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Highlights of the LHC run 1 / Résultats marquants de la première période d'exploitation du GCH

The LHC collider

Le collisionneur GCH

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ABSTRACT

The first three year run of the Large Hadron Collider (LHC) ended in the spring of 2013. During this period, the collider was operated mainly at beam energies of 3.5 and 4 TeV. The performances that have been achieved during that first run and the challenges for commissioning and operating the LHC are presented. A brief outlook into the upcoming run at an energy of 6.5 TeV will be given.

RÉSUMÉ

La première période d'opération du grand collisionneur à hadrons (GCH) s'est terminée au printemps 2013. Pendant cette période, le collisionneur a fonctionné principalement à des énergies par faisceau de 3,5 et 4 TeV. La performance atteinte pendant cette période ainsi que les défis de la mise en route du GCH sont présentés. Un apercu de la prochaine période d'opération à 6,5 TeV est donné.

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1. Introduction

As early as 1977, while the development of the Large Electron Positron (LEP) collider was ongoing, first ideas emerged to build a hadron collider after the end of LEP operation inside the same accelerator tunnel. The first Large Hadron Collider (LHC) workshop was organized in 1984. The CERN Member States approved the LHC project in 1994 and its construction was led by CERN in the following years, with international contributions from Japan, Canada and the United States. Other countries such as China, India and Russia have also contributed [1].

The LHC accelerator is installed on average 100 meters below the surface in the 26.7 km long accelerator tunnel that initially housed the LEP accelerator (Fig. 1) [2]. Two beams of protons or ions circulate in opposite direction almost at the speed of light in two independent vacuum chambers. The accelerator consists of eight arcs where the superconducting dipole magnets are installed to deflect the particles and of eight Long Straight Sections (LSS). The large particle physics experiments ALICE, ATLAS, CMS and LHCb are installed at Interaction Points (IP) in the middle of four LSS, while the other LSS house the collimation (or beam cleaning) system, the radio frequency (RF) system and beam instrumentation and a system for beam extraction (Fig. 1).

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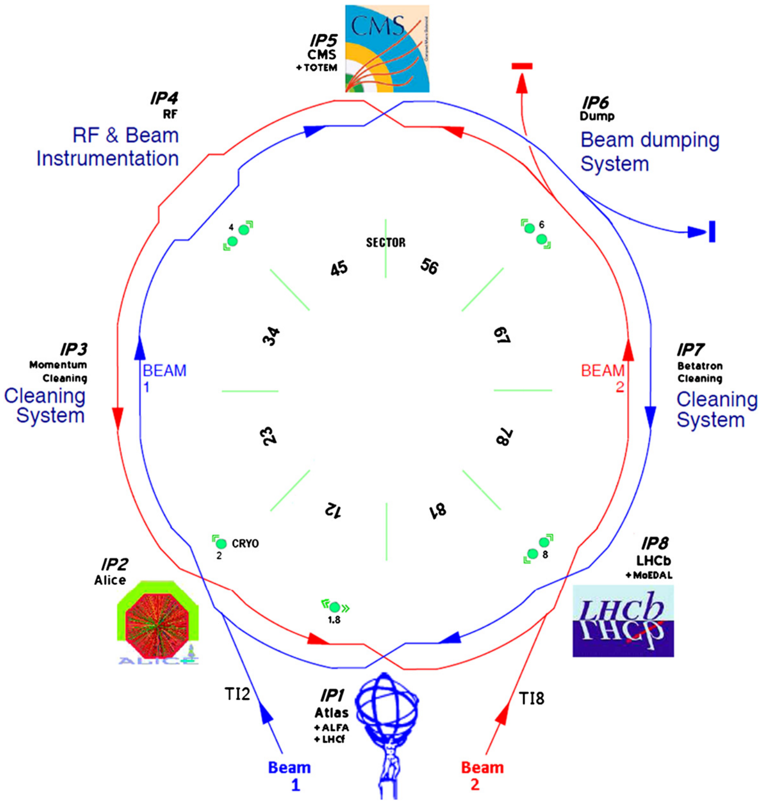

Fig. 1. Layout of the LHC with the 8 Interaction Points labeled IP1 to IP8. The experiments ATLAS, ALICE, CMS and LHCb are installed in IP1, IP2, IP5 and IP8 respectively. Beam 1 is injected close to IP2 and circulates clockwise, beam 2 is injected close to IP8 and circulates counter-clockwise. The two beams exchange position between outside and inside of the ring at every experiment to ensure that the path length is the same for both beams. The two beam dumps are located around IP6.

