $10^5$  amp/cm<sup>2</sup> over long wires in strong fields. In 1987 and 1988 this goal appeared unrealizable. But in 1989 came the first unambiguous evidence that high-temperature superconducting materials could achieve technologically interesting critical transport currents. Progress has been rapid since that breakthrough, and prospects are now very bright. We now understand better that not all high-temperature superconducting materials are alike. In particular, we now know that the granular properties evident in the first such materials are not intrinsic to high-temperature superconductivity.

There are, in essence, two principal issues that determine  $J_{ct}$ . The first and most critical is the tendency of high-temperature superconducting materials to be only weakly coupled across the grain boundaries of bulk, polycrystalline samples. This has come to be called the weak-link or granularity problem. In this state,  $J_{ct}$  is much less than the local  $J_c$  in the flux-pinning regions. This is the difficulty that blocked the early hopes for the technology. The early prototype conductors, with  $J_{ct}$  less than 1000 amp/cm<sup>2</sup>, could carry no larger currents than could copper.

The second issue is the need to develop strong flux





**Chemical composition profile**, measured along a grain boundary in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  with a large angle between the crystal planes of the adjacent grains, shows significant variation on a scale of about 25 nanometers. (Adapted from ref. 6) **Figure 3**

pinning, so that the fluxoids of the mixed superconducting state can resist the Lorentz force. The most effective pinning occurs when the normal (non-superconducting) cores of the fluxoids find a high density of normal regions to sit on. Strong pins help the lattice of fluxoids resist flux creep and melting transitions. These essential problems—weak links, flux pinning, flux creep and phase transitions of the vortex lattice—remain controversial issues that we can touch on here only briefly.

Underlying these issues is the very complex materials science of the high-temperature superconducting compounds. At one extreme, one might simplify these matters by describing the materials as  $\text{Cu-O}_2$  planes of strong superconductivity, weakly coupled together by layers of other elements. Such a picture may be appropriate when considering critical magnetic field or temperature, but it is inadequate when considering the critical current density. Because it is the local weakening of superconductivity that controls the elementary flux-pinning interaction,  $J_c$  is ultimately determined at this very local, near-atomic scale. If the local structural perturbations are strong and the regions are isolated, they can be very effective flux-pinning centers; if the perturbations are multiply connected into a three-dimensional network, as at grain boundaries, then the superconductor becomes granular. This latter possibility was explicitly recognized very early in the game by Guy Deutscher at Tel Aviv University and Alex Müller<sup>1</sup> at IBM, Zurich.

In most of the world, the material of choice has thus far been the 92 K compound  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ , frequently referred to as YBCO. More generally such materials are often called 1-2-3 compounds, after the stoichiometry of their metal atoms. Figure 1 is a photograph of a single crystal of YBCO, taken through a light microscope. The simple elegance of this almost perfectly square crystal belies the sometimes vexing complexities with which the material confronts those who seek to make it a practical high-current superconductor.

Workers in Japan have tended to concentrate on two bismuth-based materials, known generically as BSCCO. Their compositions are  $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$  ( $T_c \sim 85$  K) and  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$  ( $T_c \sim 110$  K). The 2-2-1-2 compound was discovered in Japan by H. Maeda at the National Research Institute for Metals 1987.

In many respects the materials science of BSCCO is more complex than that of YBCO, because the stoichiometry of its metal composition is quite variable. In the 1-2-3 materials, by contrast, the metal composition appears to be fixed. In fact, there is still no general agreement on the composition range of the single-phase fields for the 2-2-1-2 and 2-2-2-3 compounds. The evidence suggests that

neither phase exists at either of these nominal stoichiometric compositions.<sup>2</sup> One consequence of this complexity is that it is very difficult to make good single crystals or single-phase thin films of the BSCCO materials or their closely related thallium analogs. For all of these reasons, there has been a greater tendency, at least outside Japan, to concentrate on the 1-2-3 compounds, and considerably more is known about them than about the bismuth and thallium compounds.

