Episode 518: Particle accelerators

This episode requires students to apply their knowledge of charged particles and fields.

Summary

Discussion and worked example: Acceleration in an electric field. (15 minutes)

Student activity: Researching accelerators. (30 minutes)

Demonstration: Electrical breakdown. (15 minutes

Discussion: How a linear accelerator works. (15 minutes)

Discussion: Particles in a magnetic field. (10 minutes)

Demonstration: Fine beam tube. (20 minutes)

Student questions: Calculations. (30 minutes)

Discussion (optional): Relativistic effects and Bertozzi's experiment. (15 minutes)

Visit (optional): Take a trip to CERN. (A long weekend)

Discussion + worked example:

Acceleration in an electric field

Why accelerate particles? Following Rutherford's alpha-scattering experiment, physicists wanted to probe matter with beams of particles that were more energetic, more intense and 'purer'.

How can particles be speeded up? (use an electric field.) Won't a magnetic field do? (particles are accelerated, but the force is centripetal, so their energy does not increase.)

Calculate the speed of an electron (or proton) accelerated through 10 kV. What equation to use?

$(½)\ mv^2 = eV$ $e = 1.6 \times 10^{-19}$ C and $m = 9.1 \times 10^{-31}$ kg

$$v = \sqrt{\frac{2qV}{m}} \approx 6x10^{7}\ ms^{-1}$$

Take care! This is approaching speeds where relativistic effects need to be taken into account.

Will a proton travel faster or slower than this? (slower, because charge is the same but mass is greater.)

In the largest research accelerators, energies are so great that they recreate the conditions minuscule fractions of a second after the Big Bang (typically 10^{-10} s for LEP and a planned 10^{-12} s for the Large Hadron Collider (LHC) opening in 2007).

Student activity:

Researching accelerators

Find out about the development of linear and circular accelerators. Identify important spin-offs (e.g. the development of www, computer graphics, body scanner magnets, isotope production for medicine and industry, material processing etc.)

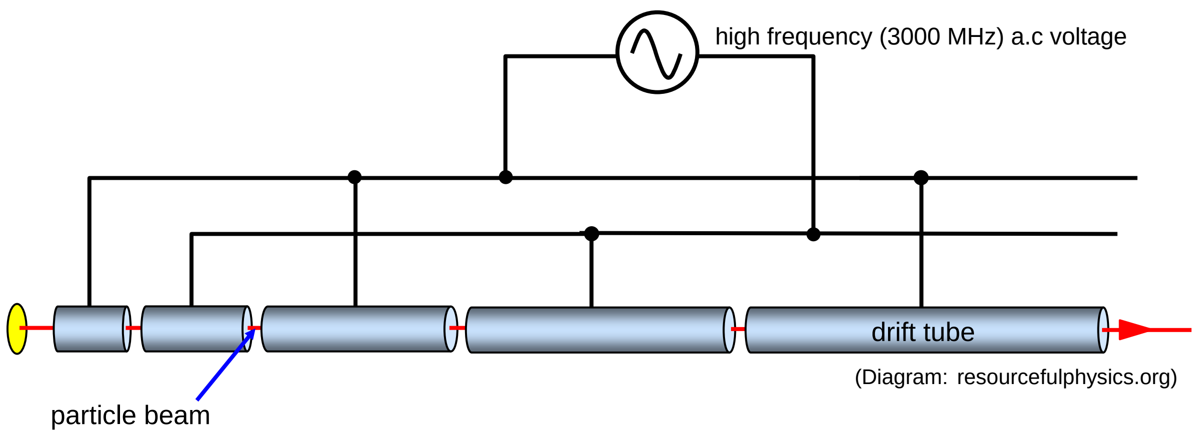
TAP 518-1: Some information about LEP at CERN

Demonstration:

Electrical breakdown

In linear accelerators, the approach is to get as large a voltage as possible, and to apply it to the particles several times. A practical limit to voltage difference is set by the ability of materials to withstand the electric fields involved. You can demonstrate electrical breakdown.

TAP 518-2: Electrical breakdown.



Discussion:

How a linear accelerator works

Explain the construction of the linear accelerator. The drift tubes get longer as the particles move faster. But at the highest speeds approaching that of light, increase in energy makes very little difference to the speed, so the drift tubes are the same length.

TAP 518-3: The linear accelerator

Discussion:

Particles in a magnetic field

There is an advantage in making the particles travel around in a circular path – they can be accelerated time and again. Discuss how the particles trajectories are bent into a circular path with a magnetic field to bring them back to the accelerating electrical field many times. Compare with an electric field.

Recap the equation for this ($mv^2/r = Bqv$).

TAP 518-4: How a magnetic field deflects an electron beam

TAP 518-5: How an electric field deflects an electron beam

Demonstration:

Fine beam tube

Do this if you haven't previously done so in episode 413

TAP 413-2: Measuring the charge to mass ratio for an electron

Show the fine beam tube with Helmholtz coils to provide a magnetic field.

TAP 518-6: The fine-beam tube

Student questions:

Calculations

Your students now know the equations needed to solve many problems relating to accelerators. You may have covered these questions in Episode 413, if not students should try them now.

TAP 413-3: Deflection with electric and magnetic fields

TAP 413-4: The cyclotron

TAP 413-6: Charged particles moving in a magnetic field

Also try:

TAP 518-7: Fields in nature and in particle accelerators

Discussion (optional):

Relativistic effects and Bertozzi's experiment

Your students should be aware that, at relativistic speeds, things become more complicated. One way to present this is to discuss Bertozzi's experiment.

Accelerators such as the synchrotron are designed to compensate for the effective increase in m by controlling the frequency of the accelerating voltage as the particles speed up.

