

Magnet

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An object or device that produces a magnetic field. Magnets are essential for the generation of electric power and are used in motors, generators, labor-saving electromechanical devices, information storage, recording, and numerous specialized applications, for example, seals of refrigerator doors. The magnetic fields produced by magnets apply a force at a distance on other magnets, charged particles, electric currents, and magnetic materials. *See also:* GENERATOR; MAGNETIC RECORDING; MOTOR.

Magnets may be classified as either permanent or excited. Permanent magnets are composed of so-called hard magnetic material, which retains an alignment of the magnetization in the presence of ambient fields. Excited magnets use controllable energizing currents to generate magnetic fields in either electromagnets or air-cored magnets. Most electromagnets use iron or its alloys, allowing efficient generation of fields up to 2 teslas. Air-cored magnets often are used to generate fields above the saturation of ferromagnetic materials. The power requirements of excited magnets can be reduced by using superconducting wire to carry the current. *See also:* ELECTROMAGNET; FERROMAGNETISM; SUPERCONDUCTIVITY.

Theory and design

Flux density *B* (in teslas), field strength *H* (in amperes meter), and magnetization *M* are related by Eq. (1), where μ

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \tag{1}$$

is the permeability of free space (4π 10   henry meter). In ferromagnetic materials, *M* is a nonlinear and hysteretic function of *B*.

Field strength *H* is related to current *I* by Ampère's law, Eq. (2).

$$\int \vec{H} \cdot \vec{ds} = I \tag{2}$$

Here the integral of the scalar product is taken around any path *s* encompassing the currents whose sum is *I*.

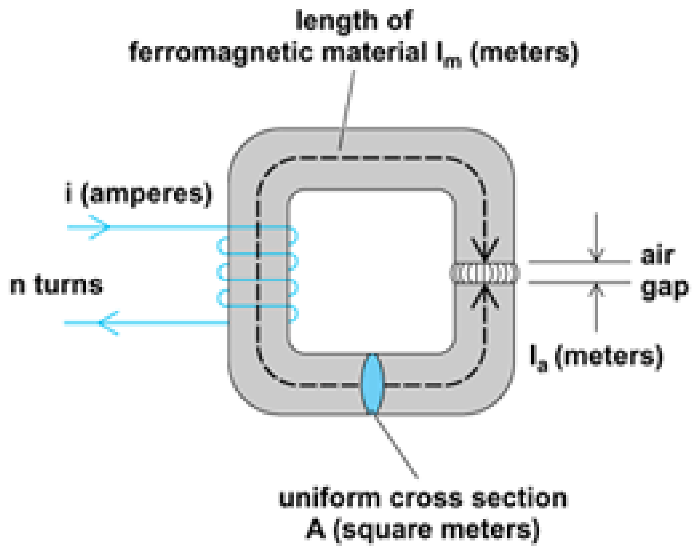

Fig. 1 **Simple electromagnetic circuit.**

The relation between B and H for a ferromagnetic material is a property of the material expressed graphically and known variously as a magnetization curve, demagnetization curve, or hysteresis loop.

The procedure for calculating B in electromagnets is illustrated by an electromagnetic circuit containing an air gap (**Fig. 1**). A simplified analysis reveals the following features:

1. The relation between the field strength in the ferromagnetic material H_m and the flux density in the air gap B is defined simultaneously by the properties of the material and by Eq. (3),

$$H_m = \left(ni - \frac{Bl_a}{\mu_0}\right) l_m \tag{3}$$

where l_m is the length of the ferromagnetic material (in meters), l_a is the distance across the air gap (in meters), i is the current through the coil (in amperes), and n is the number of turns in the coil.

2. The energy density in the air gap is given by Eq. (4). This is also the force of attraction per unit

$$W = \frac{B^2}{2\mu_0} \qquad \text{joules/m}^3 \tag{4}$$

area in pascals acting on the magnet pole faces.

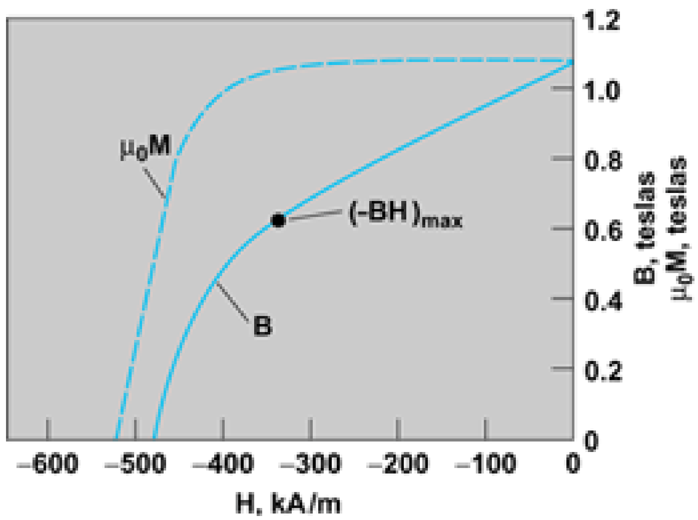

Fig. 2 **The variation of *B* (the demagnetization curve) and μ *M* as *H* is increased in the negative direction (opposite to *B* and *M*) for the permanent-magnet material Sm (Co, Cu,Fe,Zr) . B_r is the remanence, H_c the coercive force, and (*BH*) the optimum operating point. (*After Z. A. Abdelnour, H. F. Mildrum, and K. J. Strnat, Properties of various sintered rare earth–cobalt permanent magnets between 60 and 200 C, IEEE Trans. Magnet., MAG-16:944–996, 1980*)**

