Centre Number	Index Number	Name	Class
S3016			

RAFFLES INSTITUTION
2024 Preliminary Examination

PHYSICS
Higher 2

9749/02

Paper 2 Structured Questions

11 September 2024
2 hours

Candidates answer on the Question Paper.
No Additional Materials are required.

READ THESE INSTRUCTIONS FIRST

Write your index number, name and class in the spaces at the top of this page.
Write in dark blue or black pen in the spaces provided in this booklet.
You may use pencil for any diagrams or graphs.
Do not use staples, paper clips, glue or correction fluid.
The use of an approved scientific calculator is expected, where appropriate.

Answer **all** questions.

The number of marks is given in brackets [ ] at the end of each question or part question.

For Examiner's Use	
1	/ 8
2	/ 9
3	/ 5
4	/ 8
5	/ 10
6	/ 8
7	/ 10
8	/ 22
Deduction	
Total	/ 80

This document consists of **23** printed pages.

Data

speed of light in free space	c	=	3.00×10^{8} m s^{-1}
permeability of free space	μ_0	=	$4\pi \times 10^{-7}$ H m^{-1}
permittivity of free space	ε_0	=	8.85×10^{-12} F m^{-1}
		=	$(1/(36\pi)) \times 10^{-9}$ F m^{-1}
elementary charge	e	=	1.60×10^{-19} C
the Planck constant	h	=	6.63×10^{-34} J s
unified atomic mass constant	u	=	1.66×10^{-27} kg
rest mass of electron	m_e	=	9.11×10^{-31} kg
rest mass of proton	m_p	=	1.67×10^{-27} kg
molar gas constant	R	=	8.31 J K^{-1} mol^{-1}
the Avogadro constant	N_A	=	6.02×10^{23} mol^{-1}
the Boltzmann constant	k	=	1.38×10^{-23} J K^{-1}
gravitational constant	G	=	6.67×10^{-11} N m^{2} kg^{-2}
acceleration of free fall	g	=	9.81 m s^{-2}

Formulae

uniformly accelerated motion	s	=	$ut + \frac{1}{2}at^2$
	v^2	=	$u^2 + 2as$
work done on / by a gas	W	=	$p\Delta V$
hydrostatic pressure	p	=	ρgh
gravitational potential	ϕ	=	$-Gm/r$
temperature	T/K	=	$T/^{\circ}\text{C} + 273.15$
pressure of an ideal gas	p	=	$\frac{1}{3}\frac{Nm}{V}\langle c^2 \rangle$
mean translational kinetic energy of an ideal gas molecule	E	=	$\frac{3}{2}kT$
displacement of particle in s.h.m.	x	=	$x_0 \sin \omega t$
velocity of particle in s.h.m.	v	=	$v_0 \cos \omega t = \pm\omega\sqrt{x_0^2 - x^2}$
electric current	I	=	$Anvq$
resistors in series	R	=	$R_1 + R_2 + \ldots$
resistors in parallel	$1/R$	=	$1/R_1 + 1/R_2 + \ldots$
electric potential	V	=	$\frac{Q}{4\pi\varepsilon_0 r}$
alternating current/voltage	x	=	$x_0 \sin \omega t$
magnetic flux density due to a long straight wire	B	=	$\frac{\mu_0 I}{2\pi d}$
magnetic flux density due to a flat circular coil	B	=	$\frac{\mu_0 NI}{2r}$
magnetic flux density due to a long solenoid	B	=	$\mu_0 nI$
radioactive decay	x	=	$x_0 \exp(-\lambda t)$
decay constant	λ	=	$\ln 2 / t_{1/2}$

Answer **all** the questions in the spaces provided.

1 A small ball at the bottom of a frictionless slope is projected up the slope with speed u, as shown in Fig. 1.1.

The slope has a height of 4.0 m and makes an angle of 30° to the horizontal ground.

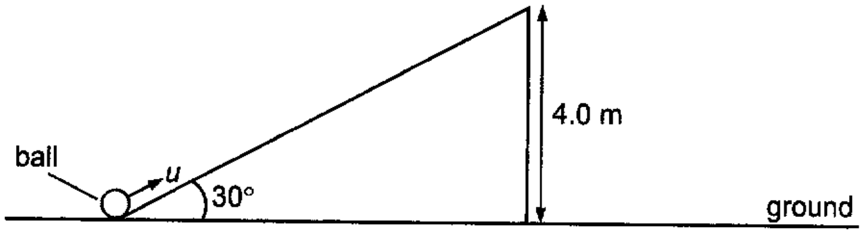

Fig. 1.1

(a) In one instance, $u = 7.0\ \text{m s}^{-1}$.

(i) Calculate the maximum distance s_0 from the bottom of the slope that the ball reaches.

s_0 = ... m [2]

(ii) As the ball moves up the slope from the bottom, draw on Fig. 1.2 the variation with distance s travelled by the ball from the bottom of the slope of its

1. kinetic energy (label as E_K),

2. potential energy (label as E_P).

Potential energy at the bottom of the slope is zero.

[2]

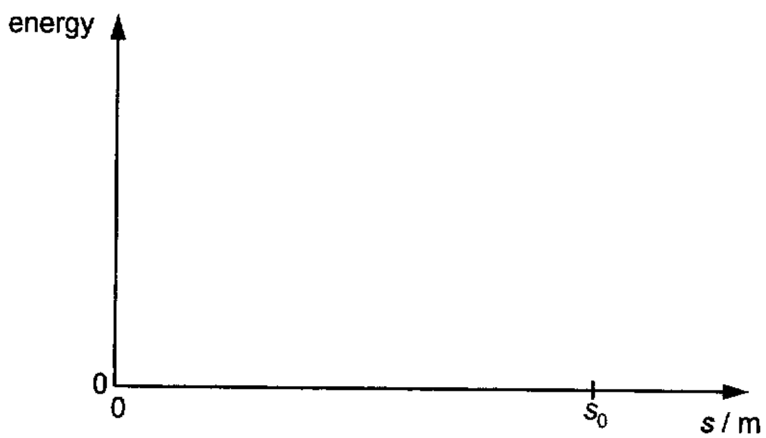

Fig. 1.2

(b) In another instance, $u = 14.0$ m s^{-1}.

The ball travels to the top of the slope, leaves the slope and hits the ground.

(i) Show that the speed of the ball at the top of the slope is 10.8 m s^{-1}.

[1]

(ii) Calculate the horizontal distance travelled by the ball after it leaves the slope.

distance = ... m [3]

[Total: 8]

2 Two identical balls A and B approach each other along the same straight line on a smooth horizontal surface, as shown in Fig 2.1.

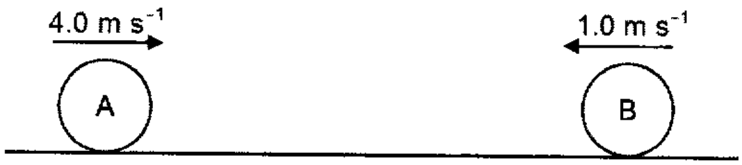

Fig. 2.1

At time $t = 0$ s, ball A moves towards ball B with a speed of 4.0 m s^{-1}, while ball B moves towards ball A with a speed of 1.0 m s^{-1}. Each ball has a mass of 0.50 kg.

