Final adjustments being made in the LHC tunnel before the return of beams. On 5 April, particles began circulating in the accelerator for the first time following the Long Shutdown. (CERN-PHOTO-201503-058-1)

Accelerators

After two years of consolidation work, the major challenge for 2015 was to operate the Large Hadron Collider (LHC) at the unprecedented collision energy of 13 TeV, as compared to 8 TeV at the end of the first run in 2013. Having being cooled down to 1.9 Kelvin (-271°C) at the end of 2014, the accelerator was switched on again at the beginning of 2015 and seven of its eight sectors were qualified at the new energy. During this phase, the current intensity was gradually ramped up to 11 080 amperes in the circuits of the 1232 superconducting dipole magnets. Each sector is trained in several steps, because some magnets quench, i.e. they go from a superconducting to a non-superconducting state, which stops the current intensity from increasing. The operation is therefore repeated several times until the nominal intensity is achieved. By the end of March, seven of the eight sectors were ready for beams at an energy of 6.5 TeV. But a spanner in the works – or rather a fragment of metal – was preventing the last sector from equalling the performance of the seven others. A short to earth, caused by a piece of metal debris, had appeared on one of the magnets. To avoid having to open up the machine, an operation that would have entailed warming up the sector and losing several weeks, the teams came up with a cunning plan: a strong current was injected into the circuit for a few milliseconds to make the fragment disintegrate. And it worked! The recommissioning tests on the rest of the accelerator chain went ahead in parallel.

Particles in the spring

On 5 April, beams were back in the LHC. Five days later, a new record energy of 6.5 TeV per beam was recorded. Two months of fine-tuning later, the LHC operators announced first collisions and stable beams for physics on 3 June. The LHC experiments were able to start taking data again (see p. 12). During the year, the operators ramped up the beam intensity by increasing the number of bunches and reducing the bunch spacing from 50 to 25 nanoseconds. By the end of proton running, in November, up to 2244 bunches with 25-ns spacing were circulating in each direction in the ring. The ATLAS and CMS experiments each recorded some 400 million million proton collisions, corresponding to an integrated luminosity of four inverse femtobarns. Luminosity is the main performance indicator for an

Preparation of one of the new beam absorbers for injection, installed during the year-end technical stop.
(CERN-PHOTO-201601-004-8)

Assembly of the HIE-ISOLDE accelerator cavities in a clean room.
(CERN-PHOTO-201603-057-16)

accelerator, corresponding to the potential number of collisions per second in a given surface area. "Integrated luminosity" is the total luminosity accumulated over a given period, in the present case the running period in 2015. For their part, the ALICE and LHCb experiments recorded a high volume of data at lower collision rates. Two special runs, with de-squeezed beams, were organised for the LHCf, ALFA and TOTEM experiments, located on either side of the ATLAS and CMS experiments.

Chasing the clouds away

To achieve this level of beam intensity, the operators had to get rid of the electron clouds. The intensity ramp-up triggers an electron cascade phenomenon that destabilises the beam and heats up the beam screens inside the beam pipes. As the number and spacing of the bunches increase, so does the formation of electron clouds. It took several weeks of running to condition the beam pipes by circulating intense but low-energy beams to scrub as many free electrons as possible from the surface of the beam pipes and thereby reduce the electron production rate.

To achieve a new beam intensity record, the cryogenics system had to be pushed to the limit, especially as the response time of the cooling system, governed by the circulation of fluids through many kilometres of pipes, is far slower than the response time of the beam controls. The particle bunches are injected and ejected in the blink of an eye. To coordinate the cryogenics system better with the beam injection phase and, above all, with the beam ejection phase, an improved control system has been developed. The new system uses 500 heaters on the beam screens that are switched on when the cryogenic power increases prior to injection and absorb the sharp fall in thermal load when the beams are ejected.

The magnet protection system performed extremely well thanks to a diagnostic tool that had been perfected before the restart. It detects the early warning signs of malfunctions and identifies their precise locations. The teams used one of the three short technical stops in 2015 to replace 1000 electronic circuit boards that were over-sensitive to radiation.

