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Thermal performance of the new superfluid helium vertical test cryostats for magnet tests at CERN

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Abstract. In the frame of the R&D program of the HL-LHC, the upgrade of the Large Hadron Collider (LHC), CERN augmented its test facility with two new large-scale vertical test stations for superconducting magnet testing. The cryostats composing the core of these test stations share design features but are of different dimensions: one allows testing magnets up to 1.5 m diameter, 2.5 m long for a maximum weight of 15 t, while the other can accommodate magnets up to 0.9 m diameter, and 5.5 m long for a maximum weight of 18 t. These test stations are designed to operate at 1.3 bar and at controlled temperatures in the range 1.9 – 4.5 K. They can provide for safe dissipation of stored energy in the magnet coils of up to 10 MJ. After a brief description of the cryostats, this paper describes the qualification measurements of heat loads at 4.5 K and 1.9 K of both cryostats, some design enhancements that were made and the performance improvements obtained.

1. Introduction

Two new vertical test stations for prototype magnets testing known as HFM and Cluster D have been recently installed and commissioned into the Vertical Magnet Test Facility of the SM18 Hall at CERN [1].

Both cryostats share design features [2] but are of different dimensions, both are designed to be as versatile as possible to be able to test large size future cryo-magnets. HFM is designed to allow testing of the so-called Fresca 2 demonstrator magnet [3] (2.35 m long, 1.03 m diameter, 8 tons) while Cluster D is designed to allow testing of HL-LHC injection quadrupole magnets (4.5 m long, 0.6 m diameter, 8 tons) before assembly into their helium vessels.

The new test cryostats are based on the Claudet bath principle, presenting a 4.5 K saturated liquid helium bath above a 1.9 K superfluid helium bath, as showed in figure 1.The pressure in the helium vessel is controlled at 1.3 bar where the superfluid helium is subcooled to the required temperature using a liquid-liquid heat exchanger filled with saturated helium at 1.8 K. A so-called lambda plate separates the two baths; it is composed of low thermal conductivity material to limit heat loads by conduction through the plate itself and to provide adequate leak tightness to limit heat transfer through superfluid helium [4]. The whole helium vessel being surrounded by an actively cooled thermal shield at an average temperature of 50 K, the remaining source of conduction heat loads to the 4.5 K bath is that through the magnet insert and the neck part of the cryostat making the transition between room temperature and liquid helium temperature. On the other hand, heat loads to the 1.9 K bath are dominated by conduction through the lambda plate.

To reduce the heat load to the 4.5 K liquid bath, the neck is actively cooled by helium vapour and its walls are locally thermalized at 20 K at an optimal distance from the helium bath surface.

To support the weight of the magnets to be inserted into the cryostats and their large dimensions, the lambda plates were manufactured from stainless steel instead of the G10 material usually used for this purpose. Although the thermal conductivity of stainless steel is four times larger than that of G10 at 4.5 K, the contribution from thermal conduction remains negligible when compared to the dominating contribution of heat conduction in superfluid helium around the lambda plate (see figure 1). Initially, sufficient leak tightness of the lambda plate was intended to be achieved by the intimate metal to metal contact between the lambda plate and the helium vessel flange on which it is supported, provided by the full weight of the magnet under test. Throughout the commissioning tests presented in this paper, this solution was found to be insufficient to limit the superfluid conduction heat loads to values within budget and alternative solutions were found to improve the leak-tightness, as presented hereafter.

