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Upgrade of the CERN cryogenic test facility for the HL-LHC superconducting magnets and superconducting links

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Abstract. New superconducting magnets, based on Nb_3Sn technology, have been developed for the HL-LHC project, the High-Luminosity upgrade of the LHC (Large Hadron Collider) at Interaction Points 1 and 5. These magnets require thorough testing in cryogenic conditions at 4.5 and 1.9 K before their installation into the LHC. Additionally, the HL-LHC includes high-current superconducting transmission lines (SC Links) for feeding the magnets of the Inner Triplets and Matching Sections at LHC Point 1 and Point 5, which also require cryogenic testing and validation before installation. The existing test benches built in the early 2000s to test the LHC magnets in CERN's SM18 facility needed to be upgraded because the HL-LHC magnet apertures and internal line routings were incompatible. CERN has upgraded five test benches of the major LHC magnet test facility to perform the cryogenic powering tests and magnetic measurements of the HL-LHC magnets and SC Links. The upgrade included additional shuffling modules, anti-cryostats and new current leads. The paper details the cryogenic characteristics of the upgraded test benches and reports on the first operational results.

1. Introduction

For more than 30 years, CERN has been testing its main superconducting magnets and superconducting radio-frequency (SRF) cavities necessary for its accelerators in a large cryogenic test facility of 7200 m^2 floor space, named SM18. It was upgraded several times to accommodate the testing and development needs of various generations of accelerators.

It started early in the 1990s with the installation of a large test facility for the series testing of SRF cavities and cryomodules devoted to the Large Electron Positron Collider upgrade (LEP2) and next for the qualification of the LHC (Large Hadron Collider) SRF cavities. This SRF test facility underwent a major upgrade in 2013 to prepare for the tests of the Crab cavities required for the HL-LHC project, the High-Luminosity upgrade of the LHC [1].

In 1994, the cryogenic infrastructure [2] and the first cryogenic test bench, including a Magnet Feed Box (MFB) [3] were designed and built to test the prototype 10-m magnets for the LHC. In 1997, a major project to upgrade the magnet testing infrastructure at SM18 was launched to prepare for serial testing of nearly 1700 magnets for the LHC construction, including about 1300 15-m-long arc dipoles. In the first phase, based on the experience gained with the first magnet test bench and the MFB, the test facility was equipped in 2000 with two pre-series Cryogenic Feeder Units (CFU) [4]. The functions of the CFU were to provide and enable the control of all the operating modes required for LHC magnet testing: cool down and warm up of a magnet, maintain of a magnet in saturated liquid helium at 4.5 K or in pressurized superfluid helium at 1.9 K for magnetic measurements and quench training, recovery of as much liquid helium as possible after a quench and automatically cool down of the magnet again. The CFU also included all the current leads (CLs) needed to feed the various coils part of the different LHC magnets (one pair of 15 kA to feed the main coil of the dipole magnets and two pairs of 0.6 kA to feed the coils of the correctors). The final magnet test facility for testing the whole series of LHC magnets was completed in 2004. It comprised 12 test benches, each including a Cryogenic Feed Box (CFB) procured from industry but designed by CERN based on the experience acquired with the previous feeder units (MFB and CFU) [5]. The test-bench powering system consisted of six clusters named "A" to "F". Each cluster, therefore, included two test benches labelled "1" and "2" of which only one could be powered at a time.

2. SM18 magnet test bench reconfiguration

After the series test of all LHC magnets from 2004 to 2008, only a few test benches were used in the following years to requalify spare magnets or to study operating limits of magnets for the LHC run. Between 2010 and 2017, five vertical magnet test benches were installed at SM18 for magnet R&D purposes, particularly for the magnets required for the HL-LHC project [6]. At the same time, an additional test stand equipped with a new Feed Box designed to supply 10 g/s of supercritical helium or variable temperature gaseous helium (GHe) between 20 K and 100 K was installed to test fast-cycled magnet and SC Links for the HL-LHC Cold Powering Systems (CPS) [7]. During this period, the cluster D [8] was dismounted and converted into a vertical test bench, leaving only ten horizontal test benches with CFBs.

Table 1. HL-LHC magnet parameters & testing requirements.