At time $t = 0.50$ s, the balls undergo a head-on elastic collision and are in contact for a duration of 0.25 s.

After the collision, ball A moves with velocity v_A and ball B moves with velocity v_B.

(a) Explain whether both balls could be stationary at the same time during the collision.

....

....

....

....

.... [2]

(b) Show that v_B is 4.0 m s^{-1}.

[2]

(c) Calculate the magnitude of the average force on ball A during the collision.
Explain your working.

force = ... N [3]

(d) Fig. 2.2 shows the variation with time t of the momentum p_A of ball A and momentum p_B of ball B before the collision.

On Fig. 2.2, complete the graphs for p_A and p_B from $t = 0.50$ s to $t = 1.5$ s.

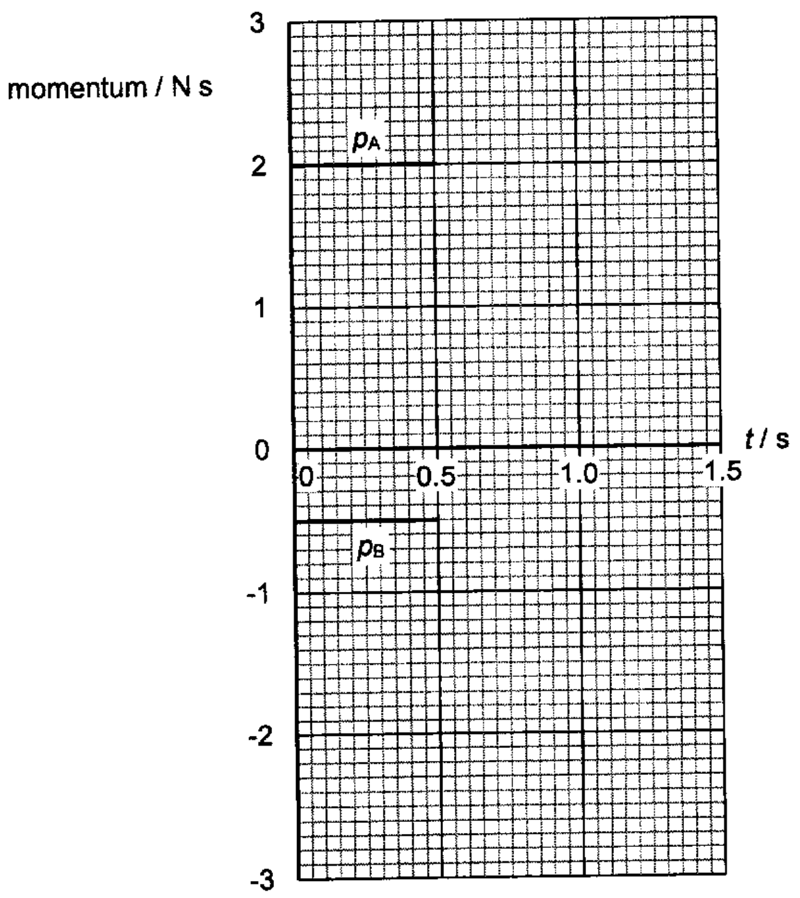

Fig. 2.2

[2]

[Total: 9]

3 A uniform circular disc of radius R and weight W is in contact with a smooth horizontal ground and the corner of a box of height $\frac{R}{2}$, as shown in Fig. 3.1.

A horizontal force F acts at the centre O of the disc to keep the disc in equilibrium.

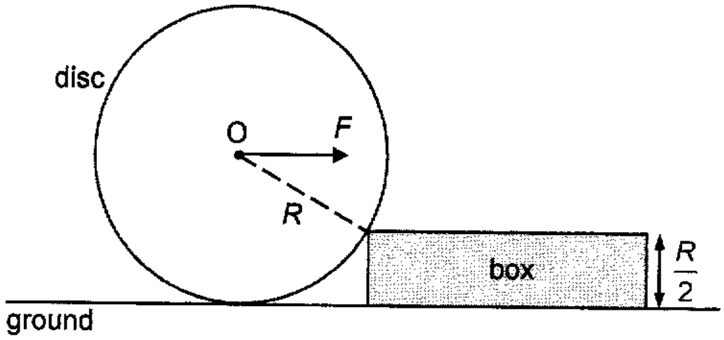

Fig. 3.1

(a) Force F is increased until the disc is just about to rotate about the corner of the box. Use the principle of moments to determine the ratio $\frac{F}{W}$. Explain your working.

$\frac{F}{W}$ = ... [3]

(b) The box is replaced with one of height R.

State and explain how the force F acting at the centre O would need to be changed for the disc to rotate about the corner of the box.

....

....

....

.... [2]

[Total: 5]

4 A ball of mass m is attached to one end of a light inextensible string of length L. The other end of the string is attached to a fixed point O.

(a) The ball is swung around in a vertical circle, as shown in Fig. 4.1. The speeds of the ball at the top and bottom of the vertical circle are v_T and v_B respectively.

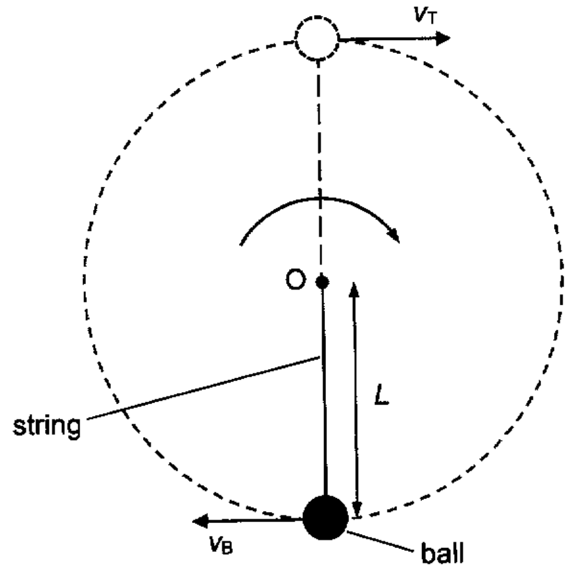

Fig. 4.1

(i) Show that for the ball to just complete the vertical circle, $v_T = \sqrt{gL}$.
Explain your working.

[2]

(ii) Explain why the ratio $\frac{v_B}{v_T}$ must be greater than 1 for the ball to complete the vertical circle.

....

....

.... [1]

(iii) A student wishes to swing the ball in a vertical circle such that $\frac{v_B}{v_T} = 3$.

With appropriate calculations, state and explain if this ratio is achievable.

....

....

.... [3]

(b) The ball is now swung in a horizontal circle around the fixed point O, as shown in Fig. 4.2.

When the ball is swinging around with angular velocity ω, the string is at an angle θ from the vertical and the tension in the string is T.

