Annual Report 2014

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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 as of January 2014. 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 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)

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Message from the President of Council

“CERN has succeeded in the goal of bringing European countries together in peaceful co-operation.”

CERN’s 60th anniversary, celebrating six decades of science for peace, was a major highlight of 2014 for CERN and its Member States represented in CERN Council. The year had a fitting start with the official ceremony to raise the Israeli flag outside CERN for the first time, following completion of the final formalities for Israel’s accession as the 21st Member State.

Over the following months, many anniversary events took place, in addition to the main celebration on 29 September. In particular, Council delegates took an active role in proposing and organizing events in almost all of the Member States, with nearly 100 external events taking place in 25 countries.

One special event at CERN commemorated a key moment in the history of Council. On 19 September, during a Council week, a symposium was dedicated to the 60th anniversary of the first session of CERN Council, held in October 1954, just one week after the CERN Convention entered into force. At the symposium, we heard speakers representing various categories of personnel and users of CERN give their own perspectives on what Council means to them.

A key activity for Council during the year concerned the selection and appointment of the next Director-General. The Search Committee, set up at the session in March, pre-selected three excellent candidates. In November, Council converged on one of these, Fabiola Gianotti, and gave formal and unanimous approval for her election as next Director-General in December. She will start her mandate at the beginning of 2016.

Another important topic on Council’s agenda in 2014 concerned the CERN Pension Fund, whose funding situation led to extensive discussions. Their main aim was to enhance Council’s understanding of the actuarial situation of the Fund and to compare its scheme with those in other international organizations.

Finally, Council approved various steps for more countries to become Member States or Associate Member States, so we can expect CERN to continue to grow in the future. Over the past 60 years, in addition to its primary mission of producing first-class scientific results, CERN has succeeded in the goal of bringing European countries together in peaceful co-operation. I sincerely believe that this collaborative model of CERN will continue to inspire people around the world for years to come.

Agnieszka Zalewska

Message from the Director-General

"The founders' ideals continue to drive our work at CERN."

CERN officially came into being on 29 September 1954, established through a Convention that, in rather formal language, summarized the dreams of the founders. It speaks not only of the construction of accelerators, experiments and infrastructure, but also of international co-operation in research, the promotion of contacts between scientists, the training of scientists, and dissemination of knowledge across borders.

The visionary scientists and diplomats who had worked together to set up CERN realized that by combining forces beyond national borders and boundaries, Europe can play a role in education and in frontier science. Over the past 60 years, CERN has amply fulfilled these dreams, building intellectual bridges, for example, between East and West, even in 'icy' times. Now it is time to cross continental boundaries, and 2014 saw the first steps in this direction — from the raising of the Israeli flag at CERN in January, to the signing in December of a document to admit Pakistan to Associate Membership.

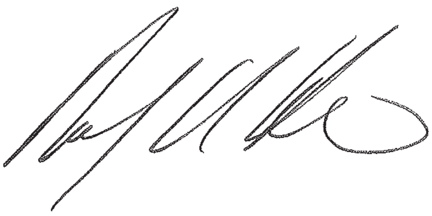
The founders' ideals continue to drive our work at CERN 60 years later. In particular, we are keen to ensure that those who shape the future fully appreciate the essential role that science must play. To this end, in 2014 we established a foundation to support the CERN & Society programme, so that CERN's expertise and technology can benefit society to the full. One example of the initiatives that can be funded this way is the 'Beamline for Schools' project that extended CERN's broad portfolio of educational activities by allowing schools to propose experiments for CERN, exactly as teams of physicists do. Also following along the lines of the Convention, the year saw CERN extend its pursuit of openness, through the start of the $SCOAP^3$ Open Access initiative and the first open release of data from the experiments at the Large Hadron Collider (LHC).

For many people at CERN and elsewhere, the first-ever long shutdown of the accelerator complex, LS1, involved a significant amount of work. During the year, it reached a positive conclusion, as one by one, the restart of the warm accelerators progressed smoothly, with research getting under way at all of the facilities they supply. At the same time there was excellent progress in preparing the LHC for the start of Run 2 in 2015. Many thanks go to all of those, not only at CERN, but also from other laboratories and institutes, who contributed to such a safe and successful LS1.

Meanwhile, there has been no shutdown for the analysis work, leading to many new precise measurements by the LHC experiments and outstanding results from experiments at other parts of the complex. Run 2 will see the LHC operate at almost double the collision energy of Run 1, and with this new energy level, CERN's flagship machine will open new horizons for physics and for future discoveries. It is certain that we are all looking forward to seeing what nature has in store for us.

Lastly, I look forward to working with Fabiola Gianotti during 2015, to ensure a smooth transition when she becomes the next Director-General in 2016.

Rolf Heuer



The official CERN60 ceremony on 29 September featured the European Union Youth Orchestra, directed by Maestro Vladimir Ashkenazy, with 42 musicians covering all of CERN Member, Associate Member and Observer States. (CERN-PHOTO-201409-196 – 120)

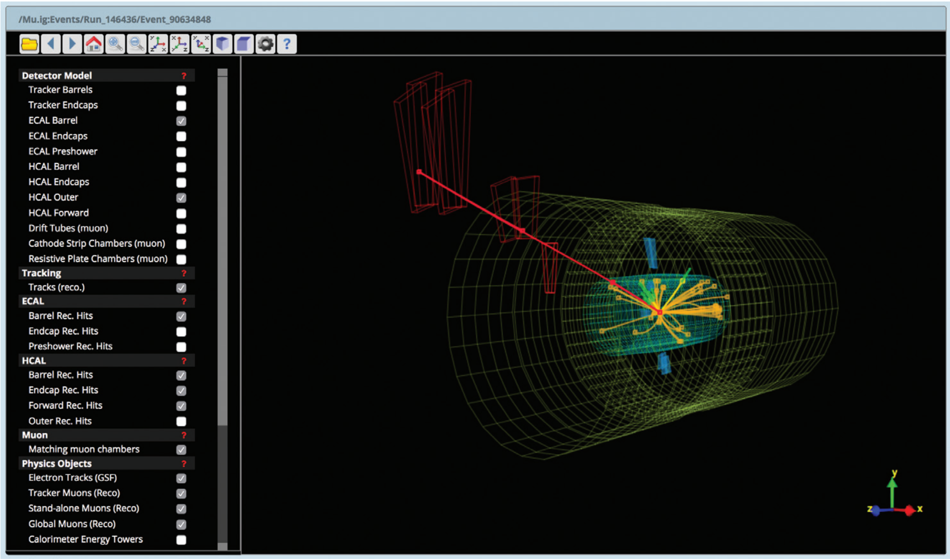
A year at CERN

On 29 September 2014, it was exactly 60 years since the European Organization for Nuclear Research — CERN — came into being. Just a few years after the Second World War, 12 European countries joined forces and built what has become the world's largest particle-physics laboratory. To mark the anniversary, CERN celebrated 60 years of science for peace with a total of 130 events throughout the year, at the Laboratory, in the local area, in the Member States and beyond.

At the beginning of July, a joint event at the Paris headquarters of the United Nations Educational, Scientific and Cultural Organization (UNESCO) commemorated the initial signing, on 1 July 1953, of the CERN Convention, which was to establish CERN under the auspices of UNESCO a year later. On the day of the 60th anniversary itself, delegations from 35 countries came to CERN for the official CERN60 ceremony. Other celebratory events at CERN and in the surrounding area invited people to listen to talks, hear music and see science in the streets (see p. 32). Finally, at a special event at the UN headquarters in New York on 20 October, CERN and the UN Economic and Social Council celebrated science for peace and development.

From LS1 to Run 2

During the year, the first Long Shutdown (LS1) of CERN's accelerator complex progressed towards a successful conclusion, nearly two years after it had begun early in 2013. Protons once again entered the Proton Synchrotron (PS) in June. They were soon serving experiments there and at the ISOLDE facility, the n_TOF neutron source and the Antiproton Decelerator (AD) — all of which had seen upgrades and refurbishment during the shutdown. The Super Proton Synchrotron (SPS) and the experiments there followed suit in October. Then, in November, beams came knocking at the door of the Large Hadron Collider (LHC) as they were successfully steered down transfer lines from the SPS.



The CMS collaboration published 2010 event data on the CERN Open Data Portal in a comprehensive manner, accompanied by detailed documentation, tutorials and visualization tools with event displays like this. (OPEN-PHO-EXP-2015-005 – 1)

In May cooling of the LHC began, and by the end of the year the whole machine was near its operating temperature of 1.9 K. In addition, the magnets of one full sector (an eighth of the LHC) had been powered up to the level needed for beams to reach 6.5 TeV, the operating energy for the LHC's Run 2. Moreover, LS1 provided the opportunity for the LHC experiment collaborations to work on refurbishment and upgrades of the detectors in preparation for the higher energy and collisions rates of Run 2. There was also a significant amount of work to optimize the performance of the Worldwide LHC Computing Grid once the huge flow of data begins again.

Preparing for the future

Given the complexity of modern accelerator projects, CERN must plan well in advance for the future, not only at the energy frontier, but also for the facilities serving other areas of particle physics. The High-Luminosity LHC project to increase the collider's luminosity by up to 10 times the original design value is already underway, with funding allocated in the Medium-Term Plan for 2014–2019. For the antiproton community, a new building has been completed for the Extra Low ENergy Antiproton (ELENA) project that will allow up to four experiments to operate in parallel with antiprotons from the AD. Elsewhere, work continued on the upgrade to ISOLDE — HIE-ISOLDE — and a new experimental area came into operation at n_TOF.

Research and development continued on both accelerator and detector concepts within the Linear Collider Collaboration and the CERN Linear Collider study. Looking further into the future, following a kick-off meeting in February, the first collaboration board for the international Future Circular Collider study was established during a meeting at CERN in September. Work also began at CERN to establish a platform to enable detector development and provide support for future participation in international experiments.

Open for all

CERN's efforts to foster international collaboration extend beyond the accelerators and experiments to the data and the final results. The beginning of the year saw the start of the Sponsoring Consortium for Open Access Publishing in Particle Physics ($SCOAP^3$). Led by CERN, $SCOAP^3$ involves an international collaboration of more than 1000 libraries, library consortia and research organizations. With the support of partners in 24 countries, a vast fraction of scientific articles in the field of high-energy physics will become Open Access at no cost for any author.

In November, CERN launched its Open Data Portal where data from real collision events are for the first time made openly available to all. This was created through a joint venture between the IT and GS Departments, and was developed together with the

At the inauguration of the Proton Synchrotron in 1960:
François de Rose, left, and John Adams. (CERN-HI-6002058)

François de Rose 1910–2014

François de Rose, French Ambassador, President of CERN Council 1957–1960, and subsequently a CERN Council Delegate, passed away on 23 March at the age of 103. The last of CERN's founding fathers, he was a loyal supporter of CERN. After World War II, he rallied to CERN's cause after meeting the great figures of physics, who were convinced that Europe's reconstruction should be driven by the development of its fundamental research tools. From then on, he was a staunch supporter of the Organization he considered to be one of his finest achievements. His passion for CERN's research endured, and he regularly sent messages of congratulation. During a visit in 2010, he promised that he would return to CERN when the so-called Higgs boson was discovered — a promise he kept in 2013.

LHC experiment collaborations. Publishing data openly means that detailed knowledge is shared about the research process and its products, allowing everyone to reuse and reinterpret the data — from citizen scientists to partner projects around the globe. The ALICE, ATLAS, CMS and LHCb collaborations all released data to the public on the portal, predominantly for outreach and training purposes.

Society at large

CERN's commitment to ensuring that the benefits of basic scientific research can reach as wide a part of society as possible finds expression not only in the activities in knowledge and technology transfer but also in the CERN & Society programme, which continued to take shape during 2014. This programme, which is now supported by the CERN & Society Foundation, serves as a focal point for a range of activities that require third-party funding. These initiatives range from student projects, such as the Beamline for Schools competition (see p. 33) to the ambitious OpenMed concept to develop the Low-Energy Ion Ring as a biomedical research facility. This latter project now comes under the remit of the CERN Medical Applications office (see p. 34), set up at the beginning of 2014 to bring all of the diverse medical-physics activities at CERN together under a single roof. Its budget line is small, but the aim is that it can be the seed for further developments and to establish collaborations with other institutes and centres.

Snapshots 2014

12/01

The Prime Minister of Hungary, Viktor Orbán, second from right, visited CERN, touring the LHC with József Pálinkás, President of the Hungarian Academy of Sciences, left, Marta Bajko, of the Technology Department, and, Rolf Heuer, the Director-General. (CERN-PHOTO-201401-002 – 1)

15/01

The Israeli flag was hoisted for the first time at the entrance to CERN, after UNESCO officially recorded Israel's accession as the Organization's 21st Member State. (CERN-PHOTO-201401-005 – 1)

02/04

During a visit to CERN, the President of Germany, Joachim Gauck, left, toured the ATLAS underground experimental area, accompanied by the deputy spokesperson for ATLAS, Thorsten Wengler. (CERN-PHOTO-201404-069 – 33)

03/05

The President of Greece, Karolos Papoulias, seated, was shown the ATLAS control room by the collaboration's Greek contact person, Evangelos Gazis, before visiting the ATLAS cavern and the LHC tunnel. (CERN-PHOTO-201405-095 – 27)

19/05

The European Commissioner for Research, Innovation and Science, Máire Geoghegan-Quinn, toured the CMS experimental cavern as part of a visit in which she also met Marie Curie fellows. (CERN-PHOTO-201405-103 – 29)

21/05

Philippe, King of the Belgians, left, toured the LHC tunnel with Frédérick Bordry, CERN's Director for Accelerators and Technology, centre (pointing), and Nobel laureate François Englert, right. (CERN-PHOTO-201405-109 – 23)

31/05

CERN took part in the parade celebrating the bicentenary of Geneva's integration into the Swiss Confederation, with a superconducting magnet from the LHC travelling through the city's narrow streets on a 20-m long lorry. (CERN-PHOTO-201406-113 – 35)

07–17/09

07–17/09

Student teams from Greece and the Netherlands — the winners of CERN's first 'Beamline for schools' competition (see p. 33) – came to CERN to work on their experiments in a test beam. (OPEN-PHO-LIFE-2015-007)

10–11/10

Tom Kibble — a contributor to the part of the Standard Model that gives mass to fundamental particles through interactions with the so-called Higgs boson — visited CERN. He saw the LHC experiments, CMS (here) and ATLAS, for the first time. (CMS-PHO-PUBLIC-2014-009 – 8)

14/10

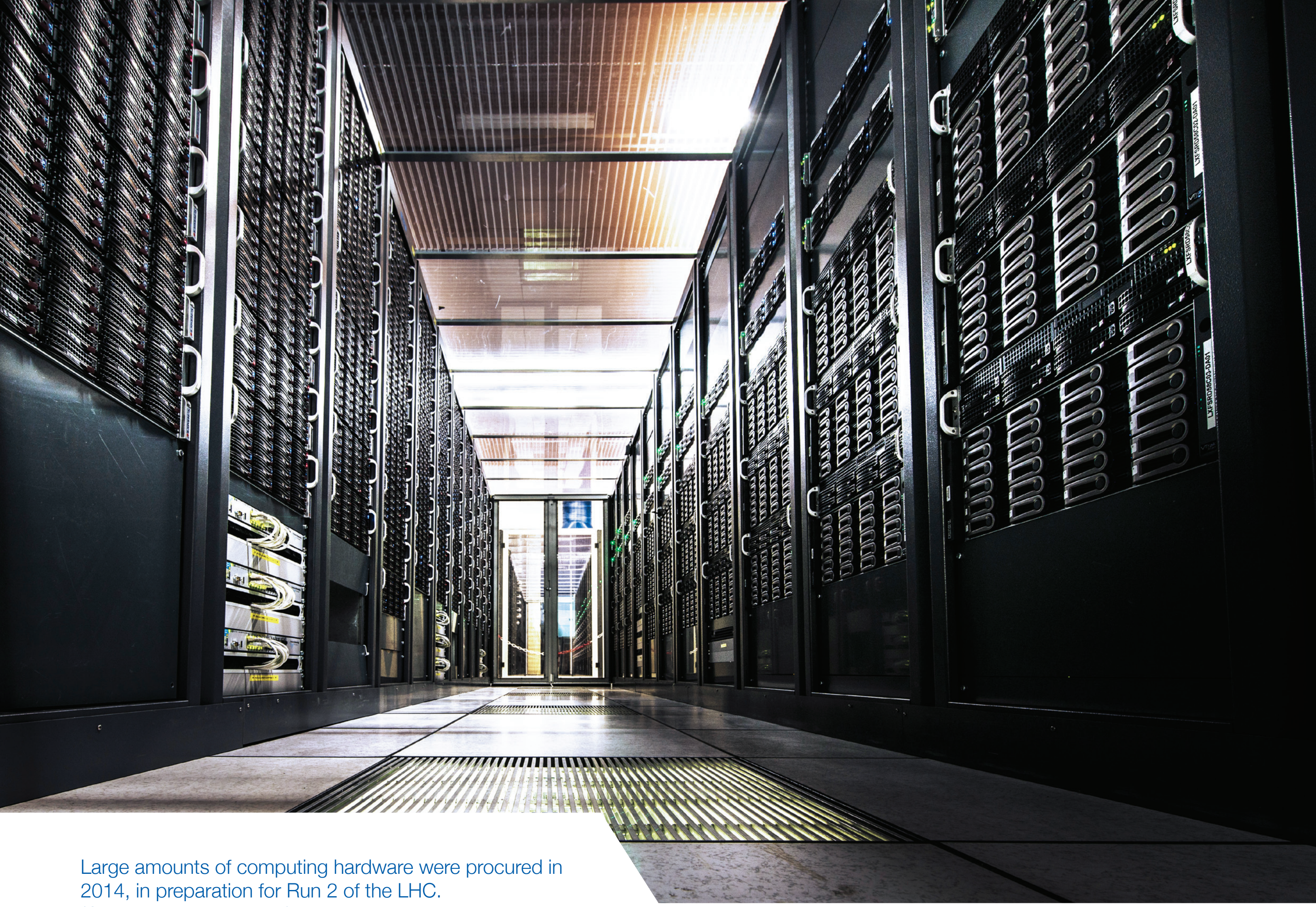
The President of Bulgaria, Rosen Plevneliev, seated, signed the CMS guestbook during his visit to the CMS experimental cavern, accompanied by the collaboration spokesperson Tiziano Camporesi. (CERN-PHOTO-201410-205 – 34)

