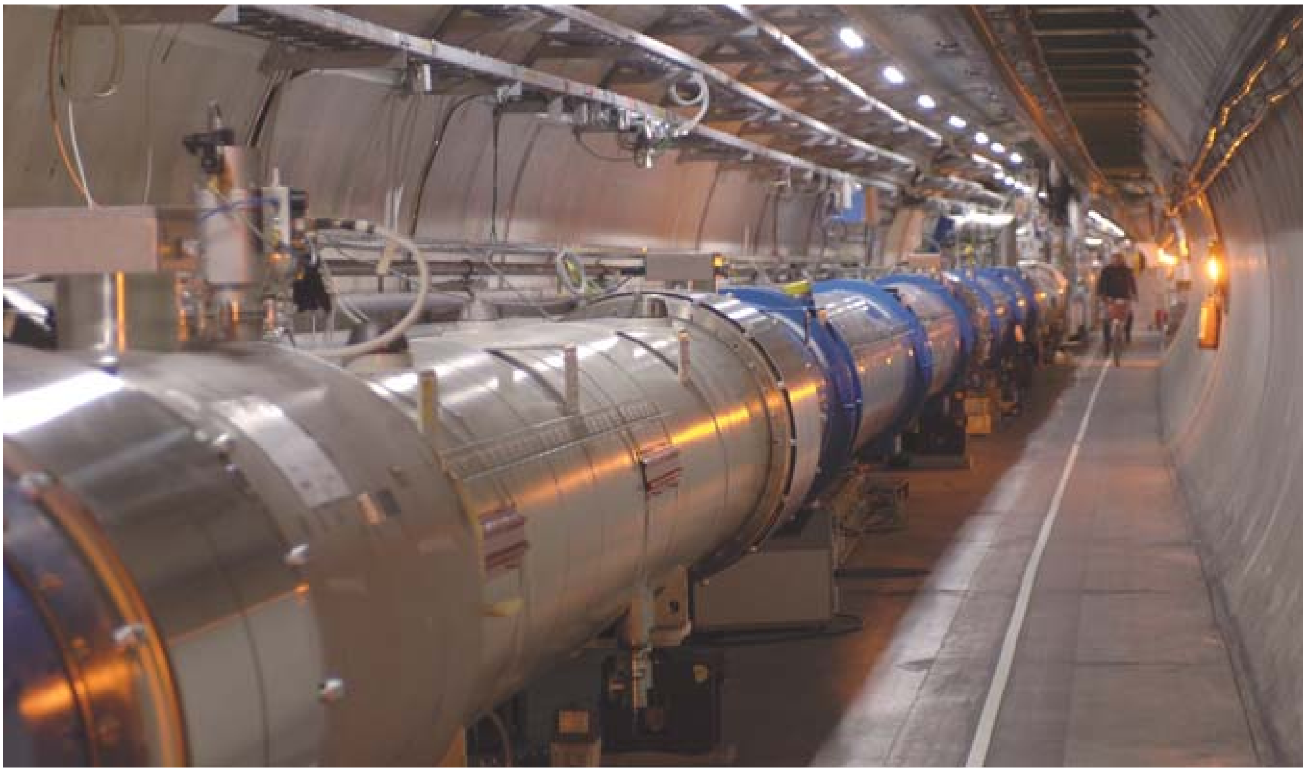
# Superconducting magnets for the LHC

**The Large Hadron Collider (LHC), the world's largest highest-energy particle collider that the CERN plans to commission in 2008, gets a double boost from superconducting magnet technology.** Superconducting magnets are first used to guide the particles scheduled for collision through the accelerator, and then to observe the events triggered by the collision inside giant detectors in a known magnetic field. Despite the installation's massive dimensions, all this is done with minimal expenditure of energy.



P. Stroppa/CEA

The tunnel housing the LHC (Large Hadron Collider), the world's largest and highest-energy proton-proton collider installed at the CERN site. The LHC has a circumference of 27 km and is fully equipped with superconducting magnets designed to guide and focus proton beams along a circular trajectory. The CEA is involved in building the LHC by deploying its expertise in the design of two of the four detectors and the construction of certain key machines such as the superconducting dipoles and quadrupoles.

Physicists are continuously pushing back the boundaries of research into the structure of matter using increasingly powerful **resolution** techniques. The primary focus of high-energy nuclear physics is to identify the elementary constituents of matter and understand how they interact. The **particle accelerators** used in this research act like microscopes, probing matter with a **spatial resolution** that improves as the energy of the accelerated particles increases(1). Indeed, since the 1950s, physicists have been steadily progressing in the construction of ever more powerful accelerators used in the field of nuclear physics (Figure 1). Technological advances, particularly in the field of **superconducting electromagnets** (Focus B, ***Superconductivity and superconductors***, p. 16), have enabled physicists to design and build the magnetic systems equipping the Large Hadron Collider (LHC)(2) currently being installed at the **CERN** "European Organization for Nuclear Research" site near Geneva. A **magnetic field** is deployed to bend particle beams, either to steer them through the accelerator on orbits with a highly specific geometry, or to analyse the products of head-on proton-proton collisions between the detectors.

