PROCEEDINGS OF SCIENCE

Status and Prospects of the HL-LHC Project

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This contribution summarizes the status of preparations and series production of key technologies for the HL-LHC upgrade project. The upgrade will be deployed in the LHC tunnel at the end of the currently ongoing third operational run of the LHC, by creating new underground areas and upgrading the existing LHC equipment, aiming to increase the data set collected by the main LHC experiments by another order of magnitude and starting operation as of 2029.

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1. Introduction

The High-Luminosity LHC project is an upgrade of the currently operated LHC, aiming at a further tenfold in-crease in integrated luminosity delivered to the ATLAS and CMS experiments and enabling LHC operation until the early 2040s. Following a first upgrade of the machine protection, collimation and shielding systems during the second long shut-down (LS2) (see Figure 1), the main installation phase of the project will commence in 2026 with the deployment of novel key technologies, including Nb3Sn based insertion region magnets, a cold powering system made of MgB2 superconducting links and the 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 in the phase of industrialization and series production for all main components. In this contribution, we provide an overview of the project status and the present plans for its 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.

The LHC performance has steadily improved over the first nine years of operation, allowing to collect already more than 160 fb^{-1} at 13 TeV during Run1 & Run2. With around 70 fb^{-1} at hand in a good operational year, the LHC is expected to deliver 400 fb^{-1} by the end of its third operational run in 2025. While only a small fraction of this data volume allowed to claim the discovery of the Higgs particle in 2012 [1], many fundamental questions remain to be answered, such as detailed measurements of the Higgs properties and its coupling to other fundamental particles or the exploration of physics beyond the standard model (BSM) as well as the dark sector. Doubling the accuracy for the experiments implies however a 4-fold increase of the underlying data volume, requiring the substantial upgrades of instantaneous and integrated luminosity provided by the HL-LHC project.

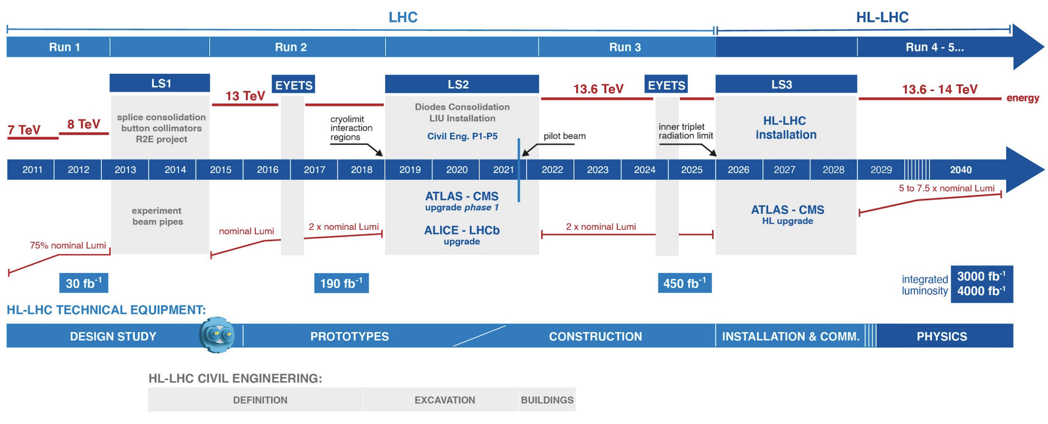

Figure 1: LHC and HL-LHC Schedule

2. HL-LHC project organisation

The HL-LHC project started at the end of 2011 with the EU funded HiLumi Design study, before being officially approved and integrated into CERNs Medium Term Plan in 2016. Today, the project is already more than half way, with the start of operation planned in the beginning of 2029 (see Figure 1). The project has an overall budget of roughly 1.1 billion Euros, and with series production well underway already more than 75% of this budget have been committed to date. The project is organised in 19 different work-packages, covering the key technologies and main competences required for the successful completion of the project, including amongst others accelerator physics, the insertion region magnets, crab cavities & RF, collimation, cold and warm powering systems, integration & (de-)installation, infrastructures and civil engineering.

3. Main technical challenges of the HL-LHC project

In the following sections, the main technical challenges of the project and their status of validation and production will be summarised.

