## Question 4

**10 points total** | **Distribution of points**

(a) 2 points

The top plate is negative.

For relating the direction of force or acceleration to the direction of the field — 1 point

For relating the direction of the electric field to the sign of the charge on the top plate — 1 point

No points are awarded for identifying that the top plate is negative with no attempt to explain why.

(b) 4 points

For using an appropriate kinematic relation to determine the acceleration of the electron while it is between the plates — 1 point

$a = (v_f - v_i)/t$

For using Newton's second law to determine an expression for the magnitude of the force needed to give the electron the calculated acceleration — 1 point

$F = ma = m(v_f - v_i)/t$

For setting $eE$ equal to the force calculated from Newton's second law — 1 point

For correctly manipulating equations to solve for the magnitude of the electric field and arriving at a correct numerical answer with units — 1 point

$E = m(v_f - v_i)/et$

$$E = \frac{(9.11 \times 10^{-31}\ \text{kg})(8.02 \times 10^{6}\ \text{m/s} - 5.40 \times 10^{6}\ \text{m/s})}{(1.6 \times 10^{-19}\ \text{C})(1.49 \times 10^{-9}\text{s})} = 10{,}000\ \text{N/C}$$

*Alternate Solution* — *Alternate Points*

*For applying conservation of energy for the time the electron is between the plates* — *1 point*

$\Delta K = \Delta U$

*For using the correct relationship between potential energy and potential difference* — *1 point*

$\Delta U = e\,\Delta V$

$$\frac{1}{2}m_e\left(v_f^2 - v_i^2\right) = e\,\Delta V$$

*For using the relation between potential difference, electric field, and plate separation* — *1 point*

$\Delta V = Ed$

$$\frac{1}{2}m_e\left(v_f^2 - v_i^2\right) = e\,Ed$$

*For correctly manipulating equations to solve for the magnitude of the electric field and arriving at a correct numerical answer with units* — *1 point*

$E = m_e\left(v_f^2 - v_i^2\right)/2ed$

$$E = \frac{(9.11 \times 10^{-31})\left((8.02 \times 10^{6}\ \text{m/s})^2 - (5.40 \times 10^{6}\ \text{m/s})^2\right)}{2(1.6 \times 10^{-19}\ \text{C})(0.010\ \text{m})} = 10{,}000\ \text{N/C}$$

**Question 4 (continued)**

**Distribution of points**

(c) 1 point

$E = Q/\varepsilon_0 A$

$Q = \varepsilon_0 AE$

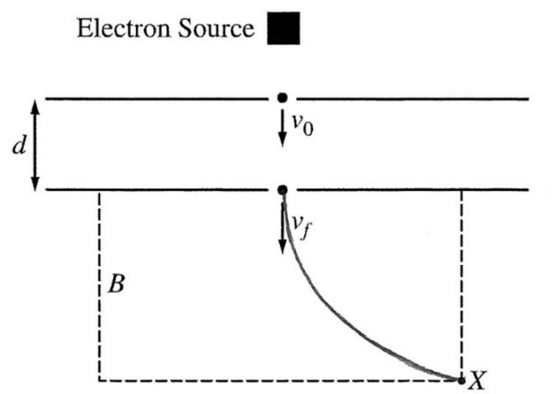
For correct substitution of values into the equation to calculate the magnitude of charge on each parallel plate — 1 point

$Q = \left(8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2\right)\left(0.25\ \text{m}^2\right)(10{,}000\ \text{N/C})$

$Q = 2.2 \times 10^{-8}\ \text{C}$

(d)

i. 2 points




Note: Figure not drawn to scale.

For drawing a reasonably circular path from the point where the electrons leave the bottom plate to point $X$ — 1 point

Note: There is no penalty for starting the path at the tip of the arrow.

For explaining that the field is always perpendicular to the velocity, so the force is also always perpendicular to the velocity which creates a curved (circular) path — 1 point

ii. 1 point

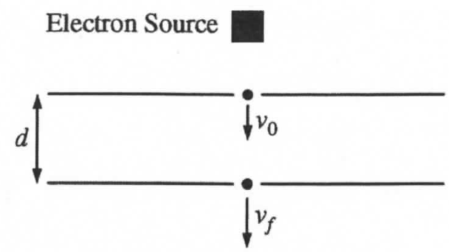
In order for the electron to reach point $X$, the magnetic field must exert a centripetal force on the electron toward the top right corner of the dashed box.

For using the right hand rule and reasoning that the force on a negatively charged object is in the opposite direction from the force exerted on a positively charged object (or using the "left hand rule") to conclude that the direction of the magnetic field is directed out of the page — 1 point

Notes:

No points are awarded for identifying that the direction of the magnetic field is out of the page without explaining why.

Credit can be earned for a correct analysis at any individual point on the path.




Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010\ \text{m}$. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6\ \text{m/s}$, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\ \text{m/s}$.

