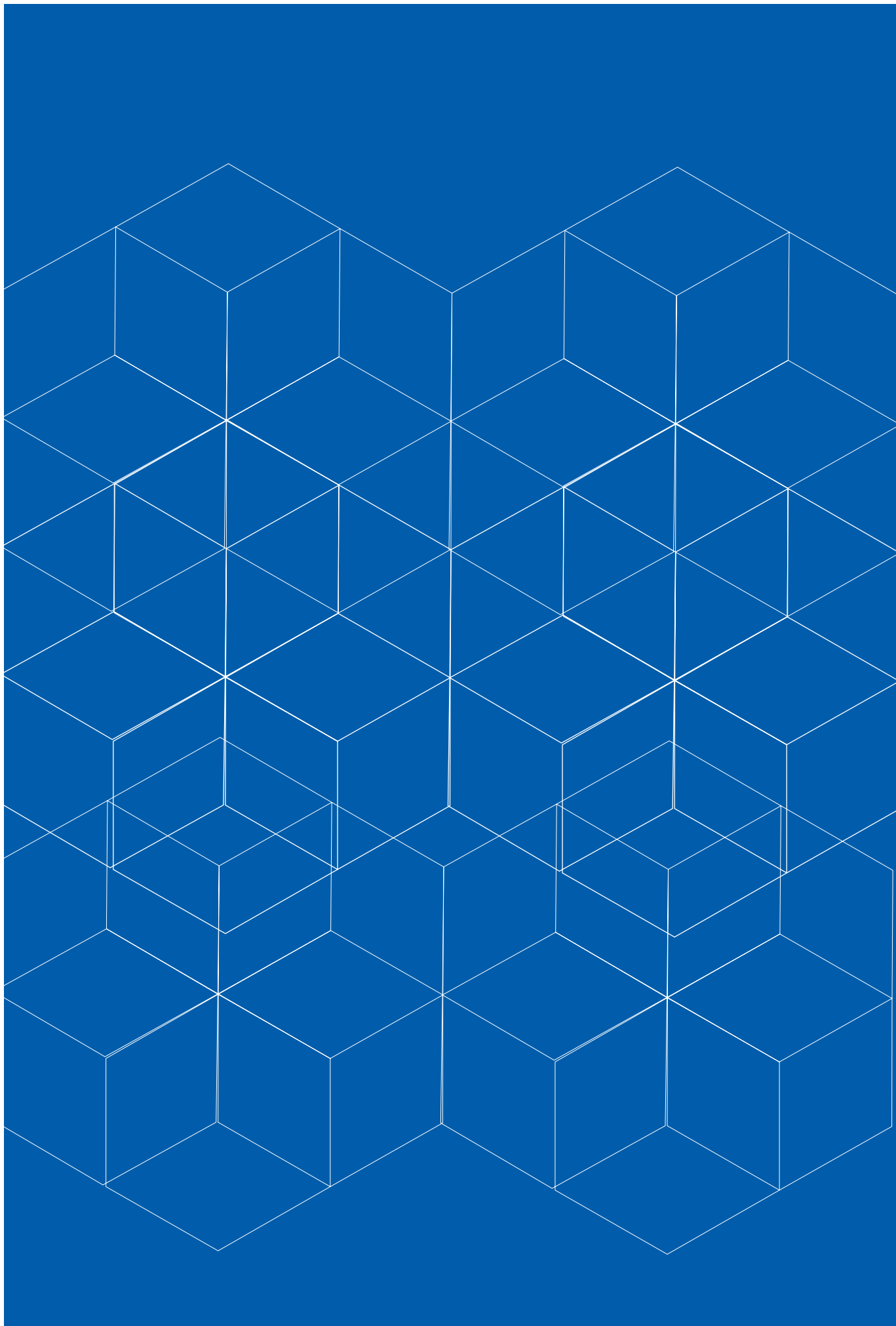


# Annual Report **2017**







# CONTENTS

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*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 now has 22 Member States as well as 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.*



**P4  
MESSAGES**

---

**P6  
2017 IN PICTURES**

---

**P12  
EXPLORING THE NATURE  
OF THE UNIVERSE**

---

**P20  
DISCOVERY MACHINES**

---

**P30  
A WORLDWIDE LAB**

---

**P32  
PUSHING THE FRONTIERS  
OF TECHNOLOGY**

---

**P36  
INSPIRING AND EDUCATING  
NEW GENERATIONS**

---

**P40  
A SUSTAINABLE RESEARCH  
ENVIRONMENT**

---

**P44  
BUILDING TOMORROW AND BEYOND**

---

**P50  
GOVERNANCE**

---

**P53  
CERN IN FIGURES**

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## MESSAGE FROM THE PRESIDENT OF THE COUNCIL

CERN's accelerators and physics experiments saw record performances again in 2017. But it was not all plain sailing. A number of major technical challenges were overcome thanks to very flexible and highly skilled problem investigations and solving by teams from CERN working alongside many visiting scientists and engineers from universities and institutes from all over the world. The Council congratulates the CERN Management on the outstanding achievements of the Laboratory, which were delivered well within the designated budget.

2017 was the last year for which CERN's Annual Progress Report and Financial Statements were audited by NIK, the Supreme Audit Office of Poland. NIK exercised its duties as External Auditors of the Organization for the statutory maximum of three years plus two. On the Council's behalf, I wish to acknowledge and express appreciation for the thoroughness, clarity and assiduity with which NIK have audited the accounts of CERN and the Pension Fund over the past five years. The Council has appointed the National Audit Office of Finland as the next External Auditors from 1 January 2018.

The Council's subsidiary bodies are essential to its proper functioning. The Scientific Policy Committee and the Finance Committee are the best known, but others also play an indispensable role. These include the Tripartite Employment Conditions Forum, TREF, and the Audit Committee, established in 2017 by the Council to succeed the Standing Advisory Committee on Audits. The Audit Committee is a cornerstone of the Council's oversight of the Organization. In particular, the Council took note with satisfaction of the Audit Committee's opinion that the CERN Management had made major progress in charting the risks to the Organization and in elaborating mechanisms to mitigate those risks.

With many of the goals outlined in the 2013 European Strategy for Particle Physics, along with other projects around the world, well on the way to being achieved, the open questions of particle physics have become better defined and new ones are emerging. This, along with the information that will be gathered until the end of 2018, makes

the time right to launch the next update of the European Strategy in September 2018. To that end, 2017 saw major preparatory steps as the Council appointed Professor Halina Abramowicz as Strategy Secretary and established the Strategy Secretariat. Chaired by the Strategy Secretary, the Secretariat's members are the Chairs of the Scientific Policy Committee, the European Committee for Future Accelerators and the European Laboratory Directors Meeting. The Secretariat immediately set to work energetically and, in December, submitted a draft plan for the update process for the Council's feedback.

CERN remains attractive for countries wishing to join the front-line research of the Organization in the spirit of international collaboration. In 2017, the Republic of Slovenia became an Associate Member State in the pre-stage to Membership. The Republic of India became an Associate Member State and the Republic of Lithuania signed an agreement to be granted the same status. 2017 was also the year in which the Laboratory for Synchrotron-light for Experimental Science and Applications in the Middle East, SESAME, formally opened in Allan, Jordan. CERN extends its warm congratulations to SESAME, which presents another great opportunity for science for peace in the grand CERN tradition. The Council was delighted to hear that CERN's application to become an Observer was approved by the SESAME Council.

Last but by no means least, 2017 was the year in which Ms Brigitte Van der Stichelen, the Head of the Council Secretariat since 2001, took her well-earned retirement. The Council wishes her all the best in this new phase of her life and is pleased to see that all the tasks of the Secretariat have been smoothly transferred to an equally competent successor.

Sijbrand de Jong

A handwritten signature in black ink, consisting of a stylized 'S' followed by a long, sweeping horizontal line that tapers to the right.



## MESSAGE FROM THE DIRECTOR-GENERAL

The year 2017 was a remarkable one for CERN, with great accomplishments across the full spectrum of the Laboratory's activities. The accelerator complex broke new records in terms of beam availability, and the LHC achieved a peak luminosity of  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , a factor of two higher than its design value. As a result, the LHC is on track to exceed the ambitious target of delivering a total of  $150 \text{ fb}^{-1}$  of data to ATLAS and CMS by the time Run 2 comes to a close at the end of 2018.

The wealth of high-quality data recorded by the experiments so far in Run 2 allowed detailed exploration of the several-TeV mass region and a large number of precise measurements. Higgs boson physics entered the precision era, and in 2017 the couplings of this very special particle to the heaviest fermions – the top quark, bottom quark and tau lepton – were established.

The upgrade projects for the injectors (LIU), the high-luminosity phase of the LHC (HL-LHC) and the experiments made substantial progress towards installation during the next two long shutdowns.

At the CERN Neutrino Platform, construction of liquid-argon detector prototypes for the DUNE long-baseline neutrino experiment in the US started in earnest. ISOLDE celebrated 50 years of physics with radioactive beams, and CERN's innovative medical isotope production facility, MEDICIS, produced its first isotopes. The ELENA ring, an upgrade to our unique Antiproton Decelerator facility, was installed and commissioned. Design studies for future colliders and projects, the Compact Linear Collider (CLIC) study, the Future Circular Collider (FCC) study and Physics Beyond Colliders (PBC), made good progress in preparing their input for the update of the European Strategy for Particle Physics.

In 2017, about 2000 young people, including fellows, doctoral students and summer students, were trained at CERN. An Alumni programme was launched, and a Data Privacy Protection Office was established to align CERN with regulations and best practices regarding the use of private data. The American Physical Society joined the Sponsoring Consortium for Open Access Publishing in Particle Physics

(SCOAP<sup>3</sup>), hosted by CERN, which now covers more than 90% of all publications in high-energy physics.

The CERN Environmental Protection Steering board (CEPS) released its first recommendations to minimise the impact of CERN on the environment, including measures to protect local watercourses and reduce greenhouse gas emissions.

In 2017, CERN attracted a record 136 000 visitors to its site, while some 400 000 people visited our travelling exhibitions.

These and the other great achievements covered in the pages of this report would not have been possible without the competence and dedication of CERN's employed and associated members of personnel and the very strong, continued support of the Council. My gratitude, and that of the entire Directorate, goes to them all.

Fabiola Gianotti

A handwritten signature in black ink that reads "Fabiola Gianotti". The signature is written in a cursive, flowing style.

# 2017 IN PICTURES

*New records for the accelerators, torrents of data for the computing systems, a cornucopia of results for the experiments, new countries joining the CERN family, and much more... discover 2017 in pictures.*



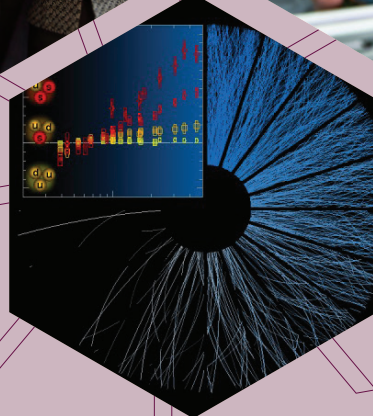
## 16 JANUARY

India becomes a CERN Associate Member State. Amandeep Singh Gill, Ambassador and Permanent Representative of India to the Conference on Disarmament, is seen here with Fabiola Gianotti, CERN Director-General. In their hands are the official notifications from the Indian government and from CERN. (CERN-PHOTO-201701-009-16)



## 18 JANUARY

The BASE antimatter experiment announces the most precise measurement ever made of the magnetic moment of the antiproton. Nine months later, the collaboration improves the precision of the previous measurement by a factor of 350 (see p. 18). (CERN-PHOTO-201710-255-8)



## 24 APRIL

New results from the ALICE collaboration reveal previously unseen phenomena in proton collisions: particles usually produced during collisions of heavy nuclei are observed (see p. 16). (OPEN-PHO-EXP-2017-003-2)

## 27 AVRIL

CERN and the American Physical Society sign an agreement on open-access publishing in the framework of the SCOAP<sup>3</sup> (Sponsoring Consortium for Open Access Publishing in Particle Physics) initiative (see p. 34).



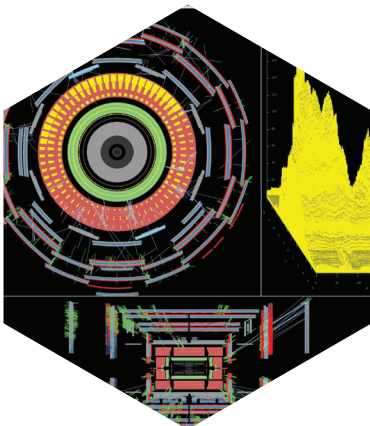
## 9 MAY

Frédéric Bordry, CERN Director for Accelerators and Technology, Fabiola Gianotti, CERN Director-General, and Maurizio Vretenar, leader of the Linac4 project, officially open the Laboratory's brand-new linear accelerator. Linac4 will supply the CERN accelerator complex from 2021 (see p. 46). (CERN-PHOTO-201705-120-19)



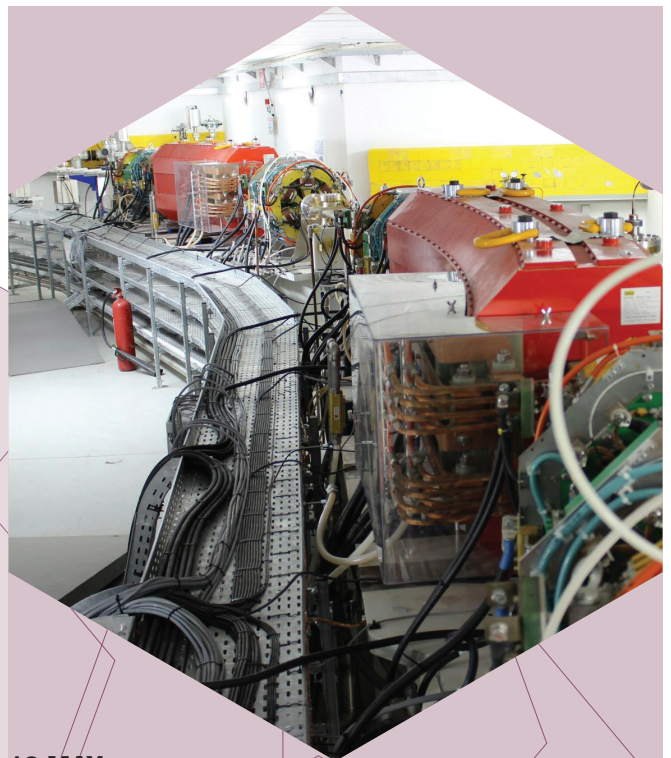
## 21 MAY

The arrival of twenty Hungarian students at CERN marks the start of the annual series of internships for high-school students from the Member States. On the agenda: two weeks of scientific discovery and discussions (see p. 38). (CERN-PHOTO-201705-131-29)



## 23 MAY

Ready for physics at the LHC! The experiments start their data-taking for 2017.



## 16 MAY

The SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East) accelerator is officially inaugurated at Allan in Jordan by King Abdullah II of Jordan, surrounded by representatives of the SESAME Member States and the directors of the international organisations that have supported the laboratory.

SESAME is a synchrotron-light source enabling research in several fields, from solid-state physics to environmental science and archaeology.

Based on CERN's governance model, SESAME is an unprecedented collaboration in the Middle East, bringing together Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey. CERN has also made a huge technical contribution through the development of magnets in the framework of the CESSAMag project, co-financed by the European Commission.

On 12 January, a beam circulated in the synchrotron for the first time. The first synchrotron light marked the start of the experimental programme and of collaboration between scientists in the Middle East.

## 12 JUNE

The ICARUS neutrino detector leaves CERN for its new home, Fermilab in the United States. ICARUS then arrives safe and sound after a six-week odyssey. (CERN-PHOTO-201612-323-10)



## 16 JUNE

Ameenah Gurib-Fakim, President of the Republic of Mauritius, signs the CERN visitors' book while Bidhya Devi Bhandari, President of the Federal Democratic Republic of Nepal, is shown around the ATLAS experiment control room by Dave Charlton, former spokesperson of the experiment. (CERN-PHOTO-201706-146-9 and CERN-PHOTO-201706-145-9)

## 27 JUNE

In the presence of Dalia Grybauskaitė, President of the Republic of Lithuania, Fabiola Gianotti, CERN Director-General, and Linas Linkevičius, Minister of Foreign Affairs of the Republic of Lithuania, sign an agreement with a view to the admission of Lithuania as an Associate Member State of CERN.

## 29 JUNE

The CERN Computer Centre sets a new record, with 200 million gigabytes (petabytes) of data, the equivalent of 1400 years of high-definition video, permanently archived in its magnetic-tape libraries (see p. 26). (CERN-PHOTO-201705-115-7)



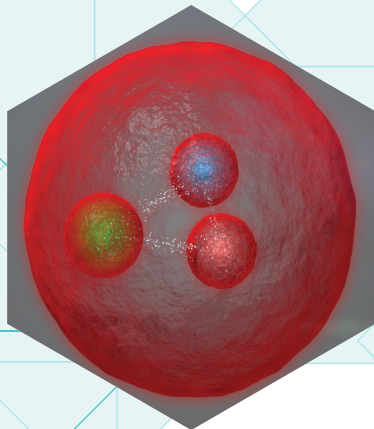
## 4 JULY

The Republic of Slovenia officially becomes an Associate Member State in the pre-stage to Membership of CERN. Vojislav Šuc, Ambassador of the Republic of Slovenia to the United Nations Office and other international organisations in Geneva, hands the official notification to Fabiola Gianotti, CERN Director-General. (CERN-PHOTO-201707-165-1)



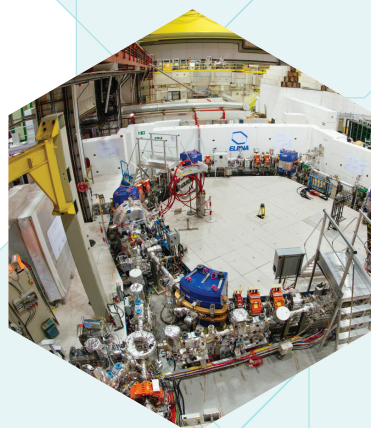
## 7 JULY

Frédéric Bordry, CERN Director for Accelerators and Technology, welcomes Duško Marković, the Prime Minister of Montenegro, to the superconducting magnet hall. (CERN-PHOTO-201707-175-45)



## 6 JULY

The LHCb collaboration observes a charming new particle belonging (along with protons) to the baryon family and containing two charm quarks and one up quark (see p. 15). (OPEN-PHO-EXP-2017-004-7)



## 2 AUGUST

Ready, steady, decelerate! ELENA, CERN's new deceleration ring for antimatter experiments, receives its first beam of antiprotons (see p. 47). (CERN-PHOTO-201611-300-1)

## 19 JULY

Physics goes musical, as the Canadian rock group Arcade Fire discovers the CERN Control Centre and the US group Pixies poses in front of a mock-up of the CMS detector.

