How to accelerate particles

Learn how the world's most powerful accelerator works

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Welcome! We are going to explore the fascinating world of subatomic particles and the Large Hadron Collider, the world's most powerful particle accelerator!

At CERN, the European Organization for Nuclear Research, physicists and engineers are probing the fundamental structure of the universe. They use the world's largest and most complex scientific instruments to study the basic constituents of matter – the fundamental particles. To do so, particle accelerators are necessary in order to create new high mass particles and recreate the conditions of the early universe. Accelerators boost beams of particles to high energies before the beams are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions.

CERN's facilities include the LHC ("Large Hadron Collider") which is the most powerful accelerator in the world, allowing scientists to probe deeper and deeper into matter. Beams of particles - mainly protons - are accelerated in the 27 km circumference of the LHC, an underground tunnel spanning the border between France and Switzerland.

In this exercise you are going to find out how particles can be accelerated inside the LHC, following the step-by-step procedures necessary. But first, let's take a quick look at what happens inside the accelerator before two particles collide:

https://youtu.be/AHT9RTlCqjQ

As you may know already, Newton's first law says that an object either remains at rest or continues to move at a constant velocity, unless acted upon by an external force. This means that in order to accelerate particles, we have to apply some kind of force on them. There are four fundamental forces in the universe:

1. The strong force, that binds the protons and the neutrons together inside the nucleus of an atom.

2.The electromagnetic force, which arises from the unification of two forces, the electric force and the magnetic force.

3.The weak force, that makes that is responsible for the Sun's energy.

4.The gravitational force, which is the dominant force only at the macroscopic scale (life on earth, planets, stars, etc).

Which one of the above forces is capable of accelerating particles in the LHC? Can you make a guess?

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

Go ahead and Make your guess for the questions below!

Question

Which one of the above forces is capable of accelerating particles in the LHC?

1. The weak force?

Exlplanation: The weak force has a limited subatomic range and, therefore, it can't accelerate particles in the LHC (which is 27 km long).

2. The gravitational force?

Explanation: It would be possible but this force is VERY weak.

3. **The electromagnetic force?**

Explanation: That's correct! Firstly, the electromagnetic force is an infinite range force and, therefore, capable of accelerating charged particles in the LHC. Secondly, it is strong enough to affect the motion of particles, and, therefore, accelerate them.

4. The strong force?

Explanation: The strong force is, of course, strong enough, but it has a very limited range of action which is not sufficient for particle acceleration.

Whether you guessed it or not, particles are accelerated using the electromagnetic force. But what **is** the electromagnetic force? As mentioned above, it is one of the four fundamental forces of the universe. Furthermore, it is a force that affects only **charged** particles. It has **infinite range**, which means that if the whole universe was empty and we only had a device that produced electromagnetic fields, these fields would travel all over the universe undisturbed. The electric force between a positive and a negative charged particle is attractive. On the other hand, it is repulsive for particles that have the same charge sign. Would you like a proof? Take a look at the boy's hair in the next video. Same sign charges accumulate on his hair as he touches an electrostatic generator. And they repel each other!

https://www.youtube.com/watch?feature=player_embedded&v=bO91e0AaGGg

What about magnets? The force between the north and the south pole of two magnets is attractive, whereas the force between the same kind of poles (north-north or south-south) is repulsive. The LHC uses superconducting magnets to bend the beams of protons. Have a look at the power of superconductivity:

https://youtu.be/TeS_U9qFg7Y

The above video is not magic of any kind! It is pure physics and laws of nature! But let's leave the fascinating physics aside for a while. Here is another question for you:

Teacher Guidelines:

Estimated duration of this activity: 20 minutes. If you want to shorten the duration of the activity watch the videos beforehand and choose the ones you find best

Hint for the above question: The gravitational force and the electromagnetic force have infinite range, however the gravitational force is the dominant force only at the macroscopic scale (planets, stars, etc). On the other hand, the weak and strong forces have limited range: their influence can be felt only in subatomic distances.

Generation of Hypotheses or Preliminary Explanations

There are many particles in nature. The best known are the constituents of the nuclei: proton s, electrons , and neutrons. Protons are positively charged, electrons are negatively charged, neutrons have no charge. Which of the above particles can be accelerated by the electromagnetic forces?

Only charged particles are accelerated with electromagnetic forces. But how exactly does that happen? What are the mechanisms involved? And how difficult is it to accelerate particles? You are going to find out how particles are accelerated in the LHC in the next phase!

Evidence

Plan Investigation

In this demonstrator you will be introduced to the main daily tasks of the LHC operators and experience the thrill of **accelerating**, **bending** and **focusing** protons, i.e. the positively charged nuclei of the hydrogen atom. Only when you complete the above tasks successfully will you be able to make two proton beams, which travel close to the speed of light, collide recreating the conditions that existed in the early Universe.

