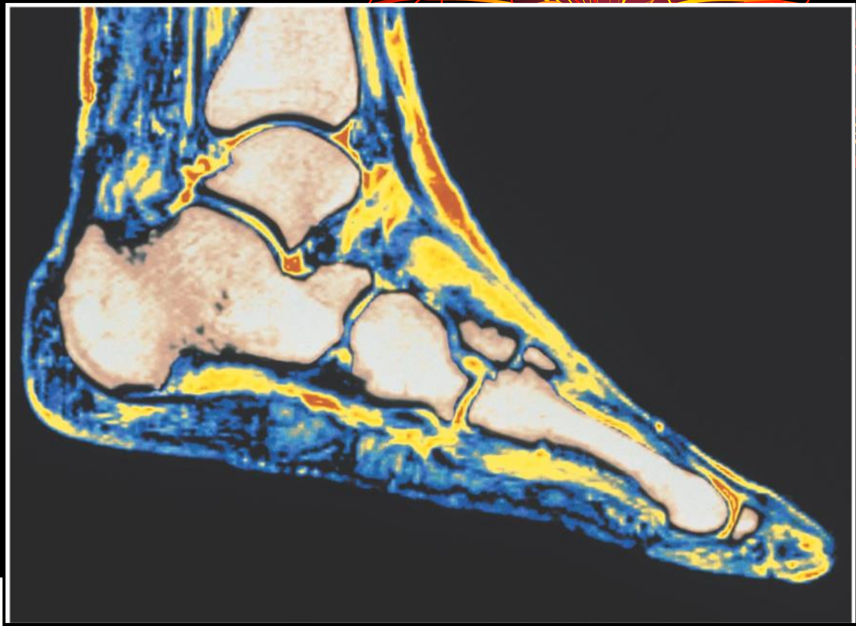
8 磁場

How is an aurora so thin yet so tall and wide?

Introduction

How does magnetic resonance imaging (MRI) allow us to see details in soft nonmagnetic tissue?



How can magnetic forces, which act only on moving charges, explain the behavior of a compass needle?

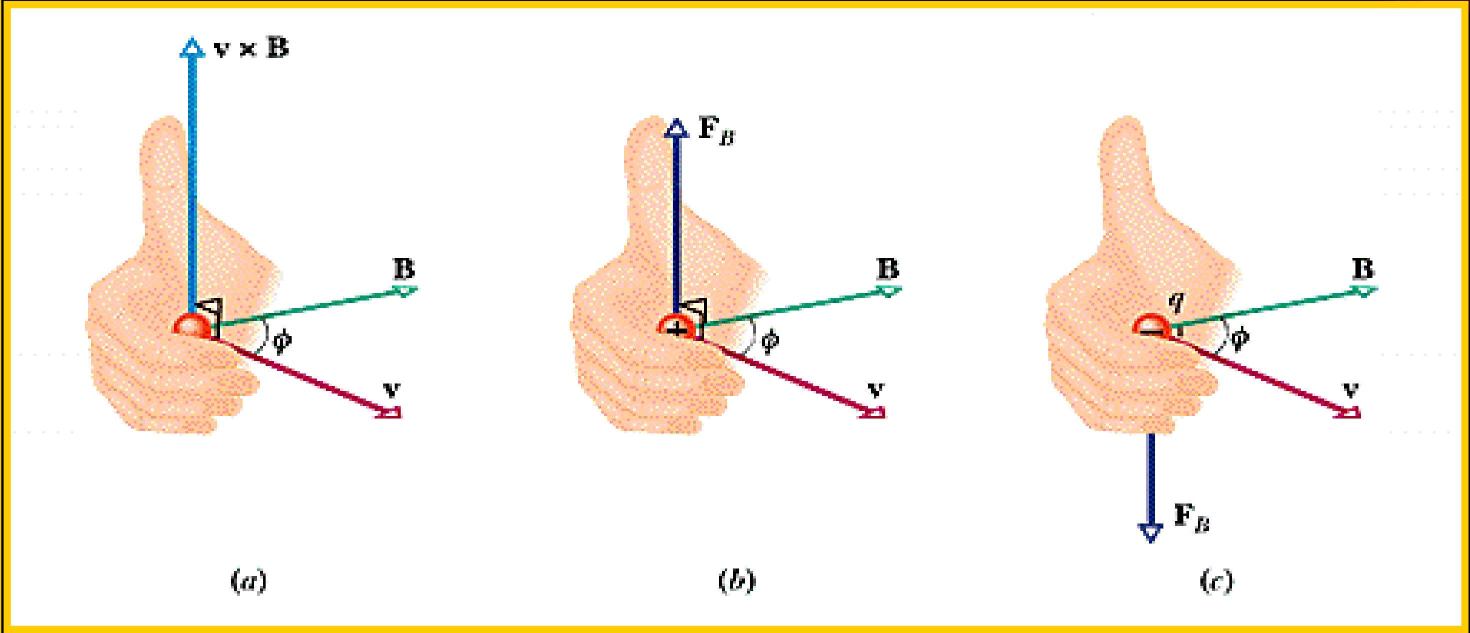
The magnetic field

- The electric field and the magnetic field
- Electromagnets and permanent magnets

