Building a behemoth

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The Large Hadron Collider makes extensive use of existing CERN infrastructure but is in many respects an unprecedented undertaking. It is a proton–proton collider; therefore, it requires two separate accelerator rings with magnetic fields of opposite polarity to guide the two beams in opposite directions around its 27-km circumference. In addition, the extraordinary energies and collision rates that it has been designed to attain pose huge challenges for controlling the beam and protecting the accelerator.

The main objective of the Large Hadron Collider (LHC) is to explore the validity of the standard model of particle physics at unprecedented collision energies and rates. The design performance envisages roughly 30 million proton–proton collisions per second, spaced by intervals of 25 ns, with centre-of-mass collision energies of 14 TeV that are seven times larger than those of any previous accelerator. Reaching and maintaining this level of performance means that the LHC collider itself — although building on experiences gained at previous accelerators such as the Tevatron, at Fermilab (Batavia, Illinois), and HERA, at DESY (Hamburg) — requires a range of novel features that stretch existing technologies to the limit.

Colliders can, in principle, be designed for many different particle species (see page 270): electrons, positrons, protons, antiprotons and ions are all used in existing machines. The Tevatron, which at present defines the energy frontier for particle colliders, operates with proton and antiproton beams. By contrast, the Large Electron–Positron Collider (LEP), the last collider project at CERN, used leptons in the form of electron and positron beams. Each choice has its advantages and disadvantages. On the one hand, because leptons are elementary particles, the centre-of-mass collision energies in machines such as the LEP are precisely defined and therefore are well suited to high-precision experiments. On the other hand, the hadrons that are smashed together by the Tevatron and the LHC are composite particles, and the collisions actually occur between constituent quarks and gluons, each carrying only a proportion of the total proton energy. The centre-of-mass energy of these collisions can vary significantly, so they are not as well suited for high-precision experiments. The hadron colliders, however, offer tremendous potential for the discovery of as-yet unknown particles, because they admit the possibility of collisions over a wide range of much higher energies than is otherwise possible. Protons are relatively heavy and so lose less energy than leptons do while following a curved trajectory in a strong magnetic field. This fact, coupled with the use of superconducting magnet technology, allows the construction of a relatively compact and efficient circular machine, in which the particle beams can collide with each other at each turn. During the lifetime of the LHC, it is planned to operate with both proton and heavy-ion (lead) beams. In this review, we discuss the crucial features of the LHC that should ensure the stability and longevity of the machine while it hosts the uniquely violent collisions of these beams.

Collision energy and beam luminosity

The crucial parameters for a collider such as the LHC are the collision energy and the event rate. Taking into account the partitioning of the proton's energy between its constituent particles (that is, quarks and gluons), the choice of a proton beam energy of 7 TeV at the LHC means that average centre-of-mass collision energies will be greater than 1 TeV. To maximize the total number of events seen by the detectors, a high collision rate is also required, meaning in turn high intensities. The production rates that are achievable for antiprotons at present are too low for the design performance of the LHC; therefore, two counter-rotating proton beams are used. As a result, unlike the Tevatron, the LHC needs two separate vacuum chambers with magnetic fields of opposite polarity to deflect the counter-rotating beams in the same direction.

The number of collision events that can be delivered to the LHC experiments is given by the product of the event cross-section (which