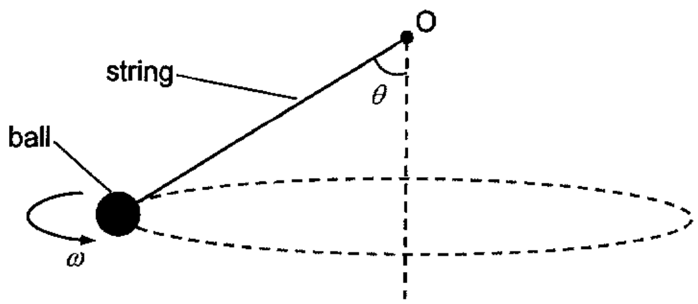

Fig. 4.2

Determine the tension in the string, in terms of T, when the angular velocity of the ball is doubled.

tension = ... [2]

[Total: 8]

5 **(a)** The value of the gravitational potential ϕ at a distance x from a point mass M is given by the expression

$$\phi = -\frac{GM}{x}$$

where G is the gravitational constant.

(i) Define *gravitational potential.*

....

....

.... [1]

(ii) Explain why gravitational potential is a negative quantity.

....

....

....

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.... [2]

(b) A satellite is launched from the surface of the Earth.

(i) The Earth has a radius of 6400 km and a mass of 6.0×10^{24} kg. The mass of the satellite is 1600 kg.

Calculate the change in gravitational potential energy ΔE_P of the satellite as it moves from the surface of the Earth to a height of 2.1×10^7 m above the surface of the Earth.

ΔE_P = ... J [2]

(ii) The satellite then orbits the Earth about the centre of the Earth.

1. Show that the speed v of the satellite in its orbit is given by the expression

$$v = \sqrt{\frac{GM_E}{r}}$$

where M_E is the mass of the Earth and r is the radius of orbit.

Explain your working.

[2]

2. While in orbit, the thruster of the satellite is fired. The satellite is given a boost such that it has just enough energy to travel out into space.

Determine the ratio

$$\frac{\text{kinetic energy of the satellite just after the boost}}{\text{kinetic energy of the satellite just before the boost}}.$$

ratio = ... [3]

[Total: 10]

6 A battery of electromotive force (e.m.f.) 9.0 V and negligible internal resistance is connected to resistors P and Q, a light dependent resistor (LDR) and ammeters A_1 and A_2, as shown in Fig. 6.1.

The resistance of P is $4.0\ k\Omega$ and the resistance of Q is $6.0\ k\Omega$.

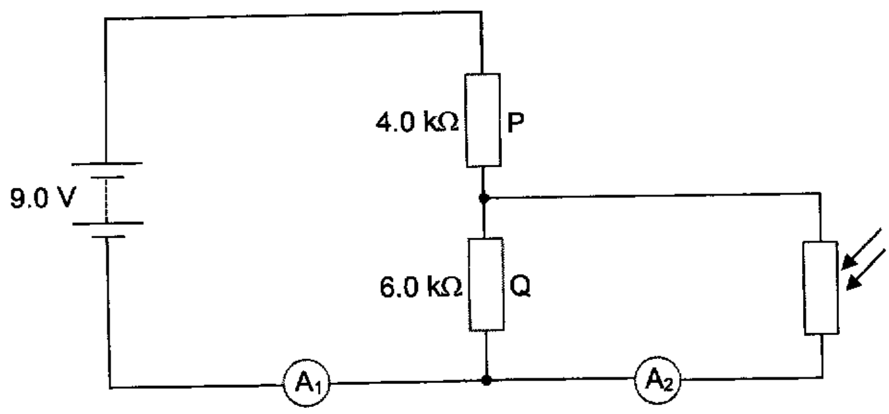

Fig. 6.1

(a) The intensity of the light incident on the LDR is such that the resistance of the LDR is $8.0\ k\Omega$.

Determine the current reading on

(i) ammeter A_1,

current = ... A [2]

(ii) ammeter A_2.

current = ... A [2]

(b) The intensity of the light incident on the LDR is lowered.

Explain the following changes:

(i) The potential difference across Q increases.

....

....

....

....

.... [2]

(ii) The current reading on ammeter A_2 decreases.

....

....

....

....

.... [2]

[Total: 8]

7 Hydrogen is the most abundant material in the universe and the most basic nuclear fusion reaction is the fusion of two hydrogen nuclei ($^{1}_{1}H$).

(a) State what is meant by *nuclear fusion*.

....

....

.... [1]

(b) Given that the radius of a hydrogen nucleus is 1.2×10^{-15} m, show that the minimum kinetic energy of each hydrogen nucleus needed to trigger a $^{1}_{1}H$-$^{1}_{1}H$ fusion reaction is 0.30 MeV. Assume fusion occurs when the two nuclei touch each other.

[2]

(c) $^{1}_{1}H$-$^{1}_{1}H$ fusion occurs naturally in the Sun and in most other stars because there is sufficient thermal energy to trigger the reaction.

By assuming that hydrogen behaves as an ideal gas, estimate the temperature of such an environment.

temperature = ... K [2]

(d) There are two possible outcomes of such a fusion reaction. In reaction (1), a helium isotope ${}^{2}_{2}He$ is formed. In reaction (2) a deuteron ${}^{2}_{1}H$ and an unknown elementary particle X is formed.

reaction (1): ${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{2}He$

reaction (2): ${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + X$

(i) State the nuclear notation for X.

$${}^{\square}_{\square}X$$

[1]

(ii) Deuteron ${}^{2}_{1}H$ is readily found on Earth, but not the helium isotope ${}^{2}_{2}He$.
Suggest a possible reason for this observation and hence deduce which reaction releases more energy.

....

....

.... [1]

(e) Data for the nuclei in reaction (2) are given in Fig. 7.1.

nucleus	mass / u
${}^{1}_{1}H$	1.007825
${}^{2}_{1}H$	2.014102
X	0.000549

Fig. 7.1

Calculate the energy released in reaction (2).

energy = ... J [2]

(f) Suggest one significant advantage in generating electrical power by a fission reaction compared to a fusion reaction.

....

....

.... [1]

[Total: 10]

8 Read the passage below and answer the questions that follow.

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It first started up on 10 September 2008 and is the crown jewel within the accelerator complex of the European Council for Nuclear Research (CERN).

Spanning across the Switzerland-France border, the LHC is a large horizontal ring in which high-energy particle beams, most commonly proton beams, are accelerated to speeds close to the speed of light in opposite directions. These proton beams circulate around the ring more than 11000 times a second as they are made to collide multiple times at different interaction points where the beams cross each other. By studying the fundamental particles produced in the aftermath of these proton-proton collisions, scientists hope to gain new insights and answers to some of the most important unsolved mysteries in Physics.

Inside the accelerator, the protons travel around the ring for hours along two separate beam pipes, both of which are kept at an ultrahigh vacuum. As the protons circulate around the LHC, they are repeatedly accelerated by strong electric fields along a short linear accelerator within the ring.

The protons are guided around the accelerator ring along the beam pipes by strong magnetic fields generated by thousands of electromagnets of different types and sizes, all of which need to be constantly kept at extremely low temperatures of about 1.9 K. This is why the LHC also houses the world's largest cryogenic system, using about 10000 tonnes of liquid nitrogen and 130 tonnes of liquid helium to maintain the operation of the magnets. (1 tonne = 1000 kg)

The most common type of these electromagnets is called dipole magnets, which help bend the protons' trajectories so that they travel successfully along the curved beam pipes. These dipole magnets consist of many coils of electric cables placed next to and at many different sections along the beam pipe, each carrying a large electric current. The dipole magnets are contained and fastened together with strong non-magnetic stainless-steel collars.

