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A FACILITY FOR ACCURATE HEAT LOAD AND MASS LEAK MEASUREMENTS ON SUPERFLUID HELIUM VALVES

A. Bézaguet, L. Dufay, G. Ferlin, R. Losserand-Madoux, A. Perin, G. Vandoni
and R. van Weelderen

Abstract

The superconducting magnets of the Large Hadron Collider (LHC) will be protected by safety relief valves operating at 1.9 K in superfluid helium (HeII). A test facility was developed to precisely determine the heat load and the mass leakage of cryogenic valves with HeII at their inlet. The temperature of the valve inlet can be varied from 1.8 K to 2 K for pressures up to 3.5 bar. The valve outlet pipe temperature can be regulated between 5 K and 20 K. The heat flow is measured with high precision using a Kapitza-resistance heatmeter and is also crosschecked by a vaporization measurement. After calibration, a precision of 10 mW for heat flows up to 1.1 W has been achieved. The helium leak can be measured up to 15 mg/s with an accuracy of 0.2 mg/s. We present a detailed description of the test facility and the measurements showing its performances.

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ABSTRACT

The superconducting magnets of the Large Hadron Collider (LHC) will be protected by safety relief valves operating at 1.9 K in superfluid helium (HeII). A test facility was developed to precisely determine the heat load and the mass leakage of cryogenic valves with HeII at their inlet. The temperature of the valve inlet can be varied from 1.8 K to 2 K for pressures up to 3.5 bar. The valve outlet pipe temperature can be regulated between 5 K and 20 K. The heat flow is measured with high precision using a Kapitza-resistance heatmeter and is also crosschecked by a vaporization measurement. After calibration, a precision of 10 mW for heat flows up to 1.1 W has been achieved. The helium leak can be measured up to 15 mg/s with an accuracy of 0.2 mg/s. We present a detailed description of the test facility and the measurements showing its performances.

INTRODUCTION

CERN, the European Laboratory for Particle physics is presently building a new particle collider (LHC) where the high magnetic fields required for particle guiding will be produced by superconducting magnets operating at 1.9 K in a static bath of pressurized superfluid helium. To protect the magnets, pressure relief valves will be mounted between the cold masses and a separate cryogenic distribution line[1]. As there will be approximately 400 of these valves on the LHC, their contribution to the total heat load must be kept below 0.3W per valve. It is of crucial importance for the proper operation of the LHC cryogenic system to ensure that the contribution of theses valves to the thermal load remains below the specified value. In addition, as all mass leakage directly translates into heat load, it is also essential to limit the mass leakage of helium across the valve. A dedicated test bench

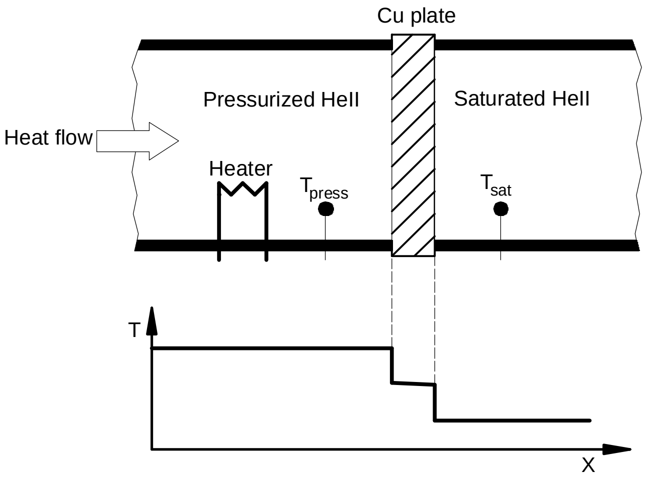


Figure 1. Schematic view of the Kapitza resistance heatmeter and temperature profile

has been developed to simulate the operating conditions of the LHC and to precisely determine the heat loads and mass leakage of such valves.

