CERN *faq*

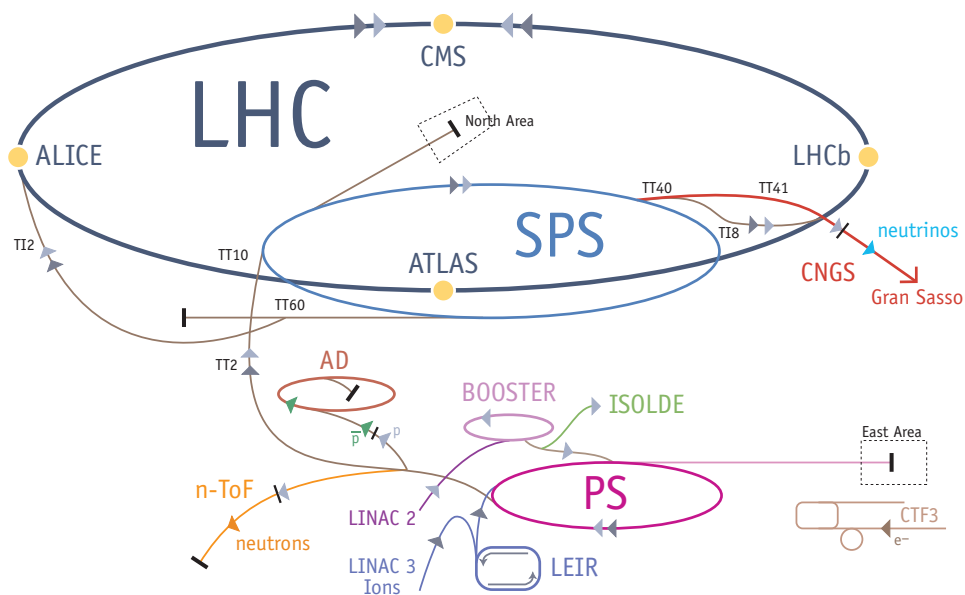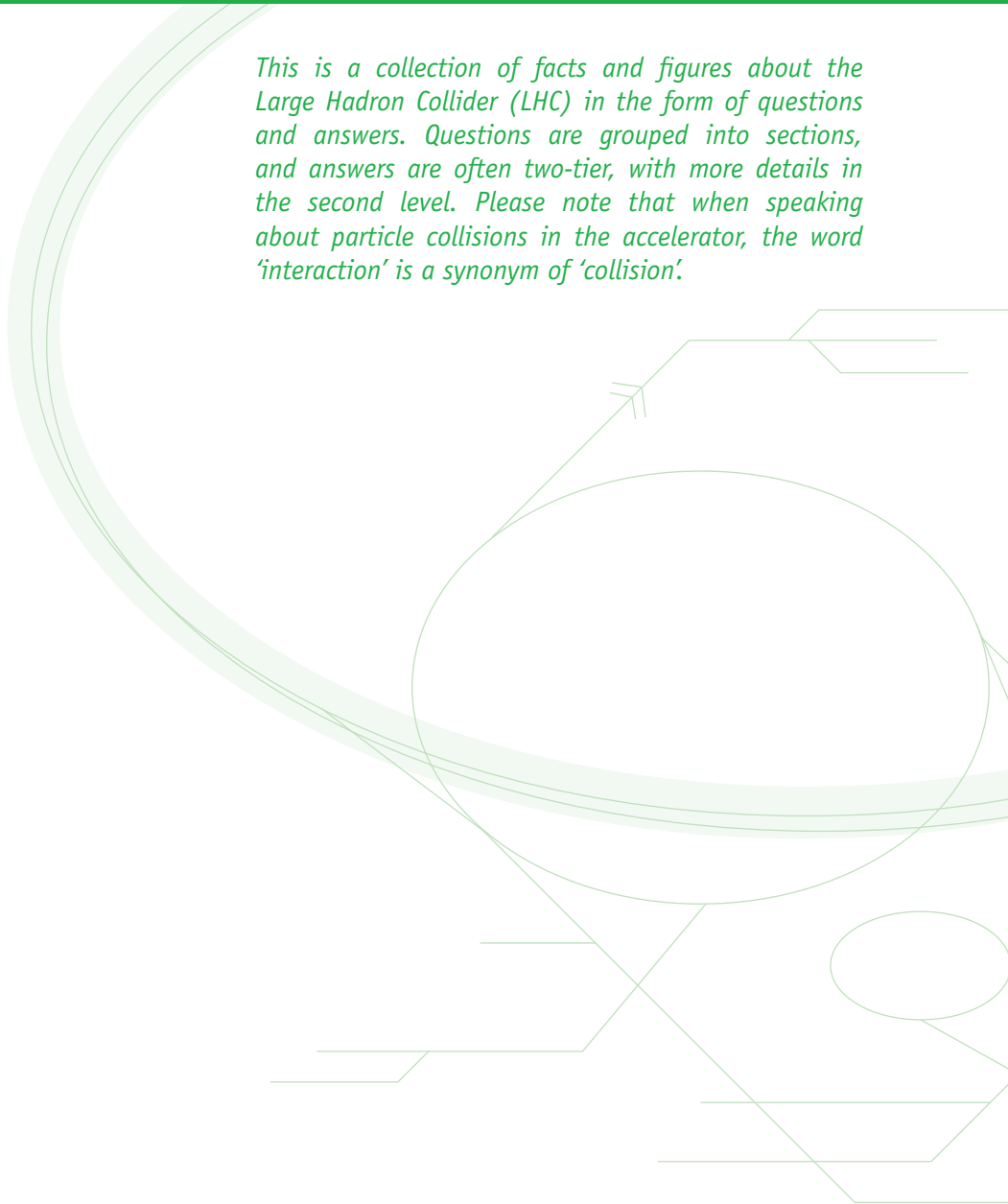## LHC
the guide

This is a collection of facts and figures about the Large Hadron Collider (LHC) in the form of questions and answers. Questions are grouped into sections, and answers are often two-tier, with more details in the second level. Please note that when speaking about particle collisions in the accelerator, the word 'interaction' is a synonym of 'collision'.

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Powers of ten

The powers of ten are commonly used in physics and information technology. They are practical shorthand for very large or very small numbers.

| Power of ten	Number	Symbol
10^{-12}	0.000000000001	p (pico)
10^{-9}	0.000000001	n (nano)
10^{-6}	0.000001	µ (micro)
10^{-3}	0.001	m (milli)
10^{-2}	0.01	
10^{-1}	0.1	
10^{0}	1	
10^{1}	10	
10^{2}	100	
10^{3}	1000	k (kilo)
10^{6}	1 000 000	M (mega)
10^{9}	1 000 000 000	G (giga)
10^{12}	1 000 000 000 000	T (tera)
10^{15}	1 000 000 000 000 000	P (peta)

Inside the atom
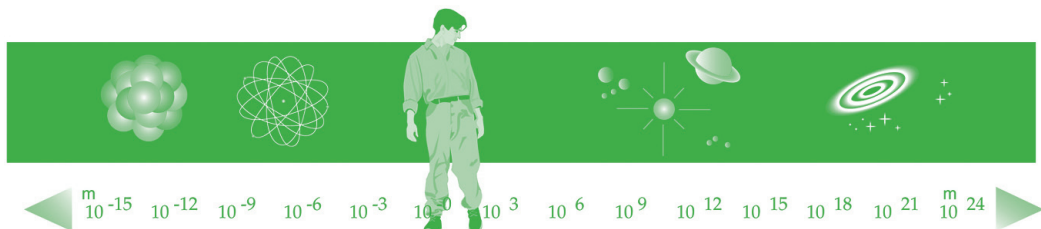
Particle physics studies the tinest objects of Nature. Looking into the very small and fundamental, it also looks very far back into time, just a few moments after the Big Bang. Here are a few examples of dimensions particle physicists deal with:

Atom: 10^{-10} m
Nucleus: 10^{-14} m
Quarks: $< 10^{-19}$ m

If the protons and the neutrons were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across. More than 99.99% of the atom is empty space.
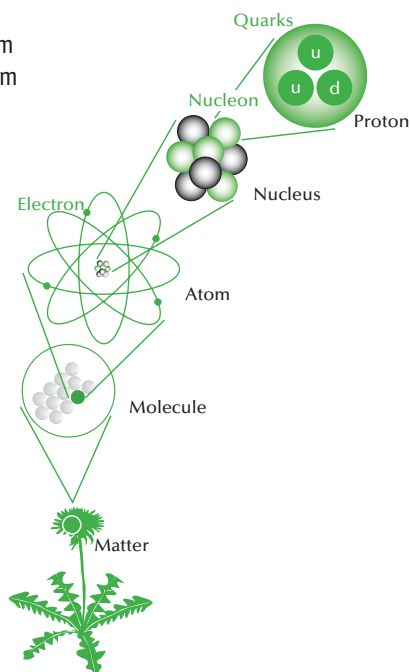
Energy units in physics

Energy has many units in physics: joules, calories, and kilowatt hours are all units of energy used in different contexts. Only the joule is an International System (SI) unit, but all of them are related by conversion factors. In particle physics, the unit that is most frequently used for energy is the electronvolt (eV) and its derivatives keV (10^3 eV), MeV (10^6 eV), GeV (10^9 eV) and TeV (10^{12} eV). The electronvolt is a convenient unit because, in absolute terms, the energies that particle physicists deal with are very small. If we take the LHC as an example, the total collision energy is 14 TeV, making it the most powerful particle accelerator in the world. Still, if we convert this into joules, we obtain:

$$14 \times 10^{12} \times 1.602 \times 10^{-19} = 22.4 \times 10^{-7} \text{ joules.}$$

This is a very small amount of energy if compared, for example, to the energy of an object weighing 1 kg and falling from a height of 1 m, that is: 9.8 joules = 6.1×10^{19} electronvolts.

