

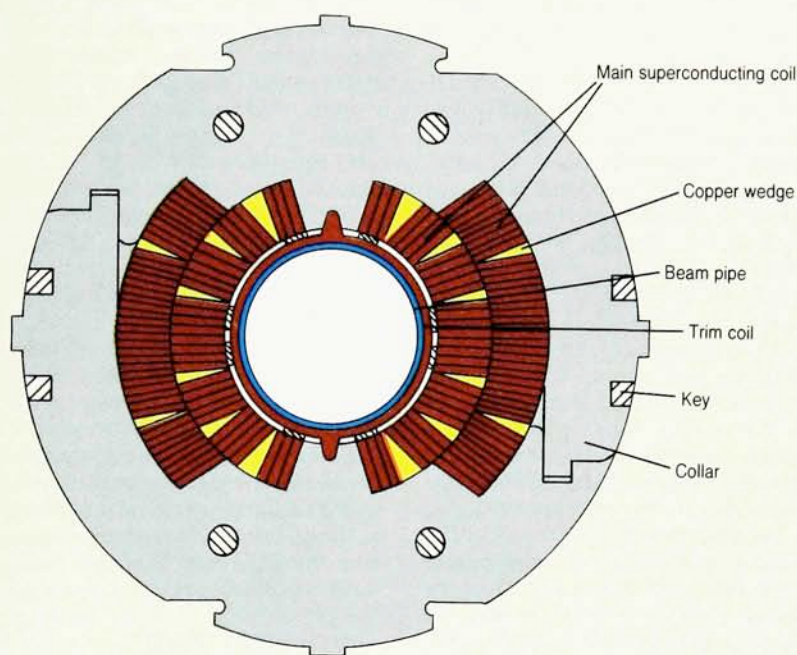
SUPER COLLIDER MAGNET PROGRAM PUSHES TOWARD PROTOTYPE

The most expensive component of the proposed multi-billion-dollar Superconducting Super Collider is the double ring of nearly 8000 17-meter-long superconducting bending magnets required to hold its countercirculating beams of 20-TeV protons in their 52-mile course. Thus the magnet program will soon undergo particular scrutiny as Congress begins to consider the President's request for \$363 million in fiscal 1989 for first-year SSC construction and continuing R&D. Some parts of the magnet program, such as the development of the superconducting cable, the cryogenic system and the achievement of good dipole-field quality, have been extremely successful.

But a satisfactory prototype bending magnet is not yet in hand, as the SSC Central Design Group had reason to hope when it selected a magnet design of proven track record in September 1985—a time when funding projections were more sanguine. Similar superconducting magnets of the same basic “cos ϑ ” design have given five years of excellent service at the Fermilab Tevatron, and a more recent cos ϑ design will soon be in full production for the HERA proton-electron collider under construction in Hamburg. The SSC magnet team was therefore surprised last year to encounter vexing difficulties in scaling up to 17 meters from shorter test models that have performed extremely well. Although such unanticipated technical problems are inevitable in an R&D effort, these troubles came upon a program already strained by spartan and uncertain funding and complicated by geographic dispersal over three principal laboratories—Brookhaven, Fermilab and the Lawrence Berkeley Lab.

The third of November was a particularly bleak day: The fourth of the initial series of full-length test magnets suffered a severe short circuit, rupturing the beam pipe that runs along its axis. After completing a painstaking autopsy on this failed magnet, the Central Design Group,

which directs the SSC program from its offices at the University of California, Berkeley, reported in February that the short circuit was not directly related to the principal problem plaguing the first four full-length test magnets, namely the occurrence of too many premature quenches (losses of superconducting current) before the 17-m magnets can be run up to full field. The autopsy supported the presumption that these excessive “training quenches” are caused by irreversible, inelastic motion in the magnet coil under the enormous Lorentz forces pulling at its ends.



Collared coil of an SSC magnet, in transverse cross section. Approximate cos ϑ distribution of current-carrying cables running along the 4-cm-diameter beam pipe yields a good vertical dipole field over most of the pipe. (The angle ϑ is zero on the horizontal axis of this drawing.) Fine field correction is provided by the additional trim coil surrounding the beam pipe and by the insulated copper wedges that refine cable placement. Keys inserted during collaring hold a group of laminar collars together and maintain compression on coils.

