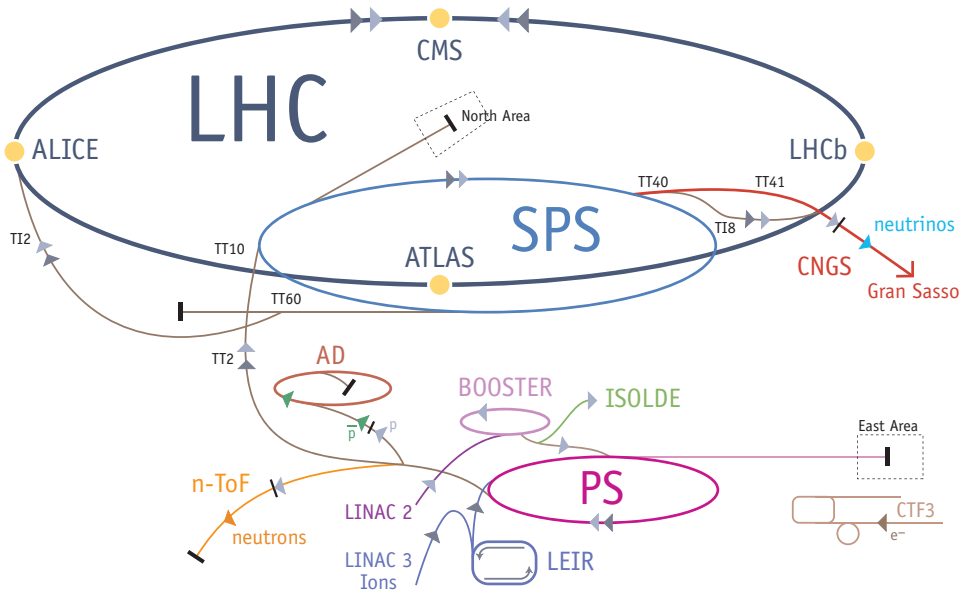


# CERN

# faq

## LHC

## the guide

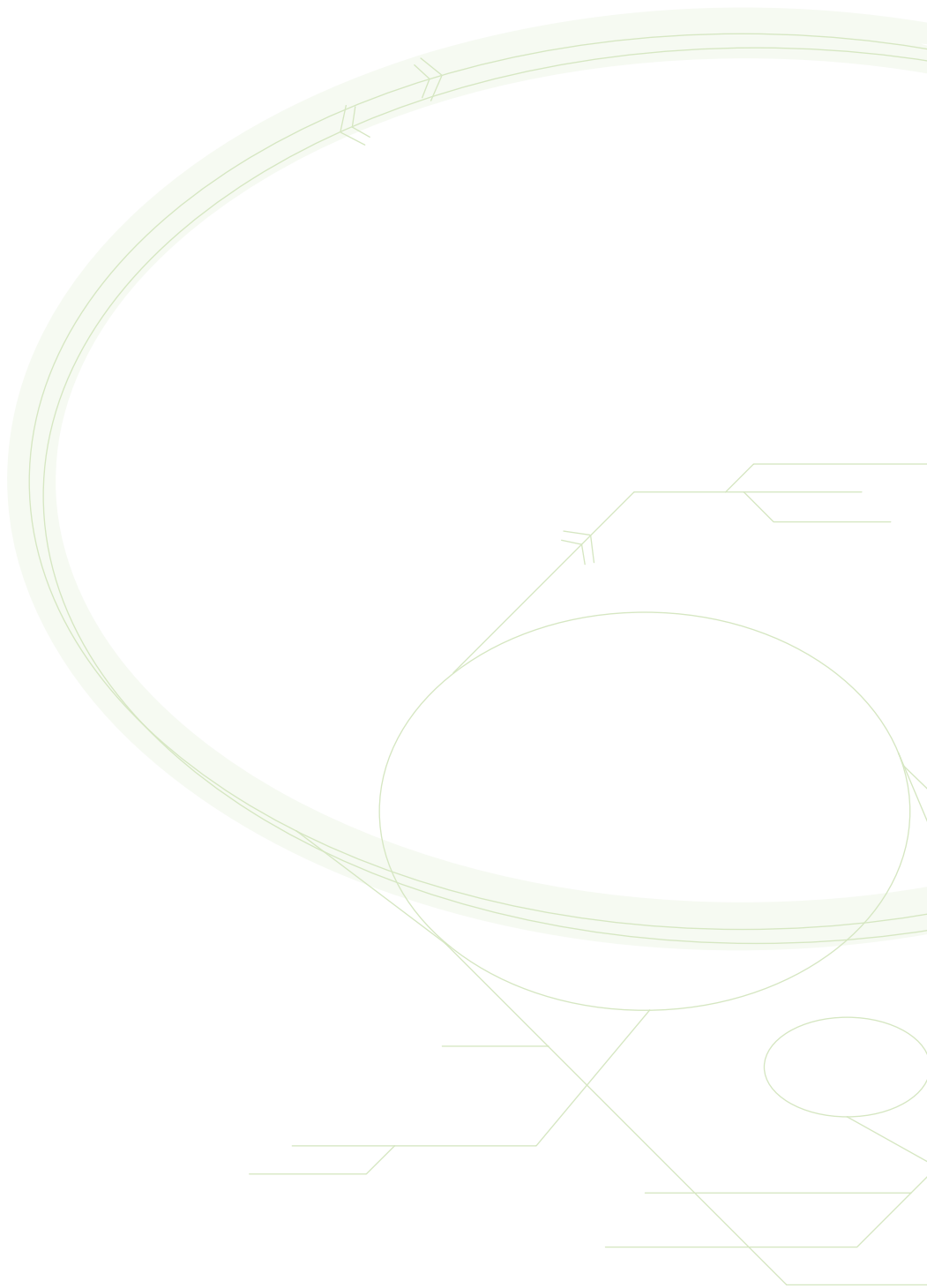




# CERN

## **LHC** the guide

*faq*  
*frequently asked questions*



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# Introduction

# faq

*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'.*

## Powers of ten

The powers of ten are commonly used in physics. 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	$\mu$ (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)

## 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 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 weighting 1 kg and falling from a height of 1 m, that is: 9.8 joules =  $6.1 \times 10^{19}$  electronvolts.

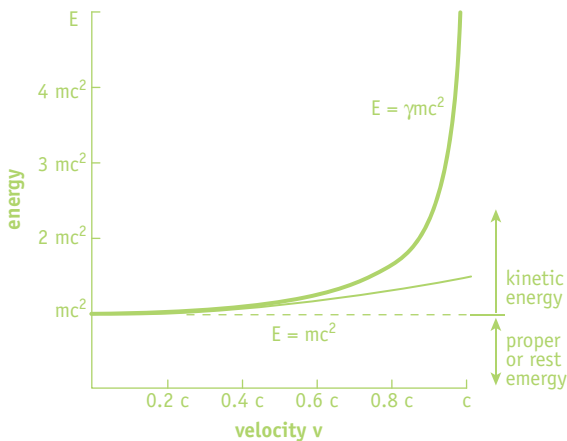
*The definition of the electronvolt comes from the simple insight that a single electron accelerated by a potential difference of 1 volt will have a discreet amount of energy,  $E=qV$  joules, where  $q$  is the charge on the electron in coulombs and  $V$  is the potential difference in volts. Hence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



# 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  $\gamma$  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](http://www.phys.unsw.edu.au/einsteinlight/jw/module5_equations.htm)

Kinetic energy of a proton (K)	Speed (%c)
50 MeV	31.4
1.4 GeV	91.6
25 GeV	99.93
450 GeV	99.9998
7 TeV	99.9999991

Relationship between kinetic energy and speed.  
The rest mass of the proton is  $0.938 \text{ GeV}/c^2$

## 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, each of the LHC’s injectors has its own experimental hall, where the beams are used for experiments at lower energies.

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

- ▶ *Hydrogen atoms are taken from a standard hydrogen bottle. We get protons by stripping orbiting electrons off 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 anticlockwise direction, the filling time is 4'20" per LHC ring) where they are accelerated for 20 minutes to their nominal 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.