> *The definition of the electronvolt comes from the simple insight that a single electron accelerated by a potential difference of 1 volt will have a discreet amount of energy, E=qV joules, where q is the charge on the electron in coulombs and V is the potential difference in volts. Hence 1 eV = (1.602 x 10⁻¹⁹ C) x (1 V) = 1.602 x 10⁻¹⁹ J.*

Energy and speed of a particle

No particle can move with speeds faster than the speed of light in a vacuum; however, there is no limit to the energy a particle can attain. In high-energy accelerators, particles normally travel very close to the speed of light. In these conditions, as the energy increases, the increase in speed is minimal. As an example, particles in the LHC move at 0.999997828 times the speed of light at injection (energy = 450 GeV) and 0.999999991 times the speed of light at top energy (energy = 7000 GeV). Therefore, particle physicists do not generally think about speed, but rather about a particle's energy.

The classical Newtonian relationship between speed and kinetic energy ($K = (1/2)mv^2$) only holds for speeds much lower than the speed of light. For particles moving close to the speed of light we need to use Einstein's equation from special relativity $K = (\gamma-1)mc^2$ where c is the velocity of light (299 792 458 m/s), and γ is related to speed via $\gamma = 1/\sqrt{(1-\beta^2)}$; $\beta = v/c$ and m = mass of particle at rest.
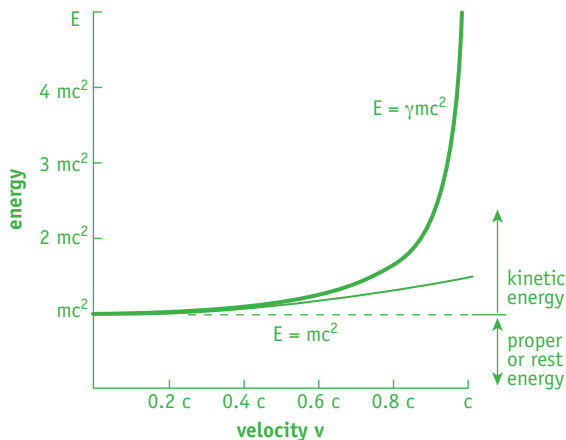
Ref: http://www.phys.unsw.edu.au/einsteinlight/jw/module5_equations.htm

Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2		

Energy and mass

Energy and mass are two sides of the same coin. Mass can transform into energy and vice versa in accordance with Einstein's famous equation ($E=mc^2$). At the LHC this transformation happens at each collision. Also, because of this equivalence, mass and energy can be measured with the same units. At the scale of particle physics these are the electronvolt and its multiples (see *Energy units in physics*).

The Standard Model
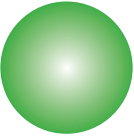
The Standard Model is a collection of theories that embodies all of our current understanding of fundamental particles and forces. According to the theory, which is supported by a great deal of experimental evidence, quarks are the building blocks of matter, and forces act through carrier particles exchanged between the particles of matter. Forces also differ in their strength. The following pictures summarize the Standard Model's basic points.

Although the Standard Model is a very powerful theory, some of the phenomena recently observed — such as dark matter and the absence of antimatter in the Universe — remain unexplained and can not be accounted for in the model. Read more about this on page 22.

LEPTONS

Electron
Together with the nucleus, it makes up the atom

Electron neutrino
Particle with no electric charge, and very small mass; billions fly through your body every second

Muon
A heavier relative of the electron; it lives for two-millionths of a second

Muon neutrino
Created along with muons when some particles decay

Tau
Heavier still; it is extremely unstable. It was discovered in 1975

Tau neutrino
Discovered in 2000

QUARKS

Up
Has an electric charge of plus two-thirds; protons contain two, neutrons contain one

Down
Has an electric charge of minus one-third; protons contain one, neutrons contain two

Charm
A heavier relative of the up; found in 1974

Strange
A heavier relative of the down.

Top
Heavier still; found in 1995

Bottom
Heavier still; measuring bottom quarks is an important test of electroweak theory

STRONG FORCE

Felt by: quarks
Carrier: gluons

Gluons
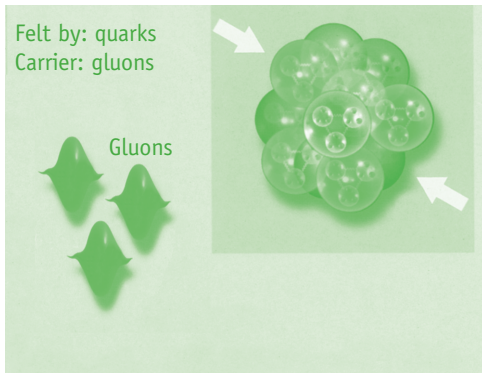
Associated phenomena
The strong force binds quarks together to make protons and neutrons (and other particles). It also binds protons and neutrons in nuclei, where it overcomes the enormous electrical repulsion between protons.
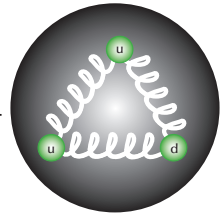
ELECTROMAGNETIC FORCE

Felt by: quarks and
              charged leptons
Carrier: photons

Photons
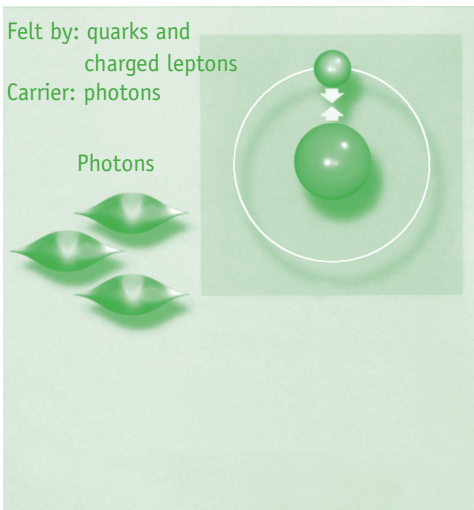
Associated phenomena
It holds electrons to nuclei in atoms, binds atoms into molecules, and is responsible for the properties of solids, liquids and gases.

WEAK FORCE

Felt by: quarks and leptons
Carrier: intermediate vector bosons

Boson

W⁻ W⁺

Z⁰
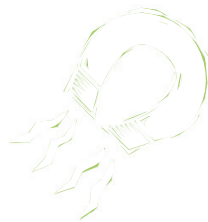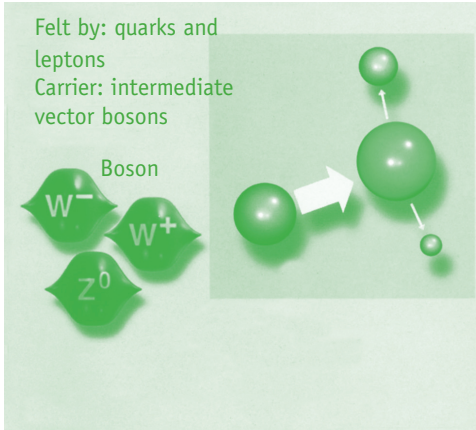
Associated phenomena
The weak force underlies natural radioactivity, for example in the Earth beneath our feet. It is also essential for the nuclear reactions in the centres of stars like the Sun, where hydrogen is converted into helium.

GRAVITATION

Felt by: all particles with mass
Carrier: Graviton
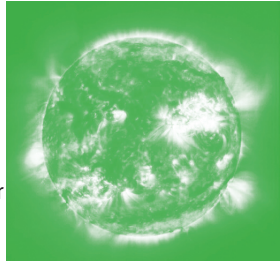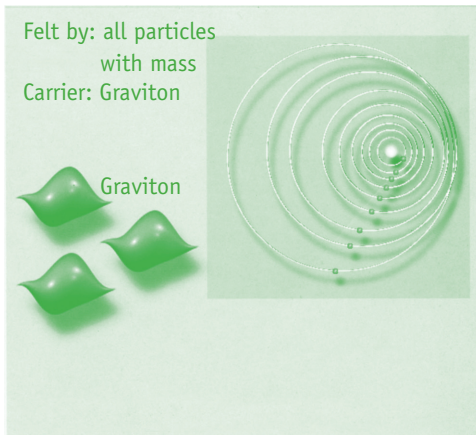
Graviton

Associated phenomena
Gravity makes apples fall to the ground. It is an attractive force. On an astronomical scale it binds matter in planets and stars, and holds stars together in galaxies.

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Back to the Big Bang

The energy density and temperature that will be made available in the collisions at the LHC are similar to those that existed a few moments after the Big Bang. In this way physicists hope to discover how the Universe evolved.