24/10

The visit of the President of Ecuador, Rafael Correa Delgado, left, included a tour of the ATLAS experimental cavern, accompanied by the collaboration spokesperson, Dave Charlton. (CERN-PHOTO-201410-216 – 12)

04/11

At its 173rd closed session, CERN Council elected Fabiola Gianotti, left, as the Organization's next Director-General. Her five-year mandate will begin on 1 January 2016. (CERN-PHOTO-201411-224 – 4)



Large amounts of computing hardware were procured in 2014, in preparation for Run 2 of the LHC.
(CERN-IT-1209226 – 01)

Computing

New run, new models

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 LS1. Large-scale tests in 2014 validated these changes. The experiment collaborations also invested significant effort to improve the performance and efficiency of their core software, with extensive work to validate the new software and frameworks in readiness for the expected increase in data.

To optimize computing and storage resources in Run 2, the experiments have adopted new computing models, in which they move away from the strict hierarchical roles of the Tier-1, -2 and -3 centres described in the original WLCG models, and make more effective use of the capabilities of all sites. This is coupled with significant changes in data-management strategies, away from explicit placement of data-sets globally to a much more dynamic system that replicates data only when necessary. Remote access to data is also now allowed under certain conditions. These ‘data federations’, which optimize the use of expensive disk space, are possible because of the excellent networking capabilities made available to the WLCG over the past few years.

To improve software performance, a major new long-term activity has been initiated: the HEP Software Foundation. This seeks to address the optimal use of modern CPU architectures and encourage more commonality in key software libraries. The initiative will provide underlying support for the significant reengineering of experiment core software that will be necessary in the coming years.

Increasing computing capacity

The IT Department regularly makes large purchases of computing and storage servers to replace ageing hardware and to increase the capacity available to the LHC experiments. However, 2014

The CERN team receiving the Superuser award at the OpenStack summit in Paris. (OpenStack)

was exceptional as the experiment collaborations had requested a doubling of capacity before the start of Run 2. This meant the procurement of some 100 petabytes (PB) of disk storage and almost 60 000 new cores.

This was a major challenge for the procurement team and for operations teams both at CERN and at the Wigner Data Centre in Hungary, where about half of the computing capacity and two thirds of the storage capacity has been installed. Four large tenders were initiated resulting in eight contracts: three for computing and three for disk-storage servers, one for intelligent power-distribution units and one for a blanket contract to allow for the purchase of more specialized configurations. Additionally, the Communication Systems Group organized a tender for the purchase of the switches necessary to connect all of this equipment to the CERN network.

Virtual machines and storage

OpenStack is an open-source software project that provides on-demand cloud computing. At CERN, the IT OpenStack service enables users to request virtual machines and storage in a few minutes, either through a web portal or from applications. It also provides the computing infrastructure powering most of the grid services and enables efficient management of the increased computing capacity installed for Run 2.

With around 10 000 virtual machines, more than 1000 people use the OpenStack cloud for many different purposes, including production IT services, compute and analysis applications, and personal test and development servers. In addition, the LHC experiments have deployed OpenStack on their high-level trigger farms for use when the accelerator is not running.

At the OpenStack community summit in Paris in November, the OpenStack Foundation presented CERN with the first Superuser award in recognition of the team's contribution to the OpenStack community.

Software-defined storage

Having significant data-storage requirements, CERN has long been a leader in the field of software-defined storage — a technology that enables the creation of open-source alternatives to traditional high-performance network storage appliances. In 2014, the IT Department's Data and Storage Services Group initiated a close collaboration with Inktank, Inc. (later acquired by Red Hat, Inc.) to evaluate their storage solution, Ceph. The initial objective of this investigation was to build a block storage-service for the CERN OpenStack cloud, but it has since expanded to include research and development of Ceph-based solutions to solve future LHC data-storage challenges.

The IT Department deployed and now operates a 3 PB Ceph cluster, one of the largest in the world. CERN's developers have contributed significant new features to this open-source project, including erasure-coding libraries for efficient use of space and an object-striping library for high-performance data-analysis applications.

Data preservation

Given the long lifetime of the LHC experiments — measured in decades — and the significant volumes of data involved, special attention has to be paid to cost-effective data storage and 'bit preservation'. Here, CERN's unique knowledge and experience in large-scale bit preservation, as well as other areas, allows the Organization to make valuable contributions to the global effort to improve long-term preservation of data.

At CERN and the WLCG Tier-1 sites, data continued to be proactively migrated to new generations of storage media on a regular basis, with 'data scrubbing' occurring in parallel. In January, CERN presented a data-curation cost model based on known industry trends and a simplified estimation of LHC data growth. This has attracted a great deal of attention for non-high-energy-physics data-preservation initiatives and is available for download as an Excel spreadsheet, allowing others to modify the basic parameters and assumptions to suit their needs.

Blue skies ahead for cloud computing

In May 2014, 'Helix Nebula — the Science Cloud Initiative' launched its pioneering cloud-computing marketplace, which offers a first-of-its-kind production service to meet the needs of researchers and facilitate innovation in science. The marketplace delivers easy and large-scale access to a range of cloud-computing services using innovative broker technology. The European Commission's Framework Progamme 7 that supported Helix Nebula finished at the end of 2013. By then, the project had found that the process to procure commercial cloud services is quite different from the existing IT-service procurement models used by many public research organizations. A follow-up Horizon 2020 project was therefore launched in October 2014 with the aim of creating a procurement network of public research organizations. Named PICSE for Procurement Innovation for Cloud Services in Europe, it will investigate the feasibility of joint cross-border pre-commercial procurement and public procurement of innovative services across public organizations.

New times for CERN openlab

CERN openlab is the public-private partnership between CERN and leading IT companies that accelerates the development of cutting-edge solutions for the worldwide LHC community and collaborating research institutes. It completed its fourth three-year phase at the end of 2014. During openlab IV, the CERN openlab partners had addressed topics crucial to CERN's scientific programme, such as cloud computing and storage, data analytics, the next generation of computer processors, and controls for complex engineering systems.

In May, together with a number of European laboratories and leading IT companies, CERN openlab published a whitepaper on future IT challenges in scientific research. This gives a detailed overview of the potential future needs of IT infrastructures supporting a wide range of scientific research fields, and serves as the basis for the fifth phase, openlab V.

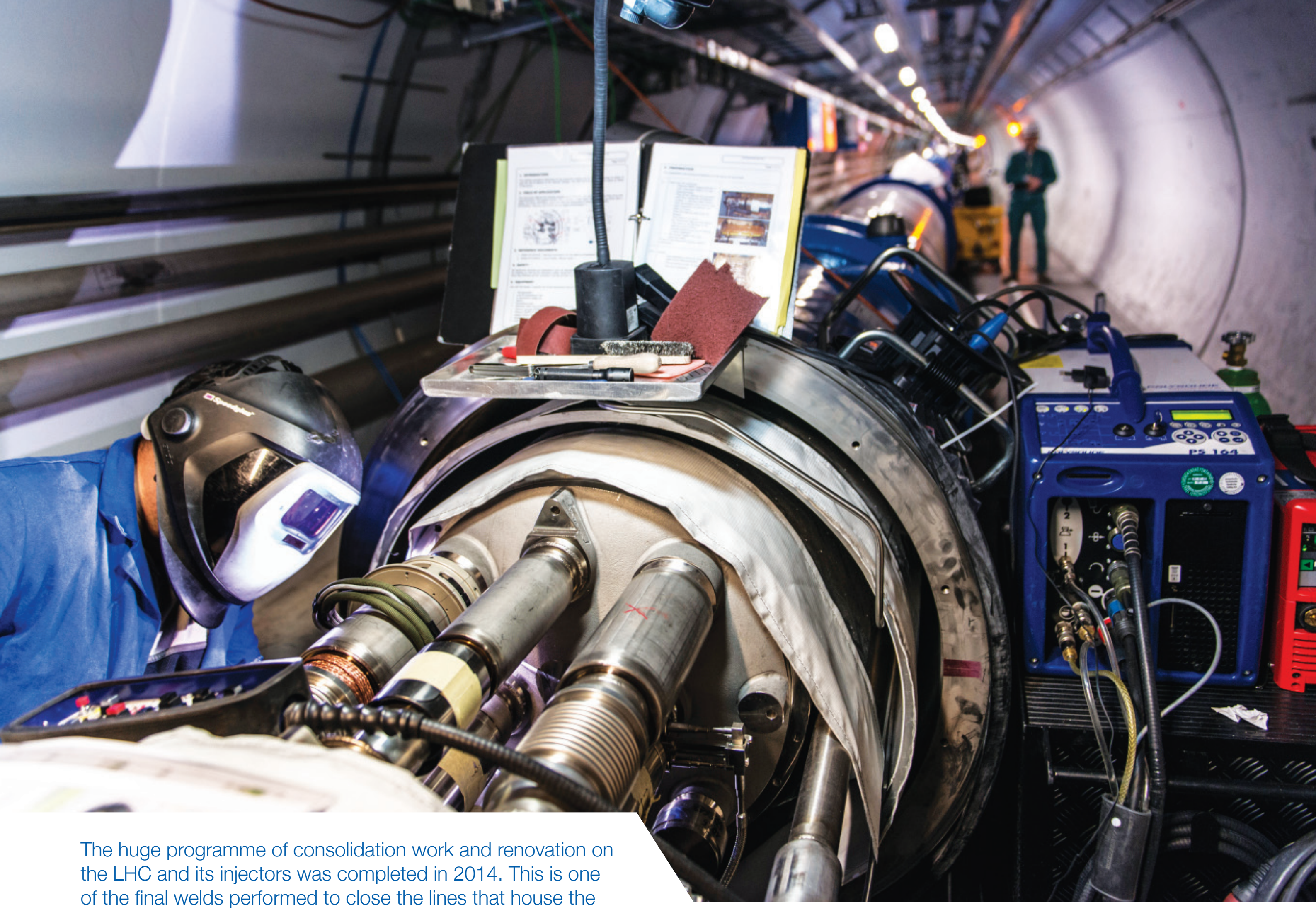
As part of its extended support for more scientific research areas, CERN openlab hosted a major workshop on IT in healthcare. In addition, the summer-student programme continued to go from strength to strength, with 23 students of 17 different nationalities coming to CERN.

Getting connected

To provide reliable network coverage for teams working during LS1, almost 300 Wi-Fi base stations were installed in the LHC tunnel early in 2013. As LS1 began to draw to a close nearly 2 years later, the time came for these base stations to be removed — work that had to be carefully choreographed with the cooling of the magnets.

The installation and removal of the Wi-Fi base stations bookended a complete renovation of the networking infrastructure for the LHC and the experiments. Ageing switches were replaced, with nearly 7500 interconnections remade in more than 300 network starpoints. This upgrade and renewal, together with the installation of 28 new fibre-optic trunks and new uninterruptible power supplies, should improve the reliability and redundancy of the network for Run 2 of the LHC. In addition, the relocation of equipment during LS1 led to the installation of more than 340 km of network cables and the complete remodelling of network installations at five of the eight LHC points.

Other work in 2014 involved a rigorous check of 'the leaky feeder' — a special cable that ensures the distribution of mobile telephony signals in the LHC tunnel. These signals include those supporting the TETRA digital radios for the Fire and Rescue Service. LS1 saw the installation of more than 1300 beacons that work with the TETRA system to locate people in the underground areas. This innovative system led to the award to CERN of two prizes by the international TETRA industry forum.



The huge programme of consolidation work and renovation on the LHC and its injectors was completed in 2014. This is one of the final welds performed to close the lines that house the interconnections between the superconducting magnets. (CERN-PHOTO-201404-084 – 7)

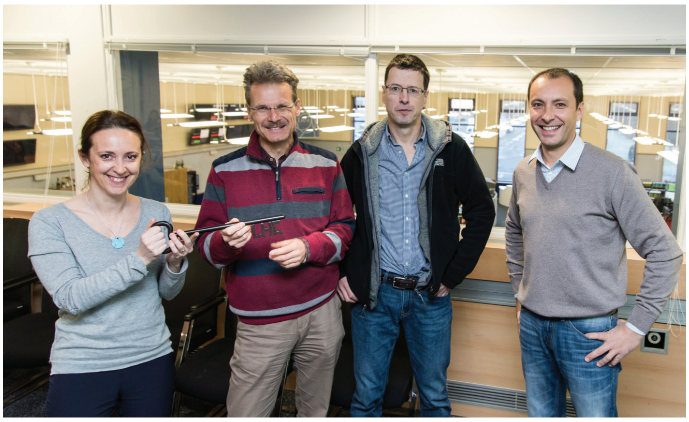
Accelerators

After an 18-month shutdown, CERN's heart began to beat again in late spring. One by one, the accelerators were restarted, pushing particles to the experiments once again. On 2 June, beam returned to Linac 2 and the Proton Synchrotron Booster injector, the first two links in the accelerator chain. Two weeks later, the third machine — the Proton Synchrotron (PS) — received beam. At the end of July, the PS delivered its first particles to the East Area and the n_TOF (neutron time-of-flight) facility, while the PS Booster supplied the ISOLDE nuclear physics facility. The Antiproton Decelerator (AD) was back in action at the start of August, and after several weeks of fine-tuning, the antimatter experiments received their first antiprotons. This included the new BASE experiment, supplied via a successfully commissioned brand-new transfer line. The Super Proton Synchrotron (SPS) was next in line for beam commissioning in mid-September. By the end of the autumn, everything was ready for the start of LHC Run 2 in 2015 and the first beams had been injected into the transfer lines as far as the LHC.

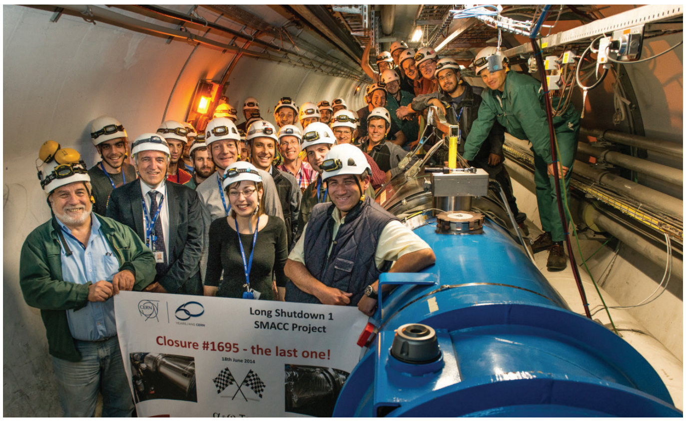
Once the accelerators had been recommissioned, tests for future operations could begin. Over the summer, argon ions circulated through the complex for the very first time, from Linac 3 to the SPS. This new mode of running will supply the NA61/SHINE experiment in 2015, the variety of energies required presenting a challenge.