Your adventure starts at the **LHC control room**, where your new colleagues, the LHC operators, will guide you through the various steps of the procedure.

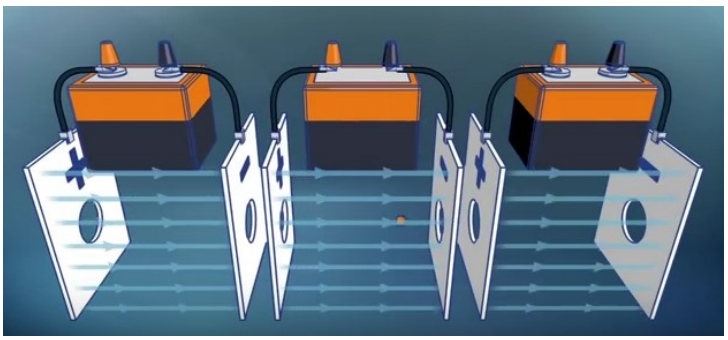
First have a look at the real LHC control room below *(Image: CERN)*.

There are three main steps you have to follow:

- Step 1: **ACCELERATING**

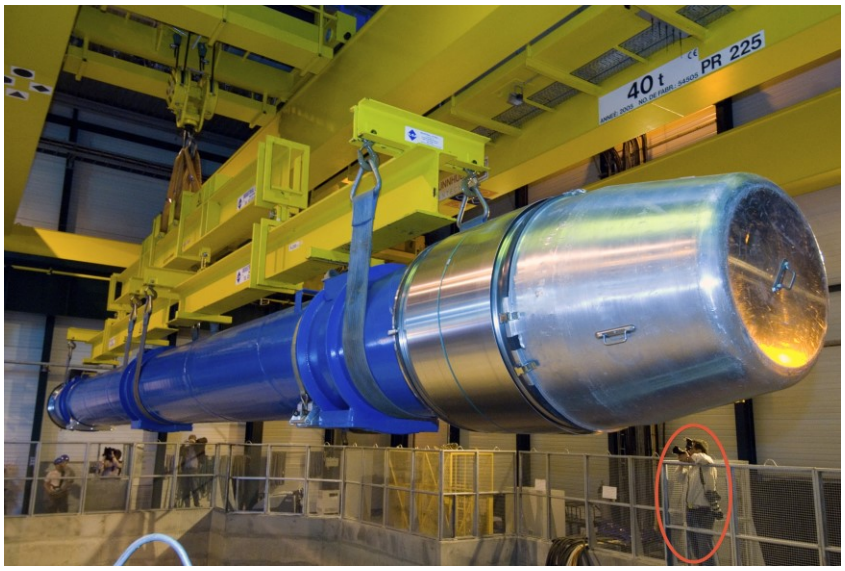
  Electric fields provide energy and therefore charged particles gain energy and go faster. These electric fields are provided by modules of **accelerating cavities**. There are four such modules (two per beam), each one of them containing four accelerating cavities, and are placed in four points along the LHC ring. One of the four modules of accelerating cavities is shown in the picture below*(Image: CERN)*.

The operation of these cavities is based on the fact that a positively charged particle, like a proton, is attracted by a negative charge and repelled by a positive charge. Therefore the accelerating cavities operate like having a few batteries (each one of them attached to two parallel metal plates of opposite polarity) next to each other, as shown in the figure below. Notice a positively charged particle in orange color, travelling from the positive towards the negative pole of the battery in the middle.



- Step 2: **BENDING**

We saw that the protons are accelerated using electric fields. But since the LHC is circular we have to bend the particles to follow a circular path. But how do the protons bend inside the ring? The magnetic forces are perpendicular to the velocity of the protons so they can change their direction of motion and make them move in a circular path around the LHC ring. The magnets that are used to bend the path of protons are called **dipole magnets**. There are 1232 such magnets at the LHC. Each magnet is about 15 m long providing a very strong magnetic field. Below you see a dipole magnet, being lowered inside the LHC tunnel *(Image: CERN)*.



