Uniform electric fields solutions

Electric fields 2 An electrostatic microbead balance

Matching answers and examiner-style commentary

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

Specification points covered

6.2.3(a) Uniform fields and E = V/d. 6.2.1(c–d) Field lines and E = F/q.

Prior learning applied: weight/equilibrium (3.2), p.d. and W = VQ (4.2.2).

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

1 Read the balance

A feedback-controlled balance holds a microbead between horizontal plates while a technician measures its charge. Only vertical forces are considered; the feedback system's stability is outside this model.

Initially m = 1.20 × 10^{-9} kg, q = +3.00 × 10^{-13} C and the gap is 10.0 mm. The upper plate is at 0 V. The lower-plate potential +V is adjustable. Neglect drag and other forces.

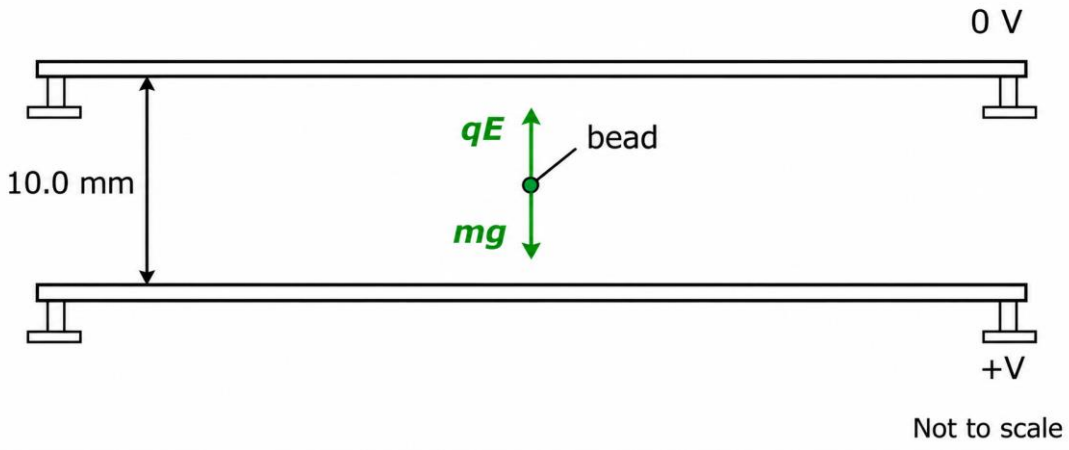


Figure 1 Adjustable plate potential

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1(a) For the positive lower-plate setting in Figure 1, state the direction of the electric field between the plates. **[1 mark]**

The field points upwards, from the positive lower plate towards the upper plate at lower potential.

Marking guidance 1: upwards.

1(b) A bead is to be held against its weight by the electric field. State the required sign of the bead's charge. **[1 mark]**

The bead must be positively charged. A positive charge feels an upward force in the upward field, opposing its downward weight.

Marking guidance 1: positive charge.

2 Draw a useful model

2(a) In the space below, sketch the two plates and at least four field lines in their central region. Show direction and how uniformity is represented. **[2 marks]**

Draw straight parallel lines perpendicular to the plates, with equal spacing and arrows upwards. Parallel equally spaced lines represent a field of constant magnitude and direction.

Marking guidance 1: parallel, equally spaced lines perpendicular to the plates. 1: upward arrows.

2(b) Explain where E = V/d is a good approximation and why the same model is less reliable close to a plate edge. **[2 marks]**

It is a good approximation in the central region of large parallel plates when the gap is small compared with their lateral dimensions. Near the edges the field fringes: its direction and magnitude vary, so it is not uniform.

Marking guidance 1: central region/appropriate geometry. 1: explained edge-field limitation.

2(c) Draw a free-body diagram for a stationary positive bead. Label both forces and state the equilibrium condition. **[2 marks]**

The electric force qE acts upward and weight mg acts downward. For vertical equilibrium they have equal magnitudes, qE = mg, so the resultant is zero.

Marking guidance 1: exactly two correctly directed and labelled forces. 1: qE = mg or equivalent zero-resultant statement.

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3 Set the field strength

3(a) Set the lower plate to +400 V while the upper plate remains at 0 V. Calculate E in the 10.0 mm gap. **[1 mark]**

Use the p.d. between the plates and convert the gap: d = 10.0 mm = 0.0100 m.

$E = |\Delta V|/d = 400/0.0100 = 4.00 \times 10^4$ V m^{-1}, upwards.

