Annual Report
2016

CERN

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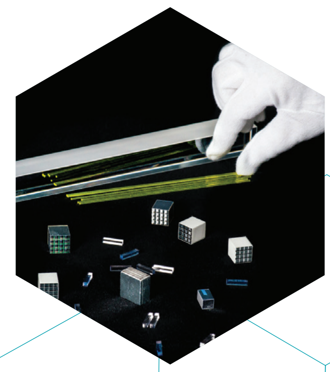
CERN, the European Organization for Nuclear Research, is the world's leading laboratory for particle physics. It provides a unique range of particle accelerator facilities enabling research at the forefront of human knowledge. Its business is fundamental physics, finding out what the universe is made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



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MESSAGE FROM THE PRESIDENT OF THE COUNCIL

CERN began the year 2016 with a new Director-General and a new President of Council, a rare coincidence but one that allowed me to forge a very strong relationship with the new Management team. Over the course of the year, the Council and the Management worked together in a very open and transparent way to advance the work of the Laboratory.

The highlight of the year at CERN was undoubtedly the exceptional performance of the LHC, the whole accelerator chain, the experiments and the computing. All worked in perfect harmony to deliver science of the highest calibre. The LHC was made possible by combing the resources of many nations, but these results could not have been realised without the concerted efforts of individuals. Such hard work does not go unnoticed, and I would like to express my gratitude, on behalf of my colleagues in the Council, to all the people who contributed to making 2016 such a success.

The healthy breadth of the CERN programme is illustrated by many new results in other research areas. To name but a few, these include the experiments at the Antiproton Decelerator and the ISOLDE radioactive beam facility, the proton-driven plasma wakefield experiment AWAKE, and the climate research experiment CLOUD. These experiments, many of which can be done only at CERN, show how the Organization strives to make the best possible use of its infrastructure, maximising the scientific return on investment.

In terms of Council business, the most important achievement of 2016 was ensuring the future success of the LHC via the formal approval of the High-Luminosity LHC project, the HL-LHC. Scheduled to come on stream in 2025, the HL-LHC will give the LHC experiments greater precision, as well as an improved discovery potential through to 2035.

The Council also worked towards a secure future across the full range of CERN research by making the first preparations for the next update of the European Strategy for Particle Physics. The work is getting under way now, and much of the relevant information is expected to be on the table by the end of 2018, with discussions in the European particle physics community taking place in 2019. The updated Strategy will be presented to the Council in spring 2020.

CERN's membership also continued to grow during the year, with Romania becoming a new Member State. Cyprus became an Associate Member in the pre-stage to Membership, and Ukraine became an Associate Member. The Council voted to admit Slovenia as an Associate Member in the pre-stage to Membership and India as an Associate Member, with the expectation that the relevant national authorities will ratify these Associate Memberships in 2017. It was my great pleasure to welcome them all. Collaboration is the lifeblood of progress, and it is always gratifying to see that the CERN ideal of uniting diverse nations and peoples remains attractive in today's rapidly evolving world. Great things come through unity.

Finally, I'd like to single out two of my colleagues on the Council. 2016 saw another rare double transition as Tatsuya Nakada and Charlotte Jamieson stepped down as Chairs of the Scientific Policy Committee and the Finance Committee respectively. I would like to thank them both warmly for their many years of service, and to welcome Keith Ellis and Ossi Malmberg as their successors.

When I was elected as President of Council in September 2015, I remarked that CERN was full of ambition and in an excellent position to move particle physics forward with the LHC in full swing. One year into the job, I can only underline how true that is.

Sijbrand de Jong

MESSAGE FROM THE DIRECTOR-GENERAL

2016 was an excellent year for CERN research and for all aspects of the Organization's activities. It began with organisational changes introduced by the new Management. To CERN's three sectors, Research and Computing, Accelerators and Technology, and Finance and Human Resources, we added a fourth, for International Relations, bringing relations with the Member States, geographical enlargement, and education, communications and outreach all together under one roof.

The LHC surpassed its design luminosity in 2016 and ran with metronomic regularity. Ably served by the injectors, the LHC delivered data for physics for 50% of its running time, an unprecedented achievement for any accelerator at the high-energy frontier, let alone one so complex. This allowed the ATLAS and CMS experiments to record over 50% more data than their target for the year and provided all the LHC experiments with a rich resource to search for new physics and explore the physics landscape with ever-greater precision. More data bring greater challenges for the computing infrastructure, which performed admirably in 2016, with about 50 petabytes of LHC data recorded, average data transfer rates of 35 gigabytes per second and two million jobs per day being run. Greater precision implies more work for the theorists, who are providing increasingly precise calculations for comparison with the emerging experimental results.

The LHC was not alone in delivering a harvest of exciting results, as the year saw highlights across the full scientific programme. For example, the ALPHA experiment provided the first measurement of spectral lines of antihydrogen, while the CLOUD experiment continued to produce valuable data for climate modelling. The extension of the North Area hall, which hosts part of the CERN neutrino platform, was completed in 2016, and excellent progress was made on the refurbishment, development and construction of detectors for neutrino experiments in the US and Japan.

The full exploitation of the LHC is our highest priority for the short to medium term, and I am grateful to the CERN Council for its formal approval of the high-luminosity upgrade, HL-LHC. A European Investment Bank credit facility, also agreed in 2016, will allow the upgrade to be financed within a constant CERN budget without compromising or delaying the rest of the scientific programme. Looking further ahead, the CLIC, FCC and AWAKE projects all took significant steps forward in 2016, with AWAKE demonstrating the self-modulated instability of proton beams traversing a plasma cell as the first step towards plasma wakefield acceleration of an electron beam.

Education and training are always highlights of the CERN programme. In 2016, some 1600 young people received high-quality training through a range of programmes including the fellows, doctoral students and summer students programmes. In 2016, the number of participants in CERN's high-school teacher programmes passed the 10 000 mark, while the number of visits from members of the public continued to grow. Over 120 000 people visited CERN during the year.

Underpinning all this is our commitment to upholding the highest standards in health, safety and environmental protection. 2016 was no exception, with the establishment of a CERN Environmental Protection Steering board and the achievement of great progress in the safe elimination of low-level radioactive waste.

Last but not least, the CERN family continued to grow in 2016, with Romania becoming CERN's 22nd Member State. Cyprus became an Associate Member in the pre-stage to Membership, and Ukraine became an Associate Member.

This is just a snapshot of CERN's diverse and exciting programme. I hope you'll enjoy learning more in the following pages of this report.

Fabiola Gianotti

2016 IN PICTURES

From the achievements of the Large Hadron Collider to the growth of the CERN family, hundreds of new physics results and visits from numerous VIPs, here we take a look back at the year's highlights in pictures.

20 JANUARY

The President of Lithuania, Dalia Grybauskaitė, visits CERN and learns about the experiments being carried out in S'Cool LAB, a laboratory for high-school students.

15 FEBRUARY

Fabiola Gianotti, CERN Director-General, opens "Physics for Health in Europe", a major medical conference co-organised by CERN. This interdisciplinary conference brings together physicists, engineers, doctors and IT specialists to look for innovative solutions in the fields of medical imaging and cancer treatment.

23 JANUARY

Muhammad Nawaz Sharif (centre), Prime Minister of Pakistan, admires the CMS experiment, guided by Tiziano Camporesi (right), the experiment's spokesperson. Pakistan became an Associate Member State of CERN in 2015.

24 MARCH

Johann Schneider-Ammann, President of the Swiss Confederation, signs CERN's guestbook in the presence of the Director-General.

25 MARCH

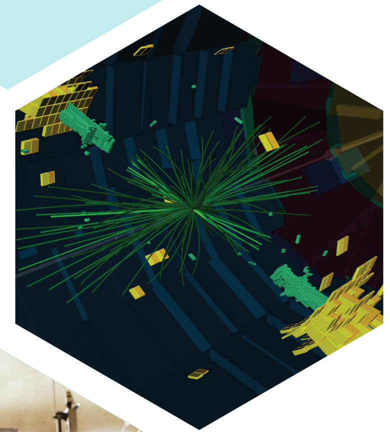
Particles begin circulating again in the LHC, marking the start of its 2016 run. After a few weeks, the intensity of the beams is increased and the experiments start to take data (see p. 21).

25 MAY

The CLOUD experiment publishes new results on the formation and growth of aerosol particles in the atmosphere, which go on to form clouds. The results suggest that the climate was cloudier in the pre-industrial age than previously thought (see p. 17).

26 JUNE

The LHC exceeds its nominal luminosity for the first time. Luminosity is a measure of a collider's efficiency and is proportional to the number of collisions delivered to the experiments (see p. 21).

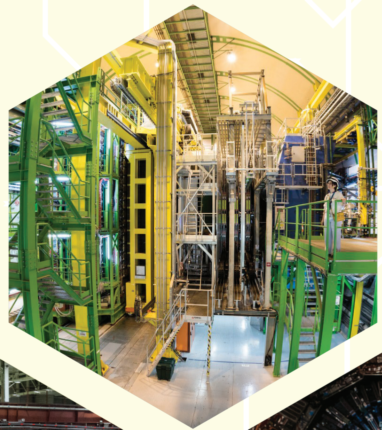


4 APRIL

The Republic of Cyprus becomes a CERN Associate Member State in the pre-stage to Membership, following the ratification by its parliament of the agreement signed four years earlier. George Pamboridis, Cyprus's Minister of Health, visits CERN in May. He is pictured here with Charlotte Warakaulle, Director for International Relations, and Frédérick Bordry, Director for Accelerators and Technology.

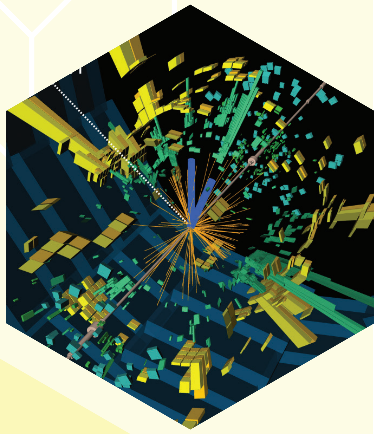
17 JUNE

The AWAKE experiment receives its first beam of particles. The project is designed to study a new acceleration technique for the accelerators of the future (see p. 49).



28 JUNE

At the LHCb experiment, three new exotic particles are observed and the existence of another is confirmed. Each are formed from two quarks and two anti-quarks (see p. 16).



19 AND 21 JULY, 13 SEPTEMBER

When physics meets music... The rock group Muse, led by singer Matt Bellamy (left), gets a behind-the-scenes look at the CERN Control Centre. Two days later, the four members of the British band Bastille discover CERN's antimatter experiments (top left). In September, CERN receives a visit from the Canadian group Nickelback (centre).

5 AUGUST

Physics in the Windy City! Particle physicists meet up in Chicago in the United States for their flagship biennial meeting, the International Conference on High Energy Physics (ICHEP). Thanks to the exceptional performance of the Large Hadron Collider (LHC), the experiments have gathered huge amounts of data and are able to present around a hundred new results.

10 AUGUST

The MoEDAL collaboration celebrates the publication of its first physics results. The experiment is searching for a hypothetical particle, the magnetic monopole (see p. 15).

16 SEPTEMBER

Students from the two winning teams of the 2016 Beamline for Schools competition, from Poland and the United Kingdom, come to CERN for a week to carry out their experiments using a CERN accelerator.

5 SEPTEMBER

The CERN family continues to grow! The Laboratory welcomes Romania as its 22nd Member State. The blue, yellow and red flag joins those of the other 21 Member States in a ceremony attended by the President of the CERN Council, Sijbrand de Jong, CERN Director-General, Fabiola Gianotti, the President of Romania, Klaus Iohannis, and the Romanian Minister for Education and Scientific Research, Mircea Dumitru.

30 SEPTEMBER

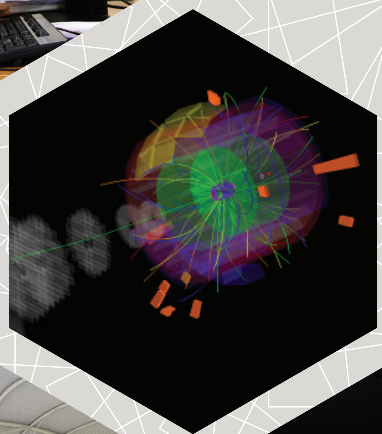
Around 600 people flock to the Globe of Science and Innovation and the ATLAS experiment's Visitor Centre for European Researchers' Night.

5 OCTOBER

Ukraine becomes an Associate Member State of CERN following ratification by its parliament of the agreement signed in October 2013.

10 OCTOBER

UNOSAT, the operational satellite applications programme of the United Nations Institute for Training and Research, celebrates its 15th birthday. UNOSAT uses the infrastructure of CERN's Data Centre for humanitarian purposes, producing extremely precise maps of regions of the world affected by natural disaster or conflict.

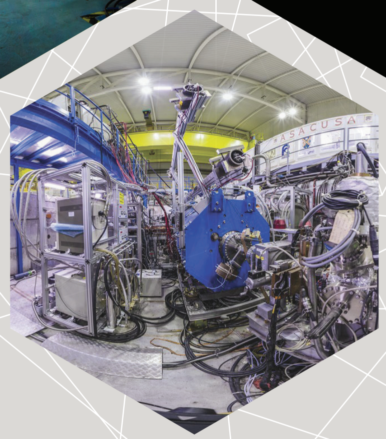


10 NOVEMBER

Lead nuclei begin circulating in the Large Hadron Collider (LHC). From now until the year-end technical stop, the LHC will produce collisions only between protons and lead ions. The image shows one of the first such collisions recorded by the ALICE experiment.

25 OCTOBER

Linac4 accelerates its first beam at its design energy of 160 MeV. The accelerator will be connected to CERN's accelerator chain in 2019 (see p. 46).



3 NOVEMBER

The ASACUSA antimatter experiment announces a new precise measurement of the mass of the antiproton compared to the mass of the electron (see p. 17).

5 NOVEMBER

The 2016 TEDxCERN event, entitled "Ripples of Curiosity", brings together 12 pioneers from various scientific fields, whose ideas have caused waves of change (see p. 38).

21 NOVEMBER

Fabiola Gianotti, CERN Director-General, and Sekhar Basu, President of India's Atomic Energy Commission and Secretary of India's Department of Atomic Energy (DAE), sign an agreement with a view to the admission of India as an Associate Member State of CERN.

19 DECEMBER

The ALPHA antimatter experiment observes the light spectrum of antimatter for the first time (see p. 17).

30 NOVEMBER

SESAME, Synchrotron-Light for Experimental Science and Applications in the Middle East, comes full circle with the installation of its accelerator. Located in Jordan, the centre is a collaboration between several Middle Eastern countries and is the region's first synchrotron laboratory. In July, it launched its first call for proposals for experiments, which are due to begin in 2017. CERN contributed to the construction of SESAME by developing magnets in the framework of the CESSAMag project, which was co-funded by the European Commission.

16 DECEMBER

The Minister of Education, Science and Sport of Slovenia, Maja Makovec Brenčič (left), and CERN Director-General, Fabiola Gianotti, sign an agreement under which the Republic of Slovenia will become an Associate Member State in the pre-stage to Membership.

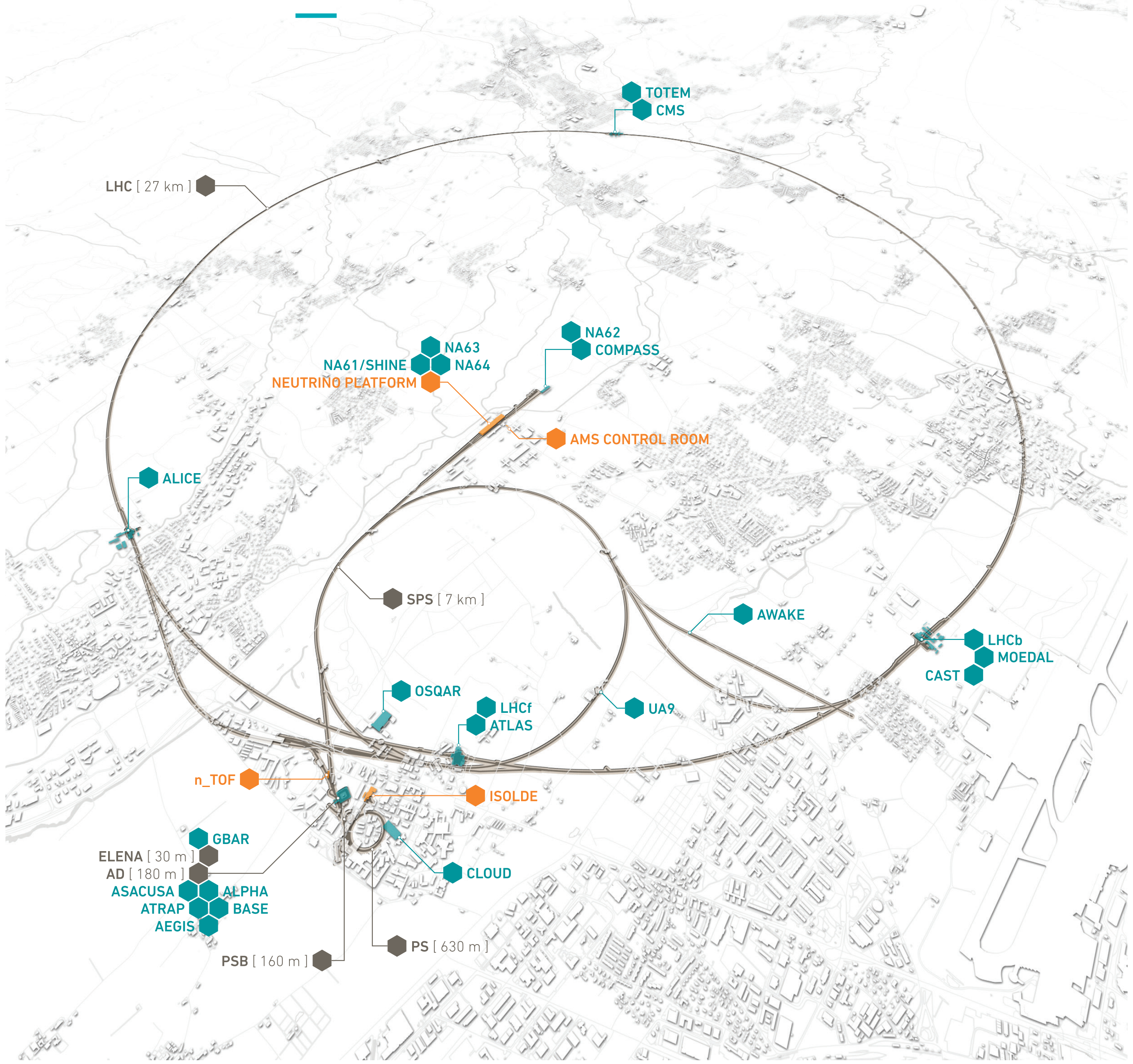
19 DECEMBER

Arturo Cabrera (left), deputy permanent representative of Ecuador to the United Nations Office and other international organisations in Geneva, and Eckhard Elsen, CERN Director for Research and Computing, mark the donation of IT equipment to an Ecuadorian educational establishment. Thanks to this equipment, the National Polytechnic School will be able to set up a data centre that will form part of the Worldwide LHC Computing Grid (WLCG). CERN has now made ten donations of IT equipment to various educational establishments around the world.

EXPLORING THE NATURE OF THE UNIVERSE

To understand what matter is made of at the smallest scales, physicists from around the world use detectors to study the collisions produced by CERN's particle accelerators. The Laboratory hosts many experiments in its quest to reveal nature's building blocks.