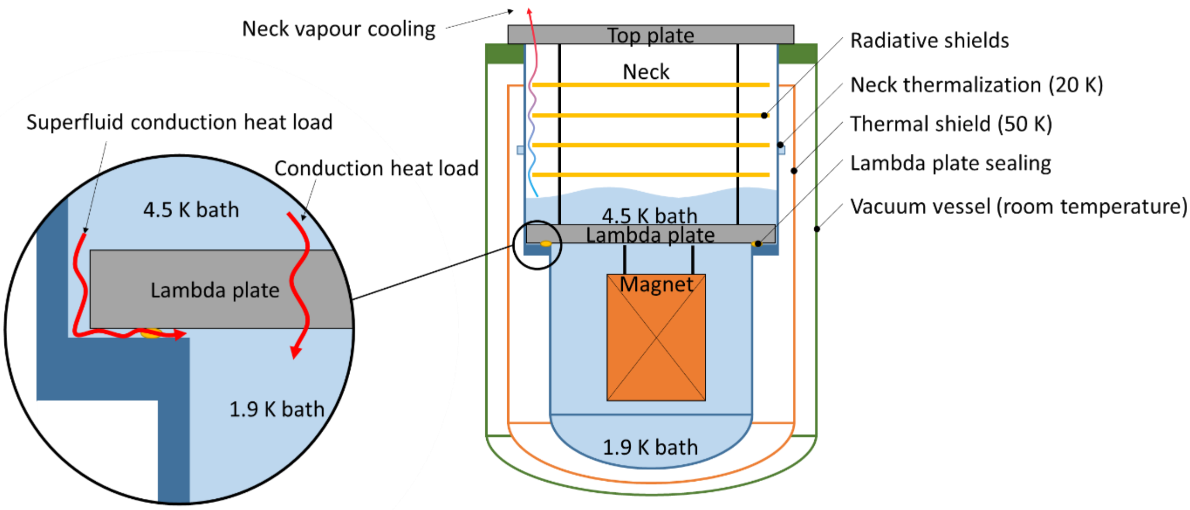

Figure 1. Schematic of a Vertical cryostat

2. Thermal performances measurements

2.1. Calorimetric measurements in 1.9 K superfluid helium

The calculation of the heat load to 1.9 K is based on an internal energy balance of the isothermal superfluid bath, using equation 1.

Considering respectively $U_{0,HL}$ and $U_{t,HL}$ to be the internal energy at the beginning and end of the test calculated using bath pressure and temperature, t_{HL} the time elapsed during the test and m_{LHe} the mass of helium composing the pressurized bath, the heat load to the superfluid bath is given by:

$$Q_{HL} = \frac{m_{LHe} \times (U_{t,HL} - U_{0,HL})}{t_{HL}} \tag{1}$$

Due to the complex shape of the cryostat and of the magnet and filling pieces needed to reduce helium inventory, the helium quantity in the superfluid bath is difficult to evaluate precisely and this leads to large uncertainty in Q_{HLe}. To resolve this issue, m_{LHe} can be measured by noting the temperature change due to a precisely known power injected into the superfluid bath via an electrical heater.

Considering P this injected power, respectively $U_{0,P}$ and $U_{t,P}$ the internal energy at the beginning and end of the test calculated using bath pressure and temperature, t_P the time elapsed during the test and m_{LHe} the mass of helium composing the pressurized bath, the heat load to the superfluid volume $Q_{bath,P}$ is given by:

$$Q_{bath,P} = \frac{m_{LHe} \times (U_{t,P} - U_{0,P})}{t_P} = Q_{bath,HL} + P \tag{2}$$

Combining equations 1 and 2, the mass of helium composing the 1.9 K bath is given by:

$$m_{LHe} = \frac{P \times t_P \times t_{HL}}{\left(t_{HL} \times \left(U_{t,P} - U_{0,P}\right) - t_P \times \left(U_{t,HL} - U_{0,HL}\right)\right)} \tag{3}$$

Which can then be used to calculate Q_{HL} from equation 1.

2.2. *Heat load to the 4.5 K saturated helium*

The measurement of the heat load at 4.5 K is based on boil off mass flow by measuring the level decrease rate of the bath.

Considering L the level of helium, t the time, A_{He} the area of the helium bath surface, ρ_{He} the density of liquid helium, L_v the latent heat of saturated helium at bath pressure and $\dot{m}$ the vaporized mass flow, the heat load to the 4.5 K bath is given by:

$$Q = \dot{m} \times L_v = \frac{dL}{dt} \times A_{He} \times \rho_{He,L} \times L_v \tag{4}$$

2.3. *Results and discussions*

2.3.1. 4.5 K saturated helium tests. The results of the measurements are presented in table 1. These exclude any contribution from the magnet current leads that were not installed in the cryostats at the time of these measurements.

Both HFM and Cluster D cryostats present heat loads lower than budgeted, confirming the efficient heat exchange to the helium vapour cooling the neck and its different parts.

Table 1. Measured and specified heat load at 4.5 K of HFM and Cluster D cryostats.