Chasing clouds

Several days of SPS running were dedicated to beam-induced 'scrubbing'. This process aims to reduce the phenomenon of electron clouds, which destabilize the beam. It involves circulating enough protons in the vacuum tubes to create an avalanche of electrons that inhibits the production of new electrons. The teams tested 'doublet' beams, consisting of pairs of bunches spaced 5 ns apart. After a week of running with these beams, the SPS vacuum chambers were performing well, validating the technique for the LHC run in 2015. The injectors were also trained to produce a new beam structure for the LHC: bunches of protons spaced at 25 ns, as opposed to the previous 50-ns bunch-spacing.



Katy Foraz, LS1 coordinator, hands a symbolic LHC key back to the machine operation teams, represented by Jorg Wenninger, Mike Lamont and Mirko Pojer (left to right). (CERN-PHOTO-201501-002 – 3)



The final interconnection of the LHC superconducting magnets was closed on 18 June, after 14 months of work to reinforce the electrical interconnections. (CERN-PHOTO-201406-127 – 3)

End of a colossal project

The restart of the accelerators followed a race against time to complete the colossal work project associated with the first long shutdown (LS1). CERN and its partners worked for 22 months on the maintenance, consolidation and improvement of the accelerator complex and infrastructures. No fewer than 1600 people were involved in LS1, totalling 3.4 million working hours while maintaining an excellent standard of safety (see p. 37). Coordinating the dozens of work packages in parallel, often entailing complex logistics, required precise orchestration. Even with the addition of some unforeseen work, LS1 finished on schedule.

Renovations were performed on all of the injectors. At the PS, the access control system was modified: the new system separates the accelerator from the transfer line linking Linac 2 and the PS Booster so that work can now be carried out in the PS without having to interrupt the PS Booster. The East Area, which receives test beams for detectors and trial installations, was partially renovated. Part of the infrastructure, the secondary beam-control system and some equipment were either replaced or improved. The DIRAC experiment was dismantled and the space that had housed it was fitted out to welcome two new radiation-hardness test facilities, IRRAD and CHARM. These facilities are designed to study the effect of radiation on detector components and electronic equipment, in particular as part of the Radiation to Electronics (R2E) project. IRRAD allows equipment to be directly exposed to proton beams, while CHARM is capable of producing a wide range of radiation-types and can be used to test particularly large items of equipment. Its installation required 16 000 tonnes of shielding material to be put in place and a new control room to be constructed. A motorized handling system was developed in order to move heavy equipment into the test area.

Significant civil-engineering work was undertaken to repair the tunnel between the PS and the SPS, while major electrical work took place on the surface on the power supply to the SPS magnets. A total of 68 new 2.5-MW transformers weighing 12 tonnes were brought in to replace the old system. During a series of tests, faults were detected in three magnets and in the beam dump. Replacing these very large and heavy components involved some extremely complicated logistics but took just three days to complete.

Close to the accelerator, the beam transfer lines and their tunnel to the North Area were completely renovated, with components of the beam lines, the ventilation water circuits and the lighting replaced. All this was accompanied by a major cabling campaign.

Work was also done at the AD, many of whose components were renovated, consolidated or replaced. An emergency repair was carried out on one essential component, the magnetic horn, which focuses the antiprotons coming from the target. The current transmission system, which transmits electrical pulses of 400 000 A to the horn, was replaced in record time after a series of tests on a specially designed test bench.

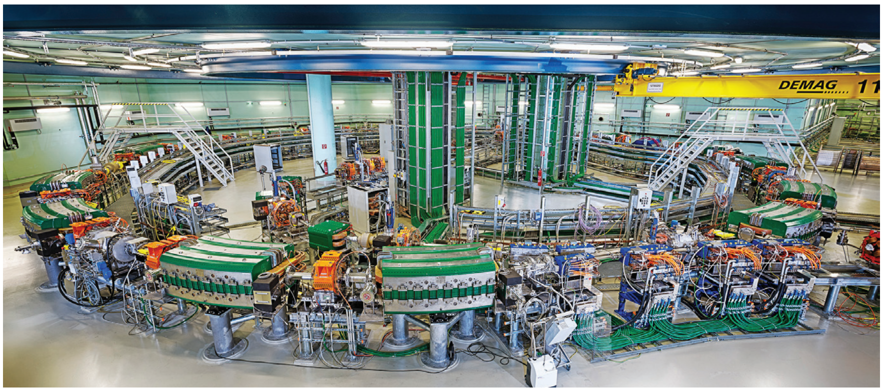
Boosting brainpower

No accelerator was spared from the LS1 work, and neither were their ‘brains’. Across all of the injectors, 90% of the front-end control computers were renovated as part of a five-year upgrade programme. More than 450 real-time control systems were changed and the architecture of the software and hardware was redefined. The recommissioning of the injectors with these new systems was a success, thanks to numerous tests carried out between January and August.

The data collected from the accelerators are processed by the computer centre in the CERN Control Centre (CCC), which, with 350 servers, is the Laboratory's second largest data centre. The electrical and cooling systems were completely redesigned in order to increase the electrical power and cooling capacity, and guarantee redundancy so that the systems can operate without

New beams for medicine

CERN accelerator teams have been contributing to the development of medical accelerators for almost 25 years. The MedAustron project, which accelerated its first beams in 2014, is a shining example of technology transfer from fundamental physics to the field of medicine. MedAustron is a hadron-therapy and research centre near Vienna, Austria, which is due to treat its first tumour patients in early 2016. CERN contributed considerably to the development and construction of the acceleration system for the centre, which is equipped with three ion sources, a linear pre-accelerator and a synchrotron that sends beams to irradiation chambers. For five years, specialists from CERN have been helping to set up and train MedAustron's team of scientists. Together, they designed the accelerator and oversaw the manufacture of its components. The 300 magnets, of 30 different types, were designed and later tested at CERN, having been manufactured at different European sites. The last magnets left CERN for Austria in 2014. The converter control system was also based on CERN technologies and the synchrotron radiofrequency system was developed jointly for MedAustron and the PS Booster. The whole acceleration system was commissioned in 2014. On 6 November, a 250-MeV proton beam was successfully sent to one of the irradiation chambers. This was an excellent result for both the MedAustron and the CERN teams, who will continue to work together to finalize the commissioning of the medical accelerator in 2015.



The synchrotron at the MedAustron medical research and treatment centre in Austria was developed in collaboration with CERN. (Thomas Kaestenbauer)

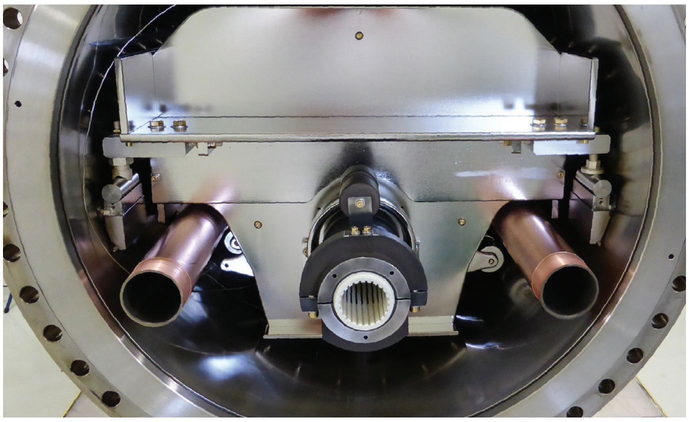
interruption. The new cooling system is fully redundant, as is the new electrical sub-station. Used exclusively to supply the CCC and its computer centre, this was equipped with uninterrupted power supplies and diesel generators. With these upgrades in place, work can be done without interruption.

The end in sight

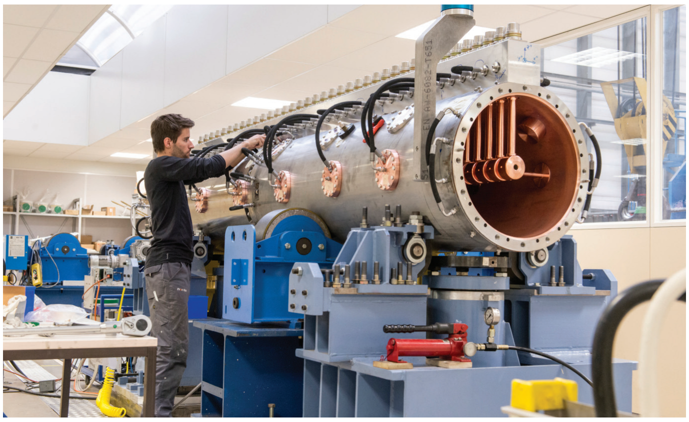
While the injectors were being recommissioned, an immense programme of work was coming to an end in the LHC. In order to circulate 6.5-TeV beams in the accelerator, the 10 170 electrical interconnections between the magnets had to be fitted with copper shunts that provide a low-resistance path for the current in the event of a quench. No fewer than 27 000 shunts were installed. As well as these reinforcements, 3000 interconnections had to be reconstructed and 5000 reinforced insulation units installed around each pair of interconnections. The teams completed this huge undertaking with the closing of the last interconnection on 18 June. Nearly 300 engineers and technicians from CERN, its contractors and partner institutes worked in two shifts for 14 months to achieve this impressive result. The equivalent of 3.3 km of welds were made to close the interconnections, and not a single fault was detected. This work was followed by pressure tests, which were all conclusive, and electrical quality assurance tests. By the end of 2014, five of the eight sectors had undergone these first electrical tests, ready for powering and qualification at an energy of 6.5 TeV. In addition to this work, 20 new collimators with integrated beam-position monitors were installed. The collimators clean the beam of particles that stray from the trajectory. The electrical distribution boxes, which guarantee the transmission of current from the resistive cables to the superconducting cables, were also renovated. The eight kicker magnets, which direct the beam from the SPS transfer lines to the LHC, were all upgraded and recommissioned.

Away from the heart of the accelerators, associated infrastructures, such as the cooling and ventilation system, also underwent major transformations. New cooling towers were installed at three points of the LHC in order to take over from the main towers when maintenance work needs to be done.

After three years of development, the electrical distribution network is now equipped with a new electrical monitoring system. Deploying the system was a painstaking task, since it manages 20 000 electrical and monitoring devices, records 250 000 measurements and comprises 200 synoptics. The new, redundant system will include new tools for simulating or helping to manage power outages. An unexpected breakdown of the electrical network in October provided an opportunity to put it to the test. The system helped the operators to understand



The kicker magnets, which transfer beams from the SPS to the LHC, were upgraded. (OPEN-PHO-ACCEL-2014 – 007)



One of the drift-tube linac (DTL) tanks for Linac4 being prepared at CERN before its installation. (CERN-PHOTO-201404-087 – 1)

the origin of the breakdown and to restore service quickly, thus validating both the tools and the architecture implemented.

All of this work necessitated considerable logistics and handling. The year 2014 saw more than 250 000 operations to transport and move approximately 200 000 tonnes of materials, and the handling equipment itself was renovated. CERN has some 350 overhead travelling cranes; 18 were replaced or renovated and a further 4 new cranes added to the fleet.

While beams were circulating in the injectors, the recommissioning of the LHC began with the cooling of the accelerator. Cooling its 36 000 tonnes of metal to 1.9 K (-271°C) requires 10 000 tonnes of nitrogen and 135 tonnes of helium. It is the equivalent of cooling five Eiffel Towers. In an impressive logistical operation, 520 lorry-loads of nitrogen and helium were delivered. The sectors were first cooled to a temperature of 20 K and then maintained at that temperature for four weeks while further tests of the magnet circuits were carried out (see box p. 20), before the temperature was taken all the way down to 1.9 K. All eight sectors were cold by the end of 2014.

Qualified for high energy

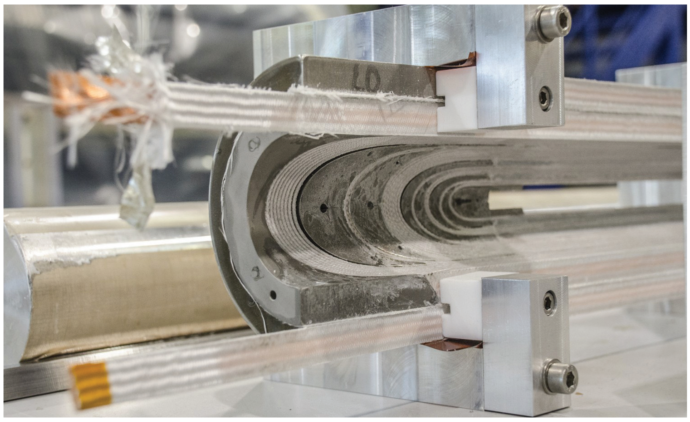
Once the sectors had been cooled, the process to qualify them for the LHC run at 6.5 TeV per beam could begin. For the accelerator to operate at this energy, the currents going through the dipole magnets will need to reach 11 080 A (compared with 6800 A during Run 1). Like athletes, the dipoles have to be 'trained' for such high currents, which entails gradually increasing the current in the magnet coils. The forces generated can cause imperceptible movements, which can sometimes lead to quenches whereby the magnets suddenly enter the conducting state. The operation is repeated several times in each sector until the nominal current is reached. By the end of 2014, one sector had been qualified at 6.5 TeV, following 20 training quenches. The forecast had been 150 quenches across all eight sectors of the accelerator. The recommissioning, at different currents, of all of the other circuits supplying the focusing and corrector magnets, as well as the instrumentation, also began with a total of 1600 circuits to be verified and re-supplied.

Another accelerator also celebrated the arrival of beam in 2014: on 5 August, Linac 4 accelerated a beam to an energy of 12 MeV, qualifying the third element in its acceleration chain. This new linear accelerator, which is scheduled to take over from Linac 2 in 2020, is composed of four types of accelerating structures. It will deliver beams at an energy of 160 MeV, compared to the 50-MeV beams delivered by Linac 2. Having already implemented the first two elements of its acceleration line in 2013, the teams installed a drift-tube linac (DTL) tank and most of the cell-coupled drift-tube linac (CCDTL) structures. The qualification of the first DTL tank on 5 August after the first tests was cause for celebration, as these structures are based on a novel design. In addition, the new ion source was tested at the required current. Components of the 80-m line that will transfer ions to the PS Booster were installed. The difficulty in developing these pieces of equipment comes from the fact that Linac 4 will accelerate negative hydrogen ions (a proton surrounded by two electrons), whereas Linac 2 accelerated protons. The final accelerating structures (the Pi Mode structures, or PIMs) are under construction. The aim is to begin beam-commissioning of Linac 4 in 2016 before connecting it to the accelerator chain in 2018. Preparation of the new injector equipment got under way in order for the PS Booster to be ready to receive new beams.

Projects taking shape

A few metres from Linac 4, the Extra Low ENergy Antiproton Ring (ELENA) was getting off the ground. This circular decelerator measures 30 m in circumference and will begin operation in 2016 and physics in 2017. It will improve the efficiency of the AD by slowing even further the antiprotons sent to the antimatter experiments. The construction of the new building was completed (see p. 36) and the AD kicker generators were moved there to make space in the AD hall for the new decelerator. The

The assembly of the first superconducting cavities for HIE-ISOLDE began in a new clean room. (OPEN-PHO-ACCEL-2015 – 004)



A niobium–tin coil for a testing an 11-T dipole-magnet model for the HL-LHC project. (CERN-GE-1310248 – 02)

technical design report was published in the spring. Numerous technical improvements were made to optimize the machine and its performance. Work on the AD extraction lines got underway with the replacement of the quadrupoles and the construction of equipment for ELENA began.

ISOLDE, CERN's nuclear physics installation, will soon produce radioactive ions at higher energies. A new accelerator, High-Intensity and Energy ISOLDE (HIE-ISOLDE), will ultimately increase ISOLDE's beam energy from 3 MeV per nucleon to between 10 and 15 MeV per nucleon and will quadruple the beam intensity. The installation of this 16-m-long superconducting linear accelerator progressed well. The cryogenics facility, partly inherited from a former experiment, was refurbished and installed. The accelerator will eventually consist of six cryomodules, each containing five superconducting cavities. Twelve cavities were produced and are being assembled in a new clean room and the first segment of the transfer line to the experiments was tested. HIE-ISOLDE will be commissioned in phases: in the first phase, scheduled to take place at the end of 2015, one cryomodule will accelerate beams to an energy of 4.3 MeV per nucleon.

