THE HL-LHC PROJECT GETS READY FOR ITS DEPLOYMENT

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Abstract

Following the successful completion of the second long shutdown (LS2), the Large Hadron Collider (LHC) is preparing for its final operational run before the majority of the High Luminosity Upgrade (HL-LHC) will be installed during the third Long Shutdown starting in 2026. The HL-LHC upgrade will enable a further tenfold increase in integrated luminosity delivered to the ATLAS and CMS experiments, starting by an upgrade of the machine protection, collimation and shielding systems in LS2, and followed by the deployment of novel key technologies, including Nb3Sn based insertion region magnets, cold powering by MgB2 superconducting links and integration of Nb crab-cavities to compensate the effects of a larger crossing angle. After a period of intensive R&D and prototyping, the project is now entering the phase of industrialization and series production for all main components. In this contribution, we provide an overview of the project status and plans for deployment and performance ramp-up. Progress on the validation of key technologies, status of prototypes and series production as well as the final integration studies for the HL equipment are summarized. These are accompanied by the imminent completion of major civil engineering work and the start of infrastructure installations. Initial operational experience will be gained at the Inner Triplet (IT) String, presently in assembly at CERN's Superconducting Magnet Test Facility, which will enable a fully integrated test of the main magnets, powering, and protection systems in the actual HL-LHC insertion configuration.

INTRODUCTION

The second run of CERN's LHC was successfully completed in 2018, producing 160 fb^{-1} of integrated luminosity over the 4 year long run, with 70 fb^{-1} attained in 2018. During the following Long Shutdown 2 (LS2), primarily devoted to the LHC Injector Upgrade (LIU) [1], the first deliverables of the HL-LHC upgrade project were installed in the LHC, including passive absorbers, secondary low impedance collimators and crystal collimators. These have been fully commissioned for the third operational run of the LHC, planned to last until the end of 2025 at a beam energy of 6.8 TeV, to potentially cumulate an additional 210 fb^{-1} and thus bringing the total integrated luminosity in the LHC well above the initial design value of 300 fb^{-1}. The third long-shutdown, starting in 2026 and lasting for three years will be devoted to the installation of the HL-LHC upgrade, before exploitation will start in 2029 (see Figure 1).

Today, the project is in the transition from prototyping to series production for all key technologies (see Figure 2), nearing completion of the important civil engineering work on the surface as well as underground and gearing up for a full-scale test of a complete insertion magnet string at CERN's Superconducting Magnet Test Facility SM18.

KEY TECHNOLOGIES

Large aperture Nb_3Sn focusing quadrupole magnets will be installed around the high luminosity experiments ATLAS and CMS, representing one of the cornerstones of the HL-LHC upgrade. They will provide the larger aperture as well as higher integrated field required to reach the nominal β^* of 15 cm at the collision points. The inner triplet magnets are designed and constructed in collaboration with the HL-LHC Accelerator Upgrade Project (AUP) in the USA [2]. The Q1 and Q3 magnets (MQXFA) will be provided as in-kind contribution from AUP, while the longer version for Q2 (MQXFB) will be produced at CERN.

At AUP, coil production is progressing at BNL and FNAL, with 70% of the coils and 40% of the magnets completed [3]. An endurance test on magnet MQXFA05 has been recently completed in vertical position to gather more information on the long-term behaviour of Nb_3Sn magnets. The test involved five thermal cycles and a total of 50 high current quenches, eight during training and 42 being provoked at nominal current via the quench heaters. At the end of this campaign, the magnet reached the required nominal performance without quenching, both at 1.9 K and at 4.5 K, confirming the large temperature margin already observed during the first powering [4]. At FNAL, the construction of the first cryostated horizontal cold mass is ongoing, integrating the first two series magnets that were successfully tested in the BNL vertical setup by fall 2020.