(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

The top plate is negatively charged. The electrons increase their speed, so their acceleration is downward. This means by F = ma, the ~~force~~ electric force points downward. Since these are electrons, the force is in the opposite direction of the field lines, which thus point up. Field lines point towards the negative plate, which is the top one

(b) Calculate the magnitude of the electric field between the plates.

$W = \Delta KE$

$Vq = \Delta KE$

$Ed = \frac{\Delta KE}{q}$

$E = \frac{1}{d}\left(\frac{1}{q}\Delta KE\right)$

~~$= \left(\frac{1}{0.010\ \text{m}}\right)(1.6\times10^{-19}\ \text{C})\left(\frac{1}{2}\right)(9.11\times10^{-31}\ \text{kg})((8.02\times10^6\ \text{m/s})^2 - (5.40\times10^6\ \text{m/s})^2) = 2.56\times10^{-24}\ \text{N/C}$~~

$E = \left(\frac{1}{0.010\ \text{m}}\right)\left(\frac{1}{1.6\times10^{-19}\ \text{C}}\right)\left(\frac{1}{2}\right)(9.11\times10^{-31}\ \text{kg})((8.02\times10^6\ \text{m/s})^2 - (5.40\times10^6\ \text{m/s})^2) = \boxed{1.0\times10^4\ \text{N/C}}$

(c) Calculate the magnitude of the charge on each plate.

$C = \frac{\varepsilon_0 A}{d}$

$\frac{Q}{V} = \frac{\varepsilon_0 A}{d}$

$Q = \frac{\varepsilon_0 E d A}{d} = \varepsilon_0 E A$

$= (8.85\times10^{-12}\ \text{C}^2/\text{Nm}^2)(1.0\times10^4\ \text{N/C})(0.25\ \text{m}^2) = \boxed{2.2\times10^{-8}\ \text{C}}$



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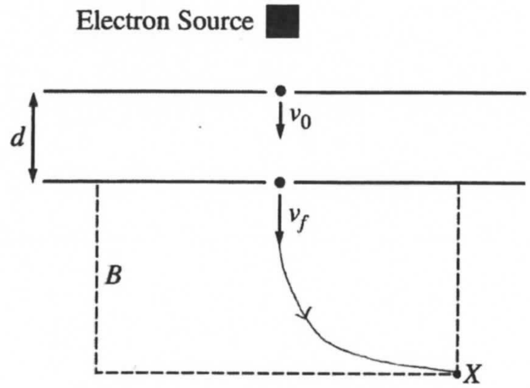
(d) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude $B$ that is perpendicular to the page. The electrons then leave the magnetic field at point $X$.



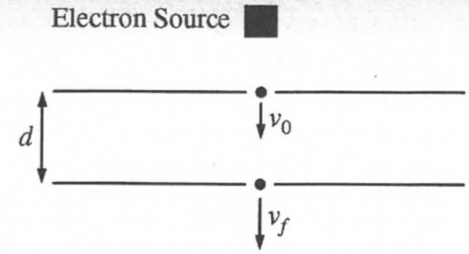

Note: Figure not drawn to scale.

i. On the figure above, sketch the path of the electrons from the bottom plate to point $X$. Explain why the path has the shape that you sketched.

The magnetic force is always perpendicular to the direction of velocity. Thus, the force acts as a centripetal force, so the electrons undergo circular motion.

ii. Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

The magnetic field is directed out of the page. By the right hand rule (force to the right, velocity down,) the magnetic field is into the page. Since the electrons are negatively charged, we switch the direction so ~~they are~~ the field is out of the page (the right hand rule applies to positively charged particles.)




Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010\ \text{m}$. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6\ \text{m/s}$, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\ \text{m/s}$.

(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

the top is negatively charged; the apparatus fires the e⁻ through the top plate. Because the e⁻ finish with a final velocity greater than their initial velocity, their attraction to the bottom plate (the positive plate) speeds up their journey.

(b) Calculate the magnitude of the electric field between the plates.

$$E = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2} = \frac{Kq}{r^2}$$

$$= \frac{(9\times10^9)(1.6\times10^{-19})}{(0.01)^2} = \boxed{1.44\times10^{-5}\ \text{N/C}}$$

$$\frac{\frac{N m^2}{C^2}\cdot C}{m^2}$$

NC

(c) Calculate the magnitude of the charge on each plate.

$$E = \frac{Q}{\varepsilon_0 A}$$

$$Q = E\varepsilon_0 A$$

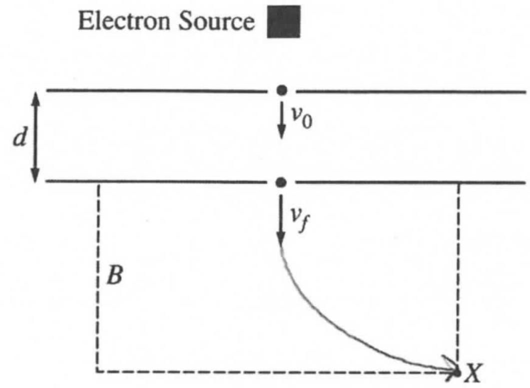
$$= (1.44\times10^{-5})(8.85\times10^{-12})(0.25)$$

$$= \boxed{3.186\times10^{-17}\ \text{C}}$$



GO ON TO THE NEXT PAGE.

