OVERALL STATUS OF THE HL-LHC PROJECT

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Abstract

The High-Luminosity LHC project aims at increasing the integrated LHC luminosity by an order of magnitude, and enabling LHC operation till the early 2040s. This presentation reviews the HL-LHC project status. Many HL-LHC achievements can be reported-upon by mid-2023, starting with the completion of the Civil Engineering through to the successful demonstration of the triplet magnets.

LHC LIFETIME LIMITATION

In addition to the usual ageing of equipment and the resulting requirement for continuous consolidation of hardware, one expects for integrated luminosities above 300 fb^{-1} inside the focusing quadrupole magnets next to the LHC experiments, the so-called triplet magnets, radiation dose levels exceeding values of 10 MGy, a radiation level where most epoxy and insulation materials become brittle and lose their mechanical integrity. As the LHC triplet magnets rely on epoxy impregnation and Kapton insulation foils for the coil construction, it is expected that the LHC triplet magnets lose their mechanical integrity or experience degradation of the electrical insulation system for integrated luminosity values between 400 fb^{-1} and 500 fb^{-1} [1]. Preparing the LHC machine for an integrated luminosity well beyond 300 fb^{-1}, therefore requires the replacement of the existing triplet magnets with new, more radiation tolerant magnets that will at the same time feature larger apertures.

HL-LHC PERFORMANCE GOALS

The main objective of the HL-LHC is to determine and build a hardware configuration and a set of beam parameters that will allow operating the LHC machine beyond 2025 and up to the early 2040ies and enable a total integrated luminosity of about 3000 fb^{-1}, ca. 10 times the nominal design luminosity, implying an integrated luminosity of 250 fb^{-1} per year [2]. An ultimate integrated luminosity of 4000 fb^{-1} could be within reach if all engineering margins are exploited. While pushing the integrated luminosity to unprecedented levels, the experiments prefer an operation with 140 simultaneous collision events per bunch crossing, corresponding to 5 times the nominal LHC design value, a peak luminosity of 5 10^{34} $cm^{-2}s^{-1}$. This could be pushed to up to 200 events per bunch crossing for the ultimate performance. To reach the intended ten-fold increase in integrated luminosity, the HL-LHC project is utilizing operation with levelled luminosity, an operation mode where the machine parameters are chosen for a 'virtual' peak luminosity that exceeds the design value requested by the experiments, while the instantaneous luminosity is dynamically levelled to the desired values by changing the cross-angle and / or ß* throughout the duration of the fill. This operation mode allows for longer physics fills and, when combined with a sufficiently high machine availability and efficiency, generates the targeted increase in integrated luminosity [3]. The HL-LHC must therefore not only be a high performance machine, but also a highly reliable machine with a minimum unintentional beam aborts. Several papers discuss performance aspects for the HL-LHC operation at this conference [4-8].

Figure 1 shows the overall schedule for the HL-LHC installation. With the official project budget implementation in 2016, the project is currently at about the mid-point of the implementation phase.

LUMINOSITY LEVELLING OPTIONS

Different options for the luminosity levelling have been explored since the start of the LHC operation. One of the first tools tested and implemented in the LHC operation was the levelling via transverse beam offsets. Initially, this scheme was requested by the ALICE experiment for data taking during the proton beam operation. Since these initial tests, this method has been fully validated and implemented already during the first operational run of the LHC. Another levelling option is the levelling through the beam crossing angle at the interaction points. As we will discuss later in the context of the Crab Cavity RF system, this would have been a very elegant tool for the luminosity levelling. However, this method does not reduce the density of events inside the LHC detectors and effectively only changes the length over which collisions will be produced within the experiments. It was thus mainly used during Run 2 for adjusting the instantaneous luminosity but is not maintained as a baseline levelling tool for the HL-LHC operation. The third option for luminosity levelling is the variation of the beam size at the collision point through changes in the magnetic focusing of the beams left and right from the detector. While this method is clearly the most elegant levelling technique, it is also the most complex technique for the operation of the machine. All three techniques have already been successfully demonstrated and have been established as standard operational tools for the LHC operation [5].

KEY HL-LHC HARDWARE UPGRADES

A considerable increase of the radiation tolerance of the triplet magnets can only be achieved through the insertion of active absorbers for the particle losses coming from the interaction points. For the HL-LHC triplet magnets this shielding is provided by actively cooled tungsten blocks that are placed between the magnet cold bore and the beam screens, which in turn, requires an increase in the triplet magnet apertures.

