BUILDING TOMORROW AND BEYOND

CERN's physicists, engineers and technicians are constantly devising, designing and building new installations that will enable the scientific community to further its quest for new knowledge. From the next-generation LHC to the accelerators of the future, the inauguration of a new linear accelerator and the first tests of an antimatter decelerator, new projects are taking shape in CERN's workshops.

Assembly of the first two crab cavities, which will tilt the beams before they meet in the heart of the experiments at the High-Luminosity LHC. (CERN-PHOTO-201708-196-5)

Manufacture of a corrector magnet for the High-Luminosity LHC. (CERN-PHOTO-201804-093-4)

ACCELERATING TOWARDS HIGH LUMINOSITY

The High-Luminosity LHC, which will begin operation after 2025, is entering its final phase of development. For certain components of this second-generation LHC, manufacturing has already begun.

The High-Luminosity LHC will supply up to ten times more collisions, allowing physicists to study in detail the phenomena discovered at the LHC. For this major upgrade of the machine, new equipment must be installed along a length of 1.2 kilometres of the current accelerator. Increasing the number of collisions involves injecting more particles into the ring, and compressing the bunches of particles more tightly before they meet in the experiments. This will be achieved with more powerful focusing magnets, using niobium-tin to generate magnetic fields of 11.4 teslas, compared to the 8.3 teslas generated by the niobium-titanium magnets in the LHC at present.

Twenty-four quadrupole magnets of two different lengths are being developed at CERN and in the framework of a collaboration between CERN and the US HL-LHC AUP (Accelerator Upgrade Program), involving several laboratories in the United States. In 2017, two short prototypes were built and tested at CERN, allowing the very delicate manufacturing process for the coils to be optimised. A full-size 4-metre prototype was completed in the United States and production of a full-size 7.2-metre prototype began at CERN.

The so-called crab cavities will give the particle bunches a transverse momentum in order to optimise their orientation before they collide. This technology, being used for the first time in a hadron collider, made a leap forward in 2017 when the first two cavities were manufactured in collaboration with the University of Lancaster and STFC in the United Kingdom, then assembled and successfully tested. At the end of the year, they were ready to be transported to the SPS accelerator. A radiofrequency test station equipped with a novel mobile helium cooler was developed to test the crab cavities with beam in 2018.

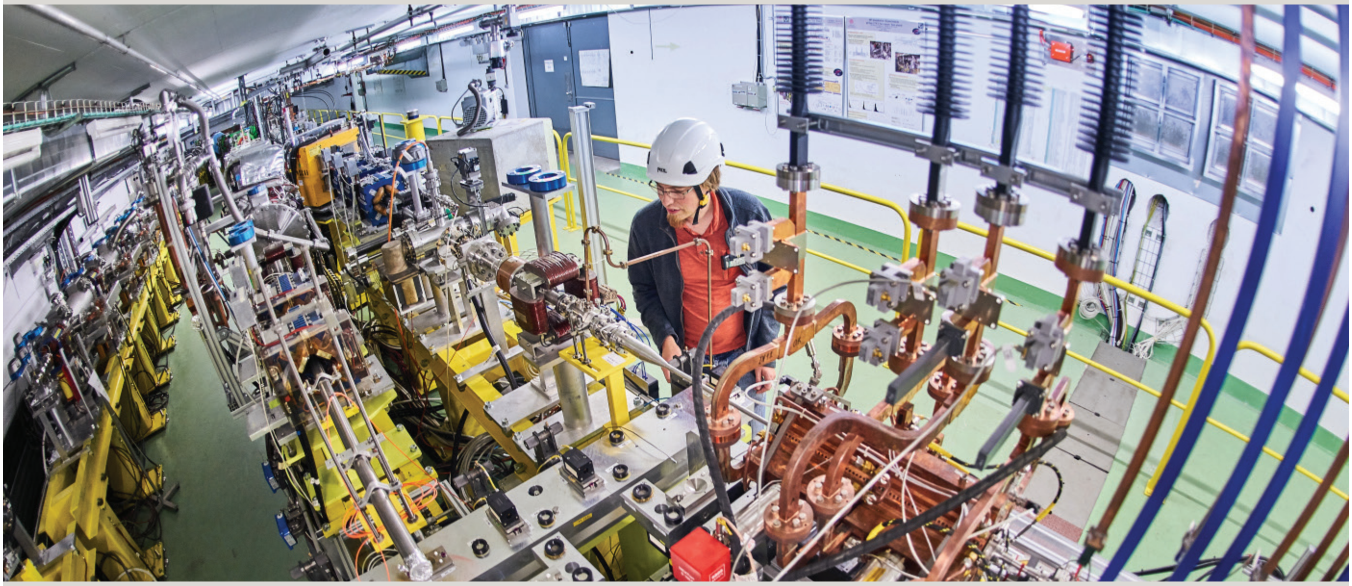
With more particles passing through the LHC, machine protection needs to be reinforced. This means a greater number of collimators, which absorb the particles that deviate from the optimum trajectory. In 2017, three new types of collimators were tested. Firstly, two wire collimators were installed in the LHC. The conductor inserted between their jaws creates an electromagnetic field that corrects interference from the beam circulating in the opposite direction. A prototype collimator made from molybdenum graphite, which interferes less with the beam, was successfully tested. Finally, crystal collimators, which divert particles that go off course towards an absorber, were also tested.