“The disassembly was a unique learning experience,” recalls John Peoples, who had taken over as head of the CDG magnet division in October upon the retirement of his predecessor, Victor Karpenko. “For the first time we could get a good look inside one of the long magnets after a series of quenches.” The magnet team is now planning to test eight or nine additional full-length magnets by September. These magnets will all be minor variants of the basic design set three years ago, differing primarily in the treatment of the longitudinal expansion of the coil when the

magnet is energized. Some magnets will constrain the coil more tightly to minimize its motion, and others will let it expand freely and elastically. All magnets will be extensively fitted out with diagnostic instrumentation. The CDG expects to learn enough from these tests to settle on the final coil-constraint scheme by this fall.

Division of responsibility

The production and testing of the full-length R&D magnets is a continent-spanning enterprise. Lawrence Berkeley Laboratory and an industrial firm prepare the superconducting cable from industrially fabricated strands. At Brookhaven the cable is wound into 17-meter-long coils, which are then shaped, collared and yoked around the beam pipe. The sealed magnet is then shipped to Fermilab for installation into its cryogenic housing and testing at liquid helium temperatures. The SSC magnet work at Brookhaven avails itself of facilities left idle in 1983 when the Isabelle collider, then under construction at Brookhaven, was canceled.

Making good use of the expertise and facilities available at the three labs "is a very good way to run a magnet research and development program," suggests Alvin Tollestrup, who played a major role in developing the Tevatron bending magnets. "But I'm not sure it's been ideal for producing a prototype." The mandate of the Central Design Group, headed by Maury Tigner (on leave from Cornell), is a temporary one. Ultimately the Department of Energy must select a general contractor for the SSC project. The contractor would then appoint a permanent SSC director. There is a perception that the CDG was for some time hampered by lack of full authority over the SSC funding at the three principal labs. "They could neither threaten nor cajole," as one well-informed observer puts it. Furthermore, the SSC work has inevitably had to contend for resources with competing long-range responsibilities of the host laboratories.

Several observers have commented that the CDG's coordination of the far-flung SSC research and development effort is now much improved. Last year, for example, Brookhaven created a separate division for the SSC magnet work to avoid any possible conflict of interest with the laboratory's own superconducting magnet program for its proposed Relativistic Heavy Ion Collider. Peoples, who was associate head of Fermilab's accelerator division when he was asked to take over the CDG magnet program, is given much of the credit for the

improved coordination. "Despite the organizational and financial obstacles that plague us," says Tigner, "we are making good progress, thanks to the skill and devotion of our colleagues across the country."

The funding for the first four years of SSC R&D has remained at about \$20 million per year, although the budget for the current year was originally planned to be more like \$60 million. With more money, the CDG could produce test magnets at a faster pace, examining alternative design options in parallel. The turnaround time for testing new ideas with full-length magnets nowadays is a burdensome seven months. It now appears that the CDG may get only part of the modest \$25 million funding upon which it has been counting for the SSC magnet program in fiscal year 1988. (See story on page 55.) Last month House and Senate subcommittees refused a request by DOE to fund from other sources the roughly \$8 million required for SSC site selection; hence money for this purpose would have to come out of this \$25 million. DOE has recently postponed the selection of the "preferred site" for the accelerator to November.

Though one might have wished that the magnet program, with more adequate funding, would be further along by now, the consensus appears to be that the CDG is on the right path to a satisfactory SSC magnet.

The magnet design

The SSC design calls for the bending magnets to reach a magnetic field of 6.6 tesla at 4.35 K, with the current distribution varying azimuthally around the beam pipe approximately like $\cos \theta$ to produce a vertical dipole field. (See the figure on page 17.) The superconducting cables, running parallel to the beam pipe, are concentrated around the horizontal midplane. The cable strands are made of filaments of niobium-titanium alloy embedded in a copper matrix. Tigner describes Nb-Ti as a "marvelously ductile" superconducting material with a very high critical current. The SSC magnet group, working with metallurgists at the University of Wisconsin and industrial firms, has made such significant advances in alloy production and cable fabrication that the superconductor will have an unprecedented critical-current density of 2750 A/mm², and a filament thickness of only 5 microns to reduce the persistent currents that distort the field just after beam injection, before the magnets are at full strength.

Teams at Brookhaven and at Law-

rence Berkeley Laboratory, under the direction of the CDG, have built a number of short test models, 1 to 4.5 meters long. The success of these short magnets in reaching and exceeding their 6.6-T design field intensity engendered confidence that the full-length magnets would perform equally well. Given these accomplishments and the good results with the Tevatron and HERA magnets, no great difficulty was foreseen in scaling up the length of the SSC test magnets from 4.5 to 17 meters.

