Ultra-high-field magnetic resonance imaging

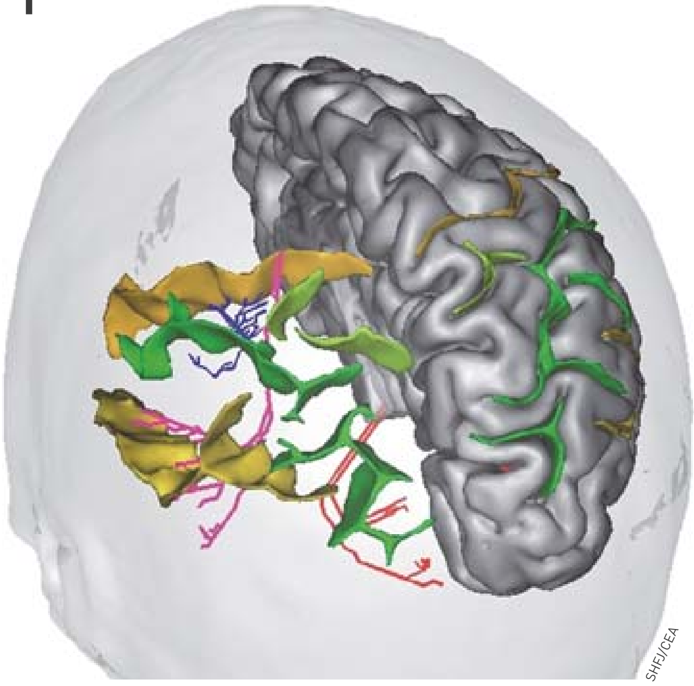
A. Gonin/CEA

The 'galeria' to the NeuroSpin building. The NeuroSpin neuroimaging platform harnesses a combination of instruments, equipment and expertise to enable the scientific community to gain a fuller understanding of how the brain works.

Understanding human brain function, brain development and brain dysfunction is one of the great challenges of the twenty-first century. Biomedical imaging has now run up against a number of technical constraints that are exposing limits to its potential. In order to overcome the current limits to high-field magnetic resonance cerebral imaging (MRI) and unleash its fullest potential, the CEA has built NeuroSpin, an ultra-high-field neuroimaging facility at its Saclay centre (in the Essonne). NeuroSpin already boasts three fully operational MRI systems. The first is a 3-tesla high-field system and the second is a very-high-field 7-tesla system, both of which are dedicated to clinical studies and investigations in humans, while the third is an ultra-high-field 17.65-tesla system designed for studies on small animals. In 2011, NeuroSpin will be commissioning an 11.7-tesla ultra-high-field system of unprecedented power that is designed for research on human subjects. The level of the magnetic field and the scale required will make this joint French-German project to build the magnet a breakthrough in the international arena.

Pushing back the limits of brain imaging: the promises of 11.7 T

The 11.7-tesla MRI magnetic resonance imaging system scheduled to equip NeuroSpin in 2011 is a world first. This one-of-its-kind system, to be equipped with the highest static magnetic field available for research in humans, was engineered with the aim of exploring the human brain to an unprecedented level of precision.



The functional exploration of the human brain has reached the boundaries of what biomedical imaging is capable of providing. The NeuroSpin facility will provide the scientific community with high-power instruments offering unparalleled imaging capabilities, including the 11.7-T magnetic resonance imager, enabling researchers to redraw the boundaries of current understanding.

The future 11.7-**tesla** **MRI magnetic resonance imager** will unleash new techniques for exploring the human brain (Focus C, ***The main methods of medical imaging***, p. 36). These techniques are currently being trialled on small animals with ultra-high-field systems: the 9.4-T system at the University of Minneapolis and the 11.7-T system run by the USA National Institutes of Health centre. Even higher-power prototypes are being developed to further fine-tune these new methods (a 14-T system at Lausanne in Switzerland, a 16.4-T system at Tübingen in Germany, and the 17.65-T system at the CEA's Saclay centre for **NeuroSpin**).
The power, precision, and novel techniques enrolled into the 11.7-T ultra-high-field MRI system for human studies promise to dovetail into an unparalleled level of image quality that will offer deeper insight into the brain and help unravel the secrets of healthy and diseased brain. The key challenge is to offer earlier, more accurate individual diagnostic capabilities.

Imaging and its pivotal role in technological challenges

Designing and engineering this system was both an instrumental challenge and a technological leap. Each of the MRI components represent challenges themselves, requiring the deployment of novel technologies: gradient **coils** vital to localising the **NMR** signal, the **radio-frequency** antenna needed to selectively excite the water **molecules** and receive the NMR signal bounced back, an electronic command-and-control system to operate the gradient coils and the radio-frequency antenna, and a computer console capable of orchestrating this entire architecture and reconstructing 3D images of the human body.
This engineering project is to be achieved through the combined efforts of the CEA, **Siemens Medical Solutions** and **Alstom MSA**, and each partner has a clearly-defined role. The CEA is tasked with project coordination and will be inputting key expertise in biomedical research and channelling its know-how into designing and tracking the manufacture of the **superconducting** magnet and the radio-frequency antenna (Focus B, ***Superconductivity and superconductors***, p. 16). Siemens Medical Solutions, in its role as recognised specialist in MRI-dedicated **magnets**, will be developing the gradient coils, the electronic command-and-control system, and the computer console. Finally, Alstom MSA will look after producing the superconducting wire and coiling it as a magnet for the MRI imager. The 150-tons magnet will be brought in from Alstom MSA's Belfort site, while the gradient coils and other electronic components will be shipped from the Siemens Medical Solutions Erlangen plant in Bavaria. A joint CEA-Siemens Medical Solutions team is tasked with assembly and integration at NeuroSpin.
The scene will then be set for specialist IT and image processing teams from NeuroSpin to enter the fray. They will have a two to three-year window in which to work on fine-tuning the instrumentation system, developing project-dedicated image processing tools, and engineering image acquisition protocols. The project will be capped by the launch of clinical research

The 3-T magnet at NeuroSpin, dedicated to clinical studies and investigations in humans. MRI makes it possible to image complex deep organs like the brain. System resolution gets increasingly sensitive with stronger magnetic fields. This is why the NeuroSpin centre, in its drive to further our understanding of the brain, is building an 11.7-T magnetic resonance imager for human applications, scheduled for completion in 2011.

A. Gonin/CEA

The increasingly ambitious research protocols being developed require increasingly high-field systems. The 7-T MRI system constructed at NeuroSpin is the first in France and the fourth in Europe to be equipped to this level of power. Dedicated to pre-clinical and clinical studies directly on human subjects, this system has an exceptionally high spatial resolution making it possible to highlight new structures. Building the 11.7-T magnet for the MRI imager, which will offer unprecedented characteristics (ultra-high magnetic field in a large-scale volume), is a huge technological challenge.

trials in the fields of **cognitive** neuroscience and brain pathology.

Fine-tuning innovative components for the imager

The *magnet*, which was engineered by the Dapnia (now known as the IRFU, Institute of Research into the Fundamental Laws of the Universe) at the CEA's Saclay centre, is obviously the keystone of the MRI system (see *The magnet, key component of imaging systems*, p. 33). Its function is to **polarise** the **proton spins** of the **hydrogen atoms** in water molecules.

The gradient coils

A **magnetic field** gradient is used to spatially characterise each individual element in the volume studied. Image quality is dependent on the linearity of the gradient. Siemens Medical Solutions will be working with the CEA on studying a *gradient coil* architecture with the characteristics needed to allow a magnetic field gradient of close on 0.1 T/m. The main challenge to be overcome will be the mechanical stresses and acoustic noise generated. The coils will need to be able to carry a 600 A current with variations clocked at just a few hundred microseconds in a static 11.7-T magnetic field. Huge forces are created that produce vibrations and impacts between the coil supports and the **cryostat**. In lower-field systems at around a 7-T field, the acoustic noise generated can reach up to 140 decibels (dB). The fact that noise will increase proportionally with an increase in static field raises a new challenge, i.e. to deploy a technology geared to an 11.7 T field and that can keep the noise capped at 140 dB in order to comply with current regulations. Faced with this challenge, Siemens Medical Solutions will be pioneering a novel coil design which will be tested stepwise, first at 7 T and then at 9.4 T, before being fitted in the 11.7-T magnetic resonance imager.

