



Rewarding Learning

ADVANCED
General Certificate of Education
2025

Centre Number

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Candidate Number

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Physics

StemUp Model Solution

Assessment Unit A2 2
assessing

Fields, Capacitors and
Particle Physics



[APH21]

APH21

MONDAY 9 JUNE, MORNING

TIME

2 hours.

INSTRUCTIONS TO CANDIDATES

Write your Centre Number and Candidate Number in the spaces provided at the top of this page.

You must answer the questions in the spaces provided.

Do not write outside the boxed area on each page or on blank pages.

Complete in black ink and use a dark HB pencil for drawings and graphs.

Do not write with a gel pen.

Answer **all nine** questions.

INFORMATION FOR CANDIDATES

The total mark for this paper is 100.

Figures in brackets printed down the right-hand side of pages indicate the marks awarded to each question or part question.

You may use a scientific calculator.

A Data and Formulae Sheet is included in this question paper.

Quality of written communication will be assessed in Question 7.

14731.05R



- 1 A circuit containing two identical capacitors of unknown capacitance is shown in Fig. 1.1.

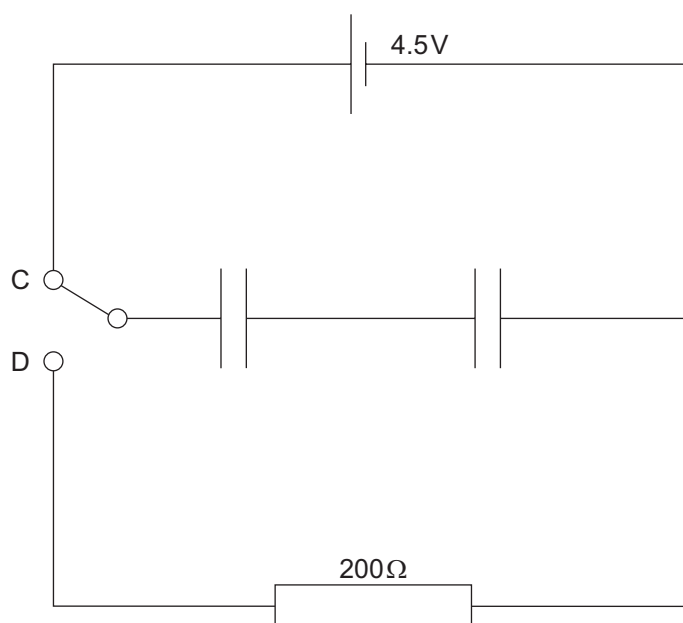


Fig. 1.1

The capacitors are charged by moving a two-way switch to position C, which connects them to a cell of voltage of 4.5V. The two-way switch is then turned to position D, so the capacitors begin to discharge through the 200Ω resistor.

- (i) Calculate the initial current that will flow through the 200Ω resistor immediately after the switch has been moved to position D.

$$V = IR$$

$$4.5 = I \times 200$$

$$I = 4.5 / 200 = 0.0225 \text{ A}$$

Initial current = 0.0225 A [3]



- (ii) If after a time of 120 s the current flowing through the resistor is 1.42 mA, calculate the time constant of the circuit.

$$I = 1.42 \text{ mA} = 1.42 \times 10^{-3} \text{ A}$$

$$I = I_0 e^{-t/\tau}$$

$$1.42 \times 10^{-3} = 0.0225 e^{-120/\tau}$$

$$\ln (0.0225 / 1.42 \times 10^{-3}) = 120 / \tau$$

$$\ln 15.85 = 2.763 = 120 / \tau$$

$$\tau = 120 / 2.763 = 43.4 \text{ s}$$

Time constant = 43.4 s [5]

- (iii) Calculate the capacitance of one of the capacitors.

$$\tau = RC_T, \text{ where } C_T \text{ is the total capacitance}$$

$$43.4 = 200 \times C_T$$

$$C_T = 43.4 / 200 = 0.217 \text{ F}$$

$$\text{Two identical capacitors in series: } 1/C_T = 1/C + 1/C = 2/C$$

$$C = 2C_T = 2 \times 0.217 = 0.434 \text{ F}$$

Capacitance = 0.434 F [3]

[Turn over]

14731.05R



- 2 (i) Explain the concept of a field of force.