The CERN-AUP joint short model program has been successful, with 5 assemblies out of 6 reaching operation at 7.5 TeV, and record peak fields above 13 T in two models [5]. The short model program allowed to verify the dependence of performance on preload, make endurance tests, and validate the assembly of the stainless steel shell around the magnet. CERN has produced two full scale prototypes MQXFBP1 and MQXFBP2, both of which have shown performance limitations to 6.5 TeV and 6.8 TeV respectively. MQXFBP1 has been disassembled, and MQXFBP2 will be used as a prototype cold mass and possibly installed in the IT string. MQXFBP2 went through a thermal cycle and a total of 50 quenches, without showing signs of degradation. Investigations on the possible causes of the performance limitations are ongoing. Tomographies and metallographic inspection revealed filament breakage in a localized region of the cross-section [6]. The next prototype MQXFBP3 has been assembled with a revised strategy for the shell welding, minimizing the mechanical coupling to the magnet. The following magnet MQXFB02 has been assembled with a revised procedure minimizing the peak load during bladdering. Both magnets will be tested in 2022. Magnet MQXFB03 will make use of coils manufactured with improvements in procedures and handling; it will be tested in 2023.

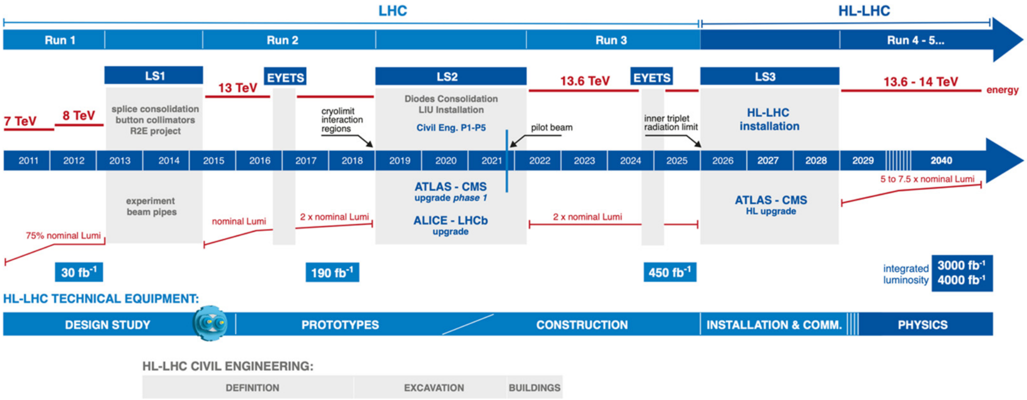

Figure 1: HL-LHC design, production, and deployment schedule.

The Nb-Ti separation dipole prototype (KEK in kind contribution) has been successfully tested in vertical position and the first magnet of the series is begin assembled. The recombination dipole prototype (INFN-Genova collaboration) will be tested in July 2022 and the winding of the series coils is starting. The nested corrector production started after the successful completion of the prototype phase, including a design iteration (CIEMAT collaboration). The recombination dipole corrector production is ongoing in China (IHEP), and the high order corrector production (INFN-Milano) has been completed.

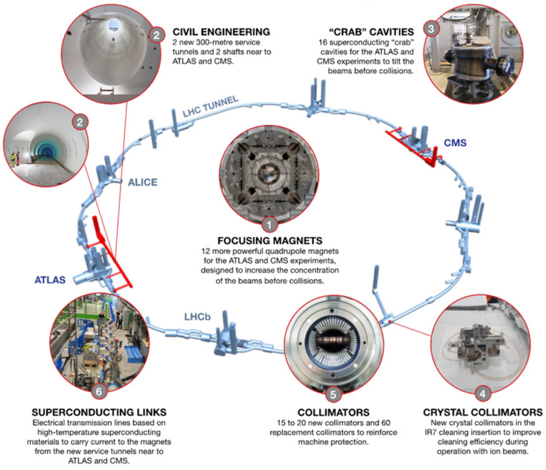

Figure 2: Overview of key-technologies to be installed in the LHC tunnel as part of the HL-LHC upgrade.

