

AP Physics C: E&M – Practice Set

AP Physics C: Electricity and Magnetism (College Board) · Total marks: 54 · Answers on the last page

Free-response-style practice on electrostatics, capacitors, DC circuits, magnetic fields and electromagnetic induction. A calculator is allowed; use $k = 8.99 \times 10^9 \text{ N m}^2\text{C}^{-2}$, $\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$ and $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$. Allow about 45 minutes.

Section A – Electrostatics and capacitors

- A point charge $q_1 = +3.0 \mu\text{C}$ is fixed at the origin and a point charge $q_2 = -5.0 \mu\text{C}$ is fixed at $x = 0.40 \text{ m}$ on the x -axis. Point P is on the x -axis at $x = 0.60 \text{ m}$.
 - Calculate the magnitude and direction of the electric field at P due to q_1 alone.
 - Calculate the magnitude and direction of the electric field at P due to q_2 alone.
 - Determine the net electric field (magnitude and direction) at P . [5]
- An infinite line of charge has linear charge density $\lambda = 4.0 \mu\text{C m}^{-1}$.
 - Using Gauss's law and a cylindrical Gaussian surface of radius r and length L coaxial with the line, show that the electric field at perpendicular distance r from the line is $E = \frac{\lambda}{2\pi\epsilon_0 r}$.
 - Calculate the magnitude of E at $r = 0.15 \text{ m}$. [5]
- A parallel-plate capacitor has plates of area 200 cm^2 separated by 1.5 mm of vacuum, connected to a 12.0 V battery.
 - Calculate the capacitance.
 - Calculate the charge on each plate.
 - Calculate the energy stored in the capacitor.
 - A dielectric slab of dielectric constant $\kappa = 4.5$ is now inserted to completely fill the gap, with the battery still connected. Calculate the new capacitance and the new energy stored, and explain physically why the stored energy changes as it does. [8]
- Capacitors $C_1 = 2.0 \mu\text{F}$ and $C_2 = 3.0 \mu\text{F}$ are connected in series with each other, and this series combination is connected in parallel with $C_3 = 4.0 \mu\text{F}$. Calculate the equivalent capacitance of the whole network. [3]

Section B – Circuits and magnetic fields (exam-style)

- A resistor $R = 2.2 \text{ k}\Omega$ and an initially uncharged capacitor $C = 4.7 \mu\text{F}$ are connected in series with a 9.0 V battery. The switch is closed at $t = 0$.
 - Calculate the time constant of the circuit.
 - Calculate the voltage across the capacitor at $t = 5.0 \text{ ms}$, using $V_C(t) = V_0 (1 - e^{-t/RC})$.
 - Calculate the charge on the capacitor at this time. [6]
- A long straight wire carries a current $I = 6.0 \text{ A}$.
 - Use Ampere's law to derive the expression $B = \frac{\mu_0 I}{2\pi r}$ for the magnetic field at perpendicular distance r from the wire.
 - Calculate B at $r = 5.0 \text{ cm}$ from the wire. [5]
- A straight wire segment of length 0.25 m carries a current of 3.0 A perpendicular to a uniform magnetic field of magnitude 0.40 T . Calculate the magnitude of the magnetic force on the segment.
 - A proton moves with speed $2.0 \times 10^6 \text{ m s}^{-1}$ perpendicular to a uniform magnetic field of

magnitude 0.50 T. Calculate the magnetic force on the proton, and the radius of its circular path.
[6]

Section C – Electromagnetic induction (extended)

8. A conducting rod of length 0.50 m slides with constant speed 4.0 m s^{-1} along frictionless conducting rails in a uniform magnetic field of magnitude 0.30 T directed perpendicular to the plane of the rails. The rails are connected by a resistor $R = 2.0 \Omega$.
(a) Calculate the motional EMF induced in the rod.
(b) Calculate the current in the circuit.
(c) Calculate the magnetic force needed on the rod to keep it moving at constant speed.
(d) Calculate the mechanical power delivered to the rod and show it equals the electrical power dissipated in R . [8]
9. A circular loop of radius 0.10 m lies in a plane perpendicular to a uniform magnetic field that increases uniformly from 0.20 T to 0.80 T in 0.50 s.
Use Faraday's law to calculate the magnitude of the EMF induced in the loop. [4]
10. (a) For the loop in Question 9, with $\vec{B}$ directed into the page and increasing, use Lenz's law to state the direction of the induced current in the loop.
(b) For the rod on rails in Question 8, explain in terms of energy conservation why an external force must do work to keep the rod moving at constant speed, even though the rails are frictionless. [4]

Answers

Check your working against these. If an answer does not match, try the question again before looking for the method.