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  $Pb^{27+}$ . 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.



# LHC in general

# faq

## 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 around the machine's circumference.

*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').*

## When was it designed?

Back in the early 1980s, while the Large Electron-Positron (LEP) collider was being designed and built, groups at CERN were 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 States 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 the official approval and construction work commenced on the four sites.

## How much does it cost?

The cost for the machine alone is about 4.7 billion of CHF (3 billion Euro). The total project cost breaks down roughly as follows:

- ▶ 4.7 billion CHF (3.03 billion Euro) total cost of the accelerator
- ▶ 1.1 billion CHF (0.71 billion Euro) total CERN contribution to the experiments (about 20% of the detector costs, supported by large collaborations of institutes worldwide)
- ▶ 0.25 billion CHF (0.16 billion Euro) total contribution to computing.

The experimental collaborations are individual entities, funded independently from CERN. CERN is a member of each experiment, and contributes to the budget of each at the 20% level.

*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 on 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 radio-frequency 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 accelerators 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 ( $E = E_{\text{beam1}} + E_{\text{beam2}}$ ), whereas in the second, it is proportional to the square root of the energy of the particle hitting the target ( $E = \sqrt{E_{\text{beam}}}$ ).*

## Why hadrons?

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 particles: 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 to be stable. 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, to obtain the highest-energy collisions it is better 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, that is, an increase in the energy that must be provided by the accelerating machine.*



## Why is the LHC built underground?

The LHC re-uses the tunnel that was built for CERN's previous big accelerator, LEP, dismantled in 2000. At the time when LEP was built, the underground tunnel was the best solution to house a 27 km circumference machine because it was 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 to that, the Earth's crust provides good shielding for radiation.

The LHC is 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 (lake Geneva site).

*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 problems and 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 already existing pilot tunnel*
- ▶ *the position of LEP was also constrained by the links to the SPS. As Points 2 and 3 were already fixed, there was only one degree of freedom (tilt). The angle was obtained by reducing the depth of the shafts as much as possible.*

## Will

### the LHC beam energy be influenced by the Moon, the Geneva lake and the TGV as was the case for the previous accelerator?

The LHC beam energy will be influenced by the Moon and the lake in much the same way as LEP was. The experiments are not so concerned with the absolute energy but we will have to take the tidal variations into account at injection. Because of the magnet design, the currents from the TGV should not be an issue for the LHC.

*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). This variation in its circumference produces changes in beam energy of up to two tenths of one in a thousand!*

*It may seem small, but measurements in the LHC are so precise that the beam energy must be known down to two hundredths of one in a thousand, ten times smaller than the effect of ground tides.*

*Thus, physicists must take the Moon into account in their measurements.*

## 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. Theories we currently use to describe it leave many unsolved questions. The reason why elementary particles – ‘point-like’ objects with no internal structure known so far – have mass and why their masses are different are among the most perplexing questions. The answer may be the so-called Higgs mechanism. The Higgs field has at least one new particle associated with it, the Higgs boson. If such a particle exists, the LHC will be able to detect it.

*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 strongly with the Higgs field are heavy, while those that have weak interactions are light.*

A very popular idea that could partly explain why all the matter we see in the Universe counts for only 4% of the total mass, is called supersymmetry, or SUSY. SUSY predicts that for each known particle there is a ‘supersymmetric’ partner. If SUSY is right, then supersymmetric particles should be found at the LHC.

