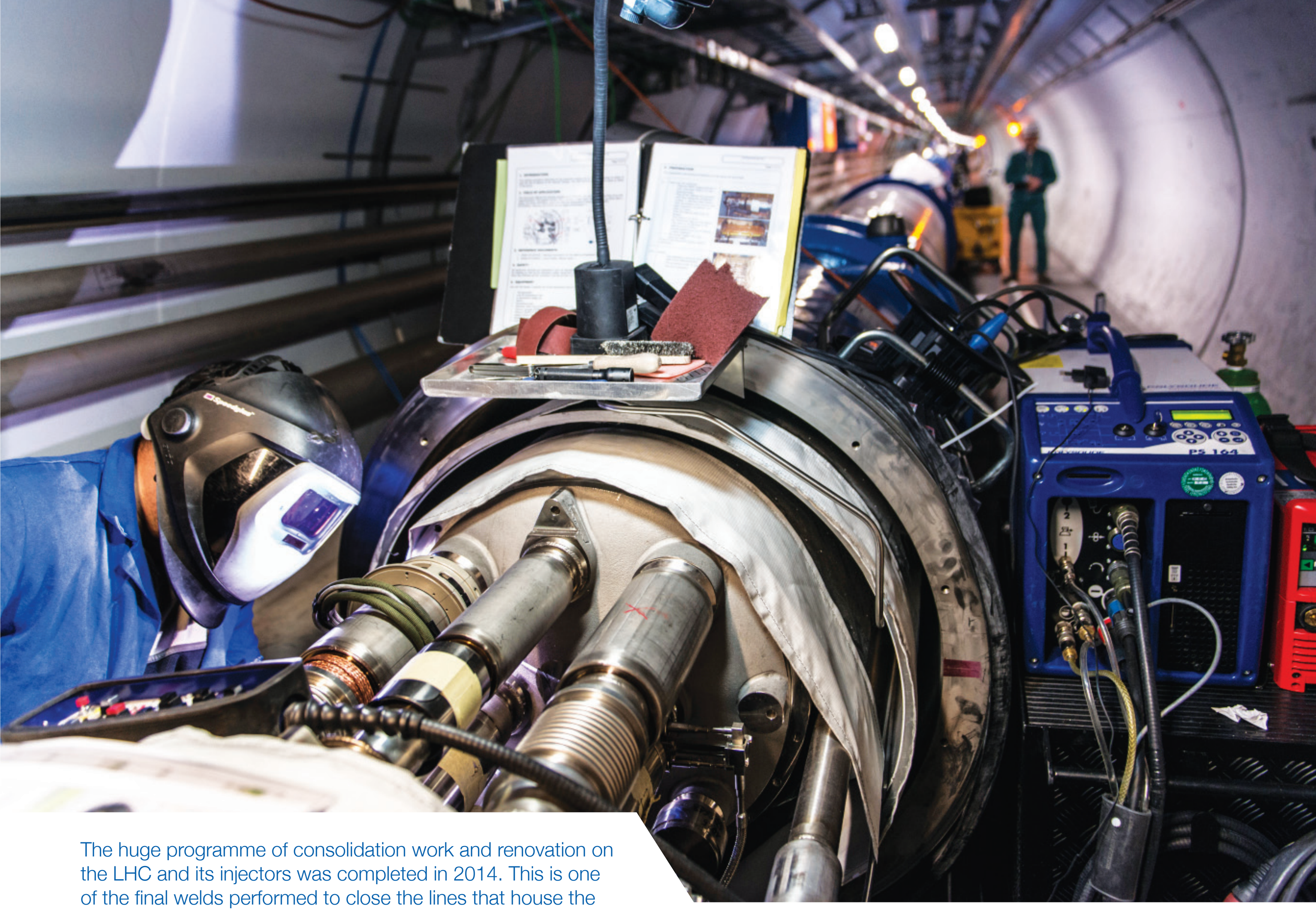


The huge programme of consolidation work and renovation on the LHC and its injectors was completed in 2014. This is one of the final welds performed to close the lines that house the interconnections between the superconducting magnets. (CERN-PHOTO-201404-084 – 7)

