Spaceborne scalar **magnetometers** to map the **Earth's magnetic field**

Current nuclear magnetic resonance magnetometer technology will soon be superseded by spaceborne helium magnetometers developed at CEA-LETI with the aim of mapping the Earth's magnetic field at unprecedented resolutions.

Christian Morel/www.morel-photos.com

Probe of the helium magnetometer developed for the Swarm project. This highly sensitive component is fixed to the end of the boom in order to keep it as far away as possible from any magnetic disturbance generated by the satellite. The Swarm mission will provide valuable data critical to building up a reliable model of the Earth's magnetic field. **EADS Astrium** has been tasked with developing and building the three satellites forming the backbone of the project.

Ever since the discovery of the compass, sailors have used the **Earth's magnetic field** (Focus D, ***The Earth's magnetic field, weak but vital***, p. 99) to navigate at sea. However, it is only recently that scientists have really begun to map this field in any detail and study its temporal variations. For many years, ground magnetic coverage of the Earth's field was provided by a diverse range of sources, mainly national magnetic observatories grouped in the Northern hemisphere, none of which offered comparable station density or resolution capabilities. Several dedicated missions undertaken in poorly covered areas, like the polar regions, at least went some way to providing insight on the average magnetic field over the continents. At the same time, systematic ocean-floor measurement surveys were organised with the aim of completing our highly fragmented picture of the Earth field's geographic distribution. The last major globally coordinated research initiative dedicated to filling in these gaps was conducted way back in the early 1970s by combining land and ocean measurements with extensive aerial surveys. This situation, however, was to change radically with groundbreaking advances in satellite technology. Thus, at the beginning of the 1980s, the data collected by the American-built satellite Magsat (Magnetic Field Satellite) launched by **NASA** made it possible to construct the world's first high-precision map of the Earth's magnetic field. Since then, spaceborne observation of the Earth's magnetic field has been a core priority of the French scientific community which is playing a central role in developing the magnetics component of the international programme "*Decade of Geopotential Research*".

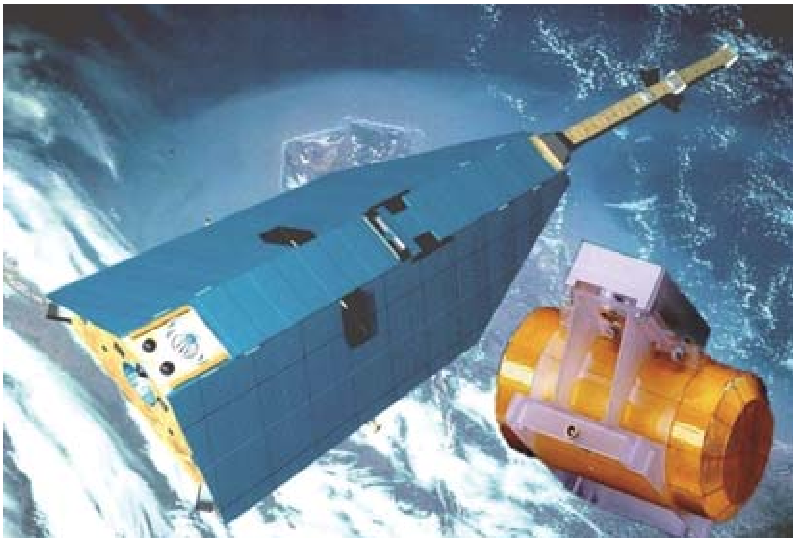
NMR probes optimised to meet the specific needs of space applications

Since the mid-1990s, the Laboratory of Electronics and Information Technologies (CEA-LETI) has been working closely with **CNES** (the French National Space Research Centre) to develop spatialised versions of high-**resolution** scalar(1) **magnetometers** specifically for use in spaceborne applications. Initially developed to detect magnetic anomalies in the Earth's field, these magnetometers are set to become the benchmark for missions involving mapping from space. Although the **magnetic field** is, as you would expect, a vector quantity(2), the vectorial magnetometers capable of measuring its component parts do not provide absolute measurements. This means they have to be regularly calibrated if they are to provide data of the desired precision, which is exactly what scalar sensors are designed to do.