High-frequency electronics and system management

A signal excitation and reception architecture based on 8 transmission channels and 32 receiver channels will be developed and finalised, and the vast data throughputs expected to be handled has prompted the system architecture to include extendibility up to 128 transmission channels and 128 receiver channels. The system also needs to handle real-time tracking of specific absorption of radio-frequency energy, which is a crucial safety parameter. This unique apparatus will require tight collaboration between Siemens Medical Solutions and CEA teams in order to seamlessly integrate the different system components. Research will be led jointly on the safety aspects related to the deployment of a high-frequency transmission system. There will be research into software solutions to predict and **model** radio-frequency distribution during the experiment and provide adaptive control accordingly.

Radio-frequency coils and amplifiers

The CEA is tasked with developing the proton excitation hardware (8 transmission channels and 32 receiver channels) geared to the 11.7-T system and operating at a frequency of 500 **MHz**. Nowhere in the world is there an equivalent MRI system. The equipment will be based on one of two systems, either using recently patent proprietary CEA architectures, or via a miniaturised microstrips[1] approach. Another technologi-

(1) Microstrip: electrical transmission line that consists of a conducting ribbon layered on one side of a dielectric substrate – an insulating material capable of storing electrostatic energy – while the other side forms a ground plane.

J.-J. Bigot/IRFU/CEA

Prototype magnetic field gradient coils for MRI designed to alleviate problems of mechanical fatigue and unwanted acoustic effects. One of the technological challenges involved will be to keep acoustic noise down to an MRI-safe 140 dB at an 11.7-T field strength.

cal challenge that the CEA will be addressing is to develop instruments that do not generate 'inhomogeneity' in the central magnet's magnetic field and thereby keep any potential heat-up in the subject's tissues down to within regulatory-defined values.

The other components

The other components of the magnetic resonance imager and its environment will be based on commercially-available solutions where available or else developed from scratch. Siemens Medical Solutions has the role of integrating them. The main tasks will involve powering the *shim* coils, which correct the fluctuation in the central magnet's main field, the non-magnetic scanner table, the consoles, the station control computers, plus management of the electrical and fluids systems (water, conditioned air) and the sound absorption and acoustic insulation panels.
All these components will need to operate in a very strong magnetic environment where they can be exposed to extreme currents and temperatures.

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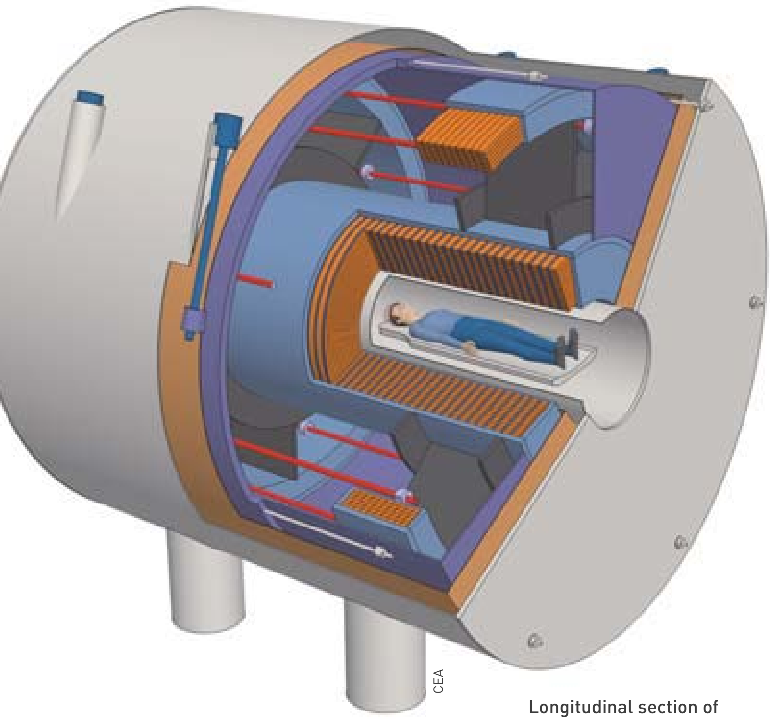
The magnet, key component of imaging systems

Building the magnet centrepiece to the future 11.7-tesla MRI magnetic resonance imaging system is a highly ambitious project set to overcome current technological barriers.



Longitudinal section of the 11.7-T magnet and the **cryostat** assembly.
The central coil passes around the patient's body, while the compensation coils are positioned towards the outer shell. The coils are mechanically connected up via a system of plates and tie-struts inside the helium chamber. Six tie-struts supporting the cold mass are attached to the vacuum chamber via the 60-K thermal shielding.

The **magnet** of the **MRI magnetic resonance imager** needs to generate a uniform 11.7-**tesla magnetic field** at its isocentre, i.e. 230,000-fold higher than the **Earth's magnetic field**, in a volume space of several m³ and with a useful opening of 90 cm in diameter allowing the passage of the whole of a patient's body. Facing this combination of challenges, there is no individual industry player capable of producing this kind of magnet on their own. Magnet development has therefore been integrated into the Franco-German Iseult project, where the CEA is partnering sector leaders **Guerbet**, **Siemens Medical Solutions** and **Alstom MSA**. Engineering and manufacture are scheduled to run over 4 years, with **NeuroSpin** expected to commission the magnet in 2011.

Three major challenges to handle

The first step is to address three technological challenges dictated by MRI-specific factors: to obtain a magnetic field that has a homogeneity around the patient brain region of just a few parts per million (ppm) of a tesla, to stabilise the field, at least for the scan time, at down to a few tens of billionths of a tesla, and lastly, to succeed in confining the field to within the MRI investigation room.
To achieve this, around 65 tons of magnet **coils** are to be positioned around the brain to ultra-high precision (down to a few tenths of a millimetre). The coil system is produced from several thousand kilometres of **niobium-titanium** (**NbTi**) wire that is only about a millimetre in diameter. This **superconducting** material offers zero **electrical resistance** to flow of current (Focus B, ***Superconductivity and superconductors***, p.16). A strand of this material can handle 400 times more electrical current pound for pound than a conventional copper wire. This superconductor has to be held at very low temperature (1.8 **K**, i.e. – 271 °C). The coils are immersed in several thousand litres of **superfluid helium** protected from the exterior by a series of enclosures, like a giant thermos flask. The magnetic field will be confined via an exterior coil system that generates a counter-field cancelling out the field generated by the core coil system outside the magnet. A conventional system would require several thousand tons of iron shielding to achieve the same results.

The specific features of the magnet

The 11.7-T whole-body magnet with active shielding, which will be operating a uniform 11.7-T field giving an effective bore diameter of 90 cm, is being designed to the following specifications:

- a *field homogeneity* of better than 0.1 ppm peak-to-peak, in a 10 cm-diameter volume and centred on the target brain;
- a *temporal stability* equal to or better than 0.05 ppm/hr total drift and a short-term (over ten minutes) stability of 10^{-4} ppm for image or MRI spectrum acquisition. The project design currently plans for the magnet to be constantly connected to an ultra-stable source of electrical power. The level of stability required needs to be at least one order of magnitude better than that offered by existing conventional power sources;
- an *actively shielded magnet*, the shielding being provided by a compensation coil. The maximum distance of the **fringe field** vector of around 5 **gauss** is 9.6 m axially from the magnet's isocentre and 7.5 m radially;
- a cryostable coil technology known as *double-pancake*;
- a magnet cooling and cryostability system employing a pressure-controlled 1.8 K helium bath in a helium chamber built to cover both coil systems;
- an *NbTi conductor* has been selected for financial reasons. It is to have the critical parameters needed to allow it to operate at 1,500 A.

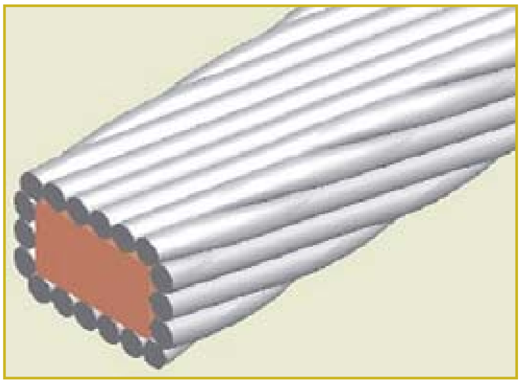


Figure 1.
A schematic diagram of the conductor for the central coil, shown here under the cable-sheathed copper core (9.2 mm x 4.6 mm) option.

