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# CHARACTERIZATION OF PROTOTYPE SUPERFLUID HELIUM SAFETY RELIEF VALVES FOR THE LHC MAGNETS

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**Abstract**

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## ABSTRACT

The Large Hadron Collider (LHC) at CERN will use high field superconducting magnets operating in pressurized superfluid helium (He II) at 1.9 K. Cold safety valves, with their inlet in direct contact with the He II bath, will be required to protect the cold masses in case of a magnet resistive transition. In addition to the safety function, the valves must limit their conduction heat load to the He II to below 0.3 W and limit their mass leakage when closed to below 0.01 g/s at 1.9 K with 100 mbar differential pressure. The valves must also have a high tolerance to contaminating particles in the liquid helium. The compliance with the specified performance is of crucial importance for the LHC cryogenic operation. An extensive test program is therefore being carried out on prototype industrial valves produced by four different manufacturers. The behavior of these valves has been investigated at room temperature and at 77 K. Precise heat load and mass leak measurements have been performed on a dedicated test facility at superfluid helium temperature. Results of cold and warm tests performed on as-delivered valves are presented.

## INTRODUCTION

The Large Hadron Collider (LHC), presently under construction at the European Laboratory for Particle Physics (CERN), will use superconducting magnets operating at 1.9 K in pressurized superfluid He. In the eventuality of a resistive transition of the superconducting cables, a part of the energy stored in the magnetic field will be transferred to the refrigerant, resulting in a fast pressure rise in the magnet cold masses. To protect the cold masses against excessive pressure, safety relief valves, directly connected to the superfluid helium container are required. Although the main characteristic of these valves must be their reliable opening in case of a magnet quench, they must also not add an excessive heat load to the He II bath and must remain tight in presence of small debris coming from the cold masses. Approximately 400 valves, distributed every 107 m (the

**Table 1.** Main specified requirements of the safety relief valves

| Parameter | Specified value |
|---|---|
| Valve type | valve lift must be proportional to inlet pressure and independent of outlet pressure |
| Valve size | DN40, proportional |
| Discharge capacity | Kv* > 30 $m^3$/h |
| Set pressure | 12 ± 0.3 bar |
| Test mode set pressure | 20 ± 0.6 bar |
| Blowdown+ | ≤ 1 bar |
| Operating temperature | inlet: 1.9 K ; outlet : 4.5 K |
| Operating pressures | inlet: 1.4 bar ; outlet 1.3 bar |
| Thermal anchoring temperature | 100 K |
| Conduction heat load to 1.9K | < 0.3 W |
| Leak tightness over the seat | < 0.01 g/s at 1.9 K, ΔP =100 mbar |

* Kv represents the valve's volumetric flow rate of water at NTP with a pressure drop 1 bar and is expressed in $m^3$/h.
+ A valve blowdown is the difference between its set and its re-seating pressure.

length of a cooling cell) along the 27 km of the machine circumference[1,2] will provide the protection of the magnets against overpressure.

In a preliminary stage CERN developed a safety relief valve[3] that was connected to the first LHC prototype magnet string. For the LHC, the valves will be produced by industry. The compliance of these valves with the specified performance[4] is of crucial importance for the operation of the LHC. An extensive test program is therefore being carried out to investigate the characteristics of prototypes produced by four different manufacturers.

## REQUIRED CHARACTERISTICS OF THE SAFETY RELIEF VALVES

The valve specification is based on the experience gained during the first stages of operation of the first LHC prototype magnet string.[4] The set pressure was fixed at 12 bar and, in addition, for pressure test purposes, the possibility to switch the set pressure to 20 bar was required.

The operating characteristics of the valves and the valve sizing have been determined by a numerical extrapolation of the results obtained on the LHC prototype magnet string[5] and on tests performed on the prototypes of the LHC magnets, resulting in a required Kv of 30 $m^3$/h.

