Operation of CERN's major tests facility with upgraded cryogenic infrastructure for superconducting magnets, power links, inner triplets String and radio-frequency cavities for HL-LHC

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Abstract. The largest cryogenic multipurpose test facility at CERN (SM18), recently significantly upgraded, provides helium refrigeration capacity for testing at nominal conditions, superconducting magnets, power links, radiofrequency (RF) cavities and the IT String (Inner Triplet) for the High Luminosity - Large Hadron Collider (HL-LHC) upgrade project, towards increased luminosity at interaction points 1 (ATLAS) and 5 (CMS) in the LHC accelerator. The SM18 cryogenics infrastructure and test benches have been progressively upgraded along the last 8 years to meet the technical requirements of the HL-LHC project. In parallel, cryogenic interfaces and process controls have been developed to adapt the operational requirements related to the use of new materials like Nb3Sn for the HL-LHC magnets, to the tests of innovative MgB2 powering links and to the new design of RF crab-cavities as well as crab-cryomodules. In addition, the inner triplets string test bench, also located in the SM18 facilities, will be dedicated to the test of HL-LHC magnet's collective effects anticipating the operational behaviour of the structure powered by a superconducting link. This paper outlines the development of advanced cryogenic process controls over the past two years, focusing on automation for safety and efficiency in the cryogenic test benches. Operational results will be presented including overall cryogenic capacity & tests parallelization. The paper concludes with perspectives for the expected future dense testing program.

1. Introduction

The SM18 large test facility for superconducting equipment has been upgraded over the past years to meet the testing requirements for the new superconducting magnets and RF cavities developed for the HL-LHC project. This document outlines the major upgrades made to the cryogenic infrastructure and test benches, aiming at adapting the cryogenic process to meet the new HL-LHC interfaces and requirements, and enhancing process operability to ensure maximum availability to comply with the increase in critical tests to be performed for the HL-LHC project.

The control logic is implemented using PLC Siemens or Schneider managed through the UNICOS framework, with a supervision handled by WinCC OA.

