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Build your own particle accelerator

The world's largest particle accelerator, the LHC, is deepening our understanding of what happened just after the Big Bang. Here's how to explore the principles of a particle accelerator in your classroom.

By **Julian Merkert, Andrew Brown and Becca Wilson**

When students think of a particle accelerator, they are likely to imagine the world's largest – CERN's Large Hadron Collider (LHC). However, not all particle accelerators are used to investigate the origins of the Universe, nor are they in a 27 km circular tunnel that crosses an international border. Much closer to home is the cathode ray tube (CRT)

found in old-fashioned computer and television monitors. A CRT is a linear particle accelerator that creates an image on a fluorescent screen by accelerating and deflecting a beam of electrons in a vacuum (figure 1). And although CRTs are many orders of magnitude less powerful than the LHC, the principles of operation are similar (table 1).

The activities described below enable students to control the same parameters in a CRT as scientists do

at the LHC: creating a particle beam, changing the path of the particles and altering their speed. All four activities could occupy a class for at least half a day, but they could also be used separately in individual lessons. For all activities, the particle accelerator needs to be set up as outlined in the worksheet that can be downloaded from the *Science in School* website^{w1}.

Particle accelerators like CERN are huge, but smaller ones can be controlled in the classroom

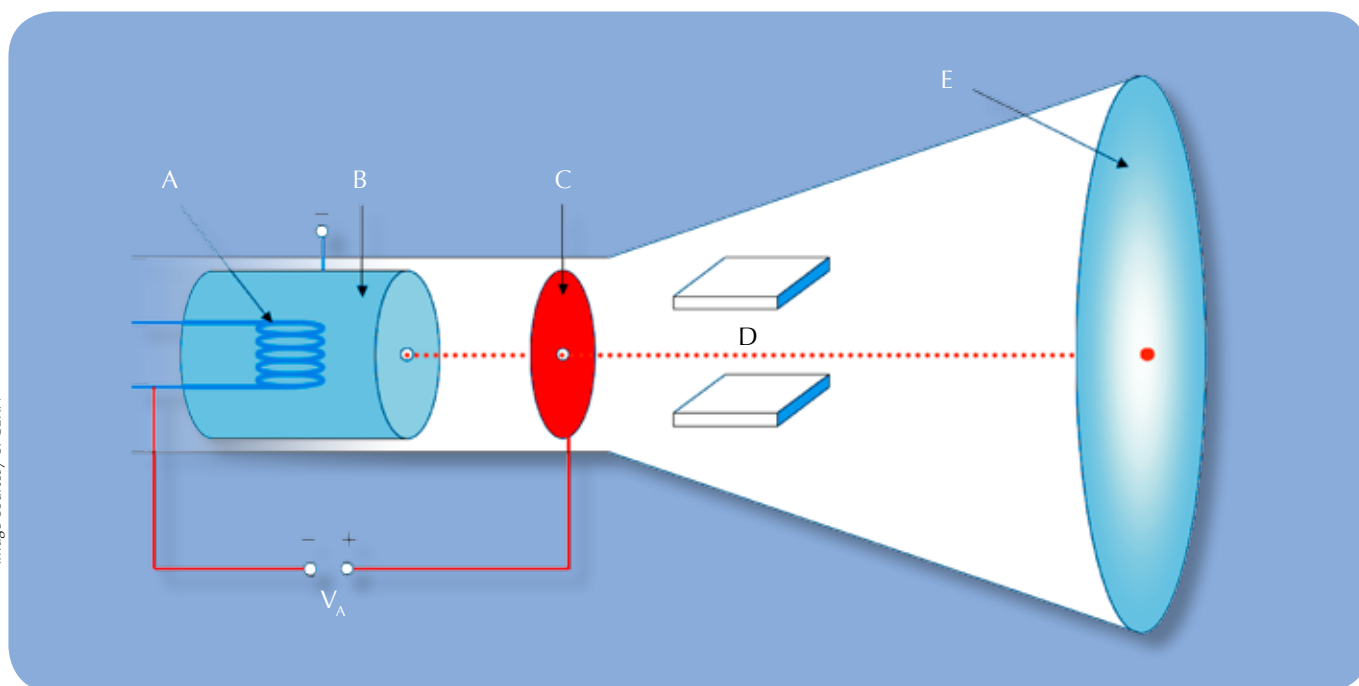


Figure 1: The cathode ray tube is a vacuum tube in which electrons are produced by a heated filament (the cathode, A), focused into a beam as they pass through the aperture of the control grid (Wehnelt cylinder, B) and accelerated by the voltage (V_A) between the cathode and the anode (C). The electrons can then be deflected by a magnetic (or in the case of oscilloscopes, an electrical) field (D) before they strike the phosphorescent screen (E), creating an image. The image could be, for example, electrical waveforms (on an oscilloscope), radio wave echoes of aircraft or ships (on a radar screen) or pictures on an old-fashioned television screen or computer monitor.

| Characteristic | CRT | LHC |
|---|--|---|
| Pressure (For comparison, a vacuum cleaner has pressure of $1-10^{-3}$ atm, and outer space has a pressure of $<10^{-15}$ atm) | $10^{-6}-10^{-10}$ atm | $10^{-9}-10^{-15}$ atm |
| Distance travelled by a particle between collisions | 0.1–100 mm | $1-10^5$ km |
| Particle types and source | Electrons produced by thermionic emission at the cathode (a heated filament) | <ul style="list-style-type: none"> Protons produced by ionisation of hydrogen atoms Lead nuclei |
