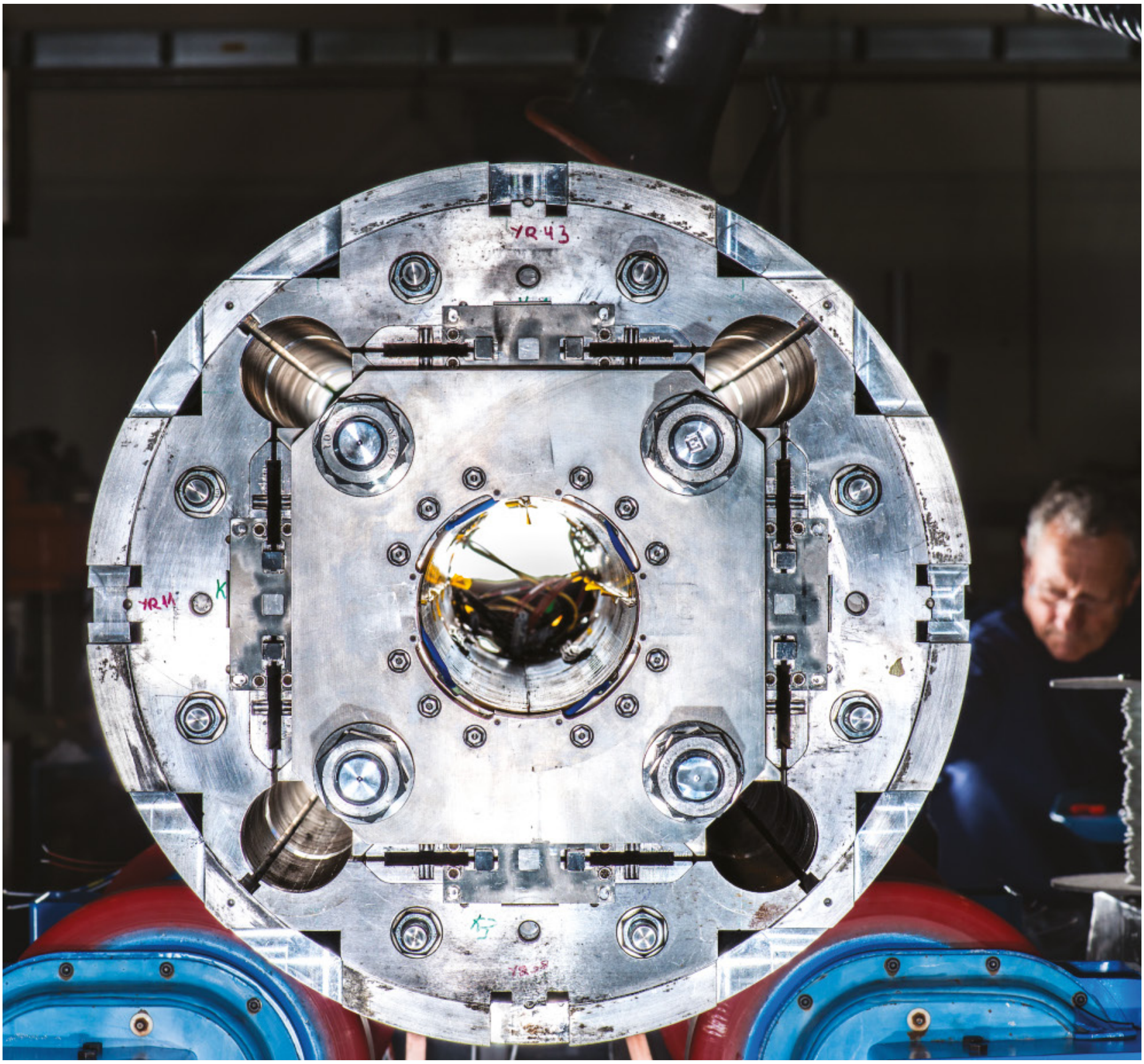
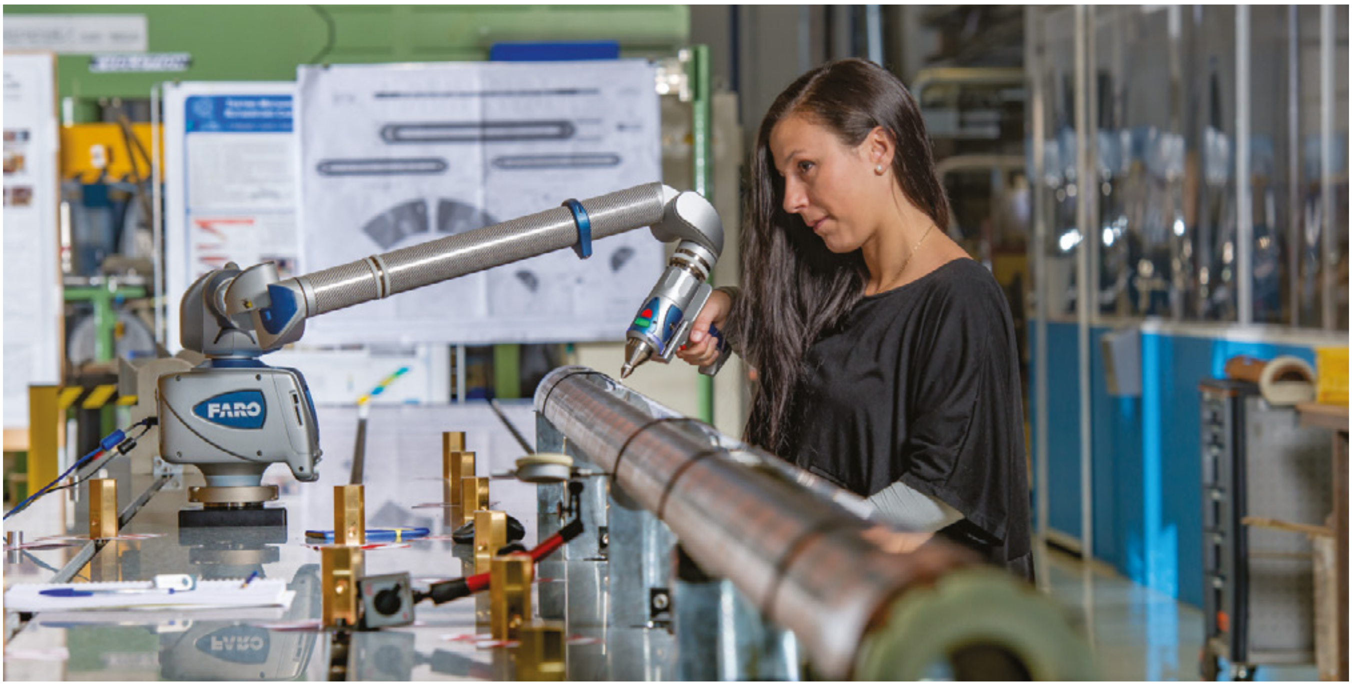
BUILDING TOMORROW AND BEYOND