A field of force is a region of space in which an object (such as a mass or a charge) will experience a force.

[2]

- (ii) State one similarity and two differences between gravitational and electric fields.

Similarity: both obey an inverse square law, the field strength is proportional to $1/r^2$, where r is the separation. Both also have infinite range.

Difference 1: gravitational fields act on masses, whereas electric fields act on charged particles.

Difference 2: gravitational fields can only attract, whereas electric fields can attract or repel.

[3]



- (iii) Fig. 2.1 represents the electric field around an electron. On Fig. 2.2 sketch the electric field lines around an alpha particle. [3]

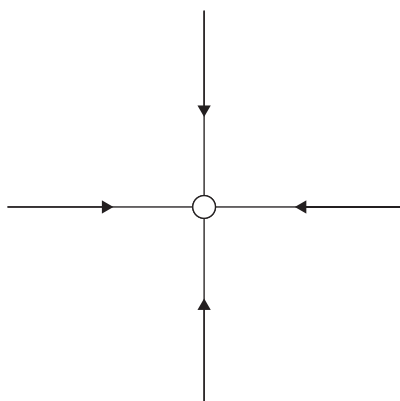


Fig. 2.1

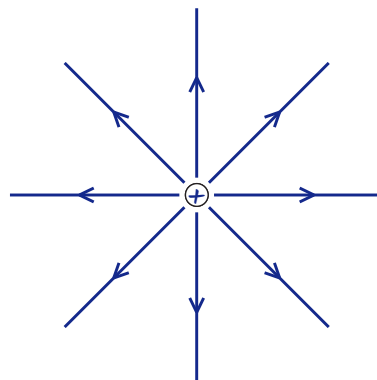


Fig. 2.2

- (iv) Explain why electric field lines can never cross.

Field lines show the direction of the force on a positive charge, i.e. the direction of the field at each point.

If two lines crossed, the field would have two directions at a single point, which is impossible.

[2]

[Turn over



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3 Kepler's third law is stated mathematically in **Equation 3.1**.

$$T^2 \propto r^3$$

Equation 3.1

- (a) (i) Express this law in words.

The square of the orbital time period of a planet is directly proportional to the cube of its mean distance (orbital radius) from the Sun.

[2]

- (ii) Show that Kepler's third law is consistent with Newton's law of universal gravitation.

The gravitational force provides the centripetal force:

$$GMm / r^2 = mr\omega^2 \quad (\text{or } mv^2 / r)$$

$$\text{and } \omega = 2\pi / T, \text{ so } GMm / r^2 = mr(2\pi / T)^2 = 4\pi^2 mr / T^2$$

Cancel the mass m of the planet and rearrange:

$$T^2 = (4\pi^2 / GM) r^3 \quad \text{or} \quad T^2 / r^3 = 4\pi^2 / GM$$

where M is the mass of the Sun.

$4\pi^2 / GM$ is a constant, since G and M are both constant,

so $T^2 \propto r^3$, which is Kepler's third law.

[5]

[Turn over]



- (b) The moon orbits Earth at a mean radius of $3.84 \times 10^8 \text{ m}$ and takes an average of 27.3 days to orbit the Earth.

The radius of Earth is $6.40 \times 10^3 \text{ km}$.

- (i) Use Kepler's third law to calculate the time period of a satellite placed in a circular orbit $12.5 \times 10^3 \text{ km}$ above Earth's surface.

$$r = 6.40 \times 10^3 + 12.5 \times 10^3 = 18.9 \times 10^3 \text{ km} = 18.9 \times 10^6 \text{ m}$$

T^2 / r^3 is the same for the Moon and the satellite:

$$27.3^2 / (3.84 \times 10^8)^3 = T^2 / (18.9 \times 10^6)^3$$

$$T^2 = 27.3^2 \times (18.9 \times 10^6 / 3.84 \times 10^8)^3 = 0.0889 \text{ days}^2$$

$$T = 0.298 \text{ days}$$

$$T = 0.298 \times 24 \times 3600 = 2.576 \times 10^4 \text{ s} \approx 2.57 \times 10^4 \text{ s}$$

