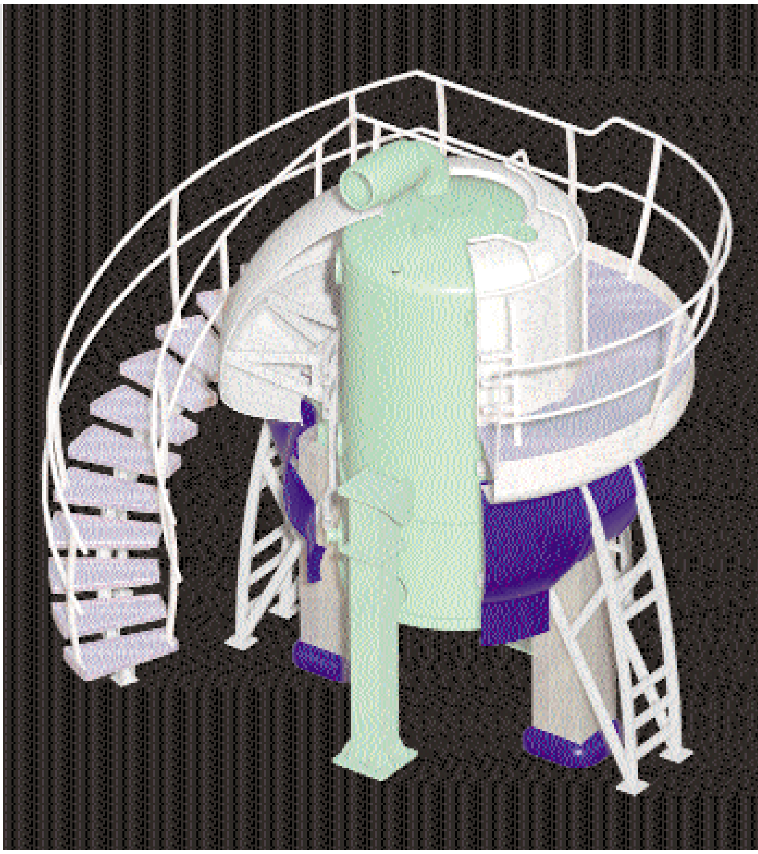
by Alan Street

Superconducting Magnets Get Bigger and Better

High-field superconducting (SC) magnets promise industry some enticing economic and analytic advantages over their more cumbersome cousins, the electromagnets. A staple of research laboratories, SC magnets first won wide recognition as the powerful tool that enabled magnetic resonance imaging (MRI), a medical diagnostic technique that greatly improved the ability to image organs inside the body. SC magnets moved more slowly into industrial settings, but the introduction two years ago of the first commercial 900-MHz devices has opened new areas in research and applications, and heralded the arrival of magnets exceeding 1 GHz.

A 900-MHz nuclear magnetic resonance device in place with its access platform (left) and a cutaway figure that shows all the elements of a similar 800-MHz device with its cryostat structure and superconducting magnet (right).



Because of superconductivity, SC magnets can carry large currents with no loss of energy. They also can provide a higher magnetic field with a smaller footprint and lower operating costs than permanent magnets or resistive electromagnets. However, building SC magnets requires solutions to complex problems, and the more powerful the device, the greater the obstacles that magnet manufacturers must overcome.

People have known about magnetism for thousands of years, although until around 1820, the only magnets available were naturally occurring rocks called lodestones (magnetite). The word magnetism arose from Magnesia in Asia Minor, where lodestones were first found. Total magnetic field strength was first measured in gauss (G), but most measurements are now given in the much larger units of tesla (1 T = 10^4 G). To put the strength of fields produced by SC magnets into perspective, Earth's relatively weak field averages 0.5 G, and a standard bar magnet produces a magnetic field strength of approximately 3,000 G (0.3 T) at its poles. A significant understanding of superconductivity and how to harness this phenomenon has emerged over the past 40 years from many laboratories, particularly in Europe, the United States, and Japan. And the end is not near.

