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HARDWARE COMMISSIONING OF THE HL-LHC INNER TRIPLET STRING FACILITY AT CERN: INDIVIDUAL SYSTEM AND SHORT CIRCUIT TESTS

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Abstract

The goal of the High Luminosity-Large Hadron Collider (HL-LHC) Inner Triplet String test, here after called IT String, is to validate the assembly, the connection procedures and the tools required for its construction, to assess the collective behaviour of the superconducting magnet circuits under conditions as close as possible to those of its operation in the HL-LHC, and to provide a training opportunity for the equipment teams for their later work in the LHC tunnel. The IT String includes all systems required for operation under nominal conditions, such as the cryogenics, warm and cold powering, and quench protection systems. This contribution describes the individual system and short-circuit tests performed on the IT String as part of the hardware commissioning and preparation for the full exploitation of the facility. After describing the IT String infrastructure, the individual system tests performed on the cryogenic and associated vacuum systems are detailed. Moreover, the individual system and short-circuit tests executed on the warm powering systems including power converters, energy extraction systems, and the DC cabling and connections are presented.

INTRODUCTION

The High Luminosity-Large Hadron Collider (HL-LHC) IT String test [1], represents an important milestone of the HL-LHC project at CERN [2, 3]. The IT String aims at validating the superconducting magnet circuits working in unison under conditions as close as possible to those of their later operation in the HL-LHC, and provide a unique opportunity for training teams for preparing their later commissionning activities in the LHC tunnel. The IT String magnet chain encompasses the main IT quadrupoles (Q1, Q2a, Q2b, Q3), their orbit correctors, the high-order correctors in the Corrector Package (CP) cryo-assembly, and the separation dipole D1 as represented in Fig. 1. The Superconducting Link (SC Link) uses MgB_2 superconducting cables to electrically connect the warm powering systems to the magnet chain [4]. The cryogenic and electrical feed box that connects the warm powering system to the SC Link is denominated by the DFHX and contains High Temperature Superconductors (HTS), working in He gas up in a temperature range goin from 20 K to 50 K. The Power Converters (PC) of the IT String, span from 35 A up to 18 kA current rating. Twenty individual HL-LHC prototypes and pre-series PC are installed and tested in the IT String facility. New technologies are introduced to these PC and namely the design of a two-quadrant high-current low-voltage converter [5]. Water-Cooled Cables (WCC), Air-Cooled Cables (ACC), and Water-Cooled Bus Bars (WCBB) are deployed to connect the power converters to the SC Link system.

The cryogenic system installed in the IT String, cools down the magnets and the SC Link to their nominal operating conditions, which are 1.9 K for the magnets and ~20 K for the gaseous helium at the SC Link entry point.

The IT String experimental program [6] includes the Hardware Commissioning (HWC) phase, which comprises the same steps foreseen during the installation of the HL-LHC. The HWC of the IT String is intended to ensure a smooth and time-efficient execution of the activities in the tunnel. The HWC tests include individual systems tests, short circuit tests and magnet powering tests. Some of which have already been successfully performed in the IT String facility. As of May 2024, the IT String cryogenic system has been successfully installed, cooled down to operational temperature and tested as well as its instrumentation and control system. The cryogenic system has undergone two cooldowns to 1.9 K to validate its performance.

The IT String "mezzanine" is an elevated metallic structure that was conceived to host the powering systems. Today all the IT String PC are installed on the mezzanine. In addition, the WCC, the ACC, and the WCBB are already in place. The new HL-LHC vacuum-based Energy Extraction Systems (EES) [7] have also been delivered and are ready for use. The new Circuit Disconnector Boxes (CDB), a separation device of the warm powering of the magnet circuits from the cold powering systems, are installed and validated. The Powering Interlock Controller (PIC) used for the global interlocking of the magnet circuits has also proven its functionalities.

CRYOGENIC SYSTEM TESTS

The IT String cryogenic system is composed of the Cryogenic Distribution Line (SQXL) shown on Fig. 2 and Proximity Cryogenic Distribution System (PCDS), which connect the IT String magnets to the cryogenic infrastructure of the building. The cryogenic system provides the magnets with the inlet an outlet helium flow to cool them to their nominal temperature of 1.9 K in Helium II. The commissioning of the cryogenic system is divided into two