| Mode of accelerating particles | A potential difference between the anode and cathode | Electric fields and radio frequencies, synchronised with particle speed |
| Mode of directing particles | Electrical or magnetic fields | Strong magnetic fields achieved using superconducting electromagnets (4 T in strength) |
| Mode of focusing particles | Wehnelt cylinder and anode hole | Quadrupole magnets |
| Ultimate aim | To cause a beam of particles to form an image on a fluorescent screen | To collide the beam of particles with a second beam and observe the result |

Table 1: A comparison of the classroom particle accelerator (the CRT) and CERN's LHC



- ✓ Physics
- ✓ Ages 14+

We have all heard about CERN and the particle acceleration experiments conducted there. However, for some it may seem like a place that is very far from the classroom. Despite this physical distance, the project described in this article succeeds in reducing the barrier between the scientists' working place and the students' classroom.

The procedure for setting up the apparatus is very detailed, hence making it accessible to teachers. While ensuring that every part of the project is explained in terms of the physics theories involved, the authors have also compared the LHC with the CRT throughout the article. This makes it extremely interesting, apart from being highly instructive.

This article can give rise to a discussion about the work being done at CERN, linked with the origin of the Universe, the progress we have made so far in the exploration of this theory, and the certainties and uncertainties surrounding it!

Catherine Cutajar, Malta

REVIEW

lower than the energy that binds them to the metal nuclei, sometimes called the work function. Consequently, no electron beam is observed and no spot appears on the screen.

How does this compare to the LHC? Instead of electrons, the LHC accelerates beams of protons or lead nuclei (table 1). The protons, however, are produced using a similar technique to the CRT – in this case with an ion source known as a *duoplasmatron*. A cathode filament emits electrons into a vacuum chamber containing small amounts of hydrogen gas. The electrons ionise the hydrogen gas, forming a plasma of hydrogen ions (protons) and free electrons. The protons are then confined by magnetic fields and accelerated to become a beam.

Producing free particles

Materials

See the list of the necessary materials in the downloadable document^{w1}.

Procedure

1. On the CRT power supply unit, disconnect the lead that supplies the voltage to the cathode (see the circuit diagram in the attached worksheet).
2. Set the voltage of the auxiliary anode – the anode of the control grid or Wehnelt cylinder – to 10 V.
3. Set the voltage of the anode to 30–50 V.
4. Set the cathode voltage to 200–300 V.
5. Connect the power unit to a source of electricity.
Can you see a spot on the fluorescent screen?
6. Reconnect the voltage lead to the cathode and repeat the previous step.
Now can you see a spot?

