HL-LHC IT STRING: Status and Perspectives

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***Abstract*—The HL-LHC IT STRING, an integrated test stand for the major components of the HL-LHC Inner Triplet (IT) zone, is in its construction phase in a surface building at CERN. The main motivation is to study and validate the collective behavior of the different systems: magnets, circuit protection, cryogenics for magnets and superconducting link, magnet powering, vacuum, alignment, and interconnections between magnets and superconducting link. During the past two years, the major focus has been on the technical infrastructure definition and implementation, while preparing the installation sequences and procedures for the major elements. The String Validation Program (SVP) has been agreed with the HL-LHC Work Packages, allowing to set up a joint and optimized test program and to integrate it in a schedule. In this paper we describe the IT String installations and describe the main differences between the HL-LHC IT String and the future HL-LHC machine. The main line of the test program and the motivation of a full thermal cycle with a cost benefit analysis will be presented.**

***Index Terms*—HL-LHC, HL-LHC IT string, HL-LHC magnets, Nb_3Sn, superconducting magnets, superconducting magnet test stand.**

I. Introduction

THE goal of the HL-LHC project is to upgrade the existing LHC machine by incorporating new components to fulfill the objective of a ten-fold increase of integrated luminosity in its 10 years of exploitation [1]. However, individual component tests do not fully encompass their behavior when integrated into the HL-LHC. The HL-LHC IT String test stand serves the comprehensive validation and testing of an entire Inner Triplet (IT) region of the HL-LHC under nominal operational conditions, offering insights into the collective behavior of its components [2]. Serving as a crucial intermediate milestone for the HL-LHC project, the HL-LHC IT String test ensures system integration verification and smooth hardware commissioning of the final installation in the LHC tunnel.

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II. Description of the HL-LHC IT String

The HL-LHC IT String is situated within a surface building, known as SM18, and serves as a representative model of the IT region located on the left side of the HL-LHC at Point 5. However, it is important to note that the HL-LHC IT String setup does not replicate the tunnel inclination, nor the modified matching section region, and excludes the beam screen from the setup. The HL-LHC IT String consists of various components, including the Q1, Q2a, Q2b, and Q3 (collectively referred to as the IT quadrupoles), the CP (Corrector Package), and the D1 (separation dipole) cryo- assemblies. These assemblies comprise a total of 19 superconducting magnets utilizing either NbTi or Nb_3Sn-based technology.

Within the HL-LHC IT String, the magnets are powered via a Superconducting Link (Sc Link) that has a total length of 74.5 m. This Sc Link is connected at its extremities to the distribution feed box (DFX) on the magnet side and to the current lead's cryostat (DFHX) on the side of the powering equipment. The DFX contains Nb-Ti bus bars inside, while the DFHX houses 19 pairs of current leads based on high temperature superconductor technology (HT CLs). These CLs serve as interface devices to transit the current being produced by the power converters connected to the circuit disconnector boxes (CDBs) to the cold side of the electrical circuits.

To maintain a suitable temperature gradient along the cable (4 K–50 K), the Sc Link is cooled using gaseous helium, which is recovered at room temperature near the DFHX and sent back to the cryogenic cooling system. The cryogenic cooling of the magnets is facilitated by a dedicated distribution line, known as the String cryogenic cooling line (SQXL), which connects to the cryo-assemblies in 3 different spots via the so-called jumpers. This SQXL line allows the HL-LHC IT String test stand to be integrated with the broader cryogenic system via the proximity cryogenics system (PCDS), which ensures the connection of the test stand to the existing cryogenic infrastructure in the SM18 test hall.

The magnet circuit protection for the HL-LHC IT String will closely resemble that of the HL-LHC machine. Protection against quenches is ensured through a complete system of detection and various protection mechanisms. These include coil active heating, energy extraction, and bypass diodes. The choice of protection systems to be deployed depends on the specific circuits and their individual characteristics. One of the noteworthy elements within the protection framework is the coupling-loss induced quench (CLIQ) [3] system. This innovative system operates directly on the magnet conductor and facilitates rapid and uniform warming of the entire magnets during quench events. This technique will be employed in conjunction with conventional quench heaters, adding an enhanced layer of redundancy to the protection system.