### 3 AUGUST

The ALPHA experiment publishes the first observation of the hyperfine structure of antihydrogen, opening the way for a better understanding of the differences between matter and antimatter (see p. 18). (CERN-PHOTO-201601-005-11)



### 12 SEPTEMBER

Charlotte Warakaulle, CERN Director for International Relations, and Rolf Heuer, President of the SESAME Council, in front of the 58 computer servers ready to be sent to Jordan for use by the brand-new SESAME synchrotron laboratory. In 2017, CERN also donated computer equipment to Algerian and Bulgarian institutes. (CERN-PHOTO-201709-215-1)



### 17-21 SEPTEMBER

Over a thousand scientists and engineers meet in Geneva for a major conference on superconductors and their applications, EUCAS 2017. To mark the occasion, a superconducting magnet takes pride of place outside the United Nations Office in Geneva. (CERN-PHOTO-201709-213-1)



### 20 SEPTEMBER

Māris Kučinskis, Prime Minister of the Republic of Latvia, takes the opportunity during his visit to CERN to discover the experiments of S'Cool Lab, the laboratory for schools. (CERN-PHOTO-201709-228-22)

### 20 SEPTEMBER

The two winning teams from the 2017 Beamline for Schools competition, from Italy and Canada, arrive at CERN to carry out their experiments using a CERN accelerator. (CERN-PHOTO-201710-242-29)

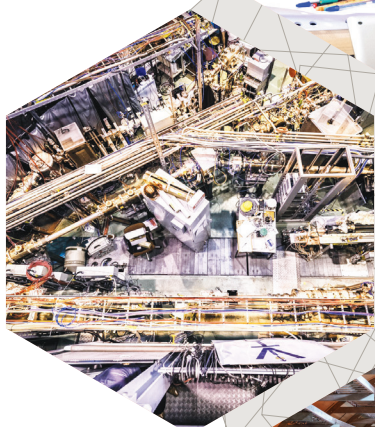


## 29 SEPTEMBER

CERN opens its doors to over 1400 people for the 2017 European Researchers' Night event. (CERN-PHOTO-201710-241-13)

## 16 OCTOBER

Happy birthday ISOLDE! The oldest experimental facility at CERN still in service celebrates 50 years of physics. (CERN-PHOTO-201511-224-5)



## 15 DECEMBER

CERN celebrates the 25<sup>th</sup> anniversary of the LHC experimental programme, which began with the Evian meeting, a vital step in the design and development of the LHC experiments. (CERN-PHOTO-201712-303-5)

## 30 OCTOBER

The LHC's data-taking goal for 2017 is reached. Three days later, the accelerator sets a new record for instantaneous luminosity, i.e. the number of collisions per second (see p. 21). (CERN-PHOTO-201802-030-6)



## 12 DECEMBER

The new CERN-MEDICIS facility produces its first radioisotopes destined for medical research (see p. 33). (CERN-PHOTO-201705-117-19)

## 10-19 NOVEMBER

A flock of passionate volunteers, plenty of activities, thousands of visitors of all ages... CERN serves up a feast of science as the guest of honour at the *Automnales*, Geneva's annual fair (see p. 37). (CERN-PHOTO-201711-279-13)

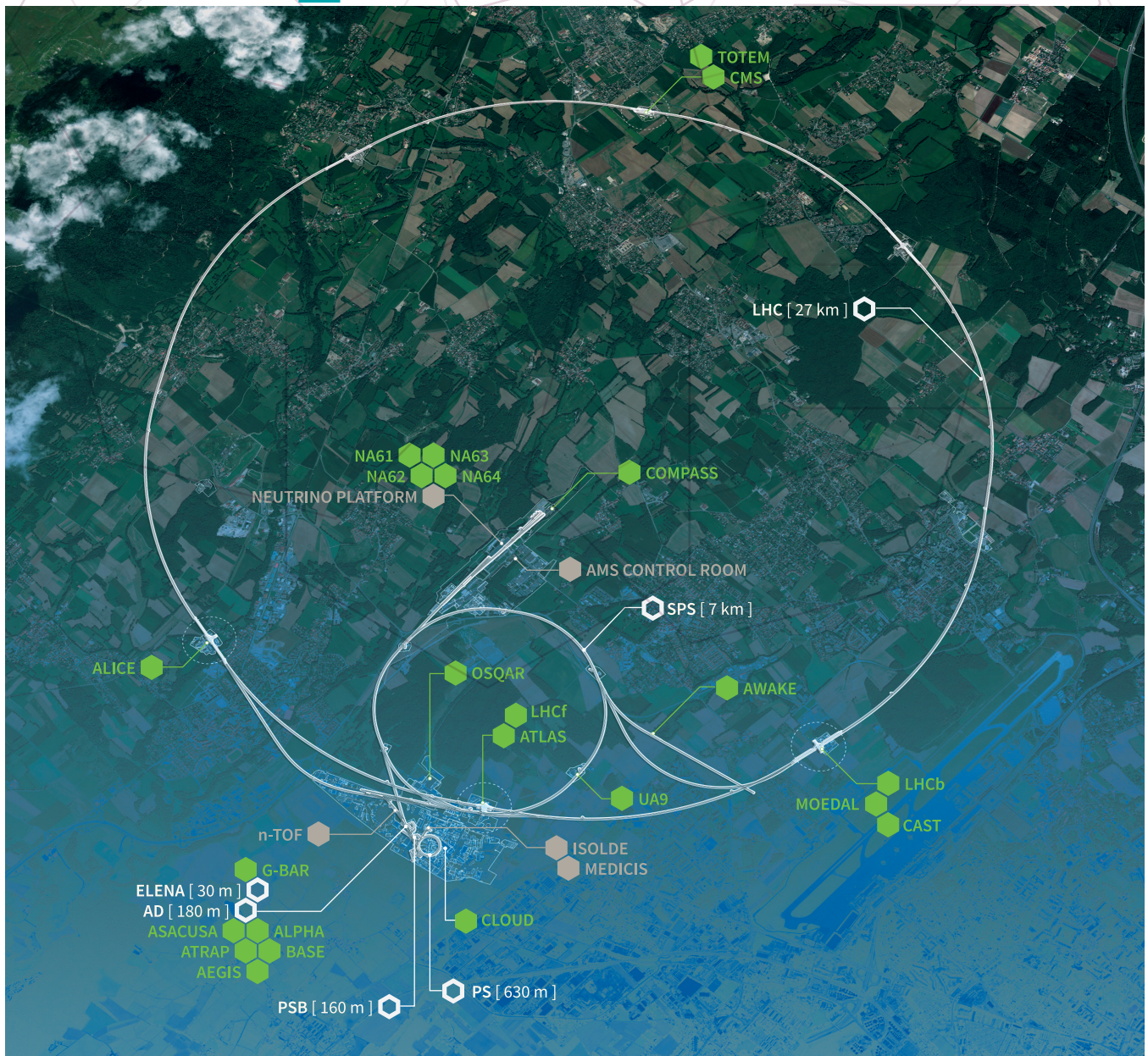




# EXPLORING THE NATURE OF THE UNIVERSE

*CERN's mission is to explore the fundamental structure of our universe by operating a unique network of accelerators that collide beams of particles or direct them to fixed-target experiments. Giant detectors record the results of these collisions, feeding the data to thousands of physicists at CERN and beyond for analysis.*

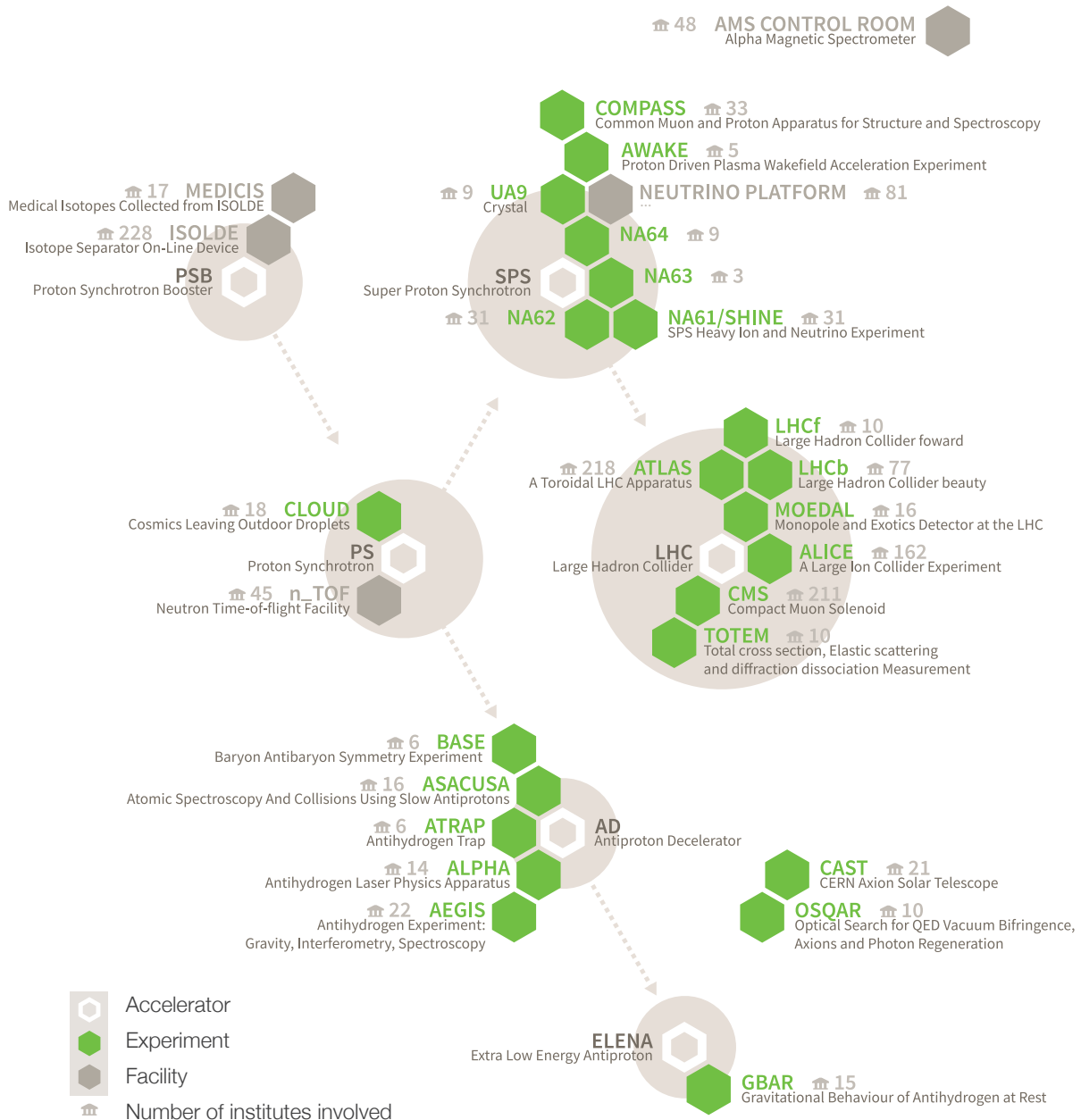
## CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS



The Large Hadron Collider (LHC) is CERN's flagship accelerator. It collides beams of protons inside four large experiments – ALICE, ATLAS, CMS and LHCb. 2017 saw the machine's second major run at a centre-of-mass energy of 13 TeV. The machine's impressive performance required ATLAS and CMS to develop new tools to cope with the record collision rates. A total of 70 petabytes of data was recorded by the LHC experiments, over 330 scientific papers were published, and some 2700 PhD students took part in analyses.

2017 was also the 25<sup>th</sup> anniversary of the LHC experimental programme, ATLAS and CMS having submitted their letters of intent in 1992, followed by ALICE and LHCb.

New knowledge gained from the LHC experiments and other experiments across CERN's physics programme included a closer understanding of the Higgs boson, stringent tests of the Standard Model of particle physics, seminal measurements of antimatter and fresh perspectives on the existence of new particles and forces.



*CERN's interconnected accelerators serve multiple experiments and facilities that are used by physicists in several hundreds of institutes around the world.*





Physicists from the LHC experiments discussing results. Around 10 000 physicists are involved in the experiments. (OPEN-PHO-EXP-2017-002)

## HIGGS BOSON UNDER THE MICROSCOPE

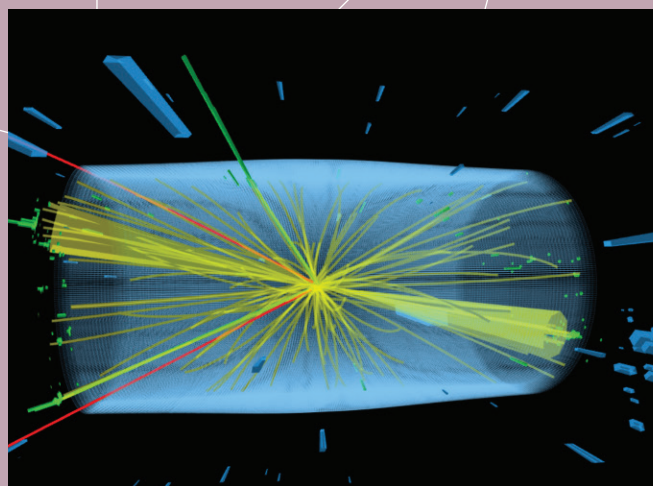
With 4 July 2017 marking the fifth anniversary of the discovery of the Higgs boson by ATLAS and CMS, the two experiments reported a wealth of new Higgs results during the year. The Standard Model of particle physics (SM) makes very specific predictions about how the Higgs boson interacts with other particles. Testing these predictions at increasing levels of precision is a major research focus at the LHC and at proposed future colliders, since any deviation in the Higgs' behaviour could open the door to new physics.

The Higgs boson was originally discovered via its decay to bosons  $\gamma\gamma$ ,  $ZZ$  and  $WW$ , and these decay processes have now been measured to better precision and in more detail with additional LHC data at 13 TeV. The complex decays and couplings of the Higgs to third-generation bottom, top and tau fermions were also well established by ATLAS and CMS in 2017.

The two experiments reported the first evidence for the decay of the Higgs to a pair of bottom quarks, and probed couplings between the Higgs boson and the top quark for the first time. CMS presented a five-sigma observation of the Higgs decay to a pair of taus, while ATLAS combined the cleanest Higgs boson channels to measure cross-sections with unprecedented precision.

OVER 330 SCIENTIFIC PAPERS WERE PUBLISHED IN 2017 AND SOME 2700 PHD STUDENTS TOOK PART IN ANALYSES.

A candidate Higgs boson event from proton-proton collisions recorded by CMS in 2016, showing the production of a pair of muons and two high energy jets. (CMS-PHO-EVENTS-2016-007-3)



## STANDARD MODEL TESTED TO NEW LIMITS

ATLAS and CMS published many beautiful results that subject the Standard Model to heightened levels of scrutiny. The large LHC datasets now available allow the collaborations to move into precision physics and gain sensitivity to extremely rare processes. Examples include ultra-precise measurements of the cross-sections for certain interactions, the masses of key particles such as the W and Higgs bosons, and electroweak WW production. ATLAS found the first direct evidence for light-by-light scattering in high-energy lead-lead collisions, an extremely rare process predicted by quantum electrodynamics (QED), and CMS made a precision measurement of the electroweak mixing angle  $\sin^2\theta$  from Run-1 data.

Precision measurements of the top quark, the least understood of the quarks so far owing to its large mass, remain a hotbed for searches for physics beyond the Standard Model. In addition to precision measurements of the top-quark mass, ATLAS measured the angular distributions of tops and their decay products and found the first evidence for a new type of rare single-top production. CMS also looked at rare top-quark processes such as the production of a single top quark and the production of four tops at once, and reported the first observation of top quarks in proton-lead collisions. In the summer, the two experiments joined forces to report measurements of asymmetries in top-quark production at the LHC, a promising avenue in the search for signs of new physics.

The LHCb experiment filled important gaps in the Standard Model during 2017, beginning with the discovery of the doubly-charmed (and doubly-charged) baryon,  $\Xi_{cc}^{++}$ . Predicted to exist by the Standard Model but never previously observed, this and similar states still to be observed could provide a rich source of information on the theory of the strong force, quantum chromodynamics (QCD). LHCb then announced that it had observed the rarest decay of the  $B^0$  meson ever, catching it decaying into a proton-antiproton pair, which occurs in around one out of every 100 million decays. The collaboration also reported the first observation by a single experiment of the rare process

whereby a B meson decays into a pair of muons, along with the first measurement of the effective lifetime of the decay, and used novel charmonium-spectroscopy techniques to make precision mass and width measurements of the  $X_{c1}$  and  $X_{c2}$  mesons. Finally, LHCb reported the first hints of CP violation in baryons, which, if seen with greater significance in future LHC data, would be a milestone in our understanding of charge-parity (CP) violation and the cosmic matter-antimatter imbalance.

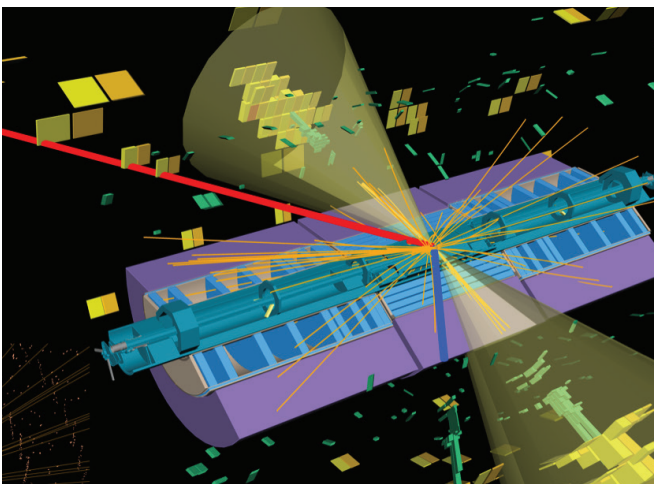
Heavy-ion collisions also allow physicists to study rarely produced particles, such as antihelium nuclei and hypernuclei (containing a  $\Lambda$  baryon, which has a strange quark), thereby improving knowledge of the strong force. The ALICE collaboration obtained the most precise measurement of the lifetime of “hypertritons” (bound states of a proton, neutron and  $\Lambda$  baryon) in lead-lead collisions, while an analysis of correlations between charged and neutral kaons allowed the collaboration to favour the tetraquark nature of the long-established  $a_0(980)$  meson. ALICE also measured the production of the antimatter partner of the alpha particle, the heaviest antinucleus observed so far.

