Magnetic Effect of Current

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Magnetic Effect of Current

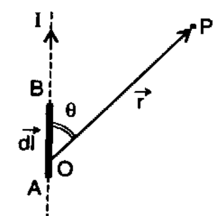
Magnetic induction

A magnet at rest produces a magnetic field around it while an electric charge at rest produces an electric field around it. A current carrying conductor has a magnetic field (and not an electric field) around it. On the other hand, a charge moving with a uniform velocity has an electric as well as a magnetic field around it. An oscillating or an accelerated charge produces electromagnetic waves also in addition to electric and magnetic fields.

Magnetic induction (Magnetic Flux Density) $\vec{B}$ is a vector quantity. It is given by the number of lines of induction threading a unit area normal to the surface. The unit of $\vec{B}$ in MKS system is weber/metre^2, in SI system is tesla, in CGS system is maxwell/cm^2 which is also called gauss. One Tesla = one (weber/m^2) = 10^4 (maxwell/cm^2) = 10^4 gauss

Biot-Savart's law

According to Biot-Savart's law, the magnetic induction *dB* at a point P due to an infinitesimal element of current (length *dl* and current *I*) at a distance *r* is given by: $dB = \frac{\mu_0}{4\pi} \times \frac{Idl \sin\theta}{r^2}$ μ_0 is called permeability of free space. In S



1. The dimensions of $\mu_0 = [M^1L^1T^{-2}A^{-2}]$
2. For vacuum: $\sqrt{(1/\mu_0\varepsilon_0}$ = c = 3 x 10^8 m/s
3. Biot-Savart law in vector form: $\vec{dB} = \frac{\mu_0}{4\pi} I \frac{(\vec{dl} \times \vec{r})}{r^3}$
4. The direction of $\vec{dB}$ is perpendicular to the plane determined by $\vec{dl} \times \vec{r}$. In the figure given here, direction of $\vec{dB}$ is into the page. (Use right hand screw rule.)
5. For θ = 0 or θ = π, sin θ = 0; thus field at a point on the axis of the wire is zero.

Magnetic induction due to straight conductor

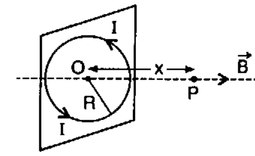
The magnetic induction B due to a straight wire of finite length carrying current I at a distance d is given by: $B = \frac{\mu_0}{4\pi} \times \frac{I}{d}[\sin\phi_1 + \sin\phi_2]$, where ϕ_1 and ϕ_2 are the angles made by upper and lower ends of the wire with the perpendicular distance d at the point of observation.

1. If the wire is infinitely long, then $\phi_1 = \phi_2 = 90°$. Hence $B = \frac{\mu_0}{4\pi} \times \frac{2I}{d} = \frac{\mu_0 I}{2\pi d}$
2. Magnetic induction at the centre of separation of two straight conductors carrying equal currents in the same direction is zero. If equal currents are flowing in two straight conductors in opposite direction, then the magnetic induction at the centre of separation (distance d) is: $B = B_1 + B_2 = 2 \times (\mu_0/2\pi) \times (I/d)$.

Magnetic induction on the axis of a circular current carrying coil

Magnetic induction on the axis of a circular current carrying coil is given by:

$$B = \frac{\mu_0}{4\pi} \times \frac{2\pi NIR^2}{(R^2 + x^2)^{3/2}} = \frac{\mu_0 NIR^2}{2(R^2 + x^2)^{3/2}}$$



where R = radius of coil, x = distance of any point on the axis from the centre of the coil,

N = number of turns in the coil and I = current in the coil.

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The direction of $\vec{B}$ is as shown in the figure. For ACW current, $\vec{B}$ is out of the page, along the axis of coil. If fingers of right hand are curled along direction of flow of current, the thumb points in the direction of $\vec{B}$.