(1) A resolution of $10^{-19}$ m (at *quark* scale) requires 1 **TeV** ($10^{12}$ **electronvolts**).

(2) Hadrons: sub**atomic** particles composed of *quarks* (or *antiquarks*) that are subject to *strong nuclear interactions*. **Protons** and **neutrons** are both hadrons.

(3) Livingston plot: diagram developed in the 1960s by the American physicist Stanley Livingston, who demonstrated the exponential increase in beam energy (as an eV multiple assuming a collision with a proton or an electron at rest) during centre-of-mass acceleration in particle accelerators, together with the increase in cost per eV of beam energy as a function of time (years).

## The main components of a circular collider

Particles travel in a circular vacuum chamber surrounded by a guiding sequence of electromagnetic systems, and are accelerated via electric fields in

high-power radio-frequency cavities. To make the most effective use of a limited number of RF cavities, the accelerator designers force the particle beam through these cavities many times by creating a closed-loop beam trajectory. The circular path of the proton beam axis is obtained by passing it through a series of ring sections with a uniform magnetic field created by dipole magnets; higher particle energies require stronger fields to bend their path (see Box). Quadrupole focusing magnets are introduced to focus the beam, prevent it scattering and constrain its width within reasonable bounds either side of the beam axis. In this type of component, the magnetic field increases linearly with increasing distance from its axis, while the focal length is inversely proportional to the transverse induction gradient. Storage rings are principally designed to produce head-on collisions between two counter-rotating beams of protons. These collisions take place at carefully chosen points on the machine's circular frame, these points being surrounded by detectors designed to track and identify the events triggered when two beams collide. Particle movement is quantified by measuring the bending of their trajectories within a known magnetic field, while their energy is measured by calorimeters.
The CEA is involved in building the LHC, the world's largest and highest-energy proton-proton collider, at the CERN, by deploying its expertise in the design of two of the four detectors and in the construction of certain key machines such as the quadrupoles. The collider will be used to accelerate two counter-rotating beams of protons around a 27-km circumference circular tunnel embedded underground at a depth of between 50 m and 170 m. These beams will travel at a speed close to the speed of light, producing violent head-on proton-proton collisions with energies of 14 TeV at the points where the beams intersect. This immense scientific challenge required the technological and industrial prowess to build 1,200 superconducting dipoles producing a magnetic field of 8.4 T, 400 superconducting quadrupoles providing a magnetic field gradient of 223 T/m, a superfluid helium cryogenic system which cools the magnets down to 1.9 K, and two gigantic detector systems, named Atlas (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid).

## The advantages of using superconducting electromagnets

A key property of superconductive bodies is that their electrical resistivity drops to zero below a certain critical temperature, meaning that there is no energy loss via a Joule effect. Some of these materials, such as niobium-titanium, can carry current densities of around 3,000 A/mm² in induction fields of 5 T to 4.2 K. By comparison, the materials used to make the coils for conventional electromagnets, typically copper or aluminium, can only produce current densities of between 5 and 50 A/mm² depending on the cooling method. Their very high current densities mean superconducting electromagnets are able to produce ultra-high magnetic fields via a system of compact coil assemblies, which significantly

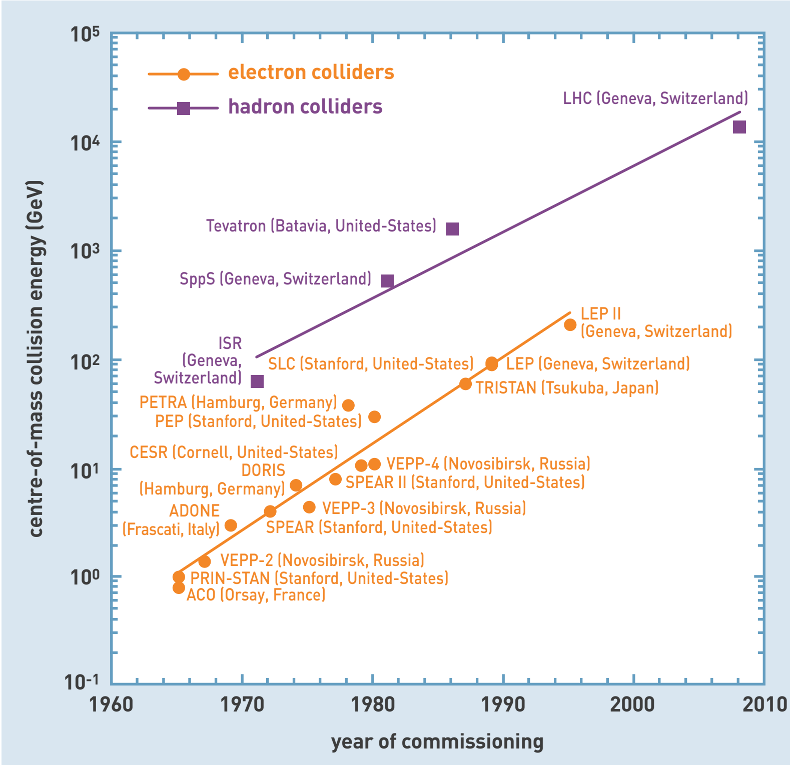
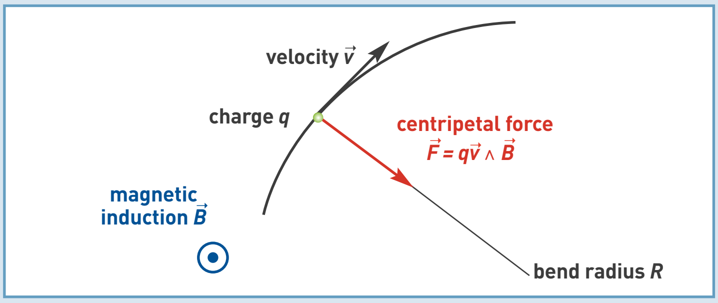



