Lecture 2B – Magnetism

Magnetic dipole moment. Magnetisation. Diamagnetism. Paramagnetism. Ferromagnetism. The B-H *characteristic (hysteresis). The normal magnetization characteristic.*

Magnetic Dipole Moment

The magnetic field produced by a loop of wire (obtained using the Law of Biot-Savart) looks similar to that of a magnet. Therefore, a current loop can be considered to be like a small permanent magnet, and it will have a magnetic dipole moment (similar to the electric dipole moment).

A current loop has a magnetic field like a permanent magnet

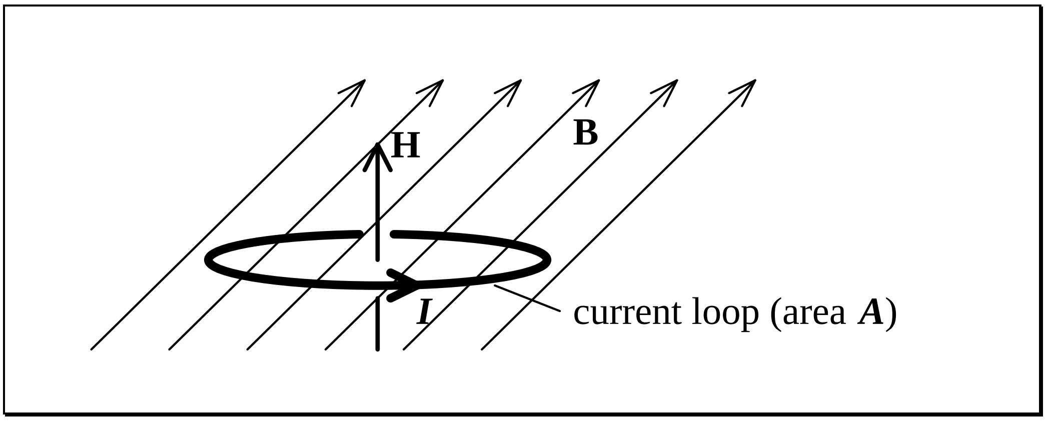

Figure 2B.1

In an external field **B,** the effect of the Lorentz Force on each element of the current loop is to produce a torque:

$$\mathbf{T} = I\mathbf{A} \times \mathbf{B} \tag{2B.1}$$

The torque on a current loop immersed in a **B** field

To make this similar to the torque experienced by an electric dipole, we define the magnetic dipole moment to be:

$$\mathbf{m} = I\mathbf{A} \tag{2B.2}$$

Magnetic dipole moment defined

The torque experienced by a current loop due to an external field can then be expressed as:

$$\mathbf{T} = \mathbf{m} \times \mathbf{B} \tag{2B.3}$$

The torque experienced by a magnetic dipole in a magnetic field

This torque will tend to align a magnetic dipole in the direction of an applied field.

Electron orbital motion is a current

An atom with an orbiting electron can be modelled as a current loop.

A permanent magnet has many dipoles in the same direction

A permanent magnet is made of many molecular magnetic dipole moments that align in the same direction:

