• → outside M. field
× → inside M. field.

B → Magnetic Field

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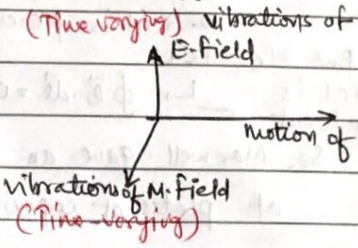
Electromagnetic waves
↳ means oscillation

Both M-field & E-field are ⊥er to each other.

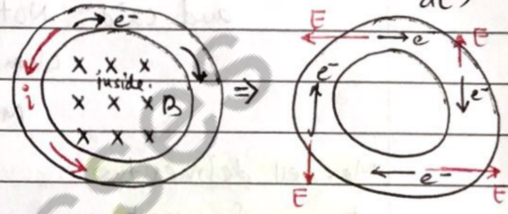


all three qts are ⊥er to each other.

Displacement current:

In 1831 → Michael Faraday $\xrightarrow{\text{gave}}$ Faraday's law of Electromagnetic Induction
↓
change in M. Flux $\xrightarrow{\text{produces}}$ emf.
$\left(e = -\frac{d\phi}{dt}\right)$

As per Faraday's law.
B increasing $\xrightarrow{\text{Results}}$ change in M. flux
↓ emf induces
Results in
current
↓ But,
current produces due to the flow of charges (e^-)
↓ to move the charges from rest
Electric field is required and this E. field is produced by change in M. field.



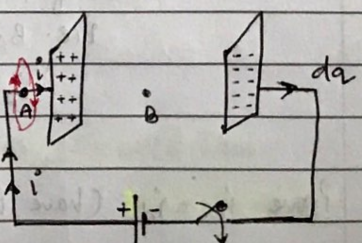
** M. field do not apply force on a charge in rest position (As $F = qvB\sin\theta$)
** M. field changes $\xrightarrow{\text{induces}}$ an E. field

$$\oint \vec{E}\cdot\vec{dl} = -\frac{d\phi_B}{dt}$$
↳ Actual equation given by Faraday

$$e = -\frac{d\phi_B}{dt}$$
↳ Faraday's Law

Q. Can changing E-field produces a Magnetic field?
Yes, A/c by James clerk Maxwell.

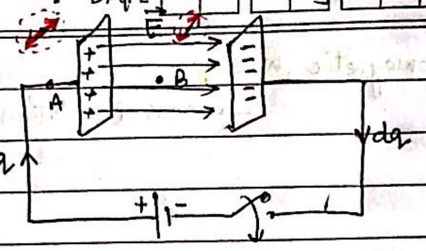
Consider a parallel plate capacitor being charged by a battery
Current flowing $i = \frac{dq}{dt}$



let us take a Point 'A' and Apply ACL
$$\oint \vec{B}\cdot\vec{dl} = \mu_0 i$$
Now take a Point 'B' between the plates of capacitors (free space/vaccume),
Apply ACL Here,
$$\oint \vec{B}\cdot\vec{dl} = \mu_0 i = 0 \quad (\because i = 0)$$

(Maxwell) He puts M. Needle at Point A ⟶ Needle shows deflection
again He put " " Point B ⟶ " " [crossed out] deflection

it means, b/w the plates of capacitor M. field is present.



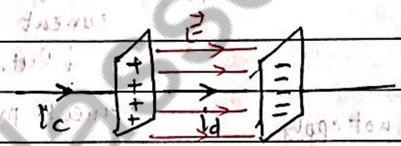
But A|c ACL
↳ $\oint \vec{B} \cdot \vec{dl} = 0$ ⟵ This shows ACL is logically inconsistent

So, Maxwell gave an another Theory that due to accumulation of charges at plates of capacitor ⟶ E. field produces inside the capacitor and this E. field is responsible for the generation of M. field.