Time period = 2.57×10^4 s [5]

- (ii) Calculate the acceleration of the satellite in this orbit.

$$a = \omega^2 r = 4\pi^2 r / T^2$$

$$a = 4\pi^2 \times 18.9 \times 10^6 / (2.576 \times 10^4)^2$$

$$a = 1.12 \text{ m s}^{-2}$$

Acceleration = 1.12 m s⁻² [3]



- (iii) Use your answer from (b)(ii) to show that the mass of Earth is 6×10^{24} kg.
You are advised to show clearly your working out.

The satellite's acceleration is the gravitational field strength g there:

$$g = GM_E / r^2$$

$$1.12 = 6.67 \times 10^{-11} \times M_E / (18.9 \times 10^6)^2$$

$$M_E = 1.12 \times (18.9 \times 10^6)^2 / 6.67 \times 10^{-11}$$

$$M_E = 5.998 \times 10^{24} \text{ kg} \approx 6.0 \times 10^{24} \text{ kg}$$

[2]



- 4 Two electrons are initially stationary 5.2 mm apart at the surface of a metal plate. A potential difference of 450 V is applied between the plate and another plate 0.15 m above, as shown in Fig. 4.1.

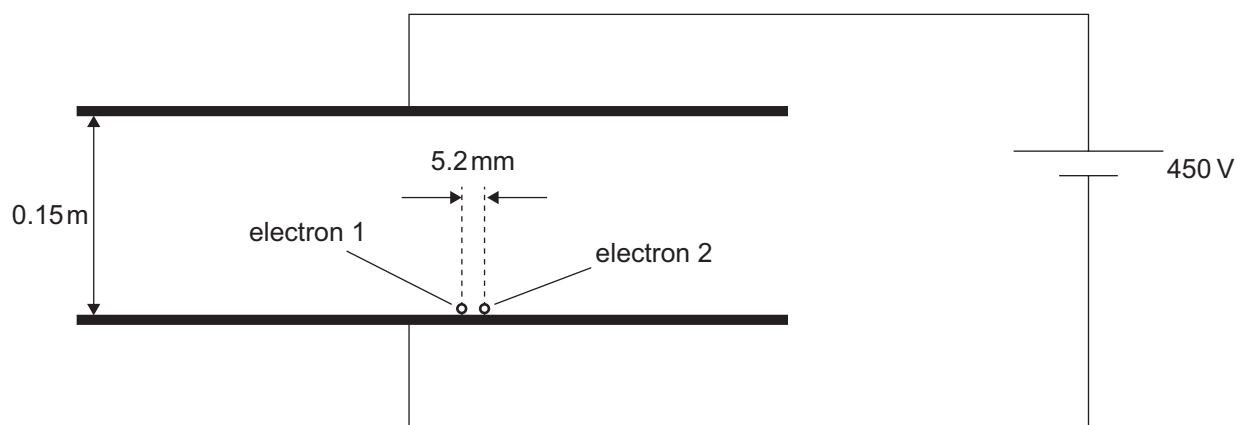


Fig. 4.1

- (i) Show that the electric field strength E_e at the position of electron 2 due to electron 1 is negligible when compared to the electric field strength E_p produced by the plates.

Field due to the plates: $E_p = V / d = 450 / 0.15 = 3000 \text{ V m}^{-1}$

Field due to electron 1 at electron 2 (point charge):

$$E_e = q / 4\pi\epsilon_0 r^2$$

$$E_e = 1.6 \times 10^{-19} / (4\pi \times 8.85 \times 10^{-12} \times (5.2 \times 10^{-3})^2)$$

$$E_e = 5.32 \times 10^{-5} \text{ V m}^{-1}$$

$$E_p / E_e = 3000 / 5.32 \times 10^{-5} \approx 5.6 \times 10^7$$

so $E_e \ll E_p$: the field due to electron 1 is negligible.

[6]



- (ii) Calculate the force on one of the electrons due to the electric field between the plates.

$$F = eE$$

$$F = 1.6 \times 10^{-19} \times 3000$$

$$F = 4.8 \times 10^{-16} \text{ N}$$

$$\text{Force} = \underline{4.8 \times 10^{-16}} \text{ N [3]}$$

The electrons accelerate from rest towards the positively charged plate.

