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CERN (HL-LHC): New underground & surface structures at Point 1 & Point 5

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ABSTRACT: The Large Hadron Collider (LHC) is the most recent and powerful accelerator constructed on the CERN site. The LHC consists of a 27 km circular tunnel, about 100 m underground, with eight sites positioned around the tunnel's circumference. High-Luminosity LHC (HL-LHC) is a new project aiming to upgrade the LHC, at Point 1 (ATLAS in Switzerland) & Point 5 (CMS in France), in order to maintain scientific progress and exploit its full capacity with new underground and surface structures. The paper describes the HL-LHC design developed by the JV ORIGIN in Point 1 represented by Setec (France), Rocksoil (Italy), and CSD Eng. (Switzerland), & JV LAP in Point 5 represented by Lombardi (Switzerland), Pini Swiss (Switzerland), and Artelia (France).The construction works contracts were awarded in March 2018. The execution of the underground works started in April 2018 and is scheduled to be finished by the end of 2021.

1 INTRODUCTION

CERN, the European Organization for Nuclear Research, is an intergovernmental organization with 22 Member States. Its headquarters are in Geneva but its premises are located on both sides of the Swiss-French border. The Large Hadron Collider (LHC) is the flagship of this complex of accelerators. The data collected by this unique instrument in the world has allowed CERN experiments ATLAS and CMS to discover the Higgs boson in 2012. The goal of the HL-LHC project is to upgrade the LHC experiment in order to produce more data, by increasing the number of particles collisions by a factor of 10. It will be operational in 2026.

The project requires new technical infrastructures near each of the two main detectors (ATLAS at Point 1, CMS at Point 5): an additional shaft and cavern, approximately 500 meters

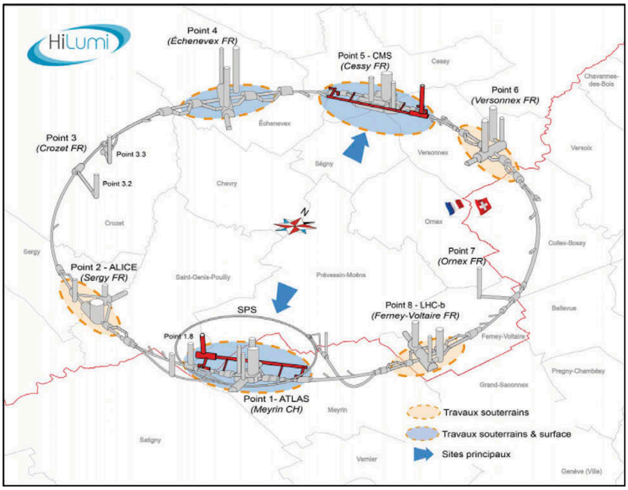


Figure 1. General view of the new works for HL-LHC, in red (https://voisins.cern/en/hl-lhc).

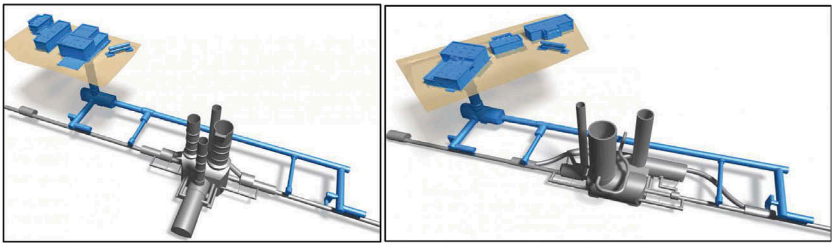


Figure 2. New underground and surface structures (in blue) in Point 1 (left view) and Point 5 (right view).

of tunnels connected to the LHC tunnel, and additional technical buildings at the surface. The design schedule and construction schedule of the civil works are very constrained by the general timeline of the HL-LHC project, and by the high vibration sensitivity of the LHC Machine.

(https://voisins.cern/en/hl-lhc)

During the design phase, it was agreed that most of the underground excavation works would be carried out whilst the LHC machine would not be in operation, i.e. during the "Long Shutdown 2" planned during the years 2019-2020 (enabling works generating vibrations).

