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Chapter 26

The International Network of Test Infrastructures for the HL-LHC Magnets and Cold Powering System

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This chapter describes the test facilities upgraded in the framework of HL-LHC for testing magnets, cryo assemblies, SC Link systems, HTS leads and cold diodes at CERN, and at the collaborators' premises.

1. Introduction

Within the HL-LHC project, more than 100 superconducting magnets are to be tested. This includes models and prototypes, and encompasses the period of 2018-2024. They are of different types and sizes, based on either NbTi or Nb_3Sn technology, which are designed-and-fabricated at CERN, at collaborating laboratories, or in industry. The testing criteria varies at different phases of the project. For example – during the R&D phases – the main purpose of testing was to obtain design feedback. Meanwhile – during serial production – the main purpose is qualification.

The HL-LHC employs innovation not only in magnet technology, but also in cold powering, quench detection and quench protection. Test infrastructures for these various systems have been set up at CERN and collaborating sites [1,2]. For example, the cold powering system uses MgB_2 – for the superconducting link (Sc link). It transports up to 150 kA between the power converters and the magnets via current leads (CLs) using REBCO conductor (see Chapter 10). Dedicated test stands have been set up to qualify both the Sc link and the CLs before their integration into the LHC tunnel.

This chapter describes the various test stands of CERN and of collaborating institutes, that have been upgraded, developed, or constructed for testing major components as described here before.

2. Cold Powering Test Facilities for Superconducting Magnets

Testing the superconducting magnets is part of the QA process. It assesses the soundness of the construction and the suitability for machine operation. In addition, during construction, the test is also an integral part of the construction chain: it must produce feedback on time to be included in eventual corrective actions in the construction process. It's also a key milestone for triggering acceptance and passage of responsibility between firms and/or institutes (in case of industrial orders), or among institutes (in case of in-kind contribution).

2.1. *Test facilities at CERN*

The CERN Superconducting Magnet Test Facility, placed in the building named SM18, an acronym sometimes used to refer directly to the test facility, is a unique asset for the accelerator magnet programs. Its history dates back more than thirty years. After testing the first generation LHC dipoles sand quadrupoles at the beginning of the nineties a prototype test bench, construction of the twelve horizontal test benches started in the mid-1990s, reaching its final configuration in 2004. Between 2004 and 2008, SM18 hosted the series test of all LHC superconducting magnets [3]: approximately 1700 cryostated magnet assemblies, for a total of 2000 test runs. Since the end of LHC series tests, the horizontal test benches of SM18 are still regularly used to qualify spare magnets [4], to study magnet operation limits [5], or to characterize off-line the magnetic behavior of the LHC magnets by repeating selected and adjusted operation cycles [6]. The first upgrade of SM18 took place in the period of 2009 to 2013. At that time, three vertical test cryostats – originally hosted in a separate test hall (also known as the Block 4), used mainly for R&D, magnet model and component tests – were migrated to SM18. In the same time frame, a cryogenic feed-box, originally planned for the test of Nb-Ti links (with up to 600 A) in supercritical helium, was upgraded to provide up to 20 kA, and a variable temperature He flow of up to 10 g/s and at 100 K.

This test station was used to power a Fast Cycled Magnet [7] and superconducting current links [8].

In spite of its unique capacity, it was clear that SM18 would not be able to cope with the demands of new projects such as the HL-LHC. For this reason, SM18 has undergone a fundamental redesign [9–17], upgrading its test stands and service infrastructures.

