The High-Luminosity LHC (HL-LHC) Project

The Council is invited to approve the HL-LHC project, described herein, which, as part of the LHC programme, implements the highest priority of the European Strategy for Particle Physics.
Foreword

The exploitation of the full physics potential of the Large Hadron Collider, including the high-luminosity upgrade of the machine and detectors, was defined as the top priority in the European Strategy for Particle Physics (ESPP), unanimously adopted by the Council in May 2013. This strategic decision is being implemented through the upgrade of the existing LHC programme, referred to as the HL-LHC project, launched in 2014. The project description, goals, timeline and cost estimates have been endorsed, and the related annual budgets approved by the Council in successive Medium-Term Plans since 2014. Furthermore, with the Council’s strong support, the HL-LHC has been included as a Landmark Project in the 2016 roadmap of ESFRI, the European Strategy Forum on Research Infrastructures.

In the context of discussions at recent Finance Committee and Council meetings, the desirability of formal approval of the HL-LHC has been advocated, following Article 5 of the CERN Financial Rules (“Where their scale so warrants, projects may be subject to separate approval by the Council”). CERN’s Management has therefore prepared the description contained herein of the scientific, technical and financial aspects of the project, as a concise summary of the information already provided in the Medium-Term Plans and other technical documents. The technical and financial status of the project during the construction period will be monitored through reviews carried out by international experts and regularly reported to the CERN Council.

The Council is invited to approve the HL-LHC project, described herein, which, as part of the LHC programme, implements the highest priority of the European Strategy for Particle Physics. Given the already well-established support for this project from CERN’s Member States, the fact that it will be realised within a constant CERN Budget, and its critical importance for the future of the Organization and particle physics worldwide, consensus would be desirable.
The High-Luminosity LHC Project

Abstract
The scientific case for a luminosity upgrade of the Large Hadron Collider (High-Luminosity LHC, HL-LHC) is presented. It includes measurements of the Higgs boson properties with unprecedented precision and increased potential in the search for new physics. Construction is expected to be completed by the mid-twenties, and by the mid-thirties the HL-LHC should have provided a tenfold increase in the integrated luminosities recorded by the experiments. Main upgrade components include new-technology superconducting magnets and current leads. The cost of the collider upgrade, which will be realised within a constant CERN Budget, is estimated to be 950 MCHF. The main technical challenges, as well as the ongoing R&D work and the main milestones of the implementation plan, are described.
Introduction

The Large Hadron Collider (LHC) at CERN is the highest-energy accelerator in the world, dedicated to the study of particle physics. It accelerates proton beams inside a 27-km underground ring up to a nominal beam energy of 7 TeV and brings them into collision at four points of the ring, where four large experiments (ALICE, ATLAS, CMS and LHCb) register the products of the proton-proton interactions. The nominal collision energy is 14 TeV and the nominal instantaneous luminosity is $L=10^{34}$ cm$^{-2}$ s$^{-1}$. The LHC has been operated successfully since 2010, and the four experiments have produced a wealth of beautiful physics results, among which the breakthrough discovery of the Higgs boson by ATLAS [1] and CMS [2]. This discovery demonstrates that the Brout-Englert-Higgs (BEH) mechanism [3,4] is at the origin of the masses of the elementary particles and marks the culmination of decades of efforts by many people around the world.

The High Luminosity LHC (HL-LHC) is an upgrade of the LHC to achieve instantaneous luminosities a factor of five larger than the LHC nominal value, thereby enabling the experiments to enlarge their data sample by one order of magnitude compared with the LHC baseline programme. Following five years of design study and R&D, this challenging project requires now about ten years of developments, prototyping, testing and implementation; hence operation is expected to start in the middle of the next decade. The timeline of the project is dictated by the fact that, at the beginning of the next decade, many critical components of the accelerator will reach the end of their lifetime due to radiation damage and will thus need to be replaced. The upgrade phase is therefore crucial not only for the full exploitation of the LHC physics potential, but also to enable operation of the collider beyond 2025.

The HL-LHC will rely on a number of key innovative technologies, including cutting-edge 11-12 Tesla superconducting magnets, compact superconducting crab cavities with ultra-precise phase control for beam rotation, new technology for beam collimation, high-power, loss-less superconducting links, etc. A detailed description of the project and its technological and operational challenges is provided in the HL-LHC Preliminary Design Report [5] and the “HL-LHC book” [6].