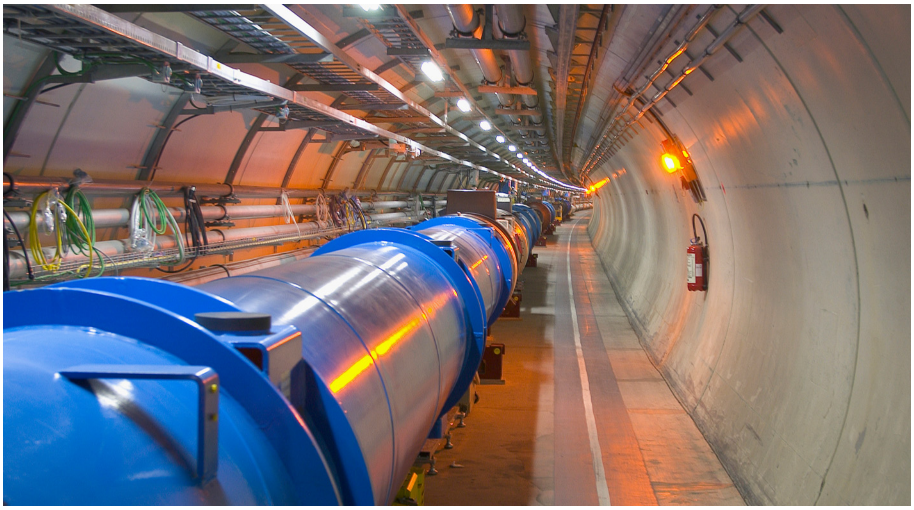

Fig. 2. View of the LHC tunnel and of the magnet cryostats in an arc section.

A dipole field of 8.3 T is required to bend hadrons with a momentum of 7 TeV per unit charge in the tunnel; this is 60% higher than in previous accelerators. Such a magnetic field strength is achieved with superconducting dipole magnets made of NbTi. With a 2-in-1 magnet design the two rings fit inside the 3.8-m diameter former LEP tunnel (Fig. 2). Both rings are accommodated in a single cryostat and the distance between the two vacuum chambers is only 19 cm. A cross-section of a dipole magnet is shown in Fig. 3. Each dipole is 14.3 m long and the cryostat is 15 m long. The coils are positioned to an accuracy of 30 μm to guarantee an excellent field quality. The contribution of higher-order multipoles at a radius of 17 mm