- (iii) Calculate the velocity of the electrons as they hit the plate.

$$F = ma, \text{ so } a = F / m = 4.8 \times 10^{-16} / 9.11 \times 10^{-31}$$

$$a = 5.27 \times 10^{14} \text{ m s}^{-2}$$

$$v^2 = u^2 + 2as, \text{ with } u = 0 \text{ and } s = 0.15 \text{ m}$$

$$v^2 = 0 + 2 \times 5.27 \times 10^{14} \times 0.15 = 1.58 \times 10^{14}$$

$$v = 1.26 \times 10^7 \text{ m s}^{-1}$$

$$\text{Velocity} = \underline{1.26 \times 10^7} \text{ m s}^{-1} \text{ [5]}$$

[Turn over]

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- 5 The graph in **Fig. 5.1** shows how the magnetic flux Φ through a coil changes with time t as the coil of an electric generator rotates.

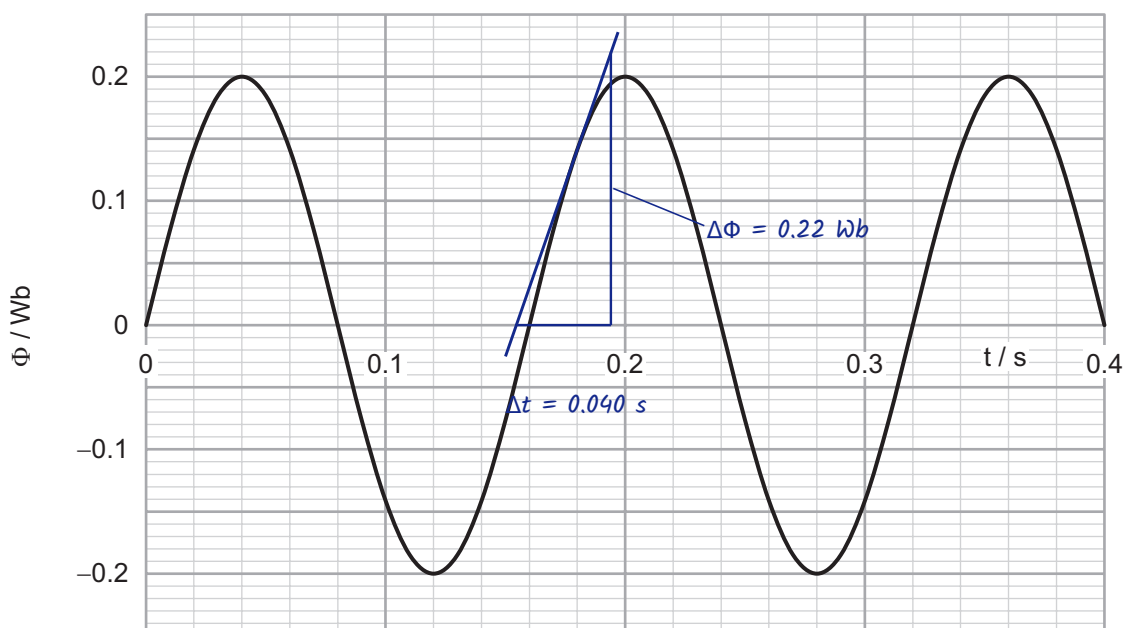


Fig. 5.1

- (a) With reference to the graph, describe how an electric generator is able to generate an alternating e.m.f.. State any physical law that may aid your explanation.

As the coil rotates, the magnetic flux linkage through the coil changes with time, as the graph shows. By Faraday's law, the induced e.m.f. is proportional to the rate of change of magnetic flux linkage (the gradient of the graph).

The flux linkage changes from increasing to decreasing every half cycle, so the gradient changes sign and the induced e.m.f. reverses: the output alternates.

[2]



(b) The coil consists of 40 turns.

- (i) Using the graph calculate the output voltage of the generator at a time of 0.18 s.

Tangent drawn to the curve at $t = 0.18$ s on Fig. 5.1.

