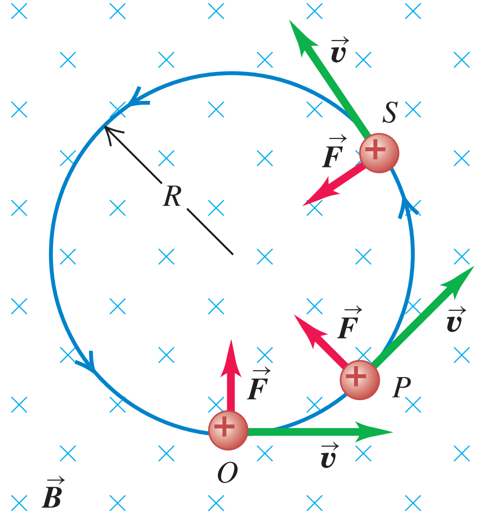
Chp 27: Magnetic Field and Magnetic Forces -II

Goals for Chapter 27

- To study magnets and the forces they exert on each other
- To calculate the force that a magnetic field exerts on a
- moving charge
- To contrast magnetic field lines with electric field lines
- To analyze the motion of a charged particle in a magnetic field
-
- To see applications of magnetism in physics and chemistry
-
- To analyze magnetic forces on current-carrying conductors
- To study the behavior of current loops in a magnetic field

Motion of charged particles in a 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.

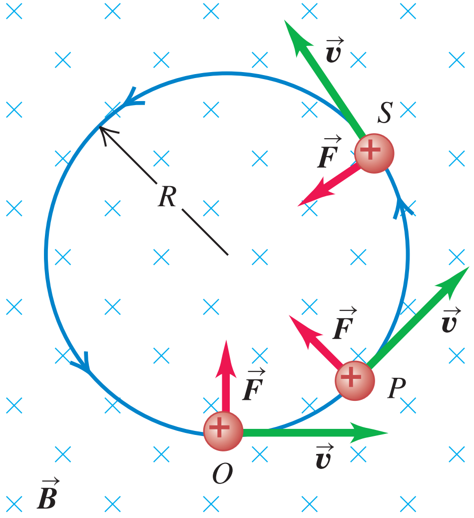


$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge q is moving with velocity v in a uniform magnetic field B directed into the plane of the figure. The vectors v and B are perpendicular, so the magnetic force $F = qvB$ and a direction as shown in the figure.

Motion of charged particles in a 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.

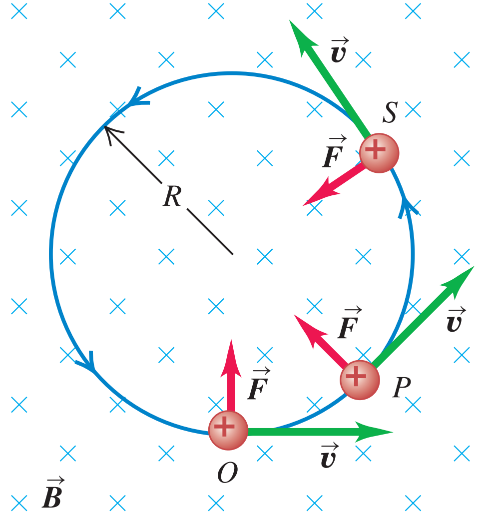


$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge *q* is moving with velocity ***v*** in a uniform magnetic field ***B*** directed into the plane of the figure. The vectors ***v*** and ***B*** are perpendicular, so the magnetic force *F* = *qvB* and a direction as shown in the figure.
- The force is *always* perpendicular to ***v***, so it cannot change the *magnitude* of the velocity, only its direction.

Motion of charged particles in a 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.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

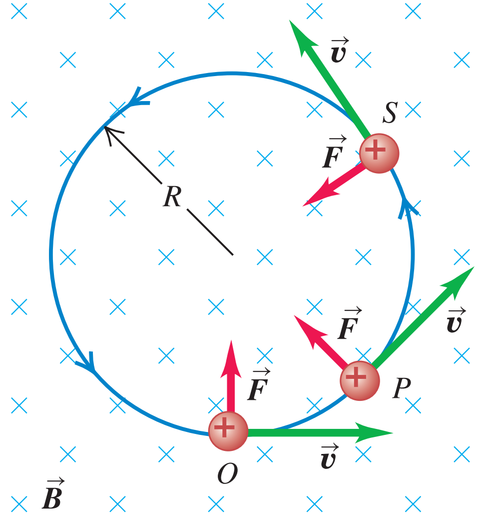
- A particle with positive charge *q* is moving with velocity *v* in a uniform magnetic field *B* directed into the plane of the figure. The vectors *v* and *B* are perpendicular, so the magnetic force $F = qvB$ and a direction as shown in the figure.

- The force is *always* perpendicular to *v*, so it cannot change the *magnitude* of the velocity, only its direction.

➔ magnetic force can never do *work* on the particle. This is true even if the magnetic field is not uniform.

Motion of charged particles in a 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.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge *q* is moving with velocity ***v*** in a uniform magnetic field ***B*** directed into the plane of the figure. The vectors ***v*** and ***B*** are perpendicular, so the magnetic force *F = qvB* and a direction as shown in the figure.

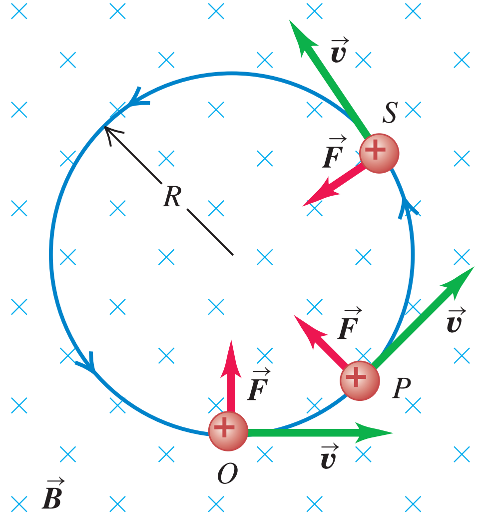
- The force is *always* perpendicular to ***v***, so it cannot change the *magnitude* of the velocity, only its direction.

➔ magnetic force can never do *work* on the particle. This is true even if the magnetic field is not uniform.

- *A charged particle in a magnetic field always moves with constant speed.*

Motion of charged particles in a 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.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge *q* is moving with velocity *v* in a uniform magnetic field *B* directed into the plane of the figure. The vectors *v* and *B* are perpendicular, so the magnetic force *F = qvB* and a direction as shown in the figure.

- The force is *always* perpendicular to *v*, so it cannot change the *magnitude* of the velocity, only its direction.

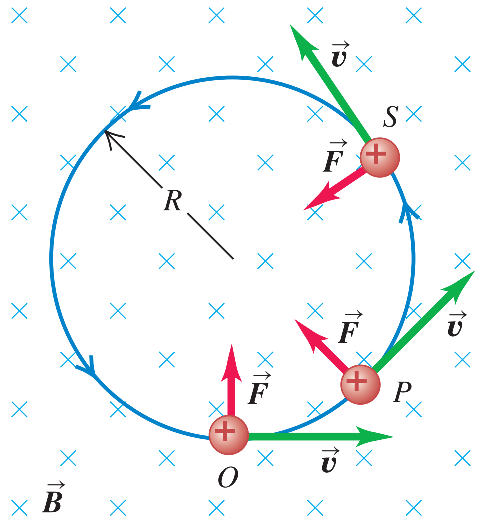
➔ magnetic force can never do *work* on the particle. This is true even if the magnetic field is not uniform.

- A charged particle in a magnetic field always moves with constant speed.

Centripetal acceleration $\dfrac{v^2}{R}$

Motion of charged particles in a 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.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge *q* is moving with velocity ***v*** in a uniform magnetic field ***B*** directed into the plane of the figure. The vectors ***v*** and ***B*** are perpendicular, so the magnetic force *F = qvB* and a direction as shown in the figure.

- The force is *always* perpendicular to ***v***, so it cannot change the *magnitude* of the velocity, only its direction.

➔ magnetic force can never do *work* on the particle. This is true even if the magnetic field is not uniform.

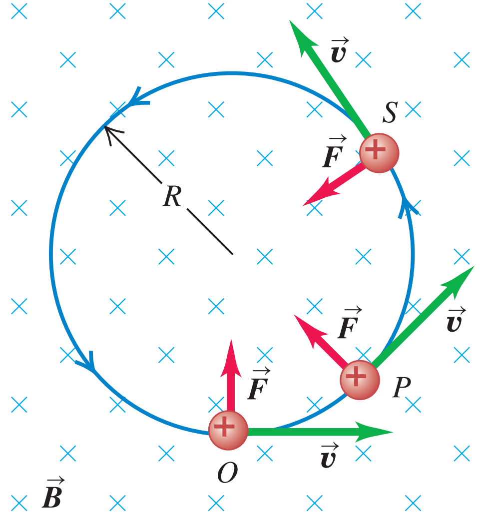
- *A charged particle in a magnetic field always moves with constant speed.*

Centripetal acceleration $\dfrac{v^2}{R}$

Newton's 2'nd law: $F = |q|vB = m\dfrac{v^2}{R}$

Motion of charged particles in a 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.



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- A particle with positive charge *q* is moving with velocity *v* in a uniform magnetic field *B* directed into the plane of the figure. The vectors *v* and *B* are perpendicular, so the magnetic force *F = qvB* and a direction as shown in the figure.

- The force is *always* perpendicular to *v*, so it cannot change the *magnitude* of the velocity, only its direction.

➔ magnetic force can never do *work* on the particle. This is true even if the magnetic field is not uniform.

- *A charged particle in a magnetic field always moves with constant speed.*

Centripetal acceleration $\dfrac{v^2}{R}$

Newton's 2'nd law: $F = |q|vB = m\dfrac{v^2}{R}$

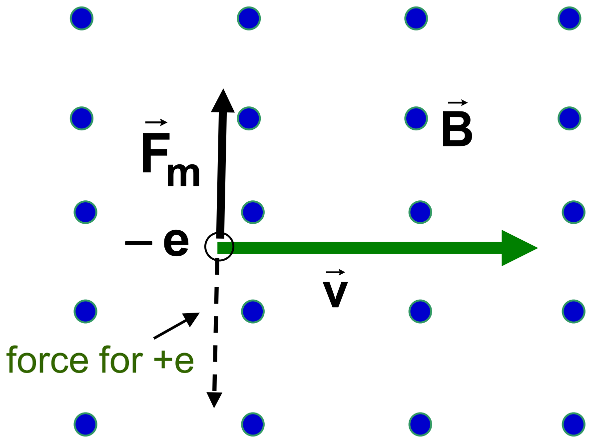
➔ $R = \dfrac{mv}{|q|B}$ (radius of a circular orbit in a magnetic field)

angular speed: $\omega = \dfrac{v}{R} = v\dfrac{|q|B}{mv} = \dfrac{|q|B}{m}$

number of revolution per unit time: $f = \omega/2\pi$

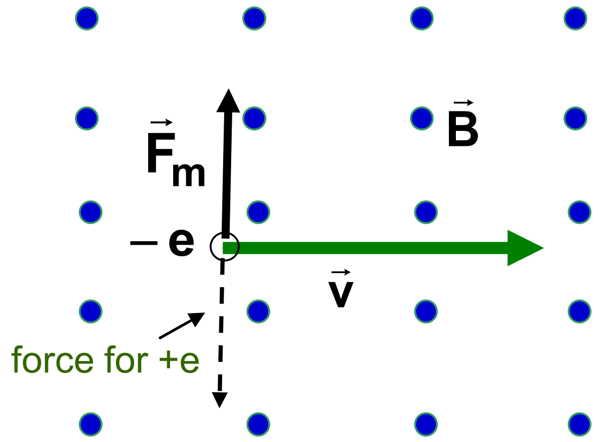
(independent of radius)

A numerical example



- Electron beam moving in plane of sketch
- $v=10^7$ m/s along+x
- $B=10^{-3}$ T.out of page along+y

