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First operational experience of the upgraded cryogenic infrastructure of the vertical magnet test facility in the SM18 hall, including HFM and cluster D test stations.

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Abstract. As part of the R&D program for HL-LHC, the future upgrade of the Large Hadron Collider (LHC), the vertical magnet test facility in the SM18 cryogenic test hall at CERN has seen significant development. Since the installation of HFM and Cluster D cryogenic test stations in 2017, the facility is comprised of five vertical test cryostats of various sizes operating at either 1.9 K or 4.2 K. It is now possible to test a wide range of superconducting high field magnets with weigh up to 18 tons, maximum stored energy of 10 MJ and powering requirements up to 30 kA. This article describes the first cryogenic operational experiences with these test stations, their cool-down and warm-up characteristics and the heat in-leak measurements of their components. Major upgrades made to the cryogenic infrastructure of the vertical magnet test facility as a whole are also detailed. This includes the adoption of an improved safety strategy to ensure the continued safe operation of the test facility during all operational modes. As well as the incorporation of quench recovery systems on four of the five test stations to reduce the amount of helium lost during testing and the installation helium guards on infrastructure operating at 1.9 K to avoid the ingress of air to cryogenic circuits.

1. Introduction

During 2016, HFM and Cluster D test stations were installed into the Vertical Magnet Test Facility (VMTF) in the SM18 Hall at CERN (SM18). Both stations comprise a cryostat [1] and cryogenic distribution system (CDS) for the testing of magnets in superfluid helium at 1.9 K. To integrate the stations into the VMTF the existing infrastructure was significantly modified, enabling the implementation of a consistent cryogenic safety and quench recover strategy across the VMTF. Installation occurred between February and June 2016, with commissioning completed during 2017.

2. Overview of the Vertical Magnet Test Facility

Along with the Horizontal Magnet Test Facility (HMTF) [2] and the Radio Frequency Test Facility, the VMTF is one of the main clients of the cryogenic infrastructure of SM18.

LHe at 4.5 K is supplied by a 6 kW Linde refrigerator, at a maximum capacity of 26 g/s [2] to a 25 m³ dewar and then to the VMTF and HMTF via the Compound Line [3]. As shown in figure 1, The VMTF is divided in to Cluster G and Cluster D. In Cluster G, LHe is supplied from the Compound Line to Siegtal/Auxiliary, Diode and Long stations via the distribution Valve Box (DVB) while HFM is connected directly to the Compound Line through the Supply Line. Cluster D is physically located in the HMTF, so receives LHe via this infrastructure through the Combined Line.

To control the mechanical strain induced in magnets during cool-down, HFM and Cluster D are connected to the pre-cooling system of the HMTF [3] which allows the circulation of GHe at a controlled temperature defined by the maximum longitudinal thermal gradient measured in the magnet.

The clients of SM18 share two warm pumping units (WPU) for the refrigeration of LHe below the lambda point. Each WPU has a pumping capacity of 6 g/s at 10 mbar [2]. The Pumping Line (PL) connects the stations in Cluster G to the WPU, Cluster D is connected though the Combined Line.

Some important parameters describing the five stations of the VMTF can be found in table.1.



