# Chapter 8
# Electromagnetic forces

Worksheet

Worked examples

Practical 1: Investigating the path described by electrons in a uniform magnetic field

Practical 2: Force on a current-carrying conductor and $F = BIl \sin$

End-of-chapter test

Marking scheme: Worksheet

Marking scheme: End-of-chapter test

# Worksheet

elementary charge $e = 1.6 \quad 10^{-19}$ C
mass of electron = $9.1 \quad 10^{-31}$ kg

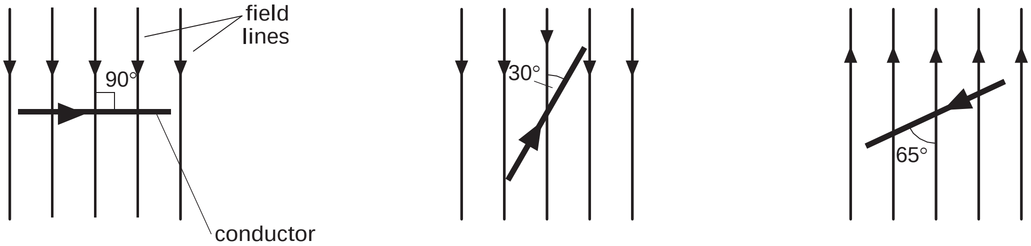
## *Intermediate level*

**1** A current-carrying wire is placed in a uniform magnetic field. When does this current-carrying wire experience:

**a** the maximum force due to the magnetic field? [1]

**b** no force due to the magnetic field? [1]

**2** A 4.0 cm long conductor carrying a current of 3.0 A is placed in a uniform magnetic field of flux density 50 mT. In each of **a**, **b** and **c** below, determine the size of the force acting on the conductor.

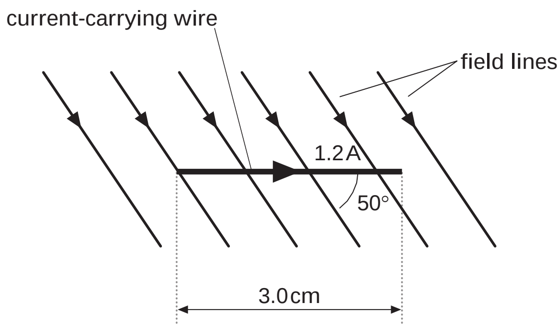



**a** [2] **b** [2] **c** [2]

**3** A copper wire carrying a current of 1.2 A has 3.0 cm of its length placed in a uniform magnetic field. The force experienced by the wire is $3.8 \quad 10^{-3}$ N when the angle between the wire and the magnetic field is 50°.

**a** Calculate the magnetic field strength. [3]

**b** What is the direction of the force experienced by the wire? [1]



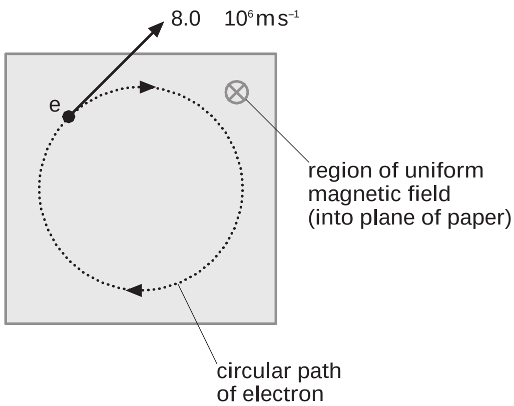

**4** Calculate the force experienced by an electron travelling at a velocity of $4.0 \quad 10^{6}$ m s$^{-1}$ at right-angles to a magnetic field of magnetic flux density 0.18 T. [3]

**5** The diagram shows an electron moving at a constant speed of $8.0 \quad 10^{6}$ m s$^{-1}$ in a plane perpendicular to a uniform magnetic field of magnetic flux density 4.0 mT.

