The wide world of accelerator physics …

… through the physics of everyday life and the universe

Phu Anh Phi NGHIEM

Illustrated by Aurélie Bordenave

Initially designed to study the very smallest components of the matter that surrounds us and of which we are composed, particle accelerators are now widely used in many different fields—fundamental and applied science, advanced technology, and various industries. Particle accelerators are even used to study and preserve objects of cultural heritage.

What are particle accelerators, and how do they work? This booklet will explain, in simple terms, the physical phenomena at work in a particle accelerator—how they accelerate particles and transport them to the place where they are used. We'll explore how these same physical phenomena are also at work in nature and in everyday objects.

No physics knowledge is required to read further; simply let yourself be guided by this exploration into particle accelerators, with a few broad forays into the physics of everyday life and the universe.

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Translated into English by Kate Robinson

From physics with accelerators to the physics of accelerators

Modern physics is fascinating for its ability to penetrate the most infinitesimal components of matter (millions of billions of times smaller than the width of a strand of hair), or to travel back in time to a fraction of a second after the Big Bang, an event that took place fourteen billion years ago. This journey towards the infinitely small in space or infinitely distant in time only becomes concrete—real and palpable—with the help of particle accelerators. Without them, the many theories that describe tiny particles like quarks or bosons would remain pure speculation. Accelerators can identify the missing piece or signpost that will justify and validate the competing theories, and then guide them towards new developments. With each new discovery that accelerators have made possible, physicists have made progress, using other bricks to gradually outline the organization of the structure and forces that govern the underpinnings of matter, the same matter that surrounds us and that we are made of.

Accelerators can point the way for particle physicists when they aren't sure which of several possible paths to take.

Many particle accelerators have been involved with historic discoveries in nuclear or particle physics. It is estimated that there are currently 200 large accelerators in the world being used for general scientific research. Since accelerators were first developed 90 years ago, another 24,000 have been built for industrial applications, in addition to 11,000 designed exclusively for medical treatments.

Accelerators have a diverse variety of applications. They are popular tools in many scientific and technical fields. But what exactly are they? What science and technology makes them work?

We will in the following introduce the physics responsible for accelerator function. After a brief presentation of the fields in which accelerators are used and of their distribution throughout the world, we will explore accelerated particle physics and associated electromagnetic forces. We'll see that the same physical principles also govern the workings of everyday objects and the larger universe, which we will also explore.

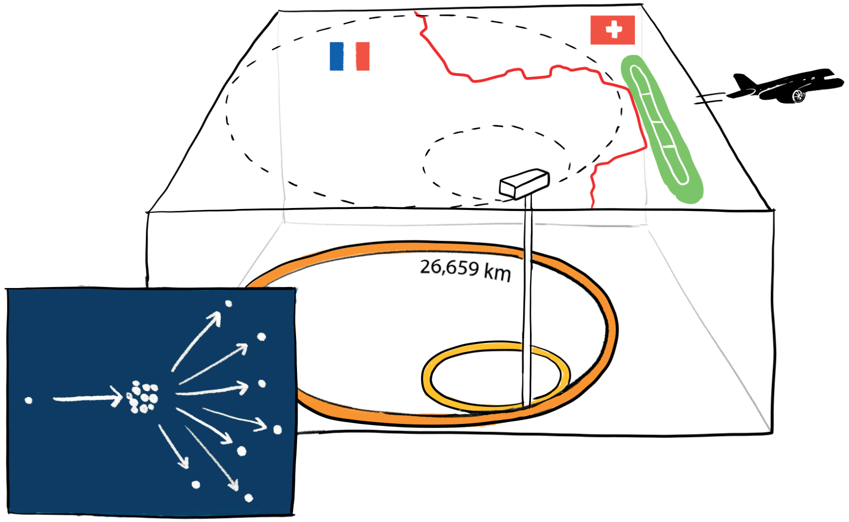
What is an accelerator, and what is it used for?

There are many different kinds of accelerators. Some are linear, while others are circular, and both types can be divided into subcategories. Accelerators come in all different sizes, from several meters in length, which can fit in a single room, to dozens of miles in length, stretching across an entire region. Accelerators can be classified according to type or size.

It is also quite practical to classify them by the function they serve. Historically, accelerators have served three primary functions: to generate collisions between particles, to produce synchrotron radiation, and to irradiate targets.

Generating collisions

Particle accelerators were originally designed to generate collisions between particles of matter, with the goal of splitting particles open to see what lay inside (and what emerged). Collisions are done in a spirit of analysis, one of the pillars of the scientific approach: to understand a complex system, it must be broken down into smaller pieces that can be studied separately, with the hope that doing so will lead to a better understanding of the whole. Curious children do this spontaneously; to figure out how a given mechanism works, they often start by taking it apart. You could say scientists are a bit like "big kids."



Particle collision: the Large Hadron Collider (LHC) on the French-Swiss border. On the right, the Geneva Airport for size comparison.

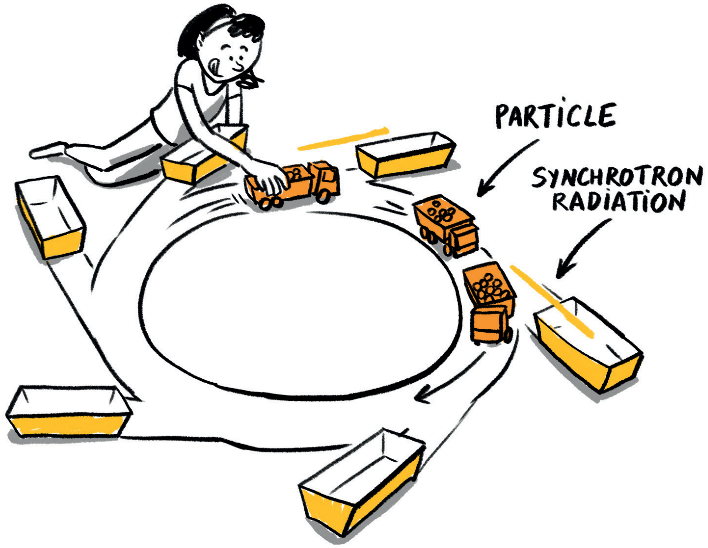
Collisions between atomic particles or their nuclei have enabled scientists to study the smallest components of matter, down to a millionth of a billionth of a meter. Accelerators that generate collisions are used for fundamental physics research by communities of particle and nuclear physicists. The largest of this type of accelerator is the Large Hadron Collider (LHC) located at the European Organization for Nuclear Research (CERN). Located on the border between France and Switzerland, LHC is 27 kilometers (nearly 17 miles) in circumference. In France, the Large Heavy Ion National Accelerator (GANIL), located in Caen, is a large accelerator center dedicated to studying nuclei.

Like children who want shinier and more powerful toys, scientists want ever more powerful accelerators, ones that can accelerate particles at higher energy levels and break down matter even further in order to study the matter's deepest hidden components. For this reason, circular accelerators were designed when scientists wanted to increase energy: it was thought the accelerators should be small, since particles traveling in a circle receive an extra boost of energy each time they make a revolution through the device. But scientists ran up against another physical process: charged particles entering a turn lose energy in the form of radiation (light), much like when a truck carrying a load of gravel takes a tight turn and loses a bit of its load. The lost radiation, called synchrotron radiation, was considered a parasitic phenomenon and one to be reduced as much as possible. Scientists realized that to reach higher energy levels, they must build larger accelerators with less-pronounced turns.

Producing synchrotron radiation

However, scientists quickly realized that synchrotron radiation possesses exceptional properties: it is up to 10,000 times brighter than sunlight, contained in a very thin guided beam similar to laser light, and has a wide spectral range (color range) from X-rays to infrared light through visible light.

