CPSC 2S98
XPHC 2S98/2S99
DPHD 2S98/2S99
DPHE 2S98/2S99

FIRST PUBLIC EXAMINATION

Preliminary Examination in Physics

SECOND PUBLIC EXAMINATION

Honour School of Physics,

Parts A and B: 3 and 4 year Courses

SHORT OPTIONS

Tuesday, 9 June 2008 (?)

9:30 a.m. to 11:00 a.m. for candidates offering ONE Short Option
9:30 a.m. to 12:30 p.m. for candidates offering TWO Short Options

---

Answer **two** *questions from each option for which you have entered.*

Start the answer to each question on a fresh page.

If you have entered for two Short Options,
keep your answers to the two options in different books
and at the end hand in two bundles, one for each option.

A list of physical constants and conversion factors accompanies this paper.

The numbers in the margin indicate the weight that the Examiners anticipate assigning to each part of the question.

Do NOT turn over until told that you may do so.

INDEX

Some sections start with a relevant rubric.

Section S19 PARTICLE ACCELERATOR SCIENCE

Formulae that you may find useful

Energy radiated by synchrotron radiation:

$$E_0 = \frac{4}{3}\pi \frac{r_e}{(m_e c^2)^3} \frac{E^4}{\rho}$$

Where E_0 is the energy radiated per turn due to synchrotron radiation by an electron with an energy E when its orbit has a radius of curvature ρ. $r_e = 2.8 \times 10^{-15}$ m is the classical radius of the electron.

Critical photon energy of synchrotron radiation:

$$\epsilon_c = \frac{3}{2} \frac{\hbar c \gamma^3}{\rho}$$

Where γ is the relativistic factor of the beam and ρ its radius of curvature.

Magnetic rigidity:

$$B\rho = \frac{p}{e}$$

Where B is the magnetic field, p the particles' momentum, e the particle charge and ρ the bending radius.

1. Figure 1 shows the accelerator chain used to produce collisions of 920 GeV protons on 27.6 GeV electrons at DESY.

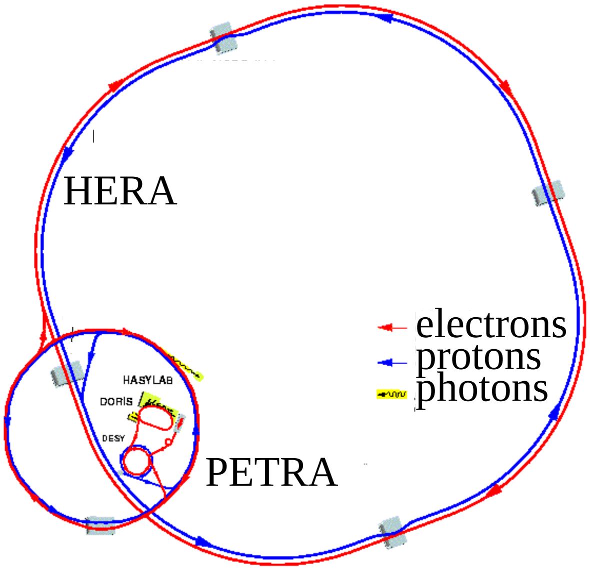

Figure 1: The HERA accelerator chain

a) *Particle sources* Explain briefly how it is possible to produce electrons and protons suitable for acceleration in particle accelerators. [4]

b) *Booster ring* Electrons, positrons and protons are then injected in booster rings. The electrons are injected in their booster ring at an energy of 450 MeV and they are ejected at an energy of 6 GeV. The booster uses 8 accelerating cells giving an acceleration of 1.7 MeV each. At the nominal frequency the particles travel 292.8 m in this circular ring. Neglecting the energy losses, estimate how many turns are necessary to reach the ejection energy and how much time such acceleration requires. Give a reason why the electrons loose energy at each turn and estimate what is the energy lost per turn and per electron at the ejection energy? [5]

c) *Beam emittance* The beam geometric emittance at injection is 10 mm mrad (both vertical and horizontal) and it is 350 nm rad (horizontal) by 35 nm rad (vertical) at ejection. Using your knowledge of storage rings, explain why the emittance has been reduced. Explain why the vertical emittance is 10 times smaller than the horizontal emittance. [6]

d) *Collider ring* The HERA ring has a circumference of 6.2 km but it is in fact made of straight sections and of curved sections. When the protons reach their maximum energy (920 GeV) the magnets reach a field of 4.7 T. Estimate the radius of curvature of the HERA ring. The electrons ring is similar to the protons ring. Calculate the field required for the bending magnets of the electrons at 27.6 GeV. [4]

2.

a) Give the formula expressing the force exerted by an electron on another electron situated at a distance d. Give the formula expressing the resulting acceleration. [1]

Assuming that the electrons are 1 um apart, calculate the force exerted by the electrons onto each other and their acceleration. [2]

b) Let's consider a spherical bunch of radius R. The bunch contains 10^{10} electrons with a uniform density. Using Gauss law derive the radial force f experienced by an electron situated inside the bunch at a position r_b, θ_b, ϕ_b (in spherical coordinates). [3]

Taking $R = 1\,\mathrm{mm}$, draw $f(r_b)$ between 0.1 mm and 2 mm. [2]

c) This electron bunch is injected in a 3 GeV accelerator used to produce X-rays. What will be in keV the critical photon energy of the synchrotron radiation produced when the bunch passes through a 2 T dipole magnet? The bunch travels 0.31 m in the magnet. Estimate the total energy of the radiation produced by the bunch. Express the result in Joules. [3]