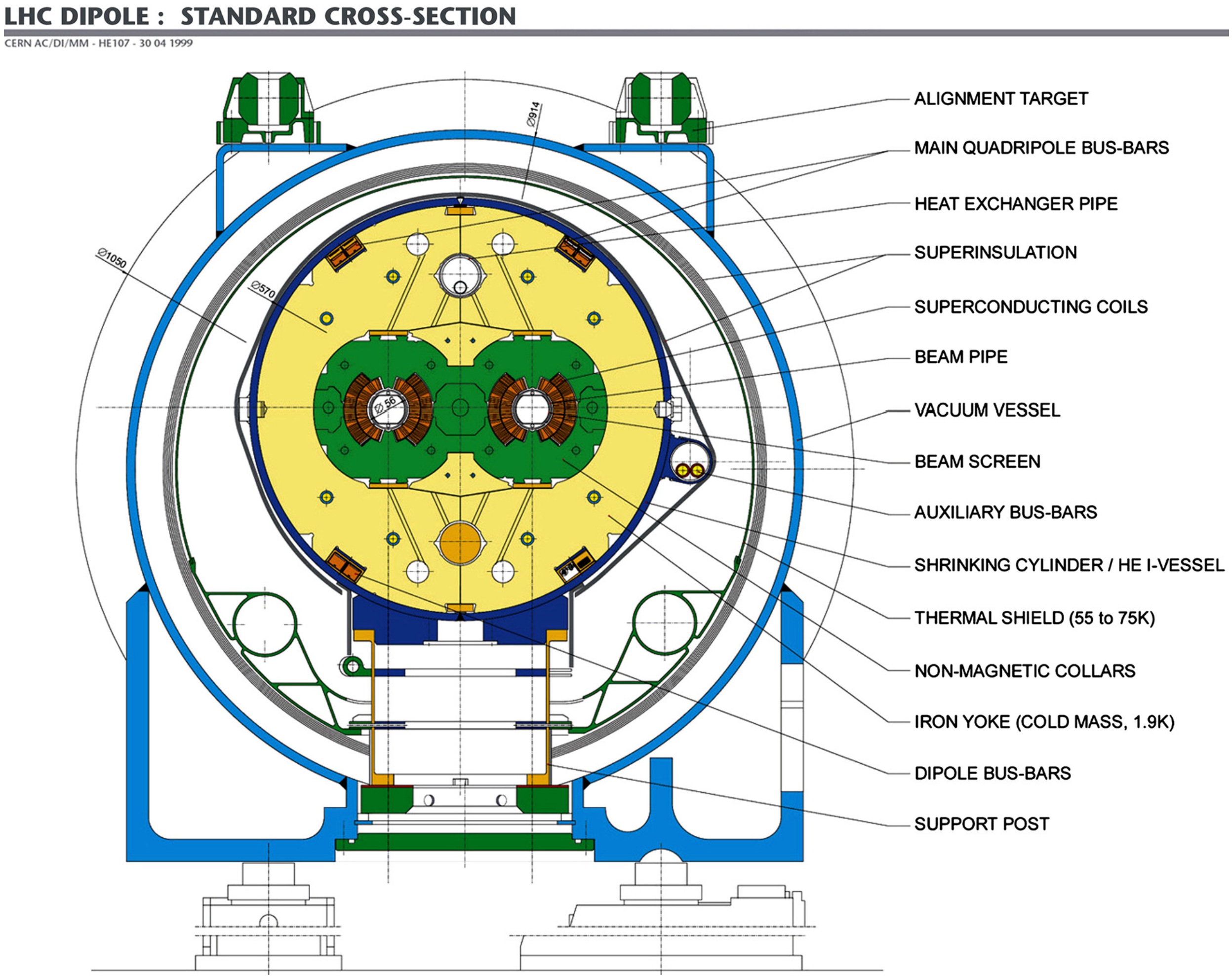

Fig. 3. Cross-section of an LHC dipole magnet.

must be controlled at the level of few parts in 10,000. In addition to the dipole magnets that make up 85% of each arc, the magnet lattice also includes quadrupole magnets that focus the beam, sextupole magnets to correct to energy dependence of the magnetic fields, and octupoles that are used to stabilize the beam. A total of 8000 superconducting magnets are used to control the two beams.

Eight continuous cryostats with a length of 2.7 km each cool the 1232 superconducting dipole magnets and the 392 quadrupole magnets of the arcs to their operating temperature of 1.9 K. Another 148 superconducting main quadrupole magnets are installed in the straight sections and the beginning of the arcs. After cooling down, the LHC cryostats contain in total 130 tons of liquid helium. Around 37,000 tons of material are cooled to 1.9 K. The magnets and the cooling system based on superfluid helium are an outstanding technical components of the LHC. The cryostats are by far the longest refrigerators on the Earth. The cryogenic system has to be extremely reliable, in 2012 the system achieved an overall uptime of 95%.

In total 1600 precision power converters provide current to the magnets, for the dipole circuits the currents reach 13 kA. For many main magnets the stability over 30 minutes must be better than 5 ppm (parts be per million). The magnetic energy stored in each arc cryostat is around 1 GJ. This energy has to be safely extracted in case one of the magnets quenches, i.e. performs a transition from the superconducting to the normal conducting state. Large dump resistors that are capable of absorbing the energy are automatically switched into the circuits in case of a quench.

The particles in the beams are stored in small packets called bunches that collide inside the four large experiments. Detectors with a size corresponding a multi-storey building are installed at each of the four collision points, registering the resulting products from the particle collisions. Since only a tiny fraction of the collisions are of interest, it is important to have a very high event rate, which is characterized by the luminosity L. The event rate of a process with cross-section σ is given by $\sigma \times L$. The luminosity may be expressed as

