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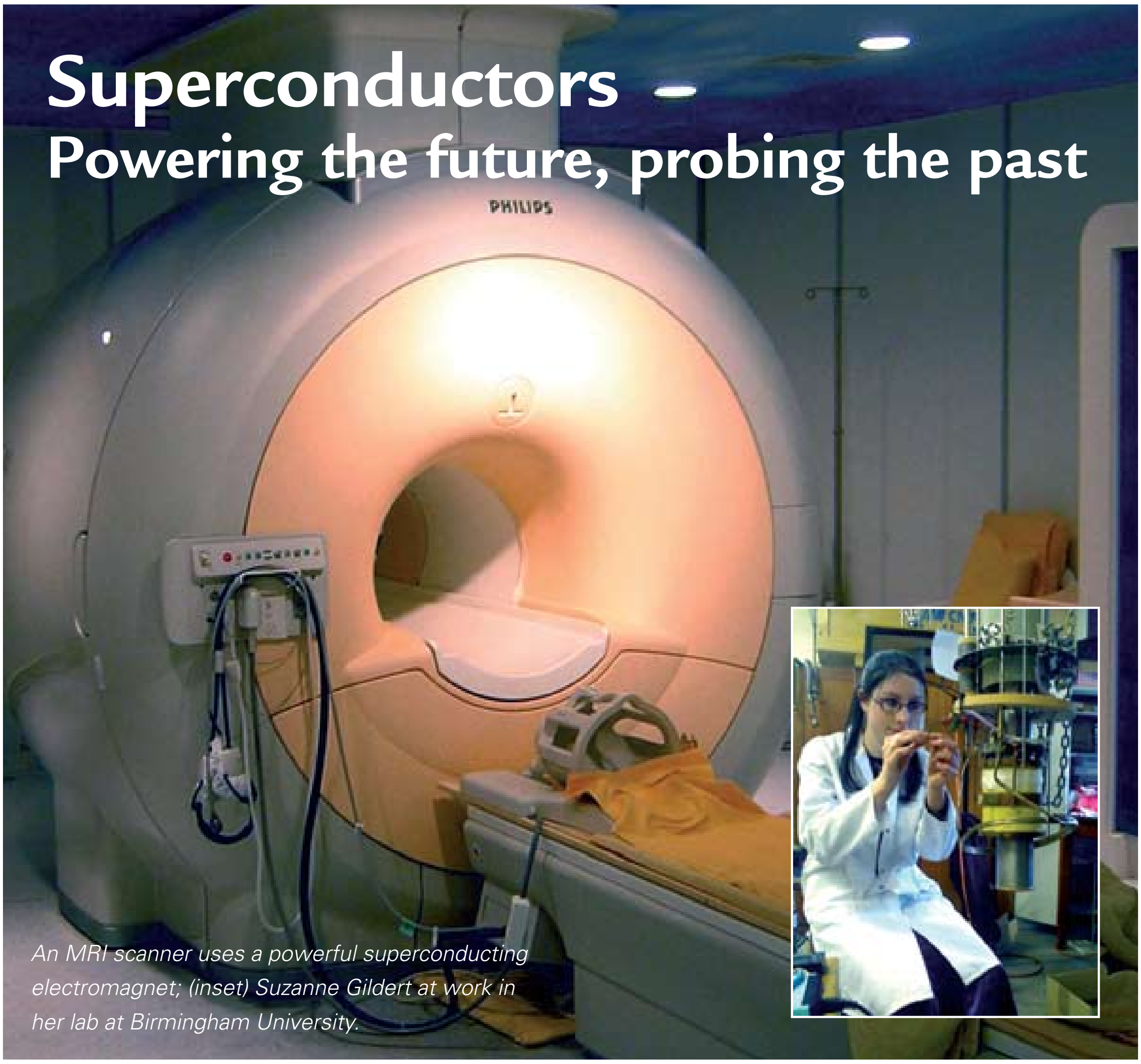
Superconductors – Powering the future, probing the past



An MRI scanner uses a powerful superconducting electromagnet; (inset) Suzanne Gildert at work in her lab at Birmingham University.

Key words

resistance

electrical conductor

current

electromagnet

What do the 1700 magnets at the Large Hadron Collider and power cables in Detroit have in common? The answer is both use amazing materials called superconductors - materials which, when cooled below a certain temperature, lose all their electrical resistance, and display some other remarkable physical properties. Tim Jackson and Suzanne Gildert of Birmingham University explain.