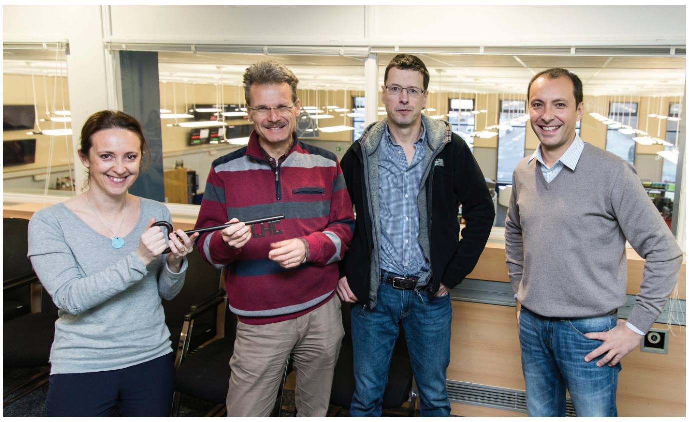
Accelerators

After an 18-month shutdown, CERN's heart began to beat again in late spring. One by one, the accelerators were restarted, pushing particles to the experiments once again. On 2 June, beam returned to Linac 2 and the Proton Synchrotron Booster injector, the first two links in the accelerator chain. Two weeks later, the third machine — the Proton Synchrotron (PS) — received beam. At the end of July, the PS delivered its first particles to the East Area and the n_TOF (neutron time-of-flight) facility, while the PS Booster supplied the ISOLDE nuclear physics facility. The Antiproton Decelerator (AD) was back in action at the start of August, and after several weeks of fine-tuning, the antimatter experiments received their first antiprotons. This included the new BASE experiment, supplied via a successfully commissioned brand-new transfer line. The Super Proton Synchrotron (SPS) was next in line for beam commissioning in mid-September. By the end of the autumn, everything was ready for the start of LHC Run 2 in 2015 and the first beams had been injected into the transfer lines as far as the LHC.

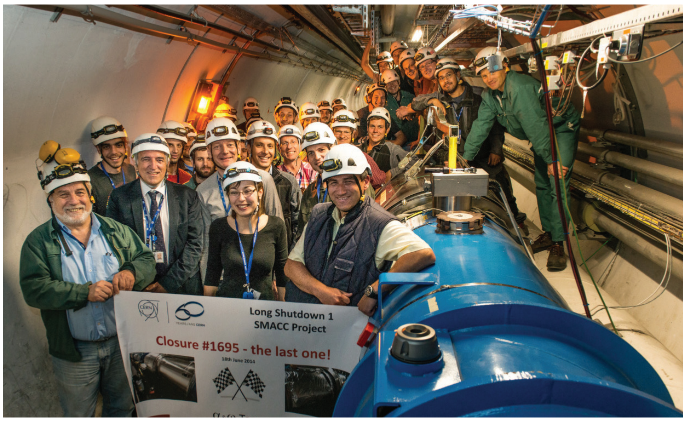
Once the accelerators had been recommissioned, tests for future operations could begin. Over the summer, argon ions circulated through the complex for the very first time, from Linac 3 to the SPS. This new mode of running will supply the NA61/SHINE experiment in 2015, the variety of energies required presenting a challenge.

Chasing clouds

Several days of SPS running were dedicated to beam-induced 'scrubbing'. This process aims to reduce the phenomenon of electron clouds, which destabilize the beam. It involves circulating enough protons in the vacuum tubes to create an avalanche of electrons that inhibits the production of new electrons. The teams tested 'doublet' beams, consisting of pairs of bunches spaced 5 ns apart. After a week of running with these beams, the SPS vacuum chambers were performing well, validating the technique for the LHC run in 2015. The injectors were also trained to produce a new beam structure for the LHC: bunches of protons spaced at 25 ns, as opposed to the previous 50-ns bunch-spacing.



Katy Foraz, LS1 coordinator, hands a symbolic LHC key back to the machine operation teams, represented by Jorg Wenninger, Mike Lamont and Mirko Pojer (left to right). (CERN-PHOTO-201501-002 – 3)



The final interconnection of the LHC superconducting magnets was closed on 18 June, after 14 months of work to reinforce the electrical interconnections. (CERN-PHOTO-201406-127 – 3)

End of a colossal project

The restart of the accelerators followed a race against time to complete the colossal work project associated with the first long shutdown (LS1). CERN and its partners worked for 22 months on the maintenance, consolidation and improvement of the accelerator complex and infrastructures. No fewer than 1600 people were involved in LS1, totalling 3.4 million working hours while maintaining an excellent standard of safety (see p. 37). Coordinating the dozens of work packages in parallel, often entailing complex logistics, required precise orchestration. Even with the addition of some unforeseen work, LS1 finished on schedule.