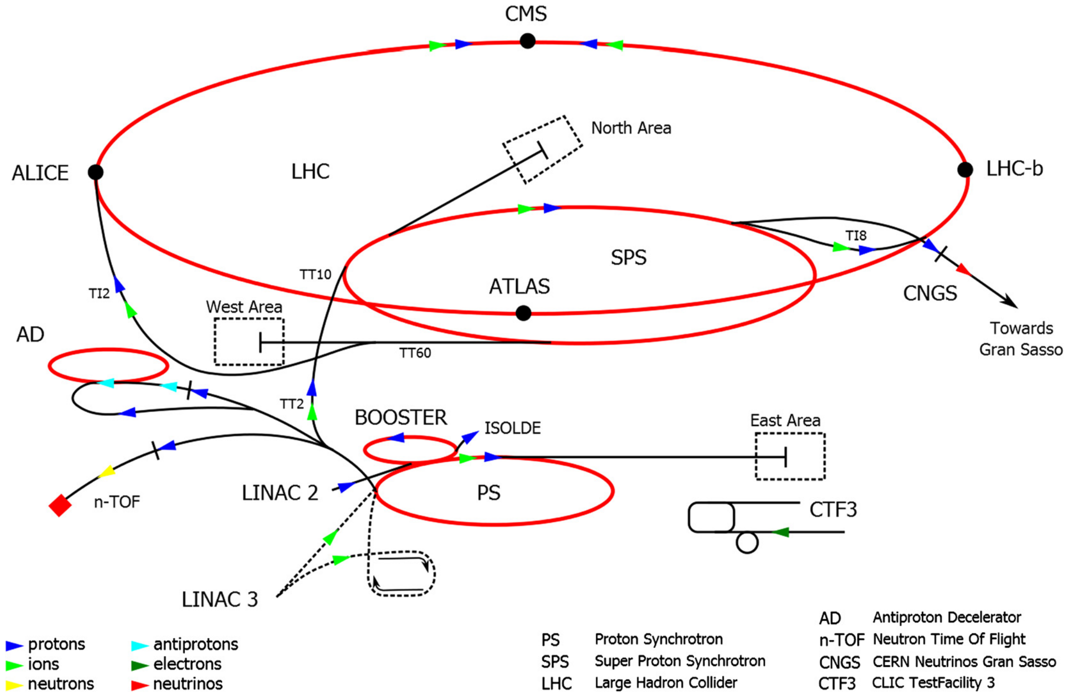

Fig. 4. The CERN accelerator complex including the LHC and its injectors. After leaving the source protons are first accelerated in LINAC2 before they are passed on to the PS Booster, the PS, the SPS and finally to the LHC.

$$L = \frac{kfN^2}{4\pi\sigma_x\sigma_y} \tag{1}$$

where f is the revolution frequency (11.24 kHz), k is the number of bunches, N is the number of particles per bunch and σ_x and σ_y are the horizontal and vertical beam sizes at the collision point. The highest luminosity is achieved with the smallest possible beam cross-section, a large number of bunches and a high bunch population. Up to 2808 bunches can be filled and accelerated in each beam, the minimum distance between bunches is 25 ns or 7.5 m. Each proton bunch consists of up to 1.7×10^{11} protons. The bunches have a typical length of 7 to 10 cm. At the interaction point the beam has a volume of about 20 microns $\times$ 20 microns $\times$ 8 cm.

At 7 TeV, each LHC beam stores an energy of up to 360 MJ. This corresponds to the energy content of 80 kg of explosives and is a hundred times higher than previously achieved accelerator records. Machine protection systems with unprecedented safety levels are required to operate the LHC. This is achieved with a combination of active protection by equipment and beam parameter monitoring, as well as with passive protection by a large number of collimators.

The existing CERN proton accelerator chain provides the beams, see Fig. 4. After leaving the source the protons are first accelerated in a linear accelerator (LINAC2) to 50 MeV. The beams from LINAC2 are further accelerated in the four Proton Synchrotron Booster (PSB) rings to 1.4 GeV, then by the Proton Synchrotron (PS) to 26 GeV. The Super Proton Synchrotron (SPS) at the end of the injection chain delivers protons for the LHC with an energy of 450 GeV through two over 3 km long transfer lines (TI2 and TI8). After the LHC injection phase that lasts 20 to 30 minutes, the beams are accelerated in about 20 minutes using a specially designed superconducting radio-frequency system (RF) to an energy of up to 7 TeV. Sixteen cavities of high-purity niobium deliver an accelerating voltage of up to 16 MV per beam.

2. LHC operation

The LHC dipole magnets were produced by three industrial firms and the last dipole magnet was delivered to CERN in November 2006. Each magnet was trained on CERN test benches to a magnetic field of 8.7 T, approximately 5% above the design target. A few training quenches were typically required to reach the nominal field of 8.3 T. Training quenches are due to the release of extremely small amounts of frictional energy (10–100 nJ) due to coil movements when the magnetic field is increased. In June 2007, the first arc (sector) of the LHC was cooled down and ready for commissioning and in April 2008 the last dipole magnet was lowered into the LHC tunnel. One of the essential components of the commissioning phase was the testing of the LHC superconducting magnets and the associated powering and protection equipment. Early 2008 it became apparent that the LHC dipole magnets had to be retrained to their nominal field, the first magnet quenches appeared at fields corresponding to beam energies of around 5.5 TeV. A training campaign on one arc revealed that the number of required re-training quenches increased rapidly with the magnetic field. The estimated number of quenches

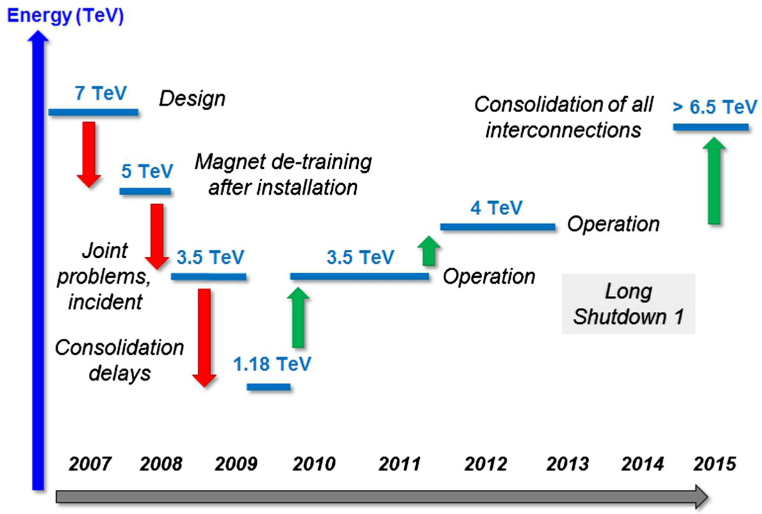

Fig. 5. Evolution of the LHC beam energy from design to the present day.

required to reach 6.5 TeV is approximately 100, while for 7 TeV the expected number can be as high as 1000. Since such a training campaign would have required a long time, it was decided to lower the energy for the commissioning and first operation phase to 5 TeV [3].