Figure 1.
Livingston plot[3] giving a timeline of energy levels increasing from 100 MeV in 1950 to several tens of GeV in 1975 and then to several hundred GeV in 1990. The LHC, which is scheduled to begin operations in 2008, will be the world's highest-energy particle accelerator, with a proton-proton head-on collision energy of 14 TeV.

## How does an electromagnetic field act on a charged particle?




Electrically charged particles are subject to the action of an electric field $\vec{E}$ or a magnetic field $\vec{B}$. The force, called the Lorentz force, experienced by a charged particle with charge $q$ moving at velocity $\vec{v}$ in an electromagnetic field is expressed as:

$$\vec{F} = q\vec{E} + q\vec{v} \wedge \vec{B}.$$

$\vec{E}$ and $\vec{B}$ act very differently on the particle's movement. The particle accelerates as it moves through an electric field $\vec{E}$, thus gaining kinetic energy: the electric force ($q\vec{E}$) is an *accelerating force*. This is the fundamental principle of accelerator cavities. Conversely, when moving through a magnetic induction field $\vec{B}$, the magnetic force or Laplace force ($q\vec{v} \wedge \vec{B}$) is perpendicular to $\vec{v}$ and $\vec{B}$ and does not cause any change in kinetic energy. This is a *bending force* used to guide particle beams. In a uniform magnetic induction field $B$, a particle with mass $m$ moving at velocity $v$ follows a circular trajectory with an average radius $R$, such that:

$$BR = \frac{mv}{q},$$

where $mv$ represents the momentum of the particle.

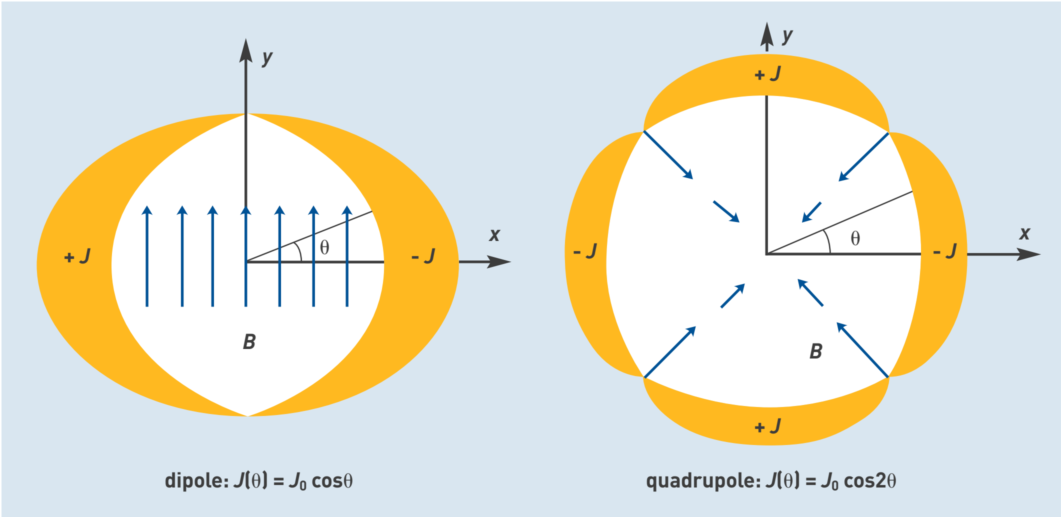
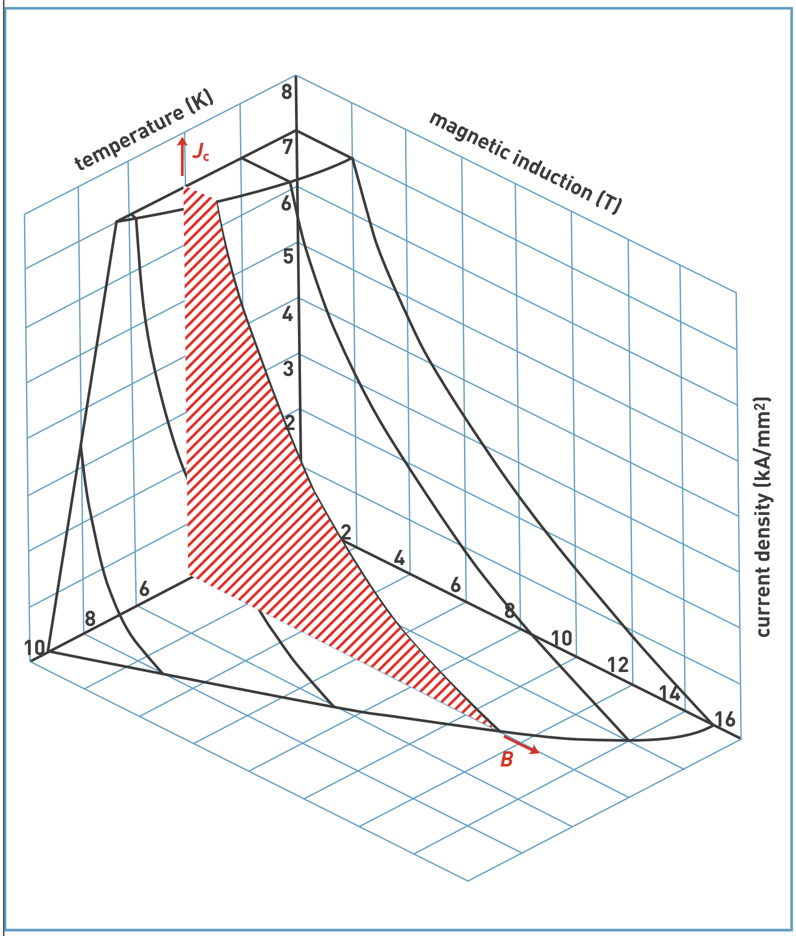



