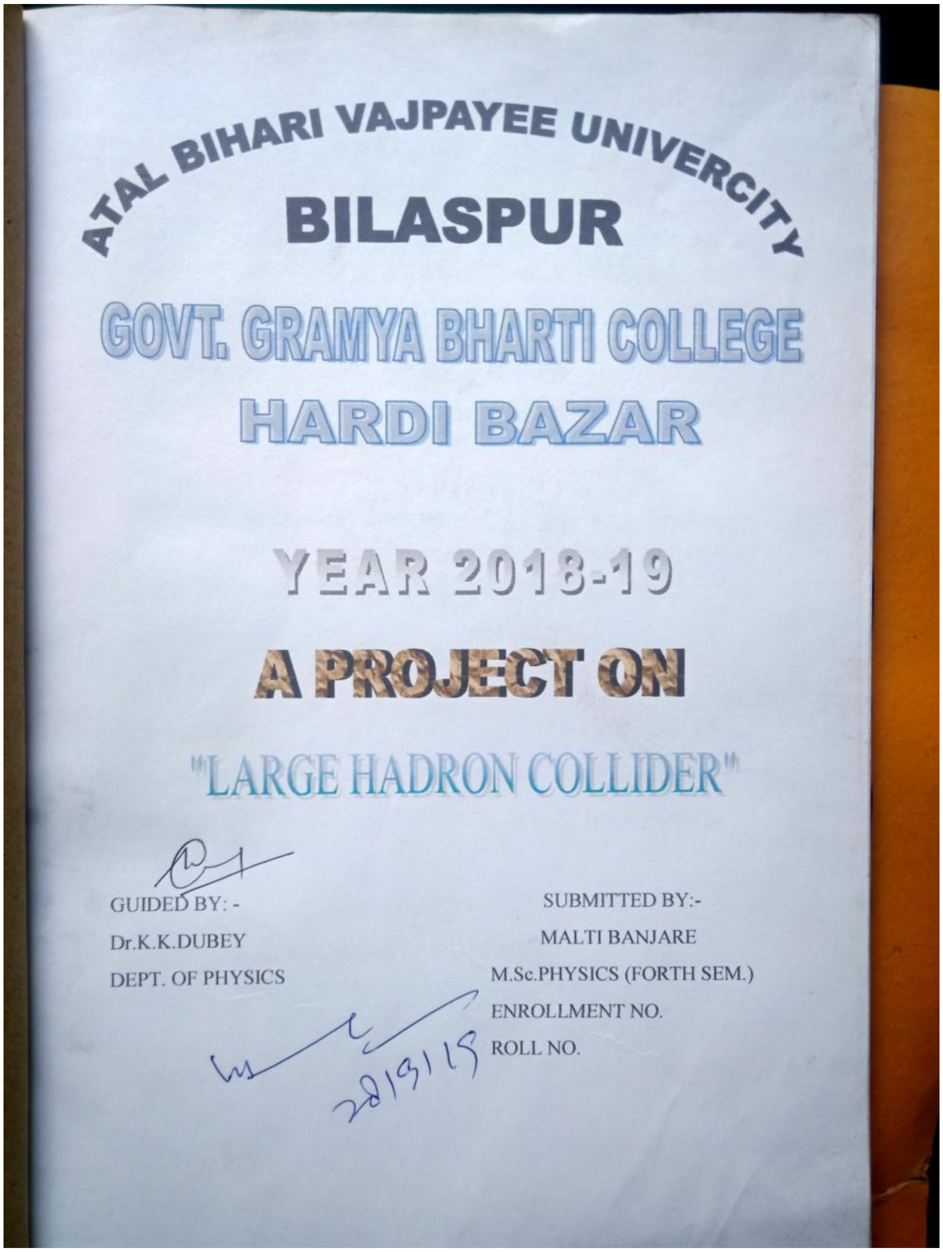


ATAL BIHARI VAJPAYEE UNIVERCITY

BILASPUR

GOVT. GRAMYA BHARTI COLLEGE
HARDI BAZAR

YEAR 2018-19

A PROJECT ON

"LARGE HADRON COLLIDER"

GUIDED BY: -
Dr.K.K.DUBEY
DEPT. OF PHYSICS

SUBMITTED BY:-
MALTI BANJARE
M.Sc.PHYSICS (FORTH SEM.)
ENROLLMENT NO.
ROLL NO.

28/3/19

CERTIFICATE

THIS IS CERTIFY THAT MALTI BANJARE HAS COMPELETED HIS PROJECT ENTITLED "LARGE HADRON COLLIDER" AND ARE SUBMITTING THAT FOR THE DEGREE OF M.Sc. FROUTH SEM PHYSICS. THE ABOVE REFERRED PROJECT IS DULY COMPLETED AND IS P TO THE STANDARD, BOTH IN RESPECT OF ITS LITERACY PRESENTATION, FOR BEING REFERRED TO THE EXAMINER. I FURTHER CERTIFY THAT THE WORK CONTAINED IN HIS PROJECT, HAS BEEN DONE BY.