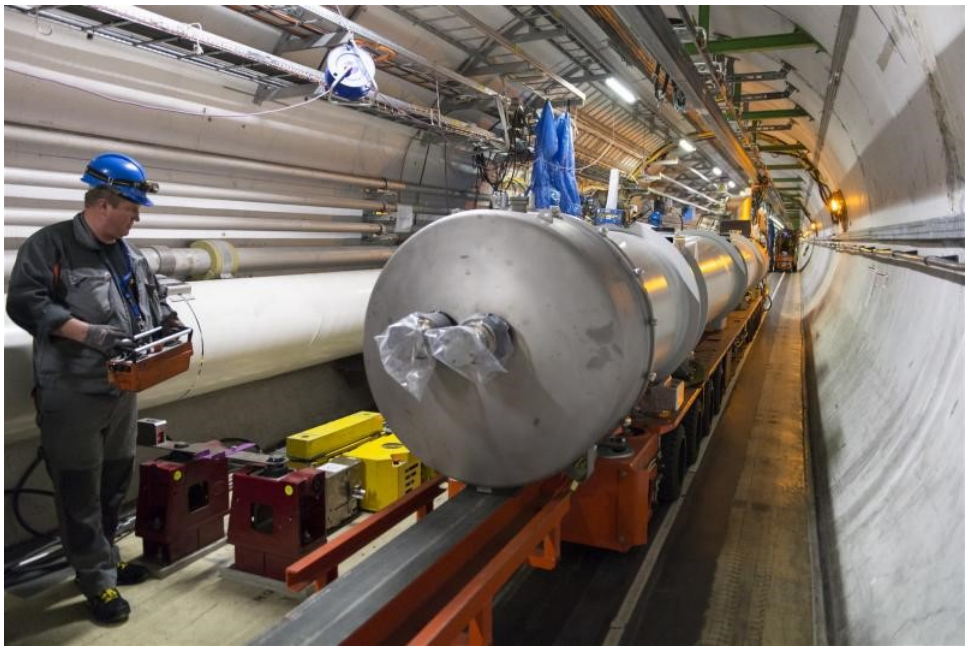
There are two counter-rotating beams of protons inside the two separate metal pipes of the accelerator. To avoid colliding with gas molecules inside the pipe, the beams must travel in a vacuum as empty as interstellar space! Therefore, these two pipes are under ultra-high vacuum. The LHC magnets are superconducting and need to be kept at very low temperature (-271.3 °C!!!) inside a special housing, a dewar. Since the two beams have to be bent in opposite directions, the engineers decided to build double magnets, i.e. two dipole magnets into a single housing. This way the double magnets not only provide two opposite fields but they also reduce the costs of building extra magnets.

As the energy of the protons slowly increases in each round, the dipole's magnetic field must also rise to keep the beams in the center of the beam pipe since the magnetic field required to bend a particle on a constant radius is proportional to its energy.

- Step 3: **FOCUSING**
  A machine consisting of only dipoles cannot function though, because the particles would diverge from the nominal orbit colliding with the inner beam pipe wall and would be rapidly lost.

  A force is needed to bring them back on track focusing the beam. This corrective force is provided by the field of the so-called, **quadrupole magnets**. There are 392 such magnets at the LHC. Each magnet is 5-7 m long.

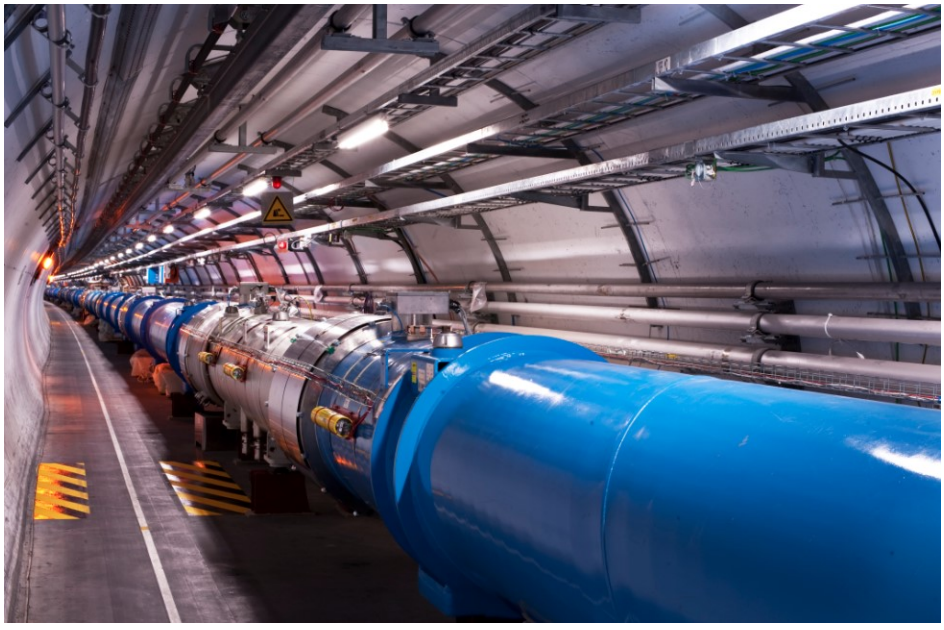
  A quadrupole magnet being placed inside the LHC tunnel, carried by a wheeled transporter to its final position, is shown in the following picture (Image: CERN).