FACILITY CONFIGURATION

Kapitza resistance heatmeter

The LHC magnets will operate in superfluid helium at 1.9 K and 1.4 bar. The heat flow measurement is performed by measuring a temperature gradient across a calibrated thermal impedance[2]. As the safety valves operate in superfluid helium, a Kapitza resistance was used as thermal impedance[3].

The Kapitza resistance heatmeter of our test bench consists of two volumes of superfluid helium separated by a copper plate. The measuring principle of such a heatmeter is described in figure 1. When heat flows across such a system a sharp temperature gradient appears at the interface between the copper and the superfluid helium. Thanks to the high conductivity of copper, the temperature gradient in the copper plate is very small compared to the Kapitza resistance effects and it will be neglected in the following.

The Kapitza conductance h_k is strongly dependent on temperature, for copper an empirical relation is given by[4] Eq. (1)

$$h_k = \frac{q}{\Delta T} \cong C_k \cdot T^3 \text{ W/m}^2 \cdot \text{K} \tag{1}$$

where q is the heat flux, T the temperature of the superfluid helium and C_k varies from about 900 for a clean surface to about 400 for a dirty surface. For the configuration described in figure 1 the characteristic temperature profile is shown in the graph and the relation between the heat flow and the temperature difference between the two superfluid helium temperatures T_{press} and T_{sat} is given by Eq. (2):

$$Q = S \cdot C_k \cdot \frac{T_{sat}^n \cdot T_{press}^n}{T_{sat}^n + T_{press}^n} \cdot (T_{press} - T_{sat}) \tag{2}$$

Where *Q* is the heat flow, *S* the area of the copper plate in contact with the superfluid helium and *n=3*.

General configuration and dimensions

A schematic description of the test bench developed for measuring the heat loads and mass leak of the safety relief valves for LHC is shown in figure 2.

Kapitza cell. As the temperature difference must be kept small enough to keep helium superfluid on both sides of the heatmeter, the dimension of the Kapitza heatmeter is determined by the maximal heat flow that shall be measured on the test bench. A Kapitza heatmeter with a diameter of 40 mm was chosen which should allow the measurement of heat flows up to 1.4 W.

As can be seen on figure 2, the saturated helium is supplied to the Kapitza cell trough a flexible corrugated pipe. A flexible pipe was chosen to allow an ample vertical mobility of the test cell, for the valves do not have all the same length. A similar flexibility has been provided for all the piping connected to the Kapitza cell. The pressurized helium is generated by the condensation of gaseous helium supplied from a gas bottle via a pressure regulator that feeds the helium at pressures between 1 and 3.5 bar. Before reaching the