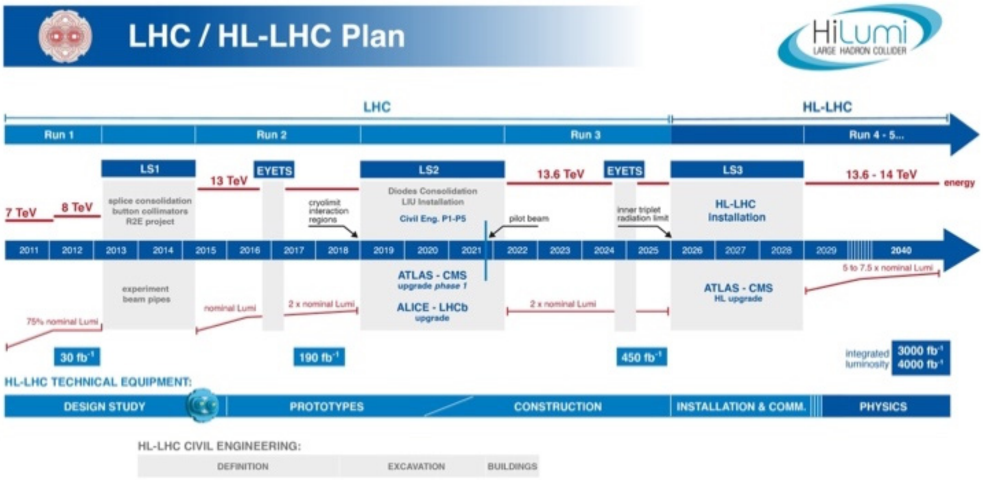

Figure 1: The HL-LHC installation schedule.

In the following, we list the key upgrade ingredients and the associated new technologies for the HL-LHC upgrade.

Nb_3Sn Magnet Technology

The HL-LHC 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 LIU beam emittances [9, 10]. The LHC triplet magnets feature gradients of 215 T/m, which implies for the 70 mm coil apertures peak fields of 8.5 T inside the magnet coils. 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). For the HL-LHC, the magnet gradient is set at 132 T/m with a peak field of 11.3 T inside the magnet coils. Figure 2 shows the peak field in the coil of the HL-LHC magnets, MQXF, and a comparison to the main dipole and the triplet magnets of the LHC, MQXA/B and MB.

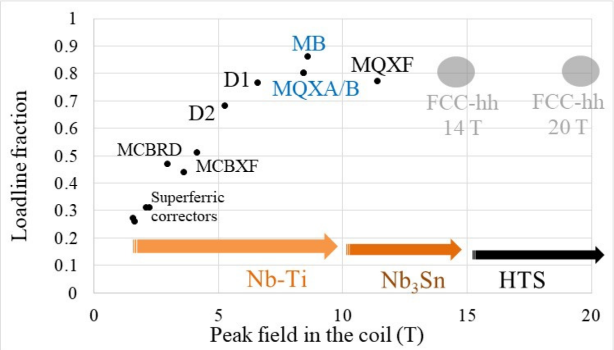

Figure 2: Peak field in the HL-LHC IR magnets versus loadline fraction, and targets for FCC-hh [10].

The development of Nb_3Sn triplets for the HL-LHC upgrade, capable of operating above 10 T, started in 2005 with the US LARP program [11, 12]. The left-hand side of Figure 3 shows the schematic cross section of the HL-LHC MQXF triplet magnets developed as part of the CERN and US joint R&D effort since 2010. The right-hand side shows the beam screen together with the tungsten absorbers and cooling capillaries inside the magnet cold bore.

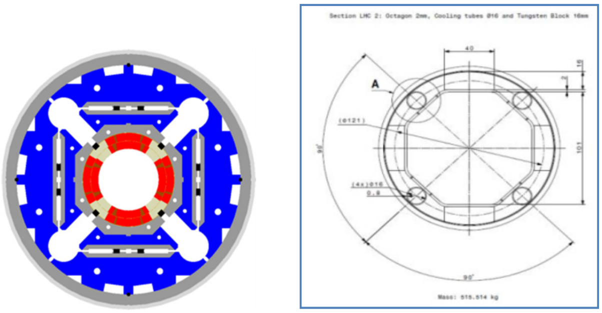

Figure 3: HL-LHC triplet magnet cross section. Left the coils in the bladder and key assembly. Right, the beam screen, Tungsten absorbers and cooling capillaries within the cold bore.