Renovations were performed on all of the injectors. At the PS, the access control system was modified: the new system separates the accelerator from the transfer line linking Linac 2 and the PS Booster so that work can now be carried out in the PS without having to interrupt the PS Booster. The East Area, which receives test beams for detectors and trial installations, was partially renovated. Part of the infrastructure, the secondary beam-control system and some equipment were either replaced or improved. The DIRAC experiment was dismantled and the space that had housed it was fitted out to welcome two new radiation-hardness test facilities, IRRAD and CHARM. These facilities are designed to study the effect of radiation on detector components and electronic equipment, in particular as part of the Radiation to Electronics (R2E) project. IRRAD allows equipment to be directly exposed to proton beams, while CHARM is capable of producing a wide range of radiation-types and can be used to test particularly large items of equipment. Its installation required 16 000 tonnes of shielding material to be put in place and a new control room to be constructed. A motorized handling system was developed in order to move heavy equipment into the test area.

Significant civil-engineering work was undertaken to repair the tunnel between the PS and the SPS, while major electrical work took place on the surface on the power supply to the SPS magnets. A total of 68 new 2.5-MW transformers weighing 12 tonnes were brought in to replace the old system. During a series of tests, faults were detected in three magnets and in the beam dump. Replacing these very large and heavy components involved some extremely complicated logistics but took just three days to complete.

Close to the accelerator, the beam transfer lines and their tunnel to the North Area were completely renovated, with components of the beam lines, the ventilation water circuits and the lighting replaced. All this was accompanied by a major cabling campaign.

Work was also done at the AD, many of whose components were renovated, consolidated or replaced. An emergency repair was carried out on one essential component, the magnetic horn, which focuses the antiprotons coming from the target. The current transmission system, which transmits electrical pulses of 400 000 A to the horn, was replaced in record time after a series of tests on a specially designed test bench.

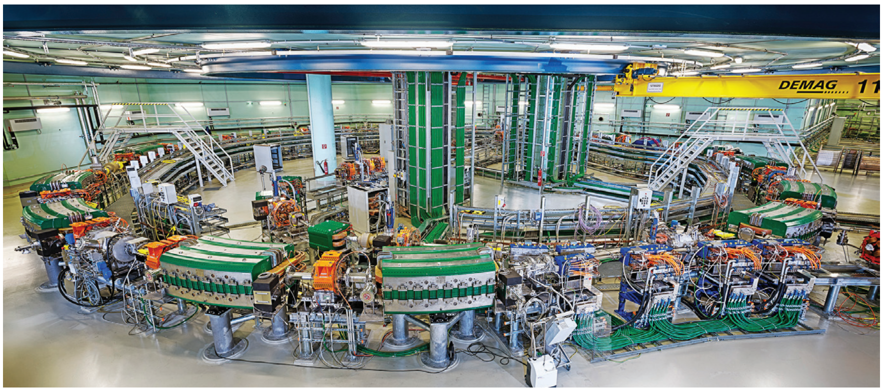
Boosting brainpower

No accelerator was spared from the LS1 work, and neither were their 'brains'. Across all of the injectors, 90% of the front-end control computers were renovated as part of a five-year upgrade programme. More than 450 real-time control systems were changed and the architecture of the software and hardware was redefined. The recommissioning of the injectors with these new systems was a success, thanks to numerous tests carried out between January and August.

The data collected from the accelerators are processed by the computer centre in the CERN Control Centre (CCC), which, with 350 servers, is the Laboratory's second largest data centre. The electrical and cooling systems were completely redesigned in order to increase the electrical power and cooling capacity, and guarantee redundancy so that the systems can operate without

New beams for medicine

CERN accelerator teams have been contributing to the development of medical accelerators for almost 25 years. The MedAustron project, which accelerated its first beams in 2014, is a shining example of technology transfer from fundamental physics to the field of medicine. MedAustron is a hadron-therapy and research centre near Vienna, Austria, which is due to treat its first tumour patients in early 2016. CERN contributed considerably to the development and construction of the acceleration system for the centre, which is equipped with three ion sources, a linear pre-accelerator and a synchrotron that sends beams to irradiation chambers. For five years, specialists from CERN have been helping to set up and train MedAustron's team of scientists. Together, they designed the accelerator and oversaw the manufacture of its components. The 300 magnets, of 30 different types, were designed and later tested at CERN, having been manufactured at different European sites. The last magnets left CERN for Austria in 2014. The converter control system was also based on CERN technologies and the synchrotron radiofrequency system was developed jointly for MedAustron and the PS Booster. The whole acceleration system was commissioned in 2014. On 6 November, a 250-MeV proton beam was successfully sent to one of the irradiation chambers. This was an excellent result for both the MedAustron and the CERN teams, who will continue to work together to finalize the commissioning of the medical accelerator in 2015.