Gradient = rise / run, from the large triangle:

points (0.154 s, 0.00 Wb) and (0.194 s, 0.22 Wb)

$$\text{gradient} = \Delta\Phi / \Delta t = (0.22 - 0.00) / (0.194 - 0.154)$$

$$= 0.22 / 0.040 = 5.5 \text{ Wb s}^{-1}$$

$$E = N \Delta\Phi / \Delta t = 40 \times 5.5$$

$$E = 220 \text{ V}$$

$$\text{Voltage} = \underline{220} \text{ V [5]}$$

- (ii) Calculate the frequency of the output voltage.

One cycle takes $T = 0.16$ s (from the graph)

$$f = 1 / T = 1 / 0.16$$

$$f = 6.25 \text{ Hz}$$

$$\text{Frequency} = \underline{6.25} \text{ Hz [3]}$$

[Turn over]

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- 6 The solar wind consists of a stream of charged particles that radiate away from the Sun, and interact with the Earth's magnetic field. **Fig. 6.1** shows Earth from space. A proton is travelling towards Earth at a speed of $5.20 \times 10^5 \text{ m s}^{-1}$. At its location X on **Fig. 6.1** the Earth's magnetic field is acting into the page and has a magnetic flux density of $4.90 \times 10^{-7} \text{ T}$.

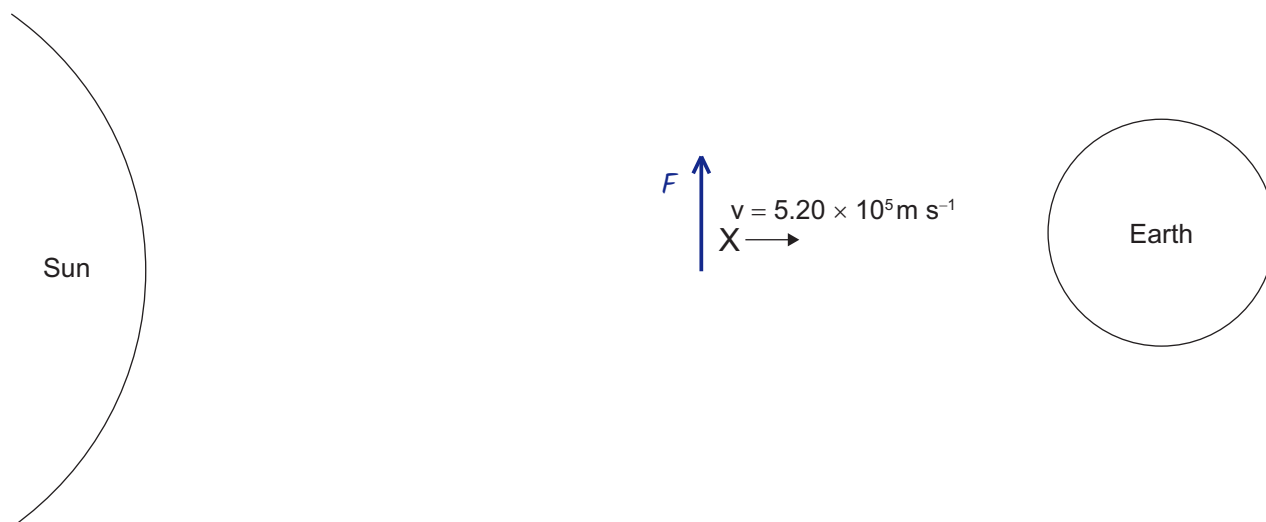


Fig. 6.1

- (i) Add an arrow at position X on **Fig. 6.1** to show the direction of the force exerted on the proton by the Earth's magnetic field. [1]
- (ii) Calculate the size of the force exerted by the magnetic field on the proton at position X.

$$F = Bqv$$

$$F = 4.90 \times 10^{-7} \times 1.6 \times 10^{-19} \times 5.20 \times 10^5$$

$$F = 4.08 \times 10^{-20} \text{ N}$$

Force = 4.08×10^{-20} N [3]



- (iii) Calculate the radius of the path that the proton will start to follow at position X.

$$Bqv = mv^2 / r, \text{ so } r = mv / Bq$$

$$r = 1.67 \times 10^{-27} \times 5.20 \times 10^5 / (4.90 \times 10^{-7} \times 1.6 \times 10^{-19})$$

$$r = 1.1 \times 10^4 \text{ m}$$

$$\text{Radius} = 1.1 \times 10^4 \text{ m [2]}$$

- (iv) The solar wind consists mainly of protons and electrons. Describe how, and explain why, the path of an electron will differ from the path of a proton travelling at the same speed.