Figure 2.
Distribution of the current density $J(\theta)$ and associated magnetic field lines in a superconducting dipole and quadrupole.

reduces the overall dimensions and cost involved in constructing a ring collider. Operating costs are also minimized by reducing the consumption of electrical power, which is only needed to run the magnet cooling facilities. If the LHC used conventional 'warm' magnets instead of superconducting magnets, the ring would have to have a circumference of 120 km in order to achieve the same collision energy, and would use 40 times more electricity.




According to M. N. Wilson

Figure 3.
Niobium-titanium phase diagram. The hatched area gives the curve $J_c(B)$ at 4 K, i.e. the maximum current density in the superconductor cooled to the temperature of liquid helium and subjected to a magnetic induction field $B$.

Ordinary electromagnets comprise pure iron poles positioned around conductive coils. The magnetic inductions created in the air gap between these devices rarely exceed 2 T, as the **saturation magnetisation** of iron is reached. Conversely, iron has only a negligible effect in superconducting magnets and is mainly used to provide magnetic shielding with regard to the outside world. The usable field is produced directly via the superconducting conductor coils while current densities are distributed throughout the coils in a specific pattern in order to obtain the exact morphology required for the dipole and quadrupole magnetic fields (Figure 2).

It is essential to set the nominal operating point of a superconducting conductor below its critical values for temperature, magnetic induction and current density (Figure 3). Superconducting materials providing ultra-high **critical fields** (up to 20 T) and high current densities are referred to as **type II superconductors** (niobium-titanium, **niobium-tin**) and exhibit critical temperatures of below 20 K (Figure 4). The coils have to be cooled and maintained at their operating temperature using a cryogenic fluid such as liquid helium, which has a boiling point of 4.2 K at atmospheric pressure. At this very low temperature, the coils react to the slightest thermal disturbance due to the material's very low heat capacities, which are about 2,000 times less than at ambient temperature; a movement of just 10 micrometers (1 µm = $10^{-6}$ m) in the conductor can generate an energy loss sufficient to heat the conductor by 3 K, which would lift the superconductor's temperature above its critical point. When employing superconducting electromagnets, it is vital to be able to control and prevent quench, which occurs when all or part of a superconducting coil suddenly and accidentally reverts from a superconducting state to a normal state.

Superconducting magnets are therefore fitted with safety systems designed to act on quench and prevent coils being damaged by the generation of heat.

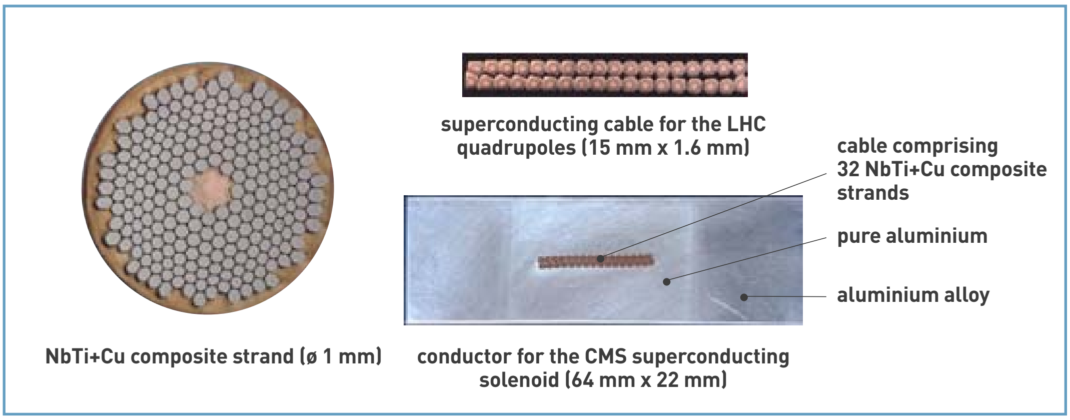



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Figure 4.
Cross-sections through superconducting conductors. Current technology deployed in superconducting electromagnets uses monolithic conductors or cabled conductors that employ **composite** strands comprised of thousands of extremely fine superconducting filaments (around ten microns) embedded in a copper matrix.

