

CUET · PHYSICS · CLASS XII · CODE 322

Electromagnetic Waves

CUET unit: Electromagnetic Waves

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Snapshot

- Maxwell removed a contradiction in Ampere's circuital law by introducing the **displacement current** $i_d = \epsilon_0 (d\Phi_E/dt)$, giving the **Ampere–Maxwell law**.
- Time-varying electric and magnetic fields regenerate each other, leading to the prediction of **electromagnetic waves** that propagate at $c = 1/\sqrt{(\mu_0 \epsilon_0)} \approx 3 \times 10^8$ m/s — the speed of light.
- EM waves are **transverse**: $E \perp B \perp$ direction of propagation, with $E_0/B_0 = c$; they need no material medium.
- The **electromagnetic spectrum** runs from γ -rays ($\lambda \sim 10^{-12}$ m) up to long radio waves ($\lambda \sim 10^6$ m), classified by production/detection mechanisms.
- CUET regularly tests: displacement current definition/formula, characteristics of EM waves, $c = 1/\sqrt{(\mu_0 \epsilon_0)}$, $E_0/B_0 = c$, and matching spectrum bands to wavelengths/uses/sources.

Detailed Notes

2.1 Core concepts

Two earlier results set the stage: an electric current produces a magnetic field (Ampere, Oersted) and a changing magnetic field produces an electric field (Faraday). James Clerk Maxwell asked the symmetric converse — does a changing electric field produce a magnetic field? — and answered yes (NCERT §8.1, p. 201). His route to the answer was through a paradox he discovered while applying Ampere's circuital law $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 i(t)$ to a charging parallel-plate capacitor (NCERT §8.2, p. 202, Eq. 8.1).

For a flat circular Amperian loop of radius r outside the capacitor and perpendicular to the wire, the conduction current $i(t)$ pierces the disk, giving $B(2\pi r) = \mu_0 i(t)$ (NCERT §8.2, p. 202, Eq. 8.2). But the same closed loop also bounds a **pot-shaped** surface whose bottom slips between the capacitor plates, and a **tiffin-box** surface with a flat circular bottom S between the plates (NCERT Fig. 8.1, p. 203). Neither pot nor tiffin-box is pierced by any conduction current — yet Ampere's law should give the same B at point P regardless of which surface we choose. The two calculations clash: a non-zero B on one surface, zero B on the other (NCERT §8.2, p. 203).

Maxwell recognised that the missing physical input is the **electric flux** between the plates. With plate area A and instantaneous charge Q , the field is $E = (Q/A)/\epsilon_0$, so $\Phi_E = |E|A = Q/\epsilon_0$ (NCERT §8.2, p. 203, Eq. 8.3). When Q changes with time, $\epsilon_0 (d\Phi_E/dt) =$

$dQ/dt = i$ — exactly the conduction current in the external wire (NCERT §8.2, p. 203, Eq. 8.4). Identifying this quantity as a new "current" — the **displacement current** $i_d = \epsilon_0 (d\Phi_E/dt)$ — restores consistency: i_d flows where i_c cannot, and the total current $i = i_c + i_d$ is the same through any surface bounded by the loop (NCERT §8.2, p. 204, Eq. 8.5). Outside the capacitor only conduction current exists ($i_d = 0$); between the plates only displacement current exists ($i_c = 0, i_d = i$).

The generalised statement is the **Ampere–Maxwell law**: $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 i_c + \mu_0 \epsilon_0 (d\Phi_E/dt)$ (NCERT §8.2, p. 204, Eq. 8.6). Maxwell wrote this together with three other equations — Gauss's law for electricity $\oint \mathbf{E} \cdot d\mathbf{A} = Q/\epsilon_0$, Gauss's law for magnetism $\oint \mathbf{B} \cdot d\mathbf{A} = 0$ (no magnetic monopoles), and Faraday's law $\oint \mathbf{E} \cdot d\mathbf{l} = -d\Phi_B/dt$ — to give the four **Maxwell's equations in vacuum** which, with the Lorentz force $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, encode all of classical electromagnetism (NCERT §8.2 box, p. 205).