3.1 Inner Triplet Magnets

Large aperture Nb3Sn focusing quadrupole magnets will be installed around the high luminosity experiments ATLAS and CMS, representing one of the cornerstones of the HL-LHC upgrade. Due to the higher collision rates in the experiments, radiation levels and integrated dose rates will increase accordingly, requiring particular care for the choice of materials used to construct the magnet coils as well as the integration of additional tungsten shielding into the beam screens. These new triplet magnets require roughly doubling the coil apertures compared to the existing LHC triplet magnets: from 70 mm to 150 mm, thus allowing a four times reduction of β^* with respect to the nominal design and with the improved beam emittances following the upgrade of the LHC injector chain [2]. For the HL-LHC upgrade a peak field of 8.5 T with the larger magnet aperture would imply a much longer triplet. Choosing Nb_3Sn allows reaching fields well above 10 T, and therefore doubling the triplet aperture while still keeping a relatively compact triplet (total length is increased from 23 m to 32 m), see Figure 2. The inner triplet magnets are designed and constructed in collaboration with the HL-LHC Accelerator Upgrade Project (AUP) in the USA. The Q1 and Q3 magnets (MQXFA) will be provided as in-kind contribution from AUP [3], while the longer version for Q2 (MQXFB) will be produced at CERN [6].

At AUP, coil production is nearing completion at BNL and FNAL, and 7 of the 16 required magnets have been accepted after reaching the acceptance criteria of nominal current +300 A at 1.9 K [4] [5]. An endurance test on magnet MQXFA05 has been very successfully 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, after which the magnet reached again 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. At FNAL, the construction of the first cryostated horizontal cold mass is ongoing (see Figure 3), integrating the first two series magnets that were successfully tested at BNL. Shipment of this first, fully validated cryoassembly to CERN is planned in fall 2023.

After completing a very successful short model program, CERN has produced two full scale prototypes and the first three series magnets of the Q2 quadrupole magnet. Following performance limitations [7] observed in one of the 4 coils of both prototype magnets, revised coil manufacturing, magnet assembly and welding procedures have been very successfully validated with short model

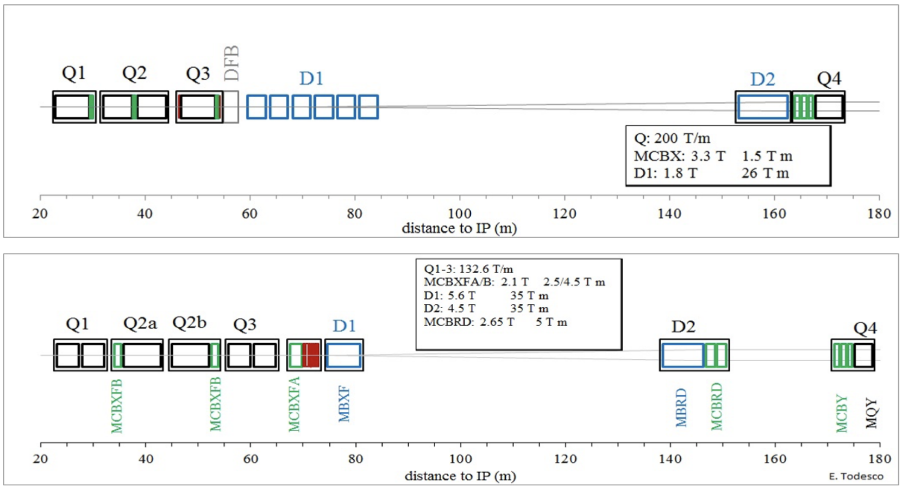

Figure 2: Layout of the insertion region magnets in present LHC (top) and HL-LHC (bottom)

Figure 3: First inner triplet quadruple cryoassembly of the AUP collaboration

and prototype magnets before being applied for the subsequent magnets of the series production. While still showing signs of limitations at 4.5 K, the two Q2 series magnets have subsequently reached the acceptance criteria at 1.9 K, with the third series magnet currently being prepared for cold tests in CERNs test infrastructure of SM18 [6].

3.2 Civil Engineering and integration

The construction of additional underground galleries to house the new infrastructures, powering and protection equipment of the accelerator components has been an early, strategic decision of the HL-LHC upgrade project. They provide the necessary space for installation and at the same time ensure the protection of sensitive equipment from the increased ionizing radiation environment in the insertion regions during the HL era. With the main galleries located around 10 m above the existing LHC tunnel (see Figure 4), this equipment will remain accessible during beam operation, which will bring major advantages for the maintainability and repair times of these complex systems and as such benefit the overall machine availability which is another key ingredient in reaching the challenging objectives of the project. All civil engineering works, both underground and for the surface buildings, have been already successfully completed at both points. The installation of the underground infrastructure has started in Point 5 following the delivery of the lift installation, and will soon be followed in November at Point 1. The main part of the technical infrastructures will be installed by the end of 2025, while the remaining installation activity will 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.