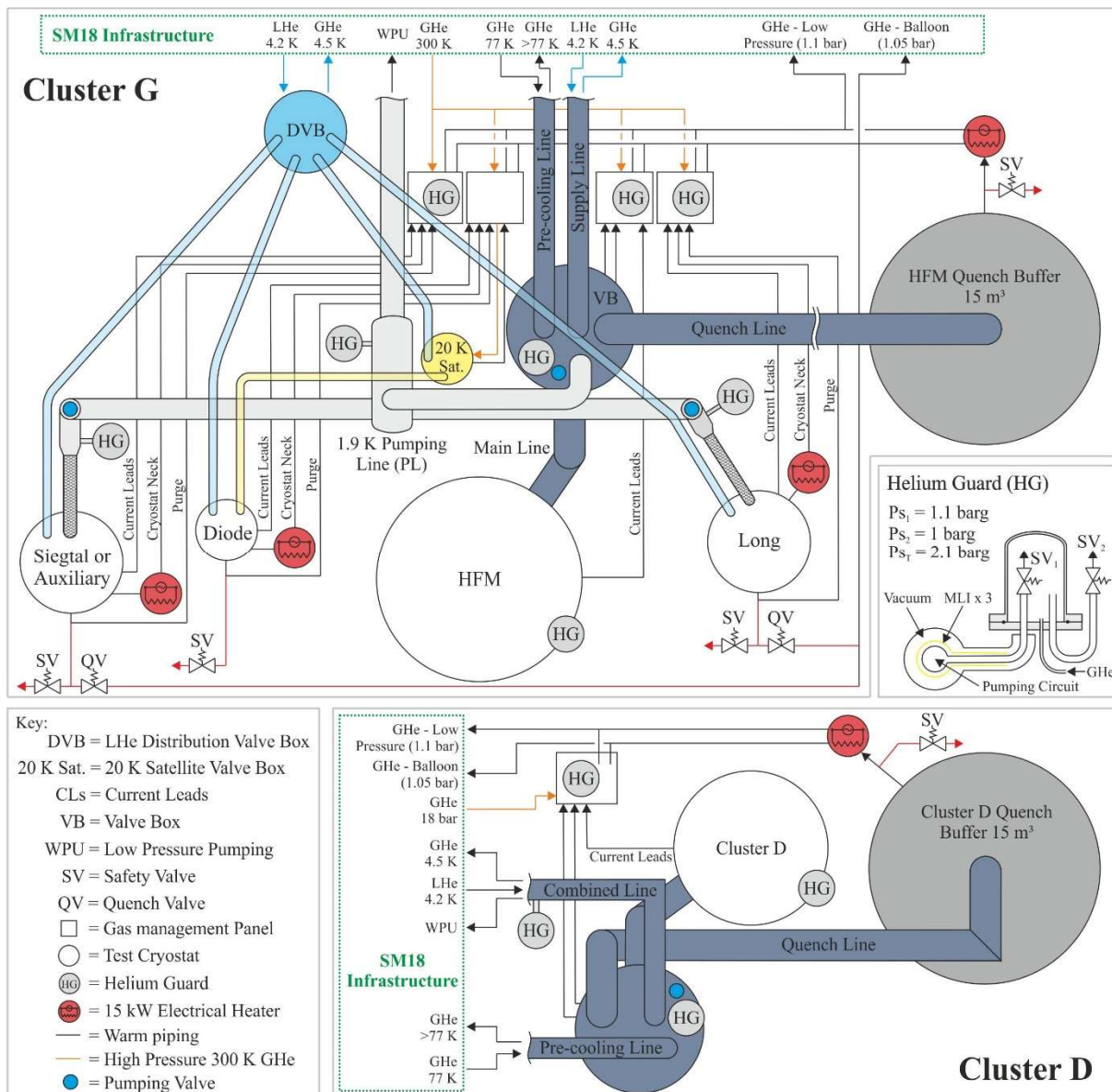


Figure 1. Overview of the vertical magnet test facility (VMTF)

3. Upgrades to the cryogenic infrastructure of the VMTF

3.1. Safety system and quench recuperation

Diode and Auxiliary are not designed to quench during normal operation. However magnets tested in the other stations of the VMTF quench routinely, dissipating part of their stored energy into the LHe bath of the cryostat. To avoid venting vaporised GHe into the atmosphere through the safety valve (SV) of the cryostat after a quench, quench recuperation systems have been implemented.

