Magnetic levitation to assist **satellite launcher** design

Using the force acting on a diamagnetic or paramagnetic body placed in a static magnetic field is one novel way of compensating the force of gravity. Paradoxically, it makes it possible to carry out ground-based studies of the behaviour of fluids in space, in particular on the cryogenic propellants used in satellite launchers, that are both simpler to perform and less costly than if carried out in space missions.

There is currently thriving research into the behaviour of fluids in space, particularly on **cryogenic** propellants[1] (liquid **hydrogen** and oxygen) used in satellite launchers such as Ariane. For safety reasons, it is virtually impossible to conduct experiments on these fluids in **microgravity** (Box 1) conditions using conventional techniques. However, there is another solution: magnetic levitation can be used to compensate the gravitational forces acting on some **paramagnetic** or **diamagnetic** bodies by using the force acting on such bodies when placed in a static **magnetic field** (Box 2). This makes it possible to recreate microgravity conditions on Earth and thereby carry out experiments at a lower cost than if performed in orbit.

Therefore, while in most cases the influence of gravitational forces was initially revealed during experiments conducted in space, these observations were then confirmed by conducting similar experiments using *magnetic levitation* back on Earth. Naturally, the microgravity conditions obtained using this technique are slightly different from those obtained in space, the main difference being that a magnetic field is also included. However, in cases where this field has little or no effect, magnetic levitation is a highly advantageous technique, even if the use of **superconducting coils** necessitates the use of highly complex related technologies (vacuum, cryogenics).

For about ten years now, the Low Temperatures Department (SBT) at the CEA Centre in Grenoble has been conducting this type of experiment in a facility equipped with a liquid **helium**-cooled superconducting coil. This coil uses the diamagnetic properties of liquid hydrogen to compensate gravitational forces with magnetic forces. Supplying a magnetic field of 10 **teslas** (20,000 times the Earth's magnetic field), this coil can levitate a volume of about 100 mm³.

The OLGA challenge

The SBT, partnered by the **CNES** and the **Air Liquide** group (Sassenage centre in Isère), recently commissioned a new magnetic levitation facility called OLGA (Oxygen Low Gravity Apparatus). This facility can

(1) Propellants: chemicals (fuels and oxidising agents) used in the propulsion (hence the French term 'propergols') of rocket engines, as a liquid (often the hydrogen-oxygen pair) or solid (mixture of ammonium perchlorate, aluminium and polybutadiene, for example).

CEA

The superconducting coil at the OLGA facility, at the CEA centre in Grenoble.

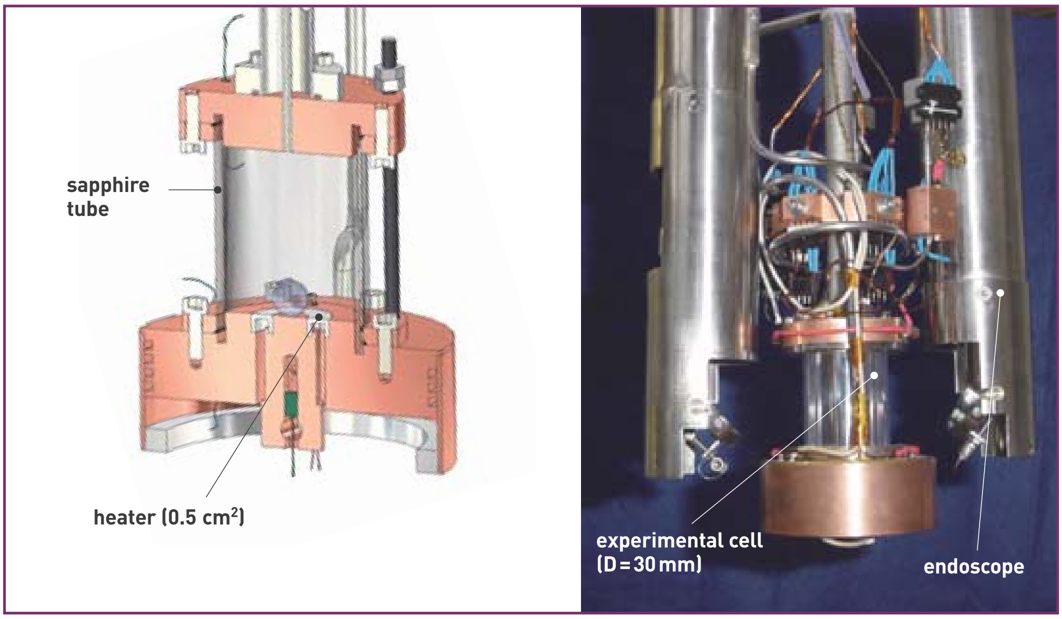


Figure 1.
The 25-cm³ OLGA experimental cell (at left) encircled by its endoscopes (at right).