If the ferromagnetic material is magnetically hard and *i* is zero, then the electromagnet becomes a permanent magnet and Ampère's law shows that H_m must be negative. It follows that the volume of ferromagnetic material equals 2*E* BH_m, where *E* is the air gap energy. Hence for economic reasons, permanent-magnet designs should maximize the product (BH_m). Moreover, the maximum attainable value of this product, (BH_m) , is an important property of a material.

In air-cored magnets, flux density may be computed by using the Biot-Savart law or one of its many derivatives.

For discussion of the theory underlying the functioning and design of magnets *See also:* AMPÈRE'S LAW; BIOT-SAVART LAW; MAGNETISM; MAGNETIZATION.

Materials for magnets

The essential characteristic of permanent-magnet materials is an inherent resistance to change in magnetization over a wide range of field strength *H* (**Fig. 2**). Resistance to change in *M* in this type of material and in a great many of its predecessors is due to two factors: (1) the material consists of particles smaller than the size of a domain, a circumstance which prevents the gradual change in *M* which would otherwise take place through the movement of domain wall boundaries; and (2) the particles exhibit a marked magnetocrystalline anisotropy. During manufacture the particles are aligned in a magnetic field before being sintered or bonded in a soft metal or polyester resin. Compounds of neodymium, iron, and boron have the highest known values of (*BH*) .
See also: IRON ALLOYS; MAGNETIC MATERIALS.

Electromagnets rely on magnetically soft or permeable materials which are well annealed and homogeneous so as to allow easy motion of domain wall boundaries. Ideally the coercive force H_c should be zero, permeability should be high, and the flux density saturation level should be high. Coincidentally the hysteresis energy loss represented by the area of the hysteresis curve is small. This property and high electrical resistance (for the reduction of eddy currents) are required where the magnetic field is to vary rapidly. This is accomplished by laminating the core and using iron alloyed with a few percent silicon that increases the resistivity.

Electromagnets

Electromagnets usually have an energizing winding made of copper and a permeable iron core. Applications include relays, motors, generators, magnetic clutches, switches, scanning magnets for electron beams (for example, in television receivers), lifting magnets for handling scrap, and magnetic recording heads. *See also:* CATHODE-RAY TUBE; CLUTCH; ELECTRIC SWITCH; RELAY.

Special iron-cored electromagnets designed with highly homogeneous fields are used for special analytical applications in, for example, electron or nuclear magnetic resonance, or as bending magnets for particle accelerators. *See also:* MAGNETIC RESONANCE; PARTICLE ACCELERATOR.

Normal-conductor air-cored magnets

Air-cored electromagnets are usually employed above the saturation flux density of iron (about 2 T); at lower fields, iron-cored magnets require much less power because the excitation currents needed then are required only to generate a small field to magnetize the iron. The air-cored magnets are usually in the form of a solenoid with an axial hole allowing access to the high field in the center. The conductor, usually copper or a copper alloy, must be cooled to dissipate the heat generated by resistive losses. In addition, the conductor and supporting structure must be sufficiently strong to support the forces generated in the magnet. The effective pressure in the magnet bore is approximately B 2μ, or 40 megapascals (6000 lbf in.) for a flux density of 10 T. *See also:* SOLENOID (ELECTRICITY).

Bitter design. A design for high-field solenoids developed by F. Bitter, which addresses these problems, employs a stack of mass-produced and interchangeable slit disks (**Fig. 3***a*). The Bitter stack is interleaved with insulation and compressed axially so as to form a compact helical conductor structurally bonded by friction. Hole patterns punched through the conducting plates and insulators are carefully aligned to allow axial flow of the cooling water. A modification of this helical structure (Figs. 3*b* and *c*) employs two parallel slit copper-plate structures as conductors (one with etched radial cooling channels). A reinforcing plate structure may also be included in either design. Radial cooling is used when higher power dissipation is required. A Bitter magnet produced a sustained field of 30 T and required 30 MW of power. A slightly more efficient but more complex magnet is composed of parallel-connected nested coils with water-cooling passages between them.