Fig. 8.1 shows the cross-section of one of the dipole magnet setups at a section of a beam pipe of the LHC. The large number of electric cables are grouped into two double-layered regions around the beam pipe, labelled as region 1 and region 2 in Fig. 8.1. These electric cables are arranged parallel to the beam pipe such that when a current is travelling along these cables, the magnetic flux density produced by these cables at the centre of the beam pipe helps bend the protons' trajectories so that they can travel along the curved beam pipe.

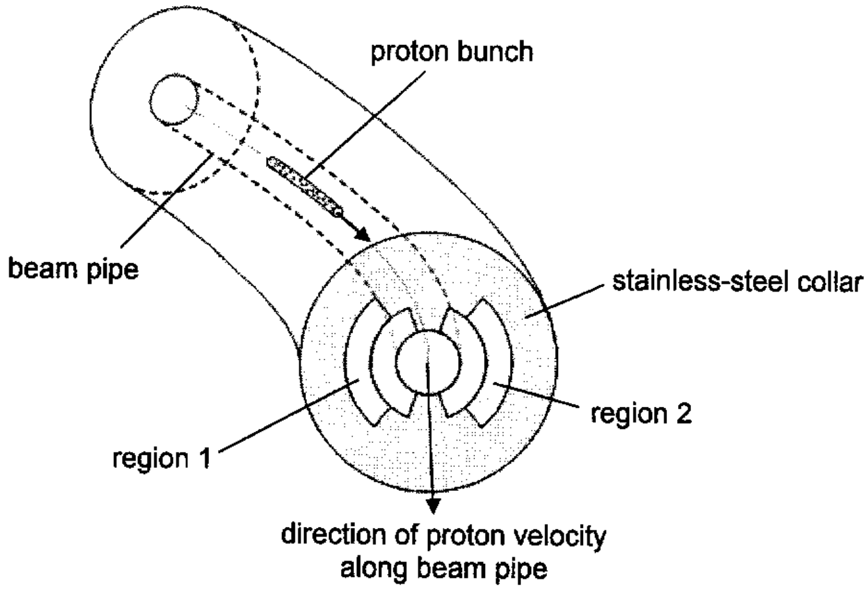

Fig. 8.1
(The electric cables parallel to the beam pipe are not shown for clarity.)

An important parameter in determining the functionality of a particle accelerator like the LHC is the beam current, which is defined as the average rate of flow of charge in the beam pipe. However, during normal operation, the protons do not travel in the beam pipe as a continuous beam. Instead, in each proton beam, the protons travel in groups called "bunches", which are approximately cylindrical in shape as shown in Fig. 8.1.

The LHC is built underground with a mean depth of 100 m for various reasons, including minimising the damage caused to the landscape and environment on the surface. In addition, protons travelling around the curved beam pipes accelerate to produce synchrotron radiation in the form of ultraviolet and X-ray photons, and interactions between the protons and the nuclei of any atoms around the beams in the beam pipes also produce ionising radiation. The Earth's crust therefore also provides natural shielding from these sources of radiation for anyone living on the surface near the LHC.

Table 8.1 shows some important data and parameters of the LHC under normal operating conditions.

Table 8.1

total circumference of LHC ring	26659 m
diameter of beam pipe	56 mm
proton energy	7.0 TeV
current in each cable of a dipole magnet setup	11850 A
length of a dipole magnet setup	14.3 m
peak dipole magnetic flux density at centre of beam pipe	8.33 T
beam current	0.58 A
number of bunches per proton beam	2808
length of one bunch	7.48 cm
cross-sectional area of one bunch	1.0 mm^2

(a) Suggest why the inside of the beam pipe needs to be maintained at an ultrahigh vacuum while the LHC is being operated.

....

....

.... [1]

(b) State and explain if an accelerator like the LHC can be used to study neutron-neutron collisions.

....

....

.... [1]

(c) **(i)** The relationship between the proton energy E and its speed v is given by

$$E = (\gamma - 1) m_0 c^2$$

where $\gamma = \dfrac{1}{\sqrt{1-\dfrac{v^2}{c^2}}}$, m_0 is the mass of a proton, and c is the speed of light in vacuum.

Show that the protons in the LHC beam pipe travel at a speed of 0.999999991 c.

[1]

(ii) Hence, by considering the beam current, show that the number of protons in each bunch within the proton beam is 1.15×10^{11}.

[3]

(d) The large number of cables in region 1 and region 2 in the dipole magnet setup in Fig. 8.1, can be modelled by combining the cables in each region into a single large cable carrying the total current in that region. The length of each single large cable is 14.3 m.

Fig. 8.2 shows a close-up of the cross section of the dipole magnet setup around the beam pipe in Fig. 8.1, where regions 1 and 2 are represented by combined cables 1 and 2 respectively. Each combined cable carries electric current of the same magnitude.

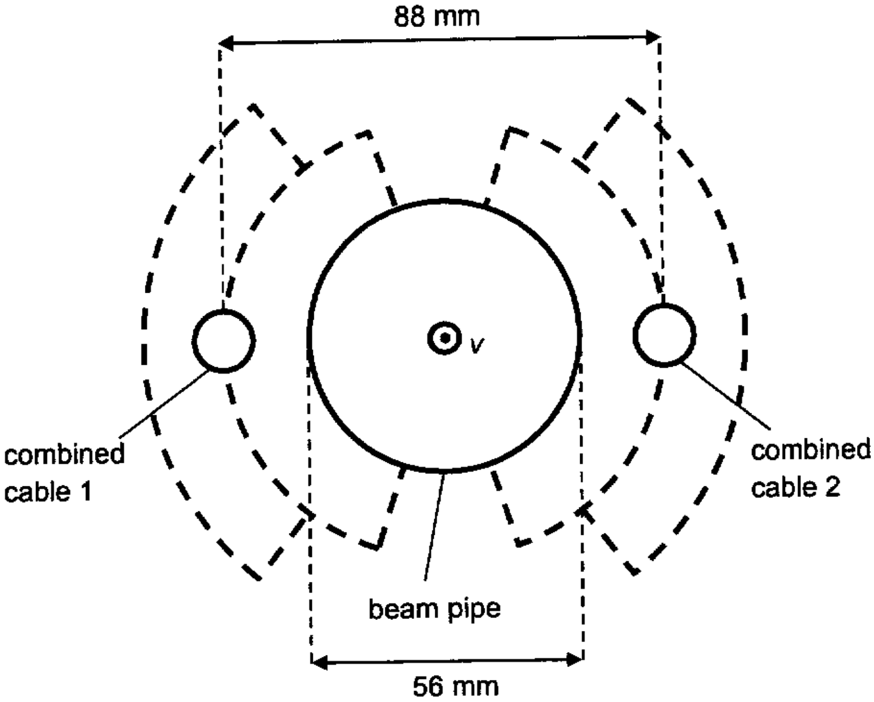

Fig. 8.2

In this model of the dipole magnet setup, the distance between the combined cables is 88 mm, while the diameter of the beam pipe is 56 mm.