To make use of this discovery, another type of accelerator was designed to produce a maximum amount of synchrotron radiation. These machines are capable of probing, observing, and studying physical and biological materials down to a millionth of a meter, much like a giant, super-powerful microscope.



Synchrotron radiation accelerator.

Synchrotron radiation accelerators are generally several hundred meters in circumference. They are used by physicists, chemists, and biologists, as well as manufacturers, doctors, pharmacists, art historians, and more. Their substantial but not excessive size, and their highly diverse user communities place these accelerators among the world's major and most widespread research instruments. Countries or regions that wish to acquire a world-class research instrument often start with a synchrotron radiation accelerator.

Synchrotron radiation is also emitted when electrons are made to oscillate at low frequencies, which amounts to a series of small turns, using a periodic magnet device called an undulator. The obtained brilliance can be very high, thanks to constructive interferences. By lining up a large number of undulators, the light produced is strongly amplified like in a laser. It is called the free-electron laser effect. The latest-generation high-luminosity synchrotron accelerators are linear machines several miles in length that accelerate electrons and then send them down long corridors of undulators.

Irradiating targets

The beam of accelerated particles can be precisely adjusted in terms of direction, size, and energy. As a result, it can be used to directly irradiate a number of different targets. At a level concentrated enough, it will destroy organic cells, meaning it can be used to eliminate malignant tumors or to sterilize medical equipment or food containers. At present, 250,000 patients have successfully been treated using protontherapy (proton beams) or hadrontherapy (ion beams), valuable alternatives to X-ray therapy. Accelerators used to irradiate a given target are also widely used in various industries for surface treatments or high-precision engraving. Art historians use them to analyze works of art. Those accelerators are generally small in size, ranging from several meters to a dozen meters, and are therefore the most commonly found.

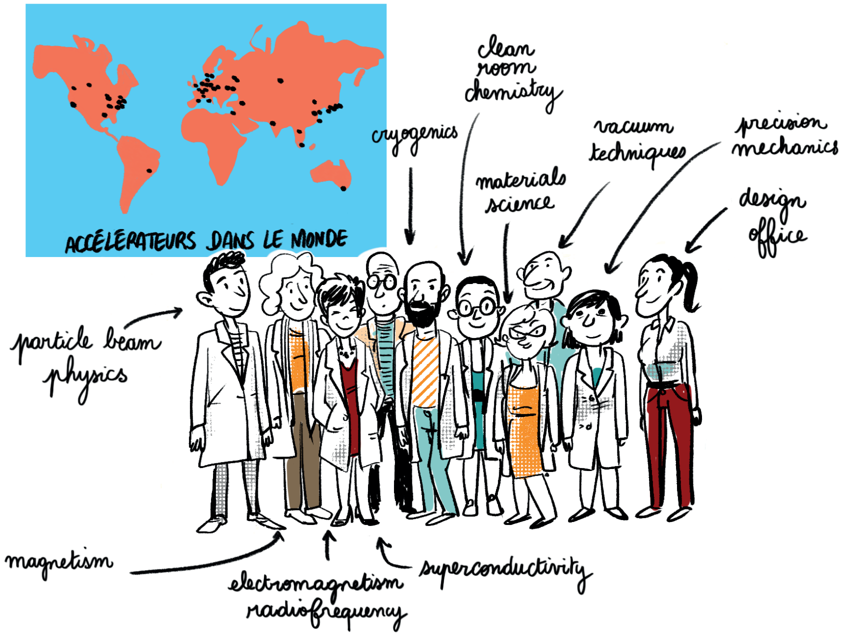
Larger accelerators measuring into the miles, both linear and circular, have been recently installed at scientific research centers in order to irradiate a target specially designed to produce neutrons (the electrically neutral component of an atom's nucleus). These neutron beams can themselves be the subjects of study, or they can serve as probes to study inert or organic materials. Applications for these beams range from science to medicine to commercial industries.

More compact neutron sources (several meters long) also exist in the form of linear accelerators used for neutron analysis or isotope production for nuclear medicine.

Where are the large accelerator centers?

Large accelerator centers, where more than a hundred researchers, engineers, and technicians work on a permanent basis, are found primarily in Western Europe, North America, and Eastern Asia. The following is a non-exhaustive list:

- France : IRFU/DACM (Saclay), IJClab (Orsay), SOLEIL (Saint Aubin), GANIL (Caen), ESRF (Grenoble)
- Switzerland : CERN (Genève), PSI (Villingen)
- Germany : DESY (Hamburg), GSI (Darmstadt), COSY (Julich), BESSY (Berlin), ANKA (Karlsruhe)
- United Kingdom : DIAMOND (Didcot), RAL (Oxford), STFC (Daresbury)
- Sweden : MAX-Lab (Lund), ESS (Lund)
- Italy : ELETTRA (Trieste), INFN (Frascati, Legnaro, Catania)
- Spain : ALBA (Barcelona), CIEMAT (Madrid)
- United States : ALS (Berkeley), FNAL (Batavia), LANL (Los Alamos), SNS (Oak Ridge), ANL (Chicago), SLAC (Stanford), BNL (Upton), CHESS (Cornell)
- Canada : TRIUMF (Vancouver), CLS (Saskatoon)
- Brazil : LNLS (Campinas)
- Japan : SPring-8 (Sayo-cho), KEK (Tsukuba), J-PARC (Tokai-mura)
- China : SSRF (Shanghai), IHEP, BEPC (Beijing), HLS (Hefei), IMP (Langzhou)
- South Korea : PAL (Pohang), PEFP (Yueong)
- Thailand : SLRI (Nakhon Ratchasima)



Distribution of large accelerator research centers throughout the world, and related fields of study.

A diverse range of fields of study use accelerators: particle beam physics, magnetism, electromagnetism, radio frequency, superconductivity, cryogenics, cleanroom chemistry, materials science, vacuum techniques, precision mechanics, design, etc.

How does an accelerator work?

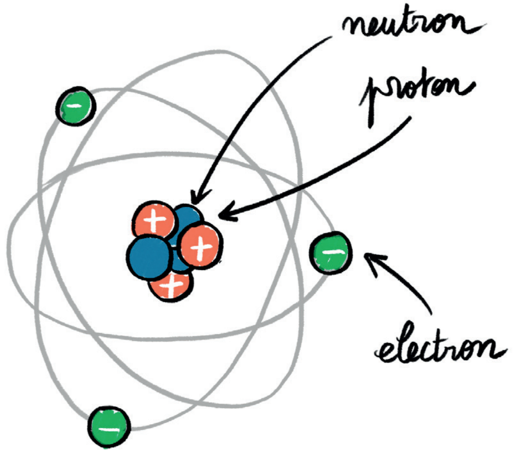
Now that we know accelerators are ubiquitous in many sectors of modern society, let's get to the heart of the matter: particle accelerator physics. In other words: how does an accelerator work?

First, we'll talk about the particle beam in an accelerator, then we'll explore the two elements that can affect the beam: the electric field and the magnetic field. Then we'll see how these fields are produced, how particles are produced, before wrapping things up with a look at the devices that serve those purposes within an accelerator. Along the way, we'll take a few wide detours to investigate objects found in our everyday lives and the universe.

What is a particle beam?

