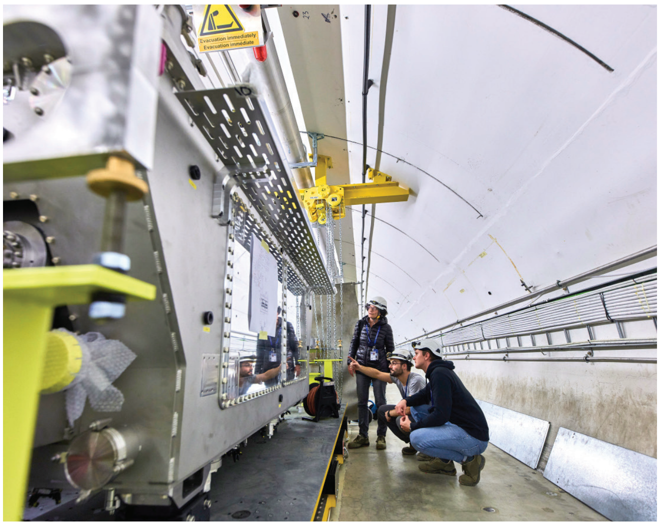
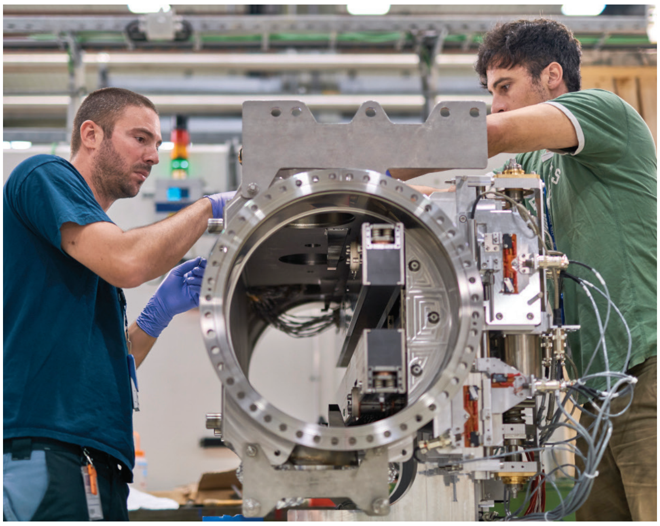
BUILDING TOMORROW AND BEYOND

Physicists, engineers and technicians at CERN are constantly designing and building new installations that will enable the scientific community to further its quest for knowledge. From the next-generation LHC to accelerators of the future, from the upgrade of CERN's accelerator complex and the LHC experiments to the successful test of a revolutionary acceleration technique, new projects are taking shape in CERN's workshops.

Civil-engineering work started at points 1 and 5 of the LHC, on the sites of the ATLAS and CMS experiments respectively, to excavate new shafts, service tunnels and caverns for the High-Luminosity LHC project. (CERN-PHOTO-201805-131-2)



The first two crab cavities, which will be used to rotate the proton beams before the collisions, have been successfully tested with beams. (CERN-PHOTO-201801-026-8)



A prototype of an absorber that will be installed at the particles' injection point in the High-Luminosity LHC was tested with beams in CERN's HiRadMat facility. (CERN-PHOTO-201808-190-5)

HALF WAY TO HIGH-LUMINOSITY LHC

Following the launch of the project in 2010, the High-Luminosity Large Hadron Collider (HL-LHC) is planned to be commissioned in 2026. This major upgrade of the LHC will increase the luminosity of the accelerator, allowing physicists to search for rare phenomena.

2018 was marked by the start of the civil-engineering work at points 1 and 5 of the LHC, where the ATLAS and CMS experiments are located. On each site, the underground constructions consist of a shaft, a service cavern, a service tunnel and several tunnels that are collectively 1 km in length. At the end of the year, the two 60-metre-deep shafts were excavated.

The HL-LHC requires the installation of new equipment in 1.2 km of the 27-km-long accelerator. Key new components include the inner-triplet quadrupoles and other magnets, crab cavities, superconducting links, cryoplants, absorbers and collimators.

To be installed on either side of the ATLAS and CMS experiments, the superconducting crab cavities will tilt the proton bunches of each beam to maximise their overlap. The first two of these cavities were tested with beams from the SPS accelerator, using a movable test bench and an innovative mobile cold box, and were able to generate a transverse field that tilted the proton bunches, a world first. Around 70 hours of tests were performed during the year.