The proton velocity v in the middle of the beam pipe is pointing out of the page, as shown in Fig. 8.2. The centre of the circular path of the proton's trajectory is on the side of combined cable 1.

(i) On Fig. 8.2, using appropriate symbols and labels, indicate the direction of

1. the magnetic flux density B at the centre of the beam pipe,

2. the currents I_1 and I_2 in the combined cables 1 and 2 respectively.

[2]

(ii) **1.** Determine the current required in each combined cable to produce the peak dipole magnetic flux density at the centre of the beam pipe.

current = ... A [2]

2. Hence, determine the number of cables in each region.

number of cables = ... [1]

3. Suggest a reason why the dipole magnets need to be contained and fastened together with strong stainless-steel collars.

Support your suggestion with appropriate calculations.

....

....

.... [3]

(e) Besides dipole magnets, another type of electromagnet used at the LHC are quadrupole magnets.

Quadrupole magnets help "squeeze" the travelling protons within each bunch closer together so that the protons stay travelling along the central axis of the beam pipe in a tightly focused beam. They do so by accounting for the electrostatic repulsion between the protons within each bunch.

(i) By approximating the average volume occupied by a proton in each bunch to be the volume of a cube, estimate the magnitude of the average repulsive force between two adjacent protons in a bunch.

force = ... N [2]

(ii) The quadrupole magnets also help to keep the protons in the proton beam on their intended path by accounting for the protons falling downwards due to their weight.

Determine the number of rounds a proton will be able to travel around the LHC accelerator ring before falling to the bottom of the beam pipe due to gravity, if there were no quadrupole magnets.

Assume that the acceleration due to gravity in the pipe is 9.81 m s^{-2}.

number of rounds = ... [2]

(iii) Suggest another reason why quadrupole magnets are needed to correct the proton's trajectory in the beam pipe.

....

....

....

....

.... [2]

(f) The International Linear Collider (ILC) is a proposed particle accelerator to be built in the future to further study the particles that have been discovered at the LHC.

Unlike the LHC, which is a circular particle accelerator, the ILC is a linear particle accelerator, in which two beams of particles travel down straight beam pipes and are made to collide with each other in the middle.

Suggest an advantage and a disadvantage of linear accelerators compared to circular accelerators.

advantage: ....

....

....

....

....

disadvantage: ....

....

....

....

.... [2]

[Total: 22]

End of Paper 2

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Year 5-6 Physics Department

2024 H2 Physics Preliminary Examination Solution and Comments

Paper 2

1 (a) (i) Take direction up the slope as positive.

$v^2 = u^2 + 2as_0$

$0 = 7.0^2 + 2(-9.81\sin 30°)s_0$

$s_0 = 4.9949 = 4.99$ m

OR

By the principle of conservation of energy,
increase in G.P.E. = decrease in K.E.

$mg(\Delta h) = \frac{1}{2}mv^2 - 0$, where Δh is the max. vertical height from ground

$\Delta h = \frac{v^2}{2g}$

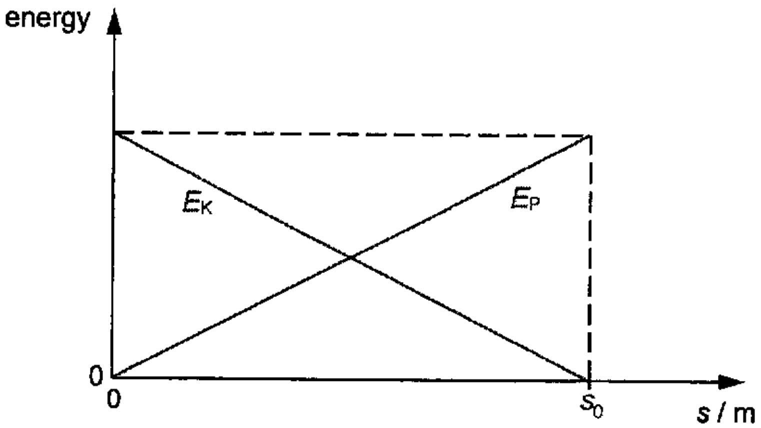
$= \frac{7.0^2}{2(9.81)}$

$s_0 = \frac{\Delta h}{\sin 30°}$

$= \frac{7.0^2}{2(9.81)} \div \sin 30°$

$= 4.9949 = 4.99$ m

(ii)



*Both graphs aligned at the same total energy and s_0 and clearly labelled.

1. $E_K = \frac{1}{2}mv^2 = \frac{1}{2}m\left(u^2 + 2[-g\sin\theta]s\right)$

$E_K = \frac{1}{2}mu^2 - (mg\sin\theta)s$

Graph of E_K-s is a straight line with negative gradient and vertical intercept $\frac{1}{2}mu^2$.

2. $E_P = mg(\Delta h) = mg(s\sin\theta)$

$E_P = (mg\sin\theta)s$

Graph of E_P-s is a straight line through the origin with positive gradient.

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(b) (i) $v^2 = u^2 + 2as$

$$v^2 = 14.0^2 + 2(-9.81\sin 30°)\left(\frac{4.0}{\sin 30°}\right)$$

$v = 10.841 = 10.8 \text{ m s}^{-1}$ (shown)

OR

decrease in K.E. = increase in G.P.E.

$$\frac{1}{2}mu^2 - \frac{1}{2}mv^2 = mg(\Delta h)$$

$$v^2 = u^2 - 2g(\Delta h) = 14.0^2 - 2(9.81)(4.0)$$

$v = 10.841 = 10.8 \text{ m s}^{-1}$ (shown)

(ii) Take directions to the right and upwards as positive.

Time of flight after the ball leaves the top of the slope to the ground:

$$s_y = u_y t + \tfrac{1}{2}a_y t^2$$

$$-4.0 = (10.8\sin 30°)t + \frac{1}{2}(-9.81)t^2$$

$t = 1.6080$ s or -0.50713 s (NA)

Horizontal distance travelled:

$$s_x = u_x t + \tfrac{1}{2}a_x t^2$$

$$= (10.8\cos 30°)(1.6080) + 0$$

$$= 15.040 = 15.0 \text{ m}$$

*State both values of *t* and reject the negative one.

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2 **(a)** The initial total momentum of both balls is not zero.

Since there is no net external force acting on the balls as a system, by the principle of conservation of momentum, the total momentum of both balls must remain unchanged and cannot be zero.

Hence, the balls could not be stationary at the same time.