As the year drew to a close, the TOTEM experiment – which studies very glancing proton collisions using detectors located 220 m either side of the CMS experiment – presented strong evidence for the existence of a three-gluon compound called an odderon. Predicted in the 1970s, the odderon had never previously been observed and the TOTEM results have implications for the cross-section of proton-proton collisions at the LHC and future high-energy colliders.

## SEARCHING FOR NEW PHYSICS

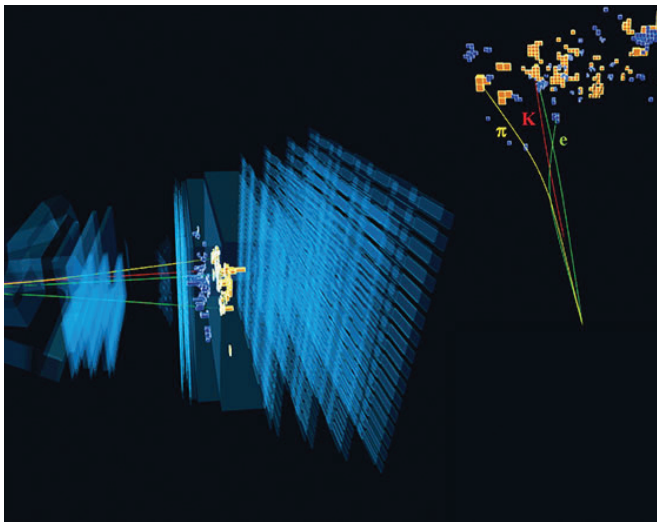
The Standard Model describes almost everything that has ever been measured in particle physics. Yet the distinct patterns that its particles fall into, and its silence on major issues such as gravity and dark matter, strongly suggest that new particles and forces exist beyond the scope of this almost 50-year-old theoretical framework.

ATLAS and CMS performed numerous searches for new physics during 2017. ATLAS pushed lower the limits on the masses of supersymmetric particles beyond 2 TeV and explored challenging regimes such as compressed-spectra supersymmetry, while CMS carried out several supersymmetry searches in the electroweak sector and explored experimentally challenging final states with low missing energy. ATLAS also reported its first search results for new heavy particles, including dark matter, from Run 2 data so far, a full diboson-resonance search including six channels based on Run-1 data, and a search for long-lived particles at 13 TeV. CMS extended its search for dark-matter particles via di-jet signatures and set tighter limits on new-physics processes including the seesaw mechanism, along



*Display of a candidate top-antitop event from proton-proton collisions recorded by ATLAS in 2016. (ATLAS-PHOTO-2018-016-1)*



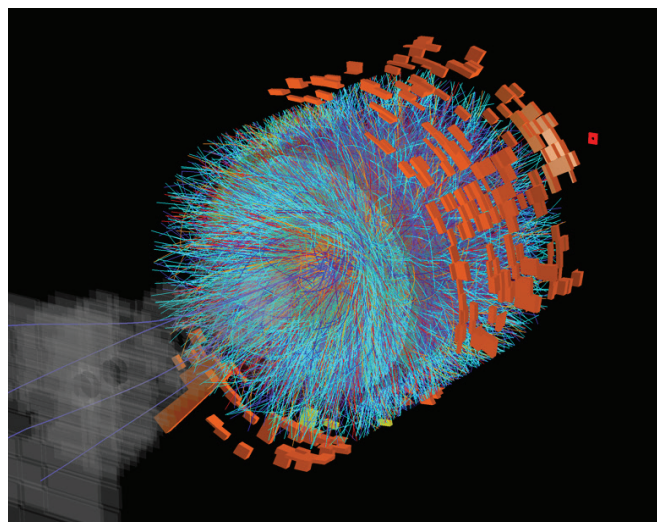


The decay of a  $B^0$  meson into a  $K^{*0}$  and an electron–positron pair in the LHCb detector, which is used for a sensitive test of lepton universality in the Standard Model. (OPEN-PHO-EXP-2018-004-1)

with setting better constraints on the possible existence of microscopic black holes, string balls and other exotic objects. All results of searches at the ATLAS and CMS experiments are so far consistent with the Standard Model explanations, allowing physicists to eliminate regions of the possible new-physics landscape.

The LHCb experiment is also hunting for new physics, specialising in less direct searches based on ultra-precise measurements of Standard Model processes. LHCb’s 2017 analyses produced further intriguing results that potentially challenge lepton universality. This tenet of the theory says that all leptons are treated equally by the Standard Model forces, so finding any difference would suggest that new particles are at work in the quantum loops of the vacuum. LHCb saw hints of lepton universality violation in their Run-1 data by studying the ratios of decay rates for processes such as  $B \rightarrow K^* \mu \mu$  and  $B \rightarrow K^* e e$ . In a related sector, where lepton universality is studied by means of ratios between  $B \rightarrow D^* \tau \nu$  and  $B \rightarrow D^* \mu \nu$  decay rates, hints of anomalies in decay ratios, previously reported by the BaBar and Belle experiments in the US and Japan, were also seen by LHCb in the Run-1 data. The hints of non-SM behaviour do not constitute firm observations yet, as they are limited by the amount of data available from Run 1, and updates with the larger dataset from Run 2, which began in 2015, are eagerly awaited.

The possibility that dark-matter particles may interact via an unknown force felt only feebly by Standard Model particles motivated LHCb to search for “dark” photons, setting tight new constraints on the coupling strength between dark and conventional photons. Also exploring the dark universe is the CAST experiment, in which a large superconducting magnet is pointed towards the sun to search for dark-matter axions as well as solar chameleons (candidates for the dark energy sector). Further results from the unique CAST set-up are expected in 2018.



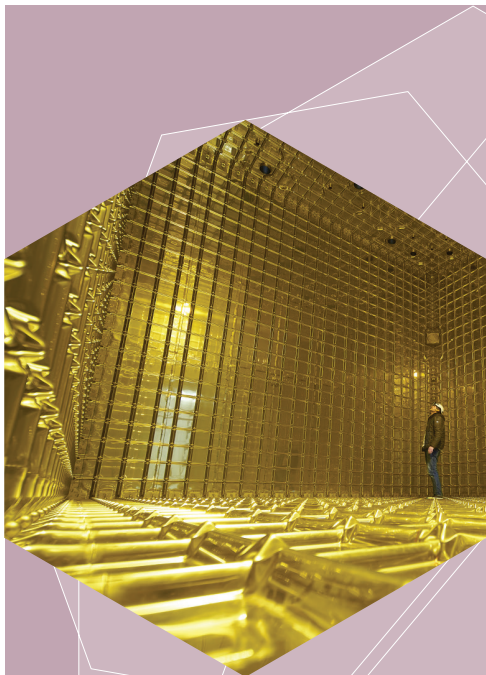
The results of a collision between two xenon nuclei inside the ALICE detector, which is optimised for the study of heavy-ion collisions. (ALICE-EVENTDISPLAY-2017-007-1)

## EXPLORING THE DYNAMICS OF THE INFANT UNIVERSE

In addition to colliding protons, the LHC collides lead and other heavy ions to generate a larger, fiercer collision environment. This fireball of extreme temperature and density, called the quark-gluon plasma (QGP), is thought to be a close approximation to the universe in its first moments of existence. In contrast to ordinary matter, where quarks and gluons are confined inside protons and neutrons, the quarks and gluons in the QGP can influence each other over much larger distances. Studying this state therefore allows powerful tests of the theory that describes the strong force, quantum chromodynamics.

In 2017, based on data collected during special heavy-ion runs in 2015 and 2016, the ALICE collaboration continued to probe the QGP from all angles. A major goal is to understand how this primordial state evolved from its creation to “freeze-out” less than a thousandth of a billionth of a billionth of a second later, after which the QGP condensed into protons, neutrons and other hadrons. Specifically, ALICE reported new measurements of the shape of the QGP fireball at freeze-out, and probed its dynamics using heavy quarks and  $J/\psi$  mesons to measure a crucial quantity called elliptic flow in a variety of ways.

Measurements reported by ALICE in 2017 provide the strongest evidence to date that QGP-like conditions are also created in proton–proton (pp) collisions. ALICE observed enhanced production of strange particles, historically considered to be one of the manifestations of QGP formation, in high-multiplicity pp interactions. These observations open new directions for theoretical and experimental studies of pp and heavy-ion collisions – directions which are being explored by all four LHC experiments.



*Inside one of the protoDUNE detectors, which are being designed for the far detectors of the Deep Underground Neutrino Experiment (DUNE) in the US. (CERN-PHOTO-201710-248-3)*

## MYSTERIOUS NEUTRINOS

The study of neutrinos is a major focus of the global high-energy physics programme, in particular the questions of whether these lightest of all particles violate charge parity (CP) symmetry and how they obtain their tiny masses in the first place. The CERN Neutrino Platform supports European participation in accelerator-based neutrino projects in the US and Japan, and significant progress in detector technology was made during 2017 for upcoming neutrino experiments.

An extension of the EHN1 facility in CERN's North Area provided charged beams and test space for neutrino detectors. R&D has been progressing apace to demonstrate large-scale liquid-argon time-projection chamber (TPC) technology, including the cryostats and detectors. Following the completion of a major refurbishment at CERN, the 600-tonne ICARUS detector (comprising two modules) was transported to the US in July to take part in Fermilab's short-baseline neutrino programme. In parallel, the 3x1x1-metre liquid-argon TPC demonstrator was completed; cosmic-ray tracks were observed and the construction of two larger cryostats with an internal volume of 8x8x8-metre each was completed, ready for the installation of prototype detectors for the international DUNE experiment in the US.

Towards the end of the year, a magnetic muon detector, Baby MIND, was shipped to Japan, where it will play an important role in understanding neutrino oscillations at the T2K experiment. The 75-tonne device was designed, built and tested with beam at CERN during 2017. Dedicated neutrino-physics activities also took place in CERN's Experimental and Theoretical Physics departments.

## 50 YEARS OF USER SCIENCE AT ISOLDE

The year 2017 marked the fiftieth anniversary of ISOLDE's delivery of radioactive isotopes for a wide variety of research in physics and, in the past few years, biophysics and medical physics. A total of 42 experiments were carried out in 2017, covering studies on the structure of exotic nuclei (rare combinations of protons and neutrons) via nuclear decay spectroscopy, mass measurements, laser spectroscopy and reactions with post-accelerated radioactive beams. Researchers also used radioactive probes as spies for solid-state physics, studies of fundamental interactions and biochemical experiments.

Highlights were the first experiments at the new HIE-ISOLDE post-accelerator, the third cryomodule for which was installed in spring as part of a major upgrade to increase the energy of ISOLDE's beams. The upgraded facility provided beams for 12 physics experiments with reaccelerated beams at three beamlines from July onwards. These included a study of the shape of selenium-70 and experiments with copper that revealed the doubly magic nature of nickel nuclei.

ISOLDE has served more than 1800 users since the first post-accelerated beams were provided in 2001, and continues to host cutting-edge science. 2017 also saw the

switch-on of MEDICIS (see p. 33), a new facility that uses the remaining protons that pass through the ISOLDE targets for the production of radioisotopes for medical research applications. MEDICIS has links with research hospitals in the region, where the isotopes produced can be used to develop new cancer therapies or nuclear diagnostics tools.

## THEORY THRIVES

In 2017, CERN's Theoretical Physics department (TH) produced cutting-edge research supporting the activities of the Laboratory and serving the international theoretical physics community. Topics included string theory, quantum field theory, the physics of (and beyond) the Standard Model, QCD, collider physics, heavy flavours, lattice field theory, high-temperature quantum field theory, heavy ions, cosmology and astroparticle physics – leading to the publication of about one paper per day during the year.

Notable examples include: a precise prediction of vector-bosons plus jets at the LHC, which allows improved sensitivity to possible dark-matter signals; a way of probing the time structure of the quark-gluon plasma by bringing together top-quark and heavy-ion physics; a thorough study of the theoretical interpretation of cosmic-ray antimatter; an exploration of the properties and phenomenological consequences of clockwork/linear dilaton theories; a





*Inside an office of CERN's Theoretical Physics department. (CERN-PHOTO-201602-026-9)*

**CERN'S THEORETICAL PHYSICS DEPARTMENT  
PUBLISHED AN AVERAGE OF  
ONE PAPER PER DAY IN 2017.**

quantitative study of how high energy can help precision measurements at hadron colliders; and a calculation of sub-leading corrections to the Veneziano amplitude and a proof of their universality.

In 2017, TH hosted 932 scientists (37 associates, 560 paid visitors and 335 unpaid visitors) and 68 fellows. The department also arranged between five and eight seminars per week, hosted six theory institutes and organised seven workshops and meetings.

## ANTIMATTER AND THE LOW-ENERGY FRONTIER

CERN's Antiproton Decelerator (AD) is a unique facility providing low-energy antiprotons for precise spectroscopy, gravitational and other measurements. The first antiatoms were created at its predecessor facility, LEAR, in the mid-1990s, and today researchers at the AD are making ever more precise comparisons between matter and antimatter to test nature's fundamental symmetries. The AD supports a community of around 200 scientists and engineers and hosts



five operational experiments – ALPHA, AEGIS, ASACUSA, ATRAP and BASE – with a sixth called GBAR in preparation.

In 2017, the ALPHA collaboration continued to build on the previous year's seminal measurement of the spectral structure of antihydrogen, by measuring its hyperfine splitting. These and further analyses from ALPHA represent the culmination of a decades-long quest to perform spectroscopy of antiatoms, and open the door to precision tests of charge-parity-time symmetry and to searches for effects beyond the Standard Model.

ASACUSA published key results regarding an alternative method to ALPHA to probe the hyperfine splitting of antihydrogen "in-flight", demonstrating that the technique works well for hydrogen atoms. The team also reported on progress towards an improved measurement of the antiproton-to-electron mass ratio using spectroscopy of antiprotonic helium atoms.

2017 was a highly productive year for BASE, which performed the most precise measurements yet of the antiproton magnetic moment – 350 times better than the collaboration's previous result less than a year earlier. The measurement was more precise than that of the proton, representing the first time that antimatter had been measured more precisely than matter. But the record didn't last for long: by the end of the year, members of the BASE team had used a double-trap apparatus to measure the proton magnetic moment to a precision five times higher, showing that the two values agree at the level of 1.5 parts per billion.

*BASE spokesperson working on his experiment at the Antiproton Decelerator. (CERN-PHOTO-201710-255-6).*



AEgIS reported important progress towards the first pulsed production of antihydrogen via charge exchange, in particular with the successful excitation of positronium in the experiment's 1T magnet. ATRAP also reported important technical progress towards laser-cooling of antihydrogen atoms and expect results from the forthcoming 2018 run. Great progress was made throughout the year towards the GBAR experiment, which plans to measure the effect of gravity on antihydrogen atoms. It will be the first experiment to be fed antiprotons by the new ELENA ring at the AD (see p. 47), which will reduce the antiproton energy further to increase the trapping efficiency of the experiments.

## EXPERIMENTS IN THE LINE OF FIRE

In parallel to their roles as injectors to the LHC, the PS Booster, PS and SPS accelerators provide beams to a variety of facilities and experiments, with around 20 such fixed-target projects supporting a community of over 1200 physicists.

NA58 (COMPASS), at the SPS, completed data-taking to investigate the nucleon's 3D structure using a muon beam and a spectrometer with a liquid hydrogen target. The

upcoming 2018 run is expected to improve the significance of the result.

NA61 continued its study of heavy-ion collisions in fixed-target mode, as well as measuring particle production in targets used for neutrino projects in Japan and the US. This year the experiment also ran with xenon ions for the first time. NA62, devoted to the study of very rare kaon decays as a possible window on new physics, had a successful run in 2017 that saw it accumulate about three trillion kaon decays. The excellent resolution of the new detector allowed NA62 to extend the search for heavy neutral leptons up to close to the kaon mass, and analysis of ultra-rare kaon decays is progressing well with data-taking continuing in 2018. NA64 (SHINE) extended its searches for dark-sector particles, continuing to provide interesting limits on possible dark-matter candidates.

CLOUD, which takes beam from the PS, is a multidisciplinary experiment that studies the influence of cosmic rays on aerosols and cloud formation, with implications for the understanding of climate change. Its 2017 run focused on marine nucleation and growth involving iodine compounds, pure biogenic nucleation and growth under realistic environmental conditions, and anthropogenic nucleation and growth under polluted urban conditions.



Participants at the second Physics Beyond Colliders workshop held at CERN in November. (OPEN-PHO-EXP-2017-04)

## PHYSICS BEYOND COLLIDERS

The Physics Beyond Colliders (PBC) initiative was launched in 2016 to explore opportunities offered by CERN's accelerator complex that are complementary to high-energy collider experiments. Throughout 2017, the PBC study continued to investigate future opportunities at CERN, with a second general workshop taking place in November with more than 230 physicists in attendance. The effort has already spawned new collaborations between different groups at CERN and with external institutes, and significant progress is already visible in many areas.

