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.

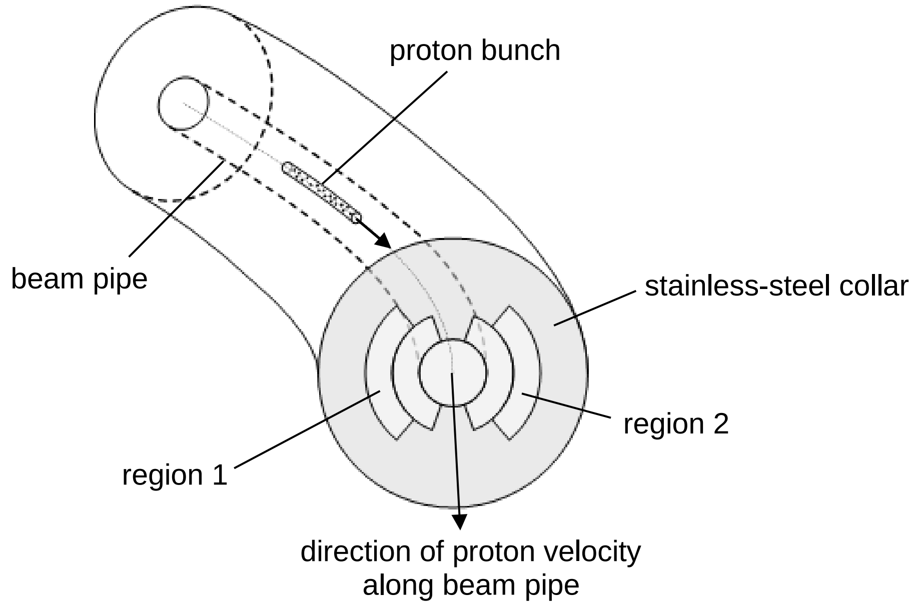

Fig. 8.1
(The electric cables parallel to the beam pipe are not shown for clarity.)

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.

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.... [1]

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

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.... [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 1.15×10^{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.

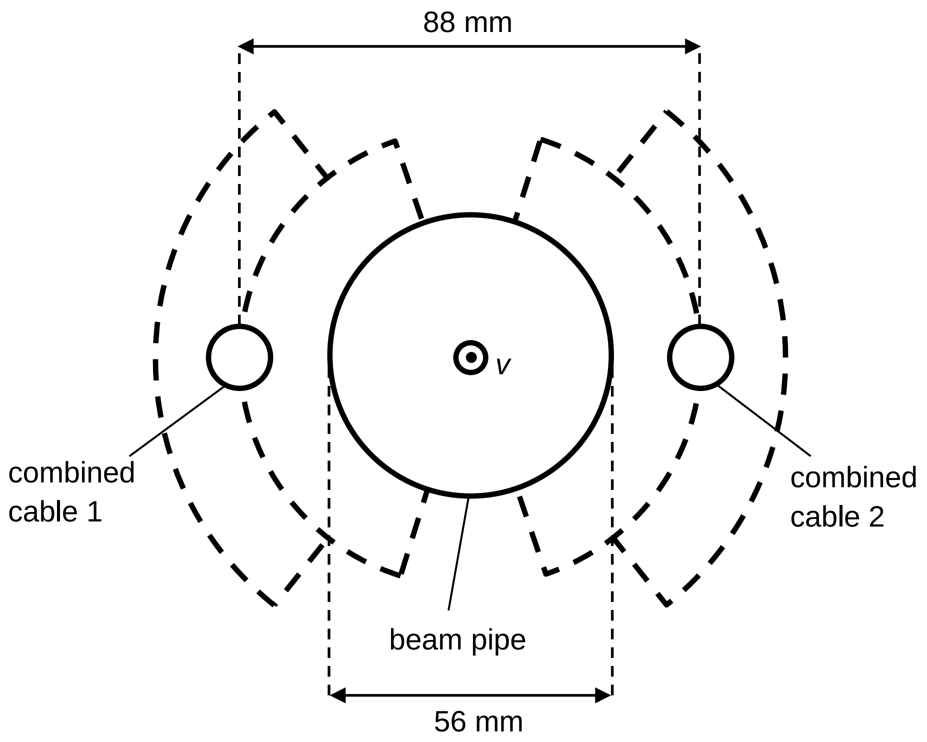

Fig. 8.2

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.

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.... [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.

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.... [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: ....

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disadvantage: ....

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.... [2]

[Total: 22]