LHC operation was rounded off in December with three weeks of lead-ion collisions, preceded by a week of proton collisions at 2.51 TeV per beam to provide reference data for the lead-ion collisions. Another energy record was set as the lead ions were accelerated to 6.37 TeV, producing 5.02 TeV collisions for each colliding neutron pair. Up to 518 lead-ion bunches were circulating in the machine per fill.

The LHC's full-body scan

To optimise the accelerator performance, the operators used a new diagnostic tool called AFT, or Accelerator Fault Tracking. This tool gives the LHC a "full-body scan", checking up on 24 separate systems, from the technical infrastructure to the subsystems, including radio-frequency, vacuum, cryogenics and collimation. It supplies a continuous stream of data on machine availability, i.e. the operating time devoted to particle production, and shows the reasons for any downtime. AFT also serves to identify any action to be taken to improve the machine's availability. To improve the LHC's availability upon injection, two new beam absorbers for injection were developed in 2015. These six-metre-long devices are used when the beams are ejected from the Super Proton Synchrotron (SPS) to the LHC and constitute an essential part of the machine protection system, absorbing the SPS beam in the event of a malfunction at the moment of injection into the LHC. The ones previously in place were showing signs of wear and tear, occasionally disrupting injection. Installation of the new absorbers, made of a different material, began as soon as the machines were shut down at the end of the year.

Away from the LHC proper, a superconducting LHC dipole was built from scratch in CERN's workshops for the very first time.

Prototype of a surface treatment process developed at CERN for use on the vacuum chambers of the Swedish synchrotron MAX IV. (OPEN-PHO-ACCEL-2016-006-1)

CERN's vacuums: more than empty promises

Two accelerators being developed elsewhere in Europe called upon CERN's expertise in vacuum technologies and surface treatments. Some of the vacuum chambers of the new Swedish synchrotron MAX IV, scheduled to begin operation in June 2016, were developed with contributions from CERN. The larger of the synchrotron's two rings is equipped with a vacuum chamber with a very narrow aperture for the beam. Some sections of the chamber also have complex geometries. The majority of the chambers (95%) are coated with a layer of NEG (non-evaporable getter), which ensures a high vacuum by trapping residual gas molecules. This material was developed at CERN in the late 1990s and is widely used in ambient temperature vacuum chambers at the LHC. The CERN team specialising in this field developed the surface treatment method used for all of the vacuum chambers in the large ring of MAX IV. They transferred the technology so that the most straightforward vacuum chambers could be treated by a European firm, and carried out the treatment of the more complex chambers themselves before delivering them in 2014 and 2015. CERN also provided expertise for the copper plating of stainless steel parts for the XFEL free-electron laser project in Germany.

The 1232 dipole magnets currently operating in the LHC were manufactured by European industry, around the turn of the century. CERN decided to start producing them itself in order to keep the know-how in-house. The "home-made" dipole is performing exceptionally well. A similar initiative is being taken for the LHC superconducting cavities: the in-house production of a cavity started at the end of 2015 in order to keep the expertise alive at CERN.

High-performance injectors

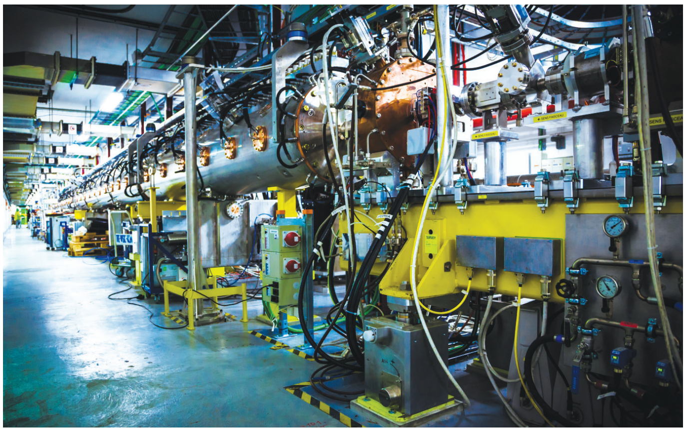
The LHC could not run without its injectors. Before the protons can be injected into the 27-kilometre ring, they have to be organised into bunches and accelerated in four successive machines: first in Linac2, then in the PS Booster and the PS (Proton Synchrotron) itself, and finally in the Super Proton Synchrotron (SPS). Heavy ions are produced in Linac3 and the Low-Energy Ion Ring (LEIR) before being injected into the PS and then the SPS. The injector chain performed tremendously well in 2015, with availability close to 90% on average.

