Five of the best

Superconductivity may be a beautiful phenomenon, but materials that can conduct with zero resistance have not quite transformed the world in the way that many might have imagined. Presented here are the top five applications, ranked in terms of their impact on society today

Perhaps no other potential application of superconductivity has captured the public's imagination more than magnetically levitated (maglev) trains; you can even buy toy models of them. There have also been science-fiction-like maglev concepts that in principle would work, featuring curved tunnels through the Earth's mantle, whereby the train first falls on a levitated track, generating electricity as it does so for the trip back up. Indeed, the first patents on the basic concept date back to 1907 – four years before superconductivity was even discovered.

However, every maglev system ever built, apart from the Yamanashi test line in Japan, has used conventional technology involving ordinary (albeit powerful) iron-core electromagnets. Moreover, the top speed of the Yamanashi superconducting prototype is 581 km h^{-1}, which, despite being a world record for mass surface transportation, is only 6 km h^{-1} faster than the ordinary wheel-on-rail French TGV trains. The message is clear: faster surface transportation may be important, but superconductivity has not – and is unlikely to – play much of a role in that quest.

So if not maglev, then what have been the most significant applications of superconductivity in terms of their impact on society? This article lists a top five selected by Paul Michael Grant from W2AGZ Technologies in San Jose, California. Superconducting wires top the list, followed by magnets for medical imaging and for particle colliders in second and third, respectively, with superconducting motors in fourth and a unique dark-matter experiment in fifth. One other application of superconductors that has not quite made the cut involves using them in electromagnets or flywheels to store energy. Such superconducting magnetic-energy storage devices store energy in the magnetic field created by an electric current flowing in a superconducting coil. As almost all the energy can be recovered instantly, these devices are incredibly efficient and would be ideal for storing electricity in the home should we be forced to rely much more on renewable sources of power that are not always on tap.

But let's start with those wires…

And the winner is...

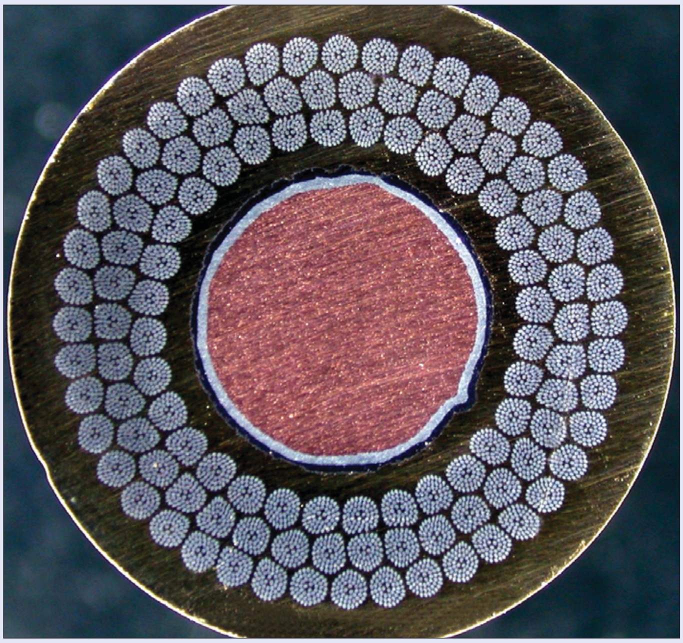
1 Wires and films

One thing is for sure: there would be no applications of superconductivity if physicists and materials scientists had not managed to develop – as they did in the 1970s – superconducting wires and films made from niobium–titanium and niobium–tin. These materials can carry high currents, even in the presence of strong magnetic fields, when cooled with liquid helium to a temperature below 4.2 K. They are generally packaged as bundles of wires in a matrix, allowing them to be sold both as wire filaments and as solid cores encased in copper. They can carry currents of up to 50 A while withstanding magnetic fields of 10 T.

Firms such as American Superconductor, SuperPower and Zenergy Power now also make high-temperature superconducting tape from yttrium–barium–copper-oxide (YBCO). It is just as robust as low-temperature niobium alloys and can be used for transmission power cables but using liquid nitrogen – not helium – as the cryogen. What is remarkable is that YBCO is a hard and brittle ceramic (like a teacup), yet it can be made in batches thousands of metres long. This is done by depositing a continuous film of it onto a specially prepared "textured substrate" base – typically a stainless-steel-like alloy coated with another layer of magnesium oxide or yttrium zirconia.

The resulting technology is truly a *tour de force*. Indeed, the "upper critical field" – the maximum field that YBCO tape can be subjected to and still superconduct – is so high at 4.2 K that it has never been, and probably cannot be, measured. These materials are ideal for use as superconducting power cables, which could carry electricity without any of the power losses that afflict conventional copper cables. (Note that superconductivity is only "perfect" for direct-current transmission; for alternating current there are always losses.)