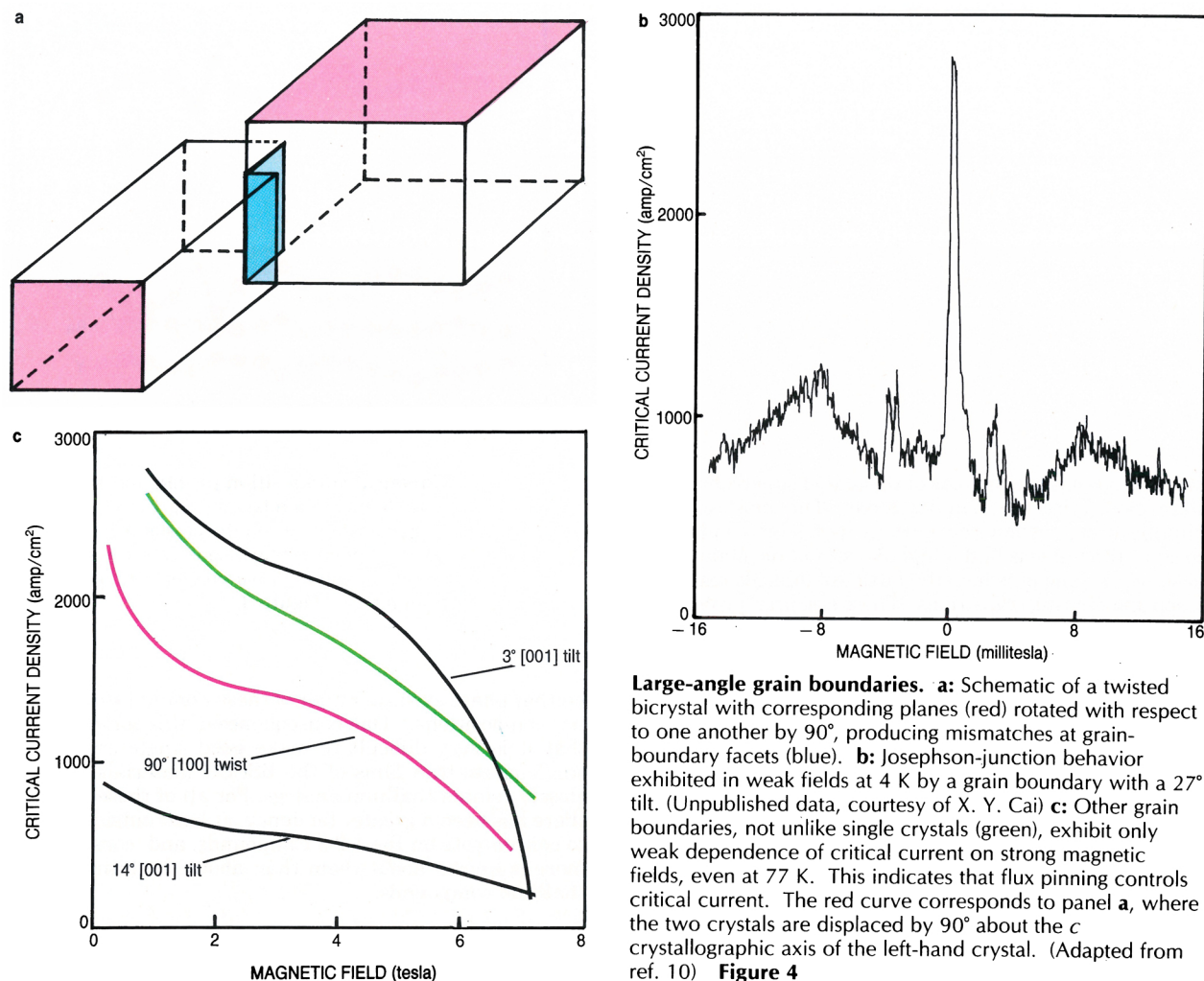
## Weak links

Grain boundaries tend to induce granularity. This crucial point was made clear in early 1988 by some elegant experiments conducted at IBM, Yorktown Heights, by Duane Dimos, Praveen Chaudhari, Jochen Mannhart and Francois LeGoues.<sup>3</sup> They grew thin films of YBCO on specially prepared  $\text{SrTiO}_3$  bicrystal substrates and showed that high-angle grain boundaries reduced the inter-granular transport by about two orders of magnitude. This deterioration of  $J_{ct}$  was observed even at 4 K and zero magnetic field, and even in the presumed favorable situation where the  $\text{Cu-O}_2$  planes are parallel to one another.