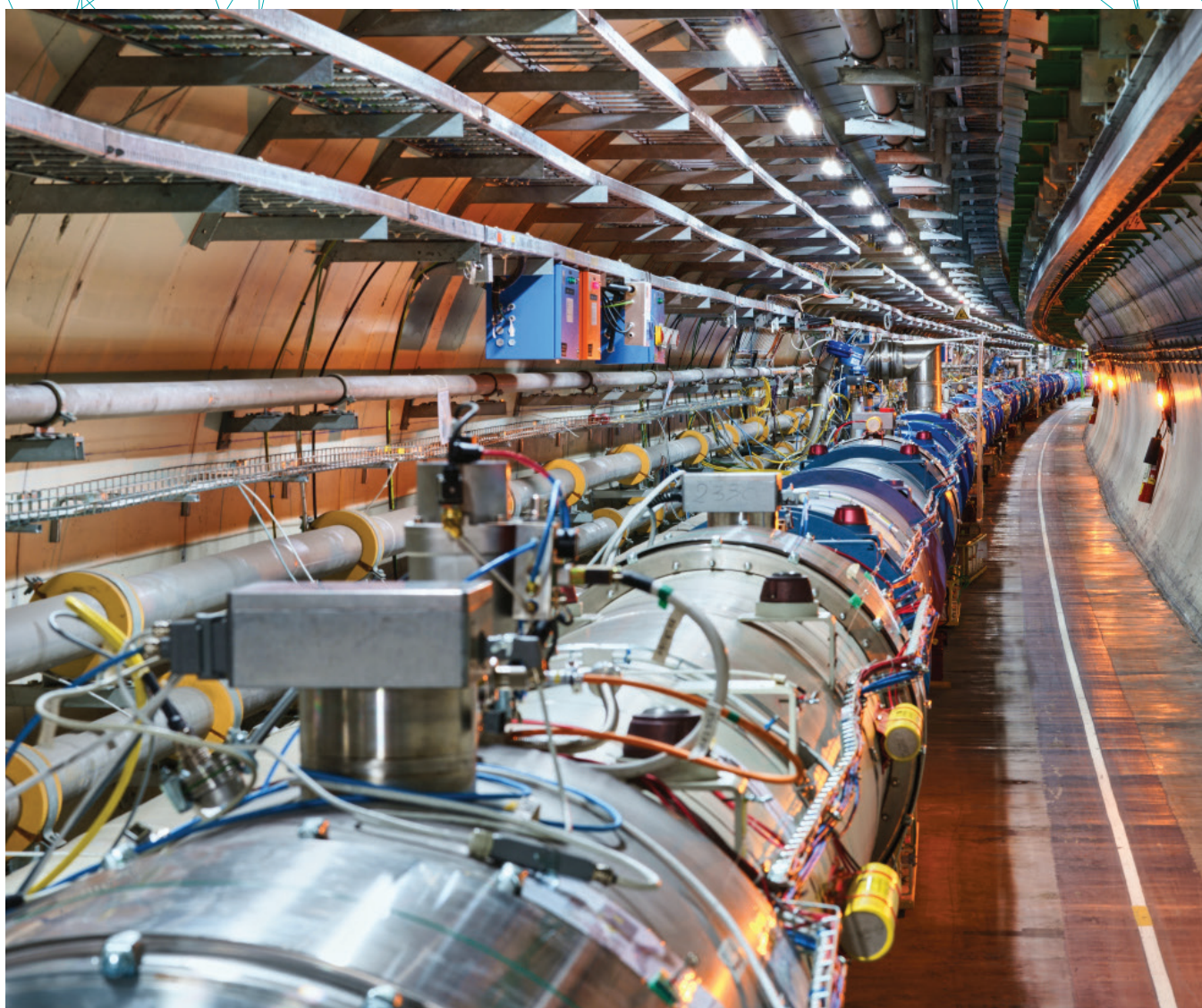
The interplay between potential future operation of the existing SPS fixed-target experiments (NA61, NA62, NA64, COMPASS) and the installation of new proposed detectors (NA64++, MUonE, DIRAC++, NA60++) has started to be addressed from both the accelerator and physics perspective. The technical study of the SPS proton beam-dump facility and the optimisation of the SHiP detector for investigating the hidden sector are also advancing well. Different options for fixed-target experiments at the LHC, for instance using gas targets or crystal extraction, are under investigation, and the novel idea of a gamma factory is also gaining traction.

The design study of a storage ring for a proton electric-dipole-moment measurement is progressing, and non-accelerator projects such as the future IAXO helioscope, proposed as a successor of CAST for the search for solar axions, are being discussed. Numerous other activities are under consideration, and the PBC study will conclude with a report by the end of 2018, in time for the update of the European Strategy for Particle Physics.

# DISCOVERY MACHINES

*To study the infinitesimally small, CERN operates a unique complex of machines. Accelerators speed up particles to almost the speed of light, before making them collide. Detectors record what happens during these collisions. All the resulting data is stored and analysed using a worldwide computing grid. Hundreds of physicists, engineers and technicians contribute to the operation and maintenance of these sophisticated machines.*

*View of the LHC. In 2017, the accelerator collected more data than expected.  
(CERN-PHOTO-201802-030-6)*







*LHC operators in the CERN Control Centre. In 2017, operators tweaked many beam parameters to optimise the LHC's operation. (CERN-PHOTO-201709-214-10)*

*THE LHC PROVIDED THE EXPERIMENTS  
WITH 10 MILLION BILLION COLLISIONS,  
25% MORE THAN IN 2016.*

## A FANTASTIC YEAR FOR THE LHC

The Large Hadron Collider (LHC) is the world's most powerful particle accelerator, smashing particles together at unprecedented energies. These collisions enable physicists to study the phenomena that govern particles and forces.

2017 was the LHC's third year at an energy of 13 TeV. The huge ring, measuring 27 kilometres in circumference, produced roughly 10 million billion collisions for the LHC experiments. Two large experiments, ATLAS and CMS, each recorded an integrated luminosity of around 50 inverse femtobarns ( $\text{fb}^{-1}$ ), compared to the 40 expected. Luminosity, which gives the number of potential collisions per surface unit over a given period of time, is the key indicator of an accelerator's performance. The integrated luminosity is measured in inverse femtobarns,  $1 \text{ fb}^{-1}$  corresponding to around 100 million million (potential) collisions.

This fantastic performance was notably due to the excellent availability of the LHC and its injectors. The LHC was in operation 81% of the time (compared to 75% in 2016), delivering collisions 49% of the time.

To increase luminosity, the operators tweaked various parameters that allow the concentration of the beams to be increased prior to collisions. A new configuration of the accelerator optics, known as Achromatic Telescopic Squeezing (ATS), was used to reduce the size of the proton bunches at the collision points. Instead of using just the quadrupole magnets either side of the experiments to squeeze the bunches, the ATS scheme also makes use of magnets located further away in the machine, transforming seven kilometres of the accelerator into a giant focusing

system. ATS was actually developed for the High-Luminosity LHC (see p. 45), but has been successfully tested at the LHC. As a result, each time the proton bunches crossed at the heart of ATLAS and CMS, up to 60 collisions occurred, compared to 40 in 2016.

Three months after the LHC restart, 2556 proton bunches were circulating in the machine – a record. But this smooth operation came to an abrupt halt in August, due to a vacuum issue. To prevent the protons from encountering any obstacles in their path, a high level of vacuum ( $10^{-10}$  millibars) is maintained inside the beam pipes. An accidental ingress of air, which froze and condensed on the vacuum chamber wall, disrupted operation for several weeks. The teams found a solution by changing the beam composition (see p. 23), so from the beginning of September onwards a beam comprising 1920 higher density bunches was used.

This new operating mode kept performance levels high. A new peak luminosity record was even set on 2 November, at  $2.05 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ , more than twice the nominal value.

For the experiments, however, higher density bunches meant more simultaneous collisions, making analysis more difficult. To limit pile-up and to level the luminosity from the beginning to the end of a run, the operators varied the crossing angle and overlap of the beams. These two changes also resulted in an overall luminosity increase of 8%.

The proton collisions ended on 11 November to allow some time for special runs. The first of these consisted of proton collisions at 5.02 TeV, the same energy as planned



*The SPS was fitted with a new beam dump during the technical stop and operated at full throttle in 2017. (CERN-PHOTO-201802-048-8)*

for the lead-ion run in 2018. This enabled physicists to collect reference data. The second special run, at very low luminosity, was carried out for the benefit of the TOTEM and ATLAS/ALFA experiments, which study the elastic scattering that occurs when two protons interact without colliding. For these studies, the beams were de-squeezed as much as possible and their energy was restricted to 450 GeV. Other tests were carried out over the course of the year, mainly in preparation for the High-Luminosity LHC.

## THE ACCELERATOR COMPLEX IN FULL SWING

CERN operates a complex of eight accelerators and one decelerator, which together supply dozens of experiments (see p. 12). The complex also accelerates particles for the LHC. The protons collided in the LHC are produced in four accelerators in series: Linac2, the PS Booster, the Proton Synchrotron (PS) and, finally, 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. A total of  $1.51 \times 10^{20}$  protons were accelerated in the complex in 2017, which is roughly the number of protons in a grain of sand. The LHC uses less than 0.084% of these protons.

In 2017, the accelerator chain achieved an average availability of over 90%, rising to 99% for Linac2 and 97% for the PS Booster. This performance is especially remarkable given that the youngest of these accelerators, the SPS, is over 40 years old, and the oldest, the PS, is approaching the ripe old age of 60! The accelerator fault-tracking system (AFT), installed in the LHC in 2015, is now used across the entire complex, supplying a constant stream of data on the availability of the accelerators, indicating

the origin of any faults and helping identify areas for improvement.

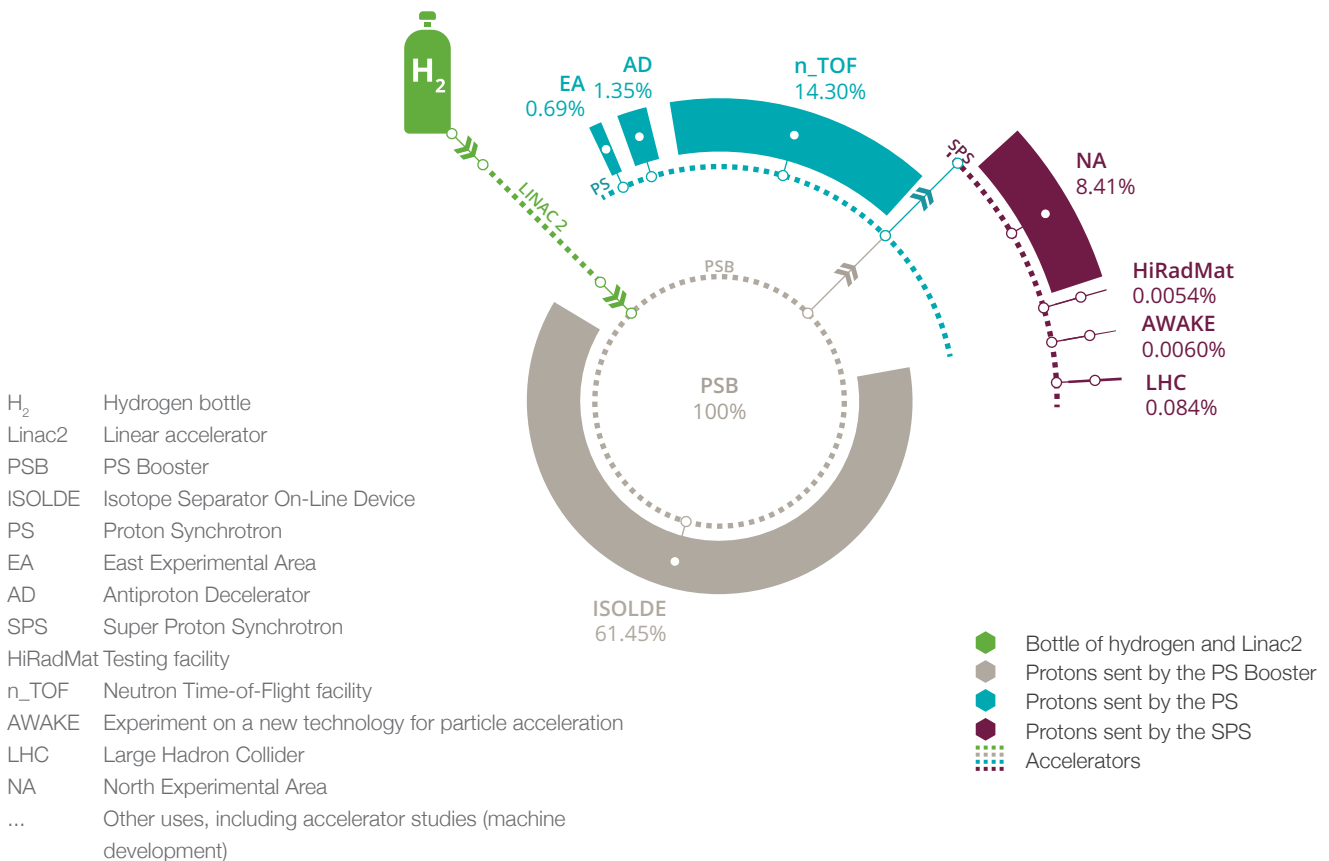
The PS Booster supplies particles to the PS and the ISOLDE nuclear physics facility, which turned fifty in 2017. ISOLDE received  $9.28 \times 10^{19}$  protons, or just over 61% of the total number injected into the accelerator chain. Moreover, thanks to its new HIE-ISOLDE superconducting accelerator, ISOLDE was able to produce radioactive ion beams at unprecedented energies. Equipped with a third cryomodule, HIE-ISOLDE delivered beams with energies of up to 7 MeV per nucleon to 12 experiments. The fourth and final cryomodule has been assembled and will be installed in 2018.

The next link in the accelerator chain, the PS, redistributes the particle bunches and accelerates them before dispatching them to various facilities. Most of the protons prepared by the PS were sent to the nuclear physics facility n\_TOF. The accelerator also feeds the Antiproton Decelerator, which supplied antiprotons to five antimatter experiments over the course of 5500 hours of operation.

The SPS was fitted with a new beam dump at the beginning of the year and was thus able to operate at full throttle in 2017, supplying the LHC, the experiments in the North Area, the HiRadMat test facility and the AWAKE experiment (see p. 49).

Linac3 and LEIR, the two accelerators that prepare heavy ions, demonstrated their flexibility by preparing their first xenon nuclei (see p. 24).

## PROTON DISTRIBUTION



### Distribution of protons to the various experimental facilities, expressed as a percentage of the total number of protons prepared in the PS Booster

The accelerator complex sends particles (mainly protons) to a dazzling array of experiments. In 2017, 151 billion billion protons ( $1.51 \times 10^{20}$ ) were prepared, which is actually a very small amount of matter, equivalent to the number of protons in a grain of sand. Most of these particles are used by the ISOLDE and n\_TOF facilities. The LHC used just a tiny fraction of these: 0.084%. Around 14% of the particles are used for operating tests (machine development) or are not used at all (beam dumps, losses, etc.)

## Clearing the air

A machine as complex as the LHC, with tens of thousands of components working together, is in constant need of adjustments and repairs. Sometimes, more serious issues require the teams to be creative. In August, the operators had to deal with mysterious beam losses at a specific point in the ring.

The cause? The presence of air in the vacuum chamber where the beams circulate. Seven litres of air had seeped in: something and nothing compared to the 110 000-litre volume of the vacuum chambers, but enough to disrupt the flow of the protons. Frozen molecules trapped on the walls of the pipe were

stripped off when the beam passed, generating showers of electrons that became greater as the intensity of the beam increased. A working group hurried to the LHC's bedside to find a cure, knowing it was impossible to open the vacuum chamber to extract the gas.

Installing a solenoid magnet to circulate the electrons resulted in a small improvement. In the end, the accelerator specialists solved the problem by changing the composition of the beam in the injectors, namely the PS Booster and the PS, splitting the beams into bunches of varying intensity, density and structure. Thanks to the great flexibility of these two

machines, the operators were able to propose several alternative beam configurations. Ultimately, a less intense beam was used, made up of sequences of eight proton bunches followed by four empty slots.

This new configuration limited the heat reaching the vacuum chamber walls and thus the phenomenon of electron clouds. The number of bunches had to be reduced to 1920, but since they were denser, excellent luminosity was maintained in the LHC. During the year-end technical stop, the teams partially warmed up the sector and pumped out 8.4 g of gas.





*As part of the consolidation programme, a new accelerating cavity has been produced for the LHC, with performance levels higher than specification. (CERN-PHOTO-201803-084-1)*

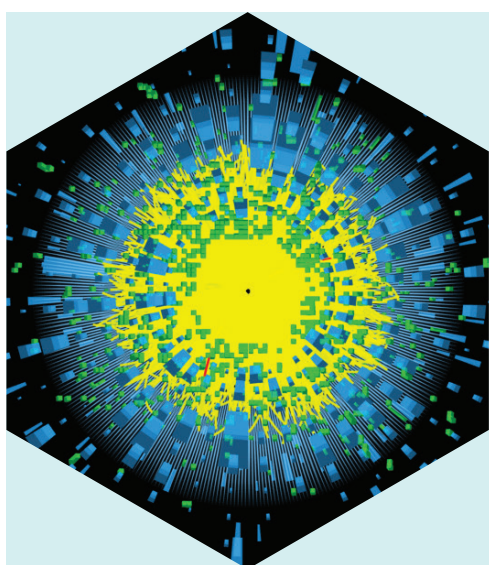
## A MAJOR CONSOLIDATION PROGRAMME

The success of the physics programme relies upon the excellent availability of the accelerators. This is why the technical teams closely monitor every nut and bolt of this huge complex. A major consolidation programme is under way on all the machines: the LHC, the injectors and the associated experimental facilities.

In 2017, maintenance and consolidation work took place during the extended year-end technical stop, which lasted until the end of April, and during a few scheduled stops over the course of the year. The teams carried out routine maintenance activities, fixed faults and upgraded certain

systems. For example, an LHC dipole magnet and the SPS beam dump were replaced. Another key job was the replacement of warm magnet power converters, thereby increasing the LHC's resistance to electrical faults, such as network voltage variations.

Consolidation work for all the accelerators focused on the beam instrumentation and on the injection, kicker, radiofrequency and vacuum systems. The technical infrastructures were also a hive of renovation activity, from the electrical distribution system to the lifts, overhead travelling cranes and ventilation system. Programmable



*A special run gave the LHC experiments an opportunity to collect data from xenon-ion collisions, like this one, recorded by the CMS detector. (CMS-PHO-EVENTS-2017-007-1)*

## A spoonful of xenon

On 12 October, the LHC had a taste of something rather different. For eight hours, the accelerator collided xenon nuclei for the first time. The collisions (xenon atoms with 54 protons and 75 neutrons) were similar to the heavy-ion collisions that are regularly performed at the LHC. The LHC experiments were able to collect a brand new type of data.

This innovation came about due to a special run organised for the NA61/SHINE fixed-target experiment, which received xenon ions at six different energies from the Super Proton Synchrotron (SPS), over a period of eight weeks.

This also gave the operators the opportunity to try out some new ideas, injecting partially ionised xenon atoms into the SPS, conserving 15 of their 54 electrons. These beams are very fragile. The teams managed to accelerate a beam, reaching an energy of 81.6 GeV per nucleon. The aim was to test the idea of a high-intensity gamma-ray source with energies of up to 400 MeV, as part of the Physics Beyond Colliders study (see p. 19).

logic controllers are widely used across CERN, and several groups, including those working on cryogenics and ventilation, renovated their systems. The group responsible for accelerator controls carried out maintenance work on its infrastructures.

In offices and workshops, teams manufactured and ordered replacement parts and prepared the upgrades. For example, additional accelerating cavities for the LHC are now being manufactured – work that is crucial to preserving this expertise at CERN. New collimators are also being developed for the High-Luminosity LHC (see p. 45).

Groups from all technical fields also prepared for the major programme of work to be carried out during Long Shutdown 2.