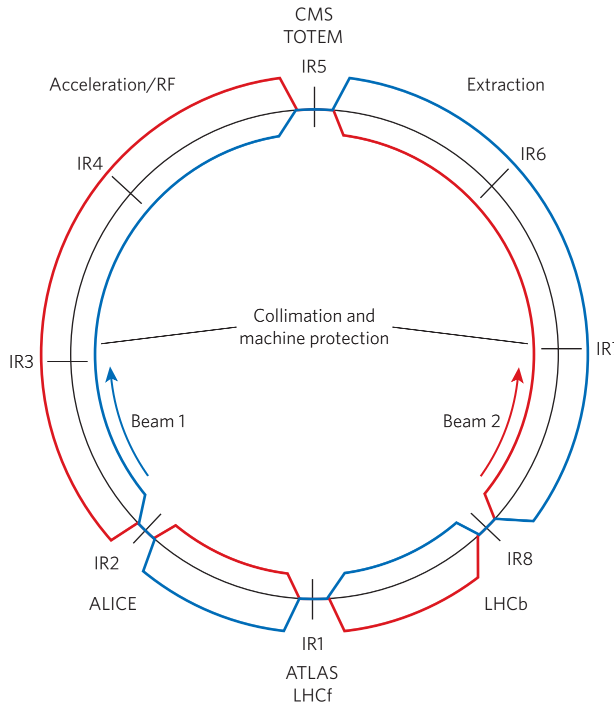

Figure 1 | Layout of the LHC collider. Two proton beams rotate in opposite directions around the ring, crossing at the designated interaction regions (IRs). Four of these (IR1, IR2, IR5 and IR8) contain the various experiments (ALICE, ATLAS, CMS, LHCb, LHCf and TOTEM). IR4 contains the radio-frequency (RF) acceleration equipment, and IR3 and IR7 contain equipment for collimation and for protecting the machine from stray beam particles. IR6 houses the beam abort system, where the LHC beam can be extracted from the machine and its energy absorbed safely.

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is a measure of the probability that a collision will produce a particular event of interest) and the machine luminosity, L. This is determined entirely by the proton beam parameters:

$$L = \frac{f_{\text{rev}} n_{\text{b}} N^2}{\sigma_x \sigma_y} F(\Phi, \sigma_{x,y}, \sigma_s)$$

Here, σ_x and σ_y are the transverse root mean squared (r.m.s.) beam sizes at the interaction points; f_{rev}, the revolution frequency; n_{b}, the number of particle packages ('bunches'); N, the number of particles within each bunch; and F, a geometric reduction factor that depends on the crossing angle of the two beams (Φ), the transverse r.m.s. beam size ($\sigma_{x,y}$) and the r.m.s. bunch length (σ_s). To provide more than one hadronic event per beam crossing, the design luminosity of the LHC has been set to $L = 10^{34}$ cm^{-2}s^{-1}. This translates as 2,808 bunches, each containing 1.15×10^{11} protons, a transverse r.m.s. beam size of 16 μm, an r.m.s. bunch length of 7.5 cm and a total crossing angle of 320 μrad at the interaction points. For the programme involving lead-ion collisions, L will be 10^{27} cm^{-2}s^{-1} at a centre-of-mass energy of 1,148 TeV. In this case, each ring of the LHC will contain 592 bunches, each with 7×10^7 lead ions. The transverse beam sizes will be similar to those of the proton beams.

The LEP tunnel

The LHC features six experiments (Fig. 1): two high-luminosity experiments (ATLAS[1] and CMS[2]); two supplementary experiments at low scattering angles (LHCf[3] and TOTEM[4]), which are near ATLAS and CMS, respectively; one B-meson experiment (LHCb[5]); and one dedicated ion physics experiment (ALICE[6,7]).

To make best use of the existing infrastructure at CERN, the LHC is being built in the 27-km-long LEP tunnel[8]. Approximately 22 km of the LEP tunnel consist of curved sections, or arcs, in which bending dipole magnets can be installed. The remaining 5 km consist of eight straight interaction regions that provide space for the experiments, injection and extraction elements for the proton beams, acceleration devices and dedicated 'cleaning' insertions that collimate the beam and protect the superconducting magnets from stray particles.

Dipoles and quadrupoles

Not all of the tunnel's curved sections can be used for the installation of dipole magnets. In addition to the bending fields of the dipole magnets, a circular accelerator also requires a focusing mechanism that keeps the particles centred on the design orbit. There are basically two types of circular accelerator: pulsed machines and storage rings. A storage ring is a circular accelerator where the beam may be kept for a significant time in steady conditions. In the case of the LHC, this will be several hours. Most modern storage rings use the concept of strong focusing[9,10], in which dedicated quadrupole magnets provide field components that are proportional to the deviation of the particles from the design orbit. The resulting Lorentz force prevents divergent trajectories: the particles, instead, oscillate around the design orbit as they circulate in the storage ring. The number of transverse oscillations per revolution is an important operational parameter and is referred to as the machine tune, Q. The stronger the focusing, the smaller the oscillation amplitudes (and thus the transverse r.m.s. beam size) and the larger Q is. In the longitudinal direction, the electric field supplied by a radio-frequency resonator focuses the particles into bunches and accelerates them. The LHC has two such systems, one for each beam, in one of the ring's straight sections (IR4) (Fig. 1).