The Evolution of the Universe

13.7 billion years	10 billion years	9.2 billion years	200 million years	380 000 years
Today	**Life on Earth**	**Solar system**	**Stars and galaxies**	**Light atoms**

Today, at CERN, we are going back in time to study the origins of matter

A soup of organic molecules appears on Earth, a small blue planet lost in the immense Universe

Gravity gathers the debris of stars into planets

Gravity gathers clouds of atoms into stars

Electrons bind to atomic nuclei to form hydrogen and helium atoms

Heavy atoms, the building blocks of life, are synthesized in the hearts of stars

Photons no longer interact with electrons: the Universe becomes transparent and illuminates

-270°C

Only 4% of the matter of the Universe is directly observable.

4%
30%
66%

● ordinary matter: atoms
● dark matter
● dark energy

4000°C
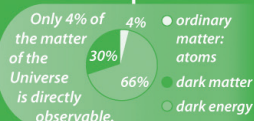
Helium atom

Hydrogen atom

LHC exploration range

10^{-25} seconds

3 minutes **0.01 millisecond** **10^{-12} seconds** **10^{-20} seconds** **10^{-35} seconds** **10^{-43} seconds**

Light nuclei   **Protons and neutrons**   **Quark–gluon plasma**

Protons and neutrons bind to form atomic nuclei

Quarks and gluons bind to form protons and neutrons

weak force

electromagnetic force

strong force

electronuclear force

electroweak force

gravity

Superforce

Big Bang

?

Photons are continuously absorbed and reemitted: the Universe is opaque

The Universe has the size of the solar system

The Universe has a radius of 300 million km

The Universe has the size of an apple

The Universe is an infinitely small point

$10^{12}°C$ $10^{15}°C$ $10^{27}°C$ $10^{32}°C$

*2 protons +
2 neutrons* = *Helium nucleus*

1 proton = *Hydrogen nucleus*

● Proton
● Neutron
● Meson

● Quark
· Electron
· Neutrino

∿ Photon
w Weak force
〰 Strong force

$10^{17}°C$

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The CERN accelerator complex

The accelerator complex at CERN is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. In the LHC—the last element of this chain—each particle beam is accelerated up to the record energy of 7 TeV. In addition, most of the other accelerators in the chain have their own experimental halls, where the beams are used for experiments at lower energies.

The brief story of a proton accelerated through the accelerator complex at CERN is as follows:

▸ *Hydrogen atoms are taken from a bottle containing hydrogen. We get protons by stripping orbiting electrons from hydrogen atoms.*

▸ *Protons are injected into the PS Booster (PSB) at an energy of 50 MeV from Linac2.*

The booster accelerates them to 1.4 GeV. The beam is then fed to the Proton Synchrotron (PS) where it is accelerated to 25 GeV. Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV. They are finally transferred to the LHC (both in a clockwise and an anticlockwise direction, the filling time is 4'20" per LHC ring) where they are accelerated for 20 minutes to their nominal energy of 7 TeV. Beams will circulate for many hours inside the LHC beam pipes under normal operating conditions.

Protons arrive at the LHC in bunches, which are prepared in the smaller machines. For a complete scheme of filling, magnetic fields and particle currents in the accelerator chain, have a look at Appendix 1 and 2.

> *In addition to accelerating protons, the accelerator complex also accelerates lead ions.*
>
> *Lead ions are produced from a highly purified lead sample heated to a temperature of about 550°C. The lead vapour is ionized by an electron current. Many different charge states are produced with a maximum around Pb^{29+}. These ions are selected and accelerated to 4.2 MeV/u (energy per nucleon) before passing through a carbon foil, which strips most of them to Pb^{54+}. The Pb^{54+} beam is accumulated, then accelerated to 72 MeV/u in the Low Energy Ion Ring (LEIR), which transfers them to the PS. The PS accelerates the beam to 5.9 GeV/u and sends it to the SPS after first passing it through a second foil where it is fully stripped to Pb^{82+}. The SPS accelerates it to 177 GeV/u then sends it to the LHC, which accelerates it to 2.76 TeV/u.*
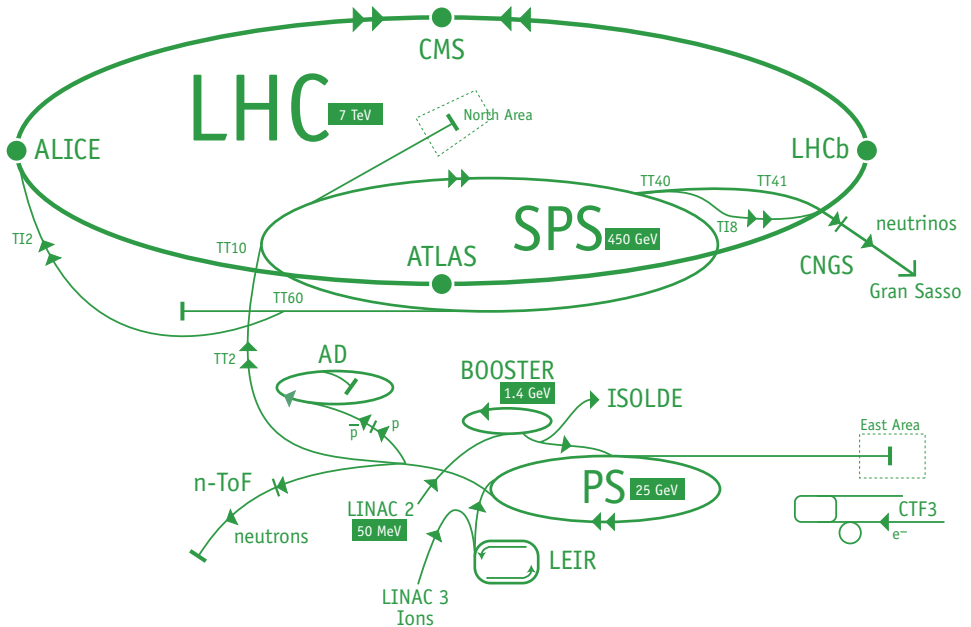
What does LHC stand for?

LHC stands for Large Hadron Collider. **Large** due to its size (approximately 27 km in circumference), **Hadron** because it accelerates protons or ions, which are hadrons, and **Collider** because these particles form two beams travelling in opposite directions, which collide at four points where the two rings of the machine intersect.

> *Hadrons (from the Greek 'adros' meaning 'bulky') are particles composed of quarks. The protons and neutrons that atomic nuclei are made of belong to this family. On the other hand, leptons are particles that are not made of quarks. Electrons and muons are examples of leptons (from the Greek 'leptos' meaning 'thin').*

Back in the early 1980s, while the Large Electron-Positron (LEP) collider was being designed and built, groups at CERN were already busy looking at the long-term future. After many years of work on the technical aspects and physics requirements of such a machine, their dreams came to fruition in December 1994 when CERN's governing body, the CERN Council, voted to approve the construction of the LHC. The green light for the project was given under the condition that the new accelerator be built within a constant budget and on the understanding that any non-Member State contributions would be used to speed up and improve the project. Initially, the budgetary constraints implied that the LHC was to be conceived as a 2-stage project. However, following contributions from Japan, the USA, India and other non-Member States, Council voted in 1995 to allow the project to proceed in a single phase. Between 1996 and 1998, four experiments—ALICE, ATLAS, CMS and LHCb—received official approval and construction work commenced on the four sites. Since then, two smaller experiments have joined the quest: TOTEM, installed next to CMS, and LHCf, next to ATLAS (see experiments, page 37).

For more information about the LHC milestones, see:
http://www.cern.ch/LHC-Milestones/

The cost for the machine alone is about 4.6 billion CHF (about 3 billion Euro). The total project cost breaks down roughly as follows:

Construction costs (BCHF)	Personnel	Materials	Total
LHC Machine and areas	0.92	3.68	4.60[*)]
CERN share to Detectors	0.78	0.31	1.09
LHC injector upgrade	0.09	0.07	0.16
LHC computing (CERN share)	0.09	0.09	0.18
Total	1.88	4.15	6.03

[*)] *(including 0.43 BCHF of in-kind contributions)*

The experimental collaborations are individual entities, funded independently from CERN. CERN is a member of each experiment, and contributes to the material budget of CMS and LHCb at the 20% level, 16% for ALICE and 14% for ATLAS. TOTEM is a much smaller experiment, with a total material cost of about 6.5 million CHF, of which CERN provides 30% of the budget.

NB: 1 billion = 1 thousand million.

Why large?

The size of an accelerator is related to the maximum energy obtainable. In the case of a collider or storage ring, this is a function of the radius of the machine and the strength of the dipole magnetic field that keeps particles in their orbits. The LHC re-uses the 27-km circumference tunnel that was built for the previous big accelerator, LEP. The LHC uses some of the most powerful dipoles and radiofrequency cavities in existence. The size of the tunnel, magnets, cavities and other essential elements of the machine, represent the main constraints that determine the design energy of 7 TeV per proton beam.

Why collider?

A collider (that is a machine where counter-circulating beams collide) has a big advantage over other kinds of accelerator where a beam collides with a stationary target. When two beams collide, the energy of the collision is the sum of the energies of the two beams. A beam of the same energy that hits a fixed target would produce a collision of much less energy.

