1 (a) Explain why a particle is accelerating even when it is moving with a uniform speed in a circular path.

___

___

___

(2)

(b) **Figure 1** shows a schematic diagram of a proton synchrotron. This is a device for accelerating protons to high speeds in a horizontal circular path.

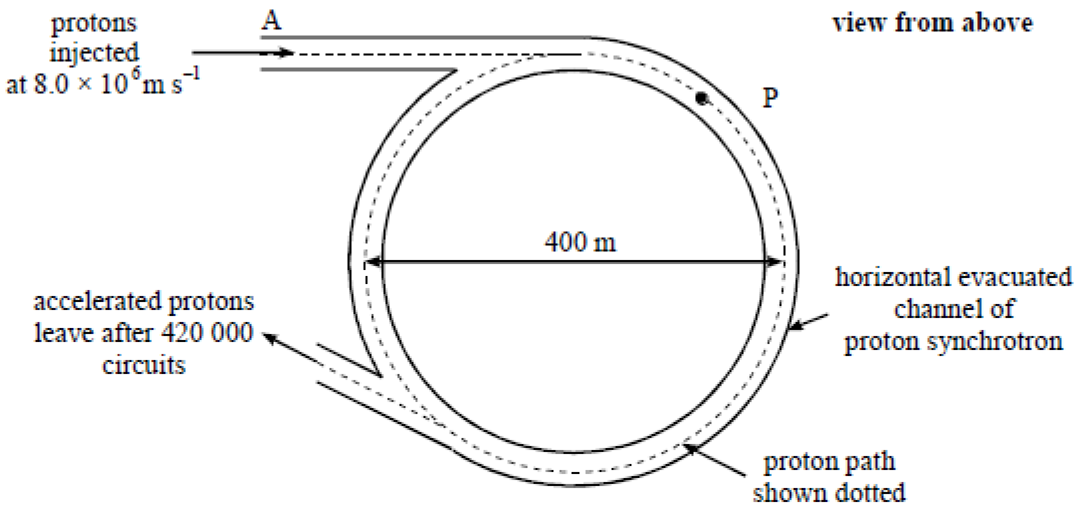


Figure 1

In the synchrotron the protons of mass 1.7×10^{-27} kg are injected at point **A** at a speed of 8.0×10^{6} m s^{-1}. The diameter of the path taken by the protons is 400 m.

(i) Show on **Figure 1** the direction of the force required to make a proton move in the circular path when the proton is at the position marked **P**.

(1)

(ii) Calculate the force that has to be provided to produce the circular path when the speed of a proton is 8.0×10^{6} m s^{-1}.

(2)

(iii) Sketch on **Figure 2** a graph to show how this force will have to change as the speed of the proton increases over the range shown on the *x*-axis. Insert an appropriate scale on the force axis.

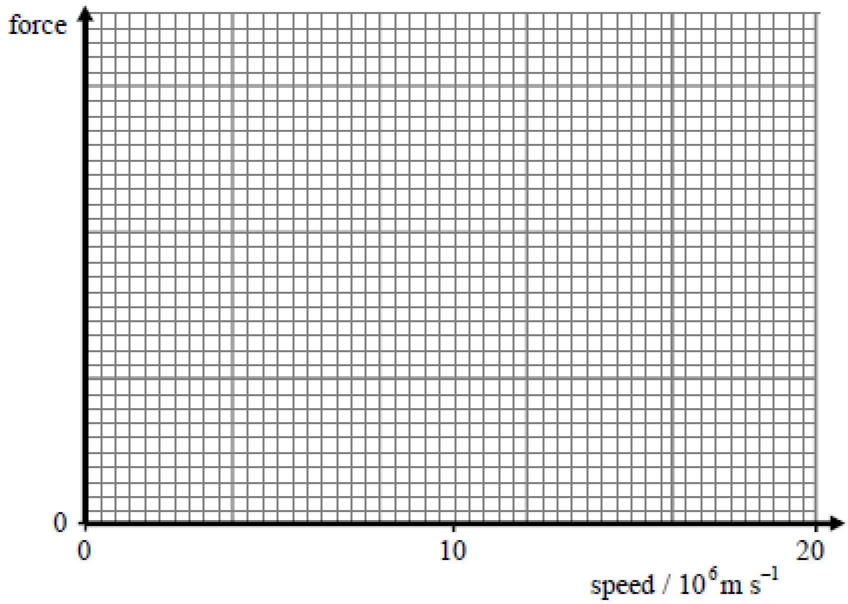


Figure 2

(c) Before reaching their final energy the protons in the synchrotron in part (b) travel around the accelerator 420 000 times in 2.0 s.

acceleration of free fall, g = 9.8 m s^{-2}

(i) Calculate the total distance travelled by a proton in the 2.0 s time interval.

(2)

(ii) Unless a vertical force is applied the protons wold fall as they move through the horizontal channel.

Calculate the distance a proton would fall in two seconds.

(2)

(iii) Determine the force necessary to prevent the vertical movement.

(1)

(Total 12 marks)

2 (a) State, in words, the two laws of electromagnetic induction.

Law 1 ____

____

____

____

Law 2 ____

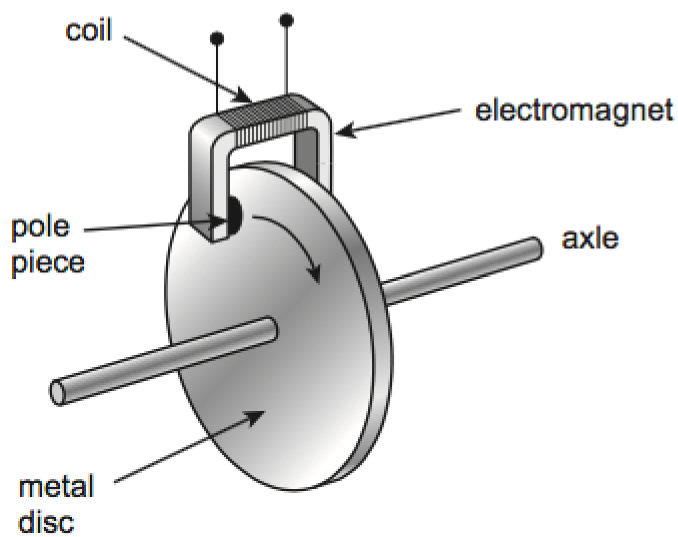
____

____

____

(3)

(b) The diagram below illustrates the main components of one type of electromagnetic braking system. A metal disc is attached to the rotating axle of a vehicle. An electromagnet is mounted with its pole pieces placed either side of the rotating disc, but not touching it. When the brakes are applied, a direct current is passed through the coil of the electromagnet and the disc slows down.



(i) Explain, using the laws of electromagnetic induction, how the device in the diagram acts as an electromagnetic brake.

(3)

(ii) A conventional braking system has friction pads that are brought into contact with a moving metal surface when the vehicle is to be slowed down.
State **one** advantage and **one** disadvantage of an electromagnetic brake compared to a conventional brake.