HL-LHC magnet	MBH 11T	Q2a/b	Q1/Q3	CP[a]	D1	D2
SC material (main / correctors)	Nb_3Sn	Nb_3Sn / Nb-Ti	Nb_3Sn	Nb-Ti	Nb-Ti	Nb-Ti
Powering requirement [kA] (main + correctors)	15	20 + 2 * 2	20	2 * 2	15	15 + 2 * 0.6
Stored energy at nominal/ultimate current [MJ]	4.75 / 5.54	8.4 / 10	9.2 / 11	0.28	2.13 / 2.5	2.26 / 2.62
Cold mass outer diameter [mm]	570	630	630	630	570	630
Aperture [mm]	60	150	150	150	150	105
Testing temperature [K]	1.9 / 4.5	1.9 / 4.5	1.9 / 4.5	1.9	1.9	1.9 / 4.5
Thermal shield temperature [K]	< 100	< 100	< 100	60 - 80*	< 100	< 100
Max ΔT during cool down/warm-up [K]	< 30	< 30	< 30	< 50	< 50	< 50

[a] CP (Corrector Package) includes also eight higher-order correctors powered via current leads installed on the side of the cryostat. Their cooling is achieved by the shield circuit regulated between 60 and 80 K and a flow of 2.5 g/s.

From 2016, CERN began preparing the infrastructure needed for the HL-LHC superconducting component testing program. It led to the procurement and installation of a new helium liquefier with a liquefaction capacity of 35 g/s to meet the future demand of liquid helium for the test benches [9] and a reconfiguration of the horizontal magnet test benches to test the different types of HL-LHC magnets and CPS. The HL-LHC magnet parameters and their testing requirements are listed in Table 1. The final test bench layout is summarized in Table 2 and results from a compromise aimed at reusing as much as possible the equipment designed and used to test the LHC magnets, while considering two main constraints and the associated costs:

- The necessary upgrade of the test bench powering system to allow testing at higher currents, particularly for the magnets based on Nb_3Sn technology.
- The size of the magnets and the CPS (up to 140 m long) with respect to the available surface area for upgrading the test benches and handling equipment.

Table 2. Magnet test bench layout for HL-LHC.

Cluster	Bench	Magnet assy	Number of tests	Powering
A	A1	Q2 proto	6	20 kA + 2 * 2 kA
	A2	Q1, Q3, CP	9	
B	B1	LHC magnet	15	15 kA + 2 * 0.6 kA
	B2	D1	6	
C	C1	MBH 11T	4[a]	15 kA + 2 * 0.6 kA
	C2	D2	7	
E	E1	LHC magnet	(Backup of B1)	15 kA + 2 * 0.6 kA
	E2	Inactive (spare)	-	
F	F1	Q2	12	20 kA + 2 * 2 kA
	F2	CPS[b]	10	

[a] Three MBH-11T were tested on the C2 bench before it was decided to upgrade it to test D2 magnets.
[b] Powering of clusters E and F is used to power CPS connected to F2 test bench.

3. The F2 test bench

3.1 Upgrade of F2 test bench to test HL-LHC CPS

The F2 test bench was selected to carry out the tests of the 10 CPS of the HL-LHC project. Each CPS is composed of four modules: the DFX/M module that supplies the cooling power to the SC Link, the SC Link, the DFHX/M module that includes all the CLs, and a Gas Management System (GMS) that controls the helium flows coming from the DFHX/M.

The functional cryogenic requirements for testing the CPS require the supply of liquid helium (LHe) at 1.3 bara with a mass flow of a maximum of 10 g/s, as well as a system to control the temperature during the cool-down and warm-up phases to maintain the temperature gradient in the SC Link below 60 K.

To provide the mass flow with variable temperature, the CFB-F2 was extended with a connection module interfaced with the DFX/M module of the CPS, including a mixing chamber. The Process Flow Diagram (PFD) of the F2 test bench to test CPS is shown in Figure 1.

In nominal operation mode, LHe is directly supplied from the CFB phase separator to the DFX/M via the mixing chamber through CV147. The LHe level in the DFX/M is regulated by CV149. The GHe flow between 5 K and 17 K required to cool down the SC Link is generated by vaporizing the LHe in the DFX/M with the electric heater EH830. The pressure in the CPS and the flow in the CLs are controlled by CV892 (DFHX/M bypass) and CV891 in the GMS.