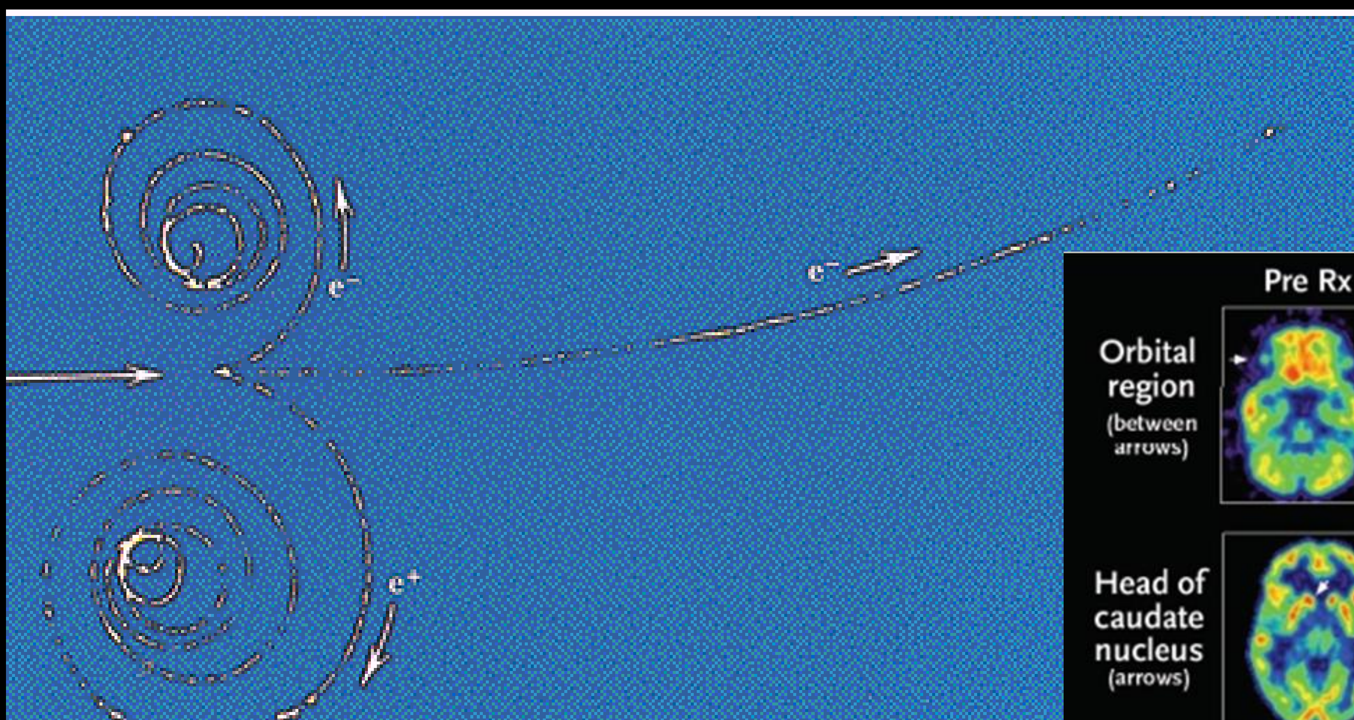
8-1 The definition of B

$$\vec{F}_B = q\vec{v} \times \vec{B}$$

$$\vec{E} = \frac{\vec{F}}{q_0} \,(\mathrm{N/C})\,(\mathrm{V \cdot m})$$



The tracks in a bubble chamber



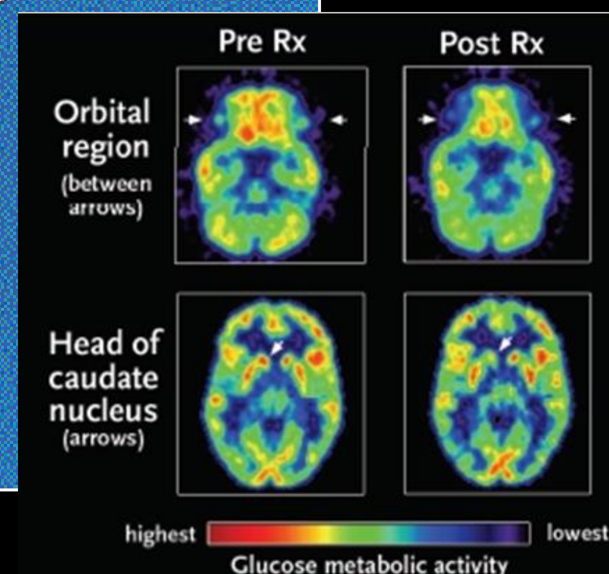
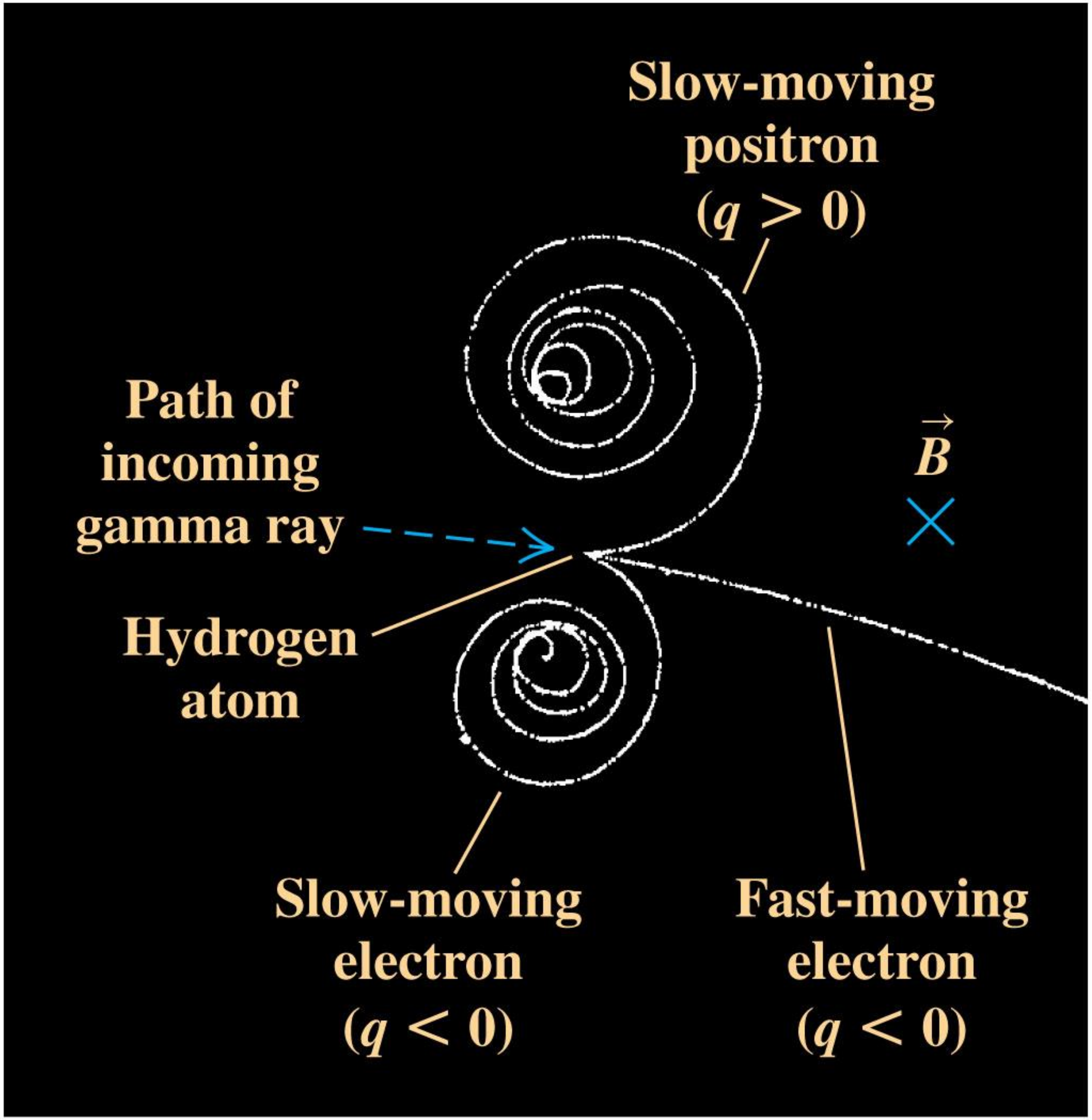


Figure 27.21



Slow-moving positron ($q > 0$)
Path of incoming gamma ray
Hydrogen atom
$\vec{B}$
Slow-moving electron ($q < 0$)
Fast-moving electron ($q < 0$)

The SI unit for B

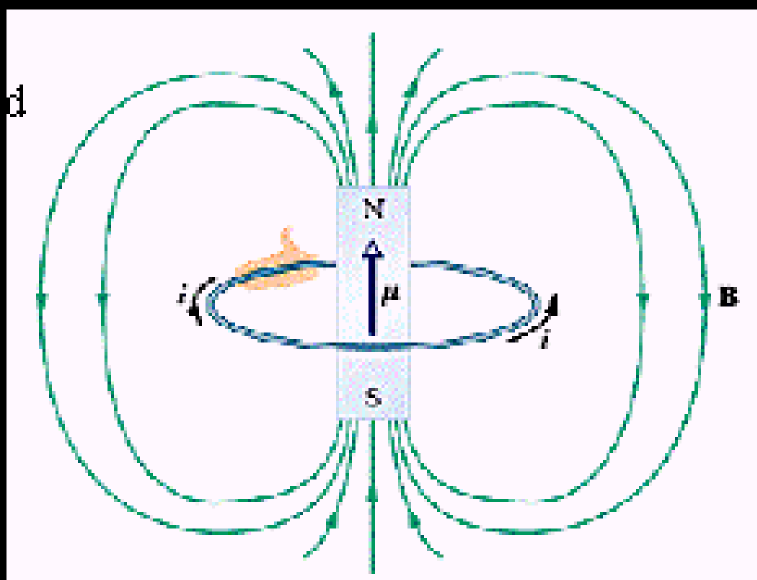
1 tesla = 1T =1 N/A・m=10^4 gauss

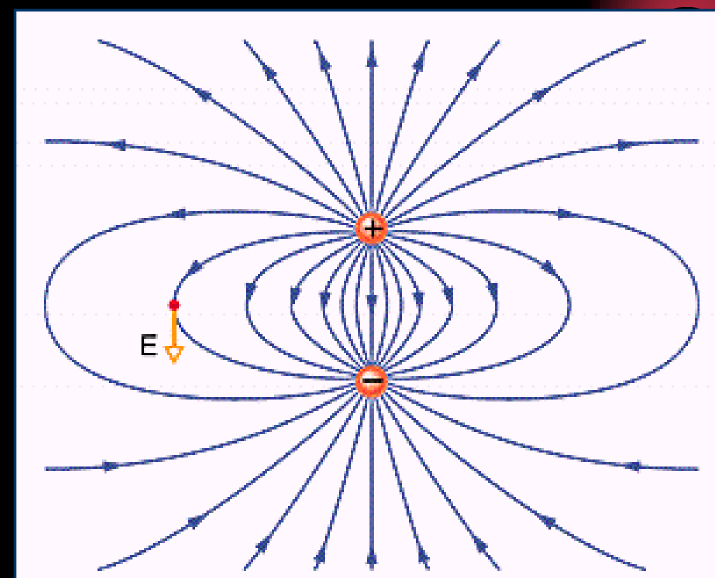
TABLE 29-1 SOME APPROXIMATE MAGNETIC FIELDS

At the surface of a neutron star	10^8 T
Near a big electromagnet	1.5 T
Near a small bar magnet	10^{-2} T
At Earth's surface	10^{-4} T
In interstellar space	10^{-10} T
Smallest value in a magnetically shielded room	10^{-14} T

