發電機原理

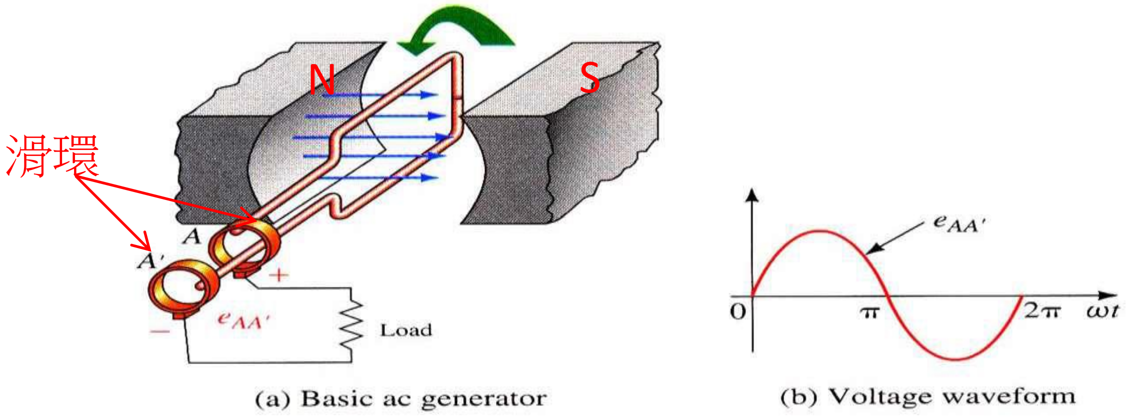
・在靠近磁鐵凹槽處，裝上兩個繞在軟鐵芯上的線圈，分別對準磁鐵的兩極。搖轉線圈時，線圈導線中就感應出交流電。每當線圈轉半周，線圈對應的磁極就改變一次，電流方向也跟著改變。

・發電機(generator)：一種將機械能轉換為電能的設備。基本上可分為直流發電機(DC generator)與交流發電機(AC generator)兩種，交流發電機又可分為單相(single phase)及三相(three phase)兩種。

・大型發電機: 一般電力公司發電廠則有水力發電機(以水流推動水輪機轉動)、火力發電機(以燃燒油、煤或瓦斯方式產生高溫高壓蒸氣，推動蒸氣渦輪機轉動)、核能發電機(以原子分裂產生高溫高壓使蒸氣渦輪機轉動)等。發電廠的發電機通常為大容量(高達數仟MW)的三相交流同步發電機。

交流電的產生

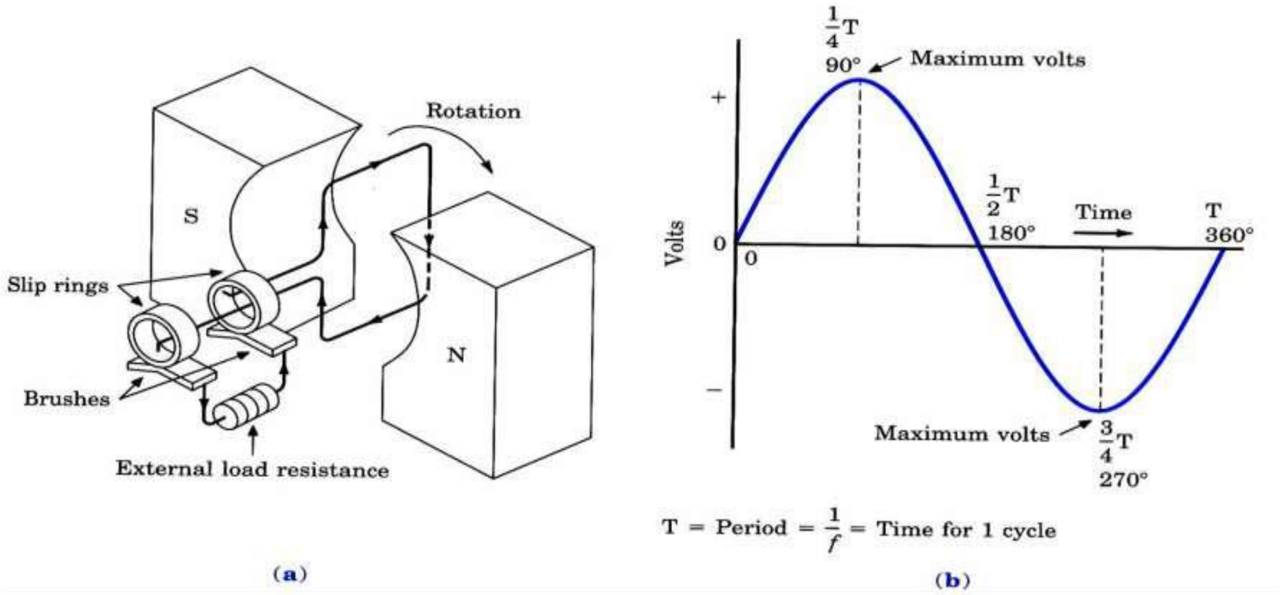
・交流電壓的產生：將一個矩形線圈放在磁鐵N極、S極所構成的固定磁場中，使該線圈以某一個特定方向、特定速度旋轉。線圈旋轉切割了磁通量(magnetic flux)使磁通量對時間發生變化，就發生了交變的感應電勢在導體中。