About what happens

A spot is only visible on the fluorescent screen when the cathode is connected. The metal filament heats

up and its electrons escape in the form of thermionic emission. The high positive potential of the anode relative to the cathode pulls the electrons into a narrow beam that strikes the fluorescent screen, appearing as a spot.

When the power is disconnected and the cathode is not heated, the electrons cannot escape from the surface because their thermal energy is

Deflecting an electron beam with an electrostatic field

Materials

See the list of the necessary materials in the downloadable document^{w1}.

Procedure

1. On the power supply unit for the deflection plate, alter the voltage

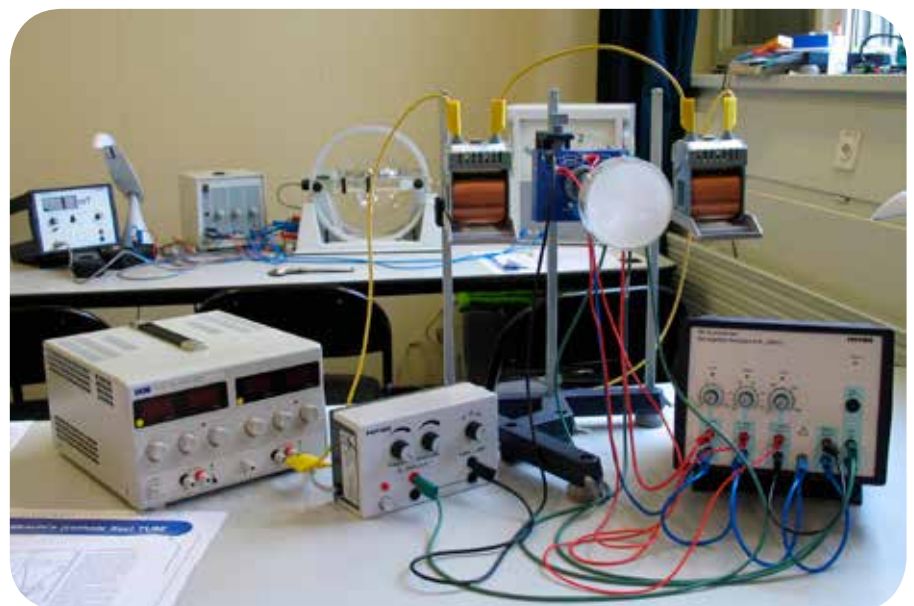


Figure 2: The completed CRT setup

Image courtesy of Jfmeler/Wikimedia Commons

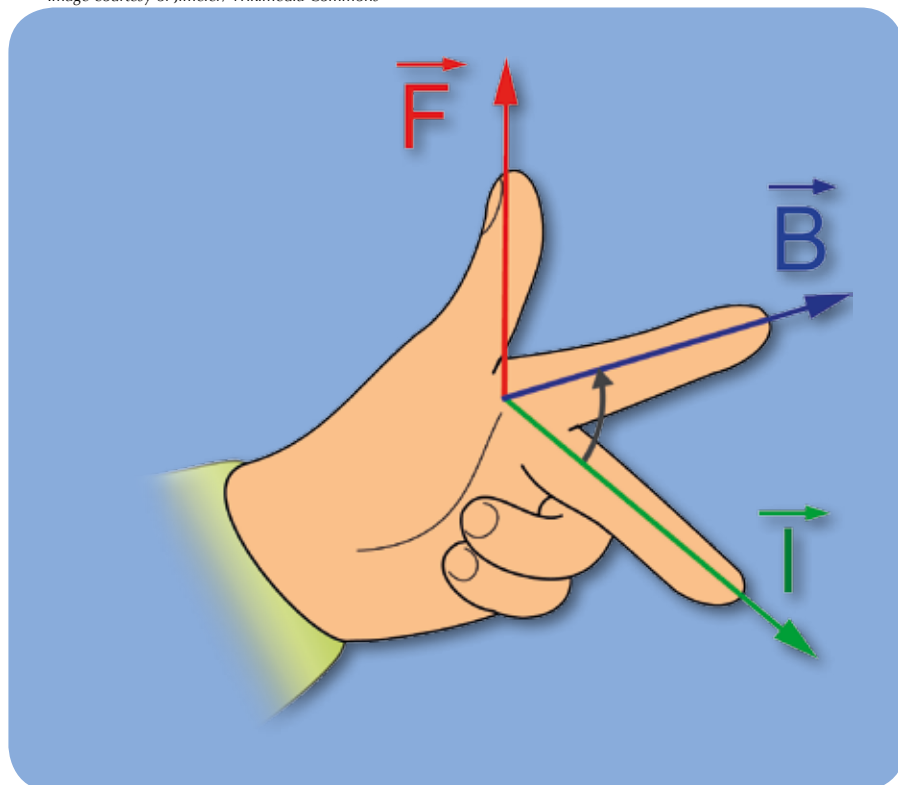


Figure 3: Fleming's left hand rule: using your left hand, your thumb indicates the direction of motion, your first finger represents the magnetic field (north to south) and your second finger shows the current (from positive to negative).

first to the left and then to the right deflection plate (between -80 V and +80 V). What happens to the spot on the screen?

2. Vary the voltage to the auxiliary anode of the control grid. How does the spot on the screen change?

About what happens

When the voltage to the left deflection plate is greater than the voltage to the right plate, the spot will be to the left of the screen and vice versa.