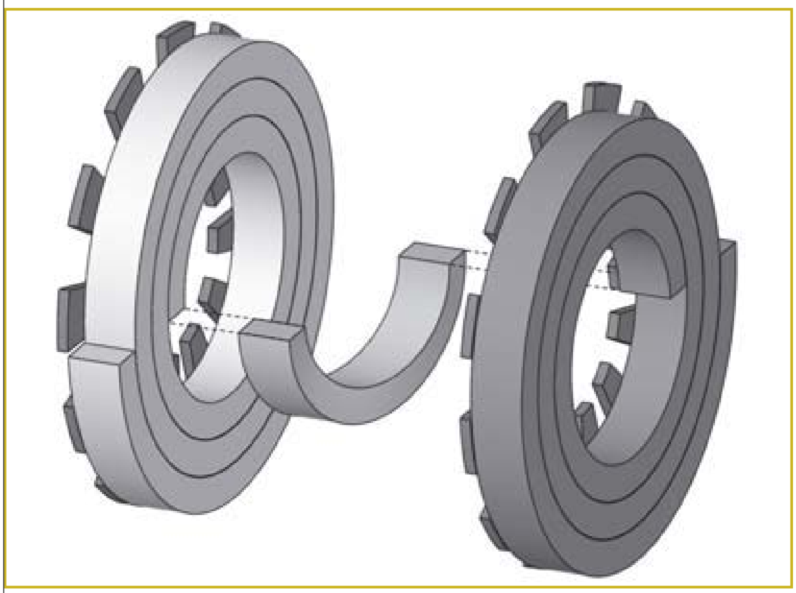


Figure 2. Schematic diagram of a double pancake split by a curve transition (dimensions are not to scale).

The coil system

The central magnet coil will be engineered using a rectangular conductor built of one or more NbTi strands. Several options are still under review, with candidates running from a pure NbTi/Cu monolith up to a **composite** solution built either by assembling NbTi/Cu strands around a copper core (Figure 1) or guiding them through a copper raceway.
The conductor will be roughly 9.2 mm wide and 4.6 mm thick, i.e. 4-fold more than the conductors conventionally used in commercially-available MRI solutions. It will boast a copper-to-superconductor cross-section ratio of 4.3-to-1. Current capacity will be 1,498 A, yielding an average in-coil **current density** of 28.9 A/mm².
As the cryostability imperatives dictate that the conductor has to be directly helium-wetted, the main coil will be built based on a double-pancake system of coil modules inter-spaced with glass fiber-epoxy shims (Figure 2). Field homogeneity will be achieved through a double-pancake system of modules in a space-adjusted block-unit configuration. The block-unit pattern is widely used in MRI magnets but never before with double-pancake coils.
The key advantages with using these double-pancake coils are that the assembly can be made modular and that the components are lightweight compared with a traditional layered **solenoid** coil setup. The main disadvantage, though, stems from the pancake-to-pancake conductor transition to the inner transition radius (Figure 2). The non-symmetrical current trajectory can, if no corrective measures are taken, generate axial field dispersion.
The double-pancake coil structure has been **modelled** and optimised to achieve field homogeneity and minimise external fringe field. The compensation coil designed to minimise this leakage is connected in series to the central coil and fitted around the outer diameter of the apparatus. It is produced using an NbTi superconducting wire that is placed in a copper raceway and then wound and vacuum-impregnated with an epoxy resin. The maximum field force on this coil is 4.4 T.

Mechanical structure, cryostat, and cryogenics

The magnet is sheathed in single-layer thermal shielding cryogenically cooled to 60 K inside a vacuum chamber. This **cold mass** weighs about 80 tons and is supported inside a vacuum chamber by 6 vertically-fitted tie-struts. Axial tie-struts are also fitted to minimize any sideways movement of the magnet. The vacuum chamber has an outer diameter of around 4.6 m and is roughly 4.9 m in length.
Both central coil and compensation coil are cooled to 1.8 K in a superfluid helium bath set at atmospheric pressure. The facilities for producing this superfluid helium will be installed in an independent cryogenic satellite cell fitted close to the magnet. This satellite cell will include the two power feeds, the 1.8 K heat exchanger, and all the shut-off valves that will be needed if the magnet switches from superconducting state to normal state (quench).
The electric power and helium supply lines will be installed inside a cryogenic transfer line several metres long connecting the magnet to the other current-generating equipment (electric power, discharge resistors,

F. Vigouroux/CEA

Revamping the LCMI's old double-pancake-coiled 8-T magnet for the 'SEHT' test station.

CEA

Figure 3.
The 'SEHT' 8-tesla test station and experiment. The 8-T magnet at right is housed in a cryostat connected to a 1.8-K satellite cell (at left) via a cryogenic transfer line. The experiment was set up to test the engineering and operating conditions expected to feature in the final magnet.

etc.) and helium production gear (liquefier generating 100 L/hr, compressors, etc.) located in the basement underneath the NeuroSpin building.

Protection

The magnet protection system was calculated based on the assumption that all the magnetic energy stored is off-loaded into an external 2.67-ohm (Ω) resistor at a maximum voltage of +/- 2,000 V. The volume of copper inside the magnet has been determined in order to keep to a peak magnet temperature of 150 K.

Designing specific models and prototypes

The magnet is to feature a certain number of properties setting it apart from conventional MRI magnets. The novel solutions put forward therefore call for a specially-geared development programme requiring specific models and prototypes to be produced.
For example, in order to demonstrate that it was possible to create a magnetic field with a homogeneity of better than 1 ppm using double-pancake technology, it was necessary to design a model incorporating 24 double-pancakes (at 1.5 T, with a 480-mm internal bore and a 805-mm outer diameter). The model had to be cold-testable, and its field quality would be measured using **NMR** probes.
The research crew actually had to reactivate an old 8-T magnet once used at the Grenoble-based **Laboratory of ultra-high magnetic fields research** (**LCMI**) in order to study the behaviour of a high-field magnet built with cryostable double-pancake coils and a 1,500-A NbTi conductor bathed in superfluid helium. This double-pancake-coiled magnet was refitted inside a new **cryostat**. The prototype thus architectured, called the 'SEHT' (8-tesla test station), was connected up to a cryogenic satellite cell feeding 1.8-K superfluid helium to the magnet via a cryogenic transfer line also including the electrical power lines (Figure 3).
This experiment also provided the opportunity to test the magnet components and manufacturing procedures and to study the operating conditions under which the final magnet is designed to operate, focusing on **electromagnetic**, thermal and thermohydraulic response. The experiment also made it possible to validate the upgrades made on the 1.8-K cryogenics solution, the electrical power supply system, and the magnet protection and control systems. The SEHT prototype is expected to go live in April 2008.

