PARTICLES AND WAVES 6 · FORCES ON CHARGED PARTICLES

Forces on Charged Particles

Fields you cannot see, doing work you can measure.

Higher Physics

Starter

2007 Higher Physics

Scan the code and answer these:

Q1 **Q8** **Q11**

Section A · vectors, a.c., R

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 1

Electric fields

A region where a charged particle feels a force — and how we draw one.

By the end of this part...

1. I can state what an electric field is, and what it does to a charge.
2. I can state the direction electric field lines are drawn in.
3. I can sketch the field pattern for point charges and parallel plates.

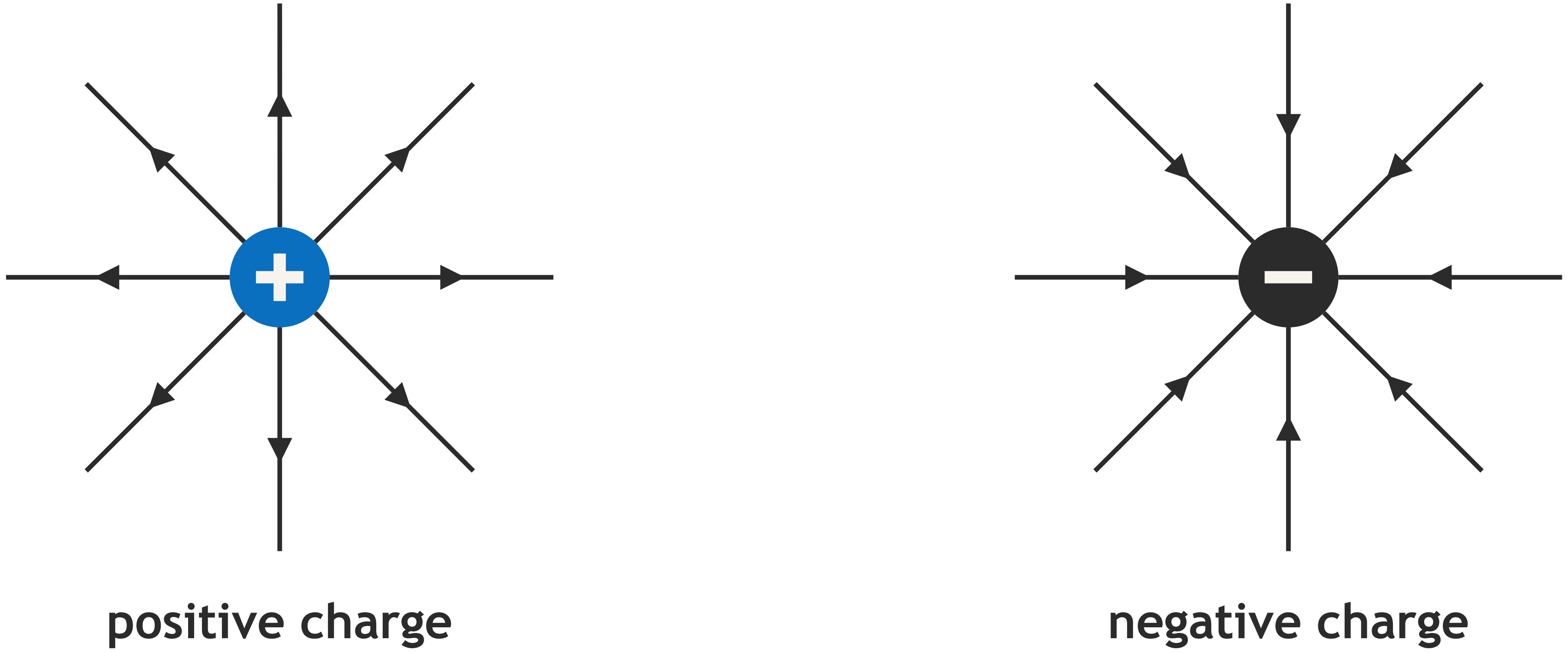
What an electric field is

Not a thing you can see — a region where something happens.

- A charged particle has an electric field around it.
- Any other charge placed in that field feels a force.
- The field is there whether or not a second charge is.
- Between two charged parallel plates the field is uniform.

Field around a single point charge

JOTTER NOTES



JOTTER NOTES

Electric field lines

A field line shows the direction of the force on a POSITIVE charge.

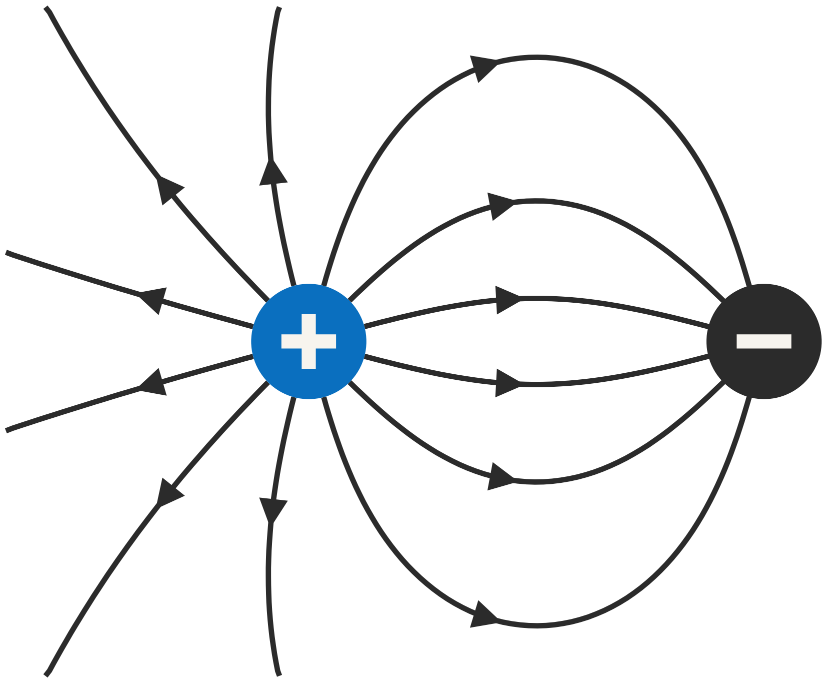
So lines point AWAY from positive, and TOWARDS negative.

Closer lines mean a stronger field.