**ONE BILLION COLLISIONS PER SECOND WERE PRODUCED AT THE HEART OF THE LARGE LHC DETECTORS.**



*Open-heart surgery for CMS: the pixel tracker, the heart of the experiment, was replaced with a superior system before the 2017 LHC restart. (CERN-PHOTO-201703-062-43)*

## A fresh crop of collisions

Every year, the LHC's large detectors achieve extraordinary feats in their quest to collect more and more data. These enormous devices, comprising millions of components, operate at mind-boggling speed to identify the particles that emerge from collisions. In 2017, the accelerator's performance pushed the detectors harder than ever before. The LHC has produced an average of almost 40 collisions with each beam crossing (up to 30 million times per second). By the end of the run, there were even 60 collisions per crossing, two and a half times the value for which ATLAS and CMS were designed. Some one billion collisions per second were produced at the heart of the two large detectors. The two experiments managed to record more than 90% of the data delivered by the LHC, i.e. more than 45 inverse femtobarns each.

At the start of the year, CMS underwent a heart transplant – the detector at its very heart, the pixel tracker, was replaced with a new system comprising an additional pixel layer and 124 million instead of 66 million pixels. The new tracker

increases the detection precision, enabling the experiment to cope better with the data pile-up. Thanks to its additional layer, the tracker continued to perform well despite the failure of 5% of the power converters. At the end of the year, all the converters were replaced as a precaution. The CMS detector also benefited from improvements made to the electronics and readout systems of several of its subdetectors.

The ATLAS collaboration also made several improvements before the restart, repairing its calorimeters and muon detection system, replacing the gas distribution system of its transition radiation tracker (TRT) and reconfiguring the front-end electronics of the inner layer (IBL) of its pixel detector. These and other improvements enabled ATLAS to take data with unprecedented quality and efficiency in 2017.

LHCb, having reinforced its trigger and real-time event reconstruction systems, took  $1.8 \text{ fb}^{-1}$  of data. Its PC farm was also upgraded. As well as the proton–proton and xenon–xenon collisions, LHCb also took data in “fixed-target” mode with neon. It does this by introducing the noble gas into its vacuum chamber, generating collisions between the injected atoms and the proton beam.

ALICE, which specialises in the physics of the quark-gluon plasma obtained in heavy ion collisions, recorded 986 million proton–proton events at an energy of 5.02 TeV, exceeding its goal. This data taking enabled the experiment to collect reference measurements in preparation for the 2018 lead-ion run. Previously, ALICE had collected one billion proton–proton events (with a “minimum bias” trigger), a fraction of them with a reduced magnetic field for specific studies. The experiment also recorded “high-multiplicity” events, data with specific triggers and xenon–xenon events.





*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 the everyday operations of CERN. (CERN-CO-1008289-04)*

## COMPUTING: DEALING WITH THE DATA DELUGE

Once again this year, the CERN computing infrastructure faced a data deluge from the LHC and dealt with it successfully. Indeed, even though overall the experiments have made tremendous progress on reducing the number of derived data files written to tape, several data-storage records were broken. The CERN Advanced STORAge system (CASTOR) reached the milestone of 200 petabytes of data stored on tape by the end of June, and by the end of the year over 230 petabytes had been accumulated. Towards the end of the year, the performance of the LHC exceeded expectations and delivered a higher integrated luminosity to ATLAS and CMS than in any previous year. In October alone, 12.3 petabytes were written to tape, setting a new monthly record.

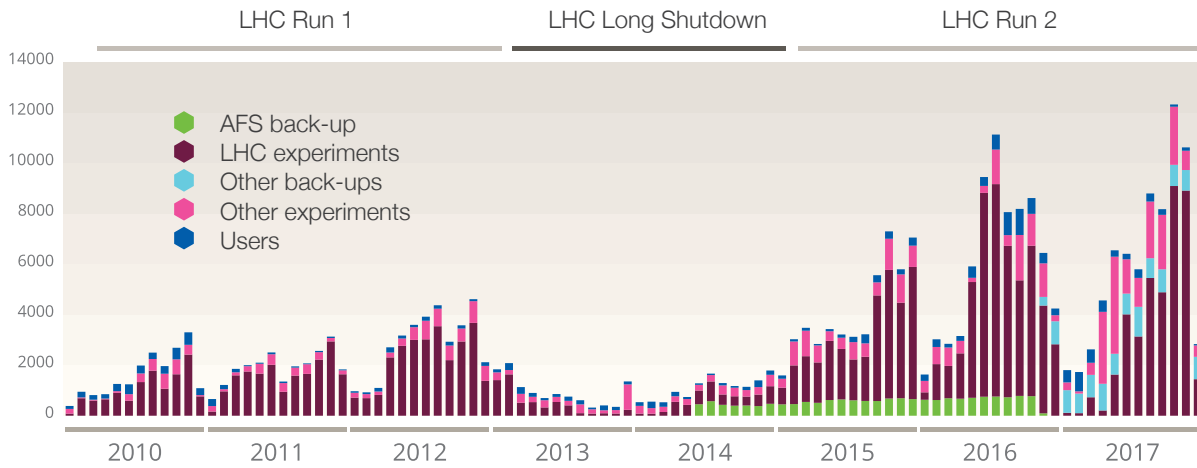
Data storage is an essential and critical component of CERN's computing infrastructure, which needs to be continuously updated to cope with ever-increasing demand while remaining within the confines of the premises. The Organization currently manages the largest scientific data archive in the field of High-Energy Physics (HEP) and is at the forefront of the field's data-preservation effort; CERN is a founding member of the DPHEP (Data Preservation in High Energy Physics) collaboration. A consequence of the greater data volumes in 2017 was increased demand for

data transfer and thus a need for a higher network capacity. Since early February, a third 100-gigabit-per-second fibre-optic circuit has linked the CERN Data Centre with its remote extension hosted 1200 km away at the Wigner Research Centre for Physics (RCP) in Budapest, Hungary. The additional bandwidth and redundancy provided by this third link allowed CERN to benefit reliably from the computing power and storage at the remote extension.

## WLCG: TOWARDS THE FUTURE

The mission of the Worldwide LHC Computing Grid (WLCG) is to provide global computing resources for the storage, distribution and analysis of the data generated by the LHC. As in previous years, WLCG performed well in 2017 and adapted to the increasing performance needs of the experiments, supporting the timely delivery of high-quality physics results. The CERN Data Centre continued to carry out essential processing and quality-checking of the data, although, due to the excellent performance of the LHC, the experiments started to see some processing backlogs in October, clearly illustrating the need for additional resources for the coming year when similar performance is expected. The export of data to the WLCG data centres proceeded smoothly, thanks to upgrades of network bandwidths in the preceding years. Finally, the collaboration





**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 2017, 72 petabytes of data in total (including 40 petabytes of LHC data) were recorded on tape, with a record peak of 12.3 petabytes in October.

of 170 participating data centres has provided the required combined capacity to process and analyse these data in an effective way and allowed service delivery to be stepped up on multiple occasions. All volunteer computing activities at CERN were consolidated in 2017 under the LHC@home project umbrella and have continued to grow, providing peaks of 400 000 simultaneously running tasks.

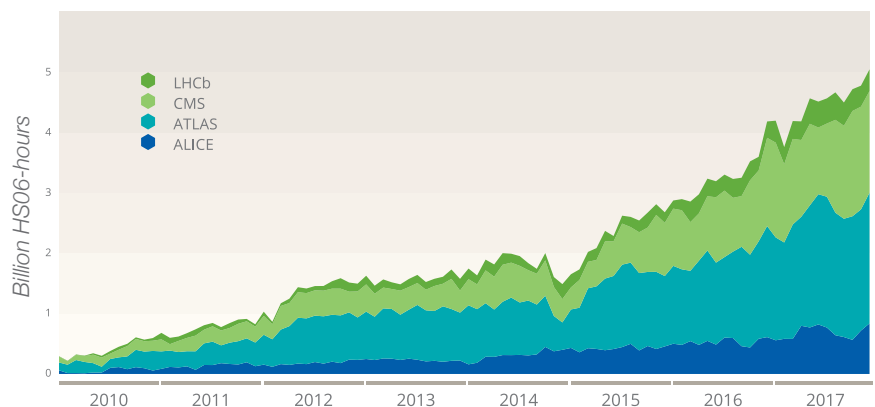
shortfall, in 2017 the HEP Software Foundation (HSF) produced a roadmap Community White Paper (see p. 54) that explores these software challenges and describes a number of potential mechanisms by which the community may overcome the shortfalls in capacity and efficiency it will face during the next decade.

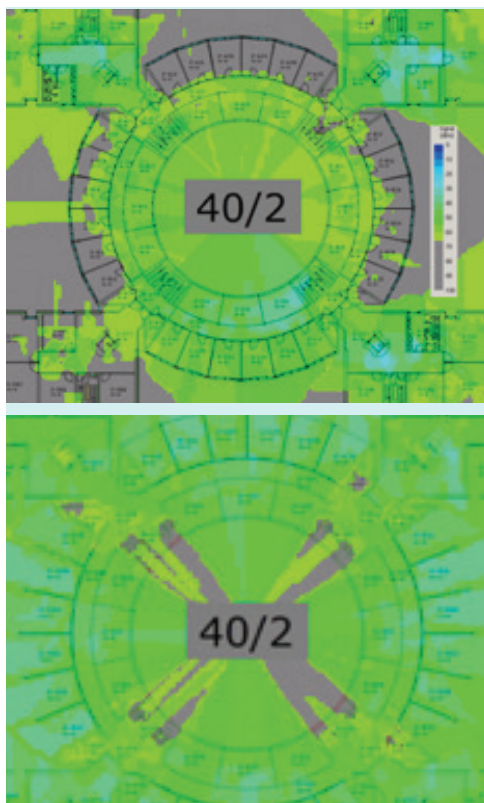
Looking to the future, the High-Luminosity LHC (HL-LHC) presents a major and significant increase in computing requirements compared with the current Run 2 and the upcoming Run 3; in fact, the demand exceeds the extrapolations of technology progress within a constant investment budget by several factors, in terms of both storage and computing capacity. In order to address this

The large-scale data challenges of the High-Luminosity LHC are being addressed in collaboration with other scientific communities. For example, WLCG and CERN have been working with the Square Kilometre Array (SKA) radio astronomy community to explore some of these common challenges. In June 2017, CERN and the SKA Organisation signed a collaboration agreement for joint work on computing and data management.

**Evolution of the global core processor time delivered by the Worldwide LHC Computing Grid (WLCG)**

As seen on the graph, the global central processing unit (CPU) time delivered by WLCG (expressed in billions of HS06 hours per month, HS06 being the HEP-wide benchmark for measuring CPU performance) shows a continual increase. In 2017, WLCG combined the computing resources of about 800 000 computer cores.





## The new campus-wide Wi-Fi service reaches key milestones

The new campus-wide Wi-Fi service project started a few years ago, as part of an overall effort to modernise the Laboratory's communication infrastructure to meet today's demands for mobility, flexibility and accessibility. After a pilot phase in 2016, 2017 saw the start of deployment of the new Wi-Fi infrastructure in some 70 buildings at CERN. The new access points are centrally managed, which allows users to move around without losing their network connection.

Thanks to the new Wi-Fi service, it is now also possible to offer a visitor service similar to the one available in many public spaces, while keeping the visitors' devices isolated from CERN's internal network.

*Wi-Fi service coverage before (top) and after (bottom) the deployment of the new infrastructure in Building 40, which hosts a large number of physicists.*

## SCIENCE IN THE CLOUDS

Over 90% of the resources for computing in the Data Centre are provided through a private cloud based on OpenStack, an open-source project to deliver a massively scalable cloud operating system. With the growth of the computing needs of the CERN experiments and services, this has now reached more than 280 000 computer cores running in the data centres at CERN and Wigner. Migrations of system software this year have simplified the configuration and allowed the capacity to continue to grow. A collaboration project was also started with SKA to enhance OpenStack for scientific use cases and to share experiences. Many of the contributions to OpenStack have been made through CERN openlab in collaboration with industry.

During 2017, four projects co-funded by the European Commission (EC) in which CERN was involved were successfully completed: ICE-DIP (Intel CERN Industrial Doctorate Programme), EGI-Engage (Engaging the EGI Community towards an Open Science Commons), INDIGO DataCloud (INtegrating Distributed data Infrastructures for Global ExpLOitation of PaaS/SaaS level services), and AARC (Authentication and Authorisation for Research and Collaboration). The positive results of these projects have led to CERN's engagement in new projects that will contribute to the European Open Science Cloud (EOSC).

The Helix Nebula Science Cloud (HNSciCloud) Pre-Commercial Procurement (PCP) project led by CERN is addressing the cloud services needs of a group of 10 research organisations (procurers) that serve data-intensive research communities. In 2017, HNSciCloud successfully

completed design and prototype phases and launched the pilot phase of the pre-commercial procurement process. HNSciCloud has been instrumental in promoting and demonstrating the advantages of procuring commercial cloud services in the public research sector. The impact of the project on European-level policy is apparent in the development of the EOSC, where commercial cloud services are now recognised as playing an important role.

## EDUCATION AND SHARING

Since the early seventies, the CERN School of Computing (CSC) has been promoting learning and knowledge exchange in scientific computing among young scientists and engineers involved in particle physics or other sciences. It is now made up of three separate schools and this year celebrated the 40th edition of its main school, which took place in Madrid, Spain. Since its inception, the CSC has been attended by 2600 students from 80 countries on five continents.

The CERN and Wigner data centres together host around 15 000 servers, which are replaced every four to five years as they become inefficient for the purposes of CERN's research. However, they remain suitable for less demanding applications. About 1990 boxes of new servers and data storage equipment were deployed in 2017, while 1000 boxes of old equipment were retired. Nine pallets of IT equipment were donated by CERN in 2017: to CERIST in Algeria (in February), to Sofia University in Bulgaria (in August), and to SESAME in Jordan (in September, see p. 10).



## CERN inaugurates its second network hub

The day-to-day operation of CERN is heavily reliant on IT services, and preventing any potential long-term interruption is therefore crucial. To this end, a project to create a second network hub was approved in 2014 and, three years later, the new network hub started operations. With fibre connectivity to the outside world, the CERN Control Centre, the CERN Data Centre and its extension at the Wigner Research Centre for Physics in Hungary, as well as to all the major network technical rooms on the CERN campus, this second network hub provides the necessary redundancy for the CERN data network.

*The second CERN network hub, located near the CERN Control Centre in Prévessin, was inaugurated on 19 July.*

The CERN Open Data portal is a testimony to CERN's policy of Open Access and Open Data. The portal allows the LHC experiments to share their data with a double focus: for the scientific community, including researchers outside the CERN experimental teams, as well as citizen scientists, and for the purposes of training and education through specially curated resources. This year, a major new release was made containing over one petabyte of CMS data, corresponding to around half of the data collected by the detector in 2012. In addition to the datasets themselves, the CMS Data Preservation and Open Data team have also assembled a comprehensive collection of supplementary material, including sample code for performing relatively simple analyses, as well as metadata such as information on how data were selected and on the LHC's running conditions at the time of data collection. The first papers based on data from the CERN Open Data portal have been published.

In January 2017, a consortium of European companies, research laboratories, universities and education networks came together to form Up to University (Up2U), a project co-funded by the European Commission (EC). CERN is playing an active part in this three-year project, which aims to create a bridge between high schools and higher education. The objective is to provide tools and technology commonly used in academia and big science to secondary-school students in order to prepare them for their future careers.

## FOSTERING COLLABORATION

CERN, with co-funding from the EC, has long invested in Zenodo, a free repository for storing data, software and other research artefacts. It is intended for use beyond the HEP community and taps into CERN's long-standing tradition and know-how in sharing and preserving scientific knowledge for the benefit of all. Zenodo is hosted at CERN and provides the wider scientific community with the option of storing its data in a non-commercial environment and making it freely available to society at large. In 2017, Zenodo incorporated Digital Object Identifier (DOI) versioning. This new and highly requested feature allows users to update a record's files after it has been made public and allows researchers to reference one or all the versions of a record.

CERN openlab's fifth three-year phase came to a close at the end of 2017. Through this unique public-private partnership, CERN has collaborated with leading ICT companies and other research organisations to accelerate the development of cutting-edge ICT solutions for the research community. Through no fewer than 20 R&D projects, CERN openlab tackled ambitious challenges covering the most critical needs of ICT infrastructures. Throughout 2017, CERN openlab's work also focused on the preparations for its sixth phase, beginning in 2018. The white paper on IT Challenges in Scientific Research (see p. 54) published in September is the culmination of these investigations and sets out specific challenges that are ripe for tackling through collaborative R&D projects with leading ICT companies.



# A WORLDWIDE LAB

*Cooperation between nations, universities and scientists is the driving force behind CERN's research. In 2017, more than 17 500 people from around the world worked together to push the limits of knowledge. CERN's staff members, numbering around 2600, take part 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 gathered for a vast community of users, comprising over 12 200 scientists of 110 nationalities, from institutes in more than 70 countries.*



## DISTRIBUTION OF ALL CERN USERS BY THE COUNTRY OF THEIR HOME INSTITUTE AS OF 31 DECEMBER 2017

**NUMBER OF USERS: 12 236**

### MEMBER STATES (7162)

Austria 104 - Belgium 153 - Bulgaria 44 - Czech Republic 247 - Denmark 66 - Finland 118 - France 867 - Germany 1323  
Greece 132 - Hungary 58 - Israel 69 - Italy 1444 - Netherlands 161 - Norway 91 - Poland 288 - Portugal 103 - Romania 110  
Slovakia 79 - Spain 336 - Sweden 96 - Switzerland 375 - United Kingdom 898

### ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP (75)

Cyprus 17 - Serbia 36 - Slovenia 22

### ASSOCIATE MEMBER STATES (403)

India 206 - Pakistan 38 - Turkey 124 - Ukraine 35

### OBSERVERS (3268)

Japan 266 - Russia 1033 - USA 1969

### OTHERS (1328)

Algeria 1 - Argentina 17 - Armenia 14 - Australia 32 - Azerbaijan 3 - Bangladesh 3 - Belarus 24 - Brazil 131 - Canada 179 - Chile 23  
Colombia 27 - Croatia 31 - Cuba 3 - Ecuador 3 - Egypt 25 - Estonia 17 - Georgia 26 - Hong Kong 20 - Iceland 2 - Indonesia 7 - Iran 17  
Ireland 5 - Korea 151 - Lebanon 9 - Lithuania 23 - Madagascar 3 - Malaysia 7 - Malta 6 - Mexico 60 - Mongolia 2 - Montenegro 7  
Morocco 12 - New Zealand 7 - Oman 4 - People's Republic of China 266 - Peru 3 - Singapore 3 - South Africa 74 - Taiwan 64  
Thailand 17



Continuing its enlargement process, the CERN family welcomed several new countries in 2017. India became an Associate Member State in January, while Slovenia became an Associate Member State in the pre-stage to membership in July. The Republic of Lithuania signed an agreement to become an Associate Member State and Croatia continued its progress towards the same status. At the end of the year, the Organization had 22 Member States and seven Associate Member States, three of which were in the pre-stage to membership.

