Annual Report
2018

CERN

CONTENTS

CERN, the European Organization for Nuclear Research, is the world's leading laboratory for particle physics. It provides a unique range of particle accelerator facilities enabling research at the forefront of human knowledge. Its business is fundamental physics, finding out what the universe is made of and how it works.

Founded in 1954, CERN had 22 Member States in 2018, with other nations from around the globe contributing to and participating in its research programmes. The Laboratory has become a prime example of international collaboration, uniting people from all over the world to push the frontiers of science and technology for the benefit of all.

MESSAGE FROM THE PRESIDENT OF THE COUNCIL

The highly successful second run of CERN's Large Hadron Collider, the LHC, concluded at the end of 2018. The experiments, both at the LHC and at CERN's other accelerators, continue to produce many new physics results, which is a great accomplishment in view of the staggering amount of data collected. Remarkable successes were also reported in accelerator research, by the AWAKE experiment for example, and in the preparation of the next generation of neutrino experiments with ProtoDUNE. All CERN personnel are to be commended for their sustained high-quality work, which makes these achievements possible.

In 2018, the Council welcomed the National Audit Office of Finland as the new CERN External Auditors. The Council is grateful to have received their reports on the 2018 CERN financial statements and annual report, as well as those of the CERN Pension Fund, and appreciates the energy with which the Finnish team have taken up this important task.

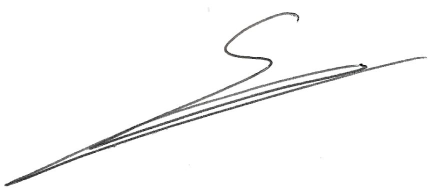
Particle physics is nearing an important crossroads at which researchers need to determine the future directions of the field. Addressing a number of important fundamental questions about the existence and nature of dark matter and dark energy, and the nature and meaning of the flavour structure of the Standard Model, will require accelerators and experiments with a reach beyond that of the present generation. Several alternatives are being studied, such as linear and circular lepton colliders, circular proton colliders, muon colliders and high-intensity neutrino beams. To examine all these options, the process of updating the European Strategy for Particle Physics was launched in 2018 with the establishment of the European Strategy Group and the Physics Preparatory group. The process will determine the optimal strategy for addressing these important questions in a resource-optimised way. It will continue throughout 2019 with thorough discussions that will engage the whole community of particle physicists. The new strategy will be presented to the Council for adoption in May 2020.

CERN remains attractive to countries wishing to join the Organization's front-line research in the spirit of international collaboration. In 2018, the Republic of Serbia was admitted as a new Member State, with membership becoming effective upon ratification by the Serbian Parliament. The Republic of Croatia was admitted as a new Associate Member State, with membership becoming effective upon ratification by the Croatian Parliament.

The Republic of Lithuania joined CERN as an Associate Member State after completing its internal approval procedures in January 2018.

This was the last year in which I had the honour to serve as President of the Council, and I look back with much pleasure on my period in office. As Council President, I discovered another aspect of this unique scientific institute that performs mind-boggling research, namely the strong spirit of co-operation between the Council and the management, for which I thank both the Council members and the CERN management team. I would also like to thank the Council Secretariat, the Legal Service and the Translation and Minutes Service, all of whom contribute to facilitating the life of the Council President. Finally, it is my pleasure to hand over the reins with confidence to the Council's next President, Dr Ursula Bassler.

Sijbrand de Jong



MESSAGE FROM THE DIRECTOR-GENERAL

The end of 2018 saw the LHC's second run conclude on a glorious note. The experiments recorded more data than our ambitious goals had predicted, thanks to an outstanding performance from the accelerator complex over the past four years. The detectors and computing took the resulting deluge of data in their stride, and beautiful physics was the result. The highlight of the year was the establishment of the Higgs boson's couplings to the top and bottom quarks. Many publications have been produced, and more will come as analysis continues during the two-year long shutdown that we've just begun.

The LHC was the star of the show in 2018, but CERN is much more than just its flagship facility. The year saw very significant progress across the full scientific programme. For example, the Advanced Wakefield Experiment, AWAKE, demonstrated for the first time electron acceleration from plasma wakefields induced by a proton beam, an encouraging result towards developing technology for compact high-energy colliders. At the CERN Neutrino Platform, the world's largest liquid-argon neutrino detector, the single-phase prototype for the DUNE experiment in the US, reconstructed beautiful tracks from test-beam particles.

Beyond the scientific programme, highlights of 2018 include the admission of Serbia as a Member State, and of Croatia and Lithuania as Associate Member States. Once Serbia's and Croatia's ratification processes are complete, the CERN family will comprise 23 Member States and eight Associate Member States. The Science Gateway project, a new facility for scientific education and outreach to be built next to the Globe, also made great progress in 2018. The project was approved by the Council, and most of the funding was secured through generous donations.

As we enter 2019, it will not be particles, but people, that circulate in CERN's accelerator tunnels. Throughout the long shutdown, the underground areas will be a hive of activity. The upgrade of the LHC injectors (the LIU project) will be completed, and much work will be done in preparation for the High-Luminosity LHC project, HL-LHC, which will succeed the LHC in 2026. The four major LHC experiments will also undergo significant upgrades during the long shutdown. The work is ambitious and demanding. Hundreds of components will be replaced, and many companies will contribute their technological expertise. The full accelerator complex will restart in 2021 for a three-year period of operation.

The year 2018 also saw the start of the process to update the strategy for particle physics in Europe. Which facilities will allow us to make the most progress towards addressing unresolved questions in fundamental physics? What kind of experiments will we need for the future? What are the priorities of accelerator and detector R&D in the coming years? These are the kinds of questions that our scientific community will be reflecting on throughout 2019 as the update of the European Strategy for Particle Physics maps out future opportunities for the field. LHC results, as well as design studies for future machines and experiments, have already provided an impressive corpus of knowledge to guide the debate.

You can discover more about these and other achievements in the pages of this report. All of them have been made possible by the great competence and dedication of CERN's personnel, along with strong and sustained support from the Council. My thanks, and those of the entire CERN management, go to them all. I am also grateful to Professor Sijbrand de Jong, the outgoing President of the Council, for the extremely fruitful, enriching and pleasant collaboration we have enjoyed over the past three years.

Fabiola Gianotti

2018 IN PICTURES

From new studies on the Higgs boson to the start-up of antimatter experiments, the inauguration of the Esplanade des Particules and the launch of the update of the European Strategy for Particle Physics, these were just some of the highlights from 2018. Discover more in pictures.

2 & 3 FEBRUARY

CERN's alumni network is officially inaugurated at a major event attended by some 400 participants from all over the world and from all professional backgrounds.
(ALUMNI-PHO-2018-002-77)

8 JANUARY

Lithuania becomes an Associate Member State of CERN, following ratification by its parliament of the corresponding agreement.
(OPEN-PHO-HIST-2017-001-2)

23 JANUARY

Fabiola Gianotti, CERN's Director-General, co-chairs the annual meeting of the World Economic Forum in Davos on the theme "Creating a shared future in a fractured world".

26 & 27 FEBRUARY

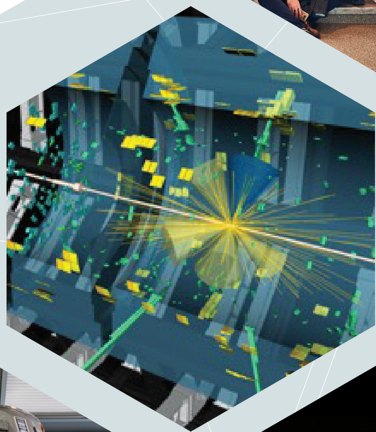
Two heads of state visit CERN: Filipe Nyusi, President of Mozambique, and Alexander Van der Bellen, President of Austria.
(CERN-PHOTO-201802-053-23)
(CERN-PHOTO-201802-054-1)

30 MARCH

Beams are back in the LHC, marking the start of its seventh year of operation and the last of Run 2.
(OPEN-PHO-ACCEL-2018-012-01)

1 JUNE

Photographers from all over the world immortalise life behind the scenes at the Laboratory during the *Global Physics Photowalk 2018* competition.
(CERN-PHOTO-201806-132-1)



4 JUNE

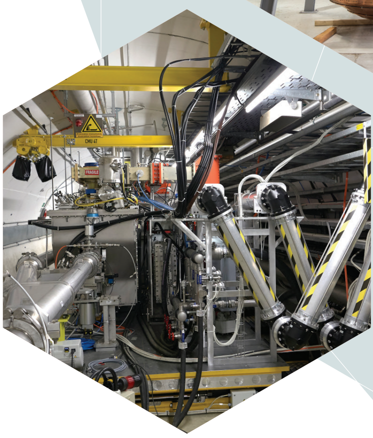
ATLAS and CMS publish the first results on the production of the Higgs boson in association with the most massive elementary particle known, the top quark.
(ATLAS-PHOTO-2019-016-3)

12 JUNE

HALO, an installation designed during an arts residency at CERN and inspired by data from the ATLAS experiment, is displayed at the international contemporary art fair Art Basel.
(OPEN-PHO-EXHI-2018-003-22)

1 JUNE

The FRESCA2 magnet, which will serve as a test station for future superconductors, establishes a new intensity record, producing a magnetic field of 14.6 teslas.
(CERN-PHOTO-201603-062-2)



29 MAY

Crab cavities tilt proton beams for the first time, validating these key components designed for the High-Luminosity LHC.
(CERN-PHOTO-201803-055-2)

15 JUNE

A ceremony marks the start of work for the High-Luminosity LHC.
(CERN-PHOTO-201806-146-4)

1 JULY

The teacher-training programme celebrates its 20th anniversary.
(OPEN-PHO-LIFE-2018-007-2)

20 JULY

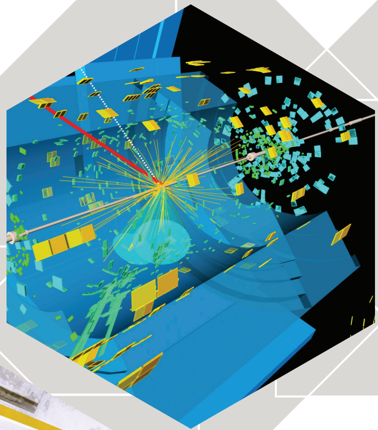
ELENA, the new antimatter decelerator, sends protons to an experiment, GBAR, for the first time. This experiment studies the effect of gravity on antimatter.
(CERN-PHOTO-201804-086-10)

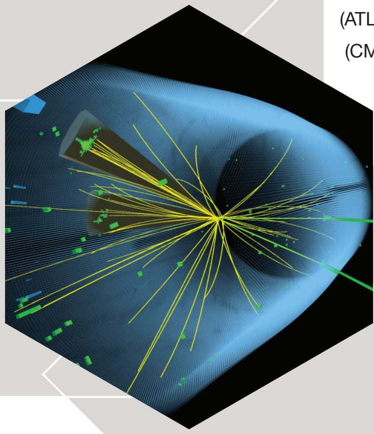
20 & 21 JUNE

Borut Pahor, President of Slovenia, and Alain Berset, President of the Swiss Confederation, visit CERN.
(CERN-PHOTO-201806-156-21)
(CERN-PHOTO-201806-158-1)

1 AUGUST

CERN is the guest of honour at the Swiss National Day celebrations in Geneva.
(CERN-PHOTO-201808-185-7)





28 AUGUST

The decay of the Higgs boson into bottom quarks is finally observed.

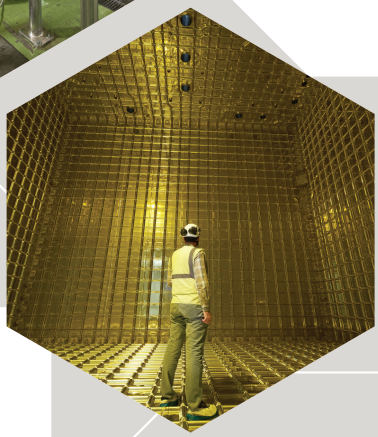
(ATLAS-PHOTO-2018-022-1)

(CMS-PHO-EVENTS-2018-008-1)

29 AUGUST

The AWAKE collaboration announces the first ever acceleration of electrons using a wakefield created by protons circulating in a plasma.

(CERN-PHOTO-201711-284-5)



18 SEPTEMBER

The prototype of the huge DUNE neutrino detector records its first particle tracks.

(CERN-PHOTO-201710-248-2)

27 SEPTEMBER

The LHCb collaboration discovers two new baryons and finds hints of the existence of a new particle made up of four quarks.

(CERN-PHOTO-201801-025-18)

28 SEPTEMBER

CERN, the state of Geneva and the commune of Meyrin inaugurate the Esplanade des Particules, which marks the entrance to the Laboratory and becomes its new official address. The same evening, CERN welcomes the public for Researchers' Night.
(CERN-PHOTO-201809-249-55)

8 OCTOBER

The winners of the 2018 Beamline for Schools competition come to CERN to perform their physics experiments. The two teams of secondary-school pupils are from India and the Philippines.
(CERN-PHOTO-201809-239-22)

28 SEPTEMBER

The CERN Council elects Ursula Bassler as its president; she will take on the role in 2019.
(CERN-PHOTO-201809-247-1)

16 OCTOBER

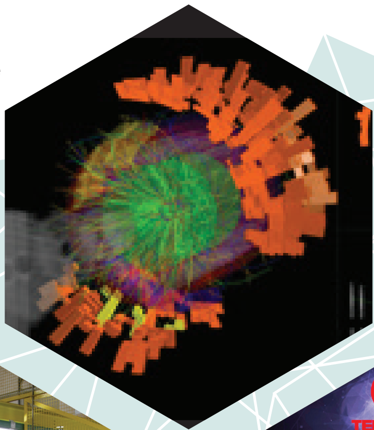
The CERN Council launches the process of updating the European Strategy for Particle Physics, which will set the course for the discipline in the coming years.

24 OCTOBER

The final protons of 2018 circulate in the LHC, marking the end of the accelerator's second run. Two weeks later, Linac2, a linear accelerator that came into operation in 1972, is definitively shut down.
(CERN-PHOTO-201811-295-2)

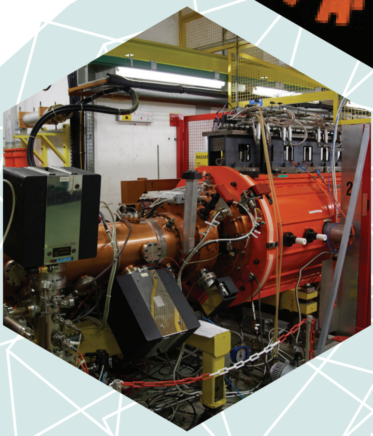
13 NOVEMBER

The first collisions of lead nuclei mark the start of a new heavy-ion run at the LHC.
(ALICE-EVENTDISPLAY-2018-003-1)



20 NOVEMBER

Digital and life-science experts attend the fifth TEDxCERN event to discuss scientific innovations with the potential to transform our world.
(CERN-PHOTO-201811-305-3)



3 DECEMBER

The accelerator complex and experiments are shut down for two years, during which major upgrade work will take place.
(CERN-PHOTO-201812-327-3)

19 DECEMBER

The first result from the HIE-ISOLDE accelerator confirms that the tin-132 nucleus belongs to the group of doubly magic nuclei.
(OPEN-PHO-ACCEL-2016-016-2)

A LABORATORY FOR THE WORLD

Cooperation between nations, universities and scientists is the driving force behind CERN's research. In 2018, more than 17 900 people from around the world worked together to push the limits of knowledge. CERN's staff members, numbering around 2600, are involved in the design, construction and operation of the research infrastructure. They also contribute to the preparation and operation of the experiments, as well as to the analysis of the data that is gathered for a vast community of users, comprising over 12 500 scientists of more than 110 nationalities from institutes in over 70 countries.