- $E_1 = \frac{kq_1}{r_1^2} = \frac{(8.99 \times 10^9)(3.0 \times 10^{-6})}{(0.60)^2} = 7.5 \times 10^4 \text{ N C}^{-1}$, directed in the $+x$ direction (away from q_1).
 - $E_2 = \frac{kq_2}{r_2^2} = \frac{(8.99 \times 10^9)(5.0 \times 10^{-6})}{(0.20)^2} = 1.12 \times 10^6 \text{ N C}^{-1}$, directed in the $-x$ direction (toward q_2 , since q_2 is negative).
 - $E_{\text{net}} = 7.5 \times 10^4 - 1.12 \times 10^6 = -1.05 \times 10^6 \text{ N C}^{-1}$, i.e. $1.05 \times 10^6 \text{ N C}^{-1}$ in the $-x$ direction.
- By symmetry $\vec{E}$ is radial with constant magnitude on the curved surface, and there is no flux through the flat ends. Gauss's law gives $E(2\pi rL) = \frac{\lambda L}{\epsilon_0}$, so $E = \frac{\lambda}{2\pi\epsilon_0 r}$.
 - $E = \frac{4.0 \times 10^{-6}}{2\pi(8.85 \times 10^{-12})(0.15)} = 4.80 \times 10^5 \text{ N C}^{-1}$
- $C = \frac{\epsilon_0 A}{d} = \frac{(8.85 \times 10^{-12})(0.0200)}{1.5 \times 10^{-3}} = 1.18 \times 10^{-10} \text{ F}$
 - $Q = CV = 1.42 \times 10^{-9} \text{ C}$
 - $U = \frac{1}{2}CV^2 = 8.50 \times 10^{-9} \text{ J}$
 - $C' = \kappa C = 5.31 \times 10^{-10} \text{ F}$; with V fixed by the battery, $U' = \frac{1}{2}C'V^2 = 3.82 \times 10^{-8} \text{ J}$. The energy increases because the battery does work to push more charge onto the plates (the dielectric increases C while V stays constant, so both Q and the stored energy increase).
- $C_{12} = \left(\frac{1}{2.0} + \frac{1}{3.0} \right)^{-1} \mu\text{F} = 1.2 \mu\text{F}$; $C_{\text{eq}} = C_{12} + C_3 = 1.2 + 4.0 = 5.2 \mu\text{F}$
- $\tau = RC = (2200)(4.7 \times 10^{-6}) = 1.03 \times 10^{-2} \text{ s}$ (10.3 ms)
 - $V_C = 9.0(1 - e^{-5.0/10.3}) = 3.45 \text{ V}$
 - $Q = CV_C = (4.7 \times 10^{-6})(3.45) = 1.62 \times 10^{-5} \text{ C}$
- By symmetry $\vec{B}$ has constant magnitude on a circular Amprian loop of radius r centred on the wire, directed tangent to the loop. Ampere's law gives $B(2\pi r) = \mu_0 I_{\text{enc}} = \mu_0 I$, so $B = \frac{\mu_0 I}{2\pi r}$.
 - $B = \frac{(4\pi \times 10^{-7})(6.0)}{2\pi(0.050)} = 2.4 \times 10^{-5} \text{ T}$
- $F = BIL = (0.40)(3.0)(0.25) = 0.30 \text{ N}$
 - $F = qvB = (1.6 \times 10^{-19})(2.0 \times 10^6)(0.50) = 1.6 \times 10^{-13} \text{ N}$; radius $r = \frac{m_p v}{qB} = \frac{(1.67 \times 10^{-27})(2.0 \times 10^6)}{(1.6 \times 10^{-19})(0.50)} = 4.2 \times 10^{-2} \text{ m}$
- $\varepsilon = BLv = (0.30)(0.50)(4.0) = 0.60 \text{ V}$
 - $I = \frac{\varepsilon}{R} = \frac{0.60}{2.0} = 0.30 \text{ A}$
 - $F = BIL = (0.30)(0.30)(0.50) = 0.045 \text{ N}$
 - $P_{\text{mech}} = Fv = (0.045)(4.0) = 0.18 \text{ W}$; $P_{\text{elec}} = I^2 R = (0.30)^2(2.0) = 0.18 \text{ W}$ – equal, as required by energy conservation.
- $A = \pi r^2 = 3.14 \times 10^{-2} \text{ m}^2$; $|\varepsilon| = A \left| \frac{dB}{dt} \right| = (3.14 \times 10^{-2}) \left(\frac{0.60}{0.50} \right) = 3.8 \times 10^{-2} \text{ V}$
- The induced current opposes the increasing inward flux, so it flows counterclockwise (as viewed with $\vec{B}$ into the page) to create its own magnetic field out of the page inside the loop.

(b) The induced current in the rod experiences a magnetic (retarding) force opposing its motion (by Lenz's law); since there is no friction, an external agent must supply exactly the mechanical power that is dissipated as electrical energy in the resistor, so mechanical energy input equals electrical energy output and total energy is conserved.

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