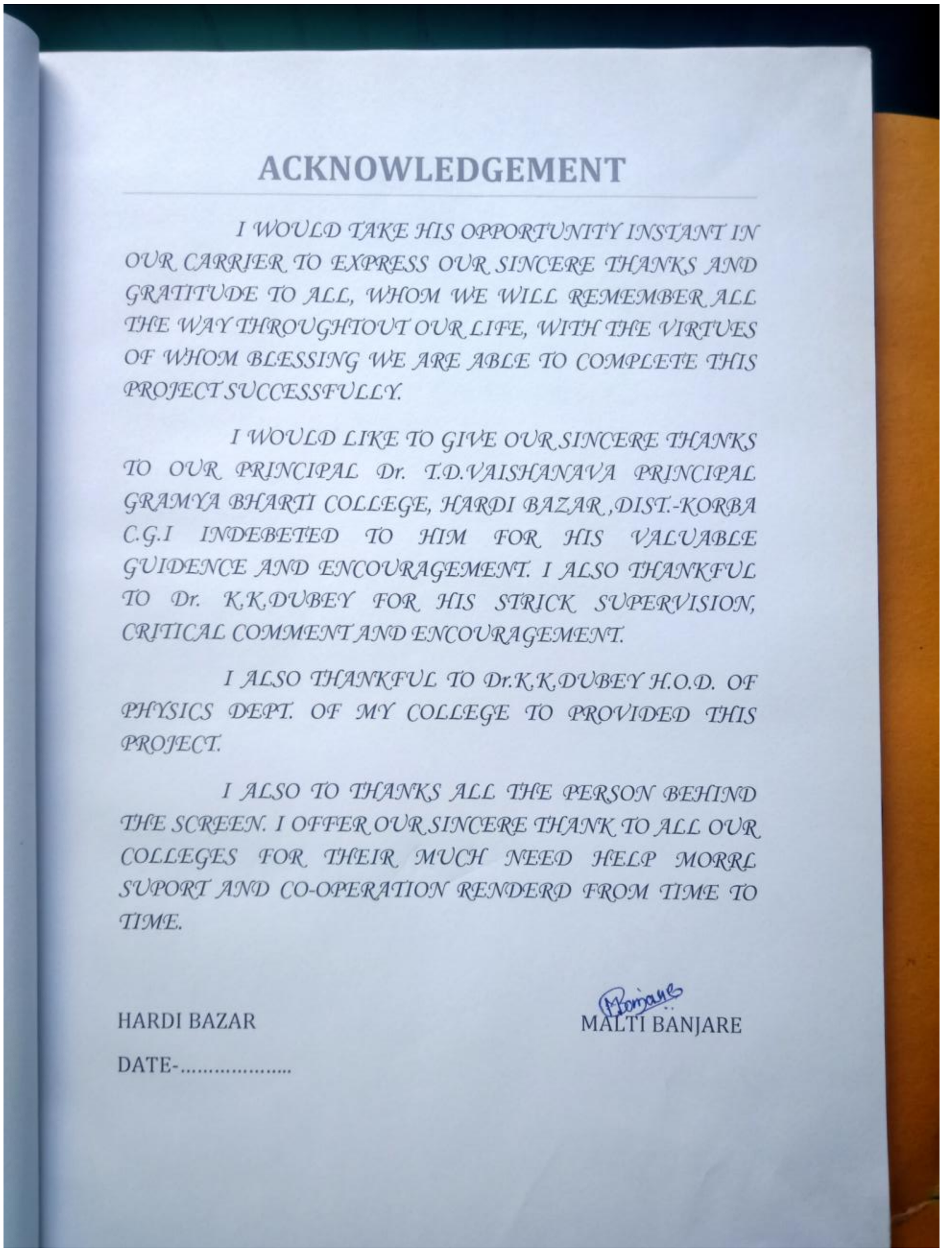
THERE BY FORWORD HIS PROJECT REPORT FOR AWARD M.Sc. FOURTH SEM. PHYSICS,GOVT. GRAMYA BHARTI COLLEGE, HARDI BAZAR, DIST.-KORBA(C.G.)

DATE-……………..

FORWORD BY:	**APPROVED BY:**
Dr.T.D.VAISHANAVA	**Dr.K.K.DUBEY**
PRINCIPAL	**H.O.D. OF PHYSICS**

GUIDED BY

Dr.K.K.DUBEY,PROFESSOR



ACKNOWLEDGEMENT

I WOULD TAKE HIS OPPORTUNITY INSTANT IN OUR CARRIER TO EXPRESS OUR SINCERE THANKS AND GRATITUDE TO ALL, WHOM WE WILL REMEMBER ALL THE WAY THROUGHTOUT OUR LIFE, WITH THE VIRTUES OF WHOM BLESSING WE ARE ABLE TO COMPLETE THIS PROJECT SUCCESSFULLY.

I WOULD LIKE TO GIVE OUR SINCERE THANKS TO OUR PRINCIPAL Dr. T.D.VAISHANAVA PRINCIPAL GRAMYA BHARTI COLLEGE, HARDI BAZAR ,DIST.-KORBA C.G.I INDEBETED TO HIM FOR HIS VALUABLE GUIDENCE AND ENCOURAGEMENT. I ALSO THANKFUL TO Dr. K.K.DUBEY FOR HIS STRICK SUPERVISION, CRITICAL COMMENT AND ENCOURAGEMENT.

I ALSO THANKFUL TO Dr.K.K.DUBEY H.O.D. OF PHYSICS DEPT. OF MY COLLEGE TO PROVIDED THIS PROJECT.

I ALSO TO THANKS ALL THE PERSON BEHIND THE SCREEN. I OFFER OUR SINCERE THANK TO ALL OUR COLLEGES FOR THEIR MUCH NEED HELP MORRL SUPORT AND CO-OPERATION RENDERD FROM TIME TO TIME.

MBanjare

HARDI BAZAR MALTI BANJARE

DATE-………………

DECLERATION

I HERE BY DECLERE THAT THE PROJECT REPORT INTITLE "LARGE HADRON COLLIDER" SUBMITTED BY ME IS NOT SUBSTANTIALLIY THE SAME AS HAVE ALL READY BEEN SUBMITTED FOR DEGREE OF M.Sc. PHYSICS OR ANY OTHER ACADEMIC QUALIFICATION AT GOVT. GYRAMYA BHARTI COLLEGE, HARDI BAZAR,DIST.-KORBA (C.G.)

DATE-………..

MALTI BANJARE
M.Sc. PHYSICS FOURTH SEM.

PREFACE

THE BASIC OBJECTIVE OF PROJECT MAKING IN INSTITUTE IS TO PROMOTE THE HABIT OF DEVELOPING THE CONFIDENCE TO TAKING NEW PROBLEMS ANS TO ENSURE THE ATTITUDE OF TEAMNG AND CREATIVITY. THE SPIRIT OF MAKING NEW THINGS AND TO DEVELOP THE CTK, IDEA IS THE MAIN AIM.

TO ACHIVE THEIR ABOVE GPALS I WORKED OVER THE PROJECT OF "LARGE HADRON COLLIDER" WE TRIED THIS PROJECT BECAUSE IT HELP ME TO GAINAND IMPROVE OUR KNOWLEDGE IN THE FIELD OF COMMUNICATION.

I OPOLOGY FOR THE ERRORS AND MISTAKE THAT MAY HAVE COMITTED IN THIS PROJECT REPORT IN SPITS OF OUR BEST EFFORTS AND CARE.

DEPARTMENT OF PHYSICS
GOVT. GRAMYA BHARTI COLLEGE,HARDI BAZAR
DIST.-KORBA (C.G.)

CONTANTS

INTRODUCTION

The **Large Hadron Collider** (**LHC**) is the world's largest and most powerful particle collider and the largest machine in the world. It was built by the European Organization for Nuclear Research (CERN) between 1998 and 2008 in collaboration with over 10,000 scientists and hundreds of universities and laboratories, as well as more than 100 countries It lies in a tunnel 27 kilometres (17 mi) in circumference and as deep as 175 metres (574 ft) beneath the France–Switzerland border near Geneva.