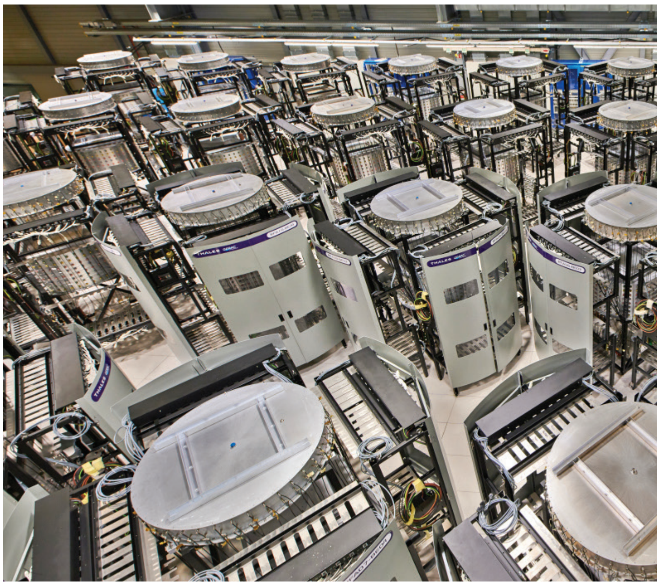
The first step in validating the long superconducting links was also taken in 2018. Composed of a cable of magnesium-diboride inserted into a flexible cryostat, these links will carry the current to the inner-triplet quadrupoles. A 60-metre-long link successfully carried 20 000 amperes during a test in 2018. Both the cryogenic and the electrical characteristics of the system exceeded expectations.

Around 100 magnets of 11 new types are being developed, including more powerful dipole and quadrupole magnets that use the niobium-tin superconducting compound. The construction of short and full-length 11-tesla dipole prototypes was completed and industrial contracts for their production started. The fourth short model of the inner-triplet quadrupole was tested, and the prototypes are currently being produced in the US and in Europe. The American collaboration received approval and full funding from the US Department of Energy.

With higher luminosity, machine protection needs to be reinforced. Innovative collimators with very low impedance, which absorb the particles that deviate from the optimum trajectory, have been tested in the machine with success. A prototype of a special collimator that will be connected to the 11-tesla dipole magnets has been built, along with a cryostat for the magnet.

Other key elements for the safe operation of the HL-LHC are protection absorbers, which are installed at the particles' injection point. A prototype capable of withstanding a high-intensity beam was successfully tested. The beam screen prototypes, which will shield the superconducting magnets from the radiation debris escaping from ATLAS and CMS, demonstrated excellent performance.

The HL-LHC collaboration is expanding: agreements were signed with KEK (Japan), IHEP (China), INFN (Italy) and Triumph (Canada), while STFC and associated UK universities made a commitment to supply certain components.



Installation of the new solid-state amplifier system developed for the SPS accelerating cavities. (CERN-PHOTO-201902-037-2)

Mock-up assembly for the new injection system from the Linac4 to the PS Booster. This system is essential to achieve the required intensity and brightness of the proton beam in the PS Booster. (CERN-PHOTO-201708-201-7)

HEADING INTO LONG SHUTDOWN 2

December 2018 marked the start of Long Shutdown 2 (LS2). For the next two years, the infrastructure, injector chain and LHC will be maintained and improved in preparation for Run 3 and HL-LHC. Most of these upgrades are being carried out in the framework of the LHC Injectors Upgrade (LIU) project. In 2018, teams continued preparations for these large-scale improvements.

Linac4 will be connected to CERN's accelerator chain during LS2. The new linear accelerator will supply protons at an energy of 160 MeV, compared with the 50 MeV achieved by the old Linac2. A stand-alone operation phase took place to assess and improve the accelerator's performance prior to its connection to the PS Booster. Linac4's average availability during its last run in 2018 was over 95%.