The safety valves will be in direct contact with superfluid helium at 1.9 K and 1.3bar. When operating at such a low temperature, the minimization of the heat loads is essential. The contribution of the valves must not exceed 0.3 W per valve at 1.9 K. As any leak of superfluid helium translates directly into a heat load, the mass leakage across the seat must be lower than 0.01 g/s in operating conditions with a pressure difference of 100 mbar. Other requirements include the compatibility with the size of the LHC underground tunnel, easy exchangeability in cold conditions and tolerance to small sized contamination. A summary of the main requirements for the safety relief valves can be found in table 1.

## INDUSTRIAL PROTOTYPES

Four manufacturers have been selected for the production of prototypes of the safety relief valves. Every manufacturer has produced two prototypes according to specified requirements.[4] The valve main dimensions and seat configurations are given in table 2 (The letter designating the valves have been randomly attributed and do not correspond to the

**Table 2.** Main characteristics of industrial safety relief valves

| Valve | L1* [mm] | L2** [mm] | Seat configuration | Stem material |
|---|---|---|---|---|
| *A* | 588 | 262 | direct pressure | Fiberglass epoxy |
| *B* | 660 | 239 | sliding seat | Stainless steel |
| *C* | 550 | 334 | direct pressure | Fiberglass epoxy |
| *D* | 660 | 239 | direct pressure | Stainless steel |
| *E* | 626 | 174 | direct pressure | Stainless steel |

* L1: length between thermal anchoring at 100 K and the valve outlet axis (see figure 2).
**L2: length between thermal anchoring at 100 K and 293 K (see figure 2).

alphabetical list given in the acknowledgements).

All manufacturers use a non-metallic material for the seal, the leak tightness being realized by either pressing the seal against a metallic seat (direct pressure in table 2) or by a specific seat configuration for the sliding seat of valve *B*. To reduce the heat conduction along the valve stem valves A and C use a fiberglass epoxy tube while the other manufacturers rely on optimized stainless steel stems.

## ROOM TEMPERATURE AND 77 K TESTS

### Test bench for room temperature and 77 K tests

A dedicated test bench has been constructed for set pressure and leakage testing. The valve properties can be measured either at room temperature or, with the valve lower part immersed in liquid nitrogen at 77 K.

The maximal gas flow of this test bench is 150 $m^3$/h (NTP) when operating at room temperature. At low temperature the flow must be kept at a much lower level to ensure a good thermalisation of the gas in the LN2/He heat exchanger integrated in the test bench. Leakage can be measured from $10^{-7}$ $cm^3$/s (NTP) up to 3 $dm^3$/s (NTP).

### Set pressures at room temperature and 77 K

The maximal flow of the test bench is not sufficient to reach the full opening of the valves; therefore only the set pressure of the valves can be measured when the valve outlet is left open to atmosphere. For the investigation of the mechanical characteristics of the valves, advantage is taken of the independence of the set pressures against outlet pressure variations: the properties can be measured in quasi-static conditions by closing the valve outlet. Table 3 presents the results of measurements performed at room temperature and at LN2 temperature. It is to be noted that valve C was mistakenly designed for pressures 1 bar higher than the specified values.

**Set pressure**. In case of a magnet quench, the valves will experience a fast pressure increase[3,4] of about 100 bar/s, the first two lines of the table show the behavior of the valves for a pressure increase rate higher than 20 bar/s. It can be seen that all valves, except *A*, open within 0.8 bar of the specified set pressures, this both for the 12 bar and the 19 bar operating modes. In the case of valve *A*, the measured set pressure is strongly dependent on the pressure increase rate. The actuator of this valve is pilot operated, the pilot being connected to the valve inlet by a capillary tube that delays the pressure equilibration required to keep the valve closed.