The main design and construction phases are:

– 07/2016 – 10/2016: Preliminary Design,
– 11/2016 – 06/2017: Tender Design,
– 07/2017 – 06/2018: Construction Design for underground structures,
– 03/2018: Award of contracts for the works at Point 1 and Point 5 (one different Contractor for each Point),
– 04/2018 – 12/2018: Preparatory works and shafts excavation (deemed possible while the LHC is in operation, with adapted methods if necessary, in case of vibration issues),
– 01/2019 – 08/2020: Excavation of the caverns and tunnels (during the "Long Shutdown 2" of the LHC),
– 09/2021 (Point 1) and 12/2021 (Point 5): contractual milestone for the completion of all underground structures,
– 08/2022: contractual milestone for the completion of the works.

2 SURFACE WORKS AND SITE WORK INSTALLATION

The construction site is located near to the ATLAS site (Point 1) and CMS site (Point 5). Both sites are equipped with the typical installations for underground works like: ventilation, water treatment plant, excavation equipment, site accommodations, workshop, lift installation, etc. The key equipment of the construction site are the gantry crane erected at the top of the shaft and the tunnel excavator. On each Point, several buildings are foreseen on the surface and have been modelled on BIM:

1) **Head Shaft Building**. Steel frame structure with dimensions of 22 m by 35 m housing one cold box for the cryogenic system. The building is about +16.0 m high.
2) **Ventilation Building (SU)**. Reinforced concrete structure with dimensions of nearly 22 m by 30 m. The building is about 13 m high. The SU building will host the necessary cooling and ventilation systems for the HiLumi Underground infrastructures.
3) **Electrical Building (SE)**. The SE building will host the necessary electrical systems for the HiLumi Underground infrastructures. The steel frame superstructure is moment resisting in the transverse direction while the longitudinal stability is ensured with cross bracings.
4) **Cooling Towers (SF)**. Reinforced concrete structure with dimensions of nearly 18 m by 30 m housing 3 cooling towers. The building is about +12.0 m high. The SF building will host the cooling tower structures that are required to extract the heat loads form the machines for the HiLumi Underground infrastructures. The cooling towers exhausts will be built with curved formwork tools.
5) **Compressor Building (SHM)**. Reinforced concrete structure with dimensions of nearly 16 m by 50 m. The building is about +11.0 m high. The SHM building will host the compressors for the cryogenic equipment required for the HiLumi Underground infrastructures.

At the surface the following main site installation works are foreseen:

1) Construction and maintenance of any required temporary roads within the Site Installation areas.
2) Electricity and telecom facilities and connection to the nearest Concessionaire of the Site able to meet the power requirements during the whole period of Works.
3) Connection to the local water supply system that runs adjacent to the Site.
4) Connection to the sewerage system.
5) Treatment of rainwater.
6) Installation and operation of the security system and of the lighting system.
7) Installation and maintenance of the ventilation systems during the underground construction phases.

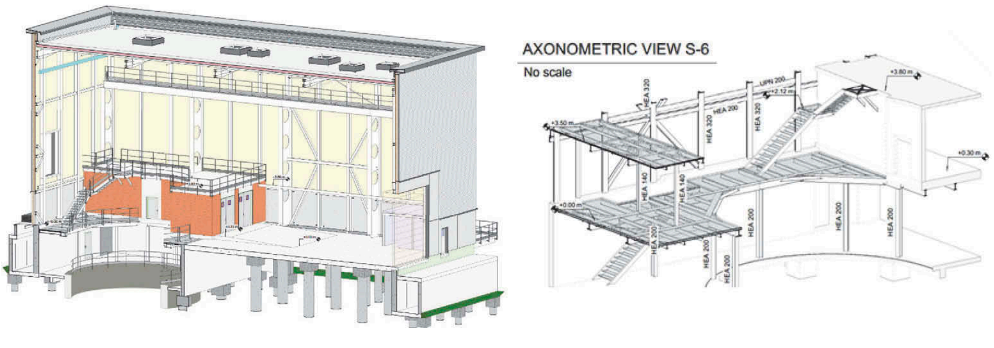


Figure 3. The Head Shaft Building.

