Annual Report 2015

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

Design and Production: CERN Education, Communications and Outreach Group

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CERN, the European Organization for Nuclear Research, operates the world's leading laboratory for particle physics. Its business is fundamental physics, finding out what the universe is made of and how it works. Founded in 1954, CERN has become a prime example of international collaboration, with 21 Member States. Additional nations from around the globe also contribute to and participate in the research programmes.

The CERN Laboratory sits astride the Franco–Swiss border near Geneva. Its flagship research facility, the Large Hadron Collider, is housed in a 27-kilometre tunnel under the plain between Lake Geneva and the Jura mountains. The photograph above is a view from the mountain Le Reculet in the Jura, showing the Laboratory in its setting north of Geneva, with the Alps, including Mont Blanc, in the distance.

(Photo Thomas Kubes)

Contents

Message from the President of the Council

The highlight of 2015 for CERN was the restart of the LHC at 13 TeV: the highest energy ever achieved in an accelerator. The CERN Council followed this development with great interest and with much appreciation of the smooth, systematic and professional way in which the machine and the experiments were brought back into operation after a long period of maintenance and upgrades. At the traditional LHC Physics Colloquium at the Council's Open Session in December, eight bright young physicists presented the fascinating achievements of the LHC collider and the experiments during the first year of LHC Run 2.

The year 2015 was also the last of Rolf Heuer's seven years in office as CERN Director-General, with the Director-General Designate, Fabiola Gianotti, preparing for her term of office. In March, Dr Gianotti presented her proposed management structure for 2016–2020 to the Council. In September, the Council approved the appointments of Dr Gianotti's directors and heads of department. Among the new features of the incoming Management is the position of Director for International Relations. This reflects the growing importance of relations with the Member States and of the process of geographical enlargement of CERN.

In 2015, the enlargement process proceeded apace. In June, the Council adopted a resolution for the admission of Romania as a Member State. Turkey became an Associate Member of CERN in May, with Pakistan becoming an Associate Member in July. And over the course of the year the Council approved International Collaboration Agreements with Lebanon and Palestine. It is my sincere wish that these will have an impact beyond the immediate benefit that they bring to the research communities they touch.

In order to mitigate the impact of the Swiss franc's appreciation in January 2015 on the contributions of the Member States, the CERN Management proposed a plan of measures, which was discussed by the Council in March and June and approved in September. Consequently, more time was needed to prepare the Medium-Term Plan for the period 2016–2020 and the Budget of the Organization for the year 2016. The 2016–2020 MTP includes the start of construction of the High-Luminosity LHC project (HL-LHC), a flagship for CERN for the period 2025 to around 2035.

A five-yearly review of the financial and social conditions of members of the CERN personnel was on the agenda of the Tripartite Employment Conditions Forum (TREF) during the years 2014 and 2015. In December, on the recommendation of the Finance Committee, the Council approved the Management's proposals in the framework of this review.

The year 2015 was my third and last year as President of the Council. In September, the Council elected my successor, and I passed the baton to Professor Sijbrand de Jong in December. Professor de Jong has a long association with CERN, both as a scientific user and as a representative to the Council. I have greatly enjoyed working with him and wish him all the very best in his new role.

I am proud to have had the opportunity to work for this magnificent research organisation as President of the Council during a period that has seen great progress with the LHC, the completion of the update of the European Strategy for Particle Physics, the celebration of 60 years of science for peace and the admission of Israel as CERN's 21st Member State. I wish to thank the Council members, the members of its advisory bodies, Professor Rolf Heuer, the whole CERN Management, the administrative services supporting the Council and many other members of the CERN personnel for their invaluable help and most enjoyable cooperation throughout my period of office. I wish the Organization continuing success, and look forward to seeing what new knowledge CERN will bring us in the years to come.

Agnieszka Zalewska

Message from the Director-General

Much can happen in seven years, and much has happened during my mandate as CERN Director-General. While an annual report by its nature reflects on the year gone by, I would like to use the occasion of my last report to reflect briefly on how much has changed since 2009.

Towards the end of that year, we saw the first high-energy beams in the LHC, and in 2010 the research programme got under way. Two years later, LHC experiments were announcing their first major discovery, the Higgs boson, messenger of the Brout-Englert-Higgs mechanism. This led to a Nobel Prize for François Englert and Peter Higgs the following year. 2010 was also the beginning of CERN's process of geographical enlargement, which has seen our membership grow, and a new category of Associate Member become firmly established.

Moving on to 2015, the highlight of the year was the restart of the LHC after its first long shutdown, LS1. Much work was carried out during LS1, not only at the LHC, but across the whole CERN accelerator chain, and at the experiments. The restart was more than just a simple switch-on; it was more akin to starting a new facility for the first time. It was done with great care, and it ran very smoothly, with all CERN's experimental facilities, not only those at the LHC, benefitting and performing well. The smooth nature of the restart augurs well for the continuation of Run 2 in 2016.

2015 was a year for building experience of the LHC in its new configuration, and for the experiments and computing teams to become accustomed to the new higher-energy running conditions. They all proved themselves to be more than adequately prepared, and by the end of 2015 the experiments were producing important new physics results. Elsewhere at CERN, a new tool at our versatile ISOLDE facility came on stream. HIE-ISOLDE will increase the reach of ISOLDE in a range of areas from nuclear structure to astrophysics. At the Antiproton Decelerator (AD), great progress was made at ELENA, a facility that will increase the efficiency of the AD tremendously.

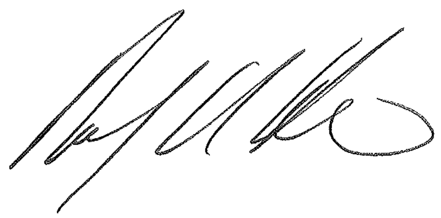
You can read all about the science highlights in this report, so I will allow myself to focus on just one. Just as the Brout-Englert-Higgs mechanism was developed in the 1960s, so was the quark model that underpins our understanding of particles such as the protons and neutrons that make up atomic nuclei. The quark model is very well experimentally established, but there remained one little gap: its protagonists had predicted configurations of quarks and antiquarks consisting of five particles, but until 2015, no experiment had ever reliably detected the existence of these so-called pentaquarks. In 2015, thanks to the performance of the LHC, the precision of the LHCb detector and the ingenuity of its researchers, that changed, and one more 50-year-old prediction had been confirmed.

As well as being a world-leading laboratory, CERN is also a very complex organisation, with all the attendant challenges that brings. In 2015, one of the largest was the removal of the cap from the Swiss franc/euro exchange rate, which led to a difficult situation for many of our Member States. The Management and the Council worked together proactively to minimise the impact both on the CERN programme and on our Member States. This is typical of the relationship between the CERN Management and Council – one of the great strengths of this Organization.

I cannot end without a mention of the enlargement process. Among my final duties as Director-General was to sign two new agreements during the December meetings of the Council. One, signed with the United States under the umbrella agreement concluded in March, heralds a new era of transatlantic collaboration in particle physics. It outlines US participation in the continuing exploitation of the LHC and CERN participation in exciting neutrino projects getting under way at Fermilab. The second underlines the spirit of inclusion that is a hallmark of CERN. It is an International Collaboration Agreement with Palestine, opening up the way for Palestinian universities and scientists to intensify their links with CERN. It was approved by the unanimous vote of the Council.

Last but not least, I would like to thank everyone I have had the pleasure to work with over the last seven years: the Council, the Management and all the CERN personnel, whether staff, fellows, associates, users or contractors. It has been a privilege. I wish the new Management and the Council a mandate full of success and many great discoveries.

Rolf Heuer



On 3 June 2015, the LHC operators announced the first stable beams for physics of LHC Run 2. A new world-record collision energy was set at 13 TeV.
(CERN-PHOTO-201506-125-36)

A year at CERN

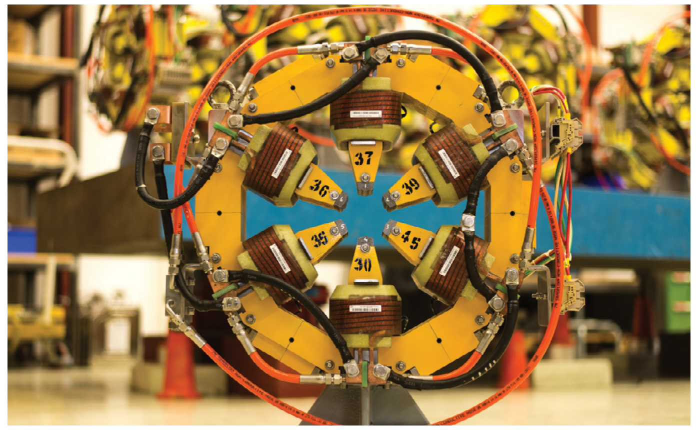
On 12 January 2015, following two years of work on the entire CERN accelerator complex, the team in charge of the colossal Long Shutdown 1 (LS1) project handed the symbolic key to the LHC over to the operations team. During the two years of LS1, an impressive amount of work was accomplished in preparation for running the LHC at 13 TeV. Eighteen of the machine's 1232 dipole magnets, which guide the beams around their 27-kilometre orbit, were replaced due to wear and tear. More than 10 000 electrical interconnections between magnets were fitted with shunts to provide an alternative path for the 11 000-amp current, protecting the interconnection if there is a fault. Many of the machine's electronic components were replaced, the vacuum system that keeps the beam pipe clear of stray molecules was upgraded and the cryogenics systems were refurbished.

With the LHC restarting not only at higher energy, but also with higher luminosity – a measure of the rate of particle collisions delivered to the experiments – the LHC experiments were also busy during LS1. To prepare for the challenge of more collisions, the experiments carried out full consolidation and maintenance programmes, including upgrades to their subdetectors and data-acquisition systems, while CERN's computing facilities installed almost 60 000 new cores and over 100 petabytes of additional disk storage to cope with the increased amount of data that is expected during LHC Run 2.

But it was not just the LHC, experiments and computing facilities, that underwent rejuvenation during LS1. CERN's accelerators upstream of the LHC support a vibrant research programme, as well as serving as the injector chain for the LHC itself. The oldest accelerator still in operation, the Proton Synchrotron, first started up in 1959, and LS1 provided an ideal opportunity to carry out essential maintenance to ensure optimum performance and reliability for the future. When the key was handed over on 12 January, it was to an entirely renovated accelerator complex.

Three months later, all the hard work of LS1 paid off as proton beams circulated in the LHC on 5 April, an important milestone on the way to the start of physics data-taking at 13 TeV on 3 June. The Brout-Englert-Higgs mechanism, dark matter, antimatter and quark-gluon plasma are all on the menu for LHC Run 2. After the discovery of the Higgs boson in 2012, physicists will be putting the Standard Model of particle physics to its most stringent test yet as they continue their search for new physics.

In December, Pamela Hamamoto, US Permanent Representative to the United Nations in Geneva, and CERN Director-General Rolf Heuer signed protocols paving the way towards a truly integrated transatlantic research programme in particle physics (CERN-PHOTO-201512-258-18).



Sextupole magnets produced through the CESSAMag project await shipment to the SESAME laboratory following tests at CERN (CERN-PHOTO-201503-041-7).

A growing family

CERN continued to pursue its enlargement policy in 2015. On 6 May, Turkey became an Associate Member, and on 31 July, Pakistan followed suit: both countries ratifying agreements signed in 2014. Associate Membership will strengthen long-term partnerships between CERN and the Turkish and Pakistani scientific communities. It will allow Turkey and Pakistan to attend meetings of the CERN Council. Turkish and Pakistani scientists may become CERN staff members and participate in CERN's training and career development programmes. Finally, it will allow Turkish and Pakistani companies to bid for CERN contracts.

On 7 May, CERN signed an umbrella agreement with the United States of America paving the way for renewed collaboration in particle physics. The agreement was signed in a ceremony at the White House by the US Department of Energy, the US National Science Foundation and CERN. It was followed in December by protocols confirming the US's commitment to the LHC project and, for the first time, setting out in black and white European participation in pioneering neutrino research in the US. In anticipation of this agreement, CERN no longer runs its own neutrino beams. Instead, it will serve as a platform for European scientists engaged in neutrino detector R&D who will go on to work at neutrino experiments in the US and elsewhere. Looking further ahead, these protocols codify the ongoing collaboration between CERN and the US on future facilities that might succeed the LHC from around 2040. These protocols are a significant step on the way towards a truly integrated transatlantic research programme in particle physics.

The end of the year also saw CERN extend its scientific collaboration with the Middle East. On 3 December, CERN signed an International Cooperation Agreement (ICA) with the Lebanese National Council for Scientific Research (CNRSL), paving the way for future collaboration with Lebanese academia. Soon after, on 18 December, a second ICA was signed with Palestine, allowing CERN to forge stronger links with Palestinian universities. CERN already has a high level of engagement in the Middle East and North Africa region. These two agreements complement existing ICAs with Iran, Jordan, Saudi Arabia and the United Arab Emirates, and well-established contacts with Oman and Qatar. In 2014, Israel became CERN's 21st Member State, cementing a long-standing partnership. Moreover, CERN plays an important role in the region's first intergovernmental research organisation, SESAME, a third-generation light source scheduled to start commissioning in 2016.

Open SESAME

SESAME, Synchrotron-light for Experimental Science and Applications in the Middle East, is a pioneering facility for the Middle East and neighbouring countries. It will allow researchers from the region to investigate the properties of advanced materials, biological processes and cultural artefacts. SESAME is an intergovernmental organisation based in Jordan that brings together scientists from its members Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey, as well as being open to scientists from further afield. Alongside its scientific aims, SESAME aims to promote peace in the region through scientific cooperation. As manager of the European-Commission-funded CESSAMag project, CERN coordinated the production of magnets and power supplies for SESAME. Important milestones were passed in 2015 as CESSAMag drew to a close and components were delivered to the laboratory in readiness for commissioning in 2016.

Passing the baton

At the close of the CERN Council's 178th session on 18 December, there was a double handover as Rolf Heuer passed the mantle of Director-General to Fabiola Gianotti, and Agnieszka Zalewska handed the President of Council's gavel to Sijbrand de Jong.

Snapshots

30/01

Carlos Moedas, European Commissioner for Research, Science and Innovation, visits the CMS experiment with Sergio Bertolucci, CERN Director for Research and Scientific Computing. (CERN-PHOTO-201501-019-2)

04/02

As part of the International Year of Light and Light-based Technologies, CERN publicises its own luminous project, the High-Luminosity LHC, through a series of lectures at the Globe of Science and Innovation. (CERN-PHOTO-201502-026-8)

16/02

The CMS collaboration takes pupils from schools near CERN on a tour of its experiment. Over two days, 600 pupils descended 100 metres underground to admire the giant detector. (CERN-PHOTO-201502-034-48)

02/03

CERN donates computing equipment, including 224 servers, to the CIIT institute in Islamabad, Pakistan. In August, another batch of computing equipment was donated to Mexican institutes (see p. 31). (CERN-PHOTO-201503-042-2)

23/03

One of the highest-ranking Buddhist masters, His Holiness the Gyalwang Drukpa XII, with CERN Director-General, Rolf Heuer, during the event “Science Meets Buddhism: Great Minds, Great Matters”. (CERN-PHOTO-201503-054-20)

01/04

Eight months before the return of Star Wars to the big screen, CERN confirms the existence of the Force... it's April Fools' Day again! The joke quickly goes viral… (CERN-PHOTO-201504-062-1)

07/07

Matteo Renzi, Prime Minister of Italy, visits the LHC accelerator with Rolf Heuer, CERN Director-General, Fabiola Gianotti, CERN Director-General Designate, and Lucio Rossi, leader of the High-Luminosity LHC project. The Prime Minister also visited the ATLAS control room and experiment cavern. (CERN-PHOTO-201507-150-36)

25/09

19/07

In July, a succession of special VIP visitors get CERN rocking. The members of the German rock band Scorpions (photo) and the Irish group The Script both made a stop at CERN.
(OPEN-PHO-HIST-2016-001-1)

25/09

Nineteen amateur and professional photographers take a behind-the-scenes look at the Organization in the 2015 CERN Photowalk competition. Robert Hradil, who took the photograph below, came third in the 2015 Global Physics Photowalk competition.
(CERN-PHOTO-201509-191-2 and CERN-PHOTO-201511-221-8)

29/09

Soraya Sáenz de Santamaría, Spain's Deputy Prime Minister, visits the LHC superconducting magnet assembly hall with José Miguel Jiménez, head of the Technology department.
(CERN-PHOTO-201509-194-55)

18/09

The winners of the Beamline for Schools competition present their experiment to members of the CERN Council and ambassadors. The two teams of high-school students spent ten days at the Laboratory (see p. 33). (CERN-PHOTO-201509-183-109)

9/10

Six hundred people attend the third TEDxCERN event, held in the assembly hall of the CMS experiment, on the theme "Breaking the Rules". Scientists from various fields presented ideas and innovations with the potential to change our lives. (CERN-PHOTO-201510-198-347)

2/11

At the United Nations Office at Geneva, CERN representatives and UN delegates discuss the Laboratory's international cooperation model in a conference entitled "The CERN Model, United Nations and Global Public Goods".
(OPEN-PHO-HIST-2016-002-1)

17/11

HRH Princess Maha Chakri Sirindhorn of Thailand marvels at CERN's technology during tours of the crystals laboratory, ISOLDE and LEIR. A collaboration agreement between CERN and Thailand's Synchrotron Light Research Institute (SLRI) was signed during the visit. (CERN-PHOTO-201511-237-39)

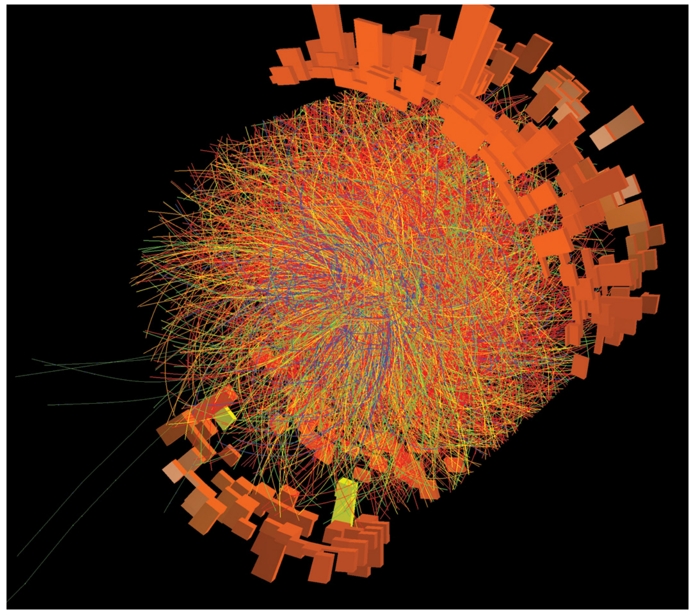
Physicists in the ATLAS control room applaud the first LHC proton collisions at the unprecedented energy of 13 TeV on 3 June 2015. (CERN-PHOTO-201506-128-7)

Physics and experiments

After two years of intense maintenance and consolidation and several months of preparation for restart, the Large Hadron Collider (LHC) was back in operation in 2015. On 3 June, the LHC started delivering physics data at the unprecedented energy of 13 TeV, almost double the collision energy of its first run. LHC Run 2 was under way.