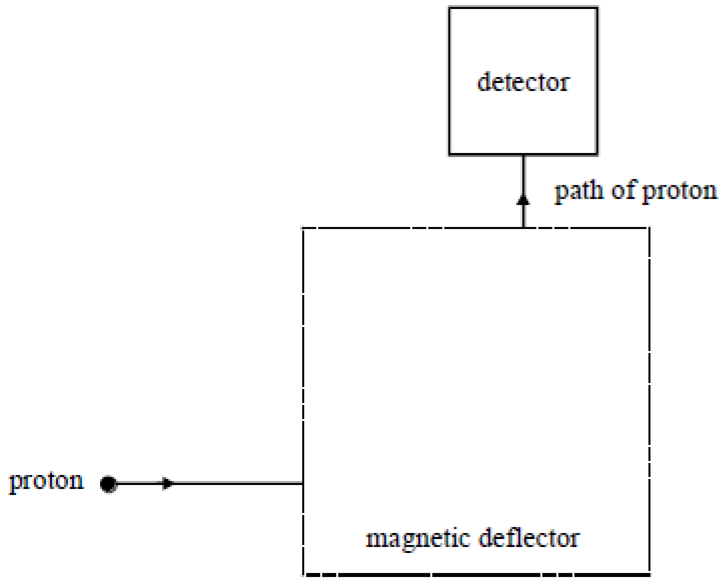
Advantage

Disadvantage

(2)
(Total 8 marks)

3 The diagram shows an arrangement in a vacuum to deflect protons into a detector using a magnetic field, which can be assumed to be uniform within the square shown and zero outside it.

The motion of the protons is in the plane of the paper.



(a) Sketch the path of a proton through the magnetic deflector. At any point on this path draw an arrow to represent the magnetic force on the proton. Label this arrow F.

(2)

(b) State the direction of the uniform magnetic field causing this motion.

___

(1)

(c) The speed of a proton as it enters the deflector is 5.0×10^6 m s^{-1}. If the flux density of the magnetic field is 0.50 T, calculate the magnitude of the magnetic force on the proton.

___

___

___

(2)

(d) If the path were that of an electron with the same velocity, what **two** changes would need to be made to the magnetic field for the electron to enter the detector along the same path?

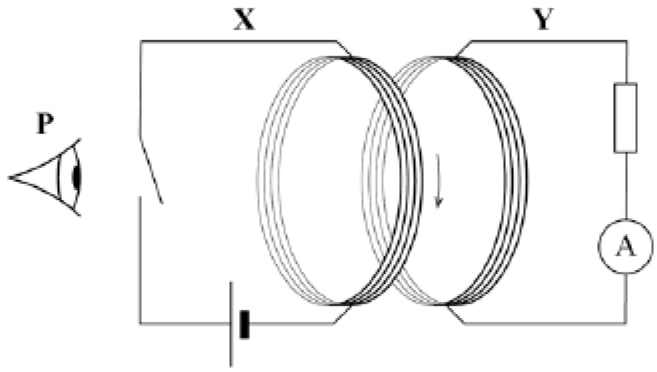
___

___

(2)
(Total 7 marks)

4 **Figure 1** shows an arrangement for investigating electromagnetic induction.

Figure 1



When the switch is closed there is a current in the coil in circuit **X**. The current is in a clockwise direction as viewed from position **P**.

Circuit **Y** is viewed from position **P**.

(a) Explain how Lenz's law predicts the direction of the induced current when the switch is opened and again when it is closed.

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(4)

An ‘Earth inductor’ consists of a 500 turn coil. **Figure 2** and **Figure 3** shows it set up to measure the horizontal component of the Earth’s magnetic field. When the coil is rotated an induced emf is produced.

Figure 2

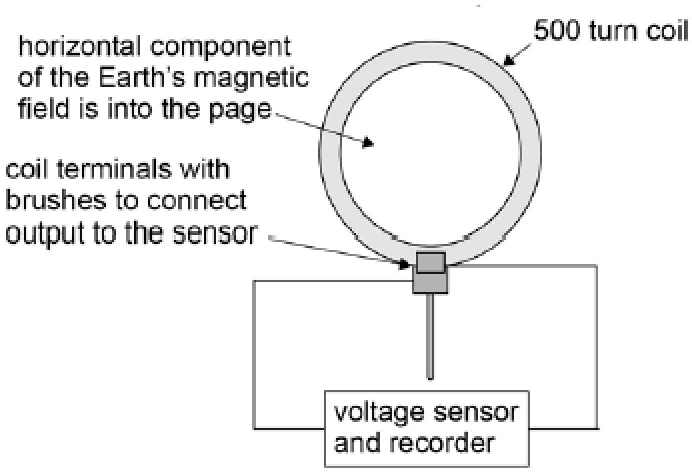
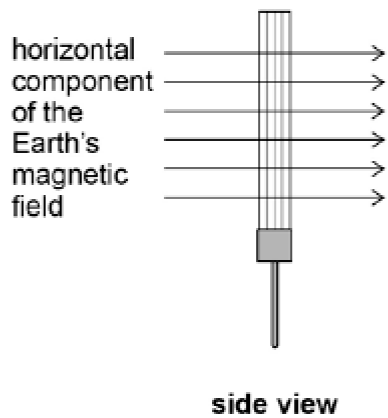
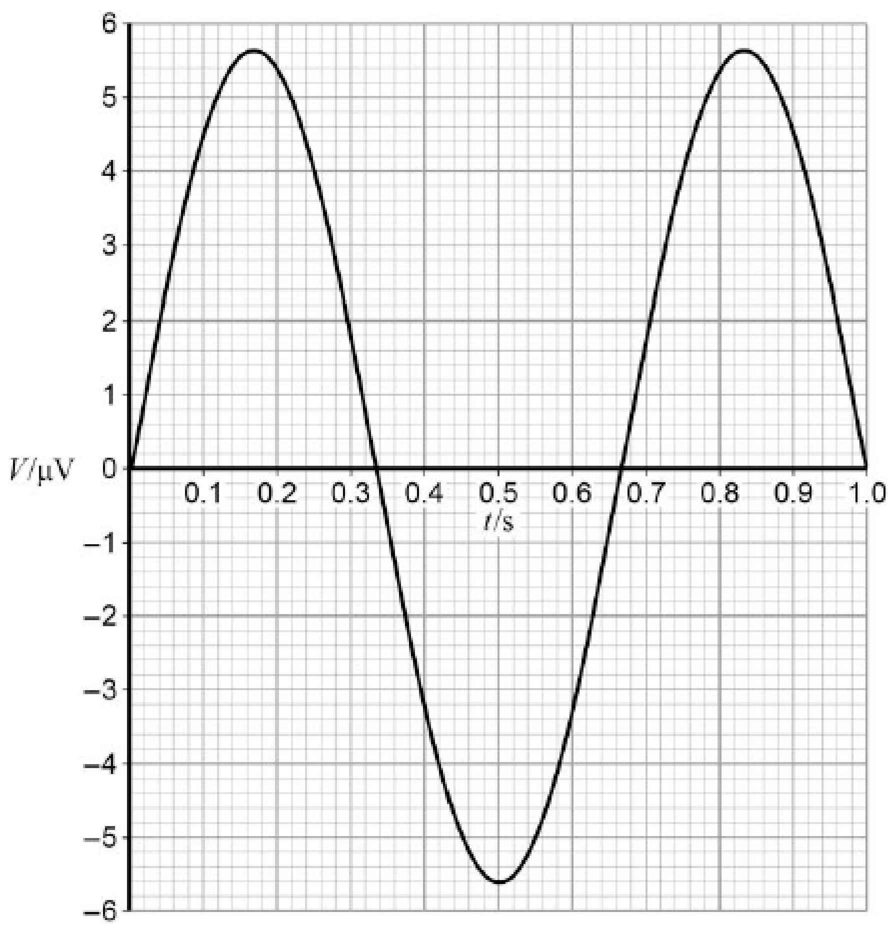