The US in particular has ploughed much money into this field, largely through a 20-year research and development effort funded by the Department of Energy that ended in 2010. Its fruits are now on the shelf, waiting to be harvested by the utility industry and its suppliers. However, it is likely that upgrading and replacing conventional cables will not happen as fast as was once envisaged. Instead, it is likely to occur gradually through mega-projects, such as the "SuperGrid" concept, which envisages electricity from nuclear power stations carried along superconducting cables cooled by hydrogen that is produced by the power plant and that could also be used as a fuel (*Physics World* October 2009 pp37–39).



Supercon Inc

Slice of magic Cross-section through a niobium–tin cable.

Best of the rest

2 Medical imaging

A peace-time offshoot of the development of radar in the Second World War was the invention of nuclear magnetic resonance (NMR), which can determine the structure and composition of materials by studying how nuclei, such as hydrogen, with a non-zero spin absorb photons when bathed in a magnetic field. By the late 1960s, with the development of "tomographic" techniques that can build up 3D X-ray images of the human body from a series of individual 2D "slices", medical physicists realized that NMR could also be used to study the distribution of hydrogen nuclei in living tissue. By the late 1970s the first full-body magnetic resonance imaging (MRI) scanners had been developed, which required a constant and uniform magnetic field surrounding the body of about 1 T – something that is only easily practical using superconducting magnets.

MRI has since become perhaps the most widespread medical diagnostic tool and there is at least one such scanner in every major hospital around the world. An MRI solenoid typically has up to 100 km of niobium–titanium or niobium–tin wire made from individual wires, each several kilometres long, connected by special joints that let the current continue to flow without any losses. Most of these magnets use mechanical cryocoolers in place of liquid helium and thus operate continuously. One variant of MRI that is also becoming popular is "functional MRI" (fMRI) – a technique that needs twice the magnetic field of "standard" MRI machines (sometimes as high as 4 T). It is used to monitor motion in the human body in real time, such as how the flow of blood in the brain changes in response to particular neural activity.

A similar medical scanning technique uses superconducting quantum interference devices, or SQUIDs, held at liquid-helium temperature, to detect the tiny magnetic fields generated by the exceedingly small currents in the heart or brain. Known as magnetocardiography (when studying the heart) or magnetoencepholography (when studying the brain), it is non-invasive and does not require any equipment to be wired directly onto the body. Magnetocardiography, which can detect cardiac anomalies that escape routine electrocardiography, has already undergone numerous successful clinical trials in the US, Europe and China, although it is not yet widely used in hospitals.

We should not forget that MRI-scale superconducting magnets have also had a big impact on condensed-matter physics and materials science. Most universities and industrial laboratories have at least one "physical properties measurement system" that can make a variety of transport, magnetic, optical and microscopy measurements from room temperature to 1.2 K (and below) in fields of up to 16 T.


Photolibrary

Take a picture An MRI scanner uses small superconducting magnet coils to produce detailed images of any part of the body.


Maximilien Brice/CERN

Interconnected A welder works on the junction between two of the LHC's superconducting magnet systems, in the LHC tunnel.

3 High-energy physics

Although it might be considered esoteric and unrelated to general human welfare, it could be argued that no human endeavour surpasses the search for our origins. Every civilization on our planet has devoted a portion of its wealth to that quest – take the pyramids of Giza or Teotihuacan, for example – and today's large particle-physics labs are continuing that tradition. However, particle colliders would be nothing without the superconducting magnets that bend accelerate particles around in a circle. The Tevatron collider at Fermilab in the US, for example, has huge bending magnets carrying currents of 4000 A that produce magnetic fields of about 4.2 T when cooled with liquid helium, while those at the Large Hadron Collider (LHC) at CERN produce fields of roughly twice that strength at 1.9 K.

The Tevatron, which is due to close later this year, can generate centre-of-mass collision energies of 2 TeV, while the LHC can currently produce 7 TeV collisions, with 14 TeV as a longer-term target. Either facility could, in principle, spot the Higgs boson and thus complete the final piece of the Standard Model of particle physics, although the LHC, operating at higher energy and still so new, is more likely to do so.

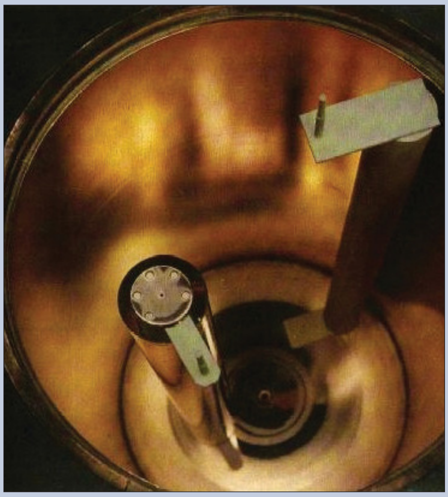
But what lies beyond the Standard Model? Many high-energy theorists suspect there may be a large energy gap before something "interesting" appears again, which might require collision energies of 100–200 TeV or more (i.e. 50–100 TeV per beam). Unfortunately, a machine that could generate these energies and that is no bigger than a conventional collider such as the LHC (i.e. with a circumference of about 27 km) would lose most of its beam energy in the form of synchrotron X-rays. (Such X-rays can, though, be extremely useful to characterize materials, which is why there are now 50 or so dedicated synchrotron radiation facilities around the world, most of which have superconducting magnets.)