TAP 518-8: The ultimate speed – Bertozzi's demonstration

TAP 518-9: Principle of the synchrotron accelerator

Visit (optional):

Take a trip to CERN (a long weekend)

You can organize a trip to CERN.

http://www.pparc.ac.uk/Pbl/Cern.asp

If you can’t make the visit this year borrow a video

http://teachingphysics.iop.org/resources/video/video_book.doc

TAP 518-1: Some information about LEP at CERN

This information is provided for interest, perhaps to stimulate further research.

- First experiments: 1989
- Particle collisions: electrons and positrons
- Maximum beam energy: 100 GeV
- Luminosity: $2.4 \times 10^3\ s^{-1}$
- Time between collisions: 22 μs
- Filling time: 20 h
- Acceleration period: 550 s
- Injection energy: 550 MeV
- Bunch length: 1 cm
- Average beam current: 55 mA
- Circumference: 27.66 km
- Dipole (bending) magnets: 3280 plus 24 weaker dipoles
- RF resonant cavities: 128
- Peak magnetic field: 0.135 T
- Vacuum: 10^{-11} Torr

Between 1983 and 1989 the construction of LEP at CERN was the biggest civil engineering project in Europe. The accelerator tube is 26.67 km in circumference and is shaped to an accuracy of better than 1.0 cm. It runs underground in a specially excavated tunnel inclined at 14° to the horizontal between Geneva airport and the Jura mountains. There are four main experimental stations positioned around the ring. As it enters each of these the beam passes through a large solenoid whose magnetic field squeezes the beam to about 10 μm by 250 μm, increasing the luminosity (and hence the probability of interactions with the oncoming beam).

From 1989 to 1995 LEP was used as a Z_0 'factory'. This was done by setting the collision energy to about 91 GeV (rest energy of the Z_0). This allowed physicists to make accurate measurements of the Z_0 lifetime. From this they showed that there are only three generations of fundamental particles. If there were more then the lifetime of the Z_0 would be lower because it would have more alternative particles into which it could decay. This conclusion agreed with that of cosmologists based on the number of different types of neutrinos needed to explain relative abundances of different nuclei in the early Universe. It is a good example of the growing links between particle physics on the smallest scale and cosmology, the study of the Universe on the largest scale.

From 2005 LEP will be replaced by the LHC (large hadron collider, a new accelerator running in the existing LEP tunnel). This will accelerate protons and antiprotons to up to 14 TeV (1 TeV = 10^{12} eV) about 10 times greater than the Tevatron at Fermilab. Why? Whereas electron–positron collisions can be used to test precise aspects of the Standard Model, more massive particles are used in the hope of detecting rare but exotic events. LHC should reveal the supersymmetric partners of ordinary matter particles (as predicted by superstring theory) and may well reveal the Higgs particle – a force-carrier in the hypothetical Higgs field that endows all other particles with mass. The LHC is an amazing project, even by the standards of high-energy physics. The momentum of the high-energy protons and antiprotons is so high that extremely powerful superconducting dipole magnets must be used to keep them in the ring. Their peak field will be about 9 T! To maintain the superconducting properties these magnets must be cooled to 1.9 K. This requires eight cryogenic plants spaced equally around the 27 km ring pumping 70 000 litres of liquid helium through 40 000 leak-proof junctions to cool 31 000 tonnes of equipment!

Practical advice

This information should provide some insight into the engineering challenges to be overcome if the fundamental physics is to be explored.

Alternative approaches

Similar information can be gleaned from Web sites dedicated to most large accelerators.

Social and human context

The cost of such projects forces collaboration on national governments.

External reference

This activity is taken from Advancing Physics chapter 16, 40T

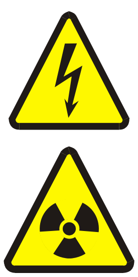
TAP 518- 2: Electrical breakdown

Introduction

Air is an insulator under normal conditions. If the potential gradient is sufficiently high, then the air may start to conduct, often with spectacular effect, as in lightning. In this demonstration you will be able to see large sparks produced by an electrostatic generator. On a smaller scale, sparking across a narrow gap can be enhanced by alpha radiation, illustrating the principle behind some radiation detectors.

You will need:

- ✓ van de Graaff generator
- ✓ EHT power supply, 0–5 kV dc
- ✓ spark counter
- ✓ pure alpha source



Wire carefully, EHT supply in use

The large protective resistor is in use to prevent dangerous currents passing though humans. The EHT power supply, being current limited will not give a fatal shock, but it can be surprising

The local rules for handling radioactive sources must be complied with.

Do not handle radioactive sources or place them in close proximity to your body

Use tongs or a source holder to handle the alpha source and put it in a secure place when not in use