For the cool-down or warm-up phases of the CPS, the mixing chamber is supplied with LHe through CV146 and with GHe at 293 K from the high-pressure line of the SM18 infrastructure through CV155. The mixed gas temperature is controlled by regulating these two inlet valves and the TT149 temperature sensor at the outlet of the mixing chamber. A bypass (CV148) allows the mixture to be prepared before it is delivered to the CPS. The required flow rate, ranging from 2 to 4 g/s, is regulated by CV149, taking into account the temperature gradient in the SC Link (difference between the inlet temperature of the DFHX/M and the outlet temperature of the DFX/M: TT892-TT832).

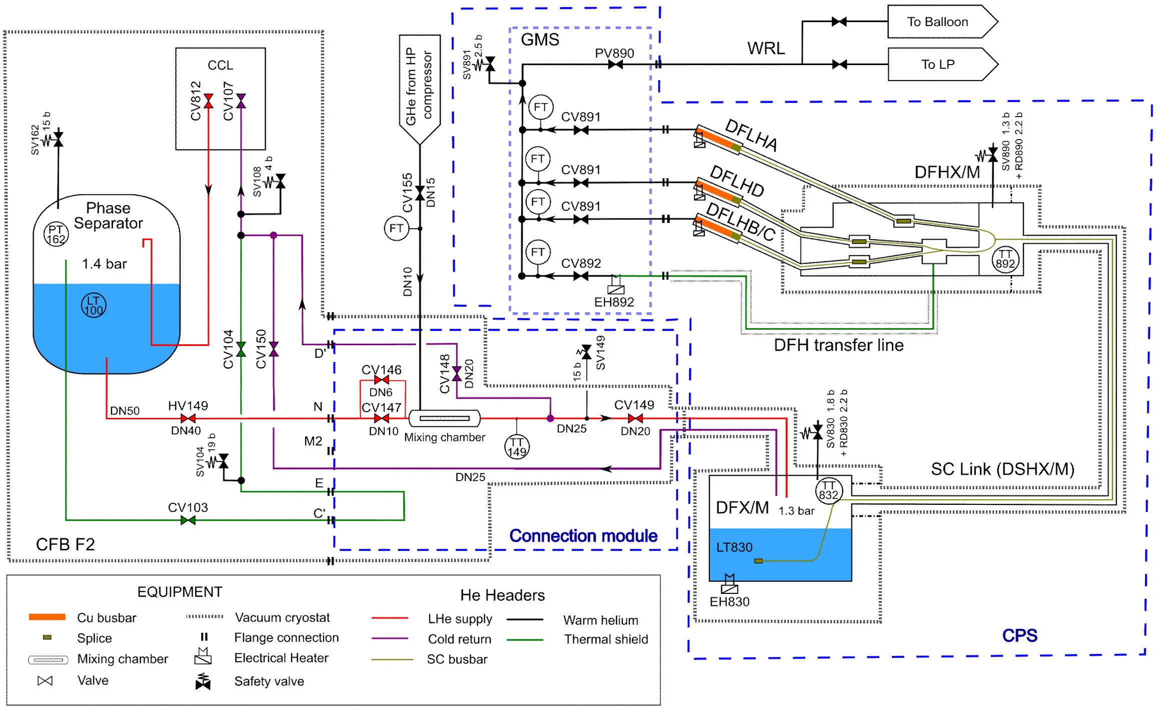

Figure 1. Simplified Process Flow Diagram of the F2 test bench to test HL-LHC CPS

3.2 First operational results with the F2 test bench, testing the HL-LHC CPS prototype for Inner Triplets

The plan was to first test the CPS for the Inner Triplets (one prototype, then four CPS that will be installed in the accelerator), followed by the CPS for the Matching Sections (four for the accelerator + one spare).

