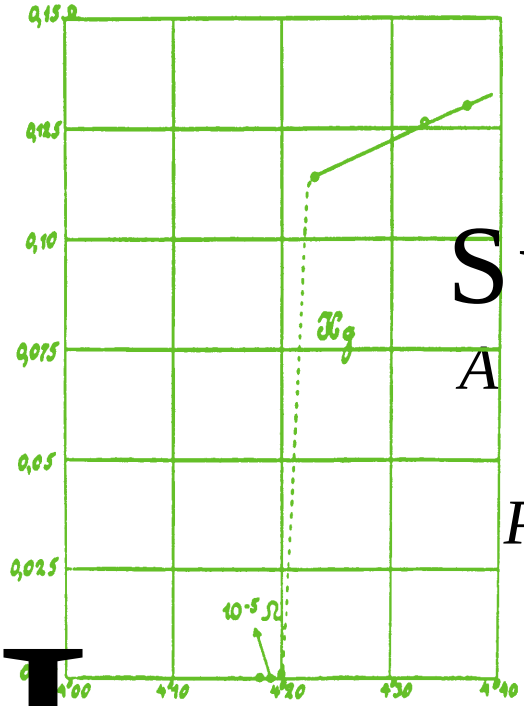


Superconductivity

A Macroscopic Quantum Phenomenon

by JOHN CLARKE

IN THE NETHERLANDS IN 1911, about a decade after the discovery of quantum theory but more than a decade before the introduction of quantum mechanics, Heike Kamerlingh Onnes discovered superconductivity. This discovery came three years after he succeeded in liquefying helium, thus acquiring the refrigeration technique necessary to reach temperatures of a few degrees above absolute zero. The key feature of a superconductor is that it can carry an electrical current forever with no decay. The microscopic origin of superconductivity proved to be elusive, however, and it was not until 1957, after 30 years of quantum mechanics, that John Bardeen, Leon Cooper, and Robert Schrieffer elucidated their famous theory of superconductivity which held that the loss of electrical resistance was the result of electron "pairing." (See photograph on next page.)

In a normal metal, electrical currents are carried by electrons which are scattered, giving rise to resistance. Since electrons each carry a negative electric charge, they repel each other. In a superconductor, on the other hand, there is an attractive force between electrons of opposite momentum and opposite spin that overcomes this repulsion, enabling them to form pairs. These pairs are able to move through the material effectively without being scattered, and thus carry a supercurrent with no energy loss. Each pair can be described by a quantum mechanical "wave function." The remarkable property of the superconductor is that all electron pairs have

Drawing of Heike Kamerlingh Onnes made in 1922 by his nephew, Harm Kamerlingh Onnes. (Courtesy Kamerlingh Onnes Laboratory, Leiden University)

Upper left: Plot made by Kamerlingh Onnes of resistance (in ohms) versus temperature (in kelvin) for a sample of mercury. The sharp drop in resistance at about 4.2 K as the temperature was lowered marked the first observation of superconductivity.

John Bardeen, Leon Cooper, and Robert Schrieffer (left to right) at the Nobel Prize ceremony in 1972. (Courtesy Emilio Segrè Visual Archives)

the same wave function, thus forming a macroscopic quantum state with a phase coherence extending throughout the material.

There are two types of superconductors. In 1957, Alexei Abrikosov showed that above a certain threshold magnetic field, type II superconductors admit field in the form of vortices. Each vortex contains one quantum of magnetic flux (product of magnetic field and area). Because supercurrents can flow around the vortices, these materials remain superconducting to vastly higher magnetic fields than their type I counterparts. Type II materials are the enabling technology for high-field magnets.

Shortly afterwards came a succession of events that heralded the age of superconducting electronics. In 1960, Ivar Giaever discovered the tunneling of electrons through an insulating barrier separating two thin superconducting films. If the insulator is sufficiently thin, electrons will "tunnel" through it. Building on this notion, in 1962 Brian Josephson predicted that electron pairs could tunnel through a barrier between two superconductors, giving the junction weak superconducting properties. Sure enough, this quantum mechanical phenomenon, called the "Josephson effect," was observed shortly afterwards at Bell Telephone Laboratories.