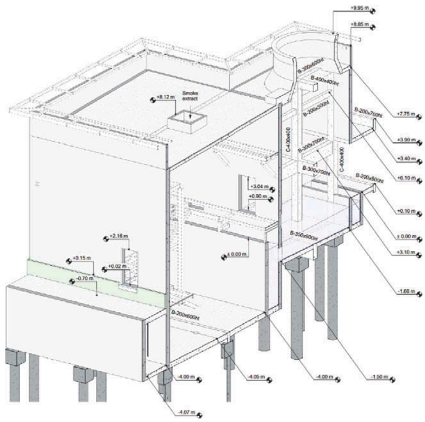


Figure 4. The Cooling towers.

3 UNDERGROUND WORKS

3.1 *Geology*

The Point 1 site lies in an area covered by Würm Quaternary moraine deposits between two outcrops of Molasse. The local geology consists of the Würmienne moraine deposits generally directly overlying Molasse. The Würmienne moraine is a base moraine and consists of compact and consolidated relatively dense sandy silt with variable amounts of sand, clay, 15-30% of 60-100 mm dia. cobbles and hard to very hard gravel. The Molasse (Chattien Inférieur) consists of sub-horizontal bedded lenses of sedimentary rock composed of grain sizes ranging from clay to sand, with a progressive lateral and vertical spatial grading.

At Point 5 the Quaternary moraine is covered by a succession of fluvio-glacial soils that consist of silty and sandy gravel deposits with cobbles and small boulders. It is a heterogeneous, semi-cohesive, compact to very compact sandy (20-35 %), slightly clayey (<10%) gravel layer in abundant (10-15 %) silt paste; light brown, rich in round cobbles and boulders up to few decimetres diameter (max observed diameter ~20 cm, but larger diameters may be expected).

Four main rock types were identified within the Molasse as follows.

1) Sandstone and marly sandstone vary from soft/poorly-cemented (UCS < 20 MPa) to very hard/cemented (UCS >35 MPa). They are composed of 40-70% Quartz, 5-10% Feldspar, 5-20% clay/mica and 5-45% calcareous cement. Stronger rocks are finer grained and more cemented.
2) Sandy marls have these proportions: 20-45% of clay, 20-40% of quartz and 20-30% of calcite.
3) Platy marls (also called marl “fissile”/“feuilletée” in French) can be assimilated to shales. They are composed of 45-60% clay, 15-30% of micro-crystalline quartz, and 20-30% calcareous minerals. The dominant clay is illite (swelling), but smectite (swelling) and chlorite (non-swelling) can also be present at up to 18%.
4) “Grumeleuse” Marl is characterised by numerous closed, polished, discontinuous multidirectional, curved micro-fissures. It can sometimes be referred to as mudstone.

The Molasse is composed of approximately 50% sandstone, 25% of platy marls and marls, and 25% sandy marls. Layers are usually 0.5 to 5 m thick and their stiffness can vary from one layer to another. Available data underline that Molasse is a highly heterogeneous rock mass (Kurzweil, 2004). Sandstone beds can be considered isotropic. The marls are lithologically heterogeneous (succession of weak ductile marls, sandy marls, strong marls, etc. which can be thinly laminated with weak lamination planes) with horizontal and inclined polished fracture surfaces. The upper part (usual range of thickness varying from 1 to 5 m) of the Molasse are usually weathered and softer, with soil-like properties.

At Point 5 two aquifers are individuated within this geological succession:

- The upper aquifer, phreatic, hosted in the fluvio-glacial soils;
- The lower aquifer, artesian, generally hosted in the deep moraine “cailloutis”.