The LHC beams consist of thousands of packets of protons. Each packet contains billions of protons. The more the protons in the packets are squeezed together (i.e. the more focused the beam is) the greater the chance of collisions is. The particles are so tiny that the task of making them collide is comparable to firing two needles 10 kilometres apart with such precision that they meet halfway!

In principle, two quadrupoles are needed to squeeze the protons in both directions: **horizontally** and **vertically**. By combining the effects of several quadrupoles, the packet of protons can be focused in both directions.

In the following picture, a section of the LHC ring is shown. Notice the white quadrupole magnet between the blue dipoles *(Image: CERN)*.



Once the proton beams are focused, the collisions can start. During these collisions their energy is transformed into new particles according to Einstein's famous equation $E = mc^2$. This equation shows that energy (E) can be converted into mass (m), while c is the speed of light.

Perform Investigation

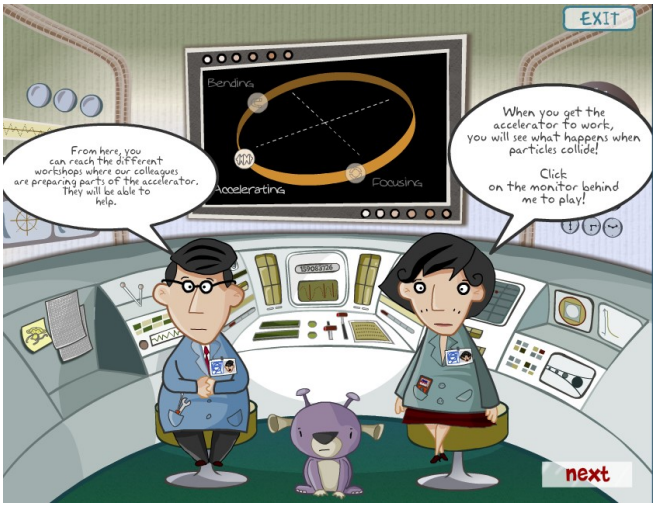
Now that you have learned about the three basic tasks needed to be performed in order to accelerate charged particles, it is time to take action and perform them yourself! Are you ready? Let's start!

Load the LHC Game (Copyright CERN) by following this link:

In this link, download and install CERNLand.exe, enable the Abode Flash Player, choose your favorite language, click at "All the games" and choose the "LHC game control room". Then navigate through the pages by following the indicated flashing arrows.

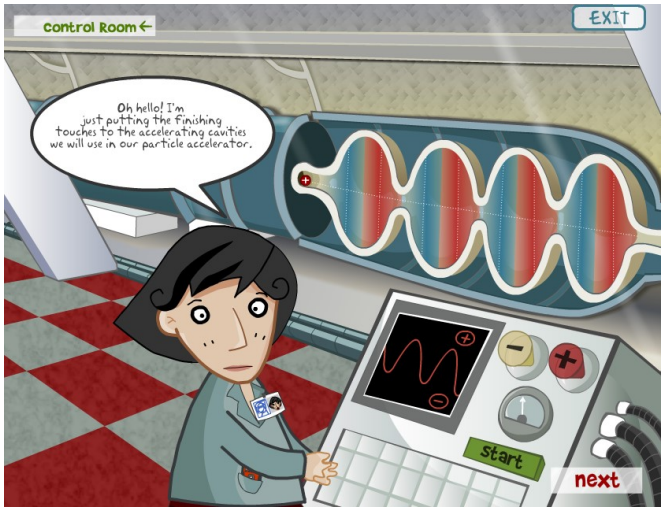
CERN scientists are very busy but they always take the time to explain their work to you.

After a brief introduction by some CERN scientists, sitting around a table, you arrive at the **LHC control room**. Two LHC operators are waiting for you and are happy to help you with your three tasks, marked as 1, 2 and 3 on the control room's main screen, as shown in the image below. Please notice the control room icon at the bottom of this image, which you can use if you want to come back to the control room.