But the 6.6-T SSC bending magnets are almost twice as long as their 9-meter, 5-T HERA cousins and three times as long as the 4-T Tevatron magnets. Furthermore, the 4-cm-diameter SSC beam pipe is unprecedentedly narrow, and the current density is uniquely high. These "aggressive" specifications, as Tigner describes them, were chosen for reasons of economy. Every additional millimeter of beam-pipe diameter adds about \$10 million to the SSC cost; and it's significantly cheaper to build and install 8000 17-m magnets than it is to use twice as many magnets half as long. The stronger the bending magnet field, of course, the smaller is the circumference of the accelerator ring one requires to store 20-TeV protons. But with stronger magnetic fields the coils are subjected to stronger Lorentz forces, which scale as the square of the field strength.

By last September it was clear that the good behavior of the short test magnets would not scale effortlessly. The long magnets were found to require excessive "training." If one increases the current in a superconducting magnet, it will eventually quench—becoming a normal ohmic conductor—when the current density and field reach critical values that ideally depend only on the temperature and the composition of the superconductor. But many superconducting magnets require training—repeated premature, subcritical quenches—before they can gradually be brought up to full field. With today's high-quality superconducting materials, most quenches are caused by small heat-generating movements of the cable or its individual strands as the Lorentz force increases. Successive quenches typically occur at higher and higher currents as the conductor settles into its final resting place. Ideally, such teething behavior is unnecessary. The Tevatron and HERA magnets have required almost no training. Slow training not only retards the installation of large numbers of magnets; it may also indicate the presence of problems that



Superconducting coil end of a full-length SSC test magnet at Brookhaven National Laboratory is visible in this photo because the last few feet of laminar collar and surrounding laminar yoke have not yet covered the inner and outer upper coils. Where they make their U turns at the coil end, the superconducting cables experience enormous longitudinal Lorentz forces tending to stretch the 17-meter-long coil. The SSC magnet program is investigating various ways of preventing these forces from causing premature quenches. When the yoke and outer skin are complete, the magnets are installed in their cryostats at Fermilab and tested at liquid helium temperatures. (Photo courtesy of Brookhaven.)

could affect magnet reliability.

The SSC magnet program had successfully produced 4.5-m magnets that required little or no training. But the first four long magnets tested last summer and fall were a different story. The first two long magnets quenched repeatedly at about 85% of the design critical current, and the quench current fluctuated from one quench to the next with little evidence of training. The third and fourth magnets behaved less erratically, but they still required about a dozen quenches before approaching the design current. (See the figure on page 20.) These two magnets had simple U-shaped cable turns at the two ends of the magnet coils (see photo above) in place of the flared "dog bone" ends of the two earlier models.

Autopsy of a magnet

Matters came to a head on 3 November, when the fourth magnet, dubbed "Z" in the arcane nomenclature of the magnet program, suffered a destructive short circuit to ground on the cryogenic test stand at Fermilab. The magnet had trained fairly normally, reaching 98% of its ideal current limit by the ninth quench. During quench 13, the instrumentation showed that some current was flowing to ground, and testing was suspended. Recognizing that the insulation had been damaged, a panel of

experts at Fermilab decided to take steps to minimize the voltage to ground and continue testing, in order to learn as much as possible from this magnet. As they increased the current toward the next quench, the final destructive ground short occurred, rupturing the beam pipe. In response, the CDG set up a committee headed by Roger Coombes (CDG) to disassemble the magnet back at Brookhaven, not only to ascertain the cause of the short circuit but also to exploit this unique chance to learn about the cause of the excessive training quenches.

The Z magnet short does not appear to have stemmed directly from the same factors that caused the slow training, but rather from a number of adjustments made to this particular magnet. The Coombes committee report places primary blame for the short circuit on excess pressure caused by too much insulating material in the Z magnet ends. The extra insulation had been wrapped around the shaping pieces that guide the coils as they make their semicircular turns at the ends. Even before the Z magnet was completed, this problem had been identified and corrected in the next full-length test magnet.

