

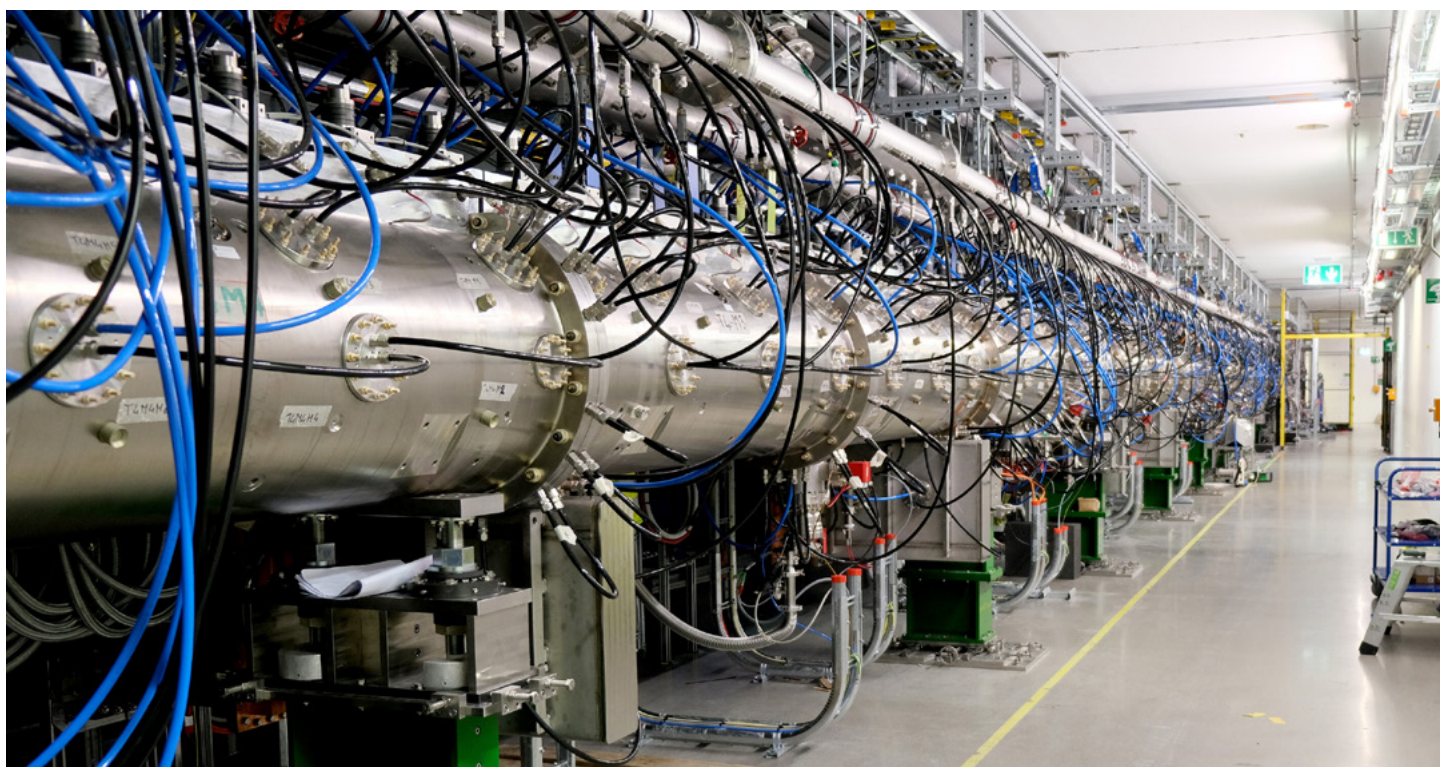


# Science in School

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## Build a linear accelerator model