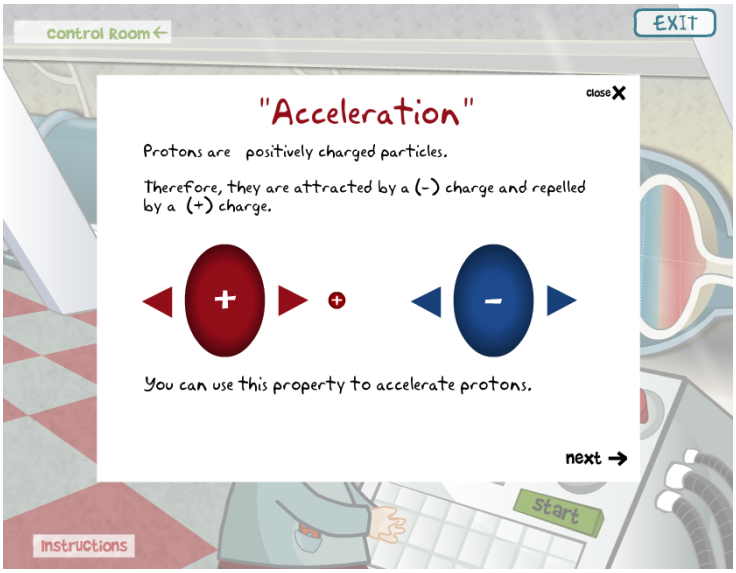


-step 1: **ACCELERATING**

Click on next on the main screen. You are now in front of the accelerating cavities, while an LHC operator is sitting at the control panel that monitors the electric fields of the cavities as shown below:



First you have to click on next so that your new colleague starts giving you helpful advice and information on the performance of this task. Click, the instructions button and the instructions will appear, as shown here:



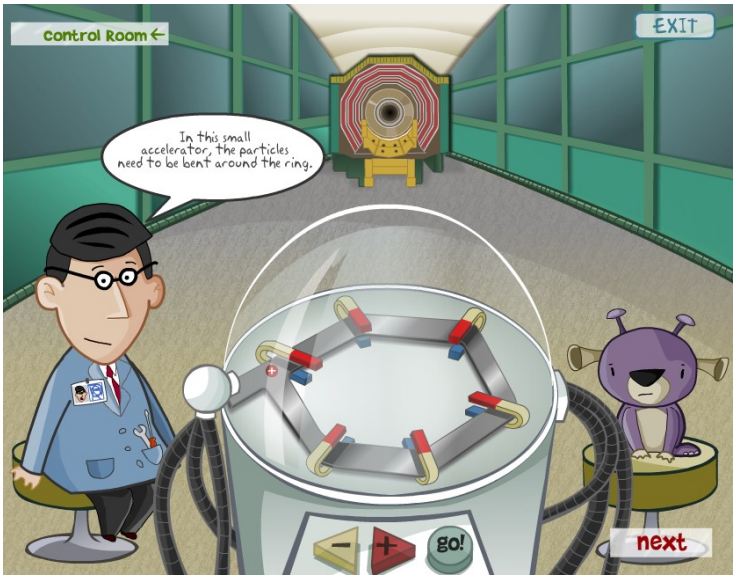
You are ready now to start, by clicking the green button on the control panel. A proton enters the cavity and it is ready to be accelerated with your help!

As the proton travels through the different sections of the cavity, you have to press the +/- button on the panel, at the right moment so that you change the polarity allowing the proton to move forward.

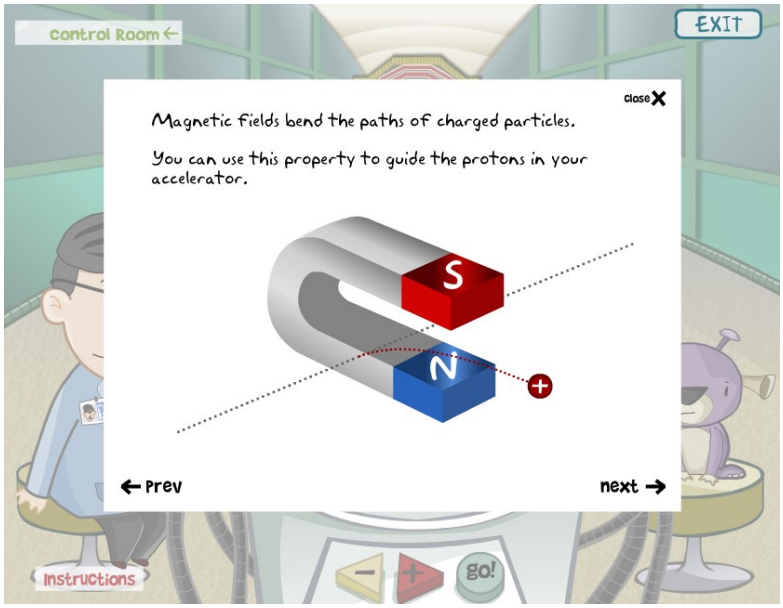
If you manage to change the polarity at the right frequency, the proton traverses the whole length of the cavity reaching its maximum energy! Well done! You are ready now to return to the control room (by clicking the control room icon indicated) and perform the next operation!

- step 2: **BENDING**

Click on next on the main screen. Here you see an LHC operator responsible for bending the paths of the protons inside the LHC ring, using **dipole magnets**.