Figure 3



The mean diameter of the turns on the coil is 35 cm. **Figure 4** shows the output recorded for the variation of potential difference V with time t when the coil is rotated at 1.5 revolutions per second.

Figure 4



(b) Determine the flux density, B_H, of the horizontal component of the Earth's magnetic field.

horizontal component of flux density = ______________ T

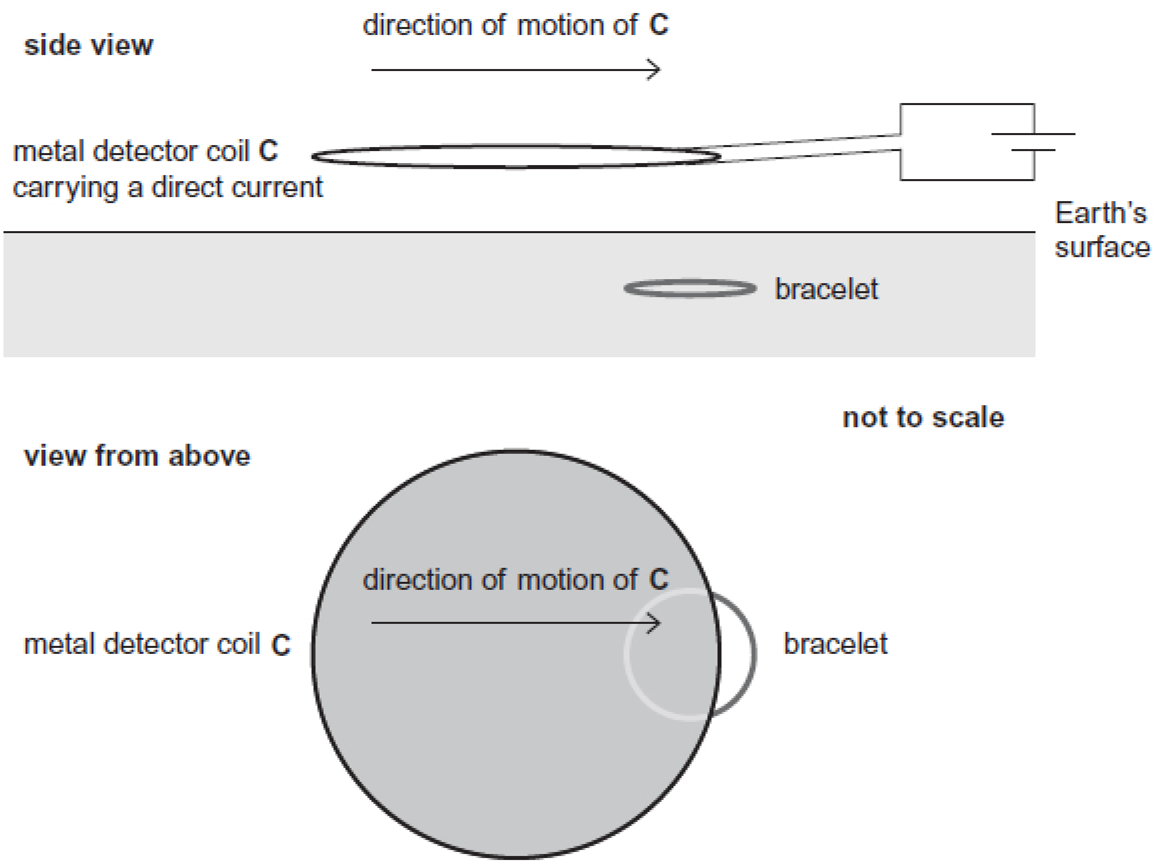
(3)

(Total 7 marks)

5 A metal detector is moved horizontally at a constant speed just above the Earth's surface to search for buried metal objects

Figure 1 shows the coil **C** of a metal detector moving over a circular bracelet made from a single band of metal. The planes of the coil and the bracelet are both horizontal.

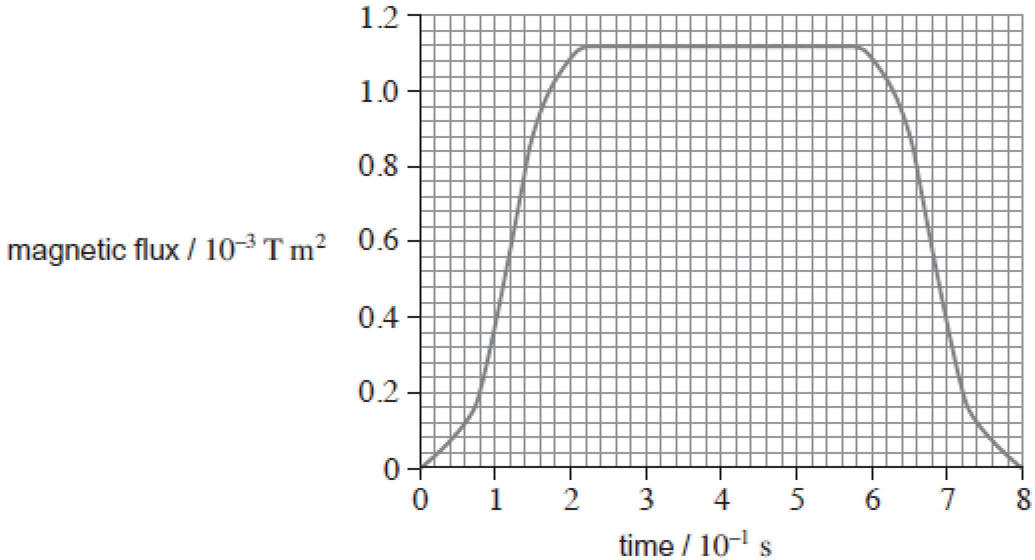
Figure 1



In this metal detector, **C** carries a direct current so that the magnetic flux produced by **C** does not vary. The bracelet is just below the surface, so the flux is perpendicular to the plane of the bracelet. The field is negligible outside the shaded region of **C**.

Figure 2 shows how the magnetic flux through the bracelet varies with time when **C** is moving at a constant velocity.

Figure 2



(a) (i) Sketch a graph on the grid to show how the emf induced in the bracelet varies with time as **C** moves across the bracelet. Use the same scale on the time axis as in **Figure 2**.