To further investigate the mechanical characteristics of the valves, tests have been performed with closed outlet. This configuration allows one to reach the full opening of the

**Table 3.** Set pressures of the safety relief valves at 293 K and 77 K for two rates of pressure increase

| Set pressure \ Valve | | *A* 293 K/ 77 K | *B* 293 K/77 K | *C*✧ 293 K/77 K | *D* 293 K/77 K | *E* 293 K/77 K |
|---|---|---|---|---|---|---|
| **12 bar mode, > 20 bar/s** | [bar] | 3.7 * / - | 11.6/- | 13.0/- | 11.8/- | 11.2 / - |
| **20 bar mode, > 20 bar/s** | [bar] | 4.0 * / - | 19.5/- | 21.3/- | 19.2/ | 18.3 / - |
| **12 bar < 1bar/sec,CO+** | [bar] | 11.5 / 11.6 | 11.4 / 13.8 | 13.2 / 13.3 | 12.0 / 11.5 | 12.4 / 12.2 |
| **20 bar < 1bar/sec,CO+** | [bar] | 19.6 / 19.2 | 19.6 / 21.5 | 21.0 / 21.1 | 19.7 / 19.2 | 20.3 / 20.0 |
| **Blowdown, CO+** | [bar] | 0.3 / 0.3 | 1.1 / 2.8 | 0.5 / 1.2 | 0.6 / 0.7 | 0.4 / 0.4 |

✧ valve C was designed for set pressures 1 bar higher than the specified values.
* the opening pressure is strongly dependent on the pressurisation speed, values are for approx. 40 bar/s
+ CO: Closed Outlet

valves in quasi-static conditions. The set pressures in this case depend directly on the accuracy of the pressure compensation. At room temperature the set pressures are very well respected (most manufacturers used this configuration to adjust the set pressures). At LN2 temperature the shift in the set pressure is, with the exception of valve *B*, smaller than 0.4 bar. Valve *B* shows on the other hand an increase of more than 2 bar of the set pressure when operating at 77 K. This shift is apparently caused by an increased friction in the sliding seat.

The blowdown (difference between the set pressure and the re-seating pressure) values are directly related to the friction in the valves; at room temperature all valves, with again valve *B* being the exception, have a blowdown smaller than 0.6 bar, indicating a smooth movement with low friction forces. When operating at 77 K, valves *A*, *D* and *E* do not show an increase of the friction while for valve *C* the blowdown is slightly increased. In the case of valve *B* the strong increase in the blowdown indicates that temperature change is directly causing an increase of the friction forces in the valve seat.

**Leakage.** Figure 1 presents the low flow part of the measurements performed with gaseous helium on the valves at LN2 temperature. As can be seen on figure 1, there is a large difference between valves. For all valves, with the exception of valve *B* equipped with a sliding seat, the leakage increases faster than the square of the pressure difference, indicating that the size and/or number of the leak paths increases with increasing pressure.