Many other countries have established formal links with the Laboratory and contribute to its activities. CERN continues to reinforce this network by supporting the countries that develop their particle physics community. In this context, the Laboratory signed cooperation agreements with Nepal and Sri Lanka. This policy of global engagement creates a cultural melting-pot that is vital to CERN's pursuit of new ideas and ever-deeper knowledge.

## Birth of a high-energy network

With users spread all over the world and hundreds of scientists trained at the Laboratory each year, CERN has gradually developed a huge community of former associates, students and employees. These alumni continue their careers in a huge variety of fields, from academia to industry, finance, information technology and medicine. In June, CERN brought this network to life by launching "CERN Alumni – The High-Energy Network". The network allows alumni to maintain links with CERN, to enjoy the wealth and diversity

of their own large community, and to leverage the experience and support of members of the network. It is also a strategic move intended to support CERN's mission and activities. An interactive web platform forms the backbone of the network, allowing alumni to stay informed and interact with each other. At the end of 2017, the network already comprised 2500 members and was preparing for its first major event at CERN in February 2018.



# PUSHING THE FRONTIERS OF TECHNOLOGY

***CERN inspires visionary thinking. Since its beginning, it has acted as a trailblazer in technologies relating to accelerators, detectors and computing. As a laboratory with a long-term research plan, it is continuously innovating, creating solutions that concretely benefit both its Member State industries and society as a whole. The year 2017 marked twenty years since CERN set up a reinforced structure to support its knowledge and technology transfer activities. Today, these activities are stronger than ever.***

*The first isotope produced by CERN-MEDICIS (Medical Isotopes Collected from ISOLDE). This new facility has begun to provide a range of innovative medical isotopes for hospitals and research centres across Europe. (CERN-PHOTO-201803-081-2)*



## DIVERSE APPLICATION FIELDS

The technological and scientific advances behind high-energy physics have historically contributed to the field of **medical and biomedical technologies**, particularly those relating to areas within therapy, diagnostics and imaging, as well as big data and medical computing. In 2017, that contribution was significantly strengthened by the Council's approval of CERN's new medical applications strategy.

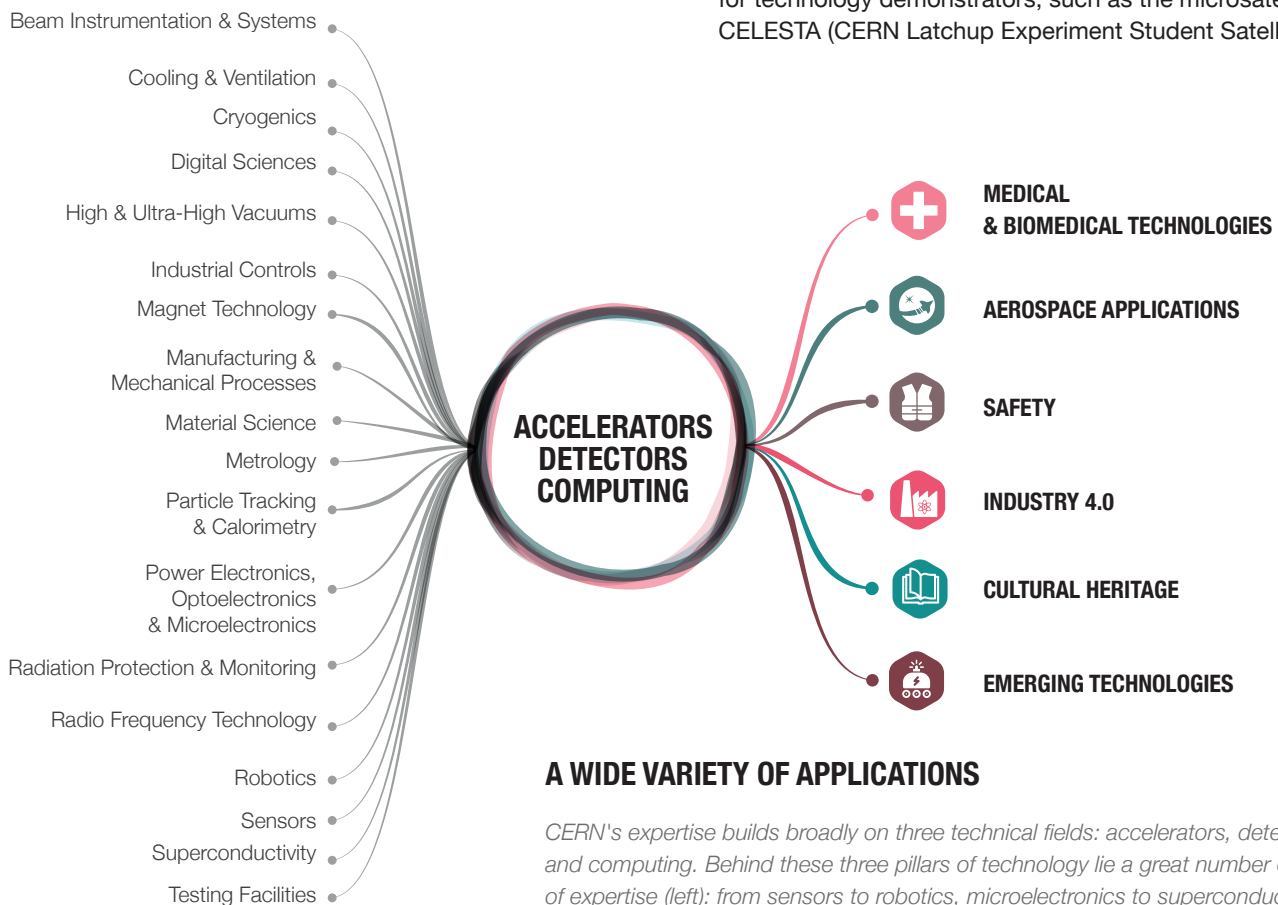
In September 2017, CERN-MEDICIS (Medical Isotopes Collected from ISOLDE) entered the commissioning phase, before producing its first isotopes in December. This unique facility is designed to produce unconventional radioisotopes with the right properties to enhance the precision of both patient imaging and treatment. It will expand the range of radioisotopes available for medical research – some of which can be produced only at CERN – and send them to hospitals and research centres in Switzerland and across Europe for further study.

International experts in accelerator design, medical physics and oncology met at CERN in October, following on from the first CERN-ICEC-STFC workshop in 2016. The ambitious plan is to design an affordable, easy-to-use and robust medical accelerator for challenging environments.

The programme aims to have facilities and trained staff available to treat patients in low- and middle-income countries by 2027.

Another medtech development involved sharing CERN's expertise in digital sciences, a field with strategic applications in industry. CERN experts trained Sanofi Pasteur, the vaccines business unit of the global life sciences company Sanofi, to apply novel machine-learning techniques to various production challenges. Continued collaboration will test and explore tools to try to improve vaccine production, helping more people to access vital vaccines.

**Aerospace** is a major application area for CERN's technologies and expertise. In April, the French space agency, CNES (Centre National d'Études Spatiales), and CERN signed an important framework cooperation agreement. With the support of the CERN Knowledge Transfer Fund, three projects formalised by the agreement have already begun: radiation tests of the Eyesat nanosatellite in CERN's CHARM facility, a NIMPH (Nanosatellite to Investigate Microwave Photonics) secondary payload based on the LHC radiation monitoring system (RadMon) and the development of fibre-optic radiation and temperature sensors. In collaboration with the University of Montpellier, CERN expertise has been used for technology demonstrators, such as the microsatellite CELESTA (CERN Latchup Experiment Student Satellite).



## A WIDE VARIETY OF APPLICATIONS

CERN's expertise builds broadly on three technical fields: accelerators, detectors and computing. Behind these three pillars of technology lie a great number of areas of expertise (left): from sensors to robotics, microelectronics to superconductivity, and many more. These technologies, and the expertise associated with them, translate into a positive impact on society in many different fields (right).





The start-up company InsightART is using the particle physics pixel detector Medipix to perform highly detailed X-ray scans of artworks such as this painting.

CERN's unique environment combines extremely low temperatures, ultra-high magnetic fields, various types of radiation and high voltages, and thus requires innovative **safety** solutions. A new CERN spin-off company, Neasens, is now developing a network of smart sensors, based on CERN technology, to monitor radon and better tackle risks relating to high radon levels. Radon is produced in the decay processes of natural isotopes and is one of the leading causes of lung cancer deaths, second only to smoking.

**Industry 4.0** is the trend of increasing automation and efficiency in manufacturing processes with connected sensors and machines, autonomous robots and big data technology. In 2017, a licence agreement was signed between LG Display and CERN, giving the company access to control-middleware software originally developed for the LHC, for use in factory automation across its plants.

Several projects relating to **cultural heritage** are also using CERN technologies. One example is the Prague-based start-up company InsightART, which is using Medipix technology in X-ray imaging detectors to inspect paintings in order to assess their condition and identify painted-over or forged works.

Scientists and engineers are working on **emerging technologies** at CERN, particularly in the field of superconductivity. Close industrial collaboration is vital for producing novel high-temperature superconductors, essential for future accelerator developments and, potentially, future energy transportation and storage solutions.

## ACCELERATING INNOVATION

The **CERN Knowledge Transfer Fund** acts as a tool to bridge the gap between research and industry, selecting innovative projects based on CERN technology with the potential for a positive impact on society. Since its establishment in 2011, it has funded 41 projects. In 2017, three projects were selected: a compact superconducting magnet for space applications, a compact accelerator for cultural heritage and a 3D laser for carrying out quality control on semiconductor devices. In addition, the **CERN Medical Applications Budget** funded 11 new projects and five new trainees, PhD students and fellows.

Convened and managed by CERN, **SCOAP<sup>3</sup>** (Sponsoring Consortium for Open Access Publishing in Particle Physics) is a global open-access initiative involving 3000 libraries, funding agencies and research institutions from 47 countries. Since it began in 2014, it has made 15 000 articles by some 20 000 scientists from more than 100 countries accessible to everyone. In April, CERN and the American Physical Society signed an agreement according to which, as of January 2018, all authors worldwide will be able to publish high-energy physics articles in *Physical Review C*, *Physical Review D* and *Physical Review Letters* at no direct cost. This extends SCOAP<sup>3</sup> to cover almost 90% of the journal literature in the field.

THE GLOBAL OPEN-ACCESS

INITIATIVE SCOAP<sup>3</sup> MAKES ALMOST

90% OF HIGH ENERGY PHYSICS

JOURNAL ARTICLES

ACCESSIBLE TO EVERYONE.



## FRUITFUL COLLABORATIONS

CERN engages with international organisations and participates in European Commission co-funded projects, five of which have a strong knowledge transfer component. Alongside AIDA-2020 in 2015 and QUACO in 2016, three new projects began in 2017: ARIES, AMICI and FuSuMaTech.

ARIES is designed to improve the performance, availability and sustainability of particle accelerators, transferring the benefits and applications of accelerator technology to both science and society, and enlarging and integrating the European accelerator community. AMICI aims to consolidate and exploit this infrastructure across the accelerator community, strengthening the capabilities of European companies to compete on the global market. FuSuMaTech aims to establish a sustainable research, development and innovation network across Europe to structure and strengthen the field of superconducting magnets and the associated industrial applications, with potential applications in neuro-imaging.

## FOSTERING ENTREPRENEURSHIP

To develop a **culture of entrepreneurship** at CERN and increase the number of start-ups using CERN technologies, 2017 saw the fiftieth entrepreneurship meet-up since the initiative began more than two and a half years ago. In addition, CERN has established a network of nine Member State Business Incubation Centres (BICs) to assist entrepreneurs

and small businesses in taking CERN technologies and expertise to the market. Five new start-ups were accepted into a BIC in 2017. Beyond the BIC network, the Knowledge Transfer group supports spin-offs and start-ups through a variety of different activities and mechanisms, from licensing of technologies to business plan development and access to training programmes. To date, there are 23 start-ups and spin-offs using CERN technology.

## A RETURNED INVESTMENT

By the nature of its activities and its structure, CERN requires a wide range of goods and services. Half of its annual budget of one billion Swiss francs returns to industry through procurement (see p. 53). In the case of high-level technological goods, contracts with CERN can boost innovation in industry. In 2017, some 782 price enquiries, 98 invitations to tender and 63 000 orders were made, including those through the CERN Stores. Contracts ranged from the purchase of data-centre infrastructure for ALICE and LHCb to the assembly of 11-tesla dipole magnets for the HL-LHC and services such as the maintenance of the cooling and ventilation system on the CERN site.

Through its dedicated procurement service, CERN targets balanced industrial returns. In practice, this is done by holding industrial exhibitions at CERN, attending industry events in Member and Associate Member States, and generally working towards creating strong links with national industries. Limited tendering – where invitations to tender are limited to countries with very poor industrial returns – is also used to improve industrial return.

## CERN PROCUREMENT: A LARGE NUMBER OF ACTIVITIES

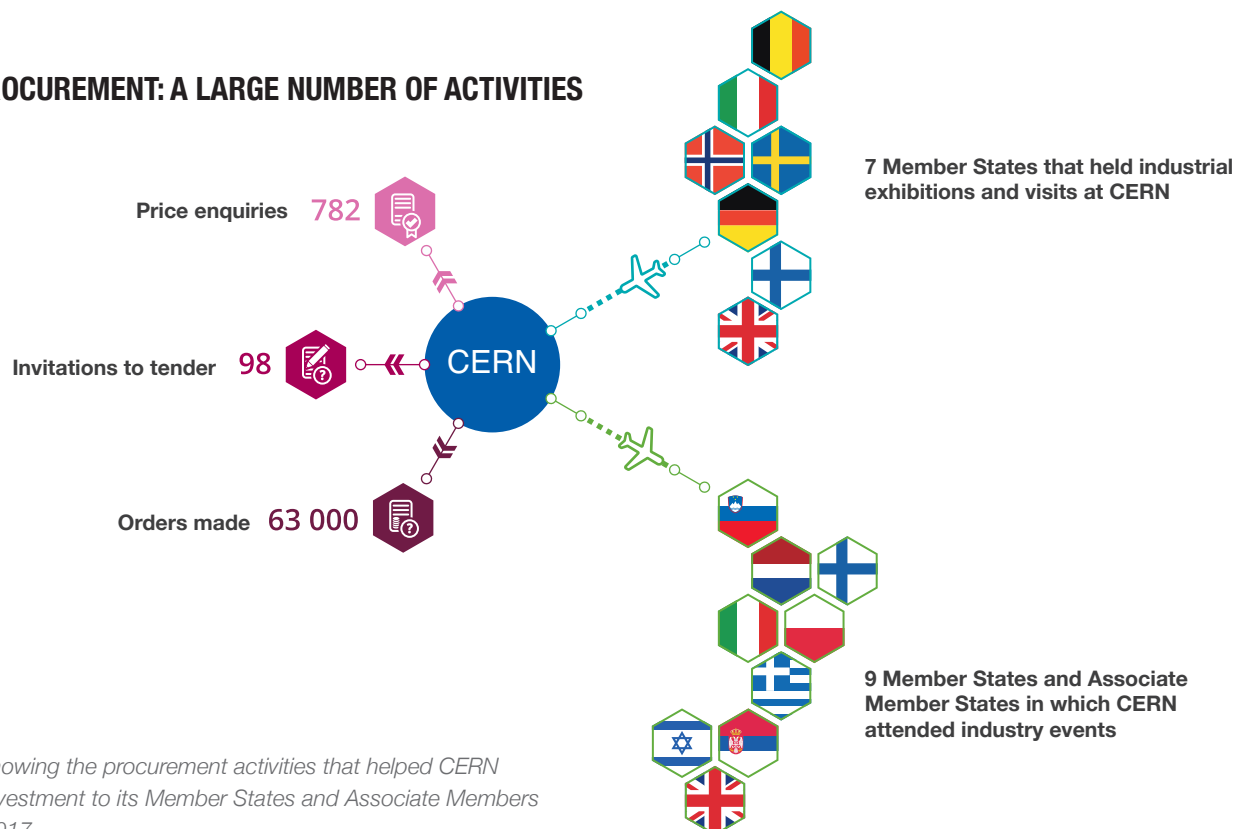


Diagram showing the procurement activities that helped CERN to return investment to its Member States and Associate Member States in 2017.

# INSPIRING AND EDUCATING NEW GENERATIONS

***CERN engages with society through a wide range of outreach, education and arts activities. These aim to broaden the understanding of science and of CERN's activities, to inspire people both young and old, to improve science education at secondary school level, and to train a new generation of scientists and engineers.***

*CERN took centre stage as guest of honour at Geneva's Automnales fair with a 1000-m<sup>2</sup> stand designed to resemble a particle collision. The 80 000 visitors were offered a virtual-reality tour of CERN, alongside workshops, shows and presentations. (CERN-PHOTO-201711-279-3)*





## WORLDWIDE INTEREST IN NUMBERS

Interest in CERN remained high in 2017, with 138 000 articles about the Laboratory published in the world's press, and the Press Office organising media visits for more than 500 journalists from around the globe. CERN's website, [home.cern](http://home.cern), had more than 3 million visits, 85% of which were from new visitors.

With more than 2 million mentions of "CERN" or "LHC" on social media, CERN continues to have a strong social media presence. In March, CERN's Twitter account passed the 2-million-follower mark and the Laboratory held its first Facebook live event from the CMS experimental cavern, reaching more than half a million people. The most successful video of the year, which went on to receive a Lovie award, involved musician Howie Day singing science-themed lyrics at CERN. Finally, several communication campaigns used new techniques such as 360° immersive photos and Instagram stories and grids.

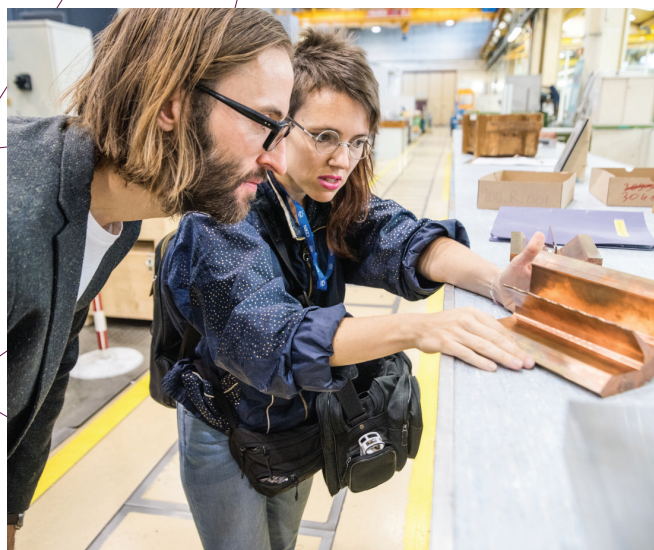
*A communication campaign highlighted female CERN scientists for the "International Day of Women and Girls in Science" on 11 February.*



## IMPACT ON LOCAL COMMUNITY AND CULTURE

The most important local event in 2017 was CERN's presence as guest of honour at Geneva's biggest local fair, the *Automnales* in November. It was an opportunity to present CERN to people who would never normally think of visiting the Laboratory. Visitors were able to find out about fundamental research and its applications via objects, activities, films, quizzes and virtual-reality headsets allowing a (virtual) trip to the huge underground CMS detector. More than 110 workshops, shows and presentations took place, led by over 170 volunteers from CERN, who welcomed, guided and informed the 80 000 visitors to the CERN stand with great enthusiasm.