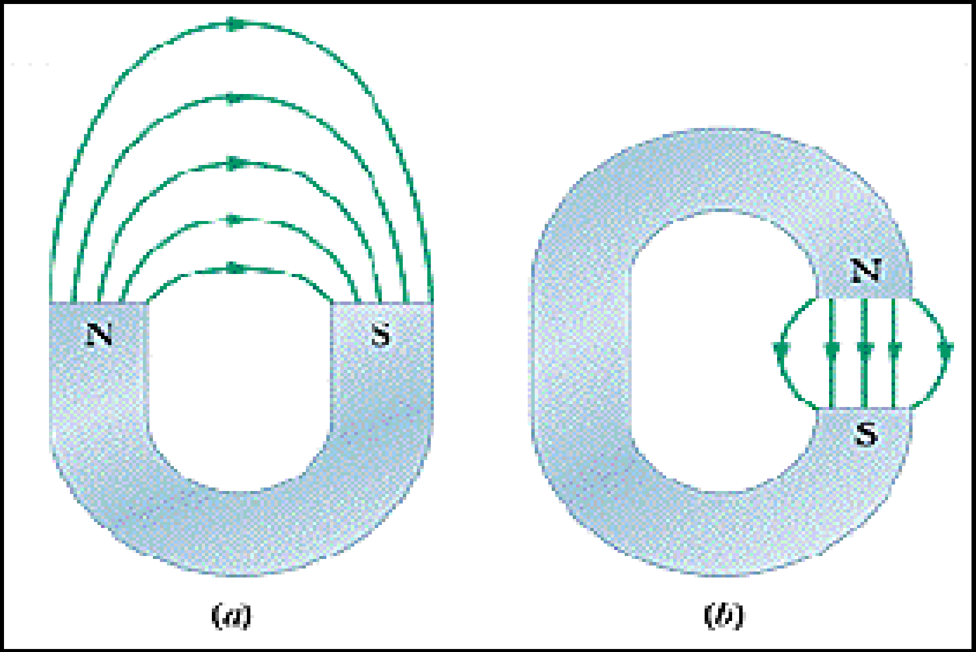
Magnetic Field Lines

- Magnetic vs. electric dipoles



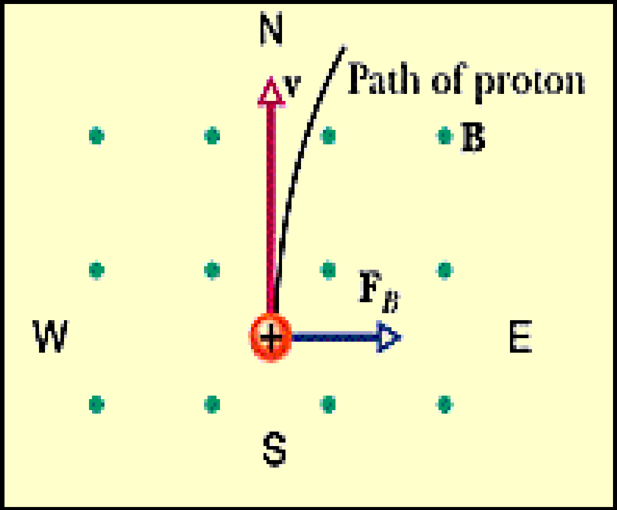


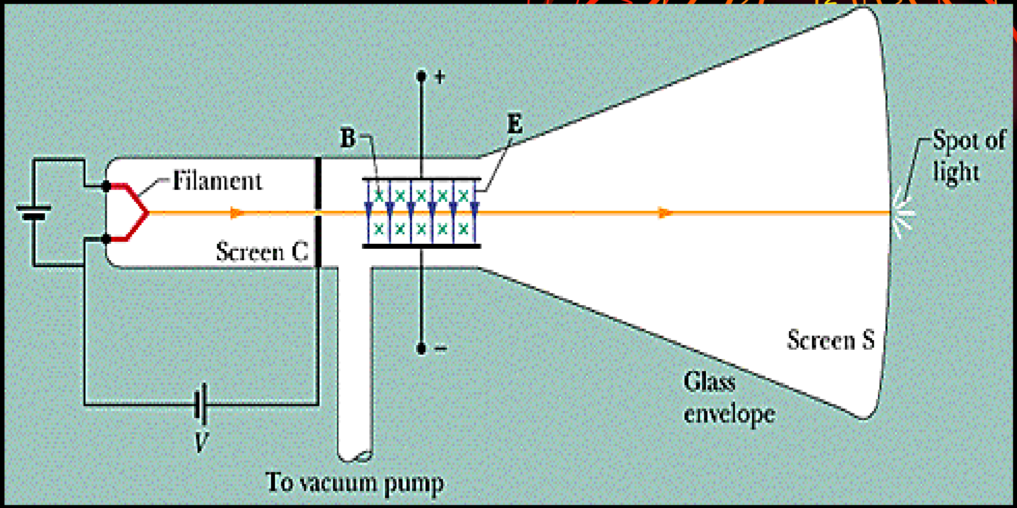
A horseshoe and a C-shaped magnets



例 1 A 5.3 MeV proton

B = 1.2 mT





$$v = \sqrt{2K/m} = 3.2 \times 10^{7}\ \mathrm{m/s}$$

$$F_B = qvB\sin\phi = 6.1 \times 10^{-15}\ \mathrm{N}$$

$$a = F_B/m = 3.7 \times 10^{12}\ \mathrm{m/s^2}$$

8-2 Crossed Fields: Discovery of the Electron

- A cathode ray tube
- Thomson's procedure:
  - 設定$E=0$、$B=0$，並記錄光點位置
  - 開啟電場、測光點偏移量
  - 開啟磁場，並調整其值，直至光點回復未偏移位置

Calculation

$$y = \frac{qEL^2}{2mv^2}, \quad qE = qvB$$

$$v = E / B, \quad \frac{m}{q} = \frac{B^2 L^2}{2yE}$$

the charge-to-mass ratio of the electron ：

1.7588196×10[11] C·kg[-1]

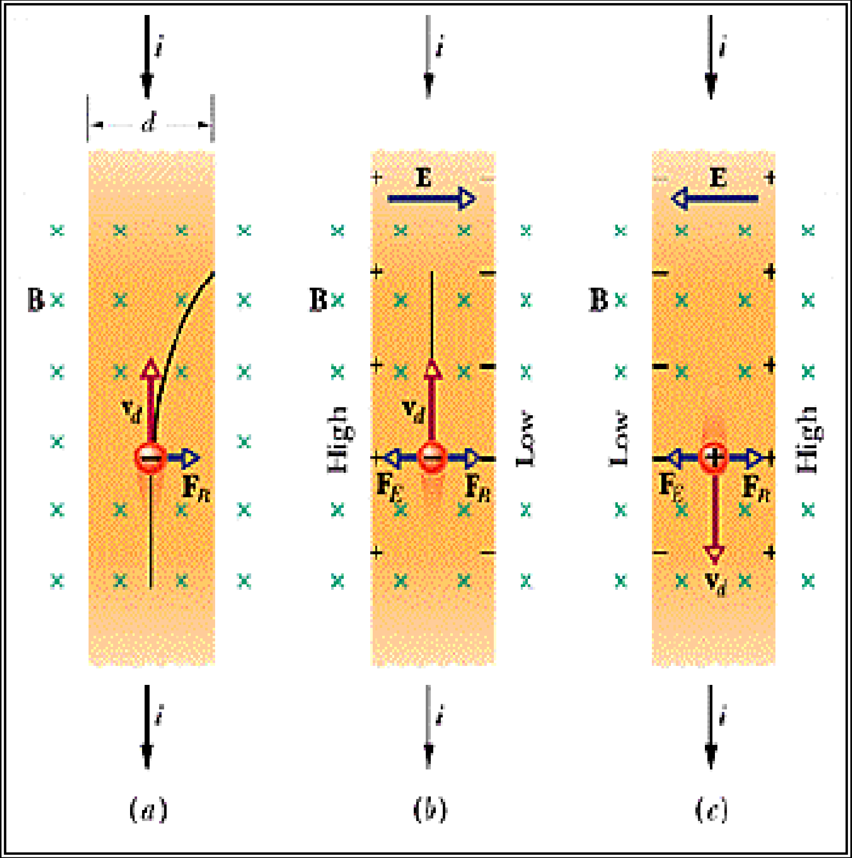
$$a_y = \frac{F}{m} = \frac{QE}{m}$$

$$y = \frac{1}{2} a_y t^2, L = v_x t$$

$$y = \frac{QEL^2}{2mv_x^2}$$

8-3 Crossed Fields: The Hall Effect

- **By the conduction electrons in copper:**



$$V = Ed$$

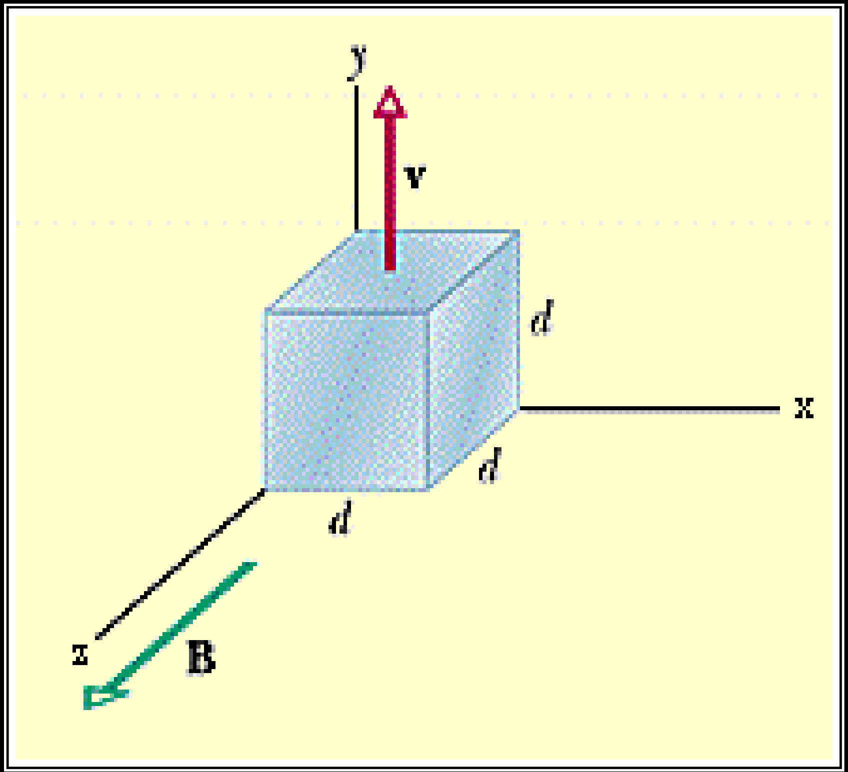
$$eE = ev_d B$$

$$v_d = \frac{J}{ne} = \frac{i}{neA}$$

$$n = \frac{Bi}{Vle} \quad \left(l = \frac{A}{d}\right)$$

例 2 A cube generator

d = 1.5 cm, v = 4.0m/s, B = 0.05T



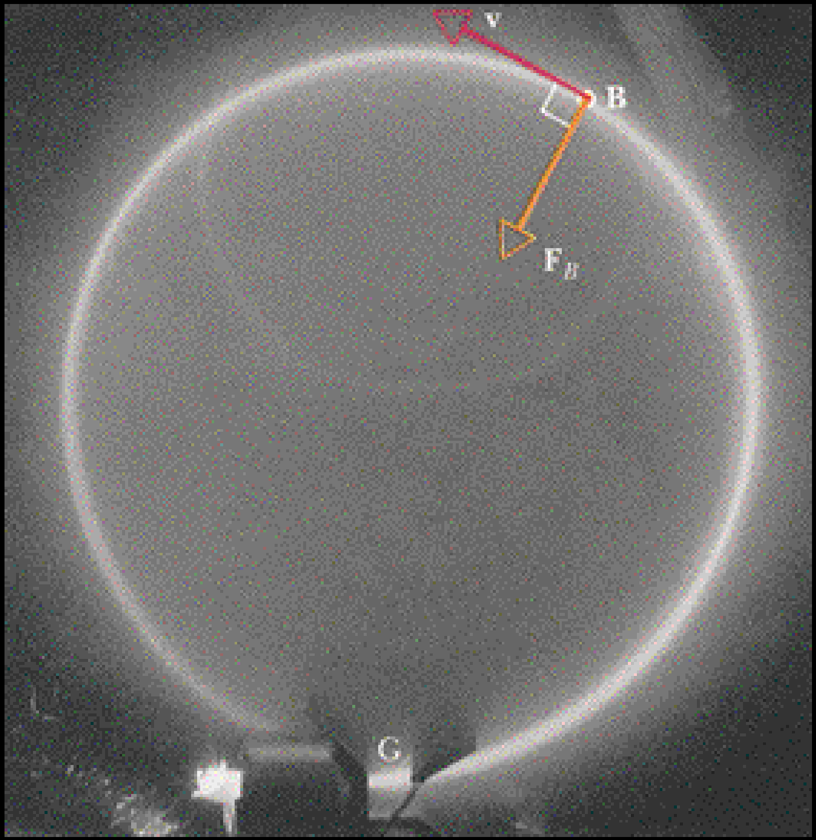
$$eE = evB$$

$$V = Ed$$

$$V = dvB$$

$$V = 3.0\text{mV}$$

8-4 A Circulating Charged Particle



$$F = ma = mv^2 / r$$

$$qvB = mv^2 / r$$

$$r = mv / qB$$

$$T = 2\pi r / v$$

$$= 2\pi m / qB$$

Figure 27.17a

(a) The orbit of a charged particle in a uniform magnetic field

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.