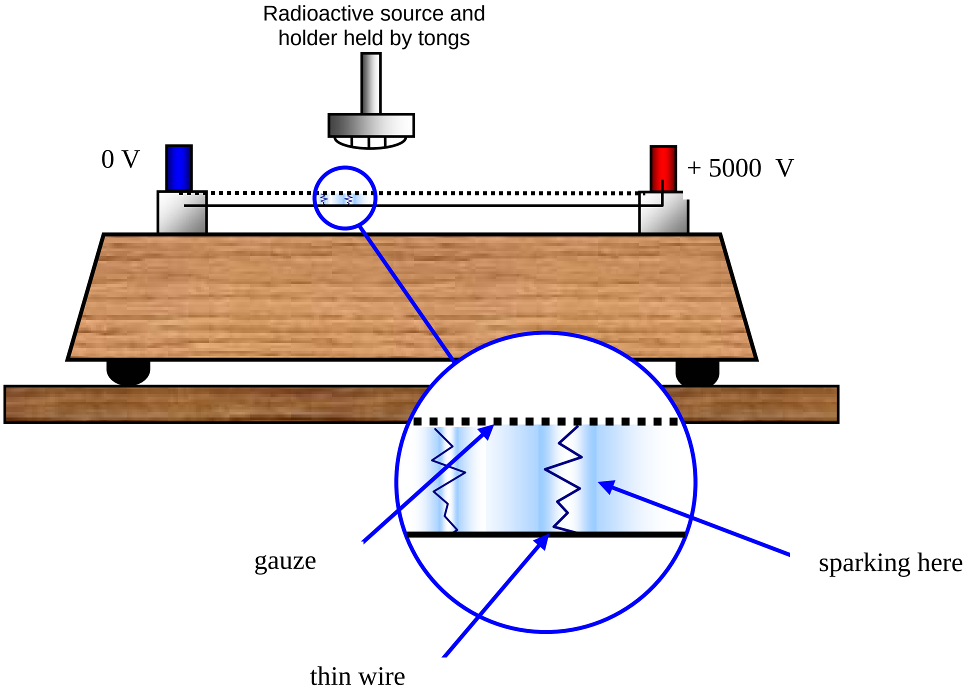
Looking at sparks

You will be able to see the sparks produced in a high potential gradient. Stray electrons in the air are accelerated and produce secondary ionisation by collisions. An electron shower develops and this allows the air to conduct for a short time so that a spark is seen. The scale of sparking varies considerably from lightning flashes, through laboratory electrostatic generators to the small discharges in radiation detectors. For these smaller events, using an alpha source ionises the air and increases the probability of a spark occurring.

1. You can charge the sphere of the van de Graaff generator to a high potential by turning it on for a short time. If you bring an earthed sphere close to the main sphere, then a spark will be seen to jump from one sphere to the other once the potential gradient is above about 3×10^{6} V m^{-1}. You should be able to estimate the potential of the main sphere from the distance across which the spark jumps but the breakdown potential gradient can vary considerably from day to day as atmospheric conditions change.

2. Smaller sparks can be seen in the spark counter. This requires a lower potential difference because the gap between the wire and the earthed plate is only a couple of millimetres. If you connect the wire to the positive terminal of the EHT power supply and

the plate to earth and turn the supply voltage up to maximum (5 kV), you will be able to see and / or hear occasional sparks between the wire and the plate (see the diagram above). It may be necessary to work in a darkened area of the laboratory. These sparks are initiated by stray electrons or ions passing close to the gap between the wire and the plate.



3. Alpha particles produce a high density of ionisation along their path. If you hold a source a short distance (2 or 3 cm) from the wire, there will be a considerable increase in the rate of sparking because the additional electrons are likely to produce secondary ionisation leading to breakdown. Many radiation detectors use this as a way of detecting particles.

You have seen

1. How sparks can be produced in a strong electric field and how this can be used in radiation detectors.

Practical advice

If students have not seen the sparks produced by a laboratory electrostatic machine, then they should now. The demonstration of the small discharges in a spark detector follows naturally and links well with the discussion of the fields found in Geiger–Müller tubes.

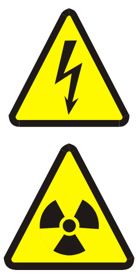
Commercial spark gaps are available, and are less likely to give shocks, but they are expensive. (Some schools may have a spark counter but not recognise it.)

TAP 509-4: Rays make ions

Episode 519: Particle detectors

Social and human context

Lightning has a place in discussions of extreme weather conditions on Earth and on other planets. Discharges from overhead power lines can be a reason for energy loss as well as a potential hazard.

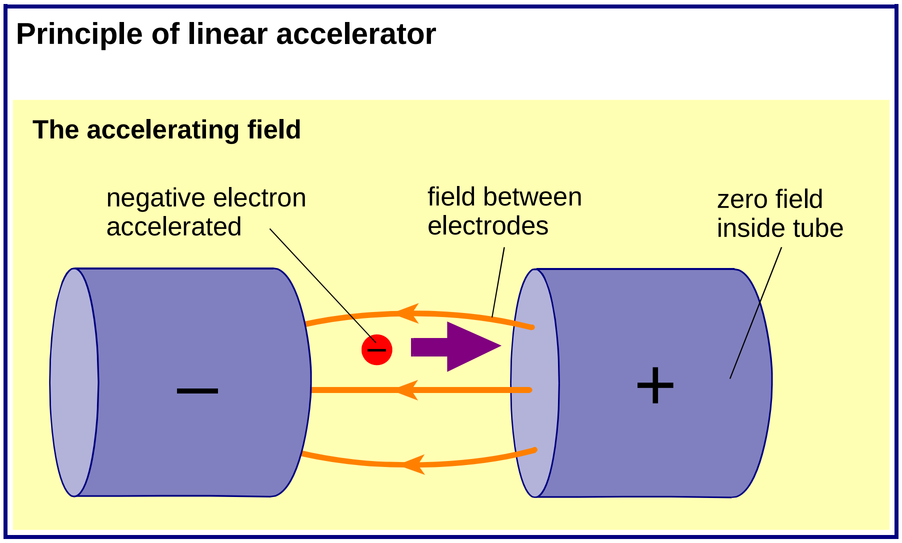
	**Wire carefully, EHT supply in use** The large protective resistor is in use to prevent dangerous currents passing though humans. The EHT power supply, being current limited will not give a fatal shock, but it can be surprising **The local rules for handling radioactive sources must be complied with.** Do not handle radioactive sources or place them in close proximity to your body Use tongs or a source holder to handle the alpha source and put it in a secure place when not in use