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FOCUS C

The main methods of medical imaging

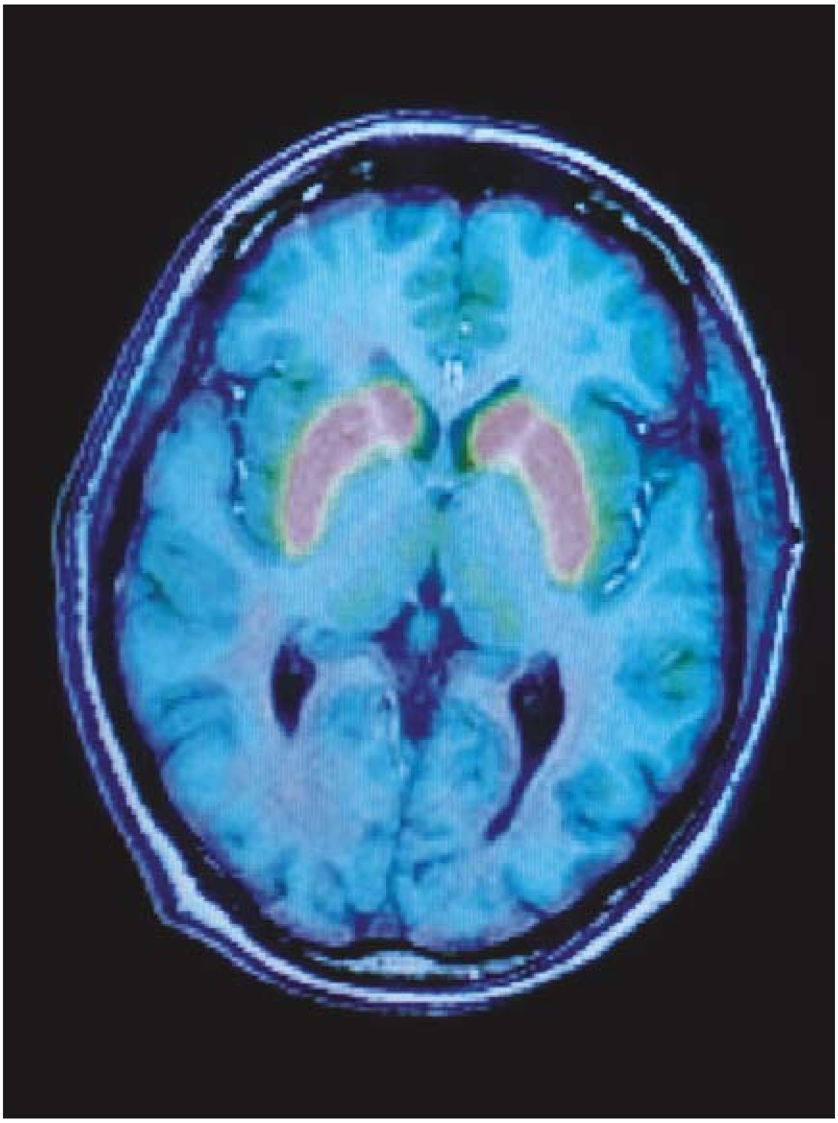
Medical imaging is a unique, non-invasive set of techniques that make it possible to visualise biological processes actually within living organisms themselves. It is a key means for providing insight into physiology and pathology, and ultimately for disease diagnosis, prognosis and therapy. Imaging is therefore the first-choice investigative tool in several branches of medicine and biology.

Medical imaging started with X-ray radiation and then developed further with the discovery of artificial radioactivity and the allied screening techniques. The next leaps forward, first to Nuclear Magnetic Resonance (NMR) and then to superconducting magnets, led to technological breakthroughs in Magnetic Resonance Imaging (MRI).

One of the key dynamic human brain imaging methods is Electroencephalography (EEG) which uses electrodes fitted on the scalp to measure the electrical activity produced by the brain through synaptic currents generated in neurons. EEG gives information on the time-locked neurophysiological activity of the brain, and in particular the cerebral cortex. This information is used in neurology for diagnostics, or in cognitive neuroscience for research.

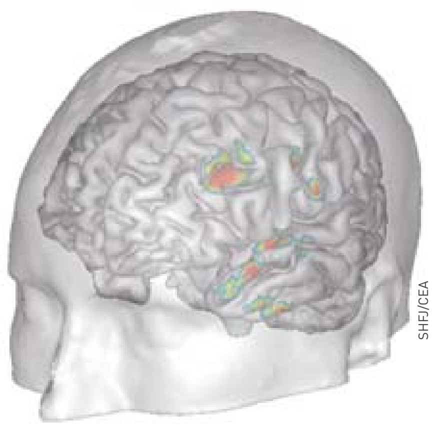
Magnetoencephalography (MEG) records the magnetic fields produced by the currents generated by neurons in the brain, using sensors fitted close to the head. MEG is employed in clinical settings by neurologists, especially when the focus is on epilepsy, and for cognitive neuroscience research. MEG can also be used to study developmental disorders like dyslexia, psychiatric disorders like schizophrenia and neurodegenerative disorders like Parkinson's and Alzheimer's.

Positron Emission Tomography (PET) consists in intravenously administering a tracer molecule labelled with a radioactive isotope and using external detection techniques to track how a normal or diseased organ functions. Radioactive tracers present the same physico-chemical properties as their non-radioactive counterparts, with the exception that they are able to emit radiation. This means that they act as a marker that is followed, using appropriate detection methods, to track the previously-labelled molecule's kinetics through the body. The data gathered is then analysed and transformed using a mathematical model to generate a screen image showing where the radiotracer settles in the body. PET is a widespread technique in physiological or pathophysiological studies on cognition and behaviour and is commonly used to study central nervous system disorders



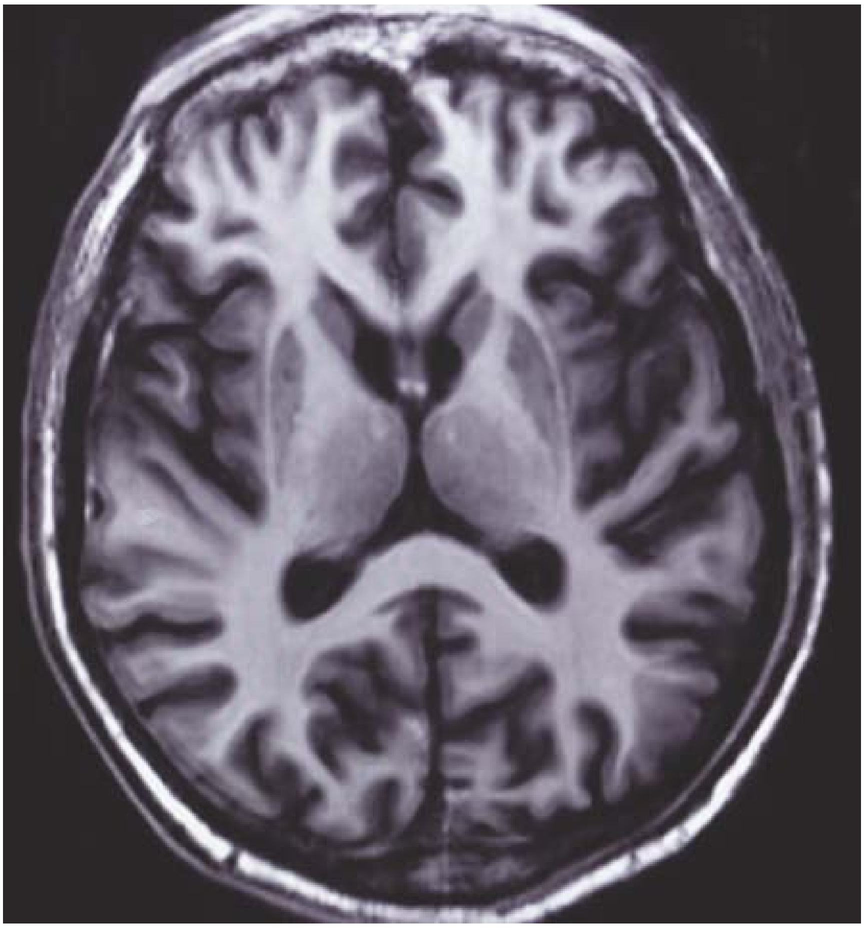
P. Stroppa/CEA

A PET image. The PET camera detects the positrons emitted by radioactive tracers previously injected into the living subject, and 3D images of the target organ are reconstructed by computer analysis.



SHFJ/CEA

Melancholic depression. PET images measuring regional energy activities merged with the aMRI image of the patient's brain. Areas of hypoactivation are individually detected.



P. Stroppa/CEA

Image acquired through the SHFJ's 3-T MRI system at Orsay (Essonne). This technique provides extremely high-precision analysis of infectious or inflammatory lesions, brain vessel damage, and tumours.

such as epilepsy, cerebral ischaemia, stroke, and neurodegenerative disorders (Parkinson's disease, Huntington's disease).