Within the scope of the HL-LHC project, a fully remote alignment system (FRAS) has been developed. This system is designed to achieve precise remote positioning, monitoring, and realignment of the magnets and accelerator components. Its implementation allows for more frequent alignment campaigns while significantly minimizing the radiation exposure to personnel operating in the tunnel during in-situ alignment activities [4]. This system will also be integrated into the HL-LHC IT String.

A notable difference between the HL-LHC IT zone and the IT String lies in the vacuum system. Notably, the beam screens will not be installed in the HL-LHC IT String. As a result, the vacuum system's design aims to establish a unified beam and insulation vacuum setup.

III. The HL-LHC IT String Infrastructure

The SM18 facility, located in Building 2173 at CERN, serves as the host for the test stand, just as it did for the LHC String 1 [5] and LHC String 2 for the LHC [6]. The selection of this site was based on its existing infrastructure, which could accommodate such testing requirements. Over the past five years, substantial upgrades have been made to the facility, including improvements to the demineralized water system, electrical network, and cryogenic infrastructure, to meet the new demands of the HL-LHC IT String and the evolving needs of individual test benches for critical HL-LHC components such as magnets and RF cavities.

The capacity of the cryogenic cooling systems, along with the demineralized water production system, has been increased. The existing 25 g/s He liquefying capacity was increased by additional 35 g/s, while the demineralized water production has been increased to a capacity of 150 m^3/h. Furthermore, a new 3 MVA transformer has been installed to connect a set of power converters required for the tests to the electrical network.

An integral part of this upgraded infrastructure is the metallic platform, which adds approximately 260 m^2 of dedicated space to the test area available in the SM18. Beyond the expansion in physical space, the platform plays a crucial role in segregating the electrical components into two distinct zones: the floor, considered a lower-risk area, and the platform itself, designated as a higher-risk area for electrical hazards.

IV. Validation Tests

The primary objective of this test stand is to allow conducting a series of verifications aimed at comprehensively understanding and validating the collective behavior of the various systems. This verification process follows the confirmation of the successful assembly of diverse components and circuits. The IT string validation program (SVP) [7] encompasses a second thermal cycle, accompanied by an optimized and streamlined test program. This program is specifically designed to prioritize and focus on hardware commissioning (HWC) procedures.

V. Thermal Cycle

In the context of the SVP, the strategic inclusion of an additional thermal cycle, followed by optimized powering tests has been explored. This decision was informed by a thorough evaluation of the technical benefits and the associated costs related to this proposed testing approach.

From a technical perspective, the thermal cycle holds paramount importance in validating the repeatability of thermomechanical contractions inherent in cryogenic operations. This phase serves as a critical examination of the robustness of magnet interconnections and the performance of the FRAS. Notably, certain specific elements, such as splices and the lambda plate in the so called "DCM" connection cryostat, are subjected to a complete thermal cycle for the first time. Furthermore, the subsequent powering tests are instrumental in verifying the electrical performance of the circuits and the associated instrumentation, proving their resilience against thermal-induced effects.

Moreover, the inclusion of the thermal cycle provides several programmatic and organizational advantages. This phase facilitates additional operator training and strives to optimize HWC procedures and their automated execution, which are foreseen for implementation in the HL LHC machine during "long shutdown 3" (LS3). It also grants the flexibility to subject systems to supplementary tests that may have been omitted during the initial powering tests, thereby reinforcing the validation process. Additionally, it allows to adapt to unforeseen challenges, such as equipment non-conformities or maintenance interruptions in the cryogenic infrastructure.