Siegtal and Long use two stage systems. Using scaled peak results from quench testing on LHC magnets [4], the heat dissipated into the LHe baths of the Siegtal and Long during quench is estimated as 5 kW and 10 kW respectively. Quench valves (QV) with a set pressure (P_s) of 1.0 barg direct vaporised GHe to SM18’s 1.05 bar balloon circuit. SV with a P_s of 2.1 barg protect against the loss of the cryostat insulation vacuum and resulting quench (LOV). The heat load from the non-insulated piping before the QV or SV is accounted for; values in table 1 include 45 kW and 38 kW heat load for Siegtal during quench and LOV respectively and 27 kW for Long for quench and LOV. It was ensured that pressure drop in the piping before and after the SV is less than 3 % and 7 % respectively.

Due to the high number of quenches planned on HFM and Cluster D, they each have a 15 m³ Quench Buffer (QB). This volume was calculated to recuperate a quench of 10 MJ stored energy, dissipated to the LHe at 10 kW with a design pressure of 5 bar. Both CDS have multiple insulation vacuums, so safety protection is staged; a SV with Ps of at 3.9 barg protects against LOV of the cryostat, while a rupture disk (RD) with a burst pressure (Pb) of 5.5 barg protects against a total LOV over the entire station.

In all cases the sizing of RD, SV and QV was undertaken in line with ISO 4126.

Table 1. Parameters of the test stations of the VMTF.

Test Station	LHe Bath			Rupture Disk, Safety Valve and Quench Valve Loads and Sizing								
	Useful Length (m)	Useful Dia. (m)	Temp. (K)	Total LOV (RD)			LOV (SV)			Quench (QV)		
				Power (kW)	Pb (barg)	Size	Power (kW)	Ps (barg)	Size	Power (kW)	Ps (barg)	Size
Diode	2.24	0.5	4.2	-	-	-	62	1.4	DN65	-	-	-
Siegtal	1.40	0.5	1.9	-	-	-	91 ^a	2.1	DN65	50 ^b	1.0	DN50
Auxiliary*	2.23	0.3	1.9	-	-	-	66 ^a	2.1	DN80	-	-	-
Long	3.45	0.6	1.9	-	-	-	104 ^c	2.1	DN80	37 ^c	1.0	DN65
HFM	2.44	1.5	1.9	490	5.5	DN100	160	3.9	DN80	10	-	-
Cluster D	5.44	0.9	1.9	490	5.5	DN100	160	3.9	DN80	10	-	-

^a 38 kW from piping

^b 45 kW from piping

^c 27 kW from piping

* Auxiliary shares Siegtal CDS

3.2. Pumping Line and use of Helium Guards

Operating at sub-atmospheric pressures, an air leak into the process circuits of the PL may pollute the SM18 refrigerator. SV and instrumentation pose a high risk due to the leak tightness of valve seats and connections. To reduce this risk they are installed in Helium Guards (HG).

As shown in figure 1, a HG is a small vessel filled with a controlled GHe atmosphere, maintained slightly above atmospheric pressure (1.025 bar) and itself protected by a SV. If protecting a SV, the total Ps on the process circuit is the sum of the Ps of the internal and external SV. It is advantageous to increase the Ps of each valve as it increases the tightness of the valve seat and reduces the risk of leaks.

One HG is located before the pumping valve of each station. To allow independent operation of the stations one HG is located after the pumping valves to protect the infrastructure of Cluster G. Instrumentation located in the gas management panels and cryostats is also mounted inside a HG.

4. Description of HFM and Cluster D

HFM and Cluster D are designed to test the new model and corrector magnets for the HL-LHC project [5]. They can have stored energy up to 10 MJ and masses up to 15 t and 18 t respectively. The functional specification of HFM is described in [6]; Cluster D is functionally identical. Both cryostats are based on the Claudet bath principle with the liquid-liquid heat exchanger (L/L HX), for refrigeration to 1.9 K, integrated into the helium vessel of the cryostat [1, 6]. To ease assembly of the magnet all active cryogenic components are in the valve box (VB), which contains 11 cryogenic valves, a phase separator (PS), a liquid/gas heat exchanger (L/G HX) for pre-cooling LHe, three electrical heaters and a cold buffer on the pumping line. HFM has four cryogenic lines, of which the Main Line, Quench Line and Supply Line are actively shielded. For Cluster D the Supply Line and Pumping Line are assembled into the Combined Line. Surfaces at LHe temperature are covered by 10 layers of MLI and actively thermally shielded, surfaces at 80 K are protected by 30 layers of MLI. The temperature gradient over the magnet longitudinal axis is controlled during cool-down and warm-up between 300 K and 80 K by mixing GHe at 80 K from the pre-cooling system with GHe at 300 K in the VB. Cool-down from 4.5 K down to 1.9 K can be achieved rapidly to allow several quenches per day.