External reference

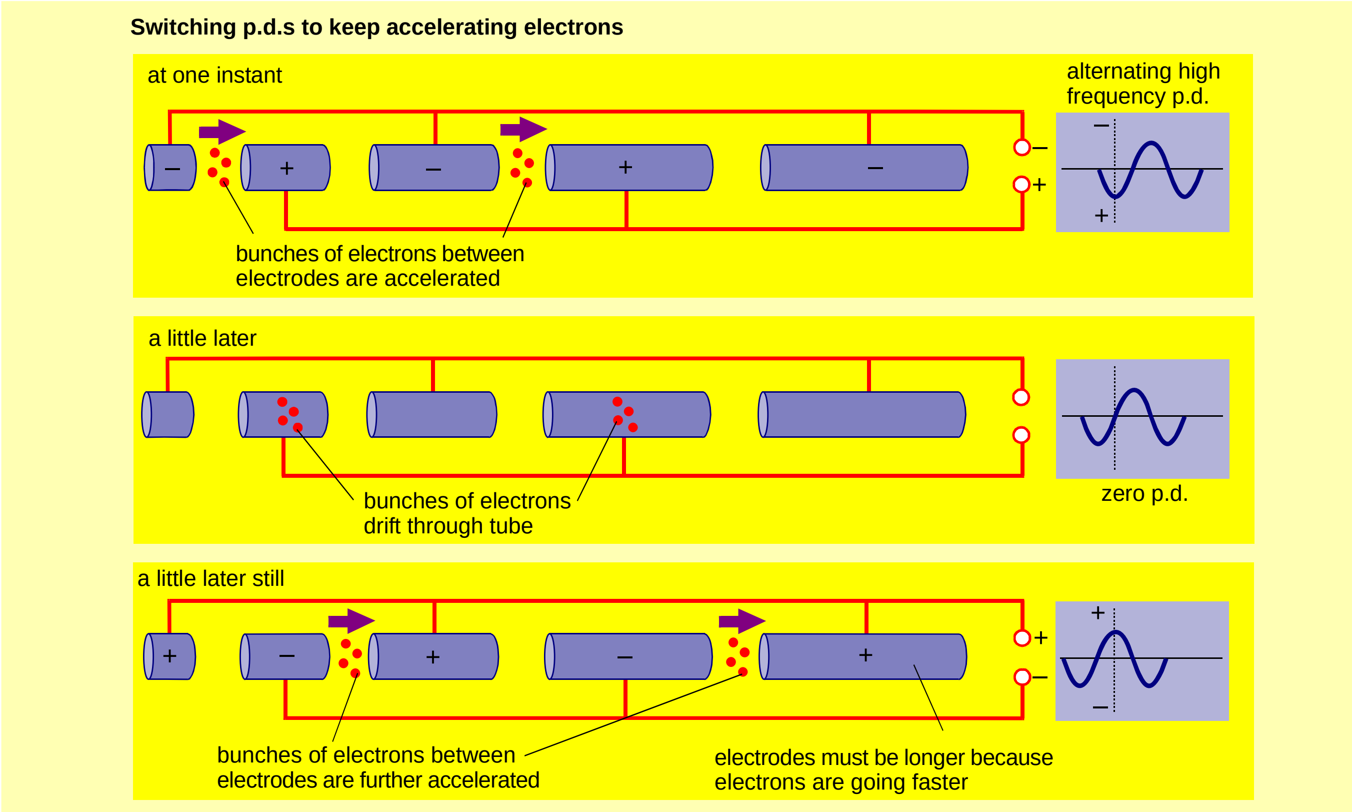
This activity is taken from Advancing Physics chapter 16, 180D

TAP 518- 3: The linear accelerator

This shows the principles of the linear accelerator, although not all of the engineering complexities.



Principle of linear accelerator



The alternating p.d. switches back and forth so that the electrons are accelerated as they pass between successive electrodes

Practical advice

This diagram is here so that you can discuss it with your class.