**a** Calculate the force acting on the electron due to the magnetic field. [3]

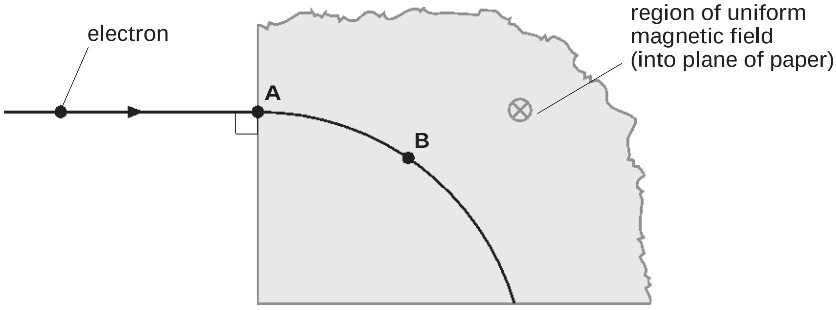
**b** What is the centripetal acceleration of the electron? [2]

**c** Use your answer to **b** to determine the radius of the circular path described by the electron. [2]



## *Higher level*

**6** The diagram shows the trajectory of an electron travelling into a region of uniform magnetic field of flux density 2.0 mT. The electron enters the region of magnetic field at 90°.




**a** Draw the direction of the force experienced by the electron at points **A** and **B**. [1]

**b** Explain why the electron describes part of a circular path while in the region of the magnetic field. [1]

**c** The radius of curvature of the path of the electron in the magnetic field is 5.0 cm. Calculate the speed $v$ of the electron. [5]

**d** Explain how your answer to **c** would change if the electron described a circular path of radius 2.5 cm. [2]

**7** A proton of kinetic energy 15 keV travelling at right-angles to a magnetic field describes a circle of radius of 5.0 cm. The mass of a proton is $1.7 \quad 10^{-27}$ kg.

**a** Show that the speed of the proton is $1.7 \quad 10^{6}\,\mathrm{m\,s^{-1}}$. [3]

**b** For this proton, calculate the centripetal force provided by the magnetic field. [3]

**c** Determine the magnetic flux density of the magnetic field that keeps the proton moving in its circular orbit. [3]

**d** How long does it take for the proton to complete one orbit? [2]

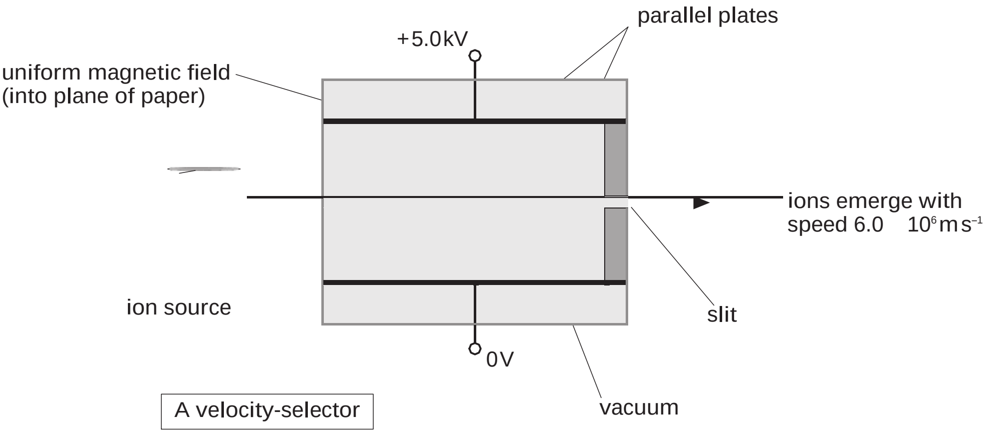
# *Extension*

**8** An electron describes a circular orbit in a plane perpendicular to a uniform magnetic field. Show that the time $T$ taken by an electron to complete one orbit in the magnetic field is independent of its speed and its radius, and is given by:

$$T = \frac{2\quad m}{Be}$$

where $B$ is the magnetic flux density of the magnetic field, $e$ is the charge on an electron and $m$ is the mass of an electron. [5]