To make room for the collimators, shorter and more powerful bending dipole magnets than those in the LHC, also made from niobium-tin, have been developed. Two new short prototypes of these 11-tesla dipoles have been manufactured and tested.

Aside from the main magnets, seven types of corrector magnets will be installed, including 16 with an unusual coil geometry, known as canted cosine theta magnets. In 2017, a short prototype exceeded the required performance, and the manufacture of components for the full-size prototype began. Thirty-six other corrector magnets, with a superferric design, are being developed in the framework of a collaboration with INFN. Two new prototypes have been constructed and tested at the INFN-LASA laboratory in Milan.

High luminosity is also a challenge for the vacuum and cryogenics experts. The electron-cloud phenomenon, which degrades the vacuum and interferes with the beams, is more amplified the more intense the beams are. In 2017, a tiny robot was developed by CERN in collaboration with British partners from STFC and the University of Dundee. It can treat parts of the vacuum chamber in situ with a laser beam in order to modify the structure of the surface, making it possible to trap electrons.

THE HIGH-LUMINOSITY LHC WILL SUPPLY UP TO TEN TIMES MORE DATA FOR PRECISION STUDIES.



The new CLEAR test facility is available not only for accelerator R&D but also for measurements in other scientific fields, such as space exploration and medical applications. (CERN-PHOTO-201711-271-12)

One of the short prototypes of the niobium-tin quadrupole magnets for the High-Luminosity LHC being inserted in the brand-new vertical test bench of the superconducting magnet test facility. (CERN-PHOTO-201708-191-20)

CUTTING-EDGE TESTING

To develop state-of-the-art components, you need to be able to measure their performance. CERN's laboratories must therefore be capable of performing cutting-edge tests.

In 2017, a new test facility for accelerator components began operation. CLEAR (CERN Linear Electron Accelerator for Research), which took over from CLIC's CTF3 facility (see p. 48), is equipped with an electron beam line to test CLIC's accelerating structures, as well as components for the High-Luminosity LHC and its injectors. Although its primary mission is R&D for accelerators, CLEAR is also open to other scientific fields. In 2017, the facility played host to radiation measurements on electronic components destined for space missions, dosimetry tests for medical applications and tests for free electron lasers, and the programme for 2018 is shaping up to be equally as rich and diverse.