BREAKDOWN OF CERN USERS ACCORDING TO THE COUNTRY OF THEIR HOME INSTITUTE, AS OF 31 DECEMBER 2018

NUMBER OF USERS: 12 569

MEMBER STATES (7395)

Austria 96 - **Belgium** 152 - **Bulgaria** 41 - **Czech Republic** 258 - **Denmark** 56 - **Finland** 116 - **France** 834 - **Germany** 1373
Greece 133 - **Hungary** 63 - **Israel** 73 - **Italy** 1528 - **Netherlands** 179 - **Norway** 89 - **Poland** 304 - **Portugal** 97 - **Romania** 106
Slovakia 86 - **Spain** 375 - **Sweden** 104 - **Switzerland** 380 - **United Kingdom** 952

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP (72)

Cyprus 16 - **Serbia*** 37 - **Slovenia** 19

*Member State since 24 March 2019

ASSOCIATE MEMBER STATES (418)

India 207 - **Lithuania** 23 - **Pakistan** 37 - **Turkey** 117 - **Ukraine** 34

OBSERVERS (3296)

Japan 258 - **Russia** 1040 - **United States of America** 1998

OTHERS (1388)

Algeria 2 - **Arab Emirates** 1 - **Argentina** 15 - **Armenia** 13 - **Australia** 30 - **Azerbaijan** 4 - **Bangladesh** 2 - **Belarus** 22 - **Brazil** 120
Canada 198 - **Chile** 19 - **Colombia** 24 - **Croatia** 38 - **Cuba** 3 - **Ecuador** 3 - **Egypt** 19 - **Estonia** 19 - **Georgia** 32 - **Hong Kong** 20
Iceland 3 - **Indonesia** 7 - **Iran** 17 - **Ireland** 6 - **Latvia** 2 - **Lebanon** 16 - **Madagascar** 2 - **Malaysia** 9 - **Malta** 5 - **Mexico** 59 - **Mongolia** 2
Montenegro 7 - **Morocco** 14 - **New Zealand** 7 - **Oman** 4 - **People's Republic of China** 327 - **Peru** 3 - **Puerto Rico** 1 - **Republic of Korea** 157
Singapore 4 - **South Africa** 69 - **Sri Lanka** 8 - **Taiwan** 57 - **Thailand** 18

The family continues to grow

As part of the continuing enlargement process, the CERN family welcomed several new countries in 2018. Lithuania became an Associate Member State in January and, during its December session, the CERN Council decided to admit Serbia as a Member State and Croatia as an Associate Member State, pending completion of each country's internal ratification process. In September, Estonia submitted an application for Membership. At the end of 2018, CERN had 22 Member States, three Associate Member States in the pre-stage to Membership and five Associate Member States.

Many other countries have established formal links with the Laboratory and contribute to its activities; CERN continues to develop this network, supporting countries that contribute to the development of particle physics. In this context, the Laboratory signed cooperation agreements with Kazakhstan, the Philippines and Thailand. A cooperation agreement with Paraguay was also approved by the Council in September. This global engagement and the cultural melting-pot that it creates are vital to CERN's pursuit of new ideas and ever-deeper knowledge.

A high-energy network

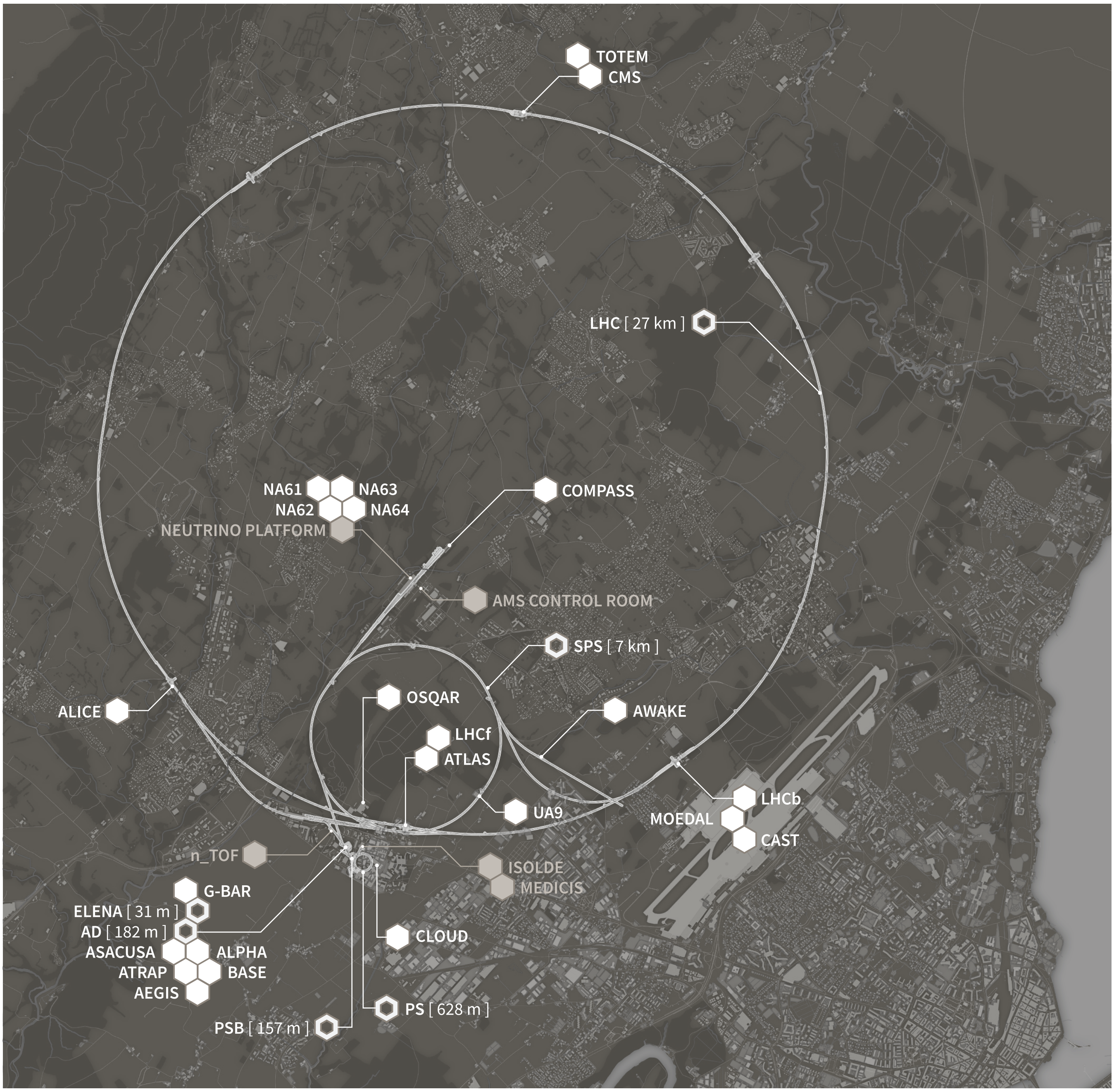
In February 2018, the "CERN Alumni – the High-Energy Network" programme was officially inaugurated at the "First Collisions" event, which was held at CERN and was attended by nearly 400 participants from all over the world. The programme will allow alumni pursuing careers in a wide variety of fields, ranging from academia to industry, economics, information technology and medicine, to maintain links with CERN, to benefit from the wealth and diversity of their large community, and to leverage the experience and support of members of the network. At the end of 2018, the network had more than 4000 members and six regional groups in the Netherlands, Switzerland, the United Kingdom and the United States.

Thirteen events were also held throughout the year, notably "Moving Out of Academia to … the Financial Sector" and "Moving Out of Academia to … Big Data", in the framework of a new series of workshops designed to support future alumni in their transition from the academic world to other professional sectors.

EXPLORING THE NATURE OF THE UNIVERSE

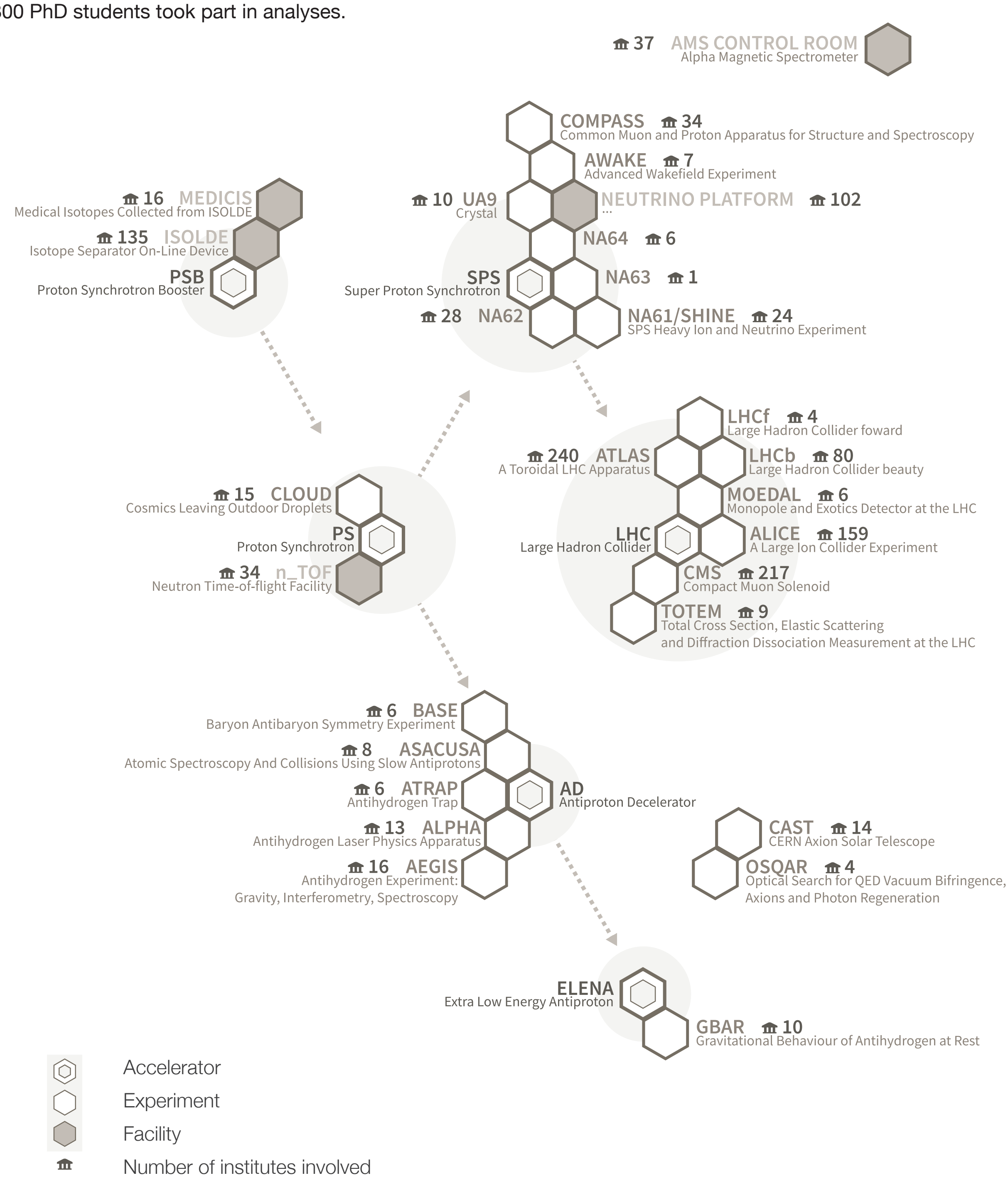
To explore the fundamental structure of the universe, CERN operates a unique network of accelerators that collide particle beams head-on or direct them onto fixed targets. The products of these collisions are recorded by sophisticated detectors and analysed by thousands of physicists at CERN and elsewhere.

CERN's accelerator complex and the experiments that it feeds

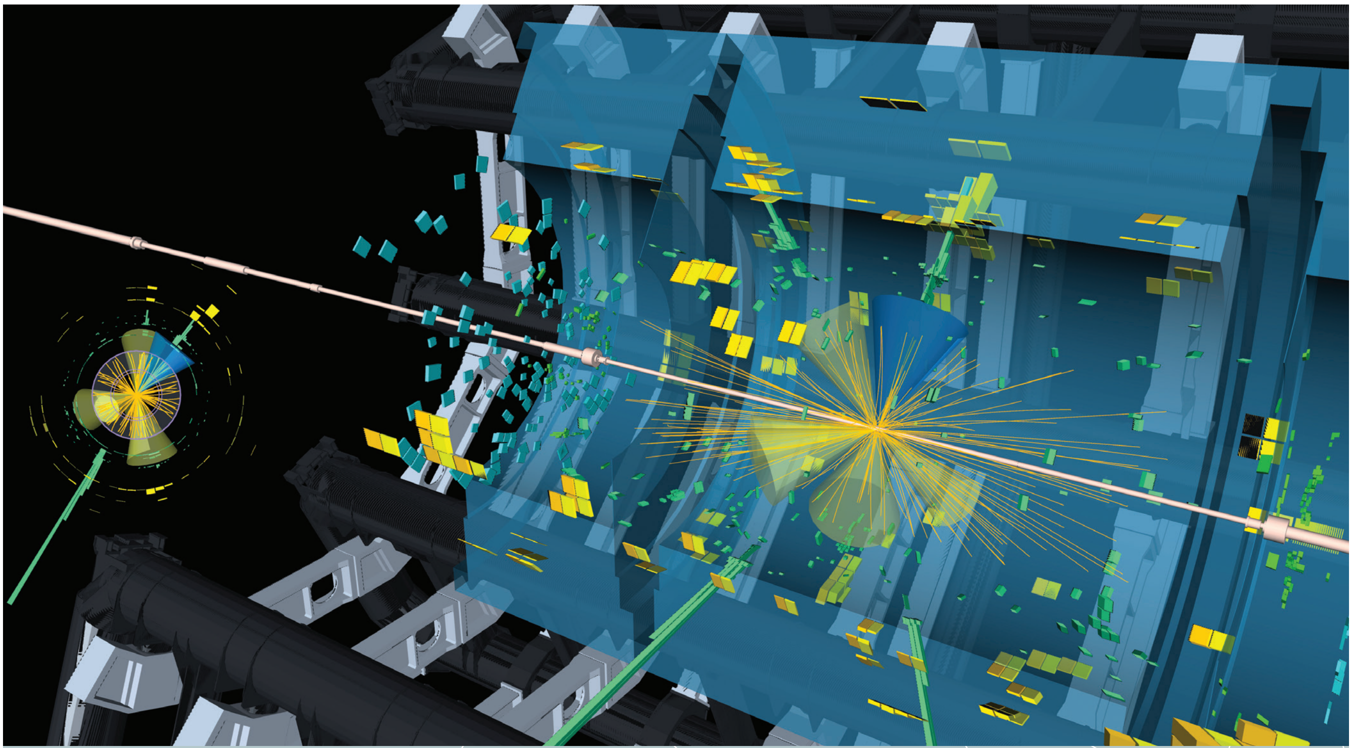


The Large Hadron Collider (LHC) is the world's most powerful particle accelerator. It collides proton beams inside four large experiments – ALICE, ATLAS, CMS and LHCb. The year 2018 saw the end of a very successful second run for the collider (2015–2018), a run during which the machine performed beyond expectations, achieving approximately 16 million billion proton–proton collisions at an energy of 13 TeV (for each of the ATLAS and CMS experiments) and large datasets for lead–lead collisions at an energy of 5.02 TeV per nucleon pair. In 2018, a total of 80 petabytes of data were recorded by the LHC experiments, over 310 scientific papers were published, and more than 2800 PhD students took part in analyses.

Excellent physics results were obtained by analysing these LHC data, as well as data from experiments at other machines in the Laboratory's accelerator complex. The findings have extended physicists' knowledge of what matter is made of at the smallest scales and have sharpened the physics arguments for the forthcoming update of the European Strategy for Particle Physics. The progress made includes precise measurements of the interactions of the Higgs boson with the third-generation fermions, rigorous tests of the Standard Model of particle physics, and ever more sensitive searches for new physics.



CERN's accelerators serve many experiments and facilities that are used by researchers across the globe.



An ATLAS candidate event for a Higgs boson being produced along with a top–antitop pair. The event contains two photon candidates and six particle jets. (ATLAS-PHOTO-2019-016-3)

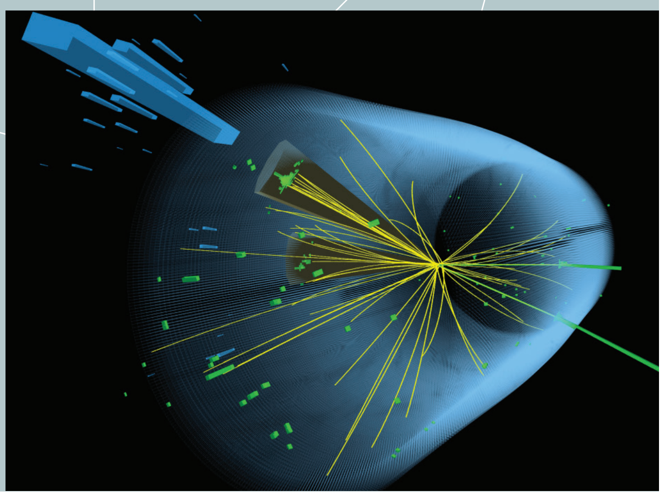
THE LHC IS TESTING PREDICTIONS OF HOW THE HIGGS BOSON INTERACTS WITH OTHER PARTICLES. ANY DEVIATIONS IN BEHAVIOUR COULD POINT TO NEW PHYSICS.

HIGGS BOSON UNDER THE LENS

The Standard Model makes precise predictions on the Higgs boson's interaction with other particles. Testing these predictions is a major line of research at the LHC and at proposed future colliders, because any deviation from the predicted behaviour could point to new physics. This can be done by examining how the Higgs boson transforms, or decays, into lighter particles almost immediately after it is produced. In 2018, both ATLAS and CMS observed the decay of the Higgs into pairs of bottom–antibottom quarks for the first time. Although the Standard Model predicts that this decay mode is the most abundant, such bottom–antibottom pairs are produced in the LHC from a variety of processes unrelated to the Higgs mode, making it challenging to isolate those that come from the Higgs.