After an extensive investigation of multiple misorientations, the IBM group concluded that all grain boundaries misoriented by more than about  $5^\circ$  were intrinsic Josephson junctions. Such junctions are extremely undesirable for conductors, because  $J_{ct}$  is then limited by the weak-link properties of the grain boundaries. Being Josephson junctions, they have a  $J_c$  that is not only lower than that of the bulk material, but also much more sensitive to magnetic fields.<sup>4</sup> Only in epitaxial thin films, where there is an extremely high degree of alignment between grains, has it been possible to get high  $J_{ct}$  values in polycrystalline 1-2-3 samples. In fact grain-boundary specialists would call such samples mosaic single crystals. In bulk polycrystalline 1-2-3 compounds, however, it has not yet proven possible to avoid extensive weak-link behavior at grain boundaries, in spite of extensive attempts at magnetic and mechanical alignment.

If grain boundaries do severely decouple the strongly superconducting grains, how do they do it? We don't know





**Large-angle grain boundaries.** **a:** Schematic of a twisted bicrystal with corresponding planes (red) rotated with respect to one another by  $90^\circ$ , producing mismatches at grain-boundary facets (blue). **b:** Josephson-junction behavior exhibited in weak fields at 4 K by a grain boundary with a  $27^\circ$  tilt. (Unpublished data, courtesy of X. Y. Cai) **c:** Other grain boundaries, not unlike single crystals (green), exhibit only weak dependence of critical current on strong magnetic fields, even at 77 K. This indicates that flux pinning controls critical current. The red curve corresponds to panel **a**, where the two crystals are displaced by  $90^\circ$  about the  $c$  crystallographic axis of the left-hand crystal. (Adapted from ref. 10) **Figure 4**

much more now than we did in 1987. The problem is that microscopes are not yet good enough. If perturbations in chemistry on the nanometer scale of the superconducting coherence length cause flux pinning and weak links, we need microscopes that can locate and identify individual atoms. A suitable microscope does not yet exist.

High-resolution transmission electron microscopy is one of the most useful techniques we do have. By comparing experimental images to computer simulations, we can infer the chemical identity of columns of atoms. A very elegant example is shown in the images of figure 2, made by Yufei Gao in Karl Merkle's group at the Argonne National Laboratory.<sup>5</sup> The micrograph (figure 2a) examines the structure of a  $3.5^\circ$  tilt boundary in a thin film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  made by metal-organic chemical vapor deposition. The image clearly shows the strongly localized distortion that can occur at a grain boundary dislocation. The simulation (figure 2c) suggests that columns of Y and Ba in the dislocation core are replaced by copper-rich columns. Thus it can be inferred, on structural as well as chemical grounds, that the dislocation cores are not superconducting. The copper-rich character of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  grain boundaries, hinting at this result, had been detected earlier by analytical transmission electron microscopy and scanning Auger microscopy.

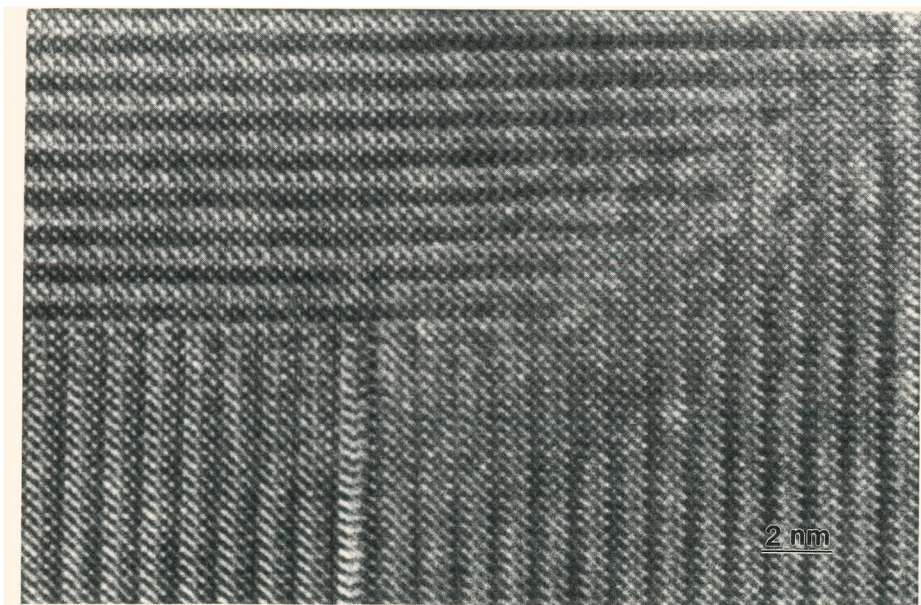
My colleague Susan Babcock detected significant, fine-scale (25–30 nm) variations in composition within the