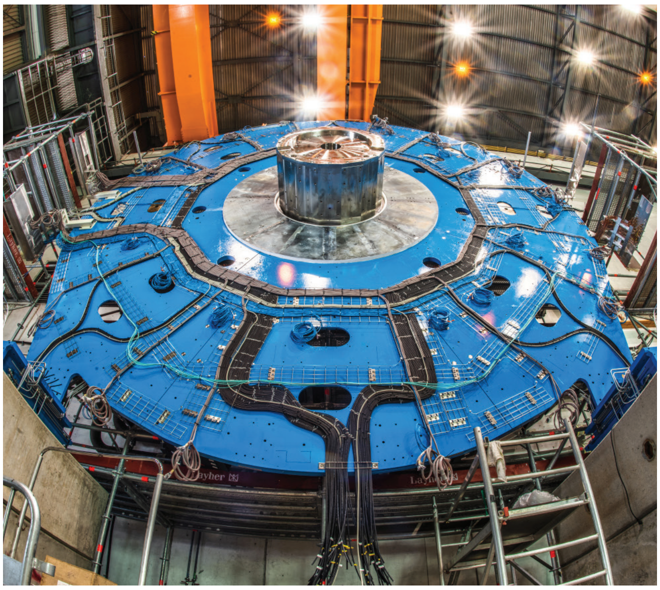
The PS Booster will be completely transformed. New systems for power supply, injection, acceleration (with radiofrequency cavities), guidance (with magnets) and extraction to the PS have been in preparation since 2011. In 2018, new equipment – notably septum and kicker magnets, as well as several dipoles, quadrupoles and corrector magnets – was tested. The new radiofrequency (RF) system is based on cavities built using a composite magnetic material (FineMet), which was developed in collaboration with the Japanese institute KEK. The 24 cavities to be installed (six in each of the accelerator's four rings), along with four spares, were delivered in 2018.

A building was also constructed to house the Booster's new power-supply system (POPS-B), which was successfully tested at the end of 2018. To guide the higher-energy beams, its power converters will supply the magnets with electrical intensities of 5500 amps, compared with 4000 amps previously.

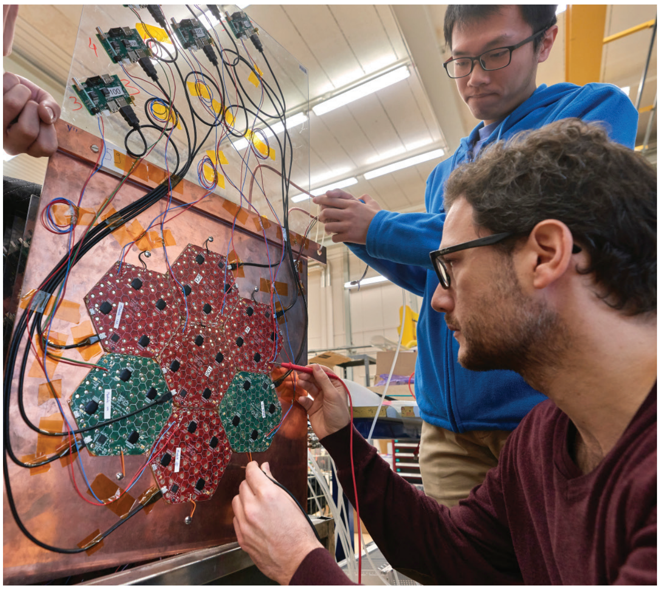
The new power-amplifier system for the SPS's accelerating cavities was validated. Based on radiofrequency transistors, it will increase the RF power supplied to the cavities and enhance the current system. A tower containing 320 transistors operated successfully for 1000 hours, giving the green light to series production. Some 10 240 transistors, distributed across 32 towers, will be installed.

Thanks to the installation of new equipment to stabilise the beams and new monitors to control their parameters, a number of milestones were reached for all the injectors. The PS successfully produced bunches of 2.6×10^{11} protons, the intensity required for the future HL-LHC, although their emittance is still too large. High-intensity beams were also transferred from the SPS to the LHC, with bunches containing up to 2.3×10^{11} protons, but in very short trains, in order to study the thermal load created in these unprecedented conditions.

A new operating mode for LEIR's RF system enabled three bunches of particles (instead of two) to be transferred to the PS. Thanks to a new RF manipulation scheme in the PS, these three bunches can also be squeezed when they are extracted to the SPS. The new configuration makes it possible to come close to the luminosity required for the HL-LHC and offers greater flexibility for dealing with potential beam manipulation difficulties in the SPS.