The symmetry is striking. Faraday says a changing \mathbf{B} produces \mathbf{E} ; Ampere–Maxwell says a changing \mathbf{E} produces \mathbf{B} . If a region has time-varying fields, each field acts as the source of the other and the disturbance need not stay put — it can detach from any source and propagate. This is the qualitative mechanism by which Maxwell predicted **electromagnetic waves** (NCERT §8.2, p. 204–205).

Sources of EM waves (§8.3.1, p. 205). Stationary charges produce only electrostatic fields; uniformly moving charges (steady currents) produce only static magnetic fields. Neither radiates. Only **accelerated charges** radiate EM waves, and an oscillating charge of frequency ν radiates waves of exactly the same frequency ν . An electric dipole is the simplest source. The wave carries off energy at the expense of the source's kinetic energy. Experimental confirmation came in 1887 from **Heinrich Hertz**, who produced and detected radio-region waves; seven years later **Jagadish Chandra Bose** at Calcutta generated much shorter wavelengths of 25 mm to 5 mm; and **Guglielmo Marconi** transmitted EM waves over many kilometres, opening up wireless communication (NCERT §8.3.1, p. 205–206).

Nature of EM waves (§8.3.2, p. 206). Solving Maxwell's equations in free space yields plane-wave solutions in which \mathbf{E} and \mathbf{B} are mutually perpendicular and both perpendicular to the direction of propagation — i.e., EM waves are **transverse**. For a wave travelling along z with \mathbf{E} along x and \mathbf{B} along y , $E_x = E_0 \sin(kz - \omega t)$ and $B_y = B_0 \sin(kz - \omega t)$ (NCERT Eqs. 8.7a, 8.7b, p. 206). The angular frequency ω and wave vector k are related by $\omega = ck$ where the constant $c = 1/\sqrt{\mu_0 \epsilon_0}$; equivalently $\nu \lambda = c$ (NCERT Eqs. 8.9a, 8.9b, p. 207). When μ_0 and ϵ_0 are inserted numerically, c works out to $\approx 3 \times 10^8$ m/s — the same as the measured speed of light. This single observation forced the conclusion that **light is an electromagnetic wave**, unifying optics with electricity and magnetism.

The amplitudes of the two oscillating fields are not independent: $B_0 = E_0/c$, so the magnetic-field amplitude is smaller than the electric-field amplitude by a factor of c (NCERT Eq. 8.10, p. 207). EM waves are self-sustaining: unlike sound or water waves they require **no material medium** and travel through vacuum. In a medium of

permittivity ϵ and permeability μ the wave speed is $v = 1/\sqrt{(\mu \epsilon)}$, which is less than c ; this dependence is the microscopic origin of the refractive index (NCERT Eq. 8.11, p. 207). The vacuum speed c is independent of wavelength to within metres-per-second and is now used to **define** the metre.

Electromagnetic spectrum (§ 8.4, p. 208–211). Classification is by frequency/wavelength and reflects production and detection methods, not sharp physical boundaries.

- **Radio waves** — $\lambda > 0.1$ m. Produced by the accelerated motion of free electrons in conducting wires and aerials. AM band 530 kHz–1710 kHz; short-wave bands up to 54 MHz; TV 54–890 MHz; FM 88–108 MHz; cellular telephones in the UHF band (NCERT §8.4.1, p. 209).
- **Microwaves** — 0.1 m to 1 mm (GHz range). Produced by klystrons, magnetrons and Gunn diodes. Short wavelengths and good directionality make them ideal for **radar** (aircraft navigation, speed guns for cars and tennis serves). In a microwave oven the frequency is chosen to match the resonant frequency of water molecules, transferring energy efficiently as kinetic energy and raising the temperature of food (NCERT §8.4.2, p. 209).
- **Infrared (heat) waves** — 1 mm to 700 nm. Produced by the vibration of atoms and molecules in hot bodies. Strongly absorbed by water, CO_2 and NH_3 , making them useful in physical therapy and Earth-observing satellites. Infrared LEDs power TV/video remotes. Infrared trapping by atmospheric CO_2 and water vapour is the **greenhouse effect** that keeps Earth warm (NCERT §8.4.3, p. 210).
- **Visible light** — 700 nm to 400 nm, frequency 4×10^{14} Hz to 7×10^{14} Hz. Produced when electrons in atoms drop between energy levels; detected by the eye, photocells and photographic film (NCERT §8.4.4, p. 210).
- **Ultraviolet** — 4×10^{-7} m down to 6×10^{-10} m. Produced by special lamps, very hot bodies and the Sun; absorbed by the ozone layer at 40–50 km altitude, so CFC-driven ozone depletion is a serious concern. Causes tanning by stimulating melanin production; used in **LASIK** eye surgery (laser-assisted in situ keratomileusis) and to sterilise water (NCERT §8.4.5, p. 210).
- **X-rays** — 10^{-8} m to 10^{-13} m. Produced by bombarding a metal target with high-energy electrons (X-ray tubes) or from inner-shell electron transitions; used for medical diagnosis and to treat certain cancers. Because they damage tissue, exposure must be minimised (NCERT §8.4.6, p. 211).
- **Gamma rays** — $\lambda < 10^{-10}$ m down to below 10^{-14} m. Produced by nuclear reactions and **radioactive decay**; used in medicine to destroy cancer cells (NCERT §8.4.7, p. 211).