core of some grain boundaries with large-angle crystallographic mismatches.<sup>6</sup> (See figure 3.) Thus, there is abundant evidence for a rich, atomic-scale structure of grain boundaries in 1-2-3 materials. Indeed the electromagnetic implications of this local structure have inspired models developed by my colleague Cai Xue Yu,<sup>7</sup> and by Robert Buhrman<sup>8</sup> (Cornell) and Alex Malozemoff<sup>9</sup> (American Superconductor Corp). But all of these models and observations suffer from the poor sensitivity of present microscopes in ascertaining precise atomic structure and composition, particularly with respect to the very important light element oxygen. Thus the models yield plausible, but not yet unique interpretations of the experimental data.

Surveying their synthetic thin-film bicrystal work, the IBM group came to the conclusion that all high-angle grain boundaries are intrinsic Josephson junctions.<sup>3</sup> In my group this view was warmly debated because polycrystalline samples had provided abundant evidence of a finite, though small, transport  $J_{ct}$  even in high magnetic fields.<sup>7</sup> From a grain-boundary perspective, the problem seemed to us more intricate than the Josephson-junction-generalization would suggest. For example, some grain misorientations have particularly low energy, and Babcock asked herself whether such boundaries might have especially good properties.

Working with bicrystals grown by Debra Kaiser at





#### Bicrystal of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

The electron micrograph is a slice through the layers of the two contiguous crystals, whose layers are rotated by  $90^\circ$  relative to one another.<sup>10</sup> The Cu-O layers, which are thought to be responsible for the superconducting transport, show up as bright bands. On the left side, the Cu-O layers of the bottom crystal appear to make no proper connection when they run into the top crystal. This probably makes for bad transport. But on the right side of the micrograph we see the sharp boundary spontaneously give way to a  $45^\circ$  facet, so that the transport layers seem to make good contact. (Courtesy of Karl Merkle) **Figure 5**

NIST, we were able to study some of these special misorientations, including some that are inaccessible by the thin-film bicrystal technique.<sup>10</sup> (See figure 4.) Some of these high-angle grain boundaries are indeed Josephson junctions, and they exhibit a strong  $J_{ct}$  reduction by even millitesla fields (figure 4b). But others (figure 4c) have the weak-field dependence associated with flux pinning, even in fields of several tesla at 77 K. Such characteristics are similar to those of the individual grains. These bi-crystals can be thinned for transmission-electron microscopy. Frustratingly, however, we have not yet seen any significant microstructural difference between Josephson junction and flux pinning boundaries in our investigations by diffraction-contrast imaging. This illustrates that the electromagnetic properties really are decided at the near-atomic level.

Tantalizing hints of the importance of the detailed grain-boundary structure are provided by a second high-resolution transmission-electron-microscope study<sup>11</sup> by the Argonne group. In this case, shown in figure 5, the grain boundary has nearly the same macroscopic crystallography as one of the large-angle boundaries found to have flux-pinning character in our own study. The boundary in the figure separates two crystals rotated  $90^\circ$  about a common axis. Thus the Cu-O<sub>2</sub> planes of one crystal are normal to those of the second crystal. Such boundaries were long thought to be intrinsically bad, because the Cu-O<sub>2</sub> layers, which play a central role in the superconducting transport, are not continuous across them. But the micrograph shows that the boundary plane can develop nanometer-scale facets, with basal-plane facets and segments aligned at  $45^\circ$  to the basal plane. One sees clearly that the bright Cu-O<sub>2</sub> planes are continuous across the  $45^\circ$  facets. It is tempting to speculate<sup>11</sup> that the flux-pinning critical current shown in figure 4 is being transmitted by these facets. Thus there is abundant evidence of great structural detail in grain boundaries.

### Breaking the weak-link barrier

Only by studying the direct coupling between microstructure and electromagnetic behavior can we expect finally to understand the crucial properties of individual grain boundaries. But the breakthroughs thus far have come

elsewhere: largely from the rather empirical fabrication studies of prototype conductors. An early stimulus was provided by partial melting experiments on YBCO done by Sungho Jin and his collaborators at AT&T Bell Labs.<sup>12</sup> These experiments appeared to show that one could increase the critical current density substantially by partial melting. K. Heine, N. Tenbrink and M. Thöner at Vacuumschmelze in Hanau, Germany, made a crucial discovery in early 1989, when they partially melted the 2-2-1-2 phase of BSCCO while it was contained within a silver tube.<sup>13</sup> In samples that were clearly polycrystalline, they measured  $J_{ct}$  exceeding  $10^4$  amp/cm<sup>2</sup> at 4.2 K in magnetic fields all the way up to 25 tesla.