The upgrade of the collider is complemented by upgrades of its injectors [7] and of the experiments, the latter aimed at enabling the detectors to fully exploit the increased physics opportunities offered by the HL-LHC [8, 9]. Due to the higher beam luminosity in the HL-LHC era, in particular the larger number of protons per bunch, the ATLAS and CMS experiments will have to cope with an average of 140 simultaneous proton-proton interactions (so-called “pile-up”) occurring at each crossing of the two beams every 25 ns, with maximum values extending up to 200 interaction events per crossing. This is only one example of the challenges the experiments will have to face to operate at the HL-LHC.
HL-LHC in the Global Context - Strategy for High-Energy Physics

The European Strategy for Particle Physics defines the priorities of the European High-Energy Physics (HEP) community in the worldwide context. The 2013 update of the strategy [10] ranks the full exploitation of the LHC, including the HL-LHC phase, as the highest-priority project in Europe:

*Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

This strategy, which was adopted by the CERN Council on 30 May 2013, was subsequently supported by roadmaps developed in the US and Japan. In the US, the report of the Particle Physics Project Prioritization Panel (P5) to the High-Energy Physics Advisory Panel (HEPAP), which in turn advises the US Department Of Energy, issued in May 2014 [11], states in its recommendation 10: “… The LHC upgrades constitute our highest-priority near-term large project.” In Japan, the High-Energy Accelerator Research Organization (KEK) updated its roadmap in 2013. This roadmap states that “The main agenda at LHC/ATLAS is to continually participate in the experiment and to take a proactive initiative in upgrade programs within the international collaboration at both the accelerator and detector facilities.” Following this recommendation, the KEK cryogenic group started R&D activities on the HL-LHC separation dipole magnets.

More recently, on 10 March 2016, the European Strategy Forum on Research Infrastructures (ESFRI), a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach, presented its 2016 Roadmap on Research Infrastructures [12]. The HL-LHC has been selected as an ESFRI Landmark Project, i.e. a research infrastructure established as a major element of competitiveness for the European Research Area.

Goals of the HL-LHC Upgrade

The timeline of the LHC baseline programme, expected to last until 2023, is shown schematically in Figure 1. After a first run at a centre-of-mass energy of 7-8 TeV up to the beginning of 2013, the LHC achieved the collision energy of 13 TeV in 2015, and is expected to reach the nominal luminosity of $1 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$ in 2016. Margins in the design of the LHC, coupled with a first series of upgrades during the second long shutdown (LS2) in 2019-2020, are expected to enable operation up to about twice the nominal luminosity in the years 2021-2023.

The main objectives of the High Luminosity LHC project are to determine a set of beam parameters and to build the necessary accelerator components to enable the LHC to reach the following targets:

- a peak luminosity of $5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$, limited by the maximum tolerable pile-up of 140 events (average) per bunch crossing in the LHC detectors. Control of the luminosity to prevent this value from being exceeded during operation is called ‘luminosity levelling’;
- an integrated luminosity of 250 fb$^{-1}$ per year, with the goal of delivering 3000 fb$^{-1}$ in about a decade after the start of HL-LHC operation in 2026. This integrated luminosity is about ten times larger than the expected value at the end of the baseline LHC programme in 2023.

The goal is to install the main hardware components of the HL-LHC and to perform the first commissioning of the new machine configuration during the third long shutdown (LS3) in 2024-2026. The HL-LHC phase following the baseline LHC programme is depicted in Figure 1.
Figure 1: Timeline of the LHC baseline programme and its upgrade phases, showing the energy of the collisions (upper line - red) and instantaneous luminosity (lower lines - green). The second long shutdown (LS2) in 2019-20 will see the consolidation of the accelerator and the upgrade of the LHC Injectors. After the third long shutdown (LS3) in 2024-2026, the machine will be in the HL-LHC configuration.

HL-LHC Physics Case

The headline result of the first LHC run was the discovery, in 2012, of a new particle, fundamentally different from those observed before. Within the experimental precision allowed by the present dataset, this new particle is consistent with the Higgs boson of the Standard Model (SM) theory. Its couplings (interaction strengths) to other particles in the dominant decay modes are measured today with a precision of 15 to 30% by both ATLAS and CMS. They scale with mass, as predicted for a Higgs boson (left panel in Figure 2). With the integrated luminosity of 3000 fb⁻¹ expected by the end of the HL-LHC phase, the precision on the couplings will be almost ten times better, i.e. 2 to 5% (right panel in Figure 2). These and other measurements are crucial because deviations of the Higgs boson properties from the SM expectations would indicate the existence of new physics. The higher the energy scale of the new physics, the tinier the expected deviations. Hence, the best possible experimental precision is essential to explore the highest energy scales indirectly using the Higgs boson as a tool. Furthermore, the HL-LHC will provide experimental access, for the first time, to Higgs boson couplings to particles of the second family through studies of the rare $H \rightarrow \mu\mu$ decay. Evidence for the production of a pair of Higgs bosons may also be uncovered, which would probe the strength of the Higgs self-interaction and provide constraints on the BEH mechanism.