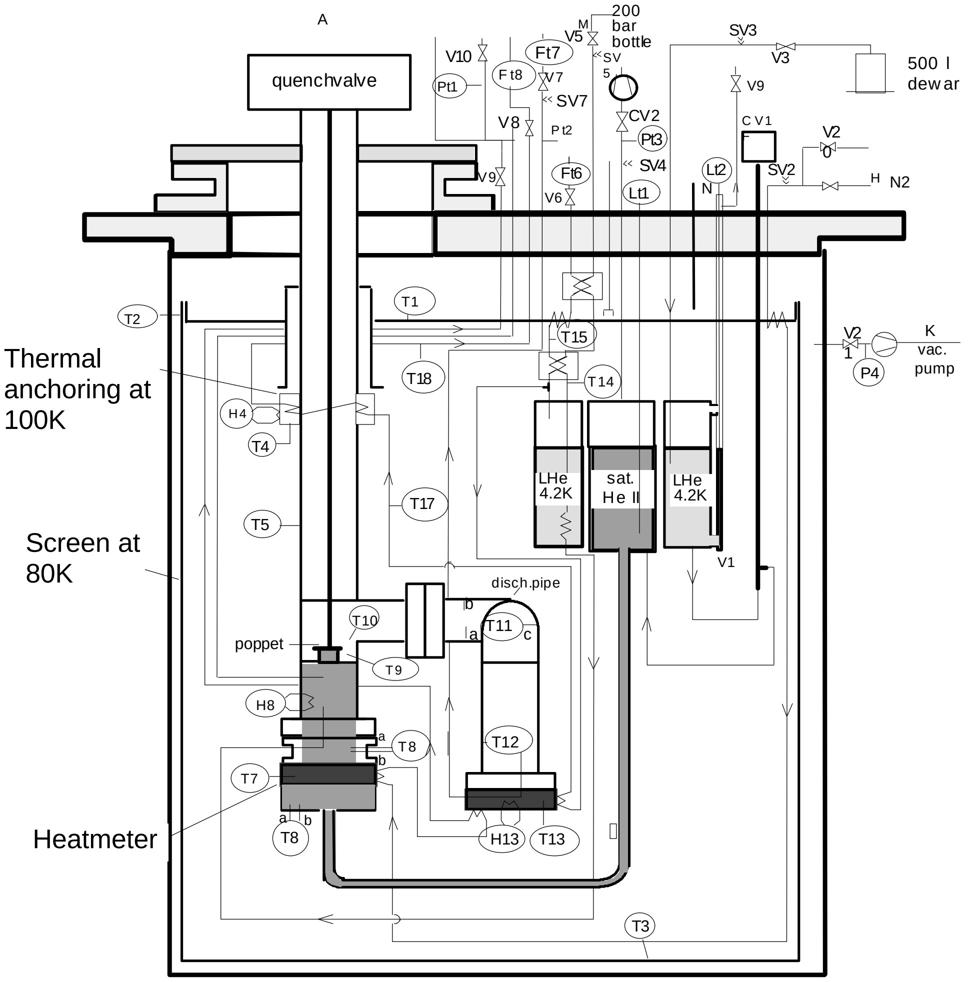
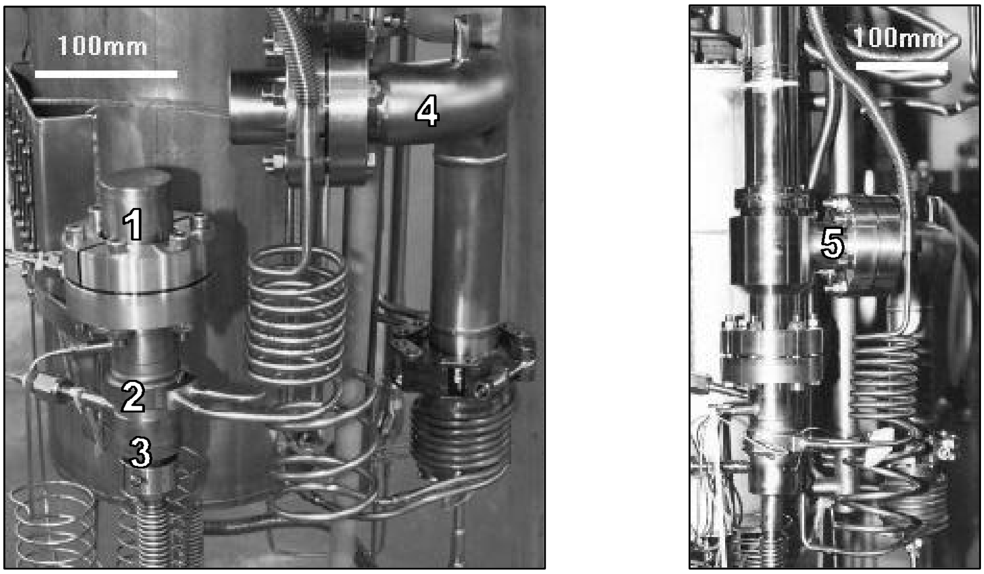


Figure 2. flow scheme of the test bench, Txx, : thermometers; Hxx: heaters; Vxx: valves; Ptx , DPtx : pressure sensors; Ftx : flow controllers/meters



a) calibration configuration

b) valve measurement

Figure 3. Pictures of the Kapitza cell . 1. pressurised HeII ; 2. Kapitza heatmeter ; 3. saturated HeII ; 4. discharge pipe; 5. valve outlet

volume under the valve inlet, the helium is first cooled by two cross-flow gas-gas heat exchangers and then by a heat exchanger immersed in the main 4.2 K helium container.