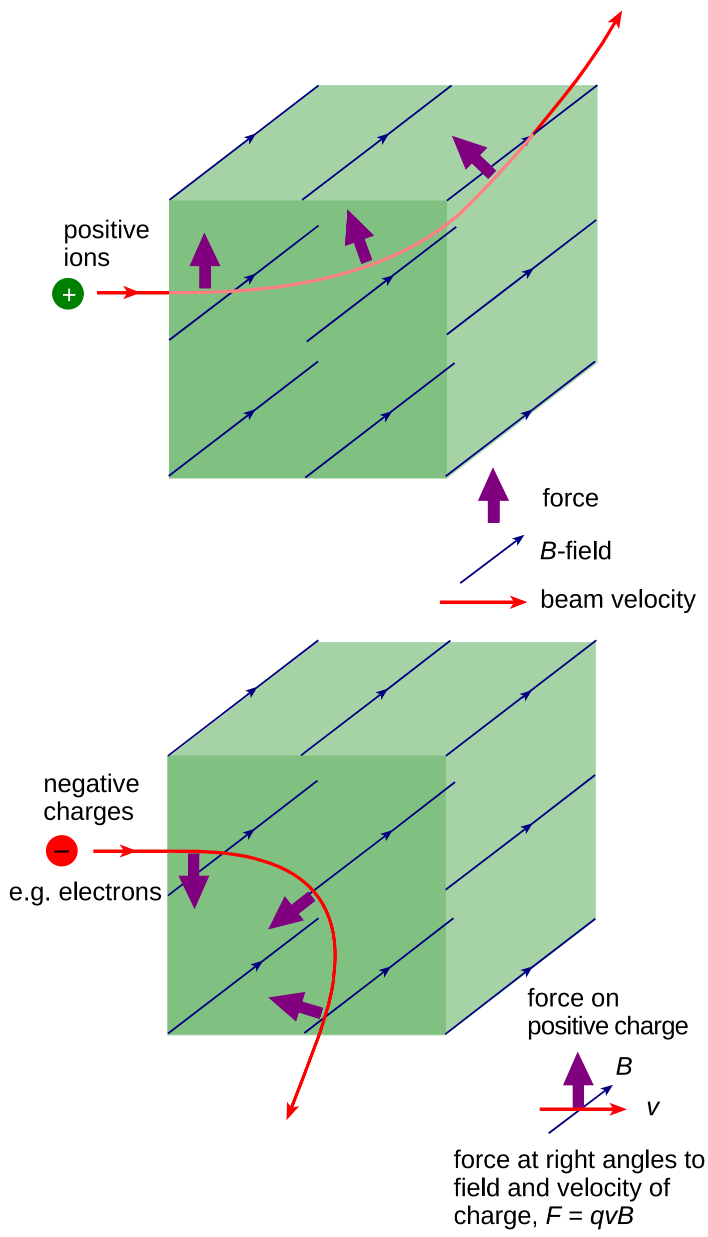
External reference

This activity is taken from Advancing Physics chapter 16, 40O

TAP 518- 4: How a magnetic field deflects an electron beam

The plane in which the deflection occurs is important, causing circular motion.

Magnetic deflection



Magnetic fields deflect moving charged particles in circular paths

Practical advice

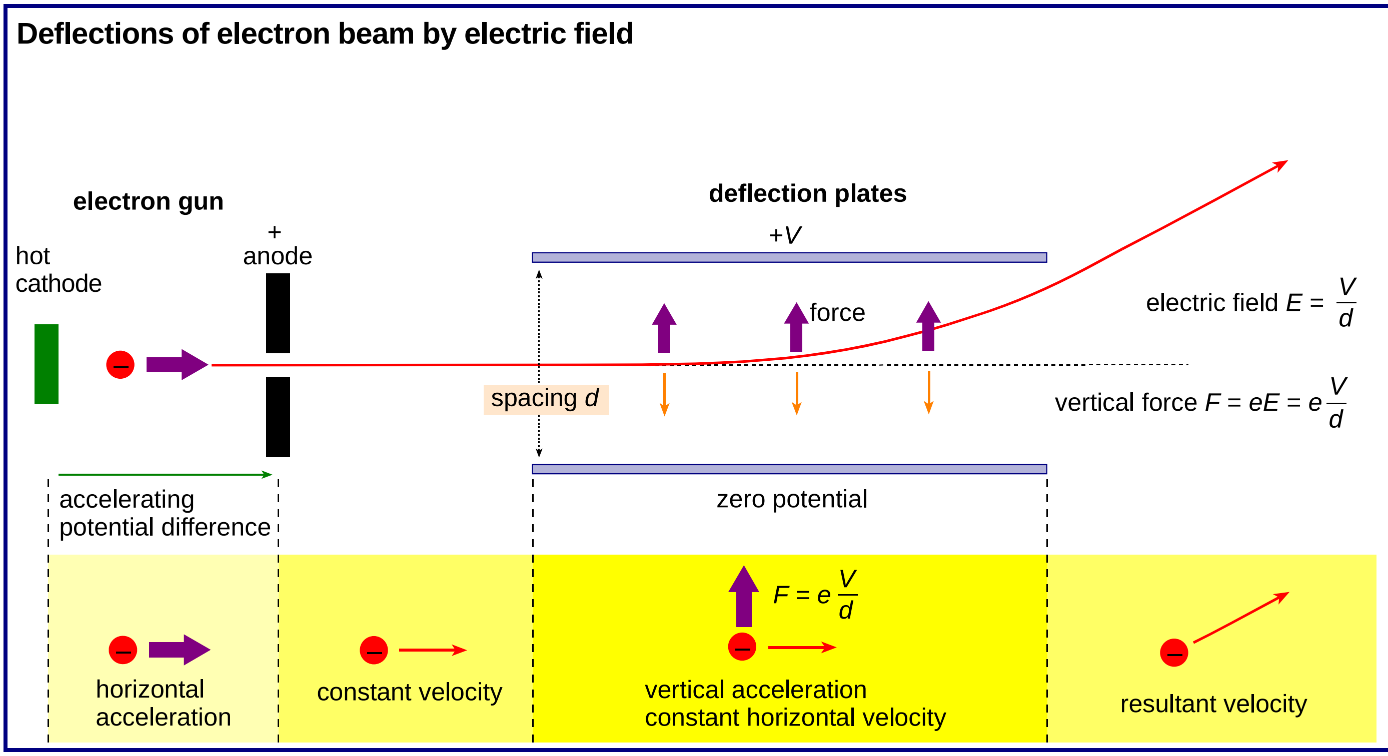
This diagram is reproduced here so that you can discuss it with your class.

External reference

This activity is taken from Advancing Physics chapter 16, 120O

TAP 518-5: How an electric field deflects an electron beam

The role of electric fields is central here.



Practical advice

This diagram is reproduced here so that you can discuss it with your class.

External reference

This activity is taken from Advancing Physics chapter 16, 100O

TAP 518-6: The fine-beam tube

Use a fine-beam tube to explore how the accelerating voltage and the magnetic field both affect the radius of the electrons' path.

You will need:

- ✓ fine-beam tube with Helmholtz coils
- ✓ power supply (6.3 V) for cathode
- ✓ ht. supply (0–300V dc) with voltmeter
- ✓ low voltage supply (0–12 V) for Helmholtz coils
- ✓ ammeter
- ✓ connecting leads with fixed or sprung shrouds over the 4mm plugs

	**Safety** Wire carefully, no bare conductor above 40 V. HT supplies are always dangerous, especially so in the dark. Shrouded plug leads MUST be used. No connections should be changed with the power switched on.

We can observe the motion of electrons in a magnetic field using a fine-beam tube. There is a small amount of gas at low pressure in the tube. When the gas molecules are struck by electrons, the molecules are excited and emit visible light. In this way we can see the path of the electrons.