Direct searches for new physics will continue at the HL-LHC with enhanced sensitivity. The discovery potential will increase by up to 30% in terms of masses of new particles compared with the baseline LHC programme, reaching 8 TeV for singly-produced particles. Several scenarios beyond the SM will be investigated, including Supersymmetry (SUSY), theories with extra dimensions (which could explain why gravity is so weak compared with the other fundamental forces), quark compositeness, etc. Supersymmetry remains one of the most attractive theories for physics beyond the SM, as it would explain the light mass of the Higgs boson and provide a candidate particle for dark matter. As an illustration, Figure 3 compares the potential of the LHC and HL-LHC in the search for electroweak SUSY particles. Since these particles are expected to be produced with relatively small cross-sections, a factor of ten increase in luminosity translates into a 30-40% increase in mass reach.
If hints of new particles or new interactions begin to emerge during the baseline LHC programme, the HL-LHC phase will be crucial in enabling the experiments to consolidate such observations and provide constraints on the underlying theory.

![Figure 2: The Higgs boson couplings to various SM particles, as a function of the particle masses, as measured with the current LHC data by the CMS experiment (left) and the expected precision at the end of the HL-LHC programme (right).](image)

![Figure 3: The reach of the ATLAS experiment in the search for the direct production of chargino-neutralino pairs at the LHC and HL-LHC. The present experimental limits are also indicated.](image)

More details about the potential of the ATLAS and CMS experiments at the HL-LHC can be found in Refs. [8,9].


“The exploration of the TeV scale and its vicinity is just beginning. The completion of this exploration, which may end up either with the discovery or the firm exclusion of new physics near the TeV scale, will require additional decades of efforts at the LHC and new facilities. These additional investigations are essential because each of their possible eventual outcomes will
deeply affect our view of the fundamental laws and of symmetries in Nature. The main physics goals are clear:

1) to push further the validation of the Standard Model at the energy frontier, in particular by measuring the properties of the newly-discovered Higgs particle and of the longitudinal components of the massive vector bosons with the highest possible precision, and with the aim of establishing whether there are any deviations from the Standard Model predictions;

2) to check whether the Higgs particle is accompanied by other new particles at the TeV scale, which could play a role in the global picture of electroweak symmetry-breaking or in the solution of the dark matter puzzle. As reflected in three of the four high-priority activities, both hadron and lepton colliders at the high-energy frontier can play essential and complementary roles in this quest.

In the next decade, the LHC is the unique machine where this physics programme can be pursued. Running at its design energy and luminosity until about 2021, the LHC should deliver an integrated luminosity of about 300 fb$^{-1}$ to the ATLAS and CMS experiments. By then, many parts of the machine and the detectors will need to be replaced in order to continue operations.

A series of improvements to the machine and the detectors would allow the collection of high-quality data amounting to a tenfold increase in integrated luminosity by around 2030. A strong scientific case for this HL-LHC, which builds upon a machine and on detectors already validated by real operations, is already in place. With this tenfold increase in statistics and from improved detection systems, ATLAS and CMS would have access to rare production modes and rare decay channels of the Higgs boson, would significantly improve the precision in the measurement of many of the Higgs couplings, would study its self-coupling via double Higgs production, and would test possible deviations from the Standard Model predictions in the scattering of longitudinal massive vector bosons. The HL-LHC would also provide additional opportunities for the searches for new physics, and the proposed upgrades of the LHCb and ALICE experiments would advance the studies of flavour physics in the quark sector and of the quark-gluon plasma, respectively. In conclusion, the full exploitation of the LHC’s potential, including the high-luminosity upgrade of the machine and of the detectors, is identified as Europe’s highest scientific priority.”

HL-LHC Technological Challenges

The HL-LHC upgrade will mainly focus on entirely renovating the most complex and critical parts of the present collider, i.e. the Insertion Regions around the high-luminosity detectors, ATLAS and CMS (see Figure 4). In addition, the Insertion Region around LHC Point 7 and the cryogenics at LHC Point 4 will be modified. This amounts in total to 1.2 km of accelerator.