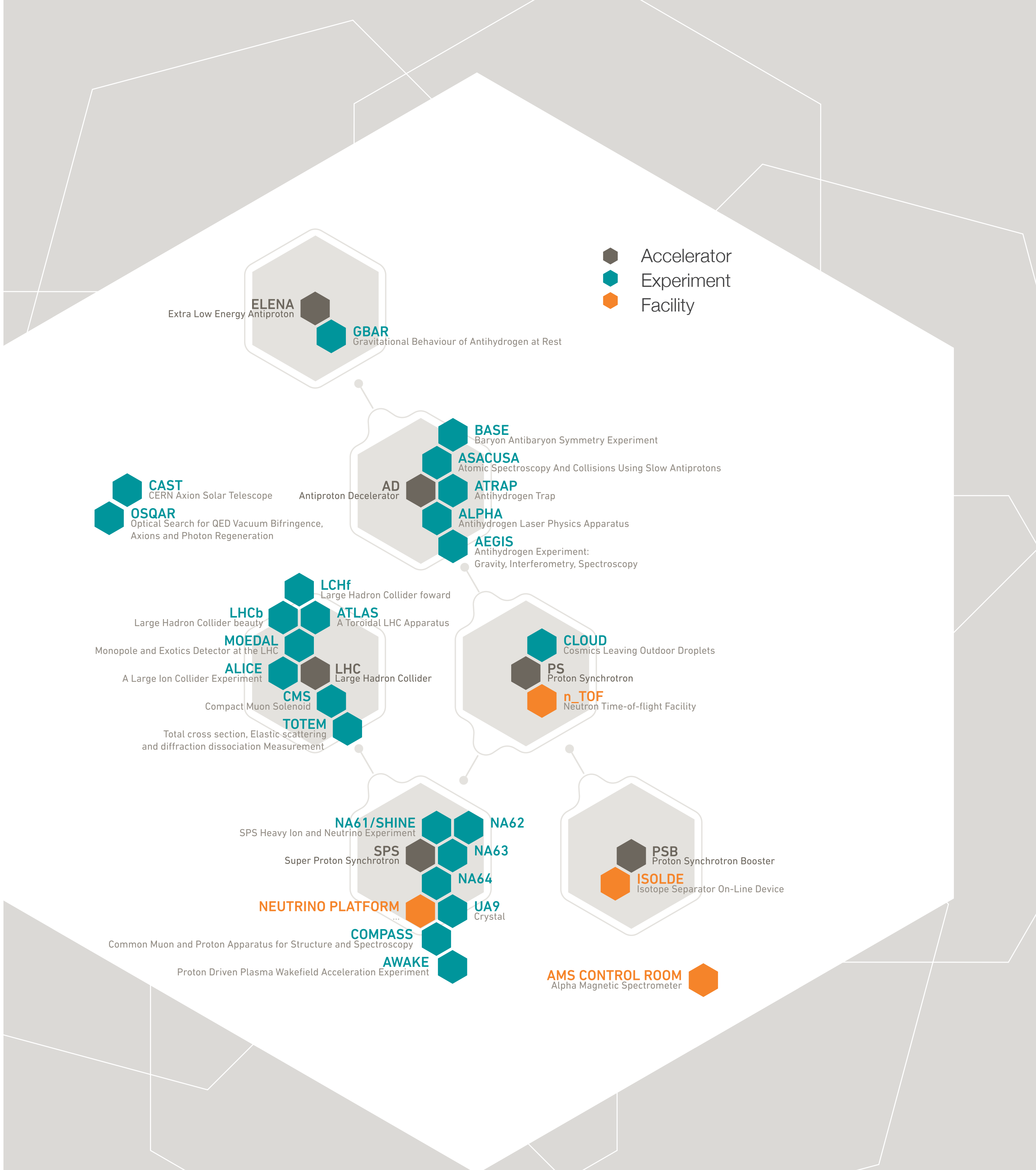
CERN'S ACCELERATOR COMPLEX AND THE EXPERIMENTS THAT IT FEEDS



Focusing an energy of several teraelectronvolts (TeV) into a region measuring a millionth of a millionth of a millimetre across, the Large Hadron Collider (LHC) is the most powerful collider ever built, allowing physicists to explore uncharted subatomic territory. Measuring 27 km in circumference, the LHC produces tens of trillions of proton-proton collisions every day at the centre of four large detectors – ALICE, ATLAS, CMS and LHCb.

Thanks to the superb performance of the LHC during 2016 (see p. 21), the experiments were able to collect over 50% more data than predicted. Hundreds of physics analyses were undertaken and over 300 scientific publications were produced by the LHC experiments during the year, with more than 100 new results approved for the ICHEP conference in Chicago by the middle of the year.

Yet the LHC would not work without the smaller accelerators that feed it, and these too drive numerous complementary experiments at CERN. The results from non-LHC experiments range from highly sensitive tests of antimatter to accurate measurements of cloud formation in the atmosphere. Taken together, they demonstrate the broad diversity of CERN's physics programme in its mission to understand the fundamental laws governing our universe.



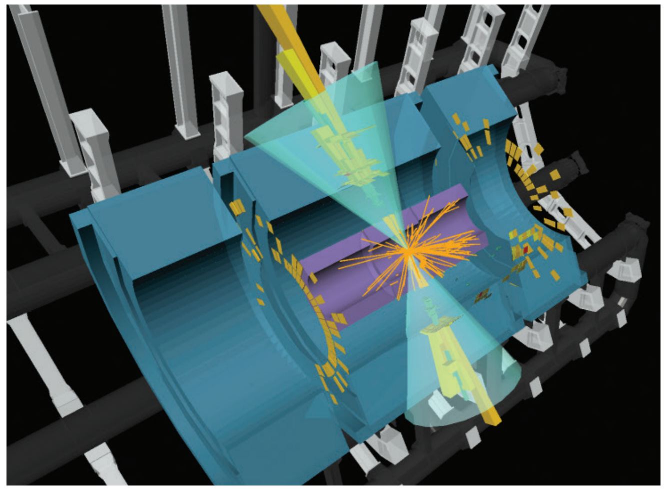
Physicists from LHC experiments working on data analysis. Around 10 000 physicists are involved in the LHC experiments. (OPEN-PHO-EXP-2017-002-1)

PROBING THE ENERGY FRONTIER

All current understanding about the behaviour of fundamental particles is embodied in a theory known as the "Standard Model" of particle physics. However, physicists have good reason to expect that new particles exist beyond those described by this theory. First and foremost, the Standard Model describes only 5% of the universe, the rest being made of invisible dark matter and dark energy. With 2016 marking the second year of running at an unprecedented energy of 13 TeV, the LHC experiments focused on searches for new phenomena, on continuing to chart the Higgs boson at 13 TeV and on understanding the performance of their huge and sophisticated detectors in the higher energy regime.

The general-purpose LHC experiments, ATLAS and CMS, are ideal for searching for direct signs of new particles. Among the physics highlights from these experiments were hotly anticipated updates about an intriguing "bump" first spotted in LHC data during 2015, which hinted that a particle with a mass of around 750 GeV was being produced. After analysing data from 2016, the bump was revealed to be a statistical fluctuation, but the modest excess generated a wave of activity in the theory community and intensified searches for new phenomena by ATLAS and CMS in a similar mass region.

ATLAS and CMS also reported the results of searches for many other new phenomena during 2016, such as those that may arise from additional dimensions of space or from new fundamental symmetries of nature. Analyses at ATLAS



A "dijet" event selected by ATLAS in its search for new phenomena, in which the two central jets (yellow) have a combined mass of 4.6 TeV. Also shown are energy deposits in the calorimeters, and reconstructed inner detector tracks. (ATLAS-PHOTO-2016-014-8)

and CMS hunting for supersymmetric particles – including updated limits on "gluinos" and "squarks" and first limits on the production of neutralinos (the supersymmetric counterparts of the neutral gauge bosons, the photon and the Higgs particle) at 13 TeV – have already pushed the mass limits beyond those achieved at energies of 7 and 8 TeV in LHC Run 1 between 2010 and 2013. Other dedicated searches concerned possible additional Higgs bosons with different properties. More generic searches for new physics, for instance seeking out "dijet" and "dilepton" resonances, heavy long-lived particles and dark matter candidates, were also updated. In the absence of any signals so far, ATLAS and CMS were able to further constrain the possible properties of such particles.

In close proximity to the LHCb detector, meanwhile, the MoEDAL experiment published the results of its search for magnetic monopoles – single magnetic charges predicted by Dirac in the 1930s. Alas, none were seen, allowing the MoEDAL collaboration to report during 2016 new mass limits for certain types of these hypothetical particles. With the LHC operating until December, analyses across the LHC experiments continue to scour the 2016 data for evidence of new particles and phenomena.

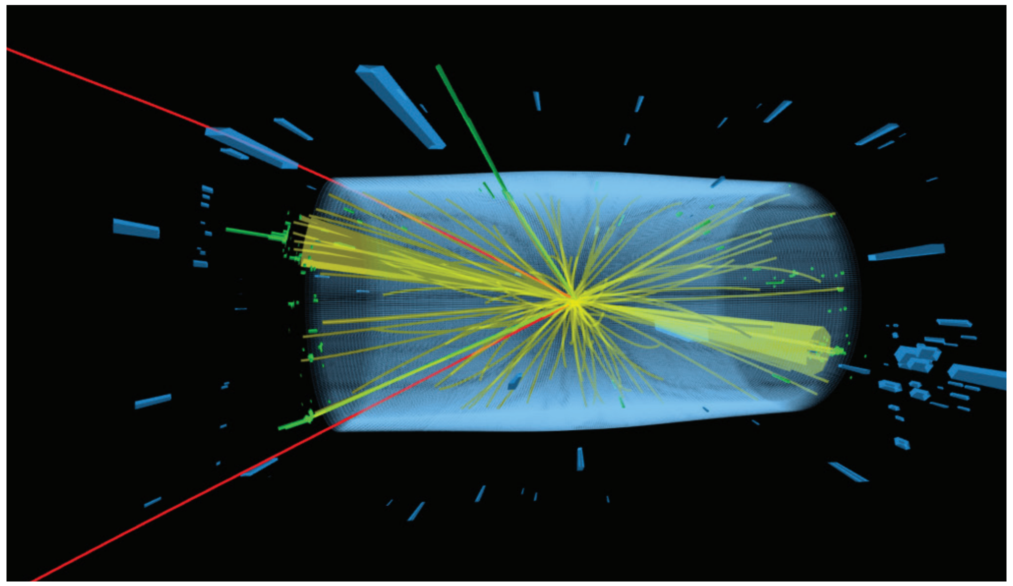
THE HIGGS BOSON AND THE STANDARD MODEL

Discovered by ATLAS and CMS in 2012, almost 50 years after it had been predicted, the Higgs boson is the final particle of the Standard Model. It is also a fundamentally new object called a scalar particle, which is completely different from other particles such as quarks and has connections to many unanswered issues in physics. First spotted at an energy of 8 TeV during LHC Run 1, the Higgs has now been "re-observed" by ATLAS and CMS in the 13 TeV Run 2 data at the rate expected by the Standard Model with a total significance above that seen in Run 1. Given the unique nature of the Higgs boson compared to the other known particles, the observation of additional Higgs production and decay modes, as well as more precise measurements of its couplings to other particles, is one of the main goals of the LHC. Many Higgs measurements were presented in 2016 by ATLAS and CMS, especially at the ICHEP conference, supporting previous findings that, within the current statistical uncertainties, the observed Higgs boson has the properties as predicted by the Standard Model.

Meanwhile, numerous precision measurements of other Standard Model processes were published by ATLAS and CMS during 2016 based on Run 1 data, which represents an extremely well understood and calibrated data sample. These include measurements at a precision of a few per cent or less of inclusive cross-sections that demand the latest "next-to-next-to-leading order" calculations from theory. ATLAS also announced the first measurement of the W boson mass from the LHC with a precision (0.023%) matching that of the best single measurement at other colliders, while both experiments released new measurements of the top quark, including its mass, pair production cross-section and width. Being the heaviest known elementary particle, the top quark is of particular interest in the search for new phenomena. The large dataset of Run 2 will allow such precision studies to progress further to check for any discrepancies between theory and experiment that would signal the existence of physics beyond the Standard Model.

Checking for chinks in Standard Model processes is firmly the business of the LHCb experiment, which concerns itself with the study of particles containing beauty quarks. The increased cross-section for beauty- and charm-flavour hadrons that comes with the higher energy of LHC Run 2 allowed the experiment to collect more than double its previous sample of decays, with many new results increasing the precision of measurements in the flavour sector. An example was the first observation of the ultra-rare decay $B^0 \rightarrow K^+K^-$, which has a branching ratio of 8×10^{-8} and is the rarest purely hadronic beauty decay ever observed. LHCb also reported the first measurement of photon polarisation in decays of B_s mesons, and the collaboration is keeping a close eye on some intriguing but not yet significant deviations from the Standard Model in a number of flavour-sector variables.

2016 also saw CERN's NA62 experiment, in which kaons are produced by a beam of protons from the Super Protron Synchrotron (SPS), begin data-taking in its search for extremely rare decays. Since kaon decays are precisely predicted by the Standard Model, any discrepancy between the measured and predicted decay rate may have profound consequences, in particular for fundamental charge parity (CP) symmetry. NA62 collected a large dataset corresponding to almost 10% of the total required statistics, and will operate for at least two more years.



A proton-proton collision event at 13 TeV in the CMS detector showing the characteristic signs of a Higgs boson decay into two high-energy electrons (green), two high-energy muons (red), and two high-energy jets (dark yellow cones). (CMS-PHO-EVENTS-2016-007-3)

Theory thrives

In 2016, CERN's Theoretical Physics department achieved important results across topics ranging from string theory to cosmology, which led to 262 original publications. Examples highlighting the breadth of CERN's theoretical research include: the most precise theoretical prediction of the Higgs boson production cross-section, which is a crucial input to the physics programme of the LHC; a systematic treatment of the leading non-linear effects in baryon acoustic oscillations, which is a key observable in cosmology to test dark energy and constrain neutrino masses; a precise determination of the photon content inside energetic protons, which helps to reduce uncertainties in some of the theory predictions relevant to the LHC; and the exploration of "clockwork" theories, which offer a mechanism for generating light particles with exponentially suppressed interactions.

CERN theory has continued to serve as a vibrant hub for the international community, and during 2016 it hosted 772 scientists, five theory institutes and eight workshops and meetings. Members of the team have contributed to all working groups on LHC physics and led major investigations on the physics opportunities of a 100-TeV hadron collider in the context of CERN's Future Circular Collider study. They also played a leading role in launching new physics research initiatives, both concerning the CERN Neutrino Platform and a new effort surveying the opportunities for physics beyond colliders (see pp. 48-9).

STRONG PHYSICS

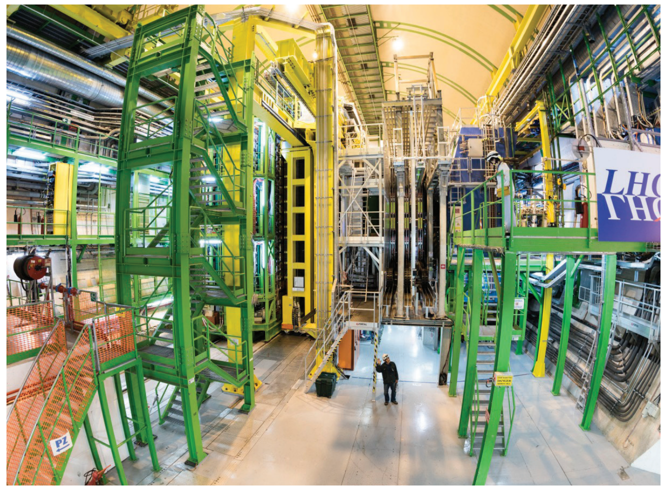
Understanding the incredibly strong force that binds protons, neutrons and other hadrons together represents a major challenge. In addressing the nature of the strong force, which is described by quantum chromodynamics (QCD, one of the pillars of the Standard Model), physicists not only learn more about everyday nuclear matter but can also probe the hot and dense quantum fireball that existed immediately after the Big Bang, 13.7 billion years ago. Studying this quark-gluon plasma (QGP) in general requires the LHC to collide heavier particles, typically lead ions. In such collisions, the QGP is formed for less than 10^{-22} of a second, after which the interacting system cools down and falls apart into individual hadrons. However, even this short time is enough to leave a significant imprint on the final-state particle distributions measured by the detectors.

Based on data collected during special heavy-ion runs in 2015 and previous years, the LHC's ALICE experiment has continued its efforts to gain a complete description of the evolution of the QGP. In 2016, the collaboration submitted 25 papers and prepared around 30 new results that were presented at major heavy-ion conferences in June and September. Three main themes dominated the results. The first concerns azimuthal anisotropies of particle production that are produced by the flow of the QGP medium, for which ALICE released first results from Run 2, as well as more detailed measurements of correlations of the azimuthal anisotropies that allow contributions from the initial stages of the collision to be disentangled from the dynamics of the flowing QGP. The second theme concerns various measurements of so-called quarkonia, which are bound states of heavy quarks that dissolve in the hot QGP but can also be formed by recombination of a charm quark and an anti-charm quark in the QGP. The third theme concerns "hard probe" measurements, which use energetic particles and jets to probe the QGP medium.

All measurements show that the higher collision energy of LHC Run 2 (5.02 TeV per nucleon pair instead of 2.76 TeV per nucleon pair in Run 1) produces a hotter QGP that may also be slightly longer-lived. In addition, more precise measurements of flow and flow correlations allow other properties of the QGP, such as the viscosity, to be determined with increasing precision. All four LHC experiments now take part in the heavy-ion programme. In 2016, ATLAS detected light-by-light scattering in the strong electric fields generated in peripheral heavy-ion collisions, while CMS presented several results including the observation of collectivity in proton-proton collisions and a study of chiral anomalous effects in proton-lead collisions.

Other experiments at CERN are studying the patterns of hadrons that emerged from the QGP in the early universe – many of which are exotic cousins of familiar nuclear particles that make up normal matter. During 2016, LHCb reported the observation of three new exotic hadrons and confirmed the existence of a fourth by analysing the full data sample from LHC Run 1. The particles each appear to be "tetraquarks" formed by two quarks and two antiquarks, although the theoretical interpretation of the new states is still under study. Together, LHCb and CMS also searched for but were unable to corroborate a tetraquark state recently spotted by the D0 experiment at Fermilab in the US.

The LHCb detector in its cavern. (CERN-PHOTO-201609-209-2)



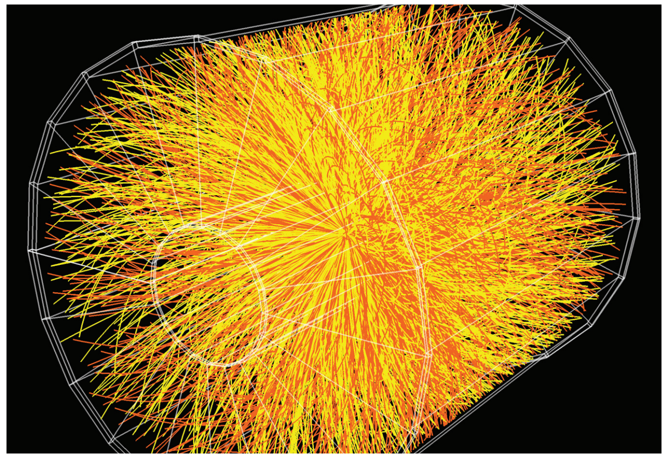
CLOUD advances climate science

CLOUD comprises an ultra-clean and controlled environment into which beams of particles from the Proton Synchrotron are injected to simulate the seeding of cloud droplets. (CERN-EX-1310264-03)

Future global climate projections have been placed on more solid empirical ground, thanks to measurements of the production and growth rates of atmospheric aerosol particles published in high-profile journals in 2016 by CERN's Cosmics Leaving OUtdoor Droplets (CLOUD) experiment.