On 2 August 2008, a low-intensity bunch of protons was injected into the LHC ring for the first time and traveled to the end of one arc. On 10 September 2008, beams were circulating for the first time in both rings. The startup was however brought to an abrupt halt on 19 September 2008, when a defective high-current soldering between two magnets triggered an electric arc that released around 600 MJ of stored magnetic energy [4]. The accelerator was damaged over a distance of around 700 m, 53 magnets had to be replaced or repaired. The beam vacuum was polluted with dust and soot over 2 km. The repair, improvement and re-commissioning of the LHC lasted until November 2009. During the repair a systematic soldering problem affecting roughly 15% of all the high current (13 kA) cable joints was discovered. Since this problem could not be repaired immediately, the beam energy had to be limited to 3.5 TeV until a complete repair campaign could be performed. The LHC therefore operated in 2010 and 2011 at this energy, before the energy was increased to 4 TeV in 2012 and 2013 because no magnet was quenched at 3.5 TeV during beam operation, thus lowering the risk of problems with the cable joints. The energy will be pushed to 6.5 TeV and above in 2015 after the repair campaign of 2013 and 2014. The evolution of the LHC beam energy over time is shown in Fig. 5.

2.1. LHC run 1

On 20 November 2009, beams circulated again in both rings. Three days later, the detectors of the four experiments registered the first collisions at 450 GeV. Due to delays in the design and procurement of a new superconducting cable protection system, the energy had to be limited to 1.18 TeV in 2009. The first long running period of the LHC began in February 2010 at a beam energy of 3.5 TeV. In October 2010, the luminosity reached 2×10^{32} cm^{-2}·s^{-1}, see Fig. 6. In late November 2010, operation was changed within two days from protons to lead ions for the first four weeks of lead–lead collisions. With the experience gained from the operation in 2010, it became possible to reach higher luminosities in 2011 by increasing the number of stored bunches and by reducing the beam size at the collision points. In the first half of 2011, the number of bunches was first gradually increased to 1380 before the number of protons per bunch was increased. The bunch spacing was 50 ns. In September 2011, the beam size was again reduced and the maximum LHC luminosity reached 3.6×10^{33} cm^{-2}·s^{-1}. After the winter break the LHC restarted in 2012 with even smaller beam sizes at the collision points, and the intensity of each bunch was further increased along the year until it became limited by instabilities and by the capabilities of the injectors. In the fall of 2012, the peak luminosity at 4 TeV was pushed to 7.7×10^{33} cm^{-2}·s^{-1}, within 25% of the design target, despite the lower energy. This achievement became possible with only half the number of bunches k thanks to much lower beam sizes and significantly higher bunch populations N. The evolution of the luminosity between 2010 and 2012 for proton beams is shown in Fig. 6 and in Table 1. The overall efficiency of the LHC varied between 30% and 35%, which corresponds to the fraction of the scheduled time that was spent colliding beams for experiments data taking. Further details about the LHC beam operation are described in [5].

The LHCb experiments is designed for an intermediate luminosity of $2 - 4 \times 10^{32}$ cm^{-2}·s^{-1}, which corresponds to a pile-up in the range of 1 to 2 events per bunch crossing. Since the LHC is able to deliver much higher luminosity at the LHCb collision point, the peak luminosity was leveled down to the desired target by off-setting slightly the two beams at the collision point. This provides almost constant luminosity to the LHCb experiment during most of the fills [6].