The design of accelerator magnets becomes easier and less expensive for small magnet apertures, so the natural inclination is to increase the number of focusing elements in the machine to minimize the transverse beam size. But a careful balance must be struck between maximizing the

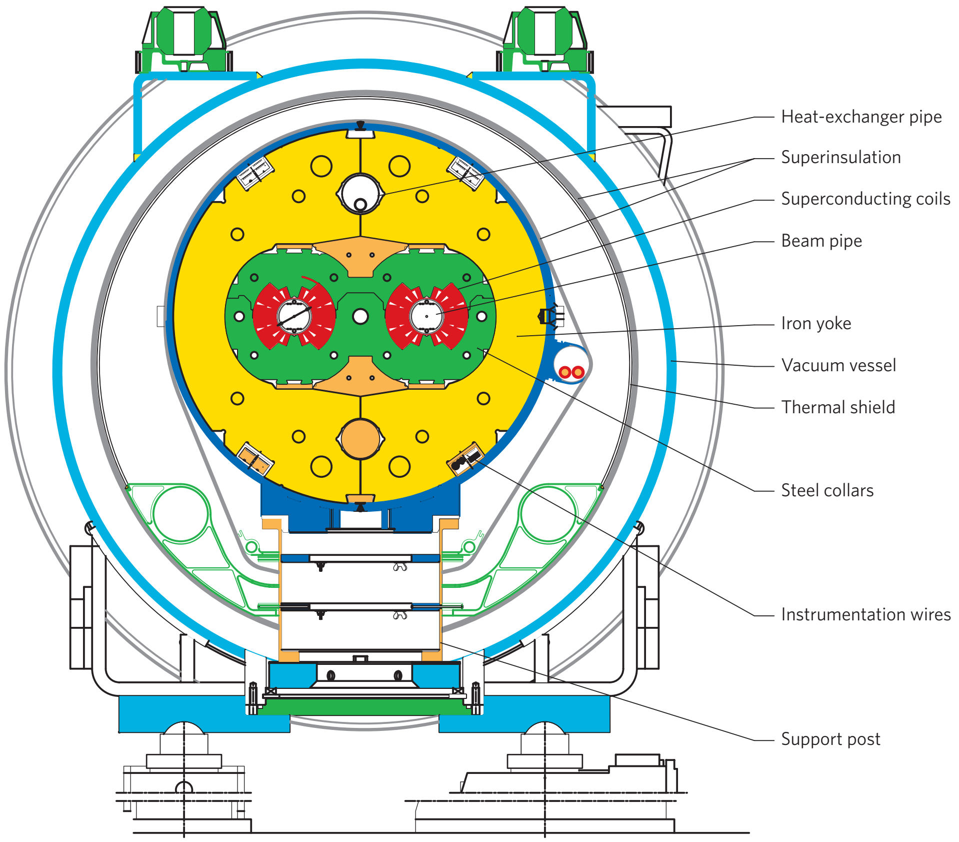


Figure 2 | Cross-section of the two-in-one design for the main LHC magnets. In the centre are the two beam pipes, separated by 194 mm. The superconducting coils (red) are held in place by collars (green) and surrounded by the magnet yoke (yellow). Together, these form the cold mass of the magnet, which is insulated in a vacuum vessel (outer blue circle) to minimize heat uptake from the surroundings.Image reproduced, with permission, from ref. 11.

space for dipole installation and providing sufficient space for transverse beam focusing. In the LHC, ~80% of the arc length is taken up by the dipole magnets, allowing the maximum transverse r.m.s. beam size in the arcs to be kept below 1.3 mm.