The energy available (for example, to make new particles) in both cases is the centre-of-mass energy. In the first case it is simply the sum of the energies of the two colliding particles ($E = E_{beam1} + E_{beam2}$), whereas in the second, it is proportional to the square root of the energy of the particle hitting the target ($E \propto \sqrt{E_{beam}}$).

The LHC will accelerate two beams of particles of the same kind, either protons or lead ions, which are hadrons. An accelerator can only accelerate certain kinds of particle: firstly they need to be charged (as the beams are manipulated by electromagnetic devices that can only influence charged particles), and secondly, except in special cases, they need not to decay. This limits the number of particles that can practically be accelerated to electrons, protons, and ions, plus all their antiparticles.

In a circular accelerator, such as the LHC, heavy particles such as protons (protons are around 2000 times more massive than electrons) have a much lower energy loss per turn through synchrotron radiation than light particles such as electrons. Therefore, in circular accelerators, to obtain the highest-energy collisions it is more effective to accelerate massive particles.

Synchrotron radiation is the name given to the radiation that occurs when charged particles are accelerated in a curved path or orbit. This kind of radiation represents an energy loss for particles, which in turn means that more energy must be provided by the accelerator to keep the beam energy constant.
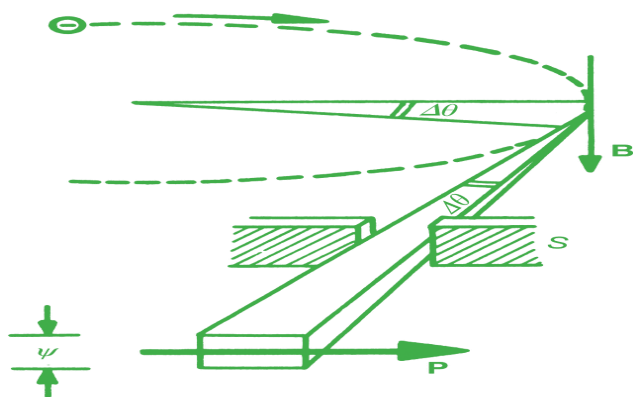
The LHC re-uses the tunnel that was built for CERN's previous big accelerator, LEP, dismantled in 2000. The underground tunnel was the best solution to house a 27-km circumference machine because it is cheaper to excavate a tunnel rather than acquire the land to build at the surface and the impact on the landscape is reduced to a minimum. In addition, the Earth's crust provides good shielding for radiation.

The tunnel was built at a mean depth of 100 m, due to geological considerations (again translating into cost) and at a slight gradient of 1.4%. Its depth varies between 175 m (under the Jura) and 50 m (towards Lake Geneva).

The tunnel has a slope for reasons of cost. At the time when it was built for hosting LEP, the construction of the vertical shafts was very costly. Therefore, the length of the tunnel that lies under the Jura was minimized. Other constraints involved in the positioning of the tunnel were:

▸ *it was essential to have a depth of at least 5 m below the top of the 'molasse' (green sandstone) stratum*

▸ *the tunnel had to pass in the vicinity of the pilot tunnel, constructed to test excavation techniques*

▸ *it had to link to the SPS. This meant that there was only one degree of freedom (tilt). The angle was obtained by minimising the depth of the shafts.*

What is the collision energy at the LHC and what is so special about it?

Each proton beam flying around the LHC will have an energy of 7 TeV, so when two protons collide the collision energy will be 14 TeV. Lead ions have many protons, and together they give an even greater energy: the lead-ion beams will have a collision energy of 1150 TeV. Both collision energies have never been reached before in a lab.

Energy concentration is what makes particle collisions so special. When you clap your hands you probably do a 'collision' at an energy higher than protons at the LHC, but much less concentrated! Now think of what you would do if you were to put a needle in one of your hands. You would certainly slow your hands down as you clapped!

In absolute terms, these energies, if compared to the energies we deal with everyday, are not impressive. In fact, 1 TeV is about the energy of motion of a flying mosquito. What makes the LHC so extraordinary is that it squeezes energy into a space about a million million times smaller than a mosquito.

What are the main goals of the LHC?

Our current understanding of the Universe is incomplete. The Standard Model of particles and forces (see page 6) summarizes our present knowledge of particle physics. The Standard Model has been tested by various experiments and it has proven particularly successful in anticipating the existence of previously undiscovered particles. However, it leaves many unsolved questions, which the LHC will help to answer.

▶ The Standard Model does not explain the origin of mass, nor why some particles are very heavy while others have no mass at all. The answer may be the so-called Higgs mechanism. According to the theory of the Higgs mechanism, the whole of space is filled with a 'Higgs field', and by interacting with this field, particles acquire their masses. Particles that interact intensely with the Higgs field are heavy, while those that have feeble interactions are light. The Higgs field has at least one new particle associated with it, the Higgs boson. If such a particle exists, experiments at the LHC will be able to detect it.

▶ The Standard Model does not offer a unified description of all the fundamental forces, as it remains difficult to construct a theory of gravity similar to those for the other forces. Supersymmetry — a theory that hypothesises the existence of more massive partners of the standard particles we know — could facilitate the unification of fundamental forces. If supersymmetry is right, then the lightest supersymmetric particles should be found at the LHC.

▶ Cosmological and astrophysical observations have shown that all of the visible matter accounts for only 4% of the Universe. The search is open for particles or phenomena responsible for dark matter (23%) and dark energy (73%). A very popular idea is that dark matter is made of neutral — but still undiscovered — supersymmetric particles.

*The first hint of the existence of **dark matter** came in 1933, when astronomical observations and calculations of gravitational effects revealed that there must be more 'stuff' present in the Universe than we could account for by sight. Researchers now believe that the gravitational effect of dark matter makes galaxies spin faster than expected, and that its gravitational field deviates the light of objects behind it. Measurements of these effects show the existence of dark matter, and can be used to estimate its density even though we cannot directly observe it.*

***Dark energy** is a form of energy that appears to be associated with the vacuum in space, and makes up approximately 70% of the Universe. Dark energy is homogenously distributed throughout the Universe and in time. In other words, its effect is not diluted as the Universe expands. The even distribution means that dark energy does not have any local gravitational effects, but rather a global effect on the Universe as a whole. This leads to a repulsive force, which tends to accelerate the expansion of the Universe. The rate of expansion and its acceleration can be measured by experiments using the Hubble law. These measurements, together with other scientific data, have confirmed the existence of dark energy and have been used to estimate its quantity.*

▶ The LHC will also help us to investigate the mystery of antimatter. Matter and antimatter must have been produced in the same amounts at the time of the Big Bang, but from what we have observed so far, our Universe is made only of matter. Why? The LHC could help to provide an answer.

It was once thought that antimatter was a perfect 'reflection' of matter — that if you replaced matter with antimatter and looked at the result as if in a mirror, you would not be able to tell the difference. We now know that the reflection is imperfect, and this could have led to the matter-antimatter imbalance in our Universe.

The strongest limits on the amount of antimatter in the Universe come from the analysis of the 'diffuse cosmic gamma-rays' and the inhomogeneities of the cosmic microwave background (CMB). Assuming that after the Big Bang, the Universe separated somehow into different domains where either matter or antimatter was dominant, it is evident that at the boundaries there should be annihilations, producing cosmic (gamma) rays. Taking into account annihilation cross-sections, distance, and cosmic redshifts, this leads to a prediction of the amount of diffuse gamma radiation that should arrive on Earth. The free parameter in the model is the size of the domains. Comparing with the observed gamma-ray flux, this leads to an exclusion of any domain size below 3.7 giga light years, which is not so far away from the entire Universe. Another limit comes from analyzing the inhomogeneities in the CMB — antimatter domains (at any size) would cause heating of domain boundaries and show up in the CMB as density fluctuations. The observed value of $\sim 10^{-5}$ sets strong boundaries to the amount of antimatter in the early Universe.

▶ In addition to the studies of proton–proton collisions, heavy-ion collisions at the LHC will provide a window onto the state of matter that would have existed in the early Universe, called 'quark-gluon plasma'. When heavy ions collide at high energies they form for an instant a "fireball" of hot, dense matter that can be studied by the experiments.

According to the current theories, the Universe, born from the Big Bang, went through a stage during which matter existed as a sort of extremely hot, dense soup — called quark-gluon plasma (QGP) — composed of the elementary building blocks of matter. As the Universe cooled, the quarks became trapped into composite particles such as protons and neutrons. This phenomenon is called the confinement of quarks. The LHC is able to reproduce the QGP by accelerating and colliding together two beams of heavy ions. In the collisions, the temperature will exceed 100 000 times that of the centre of the Sun. In these conditions, the quarks are freed again and the detectors can observe and study the primordial soup, thus probing the basic properties of the particles and how they aggregate to form ordinary matter.