A numerical example



- Electron beam moving in plane of sketch
- $v=10^7$ m/s along+x
- $B=10^{-3}$ T.out of page along+y

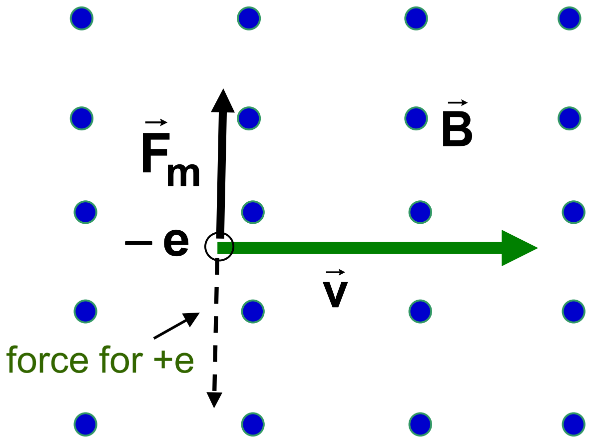
(a) Find the Force on the electron
(b) Find the acceleration

$$\vec{F}_m = -e\,\vec{v}\times\vec{B} = -1.6\text{x}10^{-19}\text{x}10^{7}\text{x}10^{-3}\text{x}\sin(90^{\circ})\,\hat{k}$$

$$\vec{F}_m = -1.6\text{x}10^{-15}\,\hat{k}$$

Negative sign means force is opposite to result of using the RH rule

A numerical example



- Electron beam moving in plane of sketch
- $v=10^7$ m/s along+x
- $B=10^{-3}$ T.out of page along+y

(a) Find the Force on the electron
(b) Find the acceleration

$$\vec{F}_m = -e\,\vec{v}\times\vec{B} = -1.6x10^{-19}x10^{7}x10^{-3}x\,\sin(90^o)\,\hat{k}$$

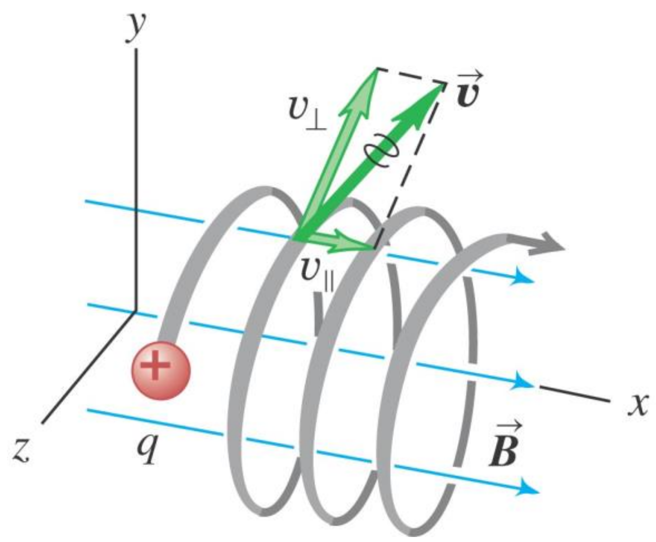
$$\vec{F}_m = -1.6x10^{-15}\,\hat{k}$$

Negative sign means force is opposite to result of using the RH rule

$$\vec{a} = \frac{\vec{F}_m}{m_e} = \frac{-1.6\,x\,10^{-15}\,N}{9\,x\,10^{-31}\,Kg}\hat{k} = -1.76\,x\,10^{+15}\hat{k}\ [m/s^2]$$

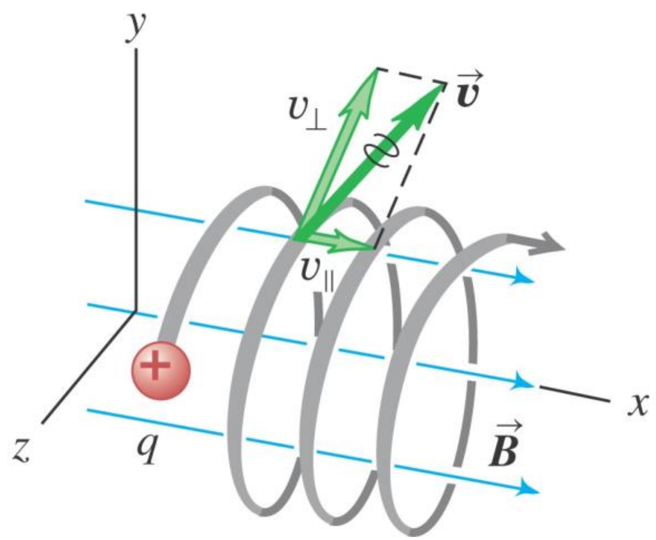
Direction is the same as that of the force

Helical motion



•If the particle has velocity components parallel to and perpendicular to the field, its path is a helix.

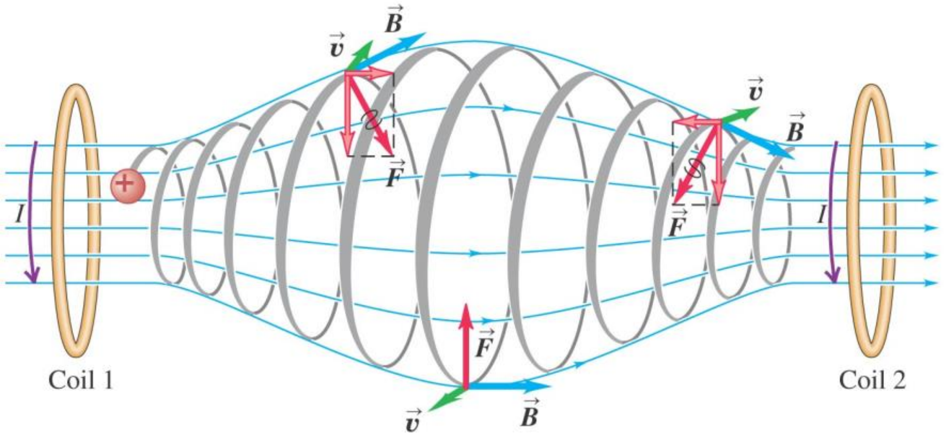
Helical motion



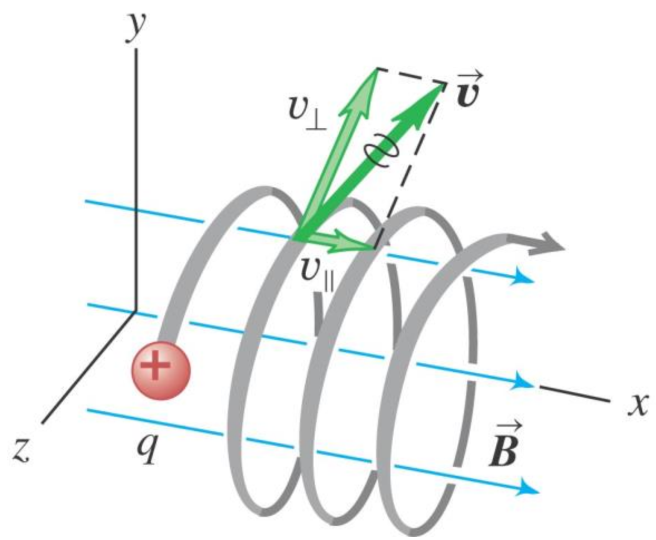
- If the particle has velocity components parallel to and perpendicular to the field, its path is a helix.

- The speed and kinetic energy of the particle remain constant.

A nonuniform magnetic field



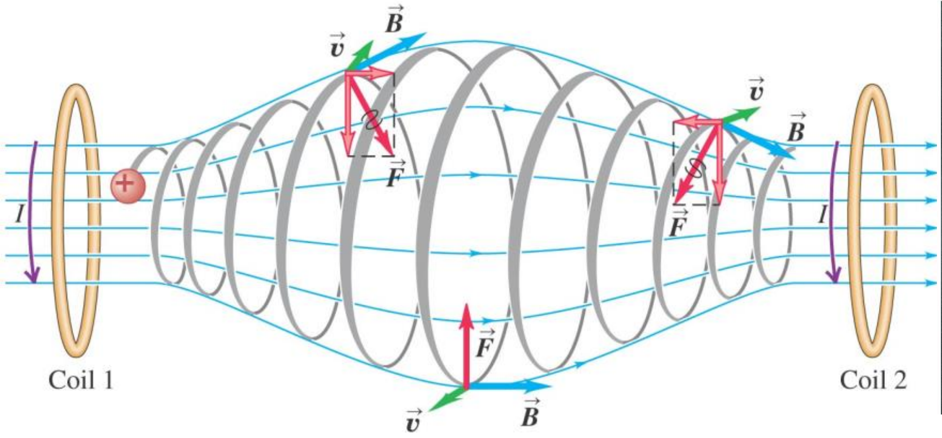
Helical motion

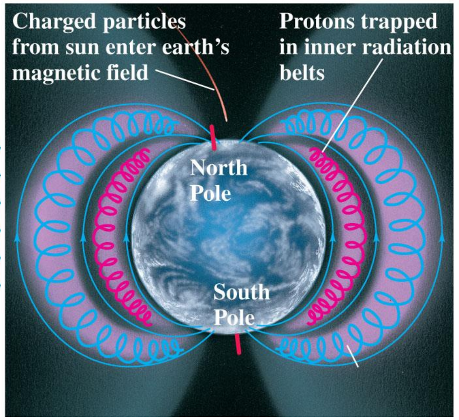


• If the particle has velocity components parallel to and perpendicular to the field, its path is a helix.

• The speed and kinetic energy of the particle remain constant.

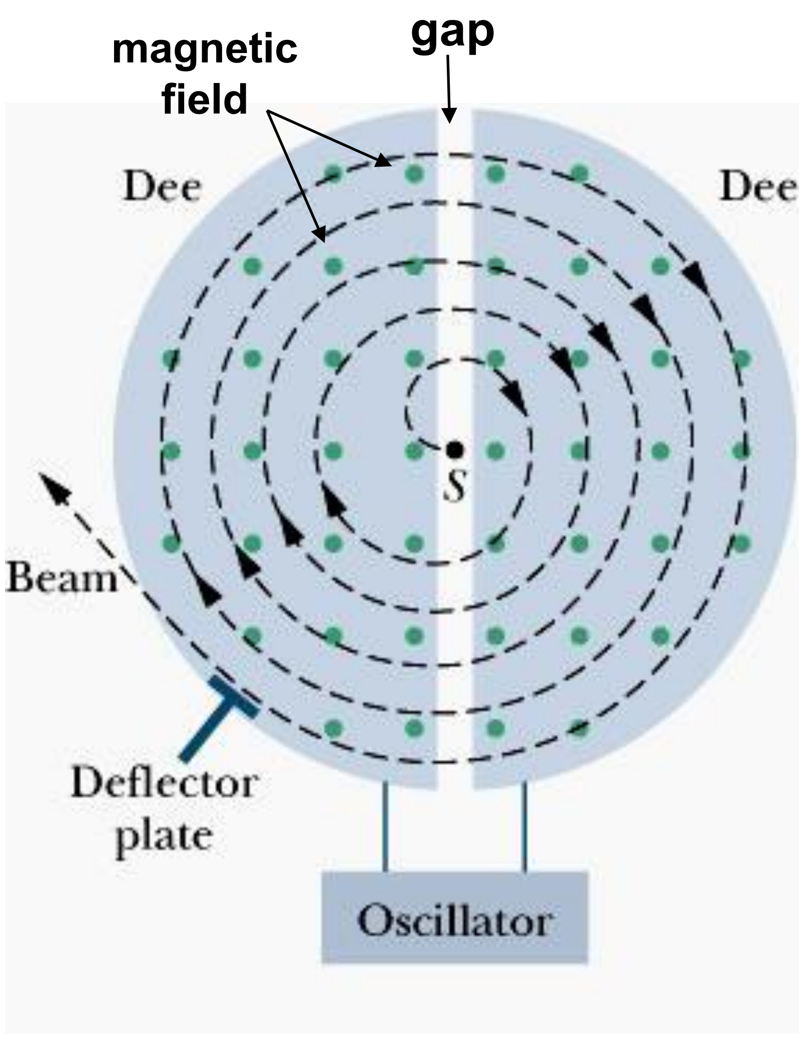
A nonuniform magnetic field

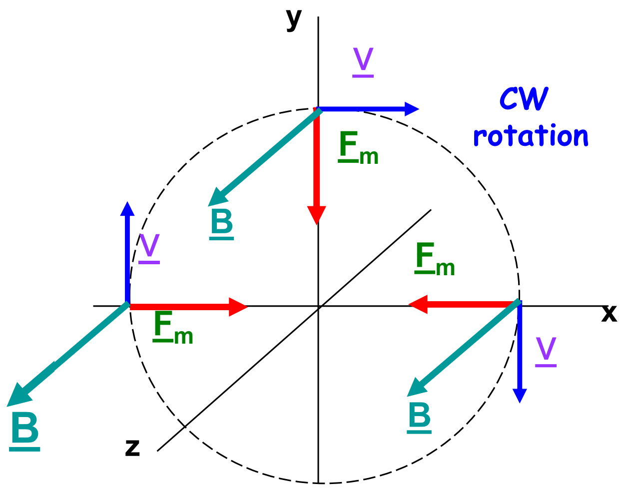




Cyclotron Frequency: Charged Particles Circle at Constant Speed in a Uniform Magnetic Field