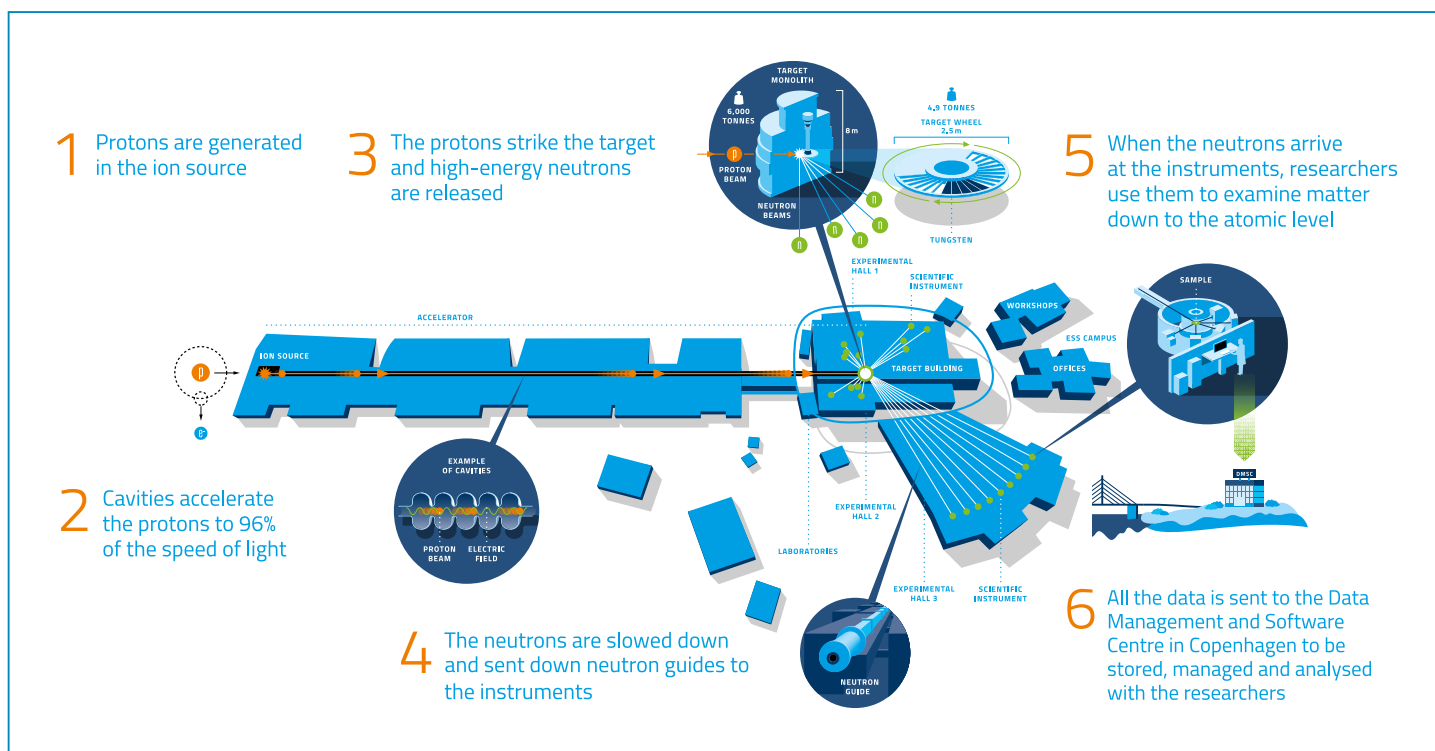
Jo Lewis, Lukasz Michalak

Build a linear accelerator to demonstrate spallation – the source of high-energy neutrons used by the new European Spallation Source being built in Sweden.

We are currently building the European Spallation Source (ESS) in Lund, Sweden.<sup>[1]</sup> ESS is a next-generation spallation source – a source of neutrons that will be used by researchers from academia and industry to study the structure and behaviour of matter from the atomic to the macroscopic scale in many different fields, including biology and medicine, chemistry, materials, physics and engineering, magnetism, and archaeology. Spallation is the production of neutrons by hitting a heavy-metal target with high-energy protons, which have been accelerated using a particle accelerator.

An important part of ESS is a linear particle accelerator, where protons will be accelerated to around 96% of the speed of light. Acceleration is achieved using strong electromagnetic waves, which propel the protons from one section to the next at ever-increasing speeds.

In this activity, we present a model of a linear accelerator (linac) called a Gauss cannon. It uses magnetic attraction and momentum transfer to accelerate a series of steel balls, representing protons. At the end of the track, one 'proton' will



A scheme of ESS, showing the different steps of the process  
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collide with a bunch of balls or marbles, which represent the neutron-rich nucleus of a tungsten atom. If the initial ‘protons’ have sufficient energy, they will be able to release the ‘neutrons’, thereby modelling the spallation process.