↓ Not accepted

So, He gave the concept of Displacement current and said " Not only current produces M. flux M. field but a changing E. field in vacuum / free space also produces M. field"

Maxwell defines two types of current



Conduction current (i_c) — due to motion of charges

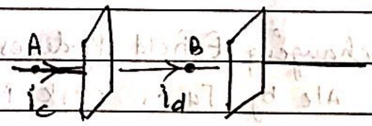
conventional current $i = \frac{dq}{dt}$

Displacement current (i_d) — produces / due to ↳ changing in E. field (or E. flux)

Maxwell's Displacement current ⟵ $i_d = \epsilon_0 \frac{d\phi_E}{dt}$

Displacement current : A current due to changing E. field or (E. flux)

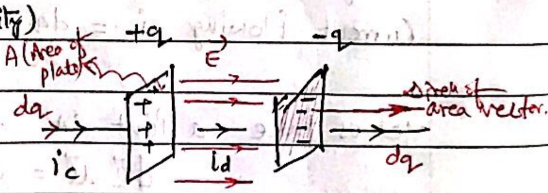
At Point A & B
Value of M. field is same
i.e. $B_A = B_B$
$\therefore i_A = i_B$ (continuity problem solved)



Prove $i_c = i_d$ (have Property of continuity)

As $i_c = \frac{dq}{dt}$

& $i_d = \epsilon_0 \frac{d\phi_E}{dt} = \epsilon_0 \frac{d}{dt}(EA)$



(Since $\phi_E = \vec{E} \cdot \vec{dA} = E\,dA\cos\theta = EA\cos 0^\circ = EA$)

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NOTE: change in E. field $\xrightarrow{\text{induces}}$ M. field $\xrightarrow{\text{is}}$ Ler to E. field] given by Maxwell.

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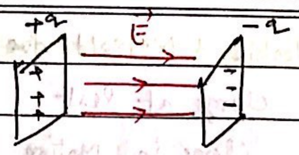
Electric field b/w these two plates is given as $\vec{E} = \frac{\sigma}{\epsilon_0}$



and $\sigma = \frac{q}{A}$

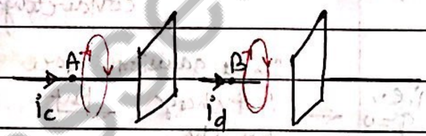
$$\therefore \ E = \frac{q}{A\epsilon_0}$$

$i_d = \frac{dq}{dt}$ = Rate of charge of charge on capacitor. i.e. displacement current.

(or) $i_d = \epsilon_0 \frac{d}{dt}\left(\frac{Aq}{A\epsilon_0}\right) = \frac{dq}{dt} = i_c$

$$i_d = i_c$$

Modification of Ampere's circuital law:-



At Point A $\oint \vec{B}\cdot d\vec{l} = \mu_0 i_c$

At Point B $\oint \vec{B}\cdot d\vec{l} = \mu_0 i_d$

$$\oint \vec{B}\cdot d\vec{l} = \mu_0 i_c + \mu_0 i_d = \mu_0(i_c + i_d) \quad \text{--- (1)}$$

At Both the Points A & B value of $\oint \vec{B}\cdot d\vec{l}$ is same.

How? At Point A $\longrightarrow$ displacement current $i_d = 0$

$$\therefore \ \oint \vec{B}\cdot d\vec{l} = \mu_0 i_c$$

At Point B $\longrightarrow$ conduction current $i_c = 0$

$$\therefore \ \oint \vec{B}\cdot d\vec{l} = \mu_0 i_d$$

Equation (1) can be rewrite as

$$\oint \vec{B}\cdot d\vec{l} = \mu_0\left(i + \epsilon_0 \frac{d\phi_E}{dt}\right)$$

known as Ampere Maxwell's Law.

Properties of displacement current:

→ displacement current produces where E. field or E. flux change w.r.t time.

→ displ. current does not exist where E. field doesn't changes or current doesn't changes.

→ displ. current in conducting wire is zero.

→ Together with the conduction current, displacement current satisfy the property of continuity.

NOTE: Maxwell concluded that region where → E. field, → M. field } changes w.r.t time
↓
(EM waves exists)

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Electric & M. field due to a charge.

CASE 1: Charge at Rest $\xrightarrow{\text{will Produce}}$ E-field.

CASE 2: Charge in Motion with uniform velocity

$q \xrightarrow{v}$

charge in Motion $\xrightarrow{\text{produces}}$ current

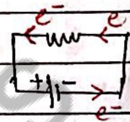
↓ produces   ↓ produces

E. field   M. field

But A/c NCERT: If a charges moves with uniform velocity, it does not Produces E-field.