**9** The diagram shows a velocity-selector for charged ions. Ions of a particular speed emerge from the slit.



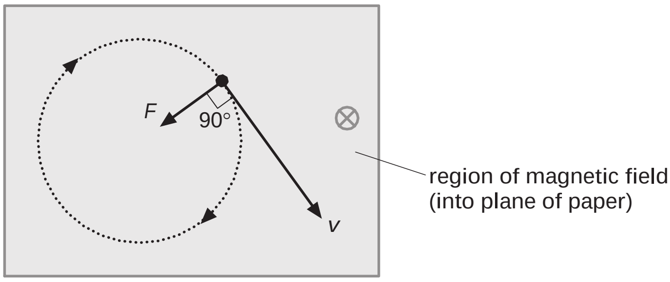

The parallel plates have a separation of 2.4 cm and are connected to a 5.0 kV supply. A magnetic field is applied at right-angles to the electric field between the plates such that the positively charged ions emerge from the slit of the velocity-selector at a speed of $6.0 \quad 10^{6}\,\mathrm{m\,s^{-1}}$. Calculate the magnetic flux density of the magnetic field. [6]

Total: $\overline{\quad 53}$ Score: %

# Worked examples

## Example 1

An electron travelling at 2.0    $10^6$ m s$^{-1}$ enters a magnetic field of magnetic flux density 8.0 mT at right-angles. Explain why the path described by the electron is a circle. Calculate the force acting on the electron due to the magnetic field.




The force $F$ acting on the electron is given by Fleming's left-hand rule. This force is at 90° to the velocity $v$. Therefore, the electron will move in a circular path.

The force $F$ experienced by the electron is given by:

$F = BQv$

$B = 8.0\quad 10^{-3}$ T    $Q = 1.6\quad 10^{-19}$ C    $v = 2.0\quad 10^{6}$ m s$^{-1}$

*The magnetic flux density must be in tesla, so do not forget the factor $10^{-3}$.*

Therefore:

$F = 8.0\quad 10^{-3}\quad 1.6\quad 10^{-19}\quad 2.0\quad 10^{6}$

$F = 2.56\quad 10^{-15}$ N    $2.6\quad 10^{-15}$ N

## Example 2

A positively charged ion describes a circular path in a plane at right-angles to a magnetic field of flux density 0.016 T. The radius of the path is 58 cm. Calculate the momentum of the charged ion given that the charge on the ion is 3.2    $10^{-19}$ C.

The path of the ion is a circle. The centripetal force $F$ is therefore given by:

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

where $m$ is the mass of the ion, $v$ is its speed and $r$ is the radius of the circle.

Therefore:

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

*The centripetal force is provided by the magnetic force BQv.*

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

$$mv = BQr$$

*Momentum is defined as: p = mv.*

But $mv$ is momentum, $p$, so:

$p = BQr = 0.016\ 3\ .2\quad 10^{-19}\quad 0.58$

$p = 2.97\quad 10^{-21}$ kg m s$^{-1}$    $3.0\quad 10^{-21}$ kg m s$^{-1}$

### Tip

In questions involving a charge moving in a circular path in a magnetic field, you can usually make a good start with the important equation:

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

and then try to figure out what you need to calculate. In this question, you do not need the actual mass of the charged ion.

# Practical 1

## *Investigating the path described by electrons in a uniform magnetic field*

### Safety

In order to minimise accidental shocks from the e.h.t. supply, it is sensible to shroud all 4 mm plugs and switch off the supply when changing connections. Teachers and technicians should follow their school and departmental safety policies and should ensure that the employer's risk assessment has been carried out before undertaking any practical work.