According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's mean temperature is predicted to rise by between 1.5 and 4.5 °C when the amount of carbon dioxide in the atmosphere doubles as expected by around 2050. One of the main reasons for the large uncertainty in global temperature predictions is a poor understanding of aerosol particles in the atmosphere and their effects on clouds. To date, all global climate models use relatively simple parameterisations for aerosol production that are not based on experimental data.

By measuring aerosol formation under atmospheric conditions in a controlled laboratory environment, CLOUD has established the main processes responsible for new particle formation throughout the troposphere, which is the source of around half of all cloud seed particles. In an earlier paper published in 2016, the collaboration showed that particles can form purely from organic vapours produced naturally by the biosphere.
Also in 2016, CLOUD published the first-ever global aerosol model results based purely on laboratory measurements, which compared closely to atmospheric observations. The measured production rates of these subtle atmospheric processes can now be fed into global-circulation models to narrow the range of projected global temperatures.



The outcome of a high-energy lead-lead collision recorded by the ALICE detector, in which a total of 3161 charged particles were detected. (ALICE-PHO-GEN-2016-001-3)

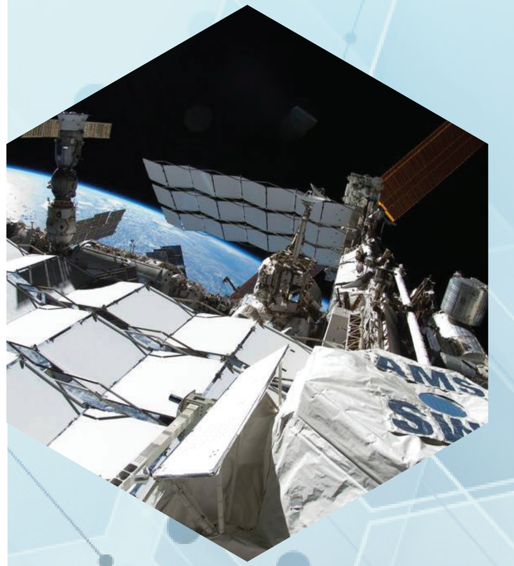
CERN's DIRAC experiment – which studies unstable hadrons produced using a beam from the Proton Synchrotron – also reported a new type of exotic "atom" made up of a pion and a kaon, which allows tests of quantum chromodynamics in the low-energy region. Shedding light on the murkier details of the strong force, two experiments at the SPS reported new results in 2016. The COMPASS facility switched to measurements of exclusive processes for generalised parton distributions, which are vital for understanding QCD contributions at the LHC, while the NA61/SHINE experiment took its first data in a programme designed to study particle production in neutrino targets.

ANTIMATTER ANTICS

Since CERN's production of the first antiatoms in 1995, a new era of tests has opened up to check if antimatter behaves the same as ordinary matter. If not, it would suggest that fundamental symmetries such as charge-parity-time (CPT) symmetry are violated and would point strongly to the existence of new physics. CERN's Antiproton Decelerator (AD) is host to five operational antimatter experiments, with another in the construction phase. In December, one of the experiments – BASE – announced that it had kept a shot of antiprotons trapped for more than one year, representing the longest-lived known anti-object in the universe. Storing antimatter for long periods, and keeping it cold, allows more precise measurements of its properties.

In 2016, the ALPHA experiment reached a goal that the antimatter community had been working towards for many years: the first optical spectroscopy of antihydrogen, opening the door to precision spectroscopy of antihydrogen and new tests of CPT symmetry. In parallel, the ASACUSA collaboration carried out the most precise measurement of the antiproton-to-electron mass ratio to date. Combined with measurements from ATRAP, BASE and ALPHA, this pushes limits on mass and charge differences between protons and antiprotons and between electrons and positrons to the level of sub-parts per billion. Preparations for tests of antimatter under gravity are equally advancing with the AEGIS and GBAR experiments, and all AD experiments will benefit from the new ELENA decelerator installed at the end of the year (see p. 47).

Results from space

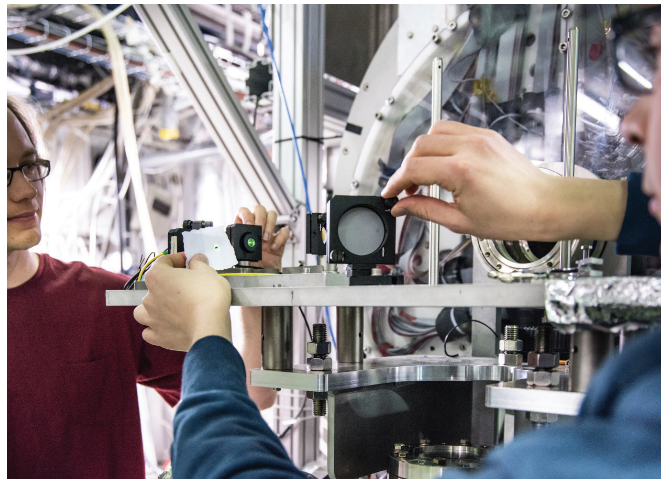


Located on board the International Space Station and operated from a control centre at CERN, the Alpha Magnetic Spectrometer experiment (AMS) released groundbreaking cosmic-ray results during 2016. AMS is a unique experiment in particle physics that is able to study cosmic rays free from atmospheric interactions to search for dark matter, antimatter and other exotic entities. 2016 marked its first five years of data since its launch, with the publication of several important papers. The latest AMS results are based on 17.6 million electrons and positrons and 350 000 antiprotons detected. In line with previous AMS measurements, the positron flux exhibits distinct differences from the electron flux that require accurate theoretical interpretation to determine whether the origin of these features is from dark matter collisions or new astrophysical sources. The latest AMS data also reveal that the proton, helium and lithium fluxes all deviate from traditional single-power-law dependence at a "rigidity" of about 300 GV, which is completely unexpected. The latest AMS measurement of the boron-to-carbon flux ratio also contains surprises, and expectations on AMS to clarify the nature of cosmic rays are high.

The Alpha Magnetic Spectrometer (AMS) is a state-of-the-art particle physics detector attached to the International Space Station.

Finding microscopic differences between antimatter and matter more generally could help explain why we see only matter on cosmological scales, whereas equal amounts of matter and antimatter should have been present at the moment of the Big Bang. Detecting CP violation is a key ingredient for this imbalance to occur, and the LHCb experiment looks specifically for new sources of this subtle asymmetry. During 2016, LHCb reported the first evidence of CP violation in baryons and also the world's most precise measurement of the unitarity triangle angle gamma, which characterises the amount of CP violation in the Standard Model. Ultra-precise searches for CP violation in the charm system were also carried out, but no clear signal has yet been seen. Further data from LHC Run 2 will be key to solving these fundamental puzzles.

The ALPHA experiment traps antihydrogen atoms in a magnetic trap and illuminates them with lasers to manipulate their electronic properties. (CERN-PHO-201603-070-11)



EXOTIC BEAMS

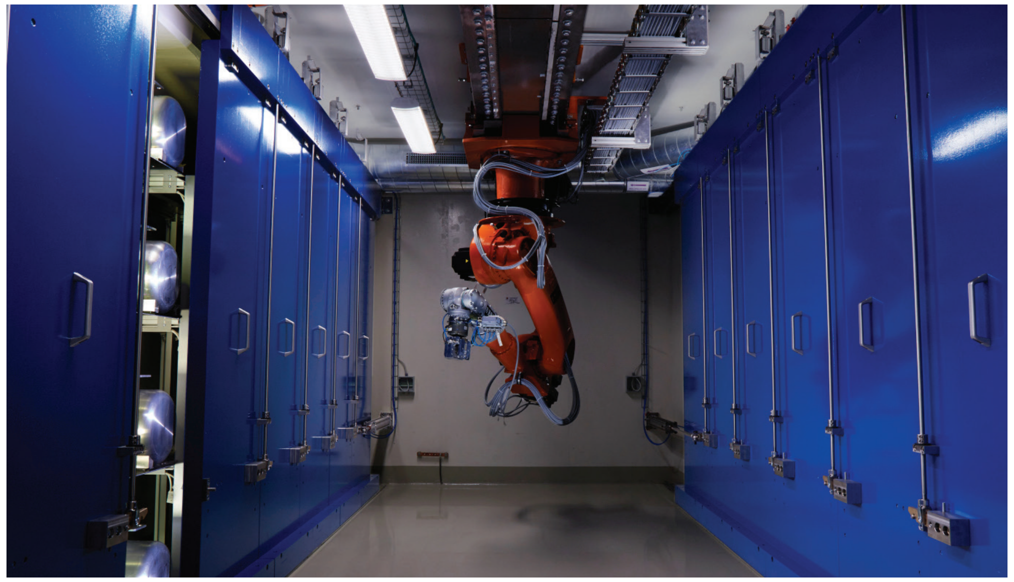
CERN doesn't just collide particles to see what matter's made of – it also generates a range of particle beams for experiments in fundamental nuclear physics, medical isotope production and materials science. The exotic-beam facility ISOLDE carried out 46 successful experiments in 2016, serving users spread mainly between nuclear structure studies (23%), decay studies (20%) and Coulomb excitation/scattering studies (23%). Nuclear astrophysics studies took up 7%, materials science 11% and biophysics and medicine dominated the remaining share. The main breakthrough of the year was the accomplishment of the HIE-ISOLDE energy upgrade, which means that the large variety of ISOLDE beams can now be accelerated to 5.5 MeV per nucleon.

2016 began with a measurement with cosmic implications: the production of a ^{7}Be sample at ISOLDE to be used at the n_TOF facility, which allowed researchers to study a vital reaction underpinning the "cosmological lithium problem". Based on astronomical observations, the universe contains much less lithium-7 than predicted by Big Bang Nucleosynthesis, the period immediately following the Big Bang during which the lightest elements were created. By studying a particular reaction relevant to lithium-7 production, n_TOF made direct measurements of the reaction rate that could help explain the missing cosmic lithium. In materials science, meanwhile, important results on the nature of doping in nitride semiconductors were obtained, as were data on the surface wetting of graphene. A new project served by proton beams from ISOLDE – CERN MEDICIS – also neared completion in 2016. MEDICIS will develop isotopes to be used as a diagnostic agent and for radiotherapy for the treatment of certain cancers, with start-up expected in 2017.

Future of physics with elusive neutrinos

Since the discovery almost 20 years ago that neutrinos can oscillate and therefore have mass, neutrinos remain one of the best hopes for discovering new physics. The CERN Neutrino Platform, inaugurated in 2014, is set up to act as a focus for the European neutrino community and undertakes R&D on detector technologies for use in accelerator-based neutrino projects outside Europe. Major progress was made during 2016 with the completion of the EHN1 hall extension in CERN's North Area, and preparation of the cryostats for the DUNE prototype liquid-argon time-projection chambers (both single- and double-phase variants). The refurbishment of the two ICARUS time-projection chambers and the construction of their new cryostats also reached completion, with the equipment ready for shipping to Fermilab in the US in 2017 to participate in the short-baseline neutrino experiment there. Other activities under way at the Neutrino Platform include the preparation of the Baby-MIND spectrometer that will form part of a neutrino experiment in Japan. To support these efforts, a neutrino group has been set up in the Experimental Physics department, and a task force for neutrino studies in the Theoretical Physics department.

A prototype detector prepared at CERN for the DUNE experiment in the US, which will be the target for neutrinos sent by Fermilab 1300 km away (CERN-PHOTO-201612-306-19)



A robotic sample changer at CERN's MEDICIS and ISOLDE facilities allows different isotopes to be produced. (OPEN-PHO-EXP-2016-013-3)

NATURE'S DARK SIDE

There could be aspects of the universe that we are blind to. In addition to direct searches for new particles at the LHC that might shed light on the dark matter in the universe at large, physicists have devised more subtle experiments to reveal the darker secrets of the vacuum.

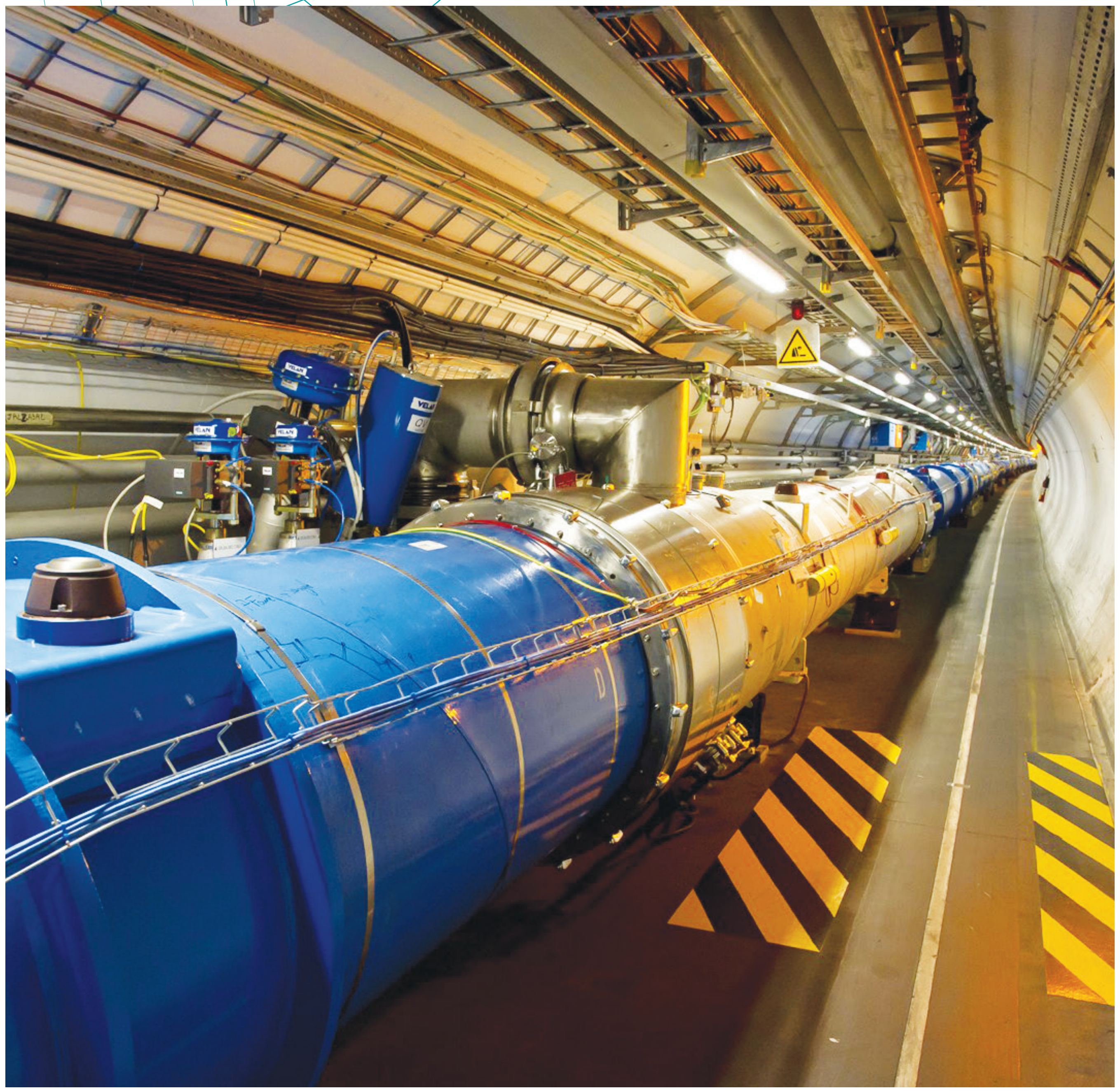
In 2016, a new experiment at CERN's SPS called NA64 reported on a direct search for sub-GeV dark photons that would decay invisibly into dark matter particles and leave a clear signature of missing energy in the detector. No evidence for such decays was found, allowing NA64 to set new limits on the dark photon's properties, in particular concerning its ability to explain the long-standing discrepancy between the measured and predicted values for the anomalous magnetic moment of the muon.

Meanwhile the CAST experiment, in which a powerful magnet is aimed at the sun to detect hypothetical particles called axions, began a new three-year measurement programme in 2016. The experiment is searching for solar chameleons – candidates for dark energy – using a pixelated detector and a force sensor, and for dark matter axions using a resonant cavity.

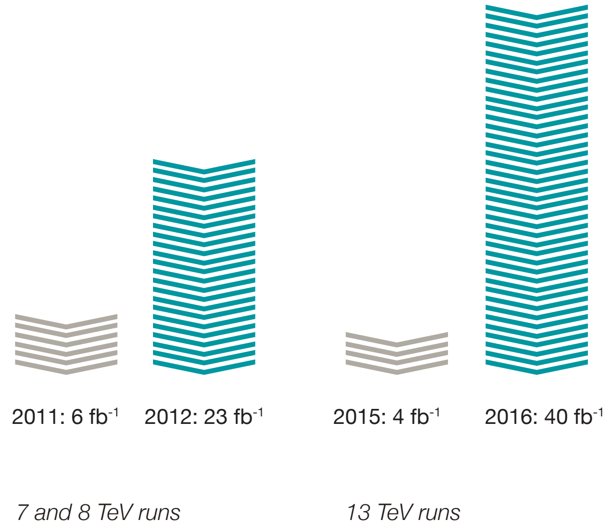
DISCOVERY MACHINES

CERN operates a unique complex of eight accelerators and one decelerator. The accelerators speed particles up to almost the speed of light before colliding them with each other or launching them at targets. Detectors record what happens during these collisions, and all the data collected 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.

The LHC performed remarkably in 2016, delivering far more collisions than expected. (CERN-GE-1101021-08)



LHC operators at the controls in July 2016. (CERN-PHOTO-201607-171-3)



Above, the amount of data delivered by the LHC to the ATLAS and CMS experiments over the course of its proton runs. These quantities are expressed in terms of integrated luminosity, which refers to the number of potential collisions during a given period.

LARGE HADRON COLLIDER IN FULL SWING

2016 was an exceptional year for the Large Hadron Collider (LHC). In its second year of running at a collision energy of 13 teraelectronvolts (TeV), the accelerator's performance exceeded expectations.

The LHC produced more than 6.5 million billion collisions during the proton run from April to the end of October, almost 60% more than originally anticipated. It delivered to the two major experiments, ATLAS and CMS, an integrated luminosity of almost 40 inverse femtobarns, compared with the target of 25. Luminosity, which measures the number of potential collisions per surface unit in a given time period, is a crucial indicator of an accelerator's performance.

The impressive availability of the LHC and its injectors was one of the keys to this success. The LHC was in operation 75% of the time during the physics run (25% for beam commissioning and preparation and 50% providing collisions for the experiments, compared with 33% in 2015). What makes this performance so remarkable is that the LHC is such a complex machine, relying on a chain of four accelerators and thousands of items of equipment.

The start-up of the machine was, moreover, hampered by several incidents. An incident at the end of April involving a transformer stopped the supply of electricity to the accelerator for one week. Then, the supply system of the Proton Synchrotron (PS), the third link in the injector chain, was damaged. Furthermore, a vacuum leak in the beam dump of the Super Proton Synchrotron (SPS), the fourth injector, restricted the quantity of particles that could be injected throughout the run. The number of proton bunches per beam had to be limited to 2220, compared with the 2808 protons per bunch planned. Finally, a fault in an LHC kicker magnet, which injects the particle bunches into the machine, limited the number of particles per bunch.