The electron curves in the opposite direction (downwards at X) because its charge is opposite (negative). The size of the force Bqv is the same because the size of the charge is the same. The radius $r = mv / Bq$ is much smaller because the electron's mass is much smaller, so it follows a much tighter circle.

[3]

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In this question you will be assessed on the quality of your written communication skills, including the use of specialist scientific terms.

- 7 A synchrotron is a type of particle accelerator. State the two main components in the ring of a synchrotron and describe their purpose.

The two main components are accelerating cavities (electrodes) and electromagnets. The cavities use alternating electric fields to accelerate the charged particles each time they pass through, increasing their speed and kinetic energy. The electromagnets produce a magnetic field which exerts a force on the moving particles to change their direction, so they keep moving in a circular path of fixed radius around the ring.

As the particles gain energy, the current supplied to one of the components stated above must be increased. Explain why this increase in current is required.

The current to the electromagnets must be increased. As the particles gain energy their speed increases, so a larger centripetal force (mv^2 / r) is needed to keep them on a circular path of the same fixed radius. A larger current produces a stronger magnetic field (larger flux density B), which gives a larger magnetic force Bqv on the particles. At very high speeds the relativistic mass of the particles also increases, so an even stronger magnetic field is needed to maintain the circular path, since $r = mv / Bq$.

[8]

[Turn over

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- 8 (i) With reference to its structure, explain why a neutron is not considered a fundamental particle.

A neutron is made up of smaller particles: three quarks, one up quark and two down quarks (udd). A fundamental particle cannot be made up of smaller particles, so a neutron is not fundamental.

[2]

- (ii) Neutrons can undergo β^- decay. A student incorrectly states **Equation 8.1** as the equation for β^- decay. With reference to all three conservation rules, explain why β^- cannot occur in this manner.

$$n \rightarrow \beta^- + \bar{p} + \nu_e$$

Equation 8.1

Charge is not conserved: left side 0, right side $(-1) + (-1) + 0 = -2$, so $0 \rightarrow -2$.

Lepton number is not conserved: left side 0, right side $(+1) + 0 + (+1) = +2$, so $0 \rightarrow 2$.

Baryon number is not conserved: left side +1, right side $0 + (-1) + 0 = -1$ (the antiproton has baryon number -1), so $1 \rightarrow -1$.

So this decay cannot occur.

[6]



(iii) State the correct equation for β^- decay below.

$$n \rightarrow p^+ + \beta^- + \bar{\nu}_e \quad (\text{the electron antineutrino})$$

[1]

(iv) Describe what happens to the structure of a neutron in β^- decay.

*A down quark in the neutron changes into an up quark ($udd \rightarrow uud$),
so the neutron becomes a proton.*

[1]

[Turn over]

14731.05R



- 9 A power station produces a power of 320 MW at 22 000 V. The voltage is stepped up by a transformer to 110 000 V before transmission across power lines. The transformer used is 95% efficient.

- (i) State two possible causes of the power loss across the transformer.

Eddy currents induced in the iron core, which heat the core.

Resistive (I^2R) heating in the copper coils.

[2]

- (ii) Calculate the current in the power lines.

$$\text{Output power} = 0.95 \times 320 \text{ MW} = 304 \text{ MW} = 304 \times 10^6 \text{ W}$$

$$P = IV, \text{ so } I = P / V = 304 \times 10^6 / 110\,000$$

$$I = 2764 \text{ A}$$

Current = 2764 A [4]



(iii) The power lines have a resistance of 0.008Ω per kilometre and are 200 km long.