Civil engineering work started for the Advanced Wakefield Experiment (AWAKE), which is scheduled to receive its first beams from the SPS in 2016. AWAKE will study the principle of acceleration using the wakefields in plasma cells. This principle, which has already been established using electrons, will be tested with protons with a view to achieving accelerator gradients hundreds of times greater than those possible using the current radiofrequency cavities. AWAKE will be installed in the tunnel that previously housed the CNGS neutrino facility. The final 100 m of the CNGS beamline were removed and a shielding wall built. Two tunnels were excavated, one to house the laser beam (which will ionize the plasma) and the other for the source and the electron beam (the 'probe beam', which will be accelerated by the plasma). Studies for the development of the electron, proton and laser beamlines made good progress. A prototype plasma cell measuring 3 m is being studied at the Max Planck Institute in Munich.

High luminosity guaranteed

CERN is pushing ahead with its flagship project for the next 20 years — the High-Luminosity LHC (HL-LHC). The project was announced as the top priority of the European Strategy for Particle Physics in 2013 and was included in the Organization's Medium-Term Plan. This new machine is scheduled to be commissioned sometime after 2025 and will increase the number of collisions by a factor of 5 to 10, giving a luminosity of 250 inverse femtobarn (fb^{-1}) per year. In order to attain this level of performance, 1.2 km of the current accelerator will be replaced with new equipment.

The project was launched in 2011 in the framework of a programme funded by the European Union and European, US, Russian and Japanese institutes, among others. It is based on the development of new, more powerful quadrupole magnets to focus the beams before collisions, radiofrequency 'crab' cavities to direct the beams, shorter and more powerful dipole magnets, an improved collimation system and new superconducting electrical connections.

The new superconducting magnets, made from a niobium–tin compound, are being developed within a collaboration between CERN and the US LHC Accelerator Research Programme (LARP), a group of four US national laboratories. An important step was taken by the LARP consortium with the building of a large-aperture quadrupole magnet that generated a magnetic field of more than 12 T. In addition, two short superconducting dipole-magnet models achieved fields of 11 T, at Fermilab and at CERN. A group of international experts selected two prototype crab cavities, which are due to be tested with beam at the SPS from 2016, and the architecture of the collimation systems was finalized. With the increase in luminosity, certain power converters will need to be moved to the surface and connected by superconducting cables dozens of metres long. A new record was set when a magnesium diboride superconducting cable operating at a temperature of 24 K successfully transported a current of more than 20 000 A over a distance of 20 m.

The success of the HL-LHC also relies on the injector chain. The LHC Injectors Upgrade (LIU) project aims to prepare the injectors for high-luminosity runs of the LHC. Together, the LIU and HL-LHC project teams have defined the parameters for the beams of all of the accelerators. Five new radiofrequency accelerating cavities using FineMet® technology, which will perform better at high intensities, were installed in the PS Booster and were tested once beam had returned to the accelerator. FineMet® technology uses a composite magnetic material instead of the traditional ferrite and has the advantage of a wider bandwidth. These tests will be used to decide whether to replace the PS Booster's entire radiofrequency system with this technology. A FineMet® cavity was also installed in the PS in order to evaluate its ability to stabilize beams. The PS was also the subject of studies on 'space charge' effects: at low energies, particles with the same electric charge tend to repel one another, which limits the beam density and therefore the luminosity. The phenomenon of electron clouds (see p. 15) was studied at the SPS, as were vacuum-tube components with the potential to destabilize the beam and a working group was set up to investigate ways of improving their design. Work began on the construction of new equipment, such as new beam-instrumentation tools for the PS and new power amplifiers for the SPS radiofrequency system, which will be installed in a brand-new building on the Prévessin site.

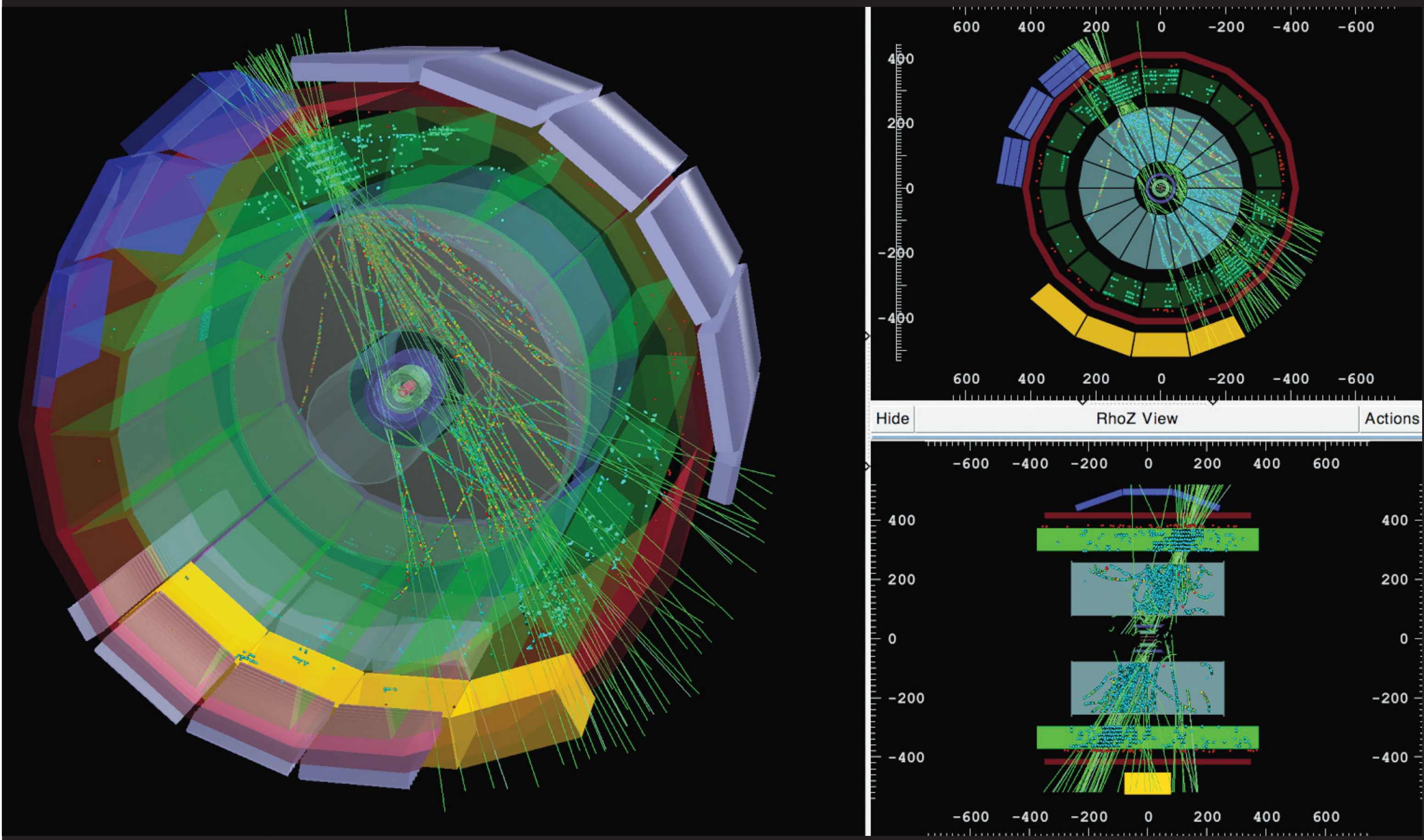
The future is bright

CERN is also preparing the way for the long-term future of particle physics beyond the HL-LHC. The Future Circular Collider (FCC) study, officially launched in 2014, centres on a hadron collider capable of reaching a collision energy of 100 TeV, to be installed in a new 80–100-km tunnel. The study will also investigate the possibility of a lepton collider as an intermediate step as well as a lepton–hadron collider option. It will also consider the installation in the existing tunnel of a high-energy LHC using magnets generating fields of 16–20 T. The FCC study kick-off meeting in February attracted almost 350 participants from 127 institutes, universities and firms from 23 countries. The governance structure for the project was established with the creation of a Coordination Group, comprising experts from around the world, and an International Collaboration Board. By the end of 2014, 43 institutes from 19 countries had officially joined the FCC collaboration and more were preparing to sign agreements. The first studies began on the physics potential and the technical parameters of the machine, and the key technologies were identified. A geological survey of the Lake Geneva region was launched, with new software that can be used to identify the optimal location for the tunnel. A research and development programme for the FCC study is currently being prepared. The aim is to publish a conceptual design study in 2018.

The FCC study is complementary to that for the Compact Linear Collider (CLIC) project, which is another possible future accelerator option. This linear collider is based on an innovative two-beam acceleration concept. The CLIC collaboration includes 50 institutes in 25 countries. Cost and performance-optimization studies were carried out in 2014, with a focus on construction of the machine in three phases with a view to reaching collision energies of 380 GeV in the first phase, then 1.5 TeV and finally 3 TeV. The first complete 2-m-long accelerator module was installed and will start being tested in 2015. By the end of 2014, three klystron test installations were operational. The partner institutes continued to work on instrumentation, magnets and vacuum studies, as well as on control, alignment and stabilization systems. CLIC is also beginning to expand beyond particle physics: high-gradient accelerating structures are also of interest to groups wishing to use compact accelerators for free-electron lasers.

LHC protection put to the test with current

'A more powerful and reliable machine.' With this key principle in mind, the LHC teams carried out numerous tests once the consolidation work had been completed. An innovative test was developed to qualify the machine's quench-protection system. When one of the LHC magnets, each of which transports currents of up to 11 080 A, loses superconductivity (as a result of an instability, for example), the current is immediately diverted to a parallel circuit to avoid a disastrous rise in temperature in the magnet. This circuit consists of power diodes and the new shunts installed on the electrical connections between the magnets to ensure that the LHC can run at 6.5 TeV. The new test, which was validated in 2013, involves testing all of the parallel circuits. To do this, the temperature of the helium is kept at 20 K so that the cables lose their superconductivity. Currents of increasing intensities are injected into the circuits. They naturally travel through the secondary network, thereby testing the reliability of the copper shunts and the magnets' protection diodes. If even the slightest resistance is observed, the current is interrupted immediately. By the end of 2014, all of the dipole circuits had successfully passed the tests.



An event display from the completed ALICE detector with the components installed during LS1, showing a shower of particles produced by a high-energy cosmic muon. (ALICE Collaboration)

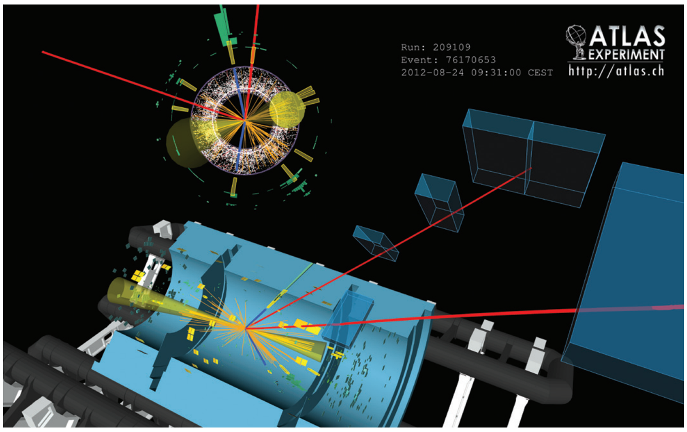
Physics and Experiments

For most of the experiments at CERN, 2014 was dominated by the final stages of the long shutdown and preparations for the gradual restart of the accelerator complex during the autumn, with beams returning to all but the LHC. While some teams worked hard on refurbishment and upgrades, others continued to analyse data from previous runs. In particular, the LHC collaborations still had much to harvest and were able to present many final results from Run 1.

ALICE: the hottest matter

By making precision measurements, the ALICE collaboration aims to answer the fundamental question of what consequences the quark structure of matter has on the behaviour of matter at extreme conditions of temperature similar to those that prevailed in the early Universe. ALICE had already established that matter created in heavy-ion collisions at the LHC has all of the features of a 'perfect' liquid. New insights from detailed analyses in 2014 of the full data set from Run 1 have helped to consolidate this picture. The equations of hydrodynamics describe well the way that the collisions evolve through a phase of freely moving fundamental constituents — 'partons' — to matter consisting of familiar hadrons. The measured final hadronic state is consistent with a statistical model in which the hadrons emerge from a hot 'bath' with a temperature of 155 MeV, although some features remain unexplained.

But what does the partonic phase — the phase known as quark-gluon plasma (QGP) — consist of? To test the possibility that



Display of a candidate event for the decay of a Higgs boson into two electrons and two muons, accompanied by two energetic jets of particles in the forward directions. (ATLAS Collaboration)

hadrons could be produced by the coalescence of quarks in the QGP, ALICE compared the spectra of protons (made of three quarks) and phi-mesons (which have the same mass, but consist only of a quark–antiquark pair). The coalescence model does not predict the observed results and leaves open the question about the composition of the QGP. However, the observation that the J/psi — a charm quark and its antiquark bound together — can be regenerated in the QGP supports the idea that unconfined charm quarks exist within this phase of matter. To gain a deeper insight, ALICE is exploiting the production of jets of particles, which have the potential to reveal what happens within the QGP at a higher resolution. The analysis of data taken in Run 1 offers the promise of future precision measurements in Run 2 and beyond, to answer the question about the makeup of QGP.

The main emphasis of the data analysis in 2014, however, was to investigate whether a droplet of QGP can be created in small systems. The question was triggered by a surprising observation in proton–lead collisions in which many particles are produced. These high-multiplicity proton–lead collisions share with lead–lead collisions most of the features attributed to the collective dynamics of the QGP. Similarly, a feature called the ‘ridge structure’, which is interpreted in lead–lead collisions as a signature of collective behaviour, has been observed unexpectedly in high-multiplicity proton–proton collisions. There is so far no unique interpretation of this observation.

In studies of central proton–lead collisions — where there is the most overlap between the proton and the lead nucleus — ALICE has measured a set of observables that are described well by the collective dynamics of a system in equilibrium. In particular, the composition of the final hadronic state (given by the production rate of the different hadrons) follows the expectation of the statistical model. The measured values of the radial and elliptic flow of identified hadrons with low transverse momentum, together with the size of the hadronic system at ‘freeze out’ (the stage where the hadrons cease to interact), follow the expectations for a system that is expanding collectively. Further measurements showed that the signals for collective behaviour observed in proton–proton and proton–lead collisions evolve gradually with the multiplicity, and approach the values measured in lead–lead collisions. These observations have been possible thanks to the development by ALICE of a new method to determine centrality in proton–nucleus collisions.

A puzzle remains, however: why are the features of jet ‘quenching’ that have been universally observed in heavy-ion collisions not observed in central proton–lead collisions?

The ALICE experiment also underwent an intensive programme of consolidation and improvement during LS1, which allowed the completion of several detector systems as well as preparations for the anticipated increase in LHC luminosity in Run 2.

The five super-modules of the transition-radiation detector that were missing in Run 1, were produced and installed. The coverage of the calorimeter system was increased through the installation of a new dijet calorimeter, back to back with the existing electromagnetic calorimeter, and an extra module was added to the photon spectrometer. A new component, the ALICE diffractive detector, was also installed. This consists of two double layers of shower counters placed far from the interaction region, at 16 m from the collision point in the ALICE cavern and at 19 m in the opposite direction in the LHC tunnel. The gas mixture of 90% neon and 10% carbon dioxide in the ALICE time-projection chamber was changed, with argon replacing neon. This will allow a more stable response at high particle-fluxes without significant degradation in the resolution of the momentum measurement at low values of transverse momentum.

Working together

Combining different analyses leads to higher precision in measurements, and the year 2014 saw the different experiments at the LHC get together in some key areas of physics. In this way, collaborative hard work by ATLAS and CMS to combine analyses resulted in the best precision so far for the mass of the Higgs boson.

Another highlight was the combination of measurements by CMS and LHCb of the decays to muons of two neutral B mesons, $B^0_s \to \mu\mu$ and $B^0 \to \mu\mu$. (These related particles consist of a b quark bound with an s quark, in B^0_s, or a d quark, in B^0.) This is a golden channel in the search for new physics, as both decays are heavily suppressed in the Standard Model; the hunt for small deviations from predictions continues.

The strengths of the CMS and TOTEM experiments were combined in a joint analysis of charged particles produced in proton–proton collisions and set a milestone for future common measurements.

The readout electronics of all of the detector systems was adapted to work at an increased speed. Together with a complete upgrade of the data-acquisition and high-level trigger computer clusters, this will allow ALICE to exploit fully lead–lead collisions at a rate as high as 10 kHz in Run 2.