↓ How?

Actually, If take a electric circuit then electron flows through the conducting wire.



just to circulate the charge (e) ← what's the role of Battery

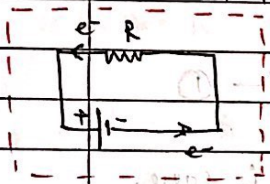
↓ But, As we know

an atom consists of e⁻ & protons.

As e⁻ moves, atoms becomes +vely charged.

Inside gaussian surface. ← But

$E=0$ ⇐ i.e., $q=0$ ← Net charge on the atom is still zero.



gaussian surface.

CASE 3: An accelerated charged Particle Produces a time-varying E & M. field.

$i \rightarrow B$

↑

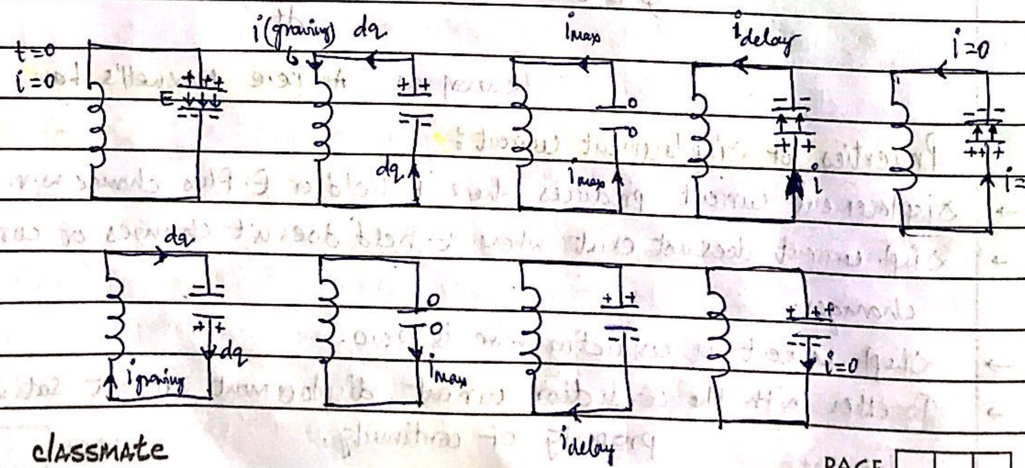
$q \rightarrow E$

↓ produces

Electromagnetic waves.

Accelerated charge $\xrightarrow{\text{known as}}$ Oscillating charge

LC oscillation:



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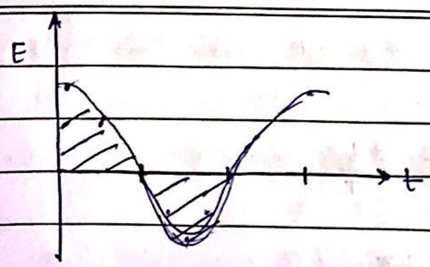
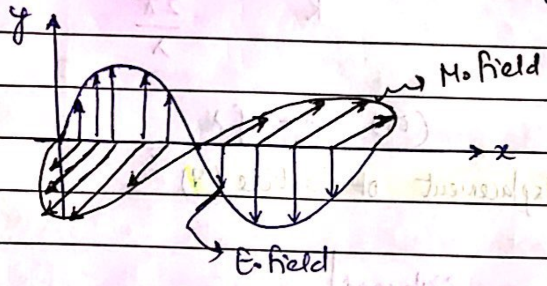


Oscillating Electric Field
↓ accelerated the charges
↓ results in
Oscillating charge.

↳ phenomena occurs in L-C oscillation.

Oscillating E-field Produces an Oscillating M. field:-



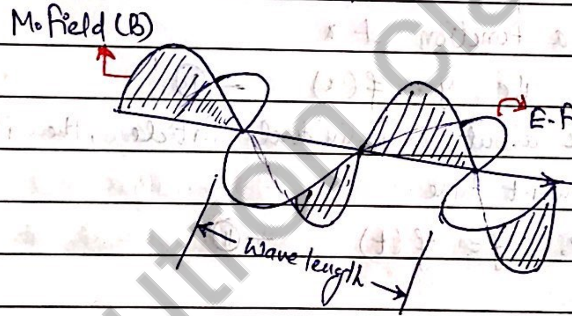
NOTE:-

→ In an atom, an e^- produces the EM waves, when it falls from Higher energy orbit to lower energy orbit

→ When a fast moving e^- suddenly stops → produces EM waves (x-rays).