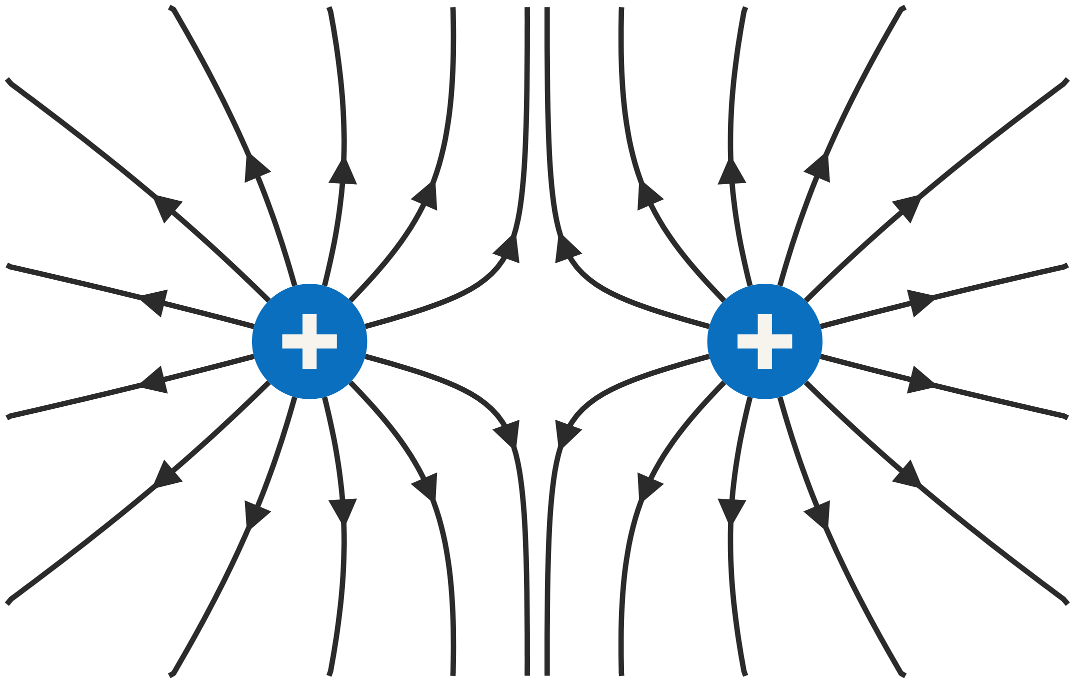
Lines never cross.

Two point charges

JOTTER NOTES



unlike charges — they attract

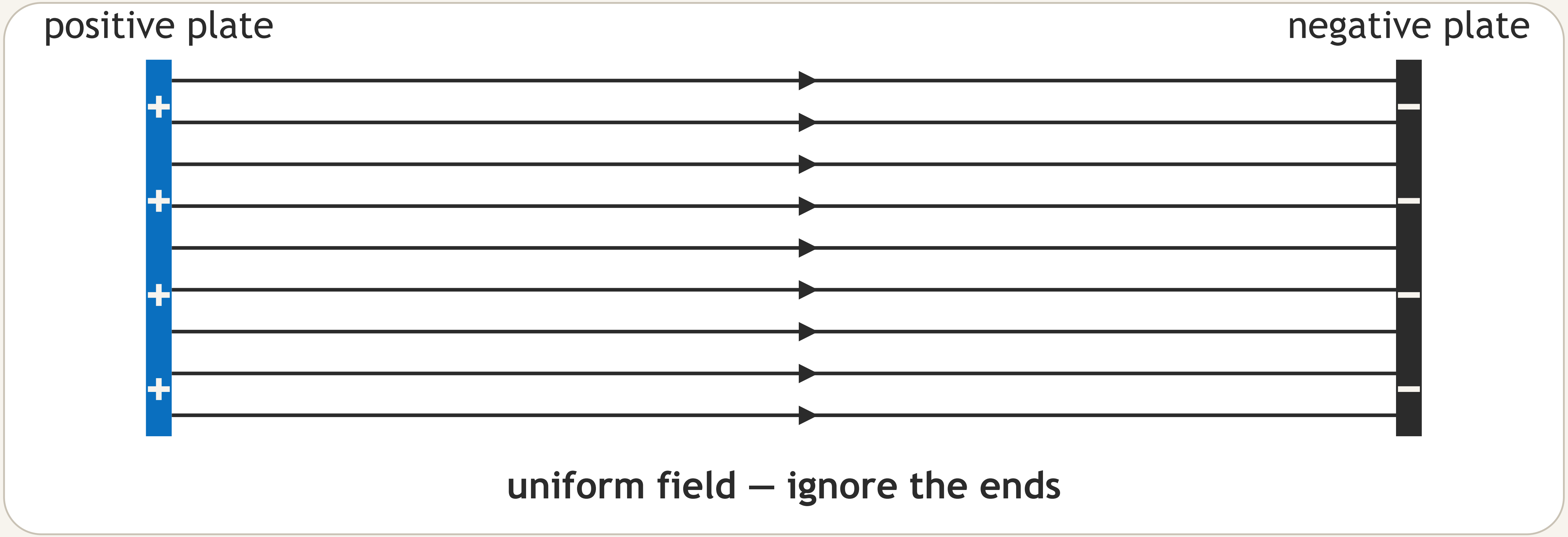


like charges — they repel

Two charged parallel plates

JOTTER NOTES

Straight, parallel, equally spaced — the same everywhere.



JOTTER NOTES

The four patterns

Single charge: straight lines, evenly spread all round.

Unlike charges: lines run out of the + and into the −.

Like charges: no line joins them; they curve apart.

Parallel plates: straight, parallel, evenly spaced, + to −.

Watch Out: which way do the arrows go

THE MISTAKE

- Arrows drawn outwards from a negative charge.
- Between plates, arrows drawn from – to +.
- Lines drawn joining two like charges.

THE CORRECT ANSWER

- Into a negative charge — always.
- From the + plate to the – plate.
- They repel: the lines curve apart instead.

Show Me: field patterns

SHOW ME BOARDS

1. Sketch the electric field pattern around a single negative point charge.
2. Sketch the field between two charged parallel plates, and state one thing your sketch shows about the field strength.
3. Two point charges attract. State what this tells you about their signs, and sketch the pattern.
4. A pupil draws field lines crossing between two charges. State and justify why this cannot be right.
5. Explain how a field-line diagram shows where the field is strongest.