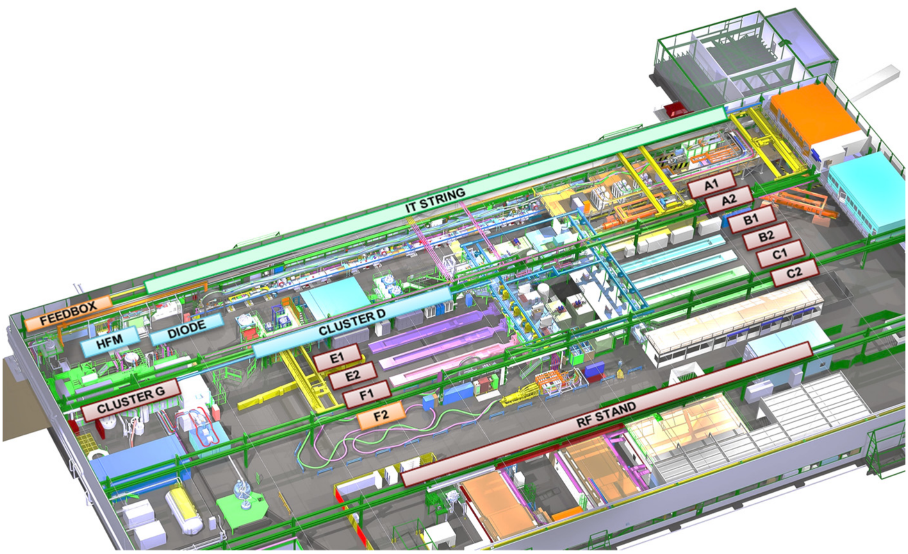


Fig. 1. Test benches at CERN for the HL-LHC

2.1.1. *Service infrastructure upgrade*

The increased quantity and dimensions of test installations, the greater dimensions of the magnets to be tested, and the larger currents required, led to an increased demand for general services. Following HL-LHC planning, during the serial production between 2020 and 2025, most of the testing installations will work in parallel to cope with a rate of 30-40 tests/year. This includes standard tests of LHC spare magnets as well as special tests. The impact of this program was translated into the needs of each of the service infrastructures, with particular consideration given to the simultaneous operation of horizontal benches, the vertical cryostat, the Sc Link, the RF cavities, and the IT String (as described in Chapter 24) in the SM18 test facility. In this evaluation, contingency was taken for a hypothetical scenario where the test stands would need to re-qualify 50 spare magnets for the LHC within a shortened timeframe (max. 5 months), as was the case in 2009 [18].

The cryogenic cooling system is one of the most critical infrastructures for the test stands. SM18 is equipped with a 6 kW refrigeration system, used as a liquefier, delivering saturated, liquid He at 1.6 bar, and a 25 m^3 LHe Dewar for storage. The initial liquid production capacity of 27 g/s was estimated to be insufficient when compared to the demand of up to 60 g/s. An upgrade has then been completed successfully in 2020, with the installation of an additional He liquefying system with 35 g/s capacity. Two warm pumping units are shared between the magnet test stands and the RF test stands for 1.9 K operation. These units are expected to be sufficient for long term operation. Nonetheless, to improve flexibility in 1.9 K operation, the two warm pumping units were connected to share, as required, their total pumping capacity of 12 g/s at 6 mbar between the RF cavity and magnet test benches [19].

Demineralized water is used to cool the power converters, the water-cooled cables and the switches. The LHC magnets are powered in the test stand in a range between 0.12 – 12 kA, while the HL-LHC needs are higher, in some cases reaching 22.5 kA. This leads to an increased consumption of demineralized water, estimated to be a total of 150 m^3/h during the time the operation of the IT String or the SC link test stand. Hence an upgrade to the demineralized water station was also necessary to cope with the increased demand.

Upgrading the demineralized water station and increasing the installed cryogenic power triggered an upgrade of the primary water station, resulting in more than 5.7 MW of extra capacity.

Such modifications in and around SM18 also required an upgrade to the electrical distribution network – both for the machine, as well as the general and UPS networks to cope with the demand of different test stands. An additional 3 MVA transformer installed in 2019 ensured that the Cluster F horizontal test stand's new 20 kA power converter can be powered in parallel with all of the IT String's power converters. The UPS network's capacity typically relating to cryogenics or protection system triggers, has been upgraded to 100 kVA, ensuring approx. 10 min autonomy at 80 kW of total consumption.

A compact, 25 t capacity overhead crane equipped with a cable of sufficient length to allow installation at the -3 m level was required. It was later completed with a 10 t crane, to ensure the handling of the SC link system and its safe installation into the IT String.