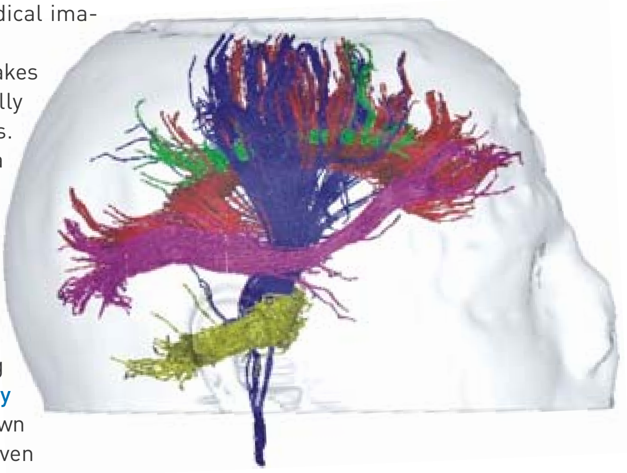
Magnetic Resonance Imaging (MRI) is a non-invasive *in vivo* imaging method. MRI is capable of studying 'soft' tissue such as the brain, bone marrow, or muscle, for example. It can be used to map anatomic structure (anatomical MRI, or aMRI), monitor organ function (functional MRI, fMRI) and track various processes of metabolism (Magnetic Resonance Spectroscopy, MRS). After its first developments in 1946, MRI uses the physical phenomenon of NMR that exploits the magnetic properties of atomic nuclei. Certain nuclei, such as the hydrogen nuclei for example, have a weak magnetic moment, or spin. NMR works by detecting variations in the magnetisation of atomic nuclei in response to an extremely powerful magnetic field and electromagnetic wave-driven excitation. When an electromagnetic wave is applied at the right frequency, i.e. the *resonance frequency*, these nuclei change alignment and emit signals as they return to their initial position. Technological advances in computing and magnetic fields have taken NMR from condensed matter physics on to chemical analysis and then structural biology, and more recently into medical imaging.

Anatomical MRI. MRI makes it possible to visually display all body organs. The resonance, under a very-high magnetic field, of water molecules, which are naturally abundant in most biological tissues, is used to generate cross-sectional images detailing brain structures (grey matter, white matter) down to the millimetre and even less. Radiologists use 'anatomical' imaging to detect and localize brain lesions.

Functional MRI. The recent acceleration in data acquisition and processing has led to the advent of 'functional' MRI, which is able to show neural activity in different brain regions. Indeed, speaking, reading, moving or thinking all activate certain areas in the brain. This neuronal activation triggers a local increase in blood flow in the brain regions concerned. Although it cannot directly detect neuronal activity, fMRI is able to detect the local, transient increase in blood flow that neuronal activity causes, which it does by gauging the magnetization of the haemoglobin contained in red blood cells.

Diffusion MRI (dMRI). Diffusion MRI is a powerful tool for measuring the movements of water molecules at the microscopic scale, thereby providing a precise architecture of the neuronal tissue and its variations. It offers a more direct method of measuring than other conventionally used imaging techniques. Diffusion MRI makes it possible to investigate tissue structure at a much finer scale than the millimetre scale offered by MRI image resolution, with the added advantage of being much faster.

This array of medical imaging technologies is rounded off by nuclear magnetic resonance spectroscopy (MRS), a non-invasive method of gaining biochemical and metabolic information on the central nervous system. MRS, which is based on the same principles as MRI, can be used to provide precise quantitative data on dozens of different molecules.



V. El Kouby, M. Perrin, C. Poupon and J.-F. Mangin, SHFJ/CEA

dMRI can diagnose certain pathologies very early on and provide images of the connective fiber clusters (white matter) that network the various brain regions together.

FOCUS B

Superconductivity and superconductors

One of the main fields of application of superconductivity is medical imaging. This is the 3-tesla magnetic resonance imager at the SHFJ hospital in Orsay (Essonne).

Some historical background

Trains "flying" above the track using magnetic levitation, electricity storage finally resolved using giant magnetic coils, electrotechnical instruments and electric power transmission cables with no joule losses, magnetic fields that can be used to explore the human body and deliver even higher resolution images. People have been marvelling at the potential uses of superconductivity since 1911 when Dutch physicist Heike Kammerlingh-Onnes first discovered the extraordinary property exhibited by superconducting materials; their electrical resistance drops to zero below a certain critical temperature (which varies with their isotopic mass). This discovery won him the Nobel Prize in Physics in 1913.

Apart from zero electrical resistance and optimal electrical conductivity, the superconductors discovered by Kammerlingh-Onnes (later named type I superconductors) possess another remarkable property manifested by the Meissner effect, discovered in 1933 by German physicists Walter Meissner and Robert Ochsenfeld. If we ignore the London penetration depth[1], superconductors can be said to exhibit perfect diamagnetism, i.e. the superconducting material fully expulses its internal magnetic field up to a certain critical field value whereas, in theory, the magnetic field of a material with perfect conduction of electricity should equal that of the externally applied field.

Herein lies the second obstacle that continues to hamper superconductor applications: superconductivity is lost at above a critical magnetic field strength. For many years physicists thought there was only one type of superconductivity and that the magnetic anomalies observed in some samples were due solely to the presence of impurities. In the 1950s, however, Russian physicists Vitaly L. Ginzburg and Lev Davidovitch Landau came up with the theory that there were actually two types of superconductors.

In 1957, the Russian-American physicist Alexei A. Abrikosov finally confirmed type II superconductivity. Type II superconductors exhibit a completely different type of magnetisation characterised by a mixed state that allows them to retain their superconducting state even in intense magnetic fields. This means they are not subject to the Meissner effect. In 2003, Abrikosov, Ginzburg and the Anglo-American physicist Anthony J. Leggett were awarded the Nobel Prize in Physics for their research into superconductors.

It was also in 1957 that American physicists John Bardeen, Leon N. Cooper and John R. Schrieffer published their theory of superconductivity, which won them the 1972 Nobel Prize in Physics. This BCS theory (named after the first letter of their surnames) postulates that electrons move through a conductor as Cooper pairs (two electrons with opposite spin). These pairs act like spin-zero bosons and condense into a single quantum state via a phonon interaction, which

(1) In 1935, Fritz and Heinz London proposed another explanation for the Meissner effect by claiming that the magnetic field decreases with depth from the surface of a superconducting material over a characteristic length λ_L known as the penetration depth.

is also a quantized mode of vibration. It is this electron-phonon interaction that underpins resistivity and superconductivity. Ions move in response to the ultra-fast passage of an electron (10^6 m/s), thereby creating an area of positive electrical charge which is held after the passage of the electron. This attracts another electron that pairs up with the first electron thereby resisting the Coulomb repulsion but not thermal agitation, which explains why temperature has such an adverse effect on superconductivity.
The BCS theory, which applies to 'conventional' superconductors, did not however provide for the appearance of superconductivity at fairly high temperatures, i.e. higher than the temperature of liquid nitrogen (77 K, i.e. – 196 °C), and *a fortiori* at ambient temperature. This 77 K threshold was reached by using compounds such as Y-Ba-Cu-O (current records stand at around 165 K, at high pressure, and 138 K, i.e. – 135 °C, at standard pressure). German physicist Johannes Georg Bednorz and Swiss physicist Karl Alexander Müller were awarded the Nobel Prize in Physics in 1987 for their work on unconventional superconductors. They discovered a lanthanum-based copper oxide perovskite material that exhibited superconducting properties at a temperature of 35 K (- 238 °C). By replacing lanthanum with yttrium, particularly in $YBa_2Cu_3O_7$, they were able to significantly raise the critical temperature thus developing the cuprate family of superconductors. Although these are highly effective superconductors, the fact that they are ceramics makes them difficult to use in electrotechnical applications. All high-critical-temperature superconductors are type II superconductors.

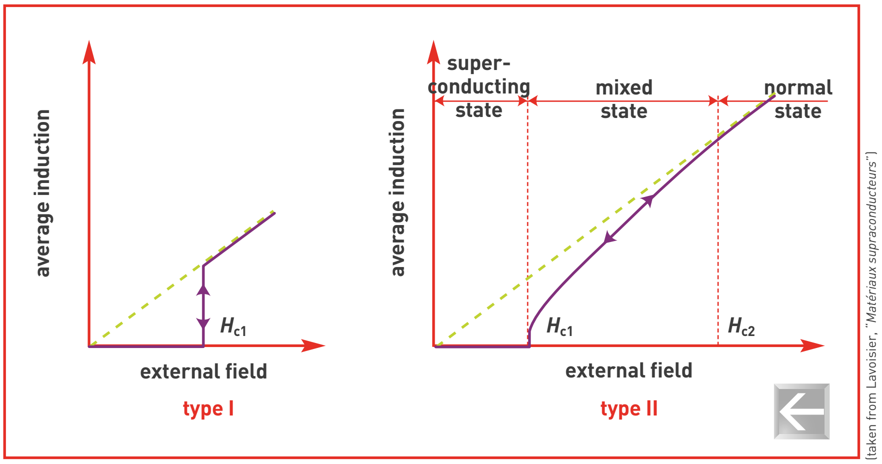


Figure 1.
Average induction in type I and type II superconductors under an externally applied magnetic field.