(b) By the principle of conservation of momentum,

$$m_A u_A + m_B u_B = m_A v_A + m_B v_B$$
$$u_A + u_B = v_A + v_B$$
$$4.0 + (-1.0) = v_A + v_B$$
$$v_A + v_B = 3.0 \quad \text{---- (1)}$$

Since collision is elastic,

$$u_B - u_A = v_A - v_B$$
$$(-1.0) - 4.0 = v_A - v_B$$
$$v_A - v_B = -5.0 \quad \text{---- (2)}$$

(1) − (2) $\quad 2v_B = 3.0 - (-5.0)$

$v_B = 4.0 \text{ m s}^{-1}$ (shown)

(c) By Newton's second law, the average force on ball B by ball A is

$$F_{net,B} = \frac{\Delta p_B}{\Delta t} = \frac{0.50(4.0 - (-1.0))}{0.25} = 10 \text{ N}$$

By Newton's third law, the average force on ball A by ball B has the same magnitude of 10 N.

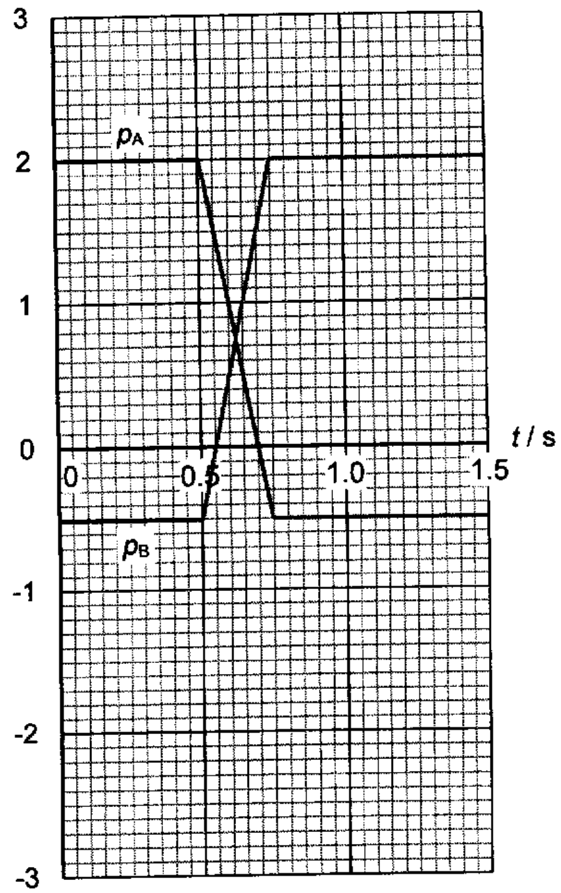
OR

From equation (1) or (2) in part (b), $v_A = 3.0 - v_B = 3.0 - 4.0 = -1.0 \text{ m s}^{-1}$.

By Newton's second law, the average force on ball A by ball B is

$$F_{net,A} = \left|\frac{\Delta p_A}{\Delta t}\right| = \left|\frac{0.50((-1.0) - 4.0)}{0.25}\right| = 10 \text{ N}$$

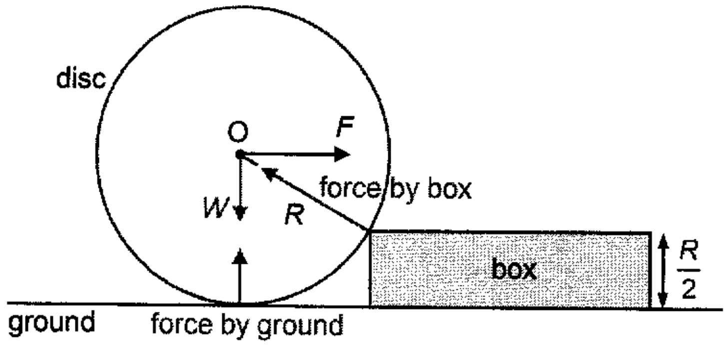
(d)



Balls A and B will exchange velocities and momenta as both balls have the same mass. From (b), $p_{B,f} = (0.50)(4.0) = 2.0$ N s.

Since duration of collision is 0.25 s, constant final momenta to start from 0.75 s to 1.5 s, with lines joining 0.50 s to 0.75 s during the collision.

3 (a)



When the disc is just about to rotate, the contact force by the ground just becomes zero.

Perpendicular distance from corner of box to line-of-action of F is $\frac{R}{2}$.

Perpendicular distance from corner of box to line-of-action of W is $\sqrt{R^2-\left(\frac{R}{2}\right)^2}=\frac{\sqrt{3}}{2}R$.

Applying the principle of moments about the corner of box,

$$F\times\frac{R}{2}=W\times\frac{\sqrt{3}}{2}R$$

$$\frac{F}{W}=\sqrt{3}=1.7321=1.73$$

(b) F acting at O needs to be inclined upwards such that it is at an angle above the horizontal to produce a clockwise moment about the corner to overcome the anticlockwise moment due to the weight.

OR

F acting at O needs to be inclined upwards so that there is an upward vertical component to produce a clockwise moment about the corner to overcome the anticlockwise moment due the weight.

OR

F needs to be shifted upwards above O so that there is a moment arm from the corner of the box to the line-of-action of F, to produce a clockwise moment about the corner to overcome the anticlockwise moment due to the weight.

Note: Increasing the magnitude of the horizontal force F acting at O will not cause any rotation as F has no moment about the corner of the box because the perpendicular distance from the corner to the line-of-action of F is zero.

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4 (a) (i) At the top of the circle,

$$T_T + mg = \frac{mv_T^2}{L}$$

For the ball to just complete the vertical circle, the tension T_T at the top of the circle is zero.

$$mg = \frac{mv_T^2}{L}$$
$$v_T^2 = gL$$
$$v_T = \sqrt{gL}$$

(ii) By the principle of conservation of energy, as the ball moves from the top to the bottom of the circle, its gravitational potential energy decreases and its kinetic energy increases. This means the speed at the bottom is greater than the speed at the top. Hence $\frac{v_B}{v_T} > 1$.

(iii) $\frac{v_B}{v_T} = 3$

$v_B = 3v_T$

As the ball moves from the top to the bottom,
increase in K.E. = decrease in G.P.E.

$$\frac{1}{2}mv_B^2 - \frac{1}{2}mv_T^2 = mg(2L)$$
$$\frac{1}{2}m(3v_T)^2 - \frac{1}{2}mv_T^2 = mg(2L)$$
$$\frac{9}{2}mv_T^2 - \frac{1}{2}mv_T^2 = 2mgL$$
$$4mv_T^2 = 2mgL$$
$$v_T = \sqrt{\frac{1}{2}}\sqrt{gL}$$

As $\sqrt{\frac{1}{2}}\sqrt{gL} < \sqrt{gL}$, where $\sqrt{gL}$ is the value of v_T at which the string just goes slack, the ball will not be able to complete a full circle if $\frac{v_B}{v_T} = 3$. Hence, $\frac{v_B}{v_T} = 3$ is not possible to achieve.

(b) Considering forces along the radial direction,

$$T\sin\theta = mr\omega^2$$

Since $r = L\sin\theta$,

$$T\sin\theta = m(L\sin\theta)\omega^2$$
$$T = mL\omega^2$$

Since m and L are constants, $T \propto \omega^2$. Hence when the angular velocity is doubled, the tension in the string is $4T$.

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5 (a) (i) Gravitational potential at a point in a gravitational field is the work done per unit mass by an external force in bringing a small test mass from infinity to that point.