Calculate the total power loss across the transformer and in the power lines.

$$\text{Resistance of power lines } R = 0.008 \times 200 = 1.6 \Omega$$

$$\text{Power loss in lines } P = I^2 R = 2764^2 \times 1.6$$

$$= 1.22 \times 10^7 \text{ W} = 12.2 \text{ MW}$$

$$\text{Power loss in transformer} = 320 - 304 = 16 \text{ MW}$$

$$\text{Total power loss} = 16 + 12.2 = 28.2 \text{ MW} \approx 28 \text{ MW}$$

$$\text{Power loss} = \underline{28} \text{ MW [5]}$$

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Physics

Assessment Units A2 1 and A2 2

[APH11/APH21]

DATA AND FORMULAE SHEET

Data and Formulae Sheet for A2 1 and A2 2

Values of constants

speed of light in a vacuum	$c = 3.00 \times 10^8 \text{ m s}^{-1}$
permittivity of a vacuum	$\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$ $\left(\frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ F}^{-1} \text{ m} \right)$
elementary charge	$e = 1.60 \times 10^{-19} \text{ C}$
the Planck constant	$h = 6.63 \times 10^{-34} \text{ J s}$
(unified) atomic mass unit	$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$
mass of electron	$m_e = 9.11 \times 10^{-31} \text{ kg}$
mass of proton	$m_p = 1.67 \times 10^{-27} \text{ kg}$
molar gas constant	$R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$
the Avogadro constant	$N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$
the Boltzmann constant	$k = 1.38 \times 10^{-23} \text{ J K}^{-1}$
gravitational constant	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
acceleration of free fall on the Earth's surface	$g = 9.81 \text{ m s}^{-2}$
electron volt	$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$
the Hubble constant	$H_0 \approx 2.4 \times 10^{-18} \text{ s}^{-1}$

Useful formulae

The following equations may be useful in answering some of the questions in the examination:

Mechanics

conservation of energy $\frac{1}{2}mv^2 - \frac{1}{2}mu^2 = Fs$
for a constant force

Hooke's Law $F = kx$ (spring constant k)
strain energy $E = \frac{1}{2}Fx = \frac{1}{2}kx^2$

Uniform circular motion

centripetal Force $F = \frac{mv^2}{r}$

Simple harmonic motion

displacement $x = A \cos \omega t$
simple pendulum $T = 2\pi \sqrt{\frac{l}{g}}$
loaded spiral spring $T = 2\pi \sqrt{\frac{m}{k}}$

Waves

two-source interference $\lambda = \frac{ay}{d}$
diffraction grating $d \sin \theta = n \lambda$

Thermal physics

average kinetic energy of
a molecule

$$\frac{1}{2} m \langle c^2 \rangle = \frac{3}{2} kT$$

kinetic theory

$$pV = \frac{1}{3} Nm \langle c^2 \rangle$$

thermal energy

$$Q = mc\Delta\theta$$

Capacitors

capacitors in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

capacitors in parallel

$$C = C_1 + C_2 + C_3$$

time constant

$$\tau = RC$$

capacitor discharge

$$Q = Q_0 e^{\frac{-t}{CR}}$$

$$\text{or } V = V_0 e^{\frac{-t}{CR}}$$

$$\text{or } I = I_0 e^{\frac{-t}{CR}}$$

Light

lens formula

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Electricity

terminal potential difference

$$V = E - Ir$$

(e.m.f., E ; Internal Resistance, r)

potential divider

$$V_{\text{out}} = \frac{R_1 V_{\text{in}}}{R_1 + R_2}$$

a.c. generator

$$E = BAN\omega \sin\omega t$$

Nuclear Physics

nuclear radius

$$r = r_0 A^{\frac{1}{3}}$$

radioactive decay

$$A = -\lambda N, \quad A = A_0 e^{-\lambda t}$$

half-life

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Particles and photons

Einstein's equation

$$\frac{1}{2} m v_{\max}^2 = hf - hf_0$$

de Broglie equation

$$\lambda = \frac{h}{p}$$

Astronomy

red shift

$$z = \frac{\Delta \lambda}{\lambda}$$

recession speed

$$z = \frac{v}{c}$$

Hubble's law

$$v = H_0 d$$