Cool Physics

Each superconductor works at a different temperature. Commonly-used superconductors include metals such as tin, lead and niobium and alloys such as niobium-tin. These materials do not become superconducting until they are cooled close to the temperature of liquid helium (4 K, which is -269°C). Some ceramic compounds such as yttrium-barium-copper-oxide, commonly known as YBCO, become superconducting at higher temperatures, around 100 degrees above absolute zero. For this reason they are known as 'high temperature superconductors' and only require cooling by liquid nitrogen, which is much less expensive. Hot and cold are relative terms – see Box 1.

Box 1 Low temperatures

Nitrogen boils at -196°C. It can be produced from nitrogen in the air and also stored and used cheaply and easily. Helium gas is much more scarce. It boils at -269°C and is expensive to produce, store and use.

While -196°C sounds cold to us, in absolute terms it is hot. Hotter still are the temperatures we describe as 'cold'. The lowest winter temperature ever recorded in Britain is -27°C. The lowest recorded temperature on earth is -89°C, in Antarctica.

Superconductors rely on the unusual and somewhat 'spooky' properties of quantum physics, which describes how the world operates on the very small scale. In the microscopic 'quantum' world, an electron behaves both as a wave and as a particle, and can be in two places at the same time. In a metal these effects are never normally seen, as the electrons are jiggling around too much. However, electrons inside a superconductor are much better behaved and work together, allowing them to flow smoothly, and transport current without generating any heat – see Box 2.

Superconductors also react to magnetic fields in an interesting way. When a magnet is placed close to a superconductor, the magnet will levitate. In addition, by placing two pieces of superconductor close together, you can also make a transistor-like 'switch', which has many applications in electronic circuits. The rather unconventional electrical and magnetic properties of superconductors mean that they can be used in cutting edge technologies.

A small magnet levitates above a superconducting electromagnet. Liquid nitrogen is used to cool the superconductor.

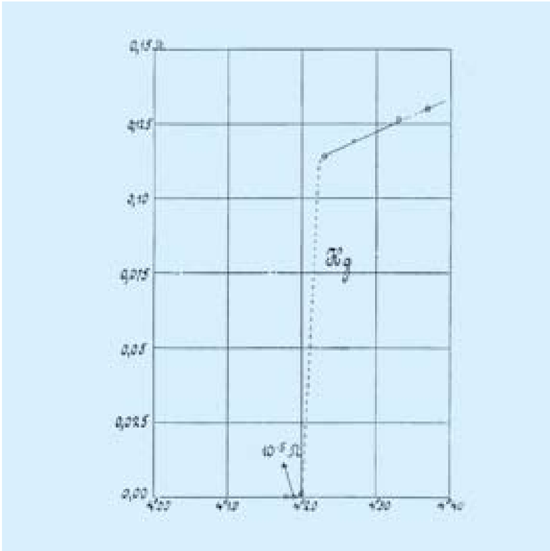
Box 2
How superconductors work

Electrical current is defined as the rate of flow of electric charge. In a metal it is negatively-charged electrons that flow to make a current. However the electrons cannot move totally freely through the metal. They collide with impurity atoms and with the vibrating atoms of the metal. This is what gives a metal its electrical resistance, and it has the effect of dissipating electrical energy as heat.

In a superconductor cooled to below its transition temperature, the electrons can move without any impediment and so an electrical current can be carried without generation of heat. The processes which enable this to happen are delicate and are sufficiently strong in only a few materials. Too large a current though, or too large a magnetic field around the superconductor, and superconductivity breaks down resulting in the material becoming resistive again. The weakness of the interaction led many to believe superconductivity would never be possible at temperatures as 'high' as the boiling point of liquid nitrogen. This is the reason why 76 years elapsed between the discovery of superconductivity in mercury and its discovery in YBCO. In fact, elucidation of the mechanism which allows superconductivity at such temperatures is one of the greatest challenges in modern physics.

Discovery

The first observation of superconductivity was made in 1911, in measurements of the resistance of mercury. At first the scientists thought that something had gone wrong with the experiment when they observed the resistance of the metal suddenly and unexpectedly drop to zero!

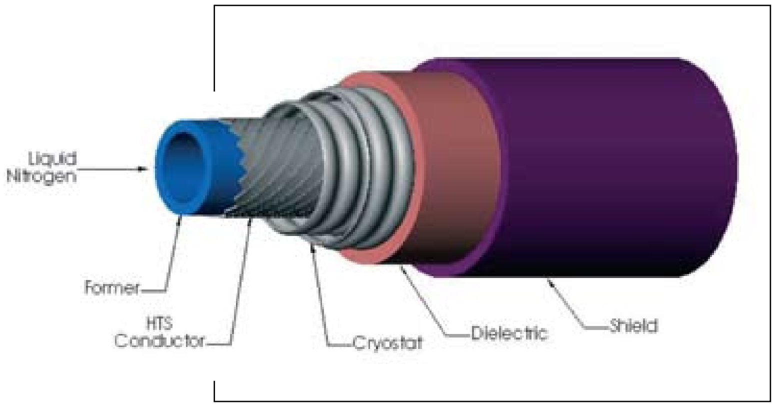


The graph obtained by Kamerlingh Onnes, the discoverer of superconductivity, when he and his student Gilles Holst investigated the resistance of mercury cooled below 4 K using liquid helium.