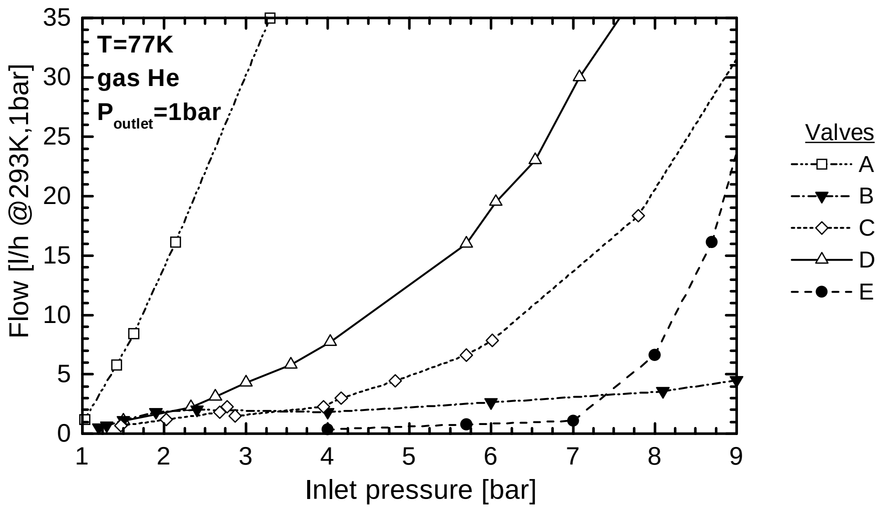


**Figure 1.** Valve leakage at 77K

## THERMAL LOADS AND MASS LEAKAGE AT 1.9 K

### Test Facility

A dedicated test bench was developed to reproduce the LHC temperature and pressure conditions. This test bench is described in detail in ref. 6. A schematic view of the test facility is given in figure 2. The valve inlet is connected to a volume (1) filled with pressurized superfluid helium at a temperature $T_{press}$ between 1.9 K and 2 K, the pressure in the valve inlet can be varied from 1 bar to 3.5 bar. This volume is thermally connected to a pumped bath of saturated He II (3) via a Kapitza resistance heatmeter[6] (2). The temperature difference $T_{press} - T_{sat}$ is used to determine the heat flow $Q_{kap}$ to the superfluid helium. The precision of the heatmeter is ±8 mW at $T_{press} = 1.9$ K and ±10 mW at $T_{press} = 2$ K. In addition, the heat flow measurement can be cross checked with a measurement of the heat flow $Q_{vap}$ based on the vaporization of saturated helium. The outlet of the valve is connected to a discharge pipe which end temperature $T_{disch}$ can be varied from 5 K to 20 K to study convection heat transfer phenomena.

The leaking helium is collected in the discharge pipe, warmed up to room temperature and measured through a mass flowmeter with a precision of 0.2 mg/s. Two thermometers, placed close to the valve seat, $T_{seat}$, and at the valve outlet, $T_{outlet}$, provide information on the temperature levels in the valve. A thermal anchoring at 100 K is provided and the heat flow to this heat sink is also measured.

### Thermal loads

The heat flow to the superfluid helium has been measured for every valve. The measurements have been performed with the discharge pipe closed and zero leakage. During these tests, the temperatures close to the valve seat were, for all valves, well above the λ temperature (see table 4). We could not observe any measurable pressure difference

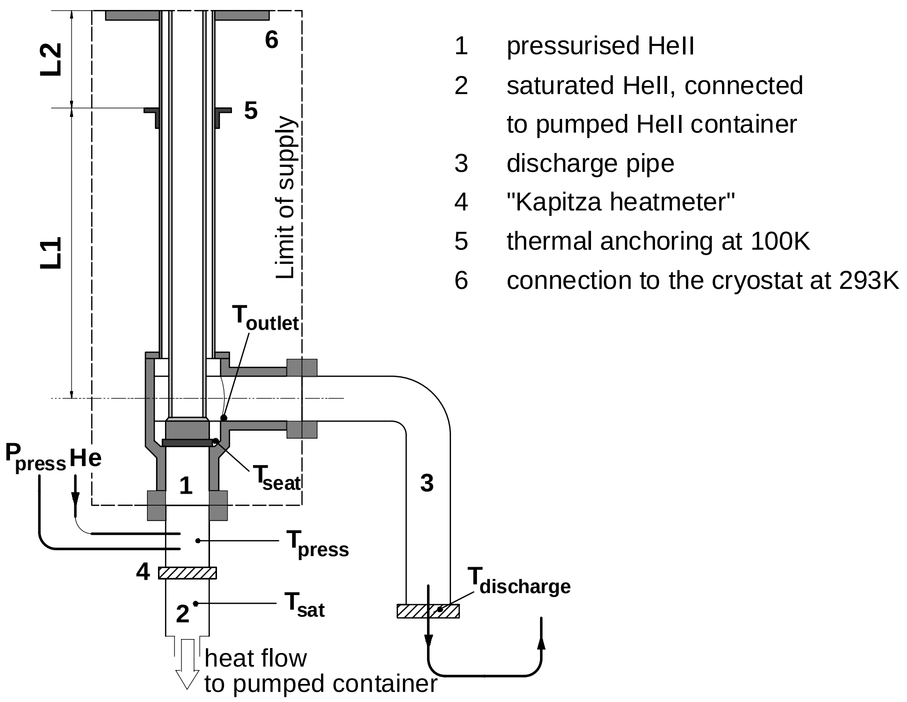


**Figure 2.** Schematic representation of the experimental configuration for the thermal characterisation of the safety relief valves