These magnetometers exploit the fact that the energy levels of certain **atoms**, when subjected to a magnetic field, split into several sub-levels separated by gaps which are directly related to the intensity of the ambient magnetic field (**Zeeman effect**). Measuring this energy using conventional **magnetic resonance** techniques makes it possible to calculate the field strength to a high level of precision. However, the performance of such instruments, particularly in terms of resolution, generally depends on the probe's orientation with respect to the target field. If no corrective measures are taken, there will always be some directions in which the probe will be unable to take measurements. In order to harness the full capabilities of such a magnetometer for onboard applications where, by definition, this relative orientation is likely to vary and is generally not known, engineers have to determine novel architectures to overcome the constraints of these dead zones.

Having identified this point as a critical issue well upstream in the development process, LETI opened its research into magnetometry technology by focusing on how to produce isotropic probes, i.e. probes whose features are fully independent of their spatial position and orientation. This research made it possible to build magnetometers with ultra-high precision, thus giving them an unbeatable edge for use in missions to map the Earth's magnetic field from space. Therefore, **nuclear magnetic resonance** (**NMR**) probes, optimised to meet the specific needs of Earth observation programmes based on orbital measurements, have been fitted onboard the Oersted and CHAMP (CHAllenging Minisatellite Payload) satellites designed to map the Earth's magnetic field and launched in 1999 and 2000, respectively. These instruments were built to provide absolute measurements of the strength of the geomagnetic field and to calibrate the vectorial magnetometers completing the onboard magnetic field instrumentation set-up. As such, they have been pivotal to the success of these missions, whose results have provided the basis for the latest geomagnetic field **models** (Figure 1).

NMR probe technology made the crossover to industry in the late 1990s, boosted by the results obtained during the many successful qualification studies carried out during the preliminary phase of these space missions.


Astrium - CEA

Artist's impression of the German-built CHAMP satellite with the LETI-built NMR probe fixed to the end of its boom (close-up at right). The CHAMP mission is being run by GeoForschungsZentrum (GFZ).

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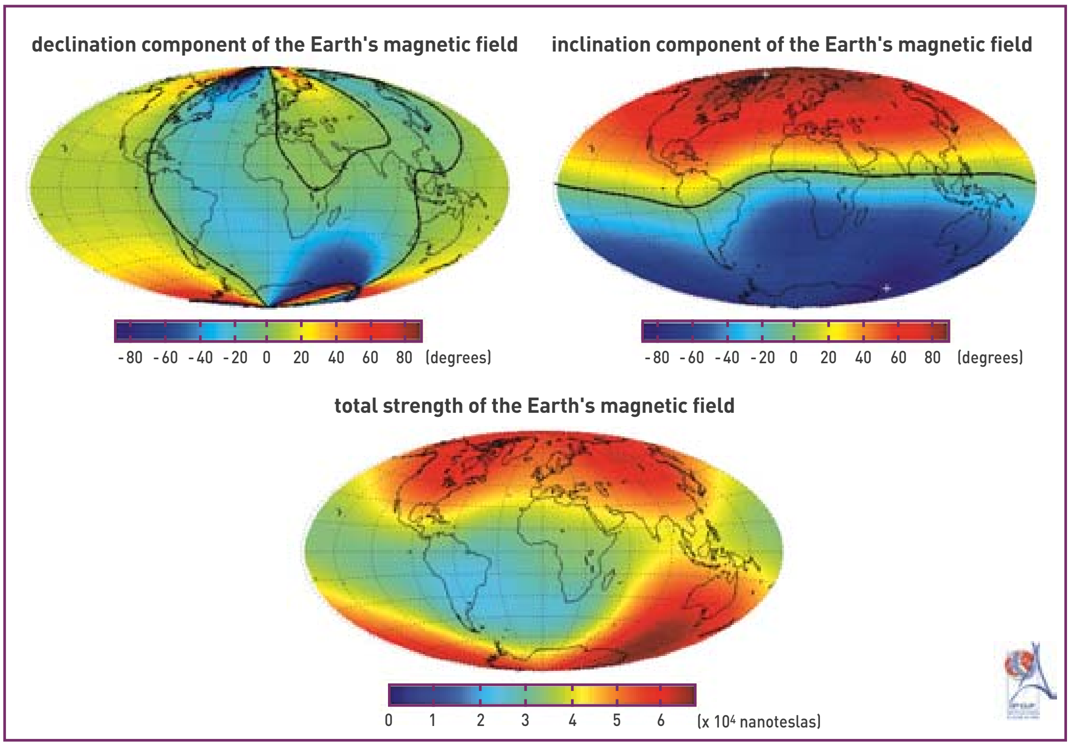
(1) Scalar magnetometers only measure the strength of a magnetic field.