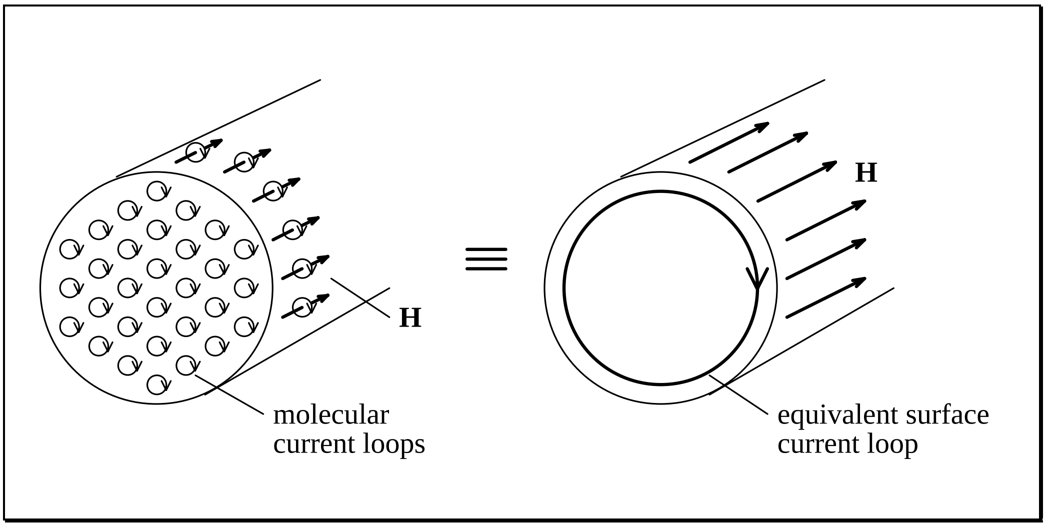

Figure 2B.2

This is why the field of a solenoid looks like that of a magnet.

Magnetisation

The tiny magnets created by circulating atomic currents are the sources of the **B** field of permanent magnets and magnetisable materials. Experiment shows that certain materials (called magnetic materials), when placed in a magnetic field, react upon it and modify it. This phenomenon is called magnetisation. The magnetization is defined as the average dipole moment per unit volume:

Magnetisation defined

$$\mathbf{M} = \frac{\mathbf{m}}{V} \tag{2B.4}$$

Remember the concept of polarization. The magnetization provides a link between the microscopic (**m**) and the measurable (**M**).

A magnetic material that is placed in a magnetic field will become magnetized. The material then contributes to the external field. A measure of this induced effect (like polarization) is the magnetization. In ferromagnetic materials, the induced **M** remains after the external field is withdrawn.

Magnetisation contributes to the external field

This explains why a rod of steel that is inserted into a solenoid increases the field.

The magnetic field **B** is modified by the induced **M**:

The relationship between **B** and **H** for a magnetisable material

$$\begin{aligned}\mathbf{B} &= \mu_0\left(\mathbf{H}+\mathbf{M}\right)\\ &= \mu\mathbf{H}\end{aligned}$$

$$\mu = \mu_0\left(1+\frac{\mathbf{M}}{\mathbf{H}}\right) = \mu_0\mu_r \qquad \text{(2B.5)}$$

Permeability defined in terms of magnetisation

Magnetic materials are classified into three groups:

(i) diamagnetic ($\mu_r \approx 0.999$). eg. molecular hydrogen, water, copper, glass.

(ii) paramagnetic ($\mu_r \approx 1.001$). eg. molecular oxygen, aluminium.

(iii) ferromagnetic ($\mu_r \geq 100$). eg. iron, nickel, cobalt.

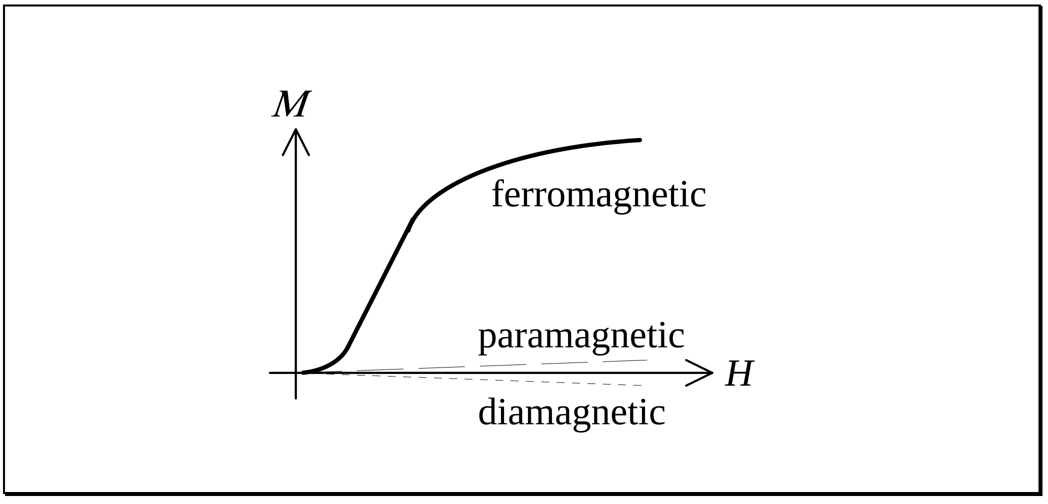

Figure 2B.3

Ferromagnetism disappears at high temperatures

Above a certain temperature T_C (called the Curie temperature), ferromagnetism disappears and ferromagnetic materials become paramagnetic.