The two aquifers do not communicate, being separated by the less pervious layers, though tracking tests carried out in the Point 5 site showed local connections, natural or maybe due to anthropic activities. The geotechnical profile at the location of the shaft (PM17) at Point 1 and (PM57) at Point 5 is presented in the following Figure.

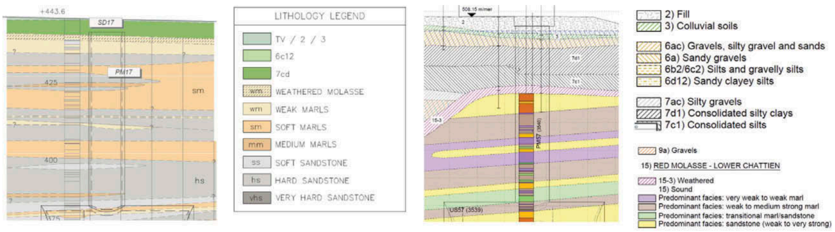
3.2 *General description of the underground works*

At Point 1 and at Point 5, the new Underground Structures are placed on the inner side of the existing LHC ring (Laigle & Boymond, 2001; Kurzweil, 2004), at an average distance of approx. 50.00 m from the LHC axis. The new HL-LHC Underground Structures will be located approx. 6.00/7.00 m above the level of the existing LHC tunnel crown. The new Underground Structures consist of the following main objects, as shown in the following figure.

Point 1 & Point 5 consist of a new shaft (PM17 & PM57), a service cavern (US17/UW17 & US57/UW57), a power converter gallery (UR15 & UR55), service galleries (UA17, UL17, UA13, UL13 & UA57, UL57, UA53, UL53), and vertical linkage cores to the existing LHC and escape exits (UPR13/UPR17 & UPR53/UPR57).

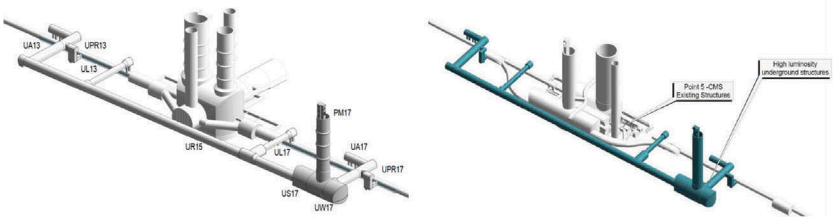
The shaft connects the surface buildings with the underground facilities (cavern and tunnels). It is approx. 60 m deep with a constant internal diameter of the final lining of 9.80 m. The thickness of the final lining varies from 0.50 m (typical cross section) to 0.80 m (junction with cavern).

The cavern is located at the bottom of the shaft. It is approx. 50 m long, 15 m wide and 11.2 m high (internal dimension). It will house the cryogenic equipment and services.



Point 1 *Point 5*

Figure 5. Geotechnical profile for the shaft at Point 1 & Point 5.



Point 1 Point 5

Figure 6. General layout underground structures Point 1 and Point 5.

The main tunnel links the cavern with the service tunnels. This tunnel is approximately 300 m long, starting from the cavern. It will mainly house the power converters and the current feed boxes of the superconducting magnets. From this main tunnel, four transversal tunnels begin; these tunnels called "service galleries" are approximately 50 m long and connect the new main tunnel and cavern with the existing LHC tunnel. The UA galleries will house the RF equipment of the crab-cavities and the UL galleries will house the cryogenic distribution system and the superconducting links. The connection with the existing LHC tunnel will be done through two interconnections, called UPR. These connections aim to provide safety escapes for the personnel.

Vertical cores, of approximately 1.0 m in diameter each, are required to let services pass from each of the 4 service tunnels to the existing LHC tunnel. These linkages will allow connecting the existing installed services to the new systems (superconducting magnets, cryogenic distribution lines and RF cavities) that will be located in the HL-LHC. These connections will be executed in a separated working phase after the completion of the civil works.

For the Temporary Support, a design working life of 10 years shall be considered. For the Final Lining and the waterproofing system a design working life of 100 years shall be considered. For the Internal Structures (steel floors, crane railways, internal concrete walls and slabs,. . .) a design working life of 50 years shall be considered.

