Question 19 **(21 marks)**

European Organisation for Nuclear Research – CERN

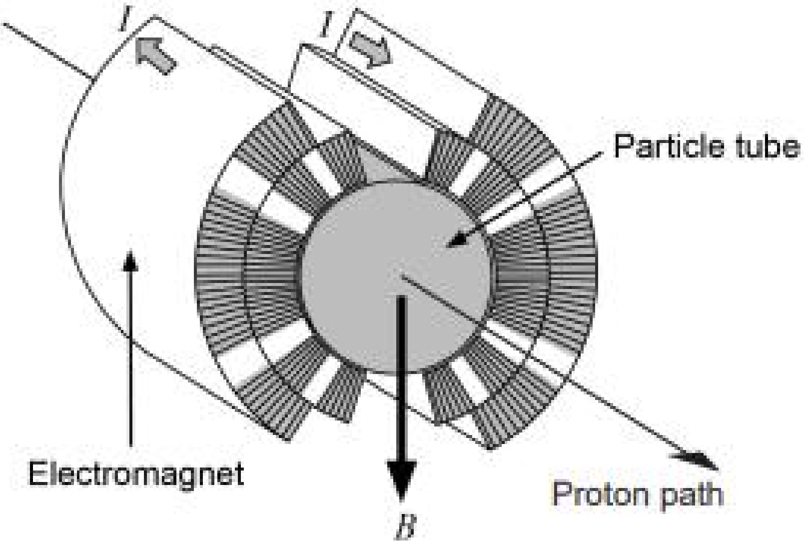
Particle accelerators are used by physicists to explore the elementary particles that might exist. In particle accelerator experiments, the particles' kinetic energy is measured in joules, often alternatively expressed in tera-electron volts (TeV).

The world's most powerful particle accelerator is based in Europe. It is known as the Large Hadron Collider (LHC). This particle accelerator is one of several at the site and the LHC can collide protons with a combined energy of up to 14.0 TeV.

At the LHC, protons are sourced by introducing hydrogen gas into an electrified metal cylinder. A 90.0 kV electric field drives the protons to 1.40% the speed of light prior to entering four sequential radiofrequency cavities. Four steps of acceleration are experienced by the protons in these radiofrequency cavities before they are injected into the LHC. These four steps of acceleration increase the kinetic energy of the protons from 90.0 kV to 50.0 MeV, to 1.40 GeV, to 25.0 GeV and then 450 GeV. The protons are then injected into the LHC where it takes sixteen radiofrequency cavities 20.0 minutes to increase the protons' kinetic energy from 450 GeV to 6.50 TeV.

Inside the LHC, these protons form high-energy particle beams and travel in opposite directions in two separate particle tubes. They travel at close to the speed of light before being made to collide. They are guided around the horizontal accelerator ring by strong magnetic fields created by precisely arranged electromagnets that bend and tighten the path of the particles' trajectory.

The accelerator is built in a ring (large circle) with the particles completing 11 000 circuits each second. The particles can be stored in the ring for hours until they are released and used in an experiment. In the case of the LHC, the accelerator ring is 27.0 km in circumference, giving it a radius of approximately 4.30 km. The diagram below illustrates the simultaneous interactions between the electromagnets and a proton, as the proton is being accelerated towards the centre of the accelerator ring.



The magnetic field (B) is created by superconductive currents on each side of the tube in which the protons travel. The current (I) moves in opposite directions on each side of the tube.

The physics principle at the heart of particle accelerators is Einstein's theory on the equivalence of mass and energy. In the LHC protons (hadrons) travel in opposite directions around the ring at very high velocities and collide. When the protons collide head on, they explode and split into very hot clouds filled with many smaller particles. The greater the total energy of collision the greater is the probability of producing more massive subatomic particles. It is hoped that the energy present at the site of the collision will be sufficient to discover new particles. Hence the discovery of the Higgs Boson.

(a) Determine the kinetic energy, in joules, that each proton has on leaving the electric field prior to entering the four accelerating radio frequency chambers of the LHC. (2 marks)

Answer ______________________ J

(b) Calculate the energy per second in watts consumed per proton to increase its kinetic energy from 450 GeV to 6.50 TeV in the LHC. (4 marks)

A proton with a kinetic energy of 6.50 TeV in the LHC has a velocity of $0.99999998c$.

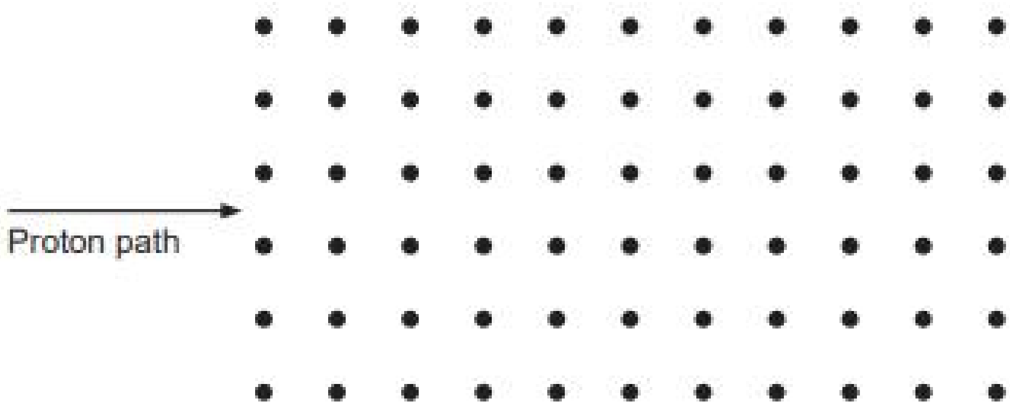
(c) Determine the relativistic momentum of a proton in the LHC with a velocity of $0.99999998c$.
(2 marks)

Answer ____________________ N s

(d) Calculate the magnetic field strength required to maintain the protons on the required path in the LHC. If you were unable to obtain an answer for part (c), use 3.50×10^{-15} N s.
(3 marks)

Answer ____________________ T

(e) The diagram below represents a magnetic field directed vertically out of the page. A proton in the LHC enters this magnetic field at an angle of 90° to the direction of the field. On the diagram below, continue the path of this proton when in the magnetic field.
(1 mark)



(f) Describe with clear reasoning, what happens to the centripetal force on a proton in the LHC as the kinetic energy of the proton increases from 450 GeV to 4.50 TeV. (3 marks)

(g) Describe why the mass of the products after a successful collision of the two protons is greater than the rest mass of the two protons before the collision. (2 marks)

(h) If the rest mass energy of a proton is 938 MeV, calculate the velocity the proton reaches when accelerated to a kinetic energy of 1.4 GeV. (4 marks)