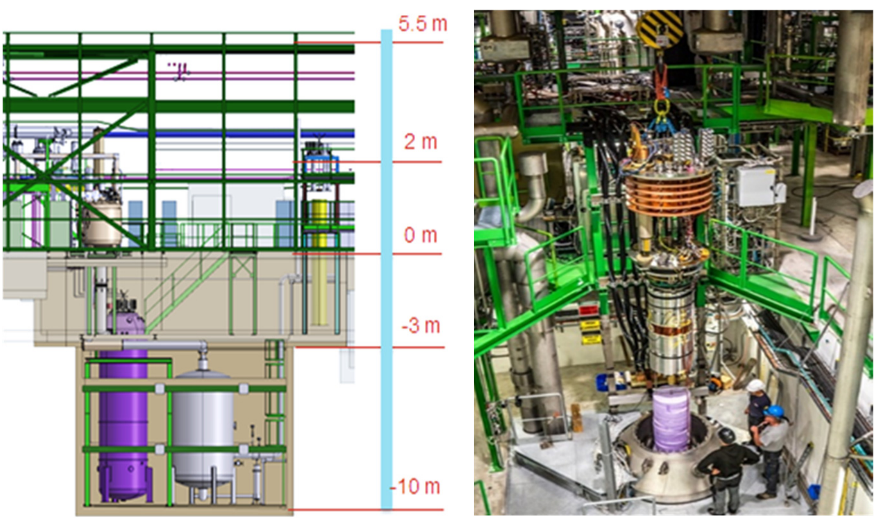
2.1.2. *Vertical test stands for magnets*

The HL-LHC magnets' overall dimensions and their powering characteristics justified an investment into vertical test stands comprised of a cryostat, powering circuits, and associated protection circuits. The most critical magnets of the upgrade were undoubtedly the Nb_3Sn quadrupoles of the Inner Triplet (IT) [20–22]. All quadrupoles have identical design, with a cold mass outer diameter of 630 mm (to be compared to the 550 mm of a standard LHC cold mass). The nominal current is 16.5 kA at 1.9 K, the ultimate design value is 18 kA, and the expected short sample limit is 21.5 kA. The operating current density and stored energy per unit mass of these magnets is significantly higher than in the LHC, requiring 3x faster detection and protection reaction times. This needs to be viewed in relation to the fact that Nb_3Sn is affected by an intrinsic voltage noise caused by flux jump spikes. Besides the high gradient IT quadrupoles, the cryo-assemblies of Q2a/Q2b also contains combined horizontal and vertical dipole corrector magnets, built with Nb-Ti, and operated at a nominal current of 1.4 kA.

Two new test stands were designed and installed, mainly in response to the requirements of the HL-LHC and future needs of magnet tests for the development of future generation colliders at CERN.

The first test stand is referred to as the High Field Magnet (HFM) test stand. It has a cryostat with a large inner diameter of 1500 mm, a useful length of 2.5 m, and is prepared for operation at 4.2 K and 1.9 K. The design of this cryostat and its ancillary equipment was primarily driven by the test of the FReSCa2 magnet, but considering its size, it could host any other larger magnet such as the models of the IT quadrupole for the HL-LHC, or future high field models. The insert is equipped with two pairs of current leads: one for 20 kA and one for 15 kA. They are powered independently, allowing, for example, the FReSCa2 magnet with a nested HTS insert coil to be tested [12,13]. The 20 kA power converter is shared among all the other vertical test stands of cluster G. An additional (existing) 10 kA converter, only usable for the HFM test stand, has been installed specifically for the insert circuit [23].