First collisions were achieved in 2010 at an energy of 3.5 teraelectronvolts (TeV) per beam, about four times the previous world record. After upgrades it reached 6.5 TeV per beam (13 TeV total collision energy, the present world record). At the end of 2018, it entered a two-year shutdown period for further upgrades.

The collider has four crossing points, around which are positioned seven detectors, each designed for certain kinds of research. The LHC primarily collides proton beams, but it can also use beams of heavy ions: Lead–lead collisions and proton-lead collisions are typically done for one month per year. The aim of the LHC's detectors is to allow physicists to test the predictions of different theories of particle physics, including measuring the properties of the Higgs boson and searching for the large family of new particles predicted by supersymmetric theories, as well as other unsolved questions of physics.

INTRODUCTION

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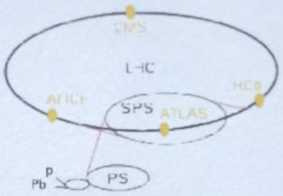
Large Hadron Collider
(LHC)



LHC experiments

ATLAS	A Toroidal LHC Apparatus
CMS	Compact Muon Solenoid
LHCb	LHC-beauty
ALICE	A Large Ion Collider Experiment
TOTEM	Total Cross Section, Elastic Scattering and Diffraction Dissociation
LHCf	LHC-forward
MoEDAL	Monopole and Exotics Detector At the LHC

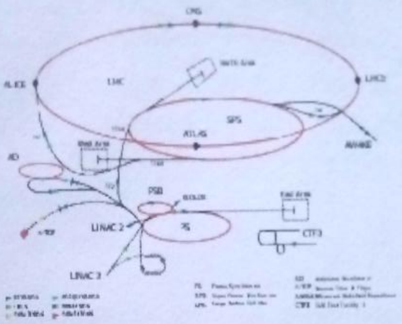
LHC preaccelerators

p and Pb	Linear accelerators for protons(Linac 2) and Lead (Linac 3)

(not marked)	Proton Synchrotron Booster
PS	Proton Synchrotron
SPS	Super Proton Synchrotron

Hadron colliders	
Intersecting Storage Rings	CERN, 1971–1984
Proton-Antiproton Collider (SPS)	CERN, 1981–1991
ISABELLE	BNL, cancelled in 1983
Tevatron	Fermilab, 1987–2011
Superconducting Super Collider	Cancelled in 1993
Relativistic Heavy Ion Collider	BNL, 2000–present
Large Hadron Collider	CERN, 2009–present
Future Circular Collider	Proposed

CERN accelerator complex



List of current particle accelerators at CERN

Linac 2	Accelerates protons
Linac 3	Accelerates ions
Linac 4	Accelerates negative hydrogen ions
AD	Decelerates antiprotons
LHC	Collides protons or heavy ions
LEIR	Accelerates ions
PSB	Accelerates protons or ions
PS	Accelerates protons or ions
SPS	Accelerates protons or ions

New particles

One of the most famous examples of the LHC in action is the famous Higgs boson.

The particle was the final missing piece of what physicists refer to as the Standard Model of particle physics - a set of laws that governs particles on the most fundamental scale.

It took almost 50 years from Peter Higgs' first calculations to its discovery in 2012. But the particle, which is said to give all other particles mass through a ubiquitous field known as the Higgs field, is not the only the beginning.

More recently, the LHCb detector – also known as the Large Hadron Collider beauty – found five new particles 'hiding in plain sight' as it was searching for objects such as antimatter. The five particles are examples of baryons, which means they are made up of three fundamental particles called quarks, and all of them were discovered at once.

Background

The term *hadron* refers to composite particles composed of quarks held together by the strong force (as atoms and molecules are held together by the electro-magnetic force). The best-known hadrons are the baryons such as protons and neutrons; hadrons also include mesons such as the pion and kaon, which were discovered during cosmic ray experiments in the late 1940s and early 1950s.

A *collider* is a type of a particle accelerator with two directed beams of particles. In particle physics, colliders are used as a research tool: they accelerate particles to relatively high kinetic energies and let them impact other particles. Analysis of the byproducts of these collisions gives scientists good evidence of the structure of the subatomic world and the laws of nature governing it. Many of these byproducts are produced only by high-energy collisions, and they decay after very short periods of time. Thus many of them are hard or nearly impossible to study in other ways.

Purpose

Physicists hope that the Large Hadron Collider will help answer some of the fundamental open questions in physics, concerning the basic laws governing the interactions and forces among the elementary objects, the deep structure of space and time, and in particular the interrelation between quantum mechanics and general relativity.

Data are also needed from high-energy particle experiments to suggest which versions of current scientific models are more likely to be correct in particular to choose between the Standard Model and Higgsless model and to validate their predictions and allow further theoretical development. Many theorists expect new physics beyond the Standard Model to emerge at the TeV energy level, as the Standard Model appears to be unsatisfactory. Issues explored by LHC collisions include:

- is the mass of elementary particles being generated by the Higgs mechanism via electroweak symmetry breaking? It was expected that the collider experiments will either demonstrate or rule out the existence of the elusive Higgs boson, thereby allowing physicists to consider whether the Standard Model or its Higgsless alternatives are more likely to be correct.
- is supersymmetry, an extension of the Standard Model and Poincaré symmetry, realized in nature,

implying that all known particles have supersymmetric partners?

- Are there extra dimensions, as predicted by various models based on string theory, and can we detect them?
- What is the nature of the dark matter that appears to account for 27% of the mass-energy of the universe?

Other open questions that may be explored using high-energy particle collisions:

- It is already known that electromagnetism and the weak nuclear force are different manifestations of a single force called the electroweak force. The LHC may clarify whether the electroweak force and the strong nuclear force are similarly just different manifestations of one universal unified force, as predicted by various Grand Unification Theories.
- Why is the fourth fundamental force (gravity) so many orders of magnitude weaker than the other three fundamental forces? See also Hierarchy problem.
- Are there additional sources of quark flavour mixing, beyond those already present within the Standard Model?
- Why are there apparent violations of the symmetry between matter and antimatter? See also CP violation.
- What are the nature and properties of quark–gluon plasma, thought to have existed in the early universe and in certain compact and strange astro-

nomical objects today? This will be investigated by *heavy ion collisions*, mainly in ALICE, but also in CMS, ATLAS and LHCb. First observed in 2010, findings published in 2012 confirmed the phenomenon of jet quenching in heavy-ion collisions.