In terms of cost analysis, various factors were considered, including the energy consumption of the equipment under examination (such as magnets, powering, control electronics, etc.), the energy usage of the cryogenic infrastructure, and labor expenses. The study revealed that the thermal cycle constitutes 20% of the total operation cost of the IT String. Furthermore, it became evident that a significant portion of these costs is attributed to the energy consumption of the cryogenic infrastructure when operating at its nominal capacity. It is important to note that this cryogenic infrastructure serves multiple users within the facility, necessitating its continuous operation, regardless of whether the thermal cycling is executed.

In summary, the integration of thermal cycling and subsequent powering tests into the SVP emerges as a valuable strategy that significantly enhances the program's contribution to the project.

The advantages stemming from this approach, including an increased level of technical validation of the system, improved practical familiarity with system operations, and increased organizational adaptability, effectively offset the associated expenditures.

VI. Progress in the Installation

Since the last update in the summer of 2021 [2], significant progress has been made in the installation of the infrastructure.

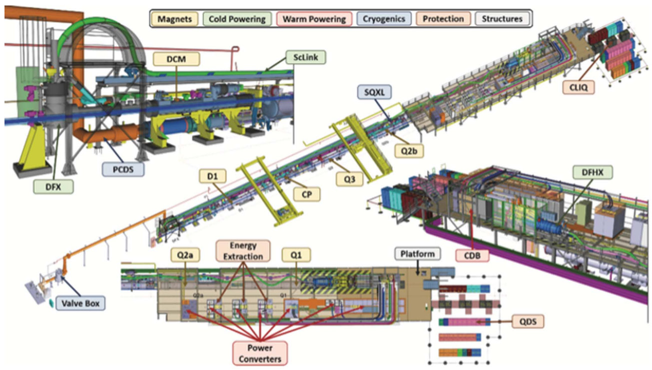

Fig. 1. HL-LHC IT STRING integration model.

Fig. 2. Overhead crane being installed in SM18 building.

Fig. 3. Metallic platform built up for the HL-LHC IT String.

This remarkable success can be attributed to the meticulous and intensive integration efforts. A collaborative effort entailed continuous refinement of 3D drawings, adjustments to the structural elements, and adaptations to equipment design and maintenance requirements. These measures enabled to replicate the precise layout of the HL-LHC and streamline the infrastructure, all while facilitating the assembly phases. Regular updates to the drawings ensure they remain in sync with the "as-built" configuration. This proactive approach has been instrumental in detecting conflicts, minimizing errors, avoiding redundant actions, and optimizing the timing of interventions, particularly those involving external contractors. Safety measures are rigorously defined during inspection visits preceding the commencement of work. The IT String benefits from the intervention management planning and coordination tool (IMPACT), which effectively cordons off work areas to prevent coactivity. To date, more than 60 IMPACT events have been registered, demonstrating our commitment to maintaining a secure and efficient working environment.

A. *Overhead Crane*

The installation of the Sc link system presented a unique challenge, requiring the simultaneous use of two overhead cranes. While the SM18 hall already had two overhead cranes, it became evident that one of them did not align with the specific geometry required for the Sc link installation. Given that this crane was an older piece of equipment, it was decided that replacing it with a more compact and modern alternative would offer an optimized solution, both technically and economically. The introduction of a new compact overhead crane (see Fig. 2) capable of handling loads of up to 10 tons, became the initial equipment installed in the designated space originally reserved and prepared for the IT String.

B. *Metallic Structure*

As the integration process advanced, the structural design underwent a refinement phase, facilitated by an external design office. This included comprehensive load simulations and the precise definition of steel profiles. Subsequently, CERN's Occupational Health & Safety and Environmental Protection Unit (HSE) conducted a thorough validation of the design, ensuring that it met all safety and environmental standards. With the design validated, the procurement process could finally commence.

The site and civil engineering (SCE) Department at CERN skillfully negotiated the construction of the metallic structure using a CERN framework contract. This strategic approach not only expedited the tendering process, but also provided greater flexibility during installation, given that the contractor was already established on the CERN site.