(used in Early nuclear physics research, Biomedical applications)



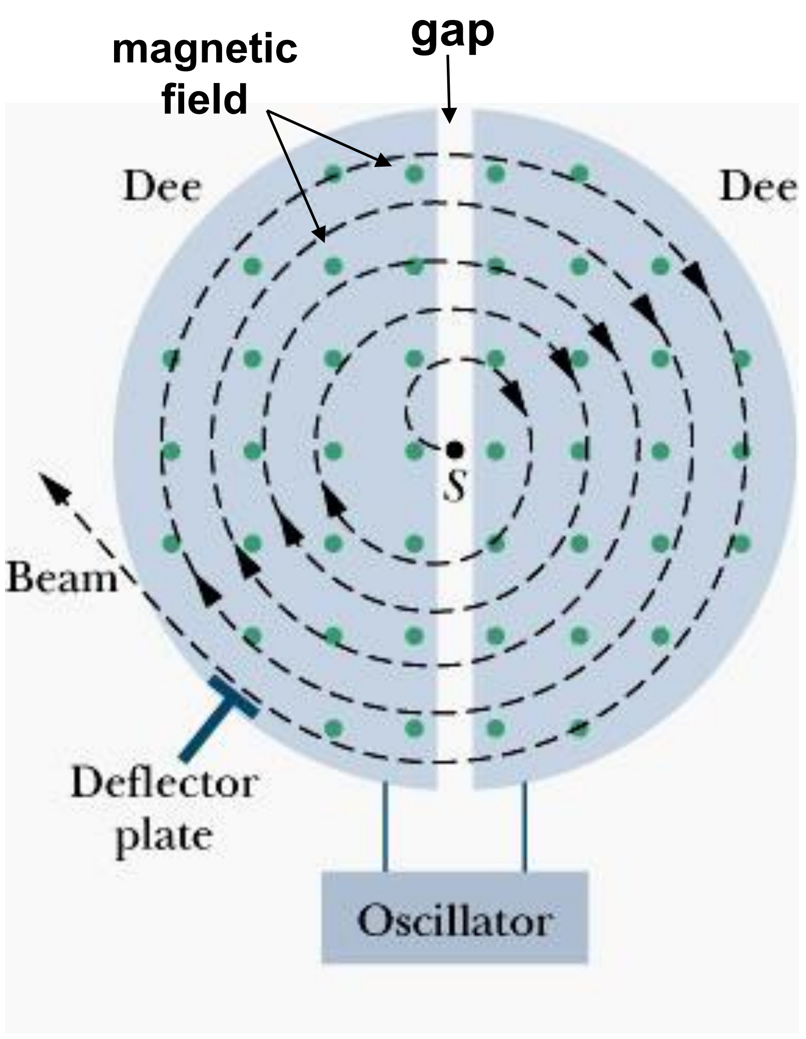


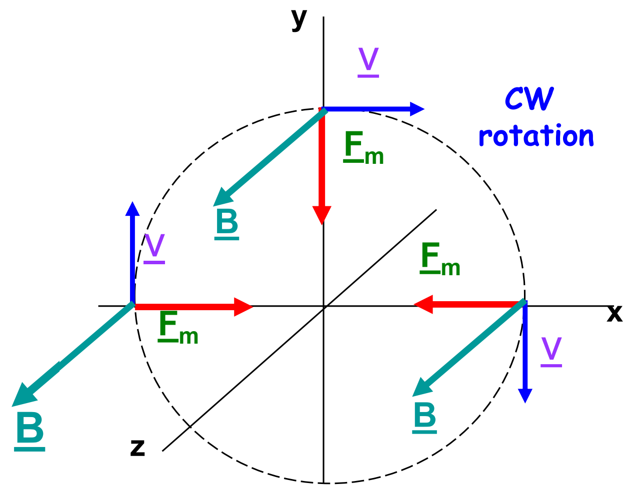
$$r = \frac{mv}{qB}$$

$$\omega_c = \frac{2\pi}{\tau_c} = \frac{qB}{m}$$

Cyclotron Frequency: Charged Particles Circle at Constant Speed in a Uniform Magnetic Field

(used in Early nuclear physics research, Biomedical applications)

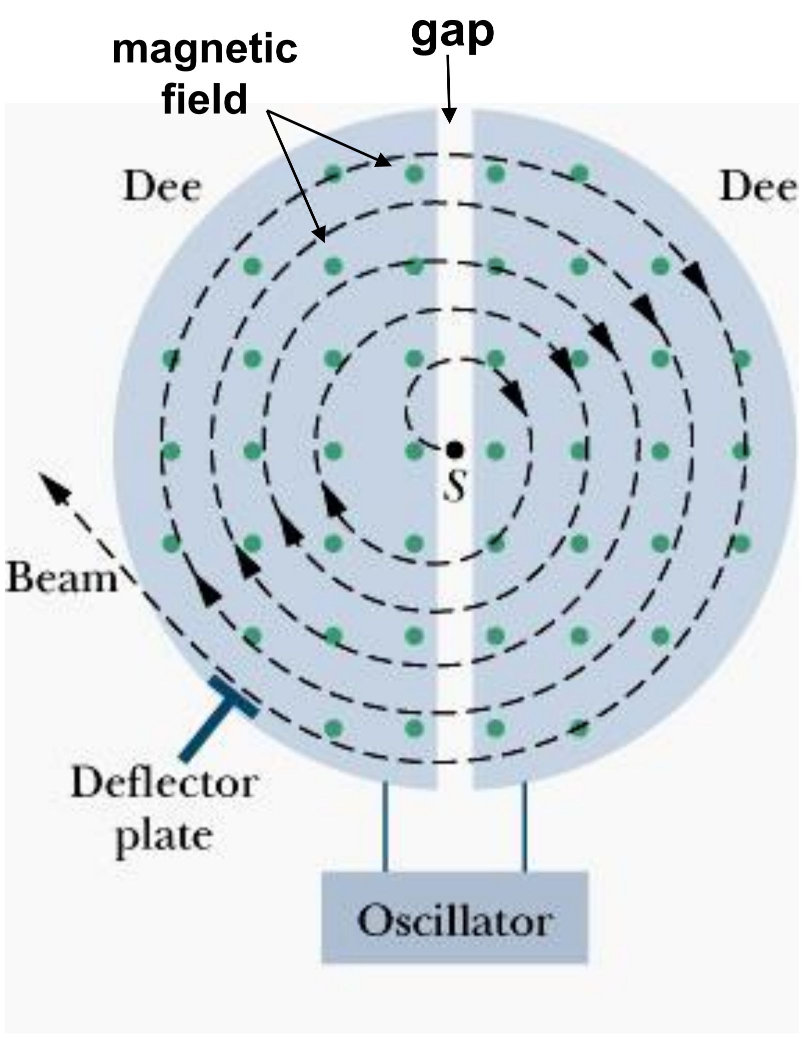


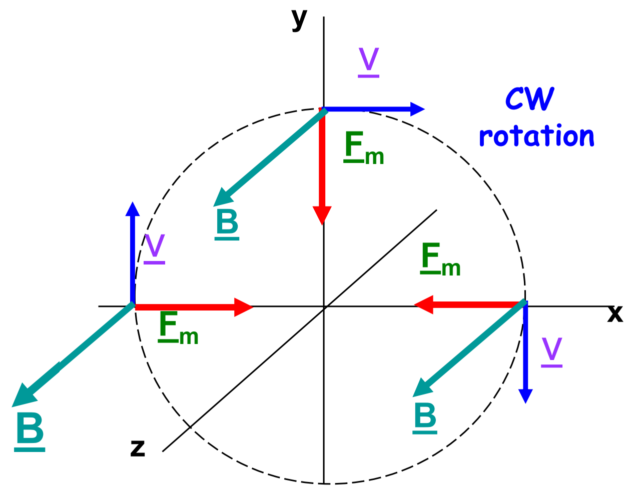


- Inject charged particles in center
  Charged "Dees" reverse polarity as particles cross gap to accelerate them.
- Particles spiral out in magnetic field as they gain KE and are detected

$$r = \frac{mv}{qB}$$

Cyclotron Frequency: Charged Particles Circle at Constant Speed in a Uniform Magnetic Field
(used in Early nuclear physics research, Biomedical applications)





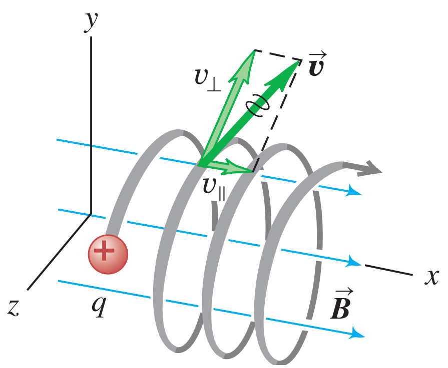
- Inject charged particles in center
  Charged "Dees" reverse polarity as particles cross gap to accelerate them.
- Particles spiral out in magnetic field as they gain KE and are detected

$$r = \frac{mv}{qB}$$

- Frequency does not depend on speed or radius

$$\omega_c = \frac{2\pi}{\tau_c} = \frac{qB}{m}$$

Ex: Helical particle motion in a magnetic field



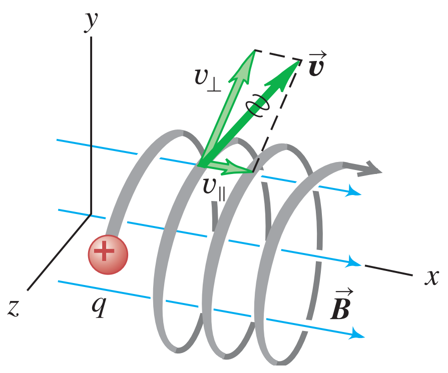
a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.

At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y= 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

Ex: Helical particle motion in a magnetic field



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

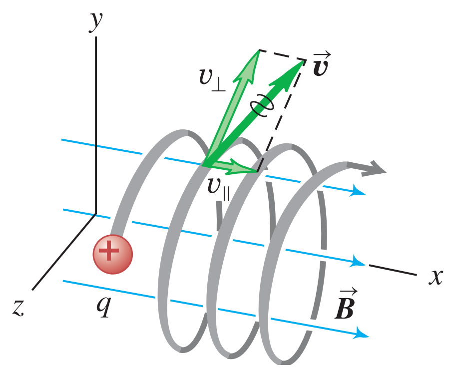
$$\vec{B} = B\hat{\imath} \text{ and } \vec{v} = v_x\hat{\imath} + v_z\hat{k}$$

a proton ($q = 1.60\times10^{-19}$, $m = 1.67\times10^{-27}$kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.
At $t = 0$ the proton has velocity components $v_x = 1.50\times10^5$ m/s, $v_y = 0$, and $v_z = 2.00\times10^5$ m/s. Only the magnetic force acts on the proton.