The synchrotron at the MedAustron medical research and treatment centre in Austria was developed in collaboration with CERN. (Thomas Kaestenbauer)

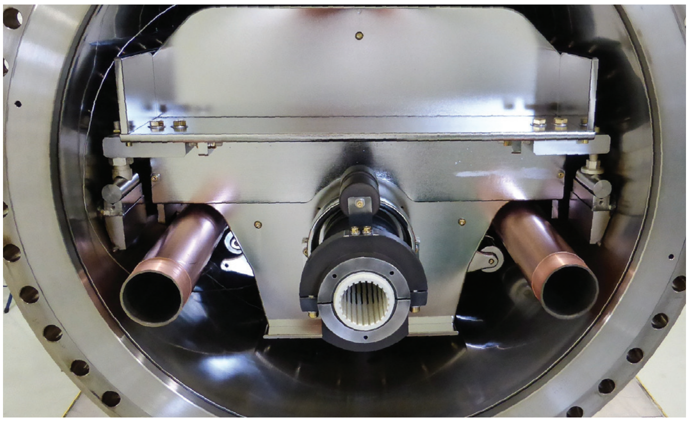
interruption. The new cooling system is fully redundant, as is the new electrical sub-station. Used exclusively to supply the CCC and its computer centre, this was equipped with uninterrupted power supplies and diesel generators. With these upgrades in place, work can be done without interruption.

The end in sight

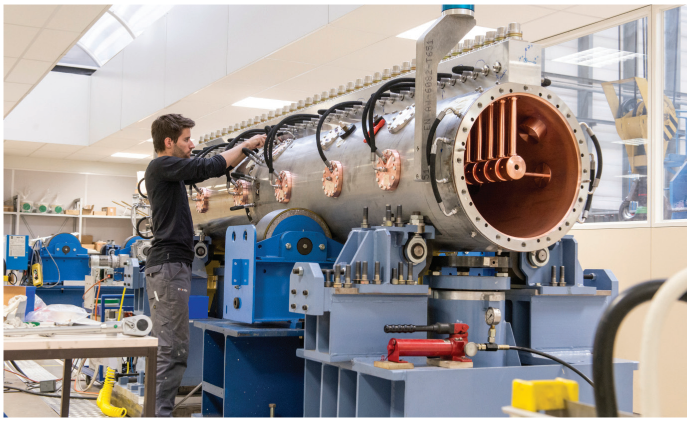
While the injectors were being recommissioned, an immense programme of work was coming to an end in the LHC. In order to circulate 6.5-TeV beams in the accelerator, the 10 170 electrical interconnections between the magnets had to be fitted with copper shunts that provide a low-resistance path for the current in the event of a quench. No fewer than 27 000 shunts were installed. As well as these reinforcements, 3000 interconnections had to be reconstructed and 5000 reinforced insulation units installed around each pair of interconnections. The teams completed this huge undertaking with the closing of the last interconnection on 18 June. Nearly 300 engineers and technicians from CERN, its contractors and partner institutes worked in two shifts for 14 months to achieve this impressive result. The equivalent of 3.3 km of welds were made to close the interconnections, and not a single fault was detected. This work was followed by pressure tests, which were all conclusive, and electrical quality assurance tests. By the end of 2014, five of the eight sectors had undergone these first electrical tests, ready for powering and qualification at an energy of 6.5 TeV. In addition to this work, 20 new collimators with integrated beam-position monitors were installed. The collimators clean the beam of particles that stray from the trajectory. The electrical distribution boxes, which guarantee the transmission of current from the resistive cables to the superconducting cables, were also renovated. The eight kicker magnets, which direct the beam from the SPS transfer lines to the LHC, were all upgraded and recommissioned.

Away from the heart of the accelerators, associated infrastructures, such as the cooling and ventilation system, also underwent major transformations. New cooling towers were installed at three points of the LHC in order to take over from the main towers when maintenance work needs to be done.

