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THE HIGH LUMINOSITY LARGE HADRON COLLIDER PROJECT*: FROM PROJECT TO REALITY AT CERN

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) project is an upgrade of the LHC aiming to increase by a factor 10 the harvested integrated luminosity foreseen early 40s. During Long Shutdown 3, scheduled to begin at the end of 2025, nearly 1.2 km of accelerator components around the two high luminosity experiments of ATLAS and CMS, including a range of services spread across surface and underground facilities, will be replaced with new equipment deploying innovative key technologies. Two 300 meter-long tunnels, with access shafts and large service caverns, were excavated in parallel to the LHC machine tunnel to house the new power converters, cryogenics, and other key systems. Ten buildings were constructed on the surface to house all the necessary new services. The civil engineering design, the system definition and equipment design phase have been managed in close synergy with the HL-LHC Integration Team, responsible for optimizing the allocation of volumes between the different stakeholders in order to guarantee the efficiency of installation, the maintainability, and the operability of the different systems. This work describes the process and the challenges that had to be overcome in the integration studies to meet the targets of maturity of the project, allowing the installation phase to start on a sound and solid basis.

HL-LHC INTEGRATION

The HL-LHC Integration Team focuses on assigning and optimizing the distribution of volumes to the equipment owners, aiming at the best efficiency for their space allocation and installation in the facilities, while ensuring access for maintenance and operability, as shown in Fig. 1. To expedite and facilitate the design development for the different providers, the HL-LHC Integration Team, in accordance with the integration methodology [1], has reused multiple reference systems that CERN developed for the LHC initial installation based on the nature of the equipment in question. The team indicates to each equipment owner in which reference system their system should be designed and provides support in case of need. These providers can be either internal or external collaborations of the project, meaning work packages or independent equipment owners.

The use of different reference systems has major advantages that facilitate the design of the different systems and services, their integration in the facilities, and the verification and validation of the 3D models. First, this fact allows abstracting the design of the component from the physical location where it will be installed, as the LHC tunnel has different slope and roll angles in each section. Thanks to this approach, it is possible to use the same 3D model for different regions in the tunnel, each one characterised by its own set of angles and orientations. It is, therefore, the central integration that has the responsibility to define the orientation of the object in the specific installation slot. The process is more robust, as knowledge and responsibility are concentrated in a single team, along with the pertinent checks of the positioning of the equipment and the availability of the related services. Last but not least, the deployment of local reference systems avoids accumulating numerical errors in the 3D integration model.

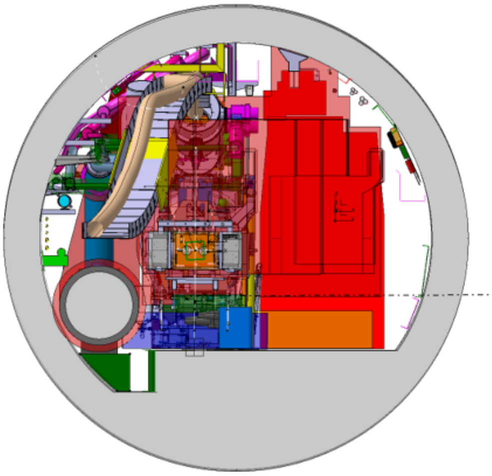

Figure 1: Cross-section of the tunnel integration 3D models.

The applied integration methodology also ensures proper staging and careful traceability in the 3D model status of the subsequent phases of installation, allowing to distinguish between what is already installed and what will be installed in the future Long Shutdown 3 (LS3). To meet this goal, it is necessary to verify that the 3D models reflect accurately the reality of the as-built machine tunnel environment through the reverse engineering approach [2]. These techniques allow faithfully to recreate the reality of the tunnel and analysing the volumes that will be available for installation, taking into account the evolution of the LHC environment since its original installation [3]. Furthermore, they also enable the identification of other non-trivial aspects such as the existence of trenches, sewers, ducts, etc. Once all the boundary conditions have been identified, the integration study can proceed on a solid basis.