(a) Basic ac generator (b) Voltage waveform

單相交流發電機

・線圈的兩個端點分別連接不同的滑環(slip-rings)，該對滑環會隨線圈轉動而旋轉，將滑環以電刷(brushes)壓住，將電刷兩端加上負載(燈泡或電阻器)，則會有交變的電流通過負載，因此負載兩端會產生交變的電壓，此種電壓即為單相交流發電機的電壓。



(a) (b)

直流發電機的基本原理

・直流發電機之作用原理，如圖 3-6所示，係在線圈兩端分別焊接在半圓形銅片上，此銅片俗稱整流子，再由電刷將電流由整流子引出。當線圈在磁場中轉動時，雖產生交流電，但整流子能使電流以一定的方向由C端電刷流出，D端電刷流入而成直流電

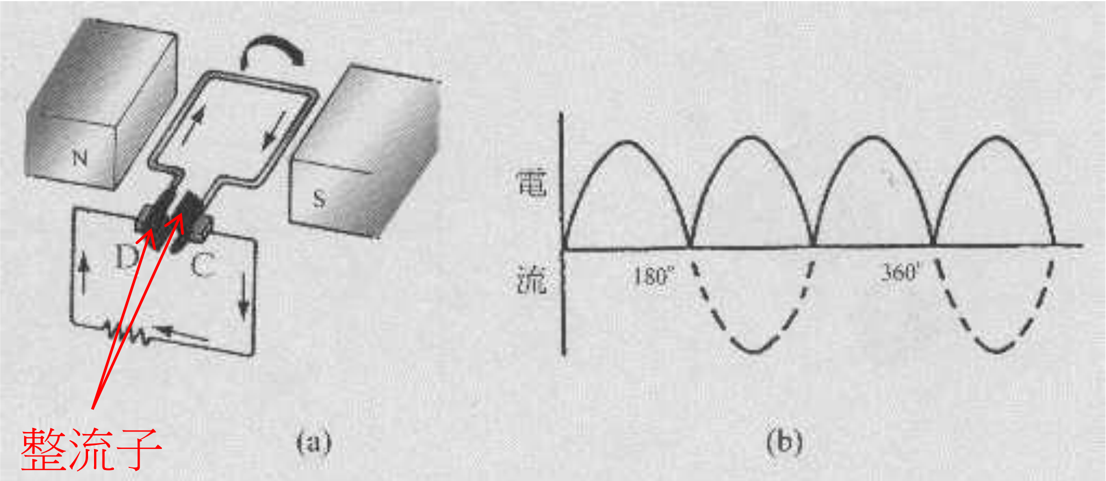
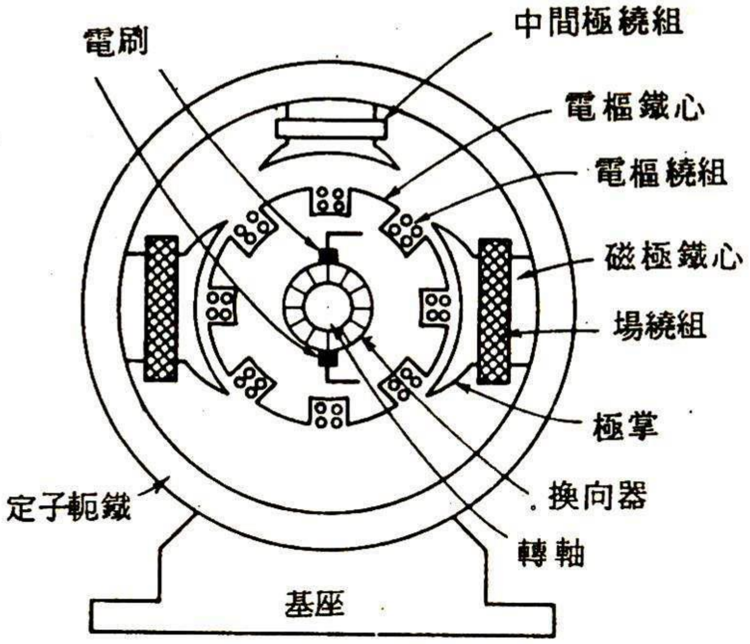


圖 3-6 直流發電機之作用原理

直流電機的結構圖



The magnetic dipole

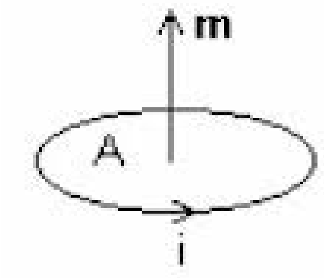
(What is the most elementary unit of magnetism)

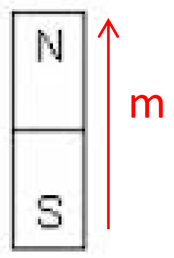
A circular loop of a conductor carrying an electric current, which can generate a magnetic field.

- A circular current loop can be considered the most elementary unit of magnetism.

