The **VKS** experiment: generating a **magnetic field** in a **turbulent conducting fluid**

Using the VKS experimental facility, researchers at the CEA, CNRS and the 'Écoles normales supérieures' in Lyon and Paris have teamed up to generate a magnetic field by stirring a liquid metal. They have thus been able to reproduce, under laboratory conditions, 'dynamo action ' that generates the magnetic fields associated with all heavenly bodies, starting with our own Earth.

VKS facility at the CEA centre in Cadarache (in the Bouches-du-Rhône).

A. Gonin/CEA

How do cosmic **magnetic fields** arise? Why does the Earth's magnetic field experience erratic reversals? (**Focus D** *The Earth's magnetic field, weak but vital*, p. 99). In pursuit of answers to these questions, the VKS(1) project team (CEA-**CNRS-ENS Paris-ENS Lyon**) conducted what turned out to be a highly instructive experiment at the CEA's Cadarache centre in the Bouches-du-Rhône. This experiment provided valuable insight into **dynamo action**, i.e. the spontaneous generation of a magnetic field in a fully **turbulent** flow of liquid sodium. The experiment also provided the first demonstration of erratic reversals and periodic magnetic field oscillations remarkably similar to those observed in natural dynamos.

Most of the astrophysical objects surrounding our planet have their own magnetic field. The Earth's magnetic field is mainly **dipolar** and experiences reversals of its polarity at irregular time intervals. The Sun's magnetic field, however, follows a regular 22-year cycle. Scientists have long been seeking to understand the origin of these magnetic fields, particularly that of our own Earth which, not unnaturally, was the first to be studied. Back in 1600, William Gilbert thought that the Earth acted as a giant **magnet**, while in 1840 Gauss considered it acted as if it concealed a giant magnet in its core. However, despite the fact that the Earth's magnetic field seems to mimic the features of the field produced by an usual magnet, the temperature in the Earth's core is far too high for any object there to conserve its **magnetisation**. It was not until 1919 that Sir Joseph Larmor suggested that the Sun's magnetic field might be generated by dynamo action, i.e. an instability resulting from the motion of a conducting fluid. Given that the Earth has a liquid iron outer core, the hypothesis was that its magnetic field could be generated by dynamo action resulting from the motion of this fluid.

Dynamo action

Dynamo action drives the spontaneous generation of a self-sustaining magnetic field. This principle underpins the operation of electric generators described by Siemens towards the end of the 19th century, where mechanical energy is converted into **electromagnetic energy**. Dynamo action can be induced by sufficiently vigorous motion in a (solid or liquid) conducting medium: an electric current circulating in a conducting medium generates a magnetic field and, conversely, a conductor moving in a magnetic field produces an electric current (Figure 1).

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(1) Von Karman and Sodium.

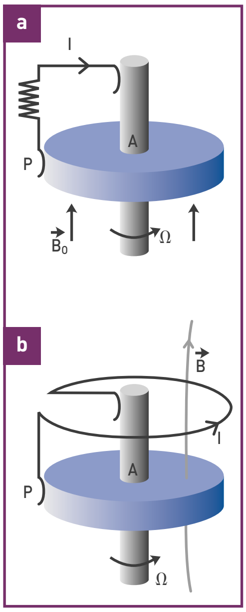
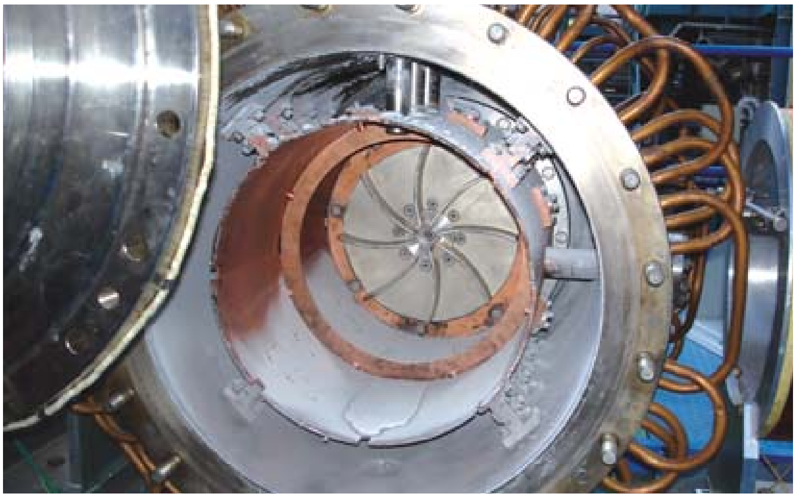