Interestingly, however, Fermilab physicist Bill Foster, now a member of the US House of Representatives, and his colleagues have proposed revisiting an old idea by Robert Wilson, a veteran of the Manhattan Project and Fermilab's first director. It would involve simply saturating a 2 T iron magnet with a high-temperature superconducting cable cooled with liquid nitrogen and carrying a current of 75 000 A. The snag is that reaching energies of 50 TeV would require a ring with a circumference of about 500 km. Such a large project would be difficult to carry out in areas of significant population, but in principle would be possible to deploy in more remote areas. As ever, all it would take is money.

4 Rotating machinery

Superconducting materials have long been touted as having a bright future in motors and generators. The problem is that conventional motors are currently quite good at converting electrical power into rotational power – being up to 95% efficient for large 100 kW–1000 MW industrial devices. Replacing the rotating electromagnet (i.e. the rotor) in a motor with a superconducting material might increase the conversion by 2%, but this will hardly make much difference.

Nevertheless, in 1983 the Electric Power Research Institute (EPRI) in the US, working with Westinghouse Electric Company, successfully demonstrated a 300 MW electric generator using



ADMX

A peek inside The cavity at the centre of the Axion Dark Matter Experiment contains a neobium–titanium superconducting magnet.

niobium–titanium wire kept at 5 K. Similar efforts were carried out at the Massachusetts Institute of Technology, while in 1988 the Japanese government inaugurated the "Super-GM" project, which sought to provide superconducting generators to meet Japan's growing electricity needs. However, when the country's power demands failed to materialize, the project, despite having succeeded from a technical point of view, never got off the ground and was never deployed by Japan's electricity utilities.

The tangible advantage of using superconducting wires – whether of the low- or high-temperature variety – in rotating machines is that they significantly reduce the amount of iron required, which normally forms the core of conventional electromagnets. Removing the iron in this way makes the generator lighter, smaller and so more efficient. These advantages have been fully recognized for many years by the US military, which has a culture in which the effectiveness of a given technology outweighs the cost. However, despite several successful demonstrations of propulsion motors by the US Navy using low-temperature materials, it ultimately did not adopt them.

The winds are now shifting. The US Navy is on the verge of using high-temperature superconducting "degaussing" cables on all of its light, high-speed destroyer-class ships to shield them from being detected by enemy submarines. (These cables are simply loops that create a magnetic field, which cancels that from the iron components of the ship.) Moreover, high-temperature superconducting motors are also likely to be deployed as "outboard" units on US submarines and surface attack resources. If so, we are likely to see such devices "trickle down" to holiday cruise ships and commercial vessels. Finally, superconducting generators are also likely to find themselves used in wind turbines, greatly reducing the ecological impact of wind farms. In the far future, we might even see superconducting motors – and possibly magnetohydrodynamic pumps – used to transport water from wet to dry areas to adapt to the effects of global warming.

5 Dark matter

As *Physics World* readers will surely know, much of the mass in our galaxy, and others too, is missing, or at least we cannot "see" it. That is, astronomers have observed deviations in the rotational motion of galaxies that cannot be accounted for by ordinary matter that we can observe simply by using electromagnetic radiation. It turns out that about four-fifths of the matter in the universe is invisible "dark matter". (All matter, dark or otherwise, makes up about 27% of the mass–energy density of the universe, with the other 73% being "dark energy", but that is another story...) The exact nature of dark matter is, of course, still not clear, which means that finding out is one of the big challenges of physics and indeed a central question underlying our existence.

Dark matter is a field wrought by, or fraught with, considerable confusion and debate. Even the names of the particles that could form dark matter are bizarre – from MACHOs, RAMBOs and WIMPs to chameleons and axions, to name but a few. Where superconductivity fits in is in the search for axions, which are postulated to result from the assumed violation of charge–parity symmetry under strong coupling within the Standard Model. The idea is that when axions of a given mass–energy (in the μeV to meV range) enter a microwave cavity sited in a 5–7 T magnetic field from a liquid-helium-cooled superconducting solenoid, they will interact with the field and decay into photons. These photons can then be amplified and detected using SQUIDs operating at 2 K. The rationale for using SQUIDs is that they lower the noise level, and thus sensitivity, to as close to the ultimate limit set by Planck's constant as possible.

Such experiments are not science fiction but are already under way as part of the Axion Dark Matter Experiment (ADMX) collaboration, previously located at the Lawrence Livermore National Laboratory and now at the University of Washington in the US. The superconducting magnet at the heart of the device consists of niobium–titanium wire wrapped 37 700 times around the core, which has a bore of 60 cm. Although ADMX has not yet managed to detect any axions, we do know that, if they exist, they cannot have masses in the $3.3–3.53 \times 10^{-6}$ eV range. Detection of axions at any energy anywhere will surely earn someone a Nobel prize and tickets to Stockholm. Stay tuned.