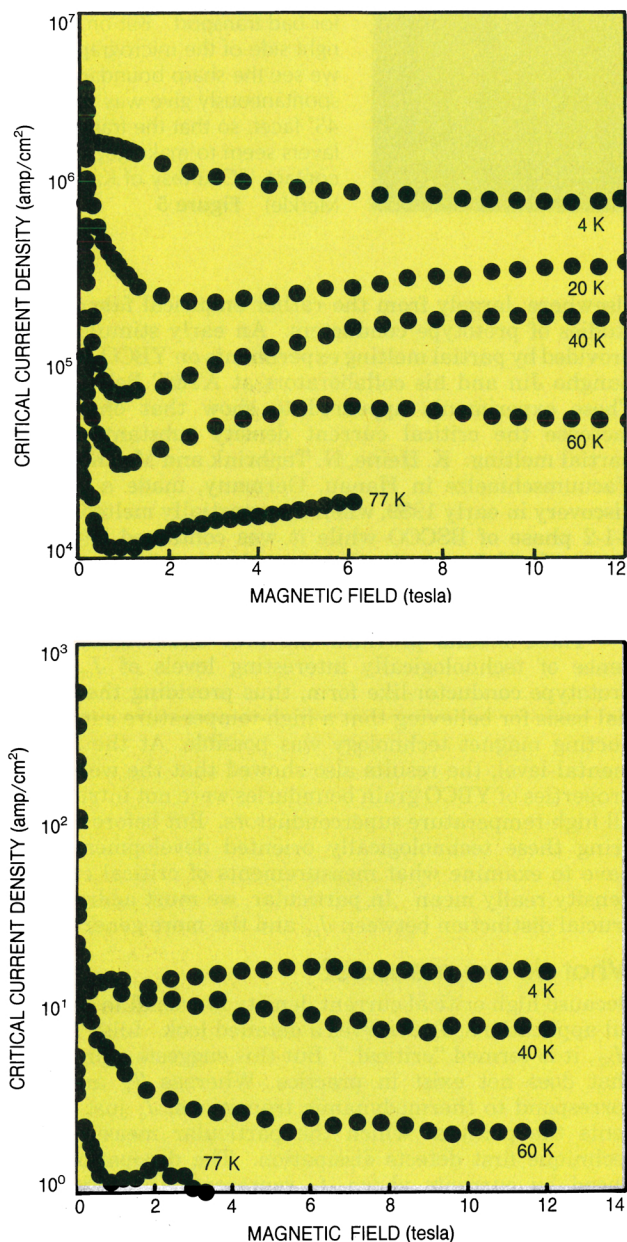
These results provided the first unambiguous evidence of technologically interesting levels of  $J_{ct}$  in a prototype conductor-like form, thus providing the essential basis for believing that a high-temperature superconducting magnet technology was possible. At the fundamental level, the results also showed that the weak-link properties of YBCO grain boundaries were not intrinsic to all high-temperature superconductors. But before considering these technologically oriented developments, we have to examine what measurements of critical current density really mean. In particular, we must address the crucial distinction between  $J_{ct}$  and the more general  $J_c$ .

### What do we measure?

Because high critical current density is crucial to successful applications,  $J_c$  deserves a detailed look. Like  $T_c$  and  $H_{c2}$ , it is termed "critical." But this suggests a precision that does not exist in practice. Whereas  $T_c$  and  $H_{c2}$  correspond to thermodynamic transitions,  $J_c$  just represents the point at which the particular measurement technique first detects dissipation. The dissipation produced by currents above  $J_c$  represents the failure of material inhomogeneities to pin fluxoids. Therefore  $J_c$  is inherently a local property with a distribution of values. It is perfectly possible for  $J_{ct}$  measurements to vary by factors of 2 or more, depending on the criteria of definition.