Additional CERN activities for the local community included various well attended public lectures at the Globe and European Researchers' Night in September, which between them involved more than 7000 participants. CERN also participated in the *Royaume du Web* event in May, with several thousand visitors to the CERN stand. Newly initiated outreach and communications campaigns this year included school visits in the days around the International Day of Women and Girls in Science, the celebration of World Teachers' Day and International Dark Matter Day with dedicated events, and the opportunity to showcase CERN's impact on society in the context of the Sustainable Development Goals at the UN Open Day in October.



*Collide Pro Helvetia 2017 artist Laura Couto Rosado with her scientific collaborator in a CERN workshop. (CERN-PHOTO-201707-166-13)*

The Arts at CERN programme hosted 12 renowned artists from around the world, who visited the Laboratory or partnered with CERN scientists for periods of one or three months. The programmes were fully supported by prominent arts institutions such as FACT in the UK, the Arts Council in the Republic of Korea, Kontejner in Croatia and ProHelvetia in Switzerland. A new scheme to support the production and exhibition of artworks resulting from the residencies was launched in collaboration with FACT.



## VISITING THE LABORATORY

CERN was again a favourite destination for high-level visitors, resulting in 136 protocol visits (see pp. 6–11). However, it is mostly the general public – plus teachers and students – who want to discover how research in the world’s largest laboratory for particle physics addresses the big questions about the Universe. Responding to the huge public demand, the annual number of visitors continued to increase, from 20 000 in 2008 to 136 000 in 2017, a 13% increase compared to 2016, the previous record year. In addition, more than 70 000 people visited the Microcosm and Universe of Particles permanent exhibitions.

*CERN WELCOMED 136 000 VISITORS  
IN 2017, A 13% INCREASE COMPARED  
TO 2016.*

For those who could not come to CERN, travelling exhibitions journeyed to different countries: the flagship Accelerating Science exhibition went to Istanbul, Turkey, for four months, attracting about 20 000 visitors, half of them from Turkish high schools. The smaller Interactive Tunnel and CERN in Images exhibitions featured at the FCC week in Berlin, at the Hannover IdeenExpo in June, with 300 000 visitors, and at the Karlsruhe KIT Open Day, also in June, which attracted 35 000 visitors.

The Science Gateway is a new initiative aimed at expanding CERN’s education and outreach activities. It is planned to be hosted in a new building constructed around CERN’s Globe of Science and Innovation and would include a new visitor reception area, spaces for permanent and temporary exhibitions, laboratories for hands-on experiments and a 1000-seat auditorium. CERN is now actively fundraising, seeking private and public donations to implement this exciting project.

## EDUCATING THE SCIENTISTS OF TOMORROW

CERN’s engagement with science education focuses mainly on secondary school teachers and students. CERN’s teacher programmes help participants to increase their insight into particle physics, share experiences with other teachers and foster a love of science in future generations of students. The success of the traditional three-week international high-school teacher programme in July, with 43 teachers from 34 countries, led to the addition of a new two-week international teacher programme in August, with 44 teachers from 37 countries. In addition, 31 one-week national teacher programmes, held in the teachers’ national language, welcomed almost 1000 participants from 58 countries.

CERN has introduced additional programmes for school students to strengthen their understanding of science, develop their skills in a high-tech environment and ignite their passion for a career as a scientist or engineer. The High-School Students Internship Programme (HSSIP) was launched in May 2017 when 22 Hungarian students, aged between 16 and 19 years, spent a two-week internship at CERN. Hungary was one of the five pilot countries (alongside Bulgaria, France, Norway and Portugal) that participated in the programme in 2017, with a total of almost 120 students. In the coming years, the programme will be made available to all CERN Member States.

*CERN’S TEACHER PROGRAMMES  
HELP TO FOSTER A LOVE OF SCIENCE  
IN FUTURE GENERATIONS OF  
STUDENTS.*



*The High-School Students Internship Programme (HSSIP) was launched in May 2017 with the arrival of 22 Hungarian students, aged between 16 and 19, seen here during their visit to CERN’s magnet testing facility. (CERN-PHOTO-201705-131-24)*

The first two-week S’Cool LAB summer camp welcomed 24 high-school students, selected from more than 2000 applicants from 24 different countries. The camp offered hands-on physics experiments in small groups. S’Cool LAB also offers regular workshops which welcomed 7230 participants in 2017. The S’Cool LAB is now operating at its maximum capacity.

The Beamline for Schools competition, running for the fourth consecutive year, received 180 proposals from student teams in 43 countries worldwide. The two winning teams, from Canada and Italy, were invited to CERN in September to conduct their experiments at the Proton Synchrotron. Both teams are aiming to follow students from previous years by writing scientific papers about the results of their experiments.

CERN supported the “Hands on Particle Physics” International Masterclasses, involving more than 13 000 high-school students in 52 countries, organised by the International Particle Physics Outreach Group. Students spent the day working with recent data from the LHC experiments. They also listened to lectures about particle physics and the process leading to a scientific discovery.

Several of these programmes were backed financially by the CERN & Society Foundation, whose aim is to “spread the CERN spirit of scientific curiosity for the benefit of society”. In 2017, the Foundation focused on the support of teacher and student activities: 90 schoolteachers received partial support for their participation in the National Teacher Programmes and 39 summer students from non-Member States were granted a full scholarship. The Foundation also fully financed the Beamline for Schools competition.

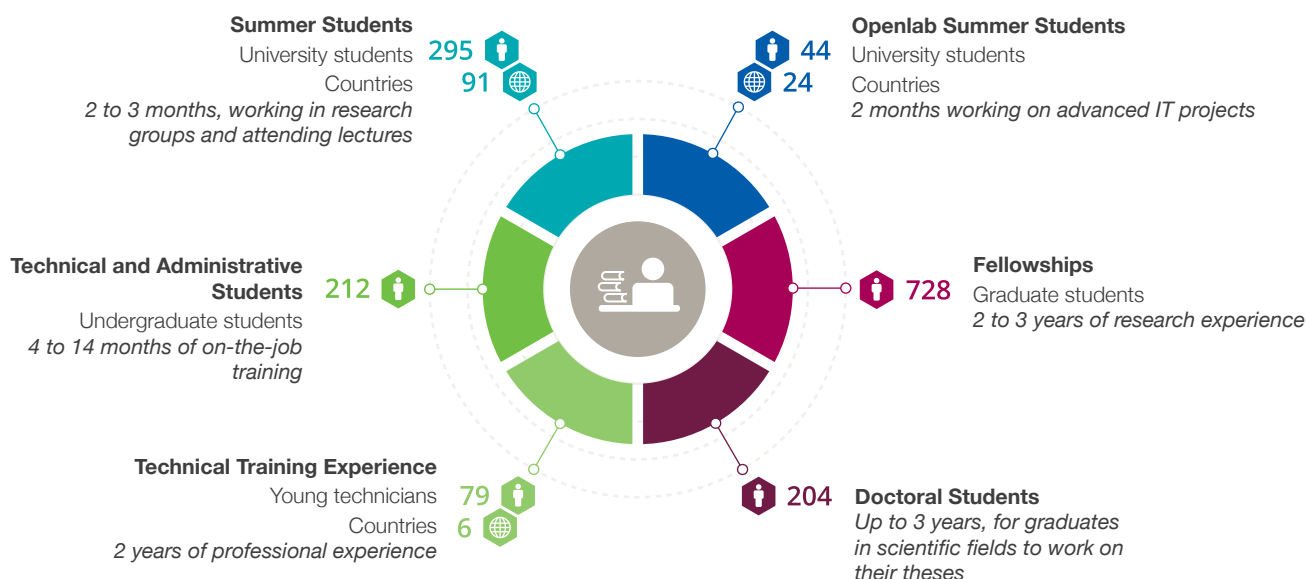


CERN’s training programmes provide opportunities to acquire early-career professional experience. Here, a summer student and her supervisor work on ATLAS physics research. (ATLAS-PHOTO-2016-015-4)

## 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 training environment for graduate and post-graduate students, providing a steady stream of highly qualified people with excellent technical skills and international experience to take back to business and industry in CERN’s Member States. More than 2000 young people were trained in 2017, including more than 800 fellows, over 400 doctoral, technical and administrative students and some 470 trainees.

## TRAINING PROGRAMMES AT CERN



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



# A SUSTAINABLE RESEARCH ENVIRONMENT

***CERN is fully committed to ensuring the health and safety of everyone participating in its activities, present on the site or living in the vicinity of its installations. CERN works to limit the impact of its activities on the environment, and to guarantee best practice in matters of safety.***

*Members of CERN's environmental protection team collect samples from a watercourse that receives effluents from several of the Laboratory's sites. Each year, some 3000 samples are taken in and around the CERN sites to monitor CERN's impact on the local environment. (CERN-PHOTO-201804-100-5)*





## PROTECTING HEALTH, SAFETY AND THE ENVIRONMENT

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In 2017, the newly established CERN Environmental Protection Steering board (CEPS) got to work, making a series of recommendations to minimise CERN's environmental impact. In parallel, CERN's Energy Management Panel (EMP) continued to ensure that the Laboratory's energy was put to the most efficient use possible. A recently formed working group on mobility also made its first recommendations to keep things moving smoothly at the Laboratory.

Other highlights from the year included a drive to increase the percentage of conventional waste that is recycled, and the elimination of a substantial volume of low-level radioactive waste.

## ENVIRONMENTALLY RESPONSIBLE RESEARCH

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CERN's Environmental Protection Steering board (CEPS) was established to examine the Laboratory's environmental impact across eleven domains, identify priorities and propose actions. In 2017, CERN's water usage and its waste water system, along with the handling and storage of hazardous substances, were the first subjects to come under scrutiny. A number of actions have been identified and are currently being planned and implemented. In some of CERN's underground installations, for example, naturally occurring hydrocarbons are present in the water that seeps out of the rock. Consolidation of the hydrocarbon capture process will ensure that these are efficiently dealt with before water is released. Furthermore, water retention basins are to be constructed at strategic points to contain any accidental release of pollutants, regulating releases triggered by heavy rain and so protecting local watercourses.

Another potential source of environmental impact is the release of gases from particle detection systems. CERN has committed to reducing such emissions considerably while in parallel launching an R&D project to identify environmentally friendly gas mixtures for future detectors.

Particle accelerators are energy-hungry machines, so CERN strives to maximise the efficiency of its energy use. To this end, it established an Energy Management Panel (EMP) in 2015, and several measures have since been put in place to economise energy wherever possible. In a recent consolidation of the East Area experimental hall, improving energy efficiency was part of the design brief, with the result that the beam line magnets will now be pulsed so that they are on only when needed. This simple expedient reduces energy consumption by 90% in the East Area hall.

Other measures include an energy economy cycle for the SPS accelerator that kicks in when beam is not available from the upstream accelerators. The major LHC experiments are also implementing low-energy modes for periods of

operational stops, and preparations are being made to recycle heat generated by CERN's cooling systems to heat local neighbourhoods and CERN's Meyrin site.

## A BOOST FOR RECYCLING

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All in all, some 50% of the conventional waste produced by CERN is recycled, putting the Laboratory in a leading position in the Geneva region, but more could be done. To this end, a recycling awareness week was held at the Laboratory in November, informing personnel of what is already recycled and encouraging people to recycle more. All the waste from CERN's offices and restaurants is sorted at a dedicated plant, with anything that is not recyclable or compostable being incinerated to generate energy. At the various worksites around the Laboratory, recycling is being proactively implemented. Such actions resulted in CERN recycling 543 tonnes of wood, 294 tonnes of paper and cardboard, and 5.4 tonnes of PET in 2016 (the most recent available data).

## A LABORATORY IN MOTION

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With increasing numbers of people at CERN, challenging commuting conditions across a busy international border, numerous daily inter-site trips and surging demand for parking, mobility is becoming a pressing issue. To address the challenge, the Organization established a mobility working group in 2017 to make mobility at CERN safer, greener and more enjoyable for all. The group's objectives are to optimise the supply and management of CERN parking spaces, to promote alternative modes of transport, and to optimise traffic safety and fluidity within

*Measures have been taken to promote the use of bicycles, involving safety improvements at site entrances and the installation of bicycle repair stations. (CERN-PHOTO-201804-087-4)*



and around the CERN sites. In 2017, the group began a fact-finding exercise with a view to presenting a mobility plan to the CERN Management in 2018. This will include an action list aimed at meeting these objectives by 2030. In the meantime, many actions have already been taken, such as the automation of CERN's entrance gates, the establishment of a CERN Mobility Centre, the construction of a cycle path between the Meyrin and Prévessin sites, safety improvements for cyclists and pedestrians at CERN's entrances, and the installation of bicycle repair stations.

Among the new ideas being studied are measures to increase traffic flow at the French entrance to the Meyrin site, which is a major rush-hour bottleneck, the introduction of cycle paths and one-way streets on the CERN sites, and the setting-up of a CERN ride-sharing scheme.

**MOBILITY INITIATIVES SUCH AS BIKE PATHS AND REPAIR STATIONS ARE MAKING CERN GREENER AND SAFER.**

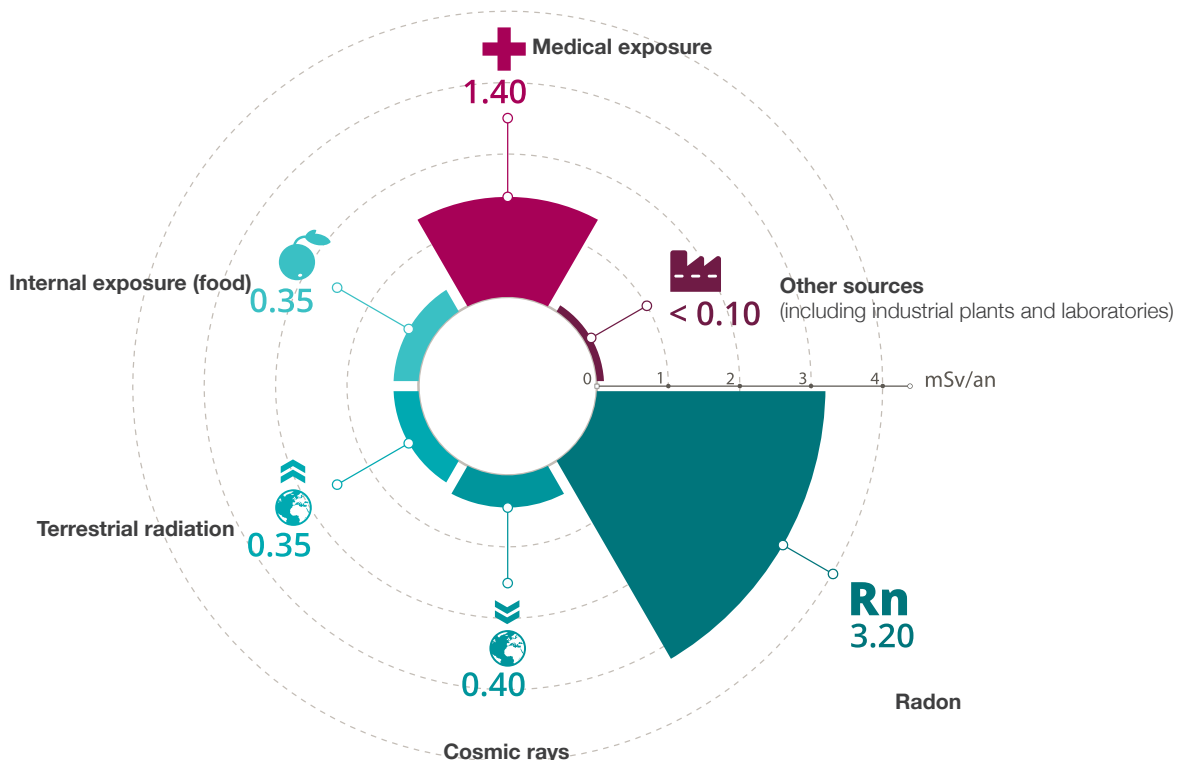
### A PARTNERSHIP THAT SAVES LIVES

The partnership established between CERN and the Geneva University Hospitals (HUG) in 2015 was designed to make the most of the synergy between CERN's emergency response teams and the largest hospital in the region. The agreement is built around the stationing of a cardiomobile and paramedical team at CERN.

### EXPOSURE TO IONISING RADIATION

People are constantly exposed to radioactivity in their everyday lives. This is known as ionising radiation because it can interact with matter and strip electrons away from atoms. Ionising radiation can come from natural sources, either on Earth or from space (cosmic rays), from our food (internal exposure) or from artificial sources such as medical examinations. The doses received vary greatly from one person to another, depending on lifestyle, and from one region to another.

The sources of radiation to which people are exposed are mainly radon, a gas that comes from uranium in the Earth and is emitted in our homes, medical treatments and natural radioactivity. Industrial plants and scientific research institutions are much weaker sources of radiation. CERN's contribution is around 0.01 to 0.02 mSv per year at the perimeter of its sites. CERN has 136 monitoring stations and takes numerous samples and analyses every year, which it submits to the competent authorities in its two Host States.



Average radiation doses received per person per year in Switzerland [in mSv/year/person] by origin. (source: Swiss Federal Office of Public Health, 2016).

The CERN-HUG partnership provides coverage not only for CERN, but also for the western side of the canton of Geneva and the surrounding area. It effectively integrates CERN into Geneva's emergency response systems. As a result of the agreement, CERN's emergency control room now has a permanent link and a single point of contact with the ambulance and emergency services control centre in Geneva. CERN's ambulance assists the Geneva fleet on request, improving service both for CERN and for the canton, and making survival much more likely in the event of an emergency.

As well as an immediate improvement in emergency response, the partnership with the HUG brings long-term benefits to CERN. For example, the HUG now provide training in emergency response to CERN personnel in the Medical and Fire and Rescue Services, and the Laboratory's ambulance personnel are now able to take a course leading to the award of a diploma recognised nationally in Switzerland (the *Brevet Fédéral de Technicien Ambulancier*). The partnership also allows on-the-job training for safety control room personnel.