Because the top quark is heavier than the Higgs boson, nature prevents a Higgs from decaying into pairs of top–antitop quarks. However, physicists can study Higgs–top-quark interactions by looking for instances where the Higgs boson is produced along with a top–antitop pair, and in 2018 ATLAS and CMS observed this "associated production" in data recorded in previous years. The production rate for this process, as well as for the Higgs decay into pairs of bottom–antibottom quarks, was found to be in agreement with expectations from the Standard Model at the current level of statistical precision.

A CMS candidate event for the Higgs boson decaying to a bottom–antibottom quark pair in association with a Z boson decaying to an electron and its antiparticle. (CMS-PHO-EVENTS-2018-008-1)



TESTING THE STANDARD MODEL

The LHC experiments tested the Standard Model to increased levels of precision and sensitivity in 2018. The top quark remains a source of novel physics measurements and observations. Alongside measurement of the Higgs mass this is a key input for reducing the uncertainties in the predictions of the Standard Model. ATLAS measured the top quark's mass to a precision of 0.3% by combining data from different decay channels. Meanwhile, CMS explored rare production modes of the top quark that are sensitive to signs of physics beyond the Standard Model. The collaboration observed the production of a top quark in association with a Z boson and a second quark, and presented evidence for the production of a top quark along with a photon and another quark. Other highlights from CMS included measurements of known Standard Model processes with improved precision, as well as novel studies in the physics of B mesons.

The Higgs boson's presence affects the probability that the W and Z bosons can bounce or "scatter" off each other. In 2018, ATLAS observed such scattering of pairs of W bosons as well as of a W and a Z boson. Future data will help measure this scattering with greater precision, as physicists look for deviations from predicted values. ATLAS also measured the electroweak mixing angle, a key parameter for defining how the Standard Model unifies the electromagnetic and weak forces, achieving for the first time at the LHC a precision that is competitive with the most precise single-experiment results from the LEP and Tevatron colliders.

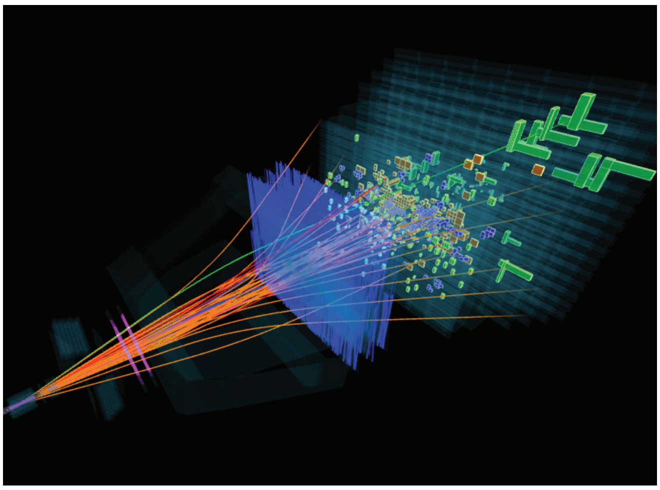
Particle physicists are seeking to explain why the universe is dominated by matter, with almost no antimatter around. This asymmetry could be explained by differences in the way in which matter and antimatter interact via the weak force. The LHCb experiment was built to study these differences, known as charge-parity (CP) violation, and has obtained a variety of precision measurements. In 2018, the LHCb collaboration measured several parameters associated with the so-called Cabibbo–Kobayashi–Maskawa (CKM) matrix, which quantifies possible CP violation among quarks. In particular, the collaboration measured the parameter γ using different methods and obtained a value of 74°, with an uncertainty of about 5° – making it the most precise measurement of this parameter from a single experiment.

The experiment also obtained the first evidence of the rare B_s meson transforming into an excited kaon and two muons, as well as the best limits on the transformation of a B^+ meson into three muons and a neutrino. Other highlights from LHCb were the measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++} , which the collaboration observed for the first time in 2017, and the lifetime of the charmed omega (Ω^0c). The latter was measured to be 268 ± 26 fs, the most precise measurement ever, but the result is nearly four times greater than previous measurements and contradicts earlier predictions.

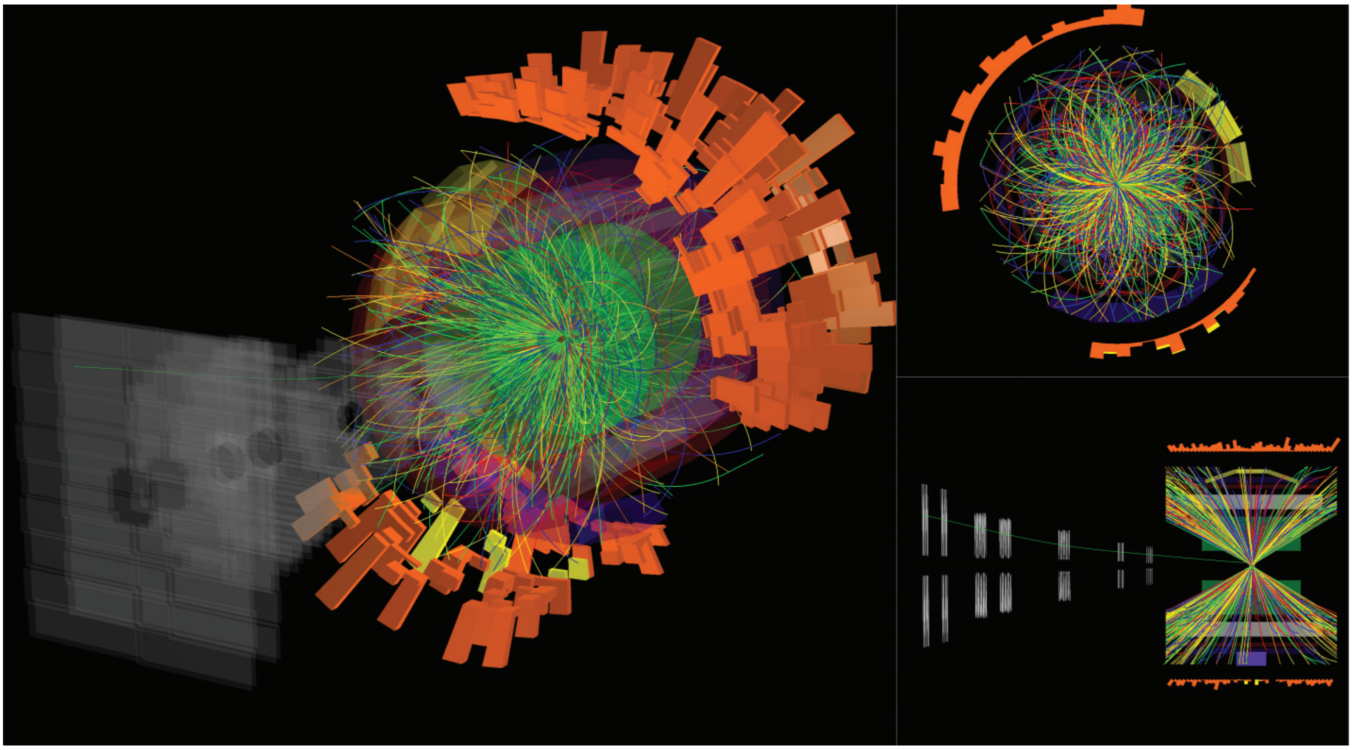
LHCb also operated in fixed-target mode besides its regular collider mode by injecting noble gases such as helium into the beam pipe in between particle bunches. The atoms of these noble gases served as stationary targets for the circulating protons, and LHCb was able to observe the production of J/ψ and D^0 particles in these collisions as well as make the first measurement of the production rate of antiprotons in proton–helium collisions.

The year 2018 also saw the TOTEM experiment, which studies very glancing proton collisions using detectors located 220 m either side of the CMS experiment, uncover possible evidence for a subatomic three-gluon compound called an odderon, first predicted in 1973. The result derives from precise measurements of the probability of proton–proton collisions at high energies, and has implications for our understanding of data produced by the LHC and future colliders.

A proton–proton collision event recorded by LHCb in early 2018.
(OPEN-PHO-EXP-2018-005-2)



THE STANDARD MODEL DOES NOT ACCOUNT FOR DARK MATTER AND DARK ENERGY, STRONGLY SUGGESTING THAT NEW PARTICLES AND FORCES MUST EXIST BEYOND THOSE THAT THE MODEL PREDICTS.



Particle trajectories and energy deposition in the ALICE detector during the first lead-nuclei collisions of 2018.
(ALICE-EVENTDISPLAY-2018-003-1)

SEARCHING FOR NEW PHENOMENA

The Standard Model has successfully passed all the experimental tests that it has been put to, yet the model fails to account for major elements such as dark matter and dark energy, a failure that strongly suggests that new physics is at work and remains to be unravelled.

ATLAS and CMS performed numerous searches for new phenomena during 2018. Examples include the ATLAS search for instances in which extremely massive particles transform into pairs of W and Z bosons, the results of which ruled out the presence of specific types of massive particles up to 4.15 TeV. Another example was the CMS search for exotic Z′ (“Z-prime”) particles, which are predicted by some extensions of the Standard Model. CMS also searched for hypothetical particles known as leptoquarks, which are thought to be hybrids of leptons and quarks. In addition, ATLAS and CMS searched for many different signatures of the presence of dark matter and supersymmetry. In all of these analyses, the collaborations found no evidence for the existence of the underlying hypothetical particles in the various parameters that were explored.

THE HOT EARLY UNIVERSE

The LHC also collides lead nuclei to generate larger and hotter collision systems. These collisions effectively recreate a dense state of free quarks and gluons known as the quark-gluon plasma (QGP), which is thought to have existed in the early universe. Results from the ALICE collaboration, which specialises in these collisions, have shown that the particle jets emerging from lead–lead collisions are narrower (more collimated) than those formed in proton–proton collisions, due to low-energy radiation at large angles from the jet axis caused by interactions between the jet particles and the QGP “soup”.

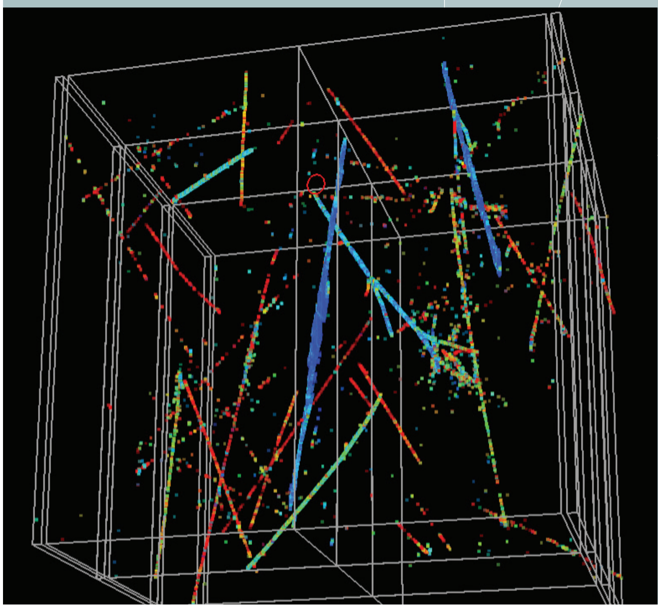
ALICE noted that the production of J/ψ mesons at the LHC was not as suppressed at low transverse momenta as in collisions at the Relativistic Heavy Ion Collider (RHIC) in the US, concluding that the suppression caused by the QGP was countered by the recombination of charm and anticharm quarks into J/ψ mesons. The collaboration also observed that the ratio of Λ_c baryons to D mesons produced in lead–lead collisions was higher than in proton–proton and proton–lead collisions. This behaviour is expected if the charm quarks bind with other quarks in the QGP around them and form baryons and mesons. The detailed dynamics of these processes will be studied precisely with datasets that ALICE will collect in future runs of the LHC. Furthermore, ALICE noted that this Λ_c-to-D ratio was higher than expected from theoretical calculations, even in proton–proton and proton–lead collisions.

CHASING NEUTRINOS

Neutrinos, the lightest known massive particles, continue to be a major focus of worldwide research in high-energy physics. Questions surrounding neutrinos include how they acquire their masses and whether they violate CP symmetry. In 2018, the collaboration behind the OPERA experiment, which is located at the Gran Sasso Laboratory in Italy and was designed to prove that muon-neutrinos can oscillate into tau-neutrinos by studying muon-neutrino beams sent from CERN 730 km away, described the observation of a total of ten candidate events for a conversion from a muon- to a tau-neutrino, demonstrating unambiguously that muon-neutrinos transform into tau neutrinos on their journey from CERN to Gran Sasso.

Meanwhile, the ATLAS and CMS collaborations looked for heavy Majorana neutrinos, hypothetical particles that may balance out the very small neutrino masses via the so-called seesaw mechanism. ATLAS and CMS found no hints of heavy Majorana neutrinos in the parameter ranges that they investigated but these null results are crucial as they allow scientists to place stringent constraints on the theoretical models.

CERN's Neutrino Platform was established to support European participation in accelerator-based neutrino projects in the USA and Japan, and provides charged beams and test space for large neutrino detectors. The developments in 2018 included completion of the construction of two large-membrane cryostats housing 6 x 6 x 6 m^3 prototypes for the future, much larger liquid-argon DUNE detector at the US Long Baseline Neutrino Facility using "single-phase" and "dual-phase" time projection chamber technologies. Single-phase ProtoDUNE, the first large prototype, was commissioned in 2018 and recorded its first particle tracks in tests at CERN, demonstrating the viability of the technology on a large scale and marking an important step towards DUNE.

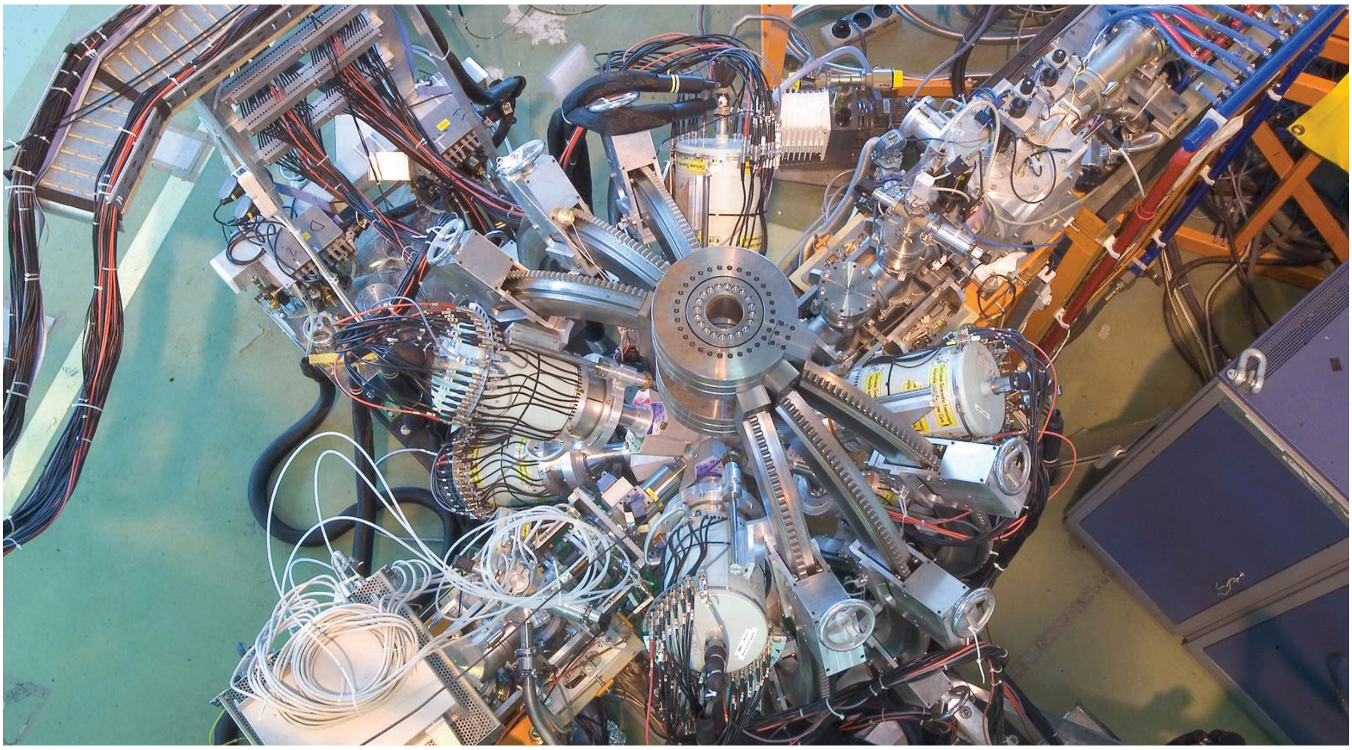


Inside the dual-phase ProtoDUNE, which is under construction and is expected to start operation in 2019. (CERN-PHOTO-201803-085-1)

Three-dimensional event display recorded by the single-phase ProtoDUNE detector at CERN.