The extra insulation could not be easily removed from the Z magnet, because it had already been assembled. Just when the magnet was ready for shipping to Fermilab, how-

ever, testing on shorter magnets revealed that certain modifications could produce improvements in performance dramatic enough to warrant opening the already sealed Z magnet. Therefore the CDG decided to open both ends of the Z magnet, primarily to fill the small voids near the ends of the magnet coils with alumina-loaded epoxy to provide additional strength. While the magnet was open, the magnet team compensated for the extra insulation by reducing the size of the shaping pieces at both ends. After the magnet was resealed, several minor shorts occurred at one end. This end *only* was reopened again to fix the suspected problem. The subsequent short that destroyed the Z magnet occurred in the opposite end, which had not been reopened a second time because it had given no trouble. An additional problem that may have contributed to the final ground short was an improperly installed piece of insulation. The first reopening of the magnet to fill both ends with epoxy may itself have caused some serious perturbations. Peoples likens this to the trauma of open-heart surgery.

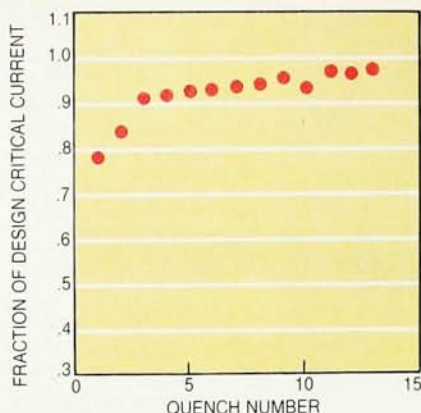
What did the disassembly of the destroyed Z magnet tell us about the chronic quenches plaguing the long magnets? Even before the autopsy, there was evidence that the magnet coil was expanding irreversibly in the longitudinal direction. With each

succeeding quench a strain gauge on one of the magnet end plates registered a further distension. The collared coil, incompletely constrained by the end plates and by friction against the surrounding yoke, was ratcheting up to greater and greater length with each quench, first in steps of about 5 mil, and then in smaller steps, up to a total accumulated distension of 25 mil, corresponding to a force of 7500 lbs pulling at each end. It was not altogether clear whether the expansions were the cause or the consequence of the quenches.

This longitudinal expansion, which occurs as a jerky, stick-and-slip motion of the laminar array of collars brushing past the laminar yoke, generates heat that can initiate quenches by raising the superconductor locally above its critical temperature. The enormous unspent mechanical energy stored in the Z magnet was dramatically evident during the autopsy. When the coil was lifted out of its bed, it expanded longitudinally by a full quarter inch, ten times the expansion permitted by the end plates and collaring system. Such an accumulation of stress is not unlike that along a tectonic fault line, relieving itself in fits and starts.

All magnet coils seek to expand under their own Lorentz forces. But the coil geometry of dipole bending magnets makes them much more difficult to constrain than the simple solenoids commonly employed in spectrometer detectors. Superconducting high-field dipoles are particularly demanding because the Lorentz force on the cables is so strong, and very small inelastic conductor movements in response to these enormous stresses can generate quenches. The collars surrounding the coils of the SSC dipole magnets constrain them against the transverse Lorentz forces. The collars are in turn enclosed by a laminar ferromagnetic yoke. (See the photo on page 19.)

The end regions, where the superconducting cables must make their U turns without obstructing the beam pipe, present the most difficult constraint problem. In the main body of the magnet the Lorentz force on the conductor is transverse, and thus easily constrained by the collars. In the ends, however, the force exerts a longitudinal outward pull of 15 000 lbs, which the collars alone cannot counter; end plates provide additional constraint. The resulting longitudinal expansion of the coil at the ends is augmented by the transverse squeezing of the coil by the collar in the body of the magnet. The longitudinal strain (Δ/l) of the magnet assembly is



Training curve for the Z magnet, which was destroyed by a short. During each training cycle the current is raised until the magnet quenches, that is, becomes normally conducting. With successive quenches the current approaches its critical design current. Trouble began with this magnet at the tenth quench, and the destructive short circuit occurred at the start of the 14th training cycle.

essentially independent of its length. Consequently the absolute expansion at the ends is proportional to the length, and thus much more severe for the 17-m magnets than for their shorter predecessors.

The end regions have been the main focus of attention. Most (although not all) of the quenches in the Z magnet and the other long magnets originated near the ends. One can localize the quenches within about 1 meter by measuring the travel time of the pressure waves the quenches induce in the liquid helium coolant. The long magnets completed after the Z failure are extensively instrumented with voltage taps that should pinpoint end quenches to within a few centimeters, thus pointing a finger directly at the most troublesome components. Furthermore, these magnets have been provided with improved insulation.