CERN's physicists, engineers and technicians are devising, designing and building new installations that will allow the scientific community to further our fundamental understanding of the universe. Various projects saw considerable progress in 2016, from the High-Luminosity LHC to the next generation of accelerators, and a new machine intended to shed light on the mysteries of antimatter.

View of a short prototype of a quadrupole magnet for the High-Luminosity LHC. (OPEN-PHO-ACCEL-2017-010-2)





A scientist carefully checks the geometry of a dipole magnet coil for the High-Luminosity LHC. (OPEN-PHO-ACCEL-2017-010-1)

FULL SPEED AHEAD FOR HIGH LUMINOSITY

In 2016, the High-Luminosity Large Hadron Collider stepped up a gear. In workshops in Europe, Japan and the United States, teams were hard at work preparing for the second-generation LHC, which is planned to begin operation in 2026. The High-Luminosity LHC will increase the number of collisions by a factor of 5 to 10, producing an integrated luminosity of 250 inverse femtobarns per year. Physicists will be able to take full advantage of this increased number of collisions to study in greater detail the phenomena discovered at the LHC. This major upgrade to the machine requires the installation of new equipment over 1.2 kilometres of the current accelerator.

Twice as many particles will circulate in the machine and they will be divided into denser bunches. New, more powerful focusing magnets will be used to squeeze the particle bunches before they collide in the centre of the ATLAS and CMS experiments. Twenty-four quadrupole magnets of two different lengths are currently being manufactured.