Design

The LHC is the world's largest and highest-energy particle accelerator.[27][28] The collider is contained in a circular tunnel, with a circumference of 26.7 kilometres (16.6 mi), at a depth ranging from 50 to 175 metres (164 to 574 ft) underground.

he 3.8-metre (12 ft) wide concrete-lined tunnel, constructed between 1983 and 1988, was formerly used to house the Large Electron–Positron Collider.[29] It crosses the border between Switzerland and France at four points, with most of it in France. Surface buildings hold ancillary equipment such as compressors, ventilation equipment, control electronics and refrigeration plants.

The collider tunnel contains two adjacent parallel beamlines (or *beam pipes*) each containing a beam, which travel in opposite directions around the ring. The beams intersect at four points around the ring, which is where the particle collisions take place. Some 1,232 dipole magnets keep the beams on their circular path (see image[30]), while an additional 392 quadrupole magnets are used to keep the beams focused, with stronger quadrupole magnets close to the intersection points in order to maximize the chances of interaction where the two beams cross. Magnets of higher multipole orders are used to correct smaller imperfections in the field geometry. In total, about 10,000 superconducting magnets are installed, with the dipole magnets having a mass of over 27 tonnes.[31] Approximately 96 tonnes of superfluid helium-4 is needed to keep the magnets, made of copper-clad niobium-titanium, at their operating temperature of 1.9 K (−271.25 °C), making the LHC the largest cryogenic facility in the world at liquid helium temperature. During LHC operations, the CERN site draws roughly 200 MW of electrical power from the French electrical grid, which, for comparison, is about one-third the energy consumption of the city of Geneva; the LHC accelerator and detectors draw about 120 MW thereof.

When running at the current energy record of 6.5 TeV per proton, once or twice a day, as the protons are accelerated from 450 GeV to 6.5 TeV, the field of the superconducting dipole magnets will be increased from 0.54 to 7.7 teslas (T). The protons each have an energy of 6.5 TeV, giving a total collision energy of 13 TeV. At this energy the protons have a Lorentz factor of about 6,930 and move at about 0.999999990 *c*, or about 3.1 m/s (11 km/h) slower than the speed of light (*c*). It takes less than 90 microseconds (μs) for a proton to travel 26.7 km around the main ring. This results in 11,245 revolutions per second for protons whether the particles are at low or high energy in the main ring, since the speed difference between these energies is beyond the fifth decimal.

Rather than having continuous beams, the protons are bunched together, into up to 2,808 bunches, with 115 billion protons in each bunch so that interactions between the two beams take place at discrete intervals, mainly 25 nanoseconds (ns) apart, providing a bunch collision rate of 40 MHz. It was operated with fewer bunches in the first years. The design luminosity of the LHC is 10^{34} $cm^{-2}s^{-1}$, which was first reached in June 2016. By 2017 twice this value was achieved.

Before being injected into the main accelerator, the particles are prepared by a series of systems that successively increase their energy. The first system is the linear particle accelerator LINAC 2 generating 50-MeV protons, which feeds the Proton Synchrotron Booster (PSB). There the protons are accelerated to 1.4 GeV and injected into the Proton Synchrotron (PS), where they are accelerated to 26 GeV. Finally the Super Proton Synchrotron (SPS) is used to increase their energy further to 450 GeV before they are at last injected (over a period of several minutes) into the main ring. Here the proton bunches are accumulated, accelerated (over a period of 20 minutes) to their peak energy, and finally circulated for 5 to 24 hours while collisions occur at the four intersection points.

The LHC physics programme is mainly based on proton–proton collisions. However, shorter running periods, typically one month per year, with heavy-ion collisions are included in the programme. While lighter ions are considered as well, the baseline scheme deals with leadions (see A Large Ion Collider Experiment).

The lead ions are first accelerated by the linear accelerator LINAC 3, and the Low Energy Ion Ring (LEIR) is used as an ion storage and cooler unit. The ions are then further accelerated by the PS and SPS before being injected into LHC ring, where they reached an energy of 2.3 TeV per nucleon (or 522 TeV per ion), higher than the energies reached by the Relativistic Heavy Ion Collider. The aim of the heavy-ion programme is to investigate quark–gluon plasma, which existed in the early universe.

Detectors

Seven detectors have been constructed at the LHC, located underground in large caverns excavated at the LHC's intersection points. Two of them, the ATLAS experiment and the Compact Muon Solenoid (CMS), are large general-purpose particle detectors. ALICE and LHCb have more specific roles and the last three, TOTEM, MoEDAL and LHCf, are very much smaller and are for very specialized research. The ATLAS and CMS experiments discovered the Higgs boson, which is strong evidence that the Standard Model has the correct mechanism of giving mass to elementary particles.

The BBC's summary of the main detectors is:

Detector	Description
ATLAS	One of two general-purpose detectors. ATLAS studies the Higgs boson and looks for signs of new physics, including the origins of mass and extra dimensions.
CMS	The other general-purpose detector, like ATLAS, studies the Higgs boson and look for clues of new physics.
ALICE	ALICE is studying a "fluid" form of matter called quark–gluon plasma that existed shortly

	after the Big Bang.
LHCb	Equal amounts of matter and antimatter were created in the Big Bang. LHCb investigates what happened to the "missing" antimatter.

Computing and analysis facilities

Data produced by LHC, as well as LHC-related simulation, were estimated at approximately 15 petabytes per year (max throughput while running not stated) a major challenge in its own right at the time.

The LHC Computing Grid was constructed as part of the LHC design, to handle the massive amounts of data expected for its collisions. It is an international collaborative project that consists of a grid-based computer network infrastructure initially connecting 140 computing centres in 35 countries (over 170 in 36 countries as of 2012). It was designed by CERN to handle the significant volume of data produced by LHC experiments, incorporating both private fibre optic cable links and existing high-speed portions of the public Internet to enable data transfer from CERN to academic institutions around the world. The Open Science Grid is used as the primary infrastructure in the United States, and also as part of an interoperable federation with the LHC Computing Grid.

The distributed computing project LHC was started to support the construction and calibration of the LHC. The project uses the BOINC platform, enabling anybody with an Internet connection and a computer running Mac OS X, Windows or Linux, to use their computer's idle time to simulate how particles will travel in the beam pipes. With this information, the scientists are able to determine how the magnets should be calibrated to gain the most stable "orbit" of the beams in the ring.[47] In August 2011, a second application went live (Test4Theory) which performs simulations against which to compare actual test data, to determine confidence levels of the results.

By 2012 data from over 6 quadrillion (6 x 10^{15}) LHC proton-proton collisions had been analysed, LHC collision data was being produced at approximately 25 petabytes per year, and the LHC Computing Grid had become the world's largest computing grid in 2012, comprising over 170 computing facilities in a worldwide network across 36 countries.