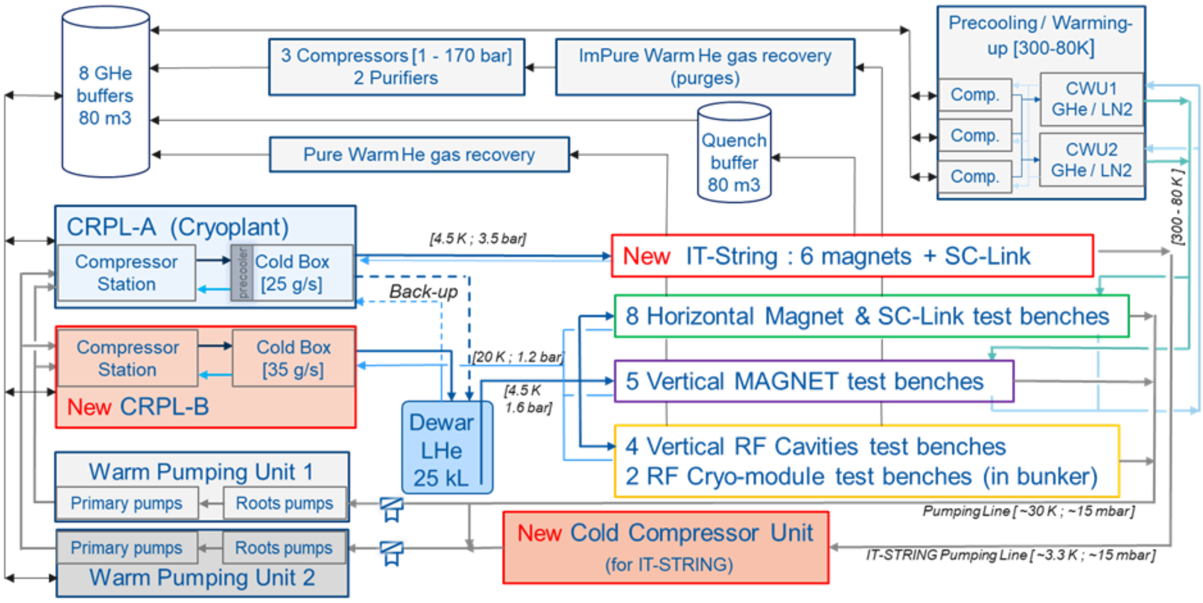

Figure 1 – Overview of SM18 test facility

2. Cryogenic infrastructure upgrades

2.1 New cryo-plant B (CRPL-B)

In 2015, CERN assessed the testing needs at the SM18 facility for the validation of future superconducting magnets and RF cavities as part of the HL-LHC project. The existing cryo-plant (CRPL-A) with a liquefaction capacity of 25 g/s at 4.5 K, was undersized to perform the planned test program. To address this, it was decided to upgrade the facility with a new higher capacity liquefier with a liquefaction rate of 35 g/s at 4.5 K. The new cryo-plant CRPL-B was installed and commissioned in 2019-2020 [1].

The connections to the 25 m³ liquid helium storage were modified to allow operation with both cryo-plants, thus enabling CRPL-A to serve as a backup for a CRPL-B issue. The liquid helium for most test benches will be provided by CRPL-B, while CRPL-A's will be mainly dedicated to the new Inner Triplets String test bench (IT String). This required the construction of additional interfaces to connect CRPL-A to IT String while maintaining the connection to the 25 m³ storage [2].

2.2 CRPL-B Operation

The CRPL-B was officially transferred to operation team in 2021. Over the operating period 2021 to 2024, the CRPL-B has cumulated a total running time of 28'200 hours, most of the time in full capacity mode. During this period the operation was affected by several technical issues as described in Table 1.

The initial operation of CRPL-B showed several aspects that required improvements, mainly concerning the warm compressor station oil injection. These issues have been solved adding a new pressure sensor with improved regulation and logic. A new air feeding valve was also added to better control regulating valves, and the pressure setpoint was decreased. Additionally, the inlet and outlet valves of both 80 K adsorber units in the cold box were not tight at 80 K, preventing the regeneration of the adsorber when the cold box is in operation (as specified). Intervention of the valve manufacturer led to a modification of the valves plugs to solve the problem.

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Table 1. SM18 cryogenics technical issues groups by categories

System	Downtime	Technical issues
25 m^3 Dewar	1441 h	Water flooding of the pit after severe weather
Cryogenics infrastructure	241 h	Cooling & Warm-up Units (CWU) multiple faults Warm Pumping Units (WPU) electrical heater defaults
Utilities fault	46 h	Water cooling stops and scaling issues, Power supply stops
CRPL-B Cold Box	20 h	Cold Box clogging due to water pollution Turbine breakdown
CRPL-B Compressor	11 h	Compressor skid: HP oil injection

2.3 25 m³ Dewar

In June 2021, the main 25 m^3 storage system was taken out of service following a flooding of the pit where the helium dewar is installed. A temporary configuration, using a 10 m^3 storage and the adaptation of the process had to be implemented for a period of three years. From 2021 to 2024, thorough analysis and thermal performance tests were conducted on the 25 m^3 storage system, showing no performance degradation or safety issues. The static heat load of ~1.5 W are of the same order than before the incident. The 25 m^3 storage was put back into service in 2024. The return to service of this high capacity dewar is crucial for the cryogenic operability of SM18. It helps to smooth out significant under-draw peaks exceeding CRPL-B capacity during magnet filling phases, as well as re-liquefaction peaks, while maintaining the cold box at a constant operating regime.

2.4 SM18 Cryogenics Infrastructure

Operation was also affected by multiple issues with the magnet Cooldown Warmup System (CWS) and the Warm Pumping Units (WPU). This led to the implementation of a consolidation program in 2024, which included the full refurbishment of the CWS electrical cabinet, a revision of the automation program, and the refurbishment of the electrical heaters of the WPU.