Discharge pipe and thermal anchoring. The temperature of the discharge pipe is controlled between 5 K and 20 K by a heater coupled with a heat exchanger using the cold gas from the boil-off of the main 4.2 K reservoir, the same gas is also used to keep the heat sink connection at 100 K. The flow of helium leaking from the valve is measured by a mass flowmeter at room temperature.

Ancillary systems. The test bench also includes the ancillary systems that permit a fast cooldown with LN2 and a gas cooled thermal screen at 80K.

Figure 3 shows two pictures of the Kapitza cell. In figure 3.a) the valve is replaced by a stainless steel cap for a calibration run and in figure 3.b) the Kapitza cell is seen connected to a safety relief valve under test.

Instrumentation, data acquisition and control

Temperatures above 30K are measured by platinum resistors. Below 30K, calibrated Allen-Bradley carbon resistors and Lake Shore Cernox® resistors are employed. All measurements are performed by a 4 wires and offset suppression measuring method.

To achieve the desired precision, all temperatures on the heatmeter and on the valve are measured with sensitive digital voltmeters equipped with scanners.

All data is recorded on a computer trough a GPIB interface and a multifunction data acquisition card. A specially developed software allows the control of the data acquisition system, the preliminary treatment of data and the remote monitoring of the bench parameters.

The regulated temperatures are handled by temperature controllers either with heaters (for the discharge pipe and the thermal anchoring at 100 K) or with gas flow regulators (for the thermal screen).

Table 1. Main functional parameters of the test bench

Characteristic	value
T_{press} stability	± 1 mK for >1000 s
($T_{press} - T_{sat}$) stability	± 2 mK for >1000 s
Heat flow precision	± 10 mW at 2 K, ± 8 mW at 1.9 K
Maximal heat flow	1.1 W at Tpress = 2K
Discharge pipe temperature	5±0.2 K to 30±0.2 K
Thermal anchoring temperature	70±0.2 K to 120±0.2 K
Thermal screen temperature	80±0.5 K
He leak mass flow	10^{-4} g/s to 10^{-2} g/s

Pressurized helium temperature regulation. As heat conductivity of superfluid helium and the Kapitza resistance are strongly dependent on temperature, the same, stable, temperature T_{press} must be kept in the pressurized helium for the calibration and for the valve measurements. The control of T_{press} is performed by varying the temperature of the saturated helium with a control valve placed on the pumping line. For this purpose a special control algorithm has been developed, which ensures a very good stability of the temperature while allowing a fast response when sharp variations of the heat flow occur. A temperature stability better than ±1 mK could be obtained for periods lasting several hours.

RESULTS AND DISCUSSION

The main performances of the test bench are summarized in table 1.

Heatmeter

For calibrating the heatmeter, the valve was replaced by a stainless steel cap as can be seen in figure 2a). The heat flow was generated by a resistance heater immersed in the pressurized superfluid helium, the power of which was measured by the four wire method

The calibration procedure consists of measuring the temperature difference T_{press}-T_{sat} while varying the applied power. The measurements were averaged on periods of several thousand seconds. Figure 4 presents the temperature difference during the calibration of the Kapitza heatmeter for applied powers of 0 and 295 mW. The results are raw, unfiltered data, showing a stability of temperature difference better than 1 mK for a period of 1200s.