The second test stand is referred to as "cluster D", as it occupies the area formerly taken by the horizontal benches with the same name (D1-D2). It has a smaller diameter of 800 mm, but a longer length of up to 5.2 m, and can similarly operate at 4.2 K or 1.9 K. The diameter was chosen to be able to host all HL-LHC magnet models (the largest cold mass is the IT quadrupole being 630 mm in diameter), with some margin for future magnets. The choice of the length was somewhat more involved. While model magnets are typically 1 m to 2 m long, the final length main magnets can be several metres long, e.g. the 7.15 m HL-LHC Q2. Between these two limits there are a number of LHC and HL-LHC magnets of different lengths. In an attempt to maintain maximum test flexibility, the depth of the 1.9 K bath was finally chosen to be 5.2 m, which is the maximum allowed in practice by the existing building and crane geometry. The present maximum height under the crane hook is 5.5 m. Additional headroom is necessary to latch the magnet under the test insert and install the insert in the cryostat. This is achieved by installing the cryostat in a pit, the working level of which is -3 m with respect to the floor (see Figure 2). The base of the cryostat is installed at a depth of -10 m.



(a) The cross section of the pit and the main installations

(b) MQXFS5 magnet ready for testing

Fig. 2. Cluster D

This way, all HL-LHC magnets can be tested in such an installation, except for the IT quadrupole Q2 and the 11 T dipole. Concerning powering, the insert of cluster D is also equipped with two pairs of current leads: one for 30 kA and one for 15 kA, thus reproducing the powering topology of HFM. For now, the plan is to equip this test stand only with the main powering circuit. The main characteristics of the two new test stands are reported in Table 1.

Table 1. Main characteristics of the new vertical cryostats

NEW VERTICAL CRYOSTATS			
		CLUSTER D	CLUSTER G*
Cryostat	Diameter [mm]	800	1500
	Useful length [m]	5.2	2.5
	Lambda plate	Stainless Steel (SS)	
	Lambda plate sealing	ePTFE	ePTFE
Cooling	Operational temperature [K]	4.2/1.9	4.2/1.9
	He gas recovery buffer [m^3]	8	10
	Pre-cooling with 80 K He gas	yes	
Power	Primary circuit [kA]	30	20
	Secondary circuit [kA]	15	15
EE	Switch type	IGBT	thyristor
	Dump resistor [mOhm]	modular	

* This particular cryostat, the 4th in the cluster G, is designed for testing the FReSCa2 magnet.

Although very different in dimensions, the designs of the two new test stands have many similarities. The HFM and cluster D cryostats are pre-cooled from 300 to 80 K by high pressure He flow chilled directly using liquid N_2. This contributes to a more efficient global cooling boosted by the dimensions of the heat exchangers integrated into the cryostat.

Finally, due to the stored magnetic energy being so high, and the sheer number of expected tests and quenches, the test stands have been equipped with a cold He recovery buffer to collect the exhaust during a quench. Both the HFM and cluster D have a cold buffer with a capacity of 10 m^3 and 8 m^3, respectively. After a quench – the cold He gas, upon attaining a pressure of 5 bar – is recovered from the cryostat to the buffer. The cold gas remains then available for cooling the cryostat, if necessary, or can be redirected into the system for recovery in the cycle.

While HFM reuses existing infrastructure, a large part of the circuit for cluster D had to be rebuilt. With the goal of minimising the cost of the SM18 upgrade project, it was decided that the two 15 kA capacity power converters already present in the test stands will be reused. Their capacity had been boosted by an increase in water flow, and by connecting them in a parallel configuration in order to deliver up to 30 kA. It should be noted that although this current level largely exceeds present demand – 30 kA of powering capacity is an interesting option for future developments. The electrical powering circuit of HFM and cluster D is designed to withstand up to 3 kV. The consequence was that to fully benefit from such a power converter, the whole electrical circuit required dimensioning for 30 kA. Starting with the warm, water-cooled copper cables, through the energy extraction (switch and dump resistor) system, and all the way through to the current leads.

Given the challenges of increased stored energy and operating current density – and to avoid potential damage to the R&D magnets during training and provoked quenches – an energy extraction system with a reaction time below 1 ms had been specified. The energy extraction system comprises of a switch and an external dump resistor. To achieve this fast reaction time, it had been decided that a switch using IGBT technology would be built. The switch for the 30 kA circuit is composed of 4 modules, 7.5 kA each. The switch – one of the most challenging elements of the test stand – was designed and built entirely at CERN [14].