A pair of coils can be used to apply a magnetic field perpendicular to the motion of the electrons. With no current in the coils, the electron beam is undeflected.

- Use a compass to determine the direction of the magnetic field.

Here are some things to try.

Make a prediction before you try each one.

- Apply the left-hand rule to the electrons to predict the direction in which they will be deflected when the magnetic field is switched on.
- What will happen if the speed of the electrons is increased (by increasing the gun voltage)?
- What will happen if the magnetic field strength is increased (by increasing the current in the coils)?
- What will happen if an electric field is applied along the direction of the magnetic field, or if the beam enters the magnetic field at an angle other than a right angle

Practical advice

If you measured e/m using a fine beam tube it would be unnecessary to repeat the fine beam tube here unless you require a quick reminder.

TAP 413-2: Measuring the charge to mass ratio for an electron

To avoid damage to the tube, it is desirable to set this experiment up in advance. At least partial blackout is required. It is also a good idea to cover the back of the tube in black cloth.

You will probably get a spread of circles, perhaps due to the field being non-uniform (a Helmholtz pair only produce an approximately uniform field in the central third of the volume they enclose), due to the electrons provided by the electron gun having a range of velocities, and due to random thermal motion superimposed on the velocity acquired from the action of the accelerating pd.

This activity is a more quantitative look at the fine-beam tube, and also provides an opportunity to revise ideas about charge, voltage and energy.

Students should be able to say that increasing the accelerating voltage will increase the speed of the electrons, and so their orbital radius in a given magnetic field will increase. They should also be able to predict that if the current in the coils in increased, the field becomes stronger, which will steer the electrons into a tighter orbit.

You might like to show that tilting the tube sends the electrons into a spiral (corkscrew-shaped) orbit; they continue to move with constant velocity along the field direction, while being deflected into circular motion around the field direction.

In this context Helmholtz coils are a pair of coils radius R and distance R apart.

Safety

Wire carefully, no bare conductor above 40 V.

HT supplies are always dangerous, especially so in the dark. Shrouded plug leads MUST be used. No connections should be changed with the power switched on.

External reference

This activity is taken from Salters Horners Advanced Physics, section PRO, activity 27

TAP 518- 7: Fields in nature and in particle accelerators

Instructions and information

Write your answers in the spaces provided. The following data will be needed when answering these questions:

- electronic charge = -1.6×10^{-19} C
- mass of electron = 9.1×10^{-31} kg
- $\varepsilon_0 = 8.9 \times 10^{-12}$ F m^{-1}

Questions

Suppose that a thundercloud has a flat horizontal base of area 1 km^2. The base of the cloud is 200 m above the Earth's surface so that a uniform electric field is formed between the cloud and the Earth. A field of 10^6 V m^{-1} between the base of the cloud and the Earth is sufficient to cause a lightning flash.

1. Calculate the potential difference between the cloud and the ground at the moment the lightning flash begins.

2. The charge on the base of the cloud is given by the formula $Q = \varepsilon_0 A E$ where A is the area of the base of the cloud and E is the electric field strength between the base and the Earth. Calculate the charge on the base of the cloud.

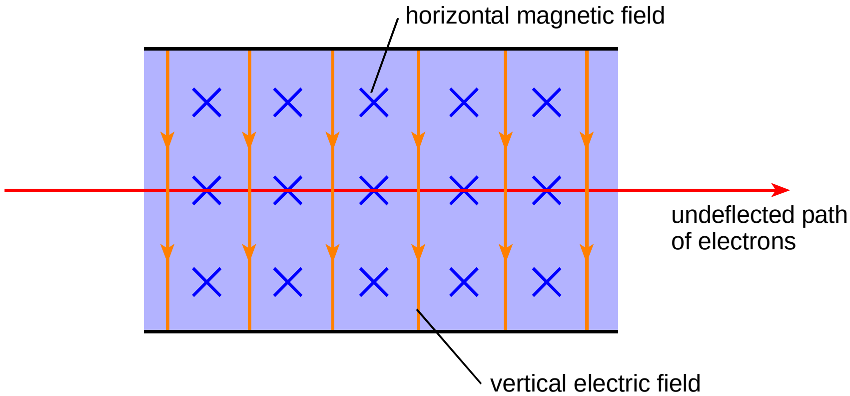
3. The cloud and the Earth can be thought of as a parallel plate capacitor that stores energy when charged. Assuming that the potential difference immediately after the flash is very small compared with the potential difference at the beginning of the flash, calculate a value for the energy released during the flash.

Electrons accelerated through a potential difference of 200 V enter a uniform magnetic field of 0.001 T perpendicular to the direction of motion.

4. Calculate the speed of the electrons when they enter the magnetic field.

5. Use your answer to question 4 to calculate the radius of the orbit in the magnetic field.

In an electron tube, electrons were passed through a region containing a vertical electric field E and a horizontal magnetic field *B*. When the forces on the electron were balanced the electrons passed through the tube undeflected.



6. Show that the electrons of charge *e* pass undeflected when they have a velocity v = E/B.

The separation of the deflector plates was 24 mm and no deflection was observed when the voltage across the plates was 3.2 kV and the magnetic field was 8.2×10^{-3} T.

7. Calculate the velocity of the electrons.

The voltage used to accelerate the electrons to this velocity was 750 V.

8. Use your answer to question 7 to calculate the ratio e/m for electrons where m is the mass of an electron.

A proton joined to a neutron is known as a deuteron or deuterium ion and is used in nuclear scattering experiments. A deuteron has a mass of 3.3×10^{-27} kg and a charge of $+ 1.6 \times 10^{-19}$ C.

9. Calculate the voltage required to accelerate a deuteron from rest in a vacuum to a velocity of 9×10^{6} m s^{-1} (3% of the speed of light).