Figure 1.
(a) The angular velocity of rotation Ω of a disc placed in a magnetic field B_0 generates an electromotive force and a current that is able to circulate in the resistor.
(b) The idea then is to select an electrical circuit geometry that will make it possible to use the induced current to generate a magnetic field. Under these conditions, a field disturbance generates a current which in turn amplifies this field provided that the direction of rotation has been selected relative to the mutual induction between the circuit and the disc, and provided the disc rotates fast enough to compensate for losses via the Joule effect.


VKS

The VKS experiment vessel in the open position, revealing one of the counter-rotating 'impellers'.

The conditions reigning in an astrophysical object differ, however, from those found in an electrical circuit in that they are typically random and highly turbulent, and the electric currents are not prescribed. The challenge for researchers then is to demonstrate that the spontaneous generation of a magnetic field in an electrically-conducting fluid can arise when the flow is carefully selected and its speed exceeds a certain threshold. Although this phenomenon is governed by well-known equations (i.e. **Maxwell's equations** and Navier Stokes's(2) equations, **Ohm's law**), the extremely high turbulence of the fluids found in natural environments means that current **numerical simulations** can only provide an approximate model of the conditions reigning there. This makes it necessary to conduct dynamo experiments in the laboratory.

Generating a magnetic field in a laboratory environment

Two key breakthroughs have made it possible to experimentally confirm the validity of the dynamo concept. First, in 1963, Lowes and Wilkinson showed that two solid rotors rotating in a conducting matrix could generate a magnetic field. Conductor motion was imposed but the currents were free. In 2000, experiments conducted by researchers in Riga and Karlsruhe used a liquid sodium flow instead of solid rotors to produce the motion. This flow was however forced to follow a pre-determined geometry. The experiments only generated simple magnetic fields, in contrast to the fields found in natural bodies that typically demonstrate highly complex dynamics.

In 2007, the VKS team - which, like five other teams worldwide, is basing its experiments on liquid sodium flows - succeeded in producing, under laboratory conditions, a magnetic field generated by dynamo action in a fully turbulent flow closer to natural conditions, i.e. that exhibits unconstrained flow motion and currents.

Sodium is a metal with excellent electrical conductivity properties that remains solid up to a temperature of 98°C. Above this temperature, it becomes a liquid with fairly moderate **density** and **viscosity**. It is therefore able to generate flows with very high Reynolds(3) numbers comparable to conventional fluid flows such as water or air. Sodium does have one drawback, however, in that it ignites spontaneously in air and reacts violently to water, which means special arrangements have to be made for its use in experiments.

The experiments for the VKS programme are being run by the VKS team at the Department of Nuclear Technology within the Nuclear Energy Division (DEN) at the CEA facility in Cadarache, where researchers have the necessary liquid-sodium dedicated facilities backed up by several years of experience in developing fast neutron reactors such as the Phenix that use huge quantities of liquid sodium as a coolant(4).

The VKS experiment

A Von Karman(5) turbulent flow is produced by counter-rotating two impellers in a copper cylinder filled with liquid sodium. The motion of the impellers pro-

Figure 2.
Diagram of the average flow between the two counter-rotating impellers. The toroidal flow is shown in blue and the poloidal pumping in red.

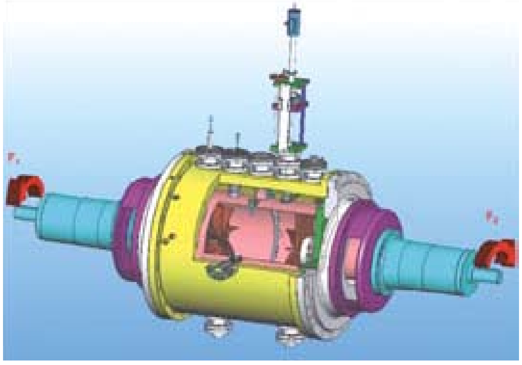


Figure 3.
Cut-away view of the VKS experimental set-up at the CEA centre in Cadarache.

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(2) Navier-Stokes equations: non linear partial differential equations that describe the motion of fluids in continuous media.

(3) Reynolds number: ratio of inertial forces to viscous forces in a fluid flow. This is used to calculate the characteristics of the boundary layer and its resistance to separation.