Finally, the current leads for both HFM and cluster D were also designed at CERN. Component fabrication took place partially at CERN and partially in industry. The final assembly and tests have been done at CERN. The current lead design relies on classical vapor-cooled technology – the same as all other current leads used in SM18 test stands.

2.1.3. *Horizontal test stands for cryo assemblies*

At the time of testing for the LHC, the SM18 hall was composed of 6 test clusters, each of them having two benches – called 1 and 2 – sharing a common powering and data acquisition (DAQ) system. Each cluster, named from A to E, was equipped with a dedicated electrical circuit for the main magnets and a secondary circuit(s) for the correctors. In the last 10 years, renovation works have been taking place with the goal of upgrading and optimising the SM18 test hall for HL-LHC magnets and future projects. One of the clusters had been transformed to a vertical test stand called cluster D, as described here before.

Each bench can host any of the LHC cryo-magnet assemblies, i.e. up to a maximum length of 16 m and a mass of 35 tonnes. The benches are designed to sustain vacuum forces acting on the cryostat ends up to 8 tonnes. Each cluster is equipped with a main powering circuit, i.e. power converter, warm cables and current leads, up to values of 13 kA/±16 V, and two powering circuits for correctors, up to 600 A/±12 V. There are neither switches, nor energy extraction (EE). Cluster A offers additional testing flexibility due to a different main circuit, equipped with a 17 kA/±61 V power converter. Cooling of the magnets is either at 4.2 K, or 1.9 K, whereby in the latter case the heat exchanger must be located in the magnet being tested, while the test bench only provides helium pumping and phase separation.

To respond to the requirements of HL-LHC serial production, the main part of the horizontal test facility required modifying the cryogenic interface and an upgrade of the electrical circuit: both the high current part (from 13 kA to 20 kA) and the low current for the corrector circuits (from 600 A to 2 kA). On some benches, the energy extraction system had to be integrated with the new CLIQ protection system, as well as the universal quench detection system (uQDS). This ensures that, at least on test bench, it is fully representative of all the systems in the tunnel configuration, prior to the HL-LHC IT String test. The testing strategy for the HL-LHC cold masses was defined so as to have redundancies, and therefore to minimise the risk of using ageing test benches. Therefore, for the most demanding tests – those of the 11 T dipoles and the triplet quadrupoles – two independent test benches were defined. Test benches C1 and C2 were modified and dedicated to the 11 T dipole, while benches A2 and F1 will be dedicated to the quadrupoles. Bench B1 was chosen to be the test stand for D1, and bench C2 for D2. The Corrector Package (CP) is foreseen to be tested on the A2 bench.

The major modification regarded powering circuits were to upgrade the 13 kA circuits to 20 kA and to change the 600 A corrector circuits without Energy Extraction (EE) into 2 kA circuits with EE (benches A2 and F1). Another important modification was the interface between the cold masses of type Q2 and the Cold Feed Units (CFU) of SM18. This is because the cooling channels of the LHC and HL-LHC magnets – with respect to the benches – are not aligned. The modification of the benches was done in two stages. Stage one – ensuring a partial solution for the prototype magnets. Stage two – a full modification for the series testing [24,25].

2.1.4. *Current leads test stand*

All the superconducting current lead assemblies (DFLH), assembled in the corresponding DFH, will be entirely qualified at nominal operational conditions in SM18 test benches and in the HL-LHC IT String, as described in Chapter 24. A type test is planned to be performed of all the pre-series leads to validate their manufacturing and design, and about 10% of the total number of each current lead assembly type, as quality control and for eventual troubleshooting. Therefore, the tests should cover aspects of cooling, powering, and protection.

The leads are using copper for the heat exchanger part, and HTS for the lower part (below 50 K), that is then connected to the MgB_2 conductor of the SC Link. The joints between HTS and copper are done during the manufacturing process, while HTS to MgB_2 is done during the assembly of the DFH. In the test station, the cold connection between leads or from leads to the power converter will be done at the level of the MgB_2-HTS joint. To avoid damage on the HTS side, the joints will be clamped [26].