levitate several cm³ of liquid oxygen which, as a paramagnetic substance, exhibits higher magnetic field sensitivity. Researchers are currently engaged in an experimental programme linked to the study of how this fluid behaves in microgravity conditions. This programme features the study of heat transfers in boiling regime.

Weightlessness and microgravity 1

Gravity plays a core role in many physical mechanisms. Its importance became apparent with the first space flights that enabled researchers to investigate microgravity conditions. Microgravity as *weightlessness* is an ideal theoretical state that does not actually exist in practice onboard a spacecraft; some interfering forces are always present, generating a residual gravitational force. This is why physicists always refer to a *microgravity* environment, which has a value close to one millionth of the Earth's gravity.

In stable orbits, space flights are characterised by a nearly total gravity compensation, ideally at the center of mass of the satellite, due to the inertial force generated by the centripetal acceleration on the orbital trajectory of an engine when it reaches the required speed (about 8 km/s for a satellite in a low Earth orbit). The absence of gravity can generate, change or eliminate phenomena or behaviour stemming from gravity in ground-based experiments. Therefore, conventional heat convection, due to gravity, is heavily modified in outer space.

There are several ways to achieve microgravity conditions, for periods varying from a few seconds to several months. Microgravity can be achieved via ground-based freefall towers, parabolic flight paths (Airbus A300 "zero G" in Europe), rocket probes or by orbital space flights, which are currently held aboard the international space station (ISS). These various solutions also offer variable levels of microgravity and experimental capacity.

Orbital zero gravity is achieved solely through inertial effects, i.e. the compensation acts on the whole body and each of its constituent parts (nuclei and electrons). Where magnetic levitation is concerned though, the magnetic forces mainly act on electrons, which means that the nuclei, and therefore the rest of the body, "follow suit" and levitate solely due to the strong cohesive forces of atoms. In a physical system that associates several materials with different susceptibilities, the compensation will only be effective for the material that obeys this condition.

OLGA is equipped with a superconducting coil (illustration 1) with an outer diameter of 650 mm, height 580 mm and bore diameter of 330 mm. One operational requirement is that it has to be submersed in liquid helium at a temperature of 4.2 K (- 269°C), which means placing it in a cryostat during the experiments. This superconducting coil delivers a 2-tesla magnetic field which is sufficient to supply liquid oxygen with a force capable of compensating the Earth's gravitational force.

The physical phenomena are studied in an experimental cell in a sapphire tube with a diameter of 30 mm and height of 50 mm (Figure 1). Two endoscopes are used to observe the fluid, in this case liquid oxygen. The cell and its endoscopes are placed in a vacuum vessel called an *anti-cryostat*. During the experiments, the tube is introduced into the centre of the coil at a specific height corresponding to the point at which the magnetic force is strongest. The centre of the base of the cell is equipped with a heater capable of delivering up to 17 watts. This heater is used to boil the oxygen, and thereby study how the oxygen boils with or without the effect of gravity.

Boiling re-examined for Vinci

The first experiments carried out using OLGA targeted the study of heat transfers in boiling regime under reduced gravity conditions. This research, carried out jointly with Air Liquide and the CNES, attracted the attention of the Snecma designers working on the Vinci engine that will equip the future cryogenic upper stage on the Ariane 5 rocket, which for a time was to be called the ESC-B. The plan is to be able to reignite this cryogenic engine in space after a period of ballistic flight, i.e. with no propulsion, solely using the effect provided by the rocket's initial momentum and the force of gravity. This forces propellants (liquid oxygen and hydrogen) into contact with hot surfaces that then have to be cooled just like for the first ignition phase. Researchers must therefore redouble their efforts to understand the mechanisms of heat transfer in this domain.