Show Me: field patterns

SHOW ME BOARDS

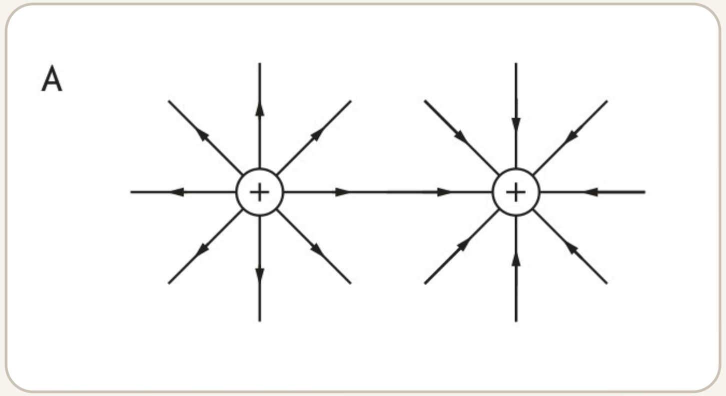
EXTRA PRACTICE

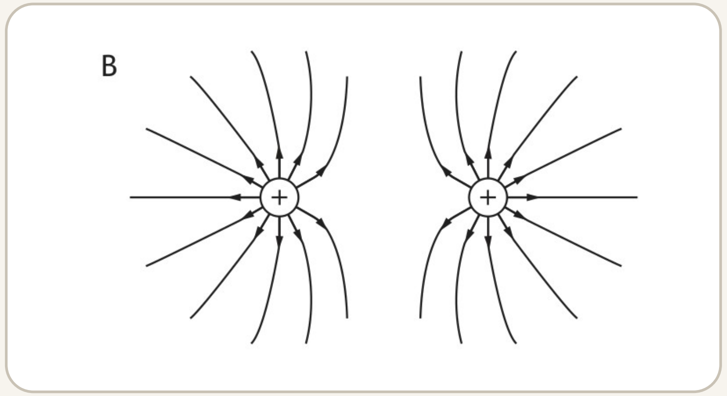
1. Sketch the field pattern for two identical positive point charges.
2. State and justify what happens to an electron released midway between two charged parallel plates.
3. A field line diagram is drawn with arrows pointing into a positive charge. State the mistake, and correct it.
4. Describe how the field between parallel plates differs from the field around a single point charge.
5. Sketch the field around a negative charge, and mark where a second negative charge would feel the largest force.

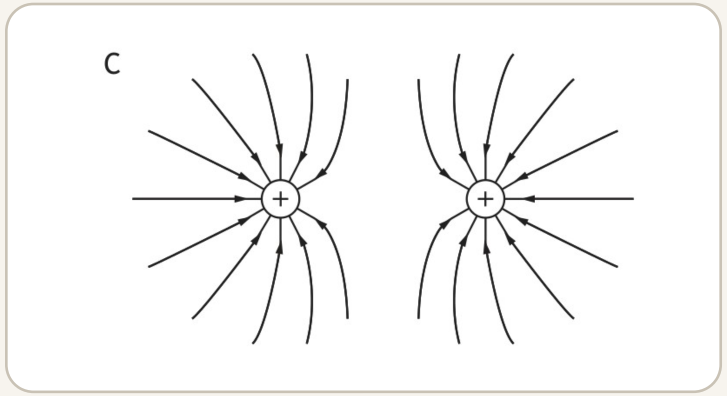
Show Me: which pattern is right

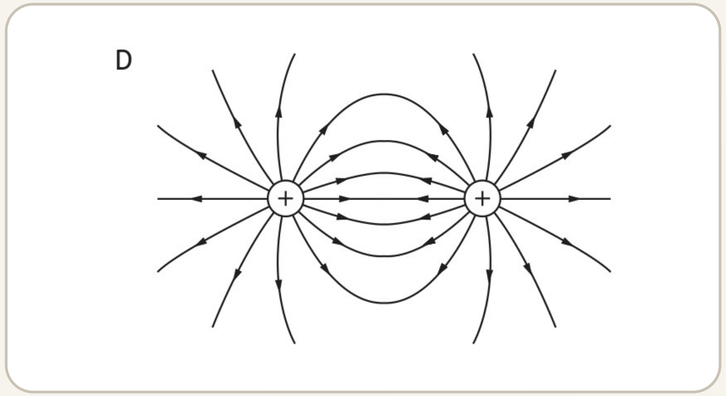
SHOW ME BOARDS

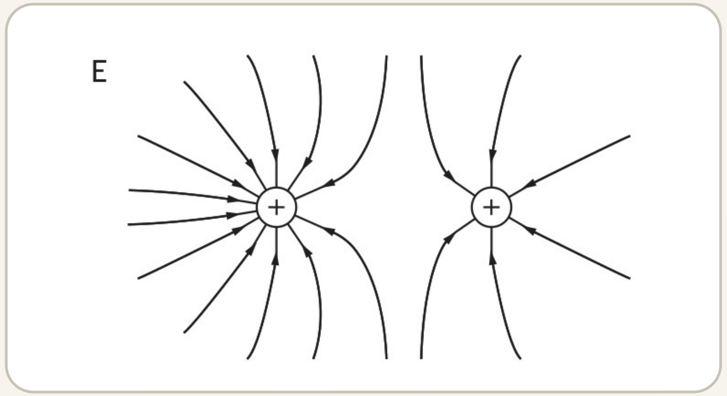
Two equal positive point charges. Which pattern is right — and why?











SQA Higher Physics 2023, Paper 1, Question 10 — reproduced with acknowledgement to SQA.

Task

Work through the electric field questions. Sketch every pattern — do not just read them.

Leckie and Leckie Exercise 1.2.3 (p156)
Past papers: 2023 Paper 1 Q10

Scholar quiz

Starter

2008 Higher Physics

Scan the code and answer these:

Q9 **Q11** **Q15**

Section A · e.m.f., a.c., uncertainty

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 2

Moving a charge

Put a charge in a field and it moves. Moving it takes work.

