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

Magnetic Confinement Fusion

As the world's demand for energy increases, harnessing energy from the process of nuclear fusion promises to be an attractive long-term solution in addressing future energy problems.

The most widely studied nuclear fusion reaction involves the nuclei of deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$) which are isotopes of hydrogen. Each reaction produces an α-particle and a neutron, releasing 17.6 MeV of energy as shown by the nuclear equation below.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

For the positively charged nuclei to fuse, they must be heated to sufficiently high temperatures to overcome the Coulomb barrier. At such temperatures, the atoms in the fuel are ionised, forming a mixture of electrons and nuclei known as a plasma. Maintaining the plasma at this temperature to produce fusion energy requires it to be confined long enough in the reactor and this is achieved using magnetic fields.

Fig. 8.1 shows the magnetic field lines of a magnetic mirror configuration involving two current-carrying coils. When a charged particle is placed between the two coils, it experiences a magnetic force and can be trapped. However, the trapping is not perfect. For instance, if the particle travels along the central axis, it can escape the trap.

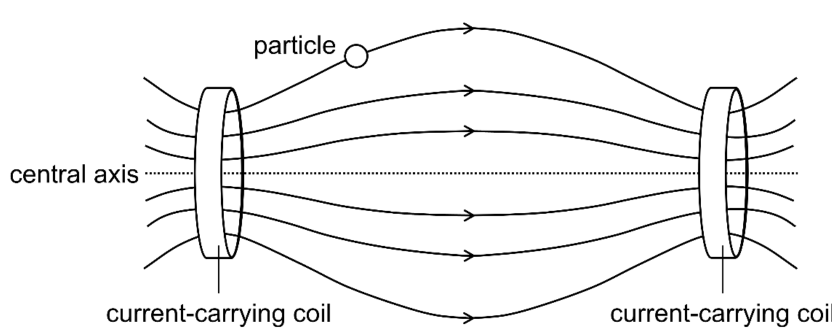

Fig. 8.1

Hence, to prevent the loss of particles, the ends of the magnetic mirror configuration can be joined together to form a torus (doughnut-like shape). Fig. 8.2 shows a cross-section of the toroidal nuclear fusion reactor where R is the major radius while a is the minor radius of the reactor. Multiple current-carrying coils, known as the toroidal field coils, are used to produce the magnetic field in the plasma.

The toroidal magnetic field causes the charged particles to move in a circular motion about the magnetic field. In addition, when current is sent through the central solenoid, it acts like the primary coil of a transformer, inducing current in the plasma around the torus. The combination of the circular motion in the cross-sectional plane of the torus and translational motion in a direction perpendicular to the plane results in the charged particles moving in a helical path.

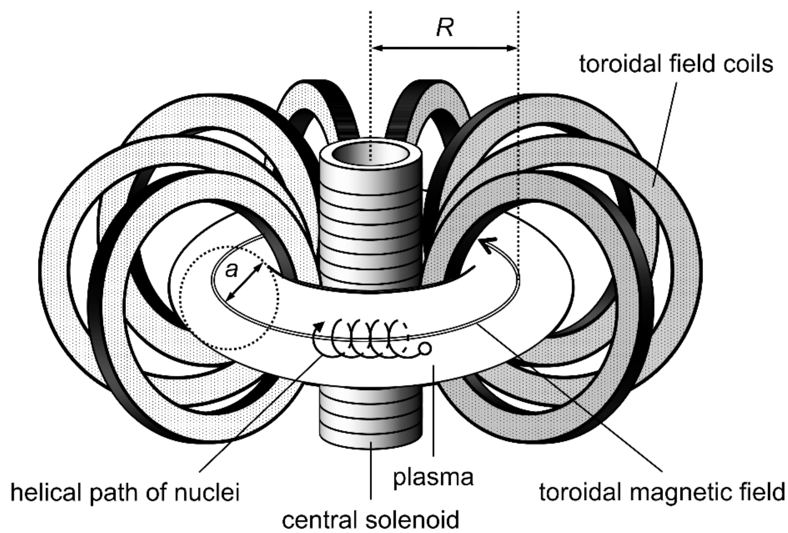

Fig. 8.2

The collisions between the nuclei and the electrons cause a resistance to the flow of charges. Similar to how a current-carrying wire heats up over time, the current in the plasma dissipates power and heats up the plasma in a process known as ohmic heating. Fig. 8.3 shows the variation with temperature of the resistivity of the plasma.