The strange magnetic properties of type II superconductors

In the presence of a magnetic field, type II superconductors exhibit perfect diamagnetism up to certain field H_{c1} just like type I superconductors. Beyond H_{c1}, however, type II superconductors enter a mixed state that allows partial field penetration up to H_{c2} (Figure 1), thereby permitting a material to be superconducting under a high magnetic field.
This mixed state resembles an array of normal-state cores that start to fill the superconducting material at H_{c1} and over. Each region contains a flux quantum ($2.07\cdot10^{-15}$ weber) and is surrounded by a vortex of superconducting currents (Figure 2). When the magnetic field increases, the network densifies until it completely fills the superconducting material at H_{c2}.
The distinction between the two types of superconductivity is coupled to the concepts of coherence length ξ and penetration depth λ_L, which characterise the interface between a normal region and a superconducting region. ξ represents the spatial variation of the superconducting state (i.e. the density of the superconducting electrons) and λ_L the London penetration depth of the magnetic field. It is the ratio of these two characteristic lengths, known as the *Ginzburg-Landau parameter* and written as κ ($\kappa = \lambda_L/\xi$), that determines which type of superconductivity is involved. If $\kappa < \sqrt{2}/2$, the superconductor is type I, and if $\kappa > \sqrt{2}/2$, the superconductor is type II.
At the interface, the penetration of the magnetic field, as defined by λ_L, corresponds to an increase in free energy in the superconducting material, while the formation of the superconducting state, characterised by the coherence length, is related to a decline in free energy. The interface's energy balance varies with the ratio κ. In type II superconductors, the

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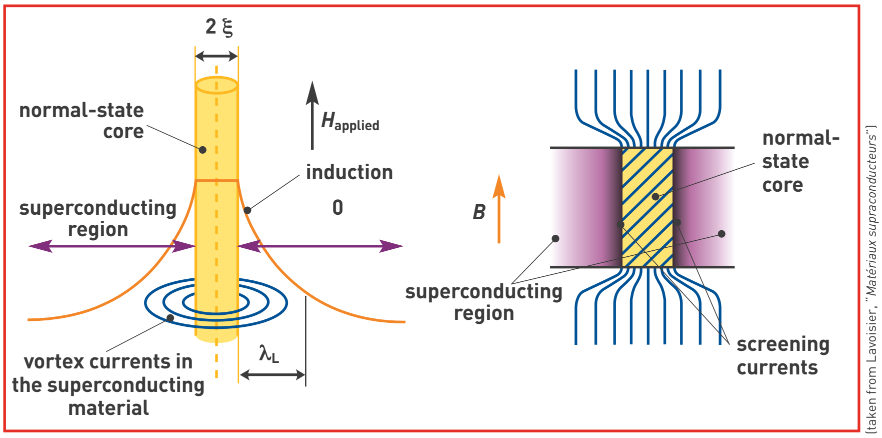
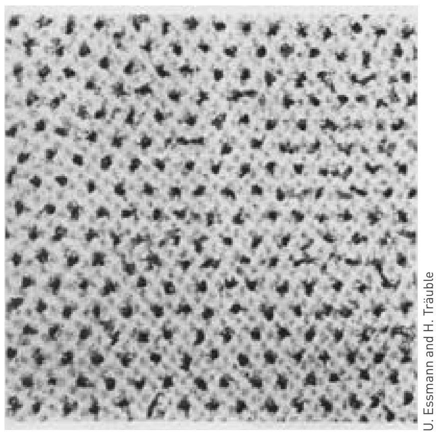


Figure 2.
Diagram of a vortex illustrating penetration depth and coherence length.



Magnetic pattern on the surface
of a superconductor in mixed state.

FOCUS B

material		ξ (μm) 0 K	λ_L (μm) 0 K	κ	T_c (K)	$\mu_0 \cdot H_{c1}$ (teslas) 0 K	$\mu_0 \cdot H_{c2}$ (teslas) 0 K
type I	Al	1.36	0.05	0.04	1.18	0.010 5	
	Pb	0.083	0.037	0.5	7.18	0.080 3	
type II	NbTi	0.005	0.3	60	9.25	0.01	14
	Nb_3Sn	0.003 6	0.065	18	18	0.017	25.5
	YBaCuO	plane 0.003	plane 0.8	≈ 300	93		140
		axis *c* 0.000 6	axis *c* 0.2				

Table.
Characteristics of some type I and type II superconductors. $\mu_0 \cdot H_{c1}$ and $\mu_0 \cdot H_{c2}$ represent magnetic inductions, where μ_0 is the magnetic permeability of a vacuum (and of the material in this particular case).

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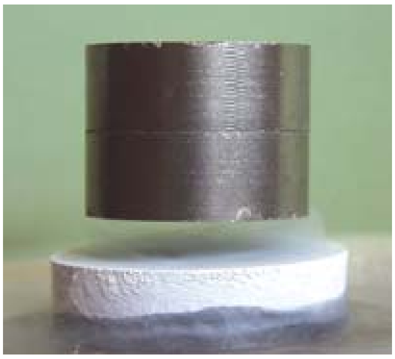
mixed state therefore results from the creation of a large number of interfaces, with each interface corresponding to a negative energy balance conducive to superconductivity above the H_{c1} field (Table).

Potential avenues for application

Type I superconductivity does not present any great potential for new areas of application. Unfortunately, the critical temperature that limits superconductivity applications is very low in the two superconducting materials that currently offer real-world applications i.e. niobium-titanium, NbTi (9.2 K) - the first superconducting cables in niobium-titanium alloy were developed in the early 1960s - and niobium-tin, Nb_3Sn (18 K). These materials have to be cooled to the temperature of liquid helium (4.2 K)[2] in order to activate their superconducting properties. This temperature was the first important milestone towards achieving superconductivity at ambient temperature, which is the ultimate goal.

Type II superconductors can withstand very strong magnetic fields, and are also able to carry extraordinarily high current densities, up to another critical value that varies with the magnetic field (Figure 3). This fact heralded the development of the first superconducting magnets. The current densities that can be generated under these conditions are huge in comparison with what can be achieved with domestic or industrial electrotechnical applications (around 10 A/mm^2).

Since the 1970s, the CEA has been focusing its research on the production of large-scale intense permanent magnetic fields (magnetic confinement of fusion plasmas, particle physics, medical imaging). In fact, these are the predominant applications of type II superconductors, mainly NbTi[3], where superconductivity significantly cuts down on electric power consumption despite the cryogenic efficiency of the facilities - in fact, one watt dissipated at 4.2 K requires a minimum consumption of 300 W at ambient temperature in the largest industrial power plants. While researchers the world over still dream of developing superconducting materials that function at room temperature, it would seem that applied superconductivity will still have to rely on the use of very low temperature cooling for the foreseeable future.



LEG Grenoble

The discovery of high-critical-temperature superconductivity made it possible to see how superconductivity manifests in the open air in the form of a magnet floating above a pellet of liquid-nitrogen cooled YBaCuO, which is now a famous example of the effect.