All this is further complicated when the material is granular. If the weakly coupled regions are grain boundaries, they form a multiply connected network through which the transport current must pass. Thus  $J_{ct}$





In polycrystalline  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ , critical current densities measured within a grain (top) at various temperatures are much higher than those measured between grains (bottom). (Adapted from ref. 14) **Figure 6**

is limited by the weakened properties of the boundaries, even though they constitute only a tiny fraction of the volume, and not by the strong flux-pinning properties of the grain interiors. A transport measurement therefore represents the *lowest* value of  $J_c$  that can be defined, although attention must still be paid to the dissipation criterion. Internationally accepted critical-current standards are very much needed.

One can also infer critical current from magnetization measurements, calling it  $J_{cm}$ . This measure of critical current relies on the fact that magnetic moment is the product of a circulating current and the area it encloses. In a granular medium this can lead to difficulties, because the appropriate area is not the area of the whole sample. One is, in fact, measuring the sum of both local and global moments. Distinguishing the two requires special ac flux penetration methods. Heinz Küper's group at Karlsruhe has been particularly careful about distinguishing between the intergranular and intragranular  $J_c$ . As we see in figure 6, they can frequently differ by three to five orders of magnitude.<sup>14</sup>

For all these reasons,  $J_c$  is sometimes very insecurely defined. Caution is in order when one hears yet another record  $J_c$  announced.

Setting the upper limit to the  $J_c$  is the "depairing current density" ( $J_d$ ), which is defined by the energy at which superelectrons are excited over the superconducting gap.  $J_d$  is approximately equal to  $H_c/\lambda$ , where  $\lambda$  is the penetration depth to which the supercurrents flow.<sup>4</sup> For YBCO, typical values of the critical field and penetration depth (0.9 tesla and 140 nm) yield a  $J_d$  of about  $5 \times 10^8$  amp/cm<sup>2</sup> for currents flowing in the  $ab$  plane. But when one is interested in macroscopic transport in bulk samples, the current is determined by the fluxon density gradient, which inevitably reduces  $J_c$  well below  $J_d$ . (A fluxon, or fluxoid, is a quantum of magnetic flux, given by  $\phi_0 = h/2e = 2.07 \times 10^{-15}$  weber.) In low-temperature superconductors, for example, the maximum current density is typically only 5% of  $J_d$ . To optimize superconductors, therefore, one must produce high densities of strong flux pinning defects within the material, so that it will sustain large fluxoid gradients.

## Flux pinning

Studies of low-temperature superconductors<sup>15</sup> have established the optimum size and density of the pinning defects. The size is set by the coherence length, which is the radius of the "normal" core of a fluxon. The optimal density of defects is determined by the fluxon spacing, given approximately by  $(\phi_0/B)^{1/2}$ , where  $B$  is the flux density. At a flux density of 5 tesla the fluxon spacing is about 22 nm, and the coherence length is on the order of a nanometer in high-temperature superconducting compounds. Therefore the optimum defect size in these materials is very



small, and the optimal defect density is very high.

So far, controlled introduction of flux-pinning centers into high-temperature superconductors has been mostly by irradiation or the controlled introduction of small concentrations of oxygen vacancies. Because neither method is particularly practical, flux pinning has not yet become an engineering tool for optimizing high-temperature superconductors. However, the flux pinning of many undoped samples is already very high. Although the critical current density of polycrystalline YBCO is limited by the intergranular weak links, the  $J_c$  of the *intragranular* regions can reach  $10^7$  amp/cm<sup>2</sup> at 4 K and  $10^6$  amp/cm<sup>2</sup> at 77 K for the best thin films. So there seems to be no fundamental problem about flux pinning in the 1-2-3 compounds, even if the best values in bulk samples are about an order of magnitude less than in thin films. This result is consistent with the short coherence length, which means that almost any atomic disorder can perturb the local superconducting order parameter.

Flux pinning is a complex and imperfectly understood field of study. The details are extremely sensitive to the particular material and its defect population. When the defects range from the visible (for example, grain boundaries, twin boundaries, dislocations, voids and particles of second phase) to the invisible (for example, cation disorder or missing oxygen atoms), it is not surprising that there is little agreement on what determines the flux pinning.