2.1.5. *SC Link test stand*

SM18 also hosts a cryogenic powering test stand for the HL-LHC's SC link system, prior to the ultimate test that is in the HL-LHC IT String, as described in Chapter 24.

An early test stand had been set up during the R&D phase of the project in order to give design feedback during the development phase. This test stand consists of a cryogenic feed-box allowing one to test with supercritical He up to 100 K and with a powering capacity of up to 20 kA. The so-called DEMO program with several tests and configurations was completed on that test stand. The most complex test was one that allowed the flow of counter current with two 20 kA power converters and several lower current power converters. This was to check electromagnetic compatibility and cross talk between conductors during the powering of a 60 m SC link equipped with HTS leads and a He recovery system.

To accommodate serial production, the test stand should allow simultaneous testing of several electrical circuits ranging between 0.12-16.5 kA, to qualify the SC link through the current leads. An adequate system for He gas recovery is also necessary. It is worth noting that the cryogenic cooling capacity required for the SC link test is 7 g/s of He gas flow in steady state and up to 10 g/s for short periods of time, at a typical inlet temperature of 5 K and an outlet temperature of 30 K. In order to optimize the test infrastructure at CERN, the aim was to reuse, as much as possible, the equipment designed and used for the LHC main dipole and quadrupole cold mass qualification tests in SM18.

Cluster F of the SM18 test hall, as described earlier, and shown in Figure 1, is going to be dedicated to the HL-LHC SC link, and is therefore going through essential transformation and adaptation. The electrical circuits composed by the SC link and the interface modules, current leads, and converters will be completed with water-cooled and air-cooled cables, depending on the respective needs. Where possible, existing cables will be reused. Regarding cooldown and warmup, the liquid helium inlet will be via the existing CFB of the F2 bench. For the outlet, the upgrade of the test bench will require a warm helium gas recovery system next to the DFHx/m module. It will collect He circulating all along the link, and exiting the current leads. There are no major modifications foreseen to the CFB in order to accommodate the interconnection of the SC link to the test bench. This interconnection will be done by means of a DFX module for the first SC link assembly, and by means of a dedicated interconnection module for the rest. The reasoning is that at least one DF module should be tested in nominal operating conditions, but there is no need to cold test all of them.

A warm helium gas ($T > 280$ K expected) recovery system from the current leads of the DFH module is implemented [27]. There are four different current rating circuits: 18 kA, 7 kA, 2 kA and 0.6 kA, that will make use of four different power converters. The 2 and 18 kA power converters are needed also for the magnet testing on the F1 test bench and they are to be installed as part of the upgrade program for the magnet test bench. The 7 kA circuit is an existing one on the closest bench in what is called cluster E. From the electrical point of view, the most demanding test will be performed on the DFHx-DSHx assembly, which will need all of the above-mentioned power converters at the same time.

The quench detection system will be, as in the machine, the so called uQDS developed for the HL-LHC.

The so-called Patch Panel Interface (PPI) will provide the flexibility needed for testing operations, while having a fixed connection to the current leads. This will simplify design and manufacturing, and prevent any potential damage to the current leads during test [28]. It will be placed upstream of the DFH current leads and will perform the role of the circuit disconnector box (CDB), albeit without circuit opening capabilities, and being driven manually.

2.1.6. *Cold diodes test stand*

Cold diodes can be tested in the vertical test cryostat developed for the testing of the LHC cold diodes at 4.2 K and 20 kA in the SM18 vertical test facility (Cluster G).

2.2. *Test facilities at collaborators' premises*

As with magnet design and fabrication, the HL-LHC collaborators play an important role – they also participate in testing activities. Several test stands have been upgraded or built with the purpose of allowing testing of one or several types of magnets or cryo magnets.