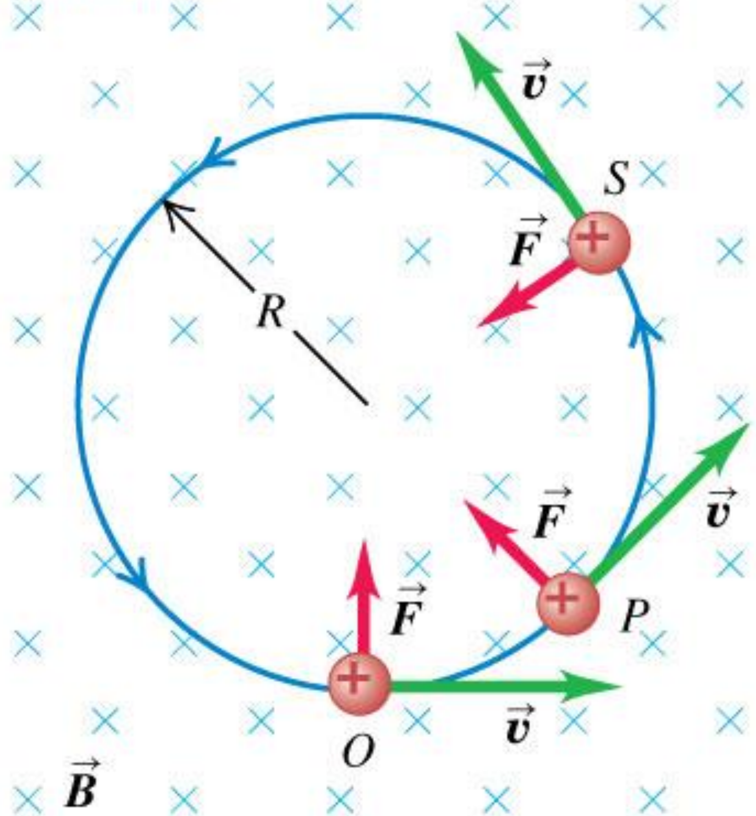
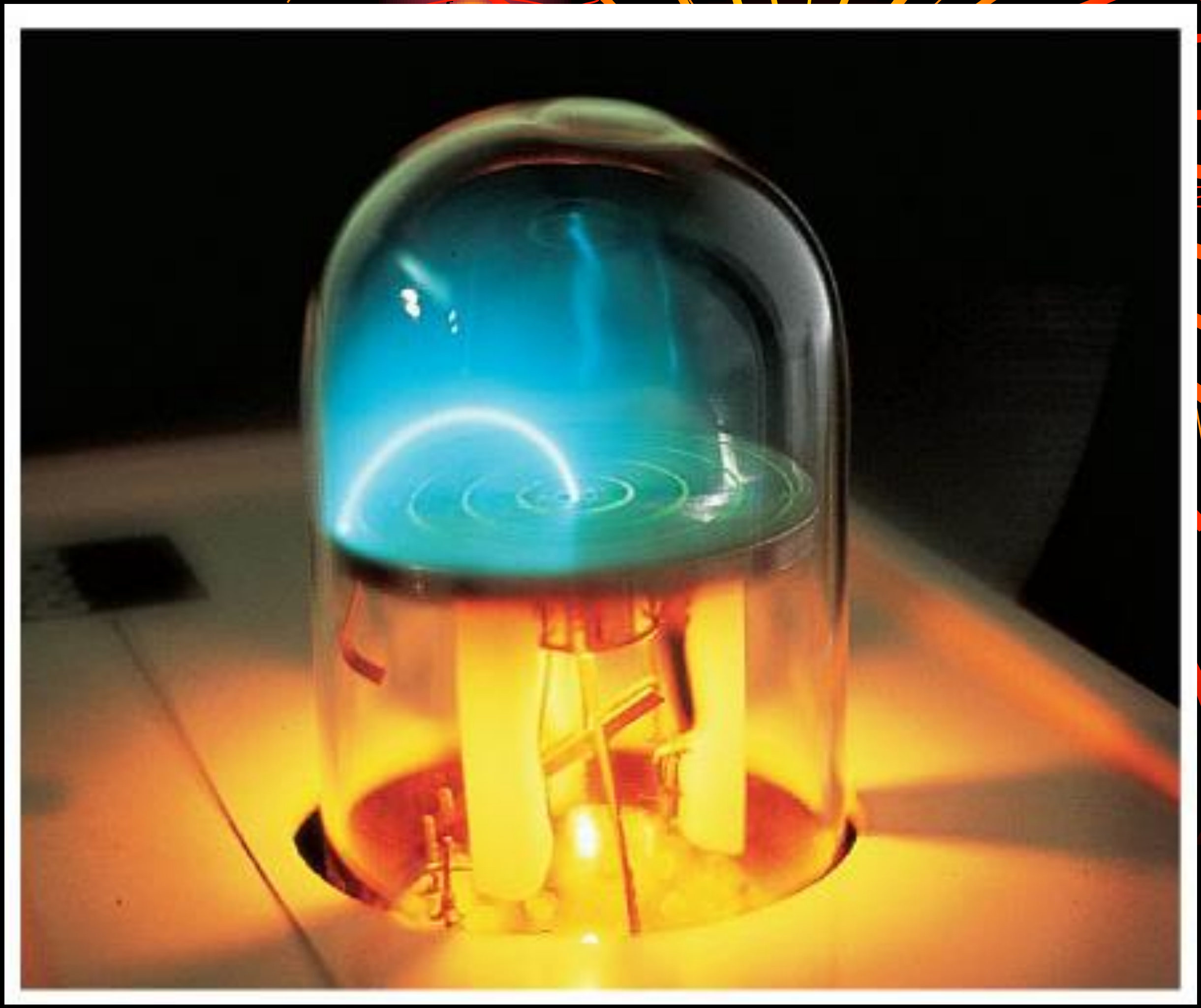


Figure 27.17b



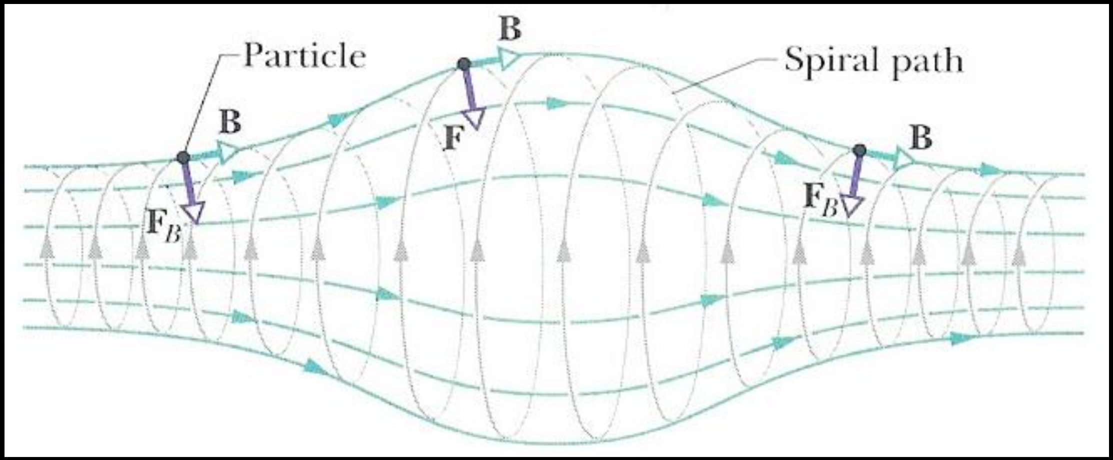
頻率與軌跡

The frequency and angular frequency

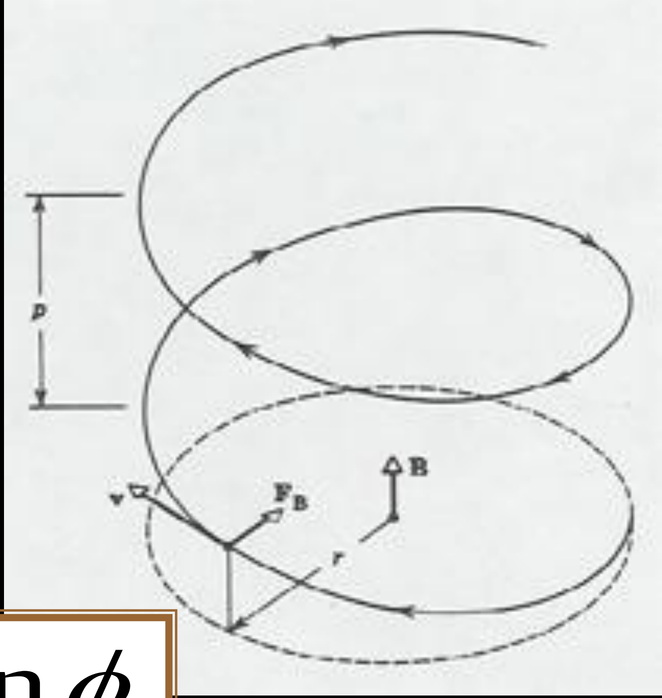
$$f = \frac{1}{T} = \frac{qB}{2\pi m} \quad \omega = 2\pi f = \frac{qB}{m}$$