Calibrations have been performed for T_{press}=1.9 K and T_{press}=2 K. The calibration curves can be seen for both temperatures in figure 5. The experimental data are presented as points, the continuous lines are fitted theoretical curves of the form described by Eq. (2). The graph shows a very good agreement of the data with the theoretical behavior of a Kapitza heatmeter, the parameter C_k, with a value of approximately 980 being close to those found in literature[4]. As can be seen on the extrapolated curve on the graph, the zero-power heat load on the Kapitza cell is approximately 140 – 150 mW.

With a precision of ±2 mK for the temperature difference, the heatmeter precision can be estimated to be approximately ±10 mW at T_{press}=2 K and ±8 mW at T_{press}=1.9 K

Measurements on safety relief valves

Five prototypes of safety relief valves for the LHC cold masses have been mounted and extensively characterized using the test bench[5]. The Kapitza cell has been checked for every measurement by measuring the offset calibration curves at 1.9 K and 2 K for each

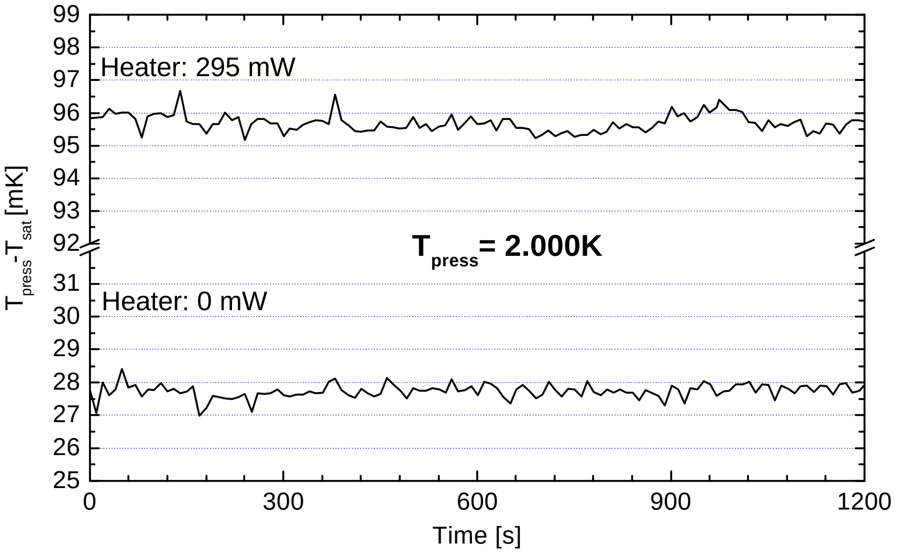


Figure 4. Temperature difference T_{press}-T_{sat} versus time during calibration for two values of the applied power (raw unfiltered data).

valve. All heat load values have been cross-checked with vaporization measurements. The results have shown that most valve manufacturers have underestimated the conduction heat flow. In addition to the determination of the thermal flow to the superfluid helium, mass leakage across the seat, heat load to the 100 K thermal anchoring and the effect on convection in the discharge pipe were measured.

The convection heat transfer effects in the discharge pipe were of particular interest, for they confirmed the importance of the geometry of the connection to the 20 K recovery line. Such a measurement is presented in figure 6, where it can be seen that the convection totally offsets the conduction heat load for one of the valves while for the other one the effect is much less pronounced. The different behavior is due to the different temperature levels in the outlet pipe of the two valves.

Reproducibility

The reproducibility of the calibration curves is of particular importance for the precision of the measurements. In particular, the influence of the time evolution of the