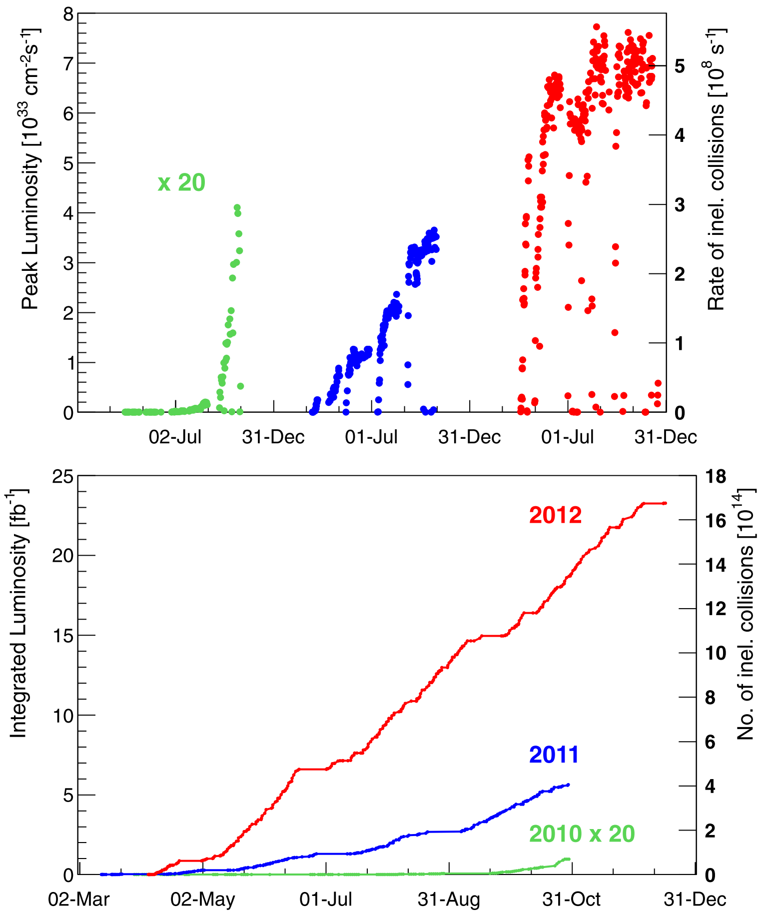

Fig. 6. Peak (top) and integrated (bottom) luminosity between 2010 and 2012 for proton operation. The 2010 luminosity values have been multiplied by a factor 20.

Table 1
Evolution of the LHC proton beam parameters in the period of 2010 to 2012 and comparison with the design target, see also Fig. 6. The luminosity figure L correspond to the ATLAS and CMS experiments, LHCb and ALICE were operated at lower luminosities. N is the bunch population and k the number of bunches per beam.

Year	Beam energy (TeV)	k	N (10^{11})	Bunch spacing (ns)	Luminosity L (cm^{-2}·s^{-1})	Stored energy (MJ)
May 2010	3.5	13	0.24	>1000	2.4×10^{29}	0.2
August 2010	3.5	50	1.0	500	1.0×10^{31}	2.8
October 2010	3.5	368	1.0	150	2.1×10^{32}	24
October 2011	3.5	1380	1.45	50	3.6×10^{33}	110
October 2012	4	1376	1.6	50	7.7×10^{33}	140
Design	7	2808	1.15	25	1.0×10^{34}	360

The absolute luminosity scale was calibrated at the LHC using a technique originally proposed by S. van der Meer [7]. The luminosity scale is determined by scanning the beams across each other which gives access to the size of the transverse beam overlap. Together with a precise determination of the beam charge and excellent control of the transverse beam profiles a luminosity determination at the level of 2% was achieved [8].

At the end of the 2010 and 2011 runs the LHC was operated successfully for around 4 weeks with lead beams. For the first lead run in 2010 the number of bunches was limited to 137 for a peak luminosity of 3×10^{25} cm^{-2}·s^{-1}. In the following year the number of bunches was increased to 358 and the luminosity pushed to 5×10^{26} cm^{-2}·s^{-1} with stronger focusing at the collision points. The total integrated luminosity by the ATLAS, ALICE and CMS is around 165 μb for each experiment. In early 2013, a few weeks were devoted to a successful run colliding a proton beam in one ring with a lead ion beam in the other ring (p-Pb run). Advantage was taken of the p-Pb run to perform a measurement of the absolute beam energy to an accuracy of 0.6% [9], an information that is important for cross-section measurements at the LHC.

3. LHC operation challenges

In many areas, the LHC operates in a parameter range that is far outside the experience from previous accelerators. A variety of innovative solutions and dedicated technical systems make possible the successful operation.

Beam optics and orbits are the result of all electromagnetic fields acting on the beams. The calculated and the measured optics must agree as well as possible for optimum performance. The orbit should be close at the target orbit. Beam orbit and optics after correction are better than initially specified. Over the length of 26.7 km, the beam position is centered to better than 1 mm, and its size agrees to better than 5% with the target value. The available space for the beam (aperture) is better than expected because the element alignment, the mechanical tolerances and the control of the beam orbit are significantly better than anticipated. As a result it is possible to focus the beams to smaller size at the collision points.

The beam–beam interaction is an important limit to the collider performance: each beam generates an electromagnetic field that acts on the counter-rotating beam and can make this beam unstable or provoke losses through tail growth. These effects occur in areas where the two beams share a common beam vacuum chamber or collide head-on inside an experiment. In the LHC careful optimization and excellent machine stability suppress these disturbing influences [10]. Together with the gain in aperture this made it possible to reach a much higher luminosity that anticipated at 4 TeV. Indeed scaling the design performance to 4 TeV a maximum luminosity of 3×10^{33} $\text{cm}^{-2}{\cdot}\text{s}^{-1}$ would be expected, less than half the achieved peak performance.