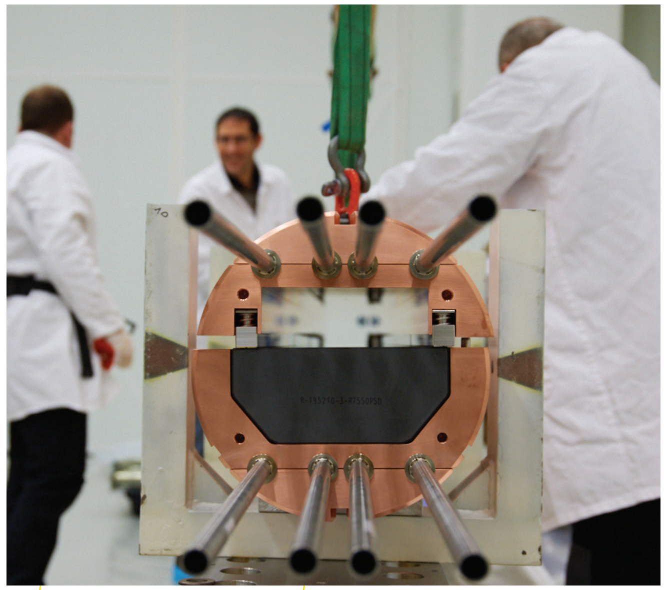
In spite of these interruptions, the performance of the machines was excellent. Numerous adjustments had been made to all systems over the previous two years to improve their availability. The cryogenics system, for example, which cools the accelerator to - 271°C, achieved 98% availability.

Adjusting the operational parameters of the LHC and its injectors also resulted in an increase in luminosity. The way in which particle bunches are assembled in the injectors was improved (see p. 22) and the beam crossing angle at the point of collision was reduced. These two parameters made it possible to achieve an average of 25 collisions per bunch crossing, compared to 14 in 2015.

The result of these optimisation efforts was a new record, which the operations teams celebrated on 26 June: the LHC surpassed the nominal peak luminosity of $10^{34}cm^{-2}s^{-1}$ defined when the machine was designed 20 years ago. This nominal value was subsequently surpassed repeatedly throughout the year, by as much as 40%.

The LHC thus provided 153 days of physics, several of which were dedicated to running with de-squeezed beams for the forward experiments TOTEM and ATLAS/ALFA. On 5 December, the last particles circulated in the machine before the technical stop. The first few days of the stop were devoted to magnet training in two of the machine's eight sectors, with a view to reaching a collision energy of 14 TeV. Using the results of this training campaign, the LHC teams will investigate the possibility of increasing the LHC's energy during Run 3, which is scheduled to start in 2021.

The TOTEM spokesperson in front of one of the experiment's detectors in the LHC tunnel, not far from the CMS detector. A special LHC run was provided for TOTEM and ATLAS/ALFA, with the beams as de-squeezed as possible. TOTEM upgraded its detectors in 2016. (CERN-PHOTO-201609-210-1)



A new SPS beam dump was designed and built in just a few months for installation in the accelerator during the extended year-end technical stop. (CERN-PHO-201704-084-15)

ENCOUNTERS OF THE THIRD KIND

On 10 November, the LHC started colliding protons with the nuclei of lead atoms – the second run of this kind to take place since 2013. This time, the collisions reached the unprecedented energy of 8.16 TeV. The experiments recorded more than 380 billion collisions at this energy, far exceeding expectations.

In order to meet the requirements of the experiments, the LHC and its injectors had to perform some complicated gymnastics. Two energy levels and three machine configurations were employed over four weeks of running. A special run was also conducted for the LHCf experiment. The luminosity reached seven times higher than the nominal value set a few years ago for these runs, and the collision periods were exceptionally long. This performance is particularly noteworthy because colliding protons with lead ions, which have a mass around 206 times greater and a charge 82 times higher than protons, requires numerous painstaking adjustments to the machine. The LHC was able to rely on a chain of highly efficient injectors.

CHAIN ACCELERATION

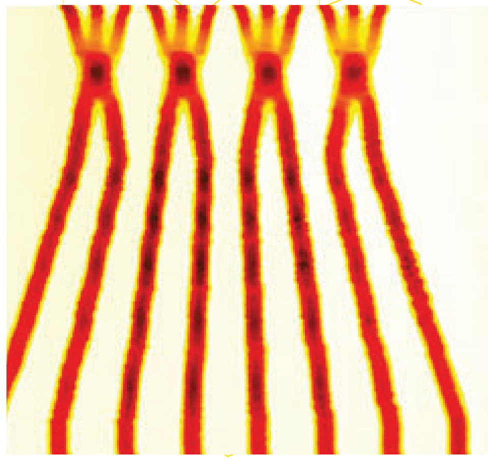
CERN operates a complex of eight accelerators and one decelerator, which together supply dozens of experiments (see p. 13). These accelerators also serve to propel particles into the LHC. The protons collided in the LHC are first bunched and accelerated by four injectors in series: Linac2, the PS Booster, 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.

The injector chain performed impressively in 2016, achieving availability of over 90% for all the accelerators. For example, the PS Booster, which groups the particles into bunches, achieved 96% availability, supplying particles to the PS and the nuclear physics facility ISOLDE.

The next link in the chain, the PS, redistributes the particle bunches and accelerates them before sending them to various facilities. Half of the protons prepared by the PS go to CERN's other nuclear physics facility, n_TOF. A spare cavity was commissioned in the PS, improving the transmission of particles to the SPS.

The SPS not only supplied the LHC but also provided 80% of the protons required by the experiments in the North Experimental Area. This performance is especially impressive considering that the number of particles in the SPS was limited by a vacuum leak detected in the beam dump. An urgent campaign to produce a new beam dump in just a few months was launched in response to this issue. At the end of the year, the accelerator demonstrated its flexibility by providing lead nuclei at three different energies to nine experiments in the North Experimental Area as well as providing the LHC with protons and lead nuclei.

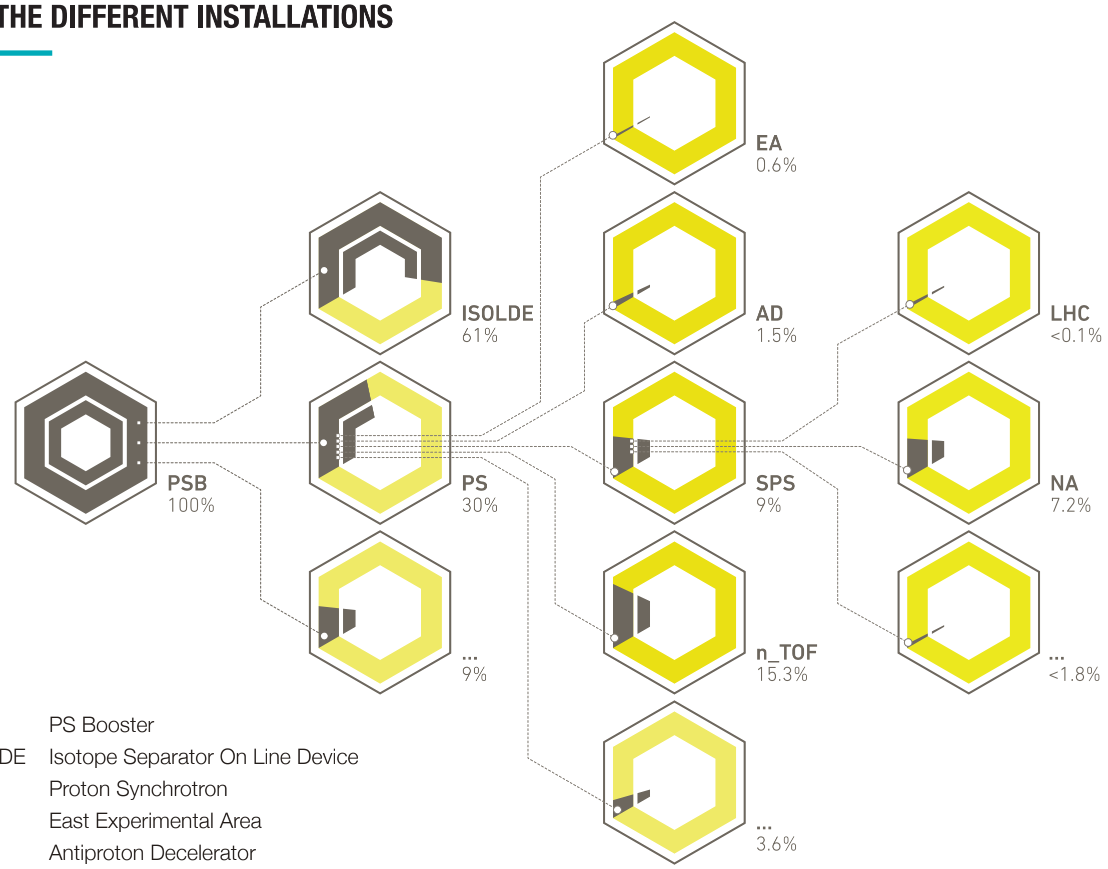
Linac3 and LEIR, the two accelerators that prepare heavy ions upstream, recorded excellent performances, bearing witness to the success of the upgrade programme that began in 2015. They delivered bunches at very high intensities, even higher than those required by the LHC



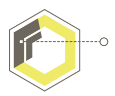
Bright bunches

This image shows how the particle bunches are joined together and pulled apart in the Protron Synchrotron (PS) using the BCMS (batch compression merging and splitting) method. This process, implemented for the first time in 2016, uses the radio-frequency cavities to form denser particle bunches, which increases the probability of collisions occurring in the LHC. These "brighter" bunches, in accelerator jargon, brought about a 20% increase in luminosity in 2016. (OPEN-PHO-ACCEL-2017-008-1)

DISTRIBUTION OF PROTONS DELIVERED BY THE ACCELERATOR CHAIN TO THE DIFFERENT INSTALLATIONS



PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

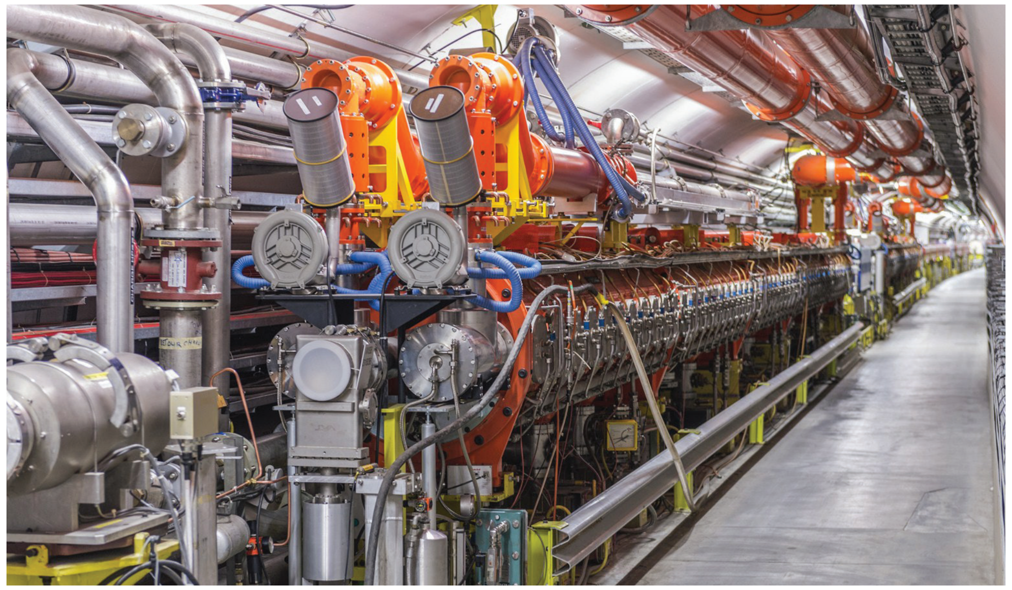


Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

***1.34×10^{20} protons** were accelerated in the accelerator complex in 2016. This might sound like a huge number, but in reality it corresponds to a minuscule quantity of matter, roughly equivalent to the number of protons in a grain of sand. In fact, protons are so small that this amount is enough to supply all the experiments. The LHC uses only a tiny portion of these protons, less than 0.1%, as shown in the diagram.*

A spy in the big tunnel

TIM, the Train Inspector Monorail, is an autonomous mini-vehicle used for real-time monitoring and inspections of the 27-kilometre tunnel of the Large Hadron Collider (LHC). It checks the tunnel structure, the oxygen percentage, the communication bandwidth and the temperature. Suspended from the tunnel's ceiling, it can move at up to 6 km/h.
In 2016, TIM performed several autonomous missions to carry out inspections and radiation-level measurements. The robot has already caught the eye of industry, in particular for autonomous monitoring of utility infrastructures such as underground water pipelines. (OPEN-PHO-TECH-2017-004-1)



The Super Proton Synchrotron (SPS), CERN's second-largest accelerator, celebrated its 40th birthday in 2016.
An essential link in CERN's accelerator chain, the SPS supplies different kinds of particle to myriad experiments. It accelerates protons and lead ions for the LHC, while also supplying experiments in the North Experimental Area. (CERN-GE-1311288-04)

Injector Upgrade programme being implemented to prepare the injectors for the High-Luminosity LHC (see p. 45).
The Antiproton Decelerator (AD), which sends antiprotons to five experiments, provided 5400 hours of physics in 2016, setting a new record.

While the machines were in operation, the teams were at work behind the scenes to prepare for maintenance and upgrades. For example, several electrical sub-stations, in particular those at the SPS, are being progressively renovated. Studies were also launched with a view to modernising the East Experimental Area during Long Shutdown 2, due to start at the end of 2018.

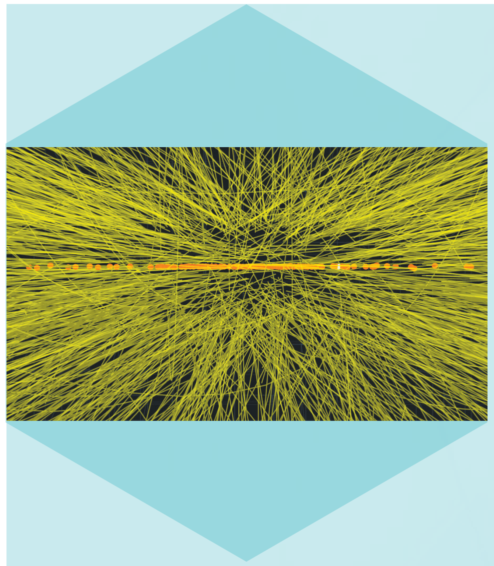
Once the machines had been stopped in early December, the maintenance and upgrade work began. The 2016-17 year-end technical stop was extended by seven weeks to allow more major work than usual to be carried out.

HIGHER-ENERGY NUCLEAR PHYSICS

The ISOLDE nuclear physics facility received an energy boost. Since September 2016, the new superconducting accelerator HIE-ISOLDE (High-Intensity and Energy ISOLDE) has been increasing the energy of its radioactive ion beams.

Equipped with two cryomodules each containing five superconducting cavities, this machine accelerated six different varieties of radioactive ion to energies ranging from 4.3 to 6.8 MeV per nucleon (compared to a maximum of 3 MeV per nucleon previously). HIE-ISOLDE provided 837 hours of beam time, supplying two experimental areas.

This upgrade makes ISOLDE the only facility in the world capable of studying medium to heavy ions in this energy range. The second phase of the project will involve the installation of two further cryomodules and a third experimental area so that the facility will be capable of reaching up to 10 MeV per nucleon for medium and heavy ions in 2018.



A pile-up of several dozen collisions recorded in one bunch crossing by the CMS experiment in 2016. Each orange dot represents one collision. (CMS-PHO-EVENTS-2016-008-5)

Experiments bombarded with data

The large LHC detectors are extremely complex machines, each made up of millions of parts that have to work together in harmony in order to identify the particles created by the collisions occurring in the accelerator. The unprecedented luminosity of the LHC posed significant challenges for the detectors' triggers, which select the collisions to record. These systems "decide" whether or not to keep the data for each individual collision, on the basis of information transmitted by dedicated sub-systems.

In 2016, the LHC generated an average of 25 collisions simultaneously, 25 million times per second – almost twice as many as in 2015. The experiments adapted their triggers to cope with this pile-up of events. ATLAS optimised its trigger's algorithms and adjusted the way in which the data is handled by the computing grid. The CMS experiment recorded data using a completely upgraded trigger system. These improvements allowed ATLAS and CMS to include more than 90% of the data delivered in their analyses.

The LHCb experiment also employed an improved trigger, as well as a real-time event reconstruction system. This experiment recorded 1.7 inverse femtobarns of proton-proton collision data, five times more than in 2015, and took heavy-ion data for the first time.

The ALICE experiment, which specialises in heavy-ion physics, recorded almost ten times more proton-lead events at an energy of 5.02 TeV than during the previous such campaign in 2013. ALICE used two selection modes: a "minimum bias" trigger that records all types of event without distinction, and a second trigger that selects rare events for specific studies. ALICE also accumulated proton data in line with the goals set.

The third cryomodule was assembled in 2016 and will be installed in 2017.

ISOLDE offers its users a wide range of beams. The facility can produce up to 1000 different isotopes of 75 chemical elements. In 2016, ISOLDE supplied 46 experiments, ranging from those studying the properties of atomic nuclei to biomedical research projects and astrophysics experiments (see p. 18).

A third cryomodule was assembled in 2016 in preparation for the second phase of the HIE-ISOLDE project. HIE-ISOLDE is a superconducting linear accelerator that increases the energy of radioactive ions before they are sent to ISOLDE. (CERN-PHOTO-201603-057-20)

CERN's Data Centre houses servers and data-storage systems not only for the Worldwide LHC Computing Grid, but also for systems critical to the daily functioning of the Laboratory. (OPEN-PHO-CCC-2017-001-1)

COMPUTING: PUSHING THE LIMITS

2016 saw unprecedented volumes of data acquired by the four big LHC experiments, due in large part to the outstanding performance and availability of the LHC itself. Expectations were initially for around 5 million seconds of stable beams, while the final total was around 7.5 million seconds, a very significant and welcome 50% increase. At a higher energy, the collisions themselves are more complex, and at a higher intensity, many collisions overlap, requiring increasingly sophisticated reconstruction and analysis, which has a strong impact on computing requirements. Consequently, 2016 saw records broken in many aspects of data acquisition, data rates and data volumes, and exceptional levels of use of computing and storage resources.