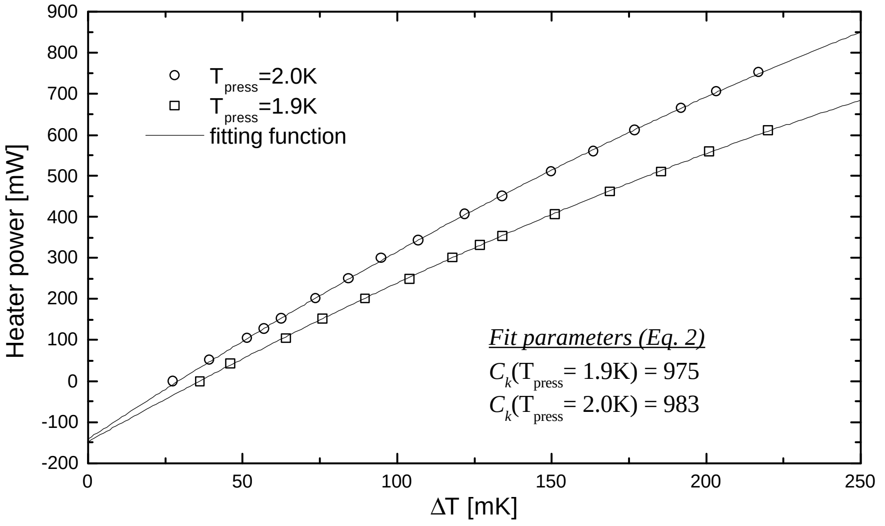


Figure 5. Calibration curves for the Kapitza resistance heatmeter

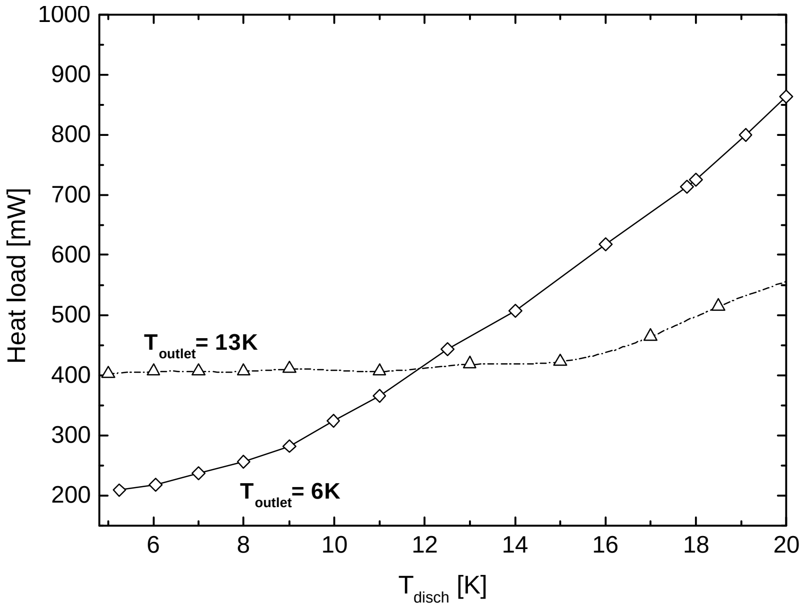


Figure 7: Heat flow to the pressurized HeII as a function of the temperature of the end of the discharge pipe (T_{disch}) (all values with zero leakage)

surface quality was investigated, for the Kapitza resistance is essentially a liquid-solid interface effect. Two calibration runs, separated by several weeks, were initially performed. During this period the Kapitza heatmeter was left in contact with air. The second calibration showed a drift of several mK in the heatmeter characteristic, probably due to a slight surface oxidization. In the successive measurements and re-calibrations the heatmeter was always kept under either vacuum or helium atmosphere, subsequently no significant variation could be observed between calibrations separated in time by several months.

CONCLUSIONS

A dedicated test bench, based on a Kapitza resistance heatmeter, has been developed for the determination of the thermal properties of superfluid helium cryogenic valves. The Kapitza resistance heatmeter has been calibrated and has shown a very good agreement with the calculated design parameters. A precision of ±10 mW could be achieved thanks to an accurate stabilization of the operating temperatures and by keeping the exposure of the Kapitza heatmeter surfaces to air/oxygen to the absolute minimum. The measurements performed during the calibration procedure showed the importance of the surface quality on the Kapitza heatmeter and the necessity of strict handling procedures to avoid any modification of the surface.

After calibration, the test bench has been successfully employed for the characterization of the properties of superfluid helium safety relief valves.

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