Between the two tunneling discoveries, in 1961, there occurred another discovery that was to have profound implications: flux quantization. Because supercurrents are lossless, they can flow indefinitely around a superconducting loop, thereby maintaining a permanent magnetic field. This is the principle of the high-field magnet. However, the magnetic flux threading the ring cannot take arbitrary values, but instead is quantized in units of the flux quantum. The superconductor consequently mimics familiar quantum effects in atoms but does so on a macroscopic scale.

For most of the century, superconductivity was a phenomenon of liquid helium temperatures; a compound of niobium and germanium had the highest transition temperature, about 23 K. In 1986, however, Alex Mueller and Georg Bednorz staggered the physics world with their announcement of superconductivity at 30 K in a layered oxide of the elements lanthanum, calcium, copper, and oxygen. Their amazing breakthrough unleashed a worldwide race to discover materials with higher critical temperatures. Shortly afterwards, the discovery of superconductivity in a compound of yttrium, barium, copper, and oxygen at 90 K ushered in the new age of superconductors for which liquid nitrogen, boiling at 77 K, could be used as the cryogen. Today the highest transition temperature, in a mercury-based oxide, is about 133 K.

Why do these new materials have such high transition temperatures? Amazingly, some 13 years after their discovery, nobody knows! While it is clear that hole pairs carry the supercurrent, it is unclear what glues them together. The nature of the pairing mechanism in high-temperature superconductors remains one of the great physics challenges of the new millennium.

LARGE-SCALE APPLICATIONS

Copper-clad wire made from an alloy of niobium and titanium is the conductor of choice for magnetic fields up to 10 tesla. Magnets made of this wire are widely used in experiments ranging from high-field nuclear magnetic resonance to the study of how electrons behave in the presence of extremely high magnetic fields. The largest scale applications of superconducting wire, however, are in magnets for particle accelerators and magnetic resonance imaging (MRI). Other prototype applications include cables for power transmission, large inductors for energy storage, power generators and electric motors, magnetically levitated trains, and bearings for energy-storing flywheels. Higher magnetic fields can be achieved with other niobium alloys involving tin or aluminum, but these materials are brittle and require special handling. Much progress has been made with multifilamentary wires consisting of the high temperature superconductor bismuth-strontium-calcium-copper-oxide sheathed in silver. Such wire is now available in lengths of several hundred meters and has been used in demonstrations such as electric motors and power transmission. At 4.2 K this wire remains superconducting to higher magnetic fields than the niobium alloys, so that it can be used as an insert coil to boost the magnetic field produced by low-temperature magnets.

The world's most powerful particle accelerators rely on magnets wound with superconducting cables. This cable contains 20–40 niobium-titanium wires in parallel, each containing 5,000–10,000 filaments capable of carrying 10,000 amperes (see Judy Jackson's article "Down to the Wire" in the Spring 1993 issue).

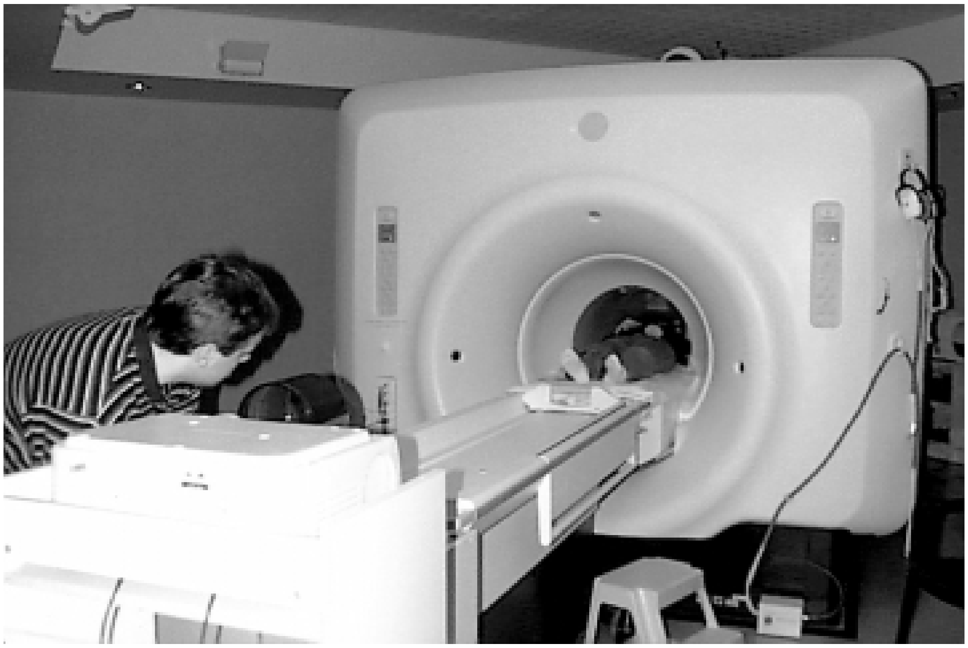
The first superconducting accelerator to be built was the Tevatron at Fermi National Accelerator Laboratory in 1984. This 1 TeV machine