There are two possible causes of magnetism:

(i) electron orbital motion around the nucleus.

(ii) electron spin (about own axis).

Diamagnetism

Diamagnetism is an induced effect caused by orbiting electrons

Diamagnetism is essentially a quantum mechanical phenomenon. To do a "classical" analysis that agrees with observed results, we have to assume that electrons are paired in orbits and move in opposite directions at the same speed. Without an applied field, there is no *net* magnetic moment.

Consider one orbiting electron:

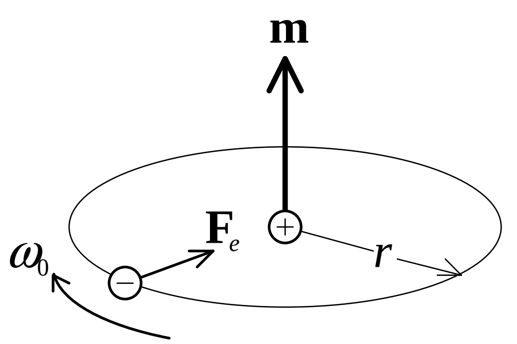

Figure 2B.4

The electron is in equilibrium in its orbit. An electric centripetal force holds the electron to its atom:

$$F_e = m_e a = m_e \omega_0^2 r \tag{2B.6}$$

An electron in an **H** field experiences a Lorentz Force

Application of a magnetic field **H** exerts an additional magnetic force on the electron (a Lorentz force). The radius of the electron orbit does not change, since we are using the Bohr model of the atom. The direction of the Lorentz force depends on the direction of the magnetic field. Assume an **H** field direction that slows down the electron:

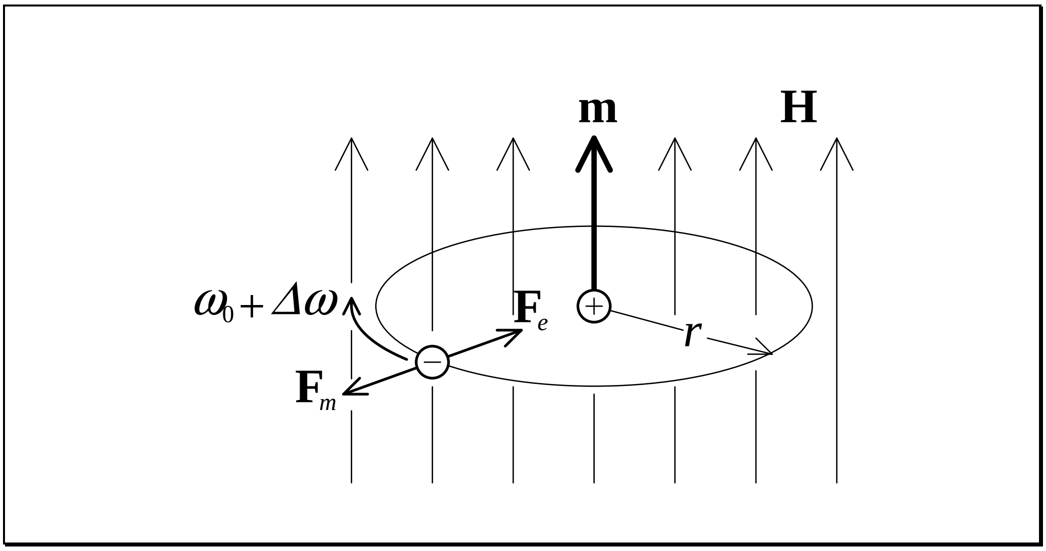

Figure 2B.5

Newton's second law gives, for the new angular velocity:

$$F_e - F_m = m_e a$$
$$m_e \omega_0^2 r - e\omega r \mu_0 H = m_e \omega^2 r$$
$$-e\omega\mu_0 H = m_e(\omega - \omega_0)(\omega + \omega_0) \qquad \text{(2B.7)}$$

Since the change in speed will be small, then:

$$\omega - \omega_0 = \Delta\omega$$
$$\omega + \omega_0 \approx 2\omega$$
$$\Delta\omega \approx -\frac{e\mu_0}{2m_e} H \qquad \text{(2B.8)}$$

An electron in an **H** field changes speed in proportion to the field strength

The decrease in electron speed is proportional to the applied field. The electron orbiting in the opposite direction would speed up. The resultant effect is to reduce the field in the material.