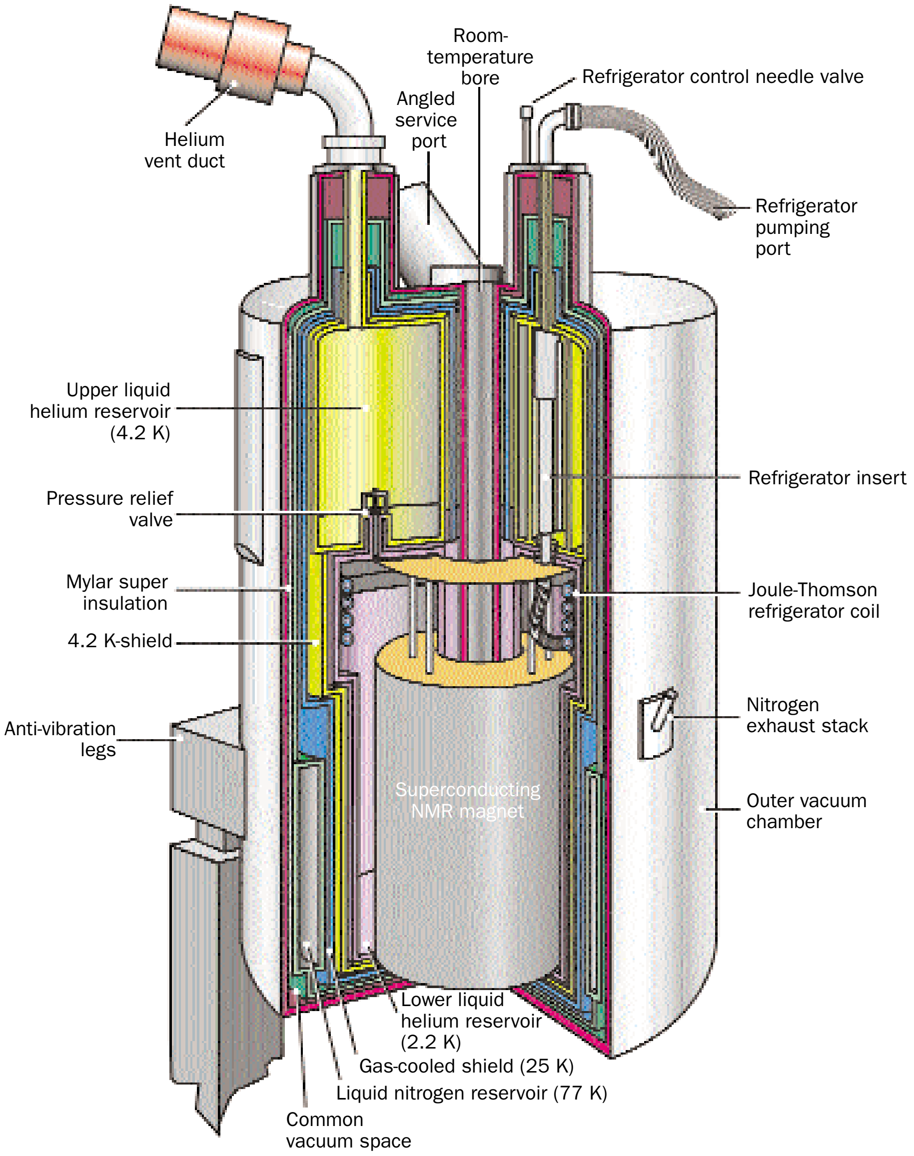
At first glance, SC magnets seem more complicated than electromagnets, especially because of their requirement for low temperatures to keep the magnet solenoid in its superconducting state. However, many of the technologies involved are the same in practice, and SC magnets have significant advantages over their electromagnetic and permanent counterparts.

SC technology allows users to produce extremely high magnetic fields without the kilowatt or megawatt power supplies needed for electromagnets. Once SC magnets are energized, or brought to field, users can disconnect them from their power source and they will remain energized, which significantly reduces electricity costs. SC magnets can also generate a far higher field than permanent magnets, which are limited to 2 T. Although electromagnets are capable of up to 35 T, the power consumption required would be considerable. SC magnets can currently generate up to 21.14 T. This figure can be extended to around 45 T with the addition of a resistive inset coil, but this would remove some of the advantages of the SC magnet because the added coil would need a permanent electricity supply.

The SC magnetic field can be kept extremely stable with a low drift rate and high homogeneity—essential features for applications such as nuclear magnetic resonance (NMR) spectroscopy and Fourier-transform mass spectrometry. Moreover, SC magnets have a smaller footprint than electromagnets (typically, the coils of a 1-T electromagnet are 10 times larger than those of a 10-T SC magnet), and their size is further reduced because they do not need water cooling for the power supply or solenoid. However, they do require a cryogen such as liquid helium to cool the magnet to below its SC critical temperature (T_c), and liquid helium is expensive in some parts of the world.

Applications

SC magnets are used worldwide for many applications. In health care, MRI—the medical term for NMR—is often used for clinical diagnosis. This technology depends on high-quality SC magnets. MRI systems hold the largest share of the SC magnet market.



Conectus, the Consortium of European Companies Determined To Use Superconductivity, forecasts that worldwide MRI sales will slightly exceed 3.5 billion euro (about $3.5 billion) in 2010, up from 2.4 billion euro (about $2.4 billion) in 2000.