The support disks for the ATLAS New Small Wheels, which will allow the identification of muons at small angles, were completed. *(CERN-PHOTO-201806-175-1)*



Prototype detector modules for the second phase of the upgrade of the CMS calorimeter. *(CERN-PHOTO-201812-333-1)*

EXPERIMENTS ON TRACK FOR HIGH LUMINOSITY

In 2018, the experiments prepared to ensure the timely and safe accomplishment of all activities required during the second long shutdown (LS2). Before the new detector components could be installed, many of the old detector parts had to be dismantled and removed.

The ALICE collaboration will completely replace the tracking detectors, including the inner tracker and the time projection chamber (TPC). In 2018, the collaboration produced all the gas electron multiplier (GEM) chambers that will form the TPC's new readout system and tested a large fraction of them in the cavern. Good progress was made with the construction of the new inner tracker, which is based on pixel sensors: the inner barrel was completed and the outer barrel and readout electronics are on track. The production of the Muon Forward Tracker, based on the ALPIDE chip, also progressed well, while the fabrication of many of the electronic components for the subdetectors and the trigger system remained on track. The services needed for the new computing room were put in place, and the installation of the two first computing modules continued.

The ATLAS collaboration made progress on the construction of the New Small Wheel detectors designed to identify muons emitted at moderate angles with respect to the beam line. These detectors, which are a combination of Micromegas and Thin Gap Chamber gas detectors, will allow the precise reconstruction of muon trajectories and their fast and efficient identification in the first level of the trigger system. Six technical design reports were approved for the second phase of the upgrade programme. The upgrades include a new silicon-based tracker, new readout electronics for the calorimeters and new muon detectors. In addition, an innovative trigger and data-acquisition system will allow ATLAS to increase the trigger and readout rates by an order of magnitude. These upgrades have progressed through their specifications and preliminary prototypes activities.

In early 2018, to sustain the increase of the LHC luminosity during Runs 2 and 3, CMS upgraded the photosensors and the front-end electronics of the Hadron Calorimeter endcaps. The collaboration also replaced all pixel voltage converters and adapted the operating procedures, achieving a faultless 2018 performance. New electronics components were installed in the readout system of the muon Drift Tube chambers. The second phase of the CMS upgrade programme, for the HL-LHC, also saw remarkable progress. A GEM demonstrator for the muon system was successfully operated in CMS and the chambers for a new GEM endcap layer were produced. Significant progress was also made in qualifying the silicon sensors for both the future tracker and endcap calorimeter systems. In addition, the prototypes of several new integrated circuits were designed or produced, and production and module assembly started at specific sites.

LHCb finished refining and testing of all 11 000 km of scintillating fibres for the Scintillating Fibres Tracker. The series production of the fibre mats was carried out at four winding centres. For the Ring Imaging Cherenkov detector systems, the collaboration successfully completed delivery and quality assurance of more than 3500 multi-anode photomultiplier tubes. The first batch of 24 custom-made front-end readout boards was received and tested. Two technical design reports for computing were produced and submitted to the LHC Committee. The preparations for the new data centre at Point 8 advanced considerably, with the first modules that will receive the CPUs being placed at their final destination.

The new ELENA antimatter decelerator has been commissioned and connected to its first experiment.
(CERN-PHOTO-201804-086-10)

EXCEPTIONALLY SLOW ANTIPROTONS

After several months of commissioning, ELENA (Extra Low Energy Antiproton), CERN's new antiproton-deceleration ring, produced beams of antiprotons with properties very close to the nominal values. This was excellent news for the antimatter experiments that will be connected to ELENA after Long Shutdown 2 and supplied with antiprotons at very low energies. Only the GBAR experiment was connected to the new ring in 2018; the installation received its first beams on 20 July.

The slower the antiprotons are, the easier it is for the experiments to trap and study them. ELENA, which is connected to the Antiproton Decelerator (AD), will therefore have the task of slowing down the antiprotons further, decreasing their energy from 5.3 MeV to just 0.1 MeV.