CMS

Octant 5
Octant 4
Octant 3
Octant 6
Octant 7
Octant 8
Octant 2
Octant 1

Beam dump
Arrêt des faisceaux

Beam cleaning
Nettoyage des faisceaux

Beam cleaning
Nettoyage des faisceaux

ALICE

LHCb

Injection

Injection

ATLAS
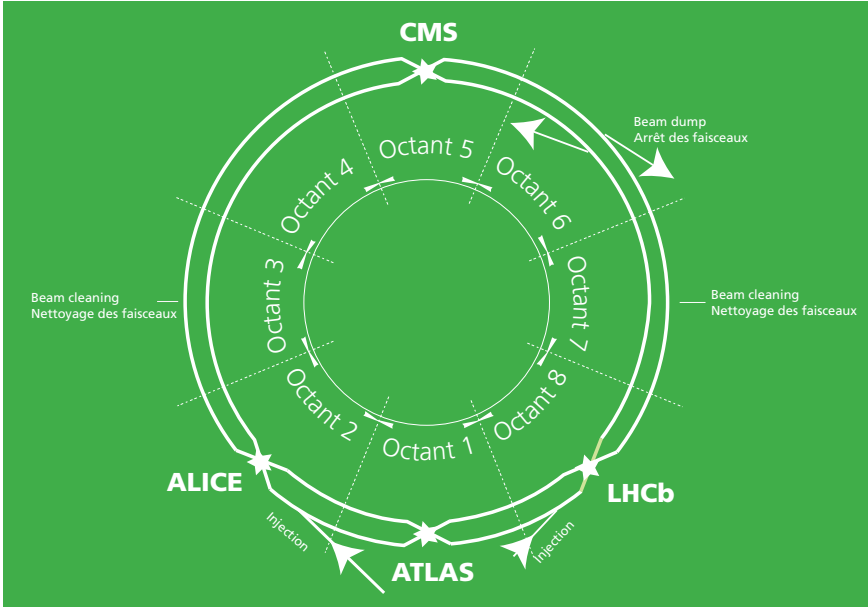
The machine *faq*

What are sectors and octants in the machine?

The LHC is not a perfect circle. It is made of eight arcs and eight 'insertions'. The arcs contain the dipole 'bending' magnets, with 154 in each arc. An insertion consists of a long straight section plus two (one at each end) transition regions — the so-called 'dispersion suppressors'. The exact layout of the straight section depends on the specific use of the insertion: physics (beam collisions within an experiment), injection, beam dumping, beam cleaning.

A sector is defined as the part of the machine between two insertion points. The eight sectors are the working units of the LHC: the magnet installation happens sector by sector, the hardware is commissioned sector by sector and all the dipoles of a sector are connected in series and are in the same continuous cryostat. Powering of each sector is essentially independent.

An octant starts from the middle of an arc and ends in the middle of the following arc and thus spans a full insertion. Therefore, this description is more practical when we look at the use of the magnets to guide the beams into collisions or through the injection, dumping, and cleaning sections.

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What are the important parameters for an accelerator?

We build accelerators to study processes whose probability varies with collision energy, and which are often rare. This means that for physicists the most important parameters are the beam energy and the number of interesting collisions. More specifically, in a collider such as the LHC the probability for a particular process varies with what is known as the luminosity — a quantity that depends on the number of particles in each bunch, the frequency of complete turns around the ring, the number of bunches and the beam cross-section. In brief, we need to squeeze the maximum number of particles into the smallest amount of space around the interaction region.

What are the main ingredients of an accelerator?

In an accelerator, particles circulate in a vacuum tube and are manipulated using electromagnetic devices: dipole magnets keep the particles in their nearly circular orbits, quadrupole magnets focus the beam, and accelerating cavities are electromagnetic resonators that accelerate particles and then keep them at a constant energy by compensating for energy losses.

Vacuum in the LHC: *the LHC has the particularity of having not one, but three vacuum systems:*

- insulation vacuum for cryomagnets

- insulation vacuum for the helium distribution line

- beam vacuum

The beam vacuum pressure will be 10^{-13} atm (ultrahigh vacuum), because we want to avoid collisions with gas molecules. The largest volume to be pumped in the LHC is the insulation vacuum for the cryomagnets ($\sim$ 9000 m^3 — like pumping down the central nave of a cathedral!)

Magnets: *There is a large variety of magnets in the LHC, including dipoles, quadrupoles, sextupoles, octupoles, decapoles, etc. giving a total of about 9600 magnets. Each type of magnet contributes to optimizing a particle's trajectory. Most of the correction magnets are embedded in the cold mass of the main dipoles and quadrupoles. The LHC magnets have either a twin aperture (for example, the main dipoles), or a single aperture (for example, some of the insertion quadrupoles). Insertion quadrupoles are special magnets used to focus the beam down to the smallest possible size at the collision points, thereby maximizing the chance of two protons smashing head-on into each other. The biggest magnets are the 1232 dipoles.*

Cavities: *The main role of the LHC cavities is to keep the 2808 proton bunches tightly bunched to ensure high luminosity at the collision points and hence, maximize the number of collisions. They also deliver radiofrequency (RF) power to the beam during acceleration to the top energy. Superconducting cavities with small energy losses and large stored energy are the best solution. The LHC will use eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz. The cavities will operate at 4.5 K (-268.7ºC)(the LHC magnets will use superfluid helium at 1.9 K or -271.3ºC). For the LHC they will be grouped in fours in cryomodules, with two cryomodules per beam, and installed in a long straight section of the machine where the transverse interbeam distance will be increased from the normal 195 mm to 420 mm.*

The following table lists the important parameters for the LHC.

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3ºC)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

Will the LHC beam energy be influenced by the Moon as was the case for the LEP accelerator?

At the LHC, beam energy will be influenced by the Moon in much the same way as at LEP. The absolute collision energy is not as critical an issue for the LHC experiments as it was at LEP, but the tidal variations will have to be taken into account when the beams are injected into the collider.

The phenomenon of tides in the ocean due to the influence of the Moon (and to a lesser extent that of the Sun) is well known. They cause the level of water on the edge of the sea to rise and fall with a cycle of some 12 hours. The ground is also subject to the effect of lunar attraction because the rocks that make it up are elastic. At the new Moon and when the Moon is full, the Earth's crust rises by some 25 cm in the Geneva area under the effect of these 'ground tides'. This movement causes a variation of 1 mm in the circumference of the LHC (for a total circumference of 26.6 km) and this produces changes in beam energy. Thus, physicists must take the Moon into account in their measurements.

What is so special about the LHC dipoles?

The dipoles of the LHC represented the most important technological challenge for the LHC design. In a proton accelerator like the LHC, the maximum energy that can be achieved is directly proportional to the strength of the dipole field, given a specific acceleration circumference. At the LHC the dipole magnets are superconducting electromagnets and able to provide the very high field of 8.3 T over their length. No practical solution could have been designed using 'warm' magnets instead of superconducting ones.

The LHC dipoles use niobium-titanium (NbTi) cables, which become superconducting below a temperature of 10 K (–263.2°C), that is, they conduct electricity without resistance. In fact, the LHC will operate at 1.9 K (–271.3°C), which is even lower than the temperature of outer space (2.7 K or –270.5°C). A current of 11 700 A flows in the dipoles, to create the high magnetic field of 8.3 T, required to bend the 7 TeV beams around the 27-km ring of the LHC. If the magnets were made to work at a temperature of 4.5 K (-268.7°C), they would produce a magnetic field of only 6.8 T. For comparison, the total maximum current for an average family house is about 100 A.

The temperature of 1.9 K (−271.3°C) is reached by pumping super-fluid helium into the magnet systems. Each dipole is 15 m long and weighs around 35 t.

> *The magnet coils for the LHC are wound from a cable consisting of up to 36 twisted 15-mm strands, each strand being made up in turn of up to 6400 individual filaments, each filament having a diameter as small as 7 micrometres (for comparison, a human hair is about 50 micrometres thick). The 27-km circumference of the LHC calls for some 7600 km of cable, corresponding to about 270 000 km of strand — enough to circle the Earth six times at the Equator. If all the component filaments were unravelled, they would stretch to the Sun and back five times with enough left over for a few trips to the Moon (see Fact 2, page 52).*

What is so special about the cryogenic system?

The LHC is the largest cryogenic system in the world and one of the coldest places on Earth. Such a cold temperature is required to operate the magnets that keep the protons on course (see question: "*what is so special about the LHC dipoles?*"). To maintain its 27-km ring (4700 tonnes of material in each of the eight sectors) at superfluid helium temperature (1.9 K, −271.3°C), the LHC's cryogenic system will have to supply an unprecedented total refrigeration capacity — some 150 kW for refrigerators at 4.5 K and 20 kW for those at 1.9 K. The layout for the refrigeration system is based on five 'cryogenic islands'. Each 'island' must distribute the coolant and carry kilowatts of refrigeration over a long distance. The whole cooling process will take a few weeks.

The refrigeration process happens in three phases:

1) cool down to 4.5 K (-268.7ºC),

2) filling with liquid helium of the magnet cold masses

3) final cool down to 1.9 K (-271.3ºC).

The first phase happens in two steps: first helium is cooled in the refrigerators' heat exchangers to 80 K by using about 10 000 t of liquid nitrogen. Then refrigerator turbines bring the helium temperature down to 4.5 K (-268.7ºC), ready for injection into the magnets' cold masses. Once the magnets are filled, the refrigeration units bring the temperature down to 1.9 K (-271.3ºC). In total, about 120 t of helium will be needed, of which about 90 t will be used in the magnets and the rest in the pipes and refrigerator units.