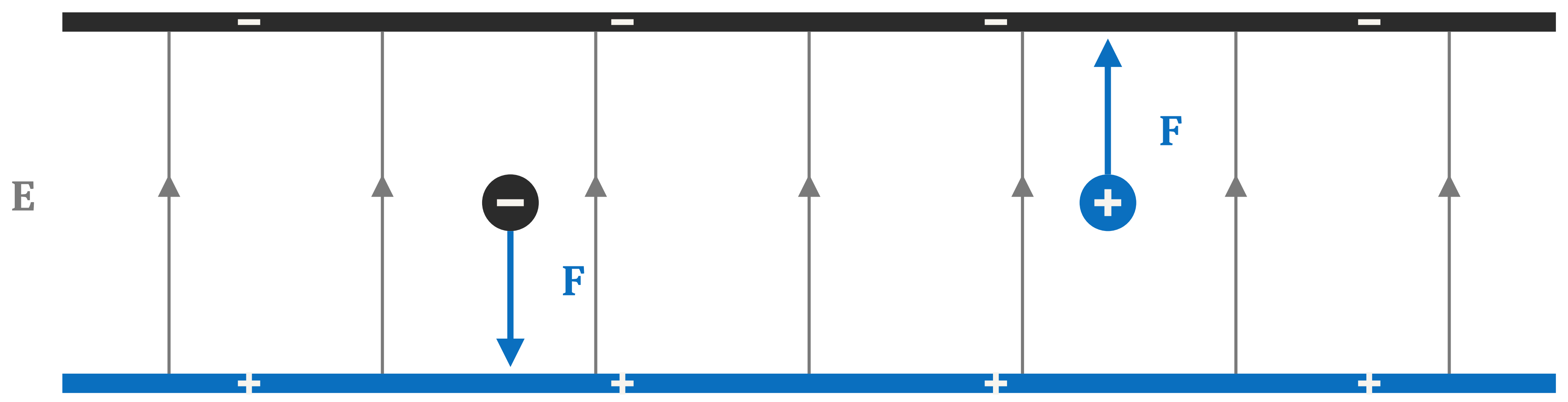
By the end of this part...

1. I can determine which way a charged particle moves in a field.
2. I can define potential difference in terms of work done and charge.
3. I can use $W = QV$ to find work done, charge or p.d.

Which way does a charge move

JOTTER NOTES

Released from rest between two charged parallel plates.



JOTTER NOTES

A charge in an electric field

A positive charge is pushed the SAME way as the field lines.

A negative charge is pushed the OPPOSITE way.

So a positive charge moves towards the negative plate.

An electron moves towards the positive plate.

The field does work on the charge, so it gains kinetic energy.

JOTTER NOTES

Potential difference

Potential difference is the work done moving unit charge between two points.

Unit charge means one coulomb.

So a p.d. of $1\,\text{volt}$ means $1\,\text{joule}$ of work per coulomb.

Work done on a charge

JOTTER NOTES

Moving a charge through a p.d. takes energy.

$$W = QV$$

W	Q	V
work done in joules (J)	charge in coulombs (C)	p.d. in volts (V)

1 volt is 1 joule per coulomb.

Worked example

An electron is moved through a p.d. of 250 V.

Calculate the work done on it.

$Q = 1{\cdot}60 \times 10^{-19}$ C

$V = 250$ V

$W = ?$

$$W = QV$$

$W = 1{\cdot}60 \times 10^{-19} \times 250$

$\underline{W = 4{\cdot}0 \times 10^{-17}\ \text{J}}$

Show Me: work done on a charge

SHOW ME BOARDS

1. A charge of $3{\cdot}0\ \mu\text{C}$ is moved through a p.d. of $40\ \text{V}$. Calculate the work done.
2. State what is meant by a potential difference of $12\ \text{V}$.
3. $9{\cdot}6 \times 10^{-18}\ \text{J}$ of work is done moving an electron between two points. Calculate the p.d. between them.
4. An electron and a proton cross the same p.d. Compare the work done on each, with justification.
5. A proton is released next to the positive plate. State which way it moves, and justify your answer.

Show Me: work done on a charge

SHOW ME BOARDS

EXTRA PRACTICE

1. A charge of $5{\cdot}0\ \mathrm{nC}$ moves through $2{\cdot}4\ \mathrm{kV}$. Calculate the work done.
2. Work of $8{\cdot}0 \times 10^{-16}\ \mathrm{J}$ is done on a charge crossing $5{\cdot}0\ \mathrm{kV}$. Calculate the charge, in terms of the electron charge.
3. State and justify what happens to the work done if the p.d. is halved and the charge is doubled.
4. An alpha particle carries a charge of $+2e$. Calculate the work done on it crossing $1{\cdot}5\ \mathrm{kV}$.
5. Explain why an electron released at the negative plate gains kinetic energy as it crosses to the positive plate.

Task

Work through the questions on fields and work done.
Show the relationship, the substitution and the unit every time.

Leckie and Leckie Exercise 1.2.4 (p159)
Read 1.2.4 Applications (p157/8)

Past Paper Finder

Starter

2013 Revised Higher Physics

Scan the code and answer these:

Q3 **Q17** **Q18**

Section A · uncertainty, R, capacitors

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 3

Accelerating a charge

All the work done becomes kinetic energy — so how fast does it go?

By the end of this part...

1. I can equate the work done on a charge to its kinetic energy.
2. I can derive a relationship for the speed of a charged particle.
3. I can calculate the speed of an electron accelerated through a p.d.

Where the energy goes

A charge released from rest in a vacuum between two plates.

- The field does work on the charge as it crosses.
- There is nothing to lose energy to — the tube is evacuated.
- So ALL of the work done becomes kinetic energy.
- Both relationships are on the relationships sheet. Equate them.

JOTTER NOTES

Accelerating a charged particle

$$W = QV$$

$$E_k = \frac{1}{2}mv^2$$

All the work done becomes kinetic energy, so:

$$QV = \frac{1}{2}mv^2$$

Rearranging for the speed

JOTTER NOTES

This one is NOT on the relationships sheet — you derive it.

$$v = \sqrt{\frac{2QV}{m}}$$

v	**Q**	**V**	**m**
speed in $\mathrm{m\ s^{-1}}$	charge in coulombs (C)	p.d. in volts (V)	mass in kilograms (kg)

JOTTER NOTES

Deriving the speed

$$QV = \frac{1}{2}mv^2$$

$$v^2 = \frac{2QV}{m}$$

$$v = \sqrt{\frac{2QV}{}}$$

Charge and mass of an electron come from the data sheet.

Worked example

A proton is accelerated from rest through 5·0 kV.

Calculate its speed as it arrives at the negative plate.

$Q = 1{\cdot}60 \times 10^{-19}$ C

$V = 5{\cdot}0 \times 10^{3}$ V

$m = 1{\cdot}673 \times 10^{-27}$ kg

$v = ?$

$$QV = \frac{1}{2}mv^2$$

$$1{\cdot}60 \times 10^{-19} \times 5{\cdot}0 \times 10^{3}$$

$$= \tfrac{1}{2} \times 1{\cdot}673 \times 10^{-27} \times v^2$$

$$\underline{v = 9{\cdot}8 \times 10^{5}\ \text{m s}^{-1}}$$

Worked example

An electron accelerated from rest reaches $3{\cdot}0 \times 10^{7}\ \text{m s}^{-1}$.