Figure 2 shows the SC Link flow rate evolution and the inlet/outlet temperatures during the CPS prototype test for Inner Triplets (IT) from February to April 2024. Two complete thermal cycles were performed. The test demonstrated that the system with the mixing chamber could smoothly control the required gradient set to a maximum 50 K during cool down and warm-up phases at a flow rate of up to 3 g/s. The first cool-down was interrupted due to an issue with the SM18 cryogenic plant. The smooth restart allowed the validation of the operation of the mixing chamber bypass.

During all nominal operations, the pressure in the DFX remained stable at 1.3 bar. A successful flow test at 10 g/s was performed, as well as all the various flow configurations required with or without powering. The control was smooth even during the powering transient. The nominal flow in the SC Link was measured at 5.85 g/s with a minimum flow of 1 g/s in the DFHX bypass (CV892) to ensure system control. At full power (94 kA), the total flow in the CLs was 4.9 g/s and reduced to 3.6 g/s without power. Heat loads were measured before and after the thermal cycle with no change in performance. The measured heat load for DFX was approximately 55 W, which is 25 W more than the specification.

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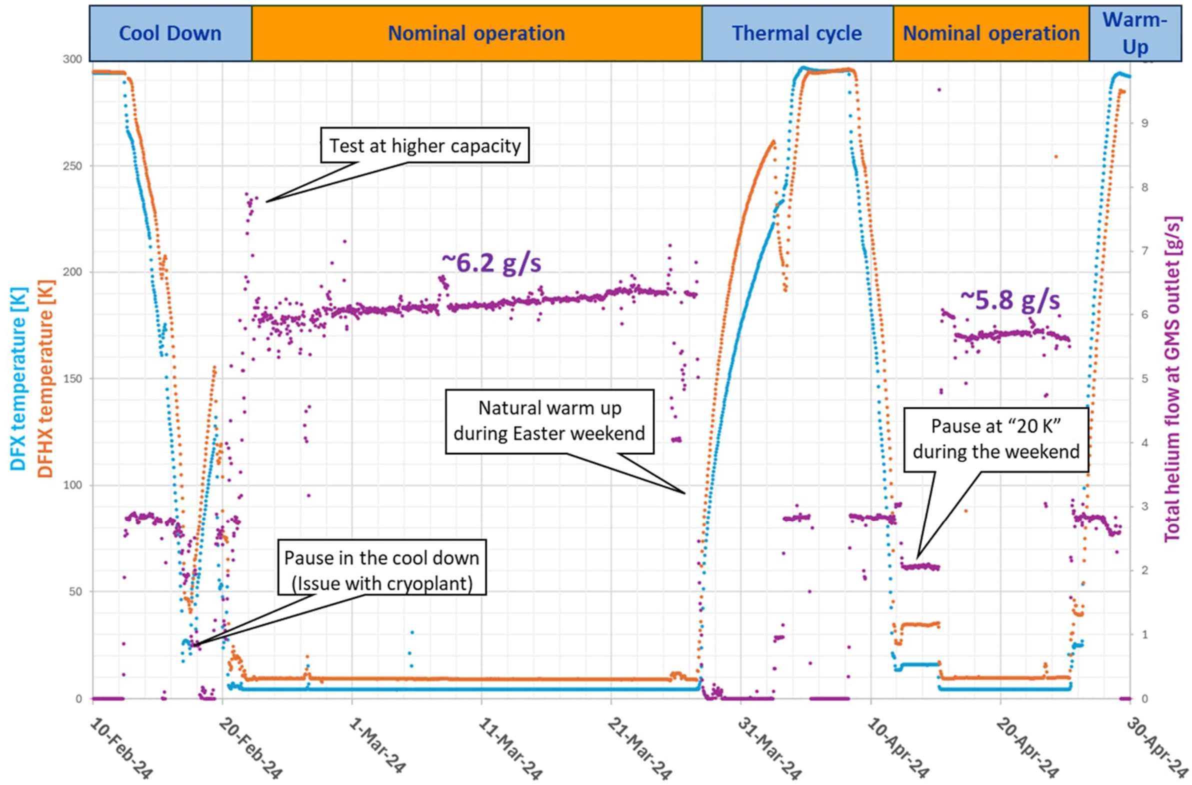

Figure 2. Flow, inlet, and outlet temperatures in SC Link of IT CPS prototype during test on F2 test bench

4. The test benches for HL-LHC magnets

4.1 Upgrade of test benches to test HL-LHC magnets

HL-LHC magnets present several design differences with respect to LHC magnets (see Table 1) for which the CFB was designed, notably :

- Larger aperture;
- Higher operating current and higher stored energy;
- Larger cold mass diameter and different arrangement of busbars and cryogenic headers;
- Different superconducting material (Nb_3Sn) and the requirement to limit the temperature gradient in the cold mass during cool down and warm up phases.