Oxygen is far easier to levitate than hydrogen

2

The force per unit of volume affecting a diamagnetic or paramagnetic body placed in a static magnetic field with magnetic induction B is given by the following relation:

$$\vec{f} = \frac{1}{2\mu_o} \chi_m \, grad \, (B^2)$$

where χ_m is the magnetic susceptibility of the body and μ_0 is the magnetic permeability of a vacuum. By defining the vector G as the product of the gradient of B by the induction B ($G = grad(B^2)$ en T^2/m), the precise compensation condition of gravity g (acceleration due to gravity) is written as:

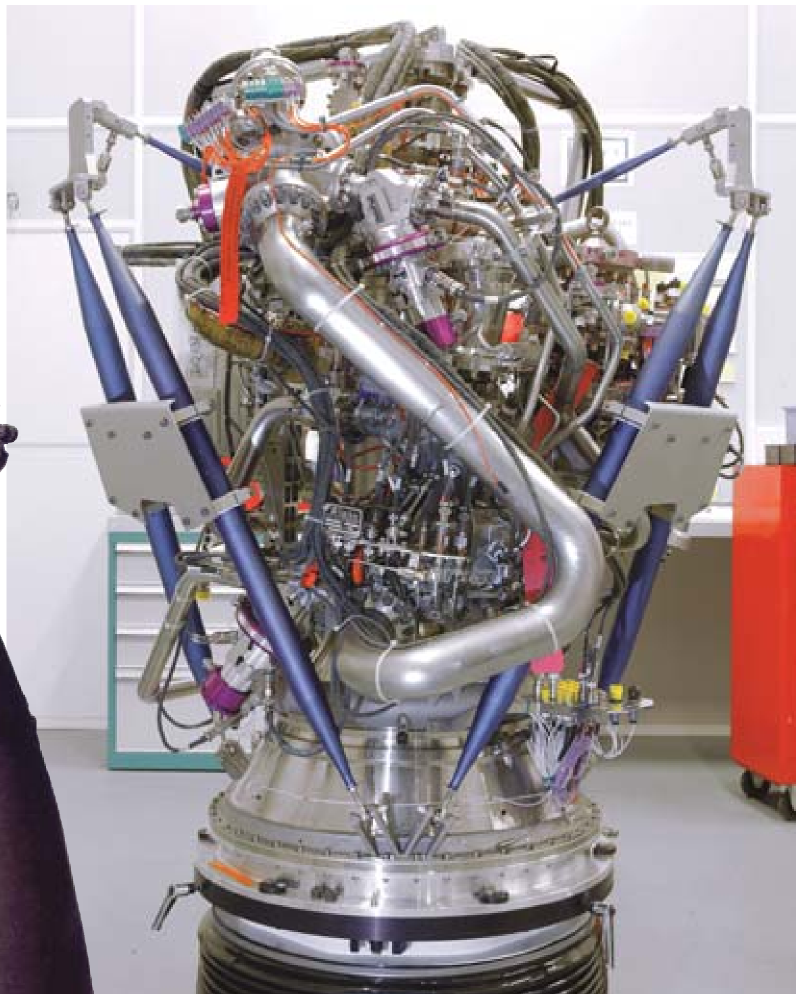
$$G = \frac{2\mu_o g \rho}{\chi_m}$$

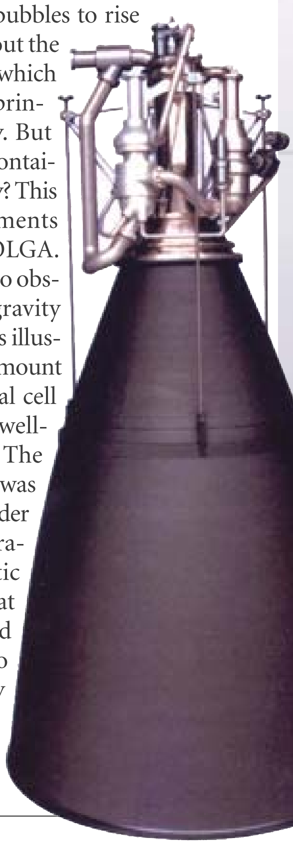
where ρ is the density of the body under consideration.
The table of G values required to exactly compensate gravity for certain substances clearly illustrates that it is far easier to levitate liquid oxygen - which being a paramagnetic body[1] has a positive G value - than water or liquid hydrogen.
Achieving similar G values for volumes of at least a few cm^3 implies being able to achieve magnetic induction values of several teslas. These high magnetic fields can be generated using superconducting coils that make it possible to achieve high induction values in larger volumes. Optimising these magnets even further will open up new avenues of exploration, other than hydrogen, by levitating water for example, and from there to proteins or even living organisms (Box 3).

substance	G (T^2/m)
liquid hydrogen	-1,000
deuterium	-2,000
water (1 °C)	-2,796
helium	- 3,900
oxygen (90 K)	8
oxygen (71 K)	7

(1) Magnetic susceptibility is positive and temperature-dependent in paramagnetic substances, but it is negative and temperature-independent in diamagnetic substances.