2.2.1. *Test stands in US laboratories*

Vertical test cryostat at BNL (USA)

In order to test the AUP-built MQXFA magnets, the vertical superconducting magnet test facility of the Superconducting Magnet Division (SMD) at BNL has been upgraded to perform testing in superfluid He at 1.9 K and 1 bar. This has involved extensive modifications to the 40-year old, 4.5 K cryogenics plant and vertical test facility at the SMD. The SMD has five vertical test cryostats, of which the 6.1 m deep Test Cryostat 2 was modified by inserting a new, redesigned inner He vessel, with a 4.5 K heat shield, into the existing outer Dewar. This extended the useful length by 200 mm in order to accommodate wider and longer magnets, up to 5 m long, and can therefore accept the MQXFA quadrupole magnets which approach 5 m in length. The facility is equipped with a 24 kA powering circuit associated with an IGBT based Energy

Extraction system, and the recently CERN designed CLIQ protection system is integrated to the magnet protection circuit. The variation of current thresholds is dealt within the software, and is therefore automatic during ramps. In addition, the ability to set a variable current threshold in the software is new feature of the test stand. It is necessary when working with Nb_3Sn magnets to avoid false alarms of the quench detection system. This test facility allows for testing of all US-collaboration-produced magnets in vertical position prior to their integration into a cold mass. In total, 27 MQXFA type magnets are to be tested in that test cryostat, including models and prototype magnets. At the time of writing 6 MQXFA magnets have been tested in the BNL facility, that is now in full operational mode [29,30].

The Horizontal test stand at FNAL (USA)

In order to test AUP-built LQXFA/B cryo-assemblies, the horizontal test stand also known as Stand 4, located in Industrial Building 1 (IB1) of the APS-TD in FNAL, is being upgraded. Various improvements have been made to improve overall reliability of the cryo-plant. Four extra tanks were added to the existing six buffer tanks for storage of helium gas. FNAL is in the process of procuring a new liquefier, increasing the total LHe production rate to 600 l/h and total liquid storage volume to 14,000 l. At the test stand, the feed box contains a liquid helium vessel within the vacuum vessel, and the liquid-nitrogen-cooled thermal shield. A removable insert includes the helium vessel top plate with three 15 kA vapour-cooled current leads and an instrumentation tree, displacers, a liquid-nitrogen-cooled baffle shield, a support plate (formerly the lambda plate) with instrumentation and power feedthroughs, and the power bus. The 15 kA current leads have been successfully tested up to 20 kA operation. The adapter box is an extension of the feed box and contains features required to test the HL-LHC Cryo-Assemblies. The adapter box allows for the use of the old feed box without modifications to accommodate the new design of the Cryo-Assembly. The separation between the 4.5 K and 1.9 K temperature levels is within the adapter box. In total, one prototype and ten series magnet tests are foreseen on that test stand to fulfil the primary test objectives that are the qualification and acceptance of the LQXFA/B cryo assemblies for the HL-LHC, including field and alignment measurements (apart from the quench performance) at 1.9 K [30,31].

2.2.2. *The test stand at INFN-LASA (Italy)*

In their LASA laboratory in Milan, INFN Italy is hosting a test stand able to test both superconducting radio frequency (RF) cavities, and magnets. For the HL-LHC project, the charmingly-titled DISCORAP[1] was modified to allow testing, in optimal conditions, the high-order corrector (HO) magnets designed and produced within Italian collaboration. The cryostat with an inner diameter of 697 mm and an operating pressure of 4.5 bars, shielded actively with LN_2, allowed initially to test magnets with lengths of up to 5 m and weights of 5 tonnes. In that space a second cryostat was inserted, called MAGIX, with 515 mm in diameter and 3000 mm in length for operation in 4 K and up to 500 A. The test configurations are such that regroups several magnets for the same cool down. The test stand is equipped with magnetic measurement shafts as well. Also, at LASA the experience of the HL-LHC is fundamental to making plans that are underway for a test bench – at 4.2 K – to serve the next generation dipole magnet development [32].

2.2.3. *The test stand at FREIA (Sweden)*

FREIA in Sweden has established with the HL-LHC project, in 2016 for cryogenic testing of both Sc RF cavities and magnets for HL-LHC. Within this collaboration agreement, the vertical magnet test facility has been designed to allow testing corrector magnets of type MCBXFA/B, MCBRD, etc. The test facility required the construction of a vertical test cryostat with 1.1 m in diameter and 2.65 m below the lambda plate for 1.9 K operation. The test stand is equipped also, as are the vertical test cryostats at CERN, with two independent powering circuits composed of a 2 kA power converter, and an Energy Extraction system using IGBT switches. The quench detection system is entirely compatible with the one used in SM18 at CERN, using the CERN developed POTAIM cards. The test stand is, however, not equipped with a magnetic measurement shaft [33].