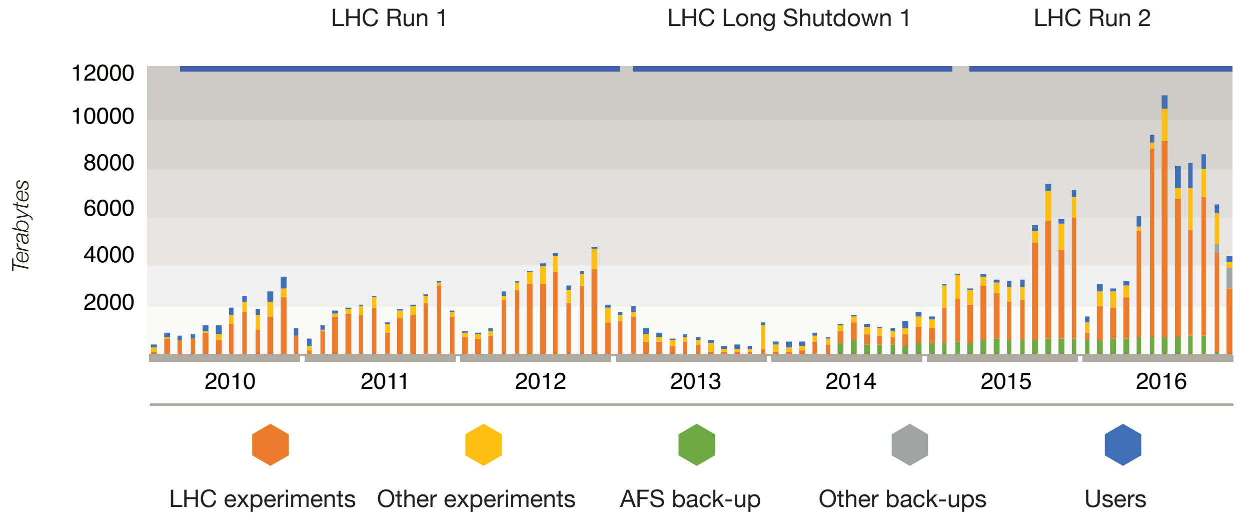
MULTIPLE RECORDS BROKEN

The Worldwide LHC Computing Grid (WLCG) project is a global collaboration of more than 170 computing centres in 42 countries, linking up national and international grid infrastructures. Its mission is to provide global computing resources to store, distribute and analyse the data generated by the LHC. Overall, the performance of the WLCG infrastructure responded very well to the increased needs and levels of use, and enabled, as in previous years, the production of high-quality physics results in a very short time. For example, analyses presented at the major ICHEP physics conference in early August included data acquired only two weeks earlier. In 2016, more than 49 petabytes of LHC data were recorded at the CERN Data Centre, with a striking 11 petabytes in the month of July alone, both being exceptional new records. The large computing capacity of the 170 WLCG sites has been used by the experiments very effectively and efficiently, and they have often made significant use of additional opportunistic computing resources, for example in the form of additional cycles on supercomputer facilities, and from volunteer computing access thanks to LHC@home.

THE NETWORK CHALLENGE

Perhaps one of the most impressive components of the WLCG grid is its networking and connectivity. It can initiate the distribution of data to the hundreds of collaborating institutes worldwide thanks to the excellent connectivity and dedicated networking infrastructure set up at CERN and subsequently worldwide. In 2016, the data transfer rates around the globe also reached new peak rates – between 30 and 40 gigabytes per second continuous rates, around a factor of two higher than had been typical during Run 1. The full WLCG collaboration of data centres managed these new rates seamlessly, in some cases thanks to specific adjustments. The increased data rates led several sites to increase the bandwidth of their connection to CERN in order to be able to manage the higher rates. In particular, the increased transatlantic bandwidth put in place for Run 2 was essential.

In addition, significantly increased traffic was observed on the network that allows the National Research and Education Networks (NRENs) to manage LHC data traffic. Consequently, significant additional capacity was deployed into the core network to deal with this increased network use.



Data recorded on tapes at CERN on a monthly basis
This plot shows, on a monthly basis, the amount of data recorded on tape generated by the LHC experiments, the other experiments, various back-ups, and the users. 2016 was a record year with over 49 petabytes (49 467 terabytes exactly) of LHC data, and a peak of 11 petabytes in July.

SCIENCE IN THE CLOUD

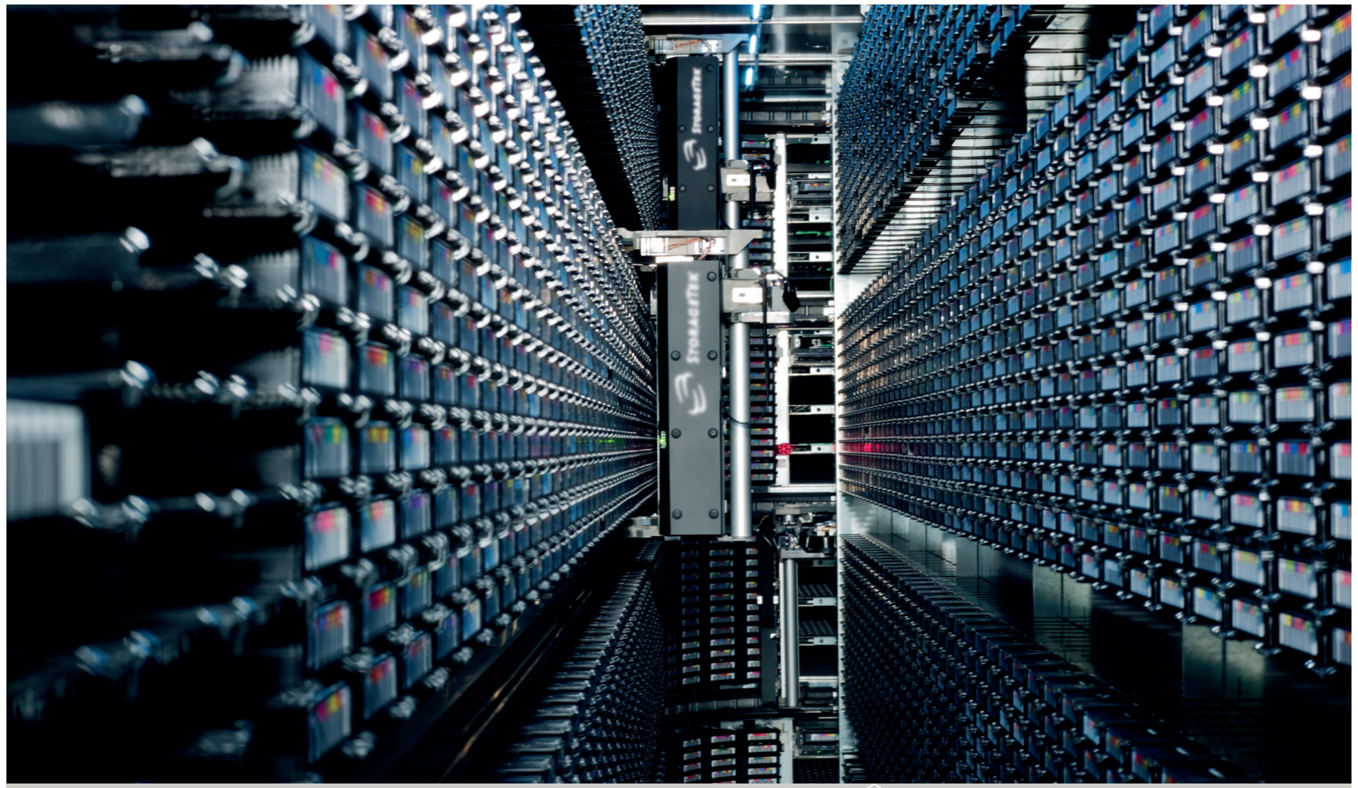
Over 90% of the compute resources in the CERN Data Centre are provided through a private cloud based on OpenStack, an open-source software project that provides on-demand cloud computing. In 2016, CERN was a major contributor to the OpenStack container service development in collaboration with Rackspace and the Indigo DataCloud project, with 40 bug fixes and enhancements in the latest release, which has been recognised by the community with one team member now having achieved core reviewer status, reflecting the quality of the submissions.

With the growth of the computing needs of the CERN experiments and services, this CERN private cloud has now reached over 190 000 compute cores running across the two CERN Data Centres in Meyrin and Budapest. With some of the hardware being retired, over 5000 virtual machines were migrated to new hardware during the year.

For the past three years, investigations have been made to see if physics applications can be run on public cloud resources. With the growth of cloud computing, this approach may be interesting in the future for short-term increases or as a more cost-effective approach for providing compute resources. In addition, this year, we have seen significant and large-scale tests of the use of commercial cloud resources in conjunction with the grid resources. These resources have been provided either in the form of research projects by some of the very large cloud vendors, or through real procurement exercises on a smaller scale.

At the start of the year 2016, CERN also successfully concluded its coordination of the PICSE project addressing Procurement Innovation for Cloud Services in Europe. The Helix Nebula Science Cloud (HNSciCloud) Pre-Commercial Procurement (PCP) project was also kicked off by CERN early on in 2016. HNSciCloud is driven by 10 leading research organisations and brings Europe's technical development, policy and procurement activities together to remove fragmentation and maximise exploitation.

Four consortia engaging a total of 16 companies and organisations were awarded contracts during a ceremony hosted by CNRS in Lyon on 2 November 2016. The Helix Nebula hybrid cloud architecture and procurement model represent significant advances for the sustainability of e-infrastructures in Europe and the planned European Open Science Cloud.

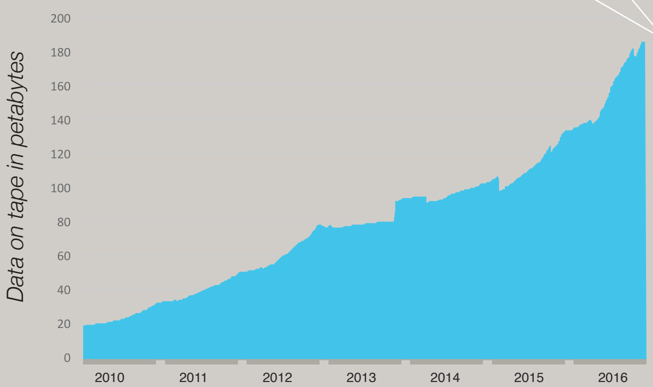


Magnetic tapes, retrieved by robotic arms, are used for long-term storage. (CERN-GE-0809016-01)

Data preservation for future generations

As an organisation with more than 60 years of history, CERN has created large volumes of data of many different types. This involves not only scientific data – to date more than 185 petabytes of data from past and present high-energy physics experiments – but also many other types, including photographs, videos, minutes, memoranda, web pages, etc. CERN hence faces the challenge of preserving its digital memory. Data formats and the tools to access them change constantly, and constant effort is required to tackle the issue, but interestingly, many of the tools that are relevant for preserving data from the LHC and other experiments are also suitable for other types of data. CERN is at the forefront of this effort and participates in the DPHEP (Data Preservation in High Energy Physics) collaboration as a founder member. The status report of the DPHEP collaboration detailing progress during the period 2013-2015 inclusive was published this year in February and is publicly available.

One of the challenges of long-term digital preservation with tape libraries is contamination by environmental hazards, such as dust or any particle that can interfere with the read or write process on tapes. CERN prototyped and built custom environmental sensors for the Data Centre, based on a Raspberry Pi board and an Arduino processor. The sensors behave comparably to proprietary systems in terms of precision and reaction time, but at a small fraction of the cost (about 50 times less than those currently available on the market with similar specifications) and with no maintenance required. In 2016, features were added to the sensor, which can now distinguish between small and large dust particles and can detect brief particle emission in high airflows. The updated sensor effectively prevented a major contamination in the CERN Data Centre in 2016. The use of the sensor is now also being evaluated at CERN for other uses. It is freely available under the CERN Open Hardware License.



Evolution of the total amount of data stored on tape at CERN
As shown on the graph, the amount of data recorded on tape at CERN is steadily increasing over time, with this trend accelerating in 2016 (+40 % data stored in 2016 compared to what had been accumulated by the end of 2015).

The CERN openlab open day in June marked 15 years of collaboration with industry in support of the LHC research community. (OPEN-PHO-TECH-2016-002-4)

CERN openlab celebrates 15 years of collaboration

For CERN openlab, 2016 marked 15 years of its unique public-private partnership, through which CERN collaborates with leading information and communication technology (ICT) companies and research institutes. Throughout the year, work was carried out to tackle ambitious challenges including activities in domains such as data acquisition, computing platforms, data-storage architectures, compute provisioning and management, networks and communication and data analytics. Work has now begun to identify the ICT challenges that will be tackled in CERN openlab's sixth phase, which will run from 2018 to 2020.

OPEN SOURCE FOR OPEN SCIENCE

The cornerstone of the open source philosophy is that the recipients of technology should have access to all its building blocks, such as software code, schematics for electronics and mechanical designs, in order to study it, modify it and redistribute it to others. Ever since releasing the World Wide Web software under an open-source model in 1994, CERN has continuously been a pioneer in this field, supporting open-source hardware (with the CERN Open Hardware Licence), open access (with the Sponsoring Consortium for Open Access Publishing in Particle Physics - SCOAP3, see p. 35) and open data (with the Open Data Portal for the LHC experiments).

Several CERN technologies are being developed with open access in mind. Invenio is an open-source library management package, now benefiting from international contributions from collaborating institutes, typically used for digital libraries. Invenio 3 was launched in 2016, featuring a whole new concept and full rewrite of the software. CERN, with co-funding from the European Commission, has also long invested in a free open data repository, for use beyond the high-energy physics community: Zenodo.

Zenodo taps into CERN's long-standing tradition and know-how in sharing and preserving scientific knowledge for the benefit of all, giving the scientific community the choice to store its data in a non-commercial environment to be freely available for society at large.

In September 2016, Zenodo was improved with a new release based on Invenio 3: searches became ten times faster, uploads up to 100 GB were also fast, and twice as many visitors and three times more records were handled. The CERN Open Data Portal, which provides seamless access to experimental data, is also built on Invenio. In collaboration with CERN's Scientific Information Service, 300 TB of CMS 2011 data were released. The release received press and media attention and over 210 000 unique site visits.

PLATFORM TECHNOLOGIES FOR OPEN COLLABORATION

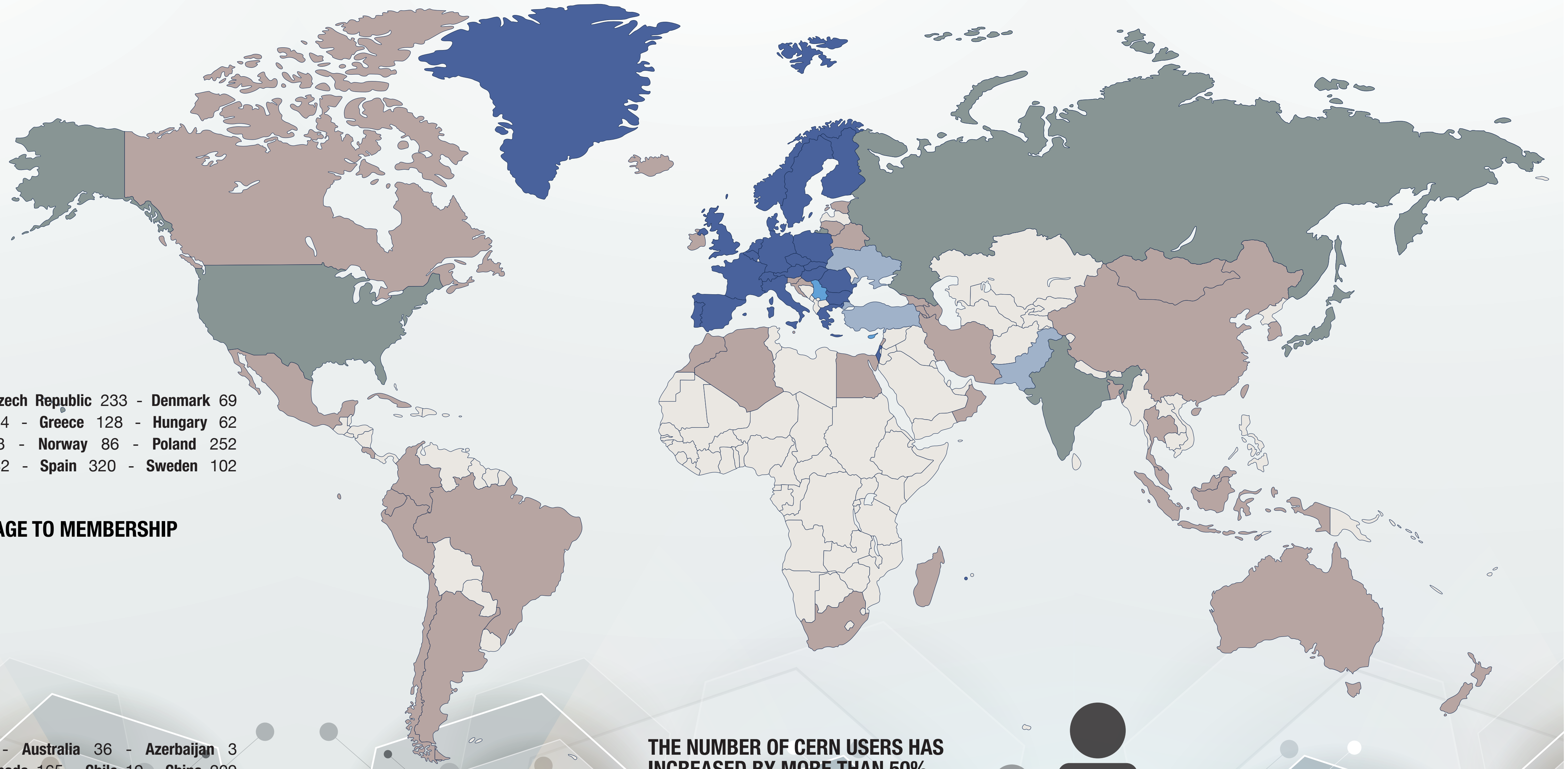
The CERN storage system, EOS, was created for the extreme LHC computing requirements. In 2016, EOS instances at CERN approached one billion files, matching the exceptional performances of the LHC machine and experiments. EOS (via the CERNBox project) already fully supports disconnected operations as well as file access and sharing via browsers. It is hence now expanding for other data storage needs across CERN, with about 7000 individual users, and beyond high-energy physics, with AARNET, the Australian Academic and Research Network, and the EU Joint Research Centre for Digital Earth and Reference Data adopting it for their big-data systems.

The Indico conferencing package is another open-source tool developed at CERN and is used by more than 200 sites worldwide, including the United Nations. In 2016, three new versions of Indico were released, improving timetable and category management and the abstract review process.

A WORLDWIDE LAB

CERN is a truly unique organisation, a genuine collaboration between countries, universities and scientists. In 2016, more than 16 000 people from across the globe worked together to push the boundaries of understanding. CERN employs over 2500 scientific, technical and administrative staff who design, build and support the research infrastructure and ensure its smooth operation. They also help to prepare, run, analyse and interpret data from complex scientific experiments for an ever-growing user community of about 12 000 scientists from institutes in over 70 countries and of 105 different nationalities.

CERN grew as an intergovernmental organisation in 2016 as Romania became the 22nd Member State and Cyprus and Ukraine became Associate Members. More Associate Memberships are set to follow, with Slovenia and India having signed agreements and other applications in progress. International Cooperation Agreements were also signed with Latvia and Qatar. In an increasingly worldwide endeavour, the Laboratory champions research, ideas and diversity.