A two-in-one design

The combination of the length of the existing tunnel and the required beam energy sets the scale for the strength of the bending magnetic fields in the main magnets of the LHC. Keeping the 7-TeV proton beams on their closed orbits implies bending fields of 8.4 T, ~30,000 times stronger than Earth's magnetic field at its surface. Such fields are at the limit of the existing superconducting magnet technology. To confine two counter-rotating proton beams, two separate magnet apertures with opposite field orientations must be squeezed into the 3.76-m diameter of the existing LEP tunnel. The LHC therefore adopted a novel two-in-one magnet design, in which the two magnetic coils have a common infrastructure and cryostat[11] (Fig. 2).

This design provides a compact structure, with a cryostat diameter of 0.914 m, that fits two separate beam apertures into the relatively small existing machine tunnel. But it also couples the construction constraints of the two magnets, imposing new challenges and tighter tolerances on their production. This is the first time this has been done, so there is no existing experience to build on.

To minimize the number of magnet interconnections, and therefore the space lost for dipole field installations, the LHC uses 30-tonne, 15-m-long dipole magnets, which are more than twice as long as the dipole magnets in previous accelerators (~6 m for the Tevatron and HERA[12,13]). These large dimensions imposed tighter geometric constraints on the construction, transportation and installation of the magnets (Fig. 3). Each of the 8 arcs of the LHC consists of 46 repeating series of 1 quadrupole and 3 dipole magnets. Each magnet is manufactured using a niobium–titanium (NbTi)-based superconducting cable (Box 1).

Figure 3 | Installing the LHC magnets. a, An LHC dipole ready for installation at the CERN site. **b**, Transport of LHC magnets in the tunnel, alongside installed elements, illustrating the tight space conditions for installation. Images reproduced with permission from CERN.

Measures against magnetic quench

The operating temperature and field strength of 1.9 K and 8.4 T mean that the LHC has a very small thermal margin before the superconducting state is lost. Even small particle losses or other thermal instabilities inside the magnets can cause local heating of the material. After a section of the NbTi cable becomes a normal conductor, ohmic losses increase the operating temperature still further, an effect known as magnet quench. Testing for when a quench occurs has been an important part of the pre-installation tests of all of the LHC magnets, but efficient operation of the collider demands that the likelihood of this happening during operation is minimized.

The small tolerances for temperature fluctuations and energy deposition in the magnet coils at the LHC are combined with the extremely high energy densities inside the magnet system. The total stored electromagnetic energy — 8.5 GJ for the dipole circuits alone — is more than ten times greater than the previous record of 0.7 GJ, set by HERA[12]. The damage potential to the accelerator hardware from this stored energy is enormous: just 1 MJ is enough energy to melt 2 kg of copper.

In case of a magnet quench, this stored energy must be extracted and dissipated quickly in a controlled manner. By separating the main LHC magnet circuits into eight independent powering sectors, the stored electromagnetic energy per sector falls to that seen in existing superconducting storage rings. The drawback of this division into sectors is that it requires accurate synchronization of the different magnet sectors during operation. Existing storage rings avoid this synchronization problem by powering all main magnets in series in a central circuit. The LHC will enter new territory in this respect.

Damage to individual magnet units during a quench is avoided by a dedicated magnet protection system that monitors the voltage drop across each magnet unit. As soon as any part of the magnet cable loses its superconducting state, the voltage drop across the magnet will become non-zero. This jump will activate special heaters inside the magnet to bring the whole magnet into a normal conducting state, thus spreading the quench over the whole magnet length. A dedicated quench diode dissipates the stored electromagnetic energy before it can damage the magnet coils.

The stored energy in the proton beams themselves is another dangerous source of energy deposition in the superconducting magnet coils. At 7 TeV and an intensity of 3.23×10^{14} protons, the kinetic energy of each of the LHC beams is 362 MJ. Safe beam extraction in case of problems during machine operation, or at the end of a period of operation for data taking by the experimental detectors (physics fill), is assured by two installations: the beam abort system, and the machine protection system. The ring of the LHC has a dedicated beam abort system, formed of specially designed absorber blocks capable of absorbing the full beam intensities at 7 TeV without damage. The machine protection system constantly monitors all critical machine parameters and initiates a beam abort if the parameters exceed the acceptable operation tolerances or if the beam losses along the storage ring become too large.