(a) At $t = 0$, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

Ex: Helical particle motion in a magnetic field



a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.

At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

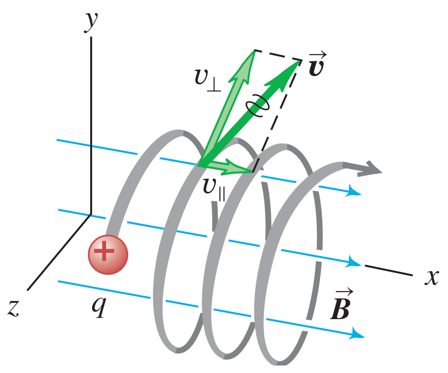
(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

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

$\vec{B} = B\hat{\imath}$ and $\vec{v} = v_x\hat{\imath} + v_z\hat{k}$ (a) ⇨

$$\begin{aligned}\vec{F} &= q\vec{v} \times \vec{B} = q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath}\\ &= (1.60 \times 10^{-19}\ \mathrm{C})(2.00 \times 10^5\ \mathrm{m/s})(0.500\ \mathrm{T})\hat{\jmath}\\ &= (1.60 \times 10^{-14}\ \mathrm{N})\hat{\jmath}\end{aligned}$$

Ex: Helical particle motion in a magnetic field



a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.
At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.
(a) At t = 0, find the force on the proton and its acceleration.
(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

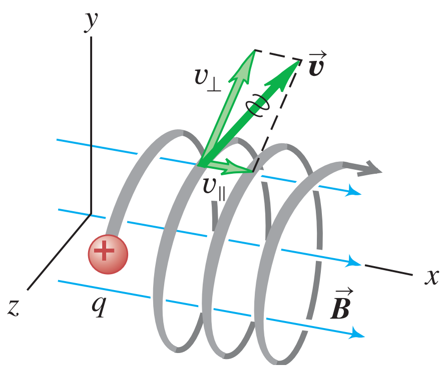
$$\vec{F} = q\vec{v} \times \vec{B}$$

$\vec{B} = B\hat{\imath}$ and $\vec{v} = v_x\hat{\imath} + v_z\hat{k}$ (a) ⇒

$$\vec{F} = q\vec{v} \times \vec{B} = q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath}$$
$$= (1.60 \times 10^{-19}\ \text{C})(2.00 \times 10^5\ \text{m/s})(0.500\ \text{T})\hat{\jmath}$$
$$= (1.60 \times 10^{-14}\ \text{N})\hat{\jmath}$$

⇒ $$\vec{a} = \frac{\vec{F}}{m} = \frac{1.60 \times 10^{-14}\ \text{N}}{1.67 \times 10^{-27}\ \text{kg}}\hat{\jmath} = (9.58 \times 10^{12}\ \text{m/s}^2)\hat{\jmath}$$

Ex: Helical particle motion in a magnetic field



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

a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.

At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

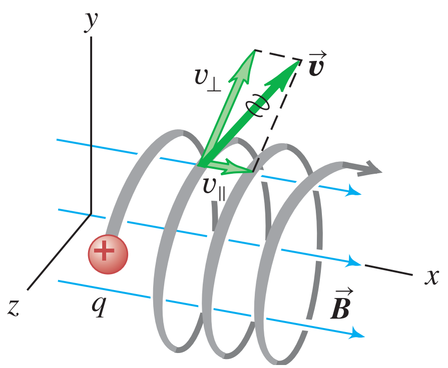
$\vec{B} = B\hat{\imath}$ and $\vec{v} = v_x\hat{\imath} + v_z\hat{k}$ (a) ⇒

$$\begin{aligned}\vec{F} &= q\vec{v} \times \vec{B} = q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath}\\ &= (1.60 \times 10^{-19}\ \text{C})(2.00 \times 10^{5}\ \text{m/s})(0.500\ \text{T})\hat{\jmath}\\ &= (1.60 \times 10^{-14}\ \text{N})\hat{\jmath}\end{aligned}$$

$$\Rightarrow \quad \vec{a} = \frac{\vec{F}}{m} = \frac{1.60 \times 10^{-14}\ \text{N}}{1.67 \times 10^{-27}\ \text{kg}}\hat{\jmath} = (9.58 \times 10^{12}\ \text{m/s}^2)\hat{\jmath}$$

(b) $$R = \frac{mv_z}{|q|B} = \frac{(1.67 \times 10^{-27}\ \text{kg})(2.00 \times 10^{5}\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(0.500\ \text{T})} = 4.18 \times 10^{-3}\ \text{m} = 4.18\ \text{mm}$$

Ex: Helical particle motion in a magnetic field



a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.

At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

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

$$\vec{B} = B\hat{\imath} \text{ and } \vec{v} = v_x\hat{\imath} + v_z\hat{k}$$

(a) ⇨

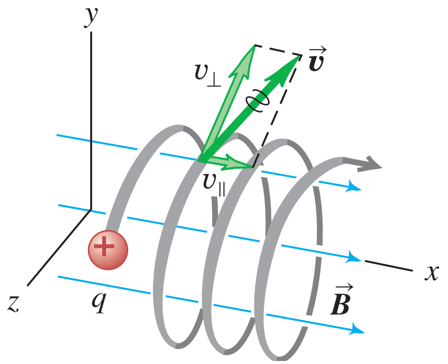
$$\vec{F} = q\vec{v} \times \vec{B} = q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath}$$
$$= (1.60 \times 10^{-19}\ \text{C})(2.00 \times 10^5\ \text{m/s})(0.500\ \text{T})\hat{\jmath}$$
$$= (1.60 \times 10^{-14}\ \text{N})\hat{\jmath}$$

⇨ $$\vec{a} = \frac{\vec{F}}{m} = \frac{1.60 \times 10^{-14}\ \text{N}}{1.67 \times 10^{-27}\ \text{kg}}\hat{\jmath} = (9.58 \times 10^{12}\ \text{m/s}^2)\hat{\jmath}$$

(b) $$R = \frac{mv_z}{|q|B} = \frac{(1.67 \times 10^{-27}\ \text{kg})(2.00 \times 10^5\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(0.500\ \text{T})} = 4.18 \times 10^{-3}\ \text{m} = 4.18\ \text{mm}$$

⇨ $$\omega = \frac{|q|B}{m} = \frac{(1.60 \times 10^{-19}\ \text{C})(0.500\ \text{T})}{1.67 \times 10^{-27}\ \text{kg}} = 4.79 \times 10^7\ \text{rad/s}$$

Ex: Helical particle motion in a magnetic field



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

a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.
At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

$\vec{B} = B\hat{\imath}$ and $\vec{v} = v_x\hat{\imath} + v_z\hat{k}$ (a) ➡

$$\begin{aligned}\vec{F} = q\vec{v} \times \vec{B} &= q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath} \\ &= (1.60 \times 10^{-19}\ \mathrm{C})(2.00 \times 10^5\ \mathrm{m/s})(0.500\ \mathrm{T})\hat{\jmath} \\ &= (1.60 \times 10^{-14}\ \mathrm{N})\hat{\jmath}\end{aligned}$$

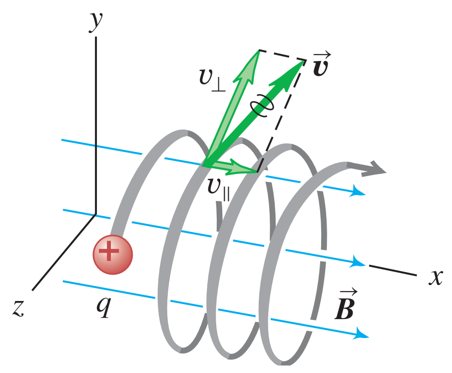
➡ $$\vec{a} = \frac{\vec{F}}{m} = \frac{1.60 \times 10^{-14}\ \mathrm{N}}{1.67 \times 10^{-27}\ \mathrm{kg}}\hat{\jmath} = (9.58 \times 10^{12}\ \mathrm{m/s^2})\hat{\jmath}$$

(b) $$R = \frac{mv_z}{|q|B} = \frac{(1.67 \times 10^{-27}\ \mathrm{kg})(2.00 \times 10^5\ \mathrm{m/s})}{(1.60 \times 10^{-19}\ \mathrm{C})(0.500\ \mathrm{T})} = 4.18 \times 10^{-3}\ \mathrm{m} = 4.18\ \mathrm{mm}$$

➡ $$\omega = \frac{|q|B}{m} = \frac{(1.60 \times 10^{-19}\ \mathrm{C})(0.500\ \mathrm{T})}{1.67 \times 10^{-27}\ \mathrm{kg}} = 4.79 \times 10^7\ \mathrm{rad/s}$$

➡ $$T = 2\pi/\omega = 2\pi/(4.79 \times 10^7\ \mathrm{s^{-1}}) = 1.31 \times 10^{-7}\ \mathrm{s}$$

Ex: Helical particle motion in a magnetic field



a proton (q = 1.60x10^{-19}, m = 1.67x10^{-27}kg) and the uniform, 0.500-T magnetic field is directed along the x-axis.
At t = 0 the proton has velocity components v_x = 1.50x10^5 m/s, v_y = 0, and v_z = 2.00 x10^5 m/s. Only the magnetic force acts on the proton.

(a) At t = 0, find the force on the proton and its acceleration.

(b) Find the radius of the resulting helical path, the angular speed of the proton, and the *pitch* of the helix (the distance traveled along the helix axis per revolution).

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

$$\vec{B} = B\hat{\imath} \text{ and } \vec{v} = v_x\hat{\imath} + v_z\hat{k}$$

(a) ➡

$$\vec{F} = q\vec{v} \times \vec{B} = q(v_x\hat{\imath} + v_z\hat{k}) \times B\hat{\imath} = qv_zB\hat{\jmath}$$
$$= (1.60 \times 10^{-19}\ \text{C})(2.00 \times 10^5\ \text{m/s})(0.500\ \text{T})\hat{\jmath}$$
$$= (1.60 \times 10^{-14}\ \text{N})\hat{\jmath}$$

➡ $$\vec{a} = \frac{\vec{F}}{m} = \frac{1.60 \times 10^{-14}\ \text{N}}{1.67 \times 10^{-27}\ \text{kg}}\hat{\jmath} = (9.58 \times 10^{12}\ \text{m/s}^2)\hat{\jmath}$$

(b) $$R = \frac{mv_z}{|q|B} = \frac{(1.67 \times 10^{-27}\ \text{kg})(2.00 \times 10^5\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(0.500\ \text{T})} = 4.18 \times 10^{-3}\ \text{m} = 4.18\ \text{mm}$$

➡ $$\omega = \frac{|q|B}{m} = \frac{(1.60 \times 10^{-19}\ \text{C})(0.500\ \text{T})}{1.67 \times 10^{-27}\ \text{kg}} = 4.79 \times 10^7\ \text{rad/s}$$

➡ $$T = 2\pi/\omega = 2\pi/(4.79 \times 10^7\ \text{s}^{-1}) = 1.31 \times 10^{-7}\ \text{s}$$ ➡ $$v_xT = (1.50 \times 10^5\ \text{m/s})(1.31 \times 10^{-7}\ \text{s})$$
$$= 0.0197\ \text{m} = 19.7\ \text{mm}$$