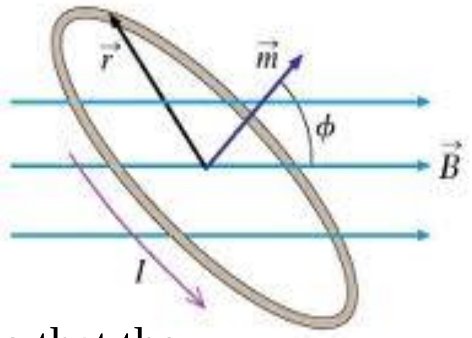
- If a current loop has area A and carries a current *i*, then its magnetic dipole moment is m=iA.

- The unit of magnetic moment: A・m^2 (amp ・meter^2)





- The torque on a magnetic dipole of moment m in a magnetic induction B is then simply $\vec{\tau} = \vec{m} \times \vec{B}$
- In free space $\vec{\tau} = \mu_o \vec{m} \times \vec{H}$

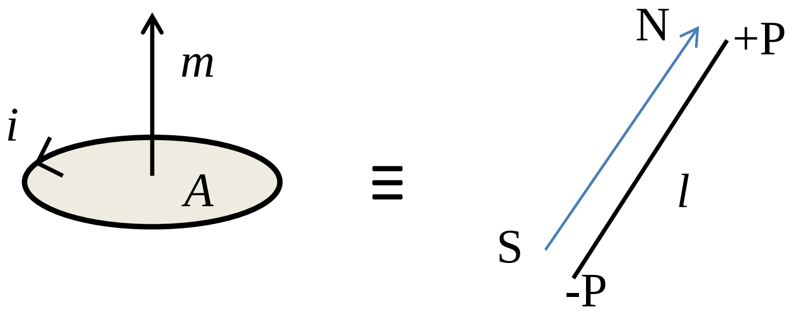


(-This mean that B tries to align the dipole so that the moment m lies parallel to the induction)

- The energy of the dipole moment m in the presence of a magnetic induction (If no frictional forces are operating, the work done by the turning force will be conserved) $E = -\vec{m} \cdot \vec{B}$

In free space $E = -\mu_o \vec{m} \cdot \vec{H}$

The field produced by a current loop is identical in form to the field produced by calculation from two hypothetical magnetic poles of strength separated by a distance *l*.



P: magnetic pole strength

l: distance

$\vec{m} = p \cdot \vec{l}$

- unit system in magnetism

The three unit systems
- CGS - Gaussian
- MKS -
  - Sommerfeld
  - Kennelly

Conversion factors:

1 oersted = 79.58 A/m

1 gauss = 10^{-4} tesla

1 emu/cm^3 = 1000 A/m

1 maxwell = 10^{-8} weber

1. The Earth's magnetic field is typically H=56 A/m (0.70e)
   B=0.7x10^{-4} tesla
2. The saturation magnetization of iron is M_0=1.7x10^6 A/m
   M_r=0.8x10^6A/m
3. Lab electromagnet H = 1.6x10^6 A/m
   B = 2 tesla

12 *Magnetic fields*

Table 1.1 Principal unit systems currently used in magnetism

Quantity		*SI (Sommerfeld)*	*SI (Kennelly)*	*EMU (Gaussian)*
Field	H	A/m	A/m	oersteds
Induction	B	tesla	tesla	gauss
Magnetization	M	A/m	–	emu/cc
Intensity of magnetization	I	–	tesla	–
Flux	Φ	weber	weber	maxwell
Moment	m	A m^2	weber metre	emu
Pole strength	p	A m	weber	emu/cm
Field equation		$B = \mu_0(H + M)$	$B = \mu_0 H + I$	$B = H + 4\pi M$
Energy of moment (in free space)		$E = -\mu_0 m \cdot H$	$E = -m \cdot H$	$E = -m \cdot H$
Torque on moment (in free space)		$\tau = \mu_0 m \times H$	$\tau = m \times H$	$\tau = m \times H$

Note: The intensity of magnetization I used in the Kennelly system of units is merely an alternative measure of the magnetization M, in which tesla is used instead of A/m. Under all circumstances therefore $I = \mu_0 M$.

$H = 56$ A/m (0.7 Oe), $B = 0.7 \times 10^{-4}$ tesla. The saturation magnetization of iron is $M_0 = 1.7 \times 10^6$ A/m. Remanence of iron is typically 0.8×10^6 A/m. The magnetic field generated by a large laboratory electromagnet is $H = 1.6 \times 10^6$ A/m, $B = 2$ tesla.

– Magnetic field calculation

– Magnetic field are usually produced by { solenoids / electromagnets }

(solenoids are often cylindrical in shape)

A solenoid is made by winding a large number of turns of insulated Cu wire, or a similar electrical conductor, in a helical fashion on an insulated tube know as a "former".