A key conceptual takeaway (NCERT Points to Ponder, p. 213) is that the **only** basic difference between bands is wavelength/frequency — every band travels at c in vacuum. The wavelength typically correlates with the size of the radiating system: γ -

rays from atomic nuclei ($\sim 10^{-14}$ m), X-rays from heavy atoms, visible light from atomic electron transitions, radio waves from antennas the size of metres.

2.2 Definitions to memorise

Term	Definition	Page
Displacement current (i_d)	The current $i_d = \epsilon_0 (d\Phi E/dt)$ due to a time-varying electric flux; acts as a source of magnetic field exactly like conduction current.	203–204
Conduction current (i_c)	Current carried by conductors due to the flow of charges.	203
Ampere–Maxwell law	$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 i_c + \mu_0 \epsilon_0 (d\Phi E/dt)$ — generalised Ampere's law including displacement current.	204
Gauss's law for electricity	$\oint \mathbf{E} \cdot d\mathbf{A} = Q/\epsilon_0$ — relates electric flux to enclosed charge.	205
Gauss's law for magnetism	$\oint \mathbf{B} \cdot d\mathbf{A} = 0$ — no isolated magnetic monopoles.	205
Faraday's law	$\oint \mathbf{E} \cdot d\mathbf{l} = -d\Phi B/dt$ — emf equals rate of change of magnetic flux.	205
Maxwell's equations	The four equations of electromagnetism in vacuum.	205
Electromagnetic wave	Coupled time-varying electric and magnetic fields propagating through space; transverse and self-sustaining.	201, 207
Speed of EM waves in vacuum	$c = 1/\sqrt{(\mu_0 \epsilon_0)} \approx 3 \times 10^8$ m/s; same for all wavelengths.	207
E_0/B_0 ratio	$E_0/B_0 = c$ (i.e., $B_0 = E_0/c$).	207
Wave number (k)	$k = 2\pi/\lambda$ — magnitude of propagation vector.	207
Angular frequency (ω)	$\omega = 2\pi\nu$; satisfies $\omega = ck$ for vacuum EM waves.	207
Wave speed in medium	$v = 1/\sqrt{(\mu \epsilon)}$, where ϵ and μ are the medium's permittivity and permeability.	207
Electromagnetic spectrum	Classification of EM waves by frequency/wavelength, from γ -rays ($\sim 10^{-12}$ m) to long radio waves ($\sim 10^6$ m).	208
Radio waves	EM waves with $\lambda > 0.1$ m, produced by accelerated electrons in aerials.	209
Microwaves	EM waves of 0.1 m–1 mm produced by klystrons/magnetrons.	209
Infrared (heat waves)	EM waves of 1 mm–700 nm produced by molecular vibration.	210
Visible light	EM waves of 700–400 nm, detected by the eye.	210
Ultraviolet	EM waves of 400 nm to 0.6 nm, mostly absorbed by ozone.	210

Term	Definition	Page
X-rays	EM waves of $10\text{ nm} - 10^{-4}\text{ nm}$ produced by bombarding metal targets.	211
Gamma rays	EM waves of $\lambda < 10^{-10}\text{ m}$ from nuclear/radioactive sources.	211
Greenhouse effect	Trapping of re-radiated infrared from earth's surface by gases like CO_2 and water vapour.	210