Transverse Nature Of Electromagnetic wave:

↳ Means M. field (B), E field (E) and Propogation direction are perpendicular to Each other.



As Electromagnetic wave is transverse in Nature:

E. field ⊥er direⁿ of Propagation

& M. field ⊥er direⁿ of Propagation

NOTE: Direⁿ of Propogation is fixed → $\vec{E} \times \vec{B}$

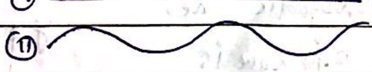
Que E field is in y-direⁿ and M. field is in z-direⁿ Then find the dirⁿ of direⁿ of Propogation.

Solⁿ $\vec{E} \rightarrow \hat{j}$

$\vec{B} \rightarrow \hat{k}$

$\therefore \vec{E} \times \vec{B} = \hat{j} \times \hat{k} = \hat{i}$

Travelling wave:



← In this wave, particles do not move But they oscillates at their position

Wavelength (λ)

Wave Number $k = \frac{2\pi}{\lambda}$

Time Period $= T$; frequency $f = \frac{1}{T}$

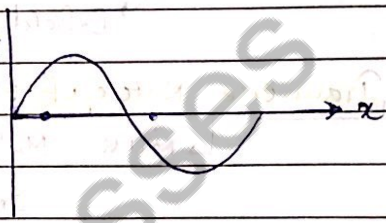
Angular frequency $(\omega) = 2\pi f$ or $\frac{2\pi}{T}$

Speed of Travelling wave $(v) = \frac{\omega}{k} = \frac{2\pi f}{\frac{2\pi}{\lambda}}$

(or) $v = f\lambda$

Equation of wave (or) Displacement of Particle (y)

At every point on x-axis Displacement of Particle is different



∴ we can say Displacement of Particle is a function of x

i.e. $y = f(x)$ —(I)

But if we talk about an individual Particle, then its displacement changes w.r.t time.

∴ $y = f(t)$ —(II)

from (I) & (II)

$y = f(x, t)$

Since the wave is sinusoidal in Nature

∴ $y = A\sin(\underbrace{kx \pm \omega t}_{\text{denotes the phase.}})$

(or)

$y = A\sin(\omega t \pm kx)$

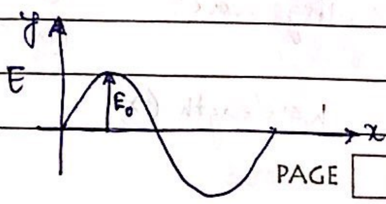
In this equ

+ denotes → wave travelling in −ve x

− denotes → " " +ve x.

Equation of Electromagnetic wave:

let us suppose E.M wave is Moving in +ve x-direc



NOTE: No phase difference in E-field & M-field

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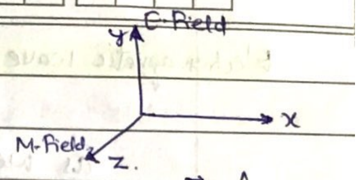
$\therefore y = A\sin(kx - \omega t)$



In terms of Electric field $\vec{E}$

$E = E_0 \sin(kx - \omega t)$ ⟵ Main equation

$\vec{E} = \hat{j}$
$\vec{B} = \hat{k}$
Dire^n of prog → $\hat{i}$
↳ +ve x-axis

$E = E_0 \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$

$E = E_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right) = E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - ft\right)\right]$

In terms of M. field $\vec{B}$

$B = B_0 \sin(kx - \omega t)$

(or)

$B_z = B_0 \sin(kx - \omega t)\hat{k}$

ex. $E_y = 2\sin(0.5\times10^3 x + 1.5\times10^{11} t)\ \frac{N}{C}$

Dire^n of propagation $\xrightarrow{\text{is in}}$ $-x$ direction

Speed of wave ⟶ $v = \frac{\omega}{k} = \frac{1.5\times10^{11}}{0.5\times10^3} = 3\times10^8$ m/s

ex. $B_y = 2\times10^{-7}\sin(0.5\times10^3 x + 1.5\times10^{11} t)$ T.

a) wavelength & frequency

b) Write expression for the E-field.