Marking guidance 1: 4.00×10^4 V m^{-1} or N C^{-1}.

3(b) A separate test requires $E = 6.50 \times 10^4$ V m^{-1} across an 8.00 mm gap. Find the required plate p.d. **[1 mark]**

$|\Delta V| = Ed = (6.50 \times 10^4)(8.00 \times 10^{-3}) = 520$ V.

Marking guidance 1: 520 V.

3(c) Relative to any initial setting, the p.d. is doubled and the gap is increased by a factor of 1.50. Find the factor by which E changes. **[1 mark]**

E is proportional to $|\Delta V|/d$, so $E_{new}/E_{old} = 2.00/1.50 = 4/3$. The field increases by one third.

Marking guidance 1: factor 4/3 or 1.33.

3(d) Show that V m^{-1} and N C^{-1} are equivalent units. **[1 mark]**

1 V = 1 J C^{-1} and 1 J = 1 N m.

V m^{-1} = J C^{-1} m^{-1} = N C^{-1}.

Marking guidance 1: valid unit argument.

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4 Use the balancing measurement

4(a) Calculate the weight of the original bead. **[1 mark]**

$W = mg = (1.20 \times 10^{-9})(9.81) = 1.1772 \times 10^{-8}$ N $\approx 1.18 \times 10^{-8}$ N, downwards.

Marking guidance 1: correct weight.

4(b) Determine the electric field required to balance this bead, whose charge is $+3.00 \times 10^{-13}$ C. **[1 mark]**

Balance requires $qE = mg$, so $E = mg/q$.

$E = (1.20 \times 10^{-9})(9.81)/(3.00 \times 10^{-13}) = 3.924 \times 10^{4}$ N C^{-1}, upwards.

Marking guidance 1: about 3.92×10^{4} N C^{-1}.

4(c) Find the balancing plate p.d. at the original 10.0 mm gap. **[1 mark]**

$V = Ed = (3.924 \times 10^{4})(0.0100) = 392.4$ V ≈ 392 V.

The lower plate must be positive relative to the upper plate.

Marking guidance 1: about 392 V.

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4 Use the balancing measurement continued

4(d) A different positive bead of the same mass balances at 500 V in the 10.0 mm gap. Determine its charge and estimate the number of electrons missing from it. **[3 marks]**

Step 1 Link the measured p.d. to the balancing condition.

$E = V/d$ and $qE = mg$, so $q = mgd/V$.

$q = (1.20 \times 10^{-9})(9.81)(0.0100)/500 = 2.3544 \times 10^{-13}$ C.

Step 2 Divide the positive charge by the elementary charge.

$N = q/e = (2.3544 \times 10^{-13})/(1.60 \times 10^{-19}) = 1.4715 \times 10^{6}$.

The bead is missing about 1.47×10^{6} electrons. The macroscopic measurement cannot identify an exact integer count.

Marking guidance 1: links field and balance to obtain q. 1: charge about $+2.35 \times 10^{-13}$ C. 1: about 1.47×10^{6} missing electrons.

4(e) A pupil says, ‘The bead is stationary, so its electric force is zero.’ Explain the error. **[2 marks]**

Stationary equilibrium requires zero resultant force, not zero individual forces. Here the non-zero upward electric force balances the non-zero downward weight.

Marking guidance 1: resultant/individual distinction. 1: correct opposing-force balance.

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5 Interpret a potential profile

For this section only, the lower plate is at 400 V and the upper plate is at 0 V. y is measured upwards from the lower plate.

Table 1

y / mm	V / V
0	400
2.5	300
5.0	200
7.5	100
10.0	0

5(a) Sketch V against y using Table 1, with labelled axes and units. Explain what the straight-line form tells you about the field magnitude. **[2 marks]**

The points lie on a straight decreasing line from (0 mm, 400 V) to (10.0 mm, 0 V). Label y/mm horizontally and V/V vertically.

Equal changes in distance give equal potential decreases, so $|\Delta V|/\Delta y$ and hence the field magnitude are constant.

Marking guidance 1: correct labelled straight-line sketch. 1: links constant potential change per distance to uniform magnitude.

5(b) Use the profile to find the magnitude of the p.d. between y = 2.0 mm and y = 7.0 mm. Check that it gives the same E as the full-gap calculation. **[2 marks]**

Linear interpolation gives V(2.0 mm) = 320 V and V(7.0 mm) = 120 V.