Molecular biology also benefits from the SC magnets found at the heart of high-resolution NMR techniques that are essential in drug discovery and development. Additionally, SC magnets make possible cutting-edge structural analysis of solid, liquid chemical, and biological samples using techniques such as Fourier transform ion cyclotron resonance.

Physical-science researchers use SC magnets to characterize novel materials down to the molecular and atomic level. High-field split-pair SC magnets with optical access enable neutron and X-ray scattering studies. SC magnets even allow the investigation of nanostructures composed of arrangements of individual electrons that may one day lead to the realization of quantum computing.

In industry, high-gradient magnetic separation can be used to remove weakly magnetic impurities from the clay kaolin, which is used in some ceramic and paper products, to improve its whiteness and, therefore, its value. Magnetic levitation research (see *The Industrial Physicist*, December 1998, pp. 12–13) in the United States, Japan, and elsewhere also relies on SC magnets, but for the more exotic application of levitation and propulsion, such as trains that will travel at more than 550 km/h.

Bigger and better

SC magnets have continually evolved over the past 40 years, culminating in 2000 in the first commercial 900-MHz (21.14-T) SC magnets, introduced for NMR uses by Oxford Instruments (Oxford, England) and then by Bruker BioSpin (Billerica, MA).

Why have people continued to demand bigger and better magnets? In the case of NMR, increased field strength improves the signal-to-noise ratio and gives better resolution. These improvements provide more information on the structure of molecules, allowing the detection and characterization of more-complex compounds and smaller amounts of material.

Developing 900-MHz NMR magnets required overcoming significant hurdles. In addition to Oxford Instruments and Bruker BioSpin, several groups have undertaken the challenge. The Tsukuba Magnet Laboratory of Japan's National Institute for Materials Science has been developing a 920-MHz (21.6-T) NMR magnet with Kobe Steel, Ltd., for use in the spectroscopic analysis of proteins. And the National High Magnetic Field Laboratory (Tallahassee, FL) is testing a 900-MHz (21.1 T) magnet and working toward one of 1.066 GHz (25 T).

In developing the first commercial 900-MHz magnet, Oxford Instruments researchers had to address several difficult issues. The first challenge was selecting a superconductor that could provide a stable field at 900 MHz, because the field drift rate must be kept to 1 in 10^8 for high-resolution NMR experiments. Niobium–titanium wire, a workhorse superconductor developed in the 1970s at the Rutherford Appleton Laboratory (Chilton, England), is used in the lower-field regions of the magnet coil, but it cannot carry sufficient current in the higher-field section.

Next-generation niobium–tin wire, made up of thousands of filaments, is used to achieve a stable field at 900 MHz. The filament structure improves the stability of the magnet by preventing small changes in the magnetic-field distribution, known as flux jumping, which would dissipate energy in the superconductor. Manufacturing this wire requires stringent quality-control procedures to maintain a constant diameter and to ensure that short samples of wire perform at field strengths in excess of 21 T. However, it is practically impossible to manufacture a single length of wire to these standards because the solenoid for a 900-MHz magnet uses about 180 miles of wire. Therefore, researchers developed low-resistance techniques to join lengths of both niobium–titanium and niobium–tin wire together.

The largest commercial 900-MHz SC magnet in the world, which is located at the Pacific Northwest National Laboratory in Richland, Washington, has a room-temperature (RT) bore of 65 mm and contains 27 MJ of stored energy when at field. Other commercial 900-MHz magnets have a RT bore of 54 mm, which reduces the stored energy to only 17 MJ. Although this may sound like a lot less, it is equivalent to the amount of energy found in 4 kg of TNT. The bore refers to the hole in the center of the magnet into which a sample is lowered. A smaller bore means less physical stress on a magnet but also less space for a sample.

For the high-field 19+ T superconducting material to carry current without resistance, it must be kept in a bath of liquid helium at 2.2 K. An increase of a few microjoules of energy, equivalent to a pin dropping from a height of a few centimeters, would raise the temperature enough to cause the magnet to quench. Once the magnet's energy is released, the liquid helium boils off quickly.

Withstanding stress

Like the amount of stored energy, the stresses in SC magnets are huge. Mechanical stress increases quadratically with the field strength for a given magnet, and at 900 MHz, it is greater than 200 metric tons. Traditional coil-reinforcing techniques based on wax impregnation are insufficient at these high fields. Therefore, for Oxford Instruments' 900-MHz project, the coils were impregnated with a cryogenically stable epoxy resin. This approach enables the coils to withstand forces greater than 200 metric tons.