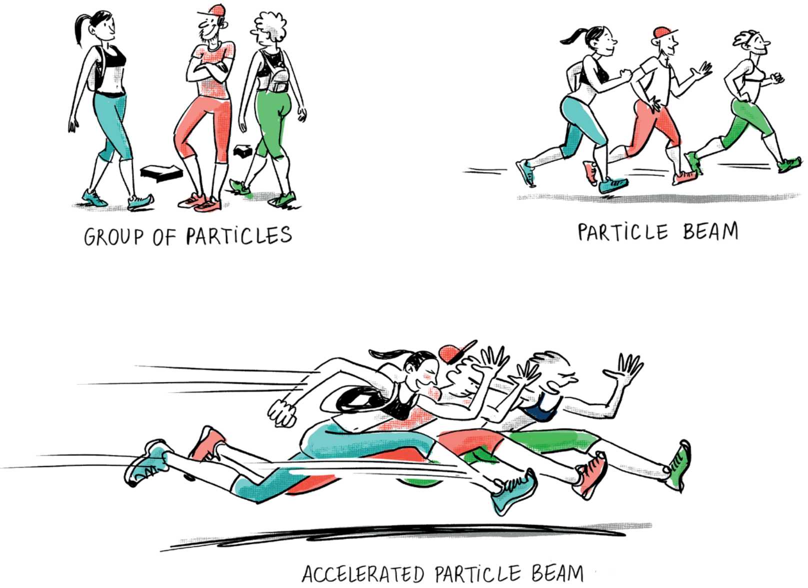
First, let's clarify that in an accelerator, the word "particle" refers to an electrically charged particle. The matter that surrounds us and that forms our very bodies is made up of atoms. Each atom is composed of a positively charged (+) nucleus surrounded by negatively charged (–) electrons. Charges of the same sign, + and +, or – and -, repel each other. Charges of opposite signs, + and –, attract. You'll encounter this basic principle again throughout this booklet.

What this means is that a stable atom is generally electrically neutral, because it contains equal quantities of positive and negative charges. And this is a good thing—it prevents us from being electrocuted every time we touch an object!



An atom made up of a nucleus composed of positive electric charges, called protons (and particles with no electric charge, called neutrons) surrounded by negative electric charges, called electrons.

When a group of charged particles is left to its own devices, the particles exhibit random, disordered movements, a bit like children at a school playground, coming and going as they please. The warmer the environment, the faster the movement becomes, and the more space the particles will occupy. This is known as **thermal agitation**. However, the group of particles remains more or less in the same place. Accelerators are not concerned with this type of particle group. Instead, they work with **particle beams**:streams of particles moving collectively, each particle at its own speed, in the same direction, much like competitors in a footrace. Scientists working at accelerators produce particle beams, and then accelerate them. In other words, they increase the speed of the group so that the footrace starts to resemble a sprint race, then eventually a car race.

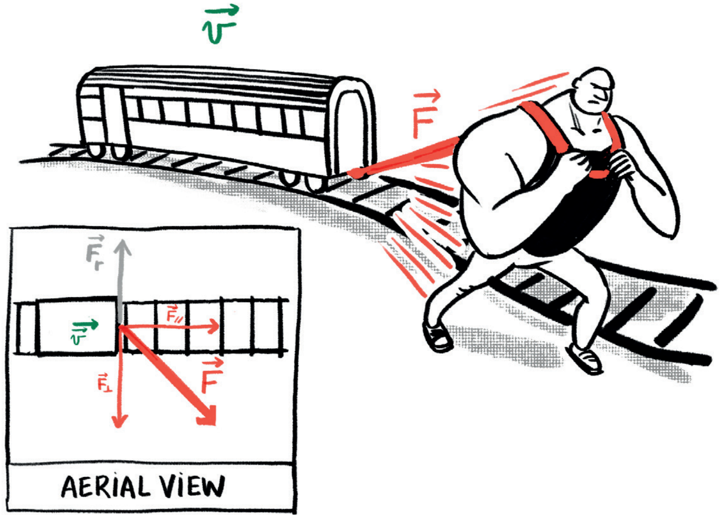


A group of particles, a particle beam, and an accelerated particle beam.

The overall speed of the particle beam is the main characteristic of an accelerator. We call “energy” the kinetic energy of the particles, in other words, **the energy related to the speed of the particle beam**. Faster speeds equal greater particle energy.

How are particles accelerated?

To accelerate an object—to increase its speed—force must be applied. For example, when you’re riding a bike and you want to go faster, you have to apply force by pedaling harder. Imagine a particle is a train car traveling down the rails at a given speed, represented by the arrow marked $\vec{v}$, which indicates the direction of travel. A muscular person pulls it forward, exerting force in an effort to accelerate the train car. His force, represented by the arrow marked $\vec{F}$, can be broken down into two components, one that is parallel to speed, that is to the direction of movement, and one that is perpendicular. Only the parallel component is going to help with acceleration. The perpendicular component is going to change the wagon’s trajectory (if it weren’t for the tracks preventing this shift).



A force parallel or perpendicular to the direction of travel.

An accelerator needs forces parallel to the direction of travel to accelerate particles. But it also needs perpendicular forces to guide the particles in a specific direction in order to accelerate or collide them, to irradiate a target; or to focus the particles, otherwise they will very quickly disperse because of the way like charges repel each other.

In short, **an accelerator must produce charged particles, then accelerate, focus, and steer them**. But the name "particle accelerator-producer-focuser-steerer" is too long. That's why we use the short version—particle accelerator. But let's not forget that the other actions are nevertheless at work in an accelerator.

Now, we're going to explore how these actions are carried out and the devices that make them possible.

First, force must be applied to the charged particles, and this can be done in only two ways: by using an electric field or a magnetic field.

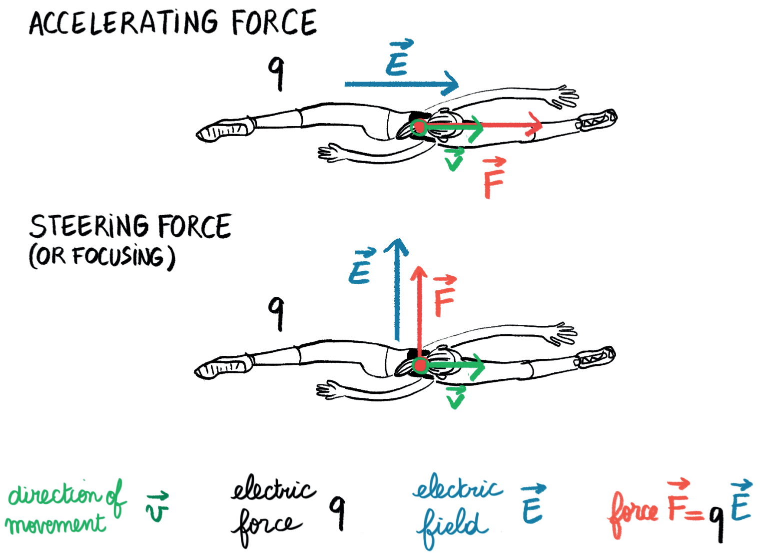
Let's see what effect an electric field or a magnetic field has on charged particles, then how these fields are produced.

Effect of electric fields and magnetic fields

Electric and magnetic fields can neither be seen nor palpable. And yet all of us, and everything in the universe, are steeped in them. It's a bit like Earth's gravitational field: we can neither see it nor touch it, and we can only understand and grasp it through its effect—the force of gravity that attracts all massive bodies downward.

Instead of trying to precisely define an electric or magnetic field, let's instead examine the effects these fields have on an (electrically) charged particle, and look at how these fields are produced in order to better understand them.