Calculate the p.d. it was accelerated through.

$m = 9{\cdot}11 \times 10^{-31}\ \text{kg}$

$v = 3{\cdot}0 \times 10^{7}\ \text{m s}^{-1}$

$Q = 1{\cdot}60 \times 10^{-19}\ \text{C}$

$V = ?$

$$QV = \frac{1}{2}mv^2$$

$1{\cdot}60 \times 10^{-19} \times V$

$= \tfrac{1}{2} \times 9{\cdot}11 \times 10^{-31} \times (3{\cdot}0 \times 10^{7})^2$

$\underline{V = 2{\cdot}6 \times 10^{3}\ \text{V}}$

Watch Out: accelerating charges

THE MISTAKE

- Using $v = \sqrt{(2QV/m)}$ straight off the relationships sheet.
- Forgetting to square v when rearranging for V.
- Using the proton mass for an electron.

THE CORRECT ANSWER

- It is not on the sheet — start from $QV = \frac{1}{2}mv^2$.
- $V = mv^2/2Q$ — the square stays with the v.
- The data sheet gives both — check which you picked.

Show Me: accelerating charges

SHOW ME BOARDS

1. An electron is accelerated from rest through $1{\cdot}5\ \mathrm{kV}$. Calculate its speed at the anode.
2. Show that the kinetic energy gained by an electron crossing $800\ \mathrm{V}$ is $1{\cdot}28 \times 10^{-16}\ \mathrm{J}$.
3. A proton and an electron cross the same p.d. State and justify which ends up faster.
4. State and justify the effect on the final speed of doubling the accelerating p.d.
5. An electron reaches $2{\cdot}0 \times 10^{7}\ \mathrm{m\ s^{-1}}$ from rest. Calculate the p.d. it crossed.

Show Me: accelerating charges

SHOW ME BOARDS

EXTRA PRACTICE

1. A proton is accelerated from rest through $12\ \mathrm{kV}$. Calculate its final speed.
2. An alpha particle ($+2e$, $6{\cdot}64 \times 10^{-27}\ \mathrm{kg}$) crosses $4{\cdot}0\ \mathrm{kV}$. Calculate its speed.
3. Explain why the tube must be evacuated for all the work done to become kinetic energy.
4. An electron gains $4{\cdot}8 \times 10^{-17}\ \mathrm{J}$. Calculate the p.d. crossed AND the final speed.
5. State and justify what happens to the final speed if the accelerating p.d. is increased by a factor of nine.

Task

Work through the accelerating-charge calculations.
Start every one from $QV = \frac{1}{2}mv^2$ — show the rearrangement.

Leckie and Leckie Exercise 1.2.4 (p159)
Past papers: 2025 P1 Q10, 2024 P2 Q6(a)

Past Paper Finder

Starter

Revised Higher Physics specimen paper

Scan the code and answer these:

Q4 **Q11** **Q12**

Section A · uncertainty, a.c., R

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 4

Magnetic fields

A moving charge makes its own magnetic field — and feels a force in one.

By the end of this part…

1. I can state that a moving charge produces a magnetic field.
2. I can find the direction of the force on a positive charge.
3. I can find it for a negative charge, including an electron.

A moving charge makes a field

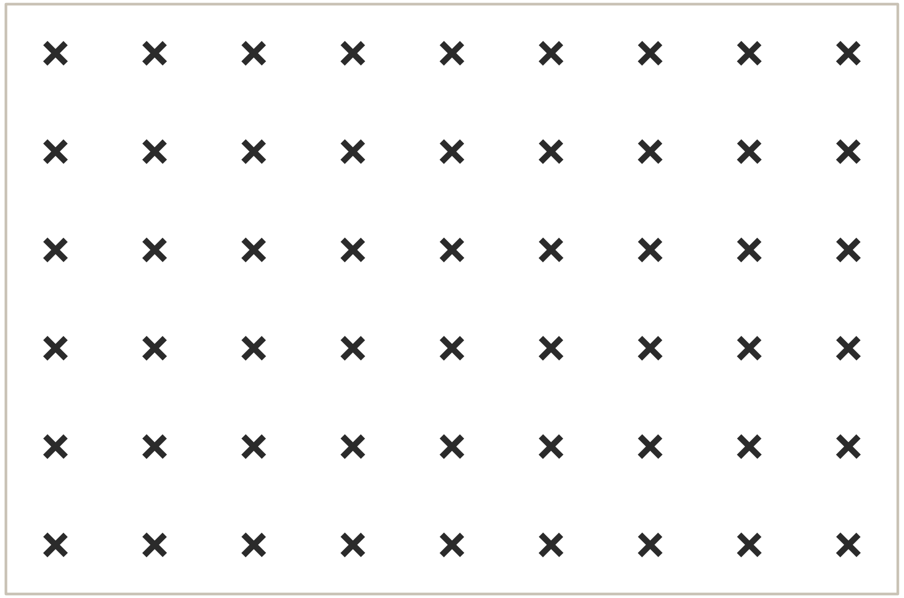
Charge at rest: electric field only. Charge moving: both.

- Any moving charge produces a magnetic field around it.
- A current in a wire is moving charge, so a wire has one too.
- Put a moving charge in ANOTHER magnetic field and it feels a force.
- That force is at right angles to both the field and the motion.

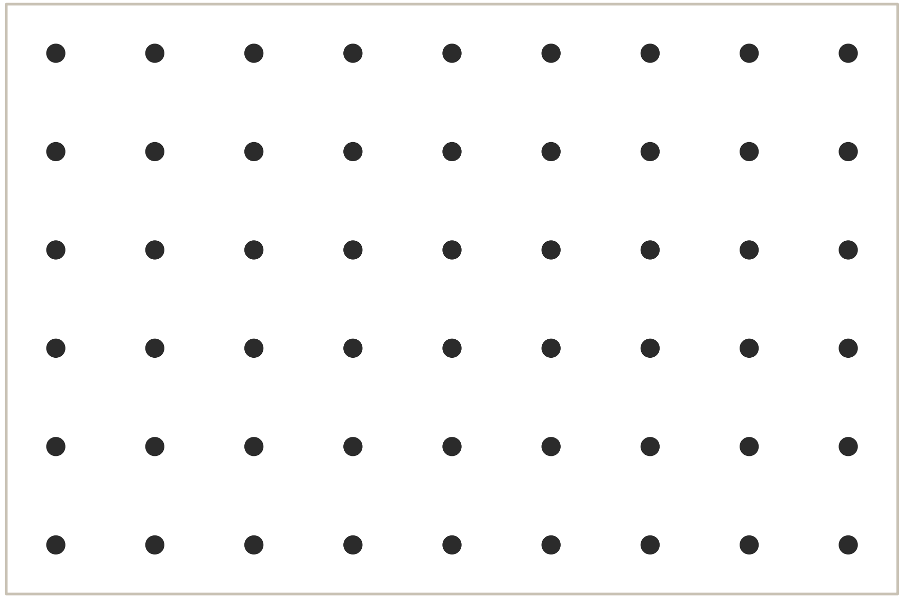
Drawing a field into or out of the page

JOTTER NOTES

An arrow flying away from you, or towards you.