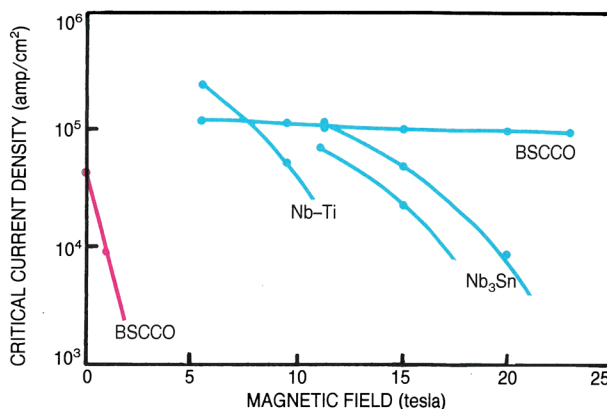
In outline the problem is easy.<sup>15</sup> Any spatial variation  $\delta$  in  $H_{c2}$  or the Ginzburg-Landau parameter  $\kappa$  will produce a binding energy  $\delta E$  between a fluxon and the defect given by:

$$\delta E = \int \mu_0 H_c^2 \left( -\frac{\delta H_{c2}}{H_{c2}} |\psi|^2 + \frac{1}{2} \frac{\delta \kappa^2}{\kappa^2} |\psi|^4 \right) dV$$

where  $H_c$  is the thermodynamic critical field that defines the superconducting condensation energy density  $\frac{1}{2}(\mu_0 H_c^2)$ ,  $V$  is the volume of the pinning reaction and  $\psi$  is the order parameter. But detailed calculations become complex, both for mathematical reasons and because the summation of all the fluxon interactions is uncertain.

Understanding flux pinning is important, because high-temperature superconductors exhibit flux creep much more strongly than do the older superconducting materials. Whereas low-temperature superconductors are routinely used to construct persistent-current magnets that decay at rates of less than a part in  $10^7$  per hour, everyone who has ever made measurements on high-temperature superconductors has watched the currents decay at much faster rates.

The basic phenomenon underlying this decay is the thermal activation of fluxons out of their flux-pinning wells at a rate proportional to the Boltzmann factor  $\exp(-U/kT)$ , where  $U$  is the depth of the pinning



**BSCCO wires**, sheathed in silver, have critical current densities that fall more slowly with increasing magnetic field than do those of commercial Nb-Ti and Nb<sub>3</sub>Sn superconductors at 4.2 K (blue). At 77 K (red), where the niobium-based superconductors no longer function, the critical current density of BSCCO wires is still high, but it falls faster with increasing field. (Adapted from ref. 21) **Figure 7**

potential well. Fluxoid core pinning is believed to dominate the pinning. The maximum well depth is obtained when fluxoid cores find normal regions, because then the entire superconducting condensation energy,  $\frac{1}{2}(\mu_0 H_c^2 V)$ , is saved. One might expect  $U$  to be very large in high-temperature superconductors, because they have much higher critical fields than do the low-temperature materials. But alas, they also have much smaller coherence lengths. And if pinning is dominated by defects at or near the atomic scale, then the interaction volume  $V$  is roughly the cube of the coherence length.

The crux of the problem, of course, is that the desired operating temperatures of the low- and high-temperature superconductors are so very different, and temperature enters *exponentially* in the Boltzmann factor. By the same token, however, even a small increase in  $U$  can enormously reduce the creep rate. One of the key goals, then, is to engineer pins that are extended in one or two dimensions so that their increased volume can make  $U$  bigger, without, however, inducing granularity or decreasing the pin density too much.

We must continue to investigate the fluxoid and pinning structure of high-temperature superconductors. This field has been particularly active recently, and I refer the reader to recent reviews by Michael Tinkham,<sup>16</sup> Archie Campbell<sup>17</sup> and Helmut Brandt.<sup>18</sup> Much of this work, however, ignores the pinning structure of the material, essentially because there is no consensus on what mechanism is responsible for the strong pinning. Understanding the interaction volume is essential if we are to manipulate  $U$ , because the critical field is set by the critical temperature.

There is no reason as yet to believe that we cannot usefully increase the pinning activation energy. This seems to be particularly evident in the experiments of M. Murakami and his colleagues at ISTEC in Tokyo.<sup>19</sup> They have been very successful at strengthening the flux pinning of melt-processed YBCO by introducing progressively smaller insulating Y<sub>2</sub>BaCuO<sub>5</sub> particles as pinning sites. The particles, no larger than 0.1  $\mu$ m, are still large by fluxoid diameter standards. Yet the ISTEC group has



already succeeded in raising  $J_c$  to  $10^5$  amp/cm<sup>2</sup> at 77 K, pushing the irreversibility line to higher fields and reducing the flux-creep rate. That is very encouraging.