Tevatron superconducting dipole magnets and correction assembly in Fermilab's Main Ring tunnel. (Courtesy Fermi National Accelerator Laboratory) incorporates 800 superconducting magnets. Other superconducting accelerators include HERA at the Deutsches Elektronen Synchrotron in Germany, the Relativistic Heavy Ion Collider nearing completion at Brookhaven National Laboratory in New York, and the Large Hadron Collider (LHC) which is being built in the tunnel of the existing Large Electron Positron ring at CERN in Switzerland. The LHC, scheduled for completion in 2005, is designed for 14 TeV collision energy and, with quadrupole and corrector magnets, will involve more than 8,000 superconducting magnets. The dipole field is 8.4 tesla. The ill-fated Superconducting Super Collider was designed for 40 TeV and was to have involved 4,000 superconducting dipole magnets. At the other end of the size and energy scale is Helios 1, a 0.7 GeV synchrotron X-ray source for lithography operating at IBM. From these examples, it becomes clear that the demanding requirements of accelerators have been a major driving force behind the development of superconducting magnets. Their crucial advantage is that they dissipate very little power compared with conventional magnets.

Millions of people around the world have been surrounded by a superconducting magnet while having a magnetic resonance image (MRI) taken of themselves. Thousands of MRI machines are in everyday use, each containing tens of kilometers of superconducting wire wound into a persistent-current solenoid. The magnet is cooled either by liquid helium or by a cryocooler. Once the current has been stored in the superconducting coil, the magnetic field is very stable, decaying by as little as a part per million in a year.

Conventional MRI relies on the fact that protons possess spin and thus a magnetic moment. In the MRI machine, a radiofrequency pulse of magnetic field induces protons in the patient to precess about the direction of the static magnetic field supplied by the superconduting magnet. For the workhorse machines with a field of 1.5 T, the precessional frequency, which is precisely proportional to the field, is about 64 MHz. These precessing magnetic moments induce a radiofrequency voltage in a receiver coil that is amplified and stored for subsequent analysis. If the magnetic field were uniform, all the protons would precess at the same frequency. The key to obtaining an image is the use of magnetic field gradients to define a “voxel,” a volume typically 3 mm across. One distinguishes structure by virtue of the fact that,

A 1.5 tesla MRI scanner at Stanford University for a functional neuroimaging study. The person in the foreground is adjusting a video projector used to present visual stimuli to the subject in the magnet. (Courtesy Anne Marie Sawyer-Glover, Lucas Center, Stanford University)



for example, fat and muscle and grey and white matter produce different signal strengths.