3. Test bench upgrade for new Crab Cavities Cryogenic Module (C3M)

Crab cavities, in the HL-LHC project, rotate proton bunches to maximize their overlap at collision points, increasing luminosity. The RF test benches in SM18 consist of 4 vertical stands (V3, V4, V5, V6) for individual cavities and 2 bunkers (M7, M9) for testing the cryomodules, as shown in Figure 2.

3.1 Cryogenics operation of Crab cavities

Crab cavities are tested individually in vertical cryostats named V3, V4 or V6, before assembly in a Cryomodule (C3M). Crab cavities are made of pure niobium rather than copper-coated niobium making them very sensitive to mechanical stress during thermal transients. Therefore, it is necessary to maintain the temperature difference (ΔT) between the coldest and warmest points below 50 K in the 300 K to 130 K range. In the vertical cryostat, this is achieved by a gradual cooldown via radiation through the thermal shield. In the C3M cryomodule, the gas injection temperature is regulated with a mixing chamber that blends warm gaseous helium with the boil-off from a saturated liquid helium bath at 4.5 K. Below 130 K, a rapid cooldown is required to minimize the risk of Q-disease.

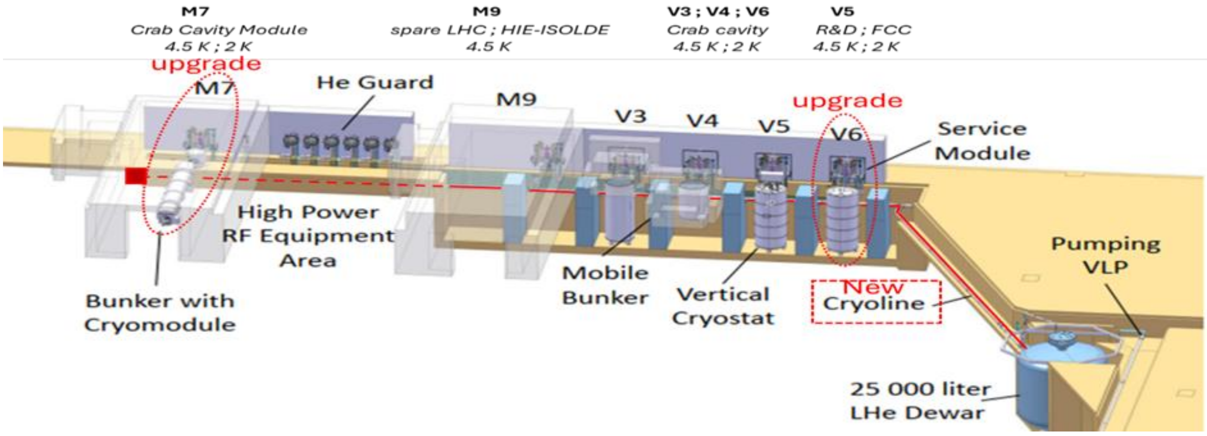

Figure 2. RF test bench overview

3.2 RF test benches upgrades and results

From 2021 to 2023, the M7 bunker was upgraded to adapt the mechanical and instrument interface, as well as the process, to the new C3M. Three tests at 2 K were performed in 2023-2024 for a total of 23 weeks, to fully test this prototype RFD C3M in SM18.