Other Insertion Magnets

In addition to the new triplet quadrupole magnets, the HL-LHC insertions [10, 13, 14] require new larger aperture magnets in the whole region up to, but excluding Q4 (see Fig. 4): new D1 and D2 separation and recombination dipole magnets to guide the two beams from the separated apertures in the arcs onto a common trajectory inside the ATLAS and CMS experiments, new orbit corrector magnets for the triplet region, new non-linear corrector magnets and new orbit corrector magnets for the D2 twin aperture dipole magnets. The D1 dipole is manufactured by Hitachi as an in-kind contribution from KEK-Japan. The first prototype magnet reached the 5.6 T operational field and recently arrived at CERN for further testing. The D2 dipole magnet is manufactured by ASG as an in-kind contribution from INFN-Italy and the first prototype magnet reached the 4.5 T operational field, along with a set of novel canted-cosine theta orbit corrector magnets, which are produced by BAMA as an in-kind contribution from IHEP-China. Nested orbit corrector magnets are produced by Elytt as an in-kind contribution from CIEMAT-Spain: prototypes and pre-series nested corrector magnets reached performance requirements, i.e. a field in each plane of 2.1 T. The nine families of non-linear corrector magnets are based on super-ferric design, and they have been produced by SAES-Rial as in-kind contribution from INFN-Italy. All non-linear corrector magnets have been tested and delivered to CERN. This is the first magnet contribution to the HL-LHC project that completed already the full production phase. Figure 4 shows the new HL-LHC layout of the long-straight section of ATLAS/CMS schematically together with the new underground constructions.

The HL-LHC triplet magnets are produced to equal parts by the AUP consortium in the US [15] and by CERN. First successful tests of a 4 m long series magnet based on the new technology took place in the US in 2020 in a vertical test stand configuration. The first prototype of the 7 m variant achieved the operational gradient in a horizontal cryostat configuration in 2022 at CERN, and a second magnet passed the acceptance criteria in spring 2023, including an endurance test. AUP also conducted an endurance test with over 50 provoked quenches at nominal current and 5 thermal cycles on one of their series magnets in 2022 and conducted its first full magnet test in a horizontal cryostat configuration in 2023. Both production sites have successfully finished their prototyping and demonstration phase and have started the series production of the new triplet magnets, which is scheduled to finish in 2026.

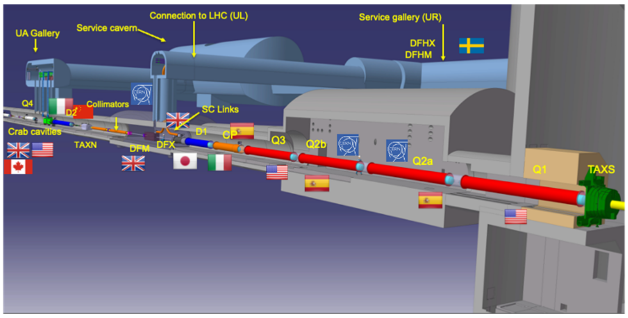

Figure 4: The new HL-LHC insertion area with the new triplet magnets, D1 and D2 separation / recombination dipole magnets, Crab Cavities inside the existing LHC tunnel [grey structures] and the new underground gallery, connection tunnels and cavern [blue-grey] with the experiment being located on the right side. The flags indicate the origin of the in-kind contributions.

