| Centre Number | Index Number | Name | Class |
|---|---|---|---|
| S3016 | | | |

**RAFFLES INSTITUTION**
**2024 Preliminary Examination**

**PHYSICS** **9749/02**
**Higher 2**

**11 September 2024**
Paper 2 Structured Questions **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 | $c$ | = | $3.00 \times 10^{8}$ m s$^{-1}$ |
| permeability of free space | $\mu_0$ | = | $4\pi \times 10^{-7}$ H m$^{-1}$ |
| permittivity of free space | $\varepsilon_0$ | = | $8.85 \times 10^{-12}$ F m$^{-1}$ |
| | | = | $(1/(36\pi)) \times 10^{-9}$ F m$^{-1}$ |
| elementary charge | $e$ | = | $1.60 \times 10^{-19}$ C |
| the Planck constant | $h$ | = | $6.63 \times 10^{-34}$ J s |
| unified atomic mass constant | $u$ | = | $1.66 \times 10^{-27}$ kg |
| rest mass of electron | $m_e$ | = | $9.11 \times 10^{-31}$ kg |
| rest mass of proton | $m_p$ | = | $1.67 \times 10^{-27}$ kg |
| molar gas constant | $R$ | = | 8.31 J K$^{-1}$ mol$^{-1}$ |
| the Avogadro constant | $N_A$ | = | $6.02 \times 10^{23}$ mol$^{-1}$ |
| the Boltzmann constant | $k$ | = | $1.38 \times 10^{-23}$ J K$^{-1}$ |
| gravitational constant | $G$ | = | $6.67 \times 10^{-11}$ 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 | $p$ | = | $\rho gh$ |
| gravitational potential | $\phi$ | = | $-Gm/r$ |
| temperature | $T$/K | = | $T$ / °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 | $\lambda$ | = | $\ln 2 / t_{1/2}$ |

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.

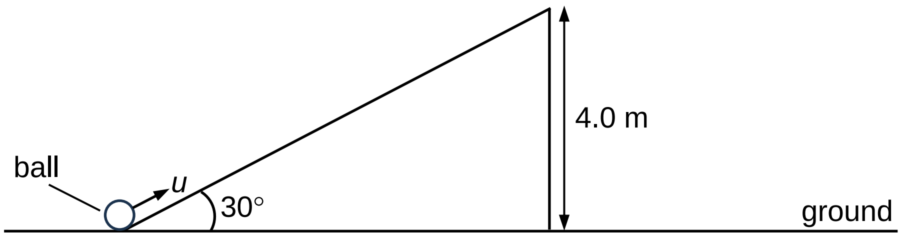


**Fig. 1.1**

**(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]

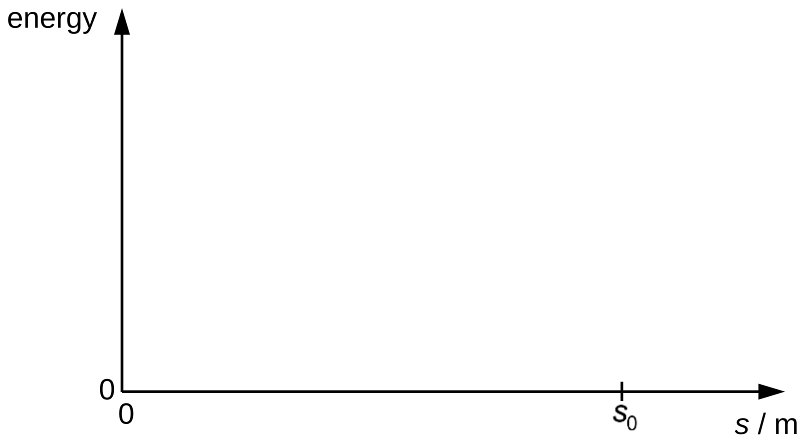


**Fig. 1.2**

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

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 $10.8\ \text{m s}^{-1}$.

[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 .