The second cornerstone of the project are superconducting crab-cavities (CC) which allow compensating for the detrimental effect of the crossing angle on luminosity by applying a transverse momentum kick to each bunch entering the interaction regions of ATLAS and CMS. Two different types of cavities will be produced and installed, the Radio Frequency Dipole (RFD) in IR1 and the Double Quarter Wave (DQW) in IR5, deflecting the bunches in the horizontal and vertical directions respectively. Pre-series production of the RFD cavities is just about to start in Italian industry under the lead of AUP [2], while the DQW cavities series production has started in German industry under the lead of CERN following the successful validation of two pre-series bare cavities. A fully assembled DQW cryomodule has been undergoing very successful beam tests in CERN SPS since 2018, demonstrating crabbing of proton beams, allowing for the development and validation of the necessary low-level RF and machine protection systems, and leading to a design change of the feedthroughs from 50 Ω to 25 Ω [7]. Two RFD dressed cavities have been delivered in 2021 to the UK collaboration after their successful qualification at CERN and are currently being assembled into a first complete cryomodule, planned to be installed in the SPS at the end of 2022 for first tests with beam. Series production of the necessary ancillaries and higher order mode couplers has equally started for both cavity types after the successful validation of prototypes.

To address the challenges of a twofold increase of the proton beam current in the HL-LHC era, an important upgrade of the collimation system is required, both to ensure the robustness and cleaning efficiency of the system in view of the increased beam energy, and to minimize the impedance contribution of the collimation system to guarantee beam stability. A total of 36 new secondary and tertiary collimators and absorbers and 15 fixed masks are part of the HL-LHC baseline upgrade, for which intensive studies and beam tests are being finalized in an effort to determine the most appropriate jaw and coating materials. Due to delays in the initially foreseen in-kind contribution, the production of this important part of the project is about to be launched within CERN Member States industries. While reaching the nominal proton beam current will only be possible after the deployment of the full HL-LHC upgrade during LS3, the successful completion of the LIU project will enable operation with $2.23{\times}10^{11}$ Pb ions in 1240 bunches already during Run 3. To mitigate the lower cleaning efficiency of the standard collimation system for operation with heavy ions, two crystal collimation systems have already been installed in the vertical planes of both beams, replacing the initial prototype systems that started to show degraded performance due to radiation damage [8]. The two systems installed in the horizontal plane will be replaced in the next year-end technical stop of 2022/23. Both new crystal primary collimators have already been tested with beam during the ongoing LHC commissioning period and were successfully aligned at 450 GeV and 6.8 TeV, showing the expected halo-

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channeling properties. Beam tests will continue, to prepare them fully for their operation with lead ion beams planned at the end of the 2022 run. This will be the first time that crystal channeling will be used as the main collimation method for regular high-intensity physics operation.

The installation of the major infrastructure, powering, and protection systems in the new HL-LHC underground galleries (see Item 2 in Figure 2) required the development and production of novel superconducting links based on MgB_2 to ensure the energy efficient connection of the accelerator magnets to their power converters located at a distance of up to 80-100 m. Two different types of links, necessary for the powering of the matching section and inner triplet magnet strings of HL-LHC have been developed and successfully validated at their nominal cryogenic temperature between 20-40 K. They can carry up to 120 kA of DC current, necessary to power the 19 individual magnet circuits of an inner triplet magnet string. Three out of the planned 10 series cables have already been delivered to CERN along with a first series flexible cryostat that will be used to assemble the first, complete cold powering system due for final testing at the end of 2022. After its successful validation in combination with the HTS current leads and the cryogenic feedboxes and connection cryostats, the assembly will integrate with the IT String test in early 2023.