## Design issues that need to be addressed early on

Cryomagnet design must ensure the system covers design imperatives regarding issues such as superconductor use, quench protection, mechanical design and the cooling system. Once designers have selected the appropriate operating temperature for the target magnetic field and have identified which properties will be exhibited by the superconducting material at this temperature, they can then determine an average current density that takes account of the amount of stabilising material, the thicknesses of the electric insulators and the empty spaces. This average current density is then used to presize the magnetic system allowing designers to define the characteristics of the superconducting conductor and, where necessary, adjust coil dimensions to obtain the target magnetic field.
Quench is an adverse event, which cannot be ignored and must be factored into the design of the magnet. As the superconductor becomes resistive during quench, the current is diverted into the stabilising material which then dissipates the energy in the form of heat via a Joule effect. The heat generated allows the quench to spread to neighbouring sections and an electrical voltage appears at the terminals of the newly-resistive area. Superconducting magnets are quench-protected by setting up a rapid quench detection system, and by dissipating part of the energy stored within the magnet to outside resistors. Heaters may be used to deliberately spread the quench to all magnets in order to limit the temperature rise at the quench source location. This effectively minimizes the amount of energy deposited per unit of volume and also curbs the electric voltage at the magnet's terminals, which could damage the insulation.
Mechanics is another key issue in cryomagnet design. The **Lorentz forces** acting on any conductor placed in a magnetic field generate enormous stresses on superconducting magnet coils. As the materials making up the coils, in particular insulating materials, have fairly low mechanical strength, the mechanical stresses have to be kept within acceptable values throughout the coil's lifetime. Designers also have to limit any potential movement of the conductors in the magnetic field as this would generate the local heating likely to result in quench. Furthermore, the magnet's structure not only has to withstand the overall stresses but also limit distortions that could modify the **magnetic field lines** and, therefore, the quality of the field.
One feature of superconductors is that they operate at very low temperatures, an aspect that must be carefully calculated in order to reduce the mechanical stresses generated by differences in thermal contraction(4) between the various materials. In addition, any heat likely to raise magnet temperature must be evacuated: this heat is usually generated when the cryostat containing the magnet transmits heat through its support posts, instruments and current feeders. This rise in temperature may also be generated by the energy deposited within the magnet itself, produced by non-static operation or by beam radiation.
Although they bring a number of different specialist areas into play, all these aspects must be dealt with jointly, taking account of the manufacturing technology used to achieve a design that meets all the requirements. Successful design also depends on running comprehensive tests to validate physical quantities or technological preferences.

## Four hundred quadrupole magnets for the LHC

A preliminary study carried out between 1989 and 1993 at the Saclay CEA centre (Essonne) as part of a joint CEA-CERN project led to the construction and testing of two quadrupole **cold masses** with a magnetic field gradient of 250 T/m. These two magnets were then inserted into a chain of magnets built to validate the design of the LHC system. As part of France's contribution to the LHC project, the CEA was commissioned to design, build and test three new cold mass prototypes with a magnetic field gradient of just 223 T/m, which have successfully validated the design choices. These quadrupole magnets are 3.2 m long and operate at 1.8 K, a temperature at which helium is superfluid. It was the

(4) Thermal contraction: decrease in the dimensions of a material as its temperature drops.


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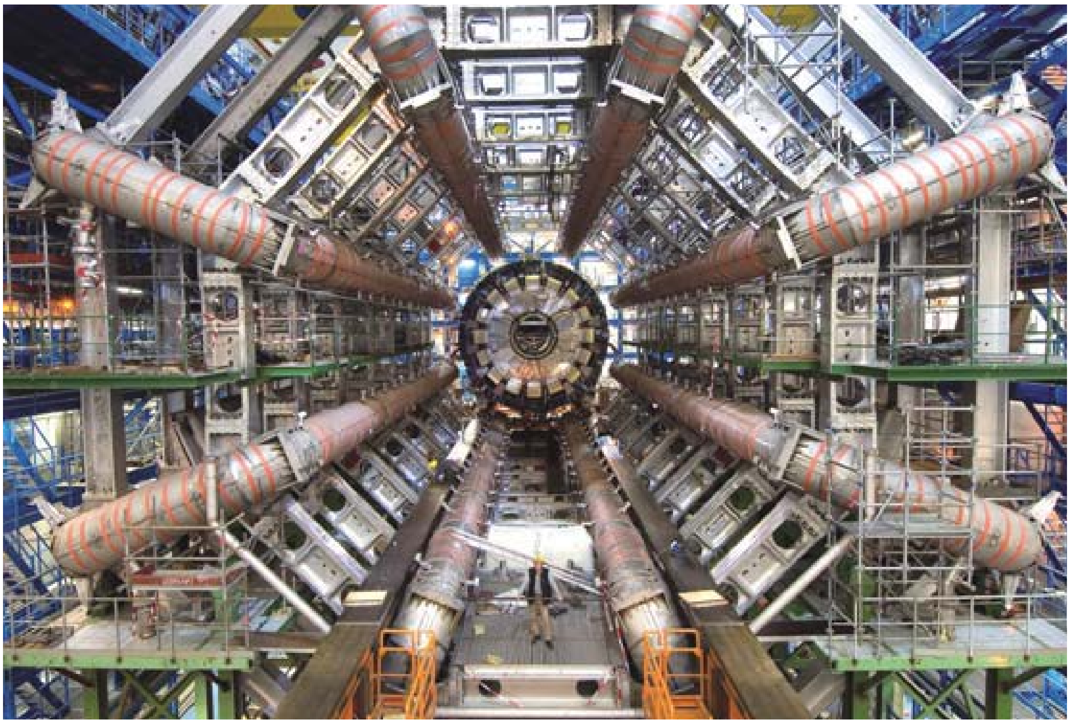
The LHC's double-aperture quadrupoles share the same magnetic and cryogenic structure. Key magnet features are a length of 3.2 m, an aperture of 56 mm and a magnetic field gradient of 223 T/m.