(3)

(ii) Use the laws of Faraday and Lenz to explain the shape of your graph.

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(4)

(b) The velocity at which **C** is moved is 0.28 m s^{-1}.

Show that the diameter of the bracelet is about 6 cm.

(1)

(c) Determine the magnetic flux density of the field produced by **C** at the position of the bracelet.

magnetic flux density ____________________ T

(2)

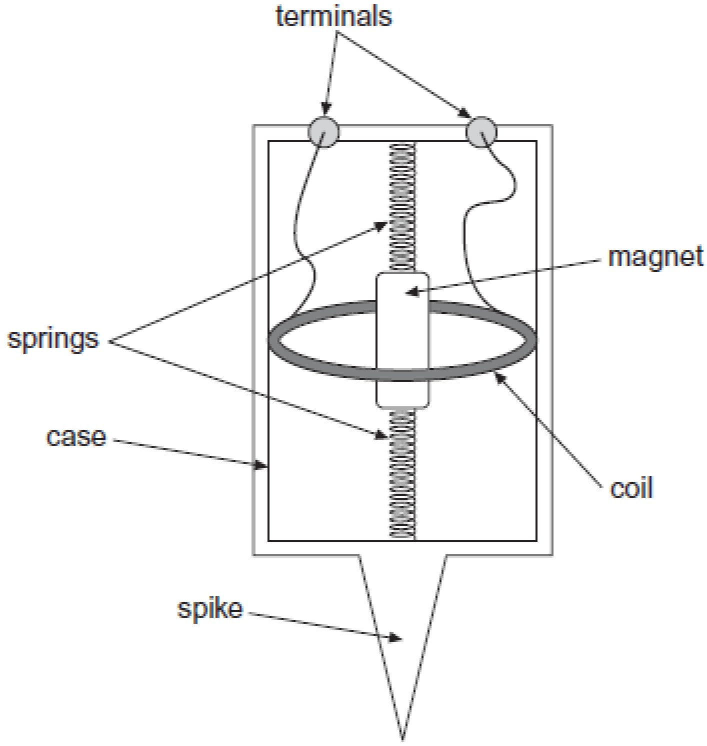
(d) Determine the maximum emf induced in the bracelet.

maximum emf ____________________ V

(3)

(Total 13 marks)

6 The diagram below shows the main parts of a geophone.



The spike attaches the geophone firmly to the ground. At the instant an earthquake occurs, the case and coil move upwards due to the Earth's movement. The magnet remains stationary due to its inertia. In 3.5 ms, the coil moves from a position where the flux density is 9.0 mT to a position where the flux density is 23.0 mT.

(a) The geophone coil has 250 turns and an area of 12 cm^2.

Calculate the average emf induced in the coil during the first 3.5 ms after the start of the earthquake.

emf ____________________ V

(3)

(b) Explain how the initial emf induced in the coil of the geophone would be affected:

if the stiffness of the springs were to be increased

____

____

if the number of turns on the coil were to be increased.

____

____

(2)

(c) (i) The geophone's magnet has a mass of 8.0×10^{-3} kg and the spring stiffness of the system is 2.6 N m^{-1}.

Show that the natural period of oscillation of the mass−spring system is approximately 0.35 s.

(2)

(ii) At the instant that the Earth stops moving after one earthquake, the emf in the coil is at its maximum value of +8 V. The magnet continues to oscillate.

On the grid below, sketch a graph showing the variation of emf with time as the magnet's oscillation decays.
Show at least **three** oscillations.

(3)

(Total 10 marks)

7 (a) (i) State **two** situations in which a charged particle will experience no magnetic force when placed in a magnetic field.

first situation____

____

____

____

second situation____

____

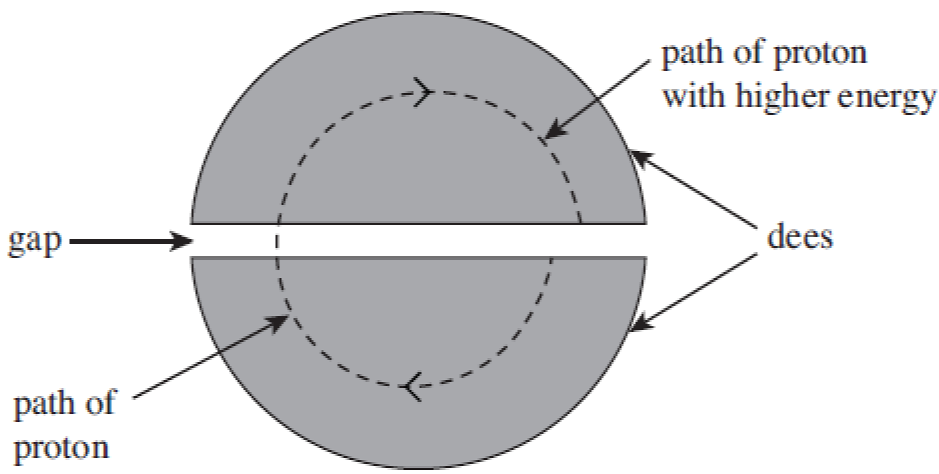
____

(2)

(ii) A charged particle moves in a circular path when travelling perpendicular to a uniform magnetic field. By considering the force acting on the charged particle, show that the radius of the path is proportional to the momentum of the particle.

(2)

(b) In a cyclotron designed to produce high energy protons, the protons pass repeatedly between two hollow D-shaped containers called ‘dees’. The protons are acted on by a uniform magnetic field over the whole area of the dees. Each proton therefore moves in a semi-circular path at constant speed when inside a dee. Every time a proton crosses the gap between the dees it is accelerated by an alternating electric field applied between the dees. The diagram below shows a plan view of this arrangement.



(i) State the direction in which the magnetic field should be applied in order for the protons to travel along the semicircular paths inside each of the dees as shown in the diagram above.

____

(1)

(ii) In a particular cyclotron the flux density of the uniform magnetic field is 0.48 T. Calculate the speed of a proton when the radius of its path inside the dee is 190 mm.

speed ____________________ ms^{-1}

(2)

(iii) Calculate the time taken for this proton to travel at constant speed in a semicircular path of radius 190 mm inside the dee.

time ____________________ s

(2)

(iv) As the protons gain energy, the radius of the path they follow increases steadily, as shown in the diagram above. Show that your answer to part (b)(iii) does not depend on the radius of the proton's path.

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(2)

(c) The protons leave the cyclotron when the radius of their path is equal to the outer radius of the dees. Calculate the maximum kinetic energy, in Me V, of the protons accelerated by the cyclotron if the outer radius of the dees is 470 mm.

maximum kinetic energy ____________________ Me V

(3)

(Total 14 marks)

8 The Large Hadron Collider (LHC) uses magnetic fields to confine fast-moving charged particles travelling repeatedly around a circular path. The LHC is installed in an underground circular tunnel of circumference 27 km.