THE MAGIC OF EXOTIC BEAMS

ISOLDE is CERN's long-running nuclear-research facility. It directs a 1.4 GeV proton beam from the PS Booster at a target station to generate exotic radioactive-ion beams for studies of the structure of atomic nuclei and other purposes. These beams can be re-accelerated using the REX/HIE-ISOLDE linear accelerators (linacs). An energy upgrade of the HIE-ISOLDE superconducting linac was completed and will enable beams with an energy of up to about 10 MeV per nucleon even for neutron-rich nuclei. A record total of 51 experiments were carried out by users from around the world. Of these, 14 experiments used 18 different beams from HIE-ISOLDE, while 37 low-energy experiments used more than 80 different isotopes.



The MINIBALL gamma-ray detector array at the HIE-ISOLDE accelerator. *(CERN-EX-0506009-07)*

Highlights from 2018 include the first direct proof by the MINIBALL and HIE-ISOLDE collaborations that the nucleus of tin-132 (^{132}Sn), which was considered to be “doubly magic”, does indeed merit this special status. Such nuclei have complete proton and neutron shells and are exceptionally stable. The result was the first to emerge from HIE-ISOLDE and shows that the facility is key to unravelling the inner workings of atomic nuclei. Another highlight was the revelation and explanation of the full extent of the odd-even shape-staggering of exotic mercury isotopes, whereby the shape of the atomic nuclei dramatically moves between that of a football and that of a rugby ball. The result was possible thanks to an unprecedented combination of experimental elements, such as ISOLDE’s Resonance Ionisation Laser Ion Source (RILIS), and theoretical and computational modelling techniques.

The year 2018 also saw ISOLDE forge, using RILIS, neutron-rich isotopes of the element chromium for the first time and in prodigious quantities. These isotopes were measured by ISOLTRAP, which has been performing mass measurements at ISOLDE for the last 30 years. The new mass values are up to 300 times more precise than previous results, offering new insight into the nuclear structure of chromium isotopes.

THEORY THRIVES

In 2018, CERN’s Theoretical Physics department (TH) produced cutting-edge research supporting the Laboratory’s activities and serving the international theoretical physics community. The research activity in TH covers all areas of relevance to particle physics and, in 2018, led to the submission of 342 papers to the arXiv preprint server.

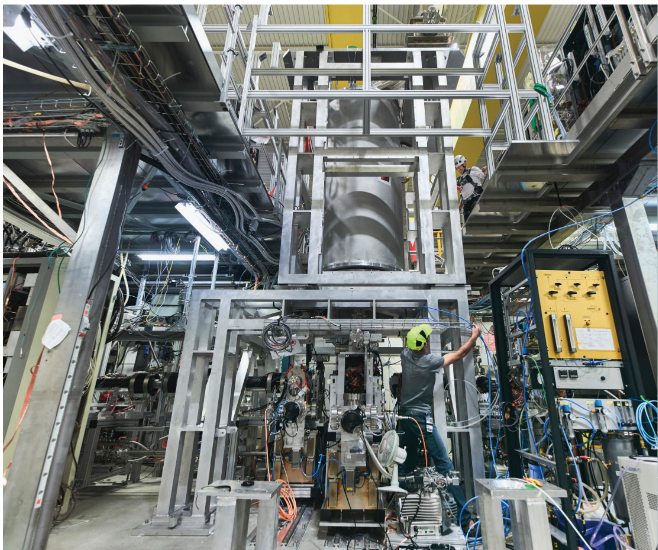
Mathematical studies included the exploration of string theory and quantum field theory, which revealed interesting connections with conjectures related to the properties of gravity in the quantum regime. Much work was devoted to all aspects of the physics studied at the LHC, from precise calculations of processes in the Standard Model to imaginative hypotheses about phenomena that could reveal new physics beyond the Standard Model. Studies in cosmology and astroparticle physics, which are among the core activities of TH, explored the evolution of the early universe and observational methods in order to extract information on dark matter and dark energy. Investigations were done in heavy-ion-collision physics, an active branch of research in TH that studies the properties of matter in extreme conditions, such as those found at the centre of stars. Work was also done in lattice gauge theory, whose goal is to explore the complex properties of strong interactions by simulating the physical space-time on a grid.

TH made fundamental contributions to the LHC Physics Centre at CERN (LPCC), to working groups on the physics of the LHC and the proposed colliders CLIC and FCC and to the Physics Beyond Colliders initiative (see p. 48). It also made important contributions to documents that were submitted as input for the update of the European Strategy for Particle Physics.

EXPERIMENTS ON TARGET

In 2018, great advances were also made in other experiments and projects, many of which are fed by beams from CERN's PS Booster, PS and SPS accelerators (see p. 25). These achievements include production-rate measurements relevant to neutrino physics, and investigation of the emergence of the QGP in heavy-ion collisions in fixed-target mode (NA61/SHINE experiment); studies of rare kaon decays and searches for new heavy neutral leptons (NA62), with the first search for the decay of a positively charged kaon into a positively charged pion and a neutrino–antineutrino pair conducted on the basis of kaon decays "in-flight"; investigations of radiation processes in strong electromagnetic fields (NA63); searches for dark-sector particles (NA64); measurements of neutron-induced processes relevant to nuclear physics and astrophysics (n_TOF); studies of the hadron structure (COMPASS); searches for chameleon particles and axion particles (CAST, OSQAR); the influence of cosmic rays on cloud formation (CLOUD), which is important for modelling climate change; and particle collimation using crystals (UA9).

The NA62 experiment in CERN's North Area. *(NA62-PHO-EXP-2017-001-2)*



The ALPHA-g experiment, seen here being installed in CERN's Antiproton Decelerator hall, received its first beam of antiprotons on 30 October 2018. (CERN-PHOTO-201810-267-37)

ANTIMATTER EXPLORATION

CERN's Antiproton Decelerator (AD) supplies low-energy antiprotons for precise spectroscopy, as well as gravitational and other measurements, allowing ever more precise comparisons between the behaviour of matter and antimatter. The AD currently hosts five operational experiments: ALPHA, AEgIS, ASACUSA, ATRAP and BASE. Two other experiments, GBAR and ALPHA-g, which is essentially a vertical version of ALPHA, are in preparation. The new ELENA ring (see p. 46) slows down antiprotons even further so that they are more easily trapped by the experiments.

In 2018, the ALPHA collaboration extended the measurements of the spectral structure of antihydrogen that it had made over the previous couple of years, by obtaining the most-precise-ever direct measurement of antimatter. The team determined the spectral structure of the antihydrogen 1S–2S transition to a precision of a couple of parts in a trillion, heralding a new era of high-precision tests of the differences between matter and antimatter and marking a milestone in the AD's scientific programme. The collaboration also obtained the first measurement of the next transition, the Lyman-alpha (or 1S–2P) transition, and measured its frequency with a precision of a few parts in a hundred million. In addition, it attained the first-ever laser cooling of antihydrogen.

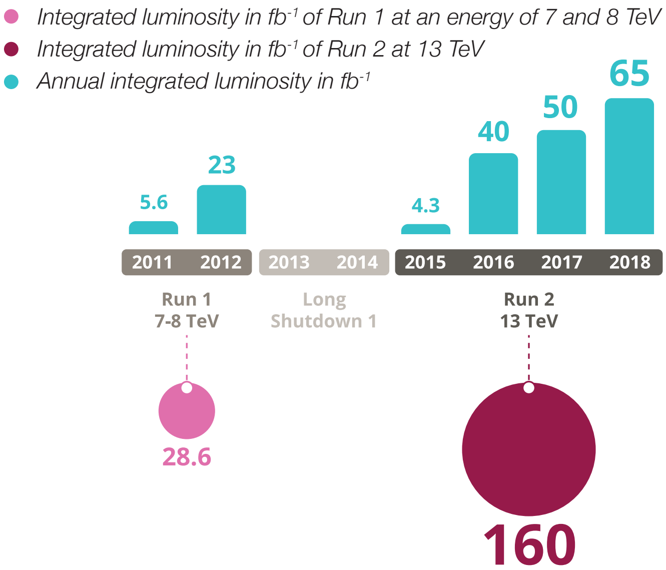
2018 also witnessed good progress from the other AD experiments, including the refinement of the BASE apparatus to allow precise measurements of antiproton properties, and the receipt of the first beams of antiprotons by the GBAR and ALPHA-g experiments, which aim to test whether antimatter falls at the same rate as matter under gravity.

DISCOVERY MACHINES

To study the infinitesimally small, CERN and the experiment collaborations operate a unique complex of accelerators and detectors. The accelerators project tiny subatomic particles at astonishing speeds in order to make them collide with each other or with targets, and the detectors record what happens during these collisions. The resulting huge quantities of data are stored and analysed using a worldwide computing grid. Hundreds of scientists contribute to the operation and maintenance of these sophisticated installations.

The Large Hadron Collider completed its second run with a record number of collisions.
(CERN-PHOTO-201802-030-4)

The team of operators and members of the CERN Management applaud as beams return to the LHC on 29 March 2018.
(OPEN-PHO-ACCEL-2018-012-01)



LHC luminosity on the rise
The quantity of proton–proton collisions delivered by the LHC to each of the ATLAS and CMS experiments since the machine began operating. These quantities are expressed in terms of integrated luminosity (in inverse femtobarns, fb^{-1}), which is the potential number of collisions for a given surface unit during a given period. This integrated luminosity is shown for the two runs that have taken place so far: the LHC reached 28.6 fb^{-1} during Run 1 and a remarkable 160 fb^{-1} during Run 2.

RECORD LUMINOSITY FOR THE LHC

In the early hours of 3 December, the operators switched off the particle beams in the Large Hadron Collider (LHC), bringing the accelerator's second run to an end, after another fruitful year. In 2018, the world's most powerful collider produced more than 13 million billion proton collisions. An integrated luminosity of 66 inverse femtobarns (fb^{-1}) was delivered to each of the two general-purpose experiments, ATLAS and CMS, exceeding the goal by 10%. Luminosity, which is one of the key parameters of a collider, is a measurement of the number of potential collisions per surface unit in a given period of time.

Thanks to continuous improvements, the LHC's performance has increased year on year, culminating in 2018. In total, the four years of Run 2 at an energy of 13 TeV enabled the ATLAS and CMS experiments to collect 160 fb^{-1} of proton data each, exceeding the planned 150 fb^{-1}.

The accelerator complex restarted with beam on 2 March, and the LHC followed on 29 March. One month later, two beams of 1200 proton bunches were circulated and LHC data collection began. The maximum number of bunches, 2556, was reached at the beginning of May, two weeks ahead of schedule. The LHC was available 75% of the time, with beams circulating and collisions being generated 49% of the time, as in 2017.

In order to increase the luminosity while avoiding too many simultaneous events for the detectors to cope with, the LHC operators implemented several techniques tested during the previous run. The new optics configuration, "achromatic telescopic squeezing", developed for the High-Luminosity LHC and designed to squeeze the beams still further at the collision point, was used systematically.

The parameter known as beta-star (β*), expressed in centimetres, is a measurement of the beam squeezing.

High-luminosity tests at the LHC

Components developed for the High-Luminosity LHC have already been installed in the LHC so that they can be tested in real conditions, i.e. with beam. The year-end technical stop saw the installation of two new wire collimators, whose integrated conductors generate a magnetic field to mitigate certain beam disruptions. A new crystal collimator was also installed; its bent crystals, which have been tested for several years in the SPS and during test runs in the LHC, steer particles that deviate from the beam path towards absorbers. For the first time, this type of collimator was used during a run with beam. Finally, two further prototype components were installed: a collimator with molybdenum graphite jaws and a faster kicker magnet with a special coating to limit heating. This magnet will optimise the filling of the LHC.

New collimators developed for the High-Luminosity LHC were installed in the LHC, two of them near the ATLAS experiment. (CERN-PHOTO-201801-011-1)

The smaller it is, the more the beam is squeezed and the greater the number of collisions. In 2018, the LHC operated with a β* of 30 cm for ATLAS and CMS, compared to the 80 cm planned when the machine was designed. In order to optimise luminosity through the cycles, the operators reduced the β* still further at the end of the cycles, lowering it to 27 and then to 25 cm. They also tweaked the beam crossing angle. These operations also aimed to test operating methods for the High-Luminosity LHC.

The LHC detectors were faced with staggering quantities of data. On average, the LHC produced close to 40 simultaneous collisions with each beam crossing (around 30 million times per second) at the heart of ATLAS and CMS, with peaks at 60 collisions per crossing. This instantaneous luminosity forced the trigger and acquisition systems to work at full throttle. ATLAS and CMS managed to collect more than 94% of the data.

The LHCb and ALICE experiments were not designed to take such large amounts of data. The instantaneous luminosity is therefore deliberately lowered by adjusting the overlap of the beams when they cross. In 2018, the two experiments obtained a higher integrated luminosity than expected: LHCb collected 2.46 fb^{-1} and ALICE 27.3 pb^{-1}. Two special runs were completed with de-squeezed beams, with the protons crossing at very small angles so that the experiments, notably TOTEM and ATLAS/ALFA, could perform specific analyses.

Operating modes and equipment were tested in preparation for future runs during four machine-development periods. Around 20 tests were carried out during each run, notably focusing on beam instabilities, the heat load transferred to the cryogenic system and adjustments to the optics, as well as tests of new equipment, such as collimators.

IONS TAKE CENTRE STAGE IN THE LHC

LHC operation in 2018 came to an end with a fourth lead-ion run. For three and a half weeks, the collider smashed together atomic nuclei comprising 208 protons and neutrons at an energy of 5.02 teraelectronvolts (TeV) per nucleon pair. Despite commissioning difficulties, including the need to repair the ion source, more physics data was collected than anticipated. A significant amount of work was done on the injectors to increase the number of ions in each bunch and the number of bunches in each beam. The bunch spacing was reduced from 100 to 75 nanoseconds. This operating mode, combined with a new optics configuration, gave improved luminosity: ATLAS and CMS each recorded record peak luminosity, six times the nominal value. Ultimately, ATLAS and CMS each collected 1.8 nb^{-1} of data, ALICE 0.9 nb^{-1} and LHCb 0.24 nb^{-1}.

Lead ions are usually entirely "stripped" of their electrons before being accelerated. But in 2018, the LHC carried out an unprecedented run with ions retaining one electron. In the framework of the "Physics Beyond Colliders" study (see p. 48), a collaboration is studying the possibility of accelerating partially ionised atoms. Thanks to the excellent vacuum conditions in the LHC, the beam lifetime of these partially stripped ions reached 40 hours.

THE LARGEST ACCELERATOR NETWORK IN THE WORLD

The LHC's performance also relies on that of the accelerator complex, which produces and accelerates the beams before they are injected into the 27-km ring. CERN operates a chain of eight accelerators and one decelerator, which supply the LHC and dozens of experiments (see p. 14). The protons collided in the LHC are prepared by a series of four accelerators: Linac2, the PS Booster, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). Heavy ions are prepared in Linac3 and the Low-Energy Ion Ring (LEIR), before being sent to the PS and the SPS.

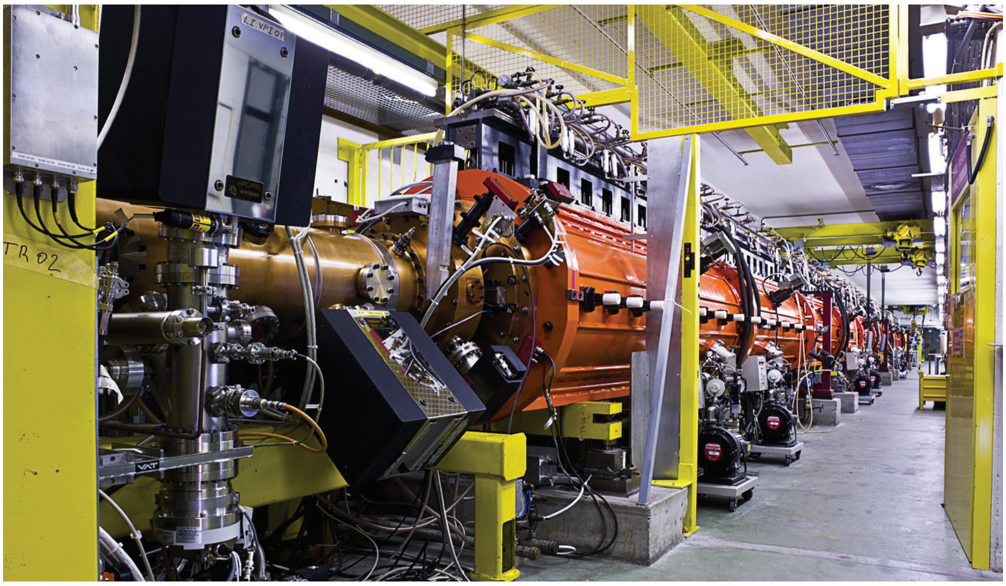
The availability of most of the accelerators exceeded 90%, rising to 95% for the PS Booster and 99% for Linac2. The achievement of Linac2 was all the more remarkable because it was accelerating beams for the last time. Having prepared 30 000 billion billion protons over its forty years of service, the first link in the accelerator chain was definitively shut down on 12 November. It will pass on the baton to the more powerful Linac4 (see p. 44).