## RECYCLING LOW-LEVEL RADIOACTIVE WASTE

The operation of particle accelerators results in the activation of certain components. Most of the isotopes produced have half-lives of minutes or even seconds, but some can have longer half-lives. Some components therefore remain radioactive for several years and have to be stored at CERN until they are prepared for disposal at CERN's waste treatment centre. In 2017, some 3000 m<sup>3</sup> of waste was safely eliminated in the course of the year. This largely consisted of accelerating modules from the LEP accelerator, recycled in Switzerland as conventional metals after release from regulatory control, and cables, disposed of as very low-level radioactive waste in France. This amount of low-level radioactive waste eliminated in 2017 was considerably higher than the 630 m<sup>3</sup> produced during the year.

## SUPPORTING THE UN'S SUSTAINABLE DEVELOPMENT GOALS

In October, the United Nations Office in Geneva held a public Open Day in which CERN was invited to participate. The Organization used the opportunity to show how research at CERN contributes to the UN's Sustainable Development Goals (SDGs). The SDGs are ambitious – the UN's goals always have been – and that ambition has paid off. Over the decades, the UN development goals have kept a range of critical challenges in the spotlight, and they have made a real difference to millions of people's lives.

The link between the SDGs and fundamental physics research might not be immediately obvious, but of the 17 goals, ranging from eliminating poverty and hunger to promoting peace and justice through strong institutions, there are five to which CERN contributes simply by carrying out its core mission.

CERN promotes health and well-being, a domain to which particle acceleration and detection technologies have been contributing for decades, through applications such as medical scanners and accelerators for hadron therapy. CERN's range of educational programmes, formal and informal, serves students and educators from around the world. The Laboratory promotes innovation through its knowledge transfer activities. The promotion of peaceful and inclusive societies is an integral part of CERN's governing convention. The final SDG goal aims to strengthen the means of implementation of the preceding 16 by revitalising the global partnership for sustainable development. CERN is a model for global cooperation in science and continues to inspire and provide practical guidance in different areas of science and in other areas of human endeavour.



### A safe space for chemicals

A brand new building housing laboratories for the surface treatment of vacuum equipment, and workshops for the manufacturing and treatment of printed circuit boards, was completed in 2017. An extensive risk assessment was carried out to ensure safe handling of chemicals, resulting in the incorporation of state-of-the-art safety systems in the building's design. The tanks in which chemicals are stored, for example, are equipped with a double skin and leak detection sensors, and are installed above high-tech retention basins able to withstand more than 100 different types of chemical. The building is equipped with solar panels and a heat recovery system, saving around half the energy that would otherwise be needed to heat it.



# BUILDING TOMORROW AND BEYOND

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

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





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

## ACCELERATING TOWARDS HIGH LUMINOSITY

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

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

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

The so-called crab cavities will give the particle bunches a transverse momentum in order to optimise their orientation before they collide. This technology, being used for the first

time in a hadron collider, made a leap forward in 2017 when the first two cavities were manufactured in collaboration with the University of Lancaster and STFC in the United Kingdom, then assembled and successfully tested. At the end of the year, they were ready to be transported to the SPS accelerator. A radiofrequency test station equipped with a novel mobile helium cooler was developed to test the crab cavities with beam in 2018.

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

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

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

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

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





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

## CUTTING-EDGE TESTING

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

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

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

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



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

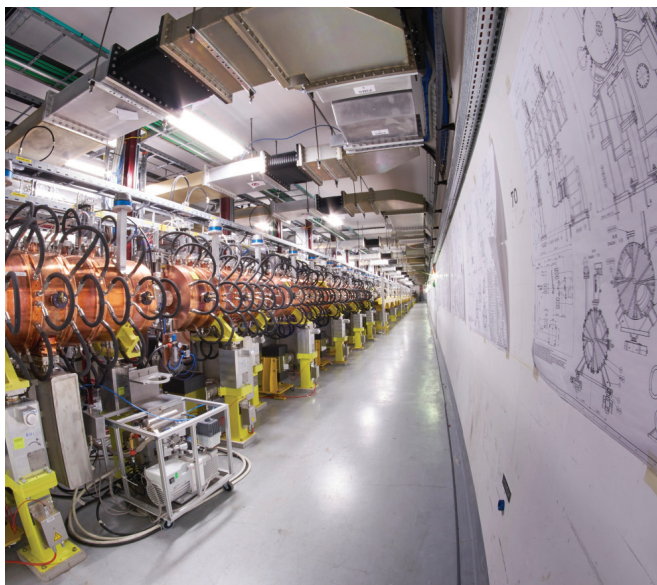
## A NEW MEMBER JOINS THE ACCELERATOR FAMILY

On 9 May, CERN's accelerator family welcomed its newest member – Linear Accelerator 4 (Linac4). This was the first inauguration of a new accelerator at CERN since the LHC started up in 2008. In 2019, it will be connected to the next accelerator in the chain, the Proton Synchrotron Booster,

and will replace Linac2 as the first link in the accelerator chain after Long Shutdown 2, in 2021. In the spring, the 160MeV Linac4 was fully commissioned and entered a stand-alone operation run to assess and improve its reliability, prior to being connected to the CERN accelerator complex.

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





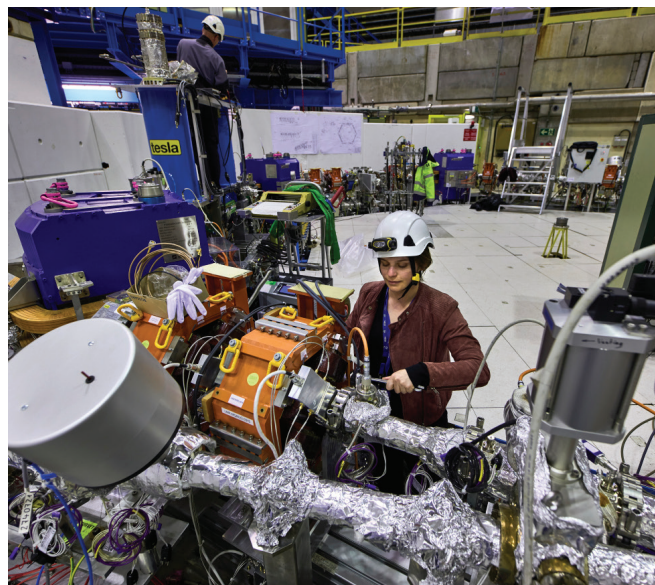
*The Linac4 accelerator, inaugurated in May 2017, is composed of four types of structure and will accelerate beams up to 160 MeV. (CERN-PHOTO-201704-093-11)*

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

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

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

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



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

## ANTIMATTER CIRCULATES IN A NEW DECELERATOR

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

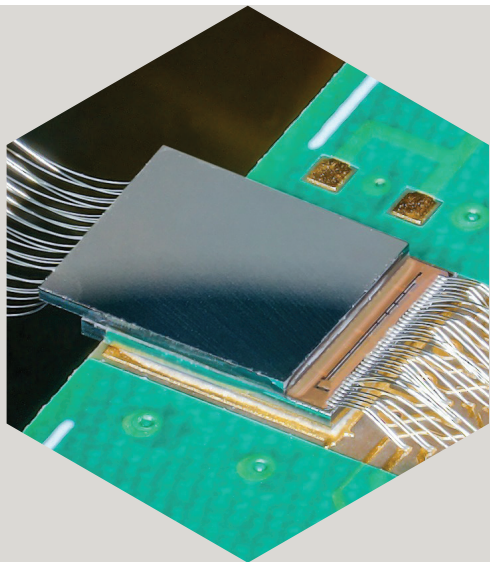
The ELENA ring is connected to the Antiproton Decelerator and is designed to slow down antiprotons even further before transferring them to the antimatter experiments. The energy level will be reduced from 5.3 MeV to just 0.1 MeV, since the slower the antiprotons are, the easier it is for the experiments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

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

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

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





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

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

### SHAPING THE FUTURE

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

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

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

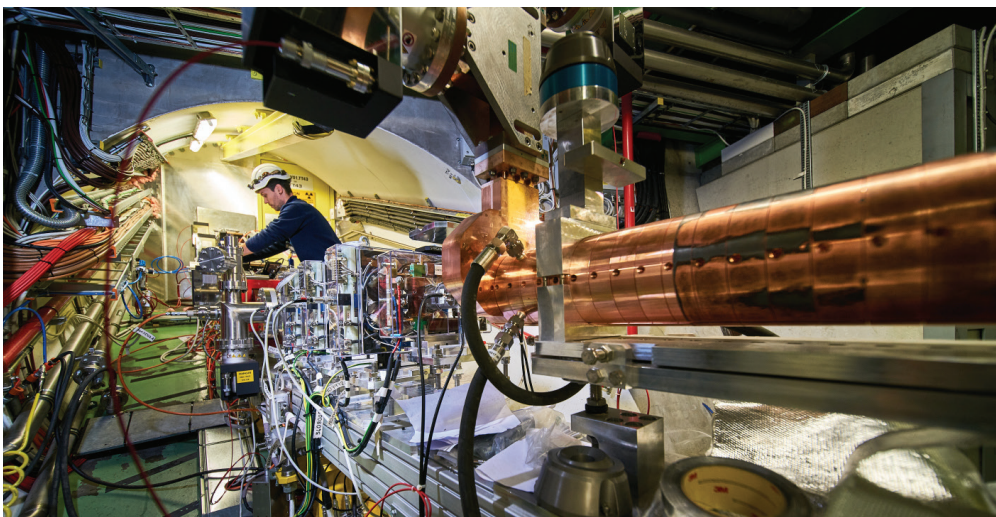
The beam optics (the way in which the beams are directed and focused) were refined and optimised. The physics opportunities were explored in depth during the first dedicated FCC physics week. Teams continued to work on the location of the tunnel in the region and produced preliminary studies demonstrating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

Key technologies for the lepton collider (FCC-ee) are superconducting radiofrequency (RF) cavities and high-efficiency RF power production. A collaboration between CERN, LNL (Italy) and STFC (UK) is evaluating the ultimate

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

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

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



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

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

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

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

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

## CLOSER TO A BREAKTHROUGH IN ACCELERATION TECHNOLOGY

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

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

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

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



# CERN COUNCIL

Composition as at 31 December 2017

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**Vice-Presidents:** Professor E. Rabinovici (Israel), Professor J. J. Gaardhøje (Denmark)

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Ms C. Durkin

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Mr A. Srivastava

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### Turkey

Mr Z. Demircan  
Mr U. Güneş

### Ukraine

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Dr A. Zagorodniy

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JINR, Russian Federation,  
UNESCO, United States of  
America

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(United Kingdom)

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Professor J. Nash

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Professor H. Abramowicz

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Professor S. de Jong

#### Chair of the Finance Committee

Mr O. Malmberg

#### Director-General

Dr F. Gianotti

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Mr O. Malmberg  
(Finland)

### Members

One or more delegates from  
each Member or Associate  
Member State



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Internal Audit, Legal Service  
Occupational Health & Safety and Environmental Protection Unit (HSE)

**Fabiola Gianotti**

Doris Forkel-Wirth

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Engineering (EN)  
Technology (TE)

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Paul Collier  
Roberto Losito  
José Miguel Jiménez

## **Director for Finance and Human Resources**

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Human Resources (HR)  
Industry, Procurement and Knowledge Transfer (IPT)  
Site Management and Buildings (SMB)

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Florian Sonnemann  
James Purvis  
Thierry Lagrange  
Lluis Miralles

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Member States, Associate & Non-Member States,  
International Organisations, Partnerships & Fundraising  
Strategic Planning & Evaluation, Protocol  
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**Charlotte Warakulle**

Ana Godinho

## **Director for Research and Computing**

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Experimental Physics (EP)  
Information Technology (IT)  
Theoretical Physics (TH)

**Eckhard Elsen**

Manfred Krammer  
Frédéric Hemmer  
Gian Giudice

## **Project Management**

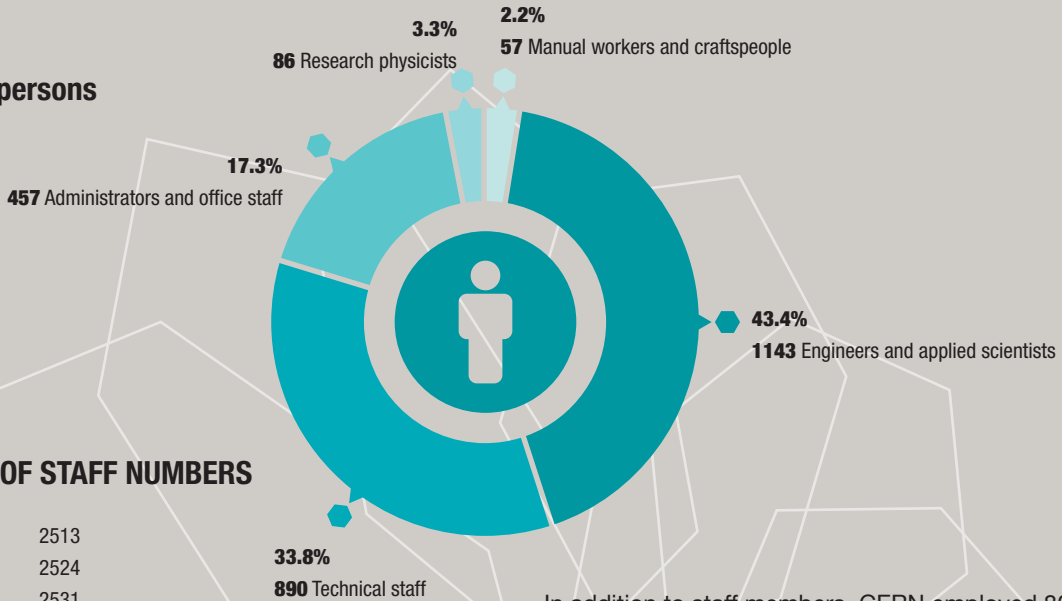
Advanced Wakefield Experiment (AWAKE)  
CERN Neutrino Platform  
Extra Low Energy Antiproton (ELENA)  
Future Circular Collider Study (FCC)  
High Intensity and Energy ISOLDE (HIE-ISOLDE)  
High Luminosity LHC (HL-LHC)  
LHC Injectors Upgrade (LIU)  
Linear Collider Studies (CLIC and LCS)  
Physics Beyond Colliders (PBC)  
Worldwide LHC Computing Grid (WLCG)

Edda Gschwendtner  
Marzio Nessi  
Christian Carli  
Michael Benedikt  
Yacine Kadi  
Lucio Rossi  
Malika Meddahi  
Steinar Stapnes  
Mike Lamont  
Ian Bird

# CERN IN FIGURES

## CERN STAFF

Total: 2633 persons



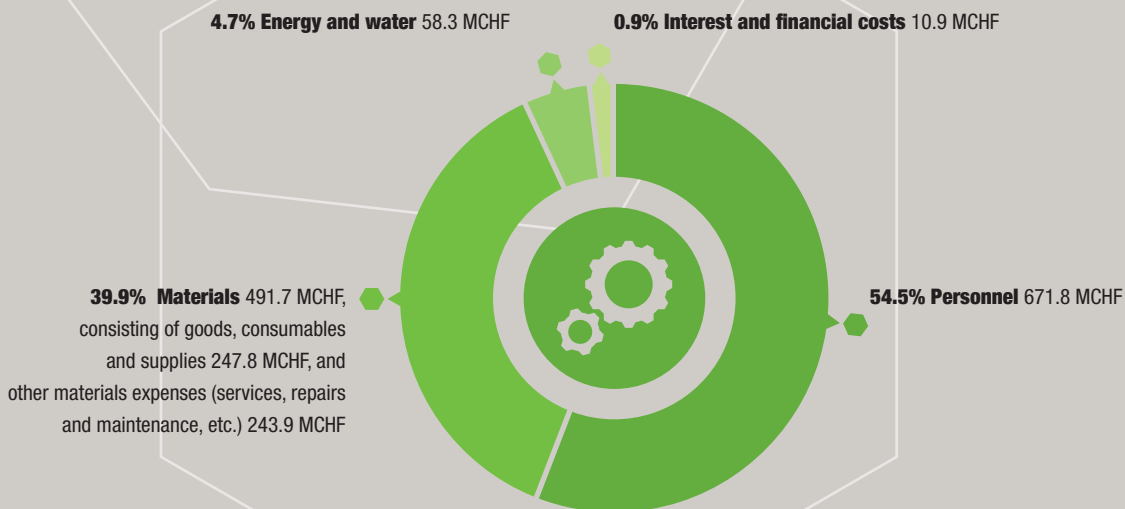
## EVOLUTION OF STAFF NUMBERS

2013	2513
2014	2524
2015	2531
2016	2560
2017	2633

In addition to staff members, CERN employed 807 fellows (including TTE technicians), trained 579 students and apprentices and hosted 1277 associates in 2017. CERN's infrastructure and services are used by a large scientific community of 12 236 scientists

## CERN EXPENSES

Total expenses 1232.7 MCHF



In 2017, more than 40% of CERN's budget was returned to industry through materials, utilities and services. CERN aims to balance its expenditure across its Member States (see p. 35).



**CERN****1211 Geneva 23, Switzerland****<http://home.cern>**

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

CERN's Annual Report aims to present the highlights and the main activities of the Laboratory. For the electronic version, see: <http://library.cern/annual-reports>

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/annual-progress-report-2017>

The 2017 Knowledge Transfer annual report is available at:

<http://kt.cern/about-us/annual-report>

The 2017 CERN openlab annual report is available at:

<http://openlab.cern/resources/annual-reports>

The 2017 CERN & Society annual report is available at: <http://cern.ch/go/cernandsociety2017>

The community white paper from the High-Energy Physics Software Foundation (HSF) is available at: <http://cern.ch/go/whitepaperHSF>

The openlab white paper on IT challenges in scientific research is available at:

<http://cern.ch/go/whitepaperopenlab>

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-2017>

A glossary of useful terms is available at: <http://cern.ch/go/glossary>

**Images:**

Robert Hradil, Monika Majer/ProStudio22.ch: p. 3 (right), 14 and 31

SESAME: p. 7, right

Robertas Dačkus/ Office of the President of the Republic of Lithuania: p. 8, bottom centre

Samuele Evolvi: p. 11, left

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**Editorial and Design Production:**

CERN Education, Communications and Outreach Group

[eco.office@cern.ch](mailto:eco.office@cern.ch)

**Translation and Proofreading:**

CERN Translation service

ISSN 0304-2901

ISBN 978-92-9083-484-7 (printed version)

ISBN 978-92-9083-485-4 (electronic version)

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