HFM Heat load [W]		Cluster D Heat load [W]	
Measured	Specified	Measured	Specified
8	26.5	16	35

During first cool-down of the Cluster D cryostat a heat load of about 200 W to 4.5 K coming from an instrumentation pipe was detected. This heat load was found to be due to a thermal bridge between room temperature and liquid helium occurring through an instrumentation support, once this support was removed the heat load to 4.5 K reduced to nominal values.

2.3.2. 1.9 K superfluid helium tests. Several tests were carried out on both cryostats during their commissioning while equipped with different magnet inserts and with various sealing solutions for the lambda plate. The results obtained are summarized in figure 2 and figure 3.

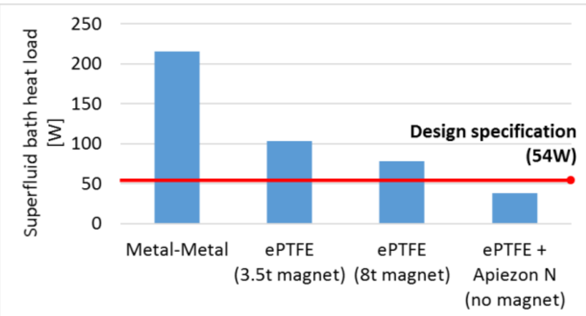

Figure 2. Heat load to HFM superfluid bath with different sealing configurations

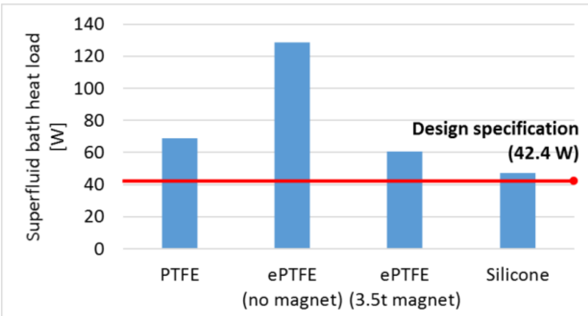

Figure 3. Heat load to Cluster D superfluid bath with different sealing configurations

The first test of the HFM cryostat presented poor thermal performance (up to 10 times higher loads than initially specified), gaps at the lambda plate seating interface were identified as the source of the superfluid conduction heat loads to 1.9K. The reasons for these gaps were identified as incorrect positioning, coming from incorrect insertion, of the lambda plate on its seat, and differential thermal contraction between tie-rods of the lambda plate and cryostat possibly lifting the lambda plate. Due to manufacturing non-conformities on the cryostat, the metal to metal sealing interface of the lambda plate onto the cryostat flange presented gaps around its circumference of up to 1.6 mm in HFM. More fundamentally it became evident on the large diameters of the cryostat flanges, that the minimum industrially achievable flatness tolerance after machining the lambda plate and cryostat would not provide sufficiently intimate contact to reach the specified thermal performance. It was therefore decided to introduce a flexible sealing ring.

This issue led also to redefining the achievable thermal performance of both cryostats considering that a perfect leak tightness to superfluid helium cannot be achieved on such a large cryostat. The budgeted heat loads were therefore relaxed from 22.5 W to 54 W and from 12.2 W to 42.4 W respectively for HFM and Cluster D.

In Cluster D, a first test with a solid PTFE ring as sealing was made, resulting in the same result as in HFM: the heat load (68.9 W) was higher than specified. The PTFE is not flexible enough to accommodate for the irregularities of the cryostat lambda plate interface and, in addition, fractured during cool-down due to its thermal contraction over the temperature range being about 5 times larger than that of stainless steel.

A first successful solution was to employ an expanded PTFE (ePTFE) gasket tape. This softer expression of PTFE material better accommodated to the irregularities between flange and lambda plate. A test using extra sensitive pressure measurement film showed a close-to-perfect contact. This seal provided adequate leak tightness to warm gaseous helium even under low compressive force and resulted in improved thermal performance at 1.9 K (Cluster D: 60.6 and 128 W respectively with no magnet and 3.5 t magnet, HFM: between 78 and 103 W respectively with 3.5 t and 8 t magnet). Further improved leak tightness of the HFM lambda plate, was achieved by adding Apiezon® N vacuum grease. The drastic reduction of the heat load that this produced, down to a value lower than specified (37.9 W with no magnet) confirmed that the main source of heat load is the improper sealing. Detailed analysis of the material however showed that superfluid helium can permeate the microstructure of the ePTFE presented in figure 4, and even with perfect sealing allows unacceptably high heat transfer between the liquid helium and superfluid helium baths.