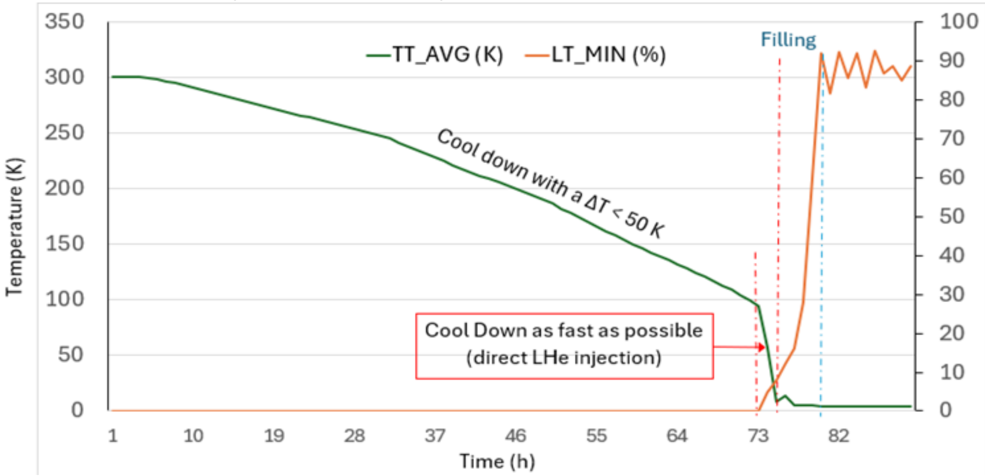

Figure 3. Cool Down of prototype RFD (RF Dipole) C3M in M7 bunker in August 2024

In 2024, the V6 test bench cryostat was replaced with a new model featuring a thermal shield. Along with a complete process overhaul, this led to significantly improved operability, with a fully automated process covering leak testing, conditioning, cooldown, pumping, and warm-up sequence. This new process logic was then adapted to the V3 and V4 cryostats so that they could also benefit from this improved automation, while also ensuring maximum homogeneity between the test benches. This ultimately simplifies cryogenic operation and makes it more efficient.

4 Horizontal Magnet test bench upgrades

The test benches built in the early 2000s to test the LHC magnets had to be upgraded because the HL-LHC magnet apertures and internal line routings were not compatible with the existing interfaces. Since 2022, five test benches have been upgraded by integration of a shuffling module (fig.4) to the existing test bench (CFB) and validated. The new configuration provides the mechanical adaptation to perform the cryogenic powering tests and magnetic measurements of the HL-LHC magnets and Super Conducting links (SC links) [3].

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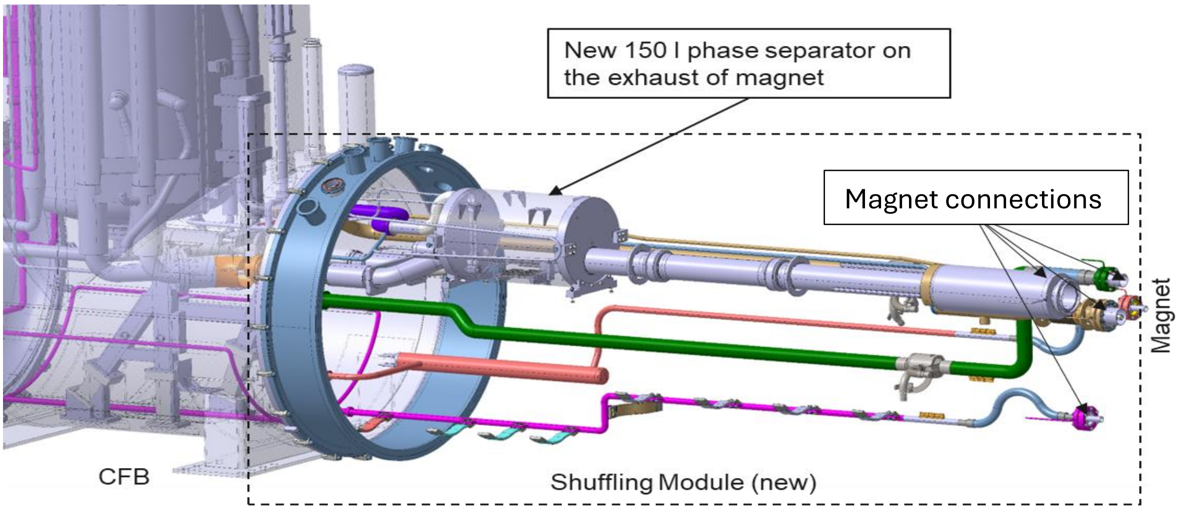

Figure 4 - 3D representation of a magnet test bench with an integrated shuffling module.