These magnets will use niobium-tin to generate magnetic fields of 11.4 Tesla, compared to 8.3 Tesla in the LHC at present, but the use of this compound presents certain challenges. Production of niobium-tin cables began at CERN three years ago and more than 21 kilometres have been produced so far. The delicate processes involved in forming magnet coils with these cables have been validated.

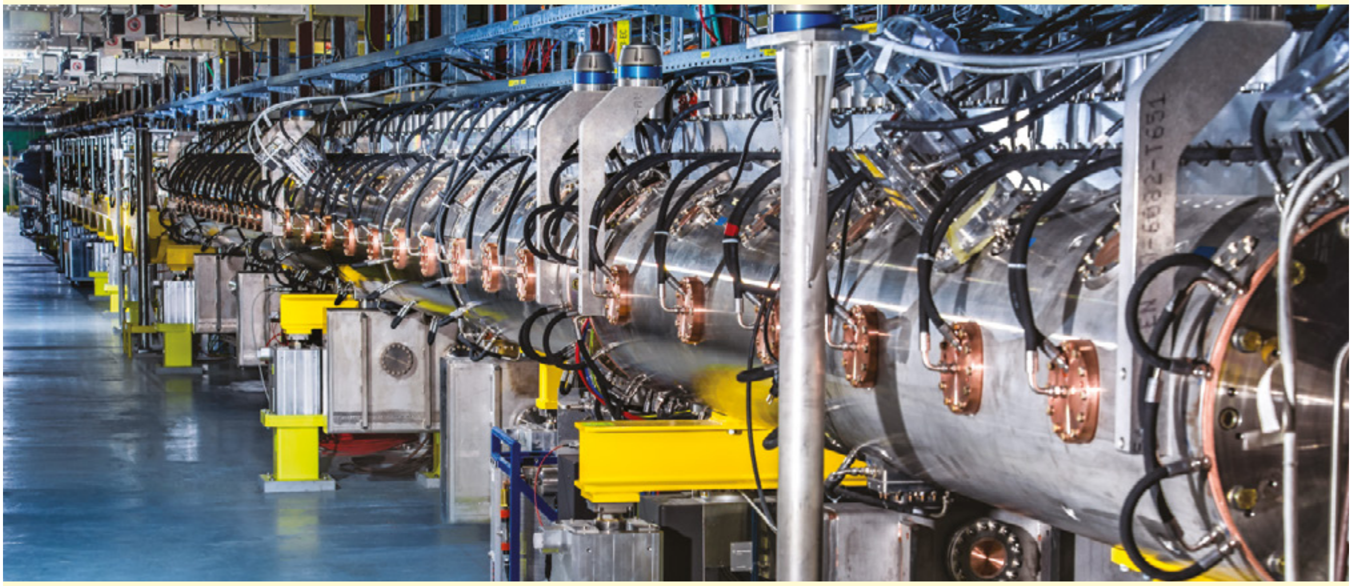
The magnets are being developed in the framework of a collaboration between CERN and the LHC Accelerator Research Programme (LARP), which involves several US laboratories. Once short prototypes had been successfully tested, the production of full-size prototypes began. The first coil, 7.5 metres long, was manufactured at CERN, and four others, each 4.5 metres long, are currently being built in the United States. In addition, bending magnets (dipoles), shorter and more powerful than those in the LHC, also made from niobium-tin, are currently under development. The manufacture of a full-size prototype has begun at CERN. Moreover, in January, the first corrector magnet was ready, paving the way for the manufacture of 35 other corrector magnets of the same type.

In preparation for the testing and qualification of the magnets for the High-Luminosity LHC, the magnet test hall has been completely renovated. New test benches have been installed, able to hold magnets of a greater diameter and to deliver currents of up to 20 000 and 30 000 amps.

The “crab cavities” are another major innovation for the future collider. They will transversely deflect the bunches before collision, resulting in a tripling of instantaneous luminosity. Two prototypes have been built, one at CERN and one in the United States, and a prototype titanium cryostat for these cavities has been successfully tested.