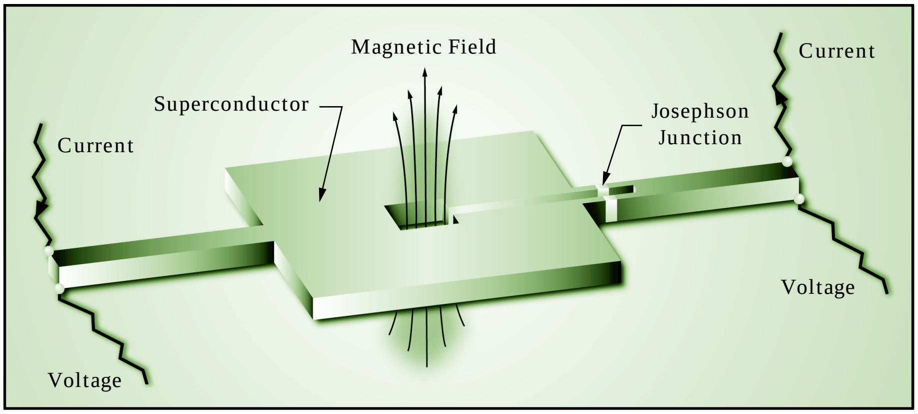
MRI has become a clinical tool of great importance and is used in a wide variety of modes. The development of functional magnetic resonant imaging enables one to locate some sites in the brain that are involved in body function or thought. During brain activity, there is a rapid, momentary increase in blood flow to a specific site, thereby increasing the local oxygen concentration. In turn, the presence of the oxygen modifies the local MRI signal relative to that of the surrounding tissue, enabling one to pinpoint the neural activity. Applications of this technique include mapping the brain and preoperative surgical planning.

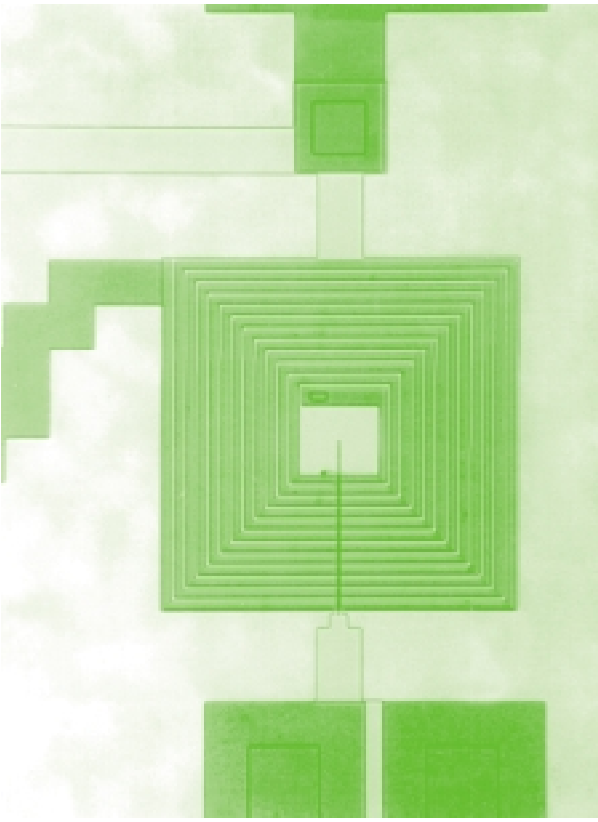
SMALL-SCALE APPLICATIONS

At the lower end of the size scale (less than a millimeter) are extremely sensitive devices used to measure magnetic fields. Called "SQUIDS" for superconducting quantum interference devices, they are the most sensitive type of detector known to science, and can turn a change in a magnetic field, something very hard to measure, into a change in voltage, something easy to measure. The dc SQUID consists of two junctions connected in parallel to form a superconducting loop. In the presence of an appropriate current, a voltage is developed across the junctions. If one changes the magnetic field threading the loop, this voltage oscillates back and forth with a period of one flux quantum. One detects a change in magnetic field by measuring the resulting change in voltage across the SQUID using conventional electronics. In essence, the SQUID is a flux-to-voltage transducer.

Squids are fabricated from thin films using photolithographic techniques to pattern them on a silicon wafer. In the usual design, they consist of a square washer of niobium containing a slit on either side of which is a tunnel junction. The upper electrodes of the junctions are connected to close the loop. A spiral niobium coil with typically 50 turns is deposited over the top of the washer, separated from it by an insulating layer. A current passed through the coil efficiently couples flux to the SQUID. A typical SQUID can detect one part per million of a flux quantum, and it is this remarkable sensitivity that makes possible a host of applications.