3.3 *Description of the execution phases*

The shafts at both Points have been designed with the following execution steps.

1. Rock excavation (soft ground for the first 25 m at Point 5) performed top down, by steps of approximately 2 m (around 30 steps)
2. Muck removal by wheel loaders and buckets
3. Primary support using reinforced shotcrete and, if needed, rock bolts
4. Laying of waterproofing system
5. Final reinforced concrete lining
6. Construction of the internal structures

The caverns have been designed with the following execution steps.

1. Excavation of the cavern for different portions using rock bolts, shotcrete (and steel ribs for Point 5) for temporary support
2. Muck removal by wheel loaders and buckets
3. Laying of umbrella waterproofing
4. Tunnel invert
5. Drainage network
6. Final reinforced concrete lining
7. Construction of the internal structures

The Tunnels have been designed with the following execution steps.

1. Excavation of the tunnel full face and installation of steel ribs (if needed), rock bolts (Point 5) and shotcrete for temporary support
2. Muck removal by wheel loaders and buckets
3. Laying of umbrella waterproofing
4. Tunnel invert
5. Drainage network
6. Final reinforced (if needed) concrete lining
7. Construction of the internal structures

3.4 *Vibrations*

The main challenges of the project are a) related to the limitation of the vibrations induced from excavation, which may degrade the operation of the LHC machine and its experiment detectors, and b) the swelling of the rock mass (Glaus & Ingensand 2002). In order to deal with these major issues, several excavation methods, a detailed monitoring system with the adoption of restrictive threshold values, and specific technical solutions have been foreseen in the design.

The excavation of the shaft in rock takes place during the operation of the LHC Machine, before the Long Shutdown Period 2 (LS2), whereas the excavation of the cavern and the galleries is foreseen during the LS2.

In order to manage the vibrations issues, the Engineer has foreseen several excavation methods that may produce different effects on the LHC Machine:

- Method A: Mechanically assisted tunnelling in rock with electrical roadheader;
- Method B: Mechanically assisted tunnelling in rock with rock breaker
- Method C: Excavation with Hydraulic rock splitter inside previously drilled holes
- Method D: bucket excavator.

The vibrations are amplified through two separate channels:

- Amplification through the geological layers from the excavation face to the LHC tunnel;
- Amplification through the support structure of the LHC machine on the LHC tunnel.

The ground displacements induced by the excavation works are expected to be amplified up to 10 times at the LHC beam. In principle, the threshold value is represented by the deformation of the LHC beam, fixed at approx. 1 μm.

During the excavation of the shaft, the vibrations are monitored by the Employer by means of the following instrumentation already installed in the LHC existing tunnels:

- Triaxial orthogonal seismometer Gulap 6T;
- Force balance accelerometer EpiSensor ES-T.

The Employer may stop the excavation works at any time and require a change of excavation method if the project requirements are not complied with. In this case, the Contractor shall quickly dispose of the ongoing excavation installation and set up the new one. In the event that all methods generate vibrations above the acceptable level for the LHC machine, the Contractor shall stop the works until the LHC shutdown. The consequence, in terms of time and money, of the change of excavation method and interruption are ruled, respectively, by the Baseline Schedule and the Bill of Quantities.

4 TENDER AND CONTRACT FOR CIVIL WORKS

The tender and the contract awarding phases have been developed between July 2017, with the dispatch of the bid documentation to the bidders, and April 2018, before the works commencement. The main steps are summarised below:
Phase A: preparatory activities

1. Market Survey: 01/12/2016 - 28/02/2017
   Prior to the Tender Phase, CERN launched a Market Survey in order to assess the interest of pre-selected construction companies in participating in the Invitation to Tender for the civil engineering works
2. Completion of the Tender Design by the Engineer: 03/11/2016 - 31/05/2017

Phase B: bid preparation by the bidders

1. Dispatch of the Invitation to Tender (IT) documents by CERN Procurement: 12/07/2017
2. Bid preparation by the bidders: 14/07/2017 - 27/10/2017

Phase C: bid evaluation

The bid evaluation process, carried out by CERN and the Engineer, was organised in two successive stages: the first one aimed to evaluate the technical compliance of the bids, through questions and answers with the bidders in order to detect possible non-compliances. Only the bids judged as “technically compliant” were admitted to the next evaluation stage, which concerned the financial evaluation.