After three years of development, the electrical distribution network is now equipped with a new electrical monitoring system. Deploying the system was a painstaking task, since it manages 20 000 electrical and monitoring devices, records 250 000 measurements and comprises 200 synoptics. The new, redundant system will include new tools for simulating or helping to manage power outages. An unexpected breakdown of the electrical network in October provided an opportunity to put it to the test. The system helped the operators to understand



The kicker magnets, which transfer beams from the SPS to the LHC, were upgraded. (OPEN-PHO-ACCEL-2014 – 007)



One of the drift-tube linac (DTL) tanks for Linac4 being prepared at CERN before its installation. (CERN-PHOTO-201404-087 – 1)

the origin of the breakdown and to restore service quickly, thus validating both the tools and the architecture implemented.

All of this work necessitated considerable logistics and handling. The year 2014 saw more than 250 000 operations to transport and move approximately 200 000 tonnes of materials, and the handling equipment itself was renovated. CERN has some 350 overhead travelling cranes; 18 were replaced or renovated and a further 4 new cranes added to the fleet.

While beams were circulating in the injectors, the recommissioning of the LHC began with the cooling of the accelerator. Cooling its 36 000 tonnes of metal to 1.9 K (-271°C) requires 10 000 tonnes of nitrogen and 135 tonnes of helium. It is the equivalent of cooling five Eiffel Towers. In an impressive logistical operation, 520 lorry-loads of nitrogen and helium were delivered. The sectors were first cooled to a temperature of 20 K and then maintained at that temperature for four weeks while further tests of the magnet circuits were carried out (see box p. 20), before the temperature was taken all the way down to 1.9 K. All eight sectors were cold by the end of 2014.

Qualified for high energy

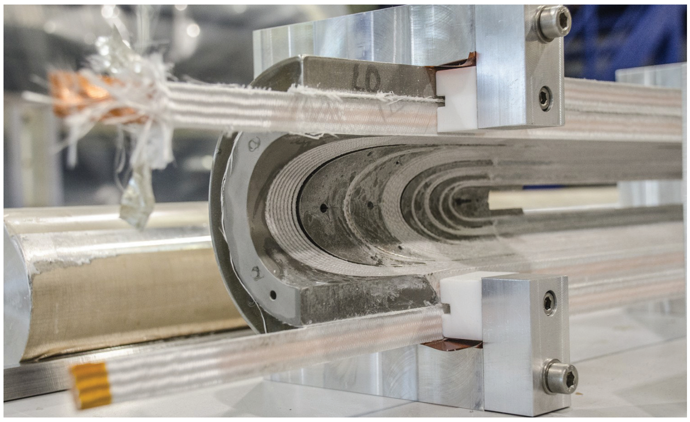
Once the sectors had been cooled, the process to qualify them for the LHC run at 6.5 TeV per beam could begin. For the accelerator to operate at this energy, the currents going through the dipole magnets will need to reach 11 080 A (compared with 6800 A during Run 1). Like athletes, the dipoles have to be 'trained' for such high currents, which entails gradually increasing the current in the magnet coils. The forces generated can cause imperceptible movements, which can sometimes lead to quenches whereby the magnets suddenly enter the conducting state. The operation is repeated several times in each sector until the nominal current is reached. By the end of 2014, one sector had been qualified at 6.5 TeV, following 20 training quenches. The forecast had been 150 quenches across all eight sectors of the accelerator. The recommissioning, at different currents, of all of the other circuits supplying the focusing and corrector magnets, as well as the instrumentation, also began with a total of 1600 circuits to be verified and re-supplied.

Another accelerator also celebrated the arrival of beam in 2014: on 5 August, Linac 4 accelerated a beam to an energy of 12 MeV, qualifying the third element in its acceleration chain. This new linear accelerator, which is scheduled to take over from Linac 2 in 2020, is composed of four types of accelerating structures. It will deliver beams at an energy of 160 MeV, compared to the 50-MeV beams delivered by Linac 2. Having already implemented the first two elements of its acceleration line in 2013, the teams installed a drift-tube linac (DTL) tank and most of the cell-coupled drift-tube linac (CCDTL) structures. The qualification of the first DTL tank on 5 August after the first tests was cause for celebration, as these structures are based on a novel design. In addition, the new ion source was tested at the required current. Components of the 80-m line that will transfer ions to the PS Booster were installed. The difficulty in developing these pieces of equipment comes from the fact that Linac 4 will accelerate negative hydrogen ions (a proton surrounded by two electrons), whereas Linac 2 accelerated protons. The final accelerating structures (the Pi Mode structures, or PIMs) are under construction. The aim is to begin beam-commissioning of Linac 4 in 2016 before connecting it to the accelerator chain in 2018. Preparation of the new injector equipment got under way in order for the PS Booster to be ready to receive new beams.