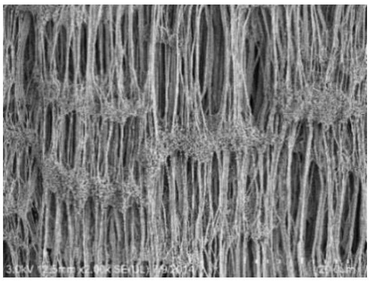

Figure 4. Microstructure of ePTFE (Gore®).

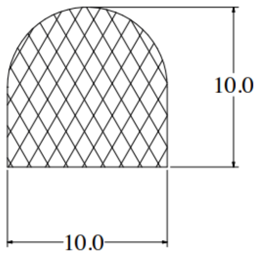

Figure 5. Silicone D-profile

At CERN the use of vacuum grease is not a design alternative and so we have pursued other solutions. The lambda plate is seated into place by the weight of the suspended magnet only (no tightening element providing uniform compression can be installed in the cryostat). The large range of magnet weights to be tested leads to considerable variation in the compressive force per unit length applied to the seal, ranging between 6.5 N/mm for the lightest magnet (3 tons, in HFM) and 56.2 N/mm for the heaviest one (18 tons, in Cluster D). The seal to be installed must cope therefore with the irregularities of the flange interface even with the lowest compressive force while being strong enough to resist the weight of the heaviest magnets

A cryostat dedicated to thermal performance measurements of seals under the same conditions of pressure, temperature and mechanical loads as in the HFM and Cluster D vertical cryostats was built and operated in the cryogenic test laboratory at CERN [5].

Silicone polymer has promising mechanical properties although it presents a glass transition at about 200 K. Several tests at liquid nitrogen temperature on a small scale model showed that a Silicone seal can be used for our application if installed in a groove, where several prototypes showed no damage after up to ten thermal cycles. If not installed in a protective groove, any contact with other element (screw, edge etc.) during thermal contraction leads to rupture of the Silicone in several places around its circumference.

A cost effective solution based on a silicone polymer seal showing very promising results on small scale prototypes was obtained with measured heat loads comparable to those expected from a perfectly leak tight connection. The Silicone seal as shown in figure 5 was installed in Cluster D and allowed a reduction of the heat loads to the superfluid bath to 46.2 W, very close to specification, and a decrease of 20% when compared with the ePTFE seal. After thermal cycles the seal was found ruptured in several places around its circumference, probably due to stress concentrations generated in the contact area with edge of the lambda plate. At time of writing, a new lambda plate designed with a groove is being manufactured to allow installation of seal in optimum conditions.

3. Conclusion

A test procedure for validating the thermal performance of a superfluid helium vertical cryostat was presented. This procedure was developed and applied during the commissioning of two new vertical test cryostats at CERN.

During first cool-down, the measured thermal performance of the cryostats at 1.9K was lower than specified. The sources of unacceptably high heat loads have been identified and after a learning curve have been eliminated. The main source of heat load to the superfluid bath remains thermal conduction in superfluid helium through gaps at the lambda plate sealing interface which were initially up to 1.6 mm around the perimeter. Improvements of the cryostat, insert design, operation procedure and development of a new cost-effective silicone based sealing solution for superfluid helium application have drastically improved thermal performance in superfluid.

The HFM and Cluster D test stations are now fully operational showing thermal performance close to specification. They are fully compatible with the densely loaded test program of the SM18 test facility at CERN. Research and development effort is still ongoing to develop a sealing solution to further reduce the electrical power consumption of the test stations.

References

[1] Lees A et al. 2018 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 *27th International Cryogenic Engineering and International Cryogenic Materials Conference, Oxford, UK, 3 – 7 September 2018*

[2] Vande Craen A et al. 2013 New Vertical Cryostat for the High Field Superconducting Magnet Test Station at CERN *AIP Conference Proceedings* **1573** 229

[3] Milanese A et al. 2012 Design of the EuCARD high field model dipole magnet FRESCA 2 *IEEE Trans. Appl. Supercond.* **22.3**

[4] Lebrun P 1997 Superfluid helium as technical coolant *CERN LHC Project report* 125

[5] Koettig T, Grosso Xavier M 2017 HFM Cryostat mock-up lambda plate seal heat inleak test in the cryolab *CERN EDMS* 1845733