As more particles will be circulating, the protection of the machine will need to be reinforced. This protection is based on collimators, which are designed to absorb particles that stray from the beam trajectory. The choice of new collimators has been validated after conclusive tests.

The options chosen for the High-Luminosity LHC project – in particular the large-scale underground structures around the ATLAS and CMS experiments and a new configuration of the equipment – have been validated by an international group of experts. The cost and schedule review carried out by this group was published in 2016.



View of the new 86-metre-long Linac4 accelerator. In 2016, Linac4 was completed and reached its design energy of 160 MeV. It will become the first link of the LHC accelerator chain after 2020. (OPEN-PHO-ACCEL-2017-011-3)

THE NEW LINEAR ACCELERATOR REACHES ITS ENERGY GOAL

CERN's new linear accelerator is now operational. On 25 October, Linac4 accelerated a beam up to its design energy of 160 MeV. This performance marked a major milestone after nine years of development.

During the upcoming long accelerator shutdown in 2019-20, Linac4 will replace the current Linac2 as the first link in the LHC accelerator chain, increasing the energy from 50 MeV to 160 MeV. Its commissioning is a cornerstone of the LHC Injectors Upgrade project, which aims to prepare the injectors for the high-luminosity runs of the LHC.

Linac4 will send negative hydrogen ions (consisting of a hydrogen atom with an additional electron) to the Proton Synchrotron Booster (PSB), the second accelerator in the LHC injection chain. The use of hydrogen ions for the first time at CERN will contribute to an increase in the luminosity of the LHC for the High-Luminosity LHC project, enabling the production of high-brightness beams.

The 86-metre-long Linac4 is composed of four types of structures, which accelerate the particles in several stages. The accelerating cavities for the last two stages were put into service in 2016, enabling the test beam to reach 100 MeV in July, and then 160 MeV several months later.

After optimising the beam parameters, an innovative principle to transfer the particles from Linac4 to the PSB was put to the test. This new method sends the 160-MeV hydrogen-ion beam to an extremely thin carbon foil that strips off the two electrons. Linac4 will undergo a year-long testing period in 2017.

EXPERIMENTS ON THE ROAD TO PERFECTION

The experiments at the high-luminosity LHC must be capable of recording five to ten times more data than today, with 140 to 200 proton collisions for each bunch crossing.

The LHC collaborations are working on major upgrades of their detectors, which will be commissioned in stages up to 2025. The aims of these upgrades are to increase the efficiency of the trigger and acquisition systems, improve the granularity of the trackers and boost the radiation-hardness of the components most exposed to radiation.

LHCb is gearing up for a total transformation for Run 3 in 2021. Practically all the tracking systems will be replaced, and the read-out electronics of all the sub-detectors will be renewed as the experiment moves from a read-out frequency of 1 to 40 Mhz. The design studies were finalised in 2016 and the prototypes are under development. LHCb will also be replacing its hardware trigger system by a software-based system operating in a new PC farm.

Big changes are also afoot for ALICE. The construction of a new inner tracker is under way, with a surface area of 10 m^2 and a new pixel detector providing excellent resolution at a modest cost.

The large tracker surrounding the inner detector, the time projection chamber, will be equipped with GEM (Gas Electron Multiplier) detectors to provide higher data acquisition speed. Construction of the read-out electronics has begun. ALICE too is developing an online read-out and reconstruction system that will provide triggerless read-out of all events into a computing facility.

In 2016, CMS completed the assembly of its new pixel detector, which will allow improved reconstruction of charged particle tracks closer to the collision. (CERN-PHOTO-201609-239-6)