into the page



out of the page

JOTTER NOTES

Field into and out of the page

Crosses: the field goes INTO the page — the tail of the arrow.

Dots: the field comes OUT of the page — the tip of the arrow.

A magnetic field direction is never “up” or “down” on a flat page.

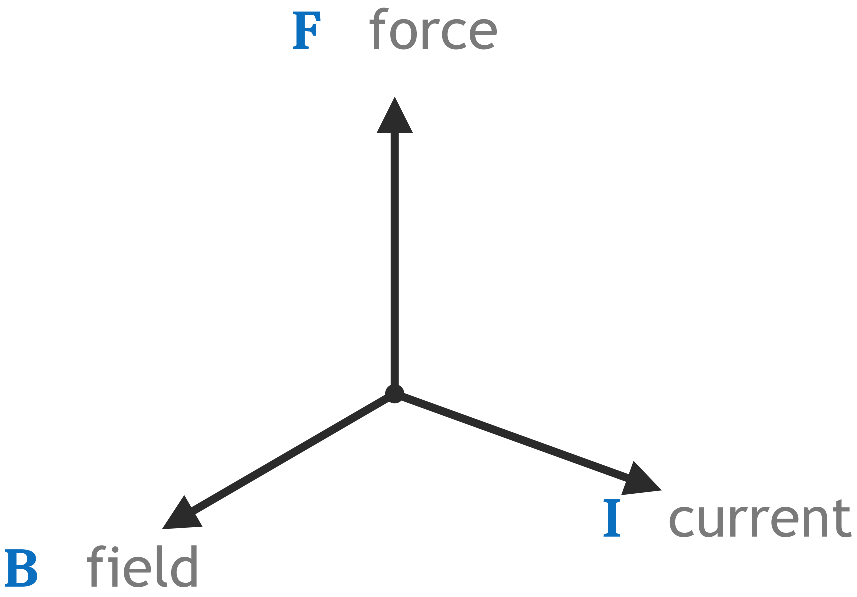
The left-hand rule

Left hand. Thumb, first finger, second finger, all at right angles.

- thuMb – Motion, the force on the particle
- First finger – Field, from N to S
- seCond finger – Current, the conventional current

F, B and I — three directions at right angles

JOTTER NOTES



JOTTER NOTES

Force on a moving charge

Use the LEFT hand: F thumb, B first finger, I second finger.

I is the CONVENTIONAL current — the way positive charge moves.

A positive charge moving right IS a current to the right.

An electron moving right is a current to the LEFT — so the force reverses.

Watch Out: magnetic force direction

THE MISTAKE

- Answering “upwards” for a field direction.
- Using the electron's direction of travel as I.
- Same force direction for an electron as a proton.

THE CORRECT ANSWER

- Say “into the page” or “out of the page”.
- For an electron, I points the OPPOSITE way.
- Opposite charge means opposite force.

Show Me: the force on a moving charge

SHOW ME BOARDS

1. A proton moves to the right through a field directed into the page. Determine the direction of the force on it.
2. An electron moves to the right through the same field. State the direction of the force, and justify why it differs.
3. State what a grid of dots on a diagram tells you about the field.
4. A beam of electrons curves upwards in a magnetic field. Explain how you would find the field direction.
5. State and justify what happens to a stationary charge placed in a magnetic field.

Show Me: the force on a moving charge

SHOW ME BOARDS

EXTRA PRACTICE

1. A proton moves down the page through a field out of the page. Determine the direction of the force.
2. Explain why a current-carrying wire in a magnetic field feels a force.
3. An electron travels into the page through a field pointing right. Determine the direction of the force on it.
4. State the two things a charge must be doing for a magnetic field to exert a force on it.
5. A beam of protons is undeflected in a magnetic field. State and justify one possible reason.

Task

Work through the magnetic force questions. Draw the three directions every time before you answer.

Past papers: 2025 P1 Q11, 2024 P2 Q6(b)

Scholar quiz

Starter

2010 Higher Physics

Scan the code and answer these:

Q7 **Q9** **Q12**

Section A · fields, R, capacitors

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 5

Particle accelerators

Electric fields to speed them up, magnetic fields to steer them.

By the end of this part…

1. I can describe how a particle accelerator works, in three steps.
2. I can explain why a cyclotron needs an alternating voltage.
3. I can state what a collider does that an accelerator alone does not.

JOTTER NOTES

What a particle accelerator does

Electric fields ACCELERATE the charged particles.

Magnetic fields DEFLECT them — steering them round or along.

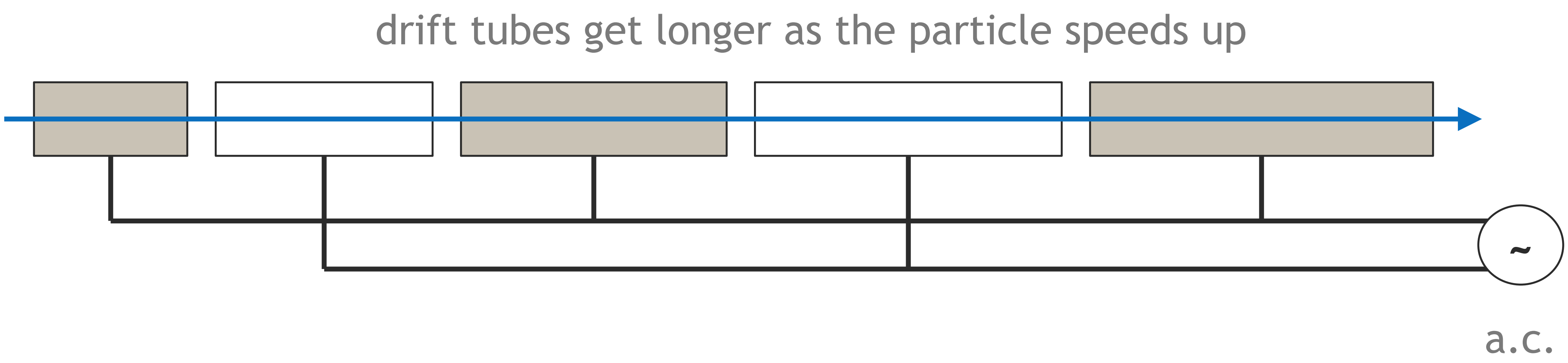
The particles are made to collide at high energy.