Projects taking shape

A few metres from Linac 4, the Extra Low ENergy Antiproton Ring (ELENA) was getting off the ground. This circular decelerator measures 30 m in circumference and will begin operation in 2016 and physics in 2017. It will improve the efficiency of the AD by slowing even further the antiprotons sent to the antimatter experiments. The construction of the new building was completed (see p. 36) and the AD kicker generators were moved there to make space in the AD hall for the new decelerator. The

The assembly of the first superconducting cavities for HIE-ISOLDE began in a new clean room. (OPEN-PHO-ACCEL-2015 – 004)



A niobium–tin coil for a testing an 11-T dipole-magnet model for the HL-LHC project. (CERN-GE-1310248 – 02)

technical design report was published in the spring. Numerous technical improvements were made to optimize the machine and its performance. Work on the AD extraction lines got underway with the replacement of the quadrupoles and the construction of equipment for ELENA began.

ISOLDE, CERN's nuclear physics installation, will soon produce radioactive ions at higher energies. A new accelerator, High-Intensity and Energy ISOLDE (HIE-ISOLDE), will ultimately increase ISOLDE's beam energy from 3 MeV per nucleon to between 10 and 15 MeV per nucleon and will quadruple the beam intensity. The installation of this 16-m-long superconducting linear accelerator progressed well. The cryogenics facility, partly inherited from a former experiment, was refurbished and installed. The accelerator will eventually consist of six cryomodules, each containing five superconducting cavities. Twelve cavities were produced and are being assembled in a new clean room and the first segment of the transfer line to the experiments was tested. HIE-ISOLDE will be commissioned in phases: in the first phase, scheduled to take place at the end of 2015, one cryomodule will accelerate beams to an energy of 4.3 MeV per nucleon.

Civil engineering work started for the Advanced Wakefield Experiment (AWAKE), which is scheduled to receive its first beams from the SPS in 2016. AWAKE will study the principle of acceleration using the wakefields in plasma cells. This principle, which has already been established using electrons, will be tested with protons with a view to achieving accelerator gradients hundreds of times greater than those possible using the current radiofrequency cavities. AWAKE will be installed in the tunnel that previously housed the CNGS neutrino facility. The final 100 m of the CNGS beamline were removed and a shielding wall built. Two tunnels were excavated, one to house the laser beam (which will ionize the plasma) and the other for the source and the electron beam (the 'probe beam', which will be accelerated by the plasma). Studies for the development of the electron, proton and laser beamlines made good progress.

A prototype plasma cell measuring 3 m is being studied at the Max Planck Institute in Munich.

High luminosity guaranteed

CERN is pushing ahead with its flagship project for the next 20 years — the High-Luminosity LHC (HL-LHC). The project was announced as the top priority of the European Strategy for Particle Physics in 2013 and was included in the Organization's Medium-Term Plan. This new machine is scheduled to be commissioned sometime after 2025 and will increase the number of collisions by a factor of 5 to 10, giving a luminosity of 250 inverse femtobarn (fb^{-1}) per year. In order to attain this level of performance, 1.2 km of the current accelerator will be replaced with new equipment.

The project was launched in 2011 in the framework of a programme funded by the European Union and European, US, Russian and Japanese institutes, among others. It is based on the development of new, more powerful quadrupole magnets to focus the beams before collisions, radiofrequency 'crab' cavities to direct the beams, shorter and more powerful dipole magnets, an improved collimation system and new superconducting electrical connections.

The new superconducting magnets, made from a niobium–tin compound, are being developed within a collaboration between CERN and the US LHC Accelerator Research Programme (LARP), a group of four US national laboratories. An important step was taken by the LARP consortium with the building of a large-aperture quadrupole magnet that generated a magnetic field of more than 12 T. In addition, two short superconducting dipole-magnet models achieved fields of 11 T, at Fermilab and at CERN. A group of international experts selected two prototype crab cavities, which are due to be tested with beam at the SPS from 2016, and the architecture of the collimation systems was finalized. With the increase in luminosity, certain power converters will need to be moved to the surface and connected by superconducting cables dozens of metres long. A new record was set when a magnesium diboride superconducting cable operating at a temperature of 24 K successfully transported a current of more than 20 000 A over a distance of 20 m.