After they had checked the result, the phenomenon was found to occur in many different materials. Niobium-tin and niobium-titanium alloys were found to be superconducting in the 1960s. Being metals, they can be relatively easily drawn into wires. However the need for cooling with liquid helium and the cost of the metals made it too expensive for large scale commercial applications. The ceramic superconductors were discovered in the late 1980s. Ceramics are much less ductile than metals – making reliable and practical wires has been challenging engineers and scientist for the last twenty years. However, meeting the challenge is worth the effort : Cheaper and easier cooling with liquid nitrogen or liquid hydrogen makes large-scale applications of superconductors much more feasible.

The ultimate energy saver

At first sight the most obvious applications of superconductors would seem to be in power transmission. Electric power is transmitted over long distances at high AC voltages (in the UK, at 440 kV or 275 kV) and low current to reduce the losses associated with cable resistance. The voltage is stepped down by transformers to 110 kV for local distribution and further to 230 V for the domestic supply. About 8 % of the power is lost along the way. Superconductors don't just save energy – they lose literally NO power at all along the way. High temperature superconducting cables can efficiently carry three times the current of conventional cables. In fact, if the familiar electrical cables which span the country were replaced with superconducting ones, the benefit to the environment over the years would be substantial.



The construction of a superconducting cable. HTS is the high-temperature superconducting material; the cryostat contains liquid nitrogen to cool the superconductor below its transition temperature.

So why don't we replace the old power cables? Replacing the whole system with superconducting cables straight away would simply not be economical. However, as we look to the future it is clear that the electricity distribution system that has served us well for thirty years will need to adapt to increasing demand and changing sources of power. In densely populated cities there is little space for adding new cabling.

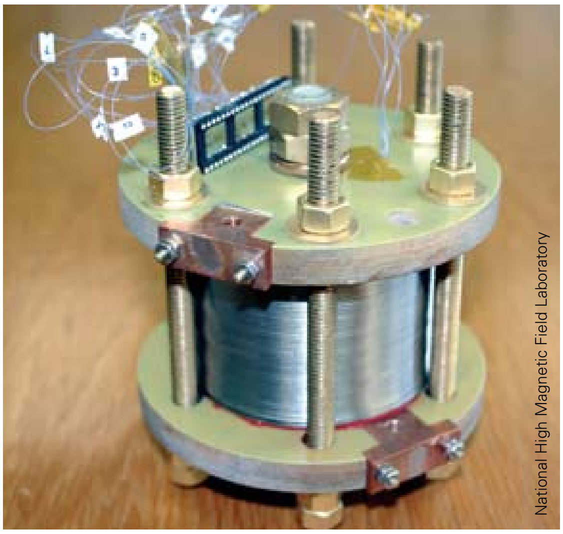
Trials of cables cooled with liquid nitrogen in the USA, China, Japan and Denmark are developing the technology and showing promising results. There are still challenges to overcome but the technology is improving all the time. Soon, superconducting cables may be coming to a home near you.

Superconducting cables may be even better adapted to heavy industrial factories, which consume vast amounts of power. By operating the cables at lower voltages, they may be safer too. Prof Bartek Glowacki, at the University of Cambridge, has described this engineering with superconductors as 'where quantum physics blends with heavy industry'.

Superconductors are everywhere!

Because superconductors can carry large currents, they are ideal for making magnets. By making the superconducting material into a wire, coils can be formed. The resulting electromagnets can generate fields of up to 40 tesla, 1000 times stronger than a fridge magnet!

The Large Hadron Collider at CERN, designed to test theories of particle physics and the nature of the Universe, uses over 1700 electromagnets made of niobium-tin superconducting wire to steer the beams of protons which will be smashed together. Neither the strongest magnets (such as neodymium iron boron) nor electromagnets made from copper wire are capable of providing the magnetic fields required. 96 tonnes of liquid helium are needed to keep the magnets cooled to just 1.9 degrees above absolute zero.



The world's most powerful electromagnet – its wires are made of the superconducting ceramic known as YBCO. It produces a field one million times the strength of the Earth's field.