Liquid nitrogen is never directly injected into the LHC to avoid any possible source of asphyxiation in the underground tunnel.

Why superfluid helium?

The choice of the operating temperature for the LHC has as much to do with the 'super' properties of helium as with those of the superconducting niobium-titanium alloy in the magnet coils. At atmospheric pressure helium gas liquefies at around 4.2 K (−269.0 °C), but when it is cooled further it undergoes a second phase change at about 2.17 K (−271.0 °C) to its 'superfluid' state. Among many remarkable properties, superfluid helium has a very high thermal conductivity, which makes it the coolant of choice for the refrigeration and stabilization of large superconducting systems (see also question : "*What is so special about the cryogenic system?*").

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In all, LHC cryogenics will need some 40 000 leak-tight pipe junctions, and 120 t of helium will be required by the LHC machine to keep the magnets at their operating temperature of 1.9 K. 60% of the helium will be in the magnet cold masses while the remaining 40% will be shared between the distribution system and the refrigerators. During normal operation most of the helium will circulate in closed refrigeration loops. Nevertheless, each year, a certain percentage of the inventory could be lost due to facility stops, leakage to the atmosphere, conditioning of installations and operational problems.

Why do we talk about bunches?

The protons of the LHC circulate around the ring in well-defined bunches. The bunch structure of a modern accelerator is a direct consequence of the radio frequency (RF) acceleration scheme. Protons can only be accelerated when the RF field has the correct orientation when particles pass through an accelerating cavity, which happens at well specified moments during an RF cycle.

In the LHC, under nominal operating conditions, each proton beam has 2808 bunches, with each bunch containing about 10^{11} protons.

The bunch size is not constant around the ring. Each bunch, as it circulates around the LHC, gets squeezed and expanded—for instance it gets squeezed as much as possible around the interaction points to increase the probability of a collision. Bunches of particles measure a few centimetres long and a millimetre wide when they are far from a collision point. However, as they approach the collision points, they are squeezed to about 16 μm (a human hair is about 50 μm thick) to allow for a greater chance of proton-proton collisions. Increasing the number of bunches is one of the ways to increase luminosity in a machine. The LHC uses a bunch spacing of

25 ns (or about 7 m), which introduces many technical challenges. (The LHC's predecessor, LEP, operated with as few as 4 bunches).

> *The bunch spacing of 25 ns corresponds to a frequency of 40 MHz, which implies that bunches should pass each of the collision points in the LHC 40 million times a second. However, for practical reasons there are several bigger gaps in the pattern of bunches, which allow time for example for the 'kicker' magnets to come on in order to inject or dump beam. The average crossing rate is equal to the total number of bunches multiplied by the number of turns round the LHC per second: 2808 × 11245 = 31.6 MHz.*

How many collisions per second take place at the LHC?

Each beam will consist of nearly 3000 bunches of particles and each bunch will contain as many as 100 billion particles. The particles are so tiny that the chance of any two colliding is very small. When the bunches cross, there will be only about 20 collisions between 200 billion particles. Bunches will cross on average about 30 million times per second (see previous question), so the LHC will generate up to 600 million particle collisions per second.

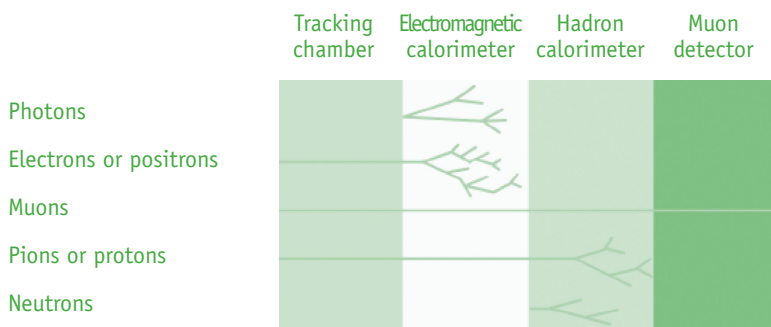## How long do the beams last in the accelerator?

A beam might circulate for 10 hours, travelling more that 10 billion kilometres, enough to get to the planet Neptune and back again. At near light-speed, a proton in the LHC will make 11 245 circuits every second.

How do we see particles?

For each collision, the physicist's goal is to count, track and characterize all the different particles that were produced in order to reconstruct the process in full. Just the track of the particle gives much useful information, especially if the detector is placed inside a magnetic field: the charge of the particle, for instance, will be obvious since particles with positive electric charge will bend one way and those with negative charge will bend the opposite way. Also the momentum of the particle (the 'quantity of motion', which is equal to the product of the mass and the velocity) can be determined: very high momentum particles travel in almost straight lines, low momentum particles make tight spirals.

	Tracking chamber	Electromagnetic calorimeter	Hadron calorimeter	Muon detector
Photons				
Electrons or positrons				
Muons				
Pions or protons				
Neutrons				

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What are the detectors at the LHC?

There are six experiments installed at the LHC: A Large Ion Collider Experiment (ALICE), ATLAS, the Compact Muon Solenoid (CMS), the Large Hadron Collider beauty (LHCb) experiment, the Large Hadron Collider forward (LHCf) experiment and the TOTal Elastic and diffractive cross section Measurement (TOTEM) experiment. ALICE, ATLAS, CMS and LHCb are installed in four huge underground caverns built around the four collision points of the LHC beams. TOTEM will be installed close to the CMS interaction point and LHCf will be installed near ATLAS.

What is ALICE?

ALICE is a detector specialized in analysing lead-ion collisions. It will study the properties of quark-gluon plasma, a state of matter where quarks and gluons, under conditions of very high temperatures and densities, are no longer confined inside hadrons. Such a state of matter probably existed just after the Big Bang, before particles such as protons and neutrons were formed. The international collaboration includes more than 1500 members from 104 institutes in 31 countries (July 2007).

Size	26 m long, 16 m high, 16 m wide
Weight	10 000 tonnes
Design	central barrel plus single arm forward muon spectrometer
Material cost	115 MCHF
Location	St Genis-Pouilly, France.

For more information, visit: http://aliceinfo.cern.ch/Public/

What is ATLAS?

ATLAS is a general-purpose detector designed to cover the widest possible range of physics at the LHC, from the search for the Higgs boson to supersymmetry (SUSY) and extra dimensions. The main feature of the ATLAS detector is its enormous doughnut-shaped magnet system. This consists of eight 25-m long superconducting magnet coils, arranged to form a cylinder around the beam pipe through the centre of the detector. ATLAS is the largest-volume collider-detector ever constructed. The collaboration consists of more than 1900 members from 164 institutes in 35 countries (April 2007).

Size	46 m long, 25 m high and 25 m wide
Weight	7000 tonnes
Design	barrel plus end caps
Material cost	540 MCHF
Location	Meyrin, Switzerland.

For more information, visit: http://atlas.ch/

What is CMS?

CMS is a general-purpose detector with the same physics goals as ATLAS, but different technical solutions and design. It is built around a huge superconducting solenoid. This takes the form of a cylindrical coil of superconducting cable that will generate a magnetic field of 4 T, about 100 000 times that of the Earth. More than 2000 people work for CMS, from 181 institutes in 38 countries (May 2007).

Size	21 m long, 15 high m and 15 m wide.
Weight	12 500 tonnes
Design	barrel plus end caps
Material cost	500 MCHF
Location	Cessy, France.

For more information, visit: http://cmsinfo.cern.ch/outreach/

What is LHCb?

LHCb specializes in the study of the slight asymmetry between matter and antimatter present in interactions of B-particles (particles containing the b quark). Understanding it should prove invaluable in answering the question: "Why is our Universe made of the matter we observe?" Instead of surrounding the entire collision point with an enclosed detector, the LHCb experiment uses a series of sub-detectors to detect mainly forward particles. The first sub-detector is built around the collision point, the next ones stand one behind the other, over a length of 20 m. The LHCb collaboration has more than 650 members from 47 institutes in 14 countries (May 2007).

Size	21m long, 10m high and 13m wide
Weight	5600 tonnes
Design	forward spectrometer with planar detectors
Material cost	75 MCHF
Location	Ferney-Voltaire, France.

For more information, visit: http://lhcb.web.cern.ch/lhcb/

What is LHCf?

LHCf is a small experiment that will measure particles produced very close to the direction of the beams in the proton-proton collisions at the LHC. The motivation is to test models used to estimate the primary energy of the ultra high-energy cosmic rays. It will have detectors 140 m from the ATLAS collision point. The collaboration has 21 members from 10 institutes in 6 countries (May 2007).

Size	two detectors, each measures 30 cm long, 10 cm high, 10 cm wide
Weight	40 kg each
Location	Meyrin, Switzerland (near ATLAS).

What is TOTEM?

TOTEM will measure the effective size or 'cross-section' of the proton at LHC. To do this TOTEM must be able to detect particles produced very close to the LHC beams. It will include detectors housed in specially designed vacuum chambers called 'Roman pots', which are connected to the beam pipes in the LHC. Eight Roman pots will be placed in pairs at four locations near the collision point of the CMS experiment. TOTEM has more than 70 members from 10 institutes in 7 countries (May 2007).

