Topic 2: The Motion of Charged Particles in Electric Fields

The concept of work done by an electric field on a charged particle is introduced. The potential difference between two points in an electric field is defined and used to determine the work, and hence energy changes, of charged particles moving in uniform electric fields in a vacuum.

The potential difference between a pair of parallel plates is used to determine the electric field between the plates. From the field, the force, and hence the acceleration, of a charged particle can be found and its motion determined. These ideas are applied to the motion of ions in a cyclotron.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Electric Potential Difference	
The electric potential difference ΔV between two points is the work W done per unit charge q on a small positive test charge moved between the points, provided that all other charges remain undisturbed: $\Delta V = W/q$. The unit of potential difference, the volt (V), is equal to a joule per coulomb (J C^{-1}). The electronvolt (eV) is the work done when a charge of one electron moves through a potential difference of 1 V.	Solve problems involving the use of $W = q\Delta V$. Convert energy from joules into electronvolts and vice versa. Derive the expression $E = \Delta V/d$ for the magnitude of the electric field (away from the edges) between two oppositely charged parallel plates a distance d apart, where ΔV is the potential difference between the plates. Solve problems involving the use of $E = \Delta V/d$.
Acceleration in a Constant Electric Field	
The force on a charged particle moving in a uniform electric field is constant in magnitude and direction, thus producing a constant acceleration.	Describe the motion of a charged particle in a uniform electric field. Perform calculations involving the movement of charged particles parallel or antiparallel to a uniform electric field.
Motion of a Charged Particle in a Constant Electric Field	
When a charged particle moves across a uniform electric field the component of the velocity perpendicular to the field remains constant.	Compare the motion of a projectile in the absence of air resistance with the motion of a charged particle in a uniform electric field. Calculate the time of flight and deflection of a charged particle that enters a uniform electric field at right angles to the field.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Application: The Use of Electric Fields in Cyclotrons	
	Describe how hydrogen atoms are given a negative charge or a positive charge in an ion source of a cyclotron.
	Describe the following parts of a cyclotron: • semicircular metal containers ('dees') • evacuated outer container.
	Explain why there is no electric field inside the dees.
	Describe how an electric field between the dees can transfer energy to an ion passing between them.
	Describe how ions could be accelerated to high energies if they could be made to move in a circular path inside the dees so that they repeatedly moved across the electric field, the direction of which was reversing every half-revolution.
	Calculate the energy transferred to an ion each time it passes between the dees.
	Explain why the cyclotron must be evacuated.

Topic 3: Magnetic Fields

Whenever a charge is moving, it produces a magnetic field in addition to its electric field. Magnetic fields may exert forces on other moving charges and hence on current-carrying conductors. The interaction between magnetic fields and electric currents is described and used to define the strength of the magnetic field in terms of the force on current-carrying conductors. The theory is applied to the moving-coil loudspeaker.

Key Ideas

Students should know and understand the following:

Magnetic Fields and Their Pictorial Representation

Moving electric charges, and hence electric currents, produce magnetic fields.

The magnetic field is in addition to the electric field produced by the charges.

A magnetic field can be represented by field lines such that the direction of the field is at a tangent to each line, and the magnitude of the field at any point is represented by the number of lines crossing a unit area perpendicular to the field in the vicinity of the point.

The direction of the magnetic field is the direction in which the north pole of a small compass needle points.

Magnetic Force on a Current-carrying Conductor

When placed in a magnetic field, a current-carrying conductor experiences a force due to the movement of charge in the conductor.

The magnitude B of a magnetic field is the force per unit current element placed at right angles to the field, where a current element is the product of the current I and its length Δl (i.e. $I\Delta l$).

Hence $B = F/I\Delta l.$

The direction of the magnetic force is perpendicular to the plane defined by $I\Delta\vec{l}$ and $\vec{B}$ and is given by a right-hand rule, where the direction of $\Delta\vec{l}$ is that of the conventional current.

The force on a current element that is parallel to a magnetic field is zero.

Intended Student Learning

Students should be able to do the following:

Sketch the magnetic field lines produced by an electric current flowing in a straight conductor, a loop, and a solenoid.

Using a right-hand rule, relate the directions of the force, magnetic field, and conventional current.

Use the unit for $\vec{B}$, tesla (T), equivalent to $\mathrm{NA^{-1}m^{-1}}$.

Solve problems involving the use of $F = I\Delta l B\sin\theta$.

Key Ideas

Students should know and understand the following:

The magnitude of the force on a current element that is at any angle θ to a uniform magnetic field is given by $F = I\Delta l B \sin\theta$, where $I\Delta l \sin\theta$ is the component of the current element perpendicular to the field.

Application: The Moving-coil Loudspeaker

Intended Student Learning

Students should be able to do the following:

Describe the following components of a moving-coil loudspeaker: a cone, a magnet structure, a voice coil, and a supporting frame.

Explain the action of a moving-coil loudspeaker.

Topic 4: The Motion of Charged Particles in Magnetic Fields

The interaction of current-carrying conductors and magnetic fields is extended to the interaction of moving charged particles and uniform magnetic fields. The magnetic force on a moving charged particle is velocity-dependent, whereas electric forces are not.

The circular path of charged particles moving at right angles to a uniform magnetic field is discussed and applied to the deflection of ions in a cyclotron.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Force on a Charged Particle in a Magnetic Field	
There is no magnetic force on either a stationary charged particle in a uniform magnetic field or a charged particle moving with velocity parallel to a uniform magnetic field. When a charged particle is moving at any angle θ to a uniform magnetic field, the magnitude of the force on the particle is given by $F = qvB\sin\theta$, where $v\sin\theta$ is the component of the velocity of the particle perpendicular to the field. The magnetic force is velocity-dependent. The direction of the magnetic force is at right angles to the plane defined by $\vec{v}$ and $\vec{B}$ and is given by a right-hand rule.	Demonstrate an understanding that the magnetic force depends on both the magnitude and the direction of the velocity of the particle. Solve problems involving the use of $F = qvB\sin\theta$. Determine the direction of the force on a charged particle moving at any angle θ to a uniform magnetic field.
Motion of a Charged Particle at Right Angles to a Magnetic Field	
A charged particle moving at right angles to a uniform magnetic field experiences a force of constant magnitude at right angles to the velocity, and hence moves with uniform circular motion.	Explain how the velocity-dependence of the magnetic force on a charged particle causes the particle to move with uniform circular motion when it enters a uniform magnetic field at right angles. Derive $r = mv/qB$ for the radius r of the circular path of an ion of charge q and mass m that is moving with speed v at right angles to a uniform magnetic field of magnitude B. Solve problems involving the use of $r = mv/qB$.

Key Ideas

Students should know and understand the following:

Application: The Use of Magnetic Fields in Cyclotrons

Intended Student Learning

Students should be able to do the following:

Describe the nature and direction of the magnetic field needed to deflect ions into a circular path in the dees of a cyclotron.

Derive the expression $T = 2\pi m/qB$ for the period T of the circular motion of an ion, and hence show that the period is independent of the speed of the ion.

Using the relationships $K = \frac{1}{2}mv^2$ and $r = mv/qB$, derive the expression $K = q^2B^2r^2/2m$ for the kinetic energy K of the ions emerging at radius r from a cyclotron. Use this expression to show that K is independent of the potential difference across the dees and, for given ions, depends only on the magnetic field and the radius of the cyclotron.

Solve problems involving the use of $T = 2\pi m/qB$ and $K = q^2B^2r^2/2m$.