(a) In the presence of a suitably directed uniform magnetic field, charged particles move at constant speed in a circular path of constant radius. By reference to the force acting on the particles, explain how this is achieved and why it happens.

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(4)

(b) (i) The charged particles travelling around the LHC may be protons. Calculate the centripetal force acting on a proton when travelling in a circular path of circumference 27 km at one-tenth of the speed of light. Ignore relativistic effects.

answer = ____________________ N

(3)

(ii) Calculate the flux density of the uniform magnetic field that would be required to produce this force. State an appropriate unit.

answer = ____________________ unit __________

(3)

(c) The speed of the protons gradually increases as their energy is increased by the LHC. State and explain how the magnetic field in the LHC must change as the speed of the protons is increased.

___

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___

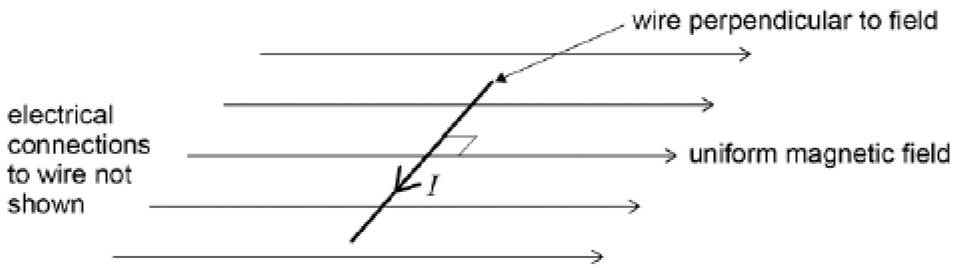
___

___

(2)

(Total 12 marks)

9 A horizontal straight wire of length 0.30 m carries a current of 2.0 A perpendicular to a horizontal uniform magnetic field of flux density 5.0×10^{-2} T. The wire 'floats' in equilibrium in the field.



What is the mass of the wire?

A 8.0×10^{-4} kg

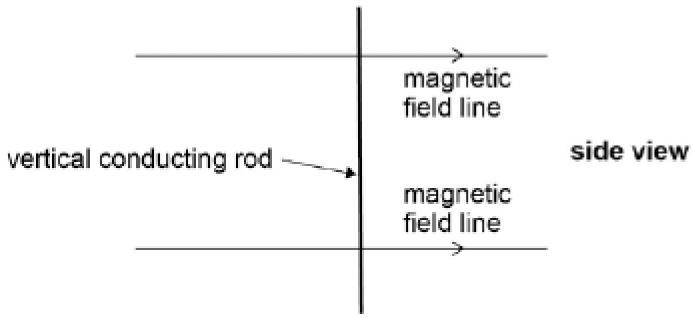
B 3.1×10^{-3} kg

C 3.0×10^{-2} kg

D 8.2×10^{-1} kg

(Total 1 mark)

10 A vertical conducting rod of length l is moved at a constant velocity v through a uniform horizontal magnetic field of flux density B.



Which of the rows gives a correct expression for the induced emf between the ends of the rod for the stated direction of the motion of the rod?

	Direction of motion	Induced emf	
A	Vertical	$\frac{B}{lv}$	⬭
B	Horizontal at right angles to the field	Blv	⬭
C	Vertical	Blv	⬭
D	Horizontal at right angles to the field	$\frac{B}{lv}$	⬭

(Total 1 mark)

11 Charged particles, each of mass m and charge Q, travel at a constant speed in a circle of radius r in a uniform magnetic field of flux density B.
Which expression gives the frequency of rotation of a particle in the beam?

A $\frac{BQ}{2\pi m}$ ⬭

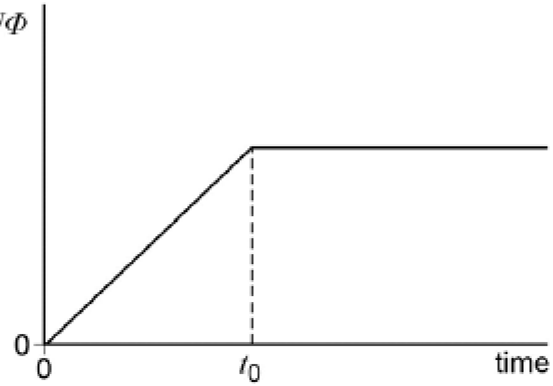
B $\frac{BQ}{m}$ ⬭

C $\frac{BQ}{\pi m}$ ⬭

D $\frac{2\pi BQ}{m}$ ⬭

(Total 1 mark)

12 The graph shows how the flux linkage, $N\Phi$, through a coil changes when the coil is moved into a magnetic field.



The emf induced in the coil

A decreases then becomes zero after time t_0.

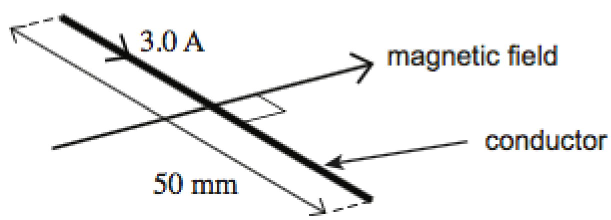
B increases then becomes constant after time t_0.

C is constant then becomes zero after time t_0.

D is zero then increases after time t_0.

(Total 1 mark)

13 The diagram shows a horizontal conductor of length 50 mm carrying a current of 3.0 A at right angles to a uniform horizontal magnetic field of flux density 0.50 T.

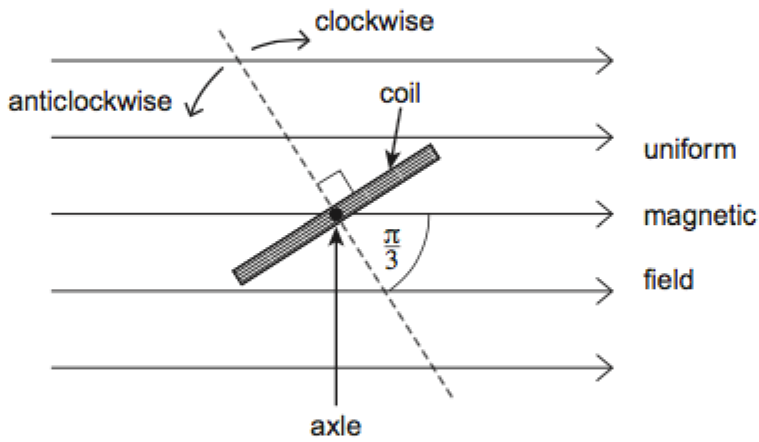


What is the magnitude and direction of the magnetic force on the conductor ?

A 0.075 N vertically upwards
B 0.075 N vertically downwards
C 75 N vertically upwards
D 75 N vertically downwards

(Total 1 mark)

14 The diagram shows a coil placed in a uniform magnetic field. In the position shown, the angle between the normal to the plane of the coil and the magnetic field is $\frac{\pi}{3}$ is rad.



Which line, **A** to **D**, in the table shows the angles through which the coil should be rotated, and the direction of rotation, so that the flux linkage becomes (i) a maximum, and (ii) a minimum?