Operational history

The LHC first went live on 10 September 2008, but initial testing was delayed for 14 months from 19 September 2008 to 20 November 2009, following a magnet quench incident that caused extensive damage to over 50 superconducting magnets, their mountings, and the vacuum pipe.

During its first run (2010–2013) the LHC collided two opposing particle beams of either protons at up to 4 teraelectronvolts (4 TeV or 0.64 microjoules), or lead nuclei (574 TeV per nucleus, or 2.76 TeV per nucleon). Its first run discoveries included the long-sought Higgs boson, several composite particles (hadrons) like the χ_b (3P) bottomonium state, the first creation of a quark–gluon plasma, and the first observations of the very rare decay of the B_s meson into two muons ($B_s^0 \rightarrow \mu^+\mu^-$), which challenged the validity of existing models of supersymmetry.

Operational challenges

The size of the LHC constitutes an exceptional engineering challenge with unique operational issues on account of the amount of energy stored in the magnets and the beams.While operating, the total energy stored in the magnets is 10 GJ (2,400 kilograms of TNT) and the total energy carried by the two beams reaches 724 MJ (173 kilograms of TNT).

Loss of only one ten-millionth part (10^{-7}) of the beam is sufficient to quench a superconducting magnet, while each of the two beam dumps must absorb 362 MJ (87 kilograms of TNT). These energies are carried by very little matter: under nominal operating conditions (2,808 bunches per beam, 1.15×10^{11} protons per bunch), the beam pipes contain 1.0×10^{-9} gram of hydrogen, which, in standard conditions for temperature and pressure, would fill the volume of one grain of fine sand.

Cost

With a budget of €7.5 billion (approx. $9bn or £6.19bn as of June 2010), the LHC is one of the most expensive scientific instruments ever built. The total cost of the project is expected to be of the order of 4.6bn Swiss francs (SFr) (approx. $4.4bn, €3.1bn, or £2.8bn as of January 2010) for the accelerator and 1.16bn (SFr) (approx. $1.1bn, €0.8bn, or £0.7bn as of January 2010) for the CERN contribution to the experiments.

The construction of LHC was approved in 1995 with a budget of SFr 2.6bn, with another SFr 210M toward the experiments. However, cost overruns, estimated in a major review in 2001 at around SFr 480M for the accelerator, and SFr 50M for the experiments, along with a reduction in CERN's budget, pushed the completion date from 2005 to April 2007.[64]The superconducting magnets were responsible for SFr 180M of the cost increase. There were also further costs and delays owing to engineering difficulties encountered while building the underground cavern for the Compact Muon Solenoid,[65] and also due to magnet supports which were insufficiently strongly designed and failed their initial testing (2007) and damage from a magnet quench and liquid helium escape (inaugural testing, 2008) Because electricity costs are lower during the summer, the LHC normally does not operate over the winter months, although exceptions operate over the winter months, although exceptions over the 2009/10 and 2012/2013 winters were made to make up for the 2008 start-up delays and to improve precision of measurements of the new particle discovered in 2012, respectively.

Construction accidents and delays

- On 25 October 2005, José Pereira Lages, a technician, was killed in the LHC when a switchgear that was being transported fell on top of him.
- On 27 March 2007 a cryogenic magnet support designed and provided by Fermilab and KEK broke during an initial pressure test involving one of the LHC's inner triplet (focusing quadrupole) magnet assemblies. No one was injured. Fermilab director Pier Oddone stated "In this case we are dumbfounded that we missed some very simple balance of forces". The fault had been present in the original design, and remained during four engineering reviews over the following years. Analysis revealed that its design, made as thin as possible for better insulation, was not strong enough to withstand the forces generated during pressure testing. Details are available in a statement from Fermilab, with which CERN is in agreement. Repairing the broken magnet and reinforcing the eight identical assemblies used by LHC delayed the start-up date, then planned for November 2007.

- On 19 September 2008, during initial testing, a faulty electrical connection led to a magnet quench (the sudden loss of a superconducting magnet's superconducting ability owing to warming or electric field effects). Six tonnes of supercooled liquid helium used to cool the magnets—escaped, with sufficient force to break 10-ton magnets nearby from their mountings, and caused considerable damage and contamination of the vacuum tube repairs and safety checks caused a delay of around 14 months.
- Two vacuum leaks were found in July 2009, and the start of operations was further postponed to mid-November 2009.

Initial lower magnet currents

In both of its runs (2010 to 2012 and 2015), the LHC was initially run at energies below its planned operating energy, and ramped up to just 2 x 4 TeV energy on its first run and 2 x 6.5 TeV on its second run, below the design energy of 2 x 7 TeV. This is because massive superconducting magnets require considerable magnet training to handle the high currents involved without losing their superconducting ability, and the high currents are necessary to allow a high proton energy. The "training" process involves repeatedly running the magnets with lower currents to provoke any quenches or minute movements that may result. It also takes time to cool down magnets to their operating temperature of around 1.9 K(close to absolute zero). Over time the magnet "beds in" and ceases to quench at these lesser currents and can handle the full design current without quenching; CERN media describe the magnets as "shaking out" the unavoidable tiny manufacturing imperfections in their crystals and positions that had initially impaired their ability to handle their planned currents. The magnets, over time and with training, gradually become able to handle their full planned currents without quenching.

WORKING

The principle behind the LHC is pretty simple. First, you fire two beams of particles along two pathways, one going clockwise and the other going counterclockwise. You accelerate both beams to near the speed of light. Then, you direct both beams toward each other and watch what happens.

The equipment necessary to achieve that goal is far more complex. The LHC is just one part of the overall CERN particle accelerator facility. Before any protons or **ions** enter the LHC, they've already gone through a series of steps.

Let's take a look at the life of a proton as it goes through the LHC process. First, scientists must strip electrons from hydrogen atoms to produce protons. Then, the protons enter the **LINAC2**, a machine that fires beams of protons into an accelerator called the **PS Booster**. These machines use devices called **radio frequency cavities** to accelerate the protons. The cavities contain a radio-frequency electric field that pushes the proton beams to higher speeds. Giant magnets produce the magnetic fields necessary to keep the proton beams on track. In car terms, think of the radio frequency cavities as an accelerator and the magnets as a steering wheel

Once a beam of protons reaches the right energy level, the PS Booster injects it into another accelerator called the **Super Proton Synchotron (SPS)**. The beams continue to pick up speed. By now, beams have divided into **bunches**. Each bunch contains 1.1 x 10^{11} protons, and there are 2,808 bunches per beam [source: CERN]. The SPS injects beams into the LHC, with one beam traveling clockwise and the other going counterclockwise.