Size	440 m long, 5 m high and 5 m wide
Weight	20 tonnes
Design	roman pot and GEM detectors and cathode strip chambers
Material cost	6.5 MCHF
Location	Cessy, France (near CMS)

For more information visit: http://totem.web.cern.ch/Totem/

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What dictates the general shape of the LHC particle detectors?

A modern general-purpose high-energy physics detector, such as ATLAS or CMS, needs to be hermetic, so that there is only a small probability of a (detectable) particle escaping undetected through a region that is not instrumented. For engineering convenience, most modern detectors at particle colliders like the LHC adopt the 'barrel plus endcaps' design where a cylindrical detector covers the central region and two flat circular 'endcaps' cover the angles close to the beam (the forward region). ALICE and LHCb have asymmetric shapes as they focus on more specific areas of physics.

What are the main components of a detector?

The purpose of the large detectors installed at the LHC is to identify the secondary particles produced in collisions, and to measure their positions in space, their charges, speed, mass and energy. To do this, the detectors have many layers or 'sub-detectors' that each have a particular role in the reconstruction of collisions. A magnet system completes the design. Its function is to separate the different particles according to their charge and to allow the measurement of their momentum — a physical quantity linked to the mass and speed of the particle.

There are two important categories of subdetector:

▶ **Tracking devices** reveal the tracks of electrically charged particles through the trails they leave by ionizing matter. In a magnetic field they can be used to measure the curvature of a particle's trajectory and hence the particle's momentum. This can help in identifying the particle. Most modern tracking devices do not make the tracks directly visible. Instead, they produce electrical signals that can be recorded as computer data. A computer program reconstructs the patterns of tracks recorded.

Two specialized types of tracking devices are vertex detectors and muon chambers. Vertex detectors are located close to the interaction point (primary vertex); muon chambers are located at the outer layers of a detector assembly because muons are the only charged particles able to travel through metres of dense material.

There are two main techniques used to build tracking devices:

▸ *Gaseous chambers, where the medium ionized is a gas and the ions or electrons are collected on electrodes usually in the form of wires or pads under strong electric fields. In drift chambers, the position of the track is found by timing how long the electrons take to reach an anode wire, measured from the moment that the charged particle passed through. This results in higher spatial resolution for wider wire separation: drift cells are typically several centimetres across, giving a spatial resolution of 50-100 μm. In a time projection chamber the drift volume is much larger, up to 2 m or more, and the sense wires are arranged on one end face.*

▸ *Semiconductor detectors, where the particle creates electrons and holes as it passes through a reverse-biased semiconductor, usually silicon. The devices are subdivided into strips or pixels; typical resolution is 10 μm.*

▶ **Calorimeters** are devices that measure the energy of particles by stopping them and measuring the amount of energy released. There are two main types of calorimeter: electromagnetic (ECAL) and hadronic (HCAL). They use different materials depending on which type of particle they are stopping. The ECAL generally fully absorbs electrons and photons, which interact readily through the electromagnetic force. Strongly interacting particles (hadrons), such as protons and pions, may begin to lose energy in the ECAL but will be stopped in the HCAL. Muons (and neutrinos) will pass through both layers. Calorimeters provide the main way to identify neutral particles such as photons and neutrons; although they are not visible in tracking devices, they are revealed by the energy they deposit in the calorimeters.

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> *Calorimeters typically consist of layers of 'passive' or 'absorbing' high density material (lead for instance) interleaved with layers of 'active' medium such as solid lead-glass or liquid argon.*

Detectors also often have sub-detectors measuring the speed of charged particles, an essential factor for particle identification.

> *There are two important methods for measuring the velocity of particles:*
>
> ▸ *Cherenkov radiation: when a charged particle traverses a medium above a certain velocity, it emits photons at a specific angle that depends on the velocity. When combined with a measurement of the momentum of the particle the velocity can be used to determine the mass and hence to identify the particle. For Cherenkov emission to occur the particle must be travelling faster than the speed of light in the medium.*
>
> ▸ *Transition radiation: when a relativistic charged particle traverses an inhomogeneous medium, in particular the boundary between materials with different electrical properties, it emits radiation more or less in proportion to its energy. This allows particle types to be distinguished from each other.*

What will be the Higgs boson production rate at the LHC?

Although the particle collision rate at the LHC will be very high, the production rate of the Higgs will be so small that physicists expect to have enough statistics only after about 2-3 years of data-taking. The Higgs boson production rate strongly depends on the theoretical model and calculations used to evaluate it. Under good conditions, there is expected to be about one every few hours per experiment. The same applies to supersymmetric particles. Physicists expect to have the first meaningful results in about one year of data-taking at full luminosity.

The LHC experiments represent about 150 million sensors delivering data 40 million times per second. After filtering there will be about 100 collisions of interest per second.
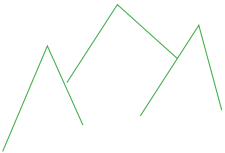
The data flow from all four experiments will be about 700 MB/s, that is around 15 000 000 GB (=15 PB) per year, corresponding to a stack of CDs about 20 km tall each year. This enormous amount of data will be accessed and analysed by thousands of scientists around the world. The mission of the LHC Computing Grid is to build and maintain a data storage and analysis infrastructure for the entire high-energy physics community that will use the LHC.

▶ *ATLAS will produce 320 MB/s*

▶ *CMS will produce 220 MB/s*

▶ *LHCb will produce 50 MB/s*

▶ *ALICE will produce 100 MB/s*

Sounding balloon (30 km)

CD stack with 1 year LHC data! (~ 20 Km)

Concorde (15 km)

Mont-Blanc (4.8 km)

faq

What is the LHC power consumption?

It is around 120 MW (230 MW for all CERN), which corresponds more or less to the power consumption for households in the Canton (State) of Geneva. Assuming an average of 270 working days for the accelerator (the machine will not work in the winter period), the estimated yearly energy consumption of the LHC in 2009 is about 800 000 MWh. This includes site base load and the experiments. The total yearly cost for running the LHC is therefore, about 19 million Euros. CERN is supplied mainly by the French company EDF (Swiss companies EOS and SIG are used only in case of shortage from France).

A large fraction of the LHC electrical consumption will be to keep the superconducting magnet system at the operating temperatures (1.8 and 4.2 K) depending on the magnets. Thanks to the superconducting technology employed for its magnets, the nominal consumption of the LHC is not much higher than that of the Super Proton Synchrotron (SPS), even though the LHC is much larger and higher in energy.

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Are the LHC collisions dangerous?

The LHC can achieve energies that no other particle accelerators have reached before. The energy of its particle collisions has previously only been found in Nature. And it is only by using such a powerful machine that physicists can probe deeper into the key mysteries of the Universe. Some people have expressed concerns about the safety of whatever may be created in high-energy particle collisions. However there are no reasons for concern.

▶ *Unprecedented energy collisions?* On Earth only! Accelerators only recreate the natural phenomena of cosmic rays under controlled laboratory conditions. Cosmic rays are particles produced in outer space in events such as supernovae or the formation of black holes, during which they can be accelerated to energies far exceeding those of the LHC. Cosmic rays travel throughout the Universe, and have been bombarding the Earth's atmosphere continually since its formation 4.5 billion years ago. Despite the impressive power of the LHC in comparison with other accelerators, the energies produced in its collisions are greatly exceeded by those found in some cosmic rays. Since the much higher-energy collisions provided by nature for billions of years have not harmed the Earth, there is no reason to think that any phenomenon produced by the LHC will do so. Cosmic rays also collide with the Moon, Jupiter, the Sun and other astronomical bodies. The total number of these collisions is huge compared to what is expected at the LHC. The fact that planets and stars remain intact strengthens our confidence that LHC collisions are safe. The LHC's energy, although powerful for an accelerator, is modest by nature's standards.

▶ *Mini big bangs?* Although the energy concentration (or density) in the particle collisions at the LHC is very high, in absolute terms the energy involved is very low compared to the energies we deal with every day or with the energies involved in the collisions of cosmic rays. However, at the very small scales of the proton beam, this energy concentration reproduces the energy density that existed just a few moments after the Big Bang—that is why collisions at the LHC are sometimes referred to as mini big bangs.

▶ *Black holes?* Massive black holes are created in the Universe by the collapse of massive stars, which contain enormous amounts of gravitational energy that pulls in surrounding matter. The gravitational pull of a black hole is related to the amount of matter or energy it contains — the less there is, the weaker the pull. Some physicists suggest that microscopic black holes could be produced in the collisions at the LHC. However, these would only be created with the energies of the colliding particles (equivalent to the energies of mosquitoes), so no microscopic black holes produced inside the LHC could generate a strong enough gravitational force to pull in surrounding matter. If the LHC can produce microscopic black holes, cosmic rays of much higher energies would already have produced many more. Since the Earth is still here, there is no reason to believe that collisions inside the LHC are harmful.

> *Black holes lose matter through the emission of energy via a process discovered by Stephen Hawking. Any black hole that cannot attract matter, such as those that might be produced at the LHC, will shrink, evaporate and disappear. The smaller the black hole, the faster it vanishes. If microscopic black holes were to be found at the LHC, they would exist only for a fleeting moment. They would be so short-lived that the only way they could be detected would be by detecting the products of their decay.*

▶ *Strangelets?* Strangelets are hypothetical small pieces of matter whose existence has never been proven. They would be made of 'strange quarks' — heavier and unstable relatives of the basic quarks that make up stable matter. Even if strangelets do exist, they would be unstable. Furthermore, their electromagnetic charge would repel normal matter, and instead of combining with stable substances they would simply decay. If strangelets were produced at the LHC, they would not wreak havoc. If they exist, they would already have been created by high-energy cosmic rays, with no harmful consequences.