The PS Booster supplies particles to the PS and the ISOLDE nuclear physics facility. ISOLDE received 10^{20} protons, or more than 50% of the total number injected into the accelerator complex. Just before starting its third year of operation, the new HIE-ISOLDE superconducting accelerator was fitted with a fourth cryomodule. The PS Booster supplied atomic nuclei to 14 experiments at energies of up to 9.5 MeV per nucleon, slightly less than expected, due to the failure of a cavity.

The next link in the chain, the PS, groups the particles into new bunches and accelerates them before dispatching them to various experimental areas. Most of the protons prepared by the PS in 2018 were sent to the nuclear physics facility n_TOF, which received 2.31×10^{19} protons, or 6.5% more than planned. In its second year of service, the CLEAR test facility operated for 36 weeks, performing tests on CERN equipment, but also on electronic components for external medical or aerospace applications.

The PS also supplied particles to the four East Area beam lines, which supplied 27 experiments, as well as to the test facilities IRRAD (81 experiments) and CHARM (61 experiments). The Antiproton Decelerator (AD), which is also fed by the PS, supplied beams to five antimatter experiments over the course of 4700 hours of operation, as well as to the new ELENA decelerator (see p. 46). However, the AD's availability was down (64%), due to a number of difficulties, mainly in the electron cooling system.

THE LHC ION RUN RESULTED IN A RECORD PEAK LUMINOSITY OF SIX TIMES THE NOMINAL VALUE.



The linear accelerator Linac2 was definitively shut down, after having prepared 30 000 billion billion protons over its forty years of service. It will be replaced by the new Linac 4 after the Long Shutdown. *(CERN-EX-0804060-05)*

A new 400 kV power transformer, the largest at CERN, was delivered to reinforce the Laboratory's electrical infrastructure.
(CERN-PHOTO-201810-254-31)

The final injector in the chain, the Super Proton Synchrotron, accelerates protons towards the LHC, as well as towards the six North Area beam lines, the HiRadMat test facility and the AWAKE experiment (see p. 49). The SPS delivered excellent quality beams to the LHC in 2018. It also supplied the North Area, which is home to more than 60 experiments, with an availability of 80%. One of these experiments, the ProtoDUNE prototype detector at the Neutrino Platform, recorded its first particle tracks (see p. 19). HiRadMat had a successful year, with a record number of experiments (ten), some of which were performed in the framework of the transnational access component of the EU-funded ARIES project.

At the beginning of December, the LHC devoted a week of tests to training its superconducting magnets to reach an energy of 7 TeV per beam, compared with the 6.5 TeV achieved thus far. The goal was to assess the number of quenches required to prepare the magnets for such an energy.

Long Shutdown 2 began on 10 December and will last two years. The preparations, which have been under way for the last two years, were stepped up in 2018 (see p. 44). A lot of work had already been done on the machines during the previous year-end technical stop, notably in the framework of the LHC injectors upgrade project. The cable removal campaign, which has been running for several years, continued, with 240 kilometres of cables removed from the PS. Around 15 magnets were replaced on the transfer line between the PS and the SPS. New beam instrumentation was installed on the transfer line between the PS and LEIR, while that of Linac3 was upgraded. In the LHC, equipment for the high luminosity upgrade was installed, the beam control systems were upgraded and instrumentation consolidation work was performed at Point 4. The renovation of the infrastructure is also in full swing. One of the highlights of the year was the spectacular delivery of a 400 kilovolt power transformer, which will provide redundancy for the Laboratory's power supply.

New infrastructures for the accelerators

A new magnetic measurement laboratory (see photo) opened on the Meyrin site in April. It has 17 test benches that can perform all the measurements and calibrations required for non-superconducting magnets and has already tested around one hundred magnets and coils. On the Prévessin site, a 400 m^2 polymer laboratory full of cutting-edge equipment (special furnaces, 3D printers, etc.) came into operation at the end of the year, replacing several workshops that were no longer able to meet CERN's requirements. Detector and accelerator components with unique designs are being manufactured there and the laboratory also contributes to the impregnation of superconducting magnet coils, notably for the High-Luminosity LHC. Finally, improvements continued in the superconducting magnet test hall, which is a crucial infrastructure for future accelerators and is at the cutting edge of the technologies they require. Test benches were altered to meet the requirements of the new niobium–tin magnets produced for the High-Luminosity LHC and a test station was set up for the superconducting power lines (see p. 43).
(CERN-PHOTO-201903-076-1)

The CERN Data Centre houses servers, data-storage systems and networking equipment, not only for the Worldwide LHC Computing Grid, but also for systems critical to everyday operations at CERN. (IT-PHO-CCC-2018-001-13)

PUSHING COMPUTING TO THE LIMITS

At the end of 2018, the LHC completed its second multi-year run (“Run 2”), which saw the machine reach a proton–proton collision energy of 13 TeV, the highest ever achieved by a particle accelerator. During this run, from 2015 to 2018, the LHC experiments produced unprecedented volumes of data, with the machine’s performance exceeding all expectations.

This resulted in exceptional use of computing resources, with many records broken in terms of data acquisition, data rates and data volumes. The CERN Advanced Storage system (CASTOR), which relies on a tape-based backend for permanent data archiving, reached 330 petabytes of data (330 million gigabytes) stored on tape, equivalent to over 2000 years of 24/7 HD video recording. In November 2018 alone, a record-breaking 15.8 petabytes of data were recorded on tape, a remarkable achievement corresponding to more than the amount recorded during the first year of the LHC’s Run 1.

The distributed storage system for the LHC experiments exceeded 200 petabytes of raw storage consisting of about 600 million files. This system, known as EOS, is disk-based and open-source, and was developed at CERN for the extreme computing requirements of the LHC.

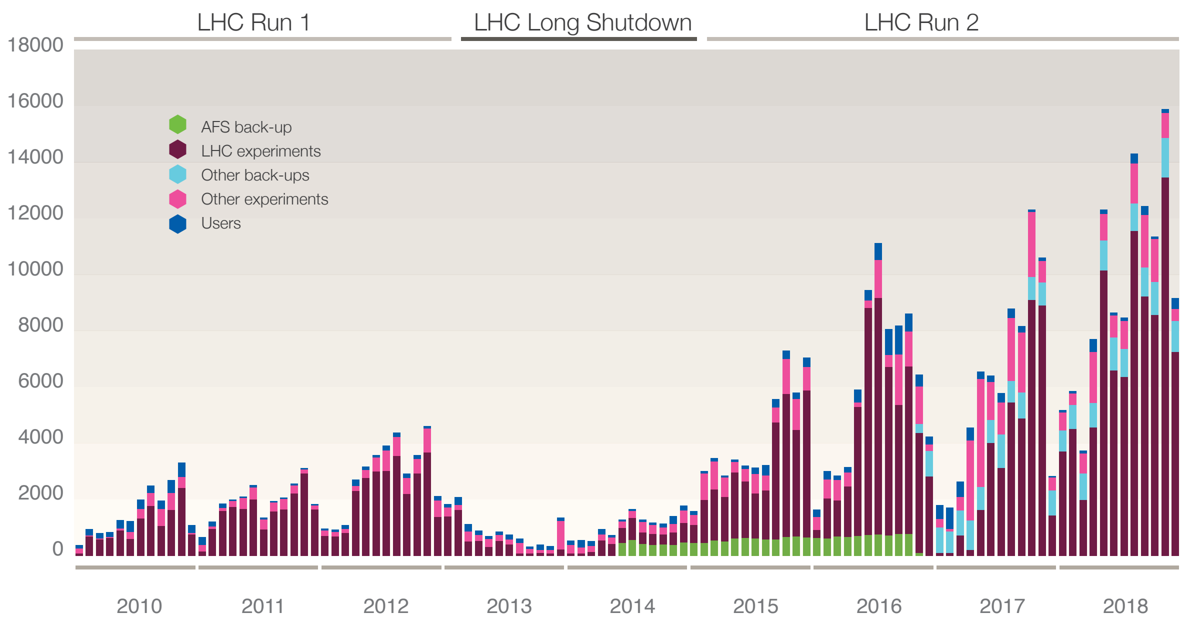
New IT R&D activities have already begun in preparation for the LHC’s Run 3. New software, named CERN Tape Archive (CTA), is being developed to replace CASTOR. The main goal of CTA is to make more efficient use of the tape drives in order to handle the higher data rate anticipated during Runs 3 and 4 of the LHC. Compared with the last year of Run 2, the amount of data to be archived is expected to be two times higher during Run 3 and at least five times higher during Run 4.

WLCG: FROM STRENGTH TO STRENGTH

In 2018, the global Worldwide LHC Computing Grid (WLCG) infrastructure performed well. It supported the significantly increased needs of the experiments, ensuring the timely delivery of high-quality physics results.

The CERN Data Centre continued to provide the essential processing and quality monitoring during data taking. Globally delivered computing time across the WLCG collaboration has continued to grow over the years, with about 800 000 computer cores available in 2018. Data delivery to the global collaboration is a key aspect of the WLCG service, and the transfer rates reached new levels of around 60 GB/s, with a smooth performance. WLCG reliably delivered data to the 170 participating computer centres worldwide.

The File Transfer Service (FTS) project, which distributes the majority of the LHC data across the WLCG infrastructure, has transferred more than 1 billion files and a total of 830 petabytes of data. It is now used by more than 20 experiments at CERN and in other data-intensive sciences. Volunteer computing for CERN, under the LHC@home umbrella, continued to provide significant capacity in 2018 and allowed peaks of 400 000 tasks to be run simultaneously.



Data (in terabytes) recorded on tape at CERN month by month

This plot shows the amount of data recorded on tape generated by the LHC experiments, other experiments, various back-ups and users. In 2018, more than 115 petabytes of data in total (including about 88 petabytes of LHC data) were recorded on tape, with a record peak of 15.8 petabytes in November.

EDUCATION AND SHARING

In 2018, the main CERN School of Computing (CSC) took place in Tel Aviv, Israel, from 1 to 14 October, and welcomed 71 students of 25 nationalities. Since the early seventies, the CSC has been promoting advanced learning in scientific computing and the exchange of information among young scientists and engineers involved in particle physics and other sciences. The CSC has up to three schools per year: the main school, a thematic school and an “inverted” school, where the lecturers are delivered by students from previous schools.

In October, the fifth CERN-UNESCO School on Digital Library in Nairobi, Kenya, brought together 35 librarians and library-system managers from Cameroon, Kenya, Somalia, Tanzania, Uganda, Zambia and Zimbabwe. They acquired new skills for running digital library systems. Participants were introduced to different approaches using Invenio, the open-source digital-repository platform, the Zenodo repository and the Open Access Africa platform.

The CERN data centres in Meyrin and Wigner together host around 15 000 servers, which are replaced every four or five years as they become inefficient for CERN’s research purposes. However, they remain suitable for less-demanding applications. In 2018, 200 servers and 12 network switches were donated to the University of Kathmandu in Nepal to support fundamental research and the development of science and technology.

CERN OPENLAB: TACKLING TOMORROW’S ICT CHALLENGES TODAY

In 2018, CERN openlab began its sixth three-year phase (2018–2020). Through this unique public–private partnership, CERN collaborates with leading ICT companies and other research organisations in order to accelerate the development of cutting-edge ICT solutions for the research community. In this new phase, no fewer than 20 R&D projects address technologies such as machine learning, data analytics, cloud computing and data acquisition.

From 5 to 6 November, CERN openlab organised a first-of-its-kind workshop on quantum computing in high-energy physics (HEP) at CERN. More than 400 people attended the workshop, which kick-started discussions of which HEP activities could benefit from quantum-computing technologies.

(CERN-HOMEWEB-PHO-2019-044-1)

OPEN-SOURCE FOR OPEN SCIENCE

Ever since releasing the World Wide Web software under an open-source model in 1994, CERN has been a pioneer in the open-source field, supporting open-source hardware (with the CERN Open Hardware Licence), open access (with the Sponsoring Consortium for Open Access Publishing in Particle Physics – SCOAP^3) and open data (with the CERN Open Data portal).

Several CERN technologies are being developed with open access in mind. The Indico conferencing package, which is used by more than 200 sites worldwide, saw two important new releases in 2018 and was used to provide tens of thousands of CERN visitors with access badges.

Zenodo, the free open-data repository co-developed by CERN and available to all sciences, received 2.5 times more visitors than the previous year. A grant was awarded by Arcadia Fund to improve the Biodiversity Literature Repository, a community on Zenodo. CERN also signed a memorandum of understanding with the Latin American network LA Referencia to facilitate the use of Zenodo in Latin America.

Invenio is an open-source library-management package that receives contributions from collaborating institutes all over the world, and a new release was published in June. CERN and the Japanese National Institute of Informatics (NII) also signed an agreement to collaborate on a new platform based on Invenio, which will be deployed in more than 500 Japanese universities.

SCIENCE IN THE CLOUDS

In 2018, the CernVM project celebrated its tenth anniversary. It is now an extensible, portable and easy way to configure user environments in order to develop and run LHC physics software locally, on grids and on clouds, independently of operating-system software and hardware platforms.

More than 90% of the computing resources in the CERN Data Centre are now provided through a private cloud based on OpenStack, an open-source project designed to deliver a massively scalable operating system for clouds. With the growth of the computing needs of the CERN experiments and services, this private cloud has reached more than 320 000 computing cores running in the CERN Data Centre.

CERN has been actively contributing to the OpenStack and CentOS communities over the years, and in 2018 began collaboration with the Cloud Native Computing Foundation and Tungsten Fabric. It also became a member of the Linux Foundation and a founding member of the Ceph Foundation.

CERN is working towards building a European Open Science Cloud (EOSC) through participation in several Horizon 2020 projects. The EOSC aims to offer 1.7 million European researchers and 70 million professionals a virtual environment with seamless services for storage, management, analysis and re-use of research data, by federating existing scientific data infrastructures currently dispersed across disciplines and national borders.

COMPUTER SECURITY AT CERN

The computer-security team protects the operations and reputation of CERN against cyber-threats. It conducts computer-security investigations, including forensic analyses, to understand computer break-ins at CERN or within the community. In 2018, no major impact was recorded for CERN.

To prevent incidents, the team has established a large network within the community and with law enforcement agencies and industry. In 2018, computer-security training and awareness sessions were held throughout CERN, including a full-scale “clicking” campaign to highlight the risks of clicking on arbitrary links. In addition, the “WhiteHat Challenges” educate and train members of the CERN community to become penetration testers and “hack” their own software to make it more secure.

PUSHING THE FRONTIERS OF TECHNOLOGY

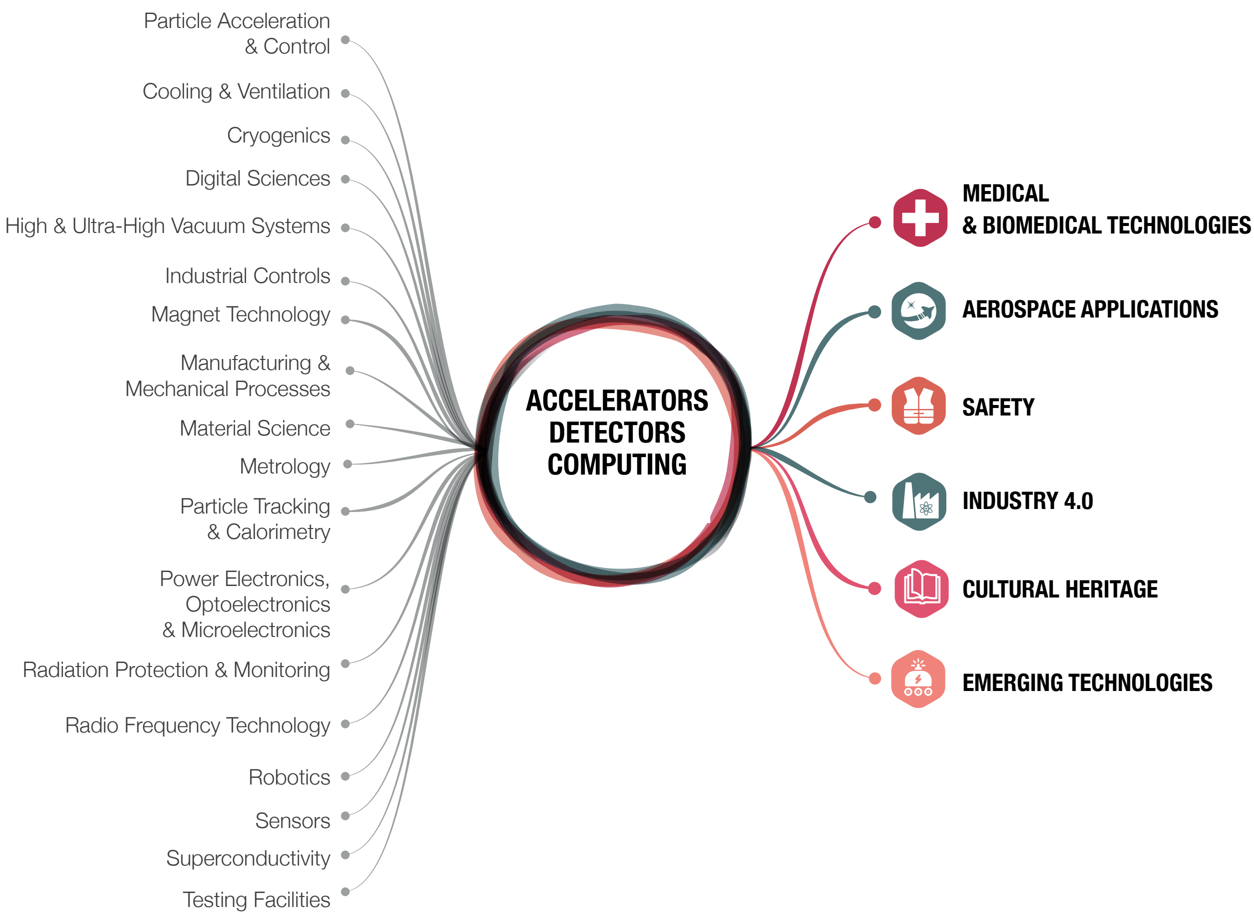
An important part of CERN's mission is to ensure that its pioneering technology and know-how have an impact beyond the walls of the Laboratory. This transfer of knowledge is beneficial not only to the industry in CERN's Member States but also to society as a whole.