ALICE rejuvenated

When the LHC resumed operation, it was with a rejuvenated ALICE experiment. During the LHC's first long shutdown (LS1), ALICE underwent an extensive facelift with the aim of improving the overall performance of the experiment. New modules were added to the Transition Radiation Detector, providing complete azimuthal coverage. Photon Spectrometer coverage was extended with the addition of a fourth module. A new electromagnetic calorimeter was added to the existing one so as to provide azimuthal back-to-back coverage, and a new trigger detector was added to the detection systems. In anticipation of increased particle flux, the gas mixture in the Time Projection Chamber was changed, and the readout electronics of several detection systems were modified. With many other minor improvements, ALICE collected large and unique data sets from proton–proton collisions at 13 TeV and 5.02 TeV and from lead–lead collisions at 5.02 TeV. The total data collected, 7 petabytes, is already equivalent to all the data collected during the LHC's first run. This was made possible by the spectacular performance of the LHC, significantly surpassing the original design luminosity for ion operation, and heralding an exciting scientific programme ahead.



One of the first heavy-ion collisions with stable beams recorded by ALICE on 25 November 2015. (OPEN-PHO-EXP-2015-013-2)

Meanwhile, analysis of data from the LHC's first run continued apace. Drawing on comprehensive in-depth analyses, a standard model of heavy-ion collisions is taking shape. These measurements firmly establish that nuclear matter heated to the temperatures reached in lead–lead collisions at the LHC has all the dynamic and thermodynamic features of the most perfect liquid known and give us a glimpse of the potential of further high statistics measurements to pin down the fundamental properties of quark-gluon plasma with high precision.

But this is not the end of the story. The observation that many signatures attributed to the collective dynamics of a medium in lead–lead collisions were also present in lighter systems, such as proton–lead collisions and even proton–proton collisions, triggered a change of focus towards a comprehensive understanding of hadronic collisions in small and large systems. Despite the fact that one feature of lead–lead collisions, the quenching of emerging particle jets by the dense and hot medium, does not seem to happen in proton–lead collisions, the question is raised of whether the fundamental mechanism giving rise to collective dynamics in lead–lead collisions is present in lighter hadronic collisions, or whether droplets of quark-gluon plasma are formed in such collisions. Answering such questions and establishing what the fundamental mechanism is have become the driving motivations guiding ALICE's data-taking and analysis in the second LHC run.

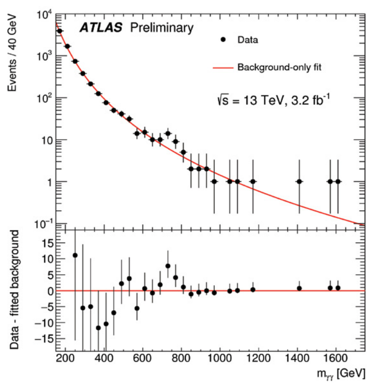
ALICE's versatility has been demonstrated in measurements leading to new and unique results. For example, a high-precision measurement, improving on previous measurements by more than one order of magnitude, has been performed on the mass difference between matter and antimatter for the deuteron and ^{3}He. This provides an important test of nature's most fundamental symmetries. In another example, a detailed analysis of the spectrum of J/Ψ particles offers the promise of new perspectives in the study of quark-gluon plasma.

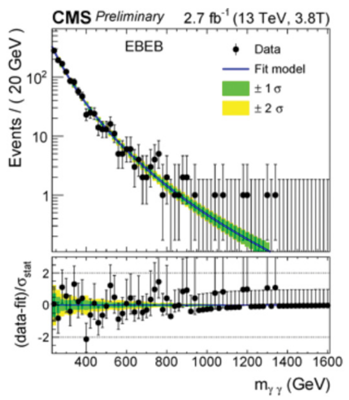
In 2015, the R&D phase for the approved ALICE upgrade programme, scheduled to be installed following the end of LHC Run 2, was drawing to a close. Prototyping is now under way and series production is scheduled to start in 2016.

ATLAS – a five-fold focus

The focus for ATLAS during 2015 was five-fold: recommissioning the detector as well as the new software and analysis model developed during the shutdown, accumulating the maximum amount of good-quality data at 13 TeV proton–proton (pp) collision energy, prompt analyses for the purpose of new physics searches and initial Standard Model measurements, continuing the completion of Run 1 analyses, and preparation of the scoping document for the Phase 2 upgrade of the ATLAS detector. That document was favourably received by the LHC Resources Review Board, successfully completing the first step of the Phase 2 upgrade approval process and giving the green light to move on to detailed Technical Design Reports (TDRs).

The year began with an intense phase of trigger and detector commissioning using cosmic-ray and pp collision data. The first data in stable-beam conditions were recorded on 3 June. More than 200 million pp collision events were taken with low-intensity beams for the alignment and detailed studies of the tracking systems, in particular the new innermost pixel layer, the Insertable B-layer (IBL). These data were used for the re-observation of the so-called ridge effect at 13 TeV, a peculiar long-range correlation pattern that could be shown by ATLAS to be due to single-particle modulation with similar underlying physics, as in proton–lead collisions. In the summer, ATLAS presented early 13-TeV measurements of soft-QCD processes and W, Z and top production. Initial searches for new strongly interacting high-mass phenomena using the first 100 pb^{-1} of data did not show a signal. ATLAS also prepared a broad set of detector performance results showing a good understanding of the early data.





Bump hunting

In particle physics, new particle discoveries can sometimes be characterised by bumps appearing on regular distributions of known physics. For example, known physics may account for a distribution of events containing photon pairs, descending smoothly with a quantity physicists call invariant mass – a measure of the total energy and momentum of the particle that produced two photons. If a new particle is produced at a particular mass, and it too produces photons, this new source of photon pairs will produce a bump on the distribution – an excess of photon pairs compared to what would be expected from known physics. This was one of the signals contributing to the discovery of the Higgs boson in 2012.

As 2015 drew to a close, a small bump at around 750 GeV was seen by both the ATLAS and CMS experiments, leading to much speculation as to what it might be. While it may well be due to statistical fluctuations, all eyes will be on ATLAS and CMS when Run 2 resumes in 2016.

Plots from the ATLAS and CMS experiments showing a small bump in the data at around 750 GeV.

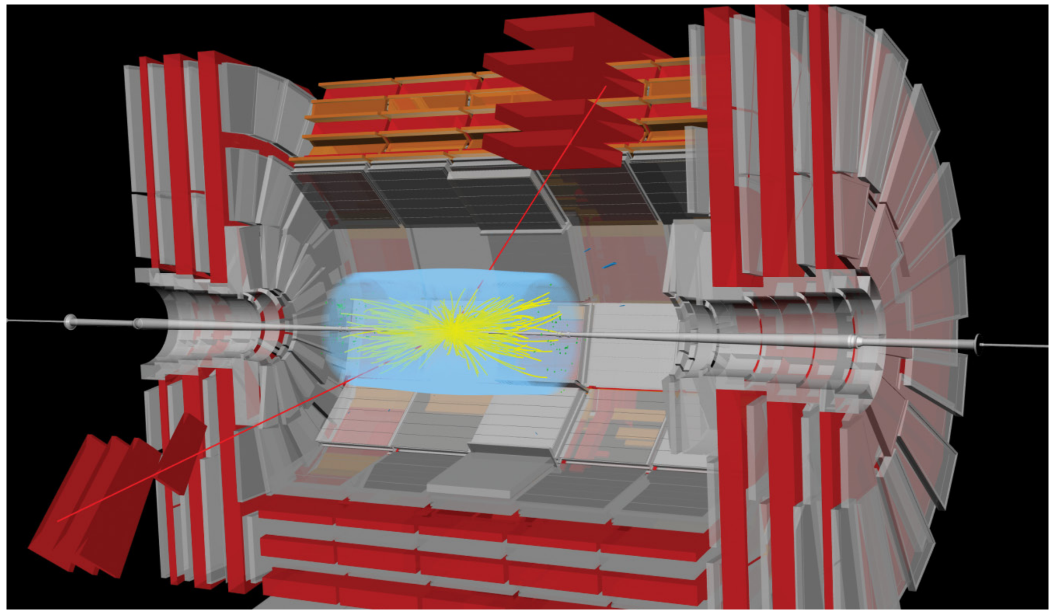
In a fast turnaround, ATLAS presented numerous analyses using the full sample of up to 3.6 fb^{-1} of 13 TeV pp data at the 2015 end-of-year seminar and the subsequent winter conferences. Among these were initial measurements of inclusive Higgs boson production via its decays to photon and Z-boson pairs, further measurements of top-quark production, including the less abundant electroweak (single top) channel and the rare top-antitop production associated with a W or Z boson.

Primary emphasis was put on searches for new phenomena, resonant or not, involving events with highly energetic jets, leptons, photons, W, Z or Higgs bosons, missing transverse momentum and combinations of these. The majority of these searches did not exhibit deviations from the Standard Model. An eye-catching exception was an unexpected bump at around 750 GeV seen in the diphoton mass spectrum. The probability of such an effect occurring in the absence of a signal is equivalent to about two standard deviations. A potential signal is not excluded by Run 1 searches although there is tension. However, no resonant signal was seen by ATLAS in the photon plus Z mass spectrum in the 13-TeV data. The upcoming restart of the LHC is expected to clarify the interpretation of these findings.

ATLAS has continued to publish analyses based on Run 1 data. A total of 525 papers will have been published by April 2016, with 122 of those released during 2015. Among these were papers on CP-violation and rare decay measurements of B mesons. Comprehensive ATLAS papers discuss W and Z boson pair production and measurements of top-quark production and decay properties. ATLAS published the complete suite of relevant Run 1 Higgs mass, production and decay property measurements in 2015. ATLAS and CMS joined forces by combining their Higgs boson mass and coupling measurements, thereby establishing the observation of the decay into a pair of tau-leptons. The Run 1 search programme was completed in 2015, including detailed summary papers. A highlight of the heavy-ion collision programme for ATLAS was a new analysis of the dijet asymmetries in lead–lead, proton–lead and proton–proton collisions, exhibiting similar properties for peripheral lead–lead and proton–proton collisions, but large modifications in central lead–lead collisions.

CMS – starting Run 2 with gusto

The CMS collaboration had a busy 2015. In the first quarter, work scheduled for LS1 was successfully completed, and intense preparation for Run 2 began. Analyses with Run 1 data were concluded and published, early installations of the Phase 1 upgrades were carried out, and an in-depth study for the Phase 2 upgrades was conducted and published in a technical proposal. A scoping document set out studies of the proposed baseline upgrades, accompanied by an analysis of cost-benefit versus loss in the physics potential of various downgrades, and was highly appreciated by reviewing committees, opening the door to further progress.



A collision event with the largest-mass muon pair so far observed by the CMS detector in proton-collision data collected in 2015. The mass of the di-muon system is 2.4 TeV. (CMS-PHO-EVENTS-2015-005-5)

With beams back in the LHC, CMS set about 13-TeV data-taking with gusto. The first results and even a first publication were presented at conferences in July. The publication concerned the number of charged hadrons produced in proton collisions as a function of energy. This is one of the first measurements performed at the start of exploration of a new energy regime because it allows researchers to check whether the theoretical models used in simulations are accurate, as proved to be the case.

Another important measurement when exploring a new energy regime is the rediscovery of known particles. CMS measured pairs of muons emerging from the collisions, revealing a spectrum that clearly showed peaks corresponding to particles ranging from the omega meson to the Z boson. The particles in this spectrum were originally discovered over several decades but it took CMS just weeks to observe them all at 13 TeV, a clear demonstration of the readiness of CMS for new physics at this energy.

As the year progressed, CMS pursued a broad range of analyses with 13-TeV data, and in December presented a large number of searches for new physics. Results included a small excess above background in the two-photon channel near a mass of 750 GeV, an effect also seen by ATLAS. In both cases, the statistical significance is small, but the fact that both experiments see the same thing is intriguing. More data is needed to determine whether this excess is just a statistical fluctuation or a sign of new physics.

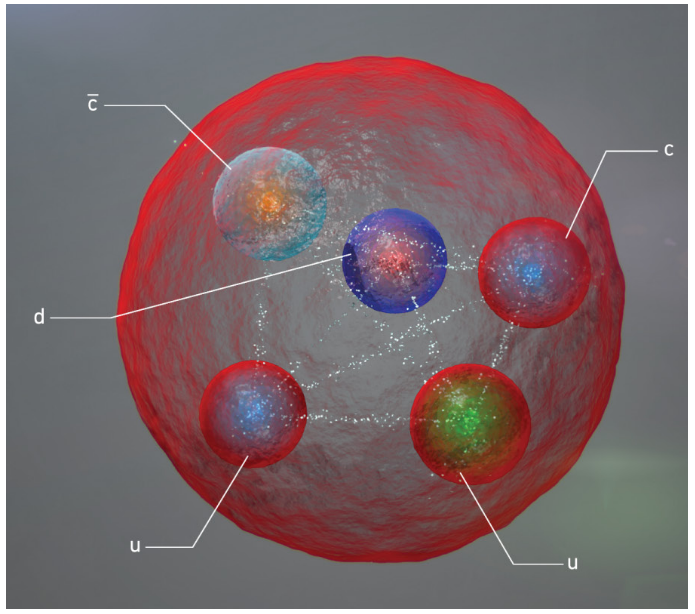
Other 2015 highlights include the continuing search for dark matter, with analyses placing new limits on the direct production of supersymmetric particles. Searches for events containing bottom quarks that could arise from dark matter produced in association with bottom or top quark pairs were carried out, along with searches for non-standard decays of the Higgs boson and for exotic Higgs bosons. So far, all avenues have drawn a blank, though the limits on supersymmetry are tightening. While Run 2 was the focus of attention in 2015, CMS also wrapped up its analysis of Run 1 data, with more than 120 new results presented at conference and published. Many results concentrated on the properties of the Higgs boson. Others concerned high-precision measurements to probe the Standard Model ever more precisely. These included measurements of the two-photon production of W-boson pairs, production rates for particle jets at 2.76 TeV compared to 8 TeV, production of two photons along with jets, and electroweak production of a W boson with two jets.

Discovered over two decades ago, the top quark continues to play a vital role in measurements and searches. New CMS results include measurements of top-antitop production rates in the fully hadronic sample and a measurement of the top-antitop+bottom-antibottom process in the lepton+jets channel. In addition, searches for signs of new physics continue, most recently in the process t→cH, where the Higgs boson transforms to photons.

Significant heavy-ion results from Run 1 include upsilon polarisation as a function of charged-particle multiplicity in proton–proton collisions, Z-boson production, jet-fragmentation functions in proton–lead collisions, and nuclear modification of upsilon states in lead–lead collisions.