*By using powerful telescopes, both on the ground and in orbit, we have found that all the visible matter counts for only 4% of the Universe. The search is open for particles or phenomena responsible for dark matter (23%) and dark energy (73%).*

The LHC will also help us to solve the mystery of antimatter. Matter and antimatter must have been produced in the same amounts at the time of the Big Bang. From what we have observed so far, our Universe is made of only matter. Why? The LHC could 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 our Universe come from the analysis of the diffuse cosmic gamma-rays arriving on Earth and the density fluctuations of the cosmic microwave background radiation. If one assumes that after the Big Bang, the Universe separated somehow into different domains where either matter or antimatter was dominant, then at the boundaries there should be annihilations, producing cosmic gamma-rays. In both cases the limit proposed by current theories is practically equivalent to saying that there is no antimatter in our Universe.*



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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 internal pressure at the LHC will be  $10^{-13}$  atm (ultrahigh vacuum), because we want to avoid collisions with gas molecules. There is  $\sim 6500 \text{ m}^3$  of pumped volume in the LHC, like pumping down 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 9300 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 either have 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 chances 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 ( $-268.7^\circ\text{C}$ ) (the LHC magnets will use superfluid helium at 1.8 K or  $-271.4^\circ\text{C}$ ). 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.

This table lists the important quantities for the LHC.

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9300
Number of dipoles	1232
Number of quadrupoles	858
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	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	$1.1 \times 10^{11}$
Number of turns per second	11 245
Number of collisions per second	600 million

(\*) Energy per nucleon

## 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 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 ( $-263.2^{\circ}\text{C}$ ), that is, they conduct electricity without resistance. In fact, the LHC will operate at the still lower temperature of 1.9 K ( $-271.3^{\circ}\text{C}$ ), which is even lower than the temperature of outer space (2.7 K or  $-270.5^{\circ}\text{C}$ ). A current of 11 700 A flows in the dipoles, to create the high magnetic field of 8.4 T, required to bend the 7 TeV beams around the 27-km ring of the LHC. For comparison, the total maximum current for an average family house is about 100 A.

The temperature of 1.9 K ( $-271.3^{\circ}\text{C}$ ) is reached by pumping superfluid helium into the magnet systems. Each dipole is 14.3 m long and weighs around 35 t.

*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 ( $-269^{\circ}\text{C}$ ), but when it is cooled further it undergoes a second phase change at about 2.17 K ( $-271^{\circ}\text{C}$ ) 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.*

## What is so special about the cryogenics system?

LHC superconducting magnets will sit in a 1.9 K (-271.3°C) bath of superfluid helium at atmospheric pressure. This bath will be cooled by low-pressure liquid helium flowing in heat-exchanger tubes threaded along the string of magnets. The reliability and effectiveness of this sophisticated cryoloop are key factors in achieving the required magnet performance. Liquid helium is used because it can keep things cool over long distances.

In all, LHC cryogenics will need 40 000 leak-tight pipe junctions, and 96 t of helium will be required by the LHC machine to keep the magnets at their operating temperature (i.e. 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.

Eight refrigerators operating at 18 kW and 4.5 K (-268.7°C) will be used to cool down the LHC machine (36 800 t of mass) in about 2 weeks. There are three main phases: 1) cool down to 4.5 K (-268.7°C), 2) filling with liquid helium of the magnet cold masses and 3) final cool down to 1.9 K (-271.3°C).

*In order to cool the magnets down to 80 K (-193.2°C) (pre-cooling), 10 080 t of liquid nitrogen will be used. Refrigerator turbines will then bring the helium temperature down to 4.5 K (-268.7°C) and fill the magnets with almost 60 t of liquid helium. Once the magnets are filled, the refrigeration units will bring the temperature down to 1.9 K (-271.3°C) by lowering the saturation pressure—and therefore the temperature—of the liquid helium in a heat exchanger in contact with the static pressurized helium of the magnets' cold masses.*

## 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  $16\ \mu\text{m}$  (a human hair is about  $50\ \mu\text{m}$  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 has opted for 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:  $2808 \times 11245 = 31.6\ \text{MHz}$ .*

## 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 among 200 billion particles. Bunches will cross on average about 30 million times per second, 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 than 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.

## 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) and the TOTal Elastic and diffractive cross section Measurement (TOTEM). 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 will have detectors in three different locations along the vacuum chamber of the LHC.

**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 like protons and neutrons were formed. The international collaboration includes more than 1000 members from 94 institutes in 28 countries (March 2006).

**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. It is 46 m long and 25 m high, the largest-volume collider-detector ever constructed. The collaboration consists of more than 1700 members from 159 institutes in 37 countries (March 2006).