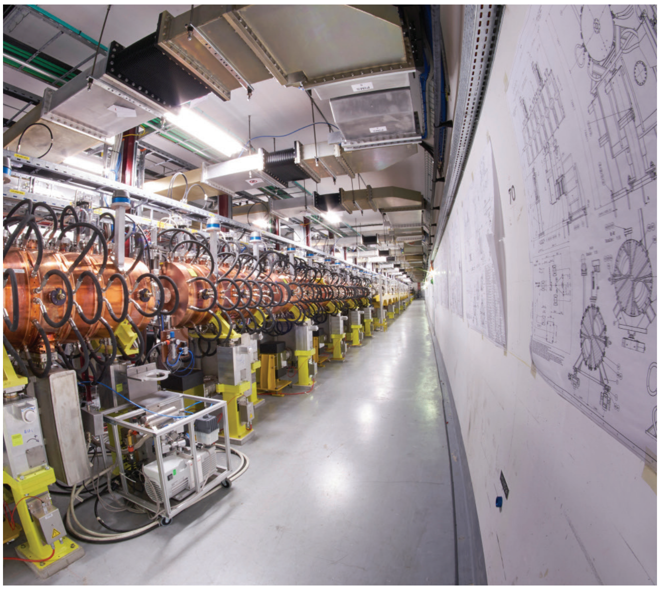
Renovation work continued at the superconducting magnet test facility, an essential resource for the High-Luminosity LHC and other future accelerators. A vertical test bench, able to deliver currents of up to 30 000 amps, started operation. A horizontal bench for longer magnets and a test station for superconducting links are under development.

In the same facility, the FRESCA2 magnet began operation, generating a magnetic field of 13.3 teslas. The magnet was developed in collaboration with France's CEA and will be used to test niobium-tin and high-temperature superconducting cables for the accelerators of the future.

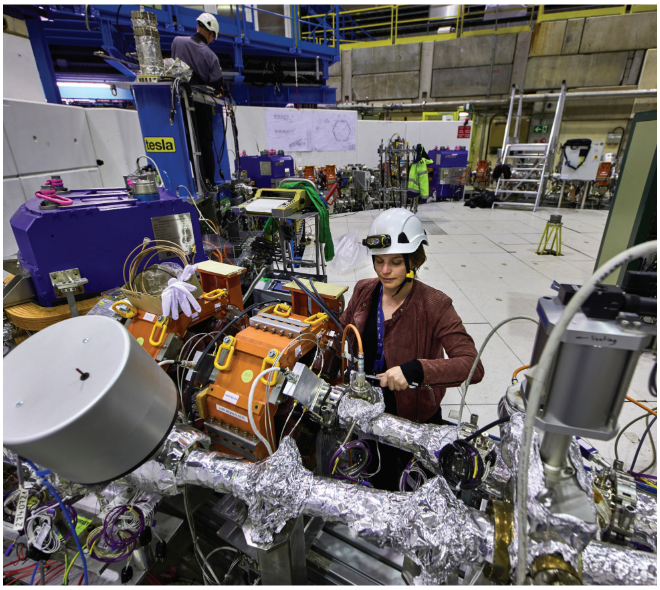
A NEW MEMBER JOINS THE ACCELERATOR FAMILY

On 9 May, CERN's accelerator family welcomed its newest member – Linear Accelerator 4 (Linac4). This was the first inauguration of a new accelerator at CERN since the LHC started up in 2008. In 2019, it will be connected to the next accelerator in the chain, the Proton Synchrotron Booster, and will replace Linac2 as the first link in the accelerator chain after Long Shutdown 2, in 2021. In the spring, the 160 MeV Linac4 was fully commissioned and entered a stand-alone operation run to assess and improve its reliability, prior to being connected to the CERN accelerator complex.

The linac's overall availability during this initial run reached 91% – an amazing value for a new machine. The Linac4



The Linac4 accelerator, inaugurated in May 2017, is composed of four types of structure and will accelerate beams up to 160 MeV. (CERN-PHOTO-201704-093-11)



The new ELENA antiproton decelerator passed many milestones in 2017 on the road to becoming operational. (CERN-PHOTO-201804-086-6).

reliability run will continue well into 2018. Particle injection from Linac4 into the PS Booster was tested and all new equipment for the transfer line between the two was prepared for installation. This included a vertical distributor, which will divide the beam coming from Linac4 into four "slices" with the help of kicker magnets. The four new beams will then be sent to newly developed vertical electromagnetic septum magnets, where a further deflection will send the beam into the four superimposed rings of the PS Booster.