To accommodate these differences, test benches of clusters A, B, C, and F were selected for an upgrade (see Table 2). Four of these (A2, B2, C2, and F1) were equipped with a shuffling module (SM) extension. The purpose of this SM was to correct the geometric differences at the interface with the CFBs designed for the LHC magnet tests at 1.9 K and 4.5 K, but incompatible for the HL-LHC magnet tests at 4.5 K. To limit engineering and hardware investments, it was decided to design a generic SM capable of meeting the requirements for the four test benches with minor changes. Figure 3 shows the Process Flow Diagram of the CFB with the SM for testing the Q1, Q2, and Q3 HL-LHC magnets. The SM enables the following functional requirements:

- The rerouting of the cryogenic headers and the SC busbars from the LHC configuration in the CFB to the HL-LHC configuration;
- An additional LHe phase separator (PS) ensures the wetting of the SC busbars routed at the top in the HL-LHC magnets, particularly during the testing phase at 4.5 K with saturated helium at 1.3 bar. It includes a level gauge and a 400 W heater to preload the

cryogenic system to manage the heat generated by current ramps that can reach 150 A/s for diagnostic purposes.

- A heater EH101 in the thermal shield header to allow the regulation of the temperature flow in the 60-80 K range for the CLs of the higher-order correctors of the CP magnet;
- Moving to the SM interface all the features located on the CFB interface that will become inaccessible once the SM is connected.