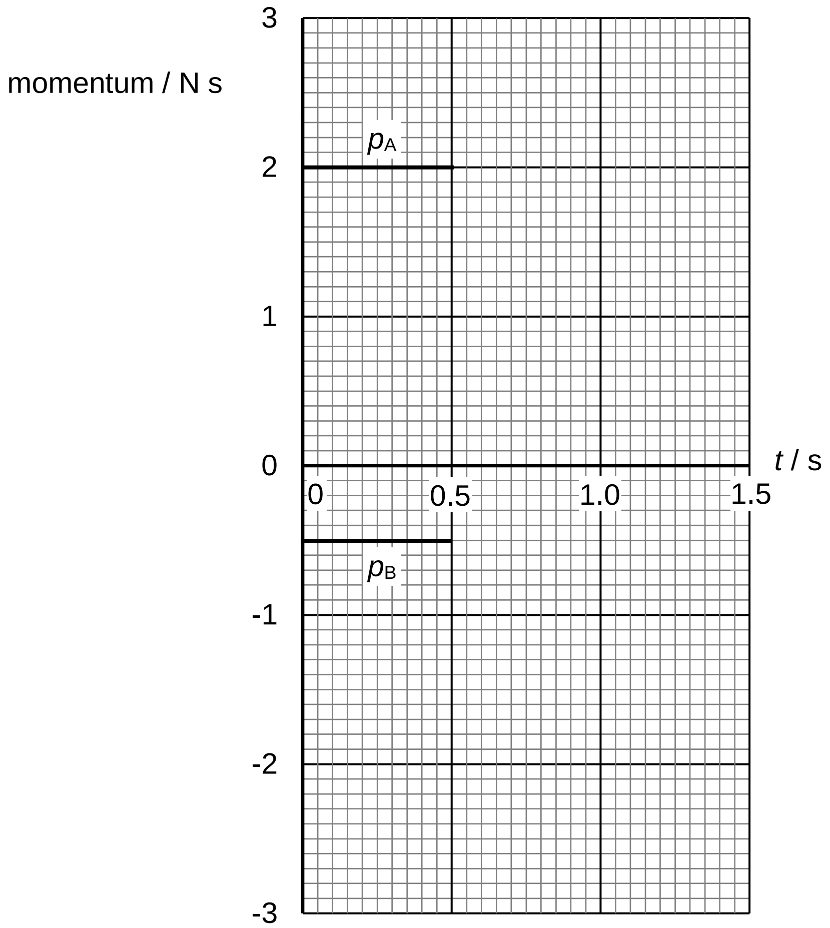


**Fig. 2.2**

[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.

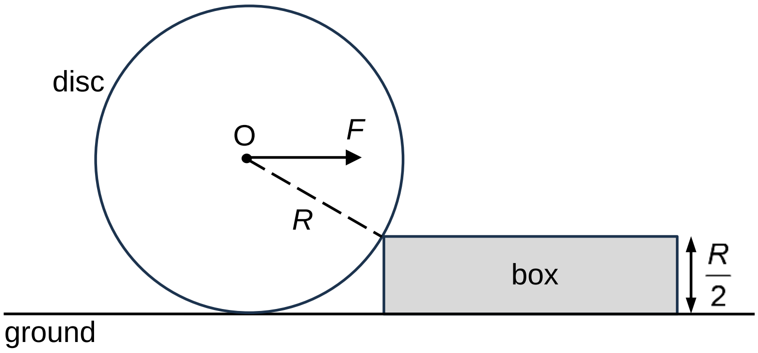


**Fig. 3.1**

**(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.

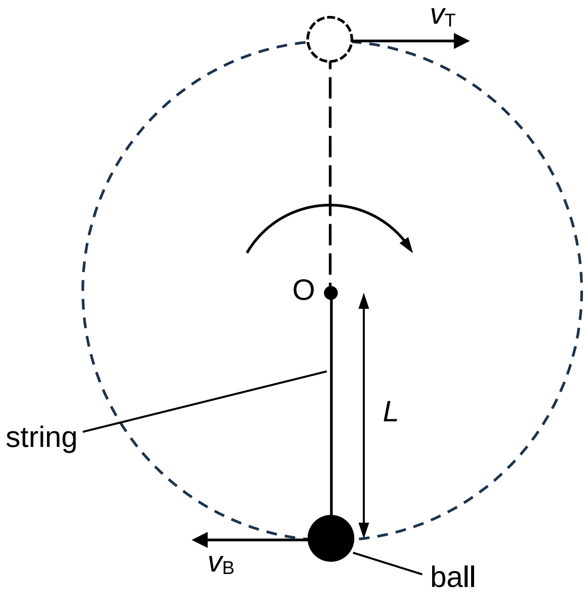


**Fig. 4.1**

**(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 $\omega$, the string is at an angle $\theta$ from the vertical and the tension in the string is $T$.