Angle of rotation / rad		
	(i) for maximum flux linkage	**(ii) for minimum flux linkage**
A	$\frac{\pi}{6}$ clockwise	$\frac{\pi}{3}$ anticlockwise
B	$\frac{\pi}{6}$ anticlockwise	$\frac{\pi}{3}$ clockwise
C	$\frac{\pi}{3}$ clockwise	$\frac{\pi}{6}$ anticlockwise
D	$\frac{\pi}{3}$ anticlockwise	$\frac{\pi}{6}$ clockwise

(Total 1 mark)

15 A train is travelling at 20 m s^{-1} along a horizontal track through a uniform magnetic field of flux density 4.0×10^{-5} T acting vertically downwards.

What is the emf induced between the ends of an axle 1.5 m long?

A 3.0×10^{-6} V

B 5.3×10^{-4} V

C 1.2×10^{-3} V

D 7.5×10^{5} V

(Total 1 mark)

Mark schemes

1 (a) acceleration is (rate of) change of velocity
or velocity is a vector
or velocity has magnitude and direction

B1

velocity is changing since direction is changing
(must be clear that it is the velocity that is changing direction)

B1

allow 1 mark for 'it would move in a straight line at constant speed if it were not accelerating'
do not allow 'because there is a force acting'
'because direction is changing'

(2)

(b) (i) arrow toward centre of circle at **P**

B1

(1)

(ii) $F = mv^2 / r$ **or** $mr\omega^2$

or numerical equivalent (r must be 200 m)

C1

5.4×10^{-16} N

A1

(2)

(iii) graph showing correct curvature with F plotted correctly (e.c.f. for F)

(should be between 5×10^{-14} and 6×10^{-16} N

B1

double v, quadruple F
(should be possible to do these tasks to ±½ a square)

B1

(2)

(c) (i) circumference = 1256 m or $2\pi r \times 420\,000$

(allow e.c.f. for incorrect r from (b)(ii))

C1

distance travelled = 5.3×10^8 m

A1

(2)

(ii) $s = ½ gt^2$ **or** $ut + ½at^2$

C1

19.6m (20m)

A1

(2)

(iii) $mg = 1.7\ (1.67) \times 10^{-26}$ N

B1

(1)

[12]

2 (a) *(Faraday's law)*

(induced) emf ∝ rate of change of flux (linkage) ✓

(Lenz's law)

<u>direction of</u> induced emf (or current) ✓

is such as to oppose the change (in flux) producing it ✓

In either order.

Allow "(induced) emf = rate of change of flux linkage".

Ignore incorrect reference to names of laws.

3

(b) (i) current in coil produces magnetic field or flux (that passes through disc) ✓

rotating disc cuts flux inducing / producing emf **or** current (in disc) ✓

induced (eddy) currents (in disc) interact with magnetic field ✓

force on (eddy) currents slows (or opposes) rotation (of disc) ✓

Alternative *for last two points:*

(eddy) currents in disc cause heating of disc ✓

energy for heating comes from ke of disc or vehicle (which is slowed) ✓

max 3

(ii) *Advantage*: any one ✓

- no material (eg pads or discs or drums) to wear out
- no pads needing replacement
- no additional (or fewer) moving parts

Disadvantage: any one ✓

- ineffective at low speed **or** when stationary
- dependent on vehicle's electrical system remaining in working order
- requires an electrical circuit (or source of electrical energy) to operate whereas pads do not

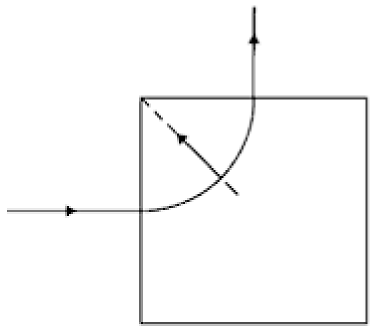
Answers must refer to advantages and disadvantages of the <u>electromagnetic</u> brake.

Only accept points from these lists.

2

[8]

3 (a)



(uniformly) curved path continuous with linear paths at entry and exit points **(1)**
arrow marked F towards top left-hand corner **(1)**

2

(b) into (the plane of) the diagram **(1)** (not accept "downwards")

1

(c) $F(= BQv) = 0.50 \times 1.60 \times 10^{-19} \times 5.0 \times 10^{6}$ **(1)**
$= 4.0 \times 10^{-13}$ N **(1)**

2

(d) B must be in opposite direction **(1)**

(much) smaller magnitude $\left(\approx \frac{1}{2000}\right)$ **(1)**

2

[7]

4 (a) Induced current such as to opposes the change producing it✓

Switch on current increases the flux through Y✓

Current opposite direction / anticlockwise to create opposing flux✓

Switch off flux thorough Y due to X decreases so current travels clockwise to create flux to oppose the decrease✓

one marks for Lenz's law statement

two for explaining what happens at switch on ***OR*** *switch off adequately*

one for completing the argument for switch on and off adequately

4

(b) Determines correctly in the calculation two of V_{pk}(5.6±1 μV) , A (0.096 m^2) and ω(9.4 rad s^{-1})β✓

Substitutes all three in $v = BAn\omega$ ignoring powers of 10 and calculation errors for A and / or ω provided they have been attempted with working shown✓

B_H = 12.4 nT✓

Allow 2 or 3 sf

3

[7]

5 (a) (i) graph showing two pulses one at start and the other at the end with no emf between the pulses

Positive and negative pulses shown

Similar shaped 'curved' pulses : negative between 0 and 0.22 ± 0.02 s and positive pulse 0.58 ± 0.02 and 0.8

3

(ii) emf induced when the flux is changing or induced emf depends on the rate of change of flux

emf induced when flux changes between 0 and 0.2(2) s and / or between 0.6(0.58)s and 0.8 s
OR
no change in flux between 0.2 and 0.6 so no induced emf

Induced emf / current produces a field to oppose the change producing it.

Flux linking bracelet increases as the bracelet enters the field produced by C and decreases as it leaves so opposite emfs

4

(b) (Takes 0.21 s or 0.22 s for flux to change from 0 to maximum so)
diameter = 0.28 × 0.21 = 0.059 (0.588) (m)
or 0.28 × 0.22 = 0.062 (0.616) (m)

must be to at least 2sf

1

(c) Area of bracelet = 3.14 × 0.031^2

B = 1120 × 10^{-6} / (3.14 × 0.031^2) = 0.38 (T)
B = 0.40 T if 3 cm used for radius

Condone incorrect power of 10

Allow answers in range 0.38T to 0.41 T (depends on value used for r)

2

(d) Use of steepest gradient of graph or tangent drawn on Figure 2
Correct data from tangent or points on the steepest part of the graph
10 to 11 mV

3

[13]

6 (a) emf = Δ*(BAN) / t*
Change in flux = *A* × Δ*B* or 12 × (23 − 9) seen

C1

Substitution ignoring powers of 10

C1

1.2 V

A1

3

(b) Reduced

M0

Magnet will move (with the case)

A1

Increased

M0

Flux <u>linkage increases</u> or emf is proportional to *N*

A1

2

(c) (i) Formula used

$2\pi\sqrt{\frac{8\times10^{-3}}{2.6}}$ seen

B1

0.348 / 0.349 seen to at least 3 sf

B1

2

(ii) Period consistent at 0.35 s or V_o = 8 V

B1

Shape shows decreasing amplitude

M1

At least 3 cycles starting at 8 V

A1

3

[10]

7 (a) (i) *Two examples (any order)*:

- when charged particle is at rest **or** not moving relative to field ✓
- when charged particle moves parallel to magnetic field ✓

2

(ii) $BQv = \frac{mv^2}{r}$ ✓ (gives $BQr = mv$)

Acceptable answers must include correct force equation (1st point).