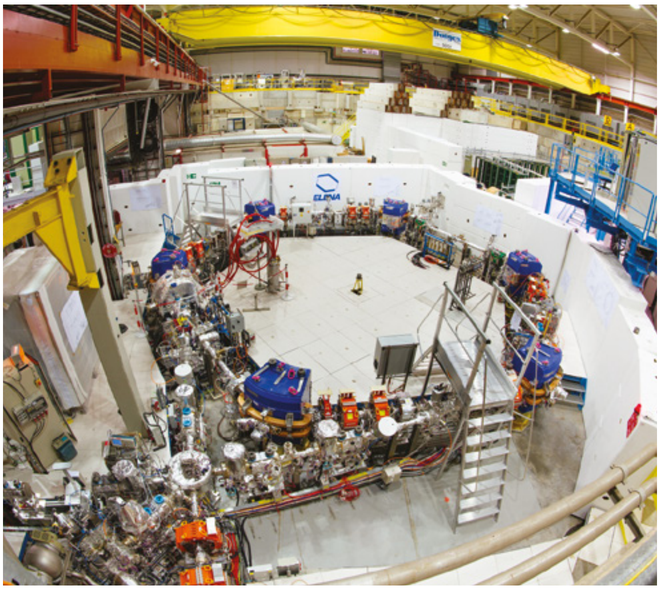
CMS has finished assembling its new pixel detector. Comprising 124 million pixels compared with 66 million previously, it will begin operation in 2017. The inner layer is closer to the collision point and the amount of material has been reduced to achieve greater measurement precision.

For the High-Luminosity LHC, CMS will be adding GEM gas detectors to its muon detection system, in the forward regions, in order to improve track reconstruction. A few prototypes of GEM chambers were installed on the detector and will be tested in 2017.

During the third Long Shutdown after 2023, CMS will also be replacing its tracker and the electromagnetic calorimeter end-caps. The silicon sensors of the future detector are currently under development.

The ATLAS detector will be equipped with two new, wheel-shaped muon detectors for particles emitted at moderate angles with respect to the beam line. These wheel modules are a combination of Micromegas and TGC (Thin Gap Chamber) gas detectors, which will all play a role in measuring muon trajectories and thus in the trigger. One Micromegas module has been assembled and tested at CERN. The first circuit boards have been produced and the manufacture of the mechanical structure of the wheels has got under way.

The ATLAS teams are also designing a new inner tracking system and have developed a new trigger system that will be commissioned in 2017 to enhance event selection by combining all the information from the muon chambers and the calorimeters.



View of the ELENA ring, 30 metres in circumference. The new antimatter decelerator started tests with beam in November 2016. (CERN-PHOTO-201611-300-2)

A NEW RING TO SLOW DOWN ANTIMATTER

With its 30-metre circumference, you could mistake it for a miniature accelerator. Unlike most accelerators at CERN, you can take it all in with just one glance, but the biggest difference is that it doesn't accelerate particles, it decelerates them. After five years of development, the ELENA (Extra Low Energy Antiproton) deceleration ring began its first test with beam in November.

ELENA's purpose is to further slow down antiprotons coming from the Antiproton Decelerator (AD) – a unique facility that sends antiprotons to experiments dedicated to the study of antimatter. ELENA will reduce the energy of the antiprotons by a factor of 50, from 5.3 MeV to just 0.1 MeV. The slower the antiprotons, the easier it is for the experiments to capture them. ELENA will receive its first antiprotons from the AD in 2017. Meanwhile, the first tests have been performed using an independent ion source.

Decelerating beams is just as complicated as accelerating them. At low energy, the beams are more sensitive to outside perturbation, which makes controlling them more challenging. ELENA is therefore equipped with optimised magnets, efficient at very weak fields.

The electron cooling system will be installed in 2017, marking the completion of ELENA. Once in place, this equipment will increase the beam density. With slower and denser beams, the efficiency with which the experiments can capture antiprotons will rise by a factor of 10 to 100.
So far, six experiments have been approved to receive antiprotons from ELENA. The first of them, GBAR, will start to be installed in 2017.

WHICH ACCELERATOR FOR THE FUTURE?

Physicists have started to sketch out the future of high-energy physics beyond 2035. Two types of collider, circular and linear, are under consideration. The aim is to present a preliminary study in 2018 as input for the update of the European Strategy for Particle Physics in 2019, which will set the course for the years to come.

The **FCC (Future Circular Collider)** collaboration, consisting of more than 100 institutes and 10 companies from 32 countries, is studying the possibility of a circular collider measuring about 100 kilometres in circumference. Such a machine would collide hadrons (like the LHC, but at an energy seven times higher, i.e. 100 TeV) or leptons. The study also covers a possible high-energy version of the LHC in the existing tunnel.