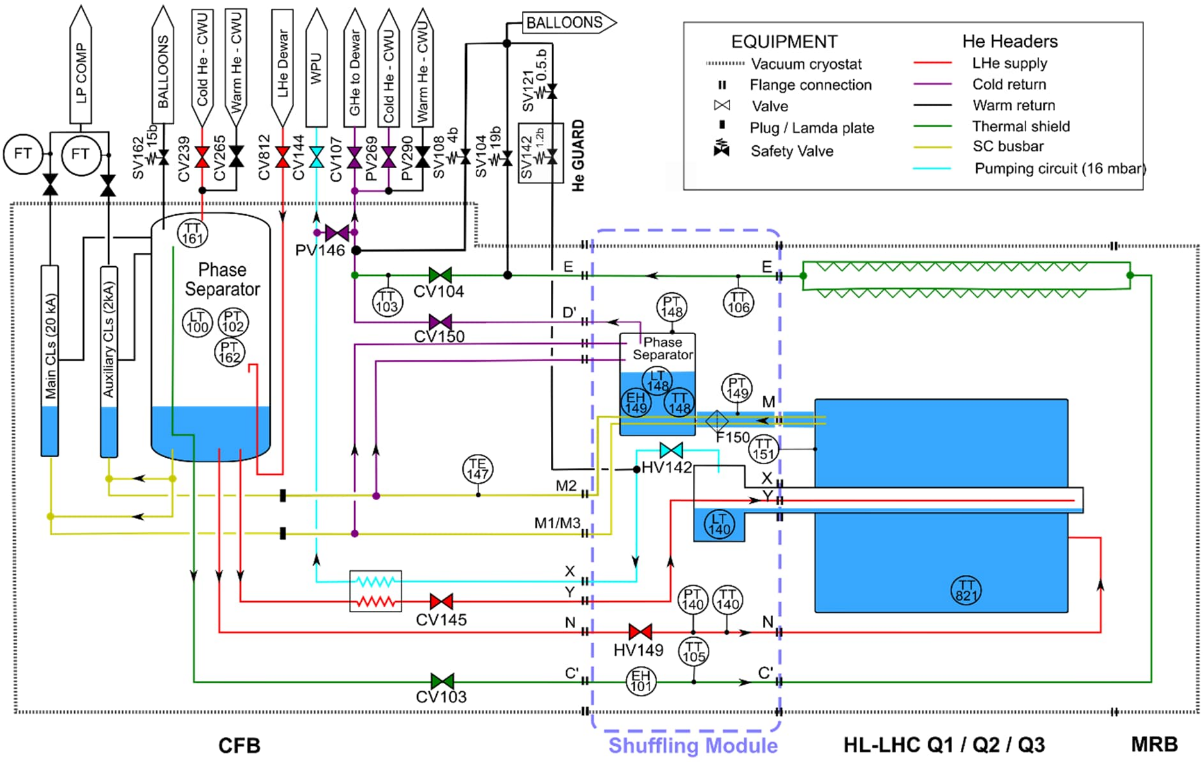

Figure 3. Simplified PFD of A2/F1 test bench to test Q1 or Q2 or Q3 HL-LHC magnet.

Considering the complexity and geometrical constraints, the design and manufacturing of the SM were performed at CERN. The design of the SM connected to the CFB is illustrated in Figure 4. The requirement to reroute and recombine the CFB busbar M1/M3 and M2 lines into a single M line while integrating a sufficiently sized PS positioned as high as possible to maintain continuous wetting of the busbars was already a complex problem. Geometric constraints stemming from the larger diameter of the HL-LHC magnets and the impossibility of raising the CFB (whose axis is aligned with the LHC magnets) without significantly modifying the entire SM18 infrastructure, exacerbated the problem. The need for a cantilevered system, combined with the pressure and cryogenic temperature operational requirements, further amplified this engineering challenge. The design must withstand mechanical stresses, potential vibrations, and thermal shrinkage while ensuring good thermal performance. To address these, the SM incorporates a cantilever support structure (CSS) that holds a 150-liter PS and the cryogenic headers. This CSS, made from 304L, is attached to an aluminium (Al6082) space frame via titanium (Ti6Al4V – Grade 5) tie-rods. The space frame is suspended from the vacuum vessel using M16 screws and a set of convex-concave washers. The horizontal tie-rods are preloaded to 6 kN, and the radial tie-rods to 2.7 kN. The total mass suspended from the tie-rods is 420 kg. The SM was designed and manufactured according to ISO and EN standards. The compatibility of the safety devices installed on the original CFB has been reassessed and validated for the new assembly, including the SM and the HL-LHC magnets.

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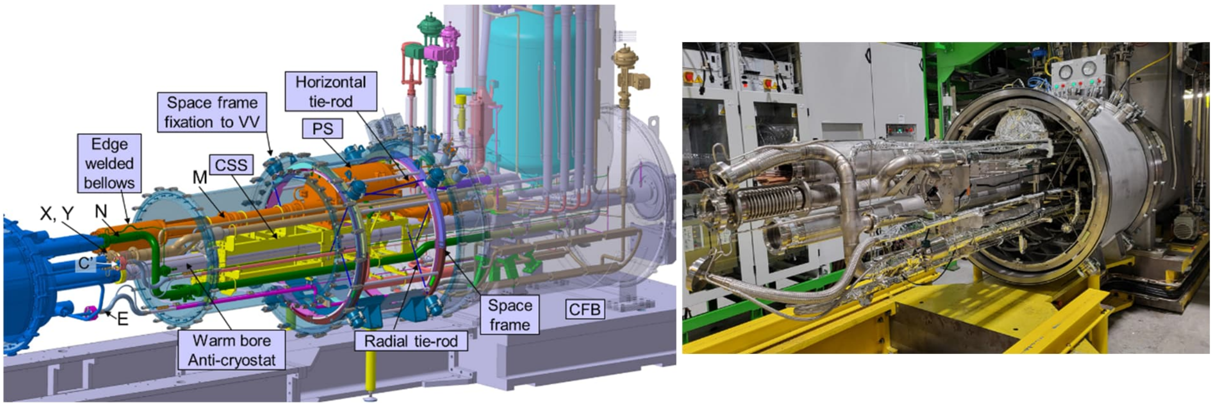

Figure 4. Shuffling module (SM) design (left), connected to the CFB-F1 test bench (right)

In addition, the following modifications were also necessary on the CFBs:

- Due to the larger aperture, new adapted warm bore anti-cryostats for performing magnetic measurements were required, which necessitated modifying the supporting system and the CFB shield;
- Exchange in CFB-A2 and CFB-F1 of 600 A CLs with new 2 kA CLs;
- Consolidation of the splices on the main busbars presenting too high resistance (100 nΩ), particularly for test benches with 20 kA powering (resistance reduced to 3 nΩ);
- Recalibration of the flowmeters to control the cooling of the CLs for higher mass flow;
- To control the temperature during the cooling and warm-up phases, temperature sensors were added at the inlet and outlet of the magnet connections, plus one on the magnet cold mass (TT140, TT148 and TT151 in Figure 3).

Given the significant work required for upgrading the four benches with a shuffling module, the A1 and C1 test benches were first accommodated to allow testing of the MBH 11T dipole and Q2 quadrupole prototypes. To address the geometric differences, a suitable cryostat was developed to hold and connect the cold mass of the Q2 prototype to CFB-A1 without SM, and level gauges were inserted in the cold mass to allow testing at 4.5 K. The CFB operation principle [10] with or without SM remains the same as for the LHC magnets: leak check, cool down 300 K to 80 K, cool down 80 K to 4.5 K, cool down 4.5 K to 1.9 K, depressurization after quench, cool down again to 4.5 K or warm-up to 300 K, magnet (de) mounting. The control system was updated to take into account the new features and the specific characteristics of each upgraded test bench.

4.2 Commissioning and first operational results with upgraded CFB test benches

In preparation for an LHC upgrade during the 2020-2021 long shutdown, C1 and C2 test benches were the first to be upgraded and used from 2019 for the testing of the MBH 11T [11]. The first Q2 prototype was tested in 2020 on the A1 test bench. It allowed to validate the update of instrumentation and the control logic for the cool-down and warm-up phases and the powering at 20 kA for the A1 test bench.

In 2023, the A2 and F1 test benches were upgraded and successfully commissioned with new 2 kA CLs. The first SM was also connected to CFB-F1 in 2023, followed by A2, B2, and C2 in 2024. After their connection to the CFB, all SM were successfully cold commissioned at full powering.

At the end of 2023, a first test of a full HL-LHC Q2 magnet was successfully carried out at 1.9 K and 4.5 K on the upgraded F1 test bench. The entire process went smoothly and was comparable to the LHC magnet tests, except for the cooling time during the phase from 4.5 K to 1.9 K. This was because the TT148 temperature sensor, which notifies the end of the cooling phase when it reaches 1.9 K, has been relocated in the PS of the SM. Indeed, since the 3 m long M-header connects the PS to the magnet cold mass housing the liquid-liquid heat exchanger (X-header) used for cooling, it takes nearly 2 hours for the helium in the PS to cool and densify by conduction. The process control logic was therefore adapted with new settings to notify the end of the magnet cooling phase at 1.9 K, reducing the cooling time to be comparable to a CFB without SM extension. It is also worth noting that the heater in the PS was not required during high current ramps. The 150-liter buffer volume of the PS, combined with optimized PID tuning of the control system, allowed the system to handle these transients effectively.

In 2024, A2 test bench was inaugurated with the first HL-LHC Q3 magnet test, followed by the first HL-LHC CP magnet test. All the operating modes were successfully validated, including the cooling by the thermal shield header of the CLs for the high-order correctors in the CP magnet. In 2024, F1 test bench housed seven test campaigns of Q2 magnets. Many tests at 1.9 K and 4.5 K with current ramps up to 100 A/s were performed, confirming the capacity of the upgraded test benches to run series tests. The first tests with D1 and D2 magnet assemblies, respectively, on B2 and C2 test benches, are planned for the second half of 2025.

5. Conclusion

CERN's test facility, designed initially for serial testing of LHC magnets, has been reconfigured and upgraded to accommodate HL-LHC magnets and CPS. This involved upgrading the powering capacity and adapting the complex interface of five CFBs. One of the test benches was adapted for testing the new HL-LHC CPS and a shuffling module was added to four CFBs, enabling all the modes required for testing HL-LHC magnets. In 2024 a CPS was successfully tested and two upgraded test benches have already housed series testing of HL-LHC magnets.

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