Electric or magnetic fields are represented by an arrow marked $\vec{E}$ or $\vec{B}$, respectively. When a charged particle is placed in an electric field represented by an $\vec{E}$ arrow, the force $\vec{F}$ this field exerts on the particle is parallel to the field itself. So if our goal is acceleration, that is increasing particle energy, we simply apply a field parallel to speed $\vec{v}$ (the direction of movement), and if we want to steer or focus, we use a field perpendicular to speed. In this way, an electric field can be used to accelerate as well as to steer or focus charged particles.



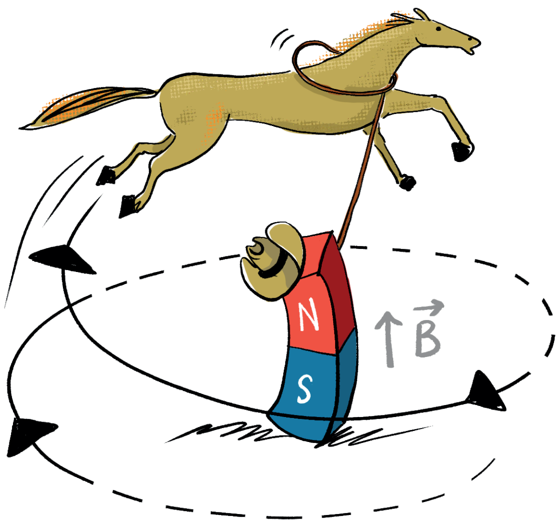
The force of an electric field can accelerate and steer (or focus) particles.

It might be tempting to think that you can do everything with an electric field. In reality, it is impossible to perfectly align a field with a given direction of motion. Tiny, inevitable imperfections mean that an electric field intended to serve as an accelerating field will also divert the particles a little bit, and vice versa.

On the other hand, a magnetic field, represented by an arrow marked $\vec{B}$, is more efficient when the kinetic energy of the particle is higher, because the force it produces is proportional to the speed of the particle. Note that this force is always perpendicular to direction of motion. So a magnetic field is used purely to steer or focus particles. At this point, note that a magnetic field is not able to give energy to or take energy from particles.

So how do particles move within a magnetic field? It's good to keep in mind that an object subjected to a force perpendicular to its direction of movement will rotate. Imagine a cowboy who happens to be very skilled with a lasso. A horse runs straight ahead of him. He throws his lasso, catches the horse, and pulls: at this moment, he is exerting a force perpendicular to the horse's direction of motion. Imagine that the horse is very stubborn, a bit like our charged particles. It continues to run at the same speed. The horse will have lost none of its energy, but is now running in a circle around the cowboy. The same happens with charged particles: they turn, or spiral, around magnetic field lines.

This principle is applied in accelerators. To make the particle beam turn at a precise angle, a magnetic field is applied to a specific length of its path. To focus or gather together particles, a magnetic field is applied, forcing them to spiral around it. The stronger the field, the closer to the center the particles must spiral, and in doing so, they group together.



Guiding or focusing particles with a magnetic field looks much like a cowboy lassoing a horse. Charged particles wrap around the magnetic field lines.

How is an electric field produced?

A simple method for producing an electric field involves gathering charges of opposite signs, positive (+) and negative (–), on two conducting plates separated by an insulating material, as in the case of a battery, cell, or condenser, with a positive and a negative pole. A positively charged particle placed between these two plates will be repelled by the positively charged plate and attracted by the negatively charged plate. This proves that an electric field has been created between the two plates, and that particles are being subjected to an electric force.

This method was applied to the earliest accelerators. But as we mentioned earlier, scientists are forever asking for more powerful machines. Gathering more charges on the two plates can increase that power, but gather too many and the device will break. Charges of opposite polarity attract each other with greater intensity, until a spark is created between the two plates with a bang, as the charges make their way to meet. This breakdown phenomenon can be very violent, like the flashes of lightning produced during storms when the base of clouds and the ground are heavily charged.

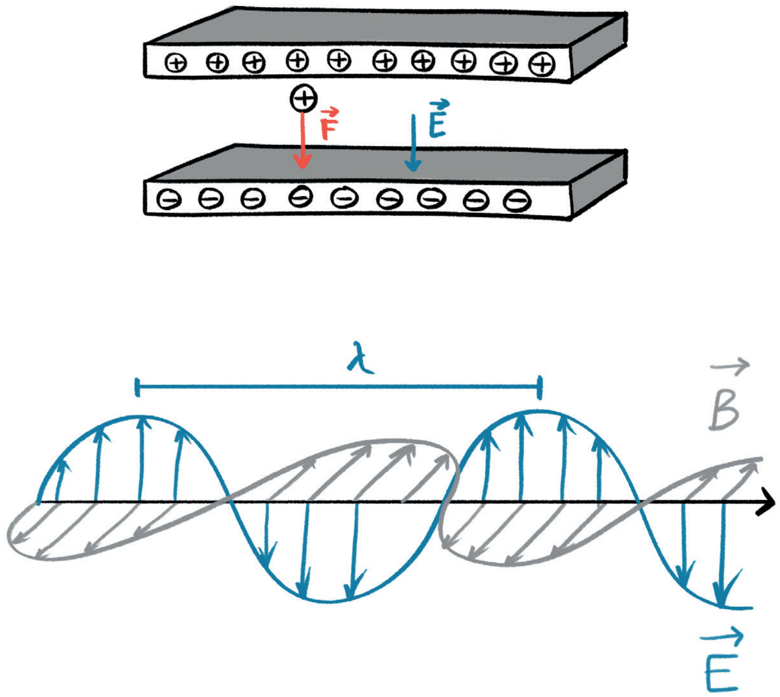
Instead, to obtain greater electric fields, scientists rely on the principle of trapped electromagnetic waves.

What is an electromagnetic wave? Think of a wave of water—a swell on the ocean's surface. This wave of matter (in this case, the matter is water) oscillates at regular intervals, and propagates over a large distance. A similar thing happens in an electromagnetic wave — two fields, an electric field and a magnetic field, oscillate and propagate.

Common examples of electromagnetic waves are: light waves, radio waves, television waves, telephone waves, Bluetooth waves, and Wi-Fi waves. Space also sends us a slew of waves known as cosmic waves. As you can see, we are constantly surrounded by different types of electromagnetic waves. They go by different names, but they are all similar.

How are electromagnetic waves formed, and what principles govern these kinds of waves? We've been talking about electric and magnetic fields as though they were two completely separate phenomena. In fact, they are connected, and their behavior was described by a series of elegant laws known as Maxwell's equations, developed by James Clerk Maxwell, a nineteenth-century British scientist at the University of Cambridge. Maxwell's equations state that a changing electric field induces a magnetic field, and vice versa. For example, electric charges are made to oscillate along an antenna in order to produce an electromagnetic wave.

The particles are accelerated using the electric field of the wave, which can be strongly amplified by trapping it in a resonant cavity. This process occurs for another common type of wave—sound waves. Sound waves are oscillations and propagation of air particles that cause our easrdrums to vibrate when reaching our ears, allowing us to hear sound. All musical instruments, whether string, wind, or percussion, have resonant cavities, also called sound boxes, without which their unamplified sounds would be inaudible at any great distance. In accelerators, a series of what are called radiofrequency (RF) cavities are used to accelerate particles to higher and higher energies. To be able to withstand significant electric fields and thus surface currents of several thousand amperes (in comparison, standard domestic circuits are on the order of several amperes), these cavities must be cooled to a cryogenic temperature approaching absolute zero.