Dire^n of propagation ($\therefore$ = $-$ve x dire^n)

Compare the above equ^n with $B_y = B_0\sin(kx + \omega t)$

$B_0 = 2\times10^{-7}$; $k = 0.5\times10^3$; $\omega = 1.5\times10^{11}$

As $k = \frac{2\pi}{\lambda}$ $\therefore$ $\lambda = \frac{2\pi}{k} = \frac{2\pi}{0.5\times10^3} = 1.26\times10^{-2}$ m

$\omega = 2\pi f = \frac{2\pi}{T} \Rightarrow f = \frac{\omega}{2\pi} = \frac{1.5\times10^{11}}{2\pi} = 2.38\times10^{10}$ Hz

Peak value of E. field (E_0) and M. field (B_0) is given as

$\frac{E_0}{B_0} = c$ given by Maxwell

$\therefore$ $B_0 \times c = E_0 = (3\times10^8)\times 2\times10^{-7} = 60$ V/m

$\therefore$ $E_z = E_0\sin(kx + \omega t)$

or $E_z = 60\sin(0.5\times10^3 x + 1.5\times10^{11} t)$

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Refractive Index $(\mu \text{ or } \eta) = \frac{c}{v}$ $c \to$ speed of light, $v \to$ speed in Medium

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Electromagnetic wave: Those waves in which there are sinusoidal variation of Electric and M. field vectors at right angles to each other as well as at right angles to the dirch of wave Propagation.

Characteristics and Properties of EM waves:-

1. EM waves are produced by accelerated or oscillating charge
2. waves do not require any material medium for Propogation
3. Travel in free space/air with a speed of 3×10^8 m/s, given as

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

In any other medium $v = \frac{1}{\sqrt{\mu_m \epsilon_m}}$

$\mu_r = \frac{\mu_m}{\mu_0}$

$K = \epsilon_r = \frac{\epsilon_m}{\epsilon_0}$

4. Both Variation in Both Electric & Magnetic field vectors occurs simultaneously. As a result, they attain the Maxm and Minm values at the same time.
5. Both $\vec{E}$ and $\vec{B}$ are in the same phase.
6. $\vec{E}\times\vec{B}$ gives the dirch of Propogation
7. EM waves are transverse in Nature.
8. velocity of EM wave in dielectric is less than $c\,(=3\times10^8$ m/s$)$
9. velocity of EM wave depends entirely on electric and Magnetic Property of the medium in which these waves travel and is independent of the amplitude of the field vectors.

Qu. A Plane electromagnetic wave $E_z = 100\cos(6\times10^8 t + 4x)$ V/m Propagates in a non magnetic medium of dielectric constant.

a) 1.5 b) 3 c) 3.5 d) 4

non magnetic medium → does not have any Magnetic property ∴ such medium occupies the magnetic properties of free space/air ∴ $\mu_m = \mu_0$

Soln
$$v = \frac{\omega}{K} = \frac{6\times10^8}{4} = \frac{3\times10^8}{2} = \frac{c}{2}$$

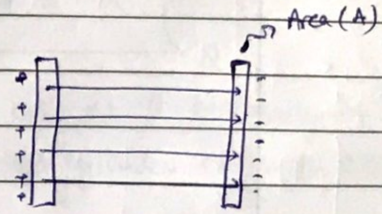
$$v = \frac{1}{\sqrt{\mu_m \epsilon_m}} = \frac{1}{\sqrt{K\epsilon_0\mu_0}} = \frac{c}{\sqrt{K}}$$

$$\therefore \frac{c}{2} = \frac{c}{\sqrt{K}} \Rightarrow K = 4 \quad \text{Ans.}$$

10. EM waves carry energy as they through space. thus, Energy is contained in Oscillating Electric & Magnetic field.
11. Equal distribution of Energy to Both Electric & Magnetic field.