Beam lifetimes

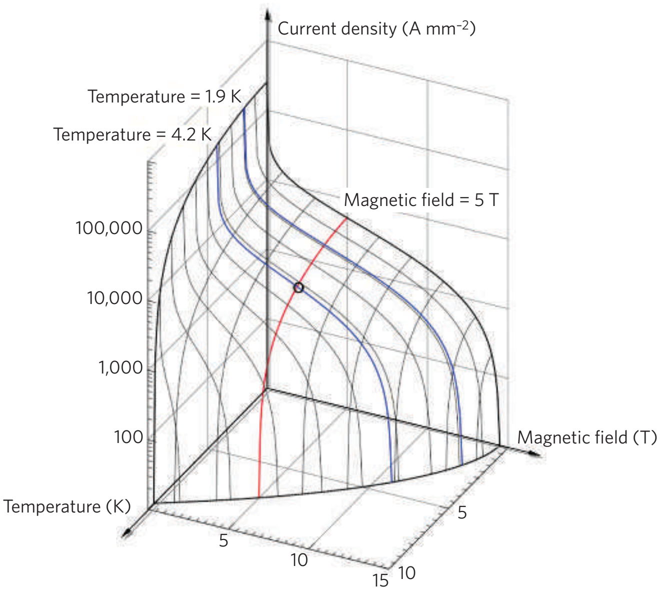
Beam intensity — and hence luminosity — decays during the operation of an accelerator in colliding mode. After these parameters become too small for efficient operation, the beams are discarded using the beam abort system, and a new fill of proton beams needs to be prepared, injected and accelerated. One of the main and unavoidable causes of reductions in beam intensity is the collisions inside the detectors themselves, because these cause the disintegration of beam particles. The rate of this disintegration is given by the product of the machine luminosity, the total cross-section for an inelastic interaction of two protons at 7 TeV, and the number of collision points. Assuming a total inelastic cross-section of 10^{-25} cm^2 at 7 TeV and two main interaction points with

Box 1 | The LHC superconductor

The superconducting magnets of the LHC are superlative devices: had the LHC been made of conventional magnets, it would have needed to be 120 km long to achieve the same energies, at the cost of a much greater electricity consumption.

Like all superconductors, NbTi (the material used for the cables of the LHC magnets) is a superconductor only if its operational parameters — temperature, current density and ambient magnetic field — are within certain bounds[15–17]. The critical surface below which this combination of parameters must lie is shown in the figure. At the preferred operating temperature for most existing superconducting accelerators such as HERA and the Tevatron[11,12], 4.2 K, the critical magnetic field is around 5 T.

The temperature of the LHC, 1.9 K, allows the generation of the required 8.4-T magnetic field using a current density of 1.5–2 kA mm^{-2} inside the superconducting cables. It also allows the use of superfluid helium, which has high thermal conductivity, as a coolant. A helium inventory of 120 tonnes or more will be needed to cool the total magnet mass of 37,000 tonnes, the largest such inventory in the world. Figure courtesy of L. Bottura (CERN).



a luminosity of 10^{34} cm^{-2}s^{-1}, the beam intensities will have dropped to half of their initial values after ~45 hours.

Particles are also lost through perturbations and resonances in the proton motion that deflect particles away from the design orbit. These are generated, for example, at the collision points, where a particle in one beam is exposed to the Coulomb field of the opposing beam, or by field imperfections in the main magnets. Thanks to the focusing mechanism of the quadrupole magnets, these deflections do not lead directly to particle losses but, initially, just to an oscillation around the design orbit. But consecutive perturbations can add up coherently if the particle oscillations are in resonance with the revolution frequency, in which case the oscillation amplitudes can grow until the particles are lost when they reach the boundary of the LHC vacuum system.