(4) This type of nuclear reactor requires the use of a coolant that does not slow neutrons down too much and that remains transparent to neutrons: this is the case with liquid sodium, a metal in liquid form.

(5) Von Karman flow: flow generated by two counter-rotating discs in a cylindrical vessel with a fixed sidewall.

duces a strong shear in the mid-plane, thus generating an "axial pumping" effect on either side, like that found in radial pumps. The whole flow strongly fluctuates and is highly turbulent (Figure 2).

The impellers' dimensions, boundary conditions and shape have been analysed extensively in theoretical, numerical and experimental studies. The current tank is 60 cm long, 60 cm in diameter and contains some 150 litres of liquid sodium. It consists in a layer of sodium at rest that surrounds the flow, a ring used to stabilize the shear layer in the mid-plane, and pure iron impellers. Magnetic field measurements are taken from probes immersed in the flow and the operating parameters (pressure, temperature, speed, power, etc.) are recorded (Figure 3).

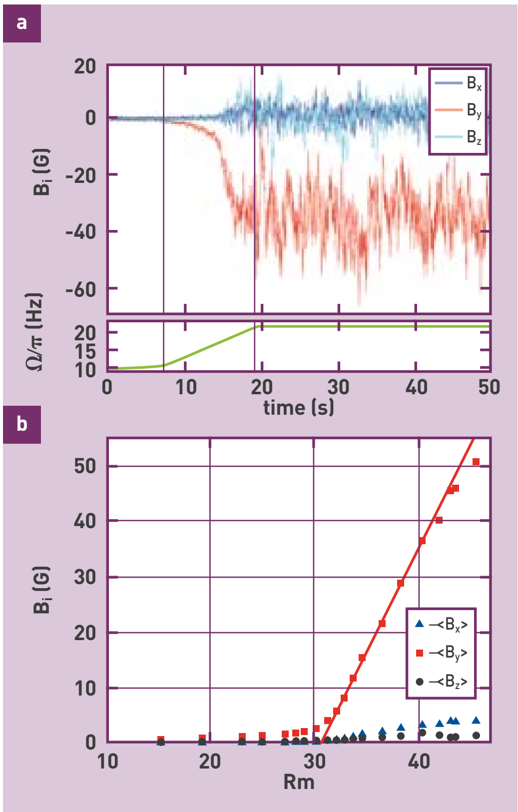

Figure 4.
(a) Time-evolution of the three magnetic field components when the rotational speed is increased above the threshold value (precise counter-rotation);
(b) Evolution of the mean values of these field components in relation to the magnetic **Reynolds number** *Rm*, a control parameter that is proportional to the speed of impeller rotation.

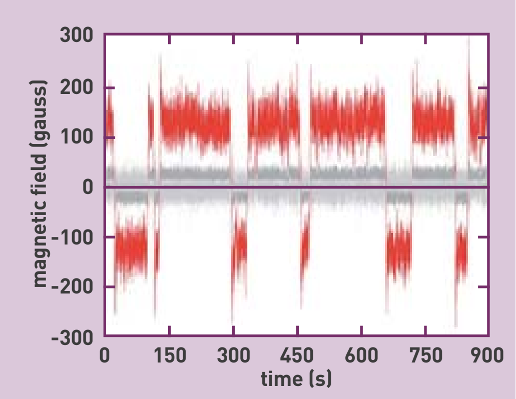

Figure 5.
Time-evolution showing erratic inversions of the magnetic field when two impellers rotate at different speeds. In this illustration, one of the impellers is rotating at 960 rpm and the other at 1,320 rpm.

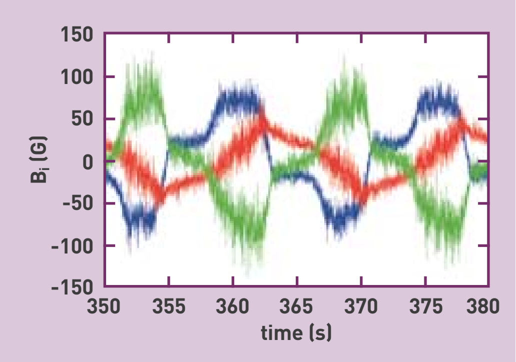

Figure 6.
Periodic oscillations of the magnetic field at other impeller rotation speeds.