4.1 HL-LHC magnets Test benches

Beyond adapting to this new interface, the cryogenic process has also been improved to enable better control of the temperature gradient ΔT during cooling and warming phases, to limit pressure rise during magnet quenches, and to reduce recovery time. These last two adjustments were made necessary by the consequences of the modifications to the shuffling module itself:

- Due to the extension of the pumping line, the volume of trapped liquid helium increased, creating a risk of overpressure in the event of a quench. While the safety valves were adapted, an optimization was also implemented in the control logic to mitigate this risk.
- Due to the presence of the new 150 L separator without a heat exchanger, the cooldown time from 4.5 K to 1.9 K was doubled (3 hours instead of 2 hours). This significantly increased the recovery time after a quench and disturbed test plans. New settings have been implemented to validate the 1.9 K running conditions status without extending the cooldown time.

4.2 Cold Powering System (SC.link) test bench

A CFB was upgraded to test the SC-links intended for powering the Inner Triplet magnets in the HL-LHC project, and the first SC link was successfully validated in April 2024. The Cold Powering system was tested at cryogenic conditions with powering up to 94 kA with a minimum helium flow of 4.9 g/s. All the required cryogenic tests were successfully performed demonstrating a smooth cryogenic control handling of the powering transient.

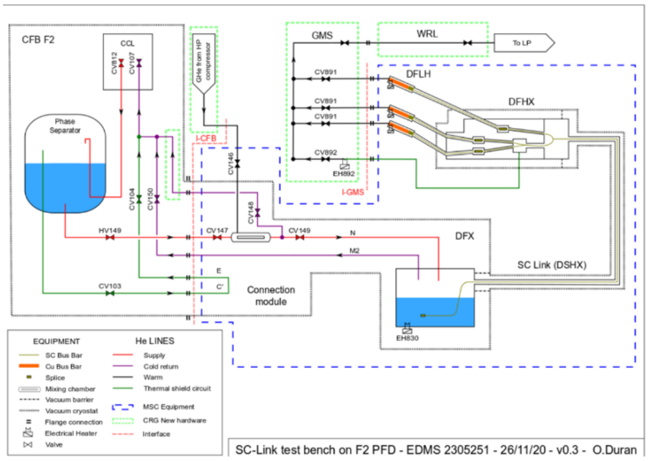

Figure 5 – Superconducting link PFD

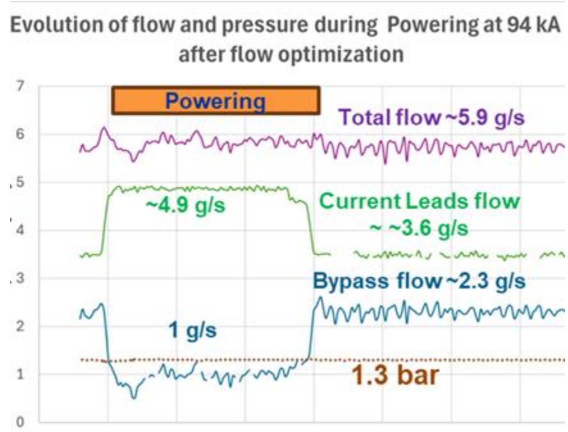

Figure 6 – SC-Link prototype flow with maximum powering in April 2024

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5. IT String project

The IT String is a new test facility built to validate the collective behaviour and assembly procedures of the Nb3Sn superconducting magnets, before installation in the LHC. As shown in figure 7, the IT String will consist of all the magnets from D1 to Q1, as well as their cold powering system, all previously individually tested on horizontal test benches in SM18. The superconducting magnets are cooled by a newly built cryogenic system, which consists of:

- a cryo-plant: CRPL-A [LINDE ; refrigeration capacity: 6 kW; liquefaction capacity: 25 g/s];
- a low-pressure pumping system equipped with a Warm Pumping Unit (WPU) and a new Cold Compressor Unit (CCU) with a maximum capacity of 18 g/s at 16 mbar;
- Two 80 m³ tanks as Warm Quench Buffer (WQB) to store the helium during a magnet quench;
- a cryogenic distribution line (SQXL) forming a 60-meter-long multi-header helium distribution system. It has a similar design as the cryogenic distribution line of the HL-LHC [4];
- a proximity cryogenic system linking the SQXL to the SM18 infrastructure.