One of the 1700 superconducting electromagnets of the Large Hadron Collider at CERN being lowered into position.

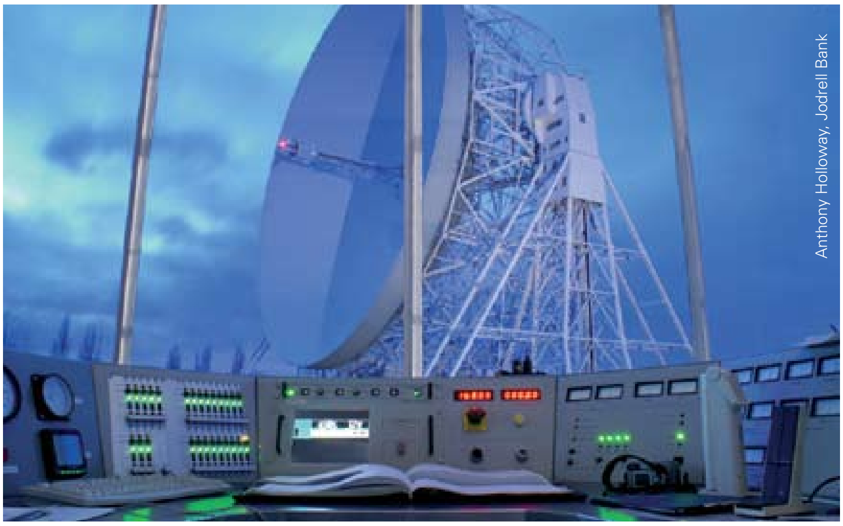
The cost and difficulties of engineering with liquid helium, and the cost of the niobium-tin wire, is one reason why superconducting power cables were never feasible until after the discovery of ceramic superconductors in 1986. Low temperature superconductors are however widely and successfully used in magnets in magnetic resonance imaging (MRI) systems. They are also used in the world's fastest train, in Japan. This train uses a combination of superconducting and conventional electromagnets to levitate 10 cm above its track. With this electromagnetic suspension system eradicating rolling resistance it can travel at speeds up to 500 km/h. Levitating trains might one day compete with short haul air travel, offering similar journey times e.g. one hour between Edinburgh and London without the air pollution associated with take-off and landing. The smooth ride would also be good news for nervous flyers.

Superconductors crop up in the most unusual places. Some engineers are considering all electric aeroplanes, powered by hydrogen and thus free of carbon emissions in take-off, flight and landing. Hydrogen would be burned to rotate turbines that would drive superconducting electricity generators. These turbines would be much lighter than conventional jet engines. Hydrogen is cleaner and cheaper than current jet fuels.

Trains of the experimental Japanese Yamanashi rail link use superconducting electromagnets to levitate them above the track.

Forward into the past

Another way in which superconductors may be used to probe the physics of the Universe is in radio astronomy. Under the direction of Prof Mike Lancaster, our research group at Birmingham University is leading the design of superconducting circuits fitted to the first stage of electronics behind the dishes of radio telescopes. These telescopes are used to study radiation from distant astronomical objects such as pulsars. Such studies have provided sensitive tests of Einstein's theory of General Relativity and may yield insights into the evolution of the Universe from the Big Bang to the present day. The radio signals which we use on Earth to communicate with each other mask the faint signals. The superconducting circuits act like



The radio telescope at Jodrell Bank observatory, seen from inside the control room. Superconducting circuits will help to separate out the radio signals coming from space from man-made electromagnetic pollution.

the bouncer at the door of a nightclub: the signals on the astronomers' list are allowed through, the radio signals are excluded.

The future

In the future, superconductors may even find their way into your iPod, mobile phone and laptop. New types of transistors are being developed which use superconductors instead of conventional silicon chips. The quantum mechanical properties of superconducting materials will allow engineers to make smaller, faster, and much more energy efficient components - an entirely new generation of processors.

A more exotic application of superconductors – quantum computing – may be on the horizon too. A quantum computer would use the uncertainty of the quantum world to greatly speed up calculations. Because the electrons in a superconductor can be in two places at the same time, they can also be used to perform two calculations in parallel. Current interest in superconducting electronics is driven by the (conflicting!) desires for greater security and privacy in communications and for the ability to crack any code. For us, this research, which draws together physicists, materials scientists, electronic engineers and computer scientists, is one of the most exciting aspects of physics today.

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Look here!

There's much more about superconductors and their uses at: *www.superconductors.org*

Dr Suzanne Gildert's blog is at: *physicsandcake.wordpress.com/*

An introduction to quantum computing: *www.cs.caltech.edu/~westside/quantum-intro.html*