CIVIL ENGINEERING AND TECHNICAL INFRASTRUCTURES

The construction of additional underground galleries (see Figure 3) to house the new infrastructure, powering and protection equipment of the accelerator components has been an early, strategic decision of the HL-LHC upgrade project. In addition to providing the necessary space, it ensures the protection of sensitive equipment from the increased ionizing radiation environment in the insertion regions during the HL era and maintains the possibility of access to this equipment during beam operation, which will bring major advantages for the maintainability and repair times and as such the overall machine availability.

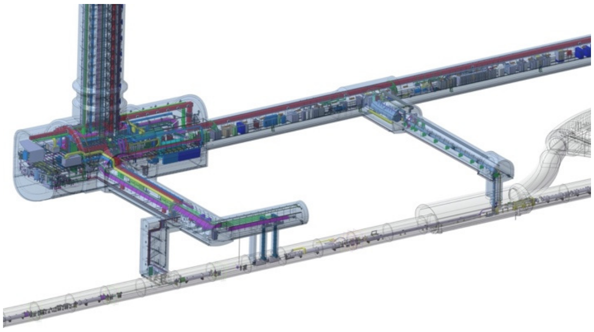

Figure 3: Existing LHC tunnel (grey) and HL-LHC underground areas (blue) integrating general and cryogenic infrastructure, powering and protection [9] equipment.

Despite concurring with the Covid-19 pandemic, all civil engineering works are progressing very well. The underground works, including the metallic structures were fully completed by October 2021 at Point 1 and by February 2022 at Point 5, with only one to two months of delay with respect to the contractual dates. Today, the main civil engineering activities are concentrating on the surface works, where 5 main buildings will house general services and cryogenic infrastructure. Final delivery of all civil engineering works at both points is expected by the end of 2022, followed by the completion of installation of technical infrastructure by the end of 2024. The remaining installation activity will then only resume after the delivery of the 24 vertical cores which will link the new HL-LHC structures with the existing LHC tunnel in summer 2026.

Integration work of both surface and underground areas is very well advanced, the latter being a particular challenge due to the large increase of new equipment and services that require installation in the existing LHC tunnel volume along with an increased set of constraints due to the more severe radiation environment.

COMMISSIONING AND PERFORMANCE RAMP-UP

Towards the end of LS3, individual system tests and hardware commissioning activities (HWC) will start to validate the new cold powering system and infrastructures for their operation as part of the LHC machine. HL-LHC operation with beam is planned to start in 2029, whereas the first year of operation is expected to take place at a minimum β^*=30 cm, without the use of crab-cavities during collisions and with a reduced bunch intensity of 1.8×10^{11} p [10]. The final beam energy for the start of Run 4 will likely only be defined during the HWC campaign. To disentangle the commissioning of the HL-LHC upgrades from possible effects of the energy increase in the remaining part of the machine, it would however be advisable to operate the LHC in the first year of Run 4 at the same energy as at the end of Run 3. With the progressing commissioning of the new HL-LHC systems with beam, the bunch intensity will be steadily increased towards the nominal value of 2.3×10^{11} ppb, and the minimum β^* further reduced to reach 20 cm at the end of this initial run. This will allow accumulating an integrated luminosity of 715 fb^{-1} during Run 4 in absence of intensity limitations.

CONCLUSION

The project, along with its in-kind partners and industry, has successfully commenced its transition to the series production for all key technologies. Progress has been impressive, and the project passed several key milestones in spite of the challenges and market uncertainties caused by the Covid-19 pandemic and the crisis in Ukraine. The completion of the major civil engineering works at the end of 2022 will be an important milestone for the project, which will soon be followed by the installation and operation of a first full inner triplet magnet string in CERNs superconducting test facility SM18. The IT String will allow a fully representative system test of the magnet string along with all concomitant systems ahead of their installation and operation in the LHC tunnel, which will be key for the development and validation of procedures, tools and expertise for an efficient installation in the LHC during LS3.

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