**CMS** is also 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. More than 2000 people work for CMS, from 182 institutes in 38 countries (April 2006).

**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?' The LHCb collaboration has more than 650 members from 48 institutes in 13 countries (April 2006).

**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 22 members from 10 institutes in 4 countries (September 2006).

**TOTEM** will measure the effective size or 'cross-section' of the proton at LHC. Also modest in size, TOTEM will be installed near the interaction point used by CMS. It will have detectors in three different locations. In particular, silicon sensors will be the installed in special sections of the vacuum chamber in the LHC tunnel some 200 m away from CMS. TOTEM has 82 members from 11 institutes in 8 countries (2005)



## What dictates the general shape of the LHC particle detectors?

A modern general-purpose high-energy physics detector needs to be hermetic, so that the probability of a (detectable) particle escaping undetected through a region that is not instrumented is small. 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).

## What are the main components of a detector?

The purpose of the large detectors installed at LHC is to identify the secondary particles produced in collisions, and measure their positions in space, their charges and energy. The detectors are divided into ‘sub-detectors’ that each have a particular role in the reconstruction of collisions. There are three categories of subdetectors:

- ▶ **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. A vertex detector is an example of a tracking device that is located close to the interaction point, with a high enough resolution to isolate tracks coming from the interaction point (the primary vertex) or from the later decay of a particle (a secondary vertex). Identifying secondary vertices is important for heavy-flavour physics (involving particles with heavy quarks). Muon chambers are examples of tracking devices located at the outer layers of a detector. Their goal is to detect muons, the only particles able to travel through metres of dense material.

There are two main types of 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 centimeters across, giving a spatial resolution of 50-100 microns. 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 passing particle creates electrons and holes in a reversely-biased semiconductor, usually silicon. The devices are subdivided into strips or pixels. Typical resolution is 10 microns.*

- ▶ **Calorimeters**, 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.*

- ▶ **Particle identification detectors** that use various techniques to identify the type of particle.

*Two methods of particle identification depend on detecting radiation emitted by charged particles.*

- ▶ *Cherenkov radiation: when a charged particle traverses a medium, depending on its velocity, it emits photons at a specific angle that depends on the velocity. 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 that medium.*
- ▶ *Transition radiation: when a relativistic charged particle traverses an inhomogeneous medium, in particular the boundary between materials of 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 is the LHC power consumption?

It is around 120 MW, which corresponds more or less to the power consumption for households in the Canton (State) of Geneva.

## Are the LHC collisions dangerous?

**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?** According to some theoretical models, tiny black holes could be produced in collisions at the LHC. They would then very quickly decay into what is known as Hawking radiation (the tinier the black hole, the faster it evaporates) which would be detected by experiments. Cosmic rays with very much more energy than that available at the LHC could also in principle produce black holes. However no evidence for such phenomena has so far been found.

**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 has various procedures to ensure that radiation exposure to the staff is as low as possible and well below the international standard safety limits. The LHC tunnel is housed 100 m underground, so deep that radiation will not be detected at the surface.

Radiation is everywhere. It is emitted by the Earth and reaches us from space, for example from stars, in particular the Sun. Particles impact the Earth after passing through our atmosphere which acts as a natural shield for many of them. This is a natural, harmless phenomenon.

*Radiation doses rise with altitude: a roundtrip flight from Paris to New York accounts for almost the half of the annual dose you get at the ground's surface at CERN (0.78 mSv per year). If you go on the top of the Mont Blanc, you get 10 times this dose (8.70 mSv per year).*

## What are the rules regarding access to the LHC?

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 will 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 known. The actual value will depend on many factors, such as how often there will be 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 96 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 turns of revolution ( $< 0.3$  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 200 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 6300 superconducting filaments of niobium–titanium in the cable produced for the LHC is about 0.006 mm thick, about 10 times thinner than a normal human hair.

**Fact 3)** 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 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 200 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.