But the LHC uses only a small fraction of the particles produced by the injector complex, which also supplies the ISOLDE nuclear physics facility, the Antiproton Decelerator (AD), the neutron Time-of-Flight (n_ToF) facility and various fixed-target experiments. For example, in 2015, the PS supplied 1.9 X 10^{19} protons to n_TOF, around 10% more than originally planned. A new system for extracting particles from the PS, known as "multi-turn extraction", was used at the end of the year for the particle-hungry fixed-target experiments at the SPS. Originally developed back in 2002 and deployed for the first time in 2010, this method was upgraded and re-deployed in 2015. It resulted in an increase in extraction efficiency from 95 to 98% compared to the continuous transfer extraction method used previously, and at the same time lowered the amount of radiation deposited in the equipment of the PS.

In addition to protons and lead ions, the SPS also accelerated argon ions for the first time, for the NA61/SHINE experiment. This special run had been under preparation for two years and resulted in the delivery of argon ions at six different energy levels. Finally, the AD facility, which serves the antimatter experiments, started up in July and racked up 3200 hours of physics with 90% availability.

New beams

Two other facilities celebrated the arrival of particles in 2015. On 22 October, a beam was accelerated by the first cryomodule of the new accelerator, HIE-ISOLDE (High Intensity and Energy ISOLDE). The energy of the radioactive ions for the ISOLDE nuclear physics facility was thus increased from 3 to 4.3 MeV per nucleon. Production and assembly of this superconducting cryomodule, complex operations in themselves, were completed at the start of the year and then had to be transported to its installation site, an extremely delicate operation in which a suspension and measurement system was used to ensure it tipped by no more than one degree! HIE-ISOLDE will ultimately comprise four cryomodules, each containing five superconducting cavities, with the aim of increasing the beam energy to 10 MeV per nucleon. By the end of 2015, the second cryomodule was ready for installation in 2016.



Linac4 in 2015, as seen by one of the photographers participating in the Photowalk competition (Photo Federica Piccinni) (CERN-PHOTO-201511-220-1)

Installation of a FineMet cavity in the PS accelerator for the stabilisation of high-intensity beams. (OPEN-PHO-ACCEL-2016-003-5)

One month later, Linac4 was accelerating beams at 50 MeV. Linac4, still under construction, is destined to replace Linac2 as the first link in the CERN accelerator chain from 2020 onwards. Linac4 will accelerate negatively charged hydrogen ions to an energy of 160 MeV and then inject them into the PS Booster. It comprises four types of accelerating structures, the first two of which have now been commissioned up to an energy of 50 MeV. The second two were installed over the course of 2015 and the power converters were all installed. By the end of the year, 80% of the accelerator components had been installed. All the equipment required to inject particles into the PS Booster is now available, which means that Linac4 is ready to step in to replace its predecessor, should the need arise.

Linac4 is a cornerstone of the LHC injectors upgrade (LIU) project. To allow the LHC to operate at high luminosity after 2025 (see p. 26), its injectors must be brought up to date. In addition to Linac4, which will replace Linac2, the other three injectors will be upgraded.