Coordinating these activities, delivering the structure on time, within budget, and according to the necessary specifications fell under the responsibility of the CERN Technology (TE) Department's Machine Protection and Electrical integrity group (MPE), specifically within the String Facility (SF) section.

From a safety standpoint, the role of the metallic platform (see Fig. 3) is unequivocal: it provides a controlled area to house potentially hazardous equipment. The fact that this equipment is situated 1.8 m higher than the ground floor, adds an extra layer of safety, particularly in scenarios involving the release of hazardous substances like helium or the occurrence of an electric arc.

C. String Control Room

To facilitate the execution of tests, the establishment of a dedicated on-site control room is of paramount importance. This control room must be thoughtfully equipped and customized to ensure the seamless and efficient operation of the testing infrastructure. Serving as the central nerve center, this room empower designated operators to proficiently carry out all the tests detailed in the HL-LHC IT string validation program.

Additionally, it will serve as a focal point where experts can convene to scrutinize test results and engage in discussions regarding key aspects of forthcoming tests.

In 2020, after a rigorous evaluation process, room 1-S06 in the SM18 facility was identified as the optimal choice to serve as the control room for the IT String test stand. Several pivotal factors were considered during the selection process: proximity to equipment, direct access, visual oversight, emergency preparedness, user convenience. The control room's positioning has been meticulously planned allowing users to access the facility with minimal exposure to potential risks in the SM18 area.

By carefully considering these factors, the elected control room not only meets the technical requirements, but also prioritizes safety, accessibility, and efficiency, thereby enhancing the overall effectiveness of the IT String testing process. The IT String control room is already operational.

D. Electrical Powering

The electrical powering system consists of two distinct components: the warm and the cold parts. The warm part commences with a set of power converters (PC) that operate at various current levels, including 18 kA, 14 kA, 2 kA, 600 A, 120 A, and 35 A. These meticulously designed PCs are responsible for supplying power to the magnets in strict accordance with predefined specifications. Notably, these PC units have been custom engineered for the HL LHC, ensuring both precision and reliability, particularly for magnets using Nb_3Sn coils.

To enhance safety and facilitate regular maintenance checks, the PC units are interconnected with CDB. These CDBs installed in 2023 play a crucial role in maintaining electrical circuit compliance and ensuring safe access for interventions.

The connections between the PC units, CDBs, and HT CLs are established using water-cooled cables (WCC). The String team has successfully overseen the design, fabrication, and installation of these WCCs (see Fig. 4).

An optimization process was undertaken to select cable sections of 500 mm^2 and 1300 mm^2, depending on the circuit type. The fabrication and installation of the WCCs were subcontracted to an external company with expertise in this domain.

The cables were produced within specifications, delivered on time, and remained within budget. The installation, conducted by the same company, has been completed, and the site acceptance test including pressure test up to 24 bars, and dielectric test up to 3 kV, yielded the expected results, validating the success of this endeavor.

The warm cables are cooled using demineralized water to efficiently extract the heat generated by the high currents flowing from the converters. The demineralized water distribution system has also been successfully implemented and configured for various tests, enabling optimization of cooling strategies, such as parallel or series configurations for the cables within the HL-LHC.

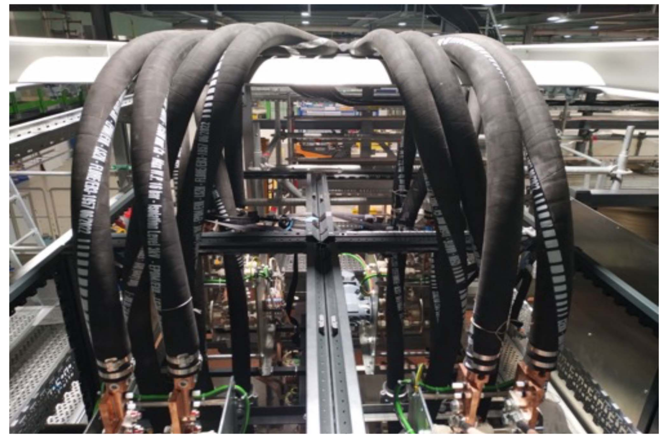

Fig. 4. Water-cooled cables for the 2kA circuits in the HL-LHC IT string.