Click on instruction for the instructions to be displayed, as the following figure shows.



Your job is to adjust the magnetic field strength by clicking on the + (increase) or – (decrease) buttons, on the replica's panel to the right. The protons should be able to travel along the whole length of the circular path reaching the point where they started. Please notice that there is only one optimal field strength setting that can accomplish that.

During your efforts, you may press the large orange button on the panel to validate your choice. If your choice in not the correct one, the operator informs you that you are losing protons, because they collide with the wall of the beam pipe.

Once the optimal setting is found and the proton can circulate without problems around the ring, your goal is achieved and your choice is validated as a success! Well done! You have adjusted the dipole magnets!

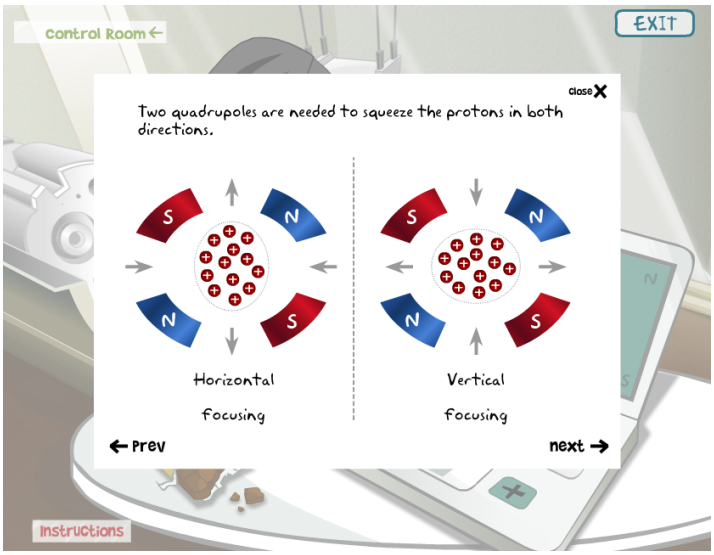
Finally, the LHC operator explains that there are actually two dipole magnets inside the same housing, given the fact that there are two proton beams circulating inside the LHC ring in opposite directions.

Please return again to the control room for the next operation.

-step 3: **FOCUSING**

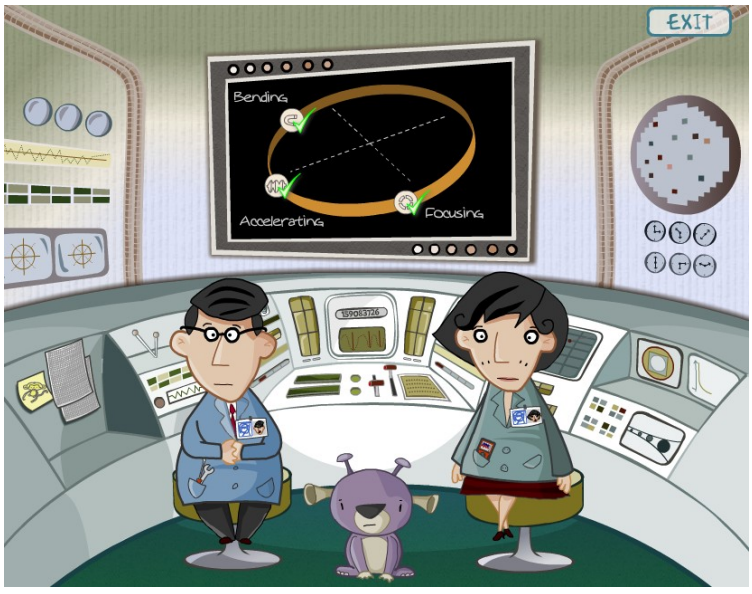
Click on next on the main screen. You are now inside a workshop with another LHC operator and you are going to focus the proton beam.

You can see a packet of protons on the screen to the right, inside a quadrupole magnet marked in green. Click on instructions and the instructions appear on the screen, as shown below:



By pressing the 1st button you may focus the protons **horizontally**, while the 2nd button focuses them **vertically**. Moreover, you have to adjust the magnetic field strength by pushing the buttons +/-. Please ensure that all protons are inside the red circle.

Once you achieve your goal, the proton collisions can start! You have to return now back to the control room and operate the accelerator!



The huge energy of the collision is transformed into mass, i.e. hundreds of new particles according to the famous Einstein's equation $E = mc^2$, where E is the energy of the collision, m the mass of the particles produced and c is the speed of light.

You can see on the main screen, the particle tracks in different colors being sprayed around the collision point and being recorded by one of the giant LHC detectors. Thousands of scientists from all over the world analyze the huge amount of data of such collisions and find out what happened

back in the early Universe, only moments after the Big Bang. In this way we can understand more about what makes up the world around us today.