2.2.4. *The test stand at CEA (France)*

CEA in Saclay, within the project STAARQ, designed a double bath vertical cryostat with a pressurized superfluid bath to test the MQYY type magnets.

For these 4 m long, double aperture, large bore (90 mm), large diameter (614 mm), heavy (8.9 t) magnet – this vertical cryostat modification is quite challenging. Taking this opportunity, the Saclay team upgraded the whole infrastructure in 4 main parts: internal and external cryogenics, the He liquefier and the powering, safety and acquisition system. This test cryostat, although not financed by HL-LHC, allows for the testing of an MQYY magnet in the vertical position [34].

2.2.5. *The test stand at IMP (China)*

The test stand in IMP is being developed following the collaboration agreement between HL-LHC and China for the production and testing of the MCBRD corrector magnets. The test stand consists of a vertical cryostat of 700 mm in diameter, allowing one to test the magnets at 4.2 K. Although the acceptance criteria of the HL-LHC magnets are at 1.9 K superfluid He temperature, a derogation was given to the collaboration to test the magnets at 4.5 K, but at a higher current. The tests are done with energy extraction. Magnetic measurement can be performed with a rotation probe [35].

2.2.6. *The test stand at KEK (Japan)*

Japan is responsible for the design and production of the D1 magnets. They are also responsible for the cold powering test in the vertical cryostat at KEK of the MBXF magnet. The magnet test cryostat allows tests at 4.2 and 1.9 K of a magnet as long as 7.5 m, with a diameter of 700 mm. The test cryostat had been equipped with a new header, allowing the test with an anti-cryostat with 141.3 mm in diameter and 15 kA current leads, for a nominal operational mode of the D1 magnet at 12 kA. The powering circuit is equipped with an Energy Extraction system with thyristor-based switches and variable dump resistors. A new DCCT has been added to the accurate and stable current measurements. Magnets, and one prototype will be tested in that cryostat for the HL-LHC [36].

Table 2. Summary table of available test facilities

Test Location	Bench Name	Device Name	Test Condition
CH CERN	A2, F1	Q2a, Q2b	Horizontal, 20 kA + 2 x 2 kA, 1.9 K
	A2, A1	Q1, Q3	Horizontal, 20 kA, 1.9 K
	B1, A1, A2	D1	Horizontal, 13 kA, 1.9 K
	C2	D2	Horizontal, 13 + 2 x 0.6 kA, 1.9 K
	A2	CP	Horizontal, 2 x 2 kA, *EE+ 8 x 0.12, 1.9 K
	C1	11T	Horizontal, 20 kA, 1.9 K
	F2	SC link	Horizontal, 0.6-20 kA, 20-300 K
	Feed Box	HTs leads	Vertical, 0.6-20 kA, 20-300 K
	Diode	Diode	Vertical, 20 kA, 4.2 K
	HFM	MQXFS, MBH	Vertical, 20 kA, *EE, 1.9 K
	Cluster D	MQXFS, MCBXFA/B, MCBRD	Vertical, 30 kA, EE, 1.9 K, 2 x 2 kA, EE
US FNAL	Stand4	Q1, Q3	Horizontal, 20 kA, 1.9 K
US BNL	SMD	LQXFA	Vertical, 24 kA, 1.9 K
Japan KEK		MBXF	Vertical, 15 kA, 1.9 K
Sweden FREIA	GERSEMI	MCBXFA/B	Vertical, 2 x 2 kA EE* + 1.9 K
Italy INFN	LASA	HO correctors	Vertical, 13 kA, 1.9 K
China IMP		MCBRD	Vertical, 0.6 kA, 4.5 K
France, CEA	SAARQ	MQYY	Vertical, 16 kA, 1.9K

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