

Section 3.1.5 – Magnetic Forces on Charged Particles

Magnetic Forces on Charge Particles

Current flowing through a wire can also be examined as a flow of **charged particles**. It is the moving electrons within the wire that experience a force when placed in a magnetic field. The sum of these individual forces results in wire movement.

In fact even without a wire a flow (or beam) of **charged particles experience a force** when projected through a **magnetic field**.

The **right hand slap rule** can be used to examine the force upon a positively charged particle (ie. current), the reverse is used for electron flow.

Example 1

Consider the alpha particle shown in Figure 6, entering a magnetic field into the page. The alpha particle has a positive charge and velocity to the right of the page. The direction of the force applied upon a positive moving charge can be predicted using the right hand slap rule.

Fingers – in the direction of the magnetic field (B) [North → South]

Thumb – in the direction of the charge velocity

Palm - in the direction of the force upon the positive charged particle

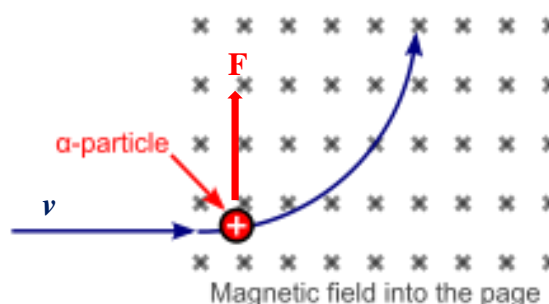
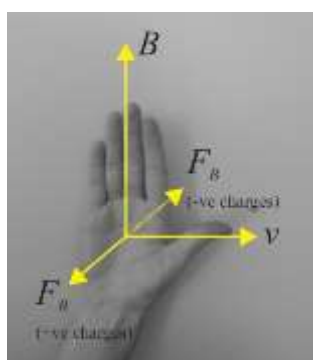


Figure 1

The equation for calculating the magnitude of force upon a charged particle is:

$$F = Bqv$$

Where F represents Force (N)

B represents the magnetic field strength (T)

q represents charge (C)

v represents velocity (ms^{-1})

Example 2

What is the magnitude of the force exerted by a 100 mT magnetic field on an electron (of charge - $1.6 \times 10^{-19}\text{C}$) moving at 5% of the speed of light?

$$F = ?$$

$$F = Bqv$$

$$B = 100 \text{ mT}$$

$$= 0.1 \times 1.6 \times 10^{-19} \times 1.5 \times 10^7$$

$$= 0.1 \text{ T}$$

$$= \underline{2.4 \times 10^{-13} \text{ N}}$$

$$q = 1.6 \times 10^{-19} \text{ C}$$

$$v = 5\% \text{ of } c$$

$$= 0.05 \times 3.0 \times 10^8$$

$$= 1.5 \times 10^7 \text{ ms}^{-1}$$

Example 3

Consider the two charged particles shown in **Figure 2**. Each has a velocity to the right and both are entering a magnetic field into the page.

Using your right hand slap (or palm) rule for charged particle we can predict the direction of force upon each particle.

Fingers – in the direction of the magnetic field (B) [North pole → South pole]

(in both cases into the page)

Thumb – in the direction of the charge velocity

(in both cases to the right of the page)

Palm - in the direction of the force upon the positive charged particle

(Scenario A – is a positive particle so palm predicts a force up the page)

(Scenario B – is a negative particle so back of hand predicts a force down the page)

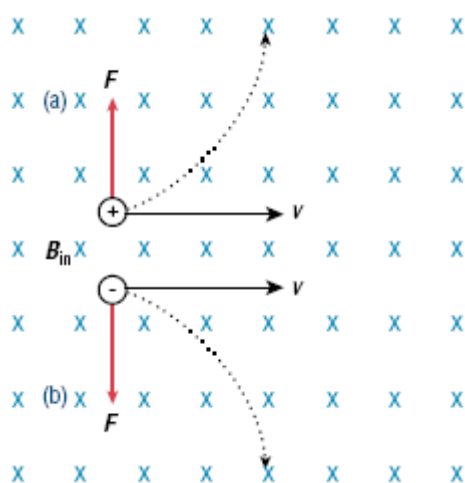


Figure 2

Application of Magnetic fields with a Particle Accelerator

The Physics of a particle accelerator is as fascinating as it is complex. Effectively a particle accelerator uses strong electric fields to accelerate charged particles to extremely high velocities. These extremely fast moving particles are then either used to:

1. Collide into a sample to investigate the smallest of all sub atomic particles
2. Generate synchrotron radiation which is used for the world's best imaging techniques

The Large Hadron Collider (LHC), shown below in **Figure 3**, is located at CERN laboratory on the France-Swiss border near Geneva, is the world's largest and most powerful particle accelerator. It is, as the name suggests, is a collision accelerator. The LHC uses protons as the accelerating particle.

Whereas, the Australian Synchrotron, shown below in **Figure 4**, is located next door to Monash University, Clayton, Melbourne generates synchrotron radiation by accelerating bunches of electrons to velocities near the speed of light.



Figure 3 The Large Hadron Collider



Figure 4 The Australian Synchrotron

Early particle accelerators used long straight paths in which particles were accelerated to extremely high velocities. These devices were called linear accelerators, or “linacs” for short. However, in order for today’s particle accelerators to reach such high velocities circular paths are required which allow hundreds of thousands of loops per second.

There are numerous magnetic fields used to control the path of charged particles within a circular accelerator. In this area of study we only need to examine the use of uniform field electromagnets to change the direction of, or bend the path of, the charged particle in order to maintain a circular path.



Figure 5 Strong dipole magnets used to bend electrons in the synchrotron

Scenario

Consider an electron travelling along the storage ring of the Australian synchrotron. It reaches a section of strong magnetic field which makes it “bend”. Use the right hand slap rule to verify the below diagram shown in **Figure 6**.

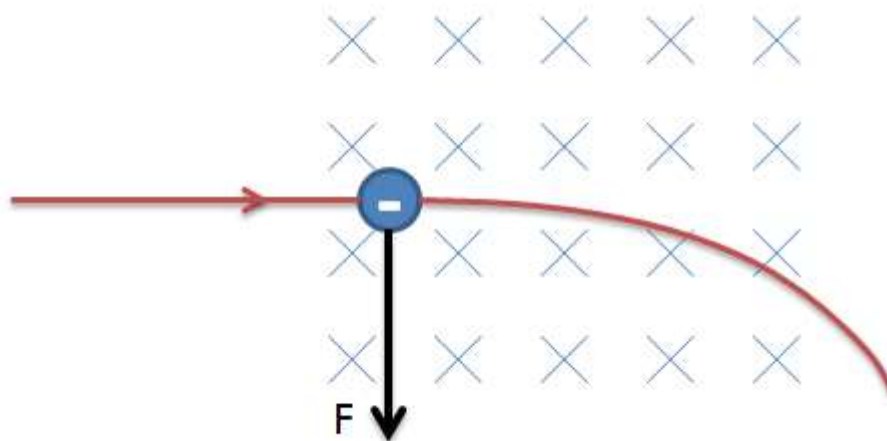


Figure 6

Fingers – in the direction of the magnetic field (B) [North pole \rightarrow South pole]
(in this cases B into the page)

Thumb – in the direction of the charge velocity
(in this cases v is to the right of the page)

Palm - in the direction of the force upon the positive charged particle
(in this case the particle is a negatively charged electron so back of hand predicts a force down the page)

The diagram has been verified!