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Sources

The 3D integration work is only possible by gathering the reference models of the facilities (cavern, tunnel, or building) where the equipment together with the required services, and ancillary equipment will be installed. These are:

- The facility models and the updated 3D models, based on cloud of points files generated from a laser scanner and that are meshed in CATIA V5® [4, 5], to match the as-built facilities.
- The 3D models including space reservations for installation, maintenance, and access are provided by the service teams such as water cooling and ventilation, signal cabling, powering cabling, fibre optic cabling, and transport.
- The simplified 3D models of the equipment to be installed in the machine tunnel including the operational and maintenance volumes are provided by the equipment owners.

The HL-LHC Integration team has the mandate to verify the accuracy of the 3D models provided with respect to the reality in case of existing equipment, and the specifications for the future components. For major upgrades, like the 1.2 km of machine that will be completely re-installed [6], the LHC 3D models cannot serve as foundation for the integration studies and completely new ones must be developed. The service teams create and modify existing services and ancillaries to match the engineering specifications of the new equipment.

LAYOUT MANAGEMENT

The machine layout [7] is the sequence of functional positions along the beam-lines, covering equipment and reserved spaces. At CERN, the Layout Database (LDB) [8, 9] is the reference for the description of each accelerator. The LDB allows to access the layout information in a time-dependent manner, meaning that it is possible to access to different layouts of the same machine at a desired date, providing access to the status of the accelerator installation at a given moment in time. It is continuously updated with the latest released machine layout. Each machine layout version is linked to the approved 3D integration models and the related 2D layout drawings that are used for formal approval by all stakeholders.

Presently, the HL-LHC data matches the layout version ”LS3 1.6” and it is evolving towards the new version ”LS3 1.7”. The HL-LHC Integration Team releases yearly updated layout versions, that provide the work packages with the Project Baseline, for their own technical development and the preparation of their installation activities.

One of the main stakeholders involved in the layout process development is *Work Package 2 – Accelerator Physics & Performance* [10]. The team ensures that the layout under development meets the beam physics requirements and that there is no showstopper that could impair the future machine operation.

Conceptual Layout Drawings Generation

These reference drawings are created based on the Digital Mock-Up toolkit [11]. This tool allows to retrieve the selected functional positions via a SQL query to the LDB and then making use of an excel engine to generate XML files to be imported in CATIA V5®CAD.

The resulting drawing is composed by a series of wireframes 2D models representing an outline of the equipment as well as the main internal and external interfaces. For example, the magnets, the cold masses, the jumper connections to the cryogenics line, and the outer flanges would be represented in the wire-frame of a magnet cryoassembly together with the functional dimensions like the magnetic centres and the magnetic lengths.

PROJECT BASELINE MANAGEMENT

The Project Baseline is described by three specific baselines: scope baseline, which mainly represents the project objectives and functional requirements of the machine; budget baseline, which represents the financial means to cover the total costs of the current baseline of the project; and schedule baseline, which represents the duration in time of the activities and deadlines for all the previously defined deliverables.

Any modification on the scope and/or schedule baselines, that affects the Project Baseline, have to be described and approved via Engineering Change Requests (ECR) by the HL-LHC Integration Team and the different work packages affected by the change request. Depending on the nature of the change request, the HL-LHC Integration Team handles two different types of ECRs. On one hand, there are ECRs that impact the current LHC machine and aim to either protect its components or upgrade them for the improvement on the present performance. On the other hand, there are ECRs that affect the scope of the HL-LHC Project but do not represent tangible modifications to physical elements of the current machine since they are not yet installed.