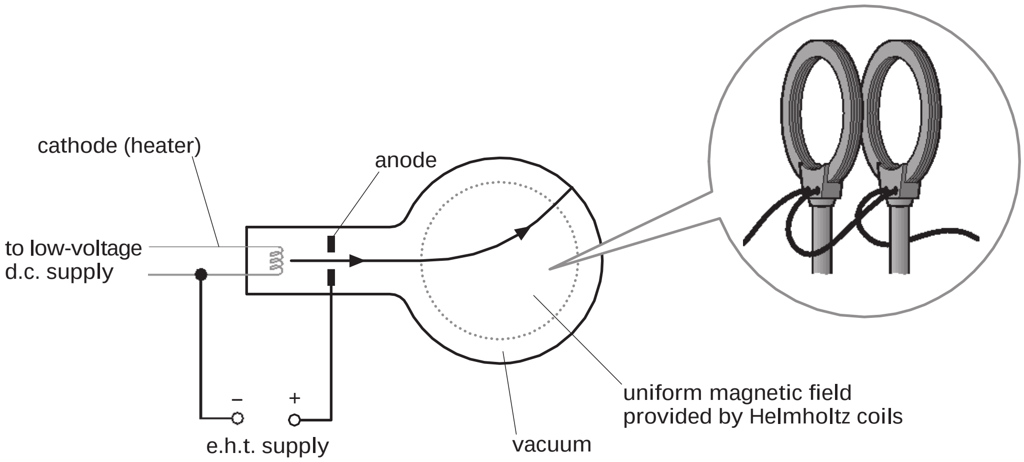
### Apparatus

- fine-beam tube
- e.h.t. supply
- pair of Helmholtz coils
- digital ammeter
- low-voltage d.c. supply
- connecting wires

### Introduction

The radius $r$ of the circle described by an electron is given by $r = \frac{mv}{Be}$.

The derivation of this formula is given on page 85 of *Physics 2*. In this experiment you will use a fine-beam tube to investigate the factors that affect the radius of curvature of electrons travelling at right-angles to a uniform magnetic field and estimate the speed of the electrons.




### Procedure

**1** Set up the fine-beam tube in a darkened room.

**2** Switch on the heater to the fine-beam tube and set the e.h.t. supply to 2.0 kV.

**3** Switch on the low-voltage supply for the Helmholtz coils. Adjust the supply so that the current in the coils is 0.2 A.

**4** Observe the path described by the electron beam.

**5** Use Fleming's left-hand rule to show that electrons have a negative charge.

**6** **Predict** what will happen to the radius of the path described by the electrons when the accelerating voltage from the e.h.t. supply is increased to 4.0 kV. Adjust the e.h.t. supply to 4.0 kV. Was your prediction correct?

**7** Now **predict** what will happen when the magnetic field strength between the coils is doubled by increasing the current in the coils to 0.4 A. Adjust the low-voltage supply so that the current in the coils is 0.4 A. Was your prediction correct?

**8** You can estimate the speed $v$ of the electrons as follows:

- Estimate the radius $r$ of the path described by the electron beam.
- The magnetic field strength $B$ in tesla for the Helmholtz coils is given by

  $$B \quad \frac{9 \quad 10^{-7}NI}{R}$$

  where $R$ is the mean radius of each Helmholtz coil, $I$ is the current in the coil and $N$ is the total number of turns on each coil. Use this equation to determine the magnetic field strength $B$.
- The mass $m$ of the electron is $9.1 \quad 10^{-31}$ kg and it has a charge $e$ of $1.6 \quad 10^{-19}$ C.

  Use the equation $r = \frac{mv}{Be}$ and your values for $B$ and $r$ to estimate the speed $v$ of an electron. What is the uncertainty in the speed of the electron?

## Guidance for teachers

This experiment is recommended as a teacher demonstration.

# Practical 2

## *Force on a current-carrying conductor and $F = BIl\sin$*

### Safety

Usual safety instructions must be followed when using mains-operated supplies. Teachers and technicians should follow their school and departmental safety policies and should ensure that the employer's risk assessment has been carried out before undertaking any practical work.