Inside the LHC, the beams continue to accelerate. This takes about 20 minutes. At top speed, the beams make 11,245 trips around the LHC every second. The two beams converge at one of the six detector sites positioned along the LHC. At that position, there will be 600 million collisions per second [source: CERN].

When two protons collide, they break apart into even smaller particles. That includes subatomic particles called **quarks** and a mitigating force called **gluon**. Quarks are very unstable and will decay in a fraction of a second. The detectors collect information by tracking the path of subatomic particles. Then the detectors send data to a grid of computer systems.

Not every proton will collide with another proton. Even with a machine as advanced as the LHC, it's impossible to direct beams of particles as small as protons so that every particle will collide with another one. Protons that fail to collide will continue in the beam to a beam dumping section. There, a section made of graphite will absorb the beam. The beam dumping sections are able to absorb beams if something goes wrong inside the LHC. To learn more about the mechanics behind particle accelerators, take a look at How Atom Smashers Work.

The LHC has six detectors positioned along its circumference. What do these detectors do and how do they work? Find out in the next section.

The LHC, the world's largest and most powerful particle accelerator, is the latest addition to CERN's accelerator complex. It mainly consists of a 27 kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.

Inside the accelerator, two beams of particles travel at close to the speed of light with very high energies before colliding with one another. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field, achieved using superconducting electromagnets. These are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss of energy. This requires chilling the magnets to about -271°C – a temperature colder than outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as to other supply services.

Thousands of magnets of different varieties and sizes are used to direct the beams around the accelerator. These include 1232 dipole magnets of 15m length which are used to bend the beams, and 392 quadrupole magnets, each 5–7m long, to focus the beams. Just prior to collision, another type of magnet is used to "squeeze" the particles closer together to increase the chances of collisions. The particles are so tiny that the task of making them collide is akin to firing needles from two positions 10km apart with such precision that they meet halfway!

All the controls for the accelerator, its services and technical infrastructure are housed under one roof at the CERN Control Centre. From here, the beams inside the LHC are made to collide at four locations around the accelerator ring, corresponding to the positions of the particle detectors.

Timeline of operations

1)DateEvent10 Sep 2008CERN successfully fired the first protons around the entire tunnel circuit in stages.

2)19 Sep 2008Magnetic quench occurred in about 100 bending magnets in sectors 3 and 4, causing a loss of approximately 6 tonnes of liquid helium

3)30 Sep 2008First "modest" high-energy collisions planned but postponed due to accident.

4)16 Oct 2008CERN released a preliminary analysis of the accident.

5)21 Oct 2008Official inauguration.

6)5 Dec 2008CERN released detailed analysis.

7)20 Nov 2009Low-energy beams circulated in the tunnel for the first time since the accident.

8)23 Nov 2009First particle collisions in all four detectors at 450 GeV.

9)30 Nov 2009LHC becomes the world's highest-energy particle accelerator achieving 1.18 TeV per beam, beating the Tevatron's previous record of 0.98 TeV per beam held for eight years.

10) 15 Dec 2009First scientific results, covering 284 collisions in the ALICE detector.

11) 30 Mar 2010The two beams collided at 7 TeV (3.5 TeV per beam) in the LHC at 13:06 CEST, marking the start of the LHC research programme.

12) 8 Nov 2010Start of the first run with lead ions.

13) 6 Dec 2010End of the run with lead ions. Shutdown until early 2011.

14) 13 Mar 2011Beginning of the 2011 run with proton beams.

15) 21 Apr 2011LHC becomes the world's highest-luminosity hadron accelerator achieving a peak luminosity of $4.67 \cdot 10^{32}$ cm^{-2}s^{-1}, beating the Tevatron's previous record of $4 \cdot 10^{32}$ cm^{-2}s^{-1} held for one year.

16) 24 May 2011ALICE reports that a Quark–gluon plasma has been achieved with earlier lead collisions.

17) 17 Jun 2011The high-luminosity experiments ATLAS and CMS reach 1 fb^{-1} of collected data.

18) 14 Oct 2011LHCb reaches 1 fb^{-1} of collected data.

19) 23 Oct 2011The high-luminosity experiments ATLAS and CMS reach 5 fb^{-1} of collected data.Nov 2011Second run with lead ions.

20) 22 Dec 2011First new composite particle discovery, the χ_b (3P) bottomonium meson, observed with proton-proton collisions in 2011.

21) 5 Apr 2012First collisions with stable beams in 2012 after the winter shutdown. The energy is increased to 4 TeV per beam (8 TeV in collisions).

22) 4 Jul 2012First new elementary particle discovery, a new boson observed that is "consistent with" the theorized Higgs boson. (This has now been confirmed as the Higgs boson itself.

23) 8 Nov 2012First observation of the very rare decay of the B_s meson into two muons ($B_s^0 \to \mu^+\mu^-$), a major test of supersymmetry theories, shows results at 3.5 sigma that match the Standard Model rather than many of its super-symmetrical variants.

24) 20 Jan 2013Start of the first run colliding protons with lead ions.

25) 11 Feb 2013End of the first run colliding protons with lead ions.

26) 14 Feb 2013Beginning of the first long shutdown to prepare the collider for a higher energy and luminosity.

27) 7 Mar 2015Injection tests for Run 2 send protons towards LHCb & ALICE5 Apr 2015Both beams circulated in the collider. Four days later, a

new record energy of 6.5 TeV per proton was achieved.

28) 20 May 2015Protons collided in the LHC at the record-breaking collision energy of 13 TeV.

29) 3 Jun 2015Start of delivering the physics data after almost two years offline for recommissioning.

30) 4 Nov 2015End of proton collisions in 2015, start of preparations for ion collisions.

31) 25 Nov 2015First ion collisions at a record-breaking energy of more than 1 PeV (10^{15} eV)

32) 13 Dec 2015End of ion collisions in 2015

33) 23 Apr 2016Data-taking in 2016 begins

34) 29 June 2016The LHC achieves a luminosity of $1.0 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, its design value. Further improvements over the year increased the luminosity to 40% above the design value.

35) 26 Oct 2016End of 2016 proton-proton collisions

36) 10 Nov 2016Beginning of 2016 proton-lead collisions

37) 3 Dec 2016End of 2016 proton-lead collisions

38) 24 May 2017Start of 2017 proton-proton collisions. During 2017, the luminosity increased to twice its design value.

39) 10 Nov 2017End of regular 2017 proton-proton collision mode.

40) 17 Apr 2018Start of 2018 proton-proton collisions.