New particles are produced out of the energy of the collision.

A linear accelerator

JOTTER NOTES

A straight line of drift tubes, each longer than the last.



JOTTER NOTES

The linear accelerator

The particle is accelerated in the GAPS, not inside the tubes.

Inside a tube there is no field, so it coasts at constant speed.

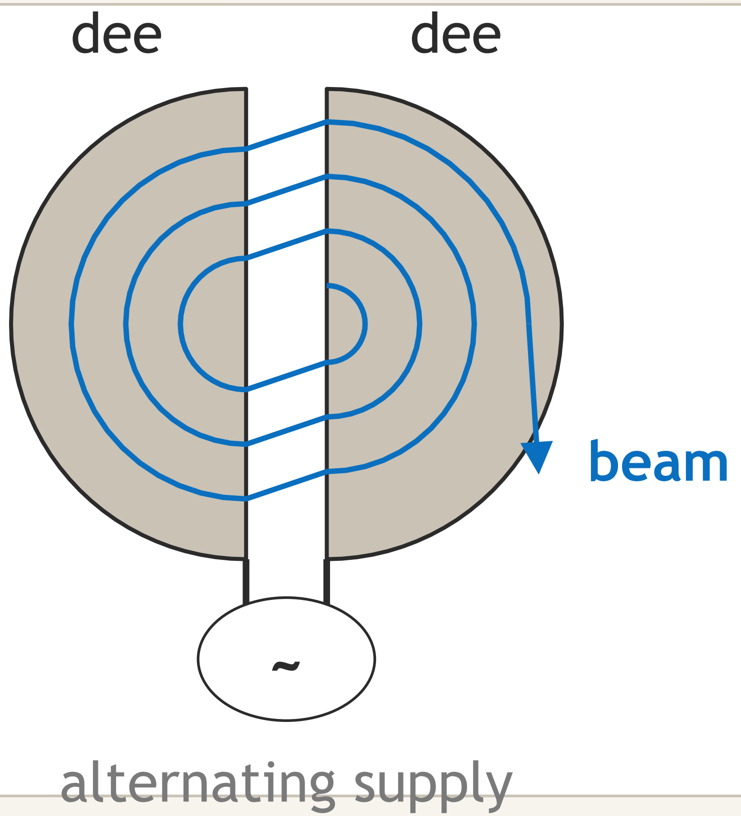
The supply alternates so every gap gives another push.

Tubes get longer because the particle covers more ground each half-cycle.

A cyclotron

JOTTER NOTES

Two hollow D-shaped electrodes in a magnetic field.



JOTTER NOTES

The cyclotron

A magnetic field bends the particle into a circle inside each dee.

It is accelerated every time it crosses the gap between them.

Faster particle, bigger radius — so the path spirals outwards.

The beam is taken out at the rim, at its highest speed.

JOTTER NOTES

Why the voltage alternates

The particle crosses the gap in one direction, then the other.

For a push each time, the field in the gap must reverse each time.

So the supply alternates, in step with the particle.

In a linear accelerator it alternates for the same reason.

Accelerator or collider

ACCELERATOR

- One beam, fired at a stationary target.
- Much of the energy goes into moving the target.
- Less energy left to make new particles.

COLLIDER

- Two beams, steered head-on into each other.
- The total momentum is zero, so nothing has to move away.
- Far more energy available to make new particles.

What the collisions produce

A single proton–proton collision recorded by the CMS detector.