### Apparatus

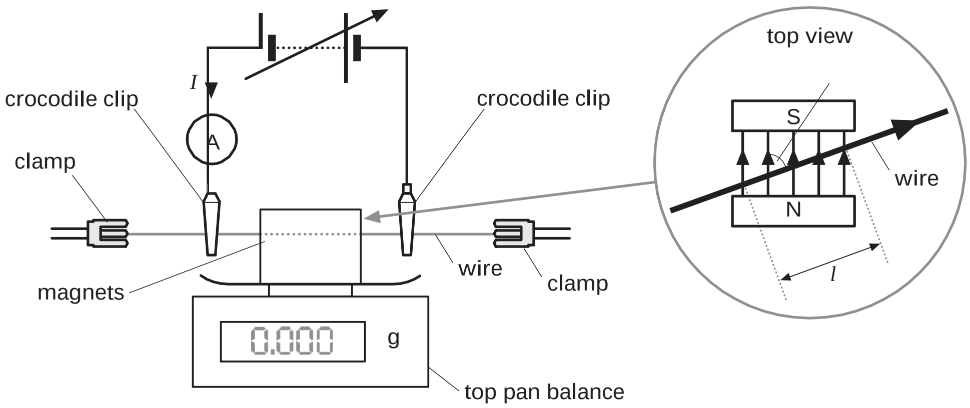
- top pan balance
- variable d.c. supply
- digital ammeter
- magnadur magnets and yoke
- thick, stiff copper wire
- protractor
- 30 cm plastic ruler
- teslameter
- clamp stands
- crocodile clips
- connecting wires

### Introduction

The force experienced by a current-carrying conductor depends on the factor sin , where is the angle between the conductor and the magnetic field (see page 82 in *Physics 2*). In this experiment you will investigate the validity of the equation:

$F = BIl\sin$

The experimental setup is shown in the diagram.




### Procedure

**1** Switch off the power supply.

**2** Place the magnet on the top pan balance and zero the balance.

**3** Switch on the power supply and adjust the e.m.f. of the supply until the current in the wire is 8.0 A.

**4** Place the wire between the poles of the magnet so that it is at 90° to the magnetic field.

**5** Record the balance reading in grams. Convert the balance reading into a force $F$ using $F = mg$, where $m$ is the balance reading in kilograms and $g$ is the gravitational field strength, 9.81 N kg$^{-1}$.

**6** Carefully measure the length $l$ of the wire in the magnetic field. (You have to assume that the field is uniform between the poles and only exists between the poles of the magnet.)

**7** Repeat the experiment for different angles between the wire and the magnetic field. (You may be limited to angles in the range 50° to 90°.)

**8** Record your results in a table.

| **Balance reading (g)** | ***l* (m)** | **F (N)** | $\frac{F}{l}$ **(N m$^{-1}$)** | **$\theta$ (degrees)** | **sin$\theta$** |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |

**9** Plot a graph of $\frac{F}{l}$ against sin and draw a straight line of best fit.

**10** The graph should be a straight line. Can you explain why?

**11** Determine the gradient of the graph and hence the magnetic flux density *B* between the poles of the magnet.

*Hint: gradient = BI, where I is the current of 8.0 A.*

**12** How does your value for the flux density compare with that measured by a commercial teslameter?

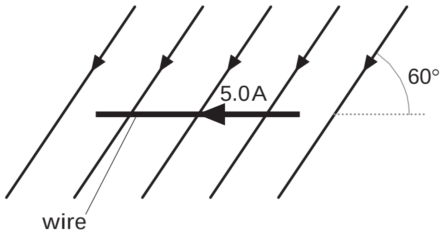
# End-of-chapter test

**Answer all questions.**

elementary charge $e = 1.6 \quad 10^{-19}$ C

mass of electron $= 9.1 \quad 10^{-31}$ kg

**1** The diagram shows a copper wire carrying a current of 5.0 A placed at an angle of 60° to a uniform magnetic field.




The force experienced per unit length by the wire is $2.0 \quad 10^{-3}$ N cm$^{-1}$.

**a** State the direction of the force experienced by the wire. [1]

**b** Calculate the magnetic flux density. [3]

**2** An  -particle from a radioactive source enters a uniform magnetic field of flux density 50 mT at right-angles. The speed of the  -particle is $4.0 \quad 10^{6}$ m s$^{-1}$.