Findings and discoveries

An initial focus of research was to investigate the possible existence of the Higgs boson, a key part of the Standard Model of physics which is predicted by theory but had not yet been observed before due to its high mass and elusive nature. CERN scientists estimated that, if the Standard Model were correct, the LHC would produce several Higgs bosons every minute, allowing physicists to finally confirm or disprove the Higgs boson's existence. In addition, the LHC allowed the search for supersymmetric particles and other hypothetical particles as possible unknown areas of physics.[27] Some extensions of the Standard Model predict additional particles, such as the heavy W' and Z' gauge bosons, which are also estimated to be within reach of the LHC to discover.

First run (data taken 2009–2013)

The first physics results from the LHC, involving 284 collisions which took place in the ALICE detector, were reported on 15 December 2009. The results of the first proton–proton collisions at energies higher than Fermilab's Tevatron proton–antiproton collisions were published by the CMS collaboration in early February

2010, yielding greater-than-predicted charged-hadron production.

After the first year of data collection, the LHC experimental collaborations started to release their preliminary results concerning searches for new physics beyond the Standard Model in proton-proton collisions.No evidence of new particles was detected in the 2010 data. As a result, bounds were set on the allowed parameter space of various extensions of the Standard Model, such as models with large extra dimensions, constrained versions of the Minimal Supersymmetric Standard Model, and others.

On 24 May 2011, it was reported that quark–gluon plasma (the densest matter thought to exist besides black holes) had been created in the LHC.

Between July and August 2011, results of searches for the Higgs boson and for exotic particles, based on the data collected during the first half of the 2011 run, were presented in conferences in Grenoble and Mumbai. In the latter conference it was reported that, despite hints of a Higgs signal in earlier data, ATLAS and CMS exclude with 95% confidence level (using the CLs method) the existence of a Higgs boson with the properties predicted by the Standard Model over most of the mass region between 145 and 466 GeV. The searches for new particles did not yield signals either, allowing to further constrain the parameter space of various extensions of the Standard Model, including its supersymmetric extensions.

On 13 December 2011, CERN reported that the Standard Model Higgs boson, if it exists, is most likely to have a mass constrained to the range 115–130 GeV. Both the CMS and ATLAS detectors have also shown intensity peaks in the 124–125 GeV range, consistent with either background noise or the observation of the Higgs boson.

On 22 December 2011, it was reported that a new composite particle had been observed, the χ_b (3P) bottomonium state.

On 4 July 2012, both the CMS and ATLAS teams announced the discovery of a boson in the mass region around 125–126 GeV, with a statistical significance at the level of 5 sigma each. This meets the formal level required to announce a new particle. The observed properties were consistent with the Higgs boson, but scientists were cautious as to whether it is formally identified as actually being the Higgs boson, pending further analysis.

On 8 November 2012, the LHCb team reported on an experiment seen as a "golden" test of supersymmetry theories in physics, by measuring the very rare decay of the meson into two muons . The results, which match those predicted by the non-supersymmetrical Standard Model rather than the predictions of many branches of supersymmetry, show the decays are less common than some forms of supersymmetry predict, though could still match the predictions of other versions of supersymmetry theory.

The results as initially drafted are stated to be short of proof but at a relatively high 3.5 sigma level of significance. The result was later confirmed by the CMS collaboration.

In August 2013 the LHCb team revealed an anomaly in the angular distribution of B meson decay products which could not be predicted by the Standard Model; this anomaly had a statistical certainty of 4.5 sigma, just short of the 5 sigma needed to be officially recognized as a discovery. It is unknown what the cause of this anomaly would be, although the Z' boson has been suggested as a possible candidate.

On 19 November 2014, the LHCb experiment announced the discovery of two new heavy subatomic particles, Ξ'^{-}_{b} and Ξ^{*-}_{b}. Both of them are baryons that are composed of one bottom, one down, and one strange quark. They are excited states of the bottom Xi baryon.

The LHCb collaboration has observed multiple exotic hadrons, possibly pentaquarks or tetraquarks, in the Run 1 data. On 4 April 2014, the collaboration confirmed the existence of the tetraquark candidate Z(4430) with a significance of over 13.9 sigma. On 13 July 2015, results consistent with pentaquark states in the decay of bottom Lambda baryons(Λ^{0}_{b}) were reported.

On 28 June 2016, the collaboration announced four tetraquark-like particles decaying into a J/ψ and a φ meson, only one of which was well established before (X(4274), X(4500) and X(4700) and X(4140)).

In December 2016, ATLAS presented a measurement of the W boson mass, researching the precision of analyses done at the Tevatron.

Second run (2015 onward)

At the conference EPS-HEP 2015 in July, the collaborations presented first cross-section measurements of several particles at the higher collision energy.

On 15 December 2015, the ATLAS and CMS experiments both reported a number of preliminary results for Higgs physics, supersymmetry (SUSY) searches and exotics searches using 13 TeV proton collision data. Both experiments saw a moderate excess around 750 GeV in the two-photon invariant mass spectrum, but the experiments did not confirm the existence of the hypothetical particle in an August 2016 report.

In July 2017, many analyses based on the large dataset collected in 2016 were shown. The properties of the Higgs boson were studied in more detail and the precision of many other results was improved.

The Brout-Englert-Higgs mechanism

In the 1970s, physicists realised that there are very close ties between two of the four fundamental forces – the weak force and the electromagnetic force. The two forces can be described within the same theory, which forms the basis of the Standard Model. This “unification” implies that electricity, magnetism, light and some types of radioactivity are all manifestations of a single underlying force known as the electroweak force.

The basic equations of the unified theory correctly describe the electroweak force and its associated force-carrying particles, namely the photon, and the W and Z bosons, except for a major glitch. All of these particles emerge without a mass. While this is true for the photon, we know that the W and Z have mass, nearly 100 times that of a proton. Fortunately, theorists Robert Brout, François Englert and Peter Higgs made a proposal

An elusive particle

A problem for many years has been that no experiment has observed the Higgs boson to confirm the theory. On 4 July 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider announced they had each observed a new particle in the mass region around 125 GeV. This particle is consistent with the Higgs boson but it will take further work to determine whether or not it is the Higgs boson predicted by the Standard Model. The Higgs boson, as proposed within the Standard Model, is the simplest manifestation of the Brout-Englert-Higgs mechanism. Other types of Higgs bosons are predicted by other theories that go beyond the Standard Model.

On 8 October 2013 the Nobel prize in physics was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

Planned "high-luminosity" upgrade

After some years of running, any particle physics experiment typically begins to suffer from diminishing returns: as the key results reachable by the device begin to be completed, later years of operation discover proportionately less than earlier years. A common response is to upgrade the devices involved, typically in collision energy, luminosity, or improved detectors. In addition to a possible increase to 14 TeV collision energy in 2018, a luminosity upgrade of the LHC, called the High Luminosity LHC, started in June 2018 that will boost the accelerator's potential for new discoveries in physics, starting in 2026.[152] The upgrade aims at increasing the luminosity of the machine by a factor of 10, up to $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, providing a better chance to see rare processes and improving statistically marginal measurements.