Teacher Guidelines: Open the LHC game using the Chrome browser and download the Adobe Flash

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

Now that you have understood how to accelerate particles try to answer the following questions:

Question
As mentioned above, positive charged particles are attracted by negative charges and repelled by positive charges. Based on this information, how would you choose to accelerate protons in the LHC?

1. I would put a positive pole at the beginning of the LHC tunnel and a negative pole at the end of the tunnel.

Feedback: That's a logical thought, but the protons have to circle the tunnel many times in order to reach the desired energy, therefore such an accelerating procedure wouldn't work since the protons would slow down after passing the negative pole (the negative pole would pull them back, the positive pole would repel them at the wrong direction).

2. I would use electric fields of oscillating polarity and adjust their frequency so that the protons would always accelerate.

Feedback: That's correct!

3. I would use magnetic fields of oscillating polarity and adjust their frequency so that the protons would always accelerate.

Feedback: Unfortunately, that's not possible. Magnetic fields can only change the direction of a particle, not its speed. We need electric fields for particle acceleration.

And why on earth is the LHC circular? Why didn't we make it linear in the first place and stop worrying about bending?

Question

Why did we choose to build a circular accelerator (the LHC) instead of a linear one?

1. The tunnel that the LHC was built in existed already from ~~an~~ earlier experiments.

Feedback: That's correct, and it significantly lowered the expenses of building a new tunnel, but this is not the main reason.

2. There is no real difference. We could have built the LHC as a linear accelerator.

Feedback: Well, no! At least not for the physics we want to do.

3. It needs to be circular for the protons to reach the desired speed.
Feedback: Protons have to go around many times until they reach the desired energy. If we tried to do the same with a linear accelerator it would have to be thousand kilometres long, spanning many many countries!

Explanation: Formulate an explanation based on the analysis of your evidence

Congratulations! You have successfully accelerated, bent, focused and collided particles! Let's explore now some further interesting details.

Question

The protons in the LHC travel with a speed close to the speed of light before they collide. The speed of light is approximately 300000 km / sec. Given the fact that the LHC is 27 km in circumference, how many turns does a proton complete in each second?

1. 11111 turns / second.

Feedback: Correct! Just divide 300000 km/ sec by 27 km. The actual number of turns per second is slightly different, since the speed of light is not exactly 300000 km / sec and the LHC tunnel is not exactly 27 km long.

2. 10000 turns / second.

Feedback: Close enough! Just divide 300000 km /sec by 27 km to get the right answer!

3. 300027 turns / second.

Feedback: I see what you did there! The answer is division, not addition! If this was the correct number it would mean that the proton travels faster than the speed of light!

As a beam circulates in the LHC its intensity decreases. This is because many protons are "lost" mainly at the interaction points. The beam lifetime is approximately 10 hours. After that, the intensity of the beam has decreased enough to render the beam "useless", in the sense that the number of collisions is not sufficient for gathering data. The beam is then dumped and the whole process starts over.

When the beams are no longer useful they are spread out and are “dumped” into two huge cylindrical blocks, eight meters long, one meter in diameter, and made of graphite composites encased in concrete. These are specially designed to withstand the full power of the beam; the center of the block is heated to almost 700°C.

Consider a proton that "survives" until the beam gets dumped. Try answering the following question!

Question

What is the distance that a proton covers during its 10-hour lifetime? Remember: the protons in the LHC travel with a speed approximately equal to 300000 km/ sec.

1. Approximately 800 thousand kilometers (the distance to the Moon and back).

Feedback: No! That's too close! Try the following: 10 hours * 60 minutes/hour * 60 seconds/minute * 300000 km/second. That's a huge distance!

2. Approximately 300 million kilometers (the distance to the Sun and back).

Feedback: They are actually going much further than that! Here is how far: 10 hours * 60 minutes/hour * 60 seconds/minute * 300000 km/second.

3. Approximately 10 billion kilometers (the distance to Neptune and back).

Feedback: Correct! Impressive, isn't it?

The answer to the above question gives you some idea of how fast light (and protons in the LHC) travels.

Teacher Guidelines: Estimated duration of this activity: 20 minutes

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Now let's use the experience you gained during this exercise to answer some more questions:

1) Two proton bunches that collide in the LHC contain approximately 200 billion protons. When the bunches cross, there will be an average of about 20 collisions each time. The bunches will cross on average about 30 million times per second. What is the maximum number of proton collisions per second that can happen in the LHC?

2) Given the information you have acquired during this activity, how much does a photon (which is an infinitesimal amount of light) travel in 10 hours, compared to the protons in the LHC?

Teacher Guidelines:

The answer to the first question is approximately 600 million collisions per second.