Generally, SQUIDs are coupled to auxiliary components, such as a superconducting loop connected to the input terminals of the coil to form a "flux transformer." When we apply a magnetic field to this loop, flux quantization induces a supercurrent in the transformer and hence a flux in the SQUID. The flux transformer functions as a sort of "hearing aid," enabling one to detect a



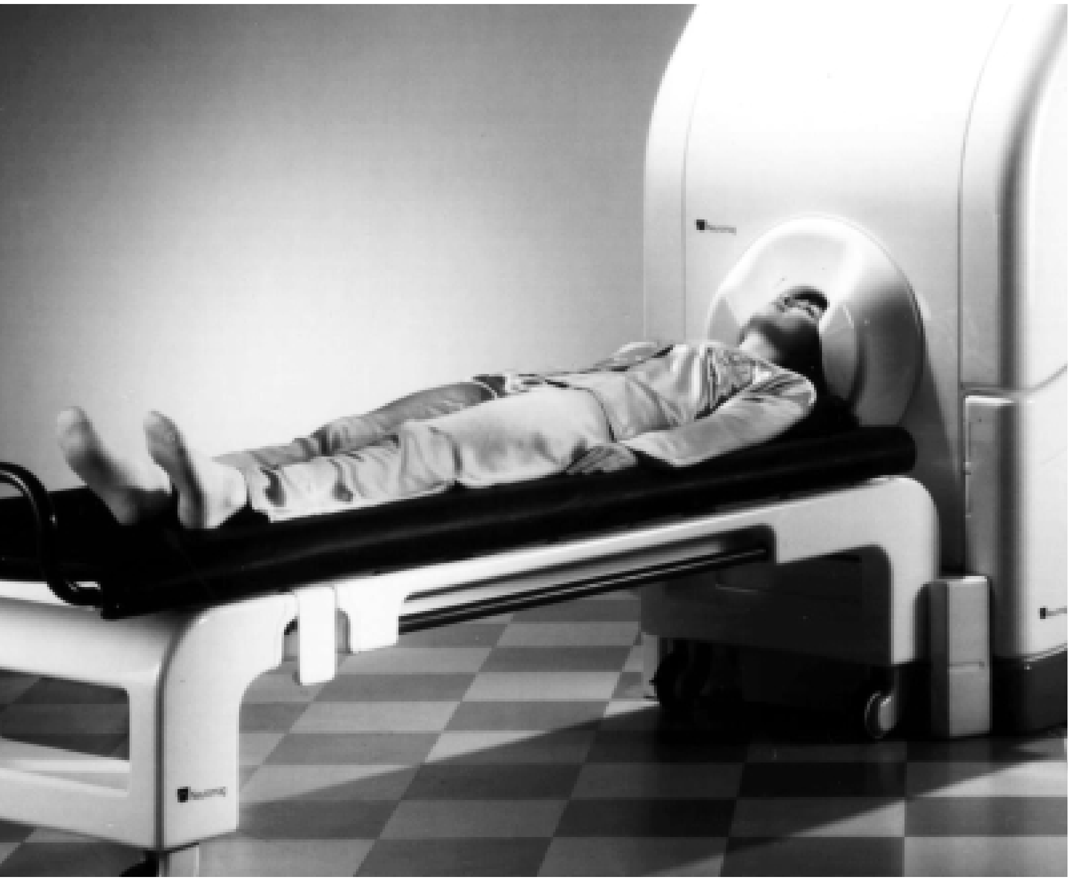


Top: A dc SQUID configuration showing two Josephson junctions connected in parallel. Bottom: A high transition temperature SQUID. The yttrium-barium-copper-oxide square washer is 0.5 mm across.

magnetic field as much as eleven orders of magnitude below that of the magnetic field of the earth. If, instead, we connect a resistance in series with the SQUID coil, we create a voltmeter that readily achieves a voltage noise six orders of magnitude below that of semiconductor amplifiers.

It is likely that most SQUIDs ever made are used for studies of the human brain. Commercially available systems contain as many as 306 sensors arranged in a helmet containing liquid helium that fits around the back, top, and sides of the patient's skull. This completely non-invasive technique enables one to detect the tiny magnetic fields produced by thousands of neurons firing in concert. Although the fields outside the head are quite large by SQUID standards, they are minuscule compared with environmental magnetic noise—cars, elevators, television stations. To eliminate these noise sources, the patient is usually enclosed in a magnetically-shielded room. In addition, the flux transformers are generally configured as spatial gradiometers that discriminate against distant noise sources in favor of nearby signal sources. Computer processing of the signals from the array of SQUIDs enables one to locate the source to within 2–3 mm.