(2) A vector quantity is characterised by both its magnitude and its direction.

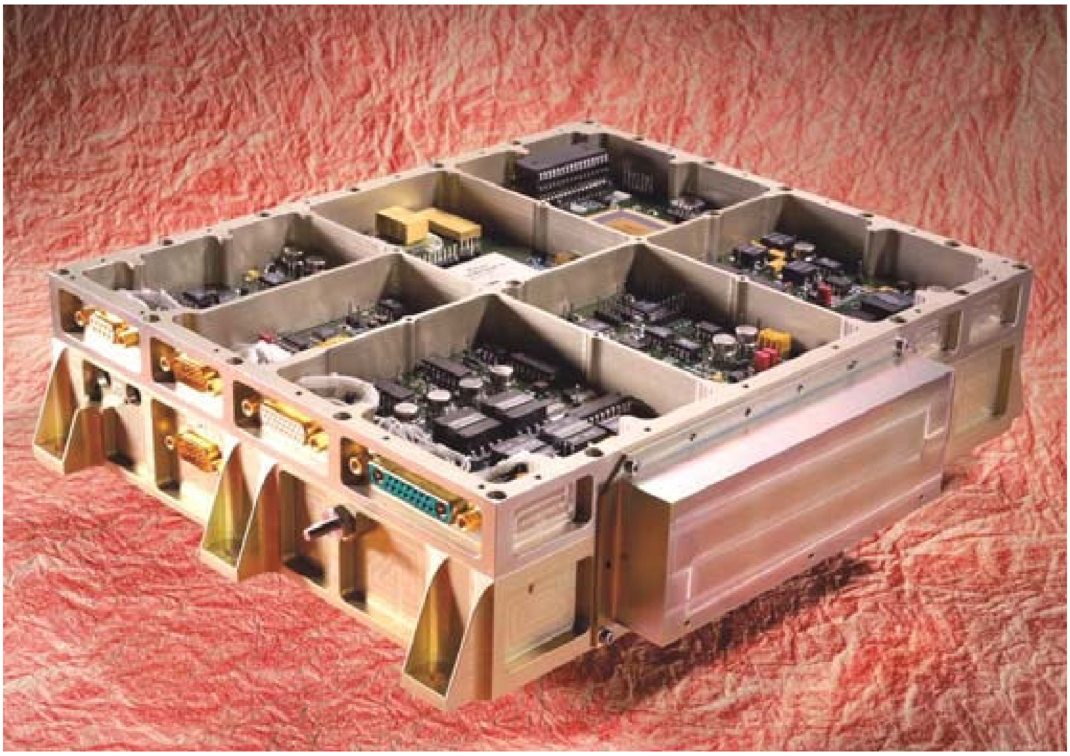

declination component of the Earth's magnetic field

inclination component of the Earth's magnetic field

total strength of the Earth's magnetic field

IPGP

Figure 1.
Map of the geomagnetic field strength at the surface of the Earth derived from the model produced using data from the Danish Oersted satellite.



Electronic unit fitted in the main satellite housing and used to control the probe on the Swarm project's helium magnetometer.

CEA/G. Galoyer

A new generation of magnetometers

At the same time, LETI began work on developing a new generation of ultra-high-resolution scalar magnetometers using **helium 4**. This new type of probe has a definite edge over its predecessors in terms of environmental susceptibility (mainly **electromagnetic** compatibility and magnetic gradient performance). Its other strengths include enhanced metrological performance such as low-field resolution - a feature that represented a huge technological challenge for NMR probes and which has been ramped up by more than an order of magnitude - and its measurement bandwidth which has been multiplied a thousand-fold. This is particularly valuable when carrying out satellite integration phases and ground tests as it makes it possible to check the integrity of the magnetometer throughout the whole testing period. This novel instrument, which incorporates several innovative technological hardware features (laser, **piezoelectric** actuator, integrated digital processing circuit developed specifically for this application) is currently undergoing qualification testing for space application being coordinated by CNES and is scheduled to be fitted onboard the three satellites making up the Swarm project for 2010.