– The ferromagnetic core of an electromagnet generate a higher magnetic induction $\vec{B}$ than a solenoid for the same magnetic field $\vec{H}$

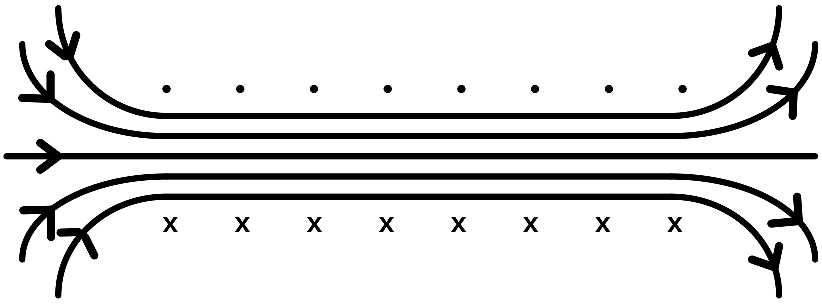
1. Field at the centre of a long thin solenoid

(what is the simplest way to produce a uniform magnetic field)

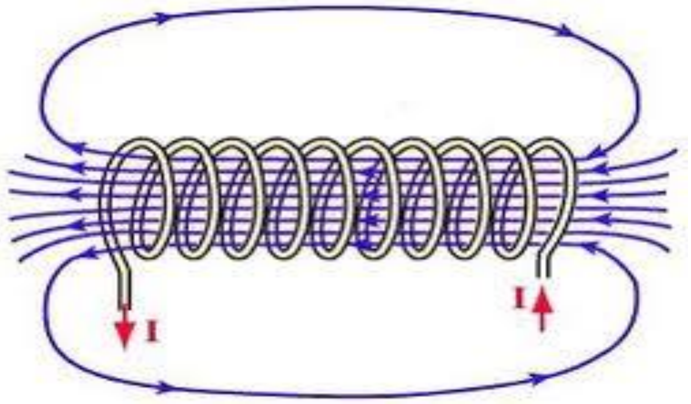
– If the solenoid has N turns wound on a former of length L and carries a current i amperes the field inside it will be

$$\vec{H} = \frac{Ni}{L} = ni \qquad \left(n = \frac{N}{L} \right)$$

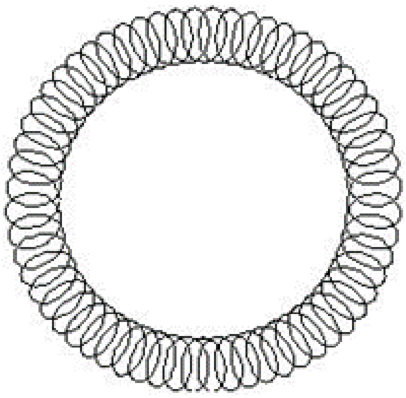
n: the no. of turns per unit length

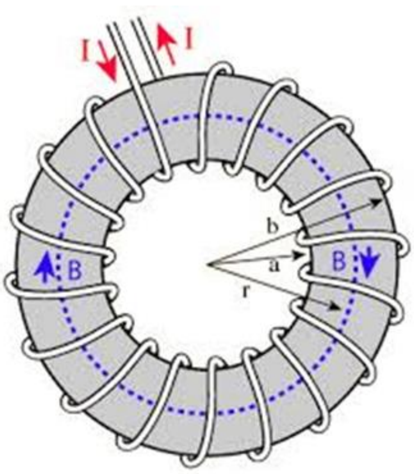


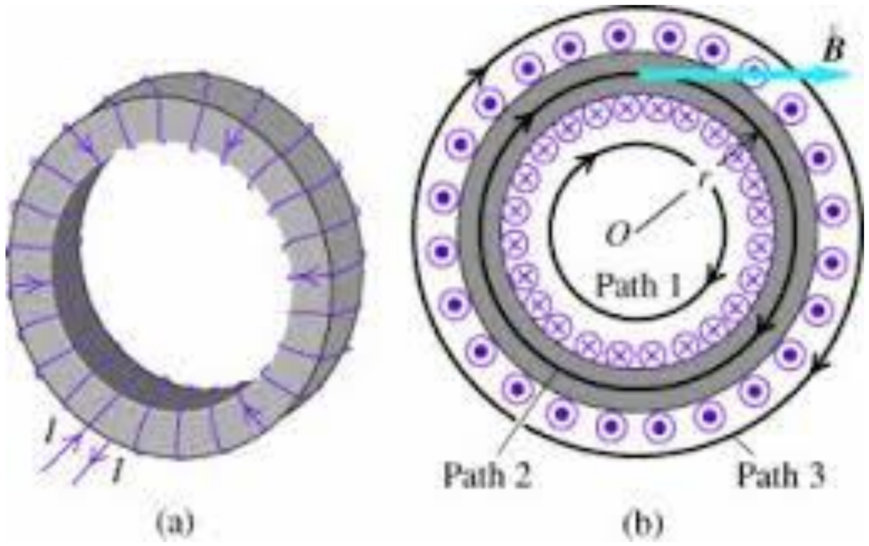
Magnetic field lines
Around a solenoid



A practical method of making an “infinite” solenoid is to make the solenoid toroidal in shape. This ensures that the field is uniform throughout the length of the solenoid.