1. **Magnetic** field **at the centre of coil:** $B_C = \frac{\mu_0 NI}{2R}$
2. When x >> R, then $B = \frac{\mu_0 NIR^2}{2x^3} = \frac{\mu_0 NI(\pi R^2)}{2\pi x^3} = \frac{\mu_0 NIA}{2\pi x^3} = \frac{\mu_0 M_C}{2\pi x^3}$

   where NIA = M_C = magnetic dipole moment of the current carrying coil. A current carrying coil of area of cross-section A and number of turns N, carrying a current I can be regarded as magnetic dipole of magnetic moment NIA.
3. Magnetic field due to a part of circular current carrying loop subtending angle ϕ at the centre is: $B = \frac{\mu_0 N\phi}{4\pi R}$
4. Magnetic field at the centre of half current carrying loop is: $B = \frac{\mu_0 I}{4R}$
5. The magnetic induction along the axis of a long current carrying solenoid at the centre part $B = \mu_0 nI$ where I = current flowing through solenoid, n = (N/l) = number of turns per unit length of solenoid.
6. Magnetic induction at the ends of the solenoid $B' = (\mu_0 nI/2)$
   (a) If the solenoid is sufficiently long, the field within it is uniform (except at the ends).
   (b) Magnetic induction produced by current carrying solenoid is independent of length and cross section area.
   (c) The magnetic induction at the ends of a very long current carrying solenoid is half of that at the centre.

Ampere's Circuital law

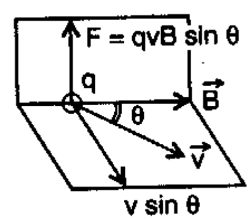
The line integral of magnetic field around any closed path is equal to μ_0 times the total current passing through the closed circuit, i.e., $\oint \vec{B} \cdot \vec{dl} = \mu_0 I$. Using $\vec{B} = \mu_0 \vec{H}$, Ampere's law can be written as $\oint \vec{H} \cdot \vec{dl} = I$.

For a long metal rod of radius R carrying a current *I*

(a) if r < R, $B = \left(\frac{\mu_0 I}{2\pi R^2}\right) r$, i.e., $B \propto r$ (b) if r = R (i.e., at the surface), $B = \left(\frac{\mu_0 I}{2\pi R}\right)$

(c) For a hollow metallic rod carrying a uniform current, for points inside the hollow rod B = 0

Force on a charged particle in uniform constant magnetic field:

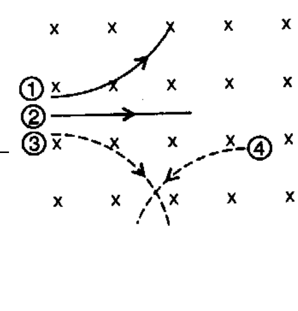


When a test charge q moves in a magnetic field of induction B with a velocity v, then it experiences a sideway deflecting force F, given by: $\vec{F} = q(\vec{v} \times \vec{B})$. The force $\vec{F}$ is always perpendicular to $\vec{v}$ and $\vec{B}$.

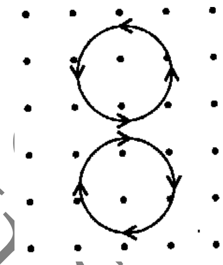
1. If the particle is at rest inside the magnetic field, no force will act on it (v = 0) and hence the particle remains at rest.
2. If the particle is moving parallel to magnetic field ($\theta = 0$) no force acts on it. Thus a charged particle initially moving parallel to magnetic field will continue to move with initial constant speed on parallel path.
3. If the particle is moving perpendicular to magnetic field, it experiences maximum force.

Motion of a Charged Particle in a Magnetic Field

Case A: When charged particle enters the magnetic field at right angles.



1. If $\vec{v}$ is perpendicular to $\vec{B}$, then magnitude of Lorentz force is F = qvB. It is directed along the direction of $\vec{v} \times \vec{B}$. In the adjoining figure, for +ively charged particle (1), the force is upwards while for negatively charged particle (3), the force is downwards. For neutral particle (2), there is no force. The path of particle (4) indicates that it must be a positively charged particle.
2. Since the force is perpendicular to velocity vector $\vec{v}$ (when particle enters the magnetic field at right angles) it moves in a circular path. For the field $\vec{B}$ shown in the adjoining figure (upwards, out of page), a negatively charged particle moves in anticlockwise path while a positively charged particle moves in a clockwise path. If the field $\vec{B}$ is into the page (downwards) then positively charged particle moves in a circular anticlockwise path, while negatively charged particle moves in a clockwise path.



3. The force equation is $mv^2/r = qvB$.
4. The radius of circular path is $r = mv/qB$ where $mv = p = (2mK)^{1/2}$ = momentum of the particle.
5. Time period of revolution is $T = 2\pi r/v = 2\pi m/qB$
6. The frequency is $f = 1/T = qB/2\pi m$
7. The angular frequency is $\omega = 2\pi f = qB/m$. This is often called cyclotron frequency.