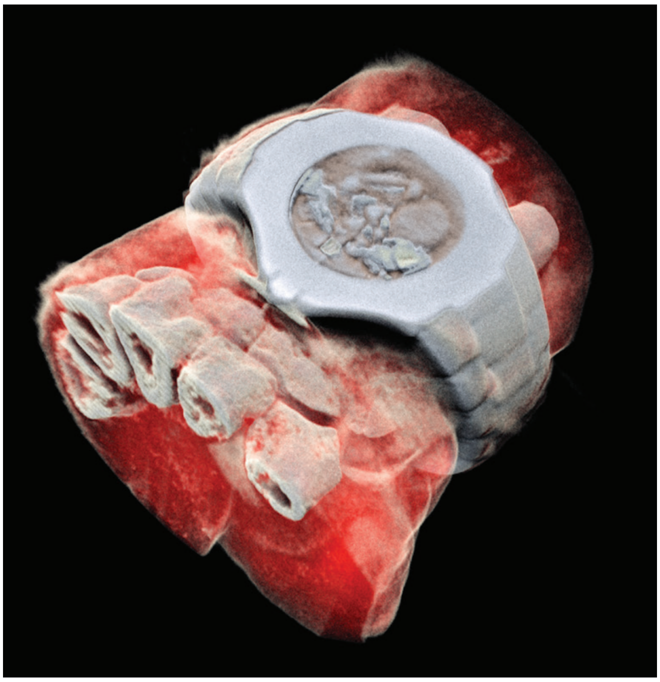
The year 2018 saw many examples of successful knowledge transfer in fields ranging from medical and biomedical technologies to aerospace applications and beyond. CERN attended the SLUSH entrepreneurship conference in Helsinki, where the 2018 State of European Tech report was presented. For the first time, CERN was a data-partner in the report and featured as an example of how fundamental research institutes act as drivers for innovation through their contribution to technological and human capital.

The introduction of Knowledge Transfer (KT) "Discovery Days" at CERN increased collaborations with multinational companies by inviting them to come to the Laboratory to explore potential solutions to industrial challenges.

Diverse Fields of Application

The technologies designed for the Large Hadron Collider and used in the discovery of the Higgs boson have led to major developments related to accelerators, detectors and computing that are relevant to society.





CERN technology was the basis for the first 3D colour X-ray scan of a human. The colours visible on this image of a wrist represent different energy levels of the X-ray photons as recorded by the detector, identifying components such as fat, water, calcium and disease markers.

MEDICAL AND BIOMEDICAL TECHNOLOGIES

CERN's long-standing contribution to medical and biomedical technologies continues to be fruitful.

MARS Bioimaging Ltd (a spin-off from the Medipix Collaborations and the University of Canterbury, New Zealand) produced the first images of a human body using their breakthrough 3D colour scanner, based on the Medipix3 technology. Medipix is a family of imaging and detection chips developed at CERN.

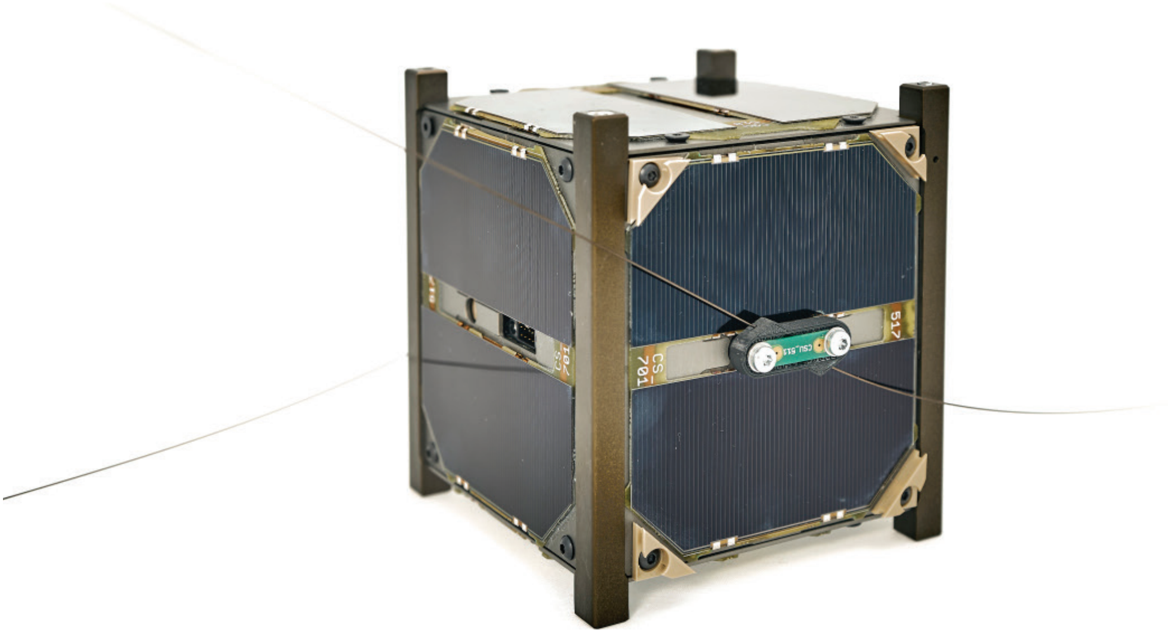
An innovative design for hadron-therapy gantries, GaToroid, was conceived in 2018 using CERN's expertise in superconducting magnets. Gantries steer the therapeutic beam around the patient so that a tumour can be treated from various angles. GaToroid promises to revolutionise the field by introducing a toroidal magnet that bends the treatment beam without needing to rotate the structure, thus substantially reducing the weight and cost compared to fully rotating gantries.

The first CERN medical-technology hackathon was organised to address challenges set by healthcare and industry partners using relevant CERN technologies. The winning teams' proposals aimed to improve access to vital healthcare in rural areas (using C2MON technology) and to screen radiopharmaceuticals more efficiently (using the GEMpix detector). Both teams won a stay at CERN to continue to develop their projects.

AEROSPACE TECHNOLOGIES

CERN continues to contribute to the aerospace community through partnerships and by providing access to its unique competences and facilities. CHARM, a facility at CERN to test electronics in complex radiation environments, tested its first full spacecraft, CELESTA (CERN Latchup and Radmon Experiment Student Satellite). The satellite was tested under a range of conditions that it can expect to encounter in space and proved its reliability. The payload, based on CERN radiation-monitoring technology, confirmed its very high sensitivity even to low fluxes and delivered outstanding performances overall.

Experts from ESA and IROC Technologies came to CERN to perform tests at VESPER (Very Energetic Electron Facility for Space Planetary Exploration Missions in Harsh Radiative Environments), which is part of CLEAR (CERN Linear Electron Accelerator for Research). VESPER was used to evaluate the effects of high-energy electrons on state-of-the art electronics that are being considered for the JUICE (Jupiter Icy Moons Explorer) mission. The outcome will help the JUICE project to optimise spacecraft.



The first full satellite was tested in CERN's CHARM facility in July. CELESTA will use CERN radiation-monitoring technology in space. (CERN-PHOTO-201807-181-2)

A WIDE VARIETY OF APPLICATIONS

CERN's unique environment combining ultra-high magnetic fields, high voltages, radiation and extremely low temperatures requires innovative safety solutions to detect and prevent threats. The goal of the start-up SAFETYN is to improve safety for general aviation by developing a novel device that acts as a pilot's guardian angel, collecting data and assisting in improving situational awareness by using the open-source ROOT/TMVA framework and machine-learning libraries. In 2018, SAFETYN SaS joined Innogex, the French incubator of CERN technologies.

The construction and operation of the accelerators, detectors and computing facilities results in expertise in industry 4.0. A2O Innovation Solutions, a start-up providing technologies for the reduction of weight and CO_2 emissions and for improving operational efficiency has been accepted by the UK BIC of CERN technologies. A2O plans to integrate the CERN technology Multi Memory System (MMS), originally developed for LHC Beam Position Monitors, into its CHASM system.

The MACHINA collaboration between CERN and INFN aims to construct a 'miniaturised' particle accelerator for use in cultural heritage. The MACHINA device will reduce the cost of using the PIXE elemental analysis technique, which is used around the world to study artworks. In April 2018, the project was launched at the *Opificio Delle Pietre Dure* (OPD) workshop in Florence, one of the world's leading institutes in art restoration.

ACCELERATING INNOVATION

The KT group supports the innovation process at CERN through its activities, collaborations and services. It provides advice, training and networks to facilitate the transfer of the Organization's technology and know-how. In 2018, CERN's scientists and engineers brought 77 new technologies to the group's attention, including software, electronics, and detector and accelerator components.

The CERN Knowledge Transfer Fund can help bridge the gap between research and industry. Established in 2011, and supported through revenue from the KT group's commercial agreements, 44 projects have been funded to date through a competitive process.

In 2018, three projects were selected: a diamond-based universal multimode-to-single-mode laser converter, a method for thin-film coating of complex shapes and an open-source research data management platform. In addition, the CERN Medical Applications Budget funded a new project on radioisotope production, as well as the work of four new researchers.

FRUITFUL COLLABORATIONS

CERN cultivates interactions between researchers, businesses and policy makers in its Member States, in order to facilitate the fruitful transfer of knowledge to industry. In particular, CERN participates in projects co-financed by the European Commission (EC). It is currently involved in six projects with a strong knowledge-transfer component (AIDA-2020, QUACO, AMICI, ARIES, FuSuMaTech, and ATTRACT), corresponding to approximately 34.5 million euros in EC co-funding.

Half of that amount comes from ATTRACT, a pioneering initiative that aims to fund 170 breakthrough concepts on detection and imaging technologies. The project represents a significant opportunity for CERN and its associated research and innovation communities to consolidate technology concepts and establish new knowledge-transfer links. ATTRACT's first call, in August 2018, received a total of 1211 proposals on topics such as sensors, front- and back-end electronics, data-acquisition systems and computing, and software and integration.

FOSTERING ENTREPRENEURSHIP

There are now 28 start-up and spin-off companies based on CERN know-how and technologies, specialising in diverse domains.

In 2018, the CERN Enlarged Directorate endorsed a new spin-off policy, which details the support given by CERN to spin-offs and clarifies the relationship with these companies.

The first CERN Entrepreneurship Student Programme (CESP) took place in late summer. CESP, a project under the umbrella of the CERN and Society Foundation and fully funded by the company Strangeworks, invited ten students from around the world to visit CERN. Over five weeks, they were coached by CERN KT experts with the aim of identifying and evaluating exploitable technologies and developing concepts for new ventures.

CERN signed its tenth Business Incubation Centre (BIC) agreement with PARK INNOVAARE in Switzerland, a centre run in collaboration with the Paul Scherrer Institute (PSI) and the University of Applied Sciences and Arts in Northwestern Switzerland (FHNW).

DOING BUSINESS WITH CERN

To construct and operate its particle accelerators, detectors and computing facilities, CERN places orders and contracts for a wide range of equipment and services every year. More than 40% of the Organization's annual budget is returned to industry through procurement activities, where contracts with CERN help industry to drive its innovation.

In 2018, CERN's procurement activities included 175 price enquires, 80 invitations to tender and 65 600 orders of various types. The Procurement Service also continued its extensive activities for the High-Luminosity LHC (HL-LHC). Major HL-LHC contracts were awarded, ranging from civil-engineering construction work and superconducting radiofrequency cavities to CO_2 pumps for the ATLAS and CMS detectors. In addition, contracts were placed for the architectural and engineering consultancy services for the new Science Gateway (see page 35), and IT contracts with Microsoft and Oracle were renegotiated. To streamline the purchasing processes at CERN, a new online procurement platform for the Organization's suppliers was launched and more than 2000 firms have already registered.

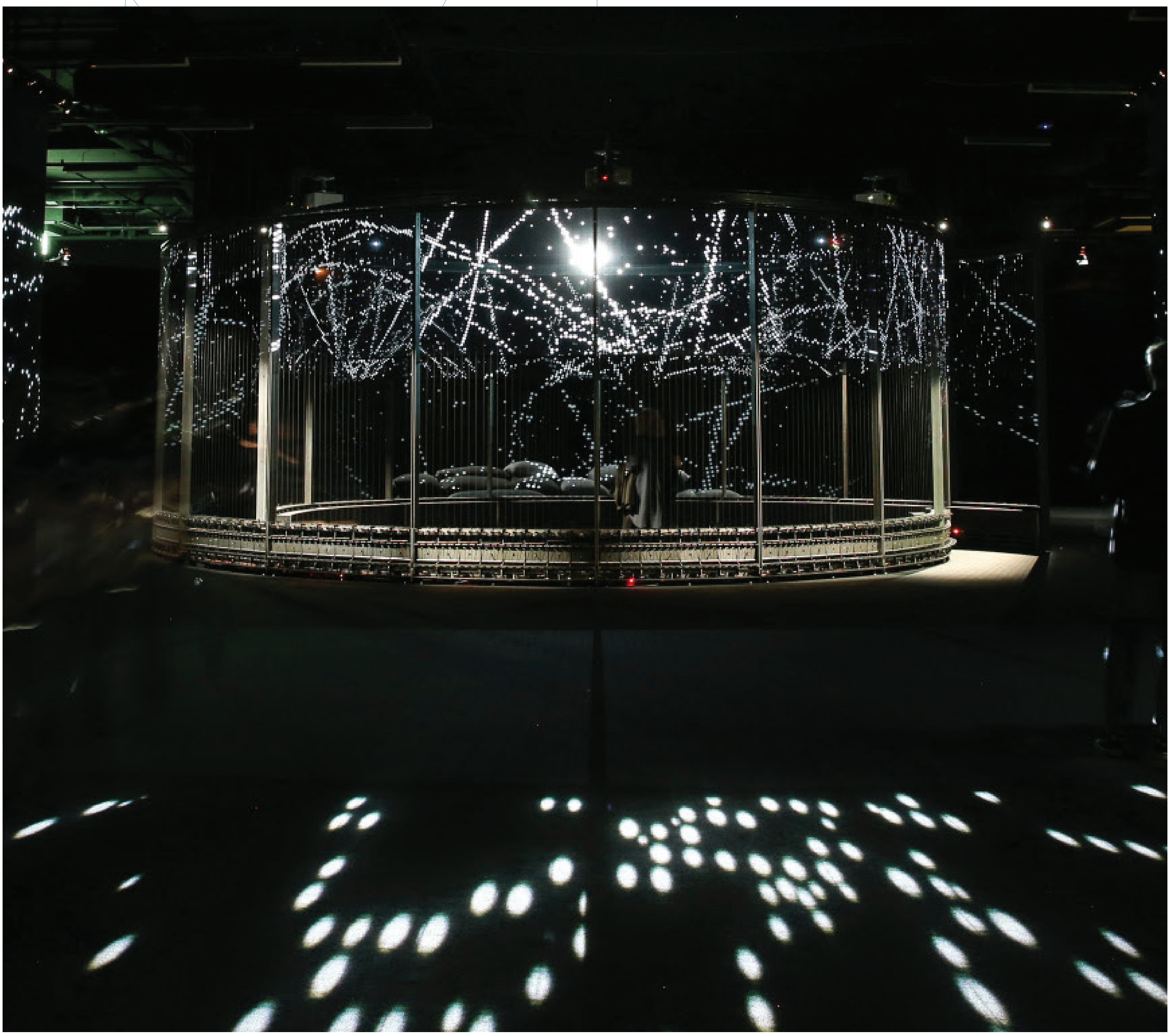
In order to create links between CERN and national industries, the Procurement Service regularly participates in a variety of conferences and events. Eight Member States organised industrial exhibitions and visits at CERN in 2018, while the Procurement Service also took part in industry events held in eight different Member and Associate Member States. One of these, the first Big Science Business Forum (BSBF), took place in Copenhagen, Denmark, gathering 18 advanced big-science organisations to meet European companies. In addition to giving presentations, CERN ran a large stand presenting ongoing and future procurement opportunities.