The magnetic field $H = \dfrac{N}{2\pi r} i$

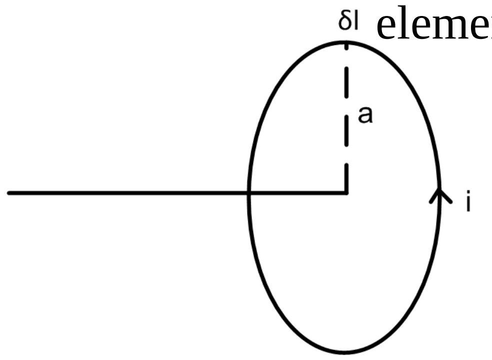
- N: the total no. of turns
- r: the radius of the toroid
- i: the current flowing

2. Field due to a circular coil

(What is the field strength produced by the simplest form of coil geometry the single-turn)

(1) Field at the center of a circular coil

δl element of conductor



By Biot-Savart, $\delta\vec{H} = \left(\frac{1}{4\pi r^2}\right) i\delta\vec{l} \ x \ \vec{u}$

$$H = \sum \frac{1}{4\pi r^2} \ i\delta l \ sin\,\theta$$

$$\sum \delta l = 2\pi a, \quad d\vec{l} \perp \vec{u} \ \Rightarrow \theta = 90^\circ \ \Rightarrow \sin 90^\circ = 1$$

$$H = \frac{i}{2a} \ A/m$$

(2) Field on the axis of a circular coil

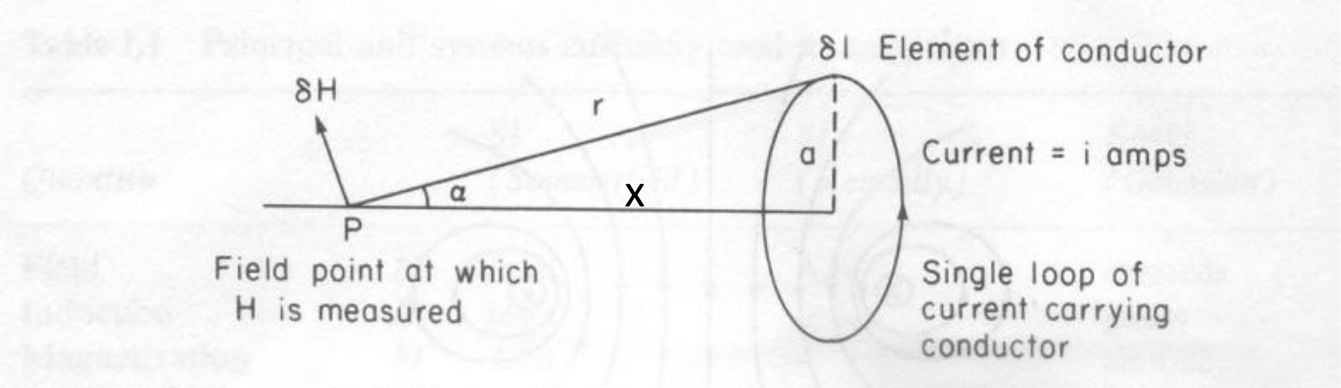
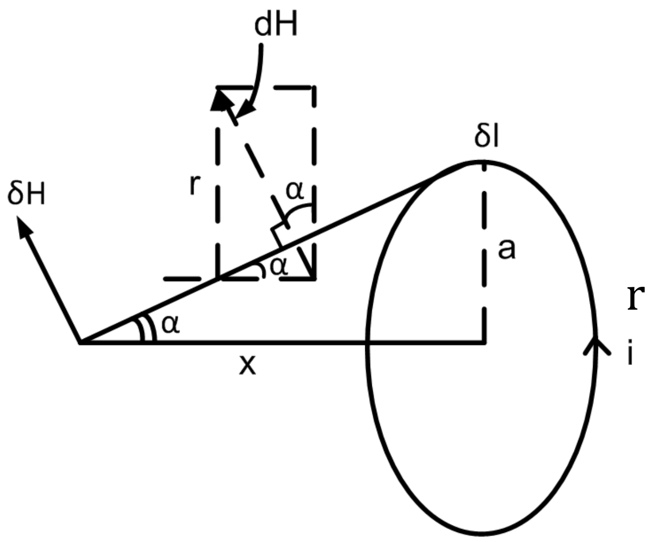


Fig. 1.4 The magnetic field due to a single circular coil carrying an electric current.



$$d\vec{H} = \frac{1}{4\pi r^2} i d\vec{l} \times \vec{u}$$

$\vec{u}$ *is a vector* long the r direction

$$r = \frac{a}{\sin\alpha} \quad , \quad d\vec{H} = \frac{1}{4\pi a^2}(\sin^2\alpha) i d\vec{l} \times \vec{u}$$

$$d\vec{H}_{axial} = d\vec{H}\sin\alpha$$

$$d\vec{H}_{\text{axial}} = \frac{1}{4\pi a^2}(\sin^3\alpha) i d\vec{l} \times \vec{u}$$

$$\int dl = 2\pi a, \; d\vec{l} \perp \vec{u}$$

$$\vec{H}_{axial} = \frac{i}{2a}\sin^3\alpha = \frac{i}{2a}\left(\frac{a^3}{r^3}\right) = \frac{ia^2}{2r^3} \qquad r = \sqrt{a^2 + x^2}$$