5.1 SQXL commissioning

In 2023, prior to installation of any magnets on this new test facility, a cooldown has been made to commission the cryogenic infrastructure. Cooldown procedures were validated, and the heat loads and pressure drop of the process lines were characterised. Heat load measured on line C (Helium supply) and D (cold return) were higher than expected, especially on transfer lines. Between two runs, X-ray investigations led to the removal of a thermal bridge between Line C and the shield through pipe modifications, resulting in a lower heat load measured on second cooldown (17 W measured instead of 7 W predicted). Another thermal bridge was identified during a validation run in 2024 between line D and the shield and a consolidation has been performed in 2025. Heat load measured before the reparation was 83 W and is expected to be lower during next cooldown. Heat load in line B is in line with the specification [5].

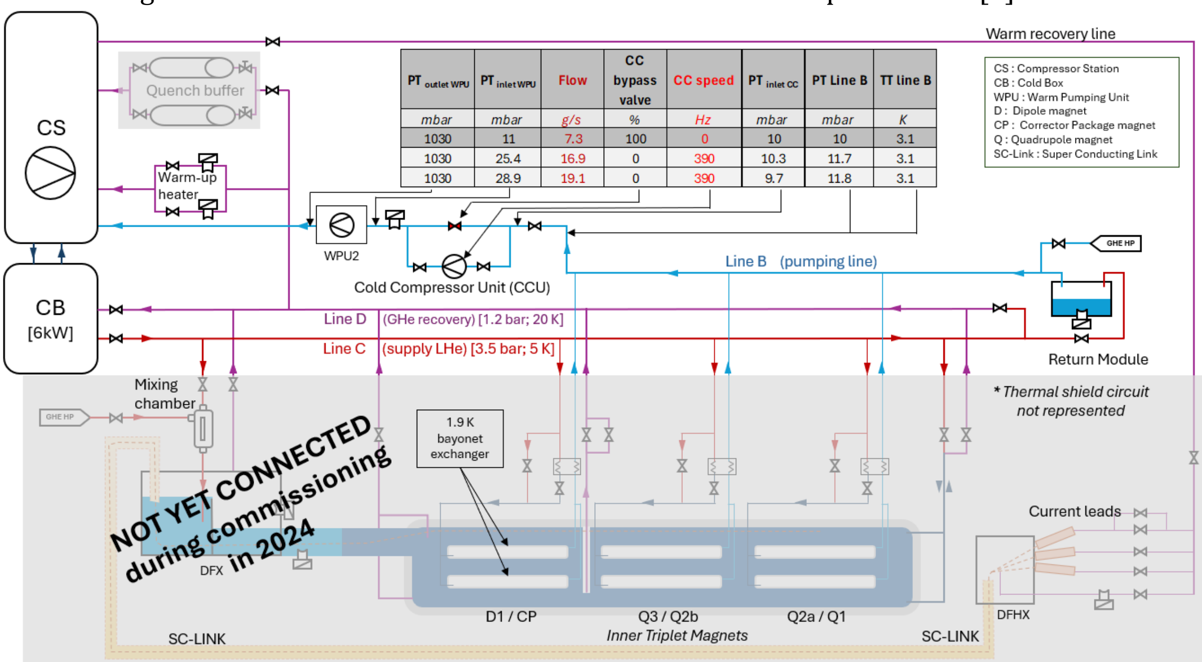

Figure 7 - IT String test bench overview *(Thermal shield circuit not represented)*

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5.2 Cold Compressor Unit (CCU) presentation