In this section, an overview of the luminosity limitations of the nominal LHC is given, together with a discussion of the technologies needed to go beyond the nominal parameters and the resulting challenges of the HL-LHC project. An exhaustive description of the hardware components and machine layout is beyond the scope of this document. Such a description is available in Refs. [5,6].
Figure 4: Schematic view of the new Insertion Region on the left side of either ATLAS or CMS. Interaction Region (top figure) features: low-β triplet quadrupoles (Q1-Q2a-Q2b-Q3, red); corrector magnet (orange); D1 separating dipole (blue). Matching Section (bottom figure) features: D2 recombination dipole (blue); crab cavity cryo-modules (pink); Q4 quadrupole (white).

The following elements are crucial to reach the required luminosity performance at the HL-LHC:

**Beam current and brightness**: The total beam current may severely limit the luminosity since it affects many systems: Radio-frequency (RF) power system and RF cavities; collimation; cryogenics; kickers; vacuum; beam diagnostics; Quench Protection Systems, etc. Radiation effects aside, all the systems were designed for a maximum beam current of 0.86 A, the so-called “ultimate” beam current. The HL-LHC will exceed the ultimate beam intensities by 30% with 25 ns bunch spacing. The beam brightness (intensity per phase space) will need to be increased at the origin of the beam generation and then preserved throughout the entire injector chain and in the LHC. Hence, the injectors upgrade project (to be completed in 2020) has the primary objective of increasing the number of protons per bunch by a factor of two above nominal value while maintaining the beam emittance at the present low value.

**Beam squeezing**: A typical method to increase the luminosity consists of increasing the beam squeezing in the interaction regions by reducing $\beta^*$ - the amplitude function at the interaction point. In the HL-LHC this method requires the deployment of larger-aperture, higher field low-$\beta$ triplet quadrupoles. A reduction in $\beta^*$ implies not only larger beam sizes in the triplet magnets, but also an increase in crossing angle if the beam separation in the part of the machine with a common beam pipe is kept constant (in terms of normalised beam separation, i.e. the separation divided by the transverse beam size). The increased crossing angle in turn requires even larger aperture triplet magnets, larger-aperture D1 magnets (first separation dipoles), and other modifications of the matching section. It also reduces the size of the luminous region in the interaction points and limits the gain in peak luminosity.

Large-aperture quadrupole magnets with sufficiently high gradient (11-12 Tesla peak fields) can only be obtained using new technologies based on Nb$_3$Sn superconductor (more powerful but more complex than the NbTi superconductor used for the baseline LHC). These and other magnets that need to be changed in the Insertion Regions (separation-recombination dipoles D1-D2, matching section quadrupoles and new corrector magnets) are currently being developed through an intense R&D and
prototyping programme. Recently, a short-length model of a large-aperture quadrupole magnet was successfully tested beyond the target field.

The larger crossing angles ($\theta_c$) required by the smaller $\beta^*$ reduce the geometrical overlap between colliding bunches in the interaction regions, a loss which is quantified by the geometrical luminosity reduction factor, $R$. The $R$ factor is shown in Figure 5 as a function of $\beta^*$. Various methods can be deployed to compensate for this effect. The most efficient and elegant solution is to use special superconducting RF cavities (crab cavities, CC). These cavities generate transverse electric fields that rotate each bunch longitudinally by $\theta_c/2$ close to the interaction point, so that the two bunches collide head on with large overlap, as illustrated in Figure 5. It can be seen that crab cavities provide a large $R$ factor down to the smallest $\beta^*$ values. While the primary function of the crab cavities is to increase the luminosity, they might also be used as a back-up solution, in combination with $\beta^*$ variations, to level the peak luminosity during the fill. This method would not only enable the control of the instantaneous luminosity, but would also allow optimisation of the size of the luminous region and thus the pile-up density through the fill.

**Collimation:** The present collimation system was designed for the first operation phases of the baseline LHC. It was optimised for robustness rather than low impedance, hence it will need to be upgraded to lower impedance and cope with increased beam intensities. Special treatment is required in the so-called Dispersion Suppression (DS) regions, in order to protect main superconducting dipoles from possible leakage of off-momentum particles which could limit the collider performance. The adopted solution is to replace an LHC dipole with two dipoles of equal total bending strength ($\sim$120 T-m) using higher-field (11 T) and shorter-length (two times 5.5 m) magnets than the standard LHC dipoles (8.3 T and 14.2 m). The space gained will be sufficient to house special collimators meeting the above-mentioned requirements. The first short-length 11 T dipole models have recently been tested with success, a prerequisite for launching the development of full-size prototypes.