Essentially, they will have to go back and rethink the whole boiling process. What happens back on Earth when a water container is placed over a flame? When the flame is fairly low, convection currents can be observed in the water: the liquid at the bottom of the pan heats up and rises to the surface; this is because hot water is less dense than cold water, which therefore sinks. If the flame is turned up, bubbles will start to appear at the bottom of the pan and then rise to the surface. The mechanisms governing the convection currents and allowing the bubbles to rise would not be possible without the Earth's gravitational force which underlies the Archimedes principle, the law of buoyancy. But what would happen if this container was placed in zero gravity? This is the focus of the experiments being carried out with OLGA. Researchers have been able to observe what happens when gravity decreases from 1 G to 0 G, as illustrated in Figure 2. First, the amount of heat on the experimental cell was regulated to deliver a well-developed boiling regime. The current in the OLGA's coil was then increased stepwise in order to gradually compensate gravitational force by magnetic field force. The result was that as gravity decreased, the speed at which the bubbles rose to the surface and the frequency at which they became detached decreased, while the size of the bubbles increa-





Snecma/ Eric Forterre

Vinci engine under development. This liquid hydrogen - liquid oxygen engine completed its preliminary reignition tests at the Lampoldshausen rocket engine test facility (Germany) in 2007. Inset: the complete engine with its divergent nozzle.

Achievements and prospects for magnetic levitation

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The results and headway achieved over the last few years prove that magnetic levitation is a reliable technology with a very promising future. It will pave the way for exploring new prospects, provided researchers can develop novel magnetic configurations specifically targeting gravity compensation, and that they no longer only reuse superconducting solenoids diverted from their initial purpose, which is to generate an intense magnetic field at their core.
Underpinned by the latest, cutting-edge technological developments (new configurations associated with new superconducting materials that make it possible to work at even higher induction values) researchers will have magnets capable of providing even larger levitation volumes (up to several cm^3 of water or several hundred cm^3 of liquid oxygen) and improved residual gravity levels (to less than 1% of gravity), and thereby able to compete with or even replace some experiments conducted in outer space.
It was the magnetic levitation of water, first achieved over fifteen years ago by E. Beaugnon and R. Tournier (CRETA - CNRS Grenoble), that paved the way to many ground-based microgravity experiments in several different domains where gravity is a crucial parameter.
The main application in biotechnology is crystal growth, where magnetic levitation makes it possible to obtain pure proteins in order to analyse their structural make-up. Gravity acts directly on convection mechanisms: reducing it will automatically result in higher protein purity.
In the materials and alloys domain, one avenue of exploration has been crystal production and control over growth defects. Chemists have been carrying out research aimed at discovering how magnetic levitation can be used to provide insight into chemical reactions, especially polymerisation. In fluid physics, cryogenic propellants illustrate the potential utility of magnetic levitation in hydrodynamic research (the study of critical phenomena, interface dynamics, etc.).
Even inertial confinement fusion could make use of magnetic levitation. Under a Euratom agreement, the Low Temperatures Department (SBT, Service des basses températures) at the CEA Centre in Grenoble, partnered by the Accelerators, Cryogenics, and Magnetism Department (SACM, Service des accélérateurs, de cryogénie et de magnétisme) at the Saclay Centre recently studied a proposal to solidify cryogenic targets by placing them in a zone with uniform microgravity, generated by a superconducting magnet. The SBT has confirmed that magnetic levitation could offer interesting avenues for obtaining a layer of liquid deuterium with a constant thickness inside the spherical target before being cooled and solidified. The magnetic levitation of these targets has been researched using a superconducting solenoid, or using a multipole superconducting magnet, modelled on the technology used in particle accelerators. The main advantage of a multipole structure is its translationally-invariant structure, which makes it possible to obtain much larger working volumes as the effective area is no longer limited by the inner coil radius, as with a solenoid.