Collective instabilities of the particles within the bunches can limit the intensity that can be stored. Such instabilities may be driven by the interaction with the vacuum chamber walls and with elements inside that chamber, for example collimator jaws (see below). Depending on the process, some instabilities can rapidly affect many or all of the particles in the beam and drive large amplitude oscillations that eventually lead to losses on the collimators. Such instabilities have been observed in particular in 2012 when the LHC was operated at the highest bunch currents. Transverse and longitudinal feedback systems and octupolar fields are used to stabilize the beams.

Electron clouds can also severely limit the intensity: various processes release electrons from the walls of the vacuum chamber (for example by synchrotron radiation of the beam). Those electrons are then accelerated by the electromagnetic field of following proton bunches to the opposite side of the chamber wall. If the number of emitted secondary electrons per primary electron, the secondary emission yield SEY, is too high (SEY above 1.4), the electron density can increase rapidly, leading to the vacuum pressure increases and to beam instabilities. The energy deposited by the e-cloud on the vacuum chamber surface also constitutes an additional heat load for the cryogenic system. This phenomenon, called electron cloud, plays an important role at the LHC. The electron cloud effect depends strongly on the bunch spacing, increasing rapidly as the spacing is reduced. Electron cloud effects explain why the LHC was first operated with a bunch spacing of 150 ns in 2010 and with 50 ns in 2011 and 2012. With larger spacing the acceptable SEY increases, for 50 ns spacing the threshold is around 1.6. The SEY can be reduced in situ by bombarding the vacuum chamber surface with the electrons generated by electron cloud itself. The principle consists in injecting a sufficiently intense beam at injection energy until the electron cloud develops. The electron cloud leads to particle losses, but since the accelerator is at injection energy, the lost beam can be easily replenished. Over time the SEY is lowered, requiring more and more beam to initiate the electron cloud. Those cleaning phases lasted typically one to two weeks in 2011 and 2012, after which the LHC could be operated with acceptable electron cloud activity. During LHC run 1 the nominal bunch spacing of 25 ns was only used in test phases, 50-ns spacing turned out to be more effective. The factor of two loss in number of bunches was compensated by a higher bunch population and a higher beam brightness, see Table 1. For the experiments the price to pay was a higher number of collisions for each bunch pair collision (event pile-up) with up to 35 overlapping collisions for each bunch pair encounter in 2012. When the LHC will restart in 2015 at higher energy, it will be essential to operate with 25 ns spacing in order to deliver high luminosity with acceptable event pile-up. It is estimated that at least two weeks of SEY conditioning will be required to achieve this goal.

In 2010 and 2011, the stored energy in the beams was increased steadily in modest increments until it reached 110 MJ at the end of 2011. In 2012 it was pushed further to around 140 MJ. This is a factor of 50 over the records of other storage rings (Tevatron, HERA and SPS) as shown in Fig. 7. Since a fast beam loss of around 2 MJ can damage vacuum chambers and magnets, the Machine Protection Systems (MPS) must constantly survey a large number of beam and equipment parameters [11]. Whenever an abnormal condition is detected the MPS fires fast pulsing magnets to extract the beams within a few turns to a beam dump to prevent damage to LHC accelerator components. The MPS worked perfectly and made it possible to increase the beam intensity and luminosity so rapidly.

The superconducting magnets in the LHC lose their superconducting state (quench) when they are heated with about 10 mJ per cubic centimeter. This is to be compared with the stored energy of over 100 MJ. To prevent that unavoidable particle losses from the beam can hit the vacuum chamber within the magnets, possibly leading to sufficiently large energy deposition to trigger a quench, a collimation system, also referred to as beam cleaning system, must intercept the beam losses with very high efficiency [12]. Approximately 100 LHC collimators are installed in the two long straight sections around IP3 and IP7 (Fig. 1). They absorb particles in a four-step process, where they cover the entire 6-dimensional phase space, catching particles with large oscillation amplitudes and energy errors. Each collimator is composed of two parallel, typically 1.2 m long material blocks (jaws) that define a variable gap through which the beams circulate. The smallest gap widths are roughly 2 mm. Depending on their location in the ring and on their role, the collimator jaws are made of fiber