LHCb – good things come in fives

The clear highlight of 2015 for the LHCb experiment was the discovery of a class of particles known as pentaquarks. These particles aggregate quarks in a pattern that had not been observed before. Studying their properties may allow us to understand better how ordinary matter, the protons and neutrons from which we are all made, is constituted.



One possible arrangement of quarks in a pentaquark particle. The five quarks are tightly bound. Another possible arrangement has the quarks assembled into a meson (one quark and one antiquark) and a baryon (three quarks) weakly bound together. LHCb announced the discovery of pentaquarks in 2015. (OPEN-PHO-EXP-2015-009-3)

Our understanding of the structure of matter was revolutionised in 1964 when American physicist Murray Gell-Mann proposed that a category of particles known as baryons, which includes protons and neutrons, are comprised of three fractionally charged objects called quarks, and that another category, mesons, are formed of quark-antiquark pairs. Gell-Mann was awarded the Nobel Prize in Physics for this work in 1969. This quark model also allows for the existence of other quark composite states, such as pentaquarks, composed of four quarks and an antiquark. Until now, however, no conclusive evidence for pentaquarks had been seen.

Earlier experiments that searched for pentaquarks proved inconclusive. Where LHCb differs is that it was able to look for pentaquarks from many perspectives, with all pointing to the same conclusion. It's as if previous searches were looking for silhouettes in the dark, whereas LHCb conducted the search with the lights on, and from all angles.

Other results from Run 1 data include the measurement of one of the key parameters describing the difference between matter and antimatter. These parameters are encapsulated in the so-called unitarity triangle, which is characterised by the angles alpha, beta and gamma. A new LHCb measurement provided the world's best measurement of the least-well known angle, gamma, marking an important step on the way to understanding matter-antimatter asymmetry. In 2015, LHCb also published a combined analysis with CMS on an extremely rare process: the decay of the B^0s particle into two muons. The Standard Model predicts that this process should happen about four times out of a billion decays, but it had never been seen before. Studying such decays could open a window to theories beyond the Standard Model, such as supersymmetry.

LHCb made a successful start to Run 2, collecting data with high efficiency. Most notably, a revolutionary approach to the data-acquisition chain enabled the first Run 2 physics results to be produced very quickly. Results on known physics, such as J/ψ particles, are an essential start to running at a new energy, and were presented at conference within a couple of weeks of the start of data-taking. In 2015, LHCb also collected data from lead-ion collisions for the first time.

Looking ahead, LHCb physicists are working towards an upgrade to be installed during the LHC's second long shutdown, starting in 2019. This is an ambitious project that involves entirely removing the hardware trigger so as to read out the detector at the crossing-rate of the LHC, making all trigger decisions in a software CPU farm. All readout electronics will be renewed, along with many subdetector systems.

Last but not least, LHCb turned 20 in 2015 and marked the occasion with a festival of physics and milestones from the history of the collaboration. LHCb officially came into existence in August 1995 when a letter of intent was submitted for the world's first dedicated b-physics experiment at a hadron collider.

LHCf – moving forward

The LHCf experiment had a busy year in 2015. LHCf looks at neutral particles emitted at very low angles to LHC collisions. Studying these so-called forward interactions helps scientists understand what happens when high-energy cosmic rays collide with the atmosphere. In 2015, LHCf collected its first 13-TeV data, recording some 40 million events in 30 hours of data-taking. While these data were being analysed, LHCf published papers based on 7-TeV data. These results showed some discrepancies with models used to interpret cosmic-ray data, and so provided input for refining the models. LHCf also started a joint analysis of proton–lead data with the ATLAS experiment, demonstrating the potential of combining data from the two experiments.

MoEDAL – towards the discovery frontier

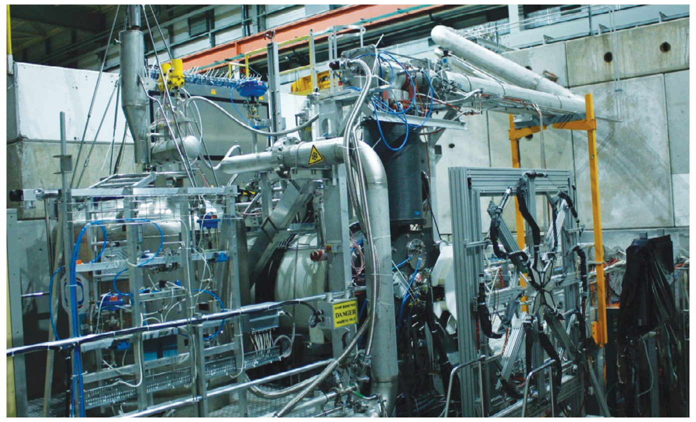
MoEDAL is a pioneering experiment designed to search for highly ionising particle (HIP) messengers of new physics. Its innovative detector, deployed on the LHC ring near the LHCb experiment, has a dual nature tuned to discovery physics. First, it acts like a giant camera, comprised of nuclear track detectors, sensitive only to new physics. Second, it is uniquely able to trap HIPs, for example the magnetic monopole, for further study. The installation of the full detector was completed early in 2015 and it took data for the first time in spring 2015. MoEDAL's first physics paper will be published in spring 2016.

TOTEM – a total measurement

After substantial upgrades, including inserting additional so-called Roman pot detectors that allow measurements very close to the beam, the TOTEM collaboration began Run 2 with a much-improved apparatus. TOTEM measures the total cross-section for pp collisions with unprecedented precision, and is a unique tool for exploring proton structure. In 2015, TOTEM published results showing how the cross-section for pp collisions varies with energy, including previously unseen features. These measurements provide vital reference points for the larger LHC experiments, and are important in interpreting cosmic-ray showers. In Run 2, TOTEM is hunting for exotic particles such as the hypothesised glueballs, formed from the gluons that hold other particles like protons and neutrons together. Thanks to an agreement with CMS, allowing the experiment to combine data with its larger neighbour, TOTEM begins Run 2 with increased sensitivity to new physics.

Experiments at the SPS

Moving upstream from the LHC we find the Super Proton Synchrotron, SPS, which in addition to providing beams for the LHC is host to four active experiments. These are designated NA58, NA61, NA62 and NA63, where NA stands for North Area, their location, and the number is simply their place in the series of North Area experiments that began in the 1970s with NA1.



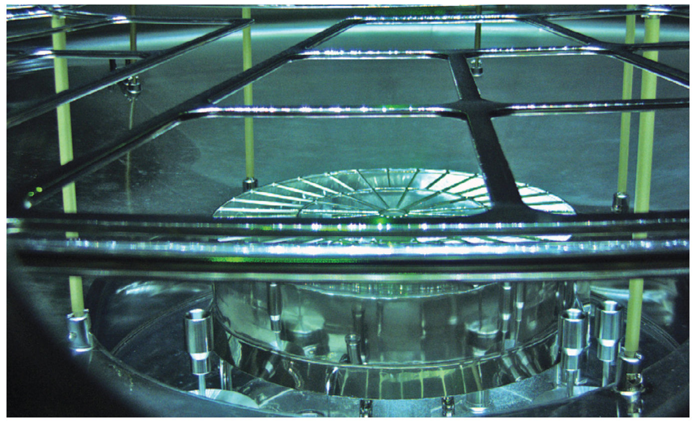
A view of the COMPASS experiment in its 2015 configuration. (OPEN-PHO-EXP-2016-005-1)

A scene from the experiment's control room as NA62 commissioning got under way. (OPEN-PHO-EXP-2016-004-1)

After a successful 2014 pilot run, the COMPASS experiment (NA58) embarked in 2015 on the study of interactions between a 190-GeV pion beam and a transversely polarised ammonia target. Measuring how the polarisation of the protons in the target affects the production of muon pairs gives COMPASS researchers a complementary approach to elucidating proton structure compared to previous COMPASS experiments. In particular, it allows the orbital angular momentum in the proton to be probed: a very eagerly awaited result. To perform this measurement, many COMPASS spectrometer elements were upgraded: the superconducting magnet of the polarised target was completely rebuilt, the tracking system was reinforced and a new data-acquisition system was successfully implemented.

The SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) studies the production of hadrons – particles taking part in the strong interaction that keeps atomic nuclei from falling apart. One of the experiment's goals is to identify the critical point at which ordinary matter transforms into quark-gluon plasma: matter as it would have been just after the birth of the universe. The technique they use is to vary the beam particles in order to explore a range of collision temperatures and densities; the salient parameters in pinpointing the critical point. In 2015, milestones were reached as argon beams were delivered by the SPS for the first time in February, followed by lead ions in November.

Commissioning of the NA62 experiment got under way in earnest in 2015. NA62 studies rare decays of particles called kaons. It will detect just 40 decay candidates per year if the Standard Model prediction is correct. This will enable scientists to investigate the likelihood that top quarks decay to down quarks. Understanding such relations between quarks is a powerful way to check Standard Model consistency. In 2015, good commissioning data were recorded from all NA62's subsystems. The detector recorded some 20 billion events: a clear demonstration of its ability to work at high intensity. A key



Inside the lower section of the CLOUD apparatus, illuminated by UV light, during an experimental run at the PS. (OPEN-PHO-EXP-2016-003-1)

The horizontal neutron beam line in EAR1 (left) and the vertical neutron beam line in the newly constructed EAR2. (OPEN-PHO-EXP-2016-006-3)

subsystem, the Gigatracker, was successfully demonstrated and the experiment's trigger, which decides which collisions to record and which to reject, was commissioned.

NA63 directs beams of electrons and positrons onto crystalline targets to study processes that occur in the extremely strong electromagnetic fields they experience there. These fields can lead to the creation of new particles from the vacuum in a process analoguous to those at work in neutron stars and black holes, and could help in understanding mechanisms that give rise to the highest energy cosmic rays. In 2015, NA63 also examined how photons are emitted by electrons and positrons passing through high fields: work that has implications ranging from new techniques for lasers to understanding Hawking radiation from black holes, which has yet to be observed.

Experiments at the PS

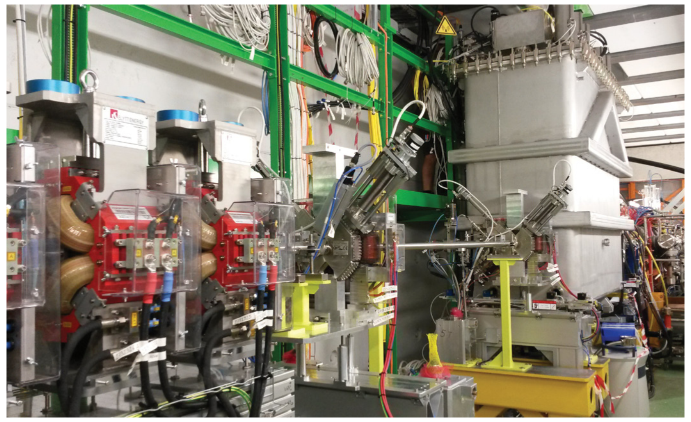
Further upstream is the veteran PS accelerator, in operation since 1959 and still the linchpin of CERN's accelerator chain. In 2015, the PS provided beams to three experiments and facilities.

The CLOUD experiment is tackling an important societal issue of our day: the science of aerosol formation in the atmosphere and its impact on clouds and climate. A PS beam allows CLOUD to study whether aerosol formation is enhanced by galactic cosmic rays. In 2015, CLOUD extended its investigations of aerosol particle nucleation and growth to include two of the most abundant biogenic vapours in the atmosphere: alpha-pinene and delta-3 carene. Sulphuric acid, ammonia and nitrogen oxides were included in the mix to recreate the complex conditions found at the Hyytiälä Forestry Field Station in Finland to reveal which vapours control aerosol particle nucleation and growth and how these processes are affected by natural radioactivity and galactic cosmic rays. Analysis is under way, and the first publications are expected in 2016.

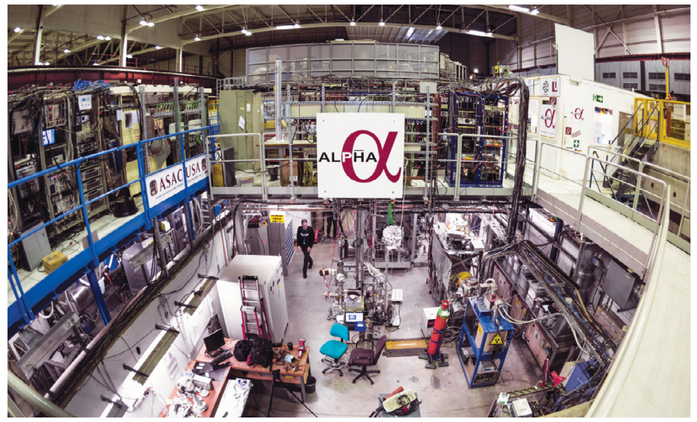
DIRAC, the Dimeson Relativistic Atom Complex, is an experiment to help physicists gain a deeper insight into the strong force by measuring the lifetimes of exotic short-lived atoms made up of pairs of particles from the meson family. In 2015, DIRAC made the first observation of atoms made of pions and kaons, π^+K^- and π^-K^+ atoms. These are made through the interaction of protons from the PS with targets of nickel and platinum. Some of them rapidly break up in the target, leaving the constituent pion and kaon to go their separate ways. Measurement of the lifetime and other properties of these atoms can then be compared to theoretical predictions with high precision, bringing greater clarity to our understanding of the strong interaction.

The neutron time-of-flight facility, n_TOF, provides pulsed beams of neutrons produced by the interactions of protons from the PS with a lead target. The neutrons are collimated and guided to two experimental areas, EAR1 and EAR2. EAR1 is 185 metres from the target horizontally and has been taking data since 2001. EAR2 is situated vertically at about 20 metres and received its first beam in 2014. Both areas work simultaneously. The time-of-flight technique allows neutron-induced reactions to be studied as a function of neutron energy, with implications for stellar nucleosynthesis and nuclear technology, for example in the elimination of nuclear waste.

The 2015 EAR1 physics programme included measurements of gamma rays accompanying neutron capture by a number of nuclei. In addition, a neutron-induced fission measurement was performed on the nucleus neptunium-237. Meanwhile at EAR2, beam-line commissioning was completed and followed by neutron capture measurements on the radioactive isotopes thulium-171 and promethium-147. Neutron-induced alpha emission cross-sections were measured on sulphur-33 and beryllium-7. The last of these could help understand why measurements of lithium abundance are at odds with the predictions of Big Bang models. A new spectrometer, STEFF



The ISOLDE beam line that supplies the Miniball array. The first HIE-ISOLDE cryomodule can be seen in the background in its light-grey cryostat. (OPEN-PHO-ACCEL-2016-007-1)



Inside the Antiproton Decelerator experimental hall. (CERN-PHOTO-201601-005-11)

(Spectrometer for Exotic Fission Fragment), was installed and took its first data, making both n_TOF experimental areas fully operational.

ISOLDE – exotic beams

CERN's exotic beam facility, ISOLDE, carried out 35 successful experiments in 2015. Notable among these was the first extraction of very difficult, refractory, boron beams through the ionised molecule, BF_2^+. A refractory material, such as boron, is one that retains its strength in extreme conditions and so is hard to ionise. This new beam will allow scientists to study the halo nucleus ^8B. Halo nuclei have a dense core of protons and neutrons, with others in a loose halo surrounding the core. Loosely bound systems such as these are important, since they allow the boundary between bound and unbound systems to be explored.

Five successful experiments were carried out at the ISOLDE decay station ranging from the nucleus ^{20}Mg at the proton drip line, so called because it is so far from stability that it literally drips protons, to the very neutron-rich doubly magic ^{132}Sn. In nuclear models, protons and neutrons are arranged in shells, and when a nucleus contains a certain number of protons or neutrons, the shells become full and are said to be closed. A nucleus with a closed shell is said to be magic, and if both proton and neutron shells are closed, it is doubly magic. Stable doubly magic nuclei have particular, easily recognisable, properties: they are spherical and difficult to excite. An important current question in nuclear theory is whether magic numbers established for stable nuclei remain magic for very unstable ones. This ISOLDE result sheds light on this question, and is very challenging for nuclear theory.

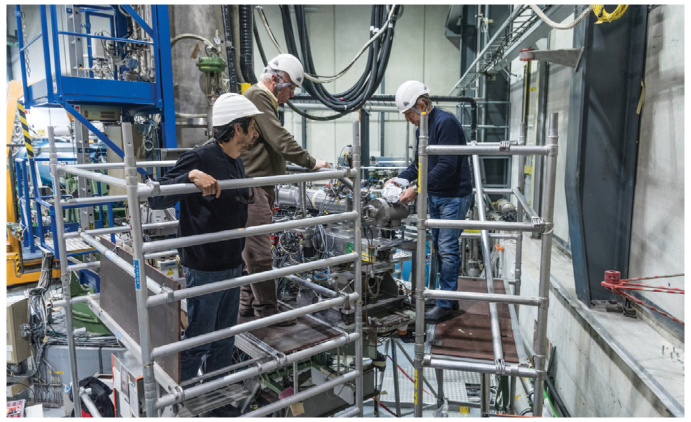
Combining data from the ISOLDE decay station with mass measurements from the ISOLTRAP detector, the heavier mass border of the island of deformed nuclei containing around 20 neutrons, such as ^{34}Mg, should soon be revealed. Measurements such as these are important for testing nuclear models and thereby understanding the physics of nuclei. Other important breakthroughs include the determination of the mean square radii of mercury and gold isotopes obtained by pushing the sensitivity limits by combining state-of-the-art techniques for production, separation and detection. These measurements confirm spectacular changes of deformation in isotopes with 104 neutrons.