Civil Engineering

The higher luminosities in the HL-LHC era imply additional heat loads in the triplet magnets and require additional cooling capacities for the insertion magnets. Furthermore, the goal of high efficiency and highly reliable operation of the HL-LHC implies that sensitive electronic components are removed from the tunnel areas where they are exposed to radiation from proton losses and moved to areas where access during operation is facilitated in order to ease preventive maintenance and shorten the intervention times. To this end, the HL-LHC project planned for new underground structures and caverns to house the new cryogenic cold boxes and distribution equipment, the new infrastructure and powering equipment along with most of the electronic racks that had previously been installed in the LHC tunnel areas. The new underground constructions feature at each of the 2 high luminosity interaction regions a new cavern and an approximately 300-meter-long gallery and two 50m-long service tunnels on both sides of the experiments that connect the new gallery to the existing LHC tunnel. In addition to the new underground structures, the HL-LHC upgrade features 5 additional surface buildings on the existing ATLAS and CMS sites. The new underground areas are constructed in what has been labelled the Double Decker configuration, where the new underground areas are located approximately 10 meters above the existing LHC tunnel structure and where the connection of the new and old structures is established via 12 vertical cores of ~1m in diameter. This configuration provides optimum shielding of the new areas against radiation effects from the existing LHC tunnel and facilitates the connection of the two structures. The bulk of the civil engineering work has been conducted during LS2, when the LHC machine was not operating, in order to minimize the perturbative effect of the work on the LHC operation [16]. All underground civil engineering work has been terminated by the end of 2022 and all new surface building have been handed over to CERN by January 2023. CERN is now conducting the installation of the technical infrastructures, like cooling and ventilation, electrical distribution, and emergency communications. The installation of the new HL-LHC equipment is scheduled to start by the end of 2023. Figure 5 shows the new underground installations.

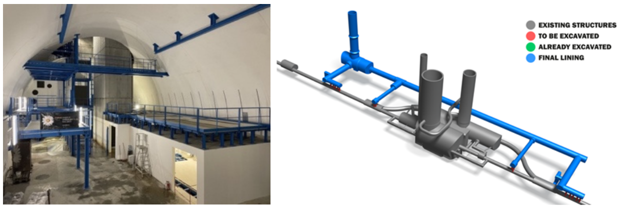

Figure 5: The new underground installation. Left: View onto the metallic structure of the cavern. Right: schematic view of the new underground structures.

Superconducting Links

The power converters and electronic racks for the magnet powering and protection of all new HL-LHC magnets will be installed in the new underground galleries, approximately 70 m to 100 m away from the actual magnets in the tunnel. The connection between the new power converters and the new magnets in the LHC tunnel will be established with novel superconducting links that utilize high temperature superconductors based on MgB_2 technology [17]. The MgB_2 superconductor is cooled by gaseous He that is evaporated inside the cryo lines of the new insertion magnets, providing temperatures between 25 K and 50 K inside the flexible cryostat of the superconducting link. The connections between the superconducting link to the power converters in the new galleries and the magnet cryostats in the tunnel are provided by new feed boxes that utilize again novel high temperature superconductors for these transitions. Prototypes of these links have been tested at the end of 2020 [Demo-2] and beginning of 2023 [Demo-3], demonstrating the ability to transport over 100 kA without Ohmic losses at a temperature between 25 K and 50 K over a distance of more than 70 meters [18]. Figure 6 shows the Demo 2 Superconducting Link at CERN. Prototypes of the new feed boxes are currently being assembled and tested at CERN, completing the prototype phase of the first fully integrated cold powering system. The project is now in the phase of series production for all components of the superconducting link, and the cryostating of the first link of the series production took place in March 2023.

Figure 6: Superconducting Link at CERN in SM18.

Crab Cavities

The longer triplet magnet length and the reduced beam size at the Interaction Points [IPs] requires a larger crossing angle at the IPs, 500 μrad compared to the 285 μrad LHC design value and the 320 μrad currently used for the LHC operation. The crossing angle mitigates the detrimental perturbations from the non-linear beam-beam interactions at the unwanted [parasitic] bunch crossings along the common beam pipe between the two D1 magnets left and right from the IPs.

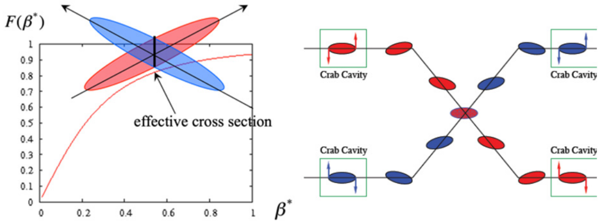

Figure 7: Functioning of Crab Cavities. Left side: the luminosity reduction factor as a function of β* for a minimum normalized beam separation of 10 σ. Right side: schematic illustration of the transverse bunch deflection that reconstitutes a perfect beam overlap at the IPs.