Case B: When the particle enters the magnetic field at an inclination (i.e., $\vec{v}$ is not perpendicular to $\vec{B}$).

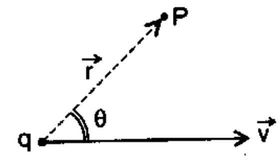
1. In this case, the path is helical.
2. Due to component of v perpendicular to $\vec{B}$, i.e., $v_\perp = v \sin\theta$, the particle describes a circular path of radius r, such that $\frac{mv_\perp^2}{r} = qv_\perp B$ or $r = \frac{mv\sin\theta}{qB}$
3. The time period, frequency and angular frequency are; (a) $T = 2\pi m/qB$ (b) $f = qb/2\pi m$ (c) $\omega = qB/m$
4. The pitch of the helical path is: $p = v\cos\theta \times T = \frac{2\pi mv}{qB}\cos\theta = \frac{2\pi r}{\sin\theta}$

Force on current element in a magnetic field

1. Force on a current element of length $\vec{dl}$ placed in a magnetic field $\vec{B}$ is: $\vec{dF} = I(\vec{dl} \times \vec{B})$
2. In special case of a straight wire of length l in a uniform magnetic field B, the force is; $\vec{F} = I(\vec{l} \times \vec{B})$ or $F = IlB\sin\theta$, where θ = angle between direction of current flow and magnetic field.
3. Force is zero if I is parallel to B and the force is maximum when direction of current flow is perpendicular to B.
4. The direction of force is given by Fleming's left hand rule. According to this rule, if the forefinger points in the direction of B and the central finger points in the direction of current I, then the thumb points in the direction of force. (Here, forefinger, central finger and thumb are kept mutually perpendicular).
5. **Force on a semicircular wire in a magnetic field:** $F = IB(2R)$, where R is the radius of semicircular wire.
6. Force between two parallel current carrying conductors:
   (a) Two parallel wires carrying currents in the same direction attract each other, while those carrying currents in the opposite direction repel each other.
   (b) The force of attraction or repulsion per unit length between two parallel conductors carrying currents I_1 and I_2 given by: $\frac{F}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}$
   (c) **Definition of ampere:** An ampere is that constant current which if maintained in two straight parallel conductors of infinite length of negligible circular cross-section, and placed 1 metre apart in

vacuum, would produce on each of these conductors a force equal to 2 x 10^{-7} newton per metre of length.

(d) **Magnetic field produced by a moving charge:** The magnetic field produced by a moving charge q, at point P is: $\vec{B} = \frac{\mu_0}{4\pi}\frac{q(\vec{v}\times\vec{r})}{r^3}$ tesla or $B = \frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}$



where v is velocity of charge, r is the distance of point P from charge q and θ is the angle between $\vec{v}$ and $\vec{r}$

Relation Between electric and magnetic forces

1. The magnetic force between two current elements of lengths dl_1 and dl_2 is: $F_m = \frac{\mu_0}{4\pi}\frac{I_1 I_2}{r^2} dl_1 dl_2$
2. We may write $Idl = q\frac{dl}{dt} = qv$. Thus the magnetic force between two charges q_1 and q_2 at drifting with speeds v_1 and v_2 is: $F_m = \frac{\mu_0}{4\pi}\frac{q_1 v_1 q_2 v_2}{r^2}$
3. The electrostatic force between two charges q_1 and q_2 is: $F_e = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
4. Therefore, the ratio: $\frac{F_m}{F_e} = (\mu_0\varepsilon_0)v_1 v_2 = \frac{v_1 v_2}{c^2}$ $\left[\because c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}\right]$
5. The drift speed of electrons in metals is very small = 10^{-3} to 10^{-5} m/s. Therefore $\frac{F_m}{F_e} = \text{neglibibly small}$

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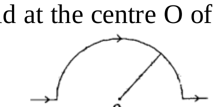
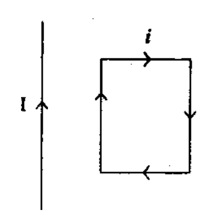
Magnetic Effect of Current Assignment