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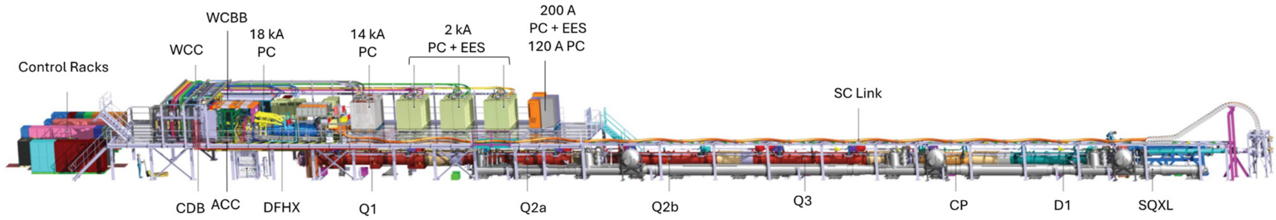

Figure 1: Systems in the HL-LHC IT String facility.

main blocks: Phase 1 without the magnets and Phase 2 with the magnets. The Phase 1 tests as part of the Individual System Tests (IST) are designated to assess the cryogenic performance of the system in a standalone mode. During this phase, the concerned instrumentation, and the control system are tested and enhanced.

Before the cool-down of the cryogenic system, a leak tightness verification is performed to ensure the absence of leaks between the helium volumes, the vacuum volumes, and the environment. During these tests in the IT String, few leaks were detected and later repaired. The cryogenic system has undergone two cooldowns, namely Phase 1a and Phase 1b. Phase 1a has the main goal of validating the mechanical integrity of the system whereas Phase 1b has the role of refining the measurements, e.g. the heat load measurements, providing a precise estimation of the total cooling power, tune the automatic control algorithms and show that required operating conditions can be achieved.

During the cooldown Phase 1a (temperature evolution in the two key process lines is shown on Fig. 3), the operational parameters of the IT String were determined. The tests allowed an optimisation of the cooling process by cooling the thermal shields in parallel to the main lines to avoid excessive temperature gradients. The mechanical behaviour of the cryogenic system was validated as no issues related to thermal contraction have been identified. However, slightly higher heat loads than designed were observed on the different cryogenic lines. The reason for this anomaly has been further investigated in Phase 1b. During Phase 1b cooldown, a more in-depth analysis of the IT String cryogenic system was performed [8]. The performance of cryogenic transfer lines was studied in detail to identify the source of the higher heat loads detected during Phase 1a which led to an X ray scan of the transfer line (i.e., TL01). With these combined methods of cryogenic measurements and X rays, a non-conformity with potential contacts between cryogenic lines has been localised, partially explaining the higher heat load measured during Phase 1a. The excess heat load has been estimated to be in the range of 10-20 W on the line called C that supplies the supercritical helium for cooling the cold masses of the magnets. The maximum cooling capacity is ~300 W at 1.9 K. It was decided to intervene on the segment where the contacts are suspected and to repair the lines. An additional Phase 1c cooldown of the cryogenic system is proposed in 2024 to validate the repair and to fine tune the cryogenic system before connection to the magnets.


Figure 2: SQXL cryogenic line in the HL-LHC IT String.

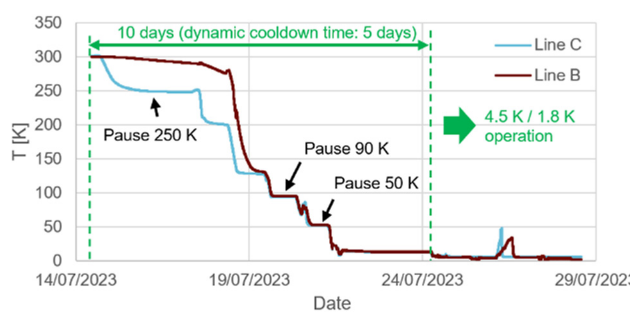

Figure 3: Phase 1a cooldown of the IT String cryogenic system where Line C represents the temperature of the magnet cryogenic input line and Line B of the magnet cryogenic return line.

INDIVIDUAL TESTS OF THE WARM POWERING SYSTEMS

An important milestone of the IT String has been achieved in 2023 and 2024 with the installation and testing of the warm powering supply systems, which consist of the components shown on Fig. 4. The water-cooling of the PC and WCC is done through direct conduction to the demineralized water network, whereas the cooling of the bus bars is done via galvanically isolated cooling plates connected to the same network of demineralized water.

For the warm powering systems, the IST covered the pressure tests for the water-cooled components. Furthermore, voltage withstand tests were systematically performed to ensure the correct dielectric withstand level before connection to the superconducting magnet circuits. Operational tests were completed afterwards e.g. opening

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of the EES, triggering of the PC faults, and ensuring commands are properly propagated and recorded. Operational safety fault mechanisms that have been checked are the earth fault detection, the water loss, the power cut, etc.