The answer to the second question is that the photon covers a longer distance than the proton since, according to Einstein, there is nothing that can travel faster than light (i.e. photons).

Here are some applications of particle accelerators:

- **Medical Applications:** The most important of all applications of particle accelerators is their application in the treatment or prevention of many diseases. Examples of such applications are:

1. Isotope production for PET scans (Positron Emission Tomography)
2. X-Ray radiotherapy
3. Proton beam therapy
4. Electron beam therapy
5. Equipment sterilisation

- **Industrial Applications:**

1. Food irradiation
2. Scratch resistant furniture

- **Energy and Security Applications:**

1. Cargo scanning

- **Historical and Cultural Applications**:

1. Radiocarbon dating
2. Detecting art fraud
3. Detecting wine fraud!

- **Other:**

1. Detecting stresses in airplane wings
2. Understanding infant lung structure

So next time someone asks you what accelerators are for:

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, spot suspicious cargo, diagnose a disease, detect an art forgery, date an archaeological find, package a Thanksgiving turkey or...**discover the secrets of the Universe!"**

Teacher Guidelines:

Ask your student to search the bibliography for other applications of accelerators.

Communicate

Communicate and justify your explanation

Make a brief report of your work so you can present your work to your fellow-students. In order to attract their attention try to be as creative as possible. You can make a small video out of it, a PowerPoint presentation or a poster like those presented by scientists during conferences. Discuss the answers which your classmates gave to the previous phases

Teacher Guidelines:

Encourage the students to discuss between themselves. and ask them to search for other applications of accelerators and make a presentation in class

Reflect on what you have learned from the learning process

1. Take a minute to think about this exercise. Have you learned anything new about accelerators?
2. Which concept/idea did you find difficult to understand?
3. Many people think that we spend a lot of money on research. What's your opinion on this? Do you think accelerators are useful or just a luxury for our society?

Teacher Guidelines:

These questions are reflective and there are no right/wrong answers. They could be used to further engage the students in the purpose of this exercise via discussion and clarification.

PSQ

1

Why do we need accelerators?

- We need them to accelerate and collide particles in order to study the microcosm.[H]
- Accelerators are our microscopes in our quest to the world of matter. [M]
- Particle accelerators are very useful for medical purposes. [L]

2

How much should we accelerate the particles before each collision?

- It depends on the collision products we are after. [H]
- It depends on the purpose of the experiment. [M]
- As much as possible. [L]

3

How do we bend the proton beams in the LHC ring?

- The strong magnetic field of the dipole magnets can change and bend the path of charged particles without changing their energy. [H]
- Powerful dipole magnets are used. Their strong magnetic field can bend the particles' path and guide them inside the LHC ring. [M]
- We use the forces provided by strong magnets installed along the 27km length of the LHC tunnel. [L]

4

How do we focus the proton beams?

- The magnetic field of quadrupole magnets squeezes the protons closer together decreasing the space between them. [H]
- The magnetic field of quadrupole magnets can focus the proton beam in two directions: horizontally and vertically. [M]
- Using magnets that act as lenses and focus the beam. [L]

5

What happens if the value of the magnetic field is not optimal in the LHC?

- As the proton beam energy increases, the field needed to keep it in orbit should be strong to avoid collisions with the walls of the beam pipe. [H]
- The field can not bend the particle path enough and make it circulate around the LHC ring damaging the beam pipe. [M]
- We lose protons as the beam collides with the walls of the beam pipe and can cause damage. [L]

6

How do we accelerate protons in the LHC?

- Devices called accelerating cavities are used. The change of polarity of their electric field is tuned at the right frequency making the protons move forward and faster. [H]
- Devices called accelerating cavities are used. They provide electric fields that increase the energy of the protons which travel through them. [M]
- The protons travel through powerful electric fields placed at four points in the LHC ring, increasing their speed. [L]

7

Two proton bunches that collide in the LHC contain approximately 200 billion protons. When the bunches cross, there will be an average of about 20 collisions each time. The bunches will cross on average about 30 million times per second. What is the maximum number of proton collisions per second that can happen in the LHC?

- It is approximately 600 million collisions per second. [H]
- It is definitely less than 200 billion collisions per second. [M]
- Millions of collisions per second. [L]

8

Given the information you have acquired during this activity, how much does a photon (which is an infinitesimal amount of light) travel in 10 hours, compared to the protons in the LHC?

- The photon covers a longer distance than the proton since, according to Einstein, there is nothing that can travel faster than light (i.e. photons). [H]
- The protons in the LHC travel with a speed approximately equal to the speed of light. So the photon travels approximately the same distance in 10 hours. [M]
- In order to answer this question we need to know the speed at which light travels. Time alone is not sufficient to provide an answer. [L]