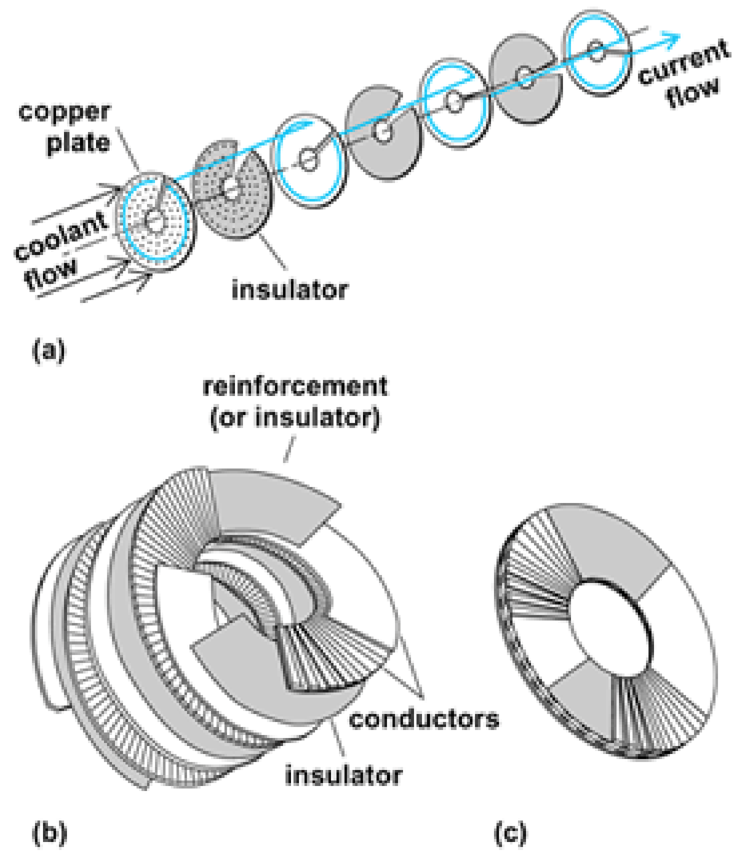

Fig. 3 **Bitter magnet stacks. (*a*) Exploded view of helical current path through slotted plates in a stack. (*b*) Expanded view of a stack that has a similar current path shared by the two conductors in a helical plate structure, but has radial grooves in one of them for cooling. (*c*) Assembled view of a few plates. (*After D. B. Montgomery, The Magnetic and Mechanical Aspects of Resistive and Superconducting Systems, Robert E. Krieger Publishing Co., 1980*)**

Pulsed magnets. Higher fields can be generated by limiting the excitation to short pulses (usually furnished by the energy stored in a capacitor bank) and cooling the magnet between pulses. The pulse length is limited by the heat capacity of the magnet and the resistive losses in the conductor. The highest fields are generally achieved in small volumes. The fundamental limit for an efficient magnet generating pulsed fields repeatedly is set by the conductivity and strength of the conductor. Often additional structures are required to support the large forces generated. A field of 75 T has been generated for 120 microseconds. Special high-strength, high-conductivity conductors for such magnets include a copper-niobium microcomposite and a copper-silver alloy. Pulse durations of 100 ms or more require very large volume magnets and large energies.

The highest fields are generated in magnets which fail during the pulse. Over 200 T is generated for a few microseconds in a single-turn magnet which explodes radially outward. Even higher fields (over 1500 T) are generated by explosive compression of magnetic flux trapped in a single-turn coil.

Superconductor air-cored magnets

Large-volume or high-field magnets are often fabricated with superconducting wire in order to avoid the large resistive power losses of normal conductors. The two commercially available superconducting wire materials are (1) alloys of niobium-titanium, a ductile material which is used for generating fields up to about 9 T; and (2) a brittle alloy of niobium and tin (Nb Sn) for fields above 9 T. Practical superconducting wires use complex structures of fine filaments of superconductor that are twisted together and embedded in a copper matrix. Practical superconducting wires can carry current densities of 10 A m with no resistive power loss. However, at sufficiently high fields the superconductor becomes resistive. The conductors are supported against the electromagnetic forces and cooled by liquid helium at 4.2 K (452 F). A surrounding thermal insulating enclosure such as a dewar minimizes the heat flow from the surroundings.

Superconducting magnets operating over 20 T have been made with niobium-titanium outer sections and niobium-tin inner sections. Niobium-titanium is used in whole-body nuclear magnetic resonance imaging magnets for medical diagnostics. Other applications of superconducting magnets include their use in nuclear magnetic resonance for chemical analysis, particle accelerators, containment of plasma in fusion reactors, magnetic separation, and magnetic levitation. The nuclear magnetic resonance magnets are usually operated as permanent magnets. Once the excitation current reaches the appropriate value, it is switched through a superconducting joint between the magnet leads so that current flows continuously with no resistive loss as long as the conductor is cooled to maintain superconductivity. *See also:* MAGNETIC LEVITATION; MAGNETIC SEPARATION METHODS; MEDICAL IMAGING; NUCLEAR FUSION; NUCLEAR MAGNETIC RESONANCE (NMR); SUPERCONDUCTING DEVICES.

Hybrid air-cored magnets

The highest continuous fields are generated by hybrid magnets. A large-volume (lower-field) superconducting magnet that has no resistive power losses surrounds a water-cooled inner magnet that operates at the highest field. The fields of the two magnets add. Over 35 T has been generated continuously.

There are active world-wide efforts to increase the high field capabilities of the various air-cooled magnets.

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