5. First experience and operation of HFM and Cluster D

During the first cold test of HFM two 5 kW electrical heaters were damaged due to faulty electrical protection. During the second cold test it became clear that the heat in-leak to the superfluid bath was much higher than anticipated; the same problem was discovered in Cluster D during its first cold test.

5.1. Operation

Operation of HFM was automated from the beginning, the control system functioning as expected.

Cool-down and warm-up of the magnet and thermal shield (TS) circuits between 300 K and 80 K occurs in parallel, taking 2 to 3 days. Small magnets cool and warm faster than the TS circuit, forcing operators to wait. An additional control valve to direct cooling flow to the TS would improve this situation. Strain gauges on the magnets confirmed that thermal gradients were controlled throughout.

Cool-down speed from 4.5 K to 1.9 K depends on the volume of LHe in the superfluid bath, pumping capacity available and the surface area and efficiency of the L/L HX. HFM has demonstrated its capability to cool 380 kg of LHe from 4.5 K to 1.9 K in 7.5 hours, the L/L HX performing as expected with a steady-state heat load on the superfluid bath of 37.9 W. Currently the maximum quench energy recorded is 1 MJ, making it impossible to judge the performance of the quench recuperation system.

Cluster D began operation automatically using a twin control system to reduce commissioning time.

5.2. System heat loads

Figure 2 shows a simplified flow scheme of the CDS and the instruments used to calculate the heat load of its components. Table 2 shows the heat loads measured and calculated for HFM and Cluster D.