Designed to underpin the **European Space Agency** (**ESA**) programme "Observing the Earth", this mission is dedicated to mapping the Earth's magnetic field at unprecedented resolutions by deploying a constellation of three cross-linked satellites orbiting the Earth on neighbouring trajectories. One advantage of this satellite constellation is that the focus on altitudes and local times makes it possible to better differentiate contributions from the various field sources (internal field, lithospheric(3) field, currents induced within the Earth and by the movement of large ocean water masses on the surface of the Earth, ionospheric(4) and **magnetospheric** currents), thus providing insight into key issues concerning the planet's internal dynamics, particularly the workings of the Earth's **dynamo**, which is still poorly understood.

Another unique feature of the instrument proposed for this project will be to test a novel concept designed to enable researchers to take absolute and vectorial geomagnetic field measurements using the same probe. This represents a major technological innovation in the field of spaceborne magnetometry, insofar as such a solution would make it possible to reduce the onboard instrument payload, thereby streamlining satellite design.

CEA's involvement in this mission will also strengthen existing research partnerships with CNES and the French (**Institut de Physique du Globe de Paris**) and European laboratories (the German **GeoForschungsZentrum**, the **Danish Space Research Center**) tasked with processing this data.

These developments are set to culminate in early 2010 when the Swarm constellation is placed in orbit. Helium magnetometers will thus symbolically take over from the NMR technology placed onboard previous missions. Combined with the set of data collected by NMR probes, the helium magnetometer measurements will provide over ten years of continuous ultra-high-resolution magnetic observations from space, thus making it possible to track mid-term changes in the strength of the geomagnetic field over the Earth's entire surface.

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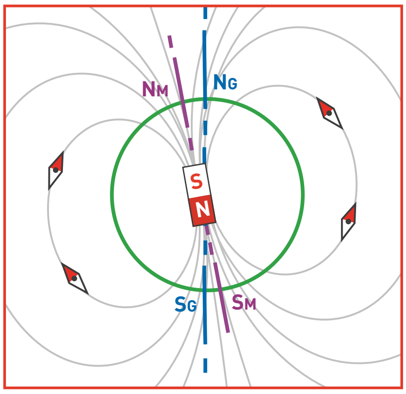
(3) Lithosphere: solid outer shell of the matter making up telluric bodies. On Earth, it comprises the crust and the outermost part of the upper mantle.

(4) Ionosphere: region of charged particles in the upper atmosphere. The Earth's ionosphere extends between 40 km to 460 km or more.

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.

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.

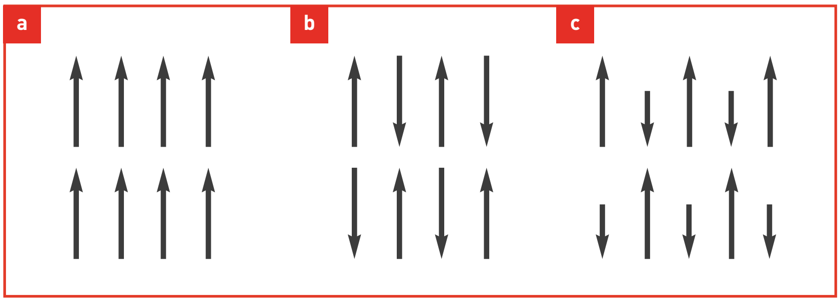


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

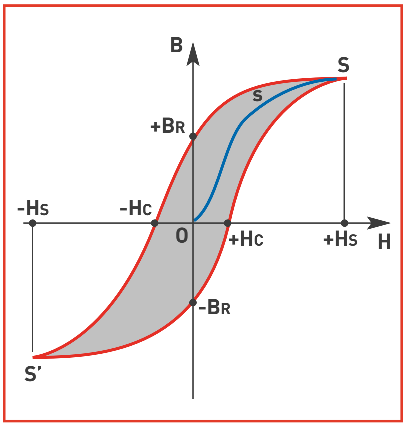


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches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

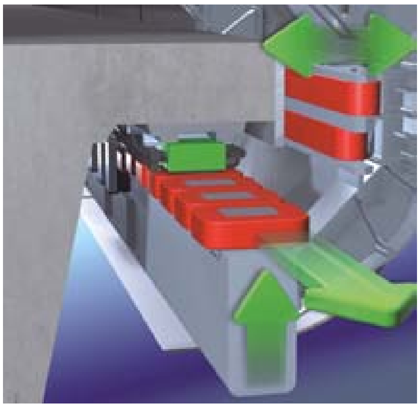
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field,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