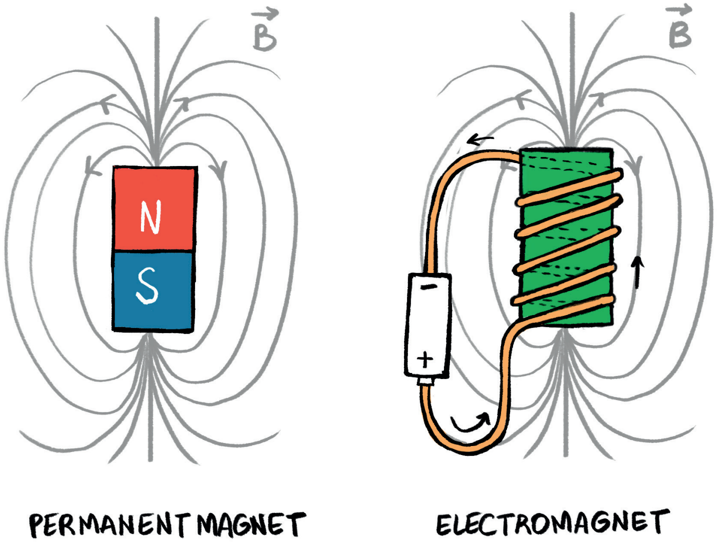


A static electric field between two charged plates, or oscillating in an electromagnetic wave.

How is a magnetic field produced?

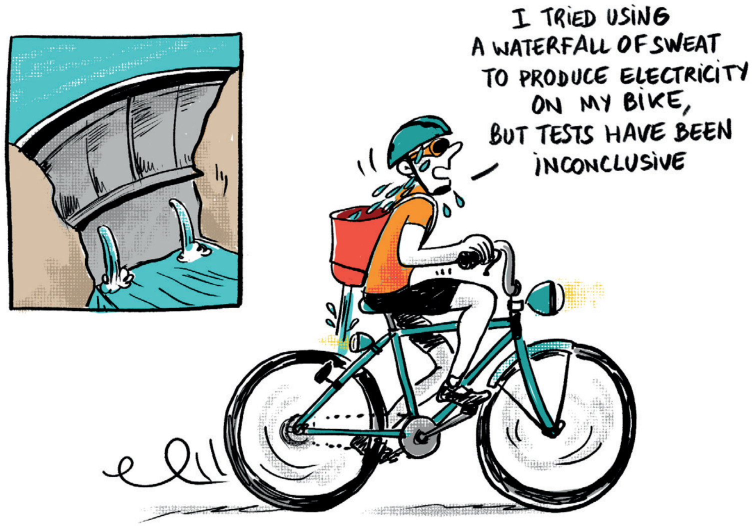
A magnetic field can be produced with permanent magnets, which are similar to the bar magnets children play with. The magnetic field is oriented outward from the North pole and inward to the South pole. Using this technique, it's possible to produce magnets with a field of up to 10,000 gauss (a gauss is a unit that measures magnetic induction), which is very powerful compared to the Earth's magnetic field at 0.5 gauss. But it is impossible to achieve stronger fields using this technique and, furthermore, permanent magnets have a fixed amplitude, which prohibits flexibility and variation.

Most accelerators need freely adjustable magnetic fields and use electromagnets to produce them. By passing an electric current—a variable electric phenomenon—through an electrical coil comprised of wound conducting cable, a magnetic phenomenon is produced, just as Maxwell's laws predict. This magnetic field is oriented along the coil's axis. In scientific jargon, this kind of coil is called a solenoid and can generate a field of up to 100,000 gauss, if it is cooled to cryogenic temperatures approaching absolute zero.



Fixed or variable magnetic field, of a permanent magnet or an electromagnet.

In fact, an electromagnet is nothing more than a dynamo in reverse: bikes are often equipped with a dynamo, a small device made of an electric coil with a small magnet at its center, which is used to produce electricity to power a bike-mounted light, for example. The magnet begins rotating when the bicycle is pedaled and the wheel begins to turn. This changing magnetic field generates the desired electric current. On a larger scale, electrical companies that produce electricity and deliver it to our homes use similar but much larger dynamos. In this case, the magnet is powered by falling water from a dam, as in a hydroelectric station, or by high-pressure steam, as in a thermal, coal, or nuclear power station.

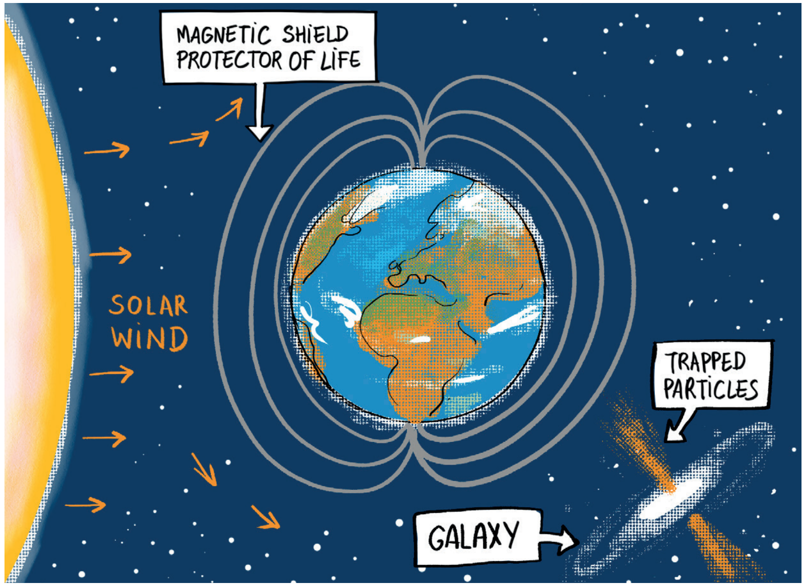


Production of electric current by dynamo for a bike or a hydroelectric station.

On an even greater scale, let's take a look at the Earth's magnetic field mentioned above, which allows us to find our bearings using a compass, with a magnetic pointer inside. Why does Earth's magnetic field exist? The Earth's core is very hot, nearly 9000°F (5000°C). Thermal agitation there is very strong, causing atoms to break apart and separating the electric charges. Since the Earth rotates on its axis, the whole system is equivalent to a giant coil with an electric current running through it, creating a large-scale magnetic field—in other words, a giant electromagnet created by a giant dynamo in reverse.

Let's take this idea a little further. The Sun, being much hotter than Earth and also rotating on its own axis, generates colossal magnetic phenomena. It also emits enormous quantities of charged particles into space and toward Earth; if these particles had been allowed to reach our planet over a long period of time, they would have sucked away our atmosphere, seriously damaged organic cells, and prevented the evolution of life as we know it. But these particles are blocked by the Earth's magnetic field, which, like a cowboy catching a horse with his lasso, forces them to spiral along the magnetic field lines and continue on their way on the opposite side. Only during large solar storms are these particles, traveling in larger numbers and with great energy, able to reach the Earth's surface, especially the polar regions at the base of the magnetic field lines. We experience the result as the aurora borealis, or northern lights. Even stronger solar storms allow more energetic solar particles to penetrate even further into Earth's atmosphere. They can cause serious damage to satellites in space and electrical infrastructure on the ground. This is what happened on March 13, 1989, when Quebec's electrical system melted, leaving six million users without electricity for nine hours.

Without the Earth's magnetic field, circumstantially called a magnetic shield, we would simply not be here today to discuss these phenomena.



A dynamo in reverse, and charged particles blocked by the Earth's magnetic shield, and galaxies.

These interactions between charged particles and magnetic fields can be observed on even grander scales within the universe. For example, certain galaxies composed of billions and billions of stars, each equivalent to our Sun, resemble a bright object made up of a diffuse disk with a rectilinear trail extending from the disk's axis (see image). The reason for this is that the galaxy rotates on its axis, generating an axial magnetic field which serves as a gateway to the galaxy for charged particles. Since the particles are forced to rotate around the axis, they emit synchrotron light that illuminates it.