$|\Delta V| = |120 - 320| = 200$ V.

The distance is 5.0 mm = 0.0050 m, so $E = 200/0.0050 = 4.0 \times 10^4$ V m^{-1}, consistent with the full gap.

Marking guidance 1: 200 V. 1: correct field check using the partial distance.

5(c) Both plate potentials are increased by 150 V. Explain what happens to the field and to the balancing force for an unchanged bead. **[2 marks]**

The potentials become 550 V and 150 V, so the p.d. remains 400 V. The gap is unchanged, so E is unchanged. Since q is unchanged, qE is also unchanged. Shifting the reference does not change the physical force.

Marking guidance 1: unchanged p.d./field. 1: unchanged force with a valid reason.

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6 Check the operating limits

6(a) A new bead has mass 1.80×10^{-9} kg and charge $+3.00 \times 10^{-13}$ C. The supply cannot exceed 500 V. Compare gaps of 8.00 mm and 12.0 mm and choose one that permits balance. **[3 marks]**

Step 1 Find the required field from the force balance.

$E = mg/q = (1.80 \times 10^{-9})(9.81)/(3.00 \times 10^{-13}) = 5.886 \times 10^{4}$ V m^{-1}.

Step 2 Calculate the p.d. for each gap.

At 8.00 mm: $V = Ed = (5.886 \times 10^{4})(0.00800) = 470.88$ V.

At 12.0 mm: $V = (5.886 \times 10^{4})(0.0120) = 706.32$ V.

Choose the 8.00 mm gap; 471 V is within the 500 V limit, whereas 706 V is not.

Marking guidance 1: required field. 1: both p.d.s. 1: justified choice.

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6 Check the operating limits continued

6(b) For the new bead, the charge may be 5% below its nominal value and the chosen gap may be 0.10 mm larger than 8.00 mm. Check whether the 500 V supply guarantees balance at this worst case. **[3 marks]**

Step 1 A smaller positive charge and a larger gap both increase the required p.d.

$q_{min} = 0.95(3.00 \times 10^{-13}) = 2.85 \times 10^{-13}$ C; $d_{max} = 8.10 \times 10^{-3}$ m.

Step 2 Use the limiting values together.

$V = mgd/q = (1.80 \times 10^{-9})(9.81)(8.10 \times 10^{-3})/(2.85 \times 10^{-13}) = 501.86$ V.

About 502 V is required, which exceeds 500 V. The nominal design works, but the stated tolerance range does not guarantee balance.

Marking guidance 1: selects both worst-case values. 1: voltage about 502 V. 1: correct guarantee conclusion.

6(c) At a previously balanced positive-bead setting, the plate polarities are reversed. State the direction of the resultant force immediately afterwards and explain. **[2 marks]**

The electric force reverses to downwards while weight remains downwards. Both forces now act downwards, so the resultant is downwards.

Marking guidance 1: reversed downward electric force. 1: downward resultant with both forces identified.

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7 Explain and evaluate the measurement

7(a) Describe how the technician could determine the charge on a bead of known mass using this balance. Link the measurements to an equation for q, and explain two relevant controls or improvements. **[4 marks]**

Measure the clear plate gap d at several positions to check parallelism and obtain a representative gap. Measure the actual plate p.d. with a suitable voltmeter.

Adjust the p.d. until the bead remains at a fixed vertical position; then its electric force balances weight. Record the balancing p.d. and repeat to judge consistency.

Use q = mgd/V, with the sign chosen from the force and field directions.

Keep the same bead and avoid charge leakage so m and q do not change. Keep the bead well inside the central plate region, shield it from air currents and account for the resolution of the gap/p.d. measurements. Any two relevant justified controls/improvements are acceptable.

Marking guidance 1: measures gap and actual p.d. 1: identifies balance and q = mgd/V. 1 each: two explained relevant controls/improvements; maximum 4 overall.

7(b) Evaluate this response: ‘A larger voltage means a larger charge on the bead. At balance the field cancels gravity, and moving both plate voltages upwards increases the force.’ Identify and correct two distinct errors. **[2 marks]**

For a given bead the charge is not set by the plate p.d.; changing the p.d. changes E and hence qE. At equilibrium it is the electric force that balances the gravitational force, not one field cancelling a different type of field.

If both plate potentials increase by the same amount, their difference and hence E and qE remain unchanged. Any two of these corrected errors earn the two available marks.

Marking guidance 1 each for two distinct correct corrections; accept equivalent precise language.

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