For the longer term, and particularly the HL-LHC project (see p. 19), a vigorous upgrade programme has begun. This will dramatically enhance the performance of the ALICE detector systems in the charm and beauty sectors and also cope with the future high luminosities that will require readout rates of up to 50 kHz for lead–lead collisions. In 2014, the LHC Committee approved two Technical Design Reports, one for a new internal tracking system and one for new electronics. Other reports for a new muon forward-tracker, for the upgrade of the time-projection chamber and for a new online/offline computing system were prepared for approval in 2015.

ATLAS: many results

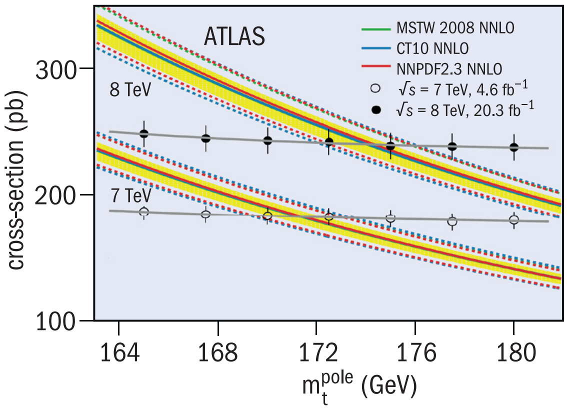
The main theme for ATLAS was to extract the maximum possible information from the large data sets from Run 1, before Run 2 takes over in 2015. After establishing the main properties of the Higgs boson and observing its bosonic and fermionic couplings in 2013, further insights came from a new set of measurements of the two high-resolution decay channels to two photons and to four charged leptons (see figure opposite). As well as providing more precise results on the Higgs boson's mass and its couplings, these measurements shed light on the various mechanisms that produce the boson in proton–proton collisions. ATLAS also firmly established the existence of the decay of the Higgs boson to two W bosons and measured the corresponding signal strength with a precision of about 20% — an important step towards gaining a complete picture of the Higgs boson's properties. No deviations from the predictions of the Standard Model have appeared so far in these investigations.

Extensive investigations of the Standard Model continued in 2014 with many new results, including the most precise measurements to date of the production rate of top quarks, with an uncertainty of around only 4%. These results agree well with theoretical predictions and can be used both to determine the mass of the top quark to good precision (see figure p. 24) and to limit the room for additional production of top quarks through processes linked to physics beyond the Standard Model, such as supersymmetry.

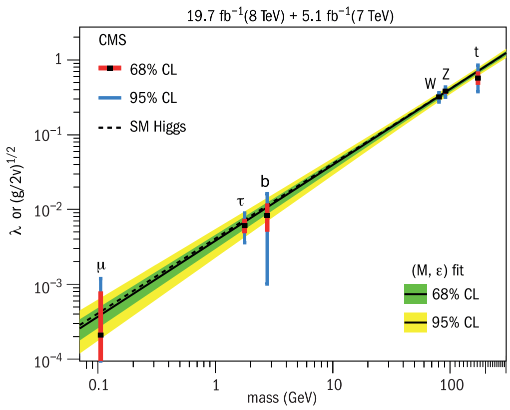
Measuring the couplings of the W and Z bosons to each other is an important test of the underlying electroweak model, which may reveal contributions from anomalous couplings and therefore point to new physics. The corresponding processes are, however, extremely rare and their observation has become possible only recently with the large centre-of-mass energy and luminosity provided by the LHC. ATLAS has extracted the purely electroweak contribution to the production of a Z boson and two jets of particles, which includes the process of weak-boson fusion, $WW \to Z$. The results are in good agreement with the Standard Model.

The many other results from ATLAS in 2014 included the rate for producing W bosons in conjunction with jets, and a very precise determination of the total probability for proton–proton interactions at the energy of Run 1, using the ALFA detectors in ATLAS. There were also new results on the collisions of protons and lead ions, using the production of jets to shed light on the geometry of such proton–nucleus collisions.

Searches for new particles or phenomena continued unabated. ATLAS took the search for supersymmetry into new areas by looking for events with two or three leptons together with missing energy, which could signify an undetected supersymmetric particle. The search found no significant excess beyond the expectations of the Standard Model in either case. This null result



Measurements by ATLAS of the top-pair production probability (the cross-section) at centre-of-mass energies of 7 and 8 TeV, compared to theoretical predictions from quantum chromodynamics as a function of the top-quark mass.



Measurement by CMS showing how the coupling of other particles to the Higgs boson increases with the mass of the particles.

can be used to narrow down the region where supersymmetry might exist in nature. Many more searches looked for new particles in a variety of scenarios, but no hints of new physics were found, thereby severely constraining models that predict exotic particles and phenomena.

The year also saw the completion of the intensive programme of detector maintenance, consolidation and upgrades that ATLAS underwent during LS1, with full-scale commissioning for Run 2 starting towards the end of the year. The Insertable B-Layer was installed inside the pixel detector to enhance its capability to identify and 'tag' heavy quarks in dense jets of particles. A series of commissioning weeks throughout the year sought to reintegrate all of the components of ATLAS and to begin rehearsing data taking at a rate of 100 kHz at the level of the first trigger, compared with 75 kHz in Run 1. This trigger now has new capabilities, notably the possibility to select events at this early stage according to their topology, rather than just to count objects. There have also been major improvements in the offline software, increasing the speed of event reconstruction by a factor of three, in preparation for a full exploitation of the LHC's enhanced performance after LS1.

CMS: high precision

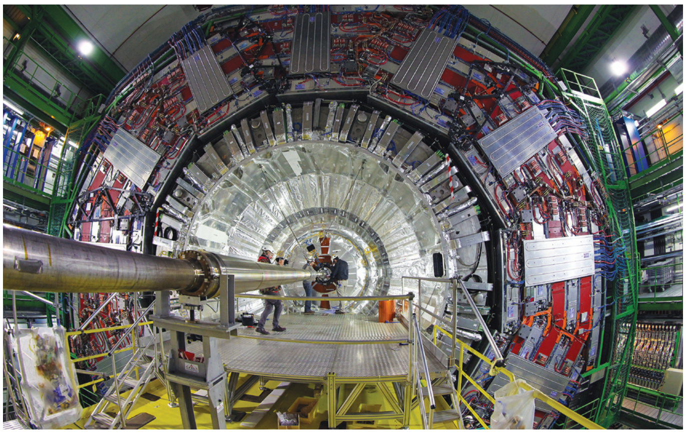
Intense scrutiny of the Higgs boson is one of the highest priorities for the physics programme and 2014 saw remarkable progress not only in finalizing the analyses for Run 1 but also in combining them to reach higher precision. Following the publication of results on the Higgs boson's dominant decay channels, such as the two-photon channel, the addition of decays into tau leptons and into b quarks was a major accomplishment, leading to strong evidence for fermionic decays. Another highlight was CMS's new bound on the Higgs boson's decay width, which improved by more than two orders of magnitude on the previous measurement. Other studies nicely confirmed the Standard Model's expectation that the coupling strength of the Higgs boson to other particles should increase with the mass of the particles (see figure above right).

The first combined results on the Higgs boson published by CMS incorporated all of the main channels analysed with the full data set from Run 1. Combining the search for Higgs bosons produced in association with top quarks with other analyses revealed an interesting deviation of about 2 sigma (σ) from the expectations of the Standard Model — a result that offers good prospects for gains in sensitivity in the future. CMS also extended the search for Higgs bosons all the way up to the scale of tera-electron-volts. Through combinations of all of the searches, CMS is interpreting the data at these high masses in the context of models with new physics and setting limits on potential discoveries.

While 'standard' searches for supersymmetric particles and, for example, dark matter are intensively pursued, other searches often employ the Higgs boson as a 'scout' for signs of new physics. This technique allowed CMS to set several exclusion limits, but produced no evidence for dark matter or other new particles. Nevertheless, several new analyses are under way to investigate remaining unexplored corners.

High-precision measurements in the physics of the Standard Model led to exceptional results. Here the top quark, the heaviest elementary particle, continued to be the main focus of attention. The historic combination of results from the LHC and from Fermilab's Tevatron announced in March provided a world average for the mass of the top-quark, but this was soon superseded by a new measurement by CMS, which on its own had even higher precision. CMS also released many results for heavy-ion physics — some unique in the field — and presented the highlights at the major Quark Matter 2014 conference.

To prepare for the new data to come in Run 2, CMS performed two intense campaigns. The Computing, Software and Analysis exercise, CSA14, generated valuable feedback to the teams



CMS ready to close, showing the beam-pipe and the extensive new environmental seal. (CMS Collaboration)

working on computing, software, validation and physics analysis. The second exercise, PHYS14, successfully targeted the readiness of high-priority analyses for the first inverse femtobarn of Run 2 data.

A big effort on the CMS Upgrade Project made substantial progress towards the Technical Proposal. This work demonstrated the need for Phase 2 of the upgrade, by fully simulating the detector for Phase 1 (including assumptions on how it will age), evaluating the expected performance of the Phase 2 detector, and expanding the physics goals to exploit fully the potential of the HL-LHC project (see p. 19).

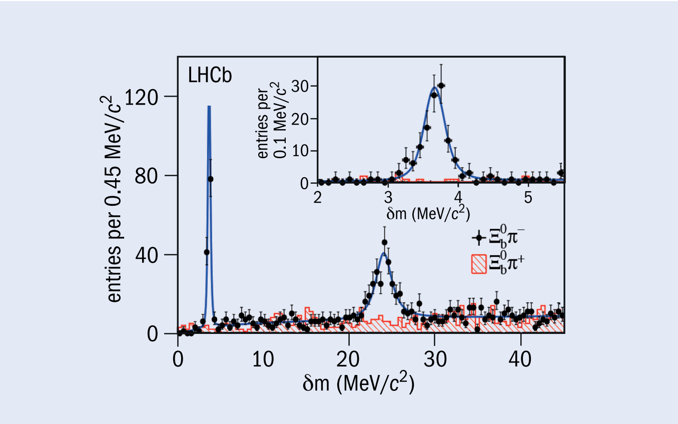
The main objectives of the LS1 programme were also completed in 2014, some even ahead of schedule, allowing time to resolve problems that surfaced during the shutdown. Challenges arose from unforeseen failures in the pixel detector and in the pre-shower detector of the electromagnetic calorimeter, but were successfully overcome. Particularly important objectives included: the installation of an extensive new environmental seal to enable the tracker to operate at a much lower temperature than in Run 1, and so prolong its lifetime in the increasing beam intensities of Run 2; the installation of the beam-pipe for Phase 1 of the upgrade; and the installation and commissioning of muon chambers to complete the original design. The replacement of the photon-detectors in the outer layer of the hadron calorimeter was successfully completed, together with major improvements in common systems and infrastructure. There were also major upgrades for the trigger and data-acquisition systems to guarantee the highest benefit from the unprecedented high-energy, high-intensity data taking anticipated in Run 2, with final preparations taking place in various campaigns and extended runs with cosmic rays.

B for beauty

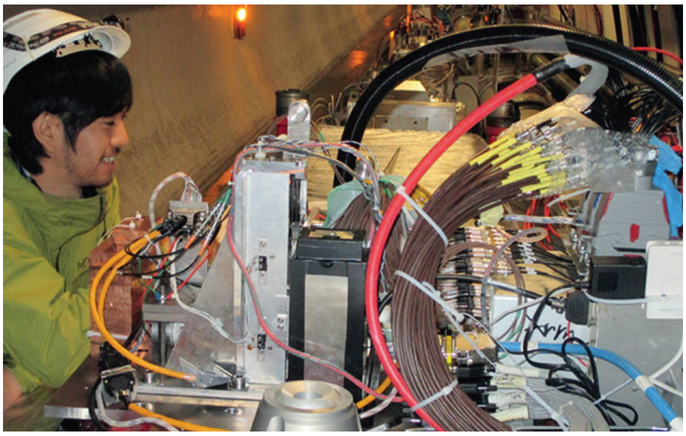
The LHCb experiment makes precise studies of particles containing beauty (b) or charm (c) quarks. It focuses on rare decays and on CP violation — a difference in behaviour between particles and their antiparticles. These are phenomena that are sensitive to new physics through quantum effects. Throughout 2014, the LHCb collaboration continued to analyse the data collected in Run 1, making great progress on benchmark measurements.

One of the most eagerly awaited measurements concerned the complete analysis for Run 1 of φ_s, the CP-violating phase-angle related to the interference between the decay and 'mixing' of the B^0_s meson with its antiparticle. This is an interesting place to search for new physics because the prediction of the Standard Model for φ_s is extremely small and precise, but new physics could enhance its value. The result $\varphi_s = -0.010 \pm 0.039$ radians is the most precise to date and is in very good agreement with the Standard Model. Another notable result is LHCb's precise measurement of the weak phase γ — one of the angles of the Cabibbo-Kobayashi-Maskawa triangle that links the interactions of the six quarks of the Standard Model. For the first time a single experiment has achieved a precision of better than 10^o.

Another interesting result concerns the ratio R_K of the probabilities that a B^+ meson decays to $K^+\mu^+\mu^-$ or to $K^+e^+e^-$. These very rare decays occur just twice in 10 million events ($2x10^{-7}$); they are driven by transitions between b and s quarks ($b \rightarrow s$) that are highly sensitive to the effects of particles that exist only in extensions to the Standard Model. In the Standard Model this ratio is expected to be very close to 1 thanks to 'lepton universality', according to which electrons (e) and muons (μ) behave in an identical manner. LHCb measured R_K to be different from 1 with a significance of 2.6 σ, which, if confirmed, may be a sign of non-universal lepton interactions. Another $b \rightarrow s$ process, the decay $B \rightarrow K^{*0} \mu^+\mu^-$, also exhibits a significant discrepancy in one angular observable (referred to as P_5') compared to predictions from the Standard



LHCb's evidence for two new particles, Ξ'^-_b (the first peak) and Ξ^{*-}_b (the second peak), seen through their decay to $\Xi^0_b\,\pi^-$. δm is the difference between the mass of the $\Xi^0_b\,\pi^-$ pair and the sum of the individual masses of the Ξ^0_b and π^-.



LHCf's Arm1 detector. (T Sako)

Model, provoking considerable discussion in the particle-physics community.

The large samples of decays allow detailed studies of particles produced in different decay channels. LHCb has, for example, published results that for the first time unambiguously demonstrate that certain hadrons, in this case the Z(4430), have an exotic nature that cannot be accommodated in the simplest form of the quark model. The collaboration has also shown that a $\bar{D}^0K^-$ structure with a mass of 2860 MeV is composed of two resonance states, one with spin 1 and the other with spin 3. This is the first time that a spin-3 particle involving heavier quarks has been observed and should lead to new insights into the spectroscopy of hadrons. Another interesting result is the discovery of two new particles, the Ξ'^-_b and Ξ^{*-}_b. Predicted to exist by the quark model, they are both baryons containing three quarks, in this case, b, s and d. By observing these particles and measuring their properties with great accuracy, LHCb is making a stringent test of models of low-energy quantum chromodynamics (QCD).

The programme to measure benchmark processes is facilitated by the excellent calibration of the luminosity that the experiment has achieved. The relative precision is 1.12%, which is the best obtained at the LHC, and the most precise luminosity measurement achieved so far at a hadron collider operating with bunched beams. In early 2013, LHCb successfully collected data in the run with lead ions, making the first observation of the production of Z bosons in proton–lead collisions, at a centre-of-mass energy per proton–nucleon pair of 5 TeV.

The approved upgrade for LHCb, to be installed during the second long shutdown of the LHC, will increase the experiment's data-taking capacity by an order of magnitude. During 2014, the collaboration approved the choice of technology for the three tracking stations behind the magnet, giving the go-ahead for the construction of a full fibre-tracker.

F for forward

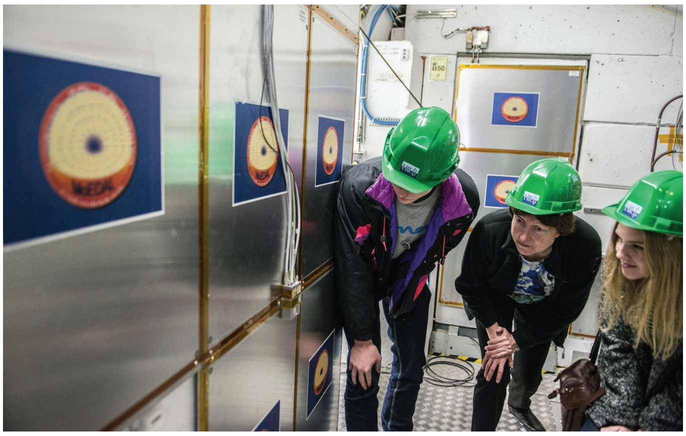
The Large Hadron Collider forward (LHCf) experiment measures neutral particles emitted at around 0° to the collisions in the LHC. These 'forward' interactions are important for the understanding of what happens when high-energy cosmic rays collide with the atmosphere. The collaboration published results on neutral pions obtained during proton–lead running in 2014. They also completed the upgrade to radiation-hard detectors. The new detectors were tested at the SPS in October before installation in the LHC tunnel, 140 m on either side of the interaction point in ATLAS. The two collaborations — LHCf and ATLAS — have started discussions on common data taking and analysis to study forward particle-production.