(d) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude $B$ that is perpendicular to the page. The electrons then leave the magnetic field at point $X$.




Note: Figure not drawn to scale.

i. On the figure above, sketch the path of the electrons from the bottom plate to point $X$. Explain why the path has the shape that you sketched.

When electrons are directed towards their exit place, their path should begin to form that of a circle. The force that pulls them is a centripetal force, so their path is curved rather than straight.

ii. Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

Out of the page; when using right hand rule, V is pointed towards the bottom of the page. We know that the electrons leave at point X. These electrons travel to the right to exit, meaning the force is to the right. However, because our test points are $e^-$ with negative charge, we flip the direction of force, meaning force is to the left. Using right hand rule with V pointed down and F pointed to the left, we find that the magnetic field is directed out of the page.



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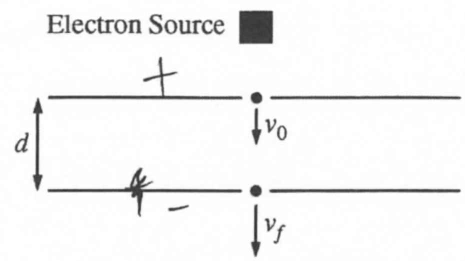



Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010\ \text{m}$. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6\ \text{m/s}$, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\ \text{m/s}$.

(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

Bottom. ~~Top~~. The eletricfield goes from positive to negative. As the election is attracted to the positive plate, its velocity pushes it past to the negative plate and from there it is repelled downwards away from the plate.

(b) Calculate the magnitude of the electric field between the plates.

~~$C = K\varepsilon_0 \frac{A}{d}$~~

$E = \frac{F_E}{q} = \frac{kQ}{r}$

$\frac{F_E}{q} = \frac{(1.6\times10^{-19})(9\times10^{9})}{(.01)^2}$

$= 1.44\times10^{-5}\ \text{N/C}$

(c) Calculate the magnitude of the charge on each plate.

$E = \frac{Q}{\varepsilon_0 A}$

$1.44\times10^{-5} = \frac{Q}{(8.85\times10^{-12})(.25)}$

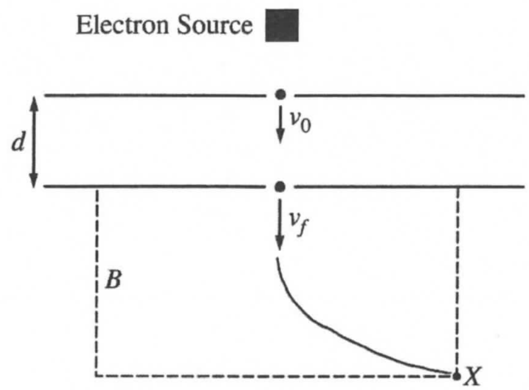
~~$\frac{N}{C} / \frac{Nm^2}{C^2}$~~

$Q = 3.186\times10^{-17}\ C$



GO ON TO THE NEXT PAGE.

(d) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude $B$ that is perpendicular to the page. The electrons then leave the magnetic field at point $X$.




Note: Figure not drawn to scale.

i. On the figure above, sketch the path of the electrons from the bottom plate to point $X$. Explain why the path has the shape that you sketched.

As the electron moves downward, its velocity force is being overcome by the ~~force of~~ the magnetic field perpendicular to the force of the electron, pushing it to the right, but gradually. ~~expon~~

ii. Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

Magnetic field is into the page, because the direction of velocity of the electron is downwards and towards the right, and by right hand rule the only way magnetic field can be directed when force is right and velocity is downwards is into the page.

## Question 4

### Overview

An electron accelerates between two oppositely charged parallel plates and then into a region with a uniform magnetic field. Students are asked to determine various quantities such as charge, field, directions of vector quantities, and trajectories.

**Sample: P2Q4 A**
**Score: 10**

This full-credit paper is easy to read and follow the logic and has complete explanations. Note the use of the alternate solution in part (b).

**Sample: P2Q4 B**
**Score: 5**

Part (a) earned 1 point for relating the change in electron velocity to the sign of the charge on the top plate. Since there is no mention of the electric field, which was specifically asked for in the question, full credit could not be earned. Part (b) earned no credit. Part (c) earned 1 point for full credit for correct substitution of values, correctly using the incorrect answer from part (b). Part (d) earned full credit.

**Sample: P2Q4 C**
**Score: 3**

Part (a) earned 1 point for relating the direction of the electric field to the sign of the charge on the plates. Part (b) earned no credit. Part (c) earned 1 point for full credit, for correct substitution of values to calculate the magnitude of the charge on each parallel plate. Part (d)(i) earned 1 point for correctly drawing a circular path from the point that the electrons leave the bottom plate to point X. Part (d)(ii) earned no credit.