**a** Explain why the speed of the  -particle remains constant in the region of the magnetic field. [2]

**b** The mass of the  -particle is $6.7 \quad 10^{-27}$ kg and it has a charge of $3.2 \quad 10^{-19}$ C. For the  -particle in the magnetic field, calculate:

**i** the force acting on it due to the magnetic field; [3]

**ii** its centripetal acceleration; [2]

**iii** the radius of its orbit. [2]

**3** A proton describes a circular path in a plane perpendicular to a magnetic field.

**a** Show that the radius $r$ of the circular path of the proton is given by:

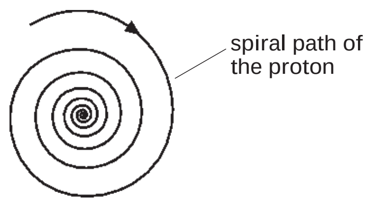
$$r = \frac{mv}{Be}$$

where $m$ is the mass of the proton, $v$ is the speed of the proton, $e$ is the charge on the proton and $B$ is the magnetic flux density. [3]

**b** Calculate the radius of the path described by a proton travelling at a speed of $4.0 \quad 10^{5}$ m s$^{-1}$ in a uniform magnetic field of magnetic flux density 60 mT. [2]
(The mass of a proton $= 1.7 \quad 10^{-27}$ kg.)

**c** Explain how your answer to **b** would change if a proton travelling at twice the speed entered a magnetic field of twice the magnetic flux density. [2]

**d** The diagram shows the actual trajectory of a proton in a particle detector when it is travelling at right-angles to the magnetic field. Suggest a possible reason why the path is not a circle but a spiral. [1]




Total: $\frac{\quad}{21}$ Score: %

# Marking scheme

## *Worksheet*

**1** **a** (The force is given by: $F = BIl\sin$ .)

The force $F$ is a maximum when the angle   between the wire and the magnetic field is 90°. [1]

**b** The force $F$ is a minimum when the angle   between the wire and the magnetic field is 0°. (The wire is parallel to the magnetic field.) [1]

**2** **a** $F = BIl\sin$

$F = 0.050 \quad 3.0 \quad 0.04 \quad \sin 90°$ [1]; $F = 6.0 \quad 10^{-3}\,\mathrm{N}$ [1]

**b** $F = 0.050 \quad 3.0 \quad 0.04 \quad \sin 30°$ [1]; $F = 3.0 \quad 10^{-3}\,\mathrm{N}$ [1]

**c** $F = 0.050 \quad 3.0 \quad 0.04 \quad \sin 65°$ [1]; $F = 5.44 \quad 10^{-3}\,\mathrm{N} \quad 5.4 \quad 10^{-3}\,\mathrm{N}$ [1]

**3** **a** $F = BIl\sin$ [1]

$B = \dfrac{F}{Il\sin} = \dfrac{3.8 \quad 10^{-3}}{1.2 \quad 0.03 \quad \sin 50°}$ [1]; $B = 0.138\,\mathrm{T} \quad 0.14\,\mathrm{T}$ [1]

**b** The direction is given by Fleming's left-hand rule. The wire experiences a force into the plane of the paper. [1]

**4** $F = BQv$ [1]

$F = 0.18 \quad 1.6 \quad 10^{-19} \quad 4.0 \quad 10^{6}$ [1]; $F = 1.15 \quad 10^{-13}\,\mathrm{N} \quad 1.2 \quad 10^{-13}\,\mathrm{N}$ [1]

**5** **a** $F = BQv$ [1]

$F = 0.004 \quad 1.6 \quad 10^{-19} \quad 8.0 \quad 10^{6}$ [1]; $F = 5.12 \quad 10^{-15}\,\mathrm{N} \quad 5.1 \quad 10^{-15}\,\mathrm{N}$ [1]

**b** $a = \dfrac{F}{m} = \dfrac{5.12 \quad 10^{-15}}{9.1 \quad 10^{-31}}$ [1]

$a = 5.63 \quad 10^{15}\,\mathrm{m\,s^{-2}} \quad 5.6 \quad 10^{15}\,\mathrm{m\,s^{-2}}$ [1]

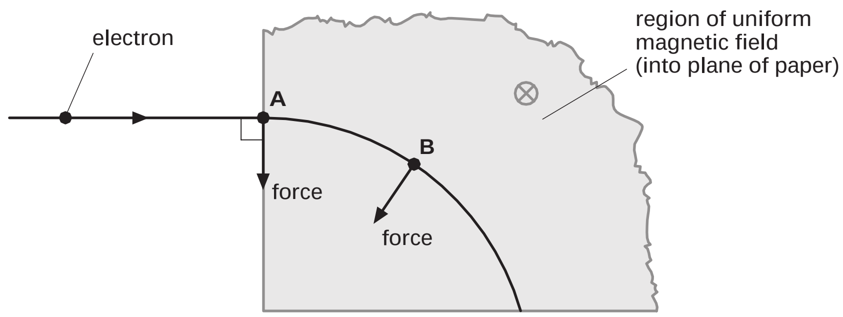
**c** From circular motion, the centripetal acceleration $a$ is given by:

$a = \dfrac{v^2}{r}$

$r = \dfrac{v^2}{a} = \dfrac{(8.0 \quad 10^{6})^2}{5.63 \quad 10^{15}}$ [1]

$r = 1.14 \quad 10^{-2}\,\mathrm{m} \quad 1.1 \quad 10^{-2}\,\mathrm{m} \quad (1.1\,\mathrm{cm})$ [1]

**6** **a**




Both arrows at **A** and **B** are towards the centre of the circle. [1]

**b** The force on the electron is at 90° to the velocity. Hence the path described by the electron is a circle. [1]

**c** The magnetic force provides the centripetal force. [1]

Therefore: $BQv = \dfrac{mv^2}{r}$ [1]

$BQ = \dfrac{mv}{r}$ or $v = \dfrac{BQr}{m}$ [1]

$v = \dfrac{2.0 \quad 10^{-3} \quad 1.6 \quad 10^{-19} \quad 5.0 \quad 10^{-2}}{9.1 \quad 10^{-31}}$ [1]

$v = 1.76 \quad 10^{7}\,\mathrm{m\,s^{-1}} \quad 1.8 \quad 10^{7}\,\mathrm{m\,s^{-1}}$ [1]

**d** $v = \dfrac{BQr}{m}$, hence the speed $v$ is directly proportional to the radius $r$. [1]

Radius is halved, so: $v = \dfrac{1.76 \quad 10^{7}}{2} = 8.8 \quad 10^{6}\,\mathrm{m\,s^{-1}}$ [1]

**7** **a** $E_k = 15 \quad 10^{3} \quad 1.6 \quad 10^{-19} = 2.4 \quad 10^{-15}\,\mathrm{J}$ $(1\,\mathrm{eV} = 1.6 \quad 10^{-19}\,\mathrm{J})$ [1]

$\dfrac{1}{2}mv^2 = 2.4 \quad 10^{-15}$

$v = \sqrt{\dfrac{2 \quad 2.4 \quad 10^{-15}}{1.7 \quad 10^{-27}}}$ [1]; $v = 1.68 \quad 10^{6}\,\mathrm{m\,s^{-1}} \quad 1.7 \quad 10^{6}\,\mathrm{m\,s^{-1}}$ [1]

**b** $F = ma = \dfrac{mv^2}{2}$ [1]

$F = \dfrac{1.7 \quad 10^{-27} \quad (1.68 \quad 10^{6})^2}{0.05}$ [1]; $F = 9.60 \quad 10^{-14}\,\mathrm{N} \quad 9.6 \quad 10^{-14}\,\mathrm{N}$ [1]

**c** $F = BQv$ [1]

$B = \dfrac{F}{Qv} = \dfrac{9.60 \quad 10^{-14}}{1.6 \quad 10^{-19} \quad 1.68 \quad 10^{6}}$ [1]; $B \quad 0.36\,\mathrm{T}$ [1]

**d** Speed= $\dfrac{\text{distance}}{\text{time}}$

$\text{time} = \dfrac{\text{circumference}}{\text{speed}} = \dfrac{2 \quad 0.05}{1.68 \quad 10^{6}}$ [1]

$\text{time} = 1.87 \quad 10^{-7}\,\mathrm{s} \quad 1.9 \quad 10^{-7}\,\mathrm{s}$ [1]

**8** The centripetal force is provided by the magnetic force. [1]

Therefore: $Bev = \dfrac{mv^2}{r}$ [1]