$$f = \frac{qB}{2\pi m_0}\sqrt{1 - v^2/c^2}$$

The magnetic bottle machine



Helical Paths



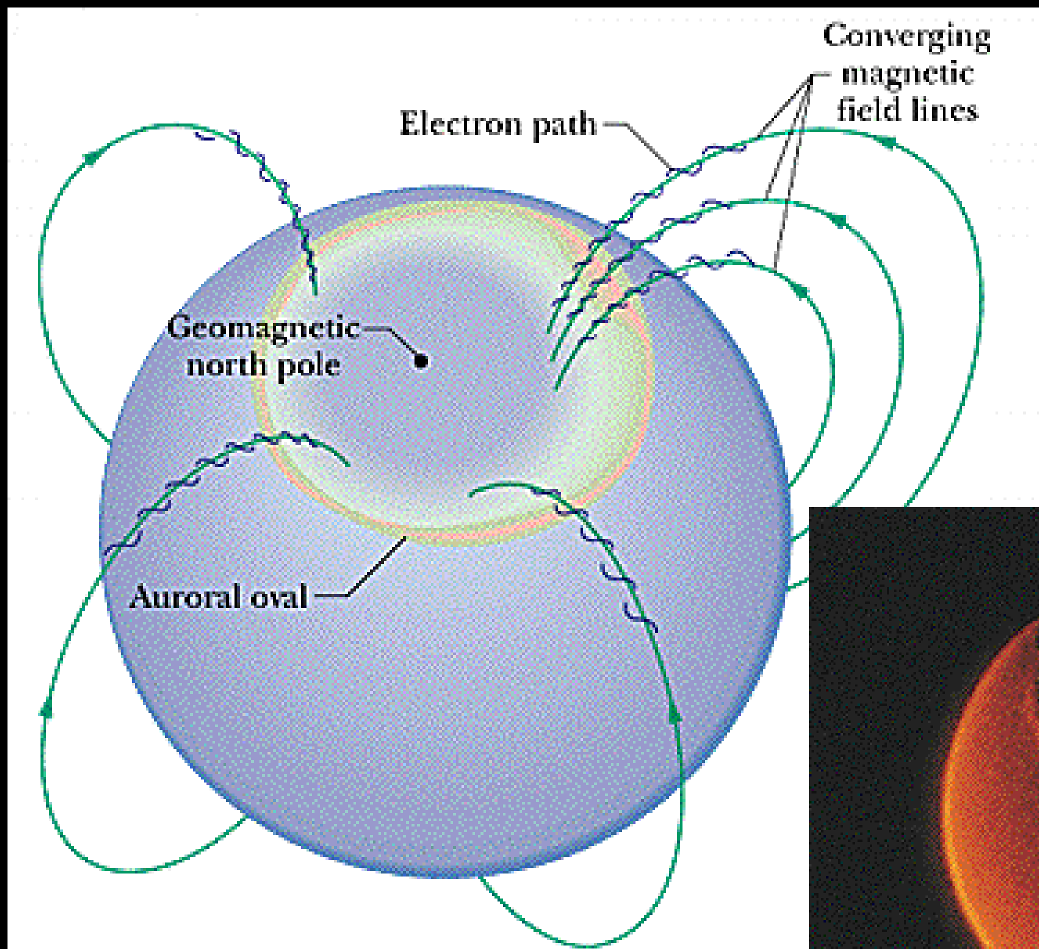
$v_{\parallel}$ and $v_{\perp}$

$$v_{\parallel} = v\cos\phi \quad v_{\perp} = v\sin\phi$$

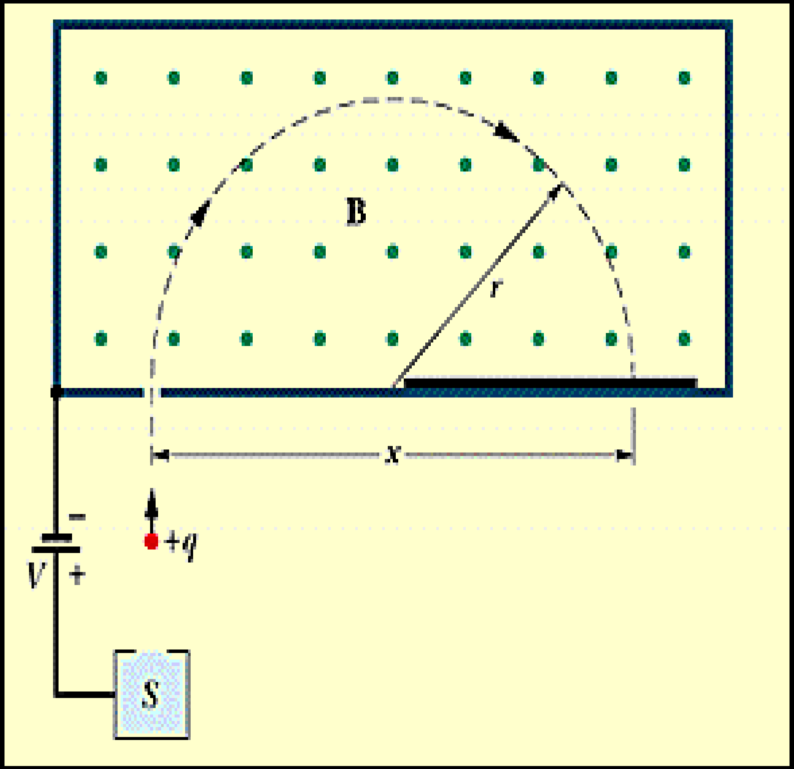
The pitch (螺距) of the helical path

$$p = v_{\parallel}T = v\cos\phi\frac{2\pi m}{qB}$$

極光橢圓圈


Converging
magnetic
field lines
Electron path
Geomagnetic
north pole
Auroral oval

例 3 The Mass Spectrometer (質譜儀)



$$\frac{1}{2}mv^2 = qV$$

$$v = \sqrt{2qV/m}$$

$$r = \frac{mv}{qB} = \frac{1}{B}\sqrt{\frac{2mV}{q}}$$

$$x = 2r$$

質譜儀

x = 1.6254m, V = 1000.0V, B = 80.000mT

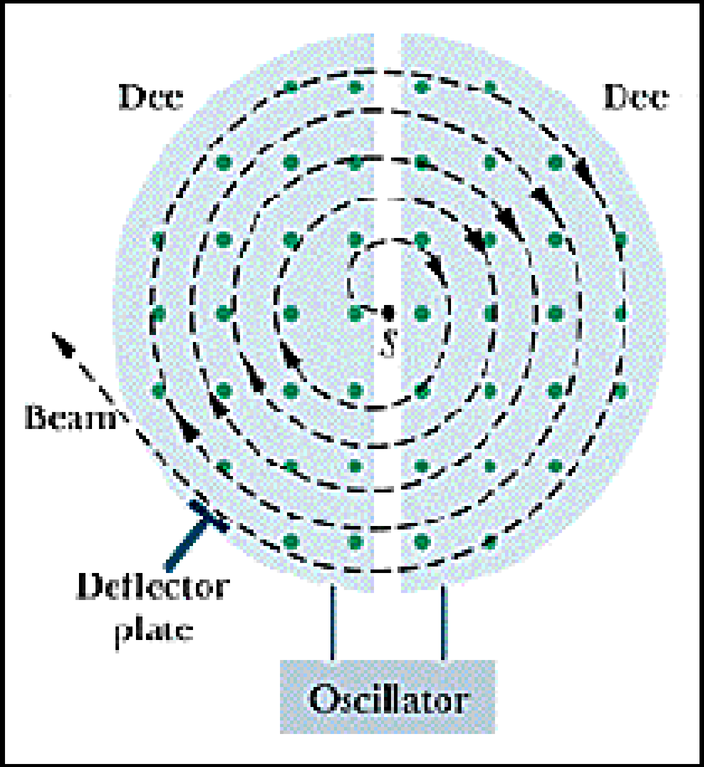
$$x = 2r = \frac{2}{B}\sqrt{\frac{2mV}{q}}$$

$$\rightarrow m = \frac{B^2 q x^2}{8V} = 203.93\text{u}$$

Isotope Separation

Centrifuge and diffusion chamber

8-5 Cyclotrons and Synchrotrons (迴旋加速器與同步加速器)