Two approaches minimize this amplitude growth. First, extreme care is taken during the magnet design, construction and installation in order to minimize any imperfections in the machine. Second, the LHC is equipped with dedicated circuits that allow the correction of the most dominant residual field errors. All magnets are measured before their installation to develop an accurate magnetic model of the entire machine's operation. In total, the LHC features 112 correction circuits per beam (not including simple steering magnets for an adjustment of the central orbit), and all of these must be adjusted during operation. To compound the difficulty, the field errors of a superconducting magnet are not constant but vary with time as a function of the magnet's powering history.

Other causes of a reduction in luminosity during operation include the scattering of protons on residual gas molecules inside the beam vacuum system, and the Coulomb scattering of the protons inside each bunch as they perform longitudinal and transverse oscillations while circulating inside the storage ring. The rate of collisions with residual gas molecules depends on the pressure and gas composition inside the machine vacuum system. An efficient operation with proton beams requires vacuum levels below 10^{15} molecules per cubic metre for all gas components (H_2, He, CO, CO_2 and so on), corresponding to a pressure of less than 10^{-7} Pa at 5 K. (Atmospheric pressure is ~10^5 Pa at sea level.) This, in turn, demands an elaborate system of different vacuum pumps. In its final phase, the pumping mainly relies on the cryo-pumping of the cold surfaces that exist at the boundary between the beam vacuum and the helium in the superconducting magnets, similar to the way that ice builds up on the surfaces of the freezing compartment of a household refrigerator.

Collimation

There are therefore several unavoidable mechanisms causing a continuous loss of particles during LHC operation through a relatively slow drift to larger oscillation amplitudes. Two dedicated collimation insertions with specially designed absorber blocks mop up these stray particles before they can reach the cold aperture of the superconducting magnets (and so possibly cause a magnet quench). This mopping up must be done with high efficiency so that only 1 in 10,000 particles that hit the primary collimators end up inside the cold aperture. Such a high cleaning efficiency requires extremely tight tolerances for the main machine parameters during operation, as well as the use of a complex two-stage collimation system with additional dedicated absorbers at crucial locations. The LHC is the first high-energy collider that requires a beam collimation during all stages of the operation to protect its machine elements — previous colliders only required a beam collimation during the physics run, mainly to reduce the background in the experiments. For additional safety, therefore, the collimator jaws at the LHC are made of fibre-reinforced graphite so as to be able to withstand the direct impact of a large proportion of the 7 TeV beam.

Working up to full beam strength

After the LHC proton beams have been prepared and injected into the accelerator using the existing accelerators at CERN[14] (Box 2), the acceleration can be initiated. This acceleration relies on a synchronous change of the machine settings with the increasing dipole field. In the case of the LHC, the final beam energy is more than 15 times greater than that of the injected beam (7,000 GeV compared with 450 GeV). With a high impedance in the main magnet circuits, the process of increasing the magnet current, and therefore the energy, is slow in the LHC, taking ~20 minutes. During this operational phase, the transverse beam dimensions shrink as the rigidity of the beam increases.

The injection and acceleration takes place with the beams separated in the experimental regions and with a lower focusing strength in these areas than in the final configuration for luminosity production. After reaching high energy, a synchronized change in the settings of the focusing elements is made at each interaction point to reduce the beam spot size at the interaction point. As a result, the beam size in the adjacent final focusing quadrupoles increases. In the final configuration, the aperture of these elements is smaller than in the rest of the machine and must be protected by further reducing the collimation gap.

The final step before the experiments can begin taking data is to remove the separation scheme and to bring the beams into collision in each experimental area. Careful optimization is required to align the beams correctly and to maximize the overlap of the 16-μm beam spots.

Once data taking has started, the luminosity will decrease as the intensity falls. In fact, because the luminosity is proportional to the square of the intensity, a reduction in the intensity by ~30% will halve the luminosity. The goal for efficient machine operation is a luminosity lifetime that is considerably longer than the average time for preparing a new fill of proton beams. Assuming an exponential decay of luminosity, and an intensity lifetime of 45 hours, the luminosity lifetime will be ~15 hours for the LHC. The overall collider efficiency depends on the ratio of the run length and the average turnaround time. Assuming a 5-hour turn-around time, the optimum run length will be ~10 hours.