1. A uniform electric field and a uniform magnetic field exist in a region in the same direction. An electron is projected with velocity pointed in the same direction. The electron will
   (a) turn to its right
   (b) turn to its left
   (c) keep moving in the same direction but its speed will increase
   (d) keep moving in the same direction but its speed will decrease.
2. A proton enters a magnetic field of flux density 1.5 Wb/m^2 with a speed of 2 x 10^7 m/s at angle of 30° with the field. The force on the proton will be
   (a) 0.24 x 10^{-12} N (b) 2.4 x 10^{-12} N
   (c) 24 x 10^{-12} N (d) 0.024 x 10^{-12} N
3. Which of the following does not affect the motion of a moving electron ?
   (a) Electric field applied, in the direction of motion.
   (b) Magnetic field applied in the direction of motion.
   (c) Electric field applied perpendicular to the direction of motion
   (d) Magnetic field applied perpendicular to the direction of motion.
4. An ion with speed 2 x 10^5 m/s enters normally into a uniform magnetic field of 4 x 10^{-2} T. If the specific charge of the ion is 5 x 10^7 C/kg, the radius of the circular path described by it will be
   (a) 0.10 m (b) 0.16m (c) 0.20 m (d) 0.25 m
5. Protons and α-particles of equal momenta enter a uniform magnetic field normally. The radii of their orbits will have the ratio
   (a) 1 (b) 2 (c) 0.5 (d) 4
6. A beam of electrons is accelerated through a potential difference V. It is then passed normally through a uniform magnetic field where it moves in a circle of radius r. It would have moved in a circle of radius 2r if it were initially accelerated through a potential difference
   (a) $\sqrt{2}$ V (b) 2 V (c) $2\sqrt{2}$ V (d) 4 V
7. A proton and α-particle, accelerated through the same potential difference, enter a region of uniform magnetic field normally. If the radius of the proton orbit is 10 cm that of the α-orbit is
   (a) 10 cm (b) $10\sqrt{2}$ cm (c) 20 cm (d) $5\sqrt{2}$ cm
8. A conducting circular loop of radius r carries a constant current i. It is placed in a uniform magnetic field B such that B is perpendicular to the plane of the loop. The magnetic force acting on the loop is
   (a) ri B (b) 2π ri B (c) zero (d) π ri B
9. A circular coil of diameter 10 cm has 10 turns and carries a current of 5 A. It is placed in a uniform field of 0.5 T with its plane parallel to the field. The torque on the coil, in Nm, is
   (a) 6.25 x π x10^{-2} (b) 6.25 x π x 10^{-3}
   (c) 6.25 x π x 10^{-4} (d) zero.
10. A deutron of kinetic energy 50 Kev describes a circular orbit in a magnetic field. The kinetic energy of a proton that describes a circular orbit of the same radius in the same field would be
    (a) 25 keV (b) 50 keV (c) 100 keV (d) 200 keV
11. An electric current is flowing in a long straight wire. The magnetic field due to this current at a distance of 5 cm from the wire is 10 gauss. The magnetic field at a distance of 10 cm from wire is
    (a) 2.5 gauss (b) 5 gauss (c) 20 gauss (d) 40 gauss
12. A portion of a long straight wire, carrying a current *I*, is bent in the form of a semicircle of radius r as shown in the figure. The magnetic field at the centre O of the semi circle, in tesla, is
    (a) $\pi I/r$ x 10^{-7} (b) $\pi I/r$
    (c) $\pi I/r$ x 10^7 (d) zero



13. A rectangular loop carrying current is situated near a long straight wire such that the wire is parallel to one of the sides of the loop and is in the plane of the loop. If a steady current *I* is established in the wire as shown in the figure, the loop will
    (a) rotate about an axis parallel to the wire
    (b) move away from the wire
    (c) move towards the wire
    (d) remain stationary.



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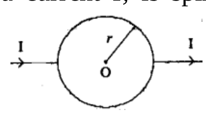
14. Two long straight wires, each carrying a current I, are separated by a distance r. If the currents are in opposite directions. then the strength of the magnetic field at any point midway between the two wires is
(a) $\frac{\mu_0 I}{\pi r}$ (b) $\frac{2\mu_0 I}{\pi r}$ (c) $\frac{\mu_I}{2\pi r}$ (d) zero

15. A current I flows in a circular arc of wire which subtends an angle $3\pi/2$ at the centre. If the radius of the circle is r then the magnetic induction at centre is
(a) $\frac{\mu_0 I}{r}$ (b) $\frac{\mu_0 I}{2r}$ (c) $\frac{3\mu_0 I}{4r}$ (d) $\frac{3\mu_0 I}{8r}$

16. A straight conductor, carrying a current *I*, is split into a circular loop of radius *r* as shown in the figure. The magnetic field at the centre O of the circle, in tesla, is



