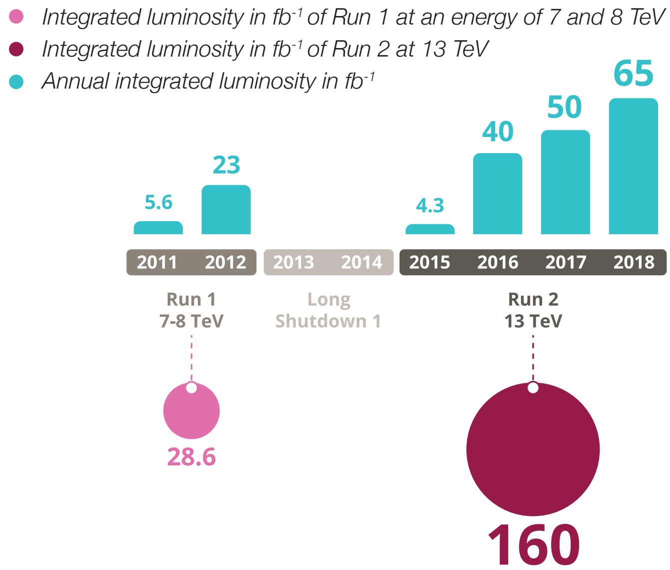
DISCOVERY MACHINES

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

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

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



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

RECORD LUMINOSITY FOR THE LHC

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

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

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

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

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

High-luminosity tests at the LHC

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

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

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

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

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

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

IONS TAKE CENTRE STAGE IN THE LHC

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

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

THE LARGEST ACCELERATOR NETWORK IN THE WORLD

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

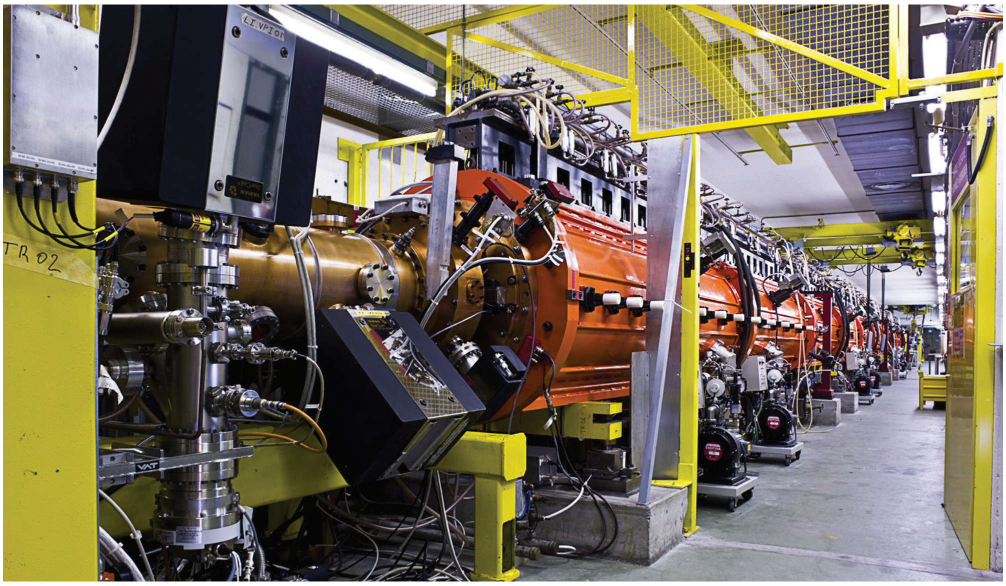
The availability of most of the accelerators exceeded 90%, rising to 95% for the PS Booster and 99% for Linac2. The achievement of Linac2 was all the more remarkable because it was accelerating beams for the last time. Having prepared 30 000 billion billion protons over its forty years of service, the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

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

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

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

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



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

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

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

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

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

New infrastructures for the accelerators

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

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

PUSHING COMPUTING TO THE LIMITS

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

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

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

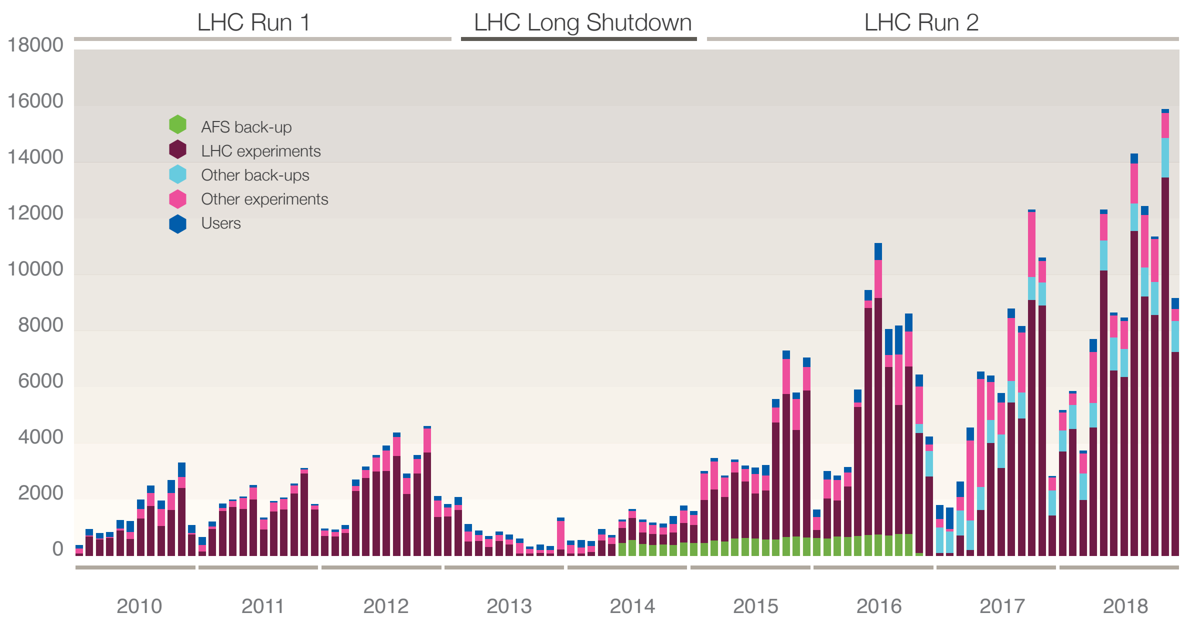
New IT R&D activities have already begun in preparation for the LHC's Run 3. New software, named CERN Tape Archive (CTA), is being developed to replace CASTOR. The main goal of CTA is to make more efficient use of the tape drives in order to handle the higher data rate anticipated during Runs 3 and 4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

WLCG: FROM STRENGTH TO STRENGTH

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

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

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



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

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

EDUCATION AND SHARING

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

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

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

CERN OPENLAB: TACKLING TOMORROW'S ICT CHALLENGES TODAY

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

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

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

OPEN-SOURCE FOR OPEN SCIENCE

Ever since releasing the World Wide Web software under an open-source model in 1994, CERN has been a pioneer in the open-source field, supporting open-source hardware (with the CERN Open Hardware Licence), open access (with the Sponsoring Consortium for Open Access Publishing in Particle Physics – SCOAP³) and open data (with the CERN Open Data portal).

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

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

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

SCIENCE IN THE CLOUDS

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

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

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

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

COMPUTER SECURITY AT CERN

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

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