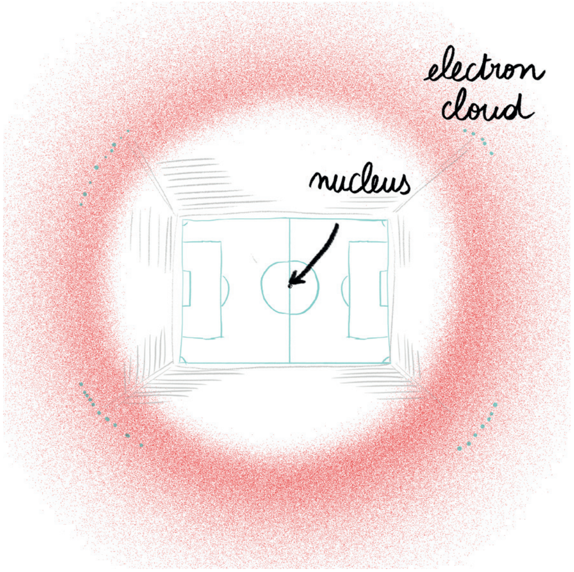
It's clear to see that the ingredients needed for accelerators—charged particles, electric current, magnetic field, dynamo, dynamo in reverse, and synchrotron radiation—are found at every level of our daily life and in the workings of the universe.

How are charged particles produced?

Earlier we said that atoms are electrically neutral because positively charged protons in the nucleus and negatively charged electrons surrounding it neutralize each other, given that they are connected by the electric force that attracts charges with opposite signs. Producing charged particles implies separating these charges.

In an atom, electrons are situated very far away from protons. Imagine if we could enlarge an atom's nucleus and its protons to the size of a soccer ball and place it at the center of a field in a huge stadium. The electrons would be sitting with the spectators in the stadium's highest rows. Consequently, the force attracting the electrons and protons to each other is very weak. A flick of the hand would be enough to separate them and therefore create charged particles. Rubbing, heating, or agitating them would also do the trick. Notice that these three actions are essentially the same, since rubbing releases heat like when you rub your hands together, and heat induces the thermal agitation discussed earlier.

As a result, all of us produce charged particles every day. Just shuffling across a carpet is enough to produce charged particles. These are then distributed all over your body, causing you to receive an electric shock when you shake hands or hug someone!



Atom and soccer stadium.

A game popular with children involves rubbing a plastic ruler with cloth and holding the ruler over small bits of paper, causing them to dance and twirl. The charged particles produced when plastic is rubbed attract particles of the opposite polarity in the paper.

Here's another everyday example: think about when you pull a sweater off over your head, and your hair stands on end. This is the work of same-sign charges produced as the sweater rubs against your hair, repelling each other. When there are enough charges produced, you might also hear small crackling noises, or even see little sparks around your hair and sweater. This is caused by opposite-sign charges that manage to make their way through the air toward each other, despite the isolating nature of air. These two examples typify the phenomena known as static electricity.

Static electricity also occurs on a larger scale—for example, in thunderstorms. Thunderstorms often break out in hot, humid tropical countries, sometimes at precise times in the late afternoon. This is due to the production and buildup of charged particles, which are triggered as soon as they are present in sufficient numbers. When it is very hot and the sun is beating down hard, the ground absorbs the most solar energy, turning it white-hot. The layer of air in contact with the ground is therefore hotter than the upper layers. Thermal agitation is stronger there; the air expands and fills a larger volume. It loses density, described as the number of air molecules in a given volume. This hotter air rises very quickly into the cooler surrounding air.

Different manifestations of charged particles.

This phenomenon is known as Archimedes' Principle, named for the Greek scientist who lived over two thousand years ago. Legend has it that Archimedes was taking a bath one day when he began to wonder why his bar of soap sank to the bottom of the water, while the sponge floated at the surface. He realized that a less-dense object rises and floats atop a denser object: the sponge is less dense than water, unlike the soap, which is more dense than water. He was so happy that he jumped out of his bath and ran naked down the street crying "Eureka! (I found it!)"

You don't have to go quite that far, but you can, for example, test the principle yourself at the pool or in a bathtub: try to push an air-filled ball into the water. It is difficult; you have to exert significant force. Furthermore, once you stop exerting force on the ball and let go, the ball will pop to the surface incredibly fast.

A similar thing happens to that layer of hotter, less-dense air during a storm: it will rise very rapidly into the atmosphere, forming enormous clouds heavy with water. Along the way, it rubs up against surrounding layers of air, producing huge quantities of charged particles. By this time, the air is heavily charged with electricity, but clouds are where an increasing number of charges build up. These attract opposite-sign charges that accumulate on the ground, creating the equivalent of two condenser plates, like those mentioned earlier in our discussion about how to generate an electric field. When more than a certain quantity of charges is present, air can no longer play the role of insulator, and the charges race towards each other, resulting in a lightning strike and an expansion of air that we know as thunder. This is the same phenomenon that we explored with a sweater and hair earlier, except that instead of several hundred volts, we are witness to hundreds of millions of volts in nature (for comparison, standard home electricity supply is 220 volts). Instead of a "crackle, crackle," we hear a "rumble, boom."

A storm is the equivalent of nature taking off her sweater — but it's a nature-sized sweater. In other words, enormous.

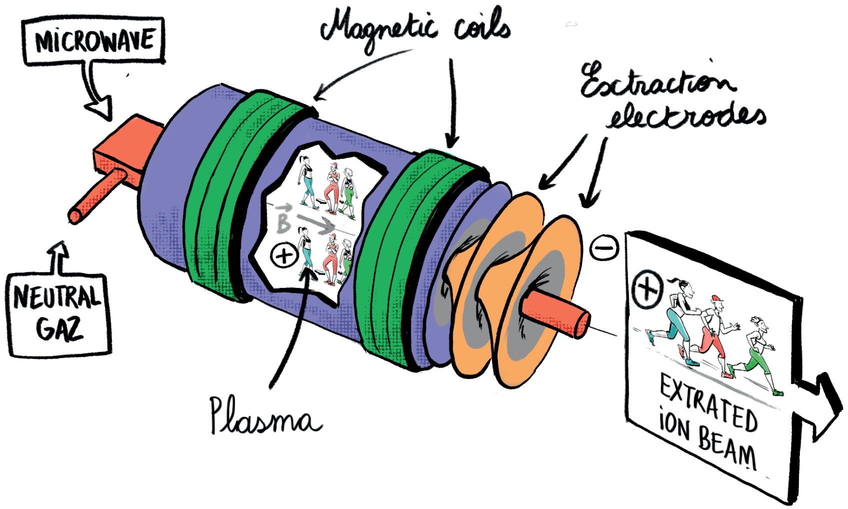


Diagram of an ion source.