Suggest and describe a device that could be used to enhance the radiation flux. [2]

d) In an accelerator it is often important to control accurately the position of the beam. Name a device that can measure the beam charge and a device that can measure the beam position and explain briefly how they operate. [4]

e) Explain what is the emittance of a beam. Describe briefly a method used to measure the transverse emittance of a beam in a single shot. [2]

In a transfer line a commonly used method of transverse emittance measurement involves the measurement of the beam size at several locations. Describe this method in details, explaining how many measurements are needed and how the transverse emittance is deduced from these measurements. [2]

f) A linac accelerates pulses of 10^{10} charged electrons at a repetition rate of 1 Hz up to an energy of 160 MeV over 33 m using 4 klystrons each delivering $1\,\mu$s, 12 MW RF pulses. What would be the length of the linac needed to reach 920 GeV and what would be the wall-plug power consumption of such linac assuming a klystron efficiency of 20%? Would this power consumption change if the single electron pulses were replaced by a 0.8 ms-long train of electron pulses $5\,\mu$s apart and containing 10^{10} electrons each (assuming that the klystrons fire for the same duration and at the same repeition rate)? How much of this energy is transferred to the electron beam (in the case of single pulses and in the case of pulses trains)? Comment on this results. [4]

3.

An electron transport line (shown on figure 2) is made of the following elements (the beam line starts at $s = 0$):

- A bending magnet BEND1, at $s = 1.0\,\mathrm{m}$;
- A sextupole sf, at $s = 2.0\,\mathrm{m}$;
- A sextupole sd, at $s = 2.5\,\mathrm{m}$;
- A quadrupole QF.0, at $s = 3.0\,\mathrm{m}$;
- A dipole giving a vertical deflection vkick, at $s = 3.5\,\mathrm{m}$;
- A quadrupole QD.1, at $s = 4.0\,\mathrm{m}$;
- A quadrupole QF.1, at $s = 5.0\,\mathrm{m}$;
- A dipole giving a horizontal deflection hkick, at $s = 5.5\,\mathrm{m}$;
- A quadrupole QD.2, at $s = 6.0\,\mathrm{m}$;
- A quadrupole QF.2, at $s = 7.0\,\mathrm{m}$;
- A bending magnet BEND2, at $s = 8.0\,\mathrm{m}$;

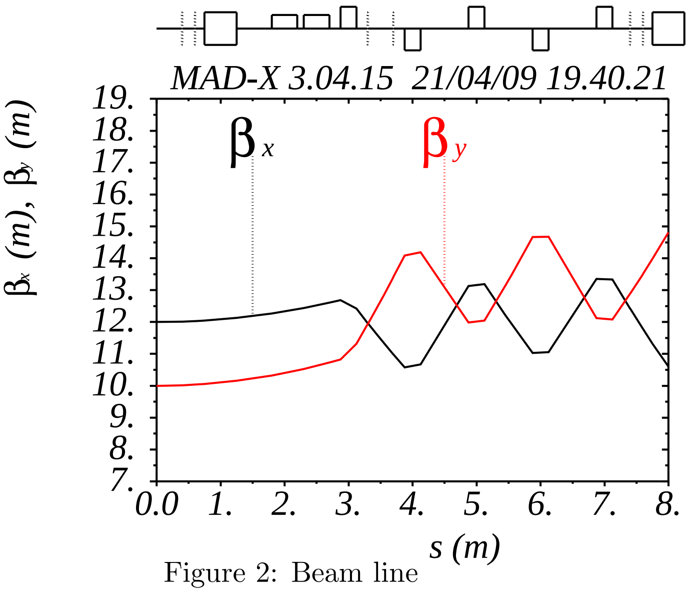

Figure 2: Beam line

a) Explain briefly how each type of magnet mentioned above affects the beam and what purpose it serves in a typical beamline. [4]

b) At $s = 0\,\mathrm{m}$, the beam horizontal β-function is $\beta_x = 10\,\mathrm{m}$ and the vertical β-function is $\beta_y = 12\,\mathrm{m}$. The beam geometric R.M.S. emittance is $1\,\mathrm{mm\,mrad}$. Estimate the horizontal R.M.S. beam size at $s = 0$. Can the beam pipe have the same size than the beam? Describe briefly two phenomena than can affect the beam quality with a too small beam pipe. Explain what is the acceptance of an accelerator. [5]

c) The quadrupoles have a focal length of 2 m. QF-type quadrupoles are focusing in the vertical plane and QD-type quadrupoles are focusing in the horizontal plane. Assume that all other elements are set so that they have no effect on the particles' vertical trajectory. The quadrupoles can be considered to have a negligible length (zero-length thin lens approximation).

Consider a particle located at $y = 1\,\mathrm{mm}$ above the beam axis at $s = 2.5\,\mathrm{m}$ and with no transverse momentum. Use matrix multiplications to estimate the particle's position with respect to the beam axis at $s = 4.5\,\mathrm{m}$. [7]

d) Assuming that the beam studied in (b) has a low intensity and an energy of 1 GeV. What diagnostics would you use to measure the beam size? Explain the basic principle of this diagnostic. [4]

e) In the beam line described above, one of the horizontally focussing quadrupoles has in fact been positioned improperly. Its magnetic axis is parallel to the beam axis but it is displaced by $x = +1\,\mathrm{mm}$ horizontally with respect to the axis of the beam line. Vertically the two axis are still properly aligned. A bunch travelling along the beam axis ($x = 0\,\mathrm{mm}; y = 0\,\mathrm{mm}$) traverses this quadrupole. Describe and calculate the effect that the quadrupole misalignement will have on the bunch (both horizontally and vertically)? A scintillating screen is installed 500 mm after this quadrupole. How the image observed on this screen compares with the one that would be observed if the quadrupole was properly aligned? [5]