The SM18 pumping system, used to decrease the temperature of saturated helium below 2 K, relies on two volumetric WPU, each with a capacity of 6 g/s at 10 mbar, 10 g/s at 15 mbar, or 18 g/s at 30 mbar. A WPU consists of a string of first three roots pumps (RUVAC RA16000; RA 13000, and RA7000) in series and then three primary pumps (LEYBOLD SV1200) in parallel. One of the two WPUs will be dedicated to the operation of the IT String, and a flow rate of 18 g/s at 16 mbar is required to extract heat from the magnets during testing phases. To achieve this, a CCU has been integrated between the WPU and the pumping line. This compressor allows the pumping line to be pumped down to 10 mbar and compresses the gas to 30 mbar with a pressure ratio of three, upstream of the WPU, thereby ensuring a flow rate of 18 g/s through the WPU. As it is an axial-centrifugal compressor, a careful logic is necessary for its correct operation considering the dynamic behaviour of the system. In 2024, the CCU was successfully commissioned with a new automatic control logic.

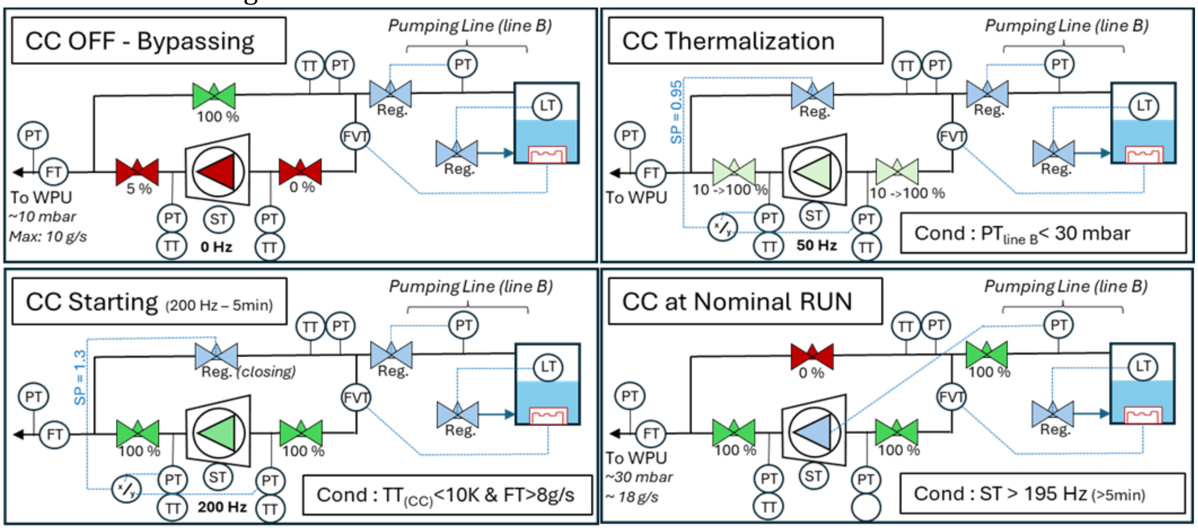

Figure 8 - Cold Compressor Unit process logic - Main start-up steps

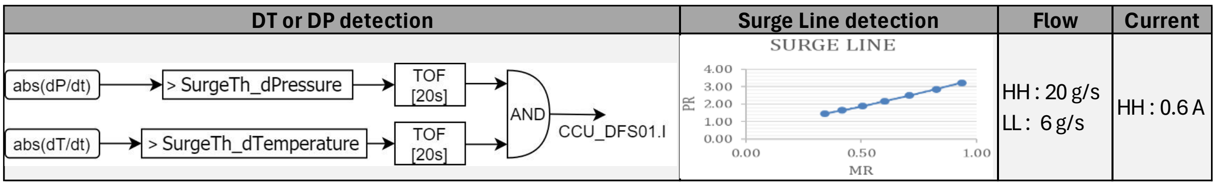

Figure 9 - Cold Compressor – Main interlocks

CONCLUSION

The upgrades carried out on the SM18 cryogenic infrastructure enabled, as early as 2020, the increase of magnet and C3M testing to meet the needs of the HL-LHC project. The necessary upgrades on the test benches were subsequently implemented in coordination with the arrival of specific magnets or C3M to be tested. Today, all the test bench upgrades have been completed and successfully validated in collaboration with the user teams, providing an optimized cryogenic process to test and qualify all the new superconducting equipment required for the HL-LHC project.