M for monopoles

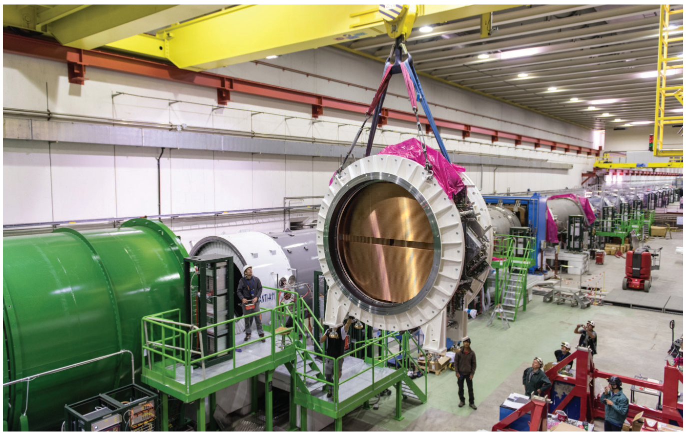
MoEDAL, the Monopole and Exotics Detector At the LHC, is designed to search for highly ionizing particles that are manifestations of new physics, such as magnetic monopoles and massive long-lived charged particles. The collaboration made substantial progress in 2014, including the publication of a paper describing MoEDAL's physics programme, which includes more than 30 discovery scenarios. The innovative MoEDAL detector was installed for the first time in the winter of 2014 for data taking in 2015. This largely passive device consists of an array (100 m^2) of plastic nuclear track detectors, which acts like a giant camera sensitive only to new physics. In addition, MoEDAL's 1-tonne Trapping Array is able to capture the high-ionizing particles associated with physics beyond the Standard Model. The radiation environment is monitored by a state-of-the-art real-time TimePix array of pixel detectors.

T for total

The TOTEM experiment, which cohabits with CMS at Point 5 on the LHC, is optimized to make precise measurements of particles that emerge from collisions close to and along the direction of the



Teacher Becky Parker, centre, at Point 8 with two members of the MoEDAL team from Simon Langton Grammar School for Boys, which joined the collaboration in 2014. (CERN-GE-1311279 – 11)



The final straw-tracker module, weighing close to 5000 kg, is lowered into position in NA62. (CERN-PHOTO-201409-176 – 4)

LHC beams. In 2014, the analysis of data collected during special runs in 2012 found surprising evidence for non-exponential behaviour in elastic proton–proton scattering at a centre-of-mass energy of 8 TeV. Previous measurements were not able to show such an effect.

In preparation for Run 2, TOTEM completed the consolidation and upgrade of the Roman Pots — devices that allow detectors to be brought very close to the beam. This included the addition of new cylindrical Roman Pots dedicated to high-precision timing detectors for high-luminosity running. The collaboration also produced a detailed upgrade proposal and Technical Design Report (TDR) for timing measurements, and has written a common TDR with CMS. The documents, endorsed by the LHC Committee, describe the consolidations and upgrades in view of the updated physics goals for Run 2.

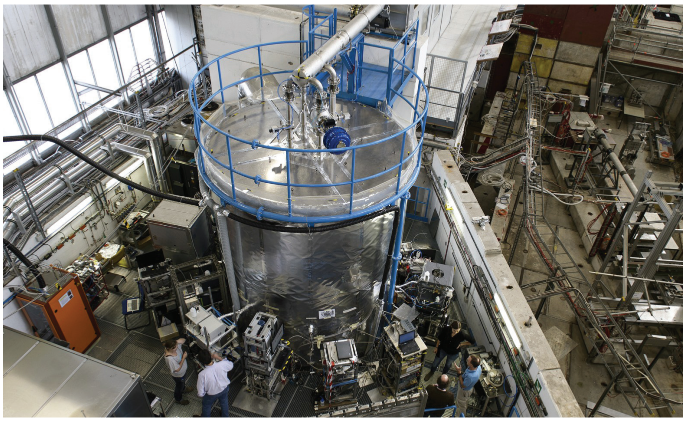
Beams from the SPS

In October, the SPS began once again to deliver protons to experiments in the North Area (NA) at CERN's Prévessin site. The COMPASS experiment (NA58) completed preparations for data taking in 2015, when the collaboration will study what happens when a 190 GeV beam of pions interacts in a transversely polarized ammonia target. The goal is to measure for the first time how the polarization of the protons in the target affects the production of pairs of muons in the reaction $\pi^- p \rightarrow \mu^+\mu^- X$. The complex modifications to the beamline involved moving the world's largest target of polarized protons and its superconducting magnets by 2 m in order to make room for a thick absorber consisting of tungsten, alumina and concrete. This stops all particles except muons (and neutrinos), but it also generates many low-energy particles, making reconstruction of the events more difficult. The two-month pilot run in 2014 allowed commissioning of the new setup, but without the target being polarized yet.

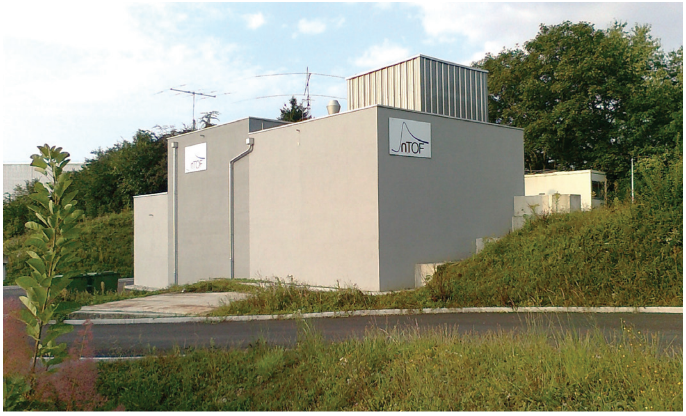
The NA61/SHINE experiment uses beam from the SPS to investigate under what conditions and how the quarks and gluons that are normally confined inside hadrons can form quark–gluon plasma — a medium in which they move freely. In 2014, the collaboration released its first results from scans through SPS energies of proton–proton and beryllium–beryllium collisions. Surprisingly, the proton–proton collisions show changes with energy similar to those that were associated with the onset of deconfinement in lead–lead collisions in NA49, an earlier experiment at the SPS. On the other hand, results from both proton–proton and beryllium–beryllium collisions showed no signs of the hypothesized 'critical point', beyond which the confined and deconfined phases of matter would transform between each other seamlessly.

With the return of beam to the SPS, NA61/SHINE was able to commission various upgrades to the beamline, the detectors and the analysis software, which had been undertaken during LS1. In addition, CERN's Research Board approved an extension of NA61/SHINE's physics programme to include measurements of hadron production to provide data for the modelling of neutrino beams in ongoing and future experiments at Fermilab.

The new NA62 detector took its first beam from the SPS in October. In early September, the last of the four 'straw-tracker' chambers had been lowered into position in the experiment. Each of these chambers consists of 16 layers of highly fragile, gas-filled tubes — straws — which detect charged particles as they pass through. The NA62 straw tracker is the first of its size to be placed directly into the vacuum tank of an experiment, allowing the direction and momentum of charged particles to be measured with high precision. The experiment's main aim is to explore distances as small as 10^{-21} m, using very rare decays of kaons.



The CLOUD experiment. (CERN-EX-1310264 – 02)



The new EAR2 building for the n_TOF neutron source. (OPEN-PHO-CIVIL-2015-002 – 1)

The NA63 experiment studies quantum effects in interactions with strong electromagnetic fields that occur when high-energy particles pass through thin amorphous and crystalline targets. In 2014, members of NA63, together with physicists from the CLIC study (see p. 20), published calculations for the phenomenon of 'beamstrahlung', based on comparisons with data from NA63. Beamstrahlung is a limiting factor in studies for next-generation electron–positron colliders, such as CLIC. It occurs when particles in one high-energy bunch 'see' a strong electric field from the opposing bunch, leading to the emission of intense radiation. The strength of these fields may lead to undesirable effects such as the loss of beam polarization and/or more diffuse beams. Conversely, as other members of NA63 have shown, the polarization effects of the extremely strong fields may allow a test of the phenomenon known as vacuum birefringence.

Beams from the PS

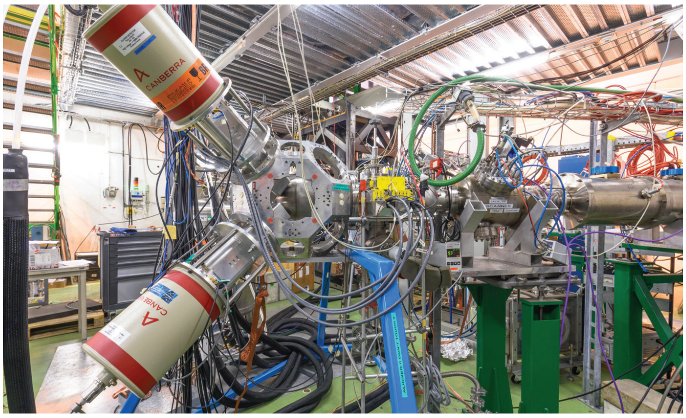
The CLOUD experiment is tackling one of the most challenging problems in atmospheric science — understanding how new aerosol particles are formed in the atmosphere and the effect that these particles have on climate. In particular, using a beam from the PS, CLOUD is studying whether the formation of aerosol particles is enhanced by ionization from galactic cosmic rays. In experimental studies published in *Science* in May, CLOUD showed that oxidized biogenic vapours form new particles with sulphuric acid and that this process can explain a large fraction of particle formation observed in the lower atmosphere. The CLOUD team also reported on global modelling studies that establish that trees play a fundamental role in forming new particles in the atmosphere, familiar as 'blue haze' when viewing distant mountains.

The DIRAC experiment, which ran at the PS during 2007–2012, has measured the lifetimes of unusual 'atoms' — $\pi^+\pi^-$ and πK — to check the low-energy predictions of QCD for light quarks. These lifetimes may be expressed as a known linear function of two scattering 'lengths', which characterize the interaction. Through continuing analysis in 2014, the DIRAC collaboration made the first measurement of the lifetime of the πK atom. Further analysis also revealed the first observation of long-lived $\pi^+\pi^-$ atoms, with a significance larger than 7σ. This gives access to an additional linear function of scattering lengths, and hence to a measurement of individual scattering lengths.

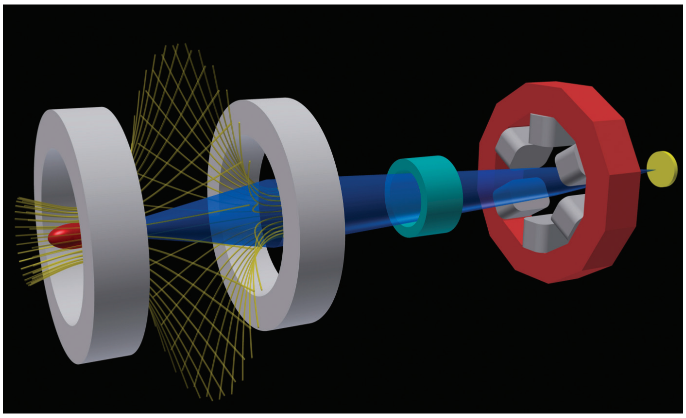
The neutron time-of-flight facility, n_TOF, provides pulsed beams of neutrons produced by the interactions of protons from the PS with a lead target. The neutrons are collimated and guided through evacuated beam tubes to two experimental areas, EAR1 and EAR2. EAR1 is located horizontally at approximately 185 m from the target, while EAR2 is situated vertically at about 20 m. The newly constructed second area, EAR2, received its first neutron beam on 25 July. The beam here complements and runs in parallel with the existing area, EAR1. The physics programme in EAR1 included measurements of neutron-capture on germanium-73 and on the radioactive thulium-171. EAR2 saw the first part of the commissioning of the new beam line, as well as a real experiment, at the end of the year, on the fission cross-section of plutonium-240. This cross-section was measured in the past in EAR1, during an experimental campaign spanning more than 2 years, where the high activity of the samples had a negative impact on the operation of the detectors and the data analysis. In EAR2, the measurement was successfully completed after 6 weeks, thanks to the higher neutron flux and the much higher neutron rate, which allowed the cross-section to be measured in the sub-threshold region as well. This clearly demonstrated the feasibility of fission experiments in EAR2.

ISOLDE reawakens

The ISOLDE Radioactive Ion Beam Facility is dedicated to the production and acceleration of radioactive nuclei. Teams took advantage of the long shutdown to upgrade existing apparatus, such as ISOLTRAP, and to build and commission two new



The ISOLDE Decay Station (IDS) is one of two new permanent experimental stations at the ISOLDE facility. It will allow physicists to study beta decay and to measure the lifetime of excited states. (CERN-PHOTO-201410-212 – 5)



ASACUSA's cusp-trap scheme. Left to right: the cusp trap to produce antihydrogen atoms, a microwave cavity (green) to induce hyperfine transitions, a sextupole magnet (red and grey) and an antihydrogen detector (gold). (Stefan Meyer Institut)

permanent set-ups, the ISOLDE Decay Station (IDS) and the Versatile Ion-polarized Technique on-line (VITO), which even took data. New ISOLDE groups also brought new travelling set-ups. These included neutron detectors used in an experiment led by groups from Caen and Madrid to study neutron–neutron correlation in lithium-11, and TATRA, the Bratislava group's tape-station used for the measurement of the decays of neutron-deficient mercury.

Following the restart of the PS Booster, which delivers protons to ISOLDE, 26 experiments and 3 test runs were scheduled between the end of July and mid-December. A fantastic atmosphere greeted the very first experimental run on 1 August. Samples of lanthanide elements were collected and shipped to other laboratories: terbium-149 and terbium-155 to the Paul Scherrer Institute in Switzerland, and neodymium-140 to the Risø campus of the Danish Technical University. The aim was to identify chemical elements with suitable isotopes for medical diagnosis and therapy.

The state-of-the-art capabilities of different devices at ISOLDE and their complementarity allowed the determination of the ground-state properties of a long series of isotopes of astatine — the rarest element on Earth — with production rates and half-lives extending over eight orders of magnitude. This successful experiment combined the synergies of three devices: the lasers of the Resonance Ionization Laser Ion Source, the Windmill set-up equipped with silicon and germanium detectors, and the ISOLTRAP Multi-Reflection Time-of-Flight mass spectrometer.

The High Intensity and Energy ISOLDE (HIE-ISOLDE) project progressed well during 2014 (see p. 19). Worldwide interest in the facility continued to grow, with everyone looking forward to its start-up with post-accelerated beams in 2015.

An exciting year came to a close with the annual ISOLDE workshop and users meeting, which took place on 15–17 December, with a golden jubilee session on 17 December, 50 years after the approval of ISOLDE in Council in 1964. The session was opened by Torleif Ericson, who was chair of the Nuclear Physics Experiments Committee at that time. Presentations followed from all of the former group leaders, who described the breakthroughs and highlights at the facility during their leadership.