2.3 Diagrams / processes to remember

- **Fig. 8.1 (p. 203):** Parallel-plate capacitor with three Amperian surfaces — flat disk (a), pot-shaped surface (b) whose bottom lies between the plates, and a tiffin-box surface (c). The three surfaces share the same circular rim, so Ampere's law must give the same B at point P regardless of which surface we choose — the contradiction that motivates id .
- **Fig. 8.2 (p. 204):** The electric and magnetic fields E and B between the capacitor plates at point M , and a cross-sectional view showing concentric circular B -lines around the displacement-current axis — the perpendicularity of E and B emerging directly from displacement current.
- **Fig. 8.3 (p. 206):** A linearly polarised plane EM wave travelling along $+z$ with E_x along the x -axis and B_y along the y -axis. The two sinusoids are in phase and of perpendicular polarisation — a visual proof that $E \perp B \perp$ direction of propagation.
- **Fig. 8.4 (p. 209):** The full electromagnetic spectrum on a logarithmic axis from 10 Hz (long radio) up to 10^{23} Hz (γ -rays), with corresponding wavelengths from 10^7 m down to 10^{-14} m and a side-bar showing the $400\text{--}700\text{ nm}$ visible band with violet \rightarrow red colours.
- **Table 8.1 (p. 211):** Wavelength range, production mechanism, and detector for each band of the spectrum — high-yield for CUET matching items. Worth memorising: aerials/receiver aerials for radio; klystron–point-contact diode for microwaves; vibrating molecules–thermopile/bolometer for IR; atomic transitions–eye for visible; inner-shell electrons–photocell for UV; X-ray tubes–Geiger tube/ionisation chamber for X-rays; radioactive decay–Geiger tube for γ -rays.
- **Worked Example 8.1 (p. 208):** Given $E = 6.3\hat{j}\text{ V/m}$ for a wave moving along x at 25 MHz , B is found from $B_0 = E_0/c = 2.1 \times 10^{-8}\text{ T}$ with direction along z from $E \times B$ pointing along the propagation direction.
- **Worked Example 8.2 (p. 208):** From $B_y = (2 \times 10^{-7}) \sin(0.5 \times 10^3 x + 1.5 \times 10^{11} t)$, comparison gives $\lambda = 1.26\text{ cm}$, $\nu = 23.9\text{ GHz}$, and $E_0 = B_0 c = 60\text{ V/m}$ along the z -axis.

2.4 Common confusions / NTA trap points

- Treating displacement current as a real flow of charge — it is **not**. It is due to a time-varying electric field but produces magnetic field exactly like conduction current (NCERT p. 203–204).
- Confusing the **wavelength order**: increasing wavelength is γ -rays < X-rays < UV < visible < IR < microwaves < radio. Many students reverse this (NCERT Summary point 6, p. 212).
- Forgetting that **all EM waves travel at the same speed c in vacuum** — they differ only in wavelength/frequency (NCERT Points to Ponder 1, p. 213).
- Mixing up the amplitude relation: it is $B_0 = E_0/c$ (not $E_0 = B_0/c$). NTA distractors swap c into the wrong position (NCERT Eq. 8.10, p. 207).
- Writing $c = \sqrt{(\mu_0 \epsilon_0)}$ instead of $c = 1/\sqrt{(\mu_0 \epsilon_0)}$ — a common slip when nervous (NCERT Eq. 8.9a, p. 207).
- Assigning the wrong source: **microwave ovens use microwaves** (resonant with water molecules), **radar uses microwaves**, **radioactive decay produces γ -rays**, **inner-shell transitions/bombarding metal produces X-rays** — NTA loves matching these (Table 8.1, p. 211).
- Believing EM waves need a medium; in fact they are **self-sustaining in vacuum** (p. 207).
- Calling EM waves longitudinal — they are transverse, with E and B oscillating perpendicular to the direction of propagation (NCERT §8.3.2, p. 206).
- Forgetting that a **uniformly moving** charge does not radiate — only accelerated (oscillating) charges do (NCERT §8.3.1, p. 205).
- Confusing UV absorption: the ozone layer at 40–50 km absorbs solar UV; ordinary glass also absorbs UV, which is why one cannot tan through a window (NCERT §8.4.5, p. 210).
- Mis-identifying who first generated short-wavelength microwaves: it was **J.C. Bose at Calcutta** (25 mm to 5 mm), not Hertz or Marconi (NCERT §8.3.1, p. 206).
- Forgetting the symmetric companion of Faraday: a changing E induces B (Ampere–Maxwell) just as a changing B induces E (Faraday) — this symmetry is the **reason** EM waves can exist (NCERT §8.2, p. 204).