The success of the HL-LHC also relies on the injector chain. The LHC Injectors Upgrade (LIU) project aims to prepare the injectors for high-luminosity runs of the LHC. Together, the LIU and HL-LHC project teams have defined the parameters for the beams of all of the accelerators. Five new radiofrequency accelerating cavities using FineMet® technology, which will perform better at high intensities, were installed in the PS Booster and were tested once beam had returned to the accelerator. FineMet® technology uses a composite magnetic material instead of the traditional ferrite and has the advantage of a wider bandwidth. These tests will be used to decide whether to replace the PS Booster's entire radiofrequency system with this technology. A FineMet® cavity was also installed in the PS in order to evaluate its ability to stabilize beams. The PS was also the subject of studies on 'space charge' effects: at low energies, particles with the same electric charge tend to repel one another, which limits the beam density and therefore the luminosity. The phenomenon of electron clouds (see p. 15) was studied at the SPS, as were vacuum-tube components with the potential to destabilize the beam and a working group was set up to investigate ways of improving their design. Work began on the construction of new equipment, such as new beam-instrumentation tools for the PS and new power amplifiers for the SPS radiofrequency system, which will be installed in a brand-new building on the Prévessin site.

The future is bright

CERN is also preparing the way for the long-term future of particle physics beyond the HL-LHC. The Future Circular Collider (FCC) study, officially launched in 2014, centres on a hadron collider capable of reaching a collision energy of 100 TeV, to be installed in a new 80–100-km tunnel. The study will also investigate the possibility of a lepton collider as an intermediate step as well as a lepton–hadron collider option. It will also consider the installation in the existing tunnel of a high-energy LHC using magnets generating fields of 16–20 T. The FCC study kick-off meeting in February attracted almost 350 participants from 127 institutes, universities and firms from 23 countries. The governance structure for the project was established with the creation of a Coordination Group, comprising experts from around the world, and an International Collaboration Board. By the end of 2014, 43 institutes from 19 countries had officially joined the FCC collaboration and more were preparing to sign agreements. The first studies began on the physics potential and the technical parameters of the machine, and the key technologies were identified. A geological survey of the Lake Geneva region was launched, with new software that can be used to identify the optimal location for the tunnel. A research and development programme for the FCC study is currently being prepared. The aim is to publish a conceptual design study in 2018.

The FCC study is complementary to that for the Compact Linear Collider (CLIC) project, which is another possible future accelerator option. This linear collider is based on an innovative two-beam acceleration concept. The CLIC collaboration includes 50 institutes in 25 countries. Cost and performance-optimization studies were carried out in 2014, with a focus on construction of the machine in three phases with a view to reaching collision energies of 380 GeV in the first phase, then 1.5 TeV and finally 3 TeV. The first complete 2-m-long accelerator module was installed and will start being tested in 2015. By the end of 2014, three klystron test installations were operational. The partner institutes continued to work on instrumentation, magnets and vacuum studies, as well as on control, alignment and stabilization systems. CLIC is also beginning to expand beyond particle physics: high-gradient accelerating structures are also of interest to groups wishing to use compact accelerators for free-electron lasers.

LHC protection put to the test with current

'A more powerful and reliable machine.' With this key principle in mind, the LHC teams carried out numerous tests once the consolidation work had been completed. An innovative test was developed to qualify the machine's quench-protection system. When one of the LHC magnets, each of which transports currents of up to 11 080 A, loses superconductivity (as a result of an instability, for example), the current is immediately diverted to a parallel circuit to avoid a disastrous rise in temperature in the magnet. This circuit consists of power diodes and the new shunts installed on the electrical connections between the magnets to ensure that the LHC can run at 6.5 TeV. The new test, which was validated in 2013, involves testing all of the parallel circuits. To do this, the temperature of the helium is kept at 20 K so that the cables lose their superconductivity. Currents of increasing intensities are injected into the circuits. They naturally travel through the secondary network, thereby testing the reliability of the copper shunts and the magnets' protection diodes. If even the slightest resistance is observed, the current is interrupted immediately. By the end of 2014, all of the dipole circuits had successfully passed the tests.