**Table 4.** Temperatures close to valve seat and valve outlet, $T_{press}$=2K

| Valve | | *A* | *C* | *D (B)* | *E* |
|---|---|---|---|---|---|
| $T_{seat}$ | [K] | 11.95 | 4.72 | 2.45 | 8.78 |
| $T_{outlet}$ | [K] | 13.01 | 5.47 | 6.31 | 10.43 |

related to the fountain effect in contrast to what was observed on an early CERN developed safety valve.[3]

Table 5 presents a summary of the main thermal conduction properties of the safety valves. Valves *B* and *D*, produced by the same manufacturer, have the same thermal properties.

**Heat flow to 100 K thermal anchoring**. The measurements of the thermal flow to the 100 K heat sink, presented in the first row of table 5, show a strong variation with values ranging from less than 3 W for valves *B* and *D* up to more than 8 W for valve *E*. Although this was not specified for the prototype valves, a maximum heat load of about 3 W will be required for the LHC valves.

**Heat flow to superfluid helium**. The conduction heat load to the He II has been measured for two temperatures $T_{press}$ = 1.9 K and $T_{press}$ = 2 K. For these measurements a temperature $T_{disch}$ = 5 K was used to suppress the convection heat flow in the discharge pipe. Under these operating conditions, a small part of the heat flow $Q_{disch}$ flows to the discharge pipe end and must be added to the measurements. The results have been cross-checked with the helium vaporization measured heat flow $Q_{vap}$. Of all valves, only valves *B* and *D* comply with the specified requirement of 0.3 W, all other valves having a conduction heat load higher than the specified value.

**Convection in the discharge pipe.** To investigate the convection heat transport in the discharge pipe the temperature $T_{disch}$ has been varied between 5 K and 20 K As it can be observed in figure 3, the convection heat load becomes a significant, and for some valves even the major part of the heat load when $T_{disch}$ = 20 K. The measurements show that the convection is strongly dependent on the temperature of the valve outlet region, with the valves having the lowest temperatures (see table 4) being more sensitive to a variation of $T_{disch}$. This result, in good agreement with the previous experience[3], confirms the necessity of a convection limiting design of the discharge pipe for the LHC.

**Table 5.** Results of the thermal measurements performed on the safety relief valves

| Heat load \ Valve | | *A* | *C* | *D (B)* | *E* |
|---|---|---|---|---|---|
| 100K heat load | [W] | 3.1 | 3.93 | ( 2.5 ) [1] | 8.5 |
| He II: $Q_{kap}(T_{press}$ =2K) | [mW] | 404 | 505 | 209 | 508 |
| He II: $Q_{kap}(T_{press}$ =1.9K) | [mW] | 409 | 509 | 203 | 503 |
| He II: $Q_{evap}(T_{press}$ =2K) | [mW] | 412 ± 40 | 498 ± 40 | 200 ± 40 | 497 ± 40 |
| $Q_{disch}$ [2] | [mW] | +10 | +6 | +2 | +2 |
| **Total heat flow** | **[mW]** | **416 ± 10** | **513 ± 10** | **208 ± 10** | **508 ± 10** |

[1] estimation, measurement not performed in nominal conditions
[2] heat flow to the discharge pipe end at 5K
All values with closed discharge pipe and zero leakage