If a SC magnet should fail, how can you manage the dissipation of 17 MJ of energy without causing electrical short circuits in the magnet structure? The answer is to develop ways of releasing the energy quickly, in a manner that avoids damage due to either excessive thermal gradients in the magnet or excessive voltages in the coil. To address this challenge, Oxford Instruments researchers developed a proprietary energy-management system to ensure that during failure mode, all coil stresses and voltages are kept within design limits to prevent large thermal gradients in the magnet. Heaters make the magnet coils resistive, which disperses the energy from the quench evenly and prevents damage to sections of the coil by excessive voltage.

Currently, most SC magnets operate in a bath of liquid helium. However, the trend is to replace the liquid helium with mechanical cryocoolers, which give more flexibility and ease of use by removing the need for helium refills. Cryocoolers also allow the use of SC magnets in industrial applications where the external environment is demanding, such as in deserts and rain forests.

High-magnetic field NMR cryostats need to maintain a temperature of 2.2 K and still allow helium refills at atmospheric pressure. This temperature demand has the effect of increasing the superconductor's critical current characteristics, thus increasing the upper critical field limit. The most straightforward way to maintain temperature is to reduce the pressure in the liquid-helium bath. The cryostat structure also must support the magnet's weight, even under changing levels of cryogen and evaporation rates, and minimize heat leaking into the system that could raise the temperature above 2.2 K. In addition, the cryostat needs to be strong enough to withstand the discharge of large volumes of helium gas if the magnet quenches.

Aside from a magnet's performance, the system's siting must be taken into account. If a high-field magnet can erase a credit card's magnetic strip from 5 m away, it needs to be

(continued on p. 38)

(continued from p. 34)

set in a controlled environment. This is where shielding plays an essential role. Active shielding utilizes a superconducting core wound in the opposite direction to the main solenoid, which results in an opposing field that limits the stray field from the main coil. However, this is not a financially viable option for larger magnets because the main solenoid needs to be made bigger to reach its target field strength, which can raise costs by 20 to 25%.

Passive shielding works by placing a specially designed structure around the magnet. Shielding systems such as Oxford Instruments' give 800- and 900-MHz NMR systems increased protection from external electromagnetic disturbances, which can interfere with the quality of the NMR data. This helps maintain high-quality data and limit the stray field. Shielding also helps with security and safety by restricting access to the system, and it enables magnets to be housed, for example, in populated areas that would not otherwise be suitable.

Beyond 900 MHz

Increasing the size and strength of SC magnets further—to 1 GHz, for example—will put a greater demand on conductor performance. Currently, no superconductors available can give 100 A/mm^2 (the critical current density needed for superconductivity) at 1 GHz (23.1 T). Using new SC materials such as niobium–aluminum alloys may solve this problem. Alternatively, high-temperature superconductors (HTSs), which are largely ceramic materials that retain their SC properties up to temperatures of more than 90 K, may prove useful. Researchers at the National High Magnetic Field Laboratory are considering using an HTS inner coil in its 1-GHz SC magnet of the future. However, it is difficult to achieve the necessary homogeneity of conductor performance with HTSs because they are brittle and difficult to wind into a wire solenoid.

Nevertheless, together with cooling systems that remove the need for liquid helium, HTS materials may help take SC magnets of 1 GHz and higher out of the laboratory and into more demanding industrial environments. Other future developments may include decreasing the size of SC magnets. Although they are now much smaller than electromagnets of equivalent strength, the most powerful high-field SC magnets are large, weighing up to 15 metric tons. Along with the constant innovations that have occurred over the past 40 years, developments such as these should mean that SC magnets will continue to expand their applications for many years to come.

Further reading

Tsukuba Magnet Laboratory, Kobe Steel 920 MHz magnet; http://akahoshi.nims.go.jp/eng/kiyoshi/zNMR.htm.

National High Magnetic Field Laboratory; www.magnet.fsu.edu.

Pacific Northwest National Laboratory, William R. Wiley Environmental Molecular Sciences Laboratory; http://www.emsl.pnl.gov:2080/hfmrf.

Manufacturers: http://www.bruker-biospin.com, http://www.oxinst.com.

Glossary

Critical current: the maximum current that a superconducting component can accommodate without losing its superconductivity. This current is usually expressed as the material's *critical current density*.

Critical field limit: the maximum field that a superconductor can withstand before becoming resistive.

Critical temperature (T_c): the maximum temperature at which a material remains superconducting.

Drift rate: the change in magnetic field over time measured in hertz per hour.

Footprint: surface area occupied by an object.

Quench: the sudden loss of superconductivity.

Superconductivity: the complete loss of electrical resistance when a material is cooled below its critical temperature. Ω

BIOGRAPHY

Alan Street is technical director of Oxford Instruments Superconductivity in Oxford, England (superconductivity@oxinst.co.uk).