In 2016, the physics case for the two scenarios, electron-positron and proton-proton, was explored. Studies of optics (the way in which the beams are directed and focused) concluded. The location of the tunnel in the Geneva region was studied and work on the configuration of the tunnels, experimental caverns and surface areas began. These studies demonstrated the feasibility of the infrastructure, as well as the compatibility of a 100-kilometre-long tunnel with the geology of the local area.

In terms of hardware, the first prototype has been built, consisting of a beam screen, which, placed inside the beam pipe, would contribute to maintaining the ultra vacuum without which the particles could not circulate.

The machine relies on a key technology, i.e. magnets with a very high field of 16 Tesla, twice that of the LHC magnets. These magnets will use innovative superconducting materials and are being developed with the Paul Scherrer Institute in Switzerland, in the framework of the EU-supported EuroCirCol project, and in conjunction with the US Magnet Development Program (US-MDP). Four coil geometries are being studied, and a demonstration coil has been designed for manufacture in 2017.

Development work on superconducting niobium-tin wires, in collaboration with several partners, has begun. The manufacture of the FRESCA2 magnet, which will be used to test the cables, has been completed. Magnets using high-temperature superconductors are also being studied for very specific purposes.

A modelling and simulation tool for the operation and availability of a very large system like the FCC is being developed in the framework of an R&D project with an industrial partner. This tool could help large firms to improve their energy efficiency.

The **CLIC (Compact Linear Collider)** project studies the feasibility of a linear electron-positron collider, based on an innovative two-beam acceleration concept, which will allow very high accelerating gradients to be achieved. The project has been redefined based on three stages of construction and operation, at a collision energy of 380 GeV initially, then 1.5 TeV and finally 3 TeV. A new test installation known as CLEAR (CERN Linear Electron Accelerator for Research) has been designed to succeed the CTF3 installation, which ceased operation in 2016.

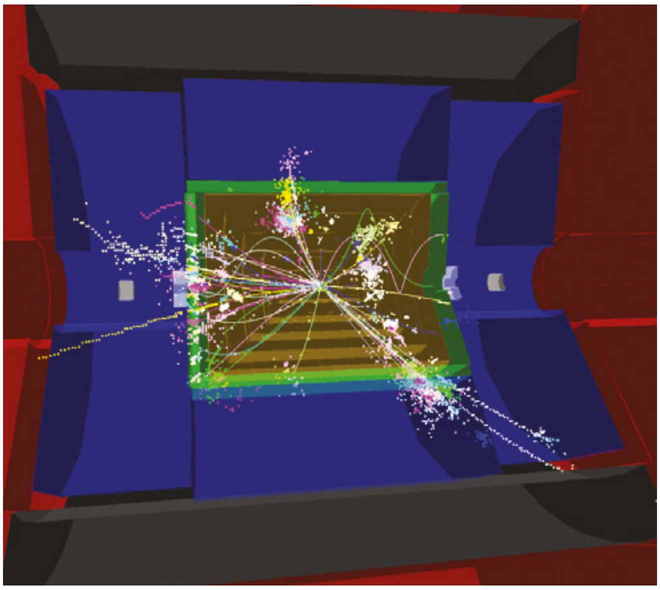
The first prototype for the FCC, a more efficient beam screen designed to disperse heat and maintain the ultra vacuum. (CERN-PHOTO-201604-074-2)

The success of CLIC depends on the development of high-performance accelerator equipment capable of reaching accelerator fields of around 100 megavolts per metre. The development of these very-high-frequency structures has continued, taking account of the three-stage commissioning process. The test capacity has been tripled. The development of klystrons to provide radiofrequency power with high efficiency has also continued.

