Motion of charged particles

Electric fields 4 Steering an ion beam

35–40 minutes independent work + 15–20 minutes review

OCR A H556 | A-level physics | Module 6 | 40 marks

Specification points covered

6.2.3(a,c), 6.2.1(d) Uniform fields, electric force and charged-particle motion.

Prior learning applied: linear/projectile motion (3.1), forces (3.2), energy (3.3) and W = VQ (4.2.2).

Use $e = 1.60 \times 10^{-19}$ C and $g = 9.81$ m s^{-2}.

Use a calculator and your OCR A data booklet. Show working, units and directions where relevant.

1 Read the beam test rig

An ion-engine test rig accelerates singly charged positive xenon ions and steers them towards an offset detector. Each ion has $q = +1.60 \times 10^{-19}$ C and $m = 2.18 \times 10^{-25}$ kg.

For steering calculations use $u_x = 2.00 \times 10^{4}$ m s^{-1}, L = 20.0 mm, d = 10.0 mm and D = 30.0 mm. The beam enters at mid-gap. Take upwards as positive.

Model a dilute beam in a vacuum: negligible drag and ion–ion interactions. The field is uniform between the plates and zero outside; neglect edge effects. The detector centre is h = 8.10 mm above the entry line.

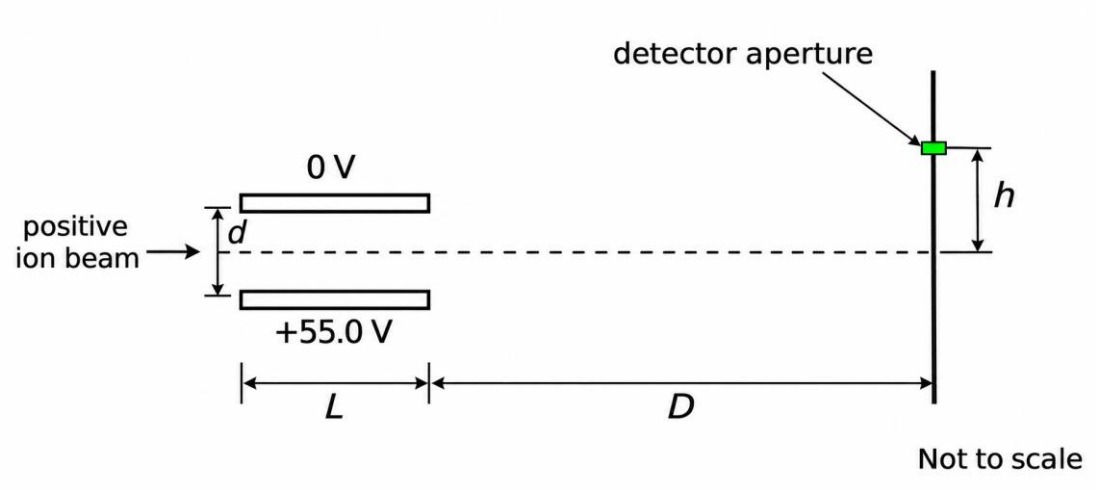


Figure 1 Steering plates and detector

1(a) State the directions of the electric field and the electric force on a positive ion between the steering plates in Figure 1. **[1 mark]**

1(b) The beam enters horizontally at speed 2.00×10^4 m s^{-1}. State its initial horizontal and vertical velocity components. **[1 mark]**

2 Accelerate the ions upstream

The accelerating p.d. U_a is separate from the steering p.d. U_s. For Question 2 only, calculate the speed specified in each part; return to the stated 2.00×10^4 m s^{-1} for Question 3 onwards.

2(a) Before the steering region, an ion starts from rest and moves through a 300 V accelerating p.d. Calculate its kinetic energy gain in joules. **[1 mark]**

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2(b) Calculate the speed produced by that 300 V accelerating p.d. **[1 mark]**

2(c) Find the accelerating p.d. that produces the 2.00×10^4 m s^{-1} entry speed used elsewhere in the worksheet. Explain whether a positive ion moves to a higher or lower electric potential while gaining this energy. **[2 marks]**

3 Establish the transverse acceleration

3(a) At U_s = 55.0 V, calculate the electric field magnitude between the steering plates. **[1 mark]**

3(b) Calculate the electric force magnitude on one ion. **[1 mark]**

3(c) Calculate the vertical acceleration and explain why the horizontal acceleration is zero in the given model. **[2 marks]**

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3(d) Calculate the ratio of electric force to weight and use it to justify neglecting gravity. Does this calculation also justify neglecting drag? **[2 marks]**

4 Follow the motion inside the plates

4(a) Calculate the time an ion spends between the steering plates. **[1 mark]**

4(b) Calculate the vertical displacement at the plate exit. **[2 marks]**

4(c) Determine the exit vertical velocity, then the exit speed and angle above the horizontal. **[3 marks]**

4(d) Treat each ion as a point. Check whether the original beam clears the upper plate. **[1 mark]**

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5 Continue to the detector

5(a) Calculate the time taken to travel the drift distance D after leaving the plates. **[1 mark]**

5(b) Calculate the additional vertical displacement in the drift region and the total displacement at the detector. Explain why the path in this region is straight. **[3 marks]**

5(c) Sketch v_x against time and v_y against time from entry at t = 0 to arrival at the detector at t = 2.50 μs. Mark the plate-exit time and the main velocity values. **[2 marks]**

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6 Align the detector

6(a) Starting from the field force and the two stages of motion, show that the detector displacement is $Y = qU_sL(D + L/2)/(md\,u_x^2)$. Define the role of the two terms D and L/2. **[3 marks]**

6(b) Find the steering p.d. needed to reach the detector centre at Y = 8.10 mm. Check both an 80.0 V supply limit and the 5.00 mm exit-clearance limit. Use the original ion and geometry data. **[3 marks]**

6(c) A pupil calculates vertical deflection using $y = (2.00 \times 10^4)t + \tfrac{1}{2}a_yt^2$. Explain the error and give the correct initial vertical velocity. **[2 marks]**

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7 Transfer the method to a different setting

7(a) At the same entry speed, geometry, steering p.d. and charge, an ion's mass is doubled. State and explain the change in detector displacement. **[2 marks]**

7(b) Instead, both ion types start from rest and are accelerated through the same U_a before entering the same steering arrangement. Substitute $u_x^2 = 2qU_a/m$ into 6(a). Explain why the mass conclusion from 7(a) no longer applies. **[3 marks]**

7(c) Return to the original positive ions and the original entry speed. Change only the lower plate from +55.0 V to −55.0 V. Describe the trajectory and state whether the original upper detector aperture will collect the beam. **[2 marks]**

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