As part of the validation plan for the magnets and C3M of the HL-LHC project at SM18, the number of tests has significantly increased in recent years. The graphs (Fig.10) also show that test durations have increased, particularly for the encapsuled magnets on the horizontal test benches and for the C3M.

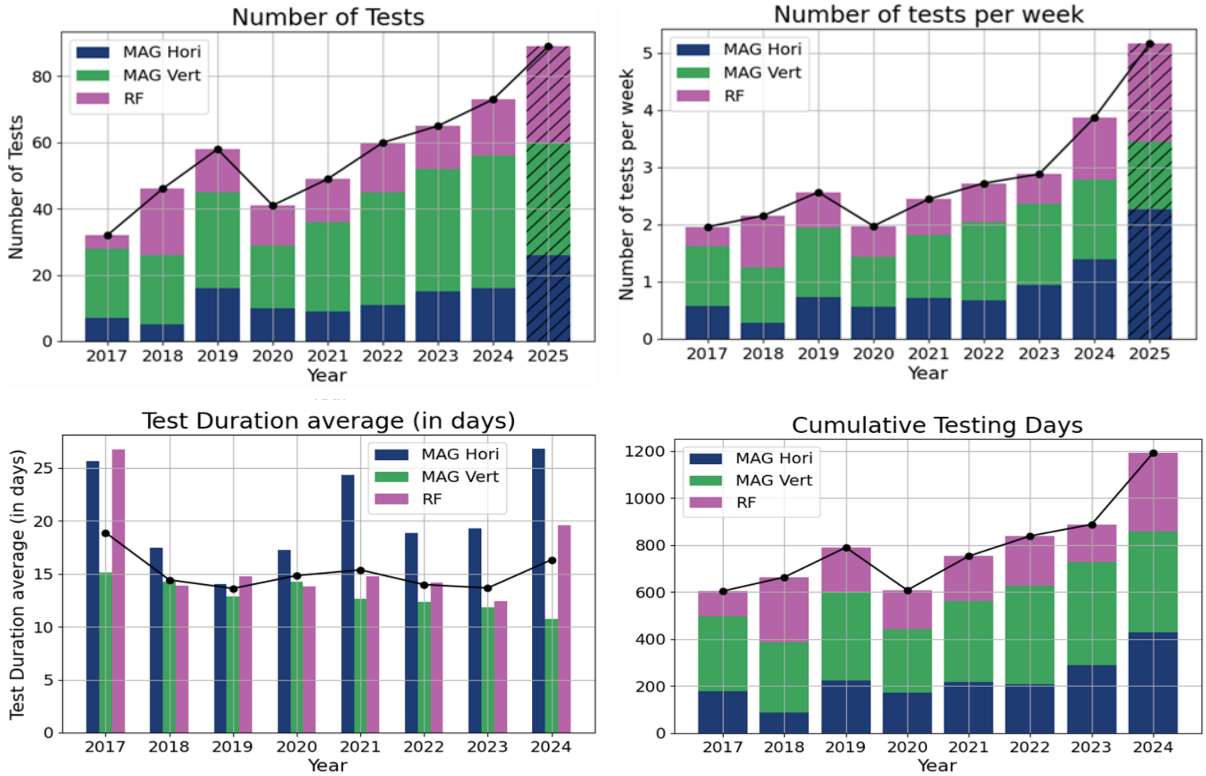

Figure 10 – Graphs showing evolution of tests over 9 years in SM18

However, with the end of prototype testing and the transition to series production, test durations are expected to return to nominal validation times. This translates into a growing need for cryogenic capacity, especially since most of the tests are conducted at 1.9 K. Thanks to the consolidations and upgrades carried out, along with good coordination of tests with user teams, the cryogenic capacity is often utilized at its maximum but is rarely exceeded.

The next challenge will be the operation of the IT String test bench with the connected magnets and SC link, scheduled to start at the end of 2025 for a duration of 18 months, running in parallel with the continued testing of the magnets and RF program.

Acknowledgments

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