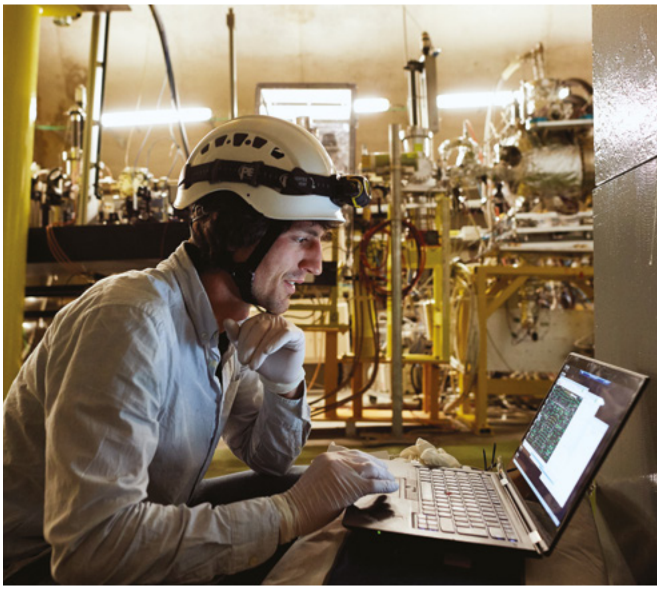
CLIC's innovative accelerating cavities could also be of interest to other fields, notably free-electron lasers driven by an accelerator. These installations provide a very specific type of laser light for the study of materials, biological samples and molecular processes. CERN is participating in a European initiative on this subject that is scheduled to publish a design study in 2017.

The CLIC collaboration, which comprises 75 institutes in 28 countries, works in close collaboration with its sister project, the ILC (International Linear Collider), in several fields.

A new collider means **new detectors**. A team at CERN is working on the physics goals and experiments of the future. A document presenting the Higgs physics studies possible at the three energies proposed for CLIC has been published. A silicon tracker to reconstruct the trajectory of charged particles is being studied; a new architecture has been defined and silicon components have been tested with a beam from the SPS. Work on detectors for the circular collider proposed by the FCC study has also begun.



Simulation of a collision within a detector of the CLIC linear collider. The CLIC project studies the feasibility of a future linear electron-positron collider. (OPEN-PHO-ACCEL-2017-009-3)



Member of the AWAKE collaboration performing tests in the experiment's underground tunnel. AWAKE explores the use of plasma to accelerate particles. (CERN-PHOTO-201612-314-9)

PHYSICS BEYOND COLLIDERS

The myriad of experiments using the CERN accelerator complex illustrates the variety of the Laboratory's physics programme (see p. 13). A "Physics Beyond Colliders" study group was formed in 2016 to explore the future potential of CERN's accelerator complex and facilities to develop and perform experiments that would complement the ongoing collider programme. The study was launched at a kick-off workshop in September 2016, which brought together more than 300 physicists from various fields. The objective is to explore the possibilities for non-collider experiments – both at CERN and possibly off-site if CERN can make a useful contribution – up to around 2040, covering the period foreseen for the exploitation of the High-Luminosity LHC. The study team is responsible for providing input for the upcoming update of the European Strategy for Particle Physics in 2019.

MAKING WAVES IN ACCELERATOR TECHNOLOGY

A new technique to reach higher energy with accelerators is currently being investigated by an experiment at CERN, the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE). In December, three years after the approval of the project, AWAKE recorded its first data.

AWAKE is a proof-of-principle experiment testing the use of plasma wakefields to accelerate charged particles. Driving wakefields in plasma has already been proven by using electrons and lasers, but what makes AWAKE a pioneer experiment is that it aims to test it using protons. Because of their higher mass, protons could generate more powerful acceleration over a longer distance.

AWAKE injects a "drive" bunch of protons from the Super Proton Synchrotron (SPS) accelerator into a plasma cell, where a gas is ionised to plasma with a laser. When the proton bunches interact with the plasma, they split into smaller bunches - a process called self-modulation. As these shorter bunches move, they generate a strong electric wakefield. An electron beam is then sent right after the proton beam and gets accelerated by the wakefield, just as a surfer accelerates by riding a wave.

In 2016, the installation of most of the experiment's components was completed, including the heart of the experiment, the 10-metre plasma cell. In June, the first test beam was sent through it. After several months of commissioning and tests, the AWAKE collaboration observed, for the first time, the self-modulation of high-energy proton bunches in plasma, signalling the generation of very strong electric fields. This first result is a decisive milestone that proves the creation of a proton-driven wakefield.

The next big step for AWAKE is to test the acceleration of electrons in the wake of the proton bunches. If validated, AWAKE's technology would allow for an acceleration hundreds of times more powerful than that achieved by the radio-frequency cavities currently used. With plasma wakefield technology, higher energies could be reached and it would become possible to create compact, table-top accelerators.