▶ *Radiation?* Radiation is unavoidable at particle accelerators like the LHC. The particle collisions that allow us to study the origin of matter also generate radiation. CERN uses active and passive protection means, radiation monitors and various procedures to ensure that radiation exposure to the staff and the surrounding population is as low as possible and well below the international regulatory limits. For comparison, note that natural radioactivity — due to cosmic rays and natural environmental radioactivity — is about 2400 μSv/year in Switzerland. A round trip Europe–Los Angeles flight accounts for about 100 μSv. The LHC tunnel is housed 100 m underground, so deep that both stray radiation generated during operation and residual radioactivity will not be detected at the surface. Air will be pumped out of the tunnel and filtered. Studies have shown that radioactivity released in the air will contribute to a dose to members of the public of no more than 10 μSv/year.

> *CERN's guidelines for the protection of the environment and personnel comply with the Swiss and French National Legislations and with the European Council Directive 96/29/EURATOM. In both the Swiss and French legislations under no circumstances can professional activities lead to an effective dose of more than 20 mSv per year for occupationally exposed persons and more than 1 mSv per year for persons not occupationally exposed and for members of the public.*

What are the rules regarding access to the LHC?

Outside beam operation, the larger part of the LHC tunnel will be only weakly radioactive, the majority of the residual dose rates being concentrated in specific parts of the machine, such as the dump caverns — where the full beam is absorbed at the end of each physics period — and the regions where beams are collimated.

Only a selection of authorized technical people will be able to access the LHC tunnel. A specialized radiation protection technician will access it first and measure the dose rate at the requested intervention place, to assess when, and for how long, the intervention can take place.

What is the helium consumption at the LHC?

The exact amount of helium loss during operation of the LHC is not yet known. The actual value will depend on many factors, such as how often there are magnet quenches, power cuts and other problems. What is well known is the amount of helium that will be needed to cool down the LHC and fill it for first operation. This amount is around 120 t.

What happens if the beam becomes unstable?

The energy stored in the LHC beams is unprecedented, threatening to damage accelerator equipment in case of uncontrolled beam loss, so everything is done to ensure that this never happens. Safe operation of the LHC requires correct operation of several systems: collimators and beam absorbers, a beam dumping system, beam monitoring, beam interlocks, and quench protection systems. If the beam becomes unstable the beam loss sensors will detect it and within three revolutions (< 0.3 ms) a set of magnets will extract the beam from the LHC. The beam will then travel through a special tunnel to the beam stop block, which is the only item in the LHC that can withstand the impact of the full beam. The core of the stop block is made of a stack of various graphite plates with different densities.

The total energy in each beam at maximum energy is about 350 MJ, which is about as energetic as a 400 t train, like the French TGV, travelling at 150 km/h. This is enough energy to melt around 500 kg of copper. The total energy stored in the LHC magnets is some 30 times higher (11 GJ).

10 Fascinating Facts about the LHC

Fact 1) *When the 27-km long circular tunnel was excavated, between Lake Geneva and the Jura mountain range, the two ends met up to within 1 cm.*

Fact 2) *Each of the 6400 superconducting filaments of niobium–titanium in the cable produced for the LHC is about 0.007 mm thick, about 10 times thinner than a normal human hair. If you added all the filaments together they would stretch to the Sun and back five times with enough left over for a few trips to the Moon.*

Fact 3) *All protons accelerated at CERN are obtained from standard hydrogen. Although proton beams at the LHC are very intense, only 2 nanograms of hydrogen(*) are accelerated each day. Therefore, it would take the LHC about 1 million years to accelerate 1 gram of hydrogen.*

Fact 4) *The central part of the LHC will be the world's largest fridge. At a temperature colder than deep outer space, it will contain iron, steel and the all important superconducting coils.*

Fact 5) *The pressure in the beam pipes of the LHC will be about ten times lower than on the Moon. This is an ultrahigh vacuum.*

Fact 6) *Protons at full energy in the LHC will be travelling at 0.999999991 times the speed of light. Each proton will go round the 27 km ring more than 11 000 times a second.*

Fact 7) *At full energy, each of the two proton beams in the LHC will have a total energy equivalent to a 400 t train (like the French TGV) travelling at 150 km/h. This is enough energy to melt 500 kg of copper.*

Fact 8) *The Sun never sets on the ATLAS collaboration. Scientists working on the experiment come from every continent in the world, except Antarctica.*

Fact 9) *The CMS magnet system contains about 10 000 t of iron, which is more iron than in the Eiffel Tower.*

Fact 10) *The data recorded by each of the big experiments at the LHC will be enough to fill around 100 000 DVDs every year.*

*(*)the total mass of protons is calculated at rest.*

Appendix 1

Scheme of filling, magnetic field and particle current in PSB, PS and SPS

1.2 s

3.6 s

SPS Magnetic field

SPS particle current

PS Magnetic field

PS particle current

PSB Magnetic field

PSB particle current
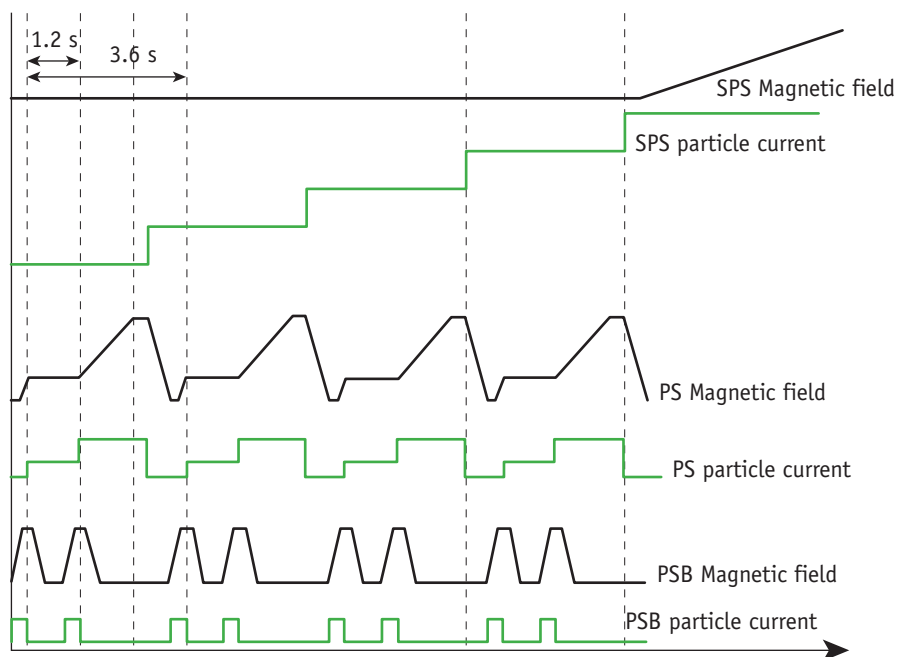
Appendix 2

Scheme of filling, magnetic field and particle current in SPS and LHC

21.6 s

SPS Magnetic field

Particle current in SPS

Particle current in one LHC ring
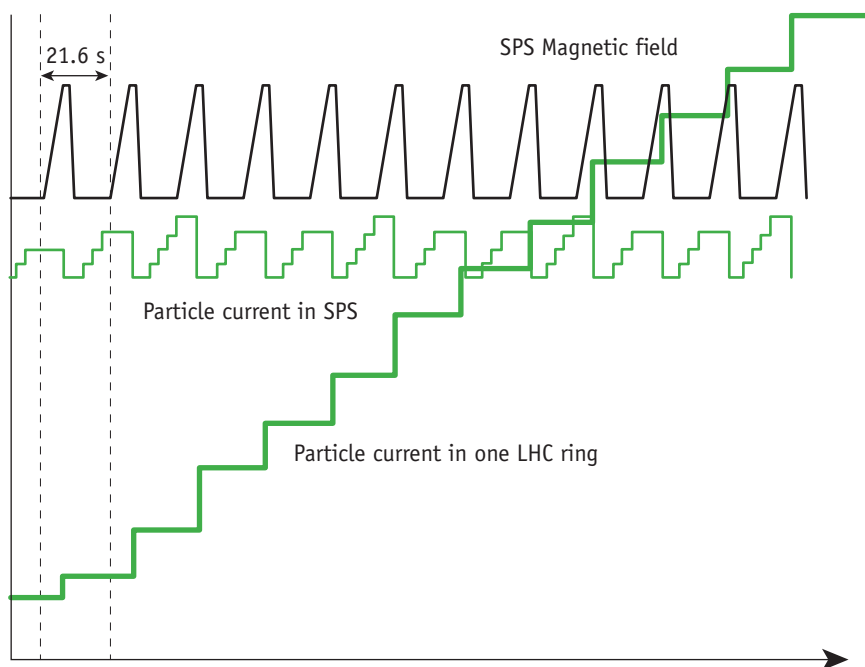
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