The High-Intensity and Energy ISOLDE project (HIE-ISOLDE) delivered its first post-accelerated beams in 2015 (see p. 24). Beams of exotic zinc with atomic numbers 74 and 76 were accelerated to 4 MeV per nucleon for the first time on 22 October. This marked the beginning of a new era at ISOLDE.

Experiments on antimatter

CERN's Antiproton Decelerator (AD) is a unique facility, delivering beams of low-energy antiprotons to a range of experiments mainly concerned with the study of antimatter. Since the hydrogen atom is among the best-understood systems in physics, one of the key aims of the AD experimental programme is to make precise measurements of antihydrogen atoms. Instead of being made up of a proton and an electron like hydrogen atoms, these are made up of their antiparticle equivalents, an antiproton and a positron. Measuring the properties of antihydrogen with similar precision to that of hydrogen will provide a powerful test of the symmetries linking matter and antimatter, and perhaps help explain why we live in a universe of matter, even though matter and antimatter would have been produced in equal amounts at the Big Bang.

In 2015, the ASACUSA experiment published results from experiments with an atomic hydrogen beam that show their apparatus is able to make spectroscopic measurements of atoms in flight. The next step will be to repeat the experiment with an antihydrogen beam.



Members of the CAST collaboration in front of the new KWISP detector. Installed on the axion helioscope, the KWISP will extend CAST's search to include the dark-energy candidates, chameleons. (CERN-PHOTO-201602-049-22)

While ASACUSA compares atoms with antiatoms, the BASE experiment makes comparisons between particles of matter and antimatter with the same objective in mind: trying to identify any differences in the properties of matter and antimatter. In 2015, BASE compared the charge-to-mass ratios of protons and antiprotons, and found there to be no difference at the level of parts per trillion.

ALPHA, ATRAP and AEgIS worked steadily towards their next goals: interaction of lasers with trapped antihydrogen atoms in the case of ALPHA and ATRAP, and pulsed production of antihydrogen atoms via pulsed production and laser-excitation of positronium in the case of AEgIS. Preparation of the AD for the installation of GBAR was completed, with the first equipment due to be in place in early 2016.

Astroparticle physics

There's more to particle physics than research with high-energy beams from accelerators. The low-energy frontier can also teach us much, as can particles coming from space. Two such experiments at CERN are on the hunt for new physics.

The OSQAR experiment explores the low-energy frontier in the quest for hypothetical particles that could make up the universe's mysterious dark matter and energy. Theories predict that such particles could be produced from a beam of light in a high magnetic field, so OSQAR shines a laser into an LHC dipole magnet at CERN's magnet test facility. In 2015, OSQAR extended its search to include chameleons, mysterious new dark-energy candidates that change mass according to the density of their surroundings. If chameleons exist, they should appear through the conversion of photons in a transverse magnetic field. No signature was detected, and the ongoing analysis should set new exclusion limits in the search for chameleons. For now, however, dark energy remains as elusive as ever.

The veteran CAST experiment has spent 14 years observing the sun with the goal of detecting axions: particles hypothesised to make up the universe's dark matter, which could be copiously produced in the sun's core. Solar axions entering the CAST detector would be converted into X-rays, which can be easily measured. So far, CAST has not observed any axions coming from the sun, and has extended its net to search for relic axions left over from the Big Bang. CAST is also installing two sensors that will allow it to be more sensitive to solar chameleons, the dark-energy candidates with variable effective mass, whose production and detection mechanisms are similar to those of axions. One of CAST's detection techniques uses a sensitive force sensor, unique in the field of astroparticle physics.

The CERN Neutrino Platform

Inaugurated at the end of 2014, the CERN Neutrino Platform provides a focal point for Europe's contribution to global neutrino research. It includes an R&D facility at CERN allowing a global community of neutrino experts to develop and prototype the next generation of neutrino detectors.

Understanding the elusive neutrino is a worldwide priority for particle physics. Neutrino research at particle accelerators is complementary to studies made in cosmology, and future measurements could cast light on outstanding questions concerning, for example, the nature of dark matter and the matter/antimatter imbalance in the universe. Experiments at accelerators will also be able to observe neutrinos from supernovae.

The CERN Neutrino Platform marks a new direction in CERN's neutrino research. In the 1970s, neutrino beams at the Laboratory allowed the discovery of neutral currents with the Gargamelle bubble chamber. The most recent neutrino beam produced at CERN went through the Earth to the INFN's Gran Sasso National Laboratory in Italy from July 2006 to December 2012.

In December 2014, the CERN Neutrino Platform took delivery of the ICARUS detector, shipped from Gran Sasso, where it studied the neutrino beam from CERN. ICARUS is now being refurbished, and in 2017, it will be shipped to Fermilab in the US where it will become part of a dedicated neutrino programme.

Detectors for a linear collider

The CERN Linear Collider Detector (LCD) project brings together institutes from around the world to study physics and detector issues for a potential future linear electron-positron collider, such as CLIC (see p. 27). Its activities are divided between three collaborations: CLIC detector and physics (CLICdp), CALICE, which focuses on energy-measuring calorimeters, and FCAL, which looks at detectors in the forward regions, close to the beam pipe.

In 2015, physics studies looked at Higgs and top quark physics, as well as simulating physics beyond the Standard Model at CLIC energies. Detector optimisation and engineering studies led to a new CLIC detector model with enhanced physics coverage in the endcaps. Software tools for event simulation and reconstruction were significantly upgraded and now include a flexible detector description and new track reconstruction software for a full silicon tracker. Successful beam tests were carried out with various CLIC vertex detector assemblies, as well as with CALICE and FCAL detectors. Meanwhile, the CALICE collaboration carried out laboratory tests of scintillator tiles read out by silicon photomultipliers, and published results of test-beam campaigns with a tungsten-scintillator calorimeter prototype. While the focus of this work is on a potential detector for CLIC, there is considerable synergy with other future options including the International Linear Collider and the Future Circular Collider (FCC) study (see p. 27).

R&D for a bright future

CERN's accelerators are host to a number of R&D projects preparing particle detection technologies for the future. The veteran among these is RD18, the Crystal Clear Collaboration, which has been investigating innovative crystal detectors for use in electromagnetic calorimetry for particle physics, medical and industrial applications since 1991. RD39 and RD50 develop silicon tracking devices that can withstand the harsh environment of hadron colliders, while RD42 looks at industrial diamond-based detectors for similar applications. RD53 is developing readout electronics for such detectors. RD51 pushes the limits of gas-filled detectors, while RD52 is developing calorimetry for high-quality energy measurements. Together, these collaborations cover the needs for future collider detectors.

Two further initiatives in the R&D phase blur the boundary between R&D and experiment. UA9 studies how bent crystals could be put to work in future colliders to channel the diffuse halo of particles accompanying the beam away from sensitive equipment, leaving tight needle-like beams to interact at the collision points. In the LHC, this process of collimation is done by tungsten jaws that mop up the halo. SHiP, the Search for Hidden Particles, is a proposed fixed-target experiment at the SPS accelerator to look for particles predicted by models of physics beyond the Standard Model. SHiP has been encouraged to perform a comprehensive design study over the next three years, with R&D to demonstrate the feasibility of the experiment.

In theory

In 2015, roughly half of the research effort of the CERN Theory group was devoted to the Standard Model or physics beyond the Standard Model. Standard Model particle physics includes research directly relevant to the LHC, in particular QCD and Higgs physics. Physics beyond the Standard Model includes research on building models of extensions to the Standard Model, dark matter, possible signatures of new physics at the LHC, and more.

The announcement on 15 December of a possible bump in the two-photon distribution in LHC data at 13 TeV generated great excitement in the theoretical physics community. CERN's Theory group actively participated in the ensuing discussions and studies on the theoretical interpretation of the data (see p.14).

Apart from particle physics phenomenology, there was intense research on astroparticle physics and cosmology, heavy-ion physics, lattice field theory, formal field theory, gravity and string theory. Projects often overlapped between fields, such as dark matter being possibly relevant both for cosmology and collider physics, or black-hole physics being holographically related to heavy-ion collisions. Another example is conformal field theory, which links together particle physics, black holes and condensed matter physics. Moreover, novel techniques to compute scattering amplitudes, as a spin-off from insights in mathematical physics, were employed to perform computations directly relevant for collider physics of a complexity never managed before. All in all, members of the group published about one paper per day on average.

CERN's Theory group comprises 18 research staff members and about 40 fellows at any given time. It also conducts a large visitor programme, which involves about a dozen scientific associates, and around 800 short-term visitors. The unparalleled high flux of visitors is an important aspect of the group's role as a world-leading centre for scientific exchanges.

Theory Institutes form an important part of the visitor programme: quick-to-setup, informal workshops that last for up to a few weeks, they help to optimise resources by bringing together visiting scientists with common interests and by sharing resources with the international community. In 2015, there were three such Institutes, covering Understanding the early Universe, Neutral Naturalness and Duality Symmetries in String and M-Theories.

Members of the Theory group attended many international conferences and workshops. They were also involved in the work of the Particle Data Group and in several teaching activities at CERN, including the Academic Training, Summer Student and High School Teacher programmes, as well as the European and Latin American Schools of High-Energy Physics. As it does every year, the Theory group hosted the annual CERN Winter School on Supergravity, Strings and Gauge Theory, as well a doctoral school on String Theory. A particularly important ongoing activity is the LHC Physics Centre at CERN (LPCC), which organises workshops, lectures and working groups. In November, the group held its annual TH retreat, offering members a comprehensive overview of all the ongoing research activities. Its purpose was to facilitate the integration of newcomers and generally exchange ideas in a stimulating environment. The programme provides a good snapshot of the group's work in 2015. (see https://indico.cern.ch/event/433779/other-view?view=standard).

In 2016, there will be a major change for CERN Theory as it regains the status of a department, recognising the leading role that theory plays as a reference centre in all areas of theoretical particle physics.

Final adjustments being made in the LHC tunnel before the return of beams. On 5 April, particles began circulating in the accelerator for the first time following the Long Shutdown.
(CERN-PHOTO-201503-058-1)

Accelerators

After two years of consolidation work, the major challenge for 2015 was to operate the Large Hadron Collider (LHC) at the unprecedented collision energy of 13 TeV, as compared to 8 TeV at the end of the first run in 2013. Having being cooled down to 1.9 Kelvin (-271°C) at the end of 2014, the accelerator was switched on again at the beginning of 2015 and seven of its eight sectors were qualified at the new energy. During this phase, the current intensity was gradually ramped up to 11 080 amperes in the circuits of the 1232 superconducting dipole magnets. Each sector is trained in several steps, because some magnets quench, i.e. they go from a superconducting to a non-superconducting state, which stops the current intensity from increasing. The operation is therefore repeated several times until the nominal intensity is achieved. By the end of March, seven of the eight sectors were ready for beams at an energy of 6.5 TeV. But a spanner in the works – or rather a fragment of metal – was preventing the last sector from equalling the performance of the seven others. A short to earth, caused by a piece of metal debris, had appeared on one of the magnets. To avoid having to open up the machine, an operation that would have entailed warming up the sector and losing several weeks, the teams came up with a cunning plan: a strong current was injected into the circuit for a few milliseconds to make the fragment disintegrate. And it worked! The recommissioning tests on the rest of the accelerator chain went ahead in parallel.

Particles in the spring

On 5 April, beams were back in the LHC. Five days later, a new record energy of 6.5 TeV per beam was recorded. Two months of fine-tuning later, the LHC operators announced first collisions and stable beams for physics on 3 June. The LHC experiments were able to start taking data again (see p. 12). During the year, the operators ramped up the beam intensity by increasing the number of bunches and reducing the bunch spacing from 50 to 25 nanoseconds. By the end of proton running, in November, up to 2244 bunches with 25-ns spacing were circulating in each direction in the ring. The ATLAS and CMS experiments each recorded some 400 million million proton collisions, corresponding to an integrated luminosity of four inverse femtobarns. Luminosity is the main performance indicator for an accelerator, corresponding to the potential number of collisions per second in a given surface area. "Integrated luminosity" is the total luminosity accumulated over a given period, in the present case the running period in 2015. For their part, the ALICE and LHCb experiments recorded a high volume of data at lower collision rates. Two special runs, with de-squeezed beams, were organised for the LHCf, ALFA and TOTEM experiments, located on either side of the ATLAS and CMS experiments.

Preparation of one of the new beam absorbers for injection, installed during the year-end technical stop.
(CERN-PHOTO-201601-004-8)

Assembly of the HIE-ISOLDE accelerator cavities in a clean room.
(CERN-PHOTO-201603-057-16)

Chasing the clouds away

To achieve this level of beam intensity, the operators had to get rid of the electron clouds. The intensity ramp-up triggers an electron cascade phenomenon that destabilises the beam and heats up the beam screens inside the beam pipes. As the number and spacing of the bunches increase, so does the formation of electron clouds. It took several weeks of running to condition the beam pipes by circulating intense but low-energy beams to scrub as many free electrons as possible from the surface of the beam pipes and thereby reduce the electron production rate.

To achieve a new beam intensity record, the cryogenics system had to be pushed to the limit, especially as the response time of the cooling system, governed by the circulation of fluids through many kilometres of pipes, is far slower than the response time of the beam controls. The particle bunches are injected and ejected in the blink of an eye. To coordinate the cryogenics system better with the beam injection phase and, above all, with the beam ejection phase, an improved control system has been developed. The new system uses 500 heaters on the beam screens that are switched on when the cryogenic power increases prior to injection and absorb the sharp fall in thermal load when the beams are ejected.

The magnet protection system performed extremely well thanks to a diagnostic tool that had been perfected before the restart. It detects the early warning signs of malfunctions and identifies their precise locations. The teams used one of the three short technical stops in 2015 to replace 1000 electronic circuit boards that were over-sensitive to radiation.

LHC operation was rounded off in December with three weeks of lead-ion collisions, preceded by a week of proton collisions at 2.51 TeV per beam to provide reference data for the lead-ion collisions. Another energy record was set as the lead ions were accelerated to 6.37 TeV, producing 5.02 TeV collisions for each colliding neutron pair. Up to 518 lead-ion bunches were circulating in the machine per fill.

The LHC's full-body scan

To optimise the accelerator performance, the operators used a new diagnostic tool called AFT, or Accelerator Fault Tracking. This tool gives the LHC a "full-body scan", checking up on 24 separate systems, from the technical infrastructure to the subsystems, including radio-frequency, vacuum, cryogenics and collimation. It supplies a continuous stream of data on machine availability, i.e. the operating time devoted to particle production, and shows the reasons for any downtime. AFT also serves to identify any action to be taken to improve the machine's availability. To improve the LHC's availability upon injection, two new beam absorbers for injection were developed in 2015. These six-metre-long devices are used when the beams are ejected from the Super Proton Synchrotron (SPS) to the LHC and constitute an essential part of the machine protection system, absorbing the SPS beam in the event of a malfunction at the moment of injection into the LHC. The ones previously in place were showing signs of wear and tear, occasionally disrupting injection. Installation of the new absorbers, made of a different material, began as soon as the machines were shut down at the end of the year.

Away from the LHC proper, a superconducting LHC dipole was built from scratch in CERN's workshops for the very first time.

Prototype of a surface treatment process developed at CERN for use on the vacuum chambers of the Swedish synchrotron MAX IV. (OPEN-PHO-ACCEL-2016-006-1)

The 1232 dipole magnets currently operating in the LHC were manufactured by European industry, around the turn of the century. CERN decided to start producing them itself in order to keep the know-how in-house. The "home-made" dipole is performing exceptionally well. A similar initiative is being taken for the LHC superconducting cavities: the in-house production of a cavity started at the end of 2015 in order to keep the expertise alive at CERN.

High-performance injectors

The LHC could not run without its injectors. Before the protons can be injected into the 27-kilometre ring, they have to be organised into bunches and accelerated in four successive machines: first in Linac2, then in the PS Booster and the PS (Proton Synchrotron) itself, and finally in the Super Proton Synchrotron (SPS). Heavy ions are produced in Linac3 and the Low-Energy Ion Ring (LEIR) before being injected into the PS and then the SPS. The injector chain performed tremendously well in 2015, with availability close to 90% on average.