Combined with a reduction of the optical beta-function from 55 cm in the nominal LHC design and 30 cm in the current LHC operation period to 15 cm at the IPs for the HL-LHC configuration, the overlap of the two colliding bunches at the IP is considerably reduced and thus the attainable luminosity by about 70%. Figure 7 illustrates this effect and shows the geometric luminosity reduction factor as a function of the optical beta-function at the IP for a minimum normalized beam separation of 10 sigma at the parasitic collision points. To recover the luminosity, two different Crab Cavity [CC] designs that allow for a transverse bunch rotation were developed in collaboration with the LARP collaboration: a Double Quarter Wave [DQW] design optimized for a crossing angle in the vertical plane [19] and an RF Dipole design [RFD] optimized for a crossing angle in the horizontal plane [20]. Figure 8 (left) shows the DQW prototype cryomodule installed in the SPS machine where the first experimental demonstration of a crab cavity with a hadron beam was realized [21]. Several key beam experiments have been conducted as a part of a test campaign with high energy proton beams in the presence of crab cavities since 2018. Figure 8 (right) shows the string assembly of two RF Dipole prototype dressed cavities under preparation for a beam test in the SPS in 2024-25. This cryostating is presently ongoing at Daresbury Lab in the framework of a collaboration agreement between CERN and UK-STFC.

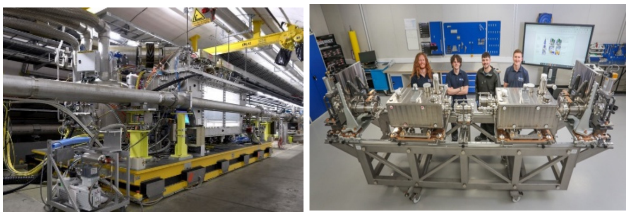

Figure 8: Left: Prototype cryomodule installed in the SPS for tests since 2018. Right: String of 2 RFD dressed cavities prior to assembly (courtesy HL-UK).

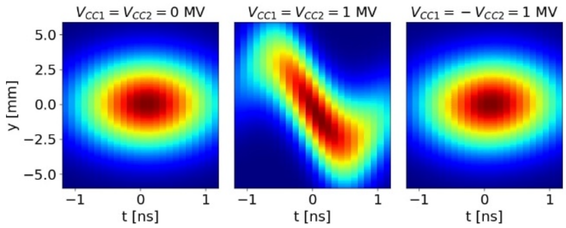

Figure 9: Intra-bunch motion from three different cases. Left: Cavities switched off ($V_T = 0$). Centre: Synchronous crabbing with both cavities in phase ($V_T = 2$ MV). Right: Cavities in counter-phase, corresponding to effective zero kick voltage ($V_T <$ 60 kV).

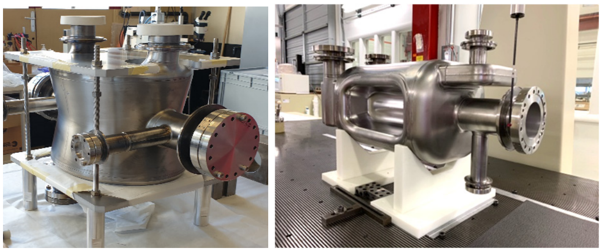

Figure 10: Left: First series DQW Crab Cavity from industry in Germany. Right: RF Dipole CC prototype from the AUP production.

Figure 9 shows a comparison of the intra-bunch transverse displacement of a single proton bunch in different conditions; CC switched off (left) and synchronous crabbing coming from two CC in phase (centre), and the two cavities counter-phased to have a zero effective kick voltage (aka transparent mode) [21].

Figure 10 shows first industrial series production of the DQW [left] and RFD prototype cavity [right]. Both cavity designs have been fully tested and validated. [22] presents studies related to required 'field' quality of the CCs.

New Collimators

The higher beam intensities in the HL-LHC operation era imply the use of more robust collimator and absorber materials that feature at the same time a lower impedance than those adopted for the start of LHC operation. The new challenges related to the operation at lower β^* and at higher peak luminosity also required a complete re-design of the collimation systems around the high-luminosity experiments. The HL-LHC upgrade therefore features new, low impedance secondary collimators and new, additional tertiary collimators in the IRs and a more performing physics-debris collimation system. The low impedance collimators feature new designs using Mo coated Molybdenum-Graphite and Cu-coated Graphite that have integrated button pickups for efficient alignment of the jaws with the beams. About half of the LHC secondary collimators has already been replaced during Long Shutdown 2 [LS2] and prior to the LHC Run3 period that started in 2022. Figure 11 shows the ongoing production of the prototype jaws for the next set of physics-debris collimators at CERN. Given the criticality of maximising the physics time at the HL-LHC, all new collimators mount in-jaw BPMs for faster alignment and easier handling of the complex level-ling gymnastics.