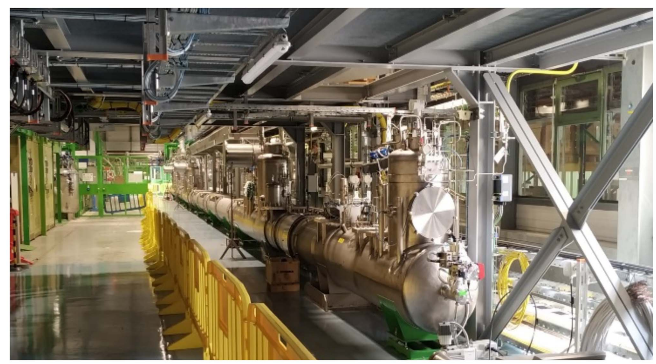

Fig. 5. SQXL, cryogenic line for the HL-LHC IT string.

As for the cold part of the powering system, the design phase has progressed, with imminent plans for prototype testing in a dedicated test bench. Following successful tests, the interconnected objects, including the Sc link and HT CLs, will be transported to the IT String platform.

Specialized handling tools have been designed and ordered to facilitate the complex installation process, which will involve the coordinated use of two overhead cranes.

E. The Cryogenic Cooling System

The installation of the cryogenic cooling systems, which encompassed the PCDS and the SQXL (See Fig. 5.) systems along with their control systems, marked one of the most challenging and significant milestones for the IT String project.

The hardware commissioning phase commenced in early summer 2023 following the installation and a checkout at warm, which included pressure and leak tests for both the PCDS and SQXL systems. These two systems were designed at CERN and then fabricated and installed by two specialized companies. The final pressure test, conducted at 25 bars, was successfully

Fig. 6. Control racks of the HL-LHC IT string.

completed under the supervision of experts from CERN's TE vacuum surface and coating (VSC) group.

During the leak detection process, several leaks were detected, up to 10^{-5} mbar l/s before the replacement of feedthrough or within the acceptable limits of 10^{-9} mbar l/s. These findings necessitated intervention from the TE Cryogenic (CRG) group. Instrumentation flanges were replaced to align with the requirements of the HL-LHC, and other leaks were efficiently repaired.

Additionally, it was discovered that the PCDS lines required reinforcement to prevent buckling caused by pressure differences. The necessary interventions were carefully planned and executed before the commencement of the cold HWC phase which aimed to achieve mechanical and thermal validation. Subsequently, control loop tuning was carried out to optimize performance and ensure precise control over the cryogenic processes.

To illustrate the complexity of the control system, it is worth noting that the instrumentation includes 376 registered devices.

The only item remaining on the repair list is the cold compressor unit. This compressor, originally an older unit, underwent a significant refurbishment of its rotating components. It achieved its nominal performance, but it was affected by a fault in subsequent tests and is now being repaired.

F. *Control Racks and Cabling*

In addition to the previously mentioned achievements, additional racks have been strategically installed on the platform to cater to various essential functionalities, encompassing communications, measurements, and alignment. Consequently, a substantial portion of the equipment on the metallic platform is now in position, contributing to the project's overall progress.

Furthermore, the primary campaign for the installation of control cabling has been successfully executed. These cables play a pivotal role in connecting the diverse equipment within the racks zone (See Fig. 6.) to the magnet line, facilitating seamless communication and control processes. The installation endeavor entailed the meticulous laying of over 300 cables and the placement of 70 racks, a prove to the intricate and comprehensive nature of this essential phase.