But the LHC uses only a small fraction of the particles produced by the injector complex, which also supplies the ISOLDE nuclear physics facility, the Antiproton Decelerator (AD), the neutron Time-of-Flight (n_ToF) facility and various fixed-target experiments. For example, in 2015, the PS supplied 1.9 X 10^{19} protons to n_TOF, around 10% more than originally planned. A new system for extracting particles from the PS, known as "multi-turn extraction", was used at the end of the year for the particle-hungry fixed-target experiments at the SPS. Originally developed back in 2002 and deployed for the first time in 2010, this method was upgraded and re-deployed in 2015. It resulted in an increase in extraction efficiency from 95 to 98% compared to the continuous transfer extraction method used previously, and at the same time lowered the amount of radiation deposited in the equipment of the PS.

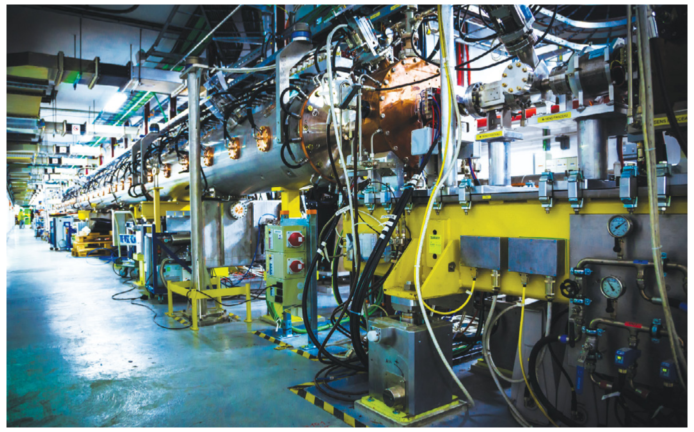
CERN's vacuums: more than empty promises

Two accelerators being developed elsewhere in Europe called upon CERN's expertise in vacuum technologies and surface treatments. Some of the vacuum chambers of the new Swedish synchrotron MAX IV, scheduled to begin operation in June 2016, were developed with contributions from CERN. The larger of the synchrotron's two rings is equipped with a vacuum chamber with a very narrow aperture for the beam. Some sections of the chamber also have complex geometries. The majority of the chambers (95%) are coated with a layer of NEG (non-evaporable getter), which ensures a high vacuum by trapping residual gas molecules. This material was developed at CERN in the late 1990s and is widely used in ambient temperature vacuum chambers at the LHC. The CERN team specialising in this field developed the surface treatment method used for all of the vacuum chambers in the large ring of MAX IV. They transferred the technology so that the most straightforward vacuum chambers could be treated by a European firm, and carried out the treatment of the more complex chambers themselves before delivering them in 2014 and 2015. CERN also provided expertise for the copper plating of stainless steel parts for the XFEL free-electron laser project in Germany.

In addition to protons and lead ions, the SPS also accelerated argon ions for the first time, for the NA61/SHINE experiment. This special run had been under preparation for two years and resulted in the delivery of argon ions at six different energy levels. Finally, the AD facility, which serves the antimatter experiments, started up in July and racked up 3200 hours of physics with 90% availability.

New beams

Two other facilities celebrated the arrival of particles in 2015. On 22 October, a beam was accelerated by the first cryomodule of the new accelerator, HIE-ISOLDE (High Intensity and Energy ISOLDE). The energy of the radioactive ions for the ISOLDE nuclear physics facility was thus increased from 3 to 4.3 MeV per nucleon. Production and assembly of this superconducting cryomodule, complex operations in themselves, were completed at the start of the year and then had to be transported to its installation site, an extremely delicate operation in which a suspension and measurement system was used to ensure it tipped by no more than one degree! HIE-ISOLDE will ultimately comprise four cryomodules, each containing five superconducting cavities, with the aim of increasing the beam energy to 10 MeV per nucleon. By the end of 2015, the second cryomodule was ready for installation in 2016.



Linac4 in 2015, as seen by one of the photographers participating in the Photowalk competition (Photo Federica Piccinni) (CERN-PHOTO-201511-220-1)

Installation of a FineMet cavity in the PS accelerator for the stabilisation of high-intensity beams. (OPEN-PHO-ACCEL-2016-003-5)

One month later, Linac4 was accelerating beams at 50 MeV. Linac4, still under construction, is destined to replace Linac2 as the first link in the CERN accelerator chain from 2020 onwards. Linac4 will accelerate negatively charged hydrogen ions to an energy of 160 MeV and then inject them into the PS Booster. It comprises four types of accelerating structures, the first two of which have now been commissioned up to an energy of 50 MeV. The second two were installed over the course of 2015 and the power converters were all installed. By the end of the year, 80% of the accelerator components had been installed. All the equipment required to inject particles into the PS Booster is now available, which means that Linac4 is ready to step in to replace its predecessor, should the need arise.

Linac4 is a cornerstone of the LHC injectors upgrade (LIU) project. To allow the LHC to operate at high luminosity after 2025 (see p. 26), its injectors must be brought up to date. In addition to Linac4, which will replace Linac2, the other three injectors will be upgraded.

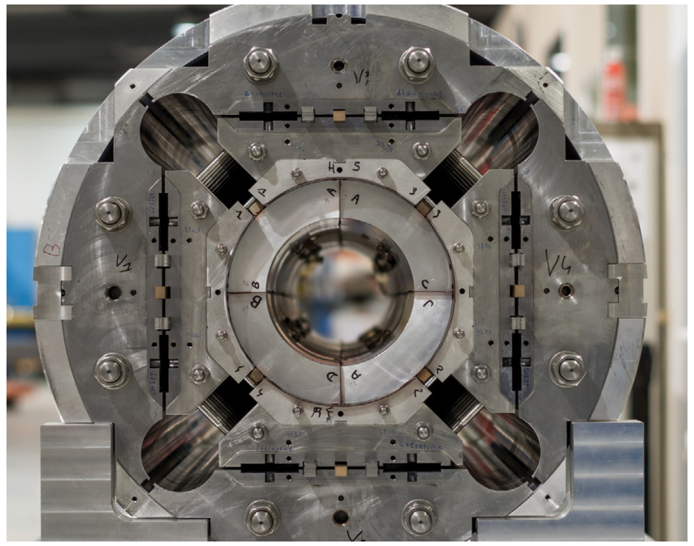
Green light for new cavities

The extraction energy of the PS Booster will be increased from 1.4 to 2 GeV. To achieve this, the accelerator will be equipped throughout with new radio-frequency accelerating cavities, which will perform better at high intensities. The FineMet technology that will be used is based on a composite magnetic material instead of on the traditional ferrites, giving a large bandwidth. The new cavities, which have already been installed on one of the accelerator's four rings, were tested intensively in 2015. One cavity was tested successfully in the PS. On the basis of these tests and a report issued by a group of independent experts, the three radio-frequency systems currently in use at the PS Booster will be completely replaced with the new cavities, which will also be used to stabilise the high-intensity beams in the PS.

A campaign to identify obsolete cables was carried out at the PS Booster, during which 2400 unused cables were identified. The goal is to remove these cables during the next technical stop at the end of 2016 to make room for the 1800 new cables required for the LIU project.

A similar campaign began at the SPS at the end of the year. In addition, several beam interception or protection devices at the SPS will need to be replaced or upgraded to cope with the increased beam intensity required for the High-Luminosity LHC. The teams continued with the design of collimators and beam stoppers for the extraction lines to the LHC. In parallel, the design and specification for a new dump block for Sextant 5 of the SPS were finalised and preparations for its installation began.

Two weeks of SPS operation were devoted to scrubbing the beam tubes in order to reduce the electron cloud phenomenon (see p. 23). One of the aims was to gain expertise with beams similar to those that will be supplied by the injector chain after its upgrade. Following these tests, a group of experts recommended the use of the beam tube scrubbing method for future SPS operation, which involves circulating high-intensity beams, and coating the inner walls of a whole sextant of the accelerator with amorphous carbon. This coating, which has a very low secondary electron yield, will limit the electron avalanche phenomenon. Twenty of the SPS magnets already coated, were tested in 2015. The remaining magnets will gradually be coated during future technical stops. Staying with the LIU project, a study programme on lead-ion operation was carried out. The detailed studies and the subsequent adjustments allowed unprecedented beam parameters and a peak luminosity of more than three times the nominal value to be achieved at the LHC. The studies were particularly focused on the Low-Energy Ion Ring (LEIR). Other upgrades of the components of LEIR were carried out at the end of the year in order to improve injection and increase the beam intensity during operations in 2016.



Structure for a "triplet" quadrupole magnet for the High-Luminosity LHC project. (OPEN-PHO-ACCEL-2015-014-2)

All systems go for high luminosity!

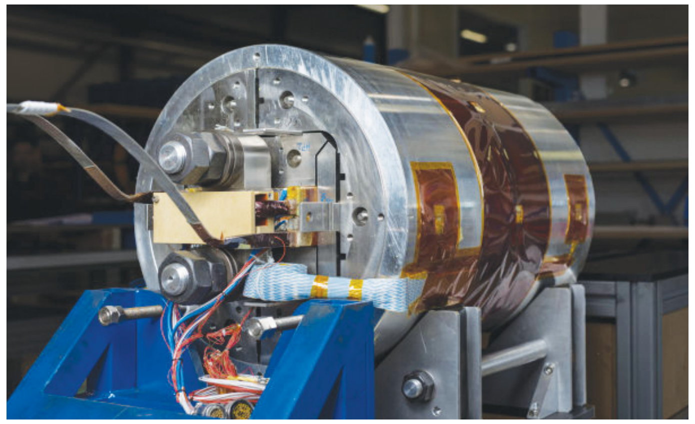
After four years of design studies, the High-Luminosity LHC project entered its construction phase at the end of October 2015. The start of this phase was signalled by the completion of the FP7-HiLumi LHC programme, co-funded by the European Union, which conducted the first studies on the project. The High-Luminosity LHC is scheduled to be commissioned at some point after 2025 and will increase the current number of collisions by a factor of 5 to 10, producing an integrated luminosity of 250 fb^{-1} per year. This increase in luminosity will allow physicists to study the new phenomena discovered at the LHC in greater detail.

To achieve this, new equipment will be installed in 1.2 km of the current accelerator, including new, more powerful quadrupole magnets ("triplets"), which will focus the beams before collisions, radio-frequency "crab" cavities to direct the beams, shorter and more powerful dipole magnets (11 Tesla as opposed to 8.3 Tesla in the LHC), an improved collimation system and new electrical connections based on high-temperature superconductors.

The new superconducting magnets, made of a niobium-tin alloy, are being developed in the framework of a collaboration between CERN and the LHC Accelerator Research Programme (LARP), which involves a group of US laboratories. In May, short coils for the triplet magnets were successfully tested. In June, a short prototype of the superconducting dipole magnet manufactured at CERN demonstrated unprecedented levels of performance. The prototype's magnetic field exceeded 12 Tesla. The design of all the collimators has been determined. It includes jaws built from new improved materials, which have been tested successfully at CERN's HiRadMat installation. The manufacture of crab cavity prototypes and their cryostats began at CERN, with the aim of testing them with a beam from the SPS in 2018.

Cooperation with industry has gone from strength to strength. The production of a high-temperature superconducting cable (made from magnesium diboride) to connect the power convertors to the magnets in the accelerator has begun. An industry day held at the end of June was attended by over 140 representatives of firms based in 19 different countries.

The beam line that will take protons from the SPS to the new AWAKE installation has been installed. (OPEN-PHO-ACCEL-2016-008-1)



A record magnetic field of 16.2 Tesla was achieved using a flat coil, in the framework of the programme to develop more powerful magnets for future accelerators. (OPEN-PHO-ACCEL-2016-005-1)

ELENA moves in

Away from the LHC injectors, other accelerator projects progressed well during 2015. The ELENA (Extra Low Energy Antiproton) project continued its preparations for the start of commissioning at the end of 2016. This decelerator ring, a small synchrotron of 30 metres in circumference, will be connected to the Antiproton Decelerator (AD) to slow down the antiprotons even further for study by antimatter experiments. The energy level will be reduced from 5.3 MeV to just 0.1 MeV and the beam density will be increased thanks to an electron cooling system, which will improve the efficiency of the existing experiments and open the way for new experiments.

Almost all of the infrastructure for the new decelerator has now been put in place and the first components of the ring and the transfer line have been installed. Many components are now being constructed in CERN's workshops and by the Laboratory's industrial partners.

The installation of AWAKE (Advanced Proton Driven Plasma Wakefield Experiment) also began. The experiment is scheduled to receive its first beams from the SPS at the end of 2016 and will study the principle of acceleration using wakefields in plasma cells. This principle, which has already been proven using electrons, will be tested with a proton beam with a view to achieving accelerator gradients hundreds of times greater than those possible using current radio-frequency cavities.

The civil engineering work has been completed and the infrastructure has been installed for the equipment, including a clean room that will house a laser. The proton beam line connecting the SPS to AWAKE has also been installed. The first tests of the 10-metre-long plasma cell, a key component of the project, were successfully completed.

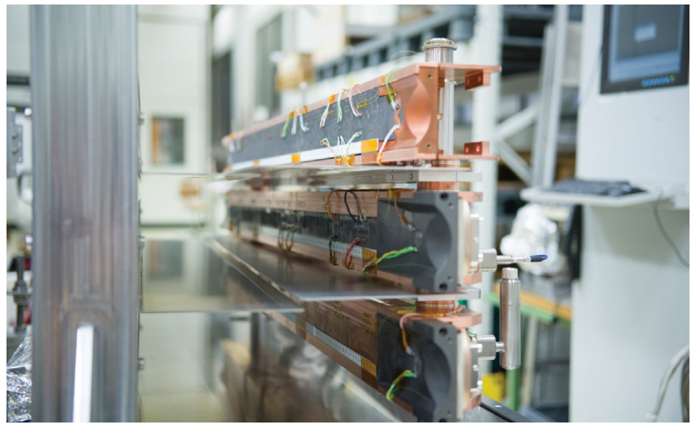
Future accelerators take shape

In addition to the High-Luminosity LHC, CERN scientists are working on the accelerators that might succeed it in around 2035. Two studies are in progress: one for CLIC (Compact Linear Collider) and one for the FCC (Future Circular Collider).

The CLIC linear accelerator project is based on an innovative two-beam acceleration concept, which will allow very high accelerating fields to be achieved. The CLIC collaboration consists of more than 50 institutes in 25 countries. In 2015, studies to redefine the project's parameters in order to optimise costs and performance were completed. On the technical side, a third test facility for the radio-frequency system was installed, doubling the existing test capacity. A complete two-metre CLIC module was commissioned in the CTF3 test facility. Three mechanical modules were tested to evaluate their thermo-mechanical performance. The R&D programme for the high-efficiency radio-frequency equipment continued. Other developments in which the collaboration was actively involved were related to beam instrumentation, magnet prototypes, vacuum systems, control systems, alignment and stability. Interest in CLIC technologies is growing, particularly with regard to their use in linear accelerators for free-electron lasers (FEL).

First results for the FCC

The Future Circular Collider (FCC) study, officially launched in 2014, completed the first stage of its work in 2015. The FCC collaboration, which involves 72 institutes in 26 countries and which is supported by the European Union, is studying the possibility of a hadron collider capable of reaching a collision energy of 100 TeV, to be installed in a new 80- to 100-km tunnel. The collaboration is investigating a potential lepton collider as an intermediate step, as well as a lepton-hadron collider option. The study also covers a possible high-energy version of the LHC in the existing tunnel. The first main objective of the FCC study



Tests on new collimators at the HiRadMat installation. (CERN-PHOTO-201507-161-37)

A new cryostat for testing future superconducting cables is being installed in the SM18 test hall. (CERN-PHOTO-201603-062-1)

is to publish a conceptual design study by 2019, in time for the next update of the European Strategy for Particle Physics.

The first annual meeting of the collaboration took place in Washington, D.C., USA, in March, attracting 340 participants from scientific institutes and industry, and including around 290 scientific contributions. Several workshops were organised throughout the year to study the possible physics reach of collisions at 100 TeV centre of mass.

A report on physics at 100 TeV has been prepared for the collaboration's second annual meeting in 2016. In the framework of the FCC study, the EuroCirCol project, co-funded by the European Union, got under way in June. Key technologies have been identified, including: superconductors able to carry higher currents, magnets generating fields of 16 Tesla, new superconducting radio-frequency cavities and innovative vacuum and radio-frequency systems.