This is because an electrostatic field is created when a potential is applied across the plates. The negatively charged electrons are deflected towards the positive plate, which makes them follow a curved path within the electrostatic field.

Once the electrons leave the electrostatic field, they travel in a straight line towards the screen, at the angle at

which they left the field. The greater the potential applied to the plate, the wider the deflection angle of the beam.

Increasing the voltage to the control grid brightens and sharpens the spot on the screen because the potential difference between the control grid and the anode is greater than that

Image courtesy of K. Aainsqatsi/Wikimedia Commons

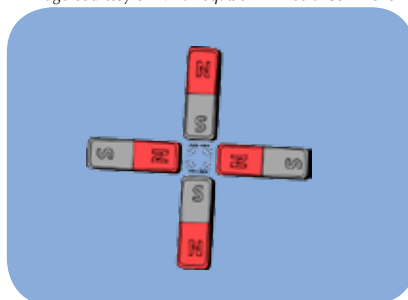


Figure 4: A quadrupole magnet consists of four magnetic poles positioned so the field lines are cancelled at the centre.

between the cathode and the anode. The electrons released by the cathode are repulsed by the control grid and focused towards the anode, resulting in a fine electron beam.

Deflecting the beam with magnetism

If you do not have access to a CRT, you could try a comparable demonstration using an old television screen^{w2}.

Procedure

1. Bring one pole of the bar magnet close to the side of the CRT, beside the path of the beam. What happens to the spot?
2. Power up some electromagnetic coils and bring them close to the side of the CRT. What happens to the spot?