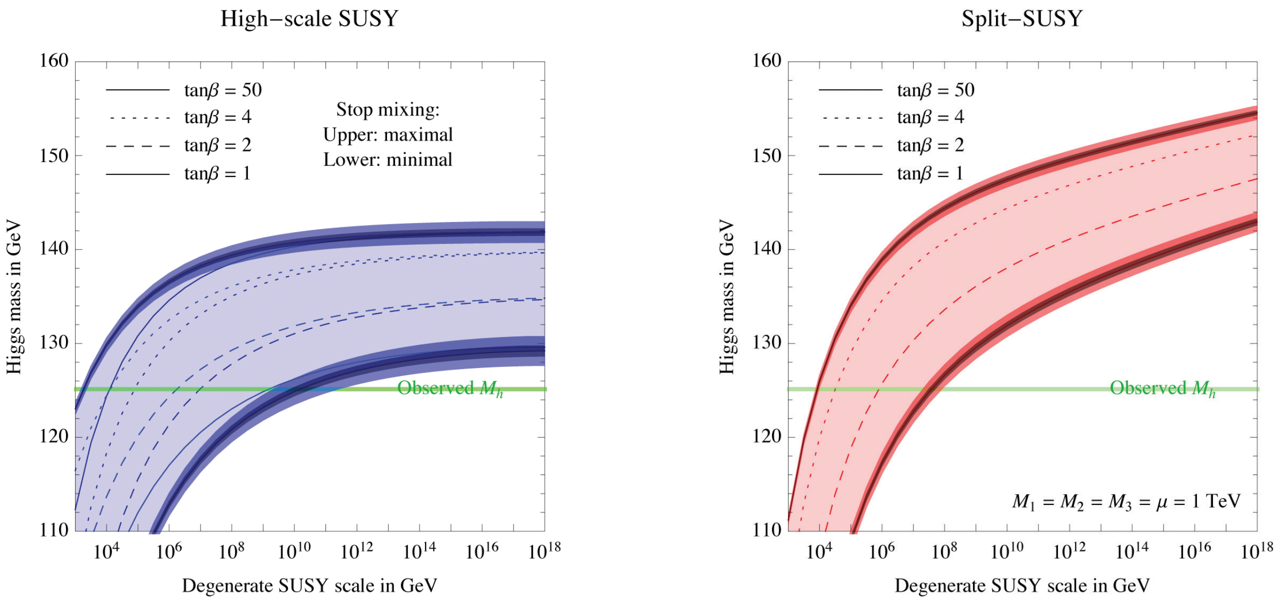
Focus on antimatter

The AD produces low-energy antiprotons for a range of studies, including the synthesis of antihydrogen. The antiprotons originate when protons from the PS strike a target, so the experiments at the AD saw beam again in October, following work on installation and upgrades during LS1.

In continuing studies of data collected before LS1, the ALPHA collaboration published a new precise measurement of the charge of antihydrogen, finding it to be compatible with zero to eight decimal places. The ASACUSA collaboration, which has high-precision microwave spectroscopy of antihydrogen in its sights, also published results from data collected in 2012, which demonstrated the first ever production of a beam of antihydrogen.

The arrival of beams during the autumn enabled the commissioning of ALPHA-2, a modified apparatus with improved access for lasers to probe trapped antihydrogen atoms. Elsewhere in the AD hall, the ATRAP collaboration completed the installation of a second-generation antihydrogen trap to allow laser access. The ASACUSA experiment also commissioned a completely new set-up, which includes a new superconducting 'double-cusp' magnet, a new tracking detector and a new final antihydrogen detector.

LS1 also saw the installation of a brand-new beamline for BASE, a new experiment that aims to take ultra-high-precision measurements of the antiproton's magnetic moment. The



collaboration installed and commissioned all of the apparatus, took data with single antiprotons and implemented an antiproton reservoir.

Both the AEgIS and GBAR experiments are designed specifically to measure the gravitational interaction of antimatter. The AEgIS collaboration completed installation of the apparatus and commissioned it with antiprotons and positrons, in readiness for operation in 2015. Meanwhile studies continued for the GBAR experiment, which will take place at the future ELENA facility at the AD (see p. 18). The team made good progress on a demonstrator at Saclay, advancing on all fronts towards the technical implementation of the apparatus at CERN from 2016 onwards.

Astroparticle physics

There was no LS1 for two experiments at CERN that search for hypothesized particles that could form dark matter, making use of LHC dipole magnets. The CAST experiment tracks the Sun in search for solar-produced axions and other dark-matter candidates. In 2014, following the commissioning of a second X-ray optics that further improves its performance for detecting solar axions, it continued to operate with vacuum in the tubes of its LHC magnet. The silicon detector working in the sub-kiloelectronvolt range has been replaced by an InGrid pixel detector at the focal plane of one of the X-ray telescopes. This should improve on the current sensitivity of CAST in the dark-energy sector.

OSQAR — a 'light shining through a wall' experiment — probes the possibility of quantum oscillations between optical photons and dark-matter candidates, such as axions or axion-like particles (ALPs), in the 9 T transverse magnetic field produced by two spare LHC dipoles. In 2014, the experiment ran with an outstanding sensitivity, using an 18.5 W continuous-wave laser emitting in the green region (532 nm), but detected no regenerated photon after the 'wall'. This pushes the limit on the possible existence of axions and ALPs down to an unprecedented level for a laboratory experiment of this kind.

Detectors for a linear collider

The Linear Collider Detector project at CERN encompasses physics and detector studies for a future high-energy linear electron–positron collider. The work is carried out together with study groups from around the globe. In particular, CERN hosts the CLIC Detector and Physics (CLICdp) collaboration, which studies the physics potential of the CLIC concept (see p. 20), in addition to designing a suitable detector. During 2014, its second year of existence, five institutes joined CLICdp, bringing the total to 25 participating institutes and over 130 members. As CLIC and the International Linear Collider design have many challenges in common, CLICdp collaborates with groups developing the ILD and SiD detector concepts.

In 2014, simulation and engineering work focused on consolidating the two detector designs featured in the CLIC Conceptual Design Report into one optimized model. This required choosing parameters such as dimensions and granularities for the tracker and calorimeters, and identifying suitable technologies. The scenario for constructing CLIC in stages was also reviewed with the aim of defining better the lowest energy stage. At this energy the production of single Higgs bosons and pairs of top quarks are both of interest, but the physics potential of each of them depends on the exact centre-of-mass energy. A compromise to enable precise top and Higgs physics is being studied and will conclude in 2015.

Physics simulation studies continued to benchmark the expected performance of the detectors and reconstruction algorithms, as well as the potential for measuring the Higgs boson's properties. Preparation of a comprehensive report on Higgs physics at CLIC is underway, for publication in 2015.

The hierarchy problem in particle physics relates to the enormous difference between the measured masses of the Higgs boson, for example, and basic predictions of quantum field theory. One familiar approach to mitigate this discrepancy is to incorporate supersymmetry (SUSY). The figures, opposite page, shows predictions for the mass of the Higgs boson as a function of the energy at which SUSY breaks down, for two possible scenarios: high-scale SUSY and split SUSY. The interesting result is the upper bound on the scale for SUSY. This means that the simple idea of a theory in which SUSY breaks at the so-called Planck scale around 10^{19} GeV, with nothing new at lower energies, is not compatible with the mass of the Higgs boson measured at CERN. (From http://arxiv.org/abs/1407.4081)

With the return of beams as LS1 neared its end, detector testing was again possible at the PS and the SPS. Prototype pixel-detector assemblies comprising Timepix3 and CLICpix chips coupled to thin sensors were assessed and showed promising results. With support from CLICdp, the CALICE collaboration tested a combined electromagnetic and hadronic calorimeter stack; the FCAL collaboration made the first demonstration of multi-plane operation of the forward calorimeter; and lab-based engineering studies verified the air-flow cooling of the vertex detector, using a full-scale 3D model and the CERN Fire Brigade's smoke machine.

In theory

In 2014, the CERN Theory Unit (PH-TH) continued to play a leading role as a reference centre in all areas of theoretical particle physics. Its research covered a broad spectrum, ranging from Standard Model physics directly related to the LHC, to formal aspects of quantum field theory and string theory.

A large effort was devoted to the consequences of the discovery of the Higgs boson, including possible implications for what is known as the hierarchy problem (see figure on opposite page for an example). A major part of this research dealt with particle-physics phenomenology beyond the Standard Model (such as extensions based on supersymmetry or more than four dimensions), astroparticle physics and cosmology and heavy-ion physics, as well as lattice field theory and mathematical physics. Roughly half of the effort was devoted to the particle physics of the Standard Model or beyond the Standard Model. Projects often overlapped between fields, such as dark matter being possibly relevant both for cosmology and for collider physics, or black-hole physics being holographically related to heavy-ion collisions. Members of the group published about one paper a day on average.

The group comprises 18 staff-members and more than 35 fellows at a given moment. In addition, it hosts 10–15 paid scientific associates and each year welcomes around 800 short-term visitors, paid and unpaid. The total head count exceeds 120 during the busy summer months. The high turnover is an important aspect of the group's role as a world-leading centre for scientific exchanges.

An important contribution towards fostering international collaboration and exchanging ideas are the 'Theory Institutes' — informal workshops that last for up to a few weeks. The aim is to optimize resources by putting together visiting scientists with common interests and by sharing resources with the international community. In 2014 there were four such events on 'Resurgence and Transseries in Quantum, Gauge and String Theories', 'Conceptual advances in lattice gauge theory', 'Results in SUSY Gauge Theories in Various Dimensions' and 'Numerical Holography'.

Members of PH-TH showed a high visibility at various 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. A particularly important on-going activity is the LHC Physics Centre at CERN (LPCC), which contributes with workshops, lectures and various working groups. In November, PH-TH held its annual 'TH retreat', offering members of the group a comprehensive overview of all of the on-going 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 2014 (see https://indico.cern.ch/event/302647/other-view?view=standard).

These Croatian students were among the many to wish CERN a happy 60th birthday by sending images via social media. (Marina Furkes/Gymnasium 'Fran Galovi' Koprivnica)

Making an impact

An eventful birthday

Throughout the year, CERN and its Member States celebrated 60 years of science for peace with events, exhibitions, talks and more. The 60th anniversary made the Laboratory a focal point, with events at CERN reaching a crescendo in September in the run up to the official anniversary event (see p. 6). These included a symposium on science for peace, a celebration of the anniversary of the first Council session, a concert by the United Nations Orchestra, screenings of the feature film *Particle Fever*, and the second TEDxCERN event, 'Forward — Charting the Future with Science', which addressed the essential role of science in solving global challenges, including climate, health, food, water and energy.

The many other events ranged from the CinéGlobe film festival and Famelab in March, through a special open-house event for neighbouring communities in May, to a public computing challenge in December. As part of the 60th anniversary programme, exhibitions about CERN went to 16 locations. The large 'Accelerating Science' exhibition travelled to Warsaw, Athens, Valencia and Thessaloniki, attracting more than 300 000 visitors, while more thematic exhibitions went on show at four other venues. The 'interactive LHC tunnel' appeared at eight different locations, together with a large poster exhibition.

Nurturing innovation

Set up in 2011, the Knowledge Transfer (KT) fund is now established as a useful tool to reduce the gap from fundamental research to applications, and to incentivize CERN researchers to bring forward their ideas. Since its inception, it has financed 25 projects, 6 of these in 2014. Other activities during the year, such as innovation days for the Beams and Engineering Departments, also helped to encourage and promote KT as part of the core activities of CERN. Further afield, the idea of a network of Business Incubation Centres (BICs) of CERN technologies in the Member States came closer to reality. Four new BICs in the Netherlands, Norway, Greece and Austria joined the existing STFC CERN BIC in the UK to assist start-up companies in bringing CERN's knowledge to market.

Researchers from CERN took part in the annual European Researchers' Night with 'Pop Science', which combined arts, poetry, theatre, music and science at multiple venues in Geneva and neighbouring France. (CERN-PHOTO-201409-198 – 64)

Young Spanish winners of a CERNland competition — launched by CERN, the Centro Nacional de Física de Partículas, Astropartículas y Nuclear (CPAN) and the Fundación Príncipe de Asturias – visit the CMS cavern. (CERN-PHOTO-201404-077 – 18)

In March, CERN signed a framework agreement with the European Space Agency (ESA) for future cooperation on research and technology in areas of mutual interest such as computing and data preservation, advanced materials, cryogenics, superconductivity and radiation resistance. In April, the two organizations shared a stand at the Hannover Messe, the world's leading trade fair for industrial technology, alongside 14 related spin-off companies.

December marked the inauguration of 'IdeaSquare', a building named after a new project designed to nurture innovation at CERN. The aim is to bring people from industry together with researchers, engineers and students to encourage new ideas to benefit society, taking inspiration from CERN's ongoing detector R&D and upgrade projects. Although the project is still in its pilot phase, two EU-funded projects have found their home there, and 46 students have participated in Challenge-Based Innovation courses. IdeaSquare also housed a 3-day problem-solving workshop, or hackathon, where interdisciplinary teams used CERN's technologies to tackle humanitarian and social issues.

The scientists of tomorrow

CERN's one-week training courses for secondary-school teachers, held in 19 different national languages in 2014, had a record participation, with 1200 school teachers from 22 different countries. In addition, the international three-week High School Teachers programme in July had 54 participants from 32 different countries, including 10 teachers from the Middle East (Bahrain, Iran, Israel, Jordan, the Palestinian Authority and Turkey) as part of a collaboration with the SESAME synchrotron light-source, which is currently under construction in Jordan. To enable educators and their students to carry out hands-on experiments during visits to CERN, a new facility — S'Cool Lab — was constructed and commissioned.

Each year CERN welcomes many visiting school groups, but two groups who arrived in September had a particularly special experience as winners of CERN's first 'Beamline for schools' competition. The student teams from Athens in Greece and Nijmegen in the Netherlands were selected from nearly 300 entries. They spent 10 days conducting their proposed experiments in a test beam at the PS. The competition — planned to coincide with CERN's 60th anniversary — mirrored the way that researchers bid for access to the Laboratory's facilities and was made possible through the CERN & Society initiative (see p. 8).

For students already at university, CERN organizes or co-organizes specialist schools throughout the year, reaching hundreds of students around the world. In 2014, particle physics was addressed at the European School of High-Energy Physics and the Asia–Europe–Pacific School of High-Energy Physics; accelerator science was covered by the Joint Universities Accelerator School, as well as five CERN Accelerator Schools, one of them a joint school with the US; and computing topics featured in the International School of Trigger and Data Acquisition, the Grid and Advanced Information Systems School and the CERN School of Computing (CSC), as well as the Inverted CSC and the Thematic CSC. This year also saw some 300 students from 77 different countries take part in CERN's flagship summer-student programme.

Collaborations and new horizons

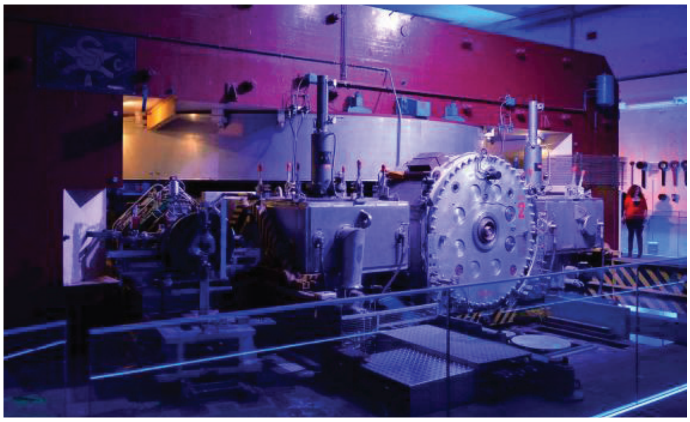
The European Commission launched its Horizon 2020 (H2020) funding programme in 2014, and proposals involving CERN were submitted to a variety of H2020 sub-programmes. Of the 17 new H2020 projects selected for funding in 2014, seven are coordinated by CERN. The range of fields and activities include: a study of isotopes for medical applications (MEDICIS-PROMED), the development of innovative fibre technologies (INTELUM), international collaboration on accelerator

Bringing 60 years of history to life

CERN's 60th anniversary proved the perfect opportunity to look back at the Organization's history. With this in mind, the Scientific Information Service embarked upon a digitization project to upload the Laboratory's entire picture archive onto the CERN Document Server. There are approximately a quarter of a million pictures in the archive, with older pictures existing as hard copies in a range of formats. Once the majority had been scanned, a crowd-sourcing campaign was launched for the CERN community and beyond to help in identifying the content of certain pictures. The year also saw the completion of the digital archive of all *CERN Courier* and *CERN Bulletin* issues.

When CERN's first accelerator, the Synchrocyclotron (SC), began operation in 1957, it was the highest-energy particle accelerator in Europe. During its 33 years of service it provided many important physics results. This year saw the completion of an extensive refurbishment project to turn the SC into a new exhibition point for visitors, which was inaugurated in June and named a European Physical Society Historic Site. Using 3D projectors to superimpose animations onto the machine, it allows visitors to witness how the accelerator once worked. This exhibition and other new visitor points at the Data Centre, the CERN Control Centre and the Magnet Test Facility in building SM18 provide additional options for an increasing number of visitors — about 103 000 visitors (40% of whom were school children) followed 1/2-day guided tours to dedicated visit points in 2014.

Archive photograph from 1956 of one of the coils for the Synchrocyclotron travelling through the village of Meyrin on its way to CERN. (CERN-CE-5661005)



The newly inaugurated Synchrocyclotron exhibition. (CERN-PHOTO-201406-130 – 16)

science and technology (E-JADE), novel NMR techniques (BetaDropNMR), new mathematical structures (MathAm), the procurement of cloud services in Europe (PICSE) and science outreach (PopScience). In addition, the European Commission's Marie Skłodowska-Curie actions provided funding for more than 130 young researchers to work at CERN in 2014.