VII. Perspectives

Over the past few years, the schedule for the HL-LHC IT String project has experienced several significant revisions, primarily influenced by the delivery timelines of components. Despite the challenges posed by delayed deliveries, the definition and sequencing of the string validation program has received unanimous approval from all stakeholders. This milestone has paved the way to shift the focus towards the testing procedures associated with the project.

Simultaneously, the IT String team has devised a comprehensive strategy for the development of the control and software layers, as detailed in [7]. This important work has already commenced and is expected to reach completion by mid-2024.

A. *Cold Powering System Installation*

The most formidable task slated for the 1st quarter of 2024, is the intricate installation of the cold powering system, which is currently in the individual test preparation phase. This undertaking presents a unique set of challenges, primarily centered around the handling of the SC link connected to the DFHX and its precise positioning on the platform. This operation necessitates the synchronized use of two overhead cranes, constituting both a technical challenge and a potential risk, as any mishap during installation could result in damage to other critical components of the test stand, such as the SQXL and the warm powering system (including bus bars, CDB, PC, etc.).

To ensure the safety of personnel and equipment, our preparations for this activity are meticulous and comprehensive. Dedicated handling and positioning tools have been designed specifically for this complex task. Before executing the installation, acceptance tests will be conducted to verify the functionality of these tools, ensuring they align with the original design specifications. This scrupulous verification process will be conducted in a dedicated zone, affording the teams the opportunity to become thoroughly acquainted with the critical aspects of the installation.

B. *Cold Mass Installation and Interconnections*

Following the installation of the cold powering system, the subsequent step involves the installation of the cryo-assemblies. Each cold mass, spanning from Q1 to D1 and housing one or several SC magnets, will undergo thorough testing in nominal conditions before being transported to the IT String zone.

The electrical circuits will be finalized by linking the cold powering system on one side to the magnets and on the other side to the CDBs, ensuring seamless power distribution and control.

To complete this puzzle, the final step entails connecting the SQXL to the cold masses through jumpers, thereby integrating all the essential components into the HL-LHC IT String system.

C. *String HWC and String Specific Test*

The HWC of the IT String will start once the magnets and powering lines are interconnected with an electrical quality assurance test, along with local and global leak and pressure tests. Once the cool-down to 1.9 K is completed, the powering

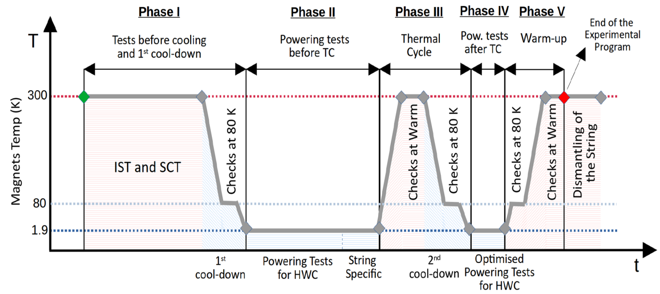

Fig. 7. Main phases of the HL-LHC IT string operation.

tests can be performed for both the HWC and the String-specific program.

The main phases of the so-called operation of the IT String are shown in Fig. 7. The detailed program is described in [7].

While "Phase I" involves tests that do not require all components, "Phase II" signifies the commencement of the extended cold operation period, which is expected to span approximately 14 months, contingent upon any necessary maintenance periods for the major infrastructures.

VIII. Conclusion

The installations for the HL-LHC IT String have progressed significantly, with the infrastructure mostly completed. The first verification test of the warm circuit in short-circuit mode is scheduled to take place by the end of 2023. The initial thermomechanical test of the cryogenic line has been successfully completed, demonstrating the readiness of the cryogenic cooling system as designed [8], [9].

The upcoming tasks include the installation of the Sc link and the cryo-assemblies containing all magnets of the IT String. This phase is expected to be completed by 2024, paving the way for the start of the operational phase.

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