System containing 306 SQUIDs for the detection of signals from the human brain. The liquid helium that cools the devices needs to be replenished only once a week. The system can be rotated so as to examine seated patients. The magnetic images are displayed on a workstation (not shown). (Courtesy 4D-Neuroimaging)



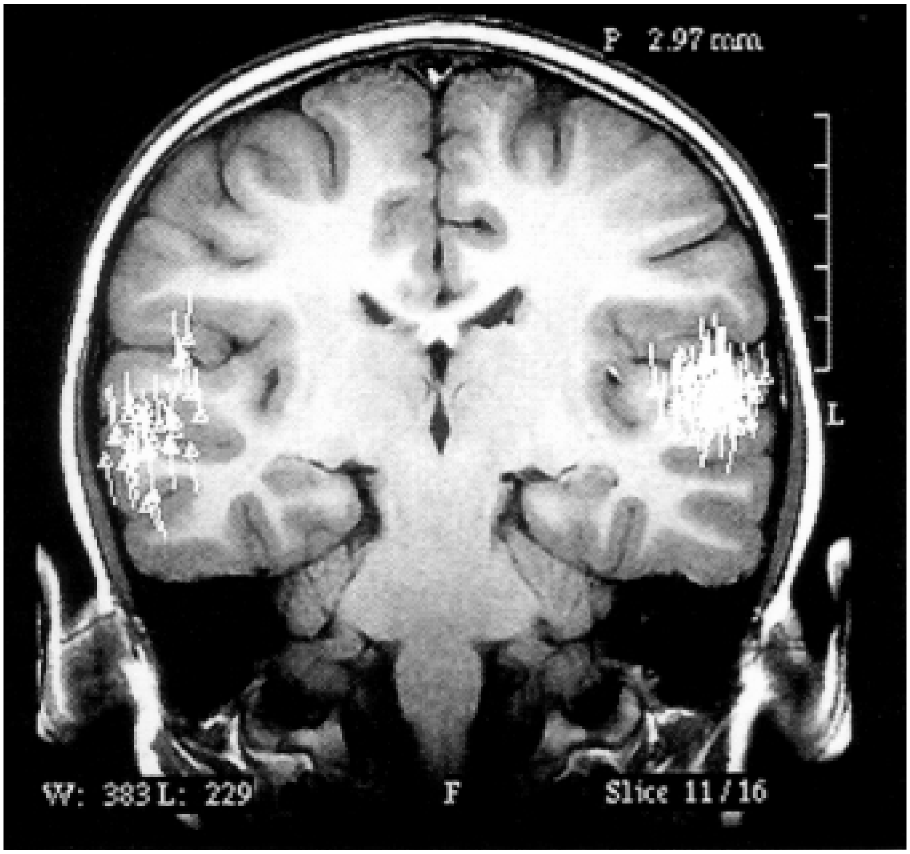
There are two broad classes of signal: stimulated, the brain's response to an external stimulus; and spontaneous, self-generated by the brain. An example of the first is pre-surgical screening of brain tumors. By applying stimuli, one can map out the brain function in the vicinity of the tumor, thereby enabling the surgeon to choose the least damaging path to remove it. An example of spontaneous signals is their use to identify the location of epileptic foci. The fast temporal response of the SQUID, a few milliseconds, enables one to demonstrate that some patients have two foci, one of which stimulates the other. By locating the epileptic focus non-invasively before surgery, one can make an informed decision about the type of treatment. Research is also under way on other disorders, including Alzheimer's and Parkinson's diseases, and recovery from stroke.

There are many other applications of low-temperature SQUIDs, ranging from the ultra-sensitive detection of nuclear magnetic resonance to searches for magnetic monopoles and studies of the reversal of the Earth's magnetic field in ancient times. A recent example of the SQUID's versatility is the proposal to use it as a high-frequency amplifier in an upgraded axion detector at Lawrence Livermore National Laboratory. The axion is a candidate particle for the cold dark matter that constitutes a large fraction of the mass of the Universe (see article by Leslie Rosenberg and Karl van Bibber in the Fall 1997 *Beam Line*, Vol. 27, No. 3).