2.5 Key formulas table

Symbol	Formula	Meaning	NCERT page
i_d	$i_d = \epsilon_0 (d\Phi_E/dt)$	Displacement current from changing electric flux	203, Eq. 8.4
Φ_E	$\Phi_E = Q/\epsilon_0$ (between capacitor plates)	Electric flux between plates of charge Q	203, Eq. 8.3

Symbol	Formula	Meaning	NCERT page
i (total)	$i = i_c + i_d = i_c + \epsilon_0 (d\Phi E/dt)$	Total current = conduction + displacement	204, Eq. 8.5
Ampere–Maxwell	$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 i_c + \mu_0 \epsilon_0 (d\Phi E/dt)$	Generalised Ampere's law	204, Eq. 8.6
Gauss (E)	$\oint \mathbf{E} \cdot d\mathbf{A} = Q/\epsilon_0$	Maxwell equation 1	205
Gauss (B)	$\oint \mathbf{B} \cdot d\mathbf{A} = 0$	Maxwell equation 2 (no monopoles)	205
Faraday	$\oint \mathbf{E} \cdot d\mathbf{l} = -d\Phi B/dt$	Maxwell equation 3	205
Plane EM wave (E)	$E_x = E_0 \sin(kz - \omega t)$	Electric component travelling along +z	206, Eq. 8.7a
Plane EM wave (B)	$B_y = B_0 \sin(kz - \omega t)$	Magnetic component, in phase with E	206, Eq. 8.7b
Wave number	$k = 2\pi/\lambda$	Magnitude of propagation vector	206, Eq. 8.8
Dispersion	$\omega = ck$	Frequency–wavevector relation	207, Eq. 8.9a
Frequency–wavelength	$\nu \lambda = c$	EM wave dispersion in vacuum	207, Eq. 8.9b
Amplitude ratio	$B_0 = E_0/c$	Magnetic to electric amplitude ratio	207, Eq. 8.10
Vacuum speed	$c = 1/\sqrt{(\mu_0 \epsilon_0)} \approx 3 \times 10^8$ m/s	Speed of light in vacuum	207, Eq. 8.9a
Medium speed	$v = 1/\sqrt{(\mu \epsilon)}$	EM wave speed in a medium	207, Eq. 8.11
Photon energy	$E = h\nu$	Energy of a photon of frequency ν	214, Ex. 8.9
EM wave power	(cylindrical capacitor) $i = \epsilon_0 A (dE/dt)$	Displacement current through plate area A	203
Refractive index	$n = c/v = \sqrt{(\mu \epsilon / \mu_0 \epsilon_0)}$	Ratio of vacuum to medium speed	207


 PYQ Alignment

CUET (UG) Physics consistently draws 6–8 MCQs each year from this chapter, most often on the displacement current formula, $c = 1/\sqrt{(\mu_0 \epsilon_0)}$, the $E_0/B_0 = c$ relation, and direct matching of EM spectrum bands with wavelength ranges, sources (klystron, radioactive decay, hot bodies, inner-shell electrons) and uses (radar, LASIK, cancer treatment, greenhouse effect). Assertion–reason and match-the-following items based on Table 8.1 are especially frequent.

CUET 2025 — Actual PYQs from this chapter

Q.30 (CUET 2025) Maxwell displacement current is due to:

- A) flow of charges B) changing gravitational field C) changing electric field D) twice rate of change of magnetic flux **Tests:** Displacement current — due to changing electric field **Answer:** Not in extracted key

Q.31 (CUET 2025) Match List-I (Electromagnetic waves) with List-II (Wavelength range).
List-I List-II (A) X-rays (i) 1 nm to 700 nm (B) Radio waves (ii) 0.1 m to 1 mm (C) Infrared waves (iii) 1 nm to 10^{-3} nm (D) Microwaves (iv) > 0.1 m Choose the correct answer.