## High- $T_c$ technology

A very recent study by the US Department of Energy and the Electric Power Research Institute<sup>20</sup> offers a detailed survey of the potential applications of high-temperature superconductors once  $J_{ct}$  reaches  $10^5$  amp/cm<sup>2</sup>. The survey predicts extensive markets for high-temperature superconductors in electric motors, power electronics, transportation, heat pumps, electromagnetic pumps and materials production. These applications offer the long-term prospect of reducing our total energy consumption by perhaps 3%.

Optimism about the near-term advance towards such applications has been greatly strengthened by the development of BSCCO conductor prototypes with high  $J_{ct}$ .<sup>21</sup> Figure 7 compares data from 2-2-2-3 BSCCO conductor prototypes fabricated by K. Sato's group at Sumitomo Electric with typical Nb-Ti and Nb<sub>3</sub>Sn conductors. At liquid-helium temperature the critical current of the new material exceeds  $10^5$  amp/cm<sup>2</sup> in a 25-tesla field, clearly besting the Nb-based superconductors in *their* temperature regime. These results are obtained on tapes with a high degree of crystallographic alignment, produced by repeated cycles of sintering and mechanical deformation.

Several groups have also made multifilament conductors, but their transport properties are not yet as good. Small filaments offer electromagnetic stability. What may be of even greater importance is their resistance to fracture. In Sumitomo's "1296" multifilament wires, degradation of critical current does not become significant until the filament strain reaches 1 or 2%. That is consistent with the experience gained from Nb<sub>3</sub>Sn. Many of the early difficulties encountered with Nb<sub>3</sub>Sn conductors in tape form disappeared when multifilament wires became available.

These are important issues because there is a sizable market waiting for laboratory-scale high-temperature superconducting magnets of various kinds. At one extreme would be very-high-field magnets, stronger than any Nb-Ti or Nb<sub>3</sub>Sn magnet. The present record is 20 tesla for powered magnets and about 15 tesla for persistent current nmr magnets. BSCCO superconductors have the potential to function in fields exceeding 20 tesla.

A second advantage of BSCCO materials is that their critical currents vary little with temperature in the range 4–20 K. This suggests an extensive market for magnets that can be cooled by cryocoolers without requiring immersion in liquid helium. Such cryocoolers work very comfortably in the range 10–20 K without Joule-Thompson expansion valves. The ability to cool superconducting magnets with refrigerators instead of liquid helium would, almost overnight, generate an enormous replacement market for laboratory magnets. Sato's Sumitomo team have already constructed a small BSCCO wire solenoid that generates 0.9 tesla at 4.2 K and 0.1 tesla at 77 K. It seems likely that we will soon see commercial superconducting magnets with cryocoolers.

At liquid *nitrogen* temperatures, the best results for BSCCO have not yet reached  $10^5$  amp/cm<sup>2</sup>. The maximum critical currents<sup>21</sup> at 77 K are about  $5 \times 10^4$  amp/cm<sup>2</sup> at zero field and  $1 \times 10^4$  amp/cm<sup>2</sup> at 1 T. Such values are very sensitive to the defining criteria for  $J_{ct}$ , the exact orientation of the crystallographic axes, the applied magnetic field and many other factors yet unknown. There is much concern that the strongly anisotropic BSCCO and TBCCO compounds cannot maintain strong flux pinning at temperatures above 30 K because of strong

flux creep and fluxoid lattice melting.

Such issues are the subject of extensive debate.<sup>16–18</sup> But we should remember that these bismuth and thallium materials are very complex; their phase relationships are not understood and their defect populations are mostly unknown. Thus, general conclusions about the long-term potential of the BSCCO materials at 77 K are not yet justified. At the same time, the much lower anisotropy of the 1-2-3 superconductors and their better flux-creep properties at present justify, for many, a continued push to understand and defeat the weak-link problem posed by the grain boundaries in the 1-2-3 compounds.

Those who have been striving to make high-field magnets with high-temperature superconductors have gone through an initial period of great euphoria (1987–88) followed by an interlude of some gloom (1988–89). But 1989 gave us the breakthrough to high transport critical currents, and the subsequent developments make us confident that some of the high hopes of the early days will be realized. There is still tremendous scientific interest in high-temperature superconductivity, and the materials problems are slowly being understood and controlled. All this progress within just five years of that innocent-sounding paper by Bednorz and Müller is surely extraordinary and very promising.

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