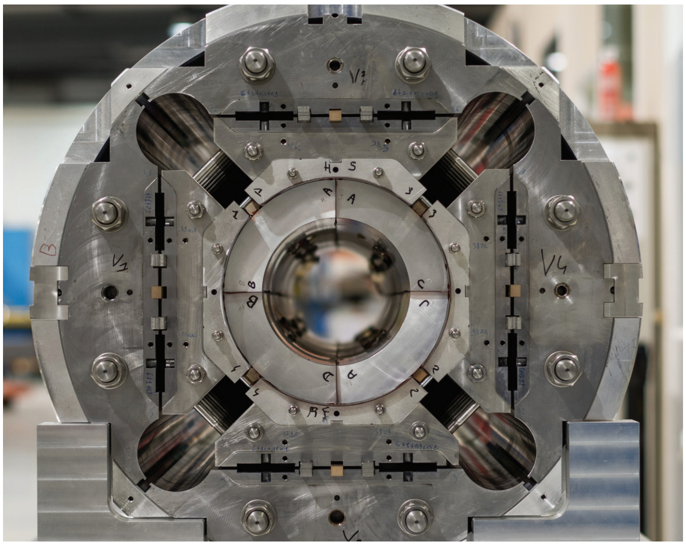
Green light for new cavities

The extraction energy of the PS Booster will be increased from 1.4 to 2 GeV. To achieve this, the accelerator will be equipped throughout with new radio-frequency accelerating cavities, which will perform better at high intensities. The FineMet technology that will be used is based on a composite magnetic material instead of on the traditional ferrites, giving a large bandwidth. The new cavities, which have already been installed on one of the accelerator's four rings, were tested intensively in 2015. One cavity was tested successfully in the PS. On the basis of these tests and a report issued by a group of independent experts, the three radio-frequency systems currently in use at the PS Booster will be completely replaced with the new cavities, which will also be used to stabilise the high-intensity beams in the PS.

A campaign to identify obsolete cables was carried out at the PS Booster, during which 2400 unused cables were identified. The goal is to remove these cables during the next technical stop at the end of 2016 to make room for the 1800 new cables required for the LIU project.

A similar campaign began at the SPS at the end of the year. In addition, several beam interception or protection devices at the SPS will need to be replaced or upgraded to cope with the increased beam intensity required for the High-Luminosity LHC. The teams continued with the design of collimators and beam stoppers for the extraction lines to the LHC. In parallel, the design and specification for a new dump block for Sextant 5 of the SPS were finalised and preparations for its installation began.

Two weeks of SPS operation were devoted to scrubbing the beam tubes in order to reduce the electron cloud phenomenon (see p. 23). One of the aims was to gain expertise with beams similar to those that will be supplied by the injector chain after its upgrade. Following these tests, a group of experts recommended the use of the beam tube scrubbing method for future SPS operation, which involves circulating high-intensity beams, and coating the inner walls of a whole sextant of the accelerator with amorphous carbon. This coating, which has a very low secondary electron yield, will limit the electron avalanche phenomenon. Twenty of the SPS magnets already coated, were tested in 2015. The remaining magnets will gradually be coated during future technical stops. Staying with the LIU project, a study programme on lead-ion operation was carried out. The detailed studies and the subsequent adjustments allowed unprecedented beam parameters and a peak luminosity of more than three times the nominal value to be achieved at the LHC. The studies were particularly focused on the Low-Energy Ion Ring (LEIR). Other upgrades of the components of LEIR were carried out at the end of the year in order to improve injection and increase the beam intensity during operations in 2016.



Structure for a "triplet" quadrupole magnet for the High-Luminosity LHC project. (OPEN-PHO-ACCEL-2015-014-2)

All systems go for high luminosity!

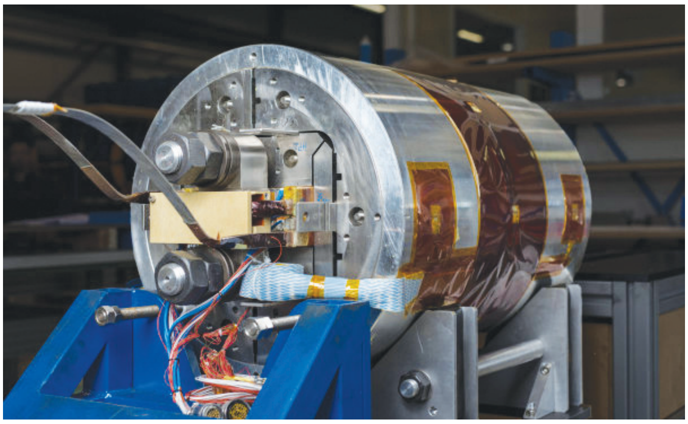
After four years of design studies, the High-Luminosity LHC project entered its construction phase at the end of October 2015. The start of this phase was signalled by the completion of the FP7-HiLumi LHC programme, co-funded by the European Union, which conducted the first studies on the project. The High-Luminosity LHC is scheduled to be commissioned at some point after 2025 and will increase the current number of collisions by a factor of 5 to 10, producing an integrated luminosity of 250 fb^{-1} per year. This increase in luminosity will allow physicists to study the new phenomena discovered at the LHC in greater detail.