Calculation of magnetic force upon moving charges

Further examination of electron paths being bent by strong magnetic fields can derive a very important equation:

Consider the following derivation:

The magnitude of the net force on a charged particle as it moves in a magnetic field is:

$$F_{\text{net}} = ma \quad \longleftarrow \text{Eqn. 1}$$

This force is equated to the magnetic force experienced by the particle

$$F = Bqv \quad \longleftarrow \text{Eqn. 2}$$

Equate Eqn. 1 & Eqn. 2

$$\therefore ma = Bqv \quad \longleftarrow \text{Eqn. 3}$$

As the electron undergoes centripetal acceleration (ie. circular motion), its acceleration can be considered to be:

$$a = \frac{v^2}{r} \quad \longleftarrow \text{Eqn. 4}$$

Substitute Eqn. 4 into Eqn. 3

$$\frac{mv^2}{r} = Bqv$$

$$\therefore \boxed{r = \frac{mv}{Bq}}$$

Where r represents the radius of the circular motion (m)
 m represents the mass of the charged particle (kg)
 v represents the velocity of the charged particle (ms^{-1})
 B represents the magnetic field strength (T)
 q represents the charge of the particle (C)

Example 4

Calculate the radius of the path of an electron travelling at $2.0 \times 10^7 \text{ ms}^{-1}$ when it enters a magnetic field of 5.0 mT.

$$r = ?$$

$$m = 9.1 \times 10^{-31} \text{ kg}$$

$$v = 2.0 \times 10^7 \text{ ms}^{-1}$$

$$B = 5.0 \times 10^{-3} \text{ T}$$

$$q = 1.6 \times 10^{-19} \text{ C}$$

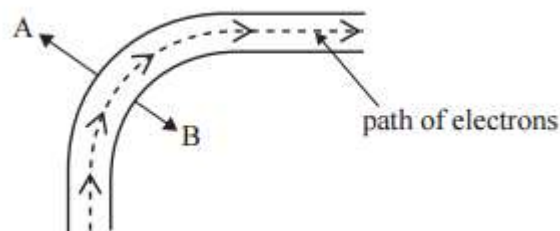
$$r = \frac{mv}{Bq}$$

$$r = \frac{9.1 \times 10^{-31} \times 2.0 \times 10^7}{5.0 \times 10^{-3} \times 1.6 \times 10^{-19}}$$

$$\underline{r = 0.0228 \text{ m or } 2.28 \text{ cm}}$$

Exam Style Questions

Electrons are travelling in the storage ring of a synchrotron at close to the speed of light. They are directed from a straight section into a curved section of the storage ring, as shown below.

**Question 1**

Which one of the following best gives the direction that the magnetic field must have to keep the electrons in this curved path?

- A. direction A on the diagram
- B. direction B on the diagram
- C. out of the page
- D. into the page

D

Use Right Hand rule

The electrons shown above (travelling at $8.4 \times 10^7 \text{ ms}^{-1}$) are deflected by a magnetic field of $2.4 \times 10^{-4} \text{ T}$ through a curved path of constant radius. Ignore any relativistic effects.

Question 2

Which one of the following best gives the radius of the path of an electron while in this magnetic field?

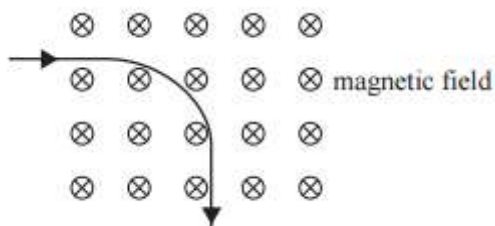
- A. 0.20 m
- B. 0.50 m
- C. 1.0 m
- D. 2.0 m

D

$$r = mv/Bq = 9.1 \times 10^{-31} \times 8.4 \times 10^7 / (2.4 \times 10^{-4} \times 1.6 \times 10^{-19}) = 2.0 \text{ m.}$$

The following information relates to Questions 3 & 4

An electron with a speed of $4.6 \times 10^7 \text{ ms}^{-1}$ enters a uniform magnetic field and moves in a circular path. The radius of the path is 0.40 m. This is shown in the diagram below.



Question 3

What is the magnitude of the magnetic field required to achieve this path?