DISTRIBUTION OF ALL CERN USERS BY THE COUNTRY OF THEIR HOME INSTITUTE AS OF 31 DECEMBER 2016

6971 — MEMBER STATES

Austria 96 - Belgium 148 - Bulgaria 37 - Czech Republic 233 - Denmark 69
Finland 119 - France 866 - Germany 1284 - Greece 128 - Hungary 62
Israel 68 - Italy 1440 - Netherlands 163 - Norway 86 - Poland 252
Portugal 103 - Romania 100 - Slovakia 82 - Spain 320 - Sweden 102
Switzerland 368 - United Kingdom 845

48 — ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus 15 - Serbia 33

182 — ASSOCIATE MEMBER STATES

Pakistan 33 - Turkey 121 - Ukraine 28

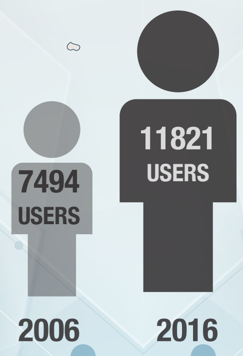
3381 — OBSERVERS

India 194 - Japan 276 - Russia 984 - USA 1927

1239 — OTHERS

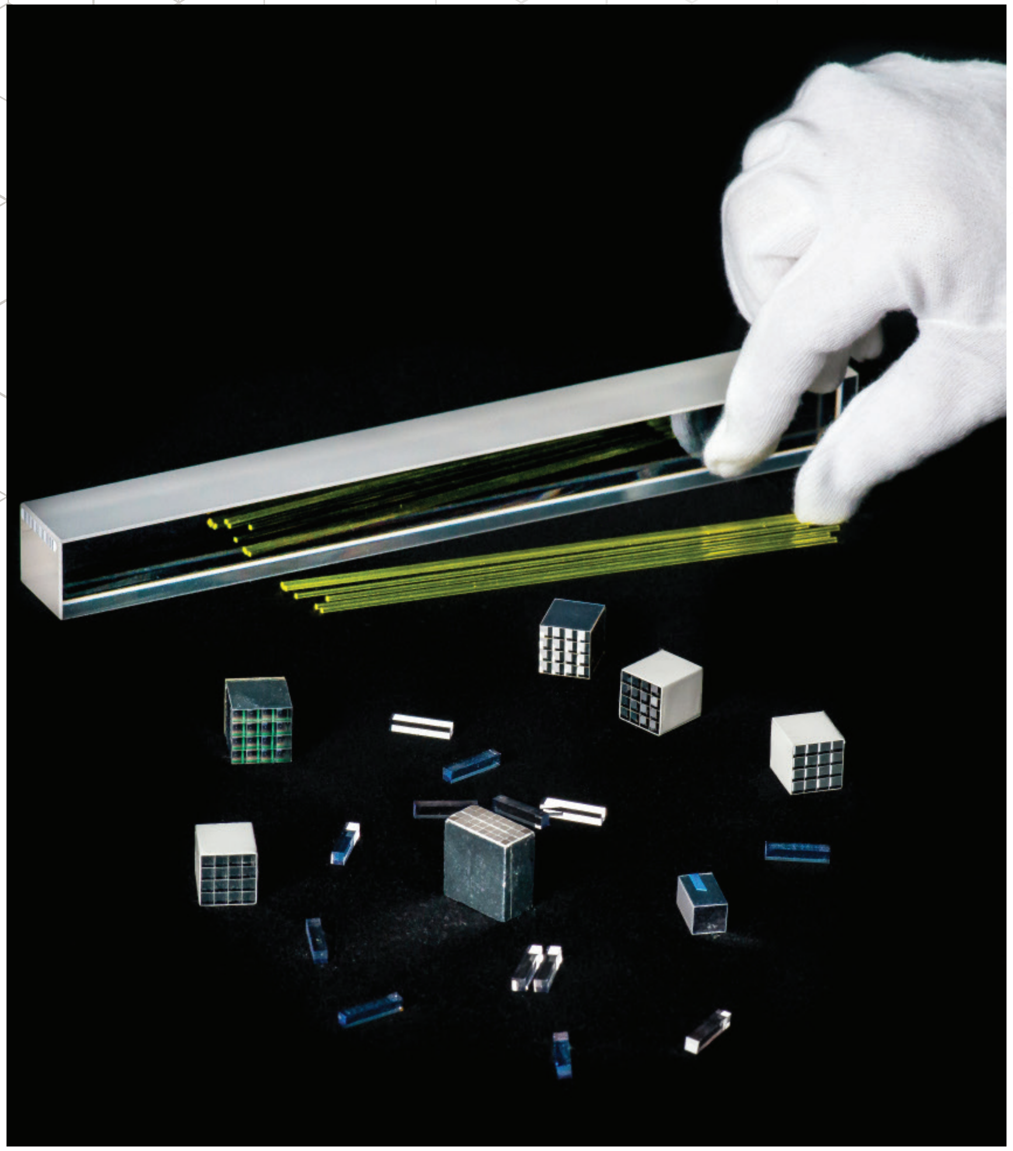
Algeria 1 - Argentina 18 - Armenia 15 - Australia 36 - Azerbaijan 3
Bangladesh 4 - Belarus 21 - Brazil 132 - Canada 165 - Chile 19 - China 209
Colombia 21 - Costa Rica 1 - Croatia 27 - Cuba 3 - Ecuador 2 - Egypt 27 - Estonia 17
Georgia 26 - Hong Kong 19 - Iceland 3 - Indonesia 9 - Iran 20 - Ireland 4 - Korea 155
Lebanon 3 - Lithuania 17 - Madagascar 2 - Malaysia 8 - Malta 6 - Mexico 61 - Mongolia 2
Morocco 10 - New Zealand 9 - Oman 3 - Peru 2- Singapore 3 - Slovenia 21
South Africa 50 - Taiwan 69 - Thailand 16

THE NUMBER OF CERN USERS HAS INCREASED BY MORE THAN 50% IN 10 YEARS



PUSHING THE FRONTIERS OF TECHNOLOGY

To conduct research at the frontiers of knowledge, CERN scientists develop, and sometimes invent, cutting-edge technologies and processes. These new technologies often find applications beyond their immediate field. CERN keeps in close contact with innovation partners in industry to allow them to benefit from the Laboratory's most recent innovations. Knowledge transfer – the transfer of technologies and know-how to society – is an important mission for the Laboratory.



These scintillating crystals were developed for high energy physics (top) and for medical imaging (small crystals and matrices in the foreground), in the framework of the Crystal Clear collaboration and the European FP7 project EndoTOFPET-US. Crystal Clear, which celebrated its 25th birthday in 2016, was initiated to develop new scintillating crystals for the LHC experiments. The collaboration's work has benefited not only particle physics but also medical imaging and other industrial applications. Today, Crystal Clear is developing new prototype detectors based on scintillating crystals for use in both high-energy physics and medical imaging, with particular emphasis on positron emission tomography (PET). (OPEN-PHO-TECH-2017-005-4)

DIVERSE APPLICATION FIELDS: FROM MEDICAL TO AEROSPACE AND MORE

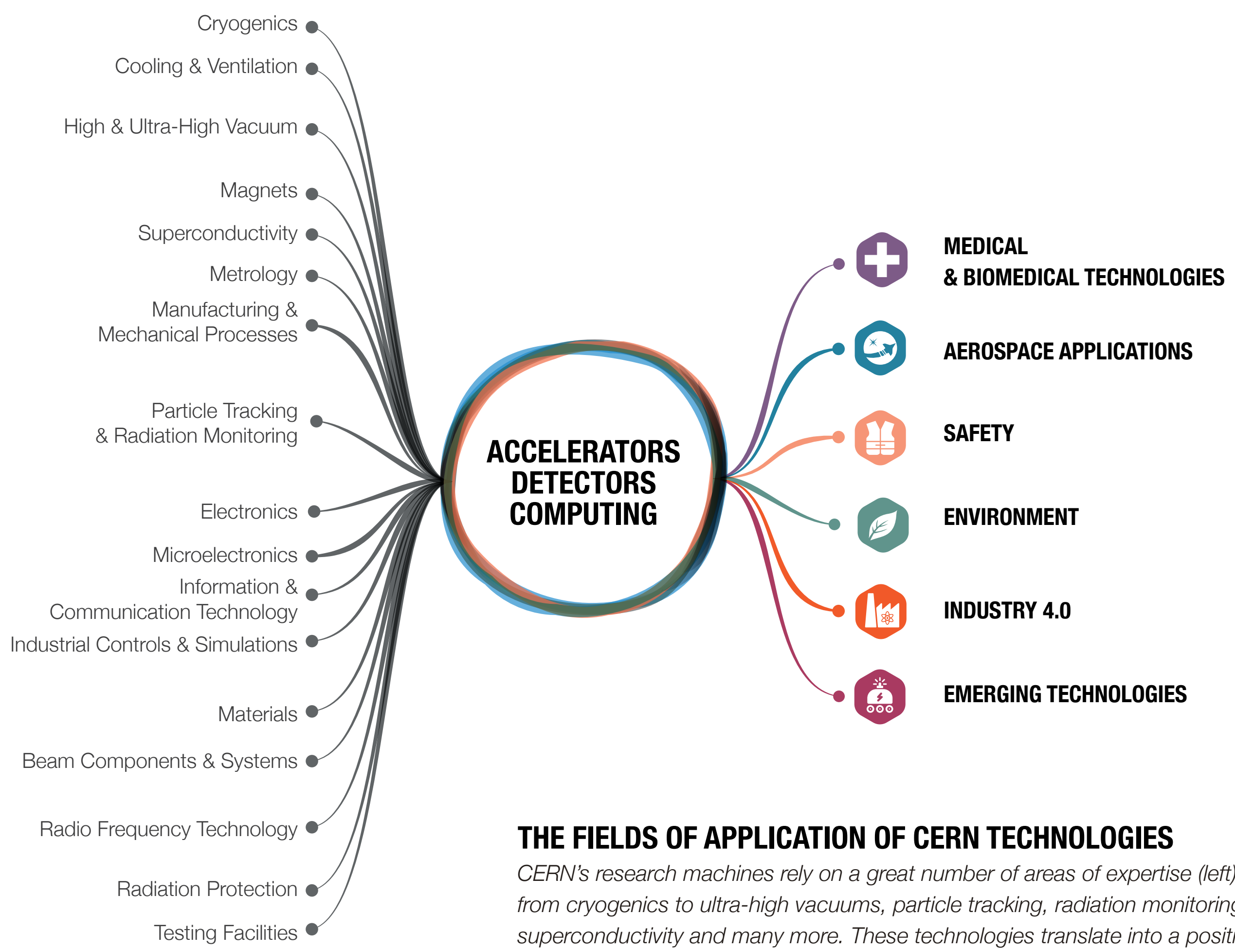
CERN's expertise builds broadly on three technical fields: accelerators, detectors and computing. Behind these three pillars of technology lie a great number of areas of expertise, ranging from cryogenics to ultra-high vacuums, particle tracking, radiation monitoring, superconductivity and many more. In 2016, these technologies, and the human expertise associated with them, translated into a positive impact on society in many different fields: medical and biomedical technologies, aerospace applications, safety, the environment and industry 4.0 (including robotics and the "Industrial Internet of Things").

In 2016, CERN's contribution to **medical and biomedical technologies** was significantly strengthened by identifying strategic avenues and implementing a new organisational set-up. By working closely with medical communities and Member and Associate Member States, CERN can ensure that it provides solutions to the end-users' needs.

The year 2016 was busy and exciting for MedAustron – a facility located in Wiener Neustadt, Austria, which uses an accelerator to generate ion beams for cancer therapy and research. The accelerator has been operating 24/7 since January, and in September the facility was legally certified to operate as an outpatient clinic, with the first medical treatment performed on 14 December. By 2020, full operation will have been reached, with about one thousand patients being treated per year. CERN contributed considerably to the development and construction of the centre's accelerator system.

In 2016, CERN and the University of Bath released new open-source software for medical imaging. This shareware toolbox provides fast, accurate 3D X-ray image reconstruction, with applications in medical imaging for cancer diagnosis and treatment. It offers a simple and accessible way to improve imaging and potentially reduce radiation doses for patients. The software is based on cone-beam computed tomography, a scanning process that takes 2D X-ray pictures and processes them into a 3D image. The toolbox is called the Tomographic Iterative GPU-based Reconstruction (TIGRE) toolbox, and is available on an open-source basis on GitHub. The collaboration hopes that its open-source approach will bring together academics and clinicians.

To support its **aerospace applications**, CERN is establishing a network of institutional partnerships with space agencies, industry, universities and international organisations, and 2016 was fruitful in this respect. In June, CERN signed an agreement with the Swiss Space Center (SSC). The agreement ensures that CERN can benefit from the SSC's



THE FIELDS OF APPLICATION OF CERN TECHNOLOGIES

CERN's research machines rely on a great number of areas of expertise (left), ranging from cryogenics to ultra-high vacuums, particle tracking, radiation monitoring, superconductivity and many more. These technologies translate into a positive impact on society in many different fields (right).

In 2016, MedAustron, a new ion therapy centre in Austria, began operation. The synchrotron of this medical research and treatment centre was developed in collaboration with CERN.

expertise in space activities and its extended network in Switzerland, supporting the transfer of CERN's technologies and expertise to the aerospace field.

In September, a memorandum of understanding was signed between CERN and the Euclid Consortium, giving the Euclid space mission the status of "recognised experiment" at CERN. Euclid – a European space mission that aims to study the nature of dark matter and dark energy – has now officially chosen the CERN Virtual Machine File System for its nine data centres. This system, called CernVM-FS, was developed by researchers at CERN as a means of sharing software and codes efficiently in big-data environments. As well as its use by Euclid, it is currently also used in high-energy physics experiments to distribute about 350 million files.

Since 2016, CERN has been participating in the Fibre Optic Sensor Systems for Irrigation (FOSS4I) research project, which has **environmental applications**. It aims to design a system for optimised irrigation based on technologies developed for high-energy physics. The irrigation system will use fibre-optic sensors designed to measure parameters such as temperature, humidity and fertilisers present in the soil of cultivated fields. The system will help to build more sustainable agriculture by enabling water savings, increasing crop yields and reducing the use of pesticides and fertilisers. The fibre humidity sensors are based on those developed for the CMS experiment. A key aspect of this project is its open approach: all hardware will be released under CERN's Open Hardware Licence, and the software will be released under an open-source licence. The research programme was launched by the UK Lebanon Tech Hub (UKLTH). CERN, as part of its knowledge transfer efforts, will lead the project and provide continued knowledge transfer support after its initiation.

Industry 4.0 is the new trend of increased automation in industry, often associated with connected sensors, autonomous robots and big-data technology. The start-up Terabee uses CERN sensor technology and has begun to provide aerial inspections and imaging services by deploying drones. After fruitful collaboration with CERN, where sensors were used to ensure the safety of operations in the complex environments of the LHC, the business has expanded to include sensor development. In 2016, the start-up won the first place in the automation category of the prestigious Startup World awards at the Automatica trade fair.

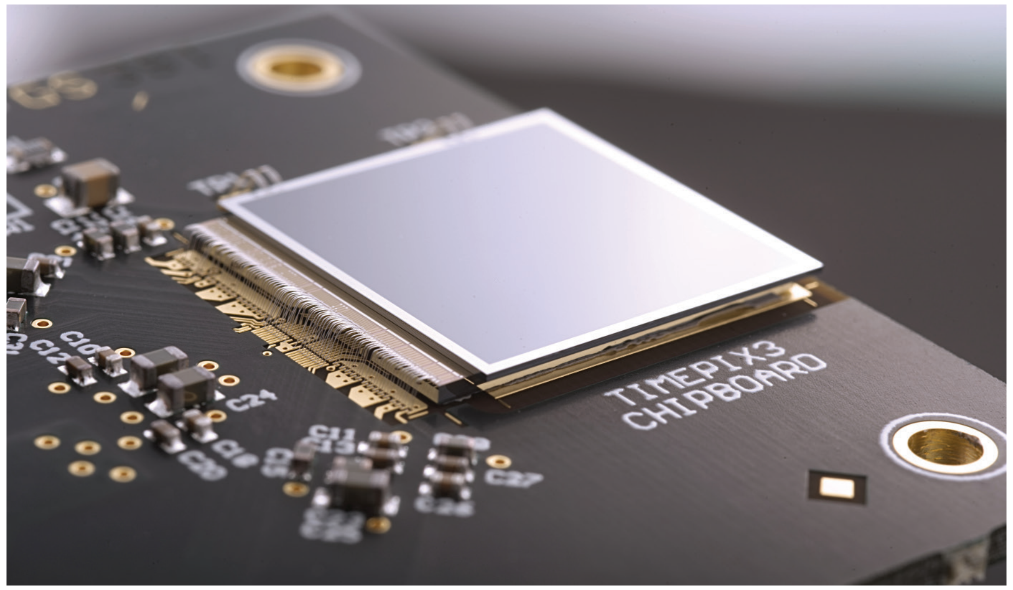
ACCELERATING INNOVATION

Innovation can happen organically, in the sense that new ideas and technologies eventually develop into new products or adapt to market needs. Actively investing in innovation can accelerate the process. To this end, CERN invests in many activities through its Knowledge Transfer group, which provides advice, support, training, networks, seminars and infrastructure to facilitate the transfer of CERN's know-how to industry and eventually to society.

In 2016, CERN was highlighted as an example of a successful regional innovation initiative in the Global Innovation Index (GII) published by the World Intellectual Property Organisation (WIPO), Cornell University and INSEAD. In 2016, a series of Knowledge Transfer seminars, which can be viewed free of charge via webcast, highlighted the impact of CERN on society.

The **CERN Knowledge Transfer Fund** selects innovative CERN projects with high potential for a positive impact on society. Over the last six years, it has become a pivotal tool for creating links between research and industry. To date, 38 projects have been funded and 21 completed in a wide range of fields. They have so far led to 17 knowledge transfer agreements with industry and research institutes.

Beyond its mission to champion innovation, the CERN Knowledge Transfer Fund has also contributed to developing



The Timepix3 chip is a multipurpose hybrid pixel detector developed in the framework of the Medipix collaborations, having applications in medical imaging, education, space dosimetry and material analysis. Originally developed for use in the LHC experiments, Medipix technologies are an outstanding example of how technology devised at CERN can create societal impact. (CERN-PHOTO-201702-048-4)

human capital. Students and young professionals have gained valuable industry-oriented experience. Today, they continue their careers in fundamental or applied research or in industry. Another milestone was reached in 2016: two projects co-funded by the European Commission, AIDA-2020 and ARIES, incorporated a Proof-of-Concept fund modelled on CERN's Knowledge Transfer Fund.

In 2016, CERN funded six new projects covering new applications for CERN technology in fields ranging from cancer diagnostics and aerospace applications to next-generation cloud computing, radiation protection and digital preservation.

After successfully concluding its first phase, **SCOAP3**, the open access initiative for particle physics has been extended for another three years. This initiative, managed by CERN, makes scientific articles available free of charge to everyone, at no direct cost to authors and readers. Since its launch in 2014, it has made 13 500 articles by some 20 000 scientists from 100 countries accessible to anyone. This success is made possible by 3000 libraries in 43 countries contributing funds previously used to subscribe to the journals, with the additional support of eight funding agencies. Participating publishers have observed a doubling of the number of article downloads since the start of the initiative.

During its second year of operation, **IdeaSquare** continued to make important progress in connecting detector-related R&D activities with cross-disciplinary Masters-level student teams working on societal challenges. IdeaSquare organised or hosted more than 80 events in 2016, including knowledge transfer workshops, challenge-based innovation courses and weekend hackathons. An online journal was created to record the education- and innovation-related processes at IdeaSquare in order to measure its longer-term societal impact.

BUILDING A CULTURE OF ENTREPRENEURSHIP

In 2016, CERN continued to work towards creating a culture of entrepreneurship within the Organization. The many avenues explored include the network of business incubation centres, entrepreneurship meet-ups and mixers and seminars, where budding entrepreneurs can share ideas and experience with experts.
CERN has established a network of business incubation centres (BICs) throughout its Member States to assist entrepreneurs and small technology businesses in taking CERN technologies and expertise to the market.
CERN signed its ninth business incubation centre agreement with the Italian National Institute of Nuclear Physics (INFN) in June 2016. Currently, 18 start-ups and spin-offs are using CERN technologies in their business. In 2016, 23 start-up companies submitted expressions of interest in entering six of the BICs.

COLLABORATIONS

CERN engages with international organisations, is establishing a network of partnerships, and participates in the knowledge transfer activities of several projects co-funded by the European Commission. The Organization is involved in several knowledge transfer networks, such as EIROforum, an umbrella organisation of eight international research organisations.