Ideally one can prevent longitudinal coil motion from causing quenches either by constraining the coil so completely that it hardly moves at all or by letting it expand freely and elastically. "Infinite friction or no friction at all," says Peoples. "Our eventual solution will approximate one of these ideals." The first four long magnets approximated neither. The interface between the laminar collar array and the surrounding yoke array had an ill-defined frictional force that made for abrupt, inelastic expansion of the collared coil. The autopsy showed that some of the collars near the magnet ends had in fact been tilted.

The test program for the next six magnets, which are already in var-

ious stages of completion, will explore a number of options for handling the coil expansion. The very next magnet is similar to the Z magnet, but far more heavily instrumented to provide diagnostic information. Two of the subsequent magnets will feature stronger end plates, and shims between the collar and yoke to prevent relative longitudinal motion. Two others will have thick end plates and aluminum rather than stainless steel collars. These more pliant collars will expand transversely with the coils until they fit tightly against the yoke. This is, in fact, similar to what the HERA magnets do at high currents. The aluminum collars are also less likely to damage the coil insulation. A sixth magnet will be designed to slide freely on tabs in a low-friction channel, unrestrained by end plates. This solution approximates the design of the Tevatron bending magnets. Once these SSC magnets and two to three more (to be built if the funds hold out) have been tested, which should be by the end of the summer, Peoples expects the CDG will have enough information to finalize the coil-constraint design.

Peoples and his CDG colleagues are confident that they will soon have a satisfactory 17-m prototype. But there is a relatively straightforward fallback position. One could build the SSC with twice as many 8.5-m bending magnets, at some penalty in cost. James Decker, acting director of the Office of Energy Research at DOE, feels that the SSC contingency budget could handle the increase in cost from such a scheme. Tigner has no plans now to build shorter magnets. "I see no reason to believe that we will not have a 17-m magnet of essentially the original design," he told us. In Congressional testimony last month, Decker pointed out that one must expect to encounter hurdles in a development program that accepts the challenge of choosing magnet parameters that go well beyond what's already been accomplished.

The next steps

Unlike the Tevatron, whose magnets were all built at Fermilab, the SSC is regarded by DOE as too massive an undertaking to build its own magnets in a laboratory setting. The CDG would like to initiate the first step of a three-phase industrialization program by the end of this fiscal year. In the first phase, as Peoples envisions it, representatives from industry would be present at the labs to acquire the specific knowledge they would require to design and manufacture the magnets in quantity. In the

second phase, to begin next year, contracts would be awarded for the fabrication of production tooling and fixtures and for the manufacture of a modest number of production magnets to demonstrate the capabilities of this special tooling. Full-scale magnet production is scheduled to be under way by 1992.

Full involvement of industry awaits the naming of a general contractor and a permanent director. The present directorship is something of an orphan. The CDG has only a temporary home and no permanent parent organization. Many of its staff are on leave from their home institutions. Its foster parent for now is the Universities Research Association, a consortium of 66 educational institutions, which DOE asked to oversee the SSC activities. Because the URA also oversees Fermilab, it has avoided possible conflicts of interest by creating an entirely autonomous CDG board of overseers, headed by Boyce McDaniel of Cornell.

Before it selects a general contractor for the SSC project, Decker told us, DOE is awaiting a positive sign of support for the SSC from Congress, such as approval of a reasonable portion of the proposed FY 1989 budget. Upon receipt of such a signal, DOE plans to expedite the selection of a general contractor so that one might be named within the following 6 months. Although organizations from the academic community have run all major accelerator programs to date, there is both speculation and apprehension that DOE, pressed by Congress, might select an industrial firm to head the SSC.

George Trilling (Berkeley) expresses "almost unlimited admiration" for the CDG's accomplishment in coordinating an enormous collaborative effort with limited means and authority. The failure of the Z magnet, he points out, is the sort of thing one has to expect in a research and development program. "It is, after all, something very different from a design flaw that has found its way into a production phase." Superconducting magnet specialist William Hassenzhl (LBL, currently on leave at DOE) stresses that "we learned more from the disassembly of that one shorted magnet than from testing half a dozen unopened magnets."