When the speed of the counter rotating impellers exceeds the *critical value* of 1,020 rpm, the flow spontaneously generates a magnetic field that is self-sustained by the motion of the fluid. This field fluctuates strongly due to the high level of turbulence in the flow. This result confirms that fluid dynamos continue to operate in the presence of strong turbulence of the kind that occurs under natural conditions where turbulence is omnipresent (Figure 4).

In order to mimic natural conditions as closely as possible, VKS team researchers counter-rotated the impellers at different speeds, thus adding a global rotation similar to that found in planets and stars. They were thus able to prove that magnetic fields generated under these conditions have more complex dynamics than those generated with impellers rotating at the same speed. The temporal evolution of the magnetic field was marked by a series of erratic reversals of polarity. The field is also affected by excursions, periods during which the magnetic field decays as if it were about to flip polarity, but then returns to its initial value (Figure 5).

Remarkable similarities with the Earth's magnetic field

These results, the latter in particular, reveal remarkable similarities with the Earth's magnetic field. In fact, just like on Earth, these experiments provide insight into three different phenomena. The first is that the field flips polarity on a random timescale and with very short transition periods between the two states. The second is that while these periods of field stability are of variable length, they are always longer than the time required for a reversal. The third concerns field excursions, periods during which the field decays before growing again without actually flipping polarity.

At other rotation speeds, the magnetic field can experience regular polarity reversals, rotating in space without cancelling itself out, mirroring the Sun for example (Figure 6). The VKS experiment demonstrates that it is now possible to conduct 'laboratory' research into certain features of the Earth's dynamo under strictly controlled experimental conditions. Furthermore, the diversity of the systems under study may well pave the way to understanding why apparently similar natural objects have different dynamos (Venus, for example, has no magnetic field) or why the duration of stellar magnetic activity cycles seems to depend on their speed of rotation.

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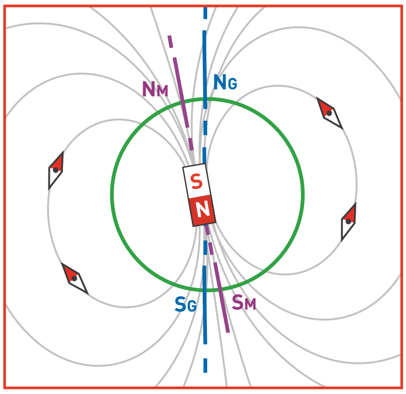
FOCUS D

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.

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.

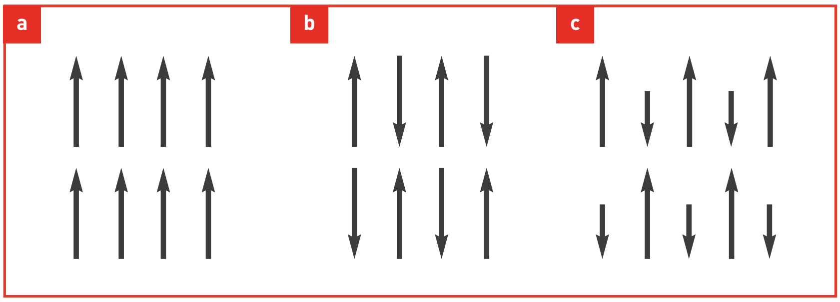


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

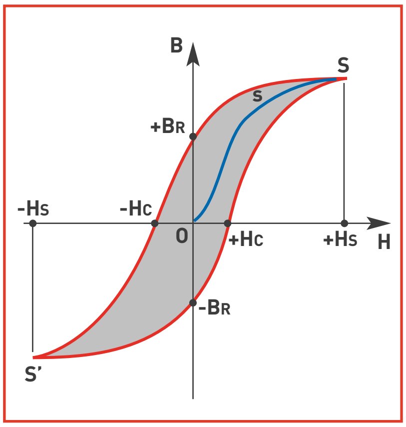


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches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

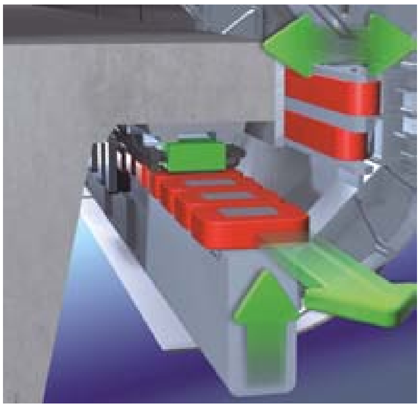
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field,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