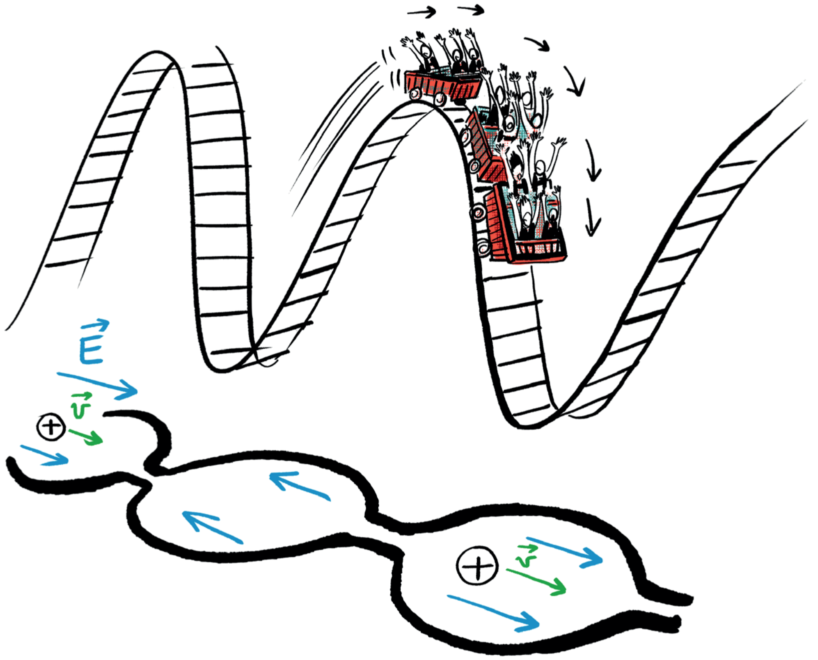
Devices for producing, accelerating, steering, and focusing charged particles

After this excursion highlighting that the same physical phenomena occur at widely different scales, let's turn our attention back to accelerators. We'll see how charged particles are produced in devices called electron guns (which carry a negative charge) and ion sources (which carry a positive charge—an ion is produced by removing electrons from a neutral atom).

Here's how an electron gun works. Electrons are much lighter than ions, so a conductive wire (e.g., tungsten) heated until white-hot creates enough thermal agitation among electrons to eject them from the conductor. A positively charged conductive plate equipped with an opening then draws the electrons in a given direction in order to form a primary accelerated beam.

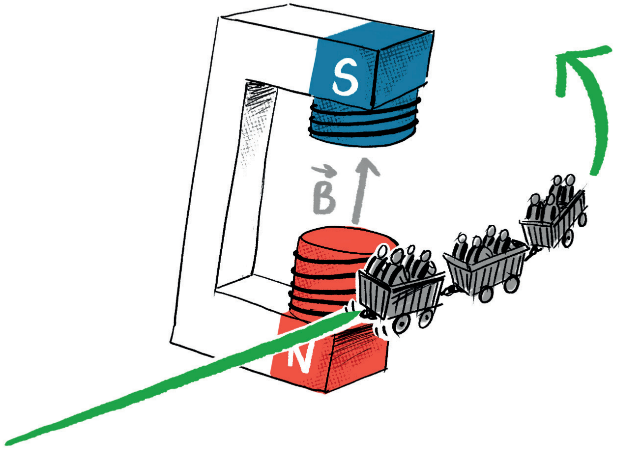
An ion source functions much like the microwaves we use to heat food: agitation (or heat) is provided by an electromagnetic wave whose oscillating electric field separates electrons from nuclei. But to produce a large quantity of ions in this way, you can't just use a more powerful microwave. We know that in this type of oven, considerably increasing power will certainly heat food faster, but it will also cause it to expand (that's right, the thermal agitation effect again) until it explodes and sticks to the walls of the oven. To avoid this phenomenon, electric coils are added around the ion source to produce an axial magnetic field that forces the ions to rotate close to the axis instead of wandering off towards the walls. Ions are then extracted from the source through an opening equipped with negatively charged conductive plates to form a primary accelerated beam.

The most efficient form of acceleration happens next, using a series of resonant cavities where an electromagnetic wave is trapped. Prior to this, the particle beam must be divided into small bunches that will travel single-file through these cavities in order to be accelerated. (Imagine a theme park, with visitors divided into small groups and asked to sit in carts that will accelerate them on rides like roller coasters.) A varying electric field is used in resonant cavities: at times it is oriented in the same direction as the beam and can accelerate it, while at other times it is oriented opposite the beam and can decelerate it. This change occurs at the frequency of the radiofrequency wave, in other words, several million times a second. In order for this field to always function as an accelerator for the beam, the particle bunches must arrive at the same frequency as the wave, synchronized with it in such a way that the electric field is always positioned in the direction of acceleration. What's more, particles in the same bunch are not necessarily all travelling at the same speed. If we apply the same energy to the entire bunch, slightly more energetic particles will pull increasingly ahead, while the slightly less energetic particles will fall increasingly behind. As a result, the beam will gradually lengthen and the structure of well-organized bunches could disintegrate, leaving a continuous beam, as opposed to a bunched beam. To avoid this, the beam's arrival must be synchronized in such a way that early particles encounter a weaker than average electric field and late particles encounter a slightly stronger than average electric field. In this way, the particles in a bunch are grouped longitudinally.



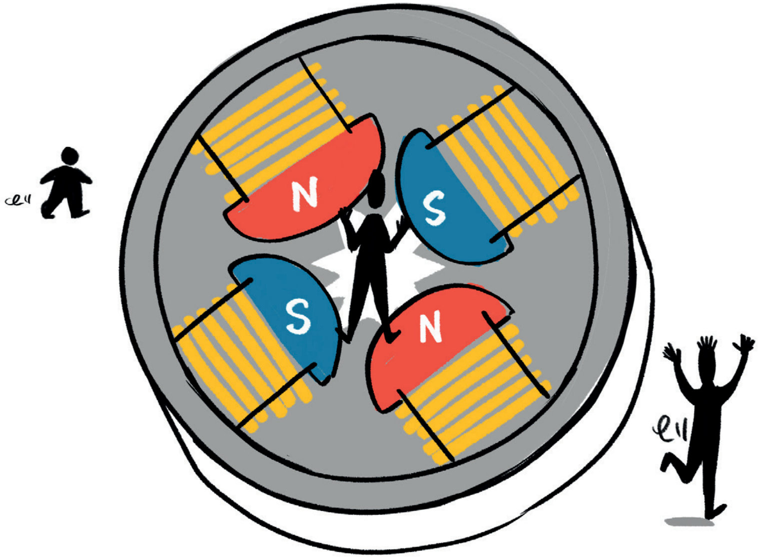
Particle acceleration using a series of resonant RF cavities.

The particle beam must also be diverted, or steered, toward precise locations, either to be accelerated or for other uses, for example to make collisions, produce synchrotron radiation, or irradiate targets. This is done using a dipole: an electromagnet with two conductive coils that create a magnetic field aligned with the North and South poles. Typically, a vertical magnetic field is generated and the beam is forced to spiral around it. In this way, the beam is diverted horizontally at the desired angle corresponding to the precise path where the magnetic field is present.



Steering particles with a magnetic dipole.

Remember that the bunches in the particle beam must also be regularly regrouped on the transverse plane; in other words, they must be focused to at least counterbalance the forces of repulsion at work between same-sign charges. This is done with electromagnets, using either a solenoid that forces the particles to rotate around its axial magnetic field, or a quadrupole with four conductive coils that generate a magnetic field with four poles. This kind of structure focuses the beam in a given plane (horizontally, for example) and defocuses it in the perpendicular plane (vertically, for example). As with telephoto lenses used in classical optics, a judiciously placed series of these focusing and defocusing quadrupoles can achieve very strong focusing. Electromagnets with six, eight, ten, or more poles can be used to focus the edges of the beam more than the center.



A quadrupole focusing the beam horizontally and defocusing it vertically.