With the advent of high-temperature superconductivity, many groups around the world chose the SQUID to develop their thin-film technology. Yttrium-barium-copper-oxygen dc SQUIDs operating in liquid nitrogen achieve a magnetic field sensitivity within a factor of 3–5 of their liquid-helium cooled cousins. High-temperature SQUIDs find novel applications in which the potential economy and convenience of cooling with liquid nitrogen or a cryocooler are strong incentives. Much effort has been expended to develop them for magnetocardiography (MCG) in an unshielded environment. The magnetic signal from the heart is easily detected by a SQUID in a shielded enclosure. However, to reduce the system cost and to make MCG more broadly available, it is essential to eliminate the shielded room. This challenge can be met by taking spatial derivatives, often with a combination of hardware and software, to reduce external interference. What advantages does MCG offer over conventional electrocardiography? One potentially important application is the detection of ischemia (localized tissue anemia); another is to locate the site of an arrhythmia. Although extensive clinical trials would be required to demonstrate its efficacy, MCG is entirely non-invasive and may be cheaper and faster than current techniques.

Ground-based and airborne high temperature SQUIDs have been used successfully in geophysical surveying trials. In Germany, high temperature SQUIDs are used to examine commercial aircraft wheels for possible flaws produced by the stress and heat generated at landing.

The advantage of the higher operating temperature of high temperature SQUIDs is exemplified



Localization of sources of magnetic spikes in a five-year-old patient with Landau-Kleffner syndrome (LKS). The sources, shown as arrows at left and right, are superimposed on a magnetic resonance image of the brain. LKS is caused by epileptic activity in regions of the brain responsible for understanding language and results in a loss of language capabilities in otherwise normal children. (Courtesy 4D-Neuroimaging and Frank Morrell, M.D., Rush-Presbyterian-St. Luke's Medical Center) in "SQUID microscopes," in which the device, mounted in vacuum just below a thin window, can be brought very close to samples at room temperature and pressure. Such microscopes are used to detect flaws in semiconductor chips and to monitor the gyrations of magnetotactic bacteria, which contain a tiny magnet for navigational purposes.

Although SQUIDs dominate the small-scale arena, other devices are important. Most national standards laboratories around the world use the ac Josephson effect to maintain the standard volt. Superconducting detectors are revolutionizing submillimeter and far infrared astronomy. Mixers involving a low temperature superconductor-insulator-superconductor (SIS) tunnel junction provide unrivaled sensitivity to narrow-band signals, for example, those produced by rotational transitions of molecules in interstellar space. Roughly 100 SIS mixers are operational on ground-based radio telescopes, and a radio-telescope array planned for Chile will require about 1000 such mixers. When one requires broadband detectors—for example, for the detection of the cosmic background radiation—the low temperature superconducting-transition-edge bolometer is the device of choice in the submillimeter range. The bolometer absorbs incident radiation, and the resulting rise in its temperature is detected by the change in resistance of a superconductor at its transition; this change is read out by a SQUID. Arrays of 1,000 or even 10,000 such bolometers are contemplated for satellite-based telescopes for rapid mapping of the cosmos—not only in the far infrared but also for X-ray astronomy. Superconducting detectors are poised to play a crucial role in radio and X-ray astronomy.

A rapidly growing number of cellular base stations use multipole high temperature filters on their receivers, yielding sharper bandwidth definition and lower noise than conventional filters. This technology enables the provider to pack more channels into a given frequency allocation in urban environments and to extend the distance between rural base stations.

THE NEXT MILLENNIUM

The major fundamental questions are "Why are high temperature superconductors superconducting?" and "Can we achieve still higher temperature superconductors?" On the applications front, the development of a high temperature wire that can be manufactured cost effectively in sufficient lengths could revolutionize power generation, transmission, and utilization. On the small-scale end, superconducting detector arrays on satellites may yield new insights into the origins of our Universe. High temperature filters will provide rapid internet access from our cell phones. The combination of SQUID arrays and MRI will revolutionize our understanding of brain function. And perhaps a SQUID will even catch an axion.