In an early form of particle accelerator, deuterons were made to move in a circular path within a toroidal tube of diameter 1 m. A toroidal tube is like a hollow ring.

10. Calculate the magnetic field required to constrain a deuteron within the tube at the velocity of 9×10^{6} m s^{-1}.

Hints

4. The charge and mass of the electron are given in the 'Instructions and information'.
6. The electric and magnetic forces are equal in magnitude.
7. You will need to change the units before calculating the electric field strength.
8. You will need to consider the equation for the electron gun used to accelerate the electrons.
9. You are used to calculating the speed of electrons when accelerated. The mass of a deuteron is not the same as the mass of an electron.
10. The question gives the diameter of the orbit and not the radius.

Practical advice

In questions 7 and 8 there are several stages in the calculation so excessive rounding in the earlier parts of the question would lead to errors in the final answer. All answers have been rounded to two significant figures, but three significant figures have been used for numerical values that have been carried through to the next stage of the calculation.

Answers and worked solutions

1.

$$\begin{aligned} V &= Ed \\ &= 10^{6}\ \text{V m}^{-1} \times 200\ \text{m} \\ &= 2 \times 10^{8}\ \text{V}. \end{aligned}$$

2.

$$\begin{aligned} Q &= \varepsilon_0 AE \\ &= (8.9 \times 10^{-12}\ \text{F m}^{-1}) \times (1000\ \text{m})^2 \times 10^{6}\ \text{V m}^{-1} \\ &= 8.9\ \text{C}. \end{aligned}$$

3.

$$\begin{aligned} \tfrac{1}{2}QV &= \tfrac{1}{2} \times 8.9\ \text{C} \times (2 \times 10^{8}\ \text{V}) \\ &= 8.9 \times 10^{8}\ \text{J}. \end{aligned}$$

4.

$$eV = \tfrac{1}{2}mv^2$$

so

$$\begin{aligned} v &= \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times (1.6 \times 10^{-19}\ \text{C}) \times 200\ V}{9.1 \times 10^{-31}\ \text{kg}}} \\ &= 8.39 \times 10^{6}\ \text{m s}^{-1} \\ &\approx 8.4 \times 10^{6}\ \text{m s}^{-1}. \end{aligned}$$

5.

$$Bev = mv^2 / r$$

so

$$\begin{aligned} r &= \frac{mv}{Be} = \frac{(9.1 \times 10^{-31}\ \text{kg}) \times (8.39 \times 10^{6}\ \text{m s}^{-1})}{0.001\ \text{T} \times (1.6 \times 10^{-19}\ \text{C})} \\ &= 0.048\ \text{m}. \end{aligned}$$

6.

$$eE = Bev$$

so

$$v = E / B.$$

7.

$$E = \frac{V}{d} = \frac{3200\ \text{V}}{0.024\ \text{m}}$$
$$= 1.33 \times 10^{5}\ \text{V m}^{-1}.$$
$$v = \frac{E}{B} = \frac{1.33 \times 10^{5}\ \text{V m}^{-1}}{8.2 \times 10^{-3}\ \text{T}}$$
$$= 1.63 \times 10^{7}\ \text{m s}^{-1}$$
$$\approx 1.6 \times 10^{7}\ \text{m s}^{-1}.$$

8.

$$eV = \tfrac{1}{2}mv^2$$

so

$$\frac{e}{m} = \frac{v^2}{2V} = \frac{(1.63 \times 10^{7}\ \text{m s}^{-1})^2}{2 \times 750\ \text{V}}$$
$$= 1.8 \times 10^{11}\ \text{C kg}^{-1}.$$

9.

$$qV = \tfrac{1}{2}mv^2$$

so

$$V = \frac{\tfrac{1}{2}mv^2}{q} = \frac{(3.3 \times 10^{-27}\ \text{kg}) \times (9 \times 10^{6}\ \text{m s}^{-1})^2}{2 \times (1.6 \times 10^{-19}\ \text{C})}$$
$$= 8.4 \times 10^{5}\ \text{V}.$$

10.

$$Bqv = mv^2 / r$$

so

$$B = \frac{mv}{qr} = \frac{(3.3 \times 10^{-27}\ \text{kg}) \times (9 \times 10^{6}\ \text{m s}^{-1})}{(1.6 \times 10^{-19}\ \text{C}) \times 0.5\ \text{m}}$$
$$= 0.37\ \text{T}.$$

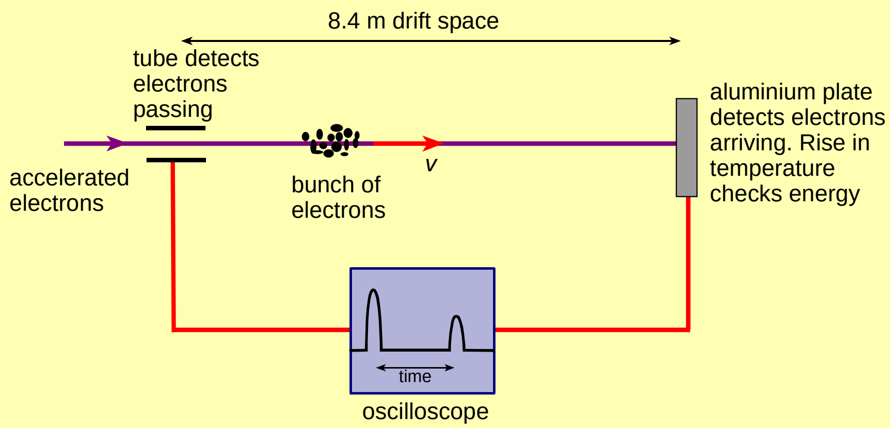
External reference

This activity is taken from Advancing Physics chapter 16, 160S

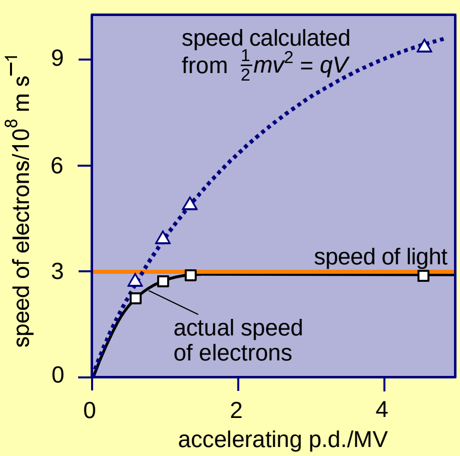
TAP 518- 8: The ultimate speed – Bertozzi's demonstration