B and *Q* are constant so *r* ∝ momentum (mv) ✓

Insist on a reference to B and Q constant for 2nd mark.

2

(b) (i) upwards (perpendicular to plane of diagram) ✓

Accept "out of the page" etc.

1

(ii) $v\left(=\frac{BQr}{m}\right) = \frac{0.48 \times 1.60 \times 10^{-19} \times 0.19}{1.67 \times 10^{-27}}$ ✓ $= 8.7(4) \times 10^6$ (m s^{-1})

2

(iii) length of path followed (= length of semi-circle) = πr ✓

time taken $t\left(=\frac{\pi r}{v}\right) = \frac{\pi \times 0.19}{8.74 \times 10^6} = 6.8(3) \times 10^{-8}$ (s) ✓

Allow ECF from incorrect v from (b)(ii).

[**or** $\frac{v}{r} = \frac{BQ}{m}$ gives $t = \frac{\pi r}{v} = \frac{\pi m}{BQ}$ ✓

$= \frac{\pi \times 1.67 \times 10^{-27}}{0.48 \times 1.60 \times 10^{-19}} = 6.8(3) \times 10^{-8}$ (s) ✓]

Max 1 if path length is taken to be 2πr (gives 1.37 × 10^{-7}s).

2

(iv) $v \propto r$ (and path length $\propto r$) ✓

t = (path length / v) **or** (πr / v)

so r cancels (∴time doesn't depend on r) ✓

[**or** $t\left(=\frac{\pi r}{v}\right)=\frac{\pi rm}{BQr}$ ✓ $=\frac{\pi m}{BQ}$ (because r cancels) ✓]

[**or** $BQv = m\omega^2 r$ gives $BQ\omega r = m\omega^2 r$ and $BQ = m\omega = 2\pi fm$ ✓

∴ frequency is independent of r ✓]

2

(c) $v_{max} = 8.74\times10^6 \times\left(\frac{0.47}{0.19}\right) = 2.16\times10^7$ (m s^{-1}) ✓

1st mark can be achieved by full substitution, as in (b)(ii), or by use of data from (b)(i) and / or (b)(ii).

E_k (= ½ $mv_{max}{}^2$) = ½ × 1.67 × 10^{-27} × (2.16 × 10^7)^2 ✓

. (= 3.90 × 10^{-13} J)

$= \frac{3.90\times10^{-13}}{1.60\times10^{-13}} = 2.4(4)$ (Me V) ✓

Allow ECF from incorrect v from (b)(ii), or from incorrect t from (b)(iii).

3

(Total 14 marks)

8 (a) (magnetic) field is applied perpendicular to path

or direction **or** velocity of charged particles ✓

(magnetic) force acts perpendicular to path

or direction **or** velocity of charged particles ✓

force depends on speed of particle **or** on B [or $F \propto v$ or $F = BQv$ explained] ✓

force provides (centripetal) acceleration towards centre of circle

[**or** (magnetic) force is a centripetal force] ✓

$BQv = \frac{mv^2}{r}$ **or** $r = \frac{mv}{BQ}$ shows that r is constant when B and v are constant ✓

4

(b) (i) radius r of path = $\frac{\text{circumference}}{2\pi} = \frac{27 \times 10^3}{2\pi}$ = 4.30 × 10^3 (m)

(allow 4.3km) ✓

centripetal force $\left(= \frac{mv^2}{r}\right) = \frac{1.67 \times 10^{-27} \times (3.00 \times 10^7)^2}{4.30 \times 10^3}$ ✓ = 3.50 × 10^{-16}(N) ✓

3

(ii) magnetic flux density $B \left(= \frac{F}{Qv}\right) = \frac{3.50 \times 10^{-16}}{1.60 \times 10^{-19} \times 3.00 \times 10^7}$ ✓

= 7.29 × 10^{-5} ✓ T ✓

3

(c) magnetic field must be increased ✓

to increase (centripetal) force **or** in order to keep r constant ✓

[**or** otherwise protons would attempt to travel in a path of larger radius]

[**or**, referring to $r = \frac{mv}{BQ}$, B must increase when v increases to keep r constant]

2

[12]

9 B

[1]

10 B

[1]

11 A

[1]

12 C

[1]

13 **A**

[1]

14 **D**

[1]

15 **C**

[1]

Examiner reports

1

(a) A number of candidates referred to the fact that there was a force and therefore acceleration but ignored the reference to uniform speed. Candidates were expected to refer to change in direction resulting in a change in velocity, owing to its vector nature, and to state the link between change in velocity and acceleration.

(b) (i) Most candidates completed this successfully.

(ii) The majority of candidates did this part correctly but some used the given diameter as the radius. Many who started with $mr\omega^2$ had difficulty determining ω.

(iii) Many candidates drew careful graphs, plotting the data from (ii) correctly and using a scale that covered the whole range. The quadrupling of force for a doubling of the velocity was also very clear in the best graphs. There were, however, many candidates whose skills in graphical communication left much to be desired. There were many instances where, for example, the value from (ii), 5.4×10^{-16} N, was plotted on the 20 mm grid line. These candidates rarely showed other values correctly.

(c) (i) Most candidates were able to complete this successfully but there were a significant number who used πr^2 as the circumference.

(ii) Most appreciated the need to use $s = ut + ½ at^2$ and the majority obtained the correct answer. There were a significant proportion of candidates who did not distinguish between horizontal and vertical motion and used 8×10^6 m s^{-1} for u. This led to a silly answer for distance fallen in 2 s that usually passed without comment.

(iii) Most completed this part successfully. Some candidates simply stated ‘gravitation’ instead of a value. A few gave 9.8 N as the answer.

2 Examiners were looking for precise statements of Faraday's and Lenz's laws, in the most general forms, in part (a). In Faraday's law, for instance, the induced emf is *proportional* to the rate of change of flux, but is *equal* to the rate of change of flux linkage. In statements of Lenz's law it was necessary to refer to the *direction* of the induced emf (or current), and to the *change* producing it, for full credit.