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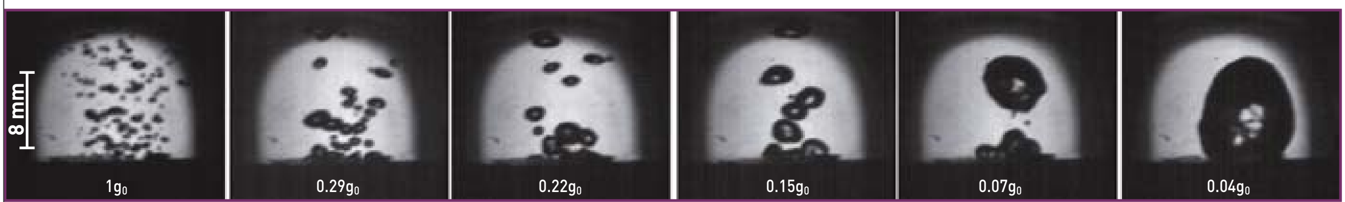

Figure 2.
Change in the size of oxygen bubbles in relation to residual gravity (g_0) in the OLGA experimental cell.

sed at the rate dictated by theory. The researchers reported that, once the Earth's gravity had been fully compensated, a single large bubble remained attached to the heating component. This bubble vibrates due to the effect of the evaporation mechanisms acting on this heating component and of condensation affecting the whole surface of the bubble in contact with the liquid. Researchers were also able to determine that the size of the bubble increased with an increase in the amount of heat delivered.

Technological research and other more fundamental research

These preliminary results from the OLGA facility have provided physicists with some highly valuable and unique data. Researchers at the CEA are now able to predict how heat is transferred in liquid oxygen in zero-gravity conditions. The results will be used to determine the size of the engines equipping future satellite launchers. Further research projects are planned in the facility, with an experimental programme scheduled to run over several years. This programme will focus on research into the behaviour of propellants in satellite launcher tanks (movements of the liquid/gas interface under rapid acceleration variation, sloshing, vibrations) coupled with fundamental research carried out close to the critical point of oxygen, at a pressure of 50 bars and a temperature of 154 K.

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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.

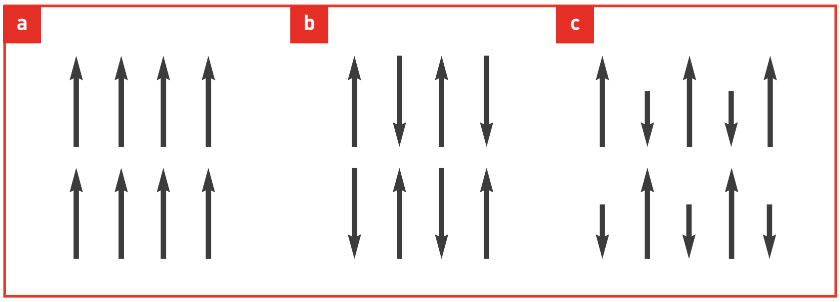


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

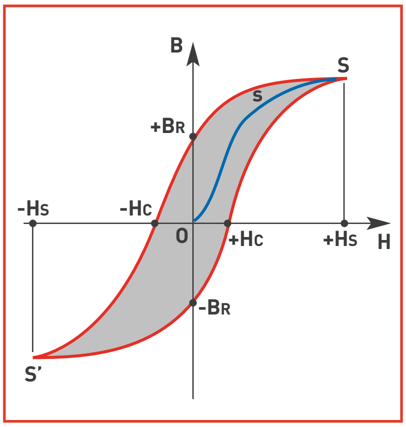


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches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

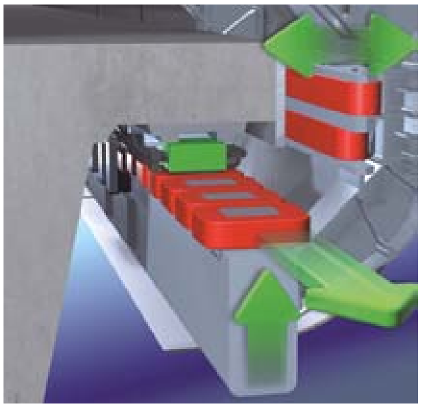
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field,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