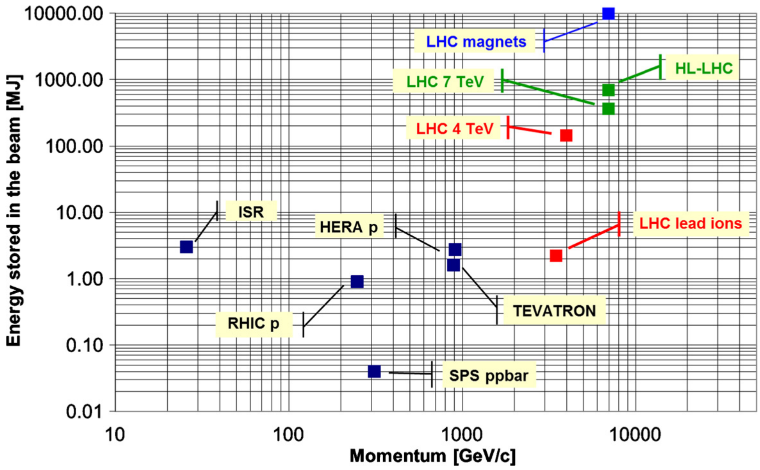

Fig. 7. Stored energy of the beams as a function of the momentum for different hadron colliders.

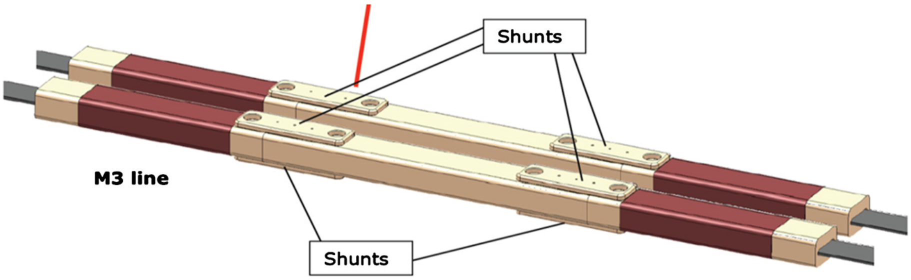

Fig. 8. The consolidated cable splices for the LHC main dipole magnets.

reinforced carbon, strongly absorbing copper and tungsten blocks. The system achieves an efficiency of up to 99.999% and is able to intercept beam losses up to 1 MW over a maximum of ten seconds without quench of the superconducting magnets.

4. Towards higher energy and luminosity

The successful first run of the LHC was followed by a one and a half year long shutdown (Long Shutdown 1, LS1). Major consolidation and maintenance work was made during LS1: the main aim was the consolidation of the magnet interconnections and cable joints to be able to safely operate above 6.5 TeV. All the high current cable joints, in total just over 10,000, were tested for excessive resistance or geometrical non-conformities. Roughly 30% of the joints were non-conform (half for resistance, half for geometry) and were redone. All the joints were consolidated with additional copper shunts, see Fig. 8, and were embedded in a support box to provide additional mechanical stability and electrical insulation. In parallel to this work, 18 magnets with non-conformities were replaced. To reduce the impact of radiation on electronics located in or very close to the LHC tunnel, major work was performed in IP1, IP5, IP7 and IP8 to relocate electronics in view of an improved machine availability after LS1.

In May 2014 the cool-down of the first of the eight LHC arcs was initiated. The other arcs followed during the summer and fall of 2014. The entire LHC was at 1.9 K in January 2015. A test campaign of 6 months that began in October 2014 aims at re-commissioning the LHC magnets for operation with beam at 6.5 TeV or higher. Early March 2015 almost 100 training quenches had already been recorded and 6 of the 8 LHC arc sectors had reached a field corresponding to 6.5 TeV. The magnet recommissioning campaign will be followed by commissioning with beam in the first half of 2015. After an initial period at low intensity of 2 to 3 months, the LHC will be operated with 50-ns beams for a few weeks to check out the machine at 6.5 TeV with high intensity, aiming to reproduce a performance similar to run 1. Once this target will be reached, operation will switch to 25 ns, first to lower the SEY below 1.4 at injection then with a progressing intensity ramp up at 6.5 TeV. If no major issues are encountered on the way, it is expected that the LHC should operate at high luminosity with 25 ns spacing in the summer of 2015. Operation under such conditions will last until approximately 2022 with a one and half year long shutdown around 2018 for an upgrade of the LHC injectors and of the LHCb and ALICE experiments. In that period extending until 2022 at least 300 fb^{-1} of integrated luminosity should be collected at 6.5 TeV or higher.

A two to three year long shutdown in the period 2022–2024 will be used to perform a major luminosity upgrade of the LHC (HL–LHC). The aim of HL–LHC is to push the potential peak luminosity well above 10^{35} $cm^{-2}{\cdot}s^{-1}$. As the experiments are not expected to operate above a luminosity of around 5×10^{34} $cm^{-2}{\cdot}s^{-1}$, the extra luminosity margin of HL–LHC will be used to level the luminosity at a constant value over many hours. This shutdown will also be used for a major upgrade of the ATLAS and CMS experiments.

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