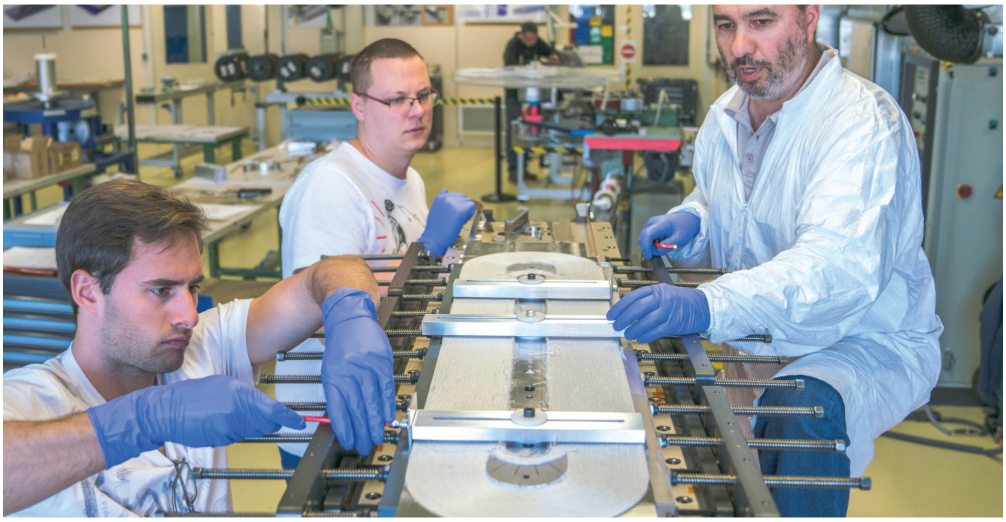
To achieve such low energies, ELENA's deceleration apparatus is paired with an electron cooling system. This system, which was tested and commissioned in the autumn, makes it possible to concentrate the particle bunches by reducing the emittance of the beam or, in other words, its transverse dimensions and energy spread. The experiments can thus be supplied with denser beams, increasing their chances of trapping antiprotons.

As soon as the tests with beam had been completed, in November, the dismantling of the magnetic transfer lines connecting the AD to the other experiments began. These lines will gradually be replaced with the electrostatic lines that will connect ELENA to the experiments.

THE FUTURE OF PARTICLE PHYSICS IS TAKING SHAPE

During its September session, the CERN Council formally launched the update of the European Strategy for Particle Physics. This two-year process involving the whole community aims to shape the future of the discipline in Europe by defining its long-term priorities. In December, as part of the process, the European Strategy Group, which was established to coordinate the update process, received 160 proposals for accelerator and experiment projects from universities, laboratories, national institutes, collaborations and individuals. Along with its partner institutes, CERN submitted several major contributions, ranging from new collider projects (the FCC and CLIC) to experiments using existing machines.

TO UPDATE THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS, 160 PROPOSALS WERE SUBMITTED FOR DISCUSSION.



A coil for the new 16-tesla model magnet being assembled at CERN.
(CERN-PHOTO-201804-088-4)

THE FUTURE CIRCULAR COLLIDER STUDY

In December, the Future Circular Collider (FCC) collaboration submitted its conceptual design report (CDR), which explores concepts for a research infrastructure housed in a new tunnel 100 km in circumference. The CDR documents the machine parameters, physics opportunities and experiments for a lepton collider (FCC-ee) designed to push the precision frontier, followed by a 100-TeV hadron collider (FCC-hh) to push the energy frontier. Further opportunities include heavy-ion collisions, lepton–hadron collisions and fixed-target experiments. The study has also developed a possible high-energy version of the LHC in the existing 27-km tunnel.

In 2018, the collaboration developed efficient injection schemes and refined the beam optics to ensure maximum performance. Civil-engineering studies progressed with international partners, including optimising tunneling costs and reusing excavation material. Preliminary results showed that such an infrastructure would be compatible with the environmental and socio-economic requirements of CERN's Host States.

Key technologies for the FCC-ee include superconducting radiofrequency (RF) cavities and high-efficiency RF power production. In 2018, the collaboration developed a detailed staging scenario for the installation of the RF equipment in the FCC-ee and made progress in developing titanium-copper RF cavities, reaching a gradient similar to bulk niobium cavities. The collaboration pursued innovative manufacturing techniques using new, efficient materials to reduce the cost and improve the quality of cavity fabrication. This was supported by the EASITrain project, co-funded by the European Union's H2020 Framework Programme. The FCC-ee collaboration also built and tested prototype models for the main dipole and quadrupole magnets for the lepton collider. The innovative twin-aperture design reduces the number of coils, thus simplifying the construction and reducing the cost and energy compared with traditional designs.