CEA's expertise in designing and building superconducting magnets, experience acquired when working on the Tore Supra project, that paved the way for using superfluid helium in the LHC system.
Two quadrupole magnets, built as separate mechanical units, are carefully placed in a magnetic yoke made out of carbon steel. Each quadrupole is able to withstand huge electromagnetic burst forces of 110 tons per metre of magnet. These forces are absorbed by non-magnetic stainless steel collars. Along with other beam-correction magnets, the double-quadrupole magnet is mounted in the cold mass, which measures some 6 m in length and contains superfluid helium. The coils have to be built to a precision of twenty microns and with a yield strength that keeps deformation down to 0.1 mm in order to ensure the magnetic field has the required quality.
The CEA took on the technology transfer and production follow-up during series fabrication at the German manufacturer **Accel Instruments**, which built 400 cold mass units. Production was successfully completed in late 2006, and out of all the magnets produced, only one cold mass was actually rejected. Once they had been assembled in their cryostat housings at the CERN, all the components were lowered into the LHC tunnel and connected up to their neighbouring magnets. The LHC accelerator is scheduled to officially begin operation before summer 2008.

## The magnets equipping two large LHC detectors

The Atlas and CMS detectors use single magnet systems which both operate at a temperature close to that of liquid helium and have their own separate helium liquefaction system. While these magnets generate weaker magnetic fields than the quadrupoles, they magnetise far greater volumes. Rapid extraction of the stored energy is, however, impossible, meaning that the conductor has to be built to withstand a high current for a period of several minutes without suffering damage (compared to a few tens of milliseconds for a quadrupole magnet). Although physicists were confronted with the same design issues during construction of the quadrupoles and the detector magnets, they had to find and apply a different set of solutions in each case. The CEA has been working on the design studies for the main toroidal magnet for the Atlas detector and the


CERN

Central toroid of the Atlas detector in its cavern at the CERN facility. The eight superconducting coils are laid out in a star-shaped configuration, resemble ellipses 25 m long and 5 m wide, and are powered by a 20,500 A current.

CERN

Assembly of the superconducting solenoid for the CMS detector at the CERN facility. The magnetic yoke (in red), housing the vacuum chamber, is slid into place around the solenoid which is encircled by its thermal screens. In yellow, the platform used to assemble the coil and tilt it from the vertical to the horizontal position.

**solenoid** for the CMS detector since the late 1980s. They are scheduled to begin operation during 2008.

### The toroidal magnet system equipping the Atlas detector

The central toroid of the Atlas system comprises 8 superconducting coils 25 m long and 5 m wide arranged like a torus around the collision point of the two particle beams. The system has a stored energy of 1,100 **MJ** for a field strength of 0.4 T at the centre of the toroid and 3.9 T at the superconductor. The Saclay Centre first developed a prototype coil at 1/3 of the full length that was tested at the CERN in 2001, successfully validating the design choices. The final coils were assembled at the CERN using components provided by European industrial partners. The CEA monitored industrial manufacture of most of the components, in addition to technical monitoring of their assembly and individual testing at CERN surface test facilities, and went on to monitor their assembly in the Atlas experiment cavern. In November 2006, the toroid assembly successfully completed the planned test series, effectively carrying a 21,000 A current (i.e. 500 A more than the nominal current) with zero quench. Assembly of the other magnets and detectors is currently in process, with the Atlas experiment scheduled to be up and running sometime during the first six months of 2008.