- A. $4.2 \times 10^{-3} \text{ T}$
- B. $6.5 \times 10^{-4} \text{ T}$
- C. $1.5 \times 10^3 \text{ T}$
- D. $3.0 \times 10^4 \text{ T}$

B

Using $r = mv/Bq$, $B = mv/rq = 9.1 \times 10^{-31} \times 4.6 \times 10^7 / (0.40 \times 1.6 \times 10^{-19}) = 6.5 \times 10^{-4} \text{ T}$

The magnetic field is now adjusted to $5.0 \times 10^{-4} \text{ T}$.

Question 4

Which of the following now best gives the magnetic force on the electron?

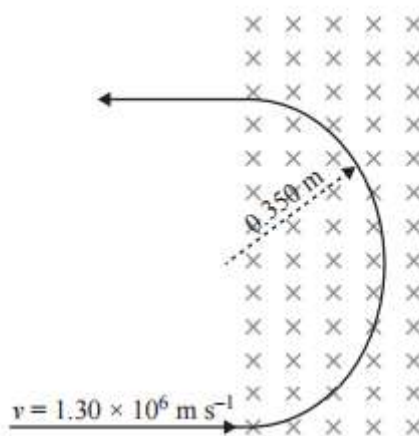
- A. $4.80 \times 10^{-17} \text{ N}$
- B. $3.68 \times 10^{-15} \text{ N}$
- C. $2.40 \times 10^{-14} \text{ N}$
- D. $3.68 \times 10^{-7} \text{ N}$

B

Using $F = Bqv$, $F = 5.0 \times 10^{-4} \times 1.6 \times 10^{-19} \times 4.6 \times 10^7 = 3.68 \times 10^{-15} \text{ N}$

The following information relates to Question 5

Electrons with a velocity of $1.30 \times 10^6 \text{ ms}^{-1}$ are injected into a uniform magnetic field, and moved in a semicircle of radius 0.350 m, as shown in the diagram below. The mass of an electron is $9.1 \times 10^{-31} \text{ kg}$ and charge is $-1.6 \times 10^{-19} \text{ C}$.



Question 5

Which of the following best gives the value of the magnetic field?

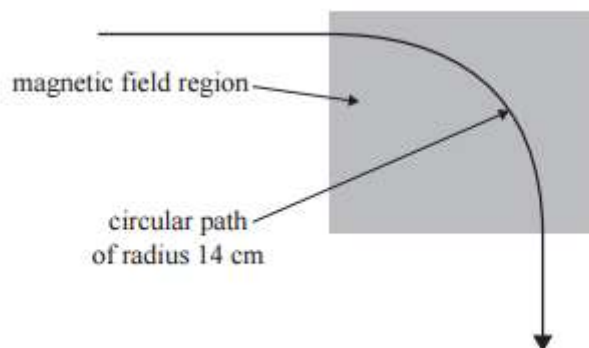
- A. $5.9 \times 10^{-13} \text{ T}$
- B. $2.1 \times 10^{-5} \text{ T}$
- C. $4.2 \times 10^{-2} \text{ T}$
- D. 27.5 T

B

Using $r = mv/Bq$, $B = (9.1 \times 10^{-31} \times 1.30 \times 10^6) / (0.350 \times 1.6 \times 10^{-19}) = 2.1 \times 10^{-5} \text{ T}$

The following information relates to Questions 6 & 7

An electron leaves the electron gun travelling at $2.7 \times 10^7 \text{ ms}^{-1}$. The electron enters a uniform magnetic field and moves in a circular path of radius 14 cm, as shown in the diagram below.



Question 6

Which of the following is the best estimate of the magnitude of the strength of the magnetic field?

- A. 1.1 mT
- B. 0.11 T
- C. 910 T
- D. 30 kT

A

$$\text{Using } B = mv/qr = 9.1 \times 10^{-31} \times 2.7 \times 10^7 / (1.6 \times 10^{-19} \times 14 \times 10^{-2}) = 1.1 \times 10^{-3} \text{ T}$$

Question 7

Which of the following best describes the direction of the magnetic field?

- A. down the page
- B. out of the page
- C. up the page
- D. into the page

D

Use Right Hand rule