- A) (A-IV), (B-III), (C-II), (D-I) B) (A-IV), (B-II), (C-I), (D-III) C) (A-III), (B-IV), (C-I), (D-II) D) (A-III), (B-IV), (C-II), (D-I) **Tests:** Electromagnetic spectrum — wavelength ranges of X-ray, radio, IR, microwave **Answer:** Not in extracted key

Q.32 (CUET 2025) The electric field associated with a progressive electromagnetic wave is $E = E_0 \sin(kx - \omega t)$ If B_0 is the amplitude of the magnetic field, then the relation between E_0 and B_0 is:

- A) $E_0/B_0 = \omega/k$ B) $E_0/B_0 = \omega^2/k^2$ C) $E_0/B_0 = k/\omega$ D) $E_0/B_0 = k^2/\omega^2$ **Tests:** EM wave — $E_0/B_0 = c = \omega/k$ **Answer:** Not in extracted key

CUET 2024 — Actual PYQs from this chapter

Q.16 (CUET 2024) Ratio of energy density electric : magnetic in EM wave:

- A) 1:1 B) 1:c C) c:1 D) $1:c^2$ **Tests:** Energy density ratio (electric : magnetic) in EM waves **Answer:** Not in extracted key

Q.17 (CUET 2024) Correct EM spectrum decreasing wavelength:

- A) Radio \rightarrow X \rightarrow IR \rightarrow Microwave \rightarrow Visible B) IR \rightarrow Microwave \rightarrow Radio \rightarrow X \rightarrow Visible C) Radio \rightarrow Microwave \rightarrow IR \rightarrow Visible \rightarrow X D) X \rightarrow Visible \rightarrow IR \rightarrow Microwave \rightarrow Radio **Tests:** Electromagnetic spectrum — order by decreasing wavelength **Answer:** Not in extracted key

Q.18 (CUET 2024) Match EM waves with production: Microwaves Infrared X-rays Radio waves Devices include LC oscillator, magnetron etc.

- (options not in extracted source — see official paper) **Tests:** Sources of EM waves — microwaves, IR, X-rays, radio **Answer:** Not in extracted key

CUET 2023 — Actual PYQs from this chapter

Q.24 (CUET 2023) Match List-I with List-II. List I List II A. X-rays I. (10^{14} – 3×10^{14}) Hz B. Microwaves II. (10^8 – 3×10^{11}) Hz C. Radiowaves III. (10^{15} – 5×10^{19}) Hz D. Infrared IV. (5×10^{11} – 10^{14}) Hz Options:

- A) A-III, B-II, C-I, D-IV B) A-II, B-I, C-IV, D-III C) A-I, B-II, C-IV, D-III D) A-IV, B-III, C-II, D-I **Tests:** Frequency ranges in the electromagnetic spectrum **Answer:** Not in extracted key

Q.25 (CUET 2023) An electromagnetic wave travelling in vacuum is described by ($E = E_0 \sin(kx - \omega t)$) and ($B = B_0 \sin(kx - \omega t)$). Which relation is correct?

- A) ($E_0 = B_0 c$) B) ($E_0 = B_0 / c$) C) ($E_0 B_0 = ck$) D) ($E_0 / B_0 = \sqrt{\mu_0 / \epsilon_0}$) **Tests:** Relation $E_0 = B_0 c$ for EM waves in vacuum **Answer:** Not in extracted key

Q.44 (CUET 2023) The height of a TV tower is 180 m. Maximum transmission distance is:

- A) 18 km B) 90 km C) 48 km D) 64 km 45. Match List-I with List-II. List I List II Modulation Retrieval of information Baseband Original signal Demodulation Extraction of signal Bandwidth Frequency range **Tests:** Line-of-sight transmission distance for a TV tower (radiowave propagation) **Answer:** Not in extracted key

Q.48 (CUET 2023) Displacement current due to time varying electric field is:

- A) ($\frac{d\phi_E}{dt}$) B) ($\epsilon_0 \frac{d\phi_E}{dt}$) C) ($\mu_0 \epsilon_0 \frac{d\phi_E}{dt}$) D) ($\phi_E \frac{d}{dt}$) **Tests:** Displacement current $I_d = \epsilon_0 \frac{d\phi_E}{dt}$ **Answer:** Not in extracted key