Safety of particle collisions

The experiments at the Large Hadron Collider sparked fears that the particle collisions might produce doomsday phenomena, involving the production of stable microscopic black holes or the creation of hypothetical particles called strangelets. Two CERN-commissioned safety reviews examined these concerns and concluded that the experiments at the LHC present no danger and that there is no reason for concern, a conclusion endorsed by the American Physical Society.

The reports also noted that the physical conditions and collision events that exist in the LHC and similar experiments occur naturally and routinely in the universe without hazardous consequences, including ultra-high-energy cosmic rays observed to impact Earth with energies far higher than those in any man-made collider.

Popular culture

The Large Hadron Collider gained a considerable amount of attention from outside the scientific community and its progress is followed by most popular science media. The LHC has also inspired works of fiction including novels, TV series, video games and films.

CERN employee Katherine McAlpine's "Large Hadron Rap" surpassed 7 million YouTube views. The band Les Horribles Cernettes was founded by women from CERN. The name was chosen so to have the same initials as the LHC.

National Geographic Channel's *World's Toughest Fixes*, Season 2 (2010), Episode 6 "Atom Smasher" features the replacement of the last superconducting magnet section in the repair of the collider after the 2008 quench incident. The episode includes actual footage from the repair facility to the inside of the collider, and explanations of the function, engineering, and purpose of the LHC.

The Large Hadron Collider was the focus of the 2012 student film *Decay*, with the movie being filmed on location in CERN's maintenance tunnels.

The feature documentary *Particle Fever* follows the experimental physicists at CERN who run the experiments, as well as the theoretical physicists who attempt to provide a conceptual framework for the

LHC's results. It won the Sheffield International Doc/Fest in 2013.

Fiction

The novel *Angels & Demons*, by Dan Brown, involves antimatter created at the LHC to be used in a weapon against the Vatican. In response, CERN published a "Fact or Fiction?" page discussing the accuracy of the book's portrayal of the LHC, CERN, and particle physics in general.The movie version of the book has footage filmed on-site at one of the experiments at the LHC; the director, Ron Howard, met with CERN experts in an effort to make the science in the story more accurate.

In the visual novel/manga/anime-series "Steins;Gate", SERN (a deliberate misspelling of CERN) is an organization that uses the miniature black holes created from experiments in the LHC to master time travel and take over the world. It is also involved in mass vigilance through the "ECHELON" project and has connection with many mercenary groups worldwide, to avoid the creation of other time machines.

The novel *FlashForward*, by Robert J. Sawyer, involves the search for the Higgs boson at the LHC. CERN published a "Science and Fiction" page interviewing Sawyer and physicists about the book and the TV series based on it.

First three-year LHC running period reaches a conclusion

On February 14th the Large Hadron Collider (LHC) at CERN switched off its particle beams bringing the machine's first three-year running period to a successful conclusion.

The LHC's first run has seen major advances in physics, including the discovery of a new particle that looks increasingly like the long–sought Higgs boson, announced on 4 July 2012. And during the last weeks of the run, the remarkable figure of 100 petabytes of data stored in the CERN mass-storage systems was surpassed. This data volume is roughly equivalent to 700 years of full HD-quality movies. Handling these unprecedented levels of data is a challenge in itself and the UK makes a significant investment in the computing infrastructure as part of the worldwide LHC Computing Grid (wLCG), including the Tier 1 computing facility at STFC's Rutherford Appleton Laboratory.

The LHC now begins its first long shutdown, LS1. Over the coming month's major consolidation and maintenance work will be carried out across the whole of CERN's accelerator chain with the LHC readied for higher energy running. LHC running is scheduled to resume in 2015, with the rest of the CERN complex starting up again in the second half of 2014.

STFC pays the UK contribution to the CERN budget as well as supporting UK participation in the four LHC experimental detector projects, including the Higgs boson detectors ATLAS and CMS, which will all undergo essential maintenance during the long shutdown. With nearly 600 UK scientists regularly working at CERN the UK has made major strategic investments in the LHC and the development of the experimental detectors and played a central role in much of the research that has taken place at the LHC in the last three years. Speaking about the shutdown Dr Victoria Martin, researcher in particle physics at the University of Edinburgh and member of the ATLAS experiment, said that for the UK research teams involved with the projects at the LHC "It is now time to assess the data we currently have in greater depth than we have been able to so far. In addition there is also a lot of planning: planning for how to analyse the data we will take in 2015 onwards, planning on how to cope with this extra amount of data and planning for the future: We hope to further upgrade the LHC experiments at the end of this decade and that requires a lot of preparatory work now."

The LHC detector upgrade programme is already underway and work will continue during the LS1 shutdown. These upgrades are essential to exploiting the LHC and the UK is playing a prominent role in this international R&D effort.

CERN's Director for Accelerators and Technology, Steve Myers is one of more than 200 UK nationals employed by CERN and has said that "There is a great deal of consolidation work to do on CERN's whole accelerator complex, as well as the LHC itself, we'll essentially be rebuilding the interconnections between LHC magnets, so when we resume running in 2015, we will be able to operate the machine at its design energy of 7TeV per beam".

The LHC exceeded all expectations in its first three-year run, delivering significantly more data to the experiments than initially foreseen. Physicists measure data quantity in units known as inverse femtobarns, and by the time the last high energy proton-proton data were recorded in December, the ATLAS and CMS experiments had each recorded around 30 inverse femtobarns, of which over 23 were recorded in 2012.

To put this into context, the Higgs boson-like particle whose discovery was announced on 4 July 2012 was found by analysing around 12 inverse femtobarns. That means CERN's experimental physics community still has plenty of data to analyse during LS1. For the first weeks of 2013, the LHC has been colliding protons with lead ions as part of the programme to understand matter as it would have been just after the Big Bang. The last four days of the run saw a return to proton-proton collisions, this time at reduced energy. These collisions will provide useful data for interpreting the data recorded with lead ions. Single beam studies will continue until the weekend, when the process of bringing the LHC up to room temperature will begin, allowing LS1 work to get under way.

Dr Adam Davison, from the High Energy Physics Group at UCL, also works on the ATLAS experiment at CERN and has said that "Obviously everyone is sad to see the LHC stop, it's more exciting when the data is flooding in. However, we all know it's for a good reason an we're looking forward to the higher energy run commencing in 2015."