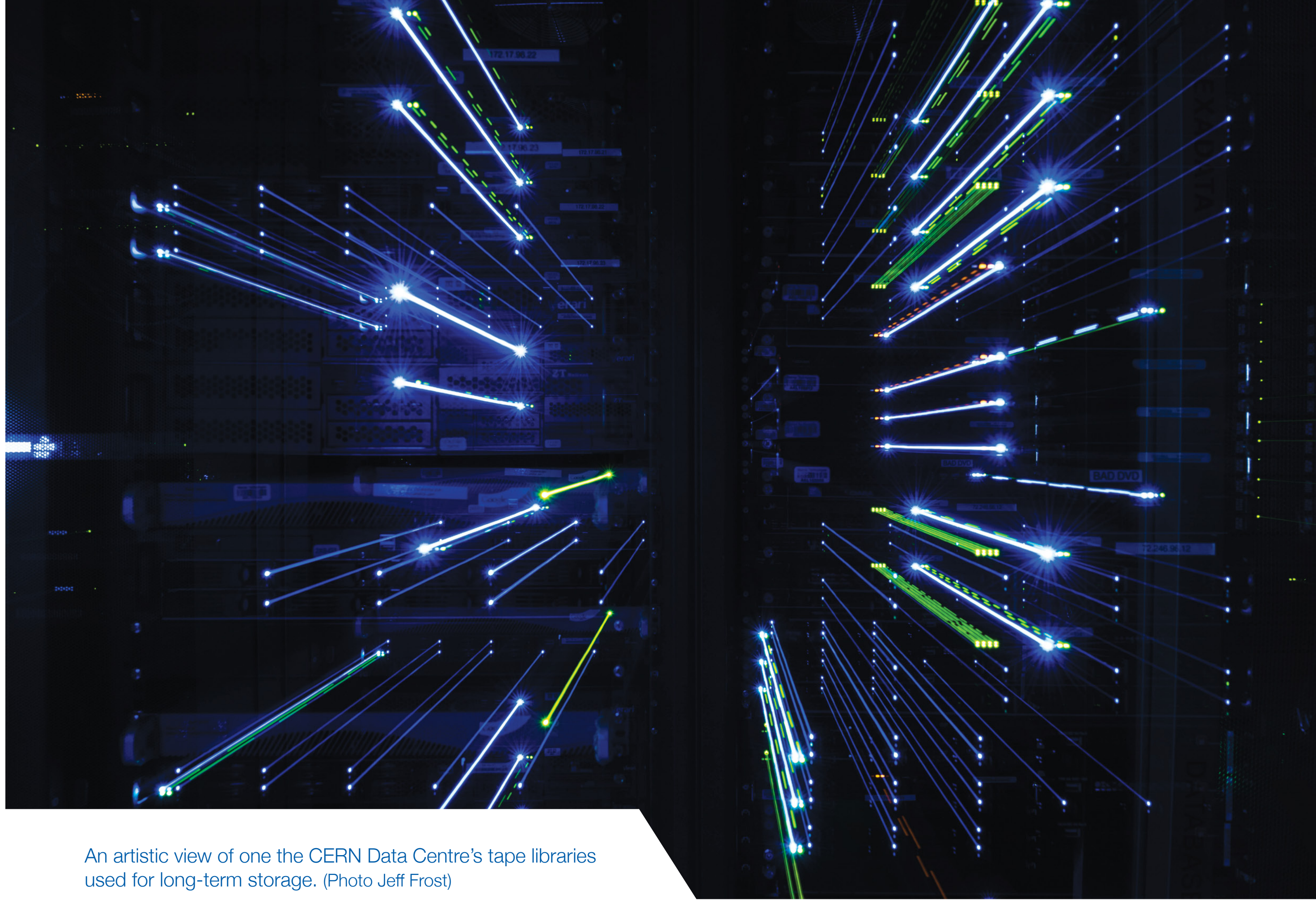
At the end of September, a team of experts settled on the initial design for the hadron collider, including its main parameters, using CERN's current accelerator complex, including the LHC, as its injector chain. This design will form the basis of the conceptual design report. Geological studies to determine the location of the ring also began, using a brand-new software package able to take account of many different parameters.

At CERN, a programme to develop more powerful magnets was set in motion. The teams involved got off to a good start by setting a new world record of 16.2 Tesla with a racetrack magnet coil, i.e. almost twice the magnetic field generated by the dipoles currently in operation at the LHC. This record was achieved with a short superconducting coil made of niobium-tin and represents a huge leap forward in terms of demonstrating the feasibility of more powerful magnets.

Improved test facilities

CERN's test installations play a vital role in the development of innovative components. During its second year of operation, the HiRadMat installation, which tests materials and components using high-intensity beams from the SPS, completed eight experiments, including important tests for future collimators. Two different materials, molybdenum-graphite and copper-diamond, were tested as possible options for the collimators of the High-Luminosity LHC. Another experiment looked at improvements to the target that produces antiprotons in the Antiproton Decelerator (AD).

An extensive programme was launched to adapt and improve the cold electric test installations for superconducting magnets in hall SM18. Work also began on a new cryogenic installation for the testing of large diameter magnets at 1.9 Kelvin and up to currents of 20 000 amps. This cryostat will be used to qualify the FReSca2 magnet, currently under construction at CERN and CEA Saclay, France, as part of the high-field magnet programme. In the framework of the High-Luminosity LHC project, a new vertical magnet test bench is being constructed, providing currents of up to 30 000 amps. Some of the horizontal test benches will also be modified to qualify magnets for the future accelerator with currents of up to 20 000 amps, compared to 15 000 at present. At the same time, studies have begun on a test chain for the triplet magnets and a test station for the superconducting connections that will link the power convertors to the magnets.



An artistic view of one the CERN Data Centre's tape libraries used for long-term storage. (Photo Jeff Frost)

Computing

Extensive upgrade and migration

To prepare for Run 2, the LHC experiment teams and the Worldwide LHC Computing Grid (WLCG) collaboration have upgraded the computing infrastructure and services. During Long Shutdown 1 (LS1), the IT department doubled the capacity available to the LHC experiments, with the addition of some 100 petabytes (PB) of disk storage and almost 60 000 new cores. The compute capacity of the CERN private cloud has nearly doubled during the last year, now providing over 150 000 computing cores. LS1 offered an ideal opportunity to migrate the archived data from legacy cartridges and formats to higher density ones. This involved migrating around 85 PB of data, and was carried out in two phases during 2014 and 2015. As an overall result of this two-year migration, no less than 30 000 tape cartridge slots were released to store more data.

New run, new records

With the start of Run 2, new data-taking records were achieved. 40 PB of data were written on tape at CERN in 2015. Out of the 30 PB from the LHC experiments, a record-breaking 7.3 PB were collected in October, and up to 0.5 PB of data were written to tape each day during the heavy-ion run. By way of comparison, CERN's tape-based archive system collected in the region of 70 PB of data in total during the first run of the LHC. The WLCG also set a new record in 2015 by running a total of 51.1 million jobs in October.

Data preservation

CERN manages the largest archive of scientific data in the high-energy physics (HEP) domain. By the end of 2015, CERN's tape-based archive system held 132 PB of data, corresponding to 410 million files spread across approximately 20 000 tape cartridges, distributed over seven tape libraries providing a total of 86 production tape drives. Most of these data, from past and present HEP experiments, are to be preserved indefinitely.

Bits in tape media are smaller than bacteria, so any damage to the tape can destroy significant amounts of data. Consequently,

The participants of the 39th CERN School of Computing in September 2015. (OPEN-PHO-CCC-2016-001-1)

to ensure long-term data preservation, it is important to protect the physical environment against contamination hazards. In 2015, CERN deployed an improved airflow-monitoring system based on custom-made environmental sensors. The sensors were prototyped and built in-house and are hosted in an empty tape drive tray inside the tape libraries. They are comparable to commercial systems in terms of precision and reaction time, but at about a fiftieth of the cost and requiring no maintenance. The hardware design, as well as all software and firmware components, are freely available via open-source licenses.

In June 2015, the first workshop and Collaboration Board meeting of the Data Preservation and Long-Term Analysis in High-Energy Physics (DPHEP) collaboration took place at CERN, aiming to address the general issues of data preservation in HEP. A significant milestone was achieved with the publication of a Status Report detailing the progress made since the publication of the DPHEP Blueprint in May 2012.

Open source for open science

The impact of CERN's broader open-source software efforts has been growing during 2015. Zenodo – a free open-data repository that benefited from European Commission co-funding for its development and that allows researchers to share articles, data and software – has grown considerably in 2015, especially as the repository of choice for publishing science software via a link with the popular software sharing site Github. More than 3000 different science packages have been released as a result.

The open-source Invenio software, initially developed at CERN, has been refactored in 2015 to enhance the reusability of individual modules, resulting in diverse software projects around the world building on these new features. The CERN spin-off company TIND has also seen strong interest and steady growth in the number of customers wishing to have Invenio installations built for them, including CALTECH and the United Nations.

The number of sites running instances of the Indico conferencing package surpassed 200 in 2015, reflecting CERN's commitment to making collaborating and conferencing more efficient. CERN also released in 2015 a dashboard for its videoconferencing infrastructure based on Vidyo, which resulted in universities, hospitals and companies installing CERN's open-source software.

Through a number of collaborations, CERN's disk-storage system for LHC computing, known as EOS, has also been made available to companies and user communities to use with their "big data" systems, or to use its data-distribution capabilities to build distributed data repositories.

Contributions to open-source projects

In addition to leading and developing its own open-source software, CERN has contributed to external projects in order to adapt them to the Organization's needs. One of the larger contributions is to ownCloud, which is used to provide the CERNBox service – a secure and scalable equivalent to Dropbox for CERN users. Other projects receiving contributions include OpenStack, which is key in enabling the deployment of cloud services in the Data Centre on the Meyrin site and remotely at the Wigner Data Centre in Budapest, and Ceph, the most popular network-block-storage backend for OpenStack.

CERN has contributed over 90 improvements to the latest OpenStack release and to significant new features in the Ceph open-source project. The initial objective with Ceph was to build a block-storage service for the CERN OpenStack cloud, but it has expanded to include R&D towards Ceph-based solutions to solve future LHC data-storage challenges. In 2015, the development team performed a number of scale tests in close collaboration with the key designers of Ceph, exploring the scalability limits of this system, which could potentially benefit other CERN partners.

Open data

In November 2014, CERN launched its Open Data Portal that allows the LHC experiments to share their data with a dual focus: firstly for the scientific community, including researchers outside of the CERN experimental teams as well as citizen scientists, and secondly for the purposes of training and education through specially curated resources. All data is in the public domain under the Creative Commons "zero" license, a first in CERN's long history, and can be cited in scientific discourse using a unique digital object identifier.

In 2015, the CERN Open Data Portal has been ramped up with further data and code releases. This last year has seen increased use of these resources, and, in the spirit of open science, unexpected applications of the data, such as training in big-data analytics and data mining. CERN's Open Data team has transferred experience and inspired many teams around the world by participating in conferences and online forums.

Science in the cloud

CERN is working towards building a European Open Science Cloud using the experience gained through various major projects together with the Helix Nebula initiative – a public-private partnership. The work of Helix Nebula instigated CERN to lead a Horizon 2020 project to create a procurement network of public research organisations, named PICSE (Procurement Innovation for Cloud Services in Europe), interested in making use of commercial cloud services to support their research programmes. In 2015, PICSE investigated the feasibility of a cross-border PCP (pre-commercial procurement) for shared procurement across public organisations. The European Commission decided to contribute funding to the HNSciCloud (Helix Nebula – The Science Cloud) PCP project led by CERN, which started in January 2016.

Education and sharing

Since the early seventies, the CERN School of Computing has been promoting advanced learning and knowledge exchange in scientific computing among young scientists and engineers involved in particle physics or other sciences. It is made up of three separate schools, each of them having a particular flavour and focus. In 2015, the Main School – which lasts two weeks and acts as a summer university, providing a series of lectures and hands-on exercises – took place at Kavala in Greece. Of the 76 participating students from 47 institutes, 68 passed the exam and received six ECTS credits.

The Meyrin and Wigner Data Centres together host around 15 000 servers, which are renewed every four to five years as they become obsolete for the purposes of CERN's research. However, they remain suitable for less demanding applications. In March 2015, 224 servers and 30 switches were donated to the COMSATS Institute of Information Technology in Islamabad, Pakistan, to be used by scientists working on the ALICE experiment at the LHC. A few months later, in August 2015, 384 servers, 24 switches and 26 racks were donated by CERN to institutes in Mexico, which are using them for a variety of scientific and educational projects in the fields of physics, mathematics, energy and environmental sciences. To date, servers and switches have been donated to nine countries, namely Bulgaria, Egypt, Ghana, Morocco, the Philippines, Senegal, Serbia and now Mexico and Pakistan.

New phase for CERN openlab

In January 2015, CERN openlab entered its fifth three-year phase. Through this unique public-private partnership, CERN collaborates with leading ICT companies and research institutes to accelerate the development of cutting-edge solutions for the LHC community worldwide. Huawei, Intel, Oracle, and Siemens are all partner companies, Brocade, Cisco, IDT, Rackspace, and Seagate are contributors, and Comtrade and Yandex are associate members. For the first time, other public research organisations — the European Bioinformatics Institute (UK), the GSI Helmholtz Centre for Heavy-Ion Research (Germany) and Newcastle University (UK) — also joined as members. The topics selected for this new phase include next-generation data-acquisition systems, optimised hardware and software-based computing platforms for simulation and analysis, scalable and interoperable data storage and management, cloud-computing operations and procurement, and data-analytics platforms and applications.

CERN openlab held two new events in 2015: a first-of-its-kind open day in June 2015, and the CERN openlab "Innovation and Entrepreneurship" event in October, organised in collaboration with CERN's Knowledge Transfer group and IdeaSquare. In addition, the CERN openlab Summer Student Programme continued to go from strength to strength, with forty students representing 27 nationalities coming to CERN.

TEDxCERN speakers included CERN's Edda Gschwendtner showcasing the AWAKE experiment and describing how her passion for science ignited at a young age. (CERN-PHOTO-201510-198-13)

Making an impact

Welcome to CERN

In 2015, CERN welcomed around 107 000 visitors from more than 70 countries on guided tours, 46% of whom were school pupils. From July onwards, visitors had the chance to discover the revamped *Microcosm* exhibition before it was fully opened in January 2016. The new layout uses real objects, 1:1 scale audio-visual supports and high-definition photography to take visitors on a journey through CERN's key installations, the network of CERN's accelerators and on to particle collisions inside vast experiments.

The travelling exhibition *Accelerating Science* was shown in the CosmoCaixa science museum in Barcelona, from October onwards. The "Interactive LHC tunnel" – a high-tech audio-visual installation allowing the audience to play with LHC proton collisions or visualise the Brout-Englert-Higgs field – has become a popular attraction in science museums and fairs. It has been shown, together with the *CERN in Images* poster exhibition, with great success at ten different locations in seven countries.

The third edition of TEDxCERN was held in October, with a local audience of 600 and an online audience of more than 10 000, including viewing parties at 23 institutes. Two TEDxCERN 2015 videos have been republished on TED.com, where videos have an average viewing figure of one million per talk. In addition, CERN organised a new CERN FameLab competition as well as the joint French, Swiss and CERN Masterclass and the Swiss final. Participants went on to succeed at the FameLab International Finals at the Cheltenham Science Festival – the overall winner had won the Swiss final and the runner-up had won the CERN competition. Concluding a two-year initiative, CERN organised the PopScience event for European Researchers' Night with activities at a large, local shopping centre and its cinema complex. The aim was to meet people who would not have come to a laboratory of their own accord and the event saw 500 visitors attend cinema showings for schools, with 700 attending the public cinema showings.

In collaboration with the University of Geneva, the French *Ministère de l'Éducation nationale* and Geneva's *Département de l'instruction publique*, CERN organised another round of its "Be a Scientist" initiative in which more than 750 children from primary schools took part, discovering the process of scientific research. As well as this, in February, more than 600 pupils from local schools visited the CMS detector. Screenings of the movie *Particle Fever* were shown, including one at Saint-Genis-Pouilly in collaboration with the French mission to the UN in Geneva. CERN was also present at the *Cité des Métiers* exhibition in November, which demonstrated the variety of CERN's and International Geneva's professions to thousands of visitors.

The new S'Cool LAB at CERN welcomed more than 4000 school students and teachers in its first full year of operation. Its hands-on experiments include cloud chamber construction and visualising X-rays using pixel detectors. (OPEN-PHO-LIFE-2016-003-17)

The new *Microcosm* exhibition takes visitors on an interactive journey through CERN, following the path of particles from the bottle of hydrogen onwards to discovery. (CERN-PHOTO-201603-050-1)

A thirst for learning

The programmes for secondary-school teachers continued with 36 one-week national language programmes taking place for a total of 1067 teachers from 41 countries. The three-week international High School Teacher programme, in English, welcomed participants of 40 different nationalities, and a special course for teachers of engineering disciplines was held for participants from Bulgaria.

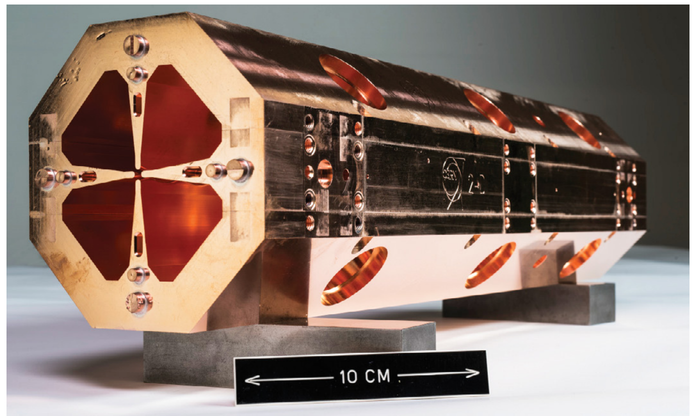
A one-week programme for school students and teachers from the SESAME members – Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey – was held in September 2015. The course brought together 28 teachers and students from the Middle East, who came to know each other and learn about CERN as a model for scientific and human collaboration, regardless of political or cultural differences. The programme also prepared the ground for a continuing future collaboration between schools in the SESAME members.