Charged particle in both E and B fields

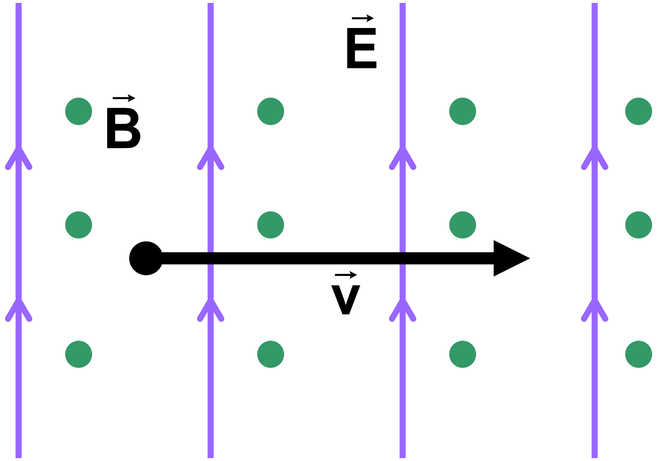
Add the electrostatic and magnetic forces

$$\boxed{\vec{F}_{tot} = q\vec{E} + q\vec{v}\times\vec{B}}$$

$\vec{F}_{tot} = m\vec{a}$ also

Example: Crossed E and B fields

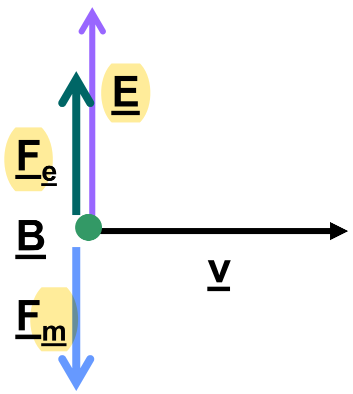
CONVENTION
● OUT ✕ IN



- B out of paper
- E up and normal to B
- \+ charge
- v normal to both E & B

$$\vec{F}_e = q\vec{E} \quad \text{(up)}$$
$$F_m = q\vec{v}\times\vec{B} \quad \text{(down)}$$

FBD of q



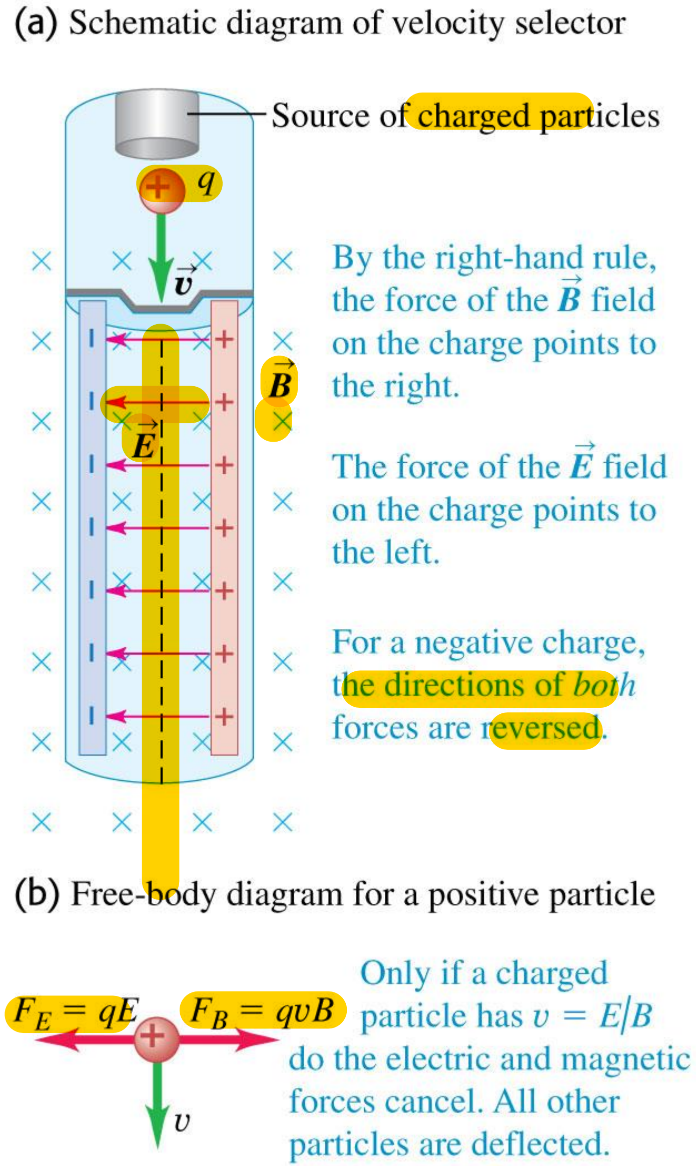
OPPOSED FORCES

Equilibrium when...

$\vec{F}_{tot} = 0$ ⟹ $qE = qvB$ ⟹ $v = |E|/|B|$

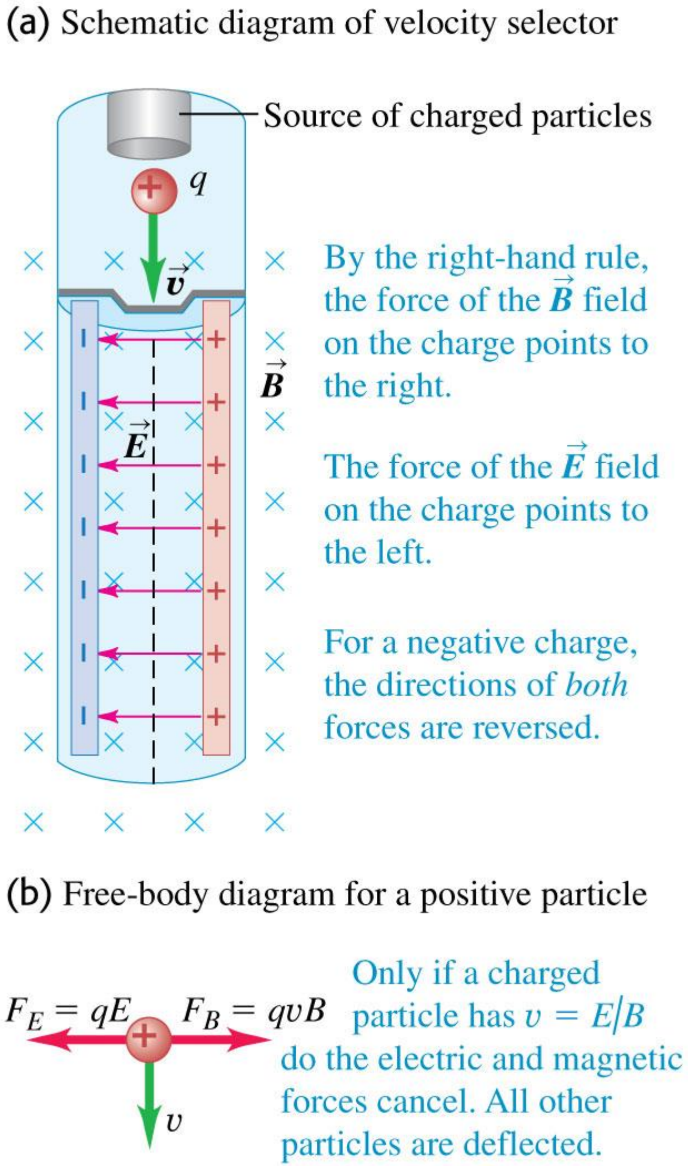
- Independent of charge q
- Only particles having speed v = E/B pass through undeflected.

Velocity selector



- A velocity selector uses perpendicular electric and magnetic fields to select particles of a specific speed from a beam.
- Only particles having speed v = E/B pass through undeflected.

Velocity selector

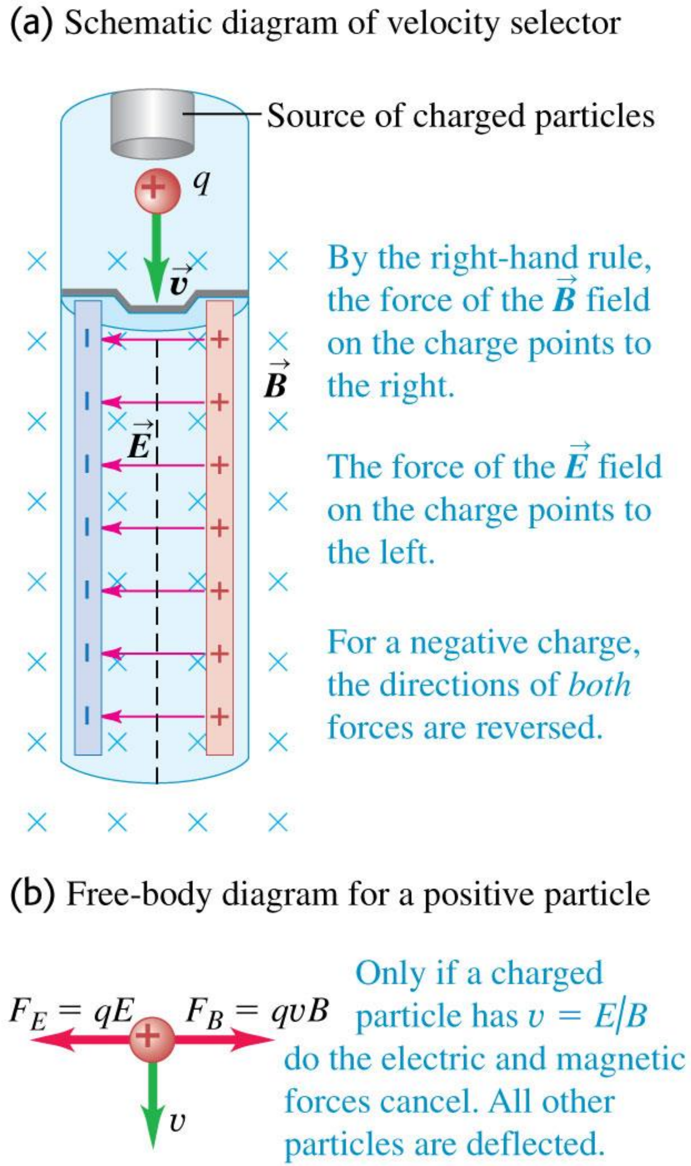


- A velocity selector uses perpendicular electric and magnetic fields to select particles of a specific speed from a beam.
- Only particles having speed v = E/B pass through undeflected.

In a beam of charged particles produced by a heated cathode or a radioactive material, not all particles move with the same speed.
If we can to create a beam in which all the particle speeds are the same, a specific speed can be selected from the beam using an arrangement of electric and magnetic fields

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Velocity selector



- A velocity selector uses perpendicular electric and magnetic fields to select particles of a specific speed from a beam.
- Only particles having speed v = E/B pass through undeflected.

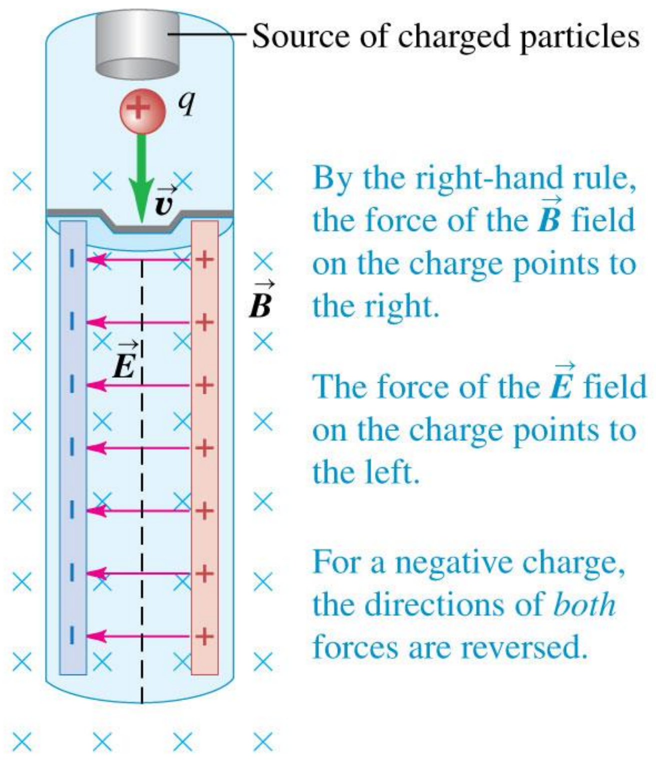
In a beam of charged particles produced by a heated cathode or a radioactive material, not all particles move with the same speed.
If we can to create a beam in which all the particle speeds are the same, a specific speed can be selected from the beam using an arrangement of electric and magnetic fields

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

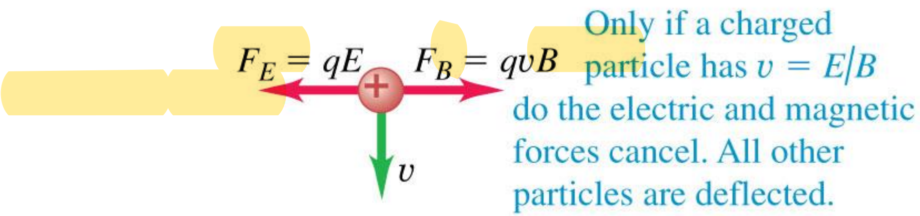
$$\sum F_y = 0 \Rightarrow -qE + qvB = 0$$

Velocity selector

(a) Schematic diagram of velocity selector



(b) Free-body diagram for a positive particle



- A velocity selector uses perpendicular electric and magnetic fields to select particles of a specific speed from a beam.
- Only particles having speed v = E/B pass through undeflected.