CERN Director for Accelerators and Technology, Frédérick Bordry, highlighted procurement opportunities for the High-Luminosity LHC upgrade project at the Big Science Business Forum.

INSPIRING AND EDUCATING

With scientific and technological developments from fundamental research transforming our society, CERN strives to engage and inspire different audiences across all sectors of the public. In 2018, the Laboratory enabled a diverse public to experience its science and technologies, with initiatives to increase accessibility and to empower students to pursue careers in science and engineering.

HALO, an immersive art installation conceived by CERN artists in residence, the Semiconductor duo Ruth Jarman and Joe Gerhardt, was showcased at Art Basel in June. The installation uses data from the ATLAS experiment. (OPEN-PHO-EXHI-2018-003-10)



ENGAGING WITH CERN

More than 135 000 visitors from 86 countries came to CERN in 2018 for guided tours of the research facilities. Offering an opportunity to go behind the scenes with a CERN scientist or engineer, such tours are increasingly appealing. In 2018, 56% of our visitors were students.

CERN guides also took part in many offsite events, engaging with the local population. In particular, CERN was the City of Geneva's guest of honour at the Swiss National Day celebrations. Researchers' Night was also popular, with workshops and hands-on activities taking place on the freshly inaugurated Esplanade des Particules in front of CERN's reception area (see p.10).

A young participant at the Swiss National Day celebrations is transported underground to an experimental cavern by a virtual-reality headset. *(CERN-PHOTO-201808-185-7)*

In November, 900 people attended TEDxCERN in Geneva. The largest audience was online as more than 4000 people watched the live webcast, either on the TEDxCERN homepage or at one of the viewing parties organised by 34 CERN-associated institutes around the world.

For the younger public, CERN's popular programme for French-speaking students, "Dans la Peau de Scientifiques", attracted 700 participants from primary schools, introducing them to the scientific method through hands-on experimentation in the classroom.

In June, 1800 professionals from science centres and museums in 58 countries worldwide came to Geneva for the annual Ecsite Conference. CERN offered participants guided tours and hosted a welcome event for all the speakers. This was a chance to communicate the material available at CERN, including interactive games and objects available for loan, to external science museums wanting to develop their own exhibitions about particle physics. In 2018, such collaborations resulted in the installation of permanent content in museums in Denmark, Vietnam and Spain.

Meanwhile, CERN's big Accelerating Science exhibition went to Riga, Latvia. Over 18 000 people visited the exhibition, learning how scientists at CERN are working to uncover the hidden secrets of the universe. CERN's LHC Interactive Tunnel toured exhibitions in Germany, Greece, the Netherlands and Switzerland. This popular digital interactive visualisation of the LHC allows visitors to attempt to collide protons themselves.

Looking to the future, the Science Gateway project received approval from the CERN Council in December, and work is now starting in earnest to develop new education labs and exhibitions to welcome visitors of all ages. The project will be housed in a series of striking new buildings designed by architect Renzo Piano, including a major new auditorium and a restaurant.

INSPIRING EDUCATION

CERN's teacher programmes turned 20 in 2018. They have grown considerably over the years and today form an important part of CERN's educational offering. The impact of such programmes is high, each teacher taking back inspiring ideas to share with other teachers locally and pass on to class after class of students. In 2018, 906 teachers from 55 countries came to CERN to participate in 31 national and two international programmes.

CERN also offers many opportunities to students directly, giving them all-important first-hand experience of where a career in science might take them. In 2018, the High-School Students Internship Programme welcomed 118 participants from the Czech Republic, Israel, the Netherlands, Poland and Sweden.

S'Cool LAB provided workshops for 7540 students aged 14 to 19 and made a range of material available to teachers for classroom use, including 3D-printable designs, new in 2018.

The Beamline for Schools competition continues to inspire students around the world to propose creative experiments to be carried out on a CERN beamline. In 2018, two winning teams were chosen from a total of 195 entries from 42 countries. The two teams, from India and the Philippines, measured the Bragg peak of pions in order to assess their potential for tumour therapy, and the effect of the Lorentz force on relativistic charged particles. The competition is one of the many outreach projects funded by the CERN and Society Foundation, which merged with the Globe Foundation in 2018.

Student winners of the Beamline for Schools competition prepare their experiments at CERN in September.
(OPEN-PHO-MISC-2018-011-514)

DIVERSITY IS ONE OF CERN'S STRENGTHS, AND IS INCREASINGLY REFLECTED IN OUR INITIATIVES.

Blind and visually impaired visitors work with CERN guides and the exhibitions team to develop tactile material. (CERN-PHOTO-201812-327-29)

SCIENCE NEEDS EVERYONE

With collaborations spanning more than 100 nationalities, diversity is certainly one of CERN's strengths, and it is one of the Organization's core values as science needs all bright minds. There is now an increased effort to reflect this diversity in CERN's public face and to ensure that our education, talent acquisition and communication actions speak to as wide a section of society as possible. Through its diversity-related activities, CERN also seeks to positively influence other research institutions.

The International Day for Women and Girls in Science on 11 February provided an excellent opportunity to introduce younger pupils to female role models. A total of 102 local classes, representing some 2400 children, signed up for talks about CERN by female scientists and engineers. Many of these were from primary schools, an important group to target in the drive to change aspirations.

In a similar vein, CERN's Women in Technology network contributed to the Girls in ICT event, which was attended by more than 500 students in Geneva, and to the Django Girls coding workshop in April, both designed to inspire more young girls to think about careers in information technology.

Across CERN's teacher programmes and student residencies, efforts are made to ensure that girls and boys have the same opportunities and come into contact with both male and female role models during their time at CERN. In addition, 50% of the S'Cool LAB workshops are facilitated by women.

An inclusive working environment, where all voices are heard, is conducive to creativity. In 2018, the EIROforum members formed a working group to join forces on diversity and inclusiveness in the work place, exchanging ideas and moving forward together to share best practices and build common actions. On 5 July, the first International Day for LGBTQ+ in STEM was another opportunity to underline the importance of diversity to all organisations in the group.

In addition to spear-heading such actions, the CERN Diversity Office launched new internships for young people with disabilities during 2018.

Reaching a diverse public means ensuring that our content is accessible to all. To this end, CERN's exhibitions team organised a workshop in December involving blind and visually impaired visitors, in order to co-develop content for its exhibitions.

MEDIA AND WEB COMMUNICATIONS

CERN and the LHC received extensive coverage in 2018, with 150 000 mentions by media outlets. This interest was stimulated in many cases by site visits, with 431 journalists coming to CERN over the course of the year. The ground-breaking ceremony for the High-Luminosity LHC generated 2000 media articles alone. CERN's press office also organised a photowalk for amateur photographers, opening up premises behind the scenes at CERN to inspire creative photos.

With 1.6 million mentions of CERN or the LHC on social media in 2018, CERN continues to have a strong and well-respected presence on social-media channels. CERN is currently active on Twitter, Facebook, Instagram, YouTube and Linkedin. The video "Voyage into the world of atoms" on Facebook was CERN's social-media post with the most engagement, with 1.3 million views. The Laboratory has continued to hold Facebook Live events, with its most successful one (from the LHC tunnel) reaching 1.7 million people.

Visitors to Researchers' Night discover stands and hands-on activities on the new Esplanade des Particules. (CERN-PHOTO-201809-250-8)

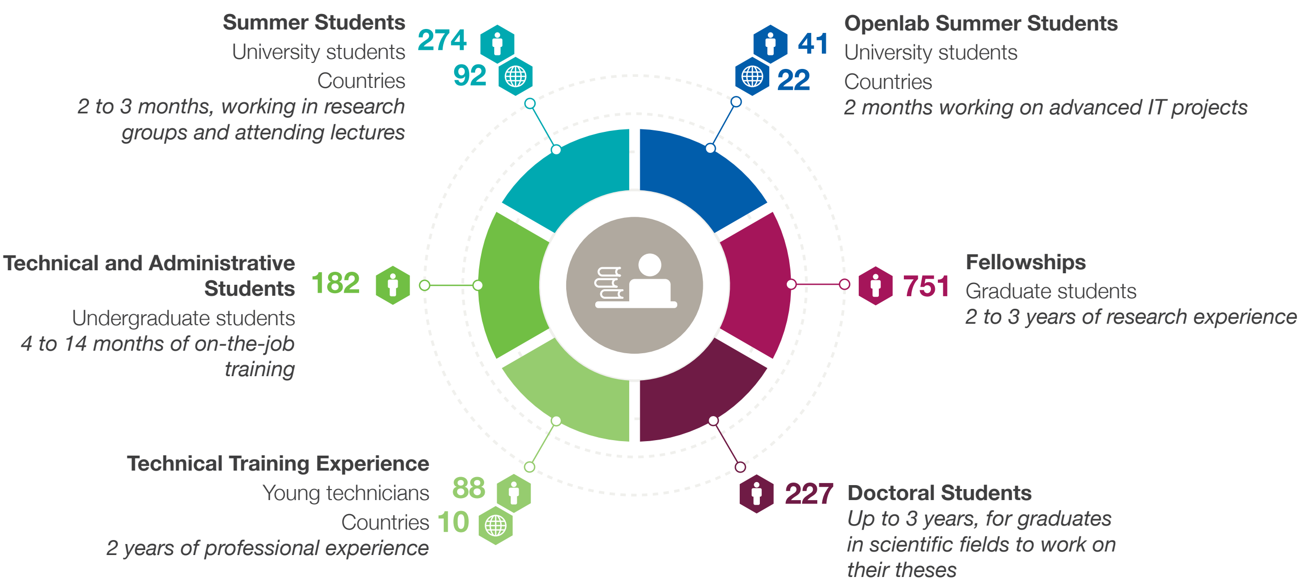
In keeping with its status as the birthplace of the web, CERN advanced its online presence with the strategy for its top-level domain ".cern", which received management approval in early 2018. This heralded a year of change for CERN's websites, a huge task that included a complete update of CERN's public website and a new content-management system for the websites across CERN. In 2018, home.cern had 9 million page views by 3.5 million users.

THE FIRST STEPS IN THEIR CAREER

The training of young researchers is also an essential part of CERN's educational activities. CERN offers an enriching environment for graduate and post-graduate students, providing business and industry in CERN's Member States with a steady stream of highly qualified people with excellent technical skills and international experience.

Training of young researchers in 2018 encompassed more than 830 fellows, including those following the technician training experience programme, as well as over 300 summer students from 100 countries, more than 400 doctoral, technical and administrative students, some 120 trainees and about 330 short-term interns.

TRAINING PROGRAMMES AT CERN



CERN offers a large range of training opportunities providing excellent technical skills and international experience.

A SUSTAINABLE RESEARCH ENVIRONMENT

Health, safety and environmental protection are of paramount importance to CERN. The Laboratory works to ensure the wellbeing of everyone using or visiting its facilities, while minimising its impact on the environment.

Bee-keepers maintaining their hives in a meadow at CERN. (CERN-PHOTO-201806-165-11)

PROTECTING HEALTH, SAFETY AND THE ENVIRONMENT

In 2018, the first recommendations of CERN's Environmental Protection Steering Board were put into practice, while the Energy Management Panel notched up a notable success in preparations for recycling CERN's waste heat. The Laboratory's mobility working group also saw its first recommendations implemented, and carried out a major survey of the daily commuting patterns of CERN personnel. Other notable highlights from 2018 include streamlining of the support provided to major projects and experiments in safety matters, and a new elimination pathway for low-level radioactive waste.

RETENTION BASINS TO PROTECT WATERCOURSES

In 2018, a significant amount of work was carried out to prevent water pollution from the CERN sites. On the main Meyrin site, several kilometres of rainwater and wastewater networks were inspected and repaired where necessary, and a comprehensive study was carried out to identify potential improvements to the sewer system. Meanwhile, a contract was awarded for the construction of a combined oil separator and water retention basin at Point 7 of the LHC ring in order to contain potential pollutants in the event of particularly heavy rain, a key recommendation of CERN's Environmental Protection Steering Board. Contracts for further retention basins at other CERN sites will be awarded in 2019.

WARMING HOMES WITH RECOVERED HEAT

Tower cranes are a common sight in the burgeoning Pays de Gex region of France, as new commercial and residential areas are constructed. One of these areas, in the town of Ferney-Voltaire, will soon be heated partly using heat recovered from the Large Hadron Collider. An agreement drawn up between CERN and the local authorities, due to be signed in 2019, provides for the construction of a heat converter at Point 8 of the LHC ring and a distribution system to carry the heat to a new residential area. The project will be financed jointly by the local authorities and CERN, with CERN recovering its investment over 15 years by selling the heat to the local authorities at an attractive price. Studies are under way for a similar project designed to heat offices on CERN's Meyrin site.

MANAGING WASTE

The operation of CERN's accelerators generates low-level radioactivity in accelerator components, which have to be stored at the end of their operational lifetime until they can be safely disposed of in the repositories of CERN's Host States. Until now, the waste-treatment process involved each item of waste being treated in CERN's radioactive-waste-treatment centre before being approved for release to a Host State repository. Much of this waste is in the form of magnets.

In 2018, a process that had begun three years earlier reached a successful conclusion, allowing waste magnets to be treated, characterised, packaged *in situ* and sent to the final repository without any intermediate further treatment or storage at CERN. This new procedure is the fruit of discussions with the French national agency for radioactive waste management, ANDRA, and a close and successful collaboration between CERN's Technology and Engineering departments and the Laboratory's Health, Safety and Environmental Protection unit (HSE). Following the conclusion of an agreement between CERN and ANDRA, the first magnets were prepared and shipped to an ANDRA storage facility in June 2018 for final disposal.

CERN also made some important advances in conventional waste management in 2018. The Laboratory already recycles over 50% of its waste, making it a leader in the Geneva region. Nevertheless, there is still room for improvement. In one significant development, the quantity of single-use plastic drinking cups was drastically reduced in the restaurants on CERN's Meyrin site. This measure promises to reduce CERN's plastic waste by 1.5 tonnes per year. All remaining single-use plastic cups will be replaced with recyclable cardboard cups in 2019.

IMPROVED SUPPORT IN SAFETY MATTERS

CERN has recently streamlined the way in which it provides the major projects and experiments with support in all matters of safety, with the exception of radioprotection, which has its own dedicated service. The Project and Experiment Safety Support (PESS) procedure was customised to provide project leaders and safety officers with a dedicated support structure to help them fulfil their roles and responsibilities in terms of safety. The procedure ensures that safety aspects are taken into account right at the beginning of projects and that HSE follows each project closely, while providing a tailored approach to each initiative. Each project leader has a single point of contact for all safety matters, and benefits from dedicated support throughout the lifecycle of the project. In 2018, PESS followed more than 130 projects.

The new insulation installed on the huge East Area building will reduce thermal losses by 90%. *(CERN-PHOTO-201805-130-3)*

GREENER MOBILITY AND BUILDINGS AT CERN

CERN's Mobility Working Group ran a two-part survey in 2018 designed to gather information about the commuting patterns and work-related travel habits of CERN personnel to help make CERN mobility greener. The survey was part of an initiative to develop a mobility plan that outlines measures, to be implemented by 2030, to facilitate movement in and around CERN and to encourage sustainable modes of transport. The survey provided the data that the working group needed to put forward a set of suggested measures. With many CERN personnel living in rural areas, the majority of commutes are by individual motorised vehicles, although car sharing and cycling account for around 8% and 13% respectively.

The survey has already allowed concrete actions to be taken. More pavements and dedicated cycle paths are being built on the CERN site. The frequency of shuttles on and between the sites has been increased, as has the size of CERN's fleet of bicycles. And for those who have no alternative but to drive, the flow of traffic through the entrances to the CERN sites at peak times has been improved. As a result of discussions involving CERN, the local authorities and Geneva's public-transport provider, improved public-transport solutions are being deployed on the French side of the border close to CERN.

A key message emerging from the 2018 surveys is that the CERN population has a green outlook on travel. Where green options exist, people use them, and the survey's results are allowing more green options to be deployed.

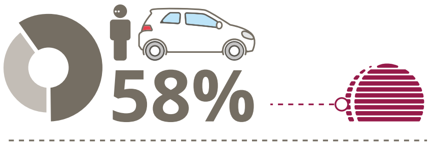
Infrastructure and building renovation projects continued in 2018. One of the largest concerns the East Area, a huge 100 000 m^3 building housing four PS beamlines and several experiment installations. The first phase of work began with the restoration of the building to reduce energy losses. New insulation will reduce thermal losses by 90%. The second phase, which will begin in 2019, consists of renovating the beamlines, in particular by replacing the magnets and their power supplies with a much more energy-efficient system.