1. Technical Bid Evaluation: 31/10/2017 - 05/12/2017
2. Financial Bid Evaluation: 06/12/2017 - 10/01/2018

Phase D: bid discussion: 09/01/2018 - 10/01/2018

The bid discussion took place at the beginning of 2018 with the two companies that, after having passed the technical compliance, offered the best price.

Phase E: contract preparation: 10/01/2018 - 14/02/2018

The contract preparation phase aimed to refine the IT documentation following the results coming from the bid discussion phase. Both construction contracts, for Point 1 and Point 5, have been signed by the parties in March 2018.

The contracts were elaborated by CERN and the Engineer on the basis of the FIDIC Red Book (1999) with the addition of specific contract appendices for the underground works – such as the Baseline Schedule and the Geological Baseline Report – which allow the parties to deal with the geological risks during construction (Watson & Osborne, 2004). In particular, a specific contract sub-clause was prepared in order to define the adjustment of time for completion in relation to the progress of underground excavation.

Time for Completion (Sections) shall be adjusted according to the difference between the encountered and the expected subsurface conditions. The adjustment may reduce or extend the Time for Completion. The expected subsurface conditions are described in the Geotechnical Baseline Report (GBR) in terms of definition of support class and geotechnical baseline condition. The quantities forecast by the Engineer and the performance rates proposed by the contractor are part of the Baseline Schedule (based on the principle defined in the SIA Norm 118/198). This tool allows the time for completion to be managed and is periodically updated with the quantities remeasured during excavation.

The contract is a remeasurement contract. To this purpose, three different Bills of Quantities (Underground Works, Surface Works and Common Items) have been prepared, based on the Civil Engineering Standard Method of Measurement, Fourth Edition (CESMM4) published by The Institution of Civil Engineers, 2012 and supplemented by all the specific clauses related to this project.

5 CURRENT STATUS OF THE WORK AND CONCLUSIONS

Current status of the works at Point 1 (December 2018)

- Start of the works: April 2018.
- Start of the excavation of the underground works: August 2018.
- Shaft excavation depth: around 50 m.
- Site Works Offices, Ventilation hall, Shaft hall and Workshop hall: completed.

Figure 7. Point 1 site works in August 2018 – Surface works.

Figure 8. Point 1 Shaft excavation.

Figure 9. Point 5 site works at September 2018 – Surface works.

Figure 10. Point 5 – Shaft excavation (1).

Current status of the works at Point 5 (December 2018)

- Start of the works: April 2018.
- Start of the excavation of the underground works: August 2018.
- Shaft excavation: the section in loose material (fluvio-glacial soils and moraines) is completed and the excavation is currently being carried out in the molasse. The depth is around 60 m and about 10 m still have to be excavated. Up to now, the excavation complies with

Figure 11. Point 5 – Shaft excavation (2).

the advance rate forecast in the design phase and no particular problems related to the monitored vibrations were encountered.
- Site Works Offices and Workshop hall: completed
- Ventilation installation and Shaft hall: completed

The design, from the preliminary design to the construction design, has been successfully provided by two different Engineer for the two different Points, following an ambitious time schedule.

The design for two similar projects for the same Employer was verified from two independent consultant JVs; the technical solutions are similar, but with some specificities. The elaboration of the tender and the contractual documents was coordinated in detail order to have a common basis. At each of the design phases a close cooperation with the Employer and the two consultants represented the key factor aimed to achieve the common goals.

The two Contractors are working according to the Construction Programme and the contractual basis. All technical problems such as vibrations and geotechnical aspects are currently fully under control.

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