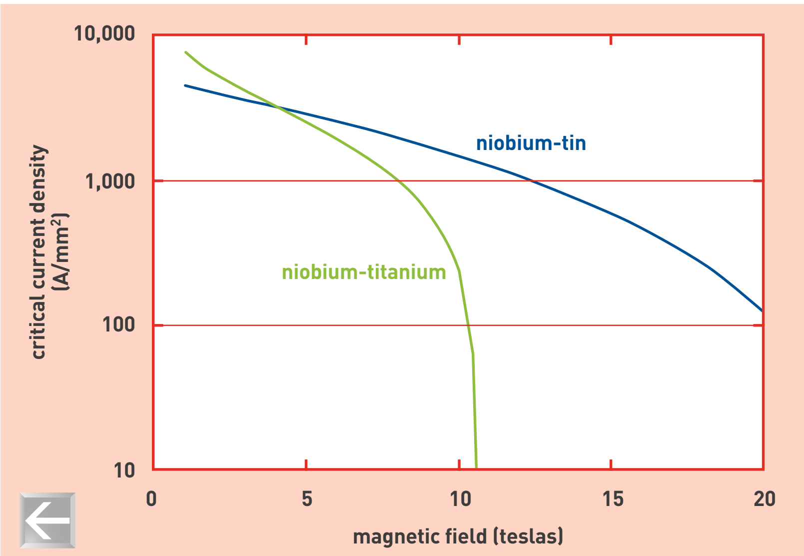


Figure 3.
Characteristic critical current densities in relation to a 4.2-K magnetic field for the two superconducting materials most widely used, particularly in the manufacture of superconducting magnets.

(2) The history of superconductivity actually goes as far back as William Ramsay who, in 1895, was the first person to isolate helium. Indeed, where would the science of superconductivity be today if it wasn't for helium which is the key component of the ultra-low cooling process? Note also that Kammerlingh-Onnes finally succeeded in producing liquid helium in 1908 following unsuccessful attempts by James Dewar in the late 19th century, thus paving the way to the discovery of superconductivity.

(3) Produced in quantities of around 1,500 to 2,000 tons per year.

FOCUS A

The different types of magnetism

The origins of magnetism lie in the properties of electrons as explained by the laws of quantum physics. Part of an electron's magnetic properties (*spin magnetism*) results from its quantum-mechanical spin state, while another part results from the orbital motion of electrons around an atom's nucleus (*orbital magnetism*) and from the magnetism of the nucleus itself (nuclear magnetism). This is put to use, in particular, for nuclear magnetic resonance imaging in the medical field. Magnetism is therefore produced by electric charges in motion. The force acting on these charges, called the Lorentz force, demonstrates the presence of a magnetic field.

Electrons have an intrinsic magnetic dipole moment (the magnetic quantum state being the Bohr *magneton*), which can be pictured as an electron's rotational motion of spin around itself in one direction or another, oriented either upwards or downwards. The *spin quantum number* (one of the four numbers that 'quantifies' the properties of an electron) equals 1/2 (+ 1/2 or - 1/2). A pair of electrons can only occupy the same *orbital* if they have opposite magnetic dipole moments.

Each atom acts like a tiny magnet carrying an intrinsic magnetic dipole moment. A nucleus (the neutron and proton individually have a half-integer spin) will have a half-integer spin if it has an odd atomic mass number; zero spin if the atomic mass number and charge are even, and an integer spin if the atomic mass number is even and the charge odd.

On a larger scale, several magnetic moments can together form magnetic domains in which all these moments are aligned in the same direction. These spatial regions are separated by domain walls. When grouped together, these domains can themselves form a macroscopic-scale magnet (Figure E1).

The type of magnetism that comes into play is determined by how these elementary constituents are ordered, and is generally associated with three main categories of material: *ferromagnetic*, *paramagnetic* and *diamagnetic*.

Any material that is not diamagnetic is by definition paramagnetic provided that its magnetic susceptibility is positive. However, ferromagnetic materials have particularly high magnetic susceptibility and therefore form a separate category.

1. Ferromagnetic materials are formed of tiny domains inside which atoms exhibiting parallel magnetisation tend to align themselves in the direction of an external magnetic field like elementary dipoles. In fact, the magnetic moments of each atom can align themselves spontaneously within these domains, even in the absence of an external magnetic field. Applying an external field triggers domain wall movement that tends to strengthen the applied field. If this field exceeds a certain value, the domain most closely oriented with the direction of the applied field will tend to grow at the expense of the other domains, eventually occupying the material's whole volume. If the field diminishes, the domain walls will move, but not symmetrically as the walls cannot fully reverse back to their original positions. This results in remanent magnetisation, which is an important feature of naturally occurring magnetite, or of magnets themselves.

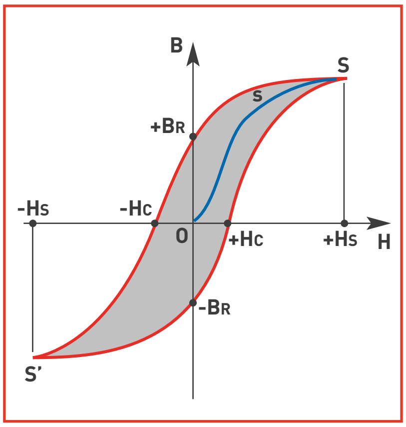


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches zero; this remanent induction can only be cancelled out by reversing the magnetic field to a "coercive" field value. This hysteresis loop illustrates the losses due to "friction" between the magnetic domains shown on the area bounded by the magnetisation and demagnetisation curves.

The whole process forms a hysteresis loop, i.e. when the induced field is plotted against the applied field it traces out a *hysteresis curve* or *loop* where the surface area represents the amount of energy lost during the irreversible part of the process (Figure E2). In order to cancel out the induced field, a coercive field has to be applied: the materials used to make artificial permanent magnets have a high coercivity.

Ferromagnetic materials generally have a zero total magnetic moment as the domains are all oriented in different directions. This ferromagnetism disappears above a certain temperature, which is known as the Curie Temperature or Curie point.

The magnetic properties of a given material stem from the way the electrons in the metallic cores of a material or of a transition metal complex collectively couple their spins as this results in all their spin moments being aligned in the same direction.

Materials whose atoms are widely distributed throughout their crystal structure tend to better align these elementary magnets via a coupling effect. This category of materials, which is characterised by a very high positive magnetic

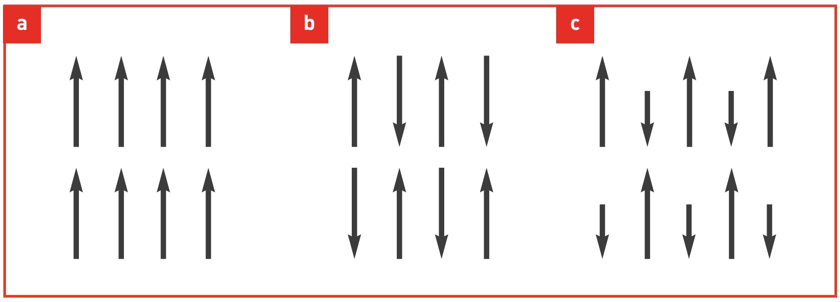


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

Stoiber Productions, München

A Transrapid train using magnetic levitation arriving at the Long Yang bus station in Shanghai (China). This German-built high-speed, monorail train was commissioned in 2004 to service the rail link to Pudong international airport.

susceptibility, includes iron, cobalt and nickel and their alloys, steels in particular, and some of their compounds, and, to a lesser extent, some rare earth metals and alloys with large crystal lattices, and certain combinations of elements that do not themselves belong to this category. In ferrimagnetic materials, the magnetic domains group into an anti-parallel alignment but retain a non-zero magnetic moment even in the absence of an external field. Examples include magnetite, ilmenite and iron oxides. Ferrimagnetism is a feature of materials containing two types of atoms that behave as tiny magnets with magnetic moments of unequal magnitude and anti-parallel alignment. Antiferromagnetism occurs when the sum of a material's parallel and anti-parallel moments is zero (e.g. chromium or haematite). In fact, when atoms are in a close configuration, the most stable magnetic arrangement is an anti-parallel alignment as each magnet balances out its neighbour so to speak (Figure E1).

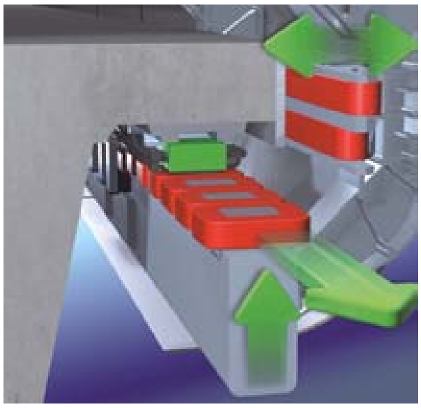
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field, the magnetic moments align up, thus amplifying this field. However, this effect decreases as temperature rises since the thermal agitation disrupts the alignment of the elementary dipoles. Paramagnetic materials lose their magnetisation as soon as they are released from the magnetic field. Most metals, including alloys comprising ferromagnetic elements are paramagnetic, as are certain minerals such as pegmatite.