After the success of the first edition in 2014, CERN repeated the Beamline for Schools (BL4S) competition in 2015, with the help of external sponsorship via the CERN and Society Foundation. Teams of high-school students proposed experiments and winning teams were invited to come to the Laboratory and perform their experiments on a fully equipped beamline in collaboration with CERN scientists. Of the 119 submitted proposals, two teams, from Florence, Italy, and Johannesburg, South Africa, made the biggest impression on CERN experts and were invited to the Laboratory for ten days in September (see p. 11).

Read all about it

The CERN-initiated SCOAP^3 consortium – the Sponsoring Consortium for Open Access Publishing in Particle Physics – is a global partnership of more than 3000 libraries, funding agencies and research institutions in 47 countries. By 2015, SCOAP^3 has supported more than 8000 open access articles in high-quality peer-reviewed high-energy-physics journals. Thanks to SCOAP^3, authors retain intellectual property rights to their work, and permissive Creative Commons licences allow immediate redistribution and reuse of the publications' content, free of charge, for any purpose, provided they are duly attributed to the authors. To date, about 20 000 authors from some 90 countries have enjoyed these benefits at no cost. Furthermore, CERN implemented its Open Access Policy in 2015. Thanks to SCOAP^3 and bilateral agreements with key publishers, more than 96% of CERN's particle physics results were published on an open-access basis in 2015. In comparison, other research institutes of a similar size publish on average about 10% of their articles open access. In the spirit of open science, the LHC experiments began sharing their data in the public domain in 2014 with the CERN Open Data Portal. In 2015, the portal was augmented with further data and code releases. Data have been used in many applications, such as training in big-data analytics and data mining.

In 2015, CERN doubled the number of albums of its historical photo archives available to the public, digitising them and adding 120 000 images distributed across 14 000 albums: the entire black and white collection from the founding of the Organization



The first of the four modules that will make up the miniature accelerator developed to be used for treating certain forms of cancer. (CERN-PHOTO-201506-138-3)

A miniature accelerator for health

With the experience gained at Linac4, a linear accelerator under development (see p. 25), CERN engineers developed a miniature version of one of its components, the radio-frequency quadrupole. This mini linac was conceived to match the needs of medical accelerators for treating certain forms of cancer with particle beams, and for producing medical isotopes.

The resulting compact accelerator will be just two metres long, and offers an attractive alternative to the much larger circular machines that have traditionally been used in this role. Tests should get under way in 2016, and, in the meantime, the first licence to use this technology has already been granted. CERN's brand new linear accelerator, in miniature form, could be about to start appearing in hospitals, making a solid contribution to health.

through to 1986. As well as archive images, new ways of seeing CERN emerged when photographers were invited to the Laboratory as part of the Global Particle Physics Photowalk. For Arts@CERN, partnerships were organised with international cultural organisations including ADMAF from the United Arab Emirates, Ars Electronica from Austria and the Rupert Centre for Art and Education from Lithuania, as well as governmental bodies such as the Pro Helvetia Swiss Arts Council, the Canton and the City of Geneva, the Ministry of Culture of Taiwan and the Federal Chancellery of Austria. The programme welcomed Collide@CERN Pro Helvetia artists "Fragment.In" from Switzerland and Collide@CERN Ars Electronica arts collective "Semiconductor" from the UK for three-month residencies at CERN, as well as curating visits for eight other artists – 15 artists in total in 2015.

CERN's Press Office welcomed around 400 media visits and registered more than 180 000 press cuttings throughout the year. Seven million unique visitors looked at CERN's core websites, and in October CERN moved its homepage to http://home.cern after receiving its own top-level domain. Social media users mentioned CERN and the LHC 1.2 million times, with notable peaks around April's LHC restart and June's 13 TeV collisions, as well as when CERN's Star Wars-themed joke was published for April Fools' Day (see p. 9) In March, CERN was awarded the Best Swiss Twitter Page 2015 at the WorldWebForum in Zurich, beating the Twitter accounts of Swiss tourism, luxury brands and tennis champion Roger Federer.

Transferring the knowledge

2015 saw the launch of CERN's Knowledge and Technology Transfer Network for SMEs and a growing network of Business Incubation Centres (BICs). The BIC initiative that began in 2012 now has eight centres in Austria, Finland, France, Greece, Norway, the Netherlands, Spain and the UK. The French incubation centre was launched in the framework of the quadripartite partnership between CERN, France, the Department of Ain and the Community of Communes of the Pays de Gex that was put in place in 2014. These centres hosted nine fledgling companies in 2015, covering technologies ranging from sensors for robotics and automation to nanocoatings for applications in electricity generation and cooling.

IdeaSquare made significant progress during its first year of operation, organising or hosting some 40 events. The facility connects detector R&D with cross-disciplinary teams working on societal challenges. Events included several Challenge-Based Innovation (CBI) courses for MSc-level students, workshops on R&D for industry and private investors, and weekend hackathons such as THE Port. IdeaSquare currently also hosts two large EU co-funded detector projects, TALENT and EDUSAFE.

The strong interest at CERN in participating in the EU Horizon 2020 (H2020) programme continues, and a number of proposals involving CERN were submitted. Out of the 12 new H2020 projects selected for funding in 2015, five are coordinated by CERN. Their range of fields and activities includes: laser spectroscopy for radionuclides (EIBT-LS), ultrafast imaging sensors for medical applications (ULTIMA), development of novel quadrupole magnets for the High-Luminosity LHC (QUACO), a private-public partnership for cloud computing (HNSciCloud), and smart sensor technologies for radiation-enhanced applications and measurements (STREAM). In addition, the EC's Marie Skłodowska-Curie Actions provided funding for more than 190 young researchers to work at CERN in 2015.

The brand-new Building 774 on the Prévessin site was officially opened on 12 June 2015. As well as housing offices for the accelerator teams, it contains an auditorium and a reception area for visitors and VIPs. (Photo Jordi Bernadó)

A place of work

The fenced part of the CERN site occupies a total area of 200 hectares, located on both sides of the French-Swiss border, and comprises numerous buildings and green spaces requiring maintenance and renovation. A host of construction and maintenance projects were carried out in 2015 to improve the quality of the Organization's infrastructure.

On the French side, a new workshop and a control room were opened on the LHCb experiment site, and a ribbon-cutting ceremony was held for Building 774. With its innovative architecture, this new building provides a focal point for the Prévessin site, housing offices for the accelerator teams, a cafeteria, an auditorium and a reception area for visitors and VIPs. On the Swiss side, an emergency response centre operated by the HUG (Geneva University Hospitals) and a building housing the radio-frequency systems for the PS Booster were opened on the main Meyrin site.

Many buildings were also renovated, including the *Microcosm* exhibition, which was completely transformed (see p. 32). With a view to enhancing the standard of comfort provided by the on-site accommodation facilities, two floors of one of the hostels were modernised in time for the arrival of the summer students. During the year, the access points of the various sites were upgraded to improve security and optimise resources. This included the installation of a new automated access system at one of the gates on the Meyrin site.

The renovation of the water tower was one of the highlights of the work carried out in 2015. To guarantee an optimum quality of drinking water, the tower's inner lining was replaced with a plastic material specifically designed for drinking-water tanks and its internal piping was modernised.

CERN and its people

CERN continued its drive to increase its visibility to potential candidates in all 21 Member States, via a proactive sourcing and outreach programme. In 2015, just over 23 000 applications were received for staff positions, and 164 limited-duration-contract boards were held. Nationals of Turkey and Pakistan have been entitled to apply for positions at CERN since these countries joined the Organization as Associate Member States (see p. 7).

The flagship Summer Student Programme, a shining example of international collaboration and a model for the training of young people, brought 276 students from 83 different countries to CERN in 2015. (CERN-PHOTO-201507-153-2)

Five-yearly review

Every five years, CERN reviews the financial and social conditions it offers its personnel. 2015 ended on a very positive note, with the Council's approval of the measures proposed in the latest five-yearly review framework. A rationalised career structure and modernised diversity-related conditions are key features of the 2015 review. Given the current economic climate, the Member States appreciated the decision to adopt a measured and rational approach. The Council's approval marked the completion of a long process, which had begun in earnest in 2014. Following the successful outcome of the five-yearly review, the updated conditions should ensure that the Organization can continue to remain attractive to personnel of the highest competence and to develop sustainably.

The Fellowship Programme continued to be extremely successful, attracting well over 2000 applications in 2015. A total of 350 fellows were selected, including 33 who had taken part in the recently introduced Technicians Training Experience set up for highly skilled technicians. Additional funding was secured through the European Commission's Marie Skłodowska-Curie Actions scheme, which is part of the new Horizon 2020 framework programme. In particular, COFUND will contribute towards the funding of 60 CERN fellows over the next five years.

In addition, 293 technical and doctoral students were selected, and the flagship Summer Student Programme was attended by 276 students. A new Spanish trainee programme was launched, giving 20 Spanish trainees per year the opportunity to work at CERN on a two-year contract. The CERN Apprentice Programme was once again recognised as outstanding by the local authorities *(Union Industrielle Genevoise)*, with one graduate receiving a "best apprentice" award.

The roll-out of the Learning and Development Policy continued as the team responsible for training embedded the CERN Competency Model in five training curricula ("Technical", "Technical Management", "Language", "Personal Development and Communication" and "Leadership"). An additional curriculum, "Your career at CERN", was created to enhance the range of learning opportunities on offer. A total of 497 training courses were attended by over 5000 registered participants.

Developing proposals for diversity-related measures within the framework of the five-yearly review was one of the Diversity Office's key tasks in 2015. The Office also celebrated the 20th anniversary of its predecessor, a working group set up back in 1995 to address the gender imbalance at CERN. In 2015, the Diversity Office continued to implement actions towards CERN's seven strategic diversity objectives, which focus on recruitment, career development and the working environment. In addition, it expanded its network of external partners to exchange best practices in the different areas of diversity management.

A new contract policy was implemented with a view to providing a more flexible workforce for the Laboratory, increased possibilities to retain key expertise and enhanced opportunities for internal mobility.

Doing business with CERN

The 2015 procurement year was marked by several events and projects, including a new information campaign targeted at companies from Member States wishing to supply products and services to CERN and the introduction of a bilingual e-learning training course for CERN employees involved in the procurement process. Expenditure on supplies and services amounted to some 298 MCHF and 126 MCHF respectively, and around 54 500 orders were placed in total.

Accountability

In April, CERN introduced a policy for preventing and managing conflicts of interest. This was followed by a campaign to raise awareness among the personnel of the risks that such conflicts pose for the Organization.

In November, the Internal Audit service also organised a joint training initiative on evaluation in conjunction with its counterparts from other international organisations based in Geneva. The aim was to equip personnel with the knowledge required to systematically and objectively evaluate the impact of CERN's programmes and policies on targeted groups of society.

One of the new water-quality-measuring stations installed in 2015, with a hydrocarbon detector designed to detect pollution immediately. (CERN-PHOTO-201603-064-6)

Safety and environment

CERN constantly measures the quality of the water and air expelled from its installations as a means of monitoring the impact of its activities on the environment. More than one hundred measuring stations keep track of numerous parameters, including those linked to ionising radiation and certain physico-chemical aspects. In addition to this data, samples taken from the sites and the surrounding areas are analysed.

This monitoring programme is regularly upgraded. In 2015, five new stations measuring atmospheric emissions from the experiments and the accelerator tunnels were installed. Six sites were newly equipped with hydrocarbon detectors that can immediately detect pollution in the water that CERN evacuates into nearby watercourses. A total of 12 sites will have been equipped with these detectors by the summer of 2016. A new tool for monitoring water-quality-measuring stations was also developed.

Guardians of the water

Installing hydrocarbon detectors was one of the first actions of a plan designed to minimise the impact of using chemical products. In order to carry out its research, CERN uses many technical installations that contain chemicals, such as hydrocarbons in the case of electrical equipment. A working group produced a full report on the matter in 2015, including an update of the inventory of areas at risk of pollution, a risk assessment and recommended priority actions.

Radiation under control

Particular attention is given to controlled radiation work areas. Only two of the 9800 or so people issued with a dosimeter received a radiation dose of 1 to 2 millisieverts (mSv). All others received doses of less than 1 mSv; 87% received a dose of 0. To put that in context, the average dose received annually by

A new facility for testing radiation-measuring devices was put into operation. (CERN-PHOTO-201411-230-2)

The new 100%-electric domestic-waste-collection vehicle, commissioned in the framework of the contract between CERN and the Transvoirie company. (BUL-NA-2015-148)

residents of France as a result of natural radiation and medical procedures is 3.7 mSv. Systematically applying the ALARA (As Low As Reasonably Achievable) approach greatly contributed to this result. This approach is now firmly embedded in the CERN culture. In addition, a new installation for testing radiation-measuring devices was put into operation, allowing the calibration and verification of all the instruments used at CERN to measure beta, gamma, X-ray and neutron radiation.

All data on radiation is passed on to CERN's two Host States: France and Switzerland. A tripartite agreement signed between CERN and its Host States in 2011 replaced the previous bilateral agreements covering radiation protection and the safety of the Laboratory's installations. In the framework of this new agreement, CERN provides the safety authorities in the two countries with all its measurements of ionising radiation. The safety authorities also carry out regular inspections. In 2015, an important inspection took place at Linac4, the future linear accelerator currently under construction (see p. 25), for which CERN submitted a safety file.

Better waste recycling

CERN is constantly optimising its waste recovery efforts. In 2015, the Laboratory produced around 5000 tonnes of conventional waste, which was managed entirely by specialised companies. A large proportion of it was repurposed via various recycling schemes; for example, 1590 tonnes of metal were sold to recycling companies. Also, to fulfil its contract with CERN, the company responsible for collecting domestic waste started using a 100%-electric waste-collection lorry – the first in French-speaking Switzerland.

Energy efficiency

The supply of electricity is a key concern for the Organization, since the operation of the accelerators requires a huge amount of electrical power. CERN entered into a new electricity supply contract following a call for tenders after the market was opened up to competition. This contract guarantees the supply of electricity for the whole of LHC Run 2 and includes assistance in optimising consumption on the conventional parts of the sites. CERN is taking steps to improve its energy efficiency under the guidance of an energy coordinator. A working group was formed with a view to defining ways to move forward. Elsewhere, CERN took part in the third edition of a series of workshops that it co-founded on energy for sustainable science in research infrastructures.

Bike to the Lab

Another measure taken by CERN to reduce its environmental impact is promoting "public" transport (i.e. the shuttle services around and between the sites), car sharing and cycling. Boasting around 600 self-service bikes, CERN's bicycle fleet is one of the largest in Switzerland. In 2015, the CERN community took to the saddle to participate for the third time in Bike2Work, an initiative that encourages commuting by bike. 504 people took part in the challenge at CERN – more than at any other participating organisation in French-speaking Switzerland. The CERN teams cycled a total of 97 500 kilometres, equating to a saving of around 15 tonnes of carbon-dioxide emissions.

Effective online training

Safety at CERN relies heavily upon the effective training of users of the infrastructure. In 2015, more than 5000 people attended a total of 580 classroom training sessions, while approximately 40 000 online courses were completed. An overhaul of the 26 online training courses began; the new courses are more interactive and modular, and they follow a coherent structure and graphic-design theme.

Safety exercises are conducted at the Laboratory on a regular basis. A large-scale exercise took place at the nuclear physics installation, ISOLDE, in October. The simulation involved roughly 20 people from ISOLDE, Radiation Protection, the Fire and Rescue Service, the CERN Medical Service and the mobile emergency response and resuscitation service. The aim of the exercise was to train the teams in the techniques and procedures that they should use in the event of an accident involving ionising radiation.

Some of the 504 CERN participants in the Bike2Work initiative, which aims to promote cycling as a means of transport for the commute to and from work. (CERN-PHOTO-201506-142-11)

The mobile emergency response service based at CERN was inaugurated by CERN Director-General Rolf Heuer and HUG Director-General Bertrand Levrat. The service ensures a better handling of medical emergencies on the CERN sites. (CERN-PHOTO-201505-083-7)

A win-win rescue situation

At the beginning of May, a mobile emergency response and resuscitation service (SMUR) started operating on the Meyrin site. This new facility is the result of a cooperation agreement between CERN and the Geneva University Hospitals (HUG). CERN provided the infrastructure while the HUG manages the facility, providing a vehicle, a doctor and a paramedic ready to respond to emergencies on both the French and Swiss parts of the CERN sites and in the western part of the Canton of Geneva. An emergency-call triangulation system integrating the emergency dispatch centres of the Canton of Geneva and CERN ensures that the appropriate service can respond to medical emergencies on the Laboratory's sites. The new system guarantees better handling of medical emergencies at CERN and quicker responses in the west Geneva area. During its eight months of operation, the SMUR vehicle has participated in 47% of call-outs on the CERN sites. The effectiveness of the new collaboration was firmly underlined at the end of the year when the victim of a cardiac arrest was saved quickly thanks to the SMUR being so close at hand. Meanwhile, the CERN firefighters were called upon to assist in a carbon monoxide poisoning incident nearby. Specialists from the HUG also began training CERN's medical personnel and firefighters, a highlight being a session on emergency protocols.