$$\vec{H}_{axial} = \frac{ia^2}{2(a^2 + x^2)^{3/2}}$$

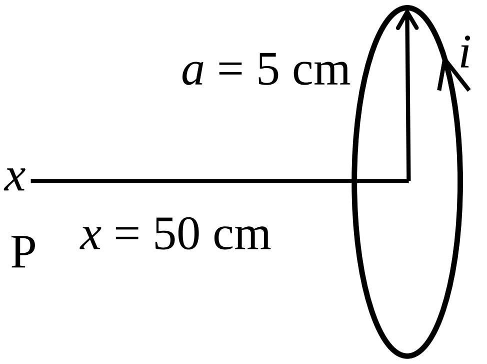
This can be expressed in the form of a series in x (and by symmetry all terms of odd order must have zero coefficients so the form of the dipole field become)

$$H = H_o(1 + C_2x^2 + C_4x^4 + C_6x^6 + ...)$$

$$H_o = \left(\frac{i}{2a}\right) \text{ (the field at the center of the coil)}$$

$$C_2 = -3/2a^2 \quad , C_4 = -15/8a^4 \quad , C_6 = -105/48a^6$$

Ex 1.3 If a coil of 100 turns and diameter 10 cm carries a current of 0.1A, calculate the magnetic field at a distance of 50 cm along the axis of the coil.



$i = 0.1\text{A}$
$a = 5 \text{ cm}$
$x = 50 \text{ cm}$
$N = 100$
$H = ?$

$$H = \frac{100(0.05)^2(0.1)}{2\left[(0.05)^2 + (0.5)^2\right]^{3/2}}$$

$$= \frac{0.025}{2(0.253)^{3/2}}$$

$$= 0.0098 \,\text{A/m}$$

(3) off-axis field a circular coil $\left(\begin{array}{l} \text{In the vast majority of cases there is no} \\ \text{closed-form analytic solution for the field} \\ \text{generated by a current-carrying conductor} \end{array} \right)$

In the case of the off-axis field of the single circular loop the analysis leads to an elliptic integral which has no exact solution.

By Biot-Savart law $\quad dH = \dfrac{idl \times u}{4\pi r^2} \quad r$: the distance from the coil

$$dH = \frac{idl \sin\theta}{4\pi(x^2 + a^2)}$$

$\left(\begin{array}{l} \text{where now } a \text{ is also a function of } \theta \text{ instead of being a constant. In the case of} \\ \text{the off-axis field, the field strength can be calculated from this eq. by a computer} \\ \text{using numerical techniques.} \end{array} \right)$

Chap 2 Magnetization and Magnetic Moment

(When going on to consider magnetic materials it is first necessary to define quantities which represent the response of these materials to the field. These quantities are magnetic moment and magnetization. Once that has been done, we can consider another property. The susceptibility, which is closely related to the permeability.)

– Consider the <u>effect</u> that a <u>magnetic materials</u> has <u>on</u> the magnetic induction <u>*B*</u> when a field pass throught it.

↓

Magnetization

– Materials can alter the <u>magnetic induction</u> (*B*)
  - lager → (paramagnets, ferromagnets)
  - Smaller → (diamagnet)

– Magnetic moment (*m*)

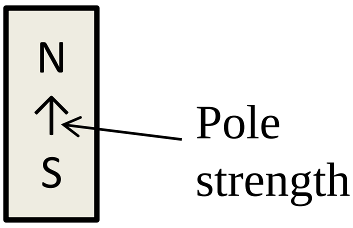
(can we use the torque on a specimen in a field of know strength to define its magnetic properties?)

– The torque on the dipole in the presence of a magnetic field in free space is given by $\vec{\tau} = \vec{m} \times \vec{B}$

– The $\vec{m}$ can be expressed as the maximum torque on a magnetic dipole τ_{max} divided by *B*

$$\vec{m} = \frac{\vec{\tau}_{max}}{\vec{B}}$$

$$= \frac{\vec{\tau}_{max}}{\mu_0 \vec{H}} \quad \text{(in free space)}$$

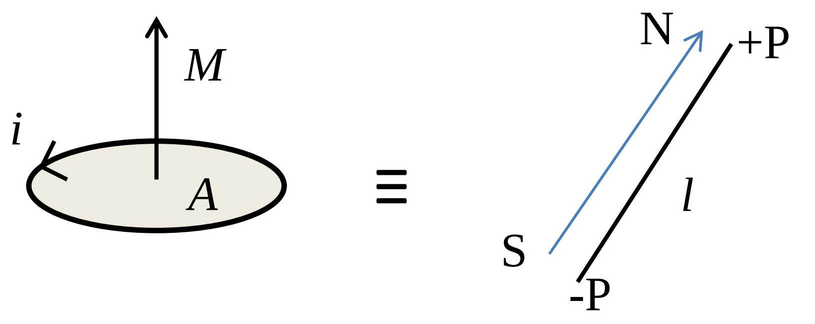


– Unit of m: $A \cdot m^2$ (ampere·meter^2)

– This formula applies equally to a <u>current loop</u> or a <u>bar magnet</u>

The unit of magnetic moment

- The magnetic moment of 1 ampere·meter^2 experiences a maximum torque of 1 newton·meter when oriented perpendicular to magnetic induction of 1 tesla.