The 100-TeV FCC–hh relies on niobium-tin superconducting magnets with a field of 16 tesla, twice that of the LHC magnets. Design work for various magnet options within the framework of the H2020 co-funded EuroCirCol project was completed. The first two high-field model magnets (the 15-tesla US MDP and the 16-tesla ERMC at CERN) were completed at CERN and Fermilab, and will be tested at CERN in 2019. The cryogenic beam vacuum system is another critical element since it will have to efficiently absorb the significant synchrotron radiation emitted by the beam. Three prototype beam screens were tested at room temperature with synchrotron radiation at KARA in Karlsruhe (co-funded by H2020 EuroCirCol). The excellent test results validated the FCC-hh vacuum design.

The FCC study is also actively involved in the RI-PATHS project, which aims to develop new tools to assess the socio-economic impact of research infrastructures in Europe. The first results from a cost-benefit analysis of the LHC and the HL-LHC were published in 2018; this work is now being extended to include the FCC.

THE COMPACT LINEAR COLLIDER STUDY

A major focus for the Compact Linear Collider (CLIC) study in 2018 was the completion of an implementation plan and the submission of documents for the update of the European Strategy for Particle Physics.

CLIC is a concept for a future high-luminosity linear electron–positron collider, planned in three stages from 380 GeV to 3 TeV. The accelerator is based on an innovative two-beam acceleration approach designed to produce accelerating fields as high as 100 megavolts per metre, keeping the size and cost of the project within reach.

Significant technical achievements in 2018 included drive-beam studies and the development of RF systems. Experimental tests of components, systems and methods for future colliders and linear electron colliders were performed in CLEAR (CERN Linear Electron Accelerator for Research), at ATF2 at KEK, at free-electron laser (FEL) facilities such as FERMI-Trieste and at low-emittance rings such as ALBA-Barcelona. The collaboration also developed and tested X-band structures at CERN and in collaborating institutes. Numerous technical developments optimised the most critical and cost/power-driving components of the CLIC accelerator as part of a complete cost and power review for the overall project.

In parallel, the collaboration started to compile a systematic overview of industry's involvement in CLIC's core technologies, partly in view of their expanding use in accelerators for other applications. Several agreements with collaboration partners supported technical developments for smaller X-band-based accelerators and components related to FEL linacs in particular. The CompactLight study, a European Commission design study for X-band-based FELs involving 24 partners, got under way in 2018.

Work on evaluating the physics reach of CLIC continued, with the aim of demonstrating the physics potential up to multi-TeV collisions, resulting in several dedicated reports on physics produced in close cooperation with the theory community. In addition, substantial advances were made in the broad and active R&D programme on vertex and tracking detectors, including the completion of a novel monolithic sensor design targeting the tracker requirements. Silicon pixel R&D was pursued in synergy with the developments in the Medipix/Timepix collaboration and in the HL-LHC R&D groups.

THE PHYSICS BEYOND COLLIDERS PROGRAMME

Around twenty projects were submitted to the European Strategy Group in the framework of the Physics Beyond Colliders programme. Launched in 2016, this initiative is exploring opportunities offered by CERN's accelerator complex that are complementary to high-energy collider experiments, and has continued to investigate the feasibility and scientific potential of a wide range of options.

The "Beyond the Standard Model" (BSM) and "Quantum Chromodynamics" groups have put together comparative analyses of the physics potential at CERN and worldwide. The BSM group has produced combined sensitivity plots for a number of benchmarks, covering scalar, vector, Higgs and axion portals to the Hidden Sector.