Diamagnetism reduces the **B** field

Ferromagnetic materials have domains

Paramagnetism

Electrons not only have orbital motion, but spin motion as well.

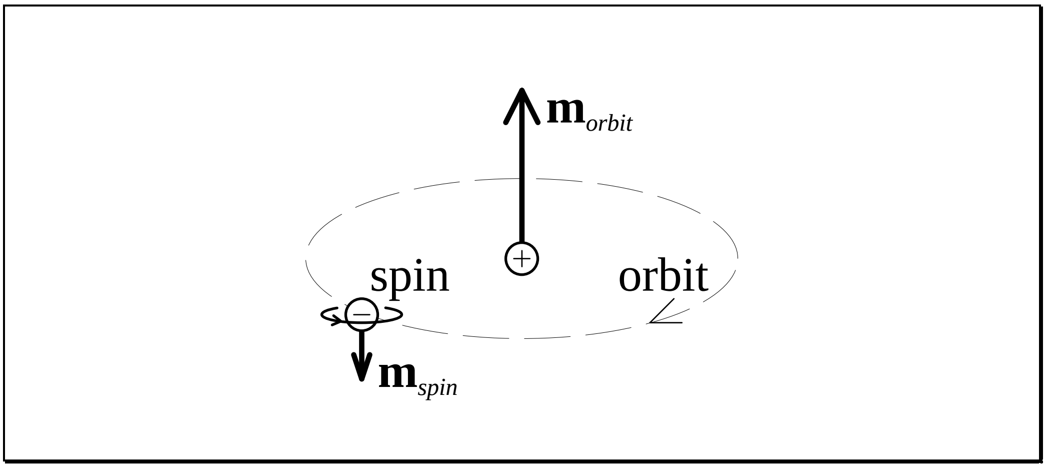

Figure 2B.6

Paramagnetism is an effect caused by spinning electrons

Each spinning electron produces a spin magnetic moment. Due to thermal vibrations, the axes of the spins are randomly distributed over all possible orientations. A piece of paramagnetic material has no net external magnetization.

Paramagnetism is an alignment of the spin magnetic moments

An applied **H** field will tend to align theses magnetic moments in its direction. The alignment is opposed by thermal agitation which for paramagnetic and diamagnetic materials is much stronger. The result is a very slight increase in the magnetic field in the material.

Ferromagnetism

Ferromagnetism is an effect caused by unpaired spinning electrons

Inner shells (close to the nucleus) of a ferromagnetic atom have unpaired electrons, which are shielded from the influence of other atoms. Each molecule therefore exhibits a strong resultant spin magnetic moment. The strong field of the molecular dipoles causes them to align over small volumes called domains. (A domain has a typical dimension between 10^{-3} and 10^{-6} m, and contains about 10^{16} atoms. They were discovered by Weiss in 1906).

Normally the domains are oriented at random and are not noticeable externally. When an external **H** field is applied, the dipoles try to align with **H** and domains with **M** in the direction of **H** grow at the expense of the others.

"Saturation" is reached when no further dipole alignment is possible. A strong **B** field results. On removal of the applied field, some magnetization is retained (the domains do not return to their original state).

Ferromagnetic materials give rise to a large increase in the resultant field

The *B*-*H* Characteristic (Hysteresis)

A piece of ferromagnetic material without any applied fields has the following microscopic structure:

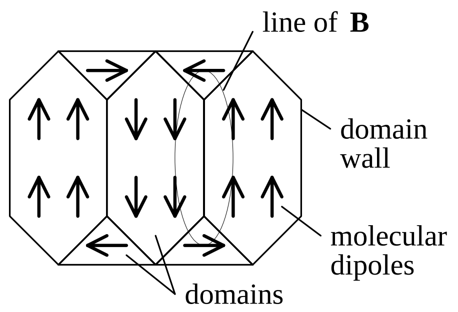

Figure 2B.7

There are large internal fields that cause the molecular dipoles to align in regions called domains. Adjacent domains are oriented so that the magnetic field lines form closed loops *easily* (using the minimum of energy).