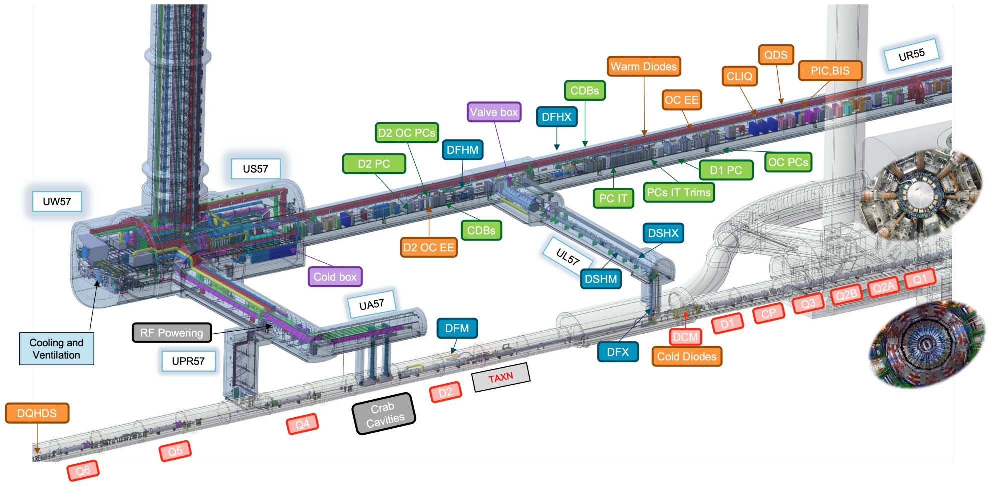

Figure 4: New underground galleries being for the HL-LHC equipment (light blue), located around 10 m above the existing LHC tunnel (grey). The left side of Point 5 is shown in this image. Galleries will continue symmetrically on the right side and are identical at Point 1.

3.3 Cold powering system

The installation of the major infrastructure, powering, and protection systems in the new HL-LHC underground galleries (see Figure 4) 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 of 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. A first complete cold powering system is currently being finalised and due for cold testing at the end of 2023. After its successful validation in combination with the HTS current leads and the cryogenic feedboxes and connection cryostats, the assembly will integrate the IT String test in early 2023.

3.4 Crab cavities

The second cornerstone of the project are so-called 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 the ATLAS and CMS experiments.

Two different types of cavities will be installed, the Radio Frequency Dipole (RFD) in IR1 and the Double Quarter Wave (DQW) in IR5, deflecting bunches in the horizontal and vertical crossing planes respectively. Series production of the RFD cavities is just about to start in Italian industry under the lead of AUP, while the DQW cavities series production is underway 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's Super Proton Synchrotron (SPS) since 2018, demonstrating the crabbing of proton beams and allowing for the development and validation of the necessary low-level RF and machine protection systems (see right in Figure 5). Two RFD dressed cavities have been delivered at the end of 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 2023 for first tests with beam (see left in Figure 5). Series production of the necessary ancillaries and higher order mode couplers has equally started for both cavity types after the successful validation of prototypes [8].

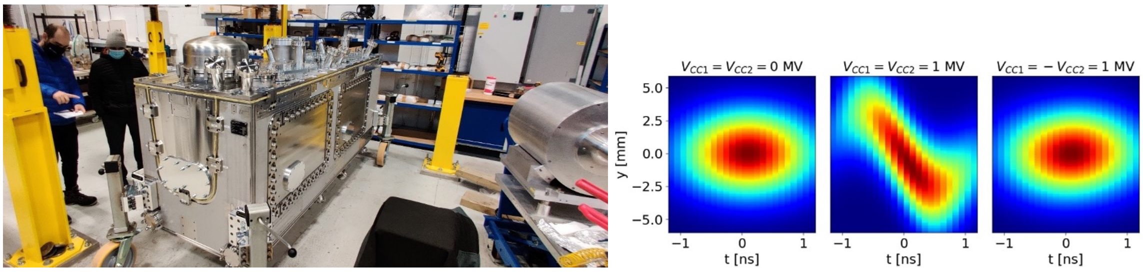

Figure 5: Cryostated assembly of 2 RFD CCs, being prepared for shipment to CERN and later installation in the SPS (left). Crabbing of proton bunches in the SPS in 2018 (right).