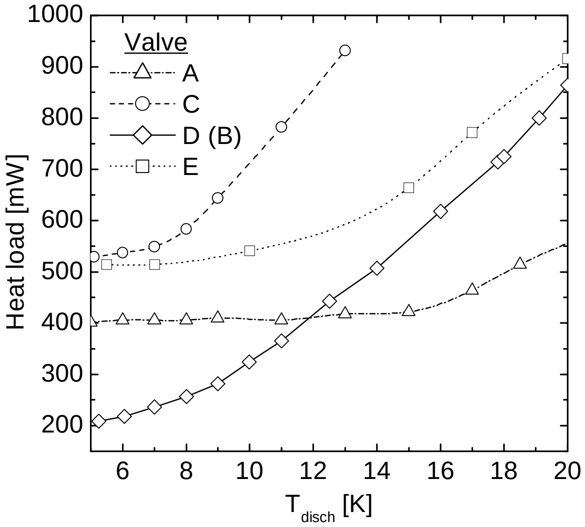


**Figure 3.** Heat flow to He II vs $T_{disch}$

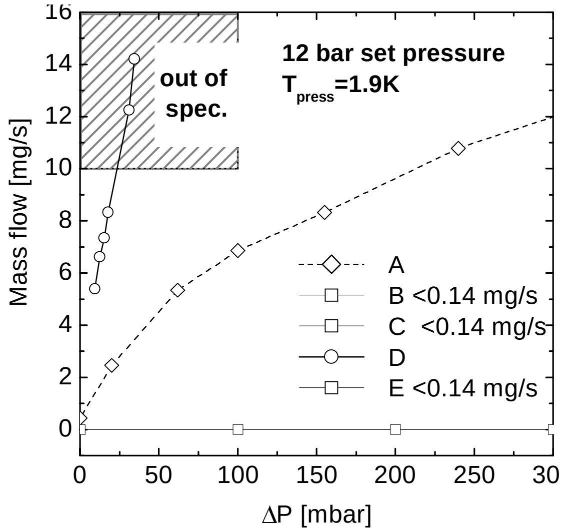


**Figure 4.** Leakage vs. ΔP for 12 bar set mode.

## Leakage at 1.9K

For the mass leakage measurements, a pressure difference was established between the valve inlet and outlet. The first result of a helium leak is a strong reduction of the measured heat flow through the Kapitza heatmeter. This effect is due to the huge amount of heat removed by the helium flow and it completely hides the supplementary heat load required to cool the helium from 4.2 K to 1.9 K. The results are given in figure 4 and are summarized in table 6. For three valves, *A*, *B* and *E* the helium leakage was below the measuring resolution up to a ΔP of 300 mbar. These valves have also the lowest leakage at 77 K. Two valves have higher leaks: valve *A* has a high leak rate, although it remains within the specified limit of 10 mg/s while valve *D* exhibits a very high leakage, exceeding the specified flow with a ΔP well below 100 mbar.

## CONCLUSIONS

The measurements performed at room temperature and at 77 K show that the required set pressures and functional characteristics can be obtained by industrially produced valves. The prototypes produced by three of the firms comply with the requirements, the pilot operated valve complies with most requirements, but its actuator design results in a set pressure that is strongly dependent upon the pressure increase rate. The sliding seat valve shows a high friction in the seat and a strong variation of its set pressures with decreasing temperature, which results in non-compliance with the specifications.

The conduction thermal loads and mass leakage have been measured in LHC operating conditions. Only one of the four valve designs complies with the required value of 0.3 W heat conduction to the He II. A global optimization of the thermal design will definitely be required for the final LHC safety valves. The measurements of the mass leakage show that the required leak tightness can be attained by four out of five prototypes. Most valves

**Table 6.** Leakage of the valves at 1.9 K for ΔP = 100mbar

| **Valve** | | ***A*** | ***B*** | ***C*** | ***D*** | ***E*** |
|---|---|---|---|---|---|---|
| **Leak, 12 bar mode** | [mg/s] | 6.9 | < 0.1 | < 0.1 | >15 | < 0.1 |

showed leakage two orders of magnitude lower than the required value. These promising results are obtained with very clean and new valves and further investigation is required for determining the influence of the contamination found in the helium circuit.

The measurements of the high convection heat transport in the discharge pipe have confirmed the necessity of a convection limiting design of the discharge line to eliminate this heat load to the superfluid helium.


## ACKNOWLEDGEMENTS

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