(12) EM waves are produced by charge (accelerated or oscillating) in L-C circuit. E. Field energy is from capacitor (C) and M. Field energy is from inductor (L)

→ **Energy density of E-field (U_E)**



$$U = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\epsilon_0 A}{d}(Ed)^2$$

$$U = \frac{1}{2}\epsilon_0 E^2 (Ad)$$

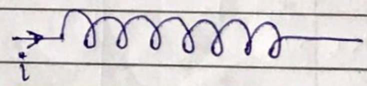
$$U = \frac{1}{2}\epsilon_0 E^2 (\text{Vol.})$$

∴ **Energy density** $= \frac{U}{\text{Vol.}} = \frac{1}{2}\epsilon_0 E^2 \Rightarrow U_E = \frac{1}{2}\epsilon_0 E^2$ → Here we take rms value of E. field.

$$\Rightarrow (U_E)_{avg} = \frac{1}{2}\epsilon_0 E_{rms}^2 = \frac{1}{2}\epsilon_0 \frac{E_0^2}{2} = \frac{1}{4}\epsilon_0 E_0^2$$

Energy density of M. field (U_B)

$$U = \frac{1}{2}Li^2$$



Self Inductance of coil $L = \frac{\mu_0 N^2 \pi R^2 l}{l} = \mu_0 n^2 \pi R^2 l$ where n = no. of turns per unit of length

& $B = \mu_0 n i$

$$\therefore U = \frac{1}{2}(\mu_0 n^2 \pi R^2 l)\frac{B^2}{\mu_0^2 n^2}$$

$$U = \frac{1}{2}\frac{B^2}{\mu_0}\pi R^2 l$$

$$U = \frac{1}{2}\frac{B^2}{\mu_0}(A.l) = \frac{1}{2}\frac{B^2}{\mu_0}\text{Vol.}$$

(or) $\frac{U}{\text{Vol.}} = \frac{1}{2}\frac{B^2}{\mu_0}$ → take rms value

$$\therefore \frac{U}{\text{vol.}} = \frac{1}{2\mu_0}\frac{B_0^2}{2} = \frac{1}{4\mu_0}B_0^2$$

$$\Rightarrow (U_B)_{avg} = \frac{1}{4\mu_0}B_0^2$$

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Qu Show that $(u_B)_{average} = (u_E)_{average}$

Sol^n We know $(u_E)_{average} = \frac{1}{4}\epsilon_0 E_0^2$ & $c = \frac{E_0}{B_0}$ & $c = \frac{1}{\sqrt{\mu_0\epsilon_0}}$

$$= \frac{1}{4}\epsilon_0 (B_0 c)^2$$

$$= \frac{1}{4}\epsilon_0 B_0^2 c^2$$

$$\therefore (u_E)_{average} = \frac{1}{4}\epsilon_0 B_0^2 \frac{1}{\mu_0\epsilon_0}$$

$$(u_E)_{average} = \frac{1}{4}\frac{B_0^2}{\mu_0} = (u_B)_{average}$$ Hence Proved.

Total Energy density in Electromagnetic wave is given as (u) (or) (u_{avg})

$u = u_E + u_B$ (or) $u = u_E + u_B$

$u = 2u_E$ $\qquad$ $u = 2u_B$

$u = 2\frac{1}{4}\epsilon_0 E_0^2$ $\qquad$ $u = 2\left(\frac{1}{4}\frac{B_0^2}{\mu_0}\right)$

$u = \frac{1}{2}\epsilon_0 E_0^2 = \epsilon_0 E_{rms}^2$ $\qquad$ $u = \frac{1}{2}\frac{B_0^2}{\mu_0} = \frac{1}{\mu_0} \times B_{rms}^2$

Note: $(u_{average})_{T.E} = \frac{1}{2}\epsilon_0 E_0^2 = \frac{1}{2}\frac{B_0^2}{\mu_0}$

and $u_E = u_B = \frac{u}{2}$ (or) $(u_E)_{avg} = (u_B)_{avg} = \frac{u_{avg}}{2}$

Intensity of an Electromagnetic wave: (I)

when EM moves → means ~~Energy passed through $1\,m^2$ area in one second.~~

" The energy crossing per unit time in a direction per to the dire^n of Propagation is called intensity of wave".

$$I = \frac{U}{\text{Area} \times \text{time}}$$

This Area should be per to the wave.

unit = watt/m^2

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NOTE: EM waves of different radiations moves with same speed in vacuum but they move with different speeds in a medium.