The 86-metre-long accelerator is a cornerstone of the LHC Injectors Upgrade (LIU) project, which aims to bring the injectors up to date for the High-Luminosity LHC.

In the framework of this project, the acceleration system of the PS Booster will be replaced. In 2017, 28 new-generation radiofrequency accelerating cavities were assembled. During LS2, 24 of these cavities will be installed in the four PSB rings, with the remaining four serving as replacement cavities if required. Thanks to this upgrade, the accelerator will be capable of supplying higher intensity beams at a higher energy of up to 2 GeV, compared with just 1.4 GeV today.

A significant amount of the activities during the year-end technical stops in 2016 and 2017 was devoted to the LIU project. A major de-cabling campaign took place in the PSB, the PS and the SPS, during which around 13 000 obsolete cables were removed. In addition, another phase of the electron cloud mitigation campaign in the SPS was successfully completed. It started back in 2015 and involves coating the inner walls of a few selected vacuum chambers with amorphous carbon, which will inhibit the electron cloud phenomenon.

ANTIMATTER CIRCULATES IN A NEW DECELERATOR

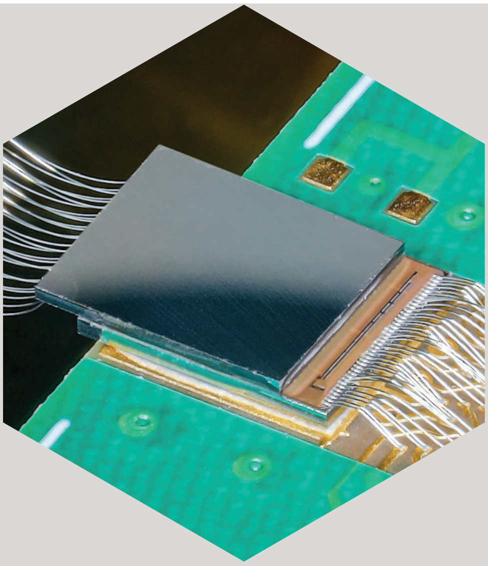
In 2017, ELENA (Extra Low ENergy Antiproton), a new antiproton deceleration ring, passed several key milestones on the road to becoming operational.

The ELENA ring is connected to the Antiproton Decelerator and is designed to slow down antiprotons even further before transferring them to the antimatter experiments. The energy level will be reduced from 5.3 MeV to just 0.1 MeV, since the slower the antiprotons are, the easier it is for the experiments to trap and study them. This decelerating machine, paired with the electron cooling system installed at the end of the year, will enable the experiments to trap 10 to 100 times more antiprotons.

Once the first beams of H^- ions (a proton between two electrons) had circulated, the radiofrequency, beam instrumentation and correction systems were tested and brought online. ELENA also received its first antiprotons from its big brother, the Antiproton Decelerator. In fact, the radiofrequency systems of the two decelerators have been synchronised.

At low energy, the beams are difficult to control as they are more sensitive to external interference, which is making the commissioning of ELENA a difficult task. The teams tested the ring with ions at very low energy, just 0.085 MeV. The beam was maintained for several hundred milliseconds and some antiprotons even travelled for several seconds – a success.

Finally, preparations began for the antiproton transfer line to the GBAR experiment, which is scheduled to receive its first test beams from ELENA in 2018. The other experiments will be connected during the second long shutdown.



A silicon pixel detector prototype developed for the vertex detector of CLIC. This chip on top is just 3 millimetres wide and contains more than 16 000 pixels. (OPEN-PHO-EXP-2017-010-1)

CERN IS WORKING ON TWO STUDIES FOR THE FUTURE OF COLLIDER PHYSICS.

SHAPING THE FUTURE

CERN is working on two studies for the future of collider physics beyond the High-Luminosity LHC, one on a circular collider (FCC) and the other on a linear collider (CLIC). A preliminary study for each machine is under way as input for the update of the European Strategy for Particle Physics.