To achieve this, new equipment will be installed in 1.2 km of the current accelerator, including new, more powerful quadrupole magnets (“triplets”), which will focus the beams before collisions, radio-frequency “crab” cavities to direct the beams, shorter and more powerful dipole magnets (11 Tesla as opposed to 8.3 Tesla in the LHC), an improved collimation system and new electrical connections based on high-temperature superconductors.

The new superconducting magnets, made of a niobium-tin alloy, are being developed in the framework of a collaboration between CERN and the LHC Accelerator Research Programme (LARP), which involves a group of US laboratories. In May, short coils for the triplet magnets were successfully tested. In June, a short prototype of the superconducting dipole magnet manufactured at CERN demonstrated unprecedented levels of performance. The prototype’s magnetic field exceeded 12 Tesla. The design of all the collimators has been determined. It includes jaws built from new improved materials, which have been tested successfully at CERN’s HiRadMat installation. The manufacture of crab cavity prototypes and their cryostats began at CERN, with the aim of testing them with a beam from the SPS in 2018.

Cooperation with industry has gone from strength to strength. The production of a high-temperature superconducting cable (made from magnesium diboride) to connect the power convertors to the magnets in the accelerator has begun. An industry day held at the end of June was attended by over 140 representatives of firms based in 19 different countries.

The beam line that will take protons from the SPS to the new AWAKE installation has been installed. (OPEN-PHO-ACCEL-2016-008-1)



A record magnetic field of 16.2 Tesla was achieved using a flat coil, in the framework of the programme to develop more powerful magnets for future accelerators. (OPEN-PHO-ACCEL-2016-005-1)

ELENA moves in

Away from the LHC injectors, other accelerator projects progressed well during 2015. The ELENA (Extra Low Energy Antiproton) project continued its preparations for the start of commissioning at the end of 2016. This decelerator ring, a small synchrotron of 30 metres in circumference, will be connected to the Antiproton Decelerator (AD) to slow down the antiprotons even further for study by antimatter experiments. The energy level will be reduced from 5.3 MeV to just 0.1 MeV and the beam density will be increased thanks to an electron cooling system, which will improve the efficiency of the existing experiments and open the way for new experiments.

Almost all of the infrastructure for the new decelerator has now been put in place and the first components of the ring and the transfer line have been installed. Many components are now being constructed in CERN's workshops and by the Laboratory's industrial partners.

The installation of AWAKE (Advanced Proton Driven Plasma Wakefield Experiment) also began. The experiment is scheduled to receive its first beams from the SPS at the end of 2016 and will study the principle of acceleration using wakefields in plasma cells. This principle, which has already been proven using electrons, will be tested with a proton beam with a view to achieving accelerator gradients hundreds of times greater than those possible using current radio-frequency cavities.

The civil engineering work has been completed and the infrastructure has been installed for the equipment, including a clean room that will house a laser. The proton beam line connecting the SPS to AWAKE has also been installed. The first tests of the 10-metre-long plasma cell, a key component of the project, were successfully completed.

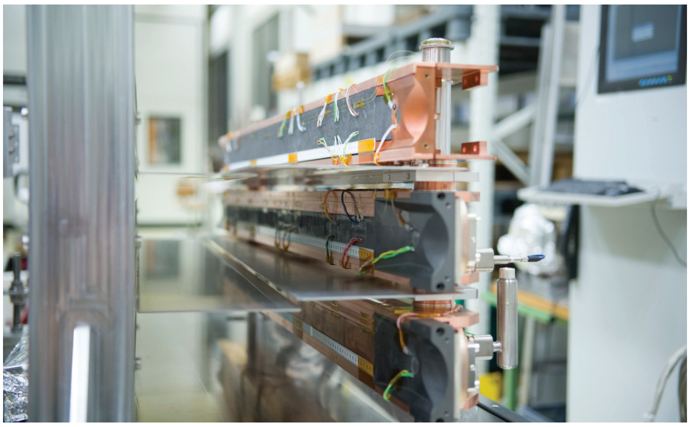
Future accelerators take shape

In addition to the High-Luminosity LHC, CERN scientists are working on the accelerators that might succeed it in around 2035. Two studies are in progress: one for CLIC (Compact Linear Collider) and one for the FCC (Future Circular Collider).