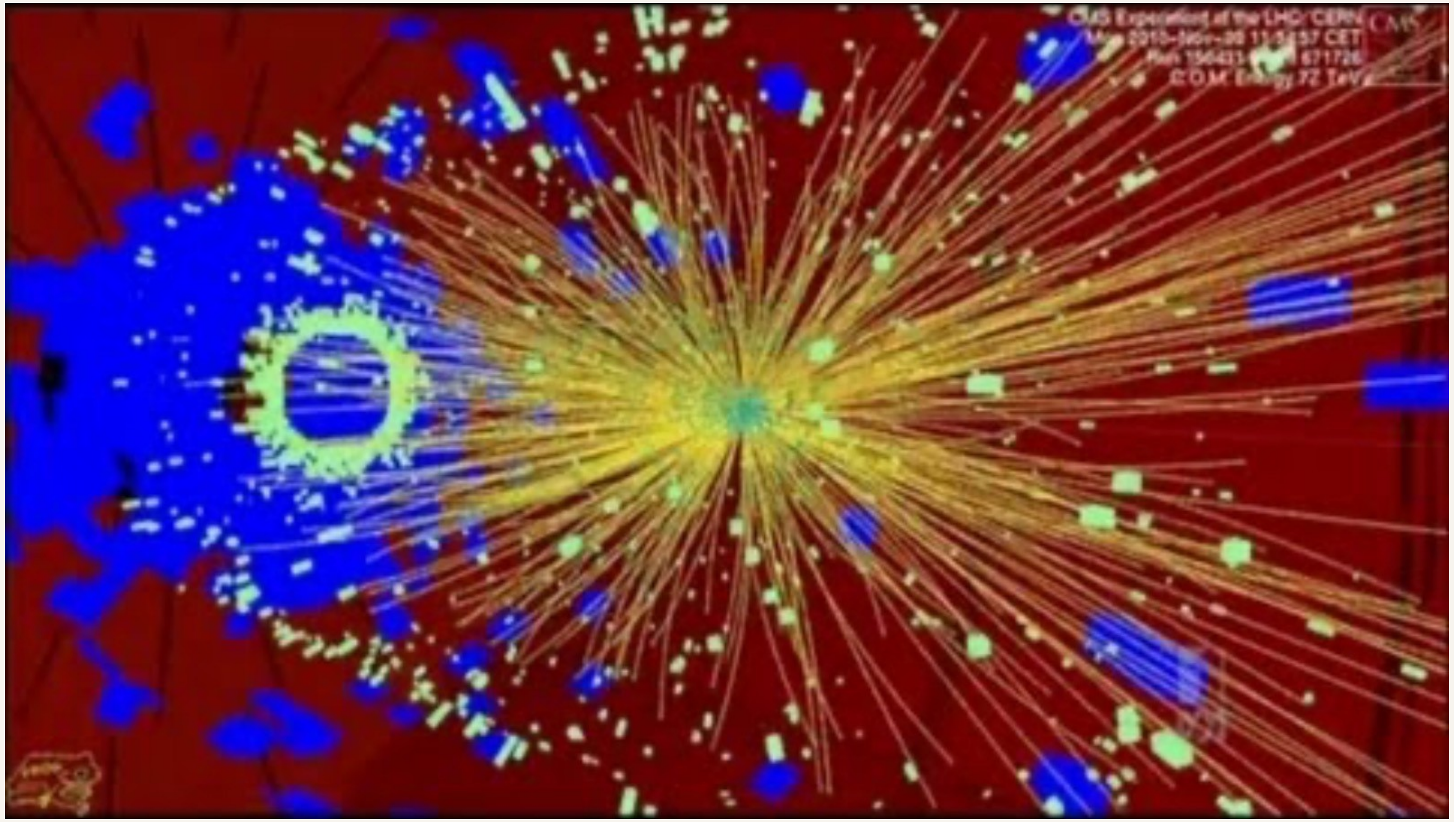


Image: CMS Experiment at the LHC. © CERN.

CERN Particle Physics Course

Create a CERN Guest account with your Glow email.
Note your password — you will need it again.
Send me your certificate once every chapter is done.

ppc.web.cern.ch

Scan to sign up

CERN course: accelerating particles

Watch the video on the CERN Particle Physics Course.
Answer the questions in the chapter before moving on.

CERN Particle Physics Course
Video 13

ppc.web.cern.ch

CERN course: detectors

Watch the video on the CERN Particle Physics Course.
Answer the questions in the chapter before moving on.

CERN Particle Physics Course
Video 14

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CERN course: what CERN is for

Watch the video on the CERN Particle Physics Course.
Answer the questions in the chapter before moving on.

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Video 15

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CERN course: the discoveries

Watch the video on the CERN Particle Physics Course.
Answer the questions in the chapter before moving on.

CERN Particle Physics Course
Video 16

ppc.web.cern.ch

Show Me: particle accelerators

SHOW ME BOARDS

1. Describe, in three steps, how a particle accelerator works.
2. Explain why the drift tubes of a linear accelerator get longer along its length.
3. Explain why a cyclotron is supplied with an alternating voltage.
4. State and justify which produces more energy for new particles: a fixed target or a collider.
5. State the job of the magnetic field in a cyclotron, and of the electric field.

Show Me: particle accelerators

SHOW ME BOARDS

EXTRA PRACTICE

1. State what happens to the radius of the path in a cyclotron as the particle speeds up, and justify it.
2. Explain why the particle is not accelerated while it is inside a drift tube.
3. A pupil says the alternating voltage keeps the force in the same direction. State and correct the error.
4. Describe how new particles can be produced in a high-energy collision.
5. Explain why a beam of neutrons could not be accelerated this way.

Task

Work through the particle accelerator questions.
Answer in full sentences — these are description marks.

Past papers: 2023 P2 Q7(b), 2018 P2 Q6

Scholar quiz

Checkpoint

SHOW ME BOARDS

1. Sketch the field pattern between two charged parallel plates, and state which way an electron released there would move.
2. An electron is accelerated from rest through $4{\cdot}0\,\mathrm{kV}$. Calculate its speed at the anode.
3. An electron enters a field directed into the page, travelling right. Determine the direction of the force, and justify it.

Exam Practice

Every one of these is on this topic, from a recent paper.

Paper	Question	Marks	What it asks you to do
2025 P1	Q10	1	Electron speed at the + plate
2025 P1	Q11	1	Magnetic force on a proton
2024 P2	Q6(a)(i)	1	Draw the field, cathode to anode
2024 P2	Q6(a)(ii)	3	Speed of the electron at the anode
2024 P2	Q6(a)(iii)	3	Acceleration across the gap
2024 P2	Q6(b)	1	Determine the field direction

Exam Practice: 2024 Paper 2 Q6

One question walks this whole lesson — 8 marks across four parts.

- (a)(i) draw the field pattern between the plates — 1 mark
- (a)(ii) the speed, from the kinetic energy gained — 3 marks
- (a)(iii) the acceleration over the 45·0 mm gap — 3 marks
- (b) the direction of the magnetic field, from the curved beam — 1 mark

SQA Higher Physics 2024, Paper 2, Question 6 — question numbers and marks only, with acknowledgement to SQA.

NEXT LESSON

Semiconductors

Conductors, insulators, and the materials that sit in between.

Plenary

SHOW ME BOARDS

1. Sketch the field pattern around a single negative point charge.
2. State what is meant by a potential difference of $5\ \mathrm{V}$.
3. A proton is accelerated from rest through $2{\cdot}5\ \mathrm{kV}$. Calculate its speed.
4. An electron moves up the page through a field out of the page. Determine the direction of the force.
5. Describe, in three steps, how a particle accelerator works.

Plenary

SHOW ME BOARDS

EXTRA PRACTICE

1. State the direction electric field lines are drawn in, and why.
2. Calculate the work done moving a charge of $8{\cdot}0\ \mu C$ through $150\ V$.
3. An electron reaches $1{\cdot}2 \times 10^{7}\ m\ s^{-1}$ from rest. Calculate the p.d. it crossed.
4. Explain why a cyclotron needs an alternating supply.
5. State and justify what happens to a stationary electron placed in a magnetic field.

Extension

SHOW ME BOARDS

1. Show that the speed of a charged particle accelerated from rest is proportional to the square root of the accelerating p.d.
2. A proton and an alpha particle cross the same p.d. Determine the ratio of their final speeds.
3. An electron enters a uniform field at right angles to the plates. Describe and justify the shape of its path.

Extension

SHOW ME BOARDS

EXTRA PRACTICE

1. An electron beam crossing both an electric and a magnetic field is undeflected. Explain what that tells you about the two forces.
2. Explain why a cyclotron cannot keep accelerating a particle indefinitely at very high speeds.
3. Two protons in a collider each carry energy E. Explain why this beats firing one proton of energy $2E$ at a stationary target.