CERN continues its collaborative activities in projects co-funded by the EC. Of the 12 new projects selected for funding in 2016, two are coordinated by CERN: ARIES, a large integrating activity involving accelerator science and technology, including industrial and societal applications, and RADSAGA, a Marie Skłodowska-Curie Innovative Training Network relating to electronics used in space, for aviation, on the ground and in accelerators.

INSPIRING AND EDUCATING NEW GENERATIONS

CERN engages with society through a wide range of outreach and education activities. Their main objectives are to broaden understanding of science and of CERN's activities, to inspire young people, to improve science education at secondary school level, and to train a new generation of scientists and engineers.

In 2016 S'Cool LAB, CERN's learning laboratory, offered more than 5800 school students the opportunity to carry out hands-on physics experiments. In this picture some of these students have just built a cloud chamber to observe the tracks left by particles. (OPEN-PHO-LIFE-2017-008-3)

EDUCATING THE SCIENTISTS OF TOMORROW

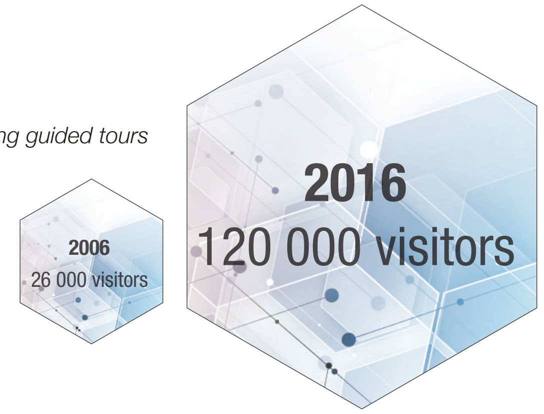
CERN's involvement with science education focuses mainly on secondary school teachers and students. A passionate and knowledgeable teacher can resonate with students and provide inspiration for young minds. CERN's goal is to empower teachers in this role by keeping them up to date on current research in particle physics.
In 2016, 953 science teachers from 46 countries took part in one of 35 one-week training programmes (in their national language) or in the three-week international high-school teacher programme (in English), to learn more about the fundamental discoveries of particle physics and cosmology, share their experience with other teachers and, most importantly, be inspired to foster a love of science in future generations of students. Visiting CERN and interacting with scientists also gives more insight into the scientific method and the interplay between hypotheses, theories, experimental data, peer review, open critical thinking and discussion.

School students represent about 60% of CERN's visitors; in 2016, the Laboratory welcomed a total of 70 000 pupils. One of the most important aspects of such visits is the potential to inspire young people and to help them understand how science works – and, for some of them, to arouse the passion for a career as a scientist or engineer.
Beyond guided tours, CERN offers educational programmes for the more motivated students. S'Cool LAB gave more than 5800 school students the opportunity to attend a workshop in CERN's learning laboratory. This initiative offers students the chance to carry out hands-on physics experiments independently in half-day workshops: in small groups of two to four they can build cloud chambers, visualise X-rays with pixel detectors, trap elementary particles and learn the basics of particle acceleration or the principles of a PET scanner.

The Beamline for Schools competition is open to teams of high-school students aged 16 or older. It gives budding scientists a chance to propose and carry out a real particle physics experiment at a fully equipped CERN beam line, using a pre-determined set of detectors that the teams can choose from. In 2016, the third edition of Beamline for Schools attracted proposals from 151 teams across 37 countries. Two teams were selected and invited to carry out their proposed experiments: the Pyramid Hunters from Poland studied the tomography of Egyptian pyramids and the absorption of muons in limestone; and the Relatively Special team from the United Kingdom tested the validity of the theory of Special Relativity using the decay rate of pions.

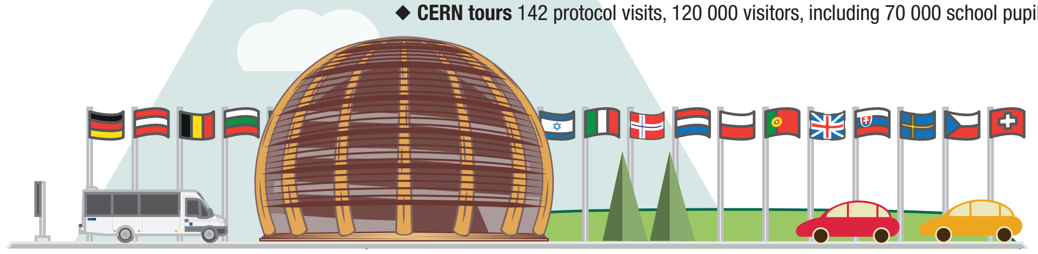
International Masterclasses are an exciting way to experience life at the cutting edge of research, giving school pupils the opportunity to become particle physicists for one day. The idea behind this annual programme, organised by IPPOG (International Particle Physics Outreach Group) and supported by CERN, is to encourage pupils to work as true scientists, using authentic and recent data from the LHC experiments. In 2016, more than 13 000 high-school students in 52 countries visited universities or research centres in their region. There, they listened to lectures about how particle physics research works, what the big questions are, and the process leading to a scientific discovery.
Reflecting the international nature of particle physics, the programme was joined in 2016 by five new countries: Bangladesh, Georgia, Montenegro, Russia and Rwanda.

Evolution of number of visitors taking guided tours of CERN from 2006 to 2016



CERN's visits and outreach were hugely successful in 2016. In particular, CERN offers a wide range of outreach activities to raise school pupils' awareness of fundamental science.

- **Teacher training** 953 teachers from 46 countries • 10 000th teacher
- **School student programmes** Beamline for Schools: 191 teams applied • S'Cool LAB: 5800 pupils
  International Masterclasses: 13 000 pupils in 52 countries
- **CERN exhibitions** Permanent exhibitions: 70 000 visitors • Travelling exhibitions: 100 000 visitors
- **CERN tours** 142 protocol visits, 120 000 visitors, including 70 000 school pupils



The fourth edition of TEDxCERN, which took place in November, explored how scientific curiosity and understanding spark innovation. (OPEN-PHO-LIFE-2017-005-2)

WORLDWIDE INTEREST BY NUMBERS

The interest of the general public and the international media in CERN is remarkable: in 2016, 145 000 articles about CERN were published in the world press, and the Press Office organised 242 media visits for 628 journalists from around the globe. Four million unique visitors to CERN's core websites and 1.7 million mentions on social media show the strength of the public's interest in CERN and its research.

Visual and multimedia resources play a crucial role in supporting all of CERN's education and outreach activities. More than 100 video clips and several animations were produced in 2016 for use in online digital content, visit points across the CERN site and exhibitions. In the spirit of being an open institution, all resources are freely available online, and are regularly used for educational and non-commercial purposes, thus spreading awareness of the process and results of fundamental research and CERN's activities internationally.

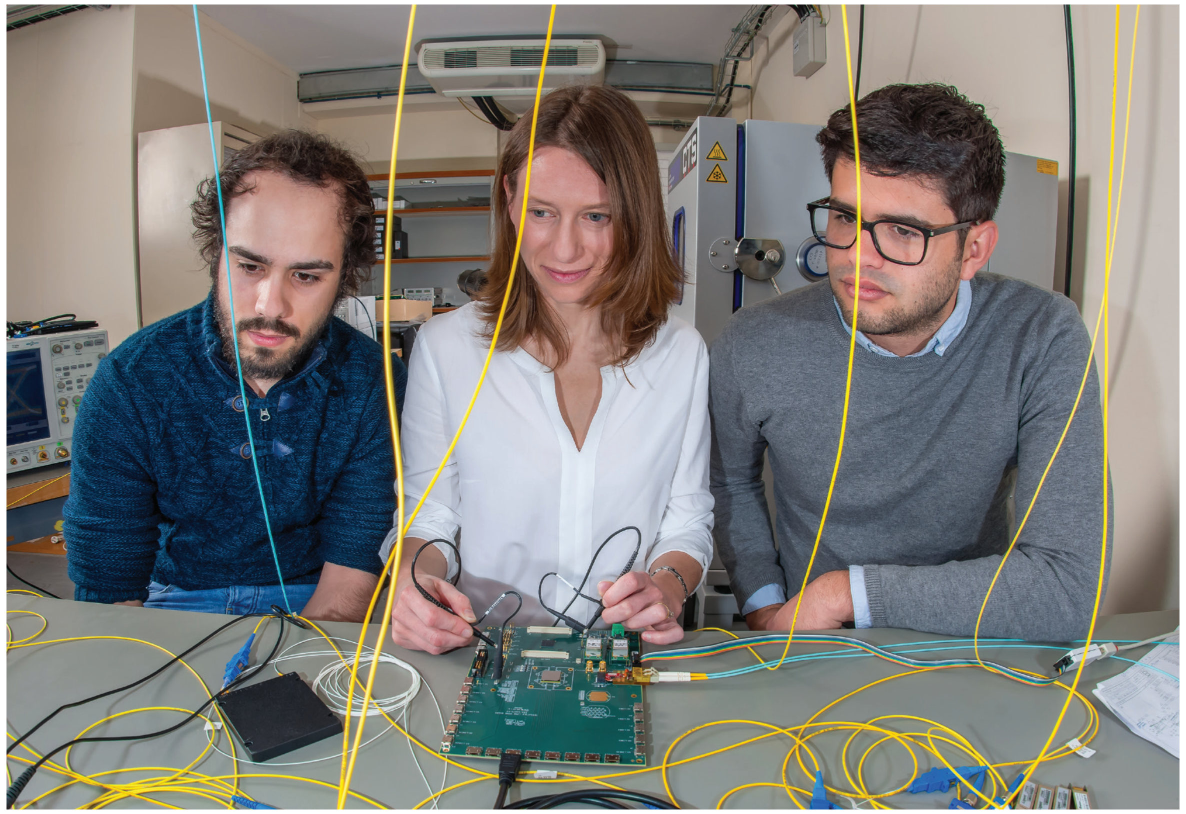
VISITING THE LABORATORY

Visiting CERN has become a popular activity, even for busy world leaders: in 2016, the Laboratory welcomed five heads of state or government and organised 142 protocol visits. CERN is also highly attractive for the general public, including teachers and students, who discover how research in the world's largest laboratory for fundamental physics helps to answer the big questions about the universe. The annual number of visitors continues to increase, rising from 26 000 in 2006 to 120 000 in 2016. However, the demand for group visits is about three times higher, and "open tours" – guided tours for individual visitors – are usually fully booked within the first five minutes after registration opens. In addition, more than 70 000 people visited the two permanent exhibitions at CERN (Microcosm and the Universe of Particles).

After 11 months of renovation work on the Globe of Science and Innovation, the Universe of Particles exhibition opened its doors again in April, and topped the TripAdvisor chart of tours and museums in the Geneva region. (BUL-PHO-VIEW-2015-002-7)

IMPACT ON LOCAL COMMUNITY AND CULTURE

Various activities for the local community took place at CERN in 2016: 12 well-attended public conferences, as well as the fourth edition of TEDxCERN, which explored how scientific curiosity and understanding spark innovation. Twelve renowned speakers shared ideas, ranging from new procedures for non-invasive prenatal testing to underground searches for dark matter. Four hundred people attended the event at CERN, and more than 3800 tuned into the webcast or watched at one of the 75 live-viewing parties in 33 countries. The "European Researchers' Night" was again well attended, attracting more than 400 people to presentations and visits at CERN.The Arts at CERN programme aims to reach new audiences using an interdisciplinary approach that brings the worlds of art and science closer together. The dialogue between artists and scientists takes place during one- or three-month residencies, fully funded by prominent art institutions such as FACT in the UK, Ars Electronica in Austria and ProHelvetia in Switzerland. The attractiveness of these residencies, whose winners are selected by a jury of artists and CERN scientists, is illustrated by the 904 applications received in 2016 for the 2017 FACT residency.



CERN's training programmes provide opportunities to acquire professional experience early in one's career. Here, a Master's student and an engineering Fellow, recently graduated, work alongside their supervisor (centre) on electronic systems for the experiments. (OPEN-PHO-TECH-2017-003-1)

THE FIRST STEPS OF THEIR CAREER

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

The Summer Student programme provides university students with a unique two- to three-month experience of working in research groups, attending dedicated lectures given by leaders in the field, visiting CERN facilities and taking part in workshops and discussions. More than 2000 applications were received, and 278 university students from 87 countries took part in 2016.

Among these, 38 students from 22 countries came to work for two months on advanced IT projects in the context of the CERN openlab Summer Student programme, tailored specifically for university students with a strong background in computing.

The CERN fellowship programme targets recent graduates from universities and technical institutes. Out of 2170 applications, 412 fellows were selected and given the opportunity of a two- to three-year research experience in particle physics or in advanced development projects in a broad range of engineering and other technical fields.

The Technician Training Experience is part of CERN's fellowship programme, and offers highly skilled technicians a two-year professional experience to further their career or before they embark on advanced study programmes. Some 167 candidates applied, and 46 young technicians from nine countries were selected.

Out of 1486 applicants, 287 university students were selected to take part in the technical and administrative student programmes, which provide on-the-job training for a period of 4 to 14 months in applied physics, engineering, computing, and administration.

The doctoral student programme allows postgraduate students in technical fields to work on their thesis at CERN for up to three years. 85 doctoral students were selected from the 205 applicants for this programme.

A SUSTAINABLE RESEARCH ENVIRONMENT

CERN is fully committed to ensuring the health and safety of everyone participating in the Organization's 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.

A view of the CERN main site with the Globe of Science and Innovation in the foreground. The Globe, conceived as a symbol of sustainable development, was reopened to the public in 2016 after a period of renovation. (OPEN-PHO-LIFE-2017-009-2)

Since the 2012 launch of a machine-tool compliance campaign, some 900 machines such as this one have been tested and declared compliant with CERN's safety rules. (CERN-PHOTO-201704-108-5)

Using the Kryolize software to test a pressure relief valve. (OPEN-PHO-SAFETY-2017-001-2)

A SOLID FOUNDATION FOR CERN RESEARCH

Highlights in the areas of health, safety and environmental protection (HSE) in 2016 include important progress towards HSE measures needed for the LHC's second long shutdown. World-leading research on cryogenic safety and detection systems for ionising radiation was carried out, and two new bodies were established: the CERN Environmental Protection Steering Board, which will oversee CERN's work to minimise its environmental impact, and a new working group charged with developing a mobility plan for CERN. Both will start work in 2017.

OCCUPATIONAL HEALTH AND SAFETY

CERN's future research programme is rich and varied, with a range of new projects getting under way. Making sure that each project achieves its goals while reaching the highest standards in health, safety and environmental protection is a top priority. Safety teams work closely with project personnel to balance each project's goals with those relating to HSE matters. In 2016, safety clearances were delivered to the NA61/SHINE and AWAKE experiments. Just as important as ensuring the safety of new projects is ensuring that established infrastructure conforms to the latest safety standards, and in 2016 the CERN Management gave the go-ahead for the SPS accelerator's fire safety consolidation project.

The LHC's second long shutdown begins at the end of 2018. Over a period of 24 months, a great deal of work will be carried out in CERN's surface and underground areas. Preparations for the safety of people and equipment are already well under way, with a review of the safety facilities needed ongoing and two dedicated safety training courses having been identified for development in the lead-up to the shutdown.

PIONEERING CRYOGENIC SAFETY

CERN hosted its first Cryogenic Safety Seminar in September. Attracting 120 participants from research institutions and companies around the world, the seminar was built around CERN's expert knowledge of cryogenics, particularly at the extremely low temperatures required by the LHC. The seminar covered topics including research and development, international standards for cryogenic safety, risk assessment, and the development of rules and regulations for cryogenic safety systems. One of the high points was the presentation of the Kryolize project, supported by CERN's Knowledge Transfer Fund (see p. 34), which is developing software for cryogenic safety systems effective from liquid helium temperatures to the relatively balmy realm of liquid nitrogen. Kryolize has many potential applications in research laboratories and industry. Seven academic and one commercial licence to use the software have already been granted.

Horses help to maintain CERN's forests

The CERN site covers 625 hectares, of which around 200 are fenced sites used for CERN's research activities. The rest of the land consists of fields rented out to farmers and about 90 hectares of forest, mainly in France and managed by the French forestry commission (*Office Nationale des Forêts*). Horses are involved in the removal of felled trees from some of CERN's woods in order to minimise the impact on the environment. (CERN-PHOTO-201703-074-12)

OCCUPATIONAL MEDICINE AND EMERGENCY PREPAREDNESS

The collaboration established in 2015 between CERN and the University Hospitals of Geneva (HUG) came into its own in 2016. Through this agreement, CERN hosts an emergency response unit on its Meyrin site. This provides a service not only for CERN's Swiss and French sites, but also for the surrounding region. This unit has helped to reduce emergency response times considerably for the area covered. In 2016, the team leapt into action some 60 times for on-site interventions.

The signing of a tripartite agreement between CERN and its Host States in December reinforced cross-border cooperation in the event of the need for emergency intervention on the CERN sites or in the surrounding areas. Such operations by Host State emergency services were previously governed by two agreements, one with the local authorities in Geneva and one with the French department of the Ain. The three partners are developing joint procedures and training exercises, and CERN's Fire and Rescue service benefits from the experience of the services in France and Switzerland.

RADIATION PROTECTION

CERN's excellent track record in radiation protection continued in 2016. Of 8909 monitored workers, only eight received an individual dose above 1 millisievert (mSv), and all were below 2 mSv. By comparison, the average dose received from natural sources and medical procedures by citizens in CERN's Member States ranges from around 3 to 4 mSv per year.

CERN's strong performance in radiation protection is the result of constant vigilance to remain in the vanguard of the field. In 2016, the Laboratory's Radiation Monitoring System for the Environment and Safety, RAMSES, which provides continuous state-of-the-art monitoring both inside and outside CERN's perimeter, was extended to cover a range of facilities. Refurbished facilities newly equipped with RAMSES include the PS East Hall and facilities in the SPS's North Experimental Area. Among the new facilities to be equipped with RAMSES are AWAKE, MEDICIS and the GBAR experiment.

Ten prototypes for the next generation of RAMSES electronics were readied for tests in 2016. Designed to provide high-performance, cost-effective and low-maintenance monitors for CERN, these will be installed during the second long shutdown and deployed from LHC Run 3, starting in 2021.

Following agreements with CERN's Host States, the Organization's radioactive waste treatment centre ramped up operations in 2016, safely eliminating some 1200 cubic metres of low-level radioactive waste, considerably more than the 310 cubic metres produced during the year. The safe elimination of radioactive waste is set to reach another milestone in 2017 following a detailed preparatory study for the disposal of the superconducting accelerating modules from CERN's former flagship accelerator, LEP, which concluded operations in 2000. CERN's proposed disposal method received approval from the Swiss authorities.

An important milestone towards future particle physics research with an optimised ecological footprint was achieved with the release of the ActiWiz3 computer programme. ActiWiz3 helps researchers to identify materials that result in a minimal dose for personnel and the lowest amount of radioactive waste for any accelerator or experimental environment. The programme became one of the standard tools for the characterisation and clearance of radioactive waste and equipment at CERN. Moreover, its use contributed to a new material clearance standard released by the US Department of Energy in 2016. Ten ActiWiz licences have been granted.

Safety training

43 866 e-learning safety courses followed
789 classroom safety courses delivered to **6 320** people
6 new or refurbished e-learning safety courses produced

Environmental protection

136 environmental monitoring stations keeping track of radiation, air and water quality
13 new hydrocarbon detectors monitoring CERN's waste water network

Radiation protection and general safety

1 200 cubic metres of low-level radioactive waste safely eliminated
18 licences granted for use of CERN-developed safety software packages
Over **500** bicycles available for personnel to travel around CERN sites

TRAINING FOR SAFETY

The overhaul of CERN's e-learning safety courses continued apace in 2016. A new modular approach launched in 2015 allows efficient delivery of courses tailored to individual needs, while also making it easier for developers to keep courses up to date. In 2016, six new or refurbished e-learning modules were released, 43 866 e-learning courses were followed, and 6320 people attended 789 classroom sessions delivered throughout the year.