R&D FOR BETTER SAFETY

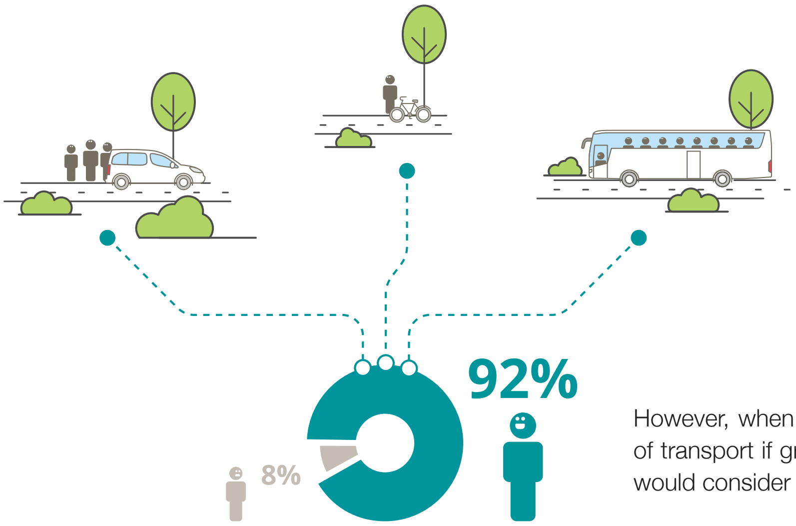
CERN's research is not confined to unravelling some of the deepest mysteries of the universe, but also covers more down-to-earth domains. The CERN radiation-monitoring electronics project, CROME, is a case in point. CROME develops high-performance, high-reliability cost-effective and low-maintenance radiation monitors for CERN, with the potential for applications beyond the field of scientific research. CROME-equipped monitors installed in and around the CERN sites will provide continuous real-time measurements, including of very low-level dose rates, and permanent, reliable data logging.

In 2018, CROME R&D for the next generation of electronics continued apace, with a prototype being produced and tested. Series production of CROME equipment, such as alarm units, uninterruptible power supplies and a first batch of monitors, began in 2018 and will ramp up in 2019 in accordance with the schedule for the installation of new monitoring equipment during the second long shutdown of CERN's accelerator complex.

THE CERN POPULATION HAS A GREEN OUTLOOK ON TRAVEL. WHERE ALTERNATIVES EXIST, PEOPLE USE THEM.



Of the 4300 people who responded to CERN's mobility survey, 58% come to work by car with a single occupant.



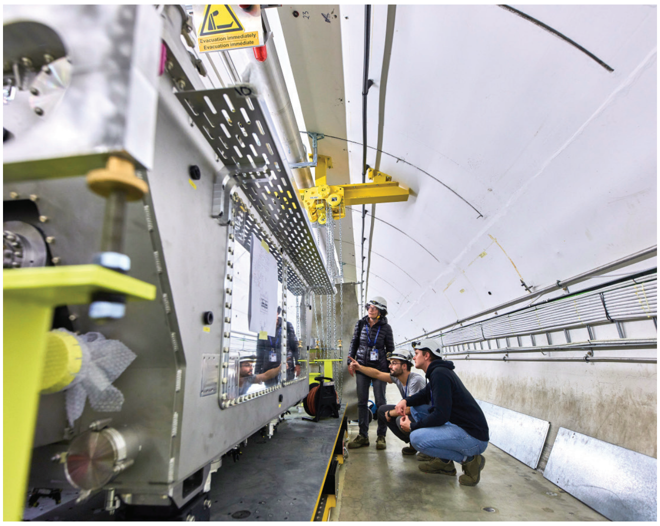
However, when asked whether they would change their mode of transport if greener alternatives were on offer, 92% said they would consider doing so.

CERN's safety-training operations received an important boost in 2018 with the inauguration of a new building at the Laboratory's safety-training centre in November. The new building allows all of the safety-training team to be located in the same place and to offer a better service to the CERN community. This will be particularly important as the second long shutdown progresses, as teams of users and contractors will be coming to the Laboratory to carry out work in a wide range of disciplines, all with their own specific safety requirements. The centre now boasts six classrooms, as well as hands-on facilities such as a fire simulator and a mock-up of the LHC tunnel. In 2018, some 6100 people received safety classroom training, and, in a typical week, around 16 separate course sessions were run. (CERN-PHOTO-201904-081-2)

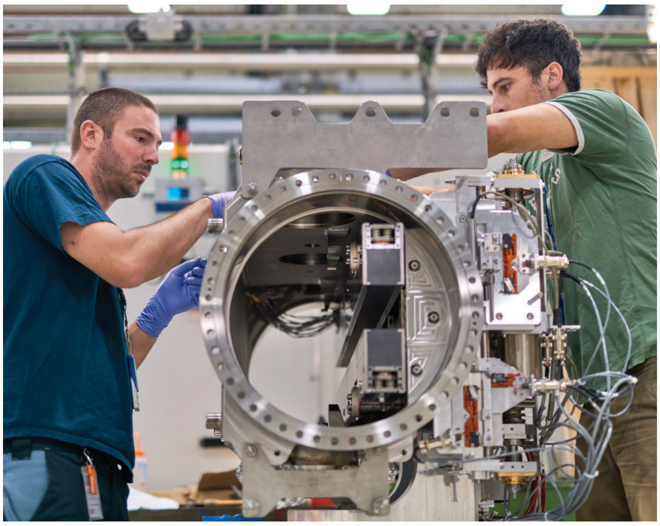
BUILDING TOMORROW AND BEYOND

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.

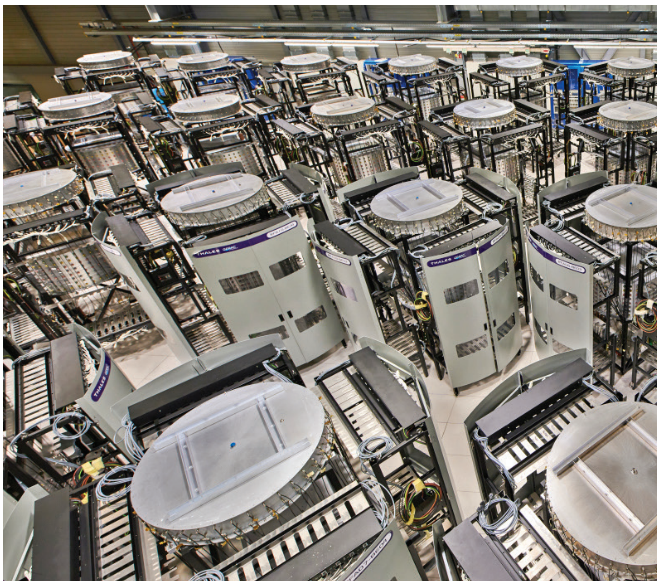
The first step in validating the long superconducting links was also taken in 2018. Composed of a cable of magnesium-diboride inserted into a flexible cryostat, these links will carry the current to the inner-triplet quadrupoles. A 60-metre-long link successfully carried 20 000 amperes during a test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

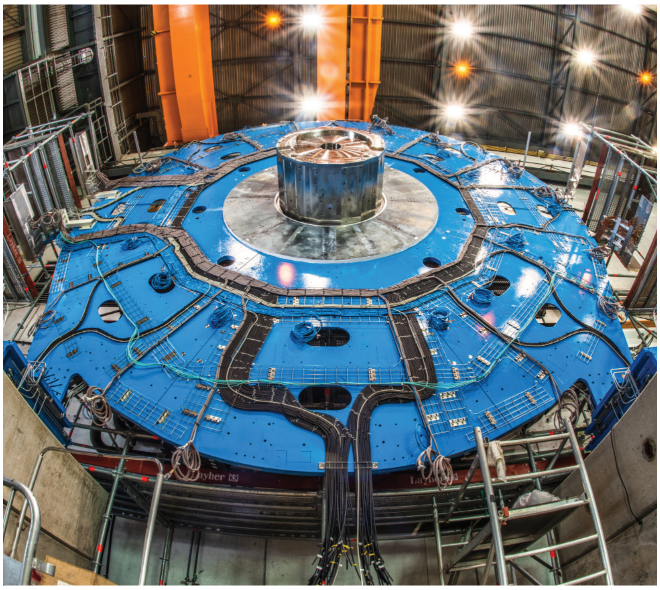
The PS Booster will be completely transformed. New systems for power supply, injection, acceleration (with radiofrequency cavities), guidance (with magnets) and extraction to the PS have been in preparation since 2011. In 2018, new equipment – notably septum and kicker magnets, as well as several dipoles, 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.

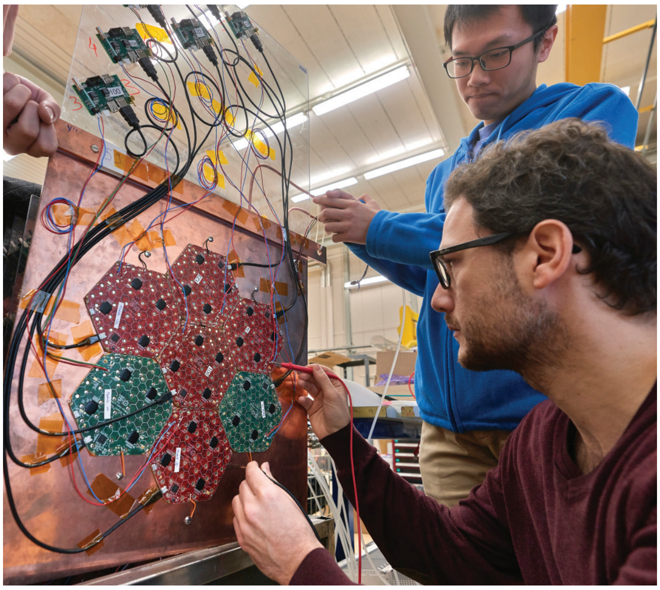
The new power-amplifier system for the SPS's accelerating cavities was validated. Based on radiofrequency transistors, it will increase the RF power supplied to the cavities and enhance the current system. A tower containing 320 transistors operated successfully for 1000 hours, giving the green light 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.

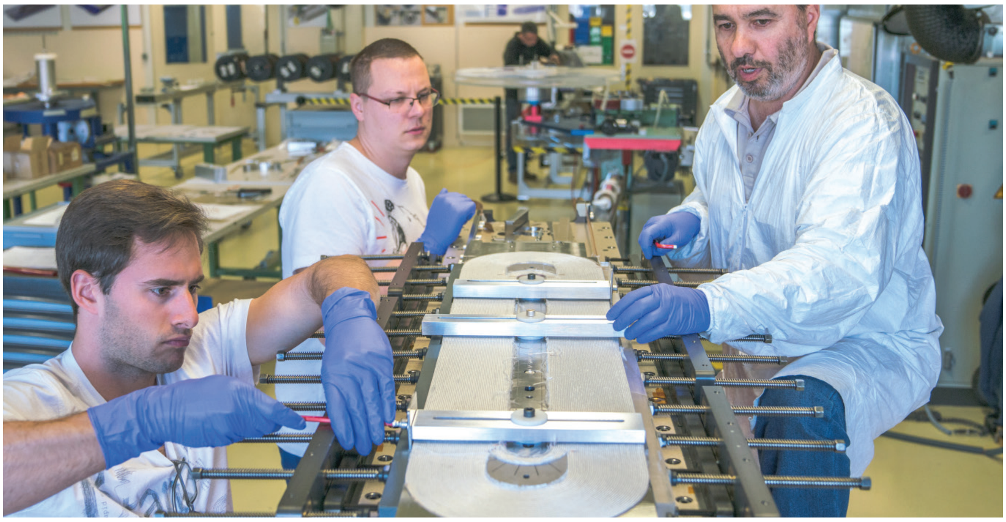
To achieve such low energies, ELENA's deceleration apparatus is paired with an electron cooling system. This system, which was tested and commissioned in the autumn, makes it possible to concentrate the particle bunches by reducing the emittance of the beam or, in other words, its transverse dimensions 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.

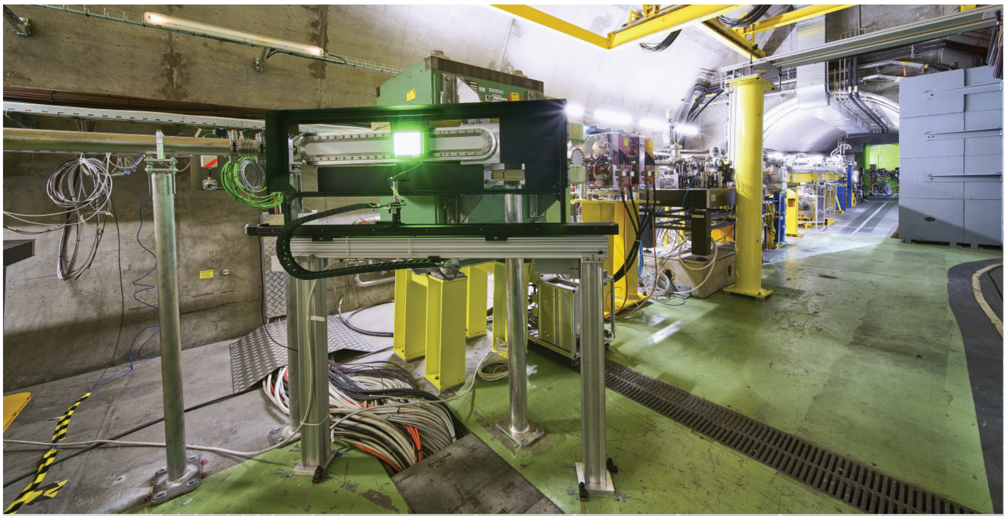
On the accelerator front, the potential of the North Area to provide the beam for dark-matter and precision searches, and to continue pushing its quantum-chromodynamics-based experiments, was investigated in depth. Significant advances were made with respect to the proposed Beam Dump Facility (BDF): 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.

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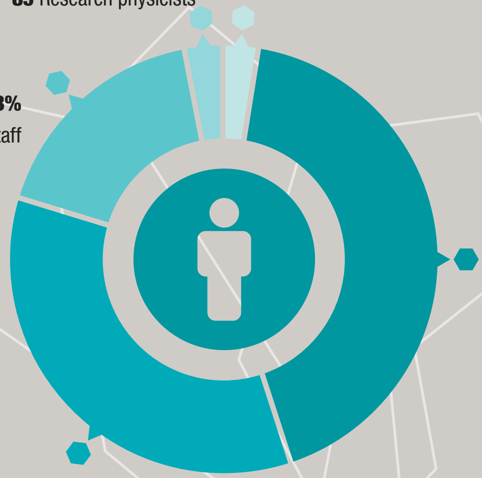


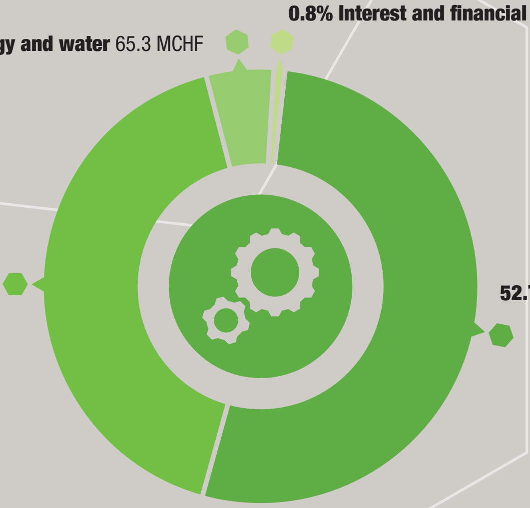
EVOLUTION OF STAFF NUMBERS

2014	2524
2015	2531
2016	2560
2017	2633
2018	2667

In addition to staff members, CERN employed 839 fellows (including TTE technicians), trained 547 students and apprentices, and hosted 1320 associates in 2018. CERN's infrastructure and services are used by a large scientific community of 12 569 scientists (see p. 12).

CERN EXPENSES

Total expenses 1313.4 MCHF



In 2018, more than 40% of the CERN budget was returned to industry through the procurement of supplies and services. CERN strives to ensure a balanced industrial return for its Member States (see p. 33).

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Sixty-fourth Annual Report of the European Organization for Nuclear Research

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In addition to this report, an annual progress report details the achievements and expenses by activity with respect to the objectives agreed by the CERN Council. This report is available at: http://cern.ch/go/annual-progress-report-2018

The 2018 Knowledge Transfer annual report is available at:
http://kt.cern/about-us/annual-report
The 2018 CERN openlab annual report is available at:
http://openlab.cern/resources/annual-reports
The 2018 CERN & Society annual report is available at: http://cern.ch/go/cernandsociety2018

CERN's list of publications, a catalogue of all known publications on research carried out at CERN during the year, is available at: http://library.cern/annual/list-cern-publications-2018
A glossary of useful terms is available at: http://cern.ch/go/glossary

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