The **Future Circular Collider (FCC)** collaboration, consisting of more than 120 institutes from 33 countries, is developing concepts for a large accelerator infrastructure with a circumference of about 100 kilometres. The new tunnel could host a lepton collider or a 100 TeV hadron collider. Further opportunities include heavy ion collisions, lepton-hadron collisions and fixed-target experiments. The study also covers a possible high-energy version of the LHC in the existing tunnel.

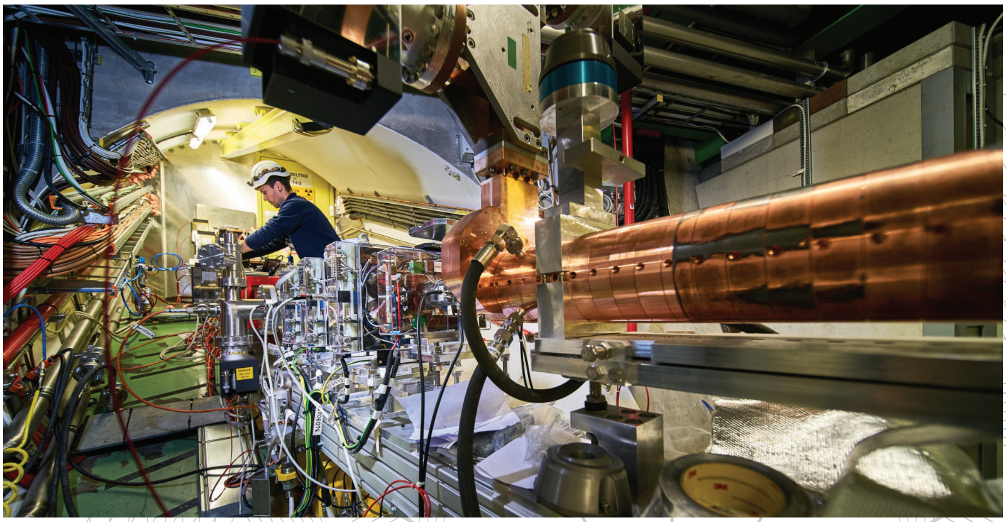
In 2017, the collaboration finalised the baseline design and parameters for these machines, as well as their technical systems and infrastructures, essential input to the FCC Conceptual Design Report due by the end of 2018.

The beam optics (the way in which the beams are directed and focused) were refined and optimised. The physics opportunities were explored in depth during the first dedicated FCC physics week. Teams continued to work on the location of the tunnel in the region and produced preliminary studies demonstrating that such an infrastructure is compatible with the environmental and socio-economic requirements of the two Host States.

Key technologies for the lepton collider (FCC-ee) are superconducting radiofrequency (RF) cavities and high-efficiency RF power production. A collaboration between CERN, LNL (Italy) and STFC (UK) is evaluating the ultimate performance of the current niobium-copper technology and studying alternative materials such as niobium-tin. In collaboration with JLAB and FNAL in the US, R&D is also focusing on techniques which could outperform standard bulk niobium. Innovative manufacturing techniques to reduce the cost of cavity fabrication and improve their quality are being pursued together with industrial partners. New technologies to increase the RF power production efficiency are being developed together with CLIC. Short models of the twin-aperture main dipole magnet for the lepton collider have been built at CERN, and currently a quadrupole model is under construction. Finally, a novel and efficient injector scheme has been designed.

The hadron collider (FCC-hh) relies on niobium-tin superconducting magnets with a field of 16 teslas, twice that of the LHC magnets. Collaborations with institutes and companies have been established to develop niobium-tin wire with increased performance and at an affordable cost. An enhanced racetrack model magnet is being built as a first demonstrator at CERN. Studies have been launched with economists and companies to identify potential benefits of niobium-tin superconducting devices with possible applications including compact and precise nuclear magnetic resonance spectroscopy and imaging, as well as lighter superconducting cyclotrons for ion therapy. In the framework of the FCC study, two synchrotron radiation beam lines have been set up at KARA in Karlsruhe (partially funded by H2020 EuroCirCol) and DAFNE in Frascati to test the beam screen prototypes for the hadron collider. EASItrain, the H2020 Marie Curie training network that was approved for funding in May 2017, covers three key technologies for the FCC, namely superconducting wires, superconducting thin films and cryogenic refrigeration.