For low-energy ions exiting the source, the interparticle repulsive forces are still very strong; therefore, the use of separate accelerating and focusing devices is not appropriate, the particles would disperse before they could be sufficiently accelerated. Instead, a special device called a RFQ cavity (radiofrequency quadrupole cavity) is used: this electromagnetic resonant cavity is equipped with four very precisely manufactured poles that ensure the axial electric field alternates between parallel and perpendicular to the beam's direction of travel every several centimeters. These cavities are several meters in length and can be used to bunch the continuous beam exiting the source, then to alternatively accelerate and focus the beam every several centimeters, until an energy is reached at which the repulsive forces become inconsequential. At this point, accelerating and focusing tasks can be carried out more efficiently by larger cavities and electromagnets several tens of centimeters in length.

What about the particle beam?

First, a particle beam in an accelerator circulates in a pipe at ultrahigh vacuum, meaning there are millions of times fewer air particles in the beam pipe than in the atmosphere; this reduces to a minimum any chance of collision between the beam particles and air particles, which would lead to beam particle loss. Indeed, loss of accelerated particles must often be limited to a millionth or a billionth of the beam, in order to limit activation of materials that would generate radiation harmful to humans, or to prevent heating of the enveloping, cryogenically cooled equipment very close to the beam.

The devices we've described must carry out their tasks with great precision. While the beam's progress in this environment is intrinsically complex: it rotates around the axis of the solenoid; is focused in one plane and defocused in the other as it passes through a quadrupole; speeds up while being focused in the longitudinal plane as it passes through an accelerating cavity; and does pretty much all of this in an RFQ cavity.

What's more, this complex behavior takes place in a six-dimensional space that humans cannot visualize. Each of the billions of particles in a bunch can be described by its position in three-dimensional space, plus the direction of its three-dimensional angle of motion, all of these necessary to determine where a particle is coming from and where it is going to. In the same way, a particle bunch is characterized by its size in the three planes and its divergence in the same three planes. The center of the bunch progresses in the six dimensions as a fictional particle would. Under the influence of accelerating and focusing devices, the center of the bunch oscillates in the six dimensions around the ideal theoretical trajectory, and the particles oscillate in the six dimensions around this center, each at its own rhythm and frequency. This behavior changes rather violently, both qualitatively and quantitatively, as the beam passes through each device.

The physics of particle accelerators could be described as "deliciously complex." It is a fascinating field of study. Physicists working in this field are akin to tamers of wild particles that, while not particularly ferocious, exhibit complex behavior—especially when there are millions or billions of them to tame.

A conclusion of sorts

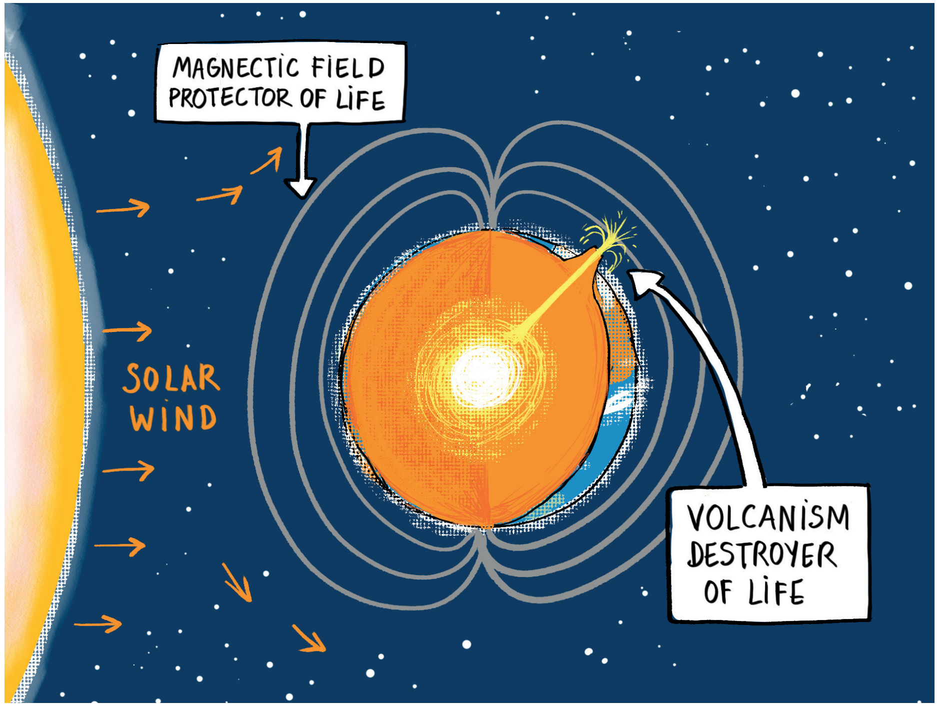
Sometimes it can be more interesting to conclude a discussion by opening it up further, rather than summarizing; the field of accelerator physics lends itself well to this.

We saw earlier that in wanting to learn the basics of accelerator physics, which might be at first glance seem highly specific, we actually learned about the physics of everyday life and our universe. Any teenage student who learns about a physics phenomenon at school will realize, as soon as they get home, that they are able to understand many other things that are merely different manifestations, sometimes at different scales, of the same phenomenon. This is probably true for science in general. Scientists hold themselves to a very strict principle of economy, which equates to describing a maximum of phenomena with a minimum of laws. In other words, scientific laws must cover the largest field possible, which means they strive to be universal. For naturally curious humans constantly seeking understanding, science is fascinating because it helps us to comprehend many things, from the infinitely small to the infinitely large, with little prior knowledge.

Nevertheless, it's interesting to note that humans have a complex relationship to science. Some people believe that scientific knowledge has paved the way for human-made products, and therefore unnatural or artificial products. This opposition between the artificial and the natural seems so obvious that it's easy to automatically assign them opposing value judgements, often to the detriment of the artificial. Let's take the particle accelerator as an example: it's a rather imposing object, entirely fabricated by humans, and therefore artificial by definition. Yet we saw that the physical principles that apply in an accelerator are the same as those that govern objects in nature. If you look at each component and each material in an accelerator, you'll see that each is created from a material that exists in nature and/or is transformed using the laws of nature. In a much broader sense, science, be it physics, chemistry, biology, or other fields, only describes the laws of nature. No scientific law was invented or created by humans. Ultimately, humans themselves, until proven otherwise, are products of nature. So it is very difficult, even impossible, to imagine that a pure product of nature, which uses natural products associated with natural laws, could produce objects that are automatically unnatural. Might this opposition between natural and artificial be purely anthropocentric in origin? An opposition that gives humans a much more significant place in nature than they have in reality? You could say that this natural/artificial opposition is rather… artificial.

But is science itself good or bad? That's a big question. Let's look at it as it relates to our discussion. For example, we pointed out that the Earth's center is very hot. This generated a magnetic shield that protects life on the Earth's surface. But it also resulted in liquefying the materials at the Earth's core. Solid tectonic plates float freely atop this liquid, and when they collide or separate, they provoke earthquakes or volcanic eruptions that destroy life. Generally speaking, every natural phenomenon, no matter what it is—rain, wind, cosmic radiation, the rotation of galaxies,—is as capable of destroying a given object or phenomenon as it is of protecting it. Depending on the context, the level of protection or destruction may be greater, supporting or inhibiting the development of said object or phenomenon. For example, a simple sharp object, made by a human hand or not, can be used for defense or to cut food that nourishes us, but it can also injure us. In short, natural (or artificial, it matters little) phenomena will always produce potentially good or bad effects on a given subject; science allows us to qualitatively and quantitatively identify these effects. Ultimately only our conscience can sort through these effects and decide which are desirable.

Accelerator physics, through the natural phenomena we have examined, can lead to exploration of the physics of the world around us, and even to reflections on our relationship with this world.



Two manifestations of Earth's molten core: a protective magnetic shield and a destructive volcanic eruption.

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