![Figure 5: The geometrical luminosity reduction factor $R$ as a function of $\beta^*$ with the indication of three operational points: nominal LHC, and HL-LHC without and with crab cavities. The crab cavity beam manipulation is depicted in the bottom right insert (small arrows indicate the torque on the bunches generated by the CC transverse RF field).](image_url)

**Remote powering of cold circuits:** Considerable efforts are under way to develop new, radiation-hard electronic boards for the power converter system supplying the necessary current to the superconducting magnets. A complementary solution is also being pursued, consisting of relocating the power converters of the Insertion Region magnets around LHC Point 1 and Point 5 and the associated electrical distribution systems outside the tunnel. This relocation will allow access to these components during the collider operation and should greatly reduce the LHC down-time due to radiation effects. The proposed solution will be implemented thanks to the development of a novel technology for transporting current over large distances: superconducting links made of High Temperature Superconducting material (YBCO or Bi-2223) or MgB$_2$. 
**Other upgrades:** To ensure operation of the collider with the greatest possible up-time, flexibility and reliability, additional changes have to be introduced for the HL-LHC phase:

- completion and modification of the cryogenic plants;
- new beam screens with tungsten shields;
- coating and surface treatment of the beam pipe to mitigate the effects of electron clouds;
- new main absorbers of experimental debris;
- new beam diagnostics and instrumentation systems;
- new absorbers for injection and extraction of more intense beams;
- new machine protection system;
- modification and improvement of the existing LHC technical infrastructure, including the civil engineering work required for the underground installation of new equipment.

**Upgrades of the experiments**

ATLAS and CMS will undergo substantial upgrades to be able to cope with the increased luminosity of the HL-LHC and with the harsher environment arising from the larger event pile-up\(^1\). Furthermore, some of the detector components will near the end of their lifetime at the beginning of the next decade due to radiation damage, and will need to be replaced. The larger pile-up requires highly-granular, very radiation-hard silicon tracking devices in the regions closer to the beamline, and the high instantaneous luminosity calls for fast, powerful and efficient online selection of the events (so-called “trigger”). The expected increases in trigger rate, pile-up and detector complexity (number of channels) will boost the data size and rate by a factor of 10 or more, which presents new challenges for the computing infrastructure in terms of storage and CPU resources and will require significant changes to the experiments’ computing models and to the way hardware resources are provided. These are only a few examples of the technical challenges the experiments will have to face to operate at the HL-LHC. More details can be found in Refs [8, 9].

**Relevance of the Project for Science and Society**


Furthermore, particle physics research requires a wide range of skills and knowledge. Many young physicists, engineers and technicians are trained at CERN and in collaborating laboratories and universities. These people transfer their expertise to society and industry either through strong partnership in the development of research projects or because they move to other fields.

Knowledge transfer is expected to continue and expand in the context of the HL-LHC project, which will require the development of innovative technologies in several domains, strong collaboration with industries, and a sustained stream of supplies and services. These will include civil engineering work

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\(^1\) ALICE and LHCb will be upgraded at an earlier stage, with installation of new detector components during LS2.
and the systems and equipment needed to build and operate the accelerator, the detectors and the computing infrastructure: power distribution, superconducting magnets, cryogenics, ultra-high vacuum, electronics, mechanical engineering, radiofrequency equipment, etc.

A Memorandum of Understanding has been signed by CERN and the European Commission, and various cooperation activities are under way. The particle physics community has been actively involved in European Union framework programmes. The HL-LHC project began as a conceptual study in 2011 within the FP7 Framework Programme grant n.284404 of the European Commission.

**HL-LHC Cost and Schedule**

An extensive Cost and Schedule Review of the HL-LHC accelerator project was carried out in March 2015. It was conducted by an international team of experts: the members of the CERN Machine Advisory Committee (CMAC)\(^2\), assisted by reviewers\(^3\) called to cover certain specific items. Project scope, schedule and cost were assessed. Following this assessment, the cost for construction from 2015 to 2026 was estimated to be 950 MCHF (2015 prices), excluding contingency, equipment spares and cost escalation. This cost does not include the upgrade of the injectors and experiments. Escalation is taken into account by CERN on a yearly basis through the application of the so-called Cost-Variation-Index (CVI) to the remaining cost-to-completion budget of projects. The CVI is calculated as a function of, *inter alia*, the impact of exchange rate fluctuations and inflation on goods, consumables, energy, industrial services, etc. The HL-LHC project will be realised within a constant CERN Budget.