### The superconducting solenoid of the CMS detector

At 7 m in diameter, 12.5 m in length and with a magnetic field strength of 4 T, the superconducting solenoid for the CMS experiment holds the record for total stored magnetic energy with an impressive 2.6 **GJ** as well as the record for the amount of magnetic energy stored per coil mass unit. The solenoid comprises 5 modules formed of 4 conductor layers stabilised by pure aluminium mechanically reinforced by an aluminium alloy (a new concept pioneered by the CEA). The conductor is wound inside an external cylinder which provides support and cools the system using helium circulated naturally via a thermosiphon heat exchanger. The 5 modules manufactured by European industrial partners were delivered and assembled in vertical position at the CERN's surface testing facility where they were successfully tested during summer 2006. The magnet was then dismantled and lowered into the CMS experiment cavern where it is currently being reassembled. It is scheduled to be commissioned during the first six months of 2008. The CEA played a central role in the design and industrial manufacture of the superconducting magnet and the subsequent assembly and cold testing operations carried out at the CERN facility.

## Planned upgrades

Even though the LHC has yet to go into operation, physicists have already started discussing options for future improvements, in particular on how to increase the machine's luminosity(5) tenfold. Projects are underway to manufacture new large-aperture (130 mm) niobium-titanium quadrupoles, produce niobium-tin dipoles supplying a field strength of 13 T within an aperture of 100 mm, and even inserts using **high-critical-temperature superconductors** (Bi2212 or YBCO). All these projects will require a significant R&D input which the CEA will provide through its solid expertise in the field.

(5) Luminosity: along with the beam energy range, one of the two fundamental parameters that sets the boundaries of particle collider design. It is given by the formula $L = f^2n^2k^2/A$ (in $cm^{-2} \cdot s^{-1}$), where $k$ is the number of particles making up a bunch in each beam, $n$ the number of bunches, $A$ is the beam cross-section, and $f$ is the beam-crossing frequency.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FOCUS B

# Superconductivity and superconductors


P. Stroppa/CEA

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 $\lambda_L$ 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.

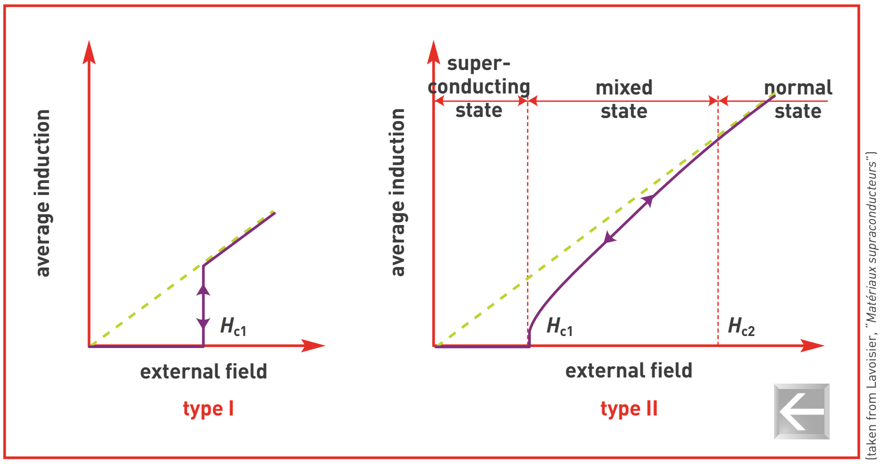


Figure 1.
Average induction in type I and type II superconductors under an externally applied magnetic field.

## 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 ($2.07 \cdot 10^{-15}$ 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 $\xi$ and penetration depth $\lambda_L$, which characterise the interface between a normal region and a superconducting region. $\xi$ represents the spatial variation of the superconducting state (i.e. the density of the superconducting electrons) and $\lambda_L$ 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 $\kappa$ ($\kappa = \lambda_L/\xi$), 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 $\lambda_L$, 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 $\kappa$. In type II superconductors, the

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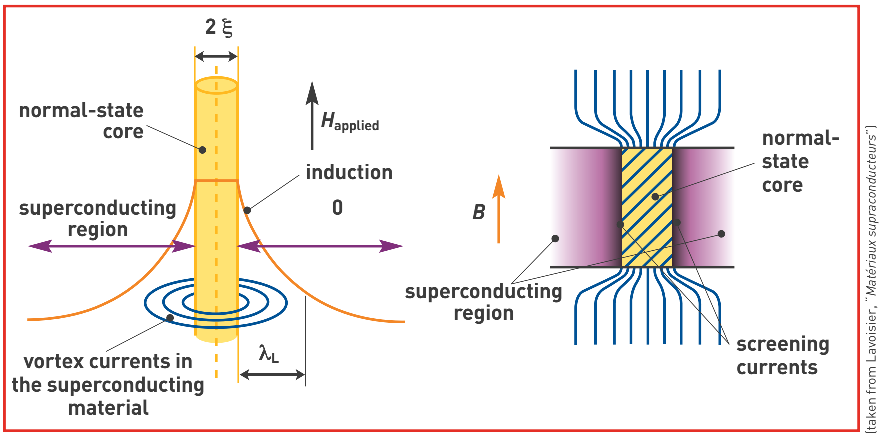
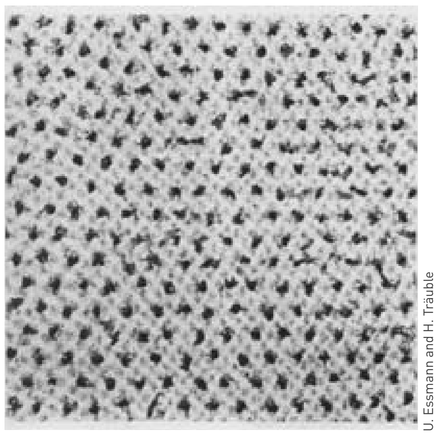



Figure 2.
Diagram of a vortex illustrating penetration depth and coherence length.