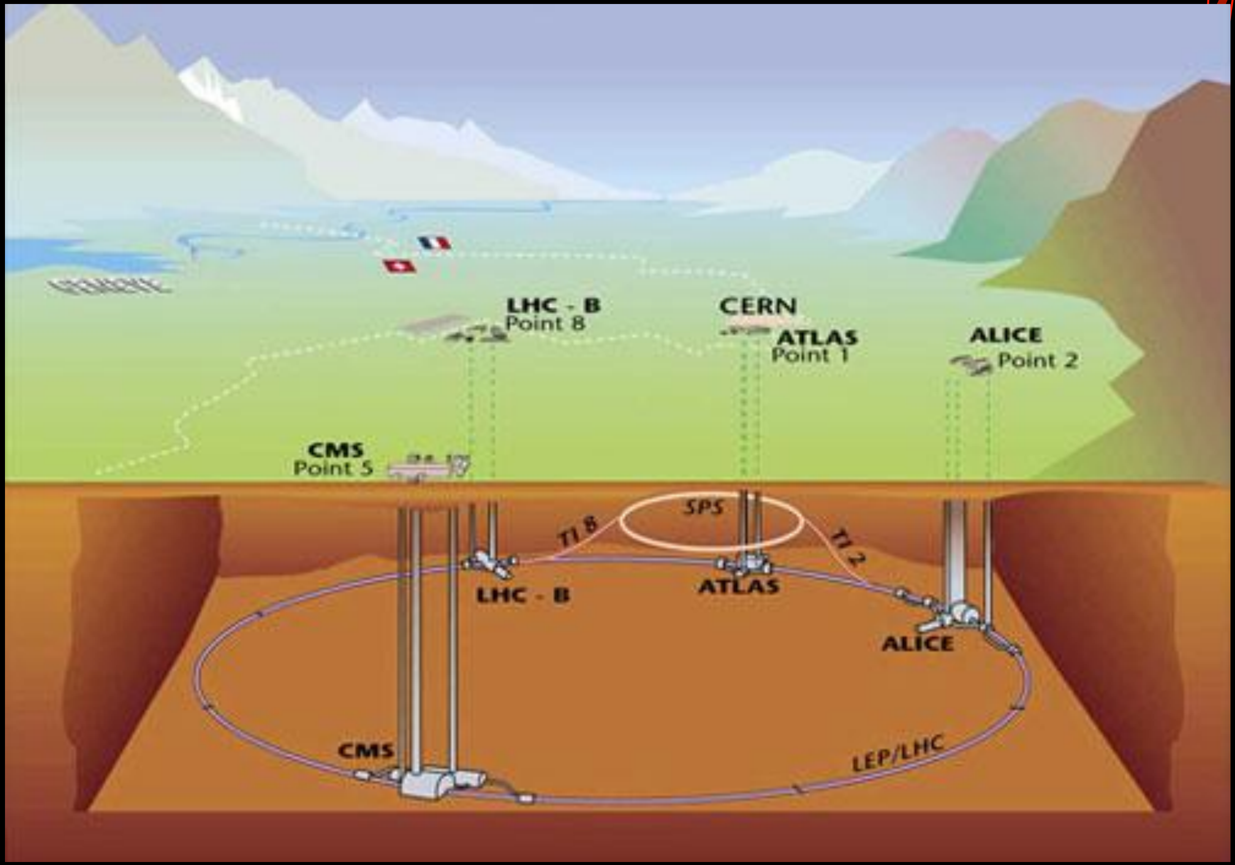
Fermilab: 6.3km ring

Synchrotrons

$$f = f_{osc}$$

- The resonance condition:
- When proton energy > 50Mev:
  - Out of resonance (relativistic effect)
  - A huge magnet (4×10^6 m^2) is needed for high energy (500Gev) protons
- The proton sychrotron at Fermilab can produces 1Tev proton

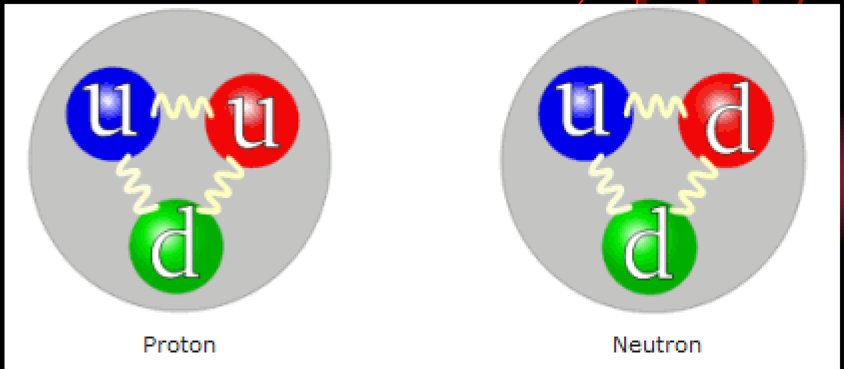
CERN LHC



The LHC is 27km long and sits 100m below the surface.

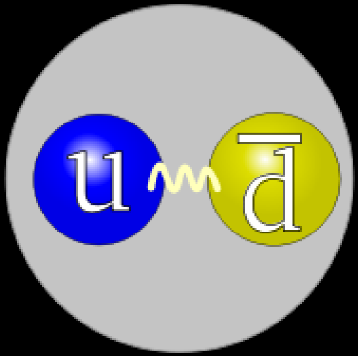
Large Hadron Collider

- **Baryon**
  fermion

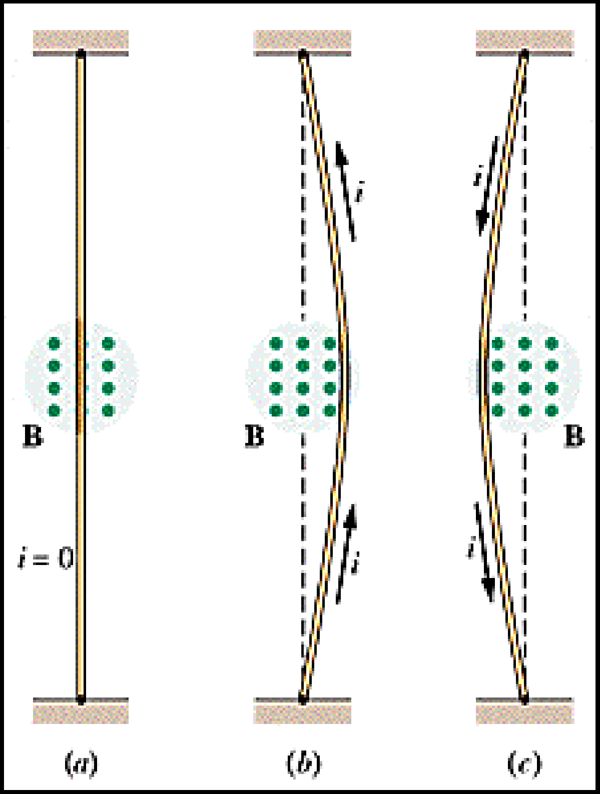


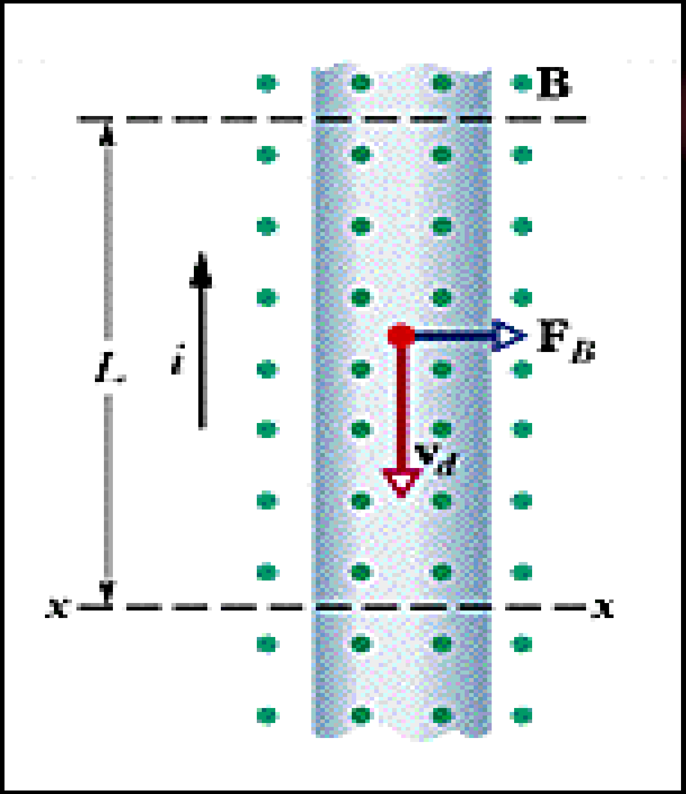
Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