P: magnetic pole strength

l: distance

In the case of current loop m=iA

i: the current flowing (A)
A: the cross-sectional area of the loop (m^2)

In the case of a bar magnet m=pl

p: the pole strength (A·m)
l:the dipole length (m)

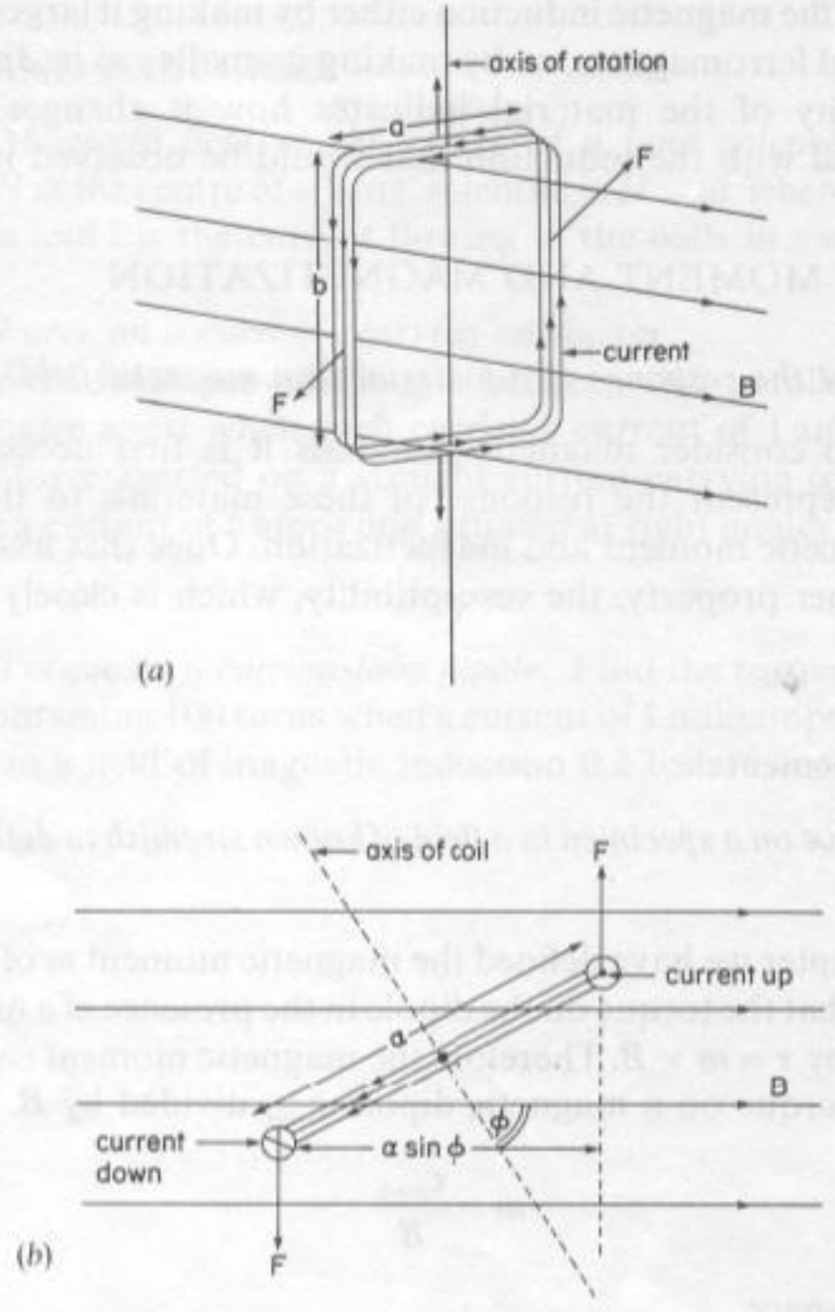


Fig. 2.1 The torque on a current loop in an external magnetic field; (a) side view, and (b) top view. If the loop is free to rotate the torque turns the loop until its plane is normal to the field direction.

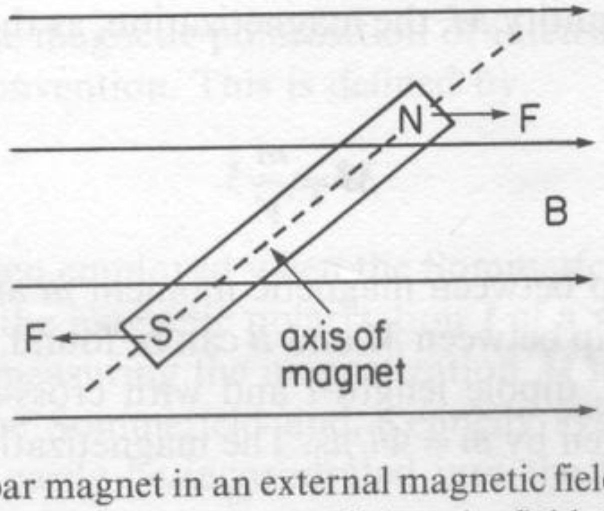
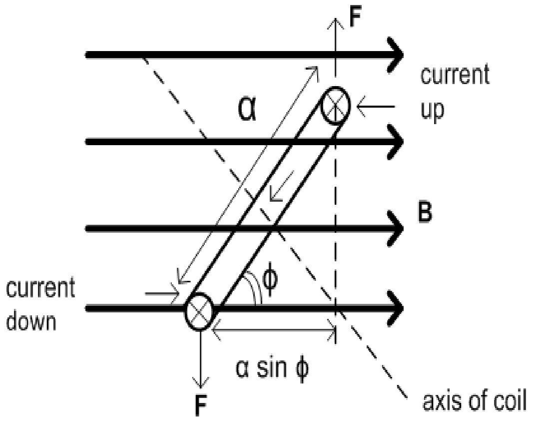