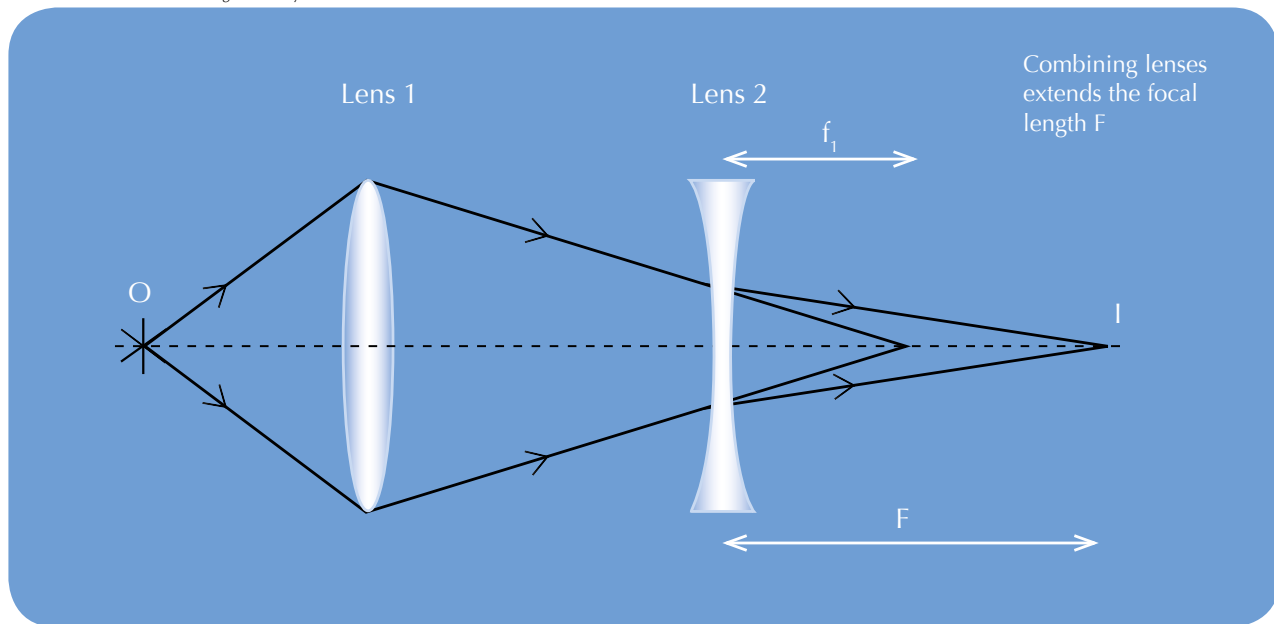
About what happens

When electrons in the beam pass through the magnetic field, they experience a force at right angles both to the direction in which they are travelling and to the magnetic field. This deflects the electron beam. You can work out the direction of force using Fleming's left hand rule (figure 3).

Electromagnets produce a stronger magnetic field so the beam is deflected more than by the bar magnet.

How does this compare to the LHC? The LHC uses superconducting quadrupole magnets to focus the particle beam. A quadrupole magnet consists of four magnetic poles, positioned so that the field lines cancel each other out at the centre (figure 4). When a particle beam passes through the very centre, where there is no magnetic field, it feels no force. The quadrupole magnet, therefore, pushes the beam into a small cross-section, akin to a lens focusing light. However, each quadrupole magnet only focuses the beam in one direction, so to produce a fully focused beam, successive quadrupole magnets at 90° to each other are used.

Image courtesy of Nicola Graf



Optical lenses can be used as an analogue for quadrupole magnets. Just as a series of quadrupole magnets at 90° to each other focuses the electron beam in the LHC, combining two lenses of the same focal length (one converging/focusing and one diverging/defocusing) results in an overall increased focal length.

The total focal length F of a system of two lenses with focal lengths f_1 and f_2 separated by the distance d is given by:

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2}$$

Because the first lens is focusing and the second defocusing, while their focal length is the same, $f_2 = -f_1$. Substituting this into the formula gives:

$$\frac{1}{F} = \frac{d}{f_1^2}$$

The total focal length is increased when two lenses are combined.

Changing the speed of particles

Procedure

1. Alter the voltage of the anode. How does the spot on the screen change?

About what happens

When the anode voltage is low, there is no electron beam. As the voltage is increased, the spot becomes visible and then brighter.

Increasing the potential difference between the anode and the cathode (by increasing the voltage to the anode) increases the velocity of the electrons towards the screen.