The CDB operation was also verified at this stage confirming that the mechanical movement of the switches takes place as specified.

SHORT CIRCUIT TESTS

From January to May 2024, the SCT were performed after the warm powering systems had been connected and put in short-circuit at the warm to cold transition extremities as shown in Figs. 4 and 5. The following steps were executed:

- Validation of PIC, EES and PC interlock loops.
- Validation of PC, CDB, WCBB and WCC interlocks.
- Tuning of the PC control loops.
- Discharge of EES and PC with current.
- 8-hour heat run test for thermal validation.

As significant currents were applied during the SCT, the test was preceded by the verification of the interlock chains. The PIC, the EES and the PC exchange signals via common interlock loops that were verified during this phase. The interlocks between the PC, the CDB, the WCBB and the WCC ensure the correct status of the systems, in particular the flow of the demineralized water to allow powering. The tuning of the PC control loops was done up to a safe current for each circuit before verifying the discharges of the EES while gradually increasing the current. At this stage, several lessons were learned, and few issues were addressed. In particular, the opening mechanisms of the vacuum based EES [7] imposed the addition of an inductor is series to the short-circuit. Moreover, the new 18 kA power converter were validated with few issues solved related to the increased number of parallel connections as described in [5].

As a last stage of the SCT and with the aim to validate the thermal performance of the warm powering systems, a heat-run test was performed for 8 hours at ultimate current of each circuit which is slightly lower than the rated PC current. Fig. 6 shows the PC current and the output voltage for a 2 kA circuit operating at 1.86 kA during the heat-run.

CONCLUSION

The commissioning of the IT String cryogenic system without the magnets has been successfully performed twice with a third cooldown planned in 2024 for a final validation. The individual system tests of the warm powering systems as well as the short circuit tests were successfully performed. Important lessons were learned during this phase and corrections were introduced to the different systems. The learned lessons will be most importantly transmitted for the installation of the HL-LHC project. These tests are an important milestone before the start of the cooldown of the IT String completed with the superconducting magnets and the start of the powering tests in fully nominal conditions.

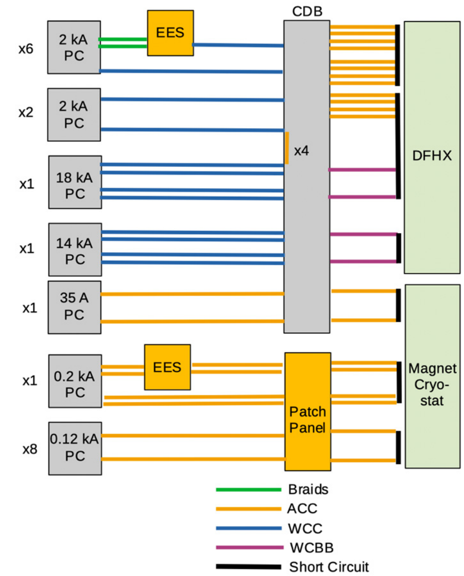

Figure 4: Scheme of the connections of the HL-LHC IT String circuits in short-circuit position.

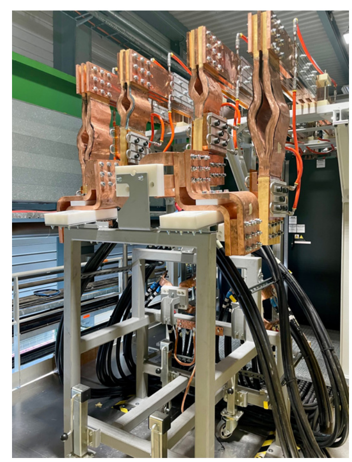

Figure 5: IT String warm powering of circuits rated 2 kA and above connected in short circuit via a frame replicating the position of the current leads of the DFHX.

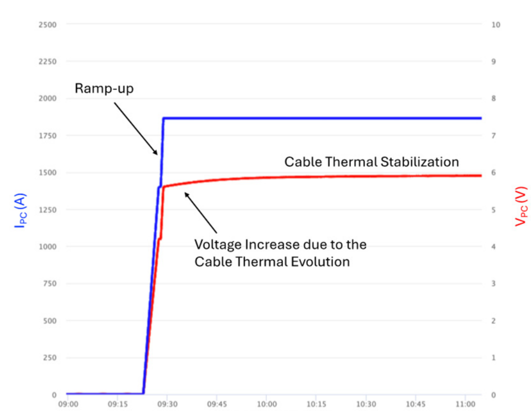

Figure 6: Current and voltage profiles of a 2 kA PC during the heat-run as a part of the HL-LHC IT String short circuit tests.

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