3.5 Inner Triplet String

One of the next major milestone of the project consists in the installation and validation of the IT String, a test setup featuring a complete IR installation including the triplet magnets and all components up to and including the D1 dipole magnet. The IT String will mimic the LHC installation left of IP5. It's setup will allow the CERN hardware teams to perform a fully integrated validation of the entire powering and protection systems as well as of the installation sequence and procedures on the surface before installation starts in the underground areas where space and access conditions are much more restricted. The main installation work for the IT-String is scheduled to be completed in 2024 and the commissioning and powering test program of the IT String is planned to start in 2025.

3.6 HL-LHC operation and performance ramp-up

Towards the end of LS3, and as soon as the installation activities in the first IR will near completion, 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, with the first year of operation expected to take place at a minimum β^* of 30 cm, without the use of crab-cavities during collisions and with the same bunch intensity of $1.8x10^{11}$ ppb as at the end of Run 3 (see left in Figure 7) [9].

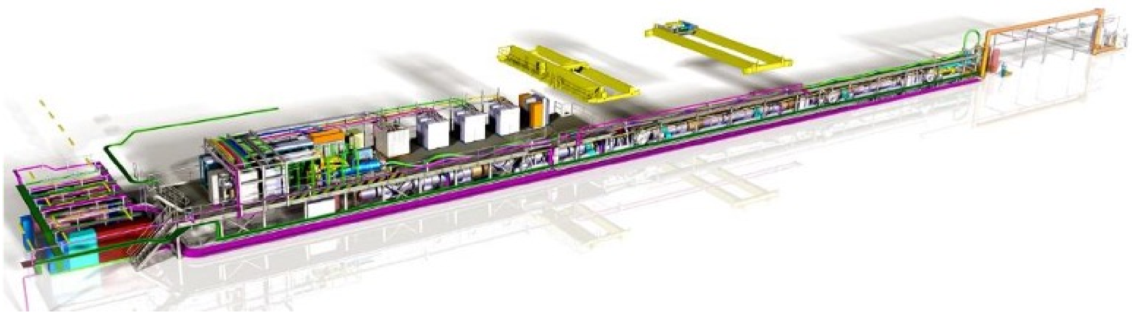

Figure 6: Inner Triplet String under installation in CERNs SM18 test facility. Magnet string from Q1 to D1 is located on the ground floor, while all powering and protection equipment is housed on a metallic platform.

With the progressing commissioning of the new HL-LHC systems with beam, the bunch intensity will be steadily increased towards the nominal value of $2.2x10^{11}$ ppb, and the minimum β^* further reduced to reach 20 cm towards the end of the first operational run. This will allow accumulating an integrated luminosity of 715 fb^{-1} during Run 4 (see right in Figure 7) and allow to reach the nominal integrated luminosity goal of 3000 fb^{-1} at the end of Run 6 in 2042.

Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ $[\mu\mathrm{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200

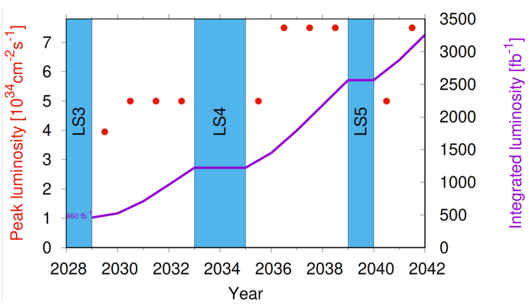

Figure 7: Intensity and performance ramp-up in Run 4 and Run 5 of the HL-LHC era (left). Prospected evolution of integrated luminosity in the HL-LHC era (right).

4. Summary

The project, along with its in-kind partners and industry, is today in full swing of series production for all key technologies of the HL-LHC upgrade. 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 has marked a very important milestone for the project, allowing to commence the installation of infrastructures and services in the new underground galleries. The key technologies for the magnets and powering systems are being installed in a first full inner triplet magnet string in CERNs superconducting test facility SM18. This IT String will allow a fully representative system test of the magnet string along with all associated 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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