The failure of the Z magnet did, however, underscore the importance of quality control. Brookhaven will soon install new coil fabrication equipment that should reduce coil thickness tolerances from 5 mils to a more satisfactory 2 mils. The short circuit also pointed up the need for

more exacting documentation to accompany the test magnets on their journey from one laboratory to the next.

The ghost of Isabelle lurks in the background of this magnet story. One is unavoidably reminded of the problems with first-generation superconducting magnets at Brookhaven that contributed to the cancellation of the Isabelle collider in 1983. Since then, however, the high-energy accelerator community has gained much experience and achieved heartening successes with superconducting magnets. For example, Brookhaven has

developed very successful 4-T superconducting cos θ prototype magnets for the Relativistic Heavy Ion Collider, which the lab proposes to install in the vacant 4-km-circumference Isabelle tunnel. Erich Willen, who heads the SSC magnet program at Brookhaven, points out that the lab now has a much more experienced team working on the SSC magnets than one could have assembled in the pioneering days of Isabelle, "and the team is addressing problems in a timely way."

—BARBARA GOSS LEVI AND
BERTRAM SCHWARZSCHILD

THE T_c TO BEAT IS 125 K

After a long year the superconductivity community worldwide is confident at last about the synthesis of stable superconducting materials with critical temperatures even higher than 90 K. There have been a series of reports since this January on the synthesis and studies of three, or perhaps four, new oxide superconductors with critical temperatures above 80 K. These discoveries strengthen the hope that the "revolution," begun only two years ago by Georg Bednorz and Alex Müller (IBM Zurich Research Laboratory at Rüschlikon, Switzerland) with the discovery of superconductivity up to 30 K in $\text{La}_{2-x}(\text{Ba})_x\text{CuO}_{4-y}$, is still young and may engender many interesting surprises.

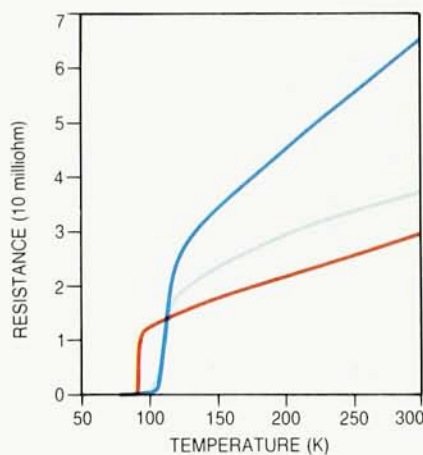
Since the discovery in March 1987 of superconductivity up to 90 K in $\text{RBa}_2\text{Cu}_3\text{O}_{7-y}$, where R is a rare earth element, many laboratories have reported seeing anomalies—in resistivity and Josephson effect measurements, for example—indicating that the critical temperature for superconductivity may be higher than 200 K in some materials. Some of these anomalies turned out to be irreproducible; others that were reproducible either arose from spurious effects or were subtle hints whose secret nature did not fully reveal, for they did not lead to the isolation or synthesis of a new superconductor with T_c even near 90 K. The discoveries announced since January 1988 bear little resemblance to the subtle hints or anomalies that earlier made headlines in national dailies and superconductivity newsletters, and they were all confirmed by several laboratories a few days after they were announced.

Like the 90-K and 40-K superconductors discovered during the past two years, the oxide superconductors reported in January and February also contain copper—in two-dimen-

sional layers of CuO_2 —and alkaline earth metals. But instead of the rare earth element of the 90-K superconductor, or of lanthanum in the 40-K superconductor, the new superconductors contain bismuth or thallium. Preliminary studies also show that, like the earlier oxide superconductors, the average valence of copper in the new superconductors is between 2 and 3.

Bi-Ca-Sr-Cu-O

On 22 January the *Japan Economic News* reported that a group led by



Resistance of two multiphase samples composed nominally of $\text{Tl}_{0.5}\text{Ca}_{1.5}\text{BaCu}_3\text{O}_{8.5+y}$ (dark blue) and $\text{Tl}_{1.862}\text{CaBaCu}_3\text{O}_{7.8+y}$ (light blue), compared with that of a 90-K $\text{EuBa}_2\text{Cu}_3\text{O}_{7-y}$ superconductor (red). Resistance of both the thallium samples vanishes above 100 K. All three curves show a linear dependence on temperature before the onset of superconductivity, which already suggests that the new thallium superconductors are similar to the ones discovered last year. (Adapted from a figure provided by Zhengzhi Sheng and Allen Hermann, University of Arkansas, Fayetteville.)