- **Meson**
  boson



8-6 Magnetic Force on a Current-Carrying Wire





Magnetic Force

$$q = it = iL / v_d$$

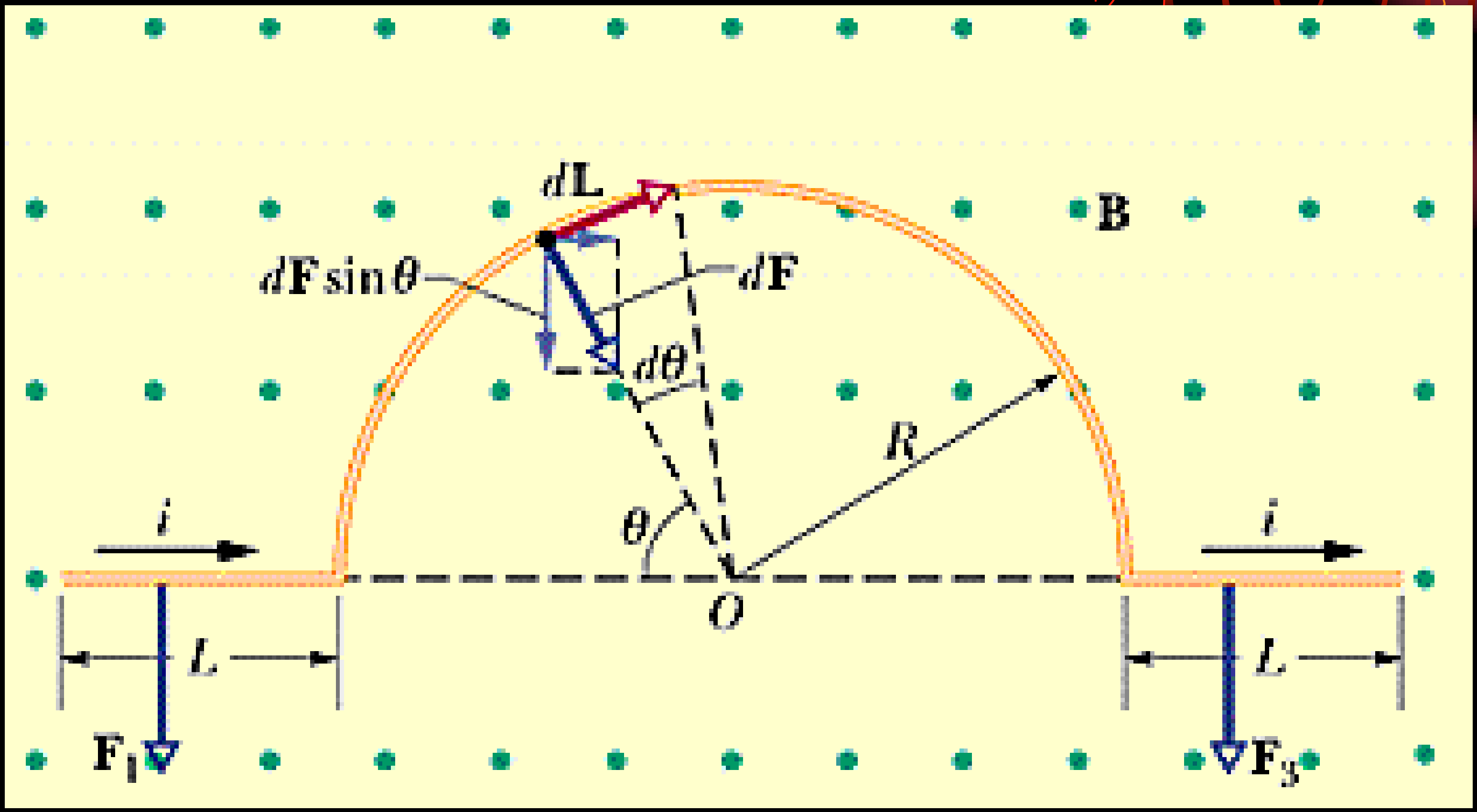
$$F_B = q v_d B \sin\phi = iLB$$

$$\vec{F}_B = i\vec{L} \times \vec{B}$$

For a wire segment:

$$d\vec{F}_B = i\,d\vec{L} \times \vec{B}$$

例 4 A length of wire with a semicircular arc



Calculation

$$F_1 = F_3 = iLB$$

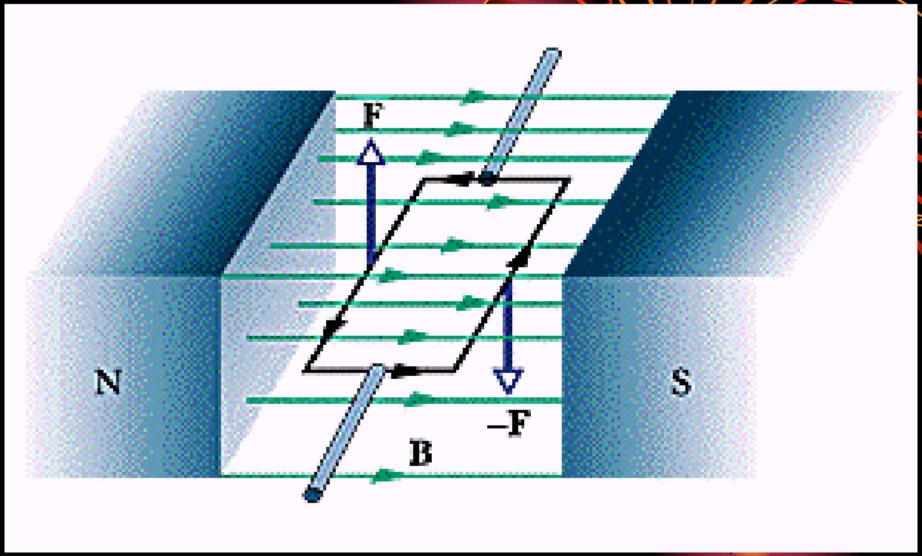
$$dF = iBdL = iB(Rd\theta)$$

$$F_2 = \int_0^\pi dF \sin\theta = iBR \int_0^\pi \sin\theta d\theta$$

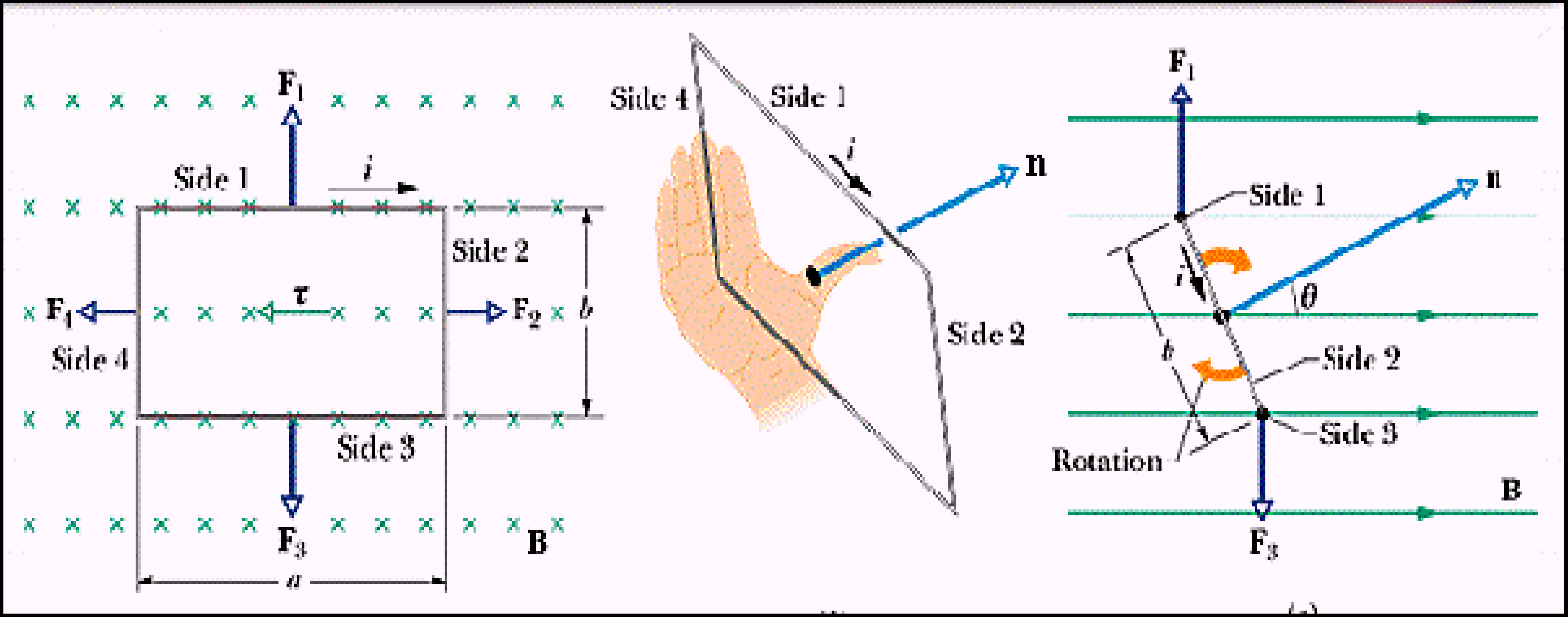
$$= -iBR\cos\theta\Big|_0^\pi = 2iBR$$

$$F = F_1 + F_2 + F_3 = 2iB(L + R)$$

線圈



F
N
S
−F
B



F_1
Side 1
i
Side 2
Side 4
F_1
τ
F_2
b
Side 3
F_3
B
a
Side 4
Side 1
i
n
Side 2
F_1
Side 1
n
i
θ
b
Side 2
Side 3
Rotation
B
F_3

8-7 Torque on A Current Loop

- F_2 and F_4 cancel
- F_1 and F_3 form a force couple

$$F_2 = ibB\sin(90^\circ - \theta) = ibB\cos\theta$$

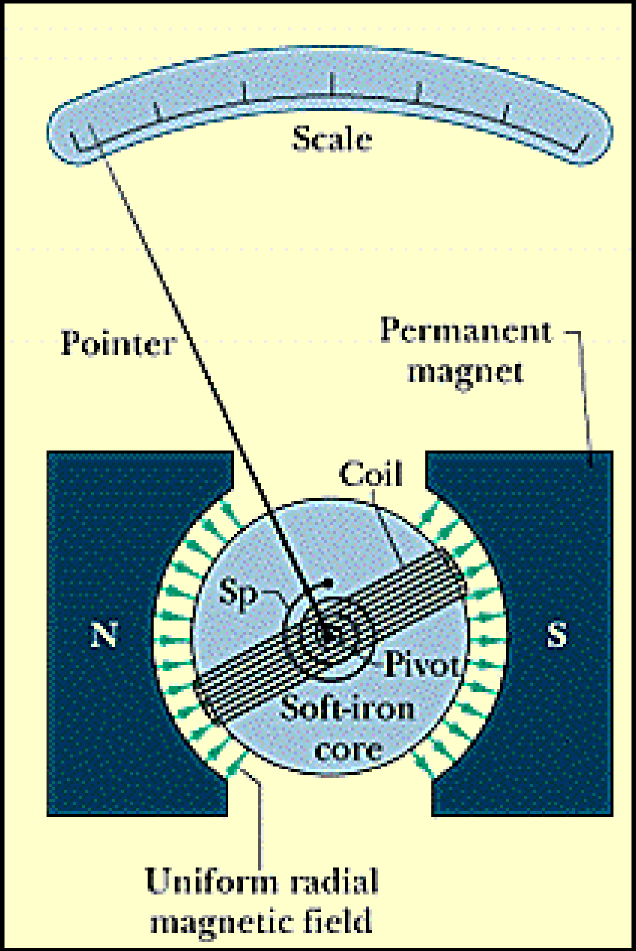
$$\tau' = (iaB\frac{b}{2}\sin\theta) + (iaB\frac{b}{2}\sin\theta)$$