The **Compact Linear Collider (CLIC)** project centres on the design of a high-luminosity linear electron-positron collider to explore the energy frontier. The accelerator is based on an innovative two-beam acceleration concept and requires the successful development of very high-gradient accelerating structures. It would operate in a staged programme with successive collision energies at 0.38, 1.5 and 3 TeV. During 2017, accelerator studies aimed at



Installation of the AWAKE experiment in 2017. AWAKE will test the acceleration of electrons using a plasma wakefield driven by protons. (CERN-PHOTO-201711-284-12)

reducing the cost and the power consumption of CLIC. The key activities included high-efficiency radiofrequency (RF) sources, permanent magnets, nano-beam tests, optimised accelerator structures and overall implementation studies related to civil engineering, infrastructure, schedules and tunnel layout. In parallel, a systematic overview of potential industrial involvement in the CLIC core technologies is being compiled.

CLIC is actively collaborating with numerous projects outside the high-energy physics field, which benefit from high-gradient accelerator technology, paving the way for wider use of the CLIC 12 GHz X-band technology. Since this technology allows a significantly more compact and power-efficient accelerator design, it is of interest for other applications such as photon sources for the study of materials, biological samples and molecular processes. The X-band test stands at CERN are important demonstrators for the RF systems in such applications. Notably, in 2017, the CompactLight design study proposal, which aims to design the first hard X-ray free-electron laser (XFEL) based on 12 GHz X-band technology, was approved by the European Commission.

Work continued on evaluating the full physics potential of the CLIC accelerator with the aim of demonstrating the physics potential up to multi-TeV collisions. A comprehensive report on the top quark physics studies that can be carried out at the three energy stages is being prepared. Substantial advances were made in the broad and active R&D programme on vertex and tracking detectors. These aim to find technologies that simultaneously fulfil all the stringent CLIC requirements on position resolution, timing capabilities and low-mass features.

Silicon pixel R&D is being pursued in synergy with the ATLAS and ALICE detector upgrades and the development of the Medipix and Timepix pixel detector chips. Test beam campaigns with different configurations of these chips were conducted and several concepts for future developments were initiated. 2017 saw the start of studies evaluating the performance of the new CLIC detector model, using a new software suite for event simulation and reconstruction.

CLOSER TO A BREAKTHROUGH IN ACCELERATION TECHNOLOGY

A new experiment at CERN got one step closer to testing a breakthrough tehnology for particle acceleration. In November, the final three key parts of the Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) were put in place: its electron source, electron beam line and electron spectrometer. This marked the end of the experiment's installation phase.

By the end of 2017, commissioning of the whole experiment, including the new parts, had begun, alongside preparations for a very important year ahead. In 2018, AWAKE will explore a new way of accelerating particles. It will turn electrons into surfers riding waves of electric charge called wakefields. AWAKE needs four key ingredients to achieve this: protons, electrons, a laser and plasma. First, a beam of protons is injected into the heart of AWAKE, a 10-metre plasma cell full of laser-ionised gas. While travelling through the plasma, the protons attract free electrons, which generates the wakefields. A second particle beam, this time of electrons, is injected into the phase right behind the proton beam. The second beam is then accelerated by the wakefields, just like a surfer riding a wave, potentially gaining several gigavolts of energy.

In 2016, AWAKE had already proved that it could create wakefields thanks to proton beams. In 2017, the phase-stability, reproducibility and robustness of these wakefields were demonstrated. The next step is to prove that they can be used to accelerate electrons.

The technology developed by AWAKE would allow us to produce accelerator gradients hundreds of times higher than those achieved in current radiofrequency cavities. This would allow future colliders to achieve higher energies over shorter distances than are possible today.