3. Diamagnetic materials exhibit a negative and an extremely weak magnetic susceptibility of around 10^{-5}. The magnetisation induced by a magnetic field acts in the opposite direction to this field and tends to head away from field lines towards areas of lower field strengths. A perfect diamagnetic material would offer maximum resistance to an external magnetic field and exhibit zero permeability. Metals such as silver, gold, copper, mercury or lead, plus quartz, graphite, the noble gases and the majority of organic compounds are all diamagnetic materials.

In fact, all materials exhibit diamagnetic properties to a greater or lesser extent, resulting from changes in the orbital motion of electrons around atoms in response to an external magnetic field, an effect that disappears once the external field is removed. As Michael Faraday showed all that time ago, all substances can be "magnetised" to a greater or lesser degree provided that they are placed within a sufficiently intense magnetic field.

Electromagnetism

It was the Danish physicist Hans Christian Ørsted, professor at the University of Copenhagen, who, in 1820, was first to discover the relationship between the hitherto separate fields of electricity and magnetism. Ørsted showed that a compass needle was deflected when an electric current passed through a wire, before Faraday had formulated the physical law that carries his name: the magnetic field produced is proportional to the intensity of the current. Magnetostatics is the study of static magnetic fields, i.e. fields which do not vary with time.



Close-up of the magnets used to guide and power the train.

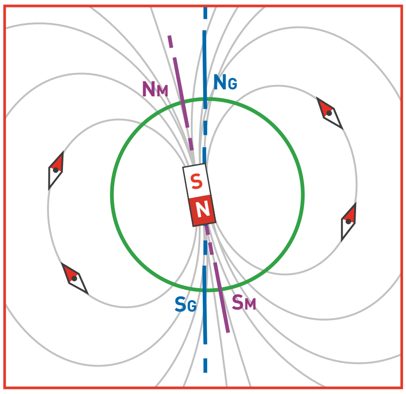
Magnetic and electric fields together form the two components of electromagnetism. Electromagnetic waves can move freely through space, and also through most materials at pretty much every frequency band (radio waves, microwaves, infrared, visible light, ultraviolet light, X-rays and gamma rays). Electromagnetic fields therefore combine electric and magnetic force fields that may be natural (the Earth's magnetic field) or man-made (low frequencies such as electric power transmission lines and cables, or higher frequencies such as radio waves (including cell phones) or television.

Mathematically speaking, the basic laws of electromagnetism can be summarised in the four Maxwell equations (or Maxwell-Lorentz equations) which can be used to provide a coherent description of all electromagnetic phenomena from electrostatics and magnetostatics to electromagnetic wave propagation. James Clerk Maxwell set out these laws in 1873, thirty-two years before Albert Einstein incorporated the theory of electromagnetism in his *special theory of relativity*, which explained the incompatibilities with the laws of classical physics.

FOCUS D

The Earth's magnetic field, weak but vital

The Earth has its own magnetic field, which acts like a giant magnet. Geomagnetism is the name given to the study of this field, which can be roughly described as a centred dipole whose axis is offset from the Earth's axis of rotation by an angle of about 11.5°. This angle varies over time in response to movements in the Earth's core (Figure). The angle between the direction of the *magnetic* and *geographic* north poles, called the



magnetic declination, varies at different points on the Earth's surface. The angle that the magnetic field vector makes with the horizontal plane at any point on the Earth's surface is called the magnetic inclination.

This centred dipole exhibits magnetic field lines that run between the north and south poles. These field lines convergent and lie vertical to the Earth's surface at two points known as the magnetic poles, which are currently located in Canada and Adélie Land. Compass needles align themselves with the magnetic north pole (which corresponds to the south pole of the 'magnet' at the Earth's core).

The Earth's magnetic field is a result of the dynamo effect generated by movements in the planet's core, and is fairly weak at around 0.5 gauss, i.e. 5 10^{-5} tesla (this is the value in Paris, for example). The magnetic north pole actually 'wanders' over the surface of the Earth, changing its location by up to a hundred kilometres every year. Despite its weakness, the Earth's dipolar field nevertheless screen the Earth from charged particles and protect all life on the planet from the harmful effects of cosmic radiation. In common with other planets in our solar system, (Mercury, Jupiter, Saturn, Uranus and Neptune), the Earth is surrounded by a magnetosphere that shields its surface from solar wind, although this solar wind does manage to distort the Earth's magnetic field lines.

The Earth's magnetic field is far from uniform. It is affected by magnetic anomalies which show up as variations in the magnetic field in relation to the global magnetic field. These anomalies can be quite large, affecting areas on a regional scale. One example is the *South Atlantic anomaly*, which affects the amount of cosmic radiation reaching the passengers and crew of any plane and spacecraft led to cross it.

The Earth's magnetic field has other, weaker, *non-dipolar* components whose effects are superimposed on the main dipole, but have far shorter time constants and so do not have any significant effect beyond the Earth's surface.

The Earth's magnetic field has fluctuated strongly over the course of geological time, suffering periods of major instability that occur with no observable regularity, and has experienced repeated reversals of its polarity. All this can be confirmed by studying the igneous or sedimentary sequences that accumulate on ocean floors. Both these rock types have the ability to acquire and lock in a magnetisation oriented parallel to the ambient geomagnetic field that existed at the time they cooled to their Curie temperature (Curie point), just below 500°C. These rocks can therefore be used to chart the polarity of the magnetic field that existed at the Earth's surface during this cooling period (or during their deposition as tiny magnetic sediment grains). This phenomenon, called magnetic remanence, was pivotal to the development of the field of paleomagnetism. The direction of the remanent field, which may be completely different from the present-day local field, provides a record of the polarity of the local field at the time the rock was formed. Volcanic rocks are first forced through the Earth's crust at a temperature higher than the Curie point of their constituent minerals. As they cool, they recross this Curie point and their constituent grains become magnetised in the direction of the ambient field. While sedimentary rocks are less sensitive to remanent magnetisation, any magnetic grains they contain will be magnetised in the direction of the Earth's magnetic field in existence at the time of their deposition.

Ocean floor sediments are particularly rich in magnetic minerals, the easiest of which to identify is the famous magnetite. This magnetisation is proportional to field strength and does not vary at standard temperatures. Other factors affecting remanent magnetisation include continuous action of the Earth's magnetic field, transient high-energy fields (due to lightning, for instance), and crystallisation processes, which can modify both the strength and direction of the magnetic field locked into the magnetic mineral grains.

Reversals and excursions in the Earth's magnetic field

The Earth's magnetic field records two types of instability, reversals and excursions. Reversals occur when the north and south magnetic poles switch polarity, an event that last took place some 790,000 years ago. This type of reversal was first suggested in France in 1906 by the geophysicist Bernard Bruhnes, but it was not until the 1960s that research started to pick up pace and confirm that these reversals were a global manifestation of the Earth's magnetic field. In particular, it was shown that these reversals were both erratic and unpredictable, alternating long periods of stable field polarity (lasting hundred thousand of years) with shorter periods of rapid field reversal (lasting just a few thousand years). It was also shown that the reversal rate had increased over the last hundred million years, from one reversal at the beginning of this period to four reversals per million years over the last five million years. This would seem to suggest that the current period of 'normal' polarity is 'abnormally' long. Geomagnetic excursions are simply shorter bursts of instability. While, like reversals, the polarity of the Earth's magnetic field flips over, it flips back to its initial polarity just as quickly. Research conducted by the Climate and Environmental Sciences Laboratory (LSCE, CEA-CNRS-Versailles-Saint-Quentin-en-Yvelines University) has demonstrated that excursion periods generally run for about 1,500 years, thus providing preliminary confirmation of the theory suggested by English geophysicist David Gubbins, according to which excursions only occur in the Earth's external *liquid* outer core and not in its inner *solid* core.