This is a presentation of some experimental data, gathered by Bertozzi that illuminates debates about motion when Einstein's theory of relativity is considered.

The ultimate speed: Bertozzi's demonstration



The results:



The difference made by relativity

As particles are accelerated

- speed v reaches a limit, c
- kinetic energy E_K increases without limit
- momentum p increases without limit

At all speeds

$E_K = qV$

At low speeds

$p \approx mv$

$E_K \approx \frac{1}{2}mv^2$

At high speeds

$v \approx c$

$E_K \approx pc$

Powerful accelerators can't increase the speed of particles above *c*, but they go on increasing their energy and momentum

Practical advice

This diagram is here so that you can discuss it with your class.

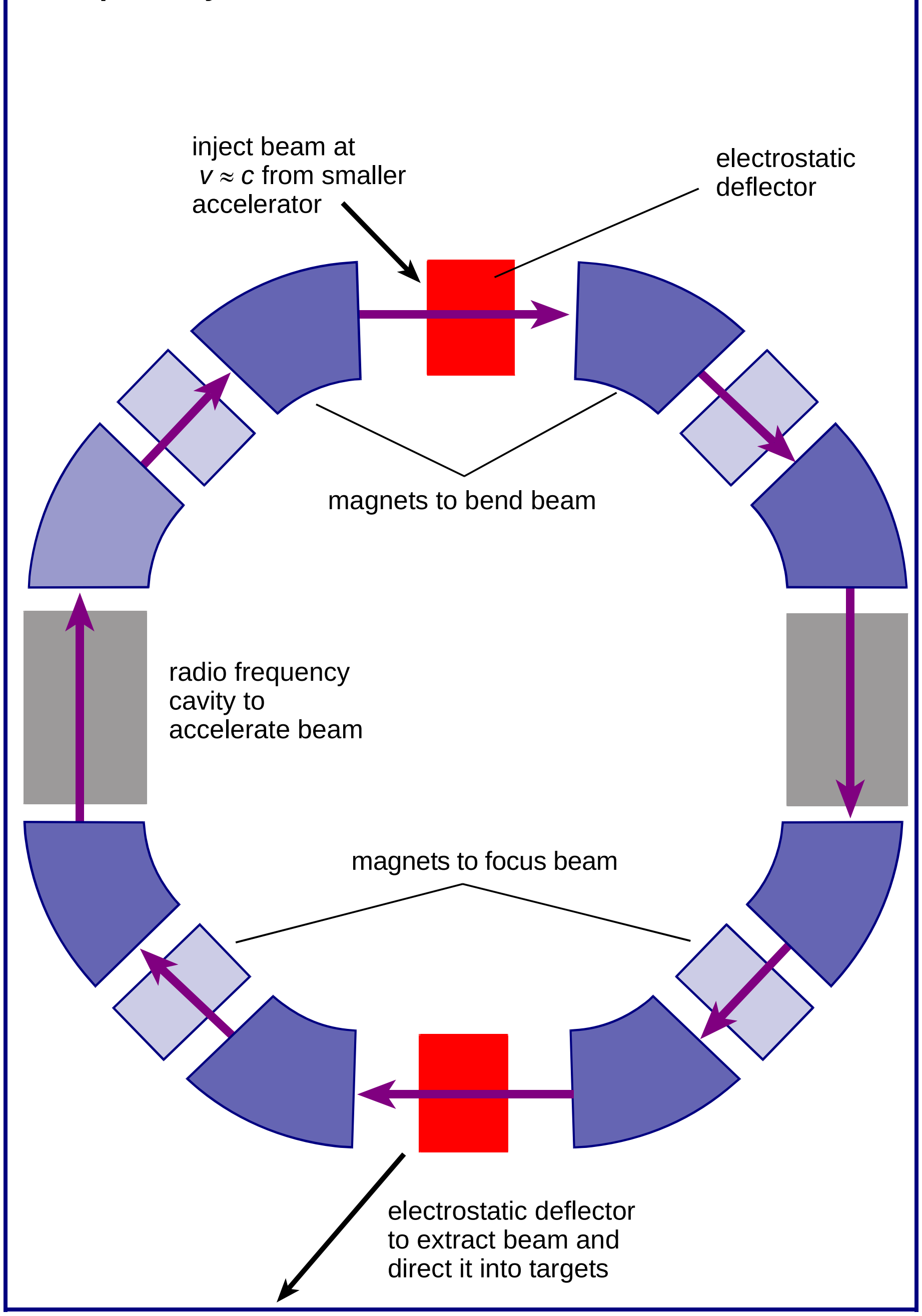
External reference

This activity is taken from Advancing Physics chapter 16, 80O

TAP 518- 9: Principle of the synchrotron accelerator

Here both electrical and magnetic fields are harnessed to the task of deflection and accelerating beams.

Principle of synchrotron accelerator



Practical advice

This diagram is here so that you can discuss it with your class.

External reference

This activity is taken from Advancing Physics chapter 16, 150O