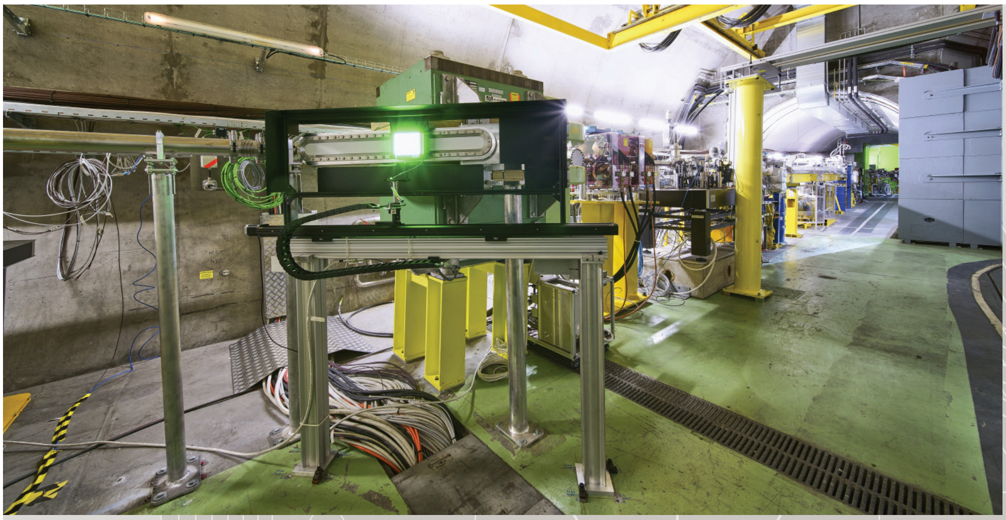
On the accelerator front, the potential of the North Area to provide the beam for dark-matter and precision searches, and to continue pushing its quantum-chromodynamics-based experiments, was investigated in depth. Significant advances were made with respect to the proposed Beam Dump Facility (BDF): a target prototype was tested and comprehensive civil-engineering and integration studies were performed. This general-purpose high-intensity fixed-target facility would use the SPS's proton beams to serve new experiments in the North Area. In its initial phase, its main client would be the Search for Hidden Particles (SHiP) experiment, which would focus on a comprehensive search

Assembly of a target prototype for the Beam Dump Facility project. Developed in the framework of the Physics Beyond Collider initiative, it aims at providing new beams to experiments in the North Area.
(CERN-PHOTO-201808-199-17)

for dark-matter particles. A group is studying the possibility of a new electron-beam facility at CERN, based on a linac injecting 3.5 GeV electrons into the SPS. Accelerated to 16 GeV, the electron beam would be sent to a dark-matter-search experiment on the Meyrin site. An expression of interest was submitted to the SPS committee. The SPS could also potentially serve nuSTORM, which aims to produce a well-calibrated neutrino beam with a muon storage ring.

The EDM collaboration, which aims to use precision measurements of the electric dipole moment of the proton and the deuteron to look for signs of physics beyond the Standard Model, developed a roadmap towards a prototype ring. The “Gamma factory” study had a remarkable year, which included the successful injection and acceleration of partially stripped ions in the LHC (see p. 25). The collaboration is now working towards a proof-of-principle experiment in the SPS.

The Physics Beyond Collider initiative also provided support for the FASER experiment proposal, a search for long-lived particles that is situated just off the LHC tunnel, 480 m from the ATLAS interaction point. An intense preparatory phase took place with a view to installing it during LS2, following approval. Studies for fixed-target experiments in the LHC continued. A gas-storage cell next to the LHCb Velo was approved for installation in LS2, and a number of options involving crystal extraction of protons were also considered.



The AWAKE experiment, with the electron spectrometer system and the 10-metre-long plasma cell.

(CERN-PHOTO-201711-284-5)

ELECTRONS RIDE THE PLASMA WAVES

The AWAKE collaboration has passed a crucial milestone: the experiment has accelerated electrons using a wakefield generated by protons passing through a plasma. This world first was achieved just two years after the installation of the experiment began.

While conventional accelerators use radio-frequency cavities to accelerate particles, AWAKE is studying the use of protons to create plasma waves (known as a wakefield) that accelerate electrons by causing them to ‘surf’ the waves. This technology is thought to be capable of producing acceleration gradients hundreds of times greater than those generated by current radio-frequency cavity technology.

Since it started, AWAKE has made some spectacular advances. The plasma cell was installed at the beginning of 2016 and a few months later the experiment recorded the first wakefields generated by protons. During the first acceleration trials carried out in 2018, electrons were accelerated by a factor of around 100 over a distance of some 10 metres: injected into the AWAKE plasma cell with an energy of approximately 19 MeV, they reached an energy of almost 2 GeV.

AWAKE has been preparing for the second run, due to begin after LS2. The objective is to accelerate particles to energies of several GeV while conserving the beam quality and to demonstrate the adaptability of the acceleration process using a wakefield.

The ultimate objective by the end of the second run is to be able to use the AWAKE model for particle physics experiments such as fixed-target experiments to look for dark photons and in future electron–proton or electron–ion colliders (the PEPIC – Plasma Electron Proton/Ion Collider – experiment), in which electrons accelerated by AWAKE will collide with protons (or ions) at the LHC.