$$= iabB\sin\theta$$

$$\tau = N\tau' = (NiA)B\sin\theta$$

N turns coil

例5 A galvanometer for analog meters



$$\tau = NiAB\sin\theta = \kappa\phi$$

$$\kappa = \frac{NiAB\sin\theta}{\phi}$$

$$= [(250)(100\times10^{-6}\,\text{A})(2.52\times10^{-4}\,\text{m}^2)$$

$$\times(0.23\text{T})(\sin 90^\circ)]/28^\circ$$

$$= 5.2\times10^{-8}\,\text{M}\cdot\text{m}/\text{degree}$$

The direct-current motor

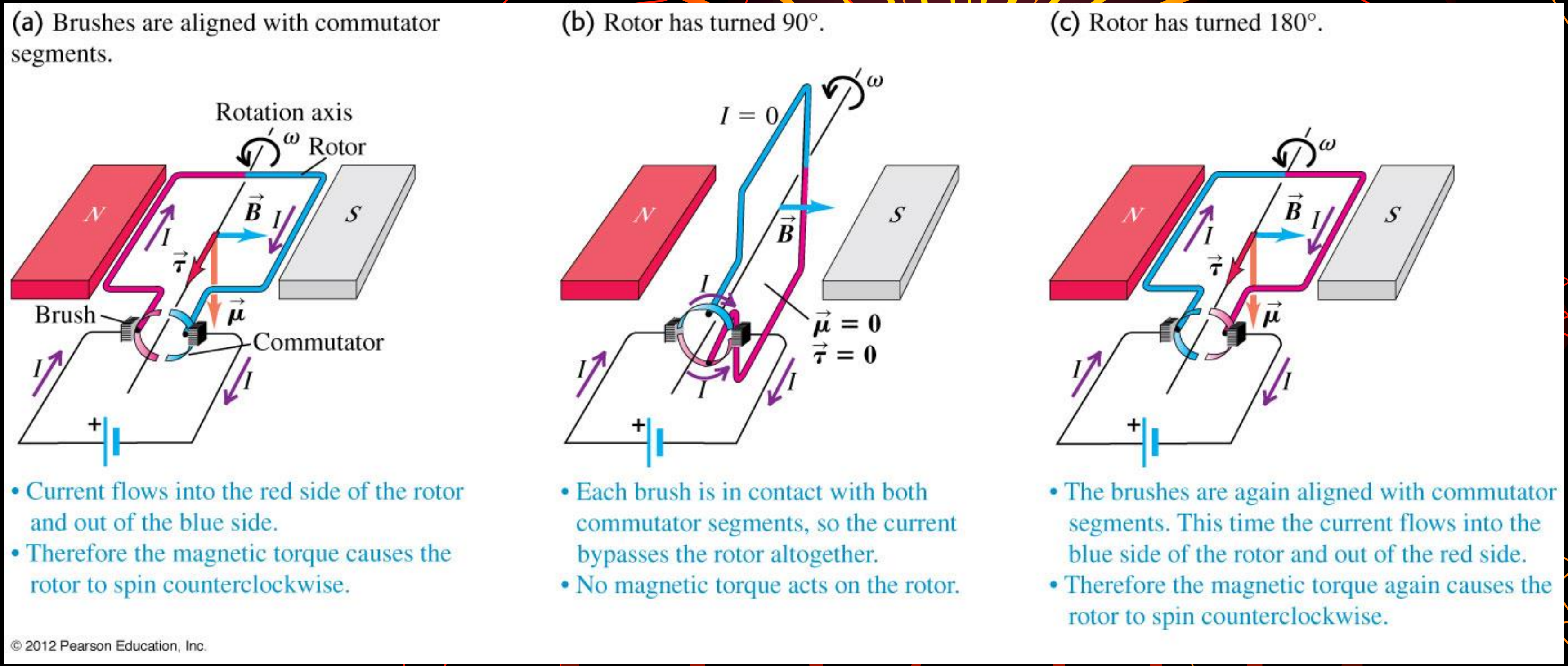
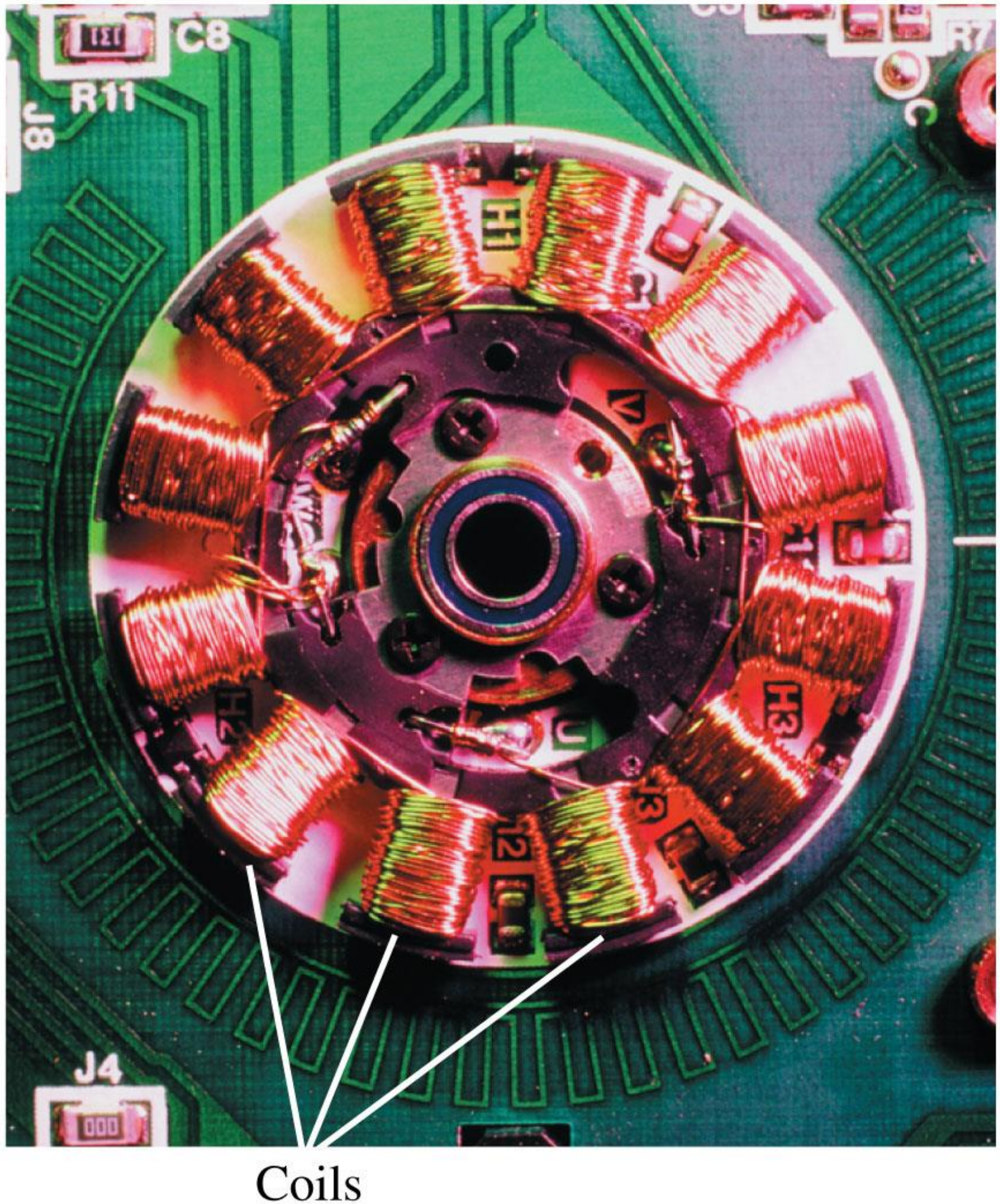


Figure 27.40



8-8 The Magnetic Dipole

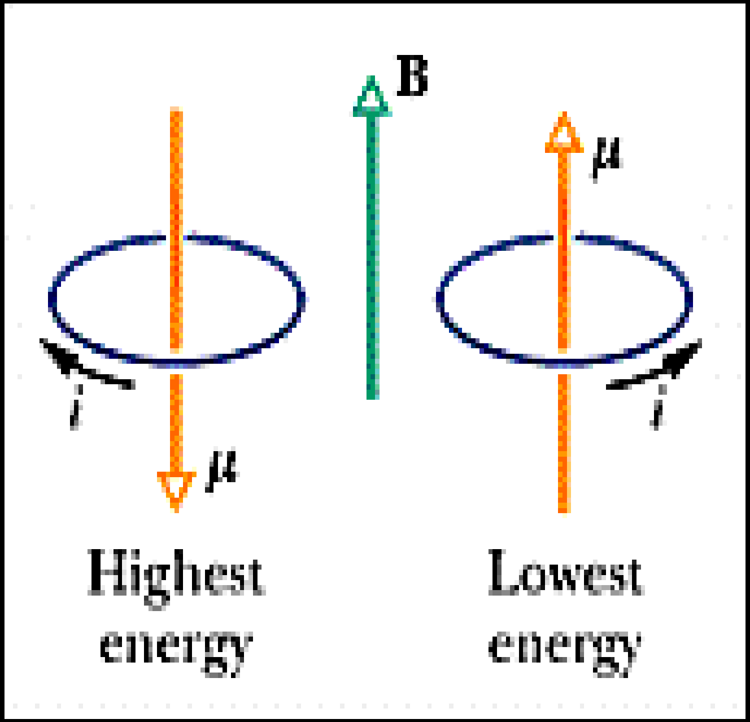
- The magnetic dipole moments

$$\mu = NiA \rightarrow \tau = \mu B \sin\theta$$
$$\rightarrow \vec{\tau} = \vec{\mu} \times \vec{B} \quad (\text{cf}: \vec{\tau} = \vec{p} \times \vec{E})$$

- The magnetic potential energy

$$U(\theta) = -\vec{p} \cdot \vec{E} \leftrightarrow U(\theta) = -\vec{\mu} \cdot \vec{B}$$

磁能



$$\Delta U = (+\mu B) - (-\mu B) = 2\mu B$$