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

# FOCUS B

| material | | $\xi$ (µm) 0 K | $\lambda_L$ (µm) 0 K | $\kappa$ | $T_c$ (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 $\mu_0$ is the **magnetic permeability** of a vacuum (and of the material in this particular case).

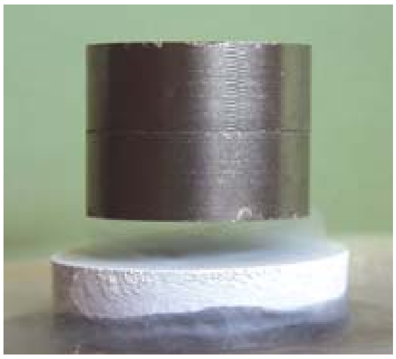
*page 17 cont'd*
mixed state therefore results from the creation of a large number of interfaces, with each interface corresponding to a negative energy balance conducive to superconductivity above the $H_{c1}$ field (Table).

## 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.

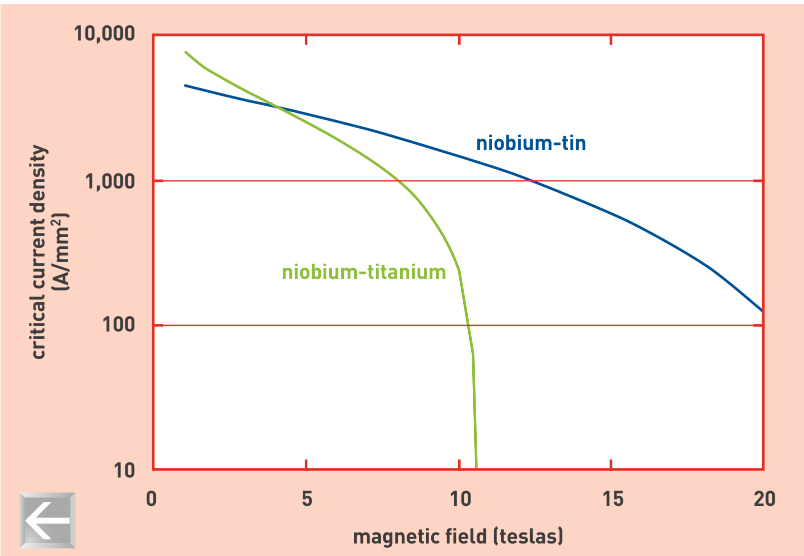



Figure 3.
Characteristic critical current densities in relation to a 4.2-K magnetic field for the two superconducting materials most widely used, particularly in the manufacture of superconducting magnets.

(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.

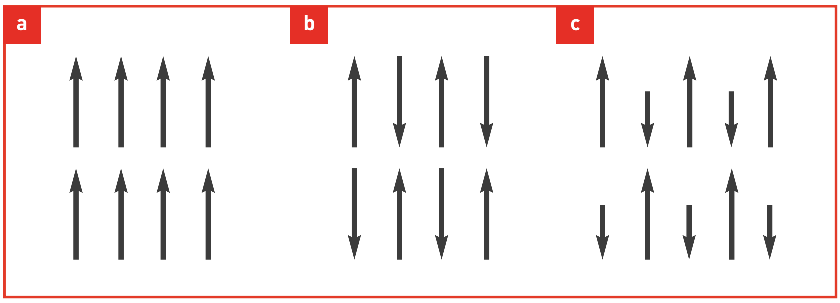



Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

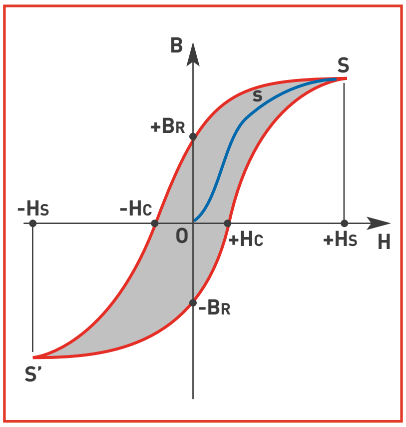



Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches 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

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. Anti-ferromagnetism 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).

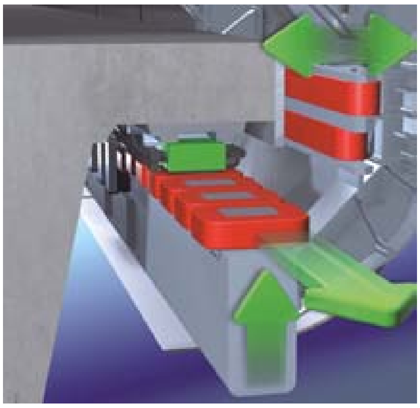
**2.** Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around $10^{-3}$). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic 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.