### Links to physics teaching

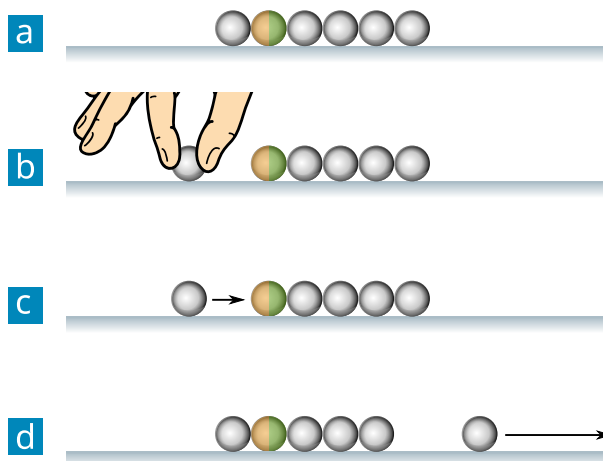
The activities demonstrate electromagnetism, conservation of energy, kinetic energy, (magnetic) potential energy, momentum and collisions, and accelerated motion.

It is best suited to students aged 16 and older, but also works as a demonstration for younger students.

## Activity 1: Build a linear Accelerator

In a Gauss cannon, a series of strong magnets are distributed evenly along a track. At one end of each magnet, two or more steel balls are placed. When another steel ball is rolled along the track towards the first set of magnets, magnetic attraction, coupled with a transfer of momentum, causes the leaving

balls to accelerate, each to a higher speed than the previous one. Acceleration thus occurs stepwise, just as in a linear particle accelerator, although the exact mechanism differs.



A scheme showing the function of a Gauss cannon. The coloured sphere is the neodymium magnet.

Image: MikeRun/Wikimedia, CC BY-SA 4.0

This can be done as a demonstration from the front, but provides more critical-thinking skills if the school can provide enough equipment for each group of students to have a complete set of the list below.

As a demonstration, this activity requires 10 minutes for preparation and 20 minutes for the demonstration and discussion. As a student workshop, this activity requires 20 minutes for preparation and 40–60 minutes for the activity and discussion.



### Safety notes

- Neodymium magnets can be very strong. Never place them near electronic devices, bank cards, or close to people with pacemakers or other metallic implants.
- When handling, be extra careful not to trap your fingers between two magnets.
- These magnets are also brittle and can break when struck, so always replace any magnets showing signs of damage.
- The final ball can move very fast. Check that the track is never directed towards people and that no one stands in the path or puts their face near the track. Always point the track towards a wall, not into the classroom.

### Materials

For each model, you will need:

- One [activity instructions sheet](#) and one [activity worksheet](#) per student
- At least six neodymium magnets (see safety notes)
- At least seven steel balls (approx. 1 cm in diameter)
- Track that can guide the balls in a straight line (wood, cardboard, plastic, etc., but must be nonmagnetic) around 60–90 cm in length
- Tape or sticky gum to fix the magnets to the track
- Box, bag, or tray to catch the balls at the end of the track
- Optional – camera app on a smartphone or tablet with slow-motion function

The setup can also be bought relatively cheaply as a whole track with the appropriate balls, sometimes called a magnetic rifle or a Gauss gun, from an education supplier (see resources section).



A pre-prepared track contains stronger magnets and uses larger steel balls, making it easier to see if used as a demonstration.

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### Procedure

#### Setup (10 min)

1. Take a piece of track and set it on the floor or on a table with a bag or a tray at the end closest to the wall. This will be the target at the 'end' of the track and the other end will be the start of the track.

#### Build a linac (10 min)

2. Using sticky gum or tape, fix magnets in pairs along the track with around 10–15 cm between each pair.
3. Place two steel balls next to each pair of magnets, and repeat with each pair of magnets. The balls should be on the same side, so each set has two magnets and then two steel balls. The balls should be facing the target end of the track.



Start \_\_\_\_\_ End

*Image courtesy of Lukasz Michalak*

4. Place your box, bag, or tray at the end of the track closest to the wall, such that the balls coming off the end will land in the 'target'. Fix it firmly in place using tape.