How does this compare to the LHC? The first electrostatic accelerator of the LHC (located inside the proton source) accelerates protons using a potential difference of 90 kV. However, these protons do not reach the velocity that the electrons in the CRT reach with a lower potential. This is due to the higher mass of the protons. Proton accelerators like the LHC, therefore, need more energy to accelerate particles to high speed.

Comprehension questions

1. What is the speed of electrons that have been accelerated by a potential difference of 250 V in the CRT?
2. What is the speed of protons that have been accelerated by a potential difference of 90 kV at the first electrostatic accelerator of the LHC?

Answers

1. Kinetic energy of the electrons:

$$E = 250 \text{ eV} = 4 \times 10^{-17} \text{ J}$$

But $E = \frac{1}{2}mv^2$, which can be rearranged to give the speed of the electrons as:

$$v = \sqrt{\frac{2E}{m_e}}$$

$$= 9.38 \times 10^6 \text{ ms}^{-1}$$

Energy of the protons:

$$E = 90 \text{ keV} = 1.44 \times 10^{-14} \text{ J}$$

Speed of the protons:

$$v = \sqrt{\frac{2E}{m_p}}$$

$$= 4.15 \times 10^6 \text{ ms}^{-1}$$

Web references

- w1 – For the list of materials and instructions on how to set up the apparatus, please download the worksheet in either Word or PDF form at www.scienceinschool.org/2014/issue30/accelerator#w1.
- w2 – An alternative to activity 3, using an old-fashioned television screen,

More about CERN



The European Organization for Nuclear Research (CERN)^{w3} in Meyrin, Switzerland, is one of the world's most prestigious research centres. It aims to understand fundamental physics – finding out what makes our Universe work, where it came from and where it is going.

CERN is a member of EIROforum^{w4}, the publisher of *Science in School*. See all CERN-related articles in *Science in School*: www.scienceinschool.org/cern



Acknowledgement

These activities were developed in Julian Merkert's thesis during his study at the University of Karlsruhe, Germany, and a two-month stay at CERN. The initial inspiration came from an idea from Prof. Dr Günter Quast at the University of Karlsruhe to "explain particle physics with school experiments".

Andrew Brown is a molecular and cellular biology graduate of the University of Bath, UK. After working for *Science in School*, he returned to the UK and is now at the Royal Institution.

Julian Merkert is a secondary-school physics and mathematics teacher working at St. Dominikus-Gymnasium Karlsruhe, Germany. During his academic studies at the University of Karlsruhe, he produced teaching materials about the LHC at CERN. He has run several teacher programmes, both at CERN and in Germany.

Dr Rebecca Wilson is a planetary scientist working on public and business engagement projects at the Space Research Centre, University of Leicester, UK. She is a project scientist for the UK's National Space Academy, collaborating with scientists and educators to develop secondary-school revision materials based on space science. She also works for the Space IDEAS Hub, giving small local businesses access to the university's space-derived expertise.



Resources

To learn more about CERN, see:

Hayes E (2012) Accelerating the pace of science: interview with CERN's Rolf Heuer. *Science in School* 25: 6–12. www.scienceinschool.org/2012/issue25/heuer

Landua R (2008) The LHC: a look inside. *Science in School* 10: 34–45. www.scienceinschool.org/2008/issue10/lhchow

Landua R, Rau M (2008) The LHC – a step closer to the Big Bang. *Science in School* 10: 26–33. www.scienceinschool.org/2008/issue10/lhcwhy

If you found this article useful, you may like to browse the other teaching activity articles on the *Science in School* website: www.scienceinschool.org/teaching

is described on the website of the Oxford University physics department. See: www.physics.ox.ac.uk (search for 'cathode ray tube') or use the direct link: <http://tinyurl.com/alq4hgl>

w3 – Find out more about CERN: www.cern.ch

The CERN education website offers resources for schools and information about CERN's residential courses for teachers. See: <https://education.web.cern.ch>

w4 – Learn more about EIROforum at www.eiroforum.org