Fig. 2.2 The torque on a bar magnet in an external magnetic field. If the bar is free to rotate the torque turns the bar until its plane is parallel to the field direction.

In a current loop



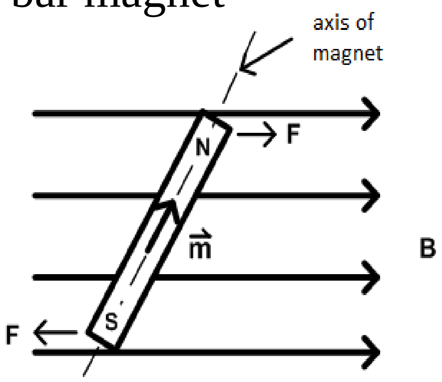
$\because E = -\vec{m}\cdot\vec{B}$

$\therefore$ 當$\vec{m} \,/\!/\, \vec{B}$時，E_{min}會產生

The torque turns the loop until its plane is normal to the field direction.

$m = iA$

In a bar magnet



The magnetic moment vector $\vec{m}$ in a bar magnet tends to align itself with B under the action at the torque.

$\because E = -\vec{m}\cdot\vec{B}$

$\therefore$ 當$\vec{m} \,/\!/\, \vec{B}$時，E_{min}會產生

A torque aligns the magnet parallel to the local direction *B*.

$m = p \cdot l$

p: amp·meter

l : dipole length

$M = \frac{m}{v}$ — m: Magnetic moment; v: Volume of a solid

In the Sommerfeld convention

this is given $p = \frac{\Phi}{\mu_0}$

$m = pl$

$= \frac{\Phi l}{\mu_0}$

Φ is the flux in webers passing through the current loop or bar dipole. *l* is the dipole length.

- The “pole strength” is arising from the more traditional CGS Treatment of magnetism, in which pole strength was defined in terms of the magnetic flux Φ emanating from a single magnetic pole

Magnetization (M)

−How are the magnetic properties of the material and the magnetic induction B related?

$$M\text{, magnetization,} = \frac{\text{the magnetic moment}}{\text{per unit volume}} \qquad M = \frac{m}{V}$$

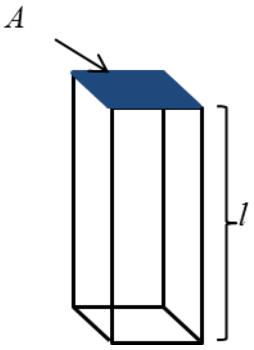
−A bar magnet with flux density ϕ at the center, dipole length l and with cross-sectional area A has a magnetic moment m, given by $m = \dfrac{\phi l}{\mu_0}$

−The magnetization M is given by

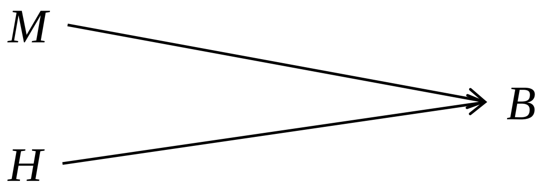
$$M = \frac{m}{Al} = \frac{\phi}{\mu_0 A} = \frac{B}{\mu_0}$$

$$M = \frac{m}{Al} = \frac{\Phi}{\mu_0 A} \quad (m = \frac{\Phi l}{\mu_0})$$

$$= \frac{B}{\mu_0} \quad (\Phi = B \cdot A)$$



- In this case there are no conventional external electric currents present to generate on external magnetic field (H), so $B=\mu_0 M$



contribution

−If both M and H are present then their contributions can be summed.

Relation between *H*, *M*, *B*

(Can we define a universal equation relating these three magnetic quantities *H, M, B*?)

– Magnetic induction *B* consists of two contribution { H, M }

$$B=\mu_0(H+M)$$

- In free space $B=\mu_0 H$ (The magnetic induction in free space)
- In a material $B=\mu_0 M$ (The contribution to the induction from the magnetization of a material)

Unit: B – tesla

$H - \text{A}/\text{m}$

$M - \text{A}/\text{m}$

– *H* is generated from { solenoid, electromagnet, permanent magnet } outside the material
(by electrical currents)

– *M* is generated by { spin, orbital angular momentum } of electrons within the solid

– A related quantity, the magnetic polarization or intensity of magnetization *I* is used in the Kennelly convention. This is defined by $I=\mu_0 M$

unit of *I* : tesla