In a beam of charged particles produced by a heated cathode or a radioactive material, not all particles move with the same speed.
If we can to create a beam in which all the particle speeds are the same, a specific speed can be selected from the beam using an arrangement of electric and magnetic fields

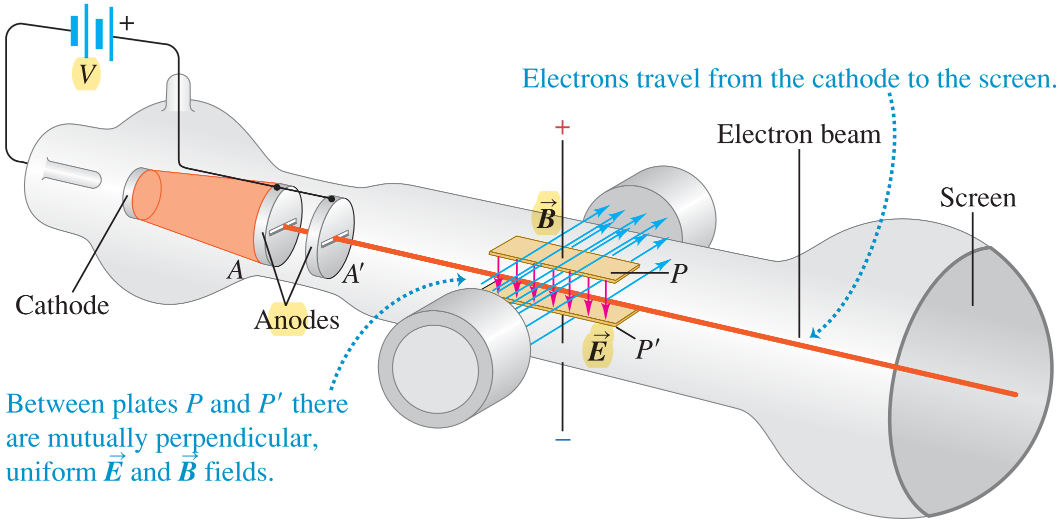
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$\sum F_y = 0 \Rightarrow -qE + qvB = 0$$

$$\Rightarrow v = \frac{E}{B}$$

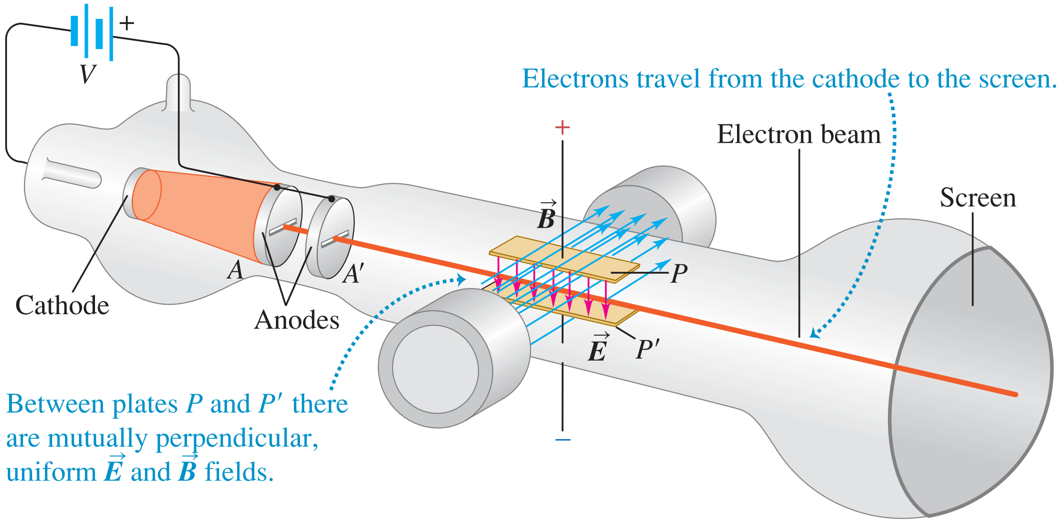
Only particles with speeds equal to *E/B* can pass through without being deflected by the fields

Thomson's *e/m* Experiment



For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

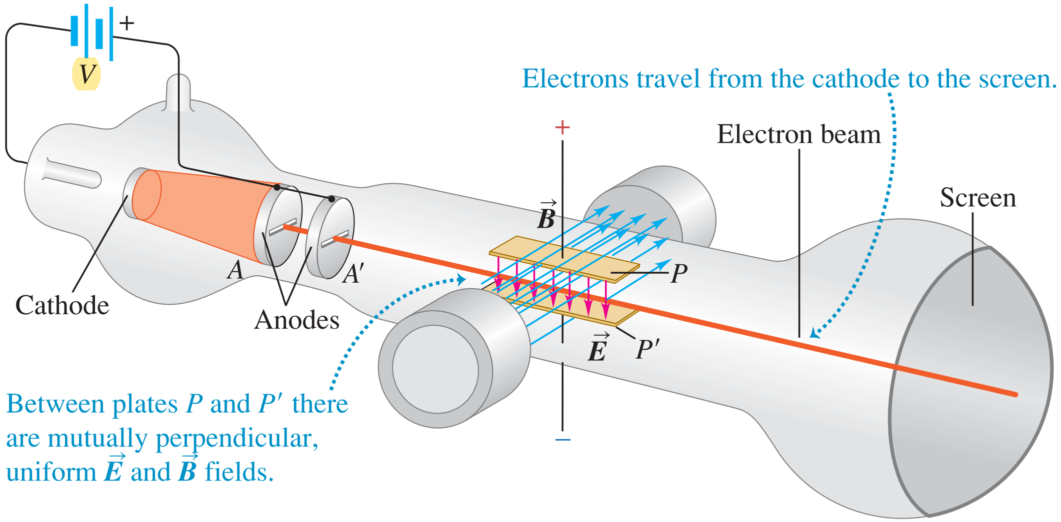
Thomson's *e/m* Experiment



For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

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

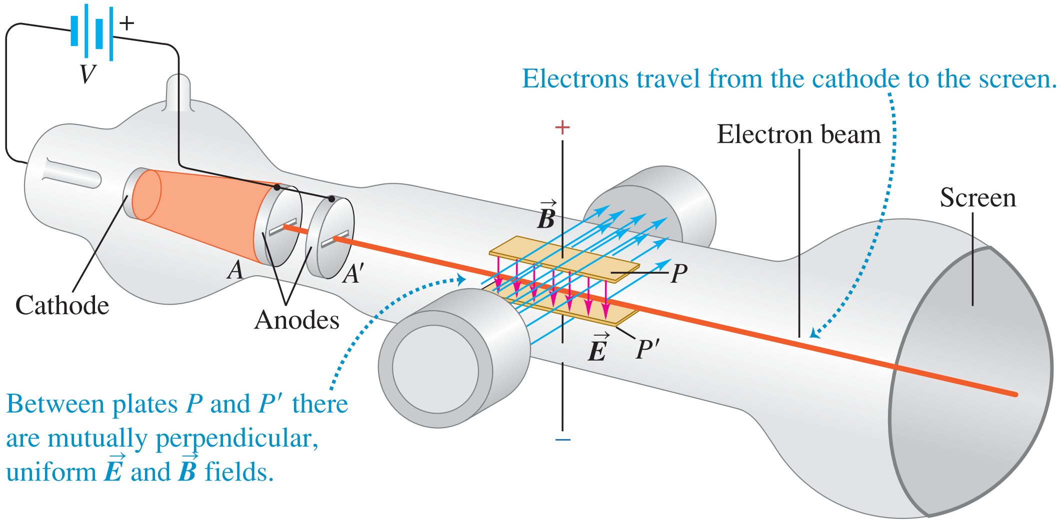
Thomson's e/m Experiment



For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

$$\frac{1}{2}mv^2 = eV \quad \Rightarrow \quad v = \sqrt{\frac{2eV}{m}}$$

Thomson's *e/m* Experiment

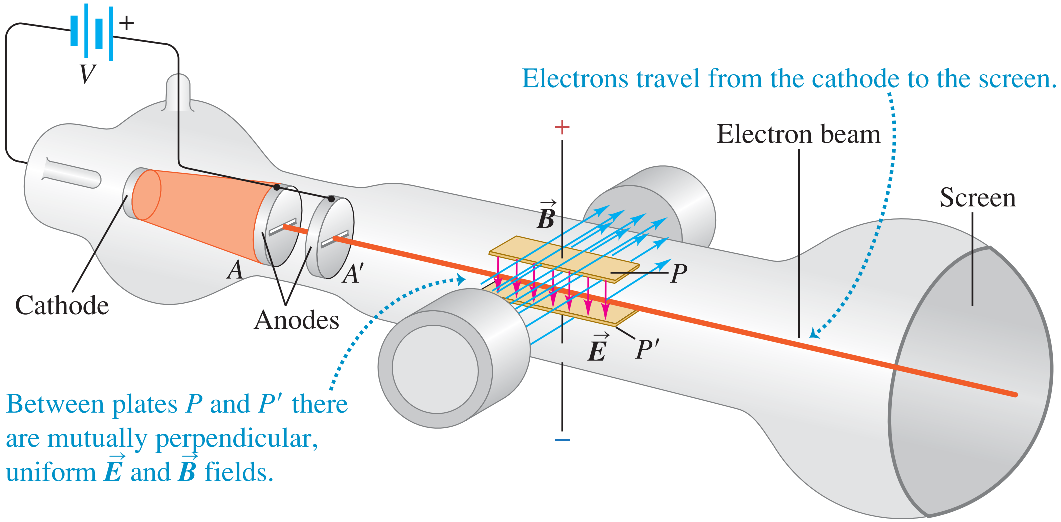


For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

$$\frac{1}{2}mv^2 = eV \quad \Rightarrow \quad v = \sqrt{\frac{2eV}{m}}$$

$-qE + qvB = 0$ (Same as in velocity selector) ➔ $\dfrac{E}{B} = \sqrt{\dfrac{2eV}{m}}$