(a) $\frac{\mu_0 I}{2r}$ (b) $\frac{\mu_0 I}{2\pi r}$ (c) $\frac{\mu_0 I}{\pi r}$ (d) zero

17. A long straight wire carries a current of 10 A. An electron travels with a speed of 5×10^6m/s parallel to the wire 0.1 m away from it. The force exerted by the magnetic field of the current on the electron is
(a) 1.6×10^{-17} N (b) 3.2×10^{-17} N
(c) 1.6×10^{-18} N (d) 3.2×10^{-18} N

18. A square coil of side 'a' carries a current *I*, The magnetic field at the centre of the coil is
(a) $\frac{\mu_0 I}{a\pi}$ (b) $\frac{\sqrt{2}\mu_0 I}{a\pi}$ (c) $\frac{\mu_0 I}{\sqrt{2}a\pi}$ (d) $\frac{2\sqrt{2}\mu_0 I}{a\pi}$

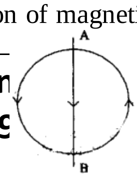
19. Two concentric coils carry the same current in opposite directions. The diameter of the inner coil is half that of the outer coil. If the magnetic field produced by the outer coil at the common centre is 1 tesla, the net field at the centre is
(a) 1T (b) 2 T (c) 3 T (d) 4 T.

20. An electron revolves in a circle of radius 0.5 Å with a speed of 2×10^6 m/s in a hydrogen atom. The magnetic field produced at the centre of the orbit due to the electron is
(a) 1.28 T (b) 12.8 T (c) 0.128 T (d) 128 T

21. A long solenoid has 20 turns/cm. The current necessary to produce a magnetic field of 20 millitesia inside the solenoid is approximately
(a) 1 A (b) 2 A (c) 4 A (d) 8 A

22. Two identical coils have a common centre and their planes are at right angles to each other. They carry equal currents. If the magnitude of the magnetic field at the centre due to one of the coils is B then that due to the combination is
(a) B (b) $\sqrt{2}$B (c) B/$\sqrt{2}$ (d) 2B

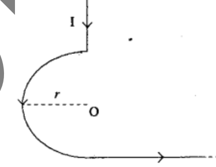
23. The figure shows a circular coil and a long straight wire AB placed close to each other, the wire being parallel to a diameter of the coil. The arrows show the directions of currents. The direction of magnetic force acting on AB is



(a) out of the page
(b) into the page
(c) towards right
(d) towards left.

24. A current of 1 A is flowing in the sides of an equilateral triangle of side 4.5×10^{-2} m. The magnetic field at the centroid of the triangle is
(a) 2×10^{-5} T (b) 4×10^{-5} T
(c) 8×10^{-5} T (d) 1.2×10^{-4} T

25. In the given figure the straight parts of the wire are very long. The magnetic induction at O is



(a) $\frac{\mu_0 I}{4r} + \frac{\mu_0 I}{2\pi r}$ out of page
(b) $\frac{\mu_0 I}{4r} + \frac{\mu_0 I}{4\pi r}$ out of page
(c) $\frac{\mu_0 I}{4r} + \frac{\mu_0 I}{4\pi r}$ into the page
(d) $\frac{\mu_0 I}{4r} + \frac{\mu_0 I}{2\pi r}$ into the page

26. When a stationary charge is placed near a stream of moving charges, then the stationary charge experiences
(a) no force
(b) a force due to the electric field only
(c) a force due to the magnetic field only
(d) forces due to both the electric and the magnetic fields.

27. A charged particle enters a region where a uniform electric field E and a uniform magnetic field B exist. If E and B are perpendicular to each other and also perpendicular to the velocity u of the particle, then the particle will move undeviated if u equals
(a) B/E (b) E/B (c) EB (d) E^2/B^2

28. An electron of charge e coulomb is going around in an orbit of radius R metres in a hydrogen atom with velocity v m/s. The magnetic flux density associated with it at the centre of the atom is
(a) $\frac{\mu_0}{4\pi}\frac{ev}{R^2}$ (b) $\frac{\mu_0 ev}{2R}$ (c) $\mu_0 evR$ (d) $\frac{\mu_0 ev}{R^2}$

ANSWERS

1d ,2b ,3b ,4a ,5b ,6d ,7b ,8c ,9a ,10c ,11b ,12a ,13c ,14b ,15d ,16d ,17a ,18d ,19a ,20b ,21d ,22b ,23d ,24b ,25b ,26b ,27b ,28a