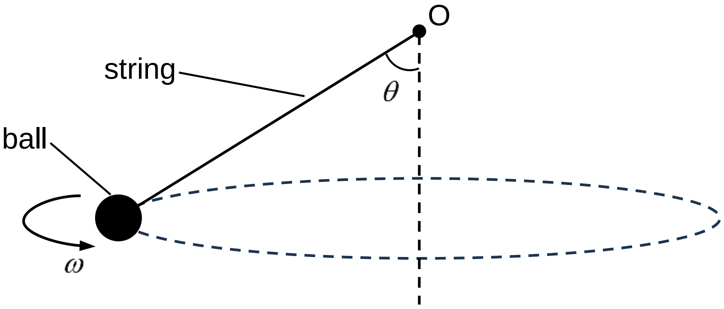


**Fig. 4.2**

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 $\phi$ 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.

..............................................................................................................................

..............................................................................................................................

..............................................................................................................................

..............................................................................................................................

.............................................................................................................................. [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 $6.0 \times 10^{24}$ kg. The mass of the satellite is 1600 kg.

Calculate the change in gravitational potential energy $\Delta E_P$ of the satellite as it moves from the surface of the Earth to a height of $2.1 \times 10^{7}$ m above the surface of the Earth.

$\Delta E_P$ = ..................................... 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 $4.0\ \text{k}\Omega$ and the resistance of Q is $6.0\ \text{k}\Omega$.

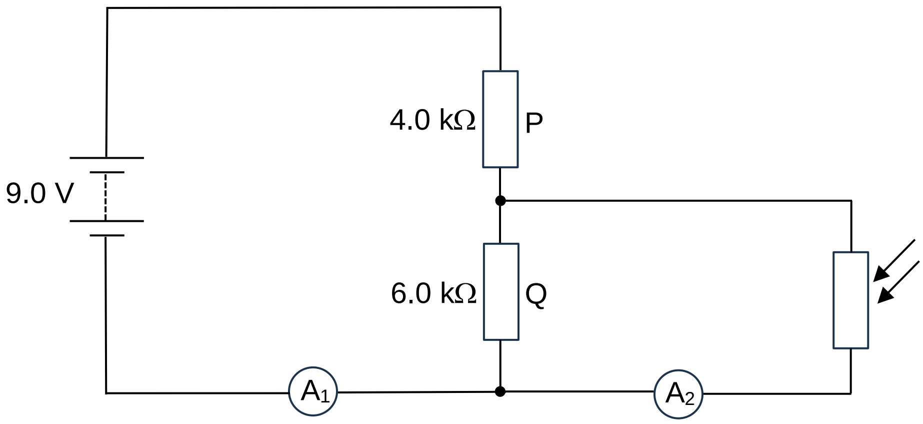


**Fig. 6.1**

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

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 ($^1_1\text{H}$).

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

..........................................................................................................................................

..........................................................................................................................................

.................................................................................................................................... [1]

**(b)** Given that the radius of a hydrogen nucleus is $1.2\times10^{-15}$ m, show that the minimum kinetic energy of each hydrogen nucleus needed to trigger a $^1_1\text{H}$ - $^1_1\text{H}$ fusion reaction is 0.30 MeV. Assume fusion occurs when the two nuclei touch each other.

[2]

**(c)** $^1_1\text{H}$ - $^1_1\text{H}$ 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 $^{2}_{2}\text{He}$ is formed. In reaction (2) a deuteron $^{2}_{1}\text{H}$ and an unknown elementary particle X is formed.

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

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

**(i)** State the nuclear notation for X.

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

[1]

**(ii)** Deuteron $^{2}_{1}\text{H}$ is readily found on Earth, but not the helium isotope $^{2}_{2}\text{He}$.
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 |
|---|---|
| $^{1}_{1}\text{H}$ | 1.007825 |
| $^{2}_{1}\text{H}$ | 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.