Thomson's *e*/*m* Experiment



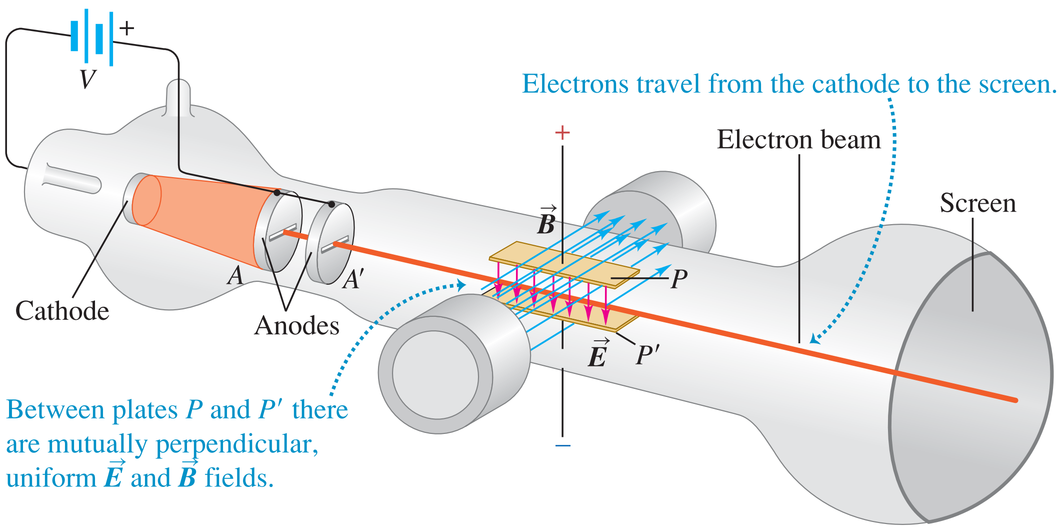
For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

$$\frac{1}{2}mv^2 = eV \quad \Rightarrow \quad v = \sqrt{\frac{2eV}{m}}$$

$-qE + qvB = 0$ (Same as in velocity selector) ➔ $\dfrac{E}{B} = \sqrt{\dfrac{2eV}{m}}$

$$\Rightarrow \quad \frac{e}{m} = \frac{E^2}{2VB^2}$$

Thomson's e/m Experiment



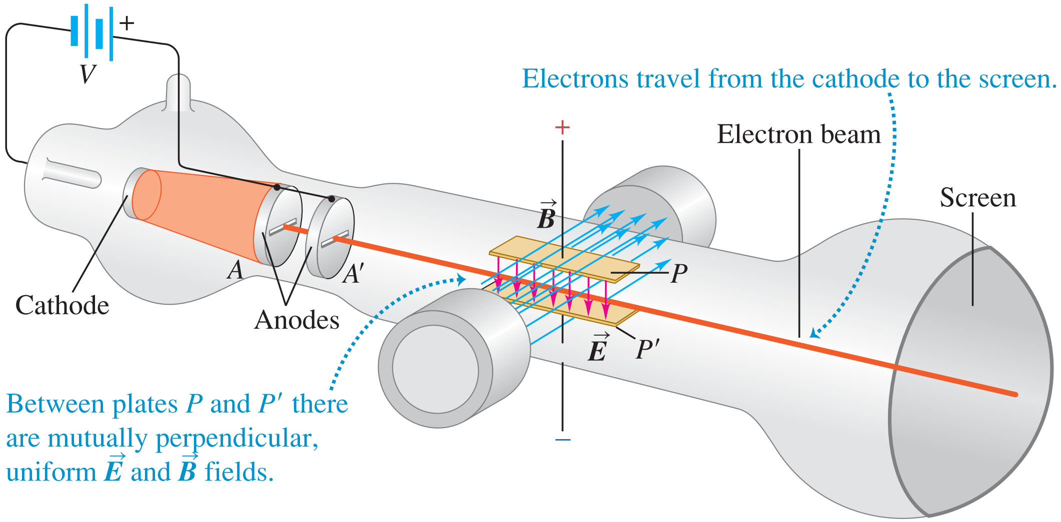
For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

$$\frac{1}{2}mv^2 = eV \Rightarrow v = \sqrt{\frac{2eV}{m}}$$

$-qE + qvB = 0$ (Same as in velocity selector) ➔ $\frac{E}{B} = \sqrt{\frac{2eV}{m}}$

$$\Rightarrow \frac{e}{m} = \frac{E^2}{2VB^2} = 1.758820150(44) \times 10^{11}\ \mathrm{C/kg}$$

Thomson's e/m Experiment



For his experiment carried out in 1897 at the Cavendish Laboratory in Cambridge, England, J.J. Thomson used the apparatus shown in the figure

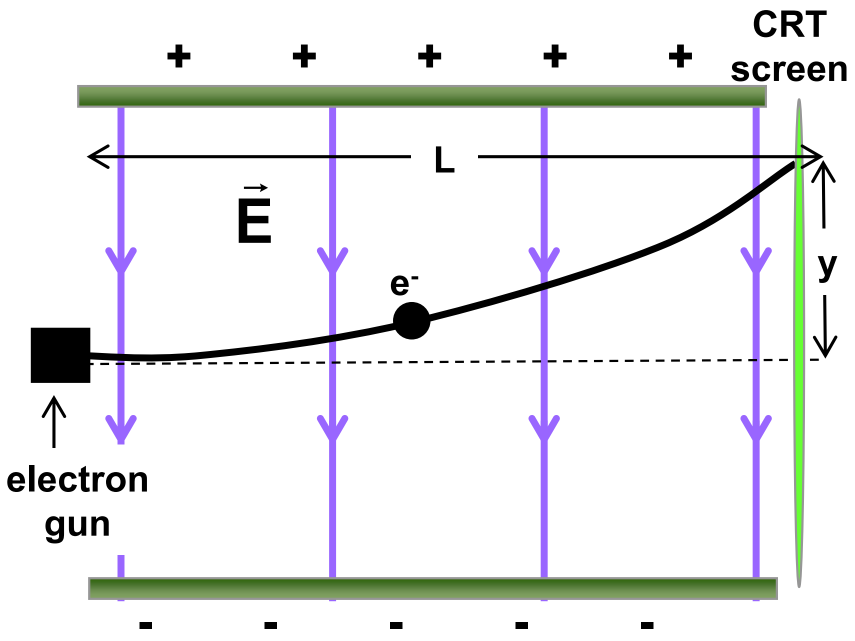
$$\frac{1}{2}mv^2 = eV \Rightarrow v = \sqrt{\frac{2eV}{m}}$$

$-qE + qvB = 0$ (Same as in velocity selector) $\rightarrow \frac{E}{B} = \sqrt{\frac{2eV}{m}}$

$$\Rightarrow \frac{e}{m} = \frac{E^2}{2VB^2} = 1.758820150(44) \times 10^{11}\ \mathrm{C/kg}$$

$$\Rightarrow m = 9.10938215(45) \times 10^{-31}\ \mathrm{kg}$$

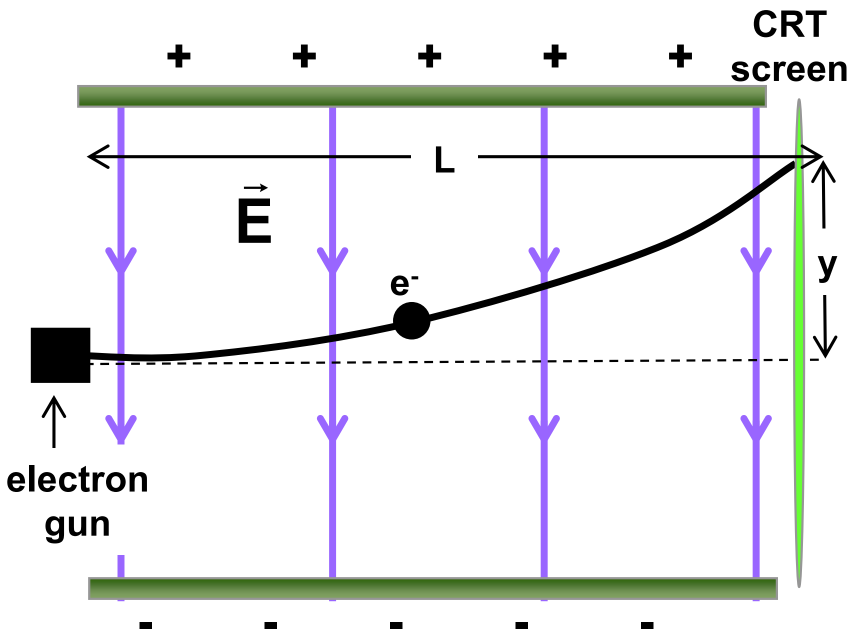
Another approach of Thomson's *e/m* Experiment



First: . Apply E field only in –y direction

. y = deflection of beam from center of the screen (position for E = 0)

Another approach of Thomson's *e/m* Experiment

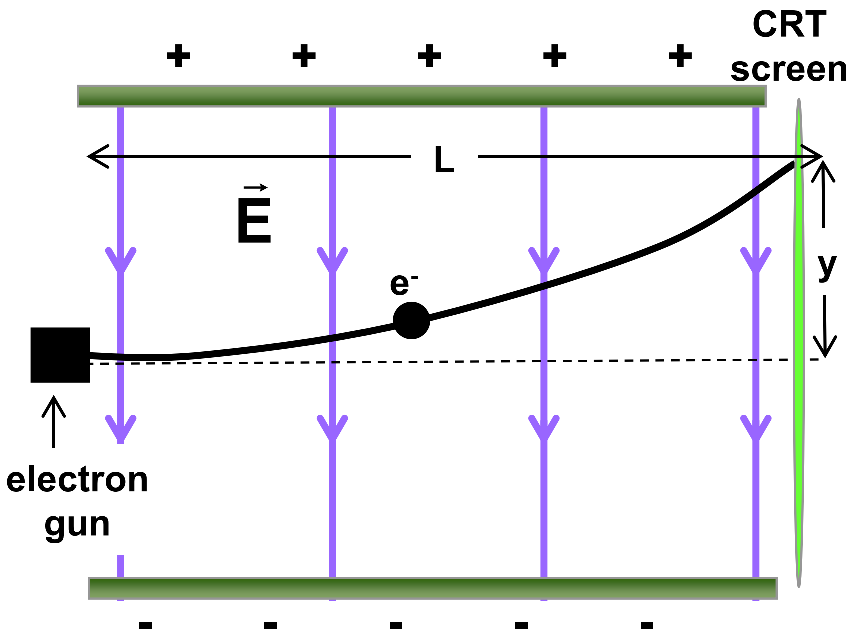


First: . Apply E field only in –y direction
. y = deflection of beam from center of the screen (position for E = 0)

$$F_y = qE = ma_y$$
$$q = -e$$

$$\boxed{\frac{e}{m} = \frac{a_y}{E}}$$

Another approach of Thomson's *e/m* Experiment



First: . Apply E field only in –y direction
. y = deflection of beam from center of the screen (position for E = 0)

$$F_y = qE = ma_y$$
$$q = -e$$

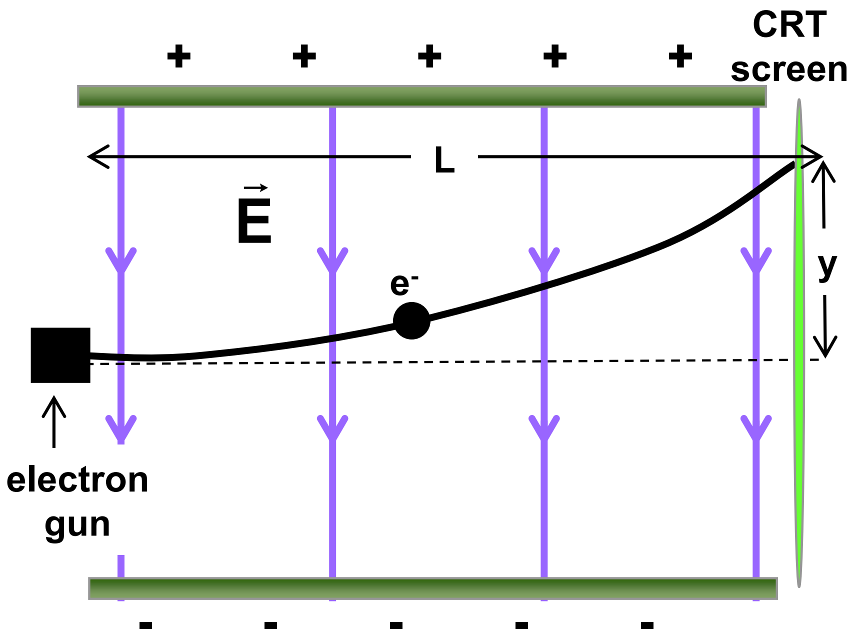
$$\boxed{\frac{e}{m} = \frac{a_y}{E}}$$

measure $y = \frac{1}{2} a_y t^2$

notethat $t = L / v_x$

Next: . Find a_y by measuring y and flight time $t = L / v_x$ (constant)