ENVIRONMENTAL PROTECTION

CERN's environmental monitoring network was consolidated in 2016 with the installation of three new monitoring stations. This brings to 136 the total number of stations continually monitoring radiation, air and water quality, while also gathering meteorological data through a total of 539 measurement channels. In addition, a further 13 hydrocarbon detectors reinforced CERN's effluent water monitoring system, allowing early detection of hydrocarbon pollutants and thereby ensuring the rapid intervention of CERN's emergency services if necessary.

In 2016, CERN finalised a detailed assessment of prevention measures against water and soil pollution in areas where liquid chemical agents are used. The methodology and tools for a CERN-wide survey and risk analysis were put in place.

MOBILITY MANAGED

Transport is a major issue for CERN, encompassing daily commutes as well as travel between and around the CERN sites for the Laboratory's large number of visiting scientists. CERN has always favoured green solutions: while CERN cars are available for visitors to rent, bicycles are provided at no cost. In addition, a new 2.4-kilometre cycle path was inaugurated in October. It allows cyclists in the local area to travel safely and easily between CERN's two main sites. It has been financed by CERN and French local authorities.

With a view to improving safety and promoting green transport solutions at CERN, the role of the CERN Mobility Coordinator was created in 2016. Working with a lab-wide working group, the Mobility Coordinator will develop a mobility plan for CERN and will work with local groups to promote green initiatives such as Switzerland's Bike2Work challenge and the French *Challenge Mobilité*, while also improving safety for all road users.

BUILDING A GREENER FUTURE

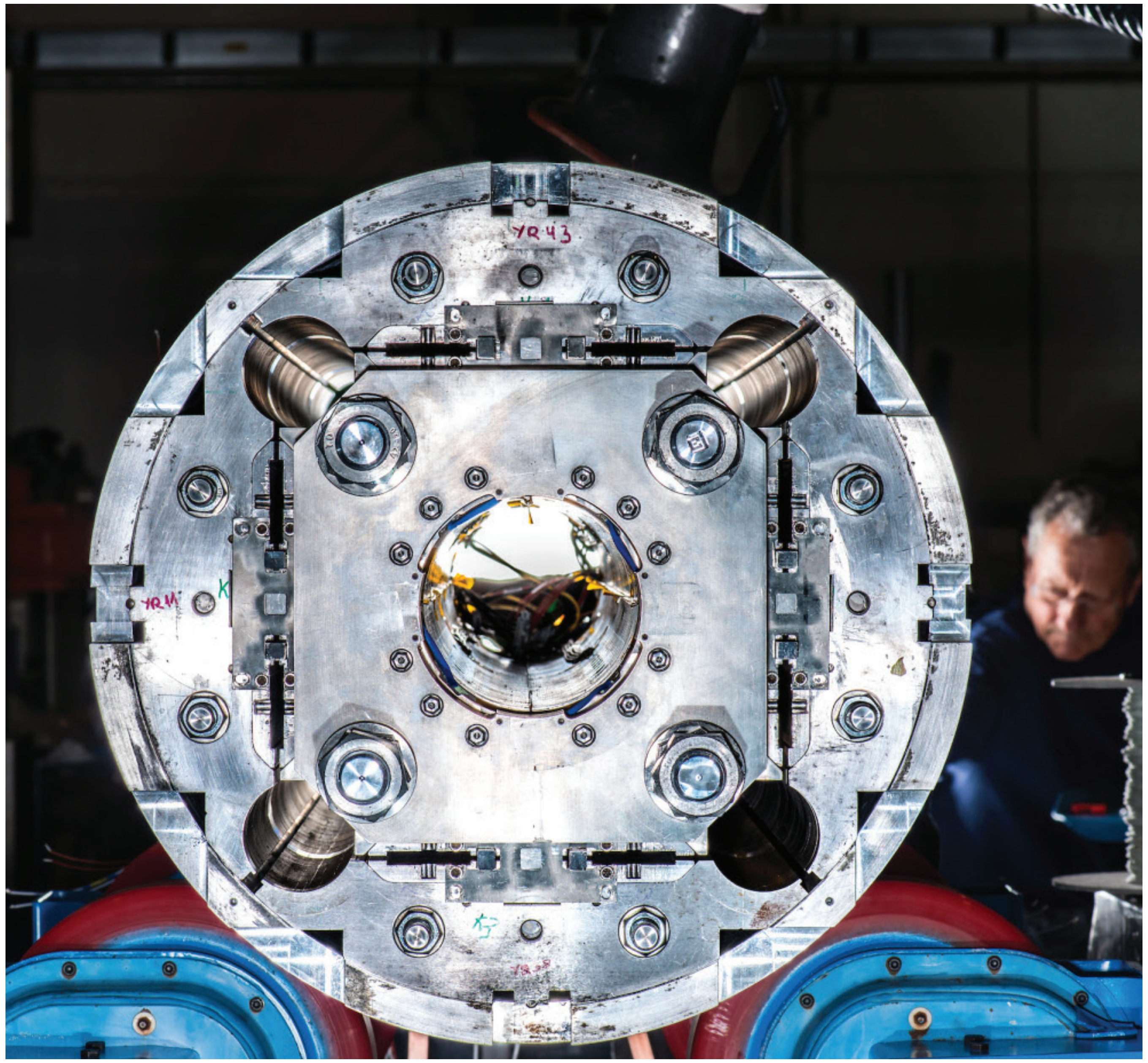
After a period of renovation, CERN's Globe of Science and Innovation reopened to the public in 2016. Conceived as a symbol of sustainable development, the Globe was just one building among many that underwent refurbishment on the CERN sites through the year.

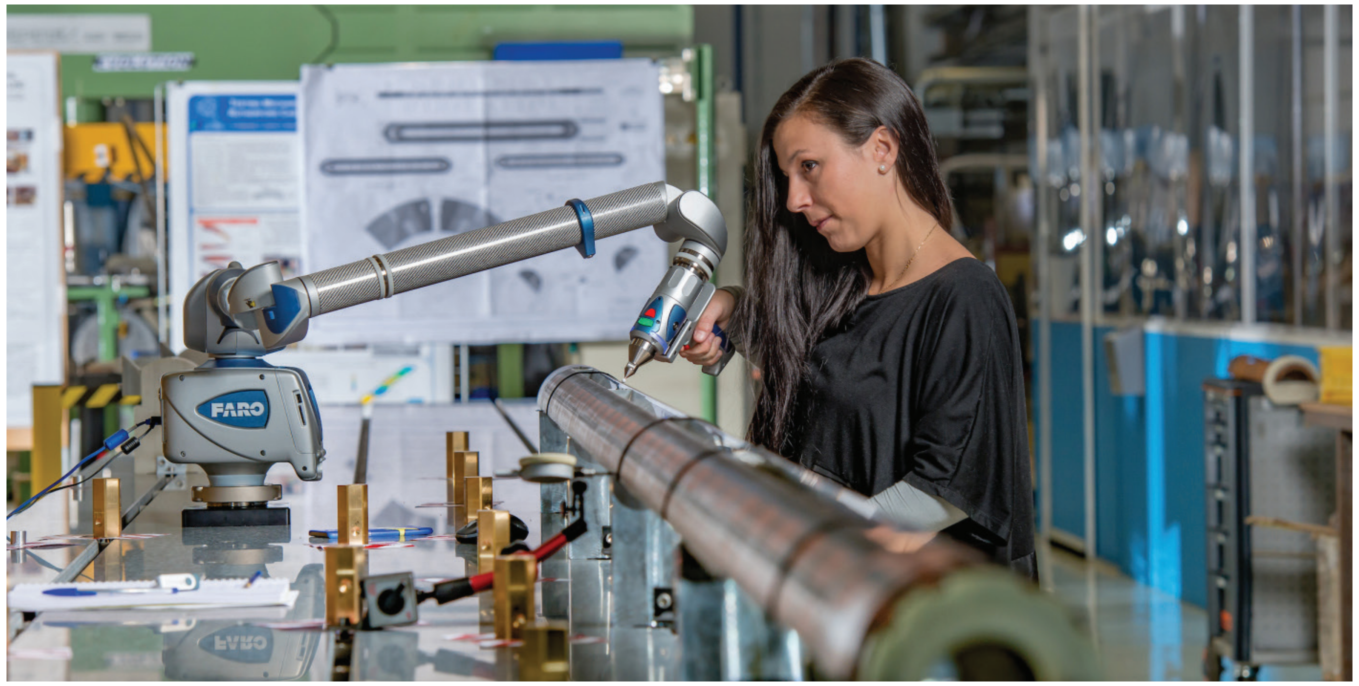
At work in one of CERN's environmental monitoring stations. (CERN-PHOTO-201603-064-1)

BUILDING TOMORROW AND BEYOND

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

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





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

FULL SPEED AHEAD FOR HIGH LUMINOSITY

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

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

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

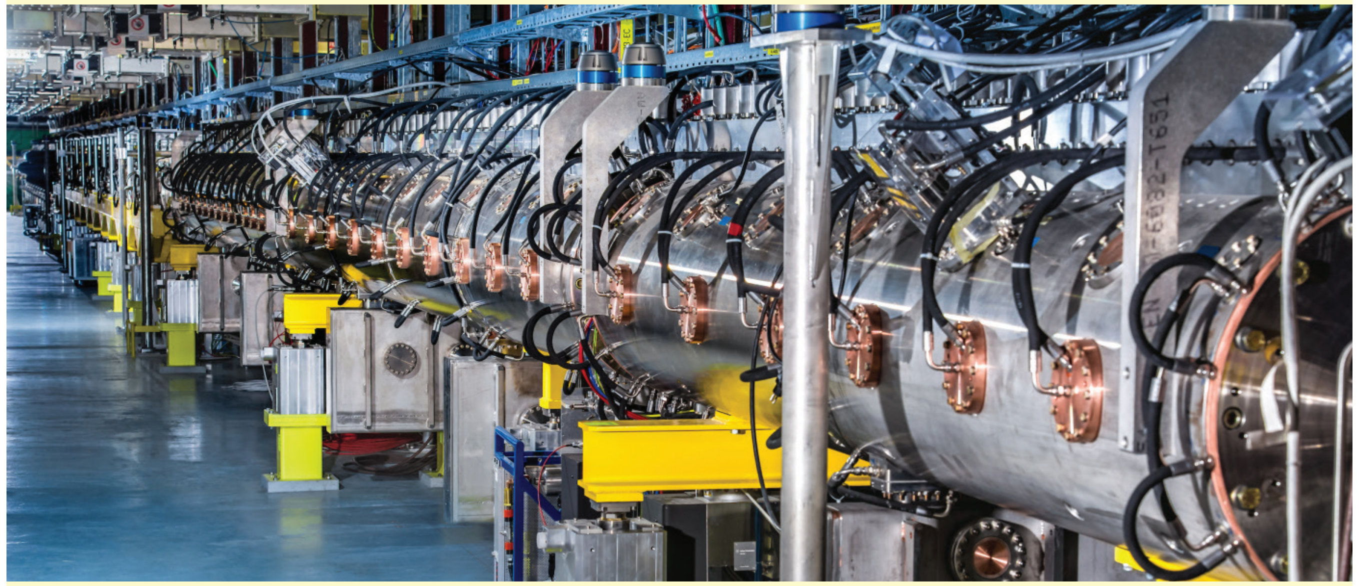
The magnets are being developed in the framework of a collaboration between CERN and the LHC Accelerator Research Programme (LARP), which involves several US laboratories. Once short prototypes had been successfully tested, the production of full-size prototypes began. The first coil, 7.5 metres long,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

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

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

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

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



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

THE NEW LINEAR ACCELERATOR REACHES ITS ENERGY GOAL

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

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

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

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

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

EXPERIMENTS ON THE ROAD TO PERFECTION

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

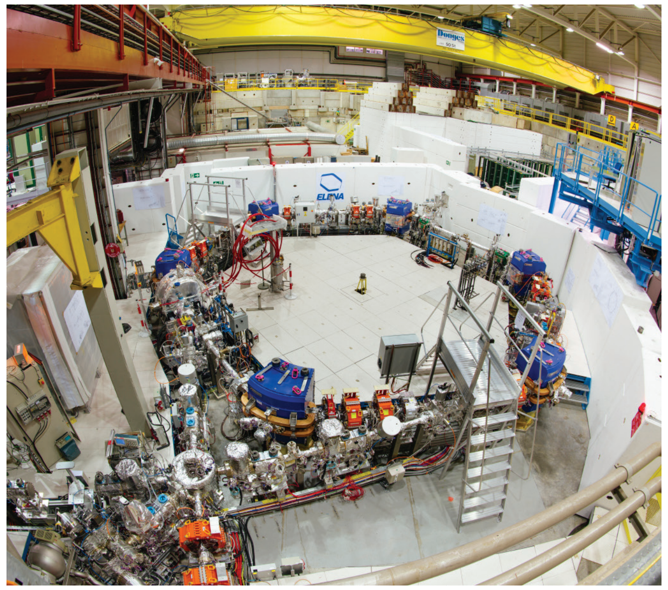
The LHC collaborations are working on major upgrades of their detectors, which will be commissioned in stages up to 2025. The aims of these upgrades are to increase the efficiency of the trigger and acquisition systems, improve the granularity of the trackers and boost the radiation-hardness of the components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

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

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

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

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



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

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

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

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

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

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

A NEW RING TO SLOW DOWN ANTIMATTER

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

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

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

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

WHICH ACCELERATOR FOR THE FUTURE?

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

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

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

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

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

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

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

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

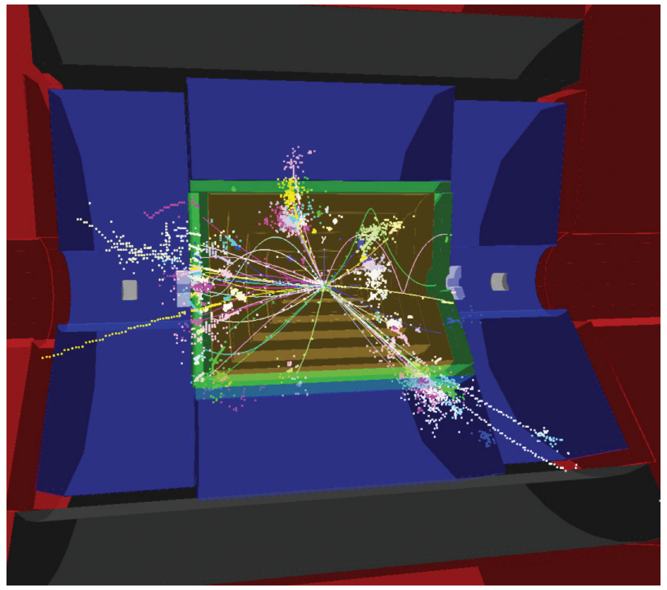
The first prototype for the FCC, a more efficient beam screen designed to disperse heat and maintain the ultra vacuum. (CERN-PHOTO-201604-074-2)

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

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

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

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



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

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

PHYSICS BEYOND COLLIDERS

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

MAKING WAVES IN ACCELERATOR TECHNOLOGY

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

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

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

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

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

CERN COUNCIL

Composition as at 31 December 2016

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Professor F. Forti

Chair of the SPS and PS Experiments Committee
Dr C. Vallée

Chair of the ISOLDE and Neutron Time-of-Flight Experiments Committee
Professor K. Blaum

Chair of the European Committee for Future Accelerators
Professor H. Abramowicz

Also present

President of the Council
Professor S. de Jong

Chair of the Finance Committee
Ms C. Jamieson

Director-General
Dr F. Gianotti

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Chair
Ms C. Jamieson (United Kingdom)

Members
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Education, Communications and Outreach (IR-ECO)	Ana Godinho
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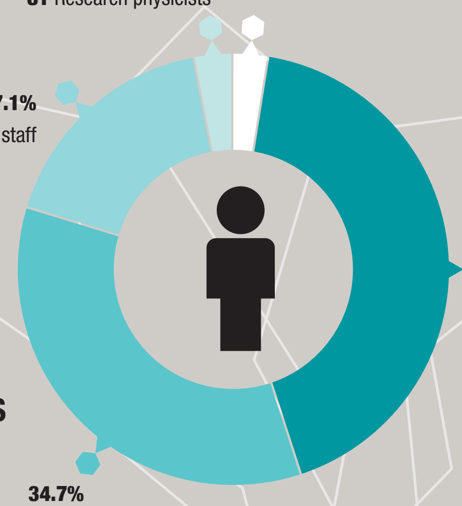
Experimental Physics (EP)	Manfred Krammer
Information Technology (IT)	Frédéric Hemmer
Theoretical Physics (TH)	Gian Giudice
Project Management	
Advanced Wakefield Experiment (AWAKE)	Edda Gschwendtner
CERN Neutrino Platform	Marzio Nessi
Extra Low ENergy Antiproton (ELENA)	Christian Carli
Future Circular Collider Study (FCC)	Michael Benedikt
High Intensity and Energy ISOLDE (HIE-ISOLDE)	Yacine Kadi
High Luminosity LHC (HL-LHC)	Lucio Rossi
LHC Injectors Upgrade (LIU)	Malika Meddahi
Linear Collider Studies (CLIC and LCS)	Steinar Stapnes
Worldwide LHC Computing Grid (WLCG)	Ian Bird

CERN IN FIGURES

CERN STAFF

Total: 2560 persons



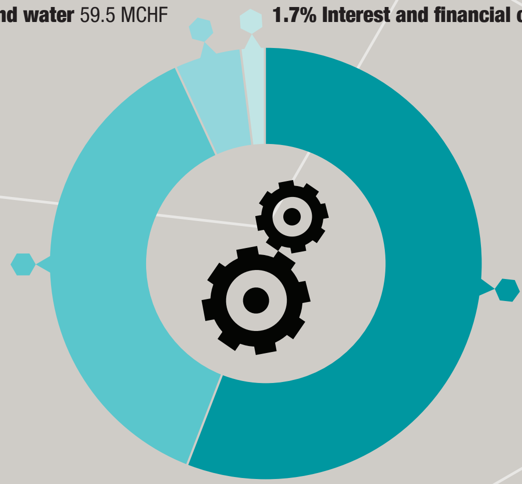
EVOLUTION OF STAFF NUMBERS

2012	2512
2013	2513
2014	2524
2015	2531
2016	2560

In addition to staff members, CERN employed 750 fellows, trained 552 students and apprentices and hosted 1185 associates in 2016. CERN's infrastructure and services are used by a large scientific community of 11 821 users (see p. 30).

CERN EXPENSES

Total expenses 1153.2 MCHF



In 2016, 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.

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Sixty-second 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-2016
The 2016 Knowledge Transfer annual report is available at: http://cern.ch/go/KT2016
The 2016 CERN Openlab annual report is available at: http://cern.ch/go/openlab2016
The 2016 CERN & Society is available at: http://cern.ch/go/cernandsociety2016

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-2016

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

Images:
Robert Hradil, Monika Majer/ProStudio22.ch: p. 3 (centre and right), p. 14 (top), p. 26, p. 32, p. 36, p. 39, p. 40, p. 41 (right), p. 44, p. 45, p. 46
Federica Piccinni: p. 10 (centre left)
NASA: p. 18 (top)
Shutterstock: p. 30 and 31
Geoffrey Dorne: p. 33
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Lucien Fortunati: p.38 (right)
CERN: all other images

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