The commissioning process

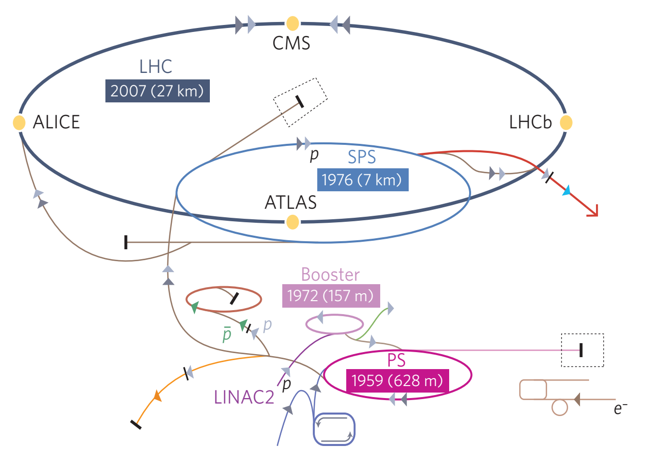
The LHC is a huge, complex facility, and careful and precise control of all machine elements is necessary. Commissioning the whole machine is a challenge in itself. Careful commissioning of each individual set of accelerator hardware will be followed by rigorous system tests and integrated operation of the whole accelerator before any beam is injected. In the early phases of beam operation, the complexity can be reduced by limiting the number of bunches, the intensity per bunch and even the final energy. At each stage in the commissioning process, the equipment and protection systems must be tested and run to allow operation with beam while minimizing the risk of damage to the accelerator itself.

For the first operation of the LHC at 7 TeV, there will be a single bunch in each ring. From there, a staged increase in the number of bunches is intended, with schemes for 43, 156 and 936 bunches per ring envisaged before arriving at the final number of 2,808 bunches per ring. The simplest scheme, with 43 bunches per ring and an intensity per bunch around half the nominal value, represents a stored energy that is already comparable to that of the Tevatron.

Box 2 | Preparing the LHC beam

The beam of the LHC starts off in a 50-MeV linear accelerator, LINAC2 (see figure). It is then passed to a multi-ring booster synchrotron for acceleration to 1.4 GeV, and then to the 628-m-circumference Proton Synchroton (PS) machine to reach 26 GeV. During acceleration in the PS, the bunch pattern and spacing needed for the LHC are generated by splitting the low-energy bunches. A final transfer is made to the 7-km Super Proton Synchroton (SPS) machine, where the beam is further accelerated to 450 GeV. At this point, it is ready for injection into the LHC. The cycle takes ~20 s and creates a ribbon, or train of bunches, with a total kinetic energy of more than 2 MJ. This is ~8% of the beam needed to fill an LHC ring completely, so the whole cycle must be repeated 12 times per ring.

The transfer of the bunch trains from the SPS to the LHC is one of the most dangerous phases of the operational cycle of the LHC. The injected beam already has sufficient energy to damage the LHC equipment, and the transfer involves the use of fast kicker magnets to abruptly change the trajectory of the beam to move it out of the SPS, down a 3-km transfer line, and into the LHC. Any mis-steering here could be disastrous, so a low-intensity 'pilot' beam is injected into the machine first. This is used to measure and correct the machine parameters before the full-intensity injection sequence is allowed to start. Each injection is positioned in the LHC circumference so as to generate the complete pattern for each beam. During the 8 minutes needed to fill the LHC completely, the stability of the whole complex is critical and must be carefully monitored. Figure modified with permission from CERN.



During the first full year of LHC operation, the number of bunches and the intensity per bunch will be increased slowly. It is hoped that a luminosity of 10^{33} $cm^{-2}s^{-1}$, or 10% of the nominal value, will be reached during this time. In subsequent runs, the performance will be slowly increased towards the nominal value as understanding of the machine and control of the machine parameters is refined.

The LHC is a machine in which all technologies are stretched towards their limit, and it has been built, in many cases, with very small operational margins in the equipment. It is probable that upgrades to certain accelerator components will be made during the lifetime of the machine. Some of these will be designed to re-introduce operational margins in crucial areas in which machine efficiency can be improved. Others will be designed to increase the nominal performance of the machine.