Another approach of Thomson's *e/m* Experiment



First: . Apply E field only in –y direction
. y = deflection of beam from center of the screen (position for E = 0)

$$F_y = qE = ma_y$$
$$q = -e$$

$$\boxed{\frac{e}{m} = \frac{a_y}{E}}$$

measure $y = \frac{1}{2} a_y t^2$

note that $t = L / v_x$

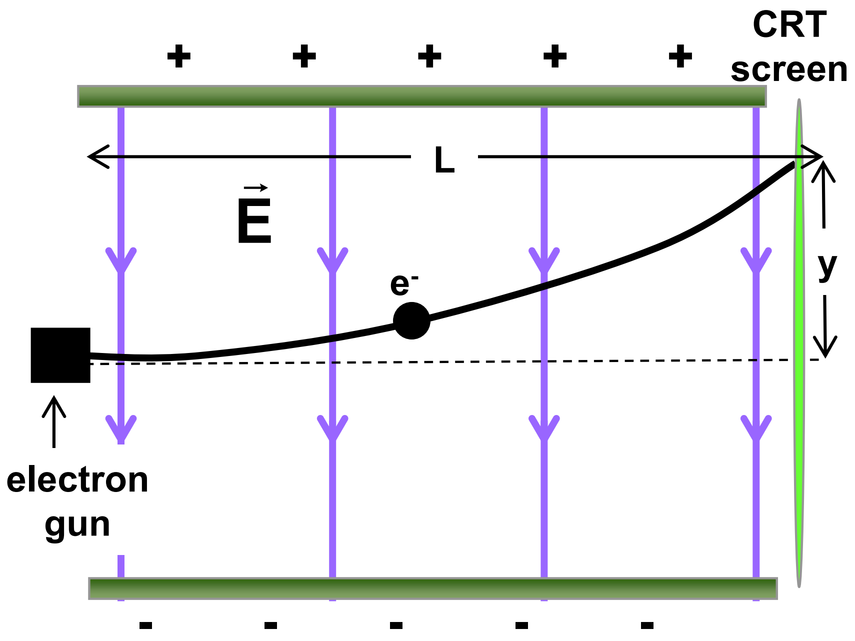
Next: . Find a_y by measuring y and flight time $t = L / v_x$ (constant)

Use crossed B and E fields to measure v_x

Let B point into the page, perpendicular to both E and Vx

F_M points along –y, opposite to FE (negative charge)

Another approach of Thomson's *e/m* Experiment



First: . Apply E field only in –y direction
. y = deflection of beam from center of the screen (position for E = 0)

$$F_y = qE = ma_y \qquad q = -e \quad \Rightarrow \quad \boxed{\frac{e}{m} = \frac{a_y}{E}}$$

measure $y = \frac{1}{2}a_y t^2$

note that $t = L / v_x$

Next: . Find a_y by measuring y and flight time $t = L / v_x$ (constant)

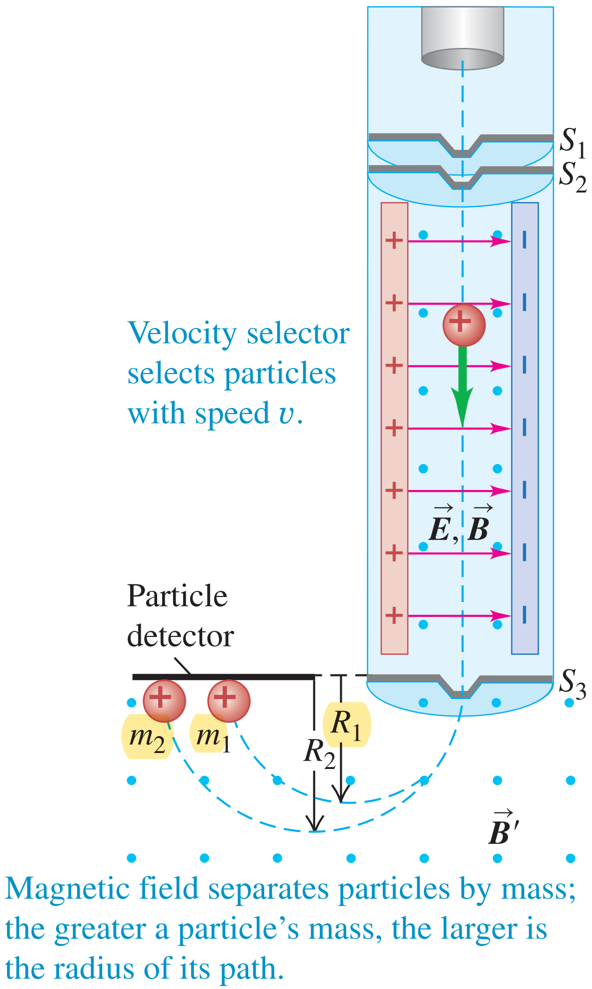
Use crossed B and E fields to measure v_x
Let B point into the page, perpendicular to both E and Vx
F_M points along –y, opposite to FE (negative charge)

$$\vec{F}_M = -e\vec{v}\times\vec{B} \quad \vec{F}_E = -e\vec{E} \quad \Rightarrow \quad \boxed{\text{at equilibrium} \quad v_x = E / B}$$

Adjust B until beam deflection = 0 (F_E cancels F_M) to find v_x and time t

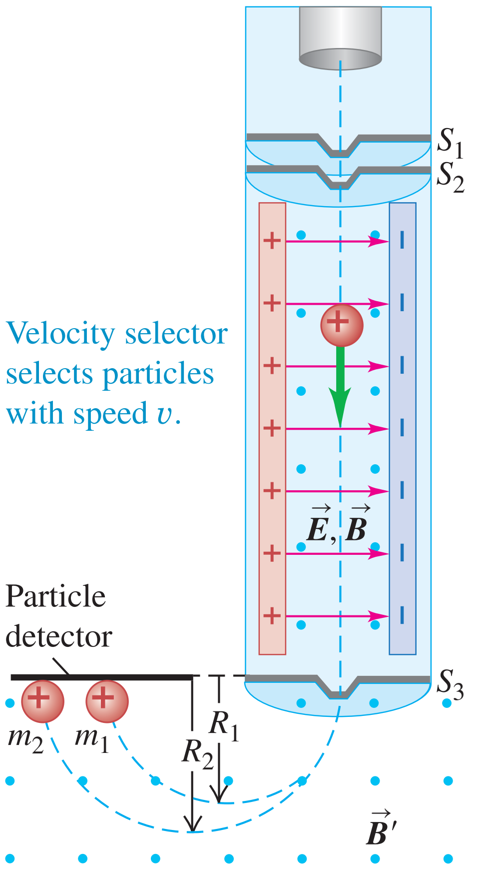
$$t = \frac{BL}{E} \Rightarrow a_y = \frac{2y}{t^2} = 2y\frac{E^2}{B^2L^2} \quad \Rightarrow \quad \boxed{\frac{e}{m} = 2y\frac{E}{B^2L^2} = 1.76 \times 10^{11} \text{ C/kg}}$$

Mass Spectrometers



Techniques similar to Thomson's e/m experiment can be used to measure masses of ions and thus measure atomic and molecular masses. In 1919, Francis Aston (1877–1945), a student of Thomson's, built the first of a family of instruments called **mass spectrometers**

Mass Spectrometers

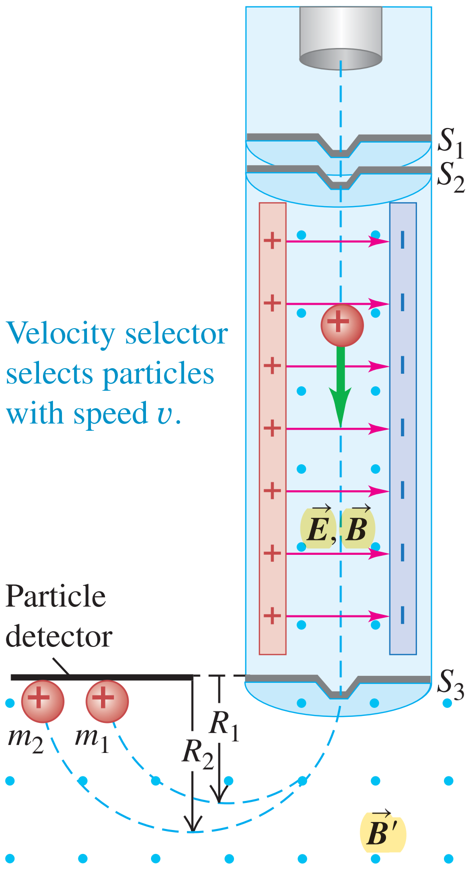


Magnetic field separates particles by mass; the greater a particle's mass, the larger is the radius of its path.

Techniques similar to Thomson's e/m experiment can be used to measure masses of ions and thus measure atomic and molecular masses. In 1919, Francis Aston (1877–1945), a student of Thomson's, built the first of a family of instruments called **mass spectrometers**

Positive ions from a source pass through the slits S_1 and S_2, forming a narrow beam. Then the ions pass through a velocity selector with crossed E and B fields, as we have described, to block all ions except those with speeds v equal to E/B.

Mass Spectrometers



Magnetic field separates particles by mass; the greater a particle's mass, the larger is the radius of its path.

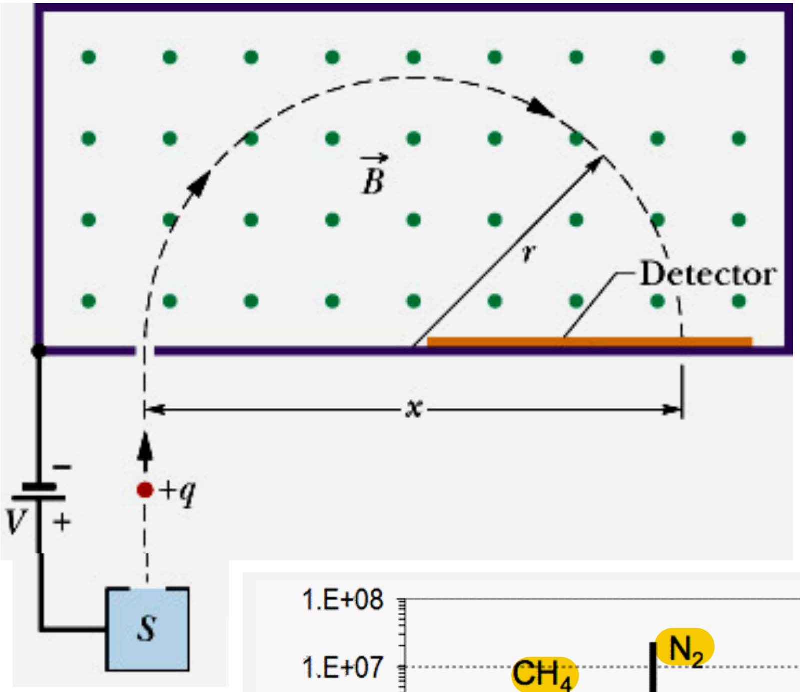
Techniques similar to Thomson's e/m experiment can be used to measure masses of ions and thus measure atomic and molecular masses. In 1919, Francis Aston (1877–1945), a student of Thomson's, built the first of a family of instruments called **mass spectrometers**

Positive ions from a source pass through the slits S_1 and S_2, forming a narrow beam. Then the ions pass through a velocity selector with crossed E and B fields, as we have described, to block all ions except those with speeds v equal to E/B.

Finally, the ions pass into a region with a magnetic field B' perpendicular to the figure, where they move in circular arcs with radius R determined by

$R = mv/qB'$

Mass spectrometer Separates particles with different charge/mass ratios



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

ionized atoms or molecules accelerated through potential V

$$r = \frac{mv}{qB}$$

ionized isotopes or molecules are separated forming a “spectrum

$$r = \frac{1}{B}\sqrt{\frac{2mV}{q}} \quad \Rightarrow \quad \boxed{\frac{q}{m} = \frac{2V}{B^2 r^2}}$$