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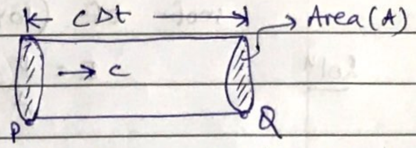
Consider an imaginary cylinder of area of cross-section A and length $c \cdot \Delta t$. Through which EM waves propogates with a speed of light (C)

let u_{avg} be the average energy density of EM wave.



The Energy of EM wave (U) crossing the area of c/s at P Normally in time Δt is the energy of wave contained in a cylinder of length $c\Delta t$ and area of c/s A.

It is given as $u = \frac{U_{avg}}{Vol.}$

or $U = u_{avg} \cdot Vol. = u_{avg}(c\Delta t)A$

$\therefore$ Intensity of EM wave at P is

$$I = \frac{U}{A\Delta t} = \frac{u_{avg}(c\Delta t\, A)}{A\Delta t} = u_{avg}\, c$$

In Terms of E field

$$(u_{avg})_{TE} = \frac{1}{2}\epsilon_0 E_0^2 \quad \therefore I = \frac{1}{2}\epsilon_0 E_0^2 c = \epsilon_0 E_{rms}^2 c$$

$$\left(\because E_{rms} = \frac{E_0}{\sqrt{2}}\right)$$

In Terms of M. field

$$(u_{avg})_{TE} = \frac{1}{2\mu_0}B_0^2 \quad \therefore I = \frac{1}{2}\frac{B_0^2}{\mu_0}c = \frac{1}{\mu_0}B_{rms}^2 c$$

$$\left(\because B_{rms} = \frac{B_0}{\sqrt{2}}\right)$$

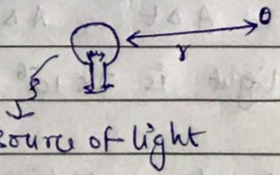
Relation in b/w Power and Intensity:

As $I = \frac{U}{A \times t} \Rightarrow \therefore I = \frac{P}{A}$ → Power

& $Power = \frac{Energy}{time} \Rightarrow \frac{Joule}{second}$

NOTE: Intensity $\propto \frac{1}{(distance)^2}$

ex.,



DATE

Que The Sun delivers 10^8 W/m² of Electromagnetic flux to the earth's surface. The total Power that is incident on a roof of (10×10) m² will be.

Sol^n $I = \frac{P}{A} \Rightarrow P = IA = 10^8 \times 10\times10 = 10^{10}$ W

Momentum of Electromagnetic wave

$\lambda = \frac{h}{p}$ → Planck's constant, → momentum } de-Broglie Hypothesis

Energy = Planck's constant × frequency

$U = h\times f = \frac{hc}{\lambda}$

$\therefore U = pc$ (or) $p = \frac{U}{c}$

NOTE: If a wave strikes somewhere and then it comes back, In such cases momentum will be $2p$ or $\frac{2U}{c}$

* If EM wave is completely absorbed by the surface, it delivers energy U and momentum $\frac{U}{c}$ to surface.

Pointing vector (or) Poynting vector $(\vec{S})$

↓ represents

the dirn of Energy flow per unit area per unit time along the direction of wave propagation.

$$\vec{S} = \frac{1}{\mu_0}(\vec{E}\times\vec{B})$$

Unit of $\vec{S}$: watt/m²

Radiation Pressure: Force exerted by EM wave on unit area of the surface.

$$R.P = \frac{\text{force}}{\text{area}} = \frac{\text{change in momentum/time}}{\text{area}}$$

$$R.\ \text{Pressure} = \frac{p}{A\Delta t} = \frac{U/c}{A\Delta t} = \frac{U}{A\Delta t}\times\frac{1}{c} = \frac{I}{c}$$

NOTE: R. Pressure of visible light is 7×10^{-6} N/m² → found by Nicols and Hull.

Then find force due to radiation pressure of visible light on the S. Area 10 cm² is $= \frac{7\times10^{-6}}{10\times10^{-4}} = 7\times10^{-9}$ N.

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