The domain structure of ferromagnetic material

If we apply a large external **H** field to the material then three things happen:

The dipoles firstly align in a direction of "easy" magnetisation

(i) magnetic dipoles tend to align with the applied field in directions of "easy" magnetisation (those directions that line up with the crystal structure of the material). Removal of the field causes the dipoles to turn back to their original state – the process is reversible:

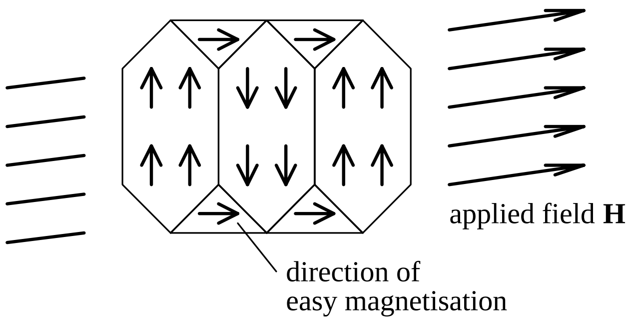

Figure 2B.8

Then the domains in the direction of **H** grow at the expense of other domains

(ii) domains in the general direction of the applied field grow at the expense of others. This involves movement of the domain walls – it takes energy and is irreversible. Eventually, there is just one domain:

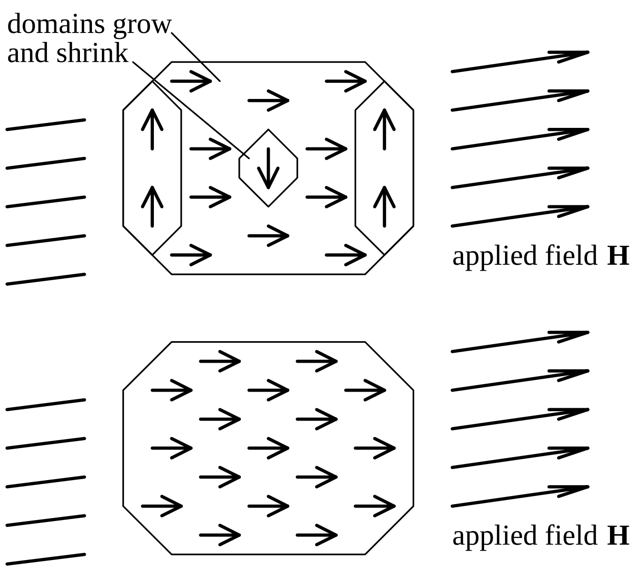

Figure 2B.9

(iii) the magnetic dipoles align with the applied field (called "hard" magnetisation because generally the field does not line up with the crystal structure of the material) until all dipoles are aligned – saturation has been achieved.

Finally, the dipoles turn in the direction of "hard" magnetisation

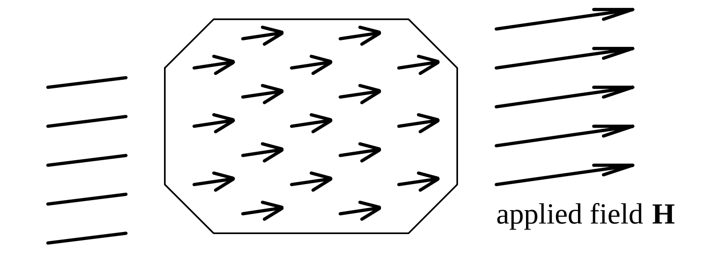

Figure 2B.10

This magnetisation process is shown macroscopically by a *B*-*H* characteristic:

Features of the *B*-*H* characteristic

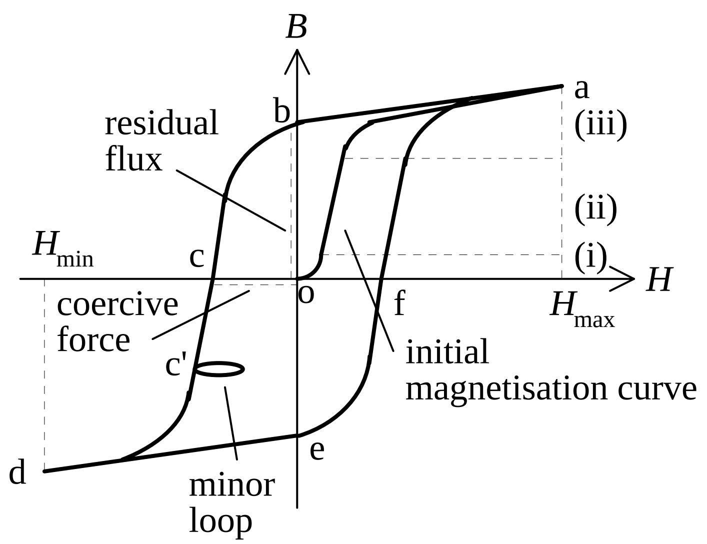

Figure 2B.11

To observe the way a *B-H* characteristic is traced out, we can use a toroidal specimen (*Why a toroid?*) and direct current:

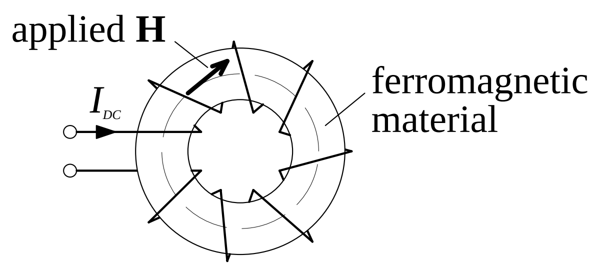

Figure 2B.12

The way in which a *B-H* characteristic is traced out

The steps to obtain the *B-H* characteristic are:

(i) **H** (or I_{DC}) is gradually increased. **B** in the material increases along *oa* until no further alignment is possible (saturation is reached at H_{max}).

(ii) **H** (or I_{DC}) is reduced. **B** decreases along *ab* (not *ao*). This property is known as hysteresis (Greek: short coming). No part of the magnetization curve is now reversible.

(iii) **H** is further reduced to H_{min} and then increased again. **B** follows the path *bcdefa*. (N.B. the path terminates at *a* only if we apply H_{max} again).

Minor Loops

Minor loops defined

If we are at point *c'* (say) and **H** is increased (made more positive) and then decreased to the previous value, the minor loop shown in Figure 2B.11 is traced.

The Normal Magnetization Characteristic

Different *B*-*H* loops are obtained for different values of H_{max}. Joining the tips of each hysteresis loop gives the "normal magnetization characteristic":

The normal magnetization characteristic defined

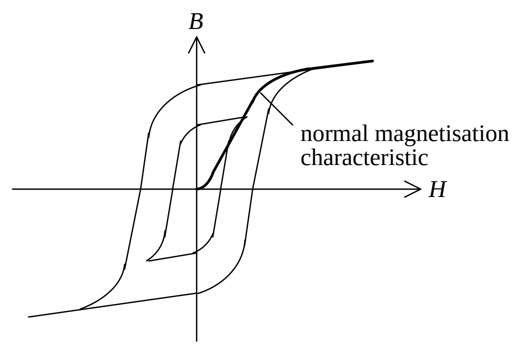

Figure 2B.13

The normal magnetization characteristic is used often. It is like an average characteristic, but it doesn't tell us about the shape of the hysteresis loop (and therefore the losses). It is well suited to analysis where AC excitation of the material is involved. (*Why?*)

and used instead of a hysteresis loop

Summary

- A magnetic dipole is a current loop. A magnetic dipole experiences a torque when subjected to an external magnetic field.

- An atom with an orbiting electron can be modelled as a current loop, i.e. as a magnetic dipole.

- A magnetic dipole placed in a magnetic field experiences magnetisation, which acts to increase the relative permeability – for an inductor, the inductance will increase due to the magnetisation.

- Magnetic materials can be categorised into three groups: diamagnetic, paramagnetic and ferromagnetic.

- Diamagnetism is caused by orbiting electrons – it reduces the **B** field slightly.

- Paramagnetism is caused by spinning electrons – it increases the **B** field slightly.

- Ferromagnetism is cause by unpaired spinning electrons – it increases the **B** field significantly.

- A ferromagnetic material's magnetic properties can be described with a *B*-*H* characteristic, which exhibits hysteresis. The *B*-*H* characteristic is a result of the physical crystal structure which is divided into domains.

References

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