In some cases the operation of the electromagnetic brake in part (b)(i) was well understood, but in most cases it was not. Common errors were to consider the metal disc as a permanent magnet that would induce a current in the coil, or to suggest that the pole pieces would clamp onto the disc in the manner of brake pads, or to consider the current in the coil as an alternating one. Many answers just gained the first mark by understanding that the current in the coil would create a magnetic field across the disc. Recognition of the flux cutting by the rotating disc that would give an emf and current in the disc was much rarer, or less explicit. The exact cause of the force on the disc – the force on the disc's induced currents in the field of the electromagnet – was seldom identified. Attempts to apply Lenz's law were usually much too vague to deserve credit. The retardation of the disc can also be explained by an argument based on energy: the currents in the disc cause heating, dissipating the kinetic energy of the disc and vehicle, but this approach only appeared in the most exceptional examples.

In part (b)(ii) the clear principal advantage of an electromagnetic brake over the conventional friction brake is that it does not contain parts such as disc pads that wear out, needing replacement. Most students were able to make reference to this, however obscurely. Its clear disadvantage, that the electromagnetic brake becomes less effective as the speed drops, was hardly mentioned at all, but many were able to spot that it relies on an electrical circuit that is functioning.

3 Apart from the very occasional script in which the candidate showed the proton to be banging around inside the 'box' like a gas molecule, the path of the proton was well recognised in part (a). The majority of candidates made an acceptable attempt at a freehand circular arc to join the entry and exit points. The direction of the magnetic force caused greater difficulty for some candidates, with arrows shown in all kinds of directions instead of towards the top left-hand corner. An arrow tangential to the path was a common wrong response.

Parts (b) and (c) were generally done well, but the charge of the proton was not always extracted correctly from the *Data booklet* as e. A value of +1 (or 9.58×10^7 which is e / m_p) was frequently encountered.

Reversal of the direction of B was usually correct as the answer for one of the marks in part (d), but many fewer candidates were able to understand that the less massive electron would require a field of much smaller magnitude in order to follow the same path as the proton. As has happened often in the past, weaker candidates tended to give incomplete responses such as "change" the field direction and "alter" the strength of the field; these answers gained no marks.

5 (a) (i) A difficult question for most students who did not realise the emf pulses occur as the bracelet enters and leaves the magnetic flux of the coil.

(ii) Since most of the graphs for (a)(i) were incorrect it was difficult or impossible to explain the shape correctly. However, marks were awarded for correct statements of the Faraday and Lenz laws.

(b) Few students knew how to tackle this one marker. Many incorrect times were chosen.

(c) Some did not read the graph scale correctly, others used $area = \pi d^2$ and there were many power of 10 errors. A final answer of 0.4 T (1 sf) was penalised.

(d) The vast majority of answers incorrectly used the average emf for the first 0.22 s, instead of using the gradient of the steepest part of the graph to find the maximum emf.

6 (a) Many candidates omitted the area in the formula, and there was some confusion over powers of 10.

(b) Very few candidates were able to give a satisfactory reason for the reduced emf when the spring stiffness increased. Of those who mentioned the magnet, most stated that it would move less, seemingly unaware that previously it did not move at all.

(c) (i) Well done by most.

(ii) Apart from some poor scripts where no scale was attempted, most answers gained at least 2 marks. The commonest errors were to start the graph at 0 instead of 8V and to draw fewer than 3 cycles.

7 The two situations expected to be given in part (a)(i) were when the charge is at rest, or when it is *moving* parallel to the direction of the magnetic field. These answers were given by a high proportion of the candidates. Inexact expressions such as “when the charge is *placed* parallel to the field” were viewed with suspicion and went unrewarded. Also unsuccessful were attempts such as “when it is not moving perpendicular to the field” and “when it does not cut any flux lines”. Some candidates thought they could answer by subjecting the moving charge to an electric field over the same region (as in an ion velocity selector) so that there would be no resultant force on the charge. This was not acceptable because the magnetic force would still be acting.

In part (a)(ii) most candidates gained the first mark by quoting $BQv = mv^2 / r$. Cancelling one v then gives mv = BQr. However, to show that $mv \propto$ r it is necessary to point out that B and Q must be constant. The large number of answers which failed to do this did not receive the second mark.

Examiners were surprised by the large number of incorrect answers to part (b)(i), on a topic that has usually been well understood. Perhaps this was because the question is set in the context of a device being used to accelerate protons (rather than electrons). Consequently many candidates could not see that the magnetic field has to act upwards, out of the plane of the diagram.

Errors in part (b)(ii) included using the wrong mass and/or charge for a proton, but the majority of answers were correct. The frequent slip of using $2\pi r$ instead of πr for the path length incurred a one mark penalty in part (b)(iii); many candidates got around this problem by dividing their answer for time by 2. Part (b)(iv) was often rewarding, but it also defeated many candidates. The expected approaches included using algebraic equations for the time, or an argument based on the proportionality of the speed and radius. Less precise attempts, such as “gwhen the speed increases the radius increases so the time is the same’ were not credited. A few candidates repeated the calculation in part (b)(iii) for a different radius to show that the time was unaltered. In part (c) the candidates who thought that the protons would still be travelling at the speed they had calculated in part (b)(ii) were under a serious misapprehension and gained no marks. Surprisingly few used $v \propto r$ to find the new velocity, most preferring to repeat their earlier calculation in full but using r = 0.47m. The conversion of the kinetic energy unit from J to MeV . which is an AS topic . defeated many.

8 It was rare for all four marks to be awarded in part (a). The essence of this question was well understood, but poor use of English and an inability to write logically limited the mark that could be given. An alarming proportion of answers made no reference at all to the magnetic field; these students appeared to be answering a more general question about circular motion. Many of the students evidently thought that the purpose of the magnetic force (presumably acting outwards) was to balance the centripetal force, rather than to *provide* it. Relatively few correct solutions were seen that used $r = mv / BQ$ to show that r is constant when B and v are constant.

The common error in part (b)(i) was failure to deduce the radius of the path of the protons from the 27 km circumference of the LHC. This only meant the loss of one of the three marks, however, provided the principles of the rest of the calculation were correct. Careless arithmetic such as failure to square v, and/or forgetting to convert km to m, was also a frequent source of loss of marks. $F = BQv$ was usually applied successfully in part (b)(ii), where the unit of magnetic flux density was quite well known. Almost inevitably, there was some confusion between *flux density* and *magnetic flux.*

The fact that had to be appreciated in part (c) was that in the LHC the radius of the path of the charged particles must remain constant as they are accelerated. A large proportion of students thought that it was necessary to maintain a constant centripetal force for this to happen, whereas it ought to have been clear to them that F must increase as v increases if r is to be constant.

13 This question, concerning the magnitude and direction of the force acting on a current-carrying wire in a uniform magnetic field, was the easiest question (facility 88%). Evidently the application of $F = B I l$ together with Fleming's left hand rule caused few problems.

14 This question required students to decide through what angle (in rad), and in which direction, a coil should be rotated in order to achieve maximum and minimum values of flux linkage. 66% of them were successful. Distractor A, which was almost the exact opposite of the correct answer, was the most popular incorrect response.

15 A straightforward calculation of the emf induced in a moving straight conductor (using $\varepsilon = B l v$) was all that was needed. 68% of the students did this correctly. One in five of them selected distractor B, which could follow from an incorrect formula or substitution ($\varepsilon = B v / l$).