The outlook

The LHC is designed to push back the frontiers of our knowledge of fundamental particle physics. With the requirement of providing both high energies and high beam intensities, there are many challenges that had to be overcome to produce a viable design for the complete machine. Realizing the designs for each component of the accelerator has often, in turn, pushed back the technical boundaries for the design and performance of the individual accelerator systems. The sheer size and complexity of the complete machine makes the commissioning and operation of the LHC a challenge in itself. But its many technical innovations mean that the LHC should be capable of helping us to explore — and, we hope, answer — some of the most fundamental questions in particle physics today. ■

1. Armstrong, W. W. *et al.* (The ATLAS Collaboration). ATLAS: *Technical Proposal for a General-Purpose pp Experiment at the Large Hadron Collider at CERN. CERN* <http://cdswebdev.cern.ch/record/290968> (1994).
2. Della Negra, M., Petrilli, A., Hervé, A. & Foà, L. *CMS Physics: Technical Design Report. Vol. 1: Detector Performance and Software. CERN* <http://cdswebdev.cern.ch/record/922757> (2006).
3. Mukari, Y., Itow, Y. & Sako, T. *LHCf Experiment: Technical Design Report. CERN* <http://cdswebdev.cern.ch/record/926196> (2006).
4. Berardi, V. *et al. Total Cross-Section, Elastic Scattering and Diffractive Dissociation at the Large Hadron Collider at CERN: TOTEM Technical Design Report. CERN* <http://cdswebdev.cern.ch/record/704349> (2004).
5. Amato, S. *et al.* (The LHCb Collaboration). *LHCb Technical Proposal, a Large Hadron Collider Beauty Experiment for Precision Measurements of CP Violation and Rare Decays CERN/LHCC 98-4. CERN* <http://cdsweb.cern.ch/record/622031> (1998).
6. Carminati, F. *et al.* (The ALICE collaboration). ALICE: physics performance report, volume I. *J. Phys. G* **30,** 1517–1763, doi:10.1088/0954-3899/30/11/00 (2004).
7. Alessandro, B. *et al.* (The ALICE collaboration). ALICE: physics performance report, volume II. *J. Phys. G* **32,** 1295–2040, doi:10.1088/0954-3899/32/10/001 (2006).
8. CERN. *LEP Design Report. CERN* <http://cdsweb.cern.ch/record/102083> (1984).
9. Christofilos, N. C. Focusing system for ions and electrons. US patent 2,736,799 (1950); reprinted in Livingston, M. S. *The Development of High Energy Accelerators* (Dover, New York, 1966).
10. Courant, E. D. & Snyder, H. S. Theory of the alternating gradient synchrotron. *Ann. Phys. (Leipz.)* **3,** 1–48 (1958).
11. Brüning, O. S. *et al.* (eds) *LHC Design Report Vol. 1: The LHC Main Ring. CERN* <http://cdsweb.cern.ch/record/782076> (2004).
12. Cole, F. T. *et al. A Fermilab Superconducting Accelerator Design Report.* Beams Document 1888, Fermilab, Batavia Illinois <http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=1888> (1979).
13. *HERA — A Proposal for a Large Electron Proton Colliding Beam Facility at DESY.* DESY Hamburg, Germany. *SLAC* <http://www.slac.stanford.edu/spires/find/hep/www?key=897230> (1981).
14. Benedikt, M., Collier, P., Mertens, V., Poole, J. & Schindl, K. (eds) *LHC Design Report Vol. 3: The LHC Injector Chain. CERN* <http://cdsweb.cern.ch/record/823808> (2004).
15. Wilson, M. N. *Superconducting Magnets* (Clarendon, Oxford, 1983).
16. Bottura, L. A practical fit for the critical surface of NbTi. *IEEE Trans. Appl. Supercon.* **10,** 1054–1057 (2000).
17. Leroy, D. Review of the R&D and supply of the LHC superconducting cables. *IEEE Trans. Appl. Supercon.* **16,** 1152–1159 (2006).

Acknowledgements
The authors would like to acknowledge the many thousands of people at CERN and in collaborating institutes who have contributed to the design and construction of the LHC machine and experiments.

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