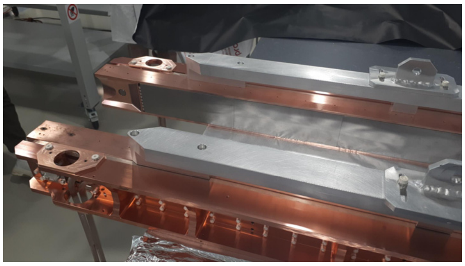

Figure 11: The new jaws of the physics-debris collimator prototype with the button pickups at the extremities.

For operation with ion beams, the cleaning efficiency in the dispersion suppressors (DS) of the ALICE experiment will be augmented by new DS collimators and by careful steering the beam trajectories in the DS so that the beam losses with Pb^{82+} ion beam collisions either end up on the new collimators. In IR1/5, losses are steered towards the connection cryostat of the DS that does not contain active magnetic elements, so no DS collimator is needed here. The installation of the new DS collimators relies on the development of new connection cryostats that allow the insertion of collimation equipment at room temperature.

Two of these devices have been installed during LS2 next to the ALICE experiment. Figure 12 shows a picture of this new collimator assembly during installation. For the cleaning insertion in IR7, the losses in the dispersion suppressor will be mitigated for Pb^{+82} operation via new Crystal collimators that enhance the cleaning efficiency in IR7 for ion beam operation. Figure 13 shows the new goniometers and the crystal collimators prior to their installation in the LHC.

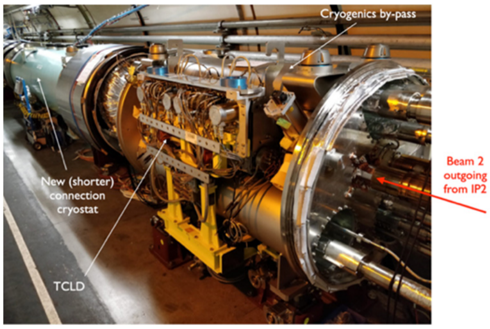

Figure 12: New Dispersion Suppressor collimator installation in IR2 next to the ALICE experiment.

Recent beam studies in the LHC indicate that additional DS collimators in IR7 are not required for magnet protection during nominal proton beam operation. The current setup with crystal collimators in IR7 therefore seems to be an adequate upgrade path for the moment, confirming the decision to delay the installation of 11T dipole magnets and dedicated DS collimators in IR7 at least until after Run3. The HL-LHC is therefore not only a performance upgrade for the LHC, but also a seedbed for various essential accelerator technologies that will find applications well beyond that of the HL-LHC project.

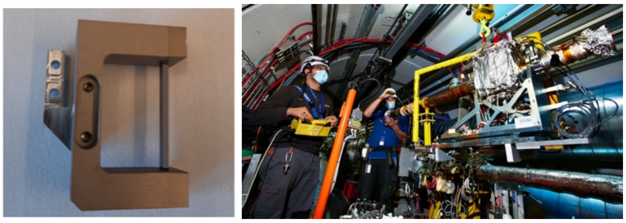

Figure 13: Left: Bent crystal. Right: Installation of new goniometer including a bent crystal in IR7.

SUMMARY

The HL-LHC project has completed essentially all prototype validation tests and is now in the phase of series component production for virtually all upgrade components. For some components, like the non-linear corrector magnets, the entire production has even already been completed. The next major milestone for the project consists of the testing and validation of the IT String [23], 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 resembles the installation left of IP5. Its setup will allow the CERN hardware teams a full integrated validation of the entire powering and protection systems and to validate 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 for 2023 and the commissioning of the IT-String is planned to start in 2024.

REFERENCES

[1] N. Karastathis *et al.*, “LHC Run 3 Configuration Working Group Report”, in *Proc. of the 9th LHC Operations Evian Workshop*, pp. 273 – 284, CERN, Switzerland 2019.