Following the review, the cost-to-completion of 950 MCHF was profiled as a function of time and integrated into CERN’s Medium-Term Plan, as shown in Figure 6. The schedule and duration of the future Long Shutdowns of CERN’s accelerator complex (LS2, LS3) were revised, and the decision was taken to stage the construction and installation of part of the crab cavities.

![Figure 6: The HL-LHC project budget allocation as a function of time over 2015–2026, as per CERN Medium-Term Plan 2017–2021. This budget does not include the upgrade of the injectors and experiments.](image)

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\(^2\) CMAC members: R. Brinkmann (DESY, Deutsches Elektronen-Synchrotron); W. Fischer (BNL, Brookhaven National Laboratory); S. Gourlay (LBNL, Lawrence Berkeley National Laboratory); N. Holtkamp (Chair of the review, SLAC National Accelerator Laboratory); K. Oide (KEK, High Energy Accelerator Research Organization in Japan); Q. Qin (IHEP, Institute of High Energy Physics); T. Roser (BNL, Brookhaven National Laboratory); J. Seeman (SLAC National Accelerator Laboratory); and V. Shiltsev (FNAL, Fermi National Accelerator Laboratory).

\(^3\) Additional review committee members were: C. Neumeyer (PPPL, Princeton Plasma Physics Lab); J. Bremer (CERN, European Organization for Nuclear Research); M. Seidel (PSI, Paul Scherrer Institute); P. Vedrine (CEA-Saclay, Commissariat à l’énergie atomique et aux énergies alternatives) and A. Yamamoto (KEK, High Energy Accelerator Research Organization in Japan).
Although the installation of the main hardware components of the HL-LHC will be carried out during LS3, work will start during LS2 with the installation of a new cryogenic plant at Point 4 and the first batch of 11 T dipole magnets for DS collimation at Point 7. Major civil engineering and preparatory work for the technical infrastructure will also be carried out during LS2.

The HL-LHC schedule is presently based on the following milestones (see Figure 7):

- 2014: Preliminary Design Report (PDR)
- 2015: First Cost and Schedule review
- 2015: End of design phase, release of the first Technical Design Report (TDR-v0) with identification of the necessary technical infrastructure
- 2016: Proof of main hardware components on test benches
- 2016: Second Cost and Schedule review
- 2017: Testing of prototypes and release of the Technical Design Report (TDR-v1), establishing the readiness for the start of construction
- 2018-2023: Construction and testing of the main hardware components (e.g. magnets, crab cavities, superconducting links, collimators)
- 2018: Start of civil engineering work
- 2019-2020: Long Shutdown 2 – Modification of the cryogenic plant at Point 4, DS collimators at Point 2, underground civil engineering (and technical infrastructure) work
- 2021-2023: String test of Insertion Region elements (low-β triplet quadrupoles, D1 dipole, corrector elements, superconducting links, powering circuits)
- 2024-2026: Long Shutdown 3 – Main installation (new magnets, crab cavities, cryoplants, collimators, absorbers, etc.) and commissioning
- 2026-2030: Completion of crab cavity installation.

During the first Cost and Schedule review, the personnel needs were estimated to be around 1600 FTE-y over the time span of the project.

The second Cost and Schedule review will take place in October 2016 and will again be conducted by the CMAC. Its mandate will be to focus on:

- the project progress, in particular the identification of any hardware component on the critical path in terms of schedule or cost;
- baseline changes (if any), their impact on the scope, schedule and cost, and the application of change-management methods;
- the global evolution of the cost and schedule of the project, the level of risks and uncertainties.
Conclusions

Fully exploiting the physics potential of the LHC, thereby maximising the scientific return on the invested resources, requires operating the collider beyond the middle of the next decade and major upgrades of accelerator and detector components. The accelerator upgrade project briefly described here, HL-LHC, is now well established in terms of beam parameters, technical requirements, necessary technological developments, cost and schedule. R&D work is well advanced, and construction of some components has started. The budget profile is included in the CERN Medium-Term Plan. The technical and financial status of the project during the construction period will be monitored through reviews carried out by international experts and regularly reported to the CERN Council.

References