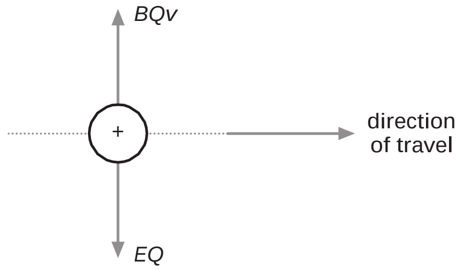
$Be = \dfrac{mv}{r}$ or $v = \dfrac{Ber}{m}$ [1]

$T = \dfrac{\text{circumference}}{\text{speed}} = \dfrac{2 \quad m}{(Ber/m)}$ [1]

The radius $r$ of the orbit cancels. Hence: $T = \dfrac{2 \quad r}{Be}$

The time $T$ is independent of both the radius of the orbit $r$ and the speed $v$. [1]

**9** In order to emerge from the slit, the net force perpendicular to the velocity must be zero. [1]




electrical force on ion = magnetic force on ion [1]

$EQ = BQv$ [1]

The charge $Q$ cancels.

$E = Bv$ [1]

The electric field strength is $E = \frac{V}{d}$. Therefore, the magnetic flux density is:

$B = \frac{E}{v} = \frac{(V/d)}{v} = \frac{(5.0 \quad 10^3/0.024)}{6.0 \quad 10^6}$ [1]

$B = 3.47 \quad 10^{-2}\,\mathrm{T} \quad 35\,\mathrm{mT}$ [1]

# Marking scheme

## *End-of-chapter test*

**1** **a** The force is at right-angles to the plane of the current-carrying wire and the field. From Fleming's left-hand rule, the force is out of the plane of the paper. [1]

**b** $F = BIl \sin \quad l = 1.0\,\text{cm} \quad I = 5.0\,\text{A} \quad = 60°$ [1]

$$B = \frac{F}{Il \sin} = \frac{2.0 \quad 10^{-3}}{5.0 \quad 0.01 \quad \sin 60°} \quad [1]$$

$B = 4.62 \quad 10^{-2}\,\text{T} \quad 4.6 \quad 10^{-2}\,\text{T}$ [1]

**2** **a** The force due to the magnetic field is at right-angles to the velocity. [1]

This force does no work in the direction of the velocity, hence there is no change in the kinetic energy of the particle. Its speed remains constant. [1]

**b** **i** $F = BQv$ [1]

$F = 50 \quad 10^{-3} \quad 3.2 \quad 10^{-19} \quad 4.0 \quad 10^{6}$ [1]

$F = 6.4 \quad 10^{-14}\,\text{N}$ [1]

**ii** $a = \frac{F}{m} = \frac{6.4 \quad 10^{-14}}{6.7 \quad 10^{-27}}$ [1]

$a = 9.55 \quad 10^{12}\,\text{m s}^{-2} \quad 9.6 \quad 10^{12}\,\text{m s}^{-2}$ [1]

**iii** From circular motion, the centripetal acceleration $a$ is given by:

$$a = \frac{v^2}{r}$$

$r = \frac{v^2}{a} = \frac{(4.0 \quad 10^{6})^2}{9.55 \quad 10^{12}}$ [1]; $r = 1.68\,\text{m} \quad 1.7\,\text{m}$ [1]

**3** **a** The centripetal force is provided by the magnetic force. [1]

Therefore: $Bev = \frac{mv^2}{r}$ [1]

$Be = \frac{mv}{r}$ or $r = \frac{mv}{Be}$ [1]

**b** $r = \frac{mv}{Be} = \frac{1.7 \quad 10^{-27} \quad 4.0 \quad 10^{5}}{0.060 \quad 1.6 \quad 10^{-19}}$ [1]

$r = 7.08 \quad 10^{-2}\,\text{m} \quad 7.1 \quad 10^{-2}\,\text{m}$ (7.1 cm) [1]

**c** From the equation $r = \frac{mv}{Be}$, we have: $r \propto \frac{v}{B}$ [1]

Since both $B$ and $v$ increase by the same factor of two, the ratio $\frac{v}{B}$ remains constant. Hence, the radius $r$ remains constant at 7.1 cm. [1]

**d** The speed of the proton is directly proportional to the radius ($v \propto r$). Since the radius is decreasing, this must mean the speed of the proton is also decreasing. [1]

(The proton is losing energy, either by radiating energy or through collisions.)