[2] High-Luminosity Large Hadron Collider, CERN, Switzerland, HL-LHC0 TDR, CERN-2020-010, ISBN 978-92-9083-587-5.

[3] R. Tomas *et al.*, “HL-LHC Run4 proton operational scenario”, CERN-ACC-2022-0001, CERN, Switzerland, 2022.

[4] R. De Maria *et al.*, “High Luminosity LHC Optics Scenarios for Run4”, presented at the 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper MOPL034, this conference.

[5] M. Hofstaettler *et al.*, “Operational beta* levelling at the LHC in 2022 and beyond”, presented at the 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper MOPL045, this conference.

[6] S. Kostoglou *et al.*, “Dynamic Aperture Studies for the High Luminosity LHC in Run 4”, presented at the 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023, paper WEPL102, this conference.

[7] B. Bradu *et al.*, “Electron Cloud Observations and Mitigation for the LHC Run 3”, presented at the 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper WEPA091 this conference.

[8] E. Montanari *et al.*, “Recent Measurements and Analysis of the Beam-Halo Dynamics at the CERN LHC using Collimator Scans”, presented at the 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper WEPA022, this conference.

[9] LHC Injectors Upgrade Technical Design Report, CERN, Switzerland, CERN-ACC-2014-0337, 2014.

[10] E. Todesco *et al.*, "Review of the HL_LHC interaction region magnets towards series production", *Supercond. Sci. Technol.*, vol. 34, no. 5, p. 053001, Mar. 2021. `doi:10.1088/1361-6668/abdba4`

[11] `https://www.uslarp.org`

[12] S. Gourlay *et al.*, "Magnet R&D for the US LHC accelerator research program (LARP)", *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 324-327, Jun. 2006. `doi:10.1109/TASC.2006.870786`

[13] E. Todesco *et al.*, "Status and challenges of the interaction region magnets for HL-LHC", *IEEE Trans. Appl. Supercond.*, vol. 33, p. 4001608, Mar. 2023. `doi:10.11/TASC.2023.3244143`

[14] G. Ambrosio *et al.*, "Lessons Learned from the Prototypes of the MQXFA Low-Beta Quadrupoles for HL-LHC and Status of Production in the US", *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, p. 4001105, Feb. 2021. `doi:10.1109/tasc.2021.3058597`

[15] `https://www.osti.gov/biblio/1594131`

[16] J. Wenninger, “Lessons Learned from the Civil Engineering Test Drilling and Earthquakes on LHC Vibration Tolerances”, in *Proc. LHC Performance Workshop Chamonix*, 2016, `https://indico.cern.ch/event/448109/contributions/1942067/attachments/1216213/1800370/HL-LHC.VibrationsEarthquakes.paper.pdf`

[17] A. Ballarino, “Development of superconducting links for the Large Hadron Collider machine”, *Supercond. Sci. Technol.*, vol. 27, no. 1, p. 044024, Mar. 2014. `doi:10.1088/0953-2048/27/4/044024`

[18] `https://hilumilhc.web.cern.ch/article/demo-3-new-successful-milestone-wp6a-team`

[19] S. Verdu-Andres *et al.*, “Design and vertical tests of double-quarter wave cavity prototypes for the high-luminosity LHC crab cavity system”, *Phys. Rev. Accel. Beams*, vol. 21, p. 082002, Aug. 2018. `doi:10.1103/PhysRevAccelBeams.21.082002`

[20] S. U. De Silva *et al.*, “Cryogenic test of a proof-of-principle superconducting rf-dipole deflecting and crabbing cavity”, *Phys. Rev. ST Accel. Beams*, vol. 16, p. 082001, Aug. 2013. `doi:10.1103/PhysRevSTAB.16.082001`

[21] R. Calaga *et al.*, “First Demonstration of the use of crab cavities on hadron beams”, *Phys. Rev. Accel. Beams*, vol. 24, p. 062001, Jun. 2021. `doi:10.1103/PhysRevAccelBeams.24.062001`

[22] F. Carlier *et al.*, “Status of the beam-based measurement of the skew-sextupolar component of the Radio Frequency field of s HL-LHC type Crab-Cavity”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper MOPL001, this conference.

[23] M. B. Bajko *et al.*, “The Inner Triplet String Facility for HL-LHC: Design and Planning”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3592-3595. `doi:10.18429/JACoW-IPAC2021-WEPAB376`