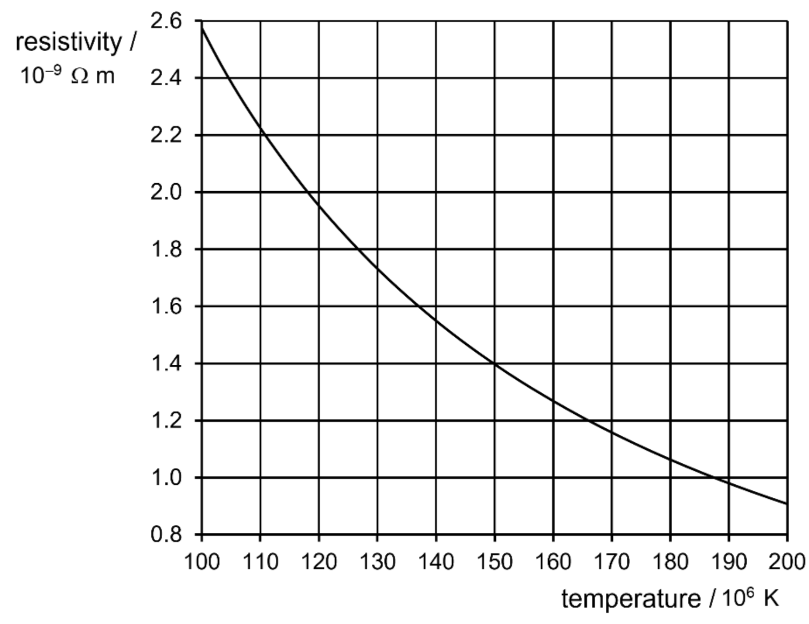

Fig. 8.3

As the resistivity of the plasma decreases when temperature rises, ohmic heating is not sufficient to raise the temperature of the plasma to the required value for fusion reactions. Hence, the plasma is further heated using two external methods – cyclotron resonance heating and neutral beam injection. In cyclotron resonance heating, radio frequency waves are transmitted to the plasma to increase the energy of the particles. In neutral beam injection, electrically neutral particles enter the plasma in a straight-line beam at high speeds and collide with the existing particles to increase the energy of the particles in the plasma.

Table 8.1 summarises the data for the operation of a proposed nuclear fusion reactor.

Table 8.1

major radius, R	6.2 m
minor radius, a	2.0 m
total number density of deuterium and tritium nuclei, n	10^{20} m^{-3}
toroidal magnetic field, B	5.3 T
plasma current, I	15 MA
average temperature, T	127×10^{6} K
cyclotron resonance heating power, P_{CRH}	20 MW
neutral beam injection heating power, P_{NBI}	33 MW

(a) The binding energy per nucleon for the nuclei in the deuterium-tritium fusion reaction are given in Table 8.2.

Table 8.2

nucleus	binding energy per nucleon / MeV
deuterium $^{2}_{1}H$	1.115
tritium $^{3}_{1}H$	2.833
α-particle $^{4}_{2}He$	7.092

Show that the energy released in this reaction is 17.6 MeV.

[2]

(b) Suggest what is meant by the 'Coulomb barrier' in a nuclear fusion reaction.

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(c) The particle shown in Fig. 8.1 is a deuterium nucleus travelling perpendicularly into the plane of the paper.

(i) On Fig. 8.1,

1. mark with a letter X a position along the central axis where the magnetic flux density is a maximum, [1]

2. mark with a letter Y a position along the central axis where the magnetic flux density is a minimum, and [1]

3. draw an arrow and label it with a letter F to show the force acting on the deuterium nucleus. [1]

(ii) Explain why a deuterium nucleus that travels along the central axis cannot be trapped by the magnetic mirror configuration.

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(d) **(i)** Using Faraday's law, explain how varying the current through the central solenoid of a nuclear fusion reactor produces plasma current around the torus.

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(ii) Using Fig. 8.3 and Table 8.1, show that the resistance of the plasma at the operating temperature in the proposed nuclear fusion reactor is $5.6 \times 10^{-9}\ \Omega$.

[2]

(iii) Hence, calculate the ohmic heating power at the operating temperature in the proposed nuclear fusion reactor.

power = ………………… W [1]

(e) In cyclotron resonance heating, energy is transferred to the particles most efficiently when the frequency of the electromagnetic waves is equal to the frequency of the circular motion in the helical path of the particles.

Determine the frequency, in MHz, of the electromagnetic waves required for cyclotron resonance heating of deuterium nuclei.

frequency = ………………… MHz [3]

(f) Suggest why the particles used for neutral beam injection must be electrically neutral.

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(g) The power gain factor Q of a nuclear fusion reactor is the ratio of the power produced from the fusion reactions to the external heating power supplied to the plasma via cyclotron resonance heating and neutral beam injection.

The fusion power produced per unit volume S is given by

$$S = kn^2E$$

where k is 3.57×10^{-23} m^3 s^{-1} and E is the energy produced for each deuterium-tritium fusion reaction.

Determine Q for the proposed nuclear fusion reactor.

$\left[\text{volume of a torus} = 2\pi^2 R a^2\right]$

Q = ………………… [3]

[Total: 20]

End of Paper