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Chair of the Finance Committee:
Ms C. Jamieson

Director-General:
Professor R.-D. Heuer

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Chair
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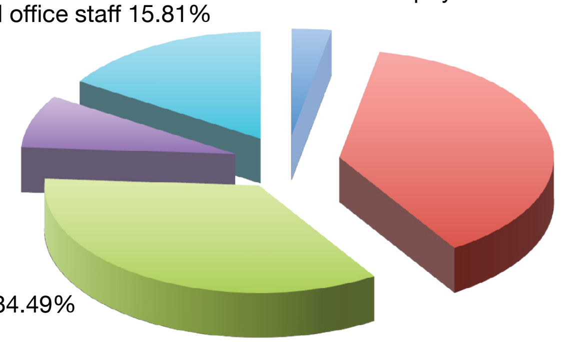
S DIR	**Director-General Sector**
DG	Director-General
DG-AS	Administrative Support
DG-CO	Communication
DG-CS	Council Secretariat
DG-DG	Office of the Director-General
DG-DI	Directorate Office
DG-EDU	Education
DG-EU	EU Projects Office
DG-IA	Internal Audit service
DG-IR	International Relations
DG-LS	Legal Service
DG-PRT	Protocol Office
DG-RH	Relations with Host States
DG-RPC	Resources Planning, Processes and Controlling
DG-TM	Translation & Minutes
DGS	Occupational Health & Safety and Environmental Protection Unit
DGS-DI	HSE Unit Head Office
DGS-RP	Radiation Protection
DGS-SEE	Safety Engineering & Environment
S AI	**Administration and General Infrastructure Sector**
FP	Finance, Procurement & Knowledge Transfer department
FP-DI	Department Head Office
FP-FAS	Financial & Accounting Services
FP-KT	Knowledge Transfer
FP-PI	Procurement & Industrial Services
GS	General Infrastructure Services department
GS-AIS	Advanced Information Systems
GS-ASE	Access, Safety & Engineering Tools
GS-DI	Department Head Office
GS-FB	Fire & Rescue Service
GS-IS	Integrated Services
GS-ME	Medical Service
GS-SE	Site Engineering
GS-SIS	Scientific Information Service
GS-SMS	Service Management & Support
HR	Human Resources department
HR-CB	Compensation & Benefits
HR-DHO	Department Head Office
HR-FL	Frontline
HR-LD	Learning and Development
HR-SA	Staff Association Secretariat (administratively attached to HR)
HR-TA	Talent Acquisition
S AT	**Accelerators & Technology Sector**
BE	Beams department
BE-ABP	Accelerator & Beam Physics
BE-ASR	Administration, Safety & Resources
BE-BI	Beam Instrumentation
BE-CO	Controls
BE-HDO	Department Head Office
BE-OP	Operations
BE-RF	Radio Frequency
EN	Engineering department
EN-CV	Cooling & Ventilation
EN-EL	Electrical Engineering
EN-GMS	General Management & Secretariats
EN-HDO	Department Head Office
EN-HE	Handling Engineering
EN-ICE	Industrial Controls & Engineering
EN-MEF	Machines & Experimental Facilities
EN-MME	Mechanical & Materials Engineering
EN-STI	Sources, Targets & Interactions
TE	Technology department
TE-ABT	Accelerator Beam Transfer
TE-CRG	Cryogenics
TE-EPC	Electrical Power Converters
TE-HDO	Head of Department's Office
TE-MPE	Machine Protection & Electrical Integrity
TE-MSC	Magnets, Superconductors & Cryostats
TE-VSC	Vacuum, Surfaces & Coatings
S RC	**Research & Scientific Computing Sector**
IT	Information Technology department
IT-CF	Computing Facilities
IT-CIS	Collaboration and Information Services
IT-CS	Communication Systems
IT-DB	Database Services
IT-DI	Departmental Infrastructure
IT-DSS	Data & Storage Services
IT-OIS	Operating Systems & Infrastructure Services
IT-PES	Platform & Engineering Services
IT-SDC	Support for Distributed Computing
PH	Physics department
PH-ADE	ATLAS Detector Systems
PH-ADO	ATLAS Detector Operation
PH-ADP	ATLAS Data Processing
PH-ADT	ATLAS DAQ & Trigger
PH-AID	ALICE Detector & Systems
PH-AIO	ALICE Management & Engineering Support
PH-AIP	ALICE Physics & Computing
PH-CMD	CMS DAQ & Trigger
PH-CMG	CMS Physics, Software & Computing
PH-CMO	CMS Organisation
PH-CMX	CMS Experiment Systems
PH-DI	Office of the Department Leader
PH-DT	Detector Technology
PH-ESE	Electronics Systems for Experiments
PH-LBC	LHCb Computing
PH-LBD	LHCb Detector
PH-LBO	LHCb Coordinator's Office
PH-LCD	Linear Collider Detector
PH-SFT	Software Design for Experiments
PH-SME	Small & Medium Experiments
PH-TH	Theoretical Physics
PH-TOT	TOTEM Experiment
PH-UAD	Antiproton Users
PH-UAI	ALICE Users
PH-UAT	ATLAS Users
PH-UC3	CTF3 Users
PH-UCM	CMS Users
PH-UFT	Fixed Target Users
PH-UGC	General Collaboration Users
PH-UHC	Other LHC Users
PH-UIS	ISOLDE Users
PH-ULB	LHCb Users
PH-ULD	Linear Collider Detector Users
PH-UNT	n_TOF Users
PH-UOP	Other Physics Users
PH-URD	R&D Users
PF	**Pension Fund**
PFMU	Pension Fund Management Unit
PF-OP	Operations
PF-IN	Investments

CERN in figures

CERN staff



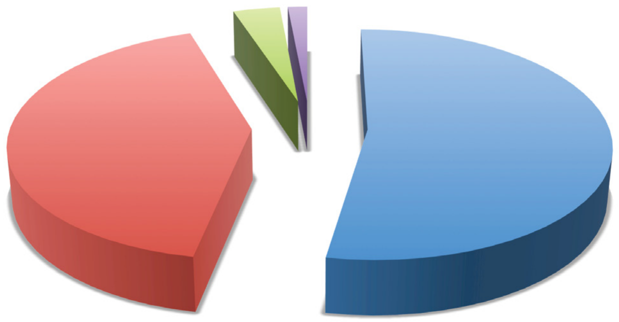
Evolution of staff numbers
Including externally funded

2012	2512
2013	2513
2014	2524
2015	2531

Evolution of fellows, associates, students, users and apprentices

2012	12 080
2013	12 313
2014	13 142
2015	13 794

CERN expenses



Total expenses	1082.9 MCHF
Personnel	628.9
Materials	379.2
Goods, consumables and supplies	*171.3*
Other materials expenses	*207.9*
Energy and water	64.6
Interest and financial costs	10.2

Glossary

Accelerating cavity
Accelerating cavities produce the electric field that accelerates the particles inside particle accelerators. Because the electric field oscillates at radio frequency, these cavities are also referred to as radio-frequency cavities.

Accelerator
A machine in which beams of charged particles are accelerated to high energies. Electric fields are used to accelerate the particles while magnets steer and focus them. Beams can be made to collide with a static target or with each other.
• A collider is a special type of circular accelerator where beams travelling in opposite directions are accelerated and made to interact at designated collision points.
• A linear accelerator (or linac) is often used as the first stage in an accelerator chain.
• A synchrotron is an accelerator in which the magnetic field bending the orbits of the particles increases with the energy of the particles. This makes the particles move in a circular path.

AD (Antiproton Decelerator)
The research facility that produces the low-energy antiprotons for the experiments AEgIS, ALPHA, ASACUSA, ATRAP, BASE and GBAR.

ALICE (A Large Ion Collider Experiment)
One of the four large experiments studying the collisions at the LHC.

Antimatter
Every kind of matter particle has a corresponding antiparticle. Charged antiparticles have the opposite electric charge to their matter counterparts. Although antiparticles are extremely rare in the universe today, matter and antimatter are believed to have been created in equal amounts at the time of the Big Bang.

ATLAS
One of the four large experiments studying the collisions at the LHC.

Beam
The particles in an accelerator are grouped together in a beam. Beams can contain billions of particles and can be divided into discrete portions called bunches. Each bunch is typically several centimetres long and just a few microns wide.

Boson
The collective name given to the particles that carry forces between particles of matter. (See also Particles.)

Calorimeter
An instrument for measuring the amount of energy carried by a particle. In particular, an electromagnetic calorimeter measures the energy of electrons and photons, whereas a hadronic calorimeter determines the energy of hadrons, that is, particles made of quarks, such as protons, neutrons, pions and kaons.

CLIC (Compact LInear Collider)
A site-independent feasibility study aiming at the development of a realistic technology at an affordable cost for an electron–positron linear collider for physics at multi-TeV energies.

CMS (Compact Muon Solenoid)
One of the four large experiments studying the collisions at the LHC.

Cosmic ray
A high-energy particle that strikes the Earth's atmosphere from space, producing many secondary particles, also called cosmic rays.

CP violation
A subtle effect observed in the decays of certain particles that betrays nature's preference for matter over antimatter.

Cryostat
A refrigerator used to maintain extremely low temperatures.

Dark matter
Only about 5% of the matter in the universe is visible. The rest is of an unknown nature and is referred to as dark matter (27%) and dark energy (68%). Finding out what it consists of is a major question for modern science.

Detector
A device used to measure properties of particles. Some detectors measure the tracks left behind by particles, others measure energy. The term "detector" is also used to describe the huge composite devices made up of many smaller detector elements. In the large detectors at the LHC each layer has a specific task.

Dipole
A magnet with two poles, like the north and south poles of a horseshoe magnet. Dipoles are used in particle accelerators to keep particles moving in a circular orbit. In the LHC there are 1232 dipoles, each 15 m long.

Electronvolt (eV)
A unit of energy or mass used in particle physics. One eV is extremely small, and units of a million electronvolts, MeV, or a thousand million electronvolts, GeV, are more common. The LHC collision energy reaches 13 million million electronvolts, or 13 TeV. One TeV is about the energy of motion of a flying mosquito.

Event
Particle collisions generate sprays of new particles that are observed by detectors. When a collision is considered potentially interesting, information about the emerging particles is recorded for further study. Such a collision is referred to by physicists as an event.

FCC study
By 2019, the Future Circular Collider collaboration (FCC) will produce a conceptual design report for a next generation large-scale particle collider on a timescale of 20 to 30 years. It studies the possibility of a 100-TeV hadron collider, a lepton collider as a potential intermediate step, and a lepton–hadron collider as an option. The study also covers a possible high-energy version of the LHC in the existing tunnel.

Forces
There are four fundamental forces in nature. Gravity is the most familiar to us, but it is the weakest. Electromagnetism is the force responsible for thunderstorms and carrying electricity into our homes. The two other forces, weak and strong, are confined to the atomic nucleus. The strong force binds the nucleus together, whereas the weak force causes some nuclei to break up. The weak force is important in the energy-generating processes of stars, including the Sun. Physicists would like to find a single theory that can explain all these forces. A big step forward was made in the 1960s when the electroweak theory uniting the electromagnetic and weak forces was proposed. This was later confirmed in a Nobel-prize-winning experiment at CERN.

GeV
See Electronvolt.

Hadron
A subatomic particle that contains quarks, antiquarks, and gluons, and so experiences the strong force. (See also Particles.)

Higgs boson
The particle linked to the Brout–Englert–Higgs mechanism that gives mass to elementary particles.

High-Luminosity LHC
The High-Luminosity LHC (HL-LHC), scheduled to be commissioned after 2025, will extend the discovery potential of the LHC by increasing the luminosity by a factor 5-10. To achieve this, new equipment will be installed in 1.2 km of the current accelerator.

Injector
System that supplies particles to an accelerator. The injector complex for the LHC consists of several accelerators acting in succession.

Ion
An ion is an atom with one or more electrons removed (positive ion) or added (negative ion).

ISOLDE
A radioactive ion beam facility that directs a beam of protons from the Proton Synchrotron Booster onto special targets to produce more than 1000 different isotopes for a wide range of research. (See also Isotope.)

Isotope
Slightly different versions of the same element, differing only in the number of neutrons in the atomic nucleus — the number of protons is the same.

Kelvin
A unit of temperature. One kelvin is equal to one degree Celsius. The Kelvin scale begins at absolute zero, –273.15°C, the coldest temperature possible.

Lepton
A class of elementary particle that includes the electron. Leptons are particles of matter that do not feel the strong force. (See also Particles.)

LHC
The Large Hadron Collider, CERN's biggest accelerator.

LHCb (Large Hadron Collider beauty)
One of the four large experiments studying the collisions at the LHC.

Linac
See Accelerator.

Luminosity
In particle physics, luminosity is a measure of how many particles pass through a given area in a certain amount of time. The higher the luminosity delivered by the LHC, the larger the number of collision events happening at each experiment. Hence, more luminosity means more precise results and an increased possibility to observe rare processes.

Muon
A particle similar to the electron, but some 200 times more massive. (See also Particles.)

Muon chamber
A device that identifies muons, and together with a magnetic system creates a muon spectrometer to measure momenta.

Neutrino
A neutral particle that hardly interacts at all. Neutrinos are very common and could hold the answers to many questions in physics. (See also Particles.)

n_TOF
A facility that uses protons from the PS to create a high-intensity neutron beam to study neutron-induced reactions over a broad range of energies.

Nucleon
The collective name for protons and neutrons.

Particles
There are two groups of elementary particles, quarks and leptons. The quarks are up and down, charm and strange, top and bottom (beauty). The leptons are the electron and electron neutrino, muon and muon neutrino, tau and tau neutrino. The quarks and leptons, which are all particles of matter, are referred to collectively as fermions. There are four fundamental forces, or interactions, between particles, which are carried by special particles called bosons. Electromagnetism is carried by the photon, the weak force by the charged W and neutral Z bosons, the strong force by the gluon; gravity is probably carried by the graviton, which has not yet been discovered. Hadrons are particles that feel the strong force. They include mesons, which are composite particles made up of a quark–antiquark pair and baryons, which are particles containing three quarks. Pions and kaons are types of meson. Neutrons and protons (the constituents of ordinary matter) are baryons; neutrons contain one up and two down quarks; protons two up and one down quark.

Positron
The antiparticle of the electron. (See also Antimatter.)

PS
The Proton Synchrotron, backbone of CERN's accelerator complex.

Quadrupole
A magnet with four poles, used to focus particle beams rather like glass lenses focus light.

Quantum chromodynamics (QCD)
The theory for the strong interaction, analogous to QED.

Quantum electrodynamics (QED)
The theory of the electromagnetic interaction.

Quark
The smallest known elementary particle that feels the strong force. (See also Particles.)

Quark-gluon plasma (QGP)
A state of matter in which protons and neutrons break up into their constituent parts. QGP is believed to have existed just after the Big Bang.

Sextupole
A magnet with six poles, used to apply corrections to particle beams. At the LHC, eight- and ten-pole magnets are also used for this purpose.

Sigma
A representation of standard deviation – the error margin on a measurement – where 5 sigma is the probability that a measurement is 99.99994% correct.

Spectrometer
In particle physics, a detector system containing a magnetic field to measure momenta of particles.

SPS
The Super Proton Synchrotron. An accelerator that provides beams for experiments at CERN, as well as preparing beams for the LHC.

Standard Model
A collection of theories that embodies all of our current understanding about the behaviour of fundamental particles.

Superconductivity
A property of some materials, usually at very low temperatures, that allows them to carry electricity without resistance. If you start a current flowing in a superconductor, it will keep flowing forever — as long as you keep it cold enough.

Supersymmetry
A theory that predicts the existence of heavy "superpartners" to all known particles. It is being tested at the LHC.

Transfer line
Carries a beam of particles, e.g. protons, from one accelerator to another using magnets to guide the beam.

TeV
See Electronvolt.

Trigger
An electronic system for spotting potentially interesting collisions in a particle detector and triggering the detector's read-out system to record the data resulting from the collision.

Vacuum
A volume of space that is substantively empty of matter, so that gaseous pressure is much less than standard atmospheric pressure.

WLCG (Worldwide LHC Computing Grid)
The mission of the WLCG is to provide data-storage and analysis infrastructure for the entire high-energy physics community using the LHC.

CERN