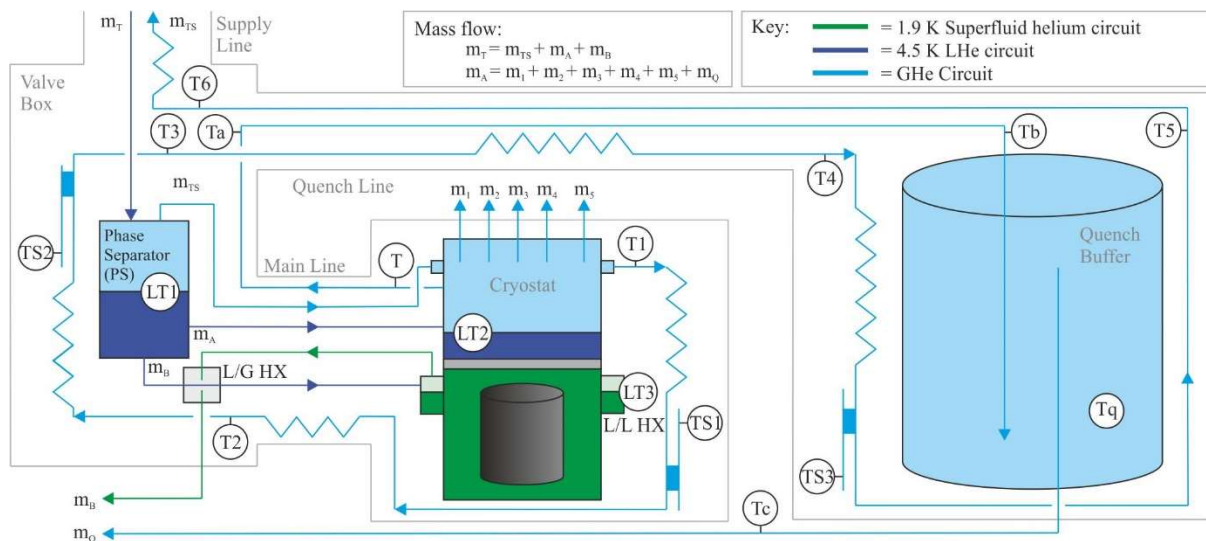


Figure 2. Simplified flow scheme of HFM and Cluster D CDS

Heat load on the TS circuit was calculated using thermometers to measure the increase in enthalpy at a constant flow of 0.8 g/s. This mass flow was larger than estimated due to high GHe content in the LHe entering the PS. This led to TS temperatures which were lower than the range of the PT100 thermometers, making it impossible to calculate heat loads for individual components of the TS circuit.

Heat load on the PS was calculated from the decreasing level of LHe with supply valves closed. Heat load on the quench line was higher than specified due to its design, which lacks thermalisation to the TS, but causes negligible effect on performance. Heat load on the helium vessel of the QB was measured from the temperature drift of the GHe inside with supply valves closed. Heat load to the 4.5 K baths of the cryostats were calculated from the decreasing level of LHe above the lambda plate with supply valves closed, it was lower than expected due to the high flow through the and neck thermalisation.

The superfluid bath is considered isothermal when its temperature is below the lambda point, so heat load was calculated by stopping pumping and measuring the temperature drift. During the first run of HFM, heat load to 1.9 K was measured as 215 W, much higher than the 22.5 W calculated based on conduction through a perfectly tight lambda plate. A superfluid leak was discovered, occurring through gaps of up to 1.6 mm around the perimeter of the lambda plate [7]. During the third and fourth runs of HFM, an expanded PTFE seal (Gore® DF10) was installed to improve the leak tightness of the lambda plate, reducing heat load to 95 W and 82 W respectively, for magnets weighing 3.5 tons and 8 tons. This showed a relationship between the compression of the seal and its performance. Pressure sensitive film showed that the seal was in perfect contact with the sealing surfaces, indicating porosity to superfluid

helium. This was confirmed during the sixth run by coating the seal with Apiezon L vacuum grease, which reduced heat load to 37.9 W with no magnet. During the first run of Cluster D a rigid Teflon seal was used. A heat load to 1.9 K of 75 W was measured, higher than the 12.2 W calculated. The expanded PTFE seal was used for the second run, however no magnet was installed to help to compress it causing heat load to increase to 130 W. For the third run a 3.5 tons magnet was installed, heat load at 1.95 K was calculated by measuring the inlet pressure of the WPU then calculating mass flow from the linear relationship published in [2]. 5.8 mbar was converted to 3.48 g/s, equating to a heat load of 74.5 W.

Table 2. Measured and specified heat loads for HFM and Cluster D

System	Component	Heat Load HFM (W)		Heat Load Cluster D (W)	
		Measured	Specified	Measured	Specified
CDS	Thermal Shield Circuit	141	190	-	-
	VB Phase Separator	1.2	-	-	-
	Quench Line	16	5	-	-
	Quench Buffer	11.7	10	-	-
Cryostat	Thermal Shield	50.6	48	42.6	58
	Neck Thermalisation	35	110 [7]	45.5	45
	4.5 K Bath	8 ^a	26.5	16 ^a	35
	1.9 K Bath	37.9 ^b	22.5	74.5 ^c	12.2

^a No current leads ^b With Apiezon Grease ^c Calculated using WPU inlet pressure

6. Conclusion

HFM and Cluster D test stations were successfully installed, commissioned and operated. The control system worked efficiently and proved its robustness. To enable magnet testing, the cryogenic infrastructure of SM18 managed the increased demand for pumping capacity at 1.9 K to compensate for the high heat load to the superfluid baths of the stations. Research to find a sealing solution and reduce heat load to the superfluid baths to an acceptable operational level is ongoing at CERN.

Other modifications to the VMFT have improved the robustness and safety of the facility.

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