(ii) Gravitational potential at infinity is zero.

Since gravitational force is attractive in nature, to bring a mass from infinity to a point in the gravitational field, the direction of the external force is opposite to the direction of displacement of the mass. This results in negative work done per unit mass by the external force.

Hence, based on its definition, gravitational potential is a negative value.

(b) (i)

$$\Delta E_P = \left(-\frac{GM_E m}{x}\right) - \left(-\frac{GM_E m}{R_E}\right)$$

$$= GM_E m\left(\frac{1}{R_E} - \frac{1}{x}\right)$$

$$= (6.67\times10^{-11})(6.0\times10^{24})(1600)\left(\frac{1}{6400\times10^3} - \frac{1}{(6400\times10^3)+(2.1\times10^7)}\right)$$

$$= 7.6681\times10^{10} = 7.67\times10^{10}\ \text{J}$$

(ii) 1. Gravitational force provides the centripetal force on the satellite.

$$\frac{GM_E m}{r^2} = \frac{mv^2}{r} \quad \text{where } m \text{ is the mass of the satellite}$$

$$v = \sqrt{\frac{GM_E}{r}}$$

2. By the principle of conservation of energy, if the satellite has just enough energy to escape to infinity, its total energy is zero.

Let E_{K1} be the kinetic energy of satellite just after the boost.

$$E_P + E_{K1} = 0$$

$$-\frac{GM_E m}{r} + E_{K1} = 0$$

$$E_{K1} = \frac{GM_E m}{r}$$

Just before the boost, kinetic energy of satellite in orbit,

$$E_K = \frac{1}{2}mv^2$$

$$= \frac{1}{2}m\left(\sqrt{\frac{GM_E}{r}}\right)^2$$

$$= \frac{GM_E m}{2r}$$

$$\text{ratio} = \frac{E_{K1}}{E_K} = \frac{GM_E m}{r} \Big/ \frac{GM_E m}{2r} = 2$$

6 (a) (i) Effective resistance of Q and LDR,

$$R_{eff} = \left(\frac{1}{R_Q} + \frac{1}{R_{LDR}}\right)^{-1}$$
$$= \left(\frac{1}{6.0} + \frac{1}{8.0}\right)^{-1}$$
$$= 3.4286 \text{ k}\Omega$$
$$I_{A_1} = \frac{E}{R_T}$$
$$= \frac{9.0}{(3.4286 + 4.0) \times 10^3}$$
$$= 1.2115 \times 10^{-3} = 1.21 \times 10^{-3} \text{ A}$$

(ii) Potential difference across Q and LDR,

$$V_{eff} = \frac{R_{eff}}{R_{eff} + R_P} \times E$$
$$= \left(\frac{3.4286}{3.4286 + 4.0}\right) \times 9.0$$
$$= 4.1539 \text{ V}$$
$$I_{A_2} = \frac{V_{LDR}}{R_{LDR}}$$
$$= \frac{4.1539}{8.0 \times 10^3}$$
$$= 5.1924 \times 10^{-4} = 5.19 \times 10^{-4} \text{ A}$$

(b) (i) Resistance of the LDR increases when light intensity is lowered. The effective resistance of Q and the LDR increases.

Since the potential difference across P and Q is the same at 9.0 V, by the potential divider principle, the potential difference across Q is a larger proportion of the 9.0 V. Hence the potential difference across Q increases.

OR

Resistance of the LDR increases when light intensity is lowered. The overall resistance of the circuit increases.

Current from the battery decreases. As the resistance of P is the same, the potential difference across P decreases. Since the potential difference across P and Q remains the same at 9.0 V, this means the potential difference across Q increases.

(ii) Since the potential difference across Q increases, the current through Q increases for the same resistance of Q.

Total current in the circuit is the sum of the current through Q and the LDR. Since the total current from the battery decreases due to overall increase in resistance, and the current in Q increases, this means the current through the LDR decreases. Hence the current reading on ammeter A_2 decreases.

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7 **(a)** In a nuclear fusion reaction, two low nucleon number (OR lighter) nuclei combine into a high nucleon number (OR heavier) nucleus.

(b) Since fusion occurs when the two nuclei touch each other, the distance at which the two nuclei fuse is $d = 2\times\left(1.2\times10^{-15}\right) = 2.4\times10^{-15}$ m.

Both nuclei must possess sufficient kinetic energy to overcome the electrostatic repulsion as they approach each other to fuse.

Minimum K.E. needed is when both nuclei just come to rest when they start to fuse.

By the principle of conservation of energy, as the two hydrogen nuclei approach each other,
decrease in K.E. = increase in E.P.E.

$$2\times E_{k,\min} - 0 = \frac{e^2}{4\pi\varepsilon_0 d}$$

$$E_{k,\min} = \frac{e^2}{8\pi\varepsilon_0 d}$$

$$= \frac{\left(1.60\times10^{-19}\right)^2}{8\pi\left(8.85\times10^{-12}\right)\left(2.4\times10^{-15}\right)}$$

$$= 4.7956\times10^{-14}\text{ J}$$

$$= \frac{4.7956\times10^{-14}}{10^6\left(1.60\times10^{-19}\right)}\text{ MeV}$$

$$= 0.299725\text{ MeV} = 0.30\text{ MeV} \quad \text{(shown)}$$

(c)

$$E_{k,\min} = \frac{3}{2}kT$$

$$T = \frac{2E_{k,\min}}{3k}$$

$$= \frac{2\left(4.7956\times10^{-14}\right)}{3\left(1.38\times10^{-23}\right)}$$

$$= 2.3167\times10^9 = 2.32\times10^9\text{ K}$$

(d) **(i)** $^{0}_{1}X$
Particle X is a positron.

(ii) Since deuteron $^{2}_{1}H$ is more readily found, it suggests that reaction (2) is more probable than reaction (1) and that $^{2}_{1}H$ is more stable than $^{2}_{2}He$.
Hence, reaction (2) releases more energy than (1).

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(e) Energy released,

$$E = \Delta mc^2$$
$$= (\text{mass of reactants} - \text{mass of products})c^2$$
$$= (2 \times 1.007825 - 2.014102 - 0.000549)(1.66 \times 10^{-27}) \times (3.00 \times 10^{8})^2$$
$$= 1.4925 \times 10^{-13} = 1.49 \times 10^{-13} \text{ J}$$

(f) Nuclear fission reaction of heavy nuclei requires much less energy to trigger (initiate) and can occur at a lower (room) temperature while the nuclear fusion reaction of light nuclei requires an extremely high temperature to trigger.

8 **(a)** This is to reduce collisions between protons and any gas molecules in the beam pipes, so that less harmful ionising radiation is produced.

OR

This is to reduce collisions between protons and any gas molecules in the beam pipes, so that the proton beam can remain focused and not get scattered by these collisions.

OR

This is to reduce collisions between protons and any gas molecules in the beam pipes, so that there is less energy loss and the protons can reach the high speed required.

(b) No. As neutrons are neutral and uncharged, their trajectories cannot be bent / curved by the presence of magnetic fields.

OR

No. As neutrons are neutral and uncharged, they cannot be accelerated by electric fields.