The CLIC linear accelerator project is based on an innovative two-beam acceleration concept, which will allow very high accelerating fields to be achieved. The CLIC collaboration consists of more than 50 institutes in 25 countries. In 2015, studies to redefine the project's parameters in order to optimise costs and performance were completed. On the technical side, a third test facility for the radio-frequency system was installed, doubling the existing test capacity. A complete two-metre CLIC module was commissioned in the CTF3 test facility. Three mechanical modules were tested to evaluate their thermo-mechanical performance. The R&D programme for the high-efficiency radio-frequency equipment continued. Other developments in which the collaboration was actively involved were related to beam instrumentation, magnet prototypes, vacuum systems, control systems, alignment and stability. Interest in CLIC technologies is growing, particularly with regard to their use in linear accelerators for free-electron lasers (FEL).

First results for the FCC

The Future Circular Collider (FCC) study, officially launched in 2014, completed the first stage of its work in 2015. The FCC collaboration, which involves 72 institutes in 26 countries and which is supported by the European Union, is studying the possibility of a hadron collider capable of reaching a collision energy of 100 TeV, to be installed in a new 80- to 100-km tunnel. The collaboration is investigating a potential lepton collider as an intermediate step, as well as a lepton-hadron collider option. The study also covers a possible high-energy version of the LHC in the existing tunnel. The first main objective of the FCC study



Tests on new collimators at the HiRadMat installation. (CERN-PHOTO-201507-161-37)

A new cryostat for testing future superconducting cables is being installed in the SM18 test hall. (CERN-PHOTO-201603-062-1)

is to publish a conceptual design study by 2019, in time for the next update of the European Strategy for Particle Physics.

The first annual meeting of the collaboration took place in Washington, D.C., USA, in March, attracting 340 participants from scientific institutes and industry, and including around 290 scientific contributions. Several workshops were organised throughout the year to study the possible physics reach of collisions at 100 TeV centre of mass.

A report on physics at 100 TeV has been prepared for the collaboration's second annual meeting in 2016. In the framework of the FCC study, the EuroCirCol project, co-funded by the European Union, got under way in June. Key technologies have been identified, including: superconductors able to carry higher currents, magnets generating fields of 16 Tesla, new superconducting radio-frequency cavities and innovative vacuum and radio-frequency systems.

At the end of September, a team of experts settled on the initial design for the hadron collider, including its main parameters, using CERN's current accelerator complex, including the LHC, as its injector chain. This design will form the basis of the conceptual design report. Geological studies to determine the location of the ring also began, using a brand-new software package able to take account of many different parameters.

At CERN, a programme to develop more powerful magnets was set in motion. The teams involved got off to a good start by setting a new world record of 16.2 Tesla with a racetrack magnet coil, i.e. almost twice the magnetic field generated by the dipoles currently in operation at the LHC. This record was achieved with a short superconducting coil made of niobium-tin and represents a huge leap forward in terms of demonstrating the feasibility of more powerful magnets.

Improved test facilities

CERN's test installations play a vital role in the development of innovative components. During its second year of operation, the HiRadMat installation, which tests materials and components using high-intensity beams from the SPS, completed eight experiments, including important tests for future collimators. Two different materials, molybdenum-graphite and copper-diamond, were tested as possible options for the collimators of the High-Luminosity LHC. Another experiment looked at improvements to the target that produces antiprotons in the Antiproton Decelerator (AD).

An extensive programme was launched to adapt and improve the cold electric test installations for superconducting magnets in hall SM18. Work also began on a new cryogenic installation for the testing of large diameter magnets at 1.9 Kelvin and up to currents of 20 000 amps. This cryostat will be used to qualify the FReSca2 magnet, currently under construction at CERN and CEA Saclay, France, as part of the high-field magnet programme. In the framework of the High-Luminosity LHC project, a new vertical magnet test bench is being constructed, providing currents of up to 30 000 amps. Some of the horizontal test benches will also be modified to qualify magnets for the future accelerator with currents of up to 20 000 amps, compared to 15 000 at present. At the same time, studies have begun on a test chain for the triplet magnets and a test station for the superconducting connections that will link the power convertors to the magnets.