Under the umbrella of the European Network for Light Ion Hadron Therapy — ENLIGHT — several European Union (EU) projects led by or involving CERN have helped to develop the field of hadron therapy. Two such EU projects came to an end in 2014: ULICE, which strengthened the collaboration among the existing and planned hadron-therapy centres in Europe, and ENVISION, which developed state-of-the-art quality-assurance tools.

With the aim of positioning CERN as an important facilitator of medical physics in Europe, January saw the creation of the CERN Medical Applications (CMA) office to coordinate and structure activities related to medical applications within the Organization, and to catalyse collaborations with external partners. Its initial workplan includes seven key areas: large-scale computing, detectors for medical imaging, radioisotopes, a new biomedical facility, optimized design for medical accelerators, simulation and dosimetry, and applications other than cancer therapy. In addition, CERN co-organized the second International Conference on Translational Research in Radiation Oncology and Physics for Health conference in Geneva in February. The event attracted a large number of participants from fields such as physics, engineering, medicine, computer science and biology.

A CERN Science Camp for staff children was piloted during the summer, featuring hands-on science activities as well as a trip to the CERN Safety Training Centre, shown here. (CERN-HSE-PHO-2014-008 – 7)

A place to work

CERN continues to remain an attractive workplace to job seekers, with a record-breaking numbers of applicants in 2014. Just over 20 000 applications were received and 146 selection boards for limited-duration contracts were held (compared with more than 18 000 applications and 106 boards in 2013). Within the Fellowship Programme, 320 fellows were recruited, totalling 617 fellows at CERN at the end of the year. Through the Technicians Training Experience Programme, which began in 2012, 48 recently qualified technicians from 9 Member States experienced their first career development at CERN. In addition, 389 technical and doctoral students were selected, and the flagship Summer Student Programme was attended by 289 students from both Member and non-Member States. As recognition of the quality of CERN's training programmes, the State of Geneva awarded CERN the 'Prix de l'entreprise formatrice' for its Apprentice Programme.

The Diversity Office continued to implement actions towards achieving the seven strategic diversity objectives agreed for the period from 2012 to 2014, which focus on the areas of recruitment, career development and work environment. In August, the Diversity Policy was adopted and was well received in presentations to the Tripartite Employment Conditions Forum (TREF) and CERN Council. In addition, a new Learning and Development Policy was devised in 2014, which led to the reorganization of training into five curricula: leadership, personal development and communication, technical management, technical and language.

The 2015 five-yearly review of financial and social conditions of members of the personnel was launched in 2014. In addition to the mandatory aspects of the review, i.e. basic salaries for staff members, stipends for fellows and subsistence indemnities for associated members of the personnel, the proposal made by the Management to review the CERN career structure and diversity-related social and financial conditions, was approved by Council in June.

The 60th anniversary of the Laboratory also marked the 20th anniversary of TREF. This discussion forum and advisory body to Council is made up of representatives of the Member States, the CERN Management and the Staff Association to examine social and financial aspects of the Organization's employment conditions. TREF grew from ad hoc working groups dating back to

A new car park, next to the Globe of Science and Innovation, was inaugurated in April, with around 100 blue spaces reserved for public-transport users. (OPEN-PHO-ACCEL-2015-006 – 1)

The new ELENA building was inaugurated after less than a year's construction work. Some 10 000 tonnes of earth had to be moved by around 500 lorries. (CERN-PHOTO-201404-075 – 1)

the 1960s and 1970s and held its first meeting on 27 September 1994. During its 20 years, innovative decisions have included the Saved Leave Scheme, pre-retirement programmes and long-term care allowances, to name a few.

From the ground up

In terms of construction work, 2014 was a busy year. On 11 April, CERN inaugurated the ELENA building (393), tacked on to the side of the AD. This building is to house a cleaning room, workshops and generators for the kickers in order to free space in the AD hall, where the future Extra Low ENergy Antiproton ring, ELENA (see p. 18), will be installed. Spring also saw the completion of a new building (380) for the n_TOF facility to house the second experimental area, EAR2 (see p. 28).

On 24 May, a new building (SL53) at CERN's Cessy site in France was inaugurated to welcome the thousands of visitors who come to learn about the CMS experiment each year. It boasts low energy-consumption and the future possibility of using recycled heat from the detector. On the Meyrin site, October saw the completion of building 179 for MEDICIS, a research facility to make radioisotopes for medical applications. The inauguration of the new building (772) on the Prévessin site for CERN's calibration facility followed in December. This building will be used to calibrate radiation-measuring devices in four different types of ionizing-radiation fields. Also at Prévéssin, a joint project between the GS and BE Departments and the DGS unit designed, installed and validated an active interlock system into the North Hall. This system allows the SPS to operate with a 'supercycle' that mixes high-intensity proton cycles for the LHC and the HiRadMat facility with low-intensity ion cycles for the North Hall. The active interlock mitigates the risk to personnel working in the North Hall of an unintentional extraction of a high-intensity proton beam.

Behind the scenes of GS

The General Services (GS) department initiated a communication campaign throughout 2014 to showcase the people that help CERN to run smoothly. Articles in the *CERN Bulletin* featured 'behind the scenes of GS' for the unsung heroes of the Laboratory. From cleaning and maintenance to logistics and access control, from the library and hostel to the stores and fire service, not to mention civil engineering and building work, the GS Department ensures that the Laboratory works as it should.

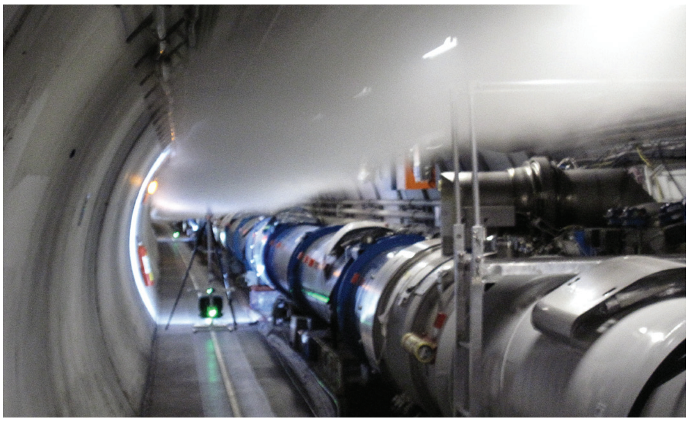
CERN has some 100 environmental monitoring stations on and around its sites. New stations capable of taking even more precise measurements were installed in 2014. (CERN-PHOTO-201504-073 – 6)

Safety and Environment

Entailing dozens of work projects taking place in parallel and with activities as diverse as handling, welding, electronics and mechanics, the long shutdown that came to an end in 2014 was a major focus for safety. Despite the impressive number of working hours (3.4 million) and personnel involved (1600), the frequency and severity of accidents remained very low. This excellent performance is a testament to the effective organization of the tasks, in which safety constraints were taken into account at every stage. The active involvement of supervisors and safety coordinators also helped to limit the number of accidents.

Particular attention was paid to work in supervised and controlled radiation areas. Some 10 000 people were issued with a dosimeter during the 18-month shutdown; only two of them received doses slightly above 3 millisieverts (mSv), the objective set for the maximum dose per person per year. More than 98% of people carrying dosimeters received a dose of less than 1 mSv. To put that in context, the average dose received annually by 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) principle greatly contributed to the outcome. This involved creating ALARA committees for higher-risk activities and conducting studies for work in controlled radiation areas in order to minimize the doses received.

The long shutdown provided an opportunity to carry out exercises to re-evaluate some of the safety standards in the LHC tunnel, in particular in the areas around the valves designed to evacuate helium in the event of a build-up of pressure. In February, three



Three helium-leak tests were performed in the tunnel. (OPEN-PHO-SAFETY-2014-001)

Several evacuation exercises were carried out at CERN, including one at the nursery. (OPEN-PHO-SAFETY-2014-002)

helium-leak tests were performed in order to measure the speed of gas propagation, the temperature, the oxygen level in the tunnel and the impact on the machine and infrastructures.

Safety exercises are regularly conducted at the Laboratory. In October, a large-scale evacuation exercise involving ten buildings on the Meyrin site took place, in which approximately 400 people were evacuated in just a few minutes. The exercise was preceded by information sessions for around 100 people, including safety officers and the emergency guides who provide assistance during evacuations. The exercise helped to identify ways of improving the level of safety in these buildings and to raise awareness among the occupants. Several similar exercises took place at the LHC experiment sites, the Globe of Science and Innovation and even the nursery.

Training is a fundamental aspect of CERN's safety policy. In 2014, more than 5600 people took part in group training courses and 23 700 people took online courses. New, more-interactive and user-friendly online courses were developed. New courses featuring practical exercises and scenario simulations were also introduced at the Safety Training Centre on the Prévessin site, where the installations were enhanced and a training workshop on electrical hazards and the use of lasers was launched. In addition, the tunnel segment and mock-up of the LHC were equipped with a TETRA radio-system for use in training in emergency communications, and new training rooms were opened with a view to centralizing safety-training courses in the centre.

In order to formalize and improve the prevention of occupational hazards, a strategy known as ProSanTra (Promotion de la Santé au Travail — promoting health at work) was implemented. Particular emphasis was placed on chemical hazards; several visits were made to work-posts that were particularly exposed to hazards relating to the use of dangerous chemicals. These visits were an opportunity to remind personnel about good practices and to introduce new work-post-specific task-sheets explaining measures to protect against and mitigate chemical hazards. This was the last stage of a three-year project to tackle this issue. Chemical hazards were also the theme of the World Day for Safety and Health at Work on 10 April, when some 420 people took part in outreach activities held at CERN.

Given the scale of CERN's sites and the growing number of users, road safety is an important consideration of safety at work. In 2014, certain sections of CERN's roads were equipped with traffic-calming measures.

With regard to medical and emergency infrastructures, the Finance Committee approved a partnership agreement between CERN and the Hôpitaux Universitaires de Genève (Geneva university hospitals, HUG). Under this agreement, an emergency response unit (a vehicle providing mobile intensive care) will be installed on the Meyrin site and run by HUG, which will thus be able to respond to incidents on 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 call centres of both the Canton of Geneva and CERN will ensure the best possible response to medical emergencies on the CERN sites. In addition, HUG will provide training for CERN's medical personnel and firefighters.

Efforts to reduce the impact of CERN's activities on the environment continued. The shutdown of the accelerators provided an opportunity to replace many stations for monitoring air, water and radiation, especially on the Prévessin site. CERN has around 100 monitoring stations on and around its sites. New radiation-measuring stations, capable of detecting even lower levels of radiation, were also installed. All of the measurements demonstrated that the radiological impact of CERN's activities on the environment in 2014 was negligible;

An electrical work certification course in the Safety Training Centre's new installation dedicated to electrical and laser hazards. (CERN-HSE-PHO-2015-006-4)

One of the stands set up to mark the World Day for Safety and Health at Work. (CERN-HSE-PHO-2014-003-6)

following the standard procedure, they were forwarded to the Swiss and French authorities. CERN remains committed to its policy of continuous improvement in this area. A working group was established to update the inventory of areas at CERN at risk of water pollution and to propose a plan of priority actions involving the installations in 2015. A hydrocarbon detector has been installed as a pilot test in the wastewater network on the Prévessin site. Depending on the results, other detectors of the same type may be installed in the coming years. These actions were taken in response to three isolated cases of wastewater pollution at CERN.

The long shutdown allowed improvements to be made to the accelerators and detectors to reduce their impact on the environment. Renovation work was carried out on several installations to reduce water consumption. The operating mode of the LHC's untreated water-supply ring, which is linked to the firefighting system and the cooling towers, was modified. The cooling systems of large installations such as ISOLDE were replaced. Tens of thousands of cubic metres of water will be saved with no reduction in performance.

To reduce the consumption of electricity, a new control system for the SPS accelerator's power supplies came into service. Previously, the magnet circuits had been powered without interruption from the moment the accelerator was ready to receive beam. The new system automatically adjusts the power supply to the magnets according to the intensity of the beam injected into the SPS, beam requests from users and the requirements of the accelerator operators. A similar renovation project to be carried out during the second long shutdown is being investigated for the power supplies for the North Area.

A new Safety Policy

CERN has expanded considerably since its creation 60 years ago, welcoming an increasing number of experiments and users. Large international collaborations have emerged and the number of firms working on the CERN sites has grown. On the day of its 60th anniversary, CERN adopted a new set of reference documents that adapt its Safety Policy to take account of this evolution and of internationally recognized best practices. A new general Safety Policy statement, designed to be more concise and enduring than its predecessor, was adopted. The organizational structure and the responsibilities relating to safety are now set out in a Safety Regulation and its accompanying documents. The new regulation reaffirms that responsibilities in matters of safety follow the hierarchical line, but it also takes account of the matrix management structure adopted for many activities and of the practical constraints within the large experiments. The document also reasserts that partner institutes and contractors must comply with CERN's Safety Rules. Finally, it emphasizes that every individual must take responsibility for safety.

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Deputy: V. Mertens

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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 Head Office of the HSE Unit
- DGS-RP Radiation Protection Group
- DGS-SEE Safety Engineering & Environment Group

S AI **Administration and General Infrastructure Sector**

FP Finance, Procurement & Knowledge Transfer Department

- FP-DI Office of the Department Head
- 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 Head of Department's Office
- GS-FB Fire Brigade
- 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 **Accelerator & Technology Sector**

BE Beams Department

- BE-ABP Accelerator & Beam Physics
- BE-ASR Administration, Safety & Resources
- BE-BI Beam Instrumentation
- BE-CO Controls
- BE-HDO Head of Department's Office
- BE-OP Operation
- BE-RF Radio Frequency

EN Engineering Department

- EN-CV Cooling & Ventilation
- EN-EL Electrical Engineering
- EN-GMS General Management & Secretariats
- EN-HDO Head of Department's 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-RPA Resources Planning Administration (until 30.09.2014)
- 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 Organization
- 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 Co-ordinators 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

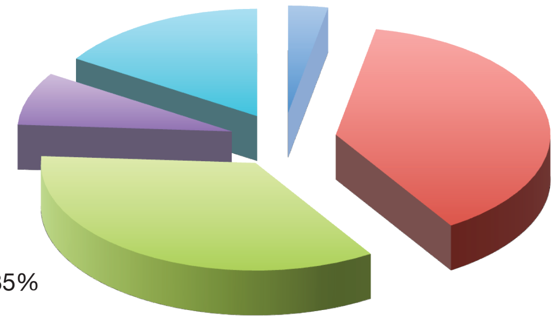
PF **Pension Fund**

PFMU Pension Fund Management Unit

- PF-BA Benefits and Accounting
- PF-AAR Asset Allocation and Risk Management
- PF-IPM Internal Portfolio Management
- PF-MO Middle Office
- PF-GMS General Management Support

CERN in figures

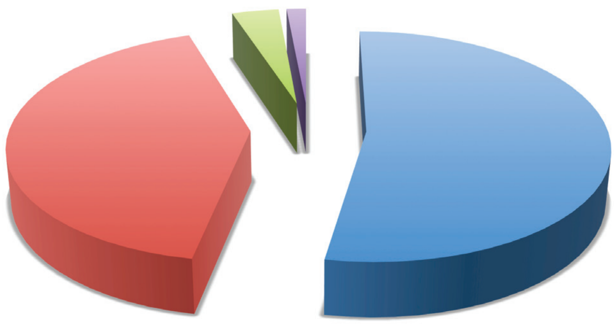
CERN Staff



Evolution of Staff numbers *Including externally funded*	
2011	2424
2012	2512
2013	2513
2014	2524

Evolution of Fellows, Associates, Students, Users & Apprentices	
2011	11 449
2012	12 080
2013	12 313
2014	13 142

CERN Expenses



Total expenses	1133.7 MCHF
Personnel	616.7
Materials	459
Goods, consumables and supplies	*228.8*
Other materials expenses	*230.2*
Energy and water	42.2
Interest and financial costs	15.8

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
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 will ultimately reach 7 million million electronvolts, or 7 TeV per beam. One TeV is about the energy of motion of a flying mosquito.

Event
A snapshot of a particle collision, as recorded by a detector.

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 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.

HL-LHC
The High-Luminosity Large Hadron Collider project aims to extend the discovery potential of the LHC by increasing the luminosity by factor of 5-10.

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 including life sciences. (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 as glass lenses focus light. There are 392 main quadrupoles in the LHC.

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 for ever — 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.

Technology transfer
The communication to third parties of technologies developed, for example at CERN, for socio-economic and cultural benefits.

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.

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