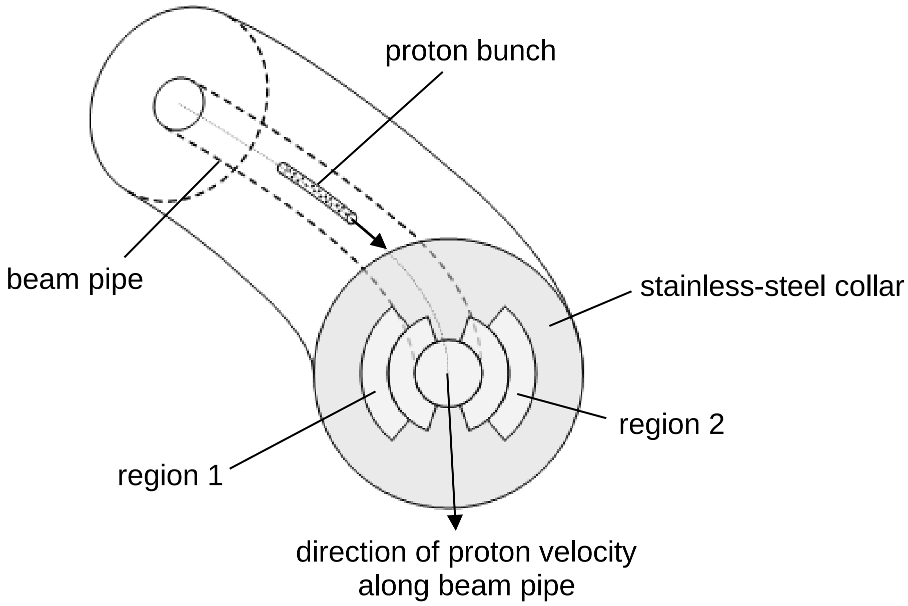


**Fig. 8.1**
**(The electric cables parallel to the beam pipe are not shown for clarity.)**

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

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

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 $1.15 \times 10^{11}$.

[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.

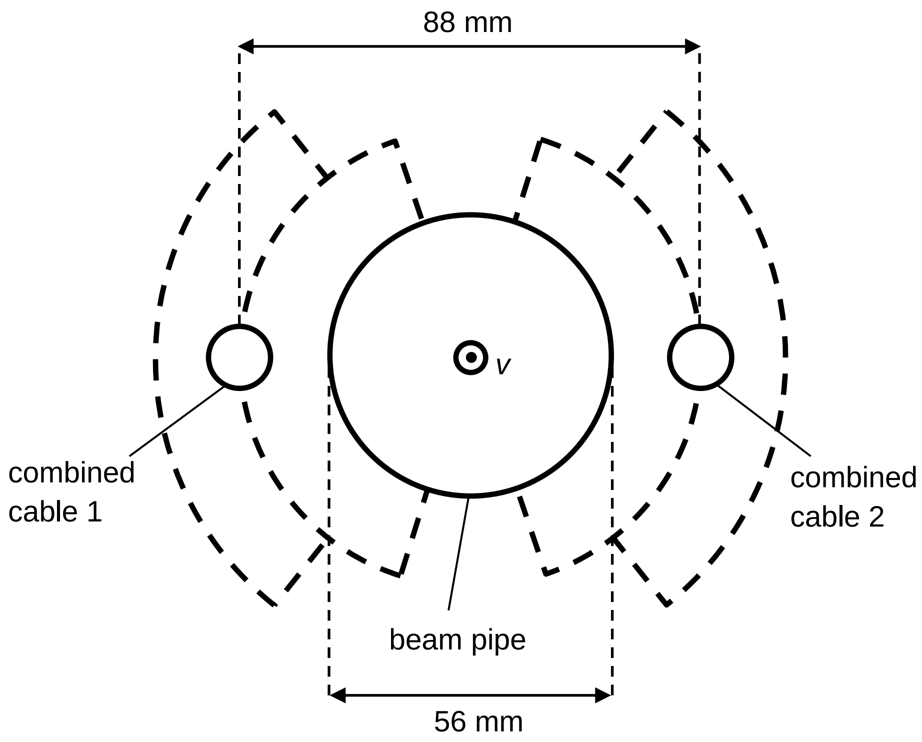


**Fig. 8.2**

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**