**Test your accelerator (5 min)**

5. Ask the students to predict what will happen when a single steel ball is released at the start of the track. They should write their prediction on their worksheet.
6. Place one steel ball at the start of the track and give it a gentle nudge towards the first pair of magnets. It will travel towards the magnet pair, speeding up slightly on approach as it is attracted to the magnets.
7. On impact, one of the balls on the other side of the magnet pair is released, with some force, and heads towards the next magnet pair. The process is repeated, with each ball approaching the magnets with more energy than the one before, until the last ball is released at relatively high speed into the bag or tray.

**Change some variables (5 min)**

8. Ask the students to suggest how they could change the starting energy of the first ball. Ask them to think of which other variables they could change and to write their answers on the worksheet.
9. Raise the start of the track so it is on a slope. This adds an additional type of energy transformation (from gravitational potential energy) to discuss.
10. Try changing the number of balls on each side of the magnets.
11. Ask the students to think about the types of energy and energy transfers that are taking place and to answer the questions on the worksheet.

**Optional extension (15 min)**

If you have access to a smartphone or tablet with a slow-motion function in the camera app:

12. Ask the students to measure the precise distance between each set of magnets.
13. Film the balls' movement with the slow-motion function of a camera app on a smartphone or tablet.
14. With the table on the worksheet, ask the students to determine the average speed of each ball and to calculate by how much the kinetic energy increases between each impact.

**Discussion**

In a Gauss Cannon, we first give some energy to the initiating ball, either by pushing it or raising the track to a slope. This initial energy causes it to roll towards the first magnet, but as it approaches, magnetic attraction causes the ball to accelerate. On impact with the magnet, this increased energy is transferred to the next balls in the system, causing the last ball to leave with the same momentum, rather like in a Newton's cradle. This ball then rolls further along the track towards the next magnet with an energy that is higher than the

initiating ball. The same magnetic attraction occurs with the next magnet, accelerating this second ball still further, and this further increased energy is transferred again on impact. Thus, with each repeating step, the energy of the released balls increases, and stepwise acceleration is observed.

The details of energy transfer might not be obvious to students, and the teacher should provide a guided discussion if necessary. Some useful resources for this are provided in the resources section.

**Activity 2: Add a target to demonstrate spallation**

Place a bunch of small balls or marbles at the end of the Gauss cannon track. When the final accelerated proton collides with the bunch of marbles – or neutrons – they will be scattered in many directions. This is similar to the real spallation process, where high-energy neutrons are released when the protons hit the neutron-rich target.

This activity takes 10 minutes.

**Materials**

- Models from Activity 1
- Around 15 additional small steel balls or marbles per demonstration

**Procedure****Add a neutron-rich target to produce spallation (10 min)**

1. Place eight small balls or marbles in a bunch at the end of the track. Remember, this should be facing towards a wall and not out into the classroom. You may wish to use a large tray to catch them.
2. Encourage the students to look at the [ESS website](#) to find out more about spallation.
3. The smaller balls represent the neutrons in the tungsten atoms. When the high-energy protons (represented by the last steel ball in the sequence on the track) hit the neutron bunch, the neutrons will be scattered in many directions, imitating the spallation process when the protons hit the neutron-rich target.
4. Ask the students to observe what happens when they release and accelerate the balls in their linac model so the final ball strikes the bunch of 'neutron' balls. Using the additional information at [www.ess.eu/explore](http://www.ess.eu/explore), students should describe on their worksheet the resulting demonstration of spallation.
5. Try with a larger number of balls or marbles.

## Discussion

### Connections to ESS

The Gauss cannon is an analogy for what actually happens in an accelerator. In a functioning particle accelerator, electric fields are used to accelerate electrically charged particles. In the Gauss cannon, magnetic fields are used to accelerate the ferromagnetic balls.

In a linac, acceleration occurs along a straight line, in a series of repeated steps, each one providing an extra kick to each of the protons (steel balls in a Gauss cannon), enabling them to get faster and faster as they proceed.

In a linac, the magnets serve to focus the beam, to limit losses from the protons, which would otherwise repel one another. In a circular accelerator, there are also focusing magnets, but, in addition, dipole magnets are used to bend and steer the beam around a near-circular track.