(c) **(i)**

$$E = (\gamma - 1)m_0c^2$$

$$(7.0\times10^{12})(1.60\times10^{-19}) = (\gamma-1)(1.67\times10^{-27})(3.00\times10^{8})^2$$

$$1.12\times10^{-6} = (\gamma-1)(1.67\times10^{-27})(3.00\times10^{8})^2$$

$$\gamma = 7452.8$$

$$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = 7452.8$$

$$v = \sqrt{\left[1-\left(\frac{1}{7452.8}\right)^2\right]c^2} = 0.999999991\,c \quad \text{(shown)}$$

(ii) Since beam current is defined as the average rate of flow of charge,

$$\text{beam current} = \frac{\text{total charge in the ring}}{\text{period}} = \frac{Q}{T}$$

$$T = \frac{\text{distance travelled along the ring}}{\text{speed of protons}} = \frac{26659}{0.999999991\,c} = 8.8863\times10^{-5}\ \text{s}$$

$$0.58 = \frac{Q}{8.8863\times10^{-5}}$$

$$Q = 5.1541\times10^{-5}\ \text{C}$$

number of protons per proton beam,

$$N = \frac{Q}{e} = \frac{5.1541\times10^{-5}}{1.60\times10^{-19}} = 3.22\times10^{14}$$

Since there are 2808 bunches per proton beam,

$$\text{number of protons in each bunch} = \frac{3.22\times10^{14}}{2808}$$

$$= 1.1467\times10^{11} = 1.15\times10^{11} \quad \text{(shown)}$$

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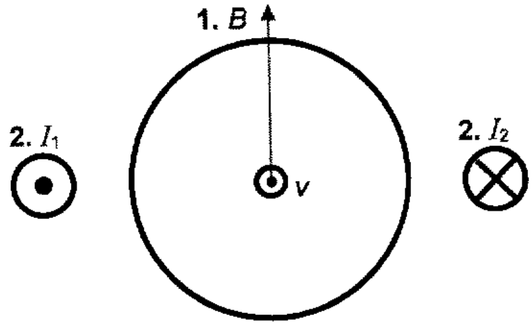
(d) (i) 1.
2.



1. Since proton velocity is out of the page, beam current is out of the page. Since centre of circular path of the proton's trajectory is on the left, the magnetic force on the proton that provides the centripetal force points to the left.
   Using Fleming's left-hand rule, direction of B is upwards.

   *Straight line with arrowhead pointing upwards at the centre of pipe.

2. Since each combined cable carries current of the same magnitude, the direction of the current in each cable must be such that each produces a magnetic flux density that points upwards at the centre of the pipe, giving a resultant magnetic flux density as deduced in **(d)(i)1.**

   Using the right-hand grip rule, I_1 points out of the page and I_2 points into the page.

   *Correct directions, positions and symbols of both currents.

(ii) 1.

$$B = \frac{\mu_0 I_1}{2\pi d} + \frac{\mu_0 I_2}{2\pi d}$$

$$8.33 = \frac{\left(4\pi \times 10^{-7}\right)\left(I_1 + I_2\right)}{2\pi\left(\frac{88}{2} \times 10^{-3}\right)}$$

$$I_1 + I_2 = 1832600 \text{ A}$$

Since $I_1 = I_2$,

$$I_1 = \frac{1832600}{2}$$

$$= 916300 \text{ A} = 9.16 \times 10^5 \text{ A}$$

2. Since current in each cable is 11850 A,
$916300 = N(11850)$ where N is the number of cables
$N = 77.3 \approx 77$

3. Force on combined cable 2 by combined cable 1,

$$F = B_1 I_2 L$$

$$= \frac{\mu_0 I_1}{2\pi d} I_2 L$$

$$= \frac{(4\pi \times 10^{-7})(916300)}{2\pi(88 \times 10^{-3})}(916300)(14.3)$$

$$= 2.7287 \times 10^{7} = 2.73 \times 10^{7} \text{ N}$$

By Newton's third law, force on combined cable 1 by combined cable 2 is equal in magnitude and opposite in direction.

The cables in the dipole magnet setup experience an extremely large repulsive force away from each other. Hence, the stainless-steel collars are used to keep the cables from moving away from the beam pipe.

(e) (i) average volume occupied by one proton

$$= \frac{\text{volume of one bunch}}{\text{no. of protons in one bunch}}$$

$$= \frac{(7.48 \times 10^{-2})(1.0 \times 10^{-6})}{1.15 \times 10^{11}}$$

$$= 6.5043 \times 10^{-19} \text{ m}^3$$

Approximating volume occupied by a proton to be volume of a cube with sides of length *d*:

$$d = \sqrt[3]{6.5043 \times 10^{-19}} = 8.6643 \times 10^{-7} \text{ m}$$

average electric force of repulsion between 2 protons,

$$F_E = \frac{e^2}{4\pi\varepsilon_0 d^2}$$

$$= \frac{(1.60 \times 10^{-19})^2}{4\pi(8.85 \times 10^{-12})(8.6643 \times 10^{-7})^2}$$

$$= 3.0663 \times 10^{-16} = 3.07 \times 10^{-16} \text{ N}$$

(ii) Initial velocity v of proton is horizontal along the central axis of the beam pipe.

displacement of proton from centre of beam pipe to bottom of beam pipe,

$$s_y = u_y t + \frac{1}{2}gt^2$$

$$\frac{1}{2}\left(56\times10^{-3}\right) = 0 + \frac{1}{2}(9.81)t^2$$

$$t = 0.075554 \text{ s or } -0.075554 \text{ s (NA)}$$

total horizontal displacement travelled by proton,

$$s_x = vt$$
$$= (0.999999991)\left(3.00\times10^8\right)(0.075554)$$
$$= 22666199.8 \text{ m}$$

$$\text{number of rounds} = \frac{s_x}{\text{circumference of ring}}$$
$$= \frac{22666199.8}{26659}$$
$$= 850.23 = 850$$

(iii) The radiation produced from the accelerating protons will cause the protons to lose energy, resulting in the protons straying away from their original path as the radius of curvature of their trajectory will decrease.

Hence, the quadrupole magnets are needed to help keep the protons travelling along the central axis of the beam pipe.

(f) Advantages:

- Linear accelerators are less expensive to build as they do not require large numbers of electromagnets to keep the particles in a circular path, which need to be kept at extremely low temperatures with large amounts of liquid nitrogen and helium.
- Synchrotron radiation due to the particles accelerating is a lot less as particles are not constantly accelerating unlike when they are travelling in circular paths where they experience centripetal acceleration.
- Synchrotron radiation due to the particles accelerating is a lot less as particles are not constantly changing direction unlike when they are travelling in circular paths.

Disadvantages:

- The chances for collisions to happen is much lower because there is only one collision point in a linear accelerator, whereas there can be multiple collision points in a circular accelerator.
- Linear accelerators are not able to reach the same high energies as a circular accelerator without being unfeasibly long, because particles in a circular accelerator can circulate many times, getting boosts in energy many times before colliding.
- For linear accelerators to reach the same high energies as a circular accelerator they need to be extremely long which is very expensive to build.