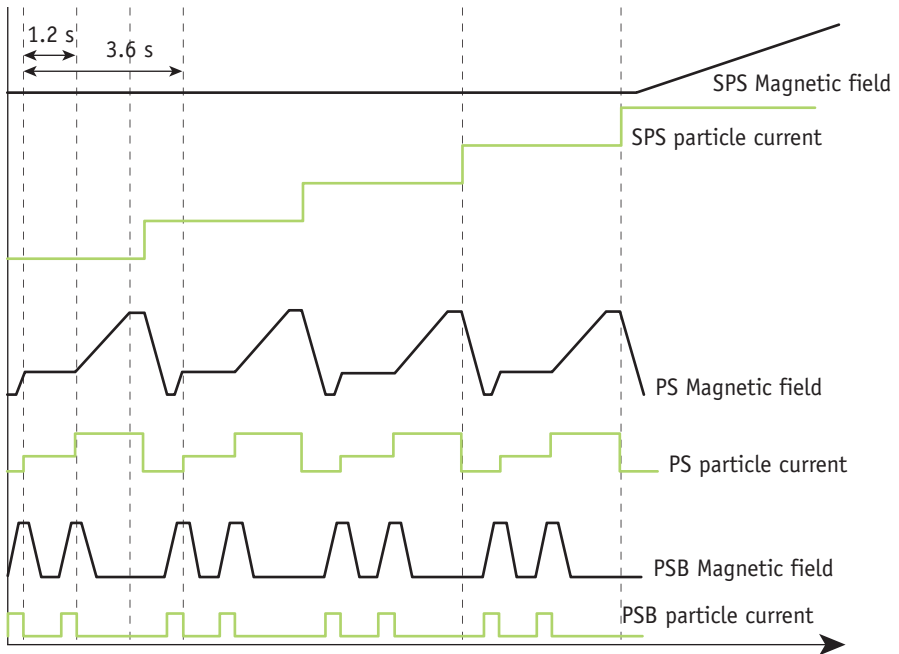
**Fact 9)** The CMS magnet system contains about 10 000 t of iron, which is more iron than in the Eiffel Tower.

**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.



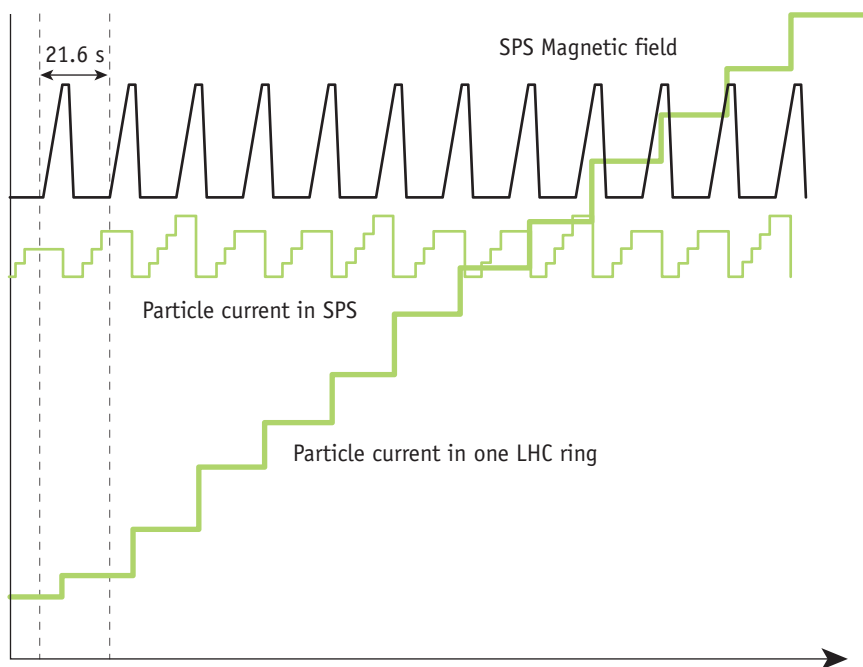
# Appendix 1

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



# Appendix 2

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





*The Publications Section would like to thank those members of the AB, AT and PH Departments who have helped to make this guide possible.*