The Integration Reports for Installation Approval (IRIA) are the documents used by the HL-LHC Integration Team to support the ECR approval from the integration and installation point of view. Furthermore, the comparison between the existing and the future configuration, the description of the changes, the differential layout drawing (showing a top and front view of the integration model of the before and after the installation) serving as reference for the work in-situ, and the impact on other systems or services are documented. Once the modification on the Project Baseline is agreed, meaning that the ECR is approved, the de-installation and installation

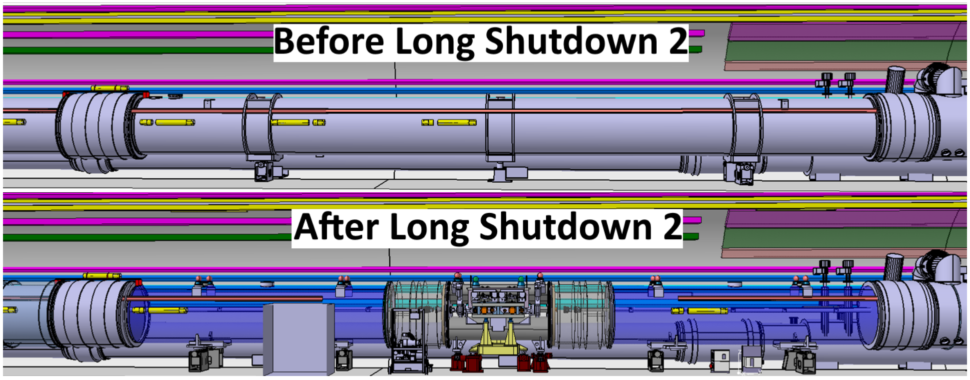

Figure 2: Dispersion suppressor cryostat before (above) with the bypass cryostat after the Long Shutdown 2 (below).

processes of the change proposal start. New version of the IRIA document is generated, containing all the discrepancies between the 3D integration studies and the reality and possible non-conformities found during on-site inspections.

Engineering Change Example

During the Long Shutdown 2 [12], in view of higher intensities expected for HL-LHC, two new connection cryostats and one bypass cryostat allowing the collimation of off-momentum particles impacting the first and second cells in the dispersion suppressor (DS) area around the interaction point 2 were installed [13], as shown in Fig. 2.

Before the integration study starts, a recollection of the current configuration is done via a reverse engineering process as mentioned above, using the existing laser scans and the available 360° photos [14]. In this integration study, the *Work Package 10 - Energy Deposition & Absorber Coordination* FLUKA team verified that the new optics would not result in a risk of a greater energy deposition in the machine protection devices located under the cryostats in the surrounding area.

At an early phase, for the preparation of the installation, the integration study is started on the basis of a wire-frame that includes the preliminary optics (provided by WP2) and a series of simplified models that represent the volumes occupied by the main equipment and ancillaries to be installed. Furthermore, the iterative process starts with a series of integration meetings held with the stakeholders to be able to evaluate the impact in their service levels in terms of existing capacity or hardware upgrade required. Additionally, it is verified that all the maintenance and installation volumes and accessibility are granted in safe working conditions. At the end of this phase, two IRIAs were created one dedicated to the cryostats under the responsibility of *Work Package 11 - 11T Dipole for the DS Regions of LHC* (WP11) and one assigned to the collimators under the management of *Work Package 5 - Collimation* (WP5).

Inside these documents, the impact on service providers was evaluated and the appropriate solutions described. The authors would like to highlight the solution found for the interference detected at an early stage between one of the safety flanges of the cryostat and the measuring tool for the roll angle installed by the *Work Package 15.4 - Alignment & internal metrology* on the alignment targets, so that a bracket was needed to install a compact inclinometer.

Once the IRIA documents were ready for approval together with the released integration models and correspondent differential layout drawings, the Integration Team gives the green light for the ECR to be approved from the integration point of view. After the installation, these documents are reviewed one last time to report on discrepancies observed and possible NCRs reported to the Integration Team.

CONCLUSION

This work presents the integration activities from ensuring that the 3D models represents faithfully the reality to the completion of the equipment installation. This is achieved by an iterative process involving all relevant stakeholders, where the Integration Team ensures the efficient space allocation for all machine systems, services, and maintenance, transport and access volumes for both de-installation and installation processes. A high quantity of changes and upgrades on the layout are continuously developed to fulfil the LS3 machine needs. The documentation, such as the ones described in the paper, that traces the change management is vital in ensuring that the many stakeholders agree to a common solution. It is paramount that the project reaches a sufficient maturity level, allowing the smooth installation of the equipment in their final location.

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