At ESS, there is a target wheel, containing tungsten bricks. When the accelerated protons hit the target, they knock neutrons out of the tungsten atoms (which each release around 30 neutrons) in a process called spallation.

These neutrons are then sent down neutron guides towards different instruments, where researchers place the samples they wish to study. The more neutrons that arrive at the instrument, the more data can be collected, which can lead to more detailed and higher-resolution experimental results. The number of neutrons produced is called the flux. ESS will have a very high flux of neutrons.

The [ESS scheme](#) can be used to discuss the similarities and differences between linacs and the Gauss cannon.

When recreating spallation in this way, the main aim is to generate as many fast-moving ‘neutrons’ as possible. Ask students how they could increase the flux of ‘neutrons’ in their model. They could for example change the element in the target to one with more neutrons, or increase the energy of the protons in the accelerator (with a higher starting energy, or more powerful magnets) so more neutrons are released on impact.

## Conclusion

This activity provides a hands-on way to teach the physics concepts demonstrated by particle accelerators, such as magnetism, energy, momentum, and accelerated motion. It also provides background information about ESS, Europe’s flagship big-science project, to provide context for students about how physicists and engineers today are using these concepts in their jobs to build and run cutting-edge research facilities.

Teachers can access this and many more teaching resources around particle accelerators at the legacy version of the massive open online course [Accelerate Your Teaching](#).<sup>[2]</sup> You will need to set up a free login at Scientix and enrol to access the materials.

## Acknowledgements

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## Resources

- Visit the [European Spallation Source website](#) page for the public and schools to explore what ESS is, how it works, and what it is for.
- Watch a demonstration of the [Gauss cannon](#) by QUASAR Group, University of Liverpool, which inspired this activity.
- Read more about the [Gauss cannon](#).
- Watch an explanation of [magnetic potential energy](#).
- [Watch a video explanation of the function of a Gauss cannon](#) that includes slow-motion footage.
- [Read an explanation and description with photos of how to build a Gauss cannon](#).

- Further teaching resources for particle physics can be found through Accelerate Your Teaching: [Accelerate your teaching with links to cutting-edge science](#). *Science in School* **67**.
- Learn how Star Wars can be used to engage students with accelerator science: Welsch CP (2021) [The physics of Star Wars: introducing accelerator science](#). *Science in School* **54**.
- Discover CERN Science Gateway, the new science education and outreach centre in Geneva: Woithe J (2024) [CERN Science Gateway: a guide for teachers](#). *Science in School* **66**.
- Read about the use of proton beams for cancer therapy: Welsch CP (2021) [Death Star or cancer tumour: proton torpedoes reach the target](#). *Science in School* **55**.
- Discover the different elements of particle accelerators by assembling a virtual one with cardboard cubes and a smartphone: Welsch CP (2021) [Build your own virtual accelerator](#). *Science in School* **54**.
- Build an accelerator in a salad bowl: Torres R (2017) [A particle accelerator in your salad bowl](#). *Science in School* **41**: 49–55.
- Learn how physicists study very small and very large objects: Akhobadze K (2021) [Exploring the universe: from very small to very large](#). *Science in School* **55**.
- Explore the conservation and transfer of energy with Rube Goldberg machines: Ferguson S et al. (2022) [Conservation and transfer of energy: project-based learning with Rube Goldberg machines](#). *Science in School* **56**.
- Let your students experience the challenges faced by particle accelerator scientists while learning about the physics of waves: Torres R (2023) [Surfatron: catch the wave of accelerators](#). *Science in School* **62**.

## AUTHOR BIOGRAPHY

**Jo Lewis** is communications and public engagement officer at ESS ERIC. She has a background in biochemistry and an MSc in science communication. Before moving to Sweden and ESS in 2020, she worked for 10 years at STFC Rutherford Appleton Laboratory in the UK, a site that houses a number of large facilities, including its own neutron spallation source, called ISIS, that is almost the same age as her.

**Lukasz Michalak** holds a PhD in physics and is a qualified secondary teacher of physics and mathematics. He works at the Department of Physics at Lund University in Sweden and coordinates the local physics teacher programme. Since 2022, he has been the director of the (Swedish) National Resource Centre for Physics Education.

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