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CERN AT/93-21 (CR)
LHC Note 233

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*Cryogenic Engineering Conference, International Cryogenic Materials Conference,
July 12-16, 1993 - Albuquerque, New Mexico, USA*

Geneva, Switzerland
5 August, 1993

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ABSTRACT

The high-field superconducting magnets of the CERN Large Hadron Collider (LHC) will operate in static pressurized helium II at a maximum temperature of 1.9 K, irrespective of their position around the 26.7 km circumference of the machine ring. Their static and dynamic heat loads will be transported by conduction in the pressurized helium II, to a heat exchanger tube threading its way along the magnet string, in which flowing saturated helium II absorbs the heat in quasi-isothermal conditions. Following promising results obtained with heated flow tests on two-phase helium II, a full-scale 20 m-long thermohydraulic model of a LHC cryoloop was designed, built and operated, addressing key issues such as flow stability, steady-state heat transfer, transient response to varying loads, control strategies, and influence of slope. We present the results obtained and show that they validate the basic design choices of the proposed LHC cryogenic system.

INTRODUCTION

The Large Hadron Collider (LHC) is the next-generation high-energy particle accelerator under study at CERN, the European Laboratory for Particle Physics. This huge experimental facility, to be installed in the 26.7 km circumference tunnel of the existing LEP machine, will accelerate and collide protons at centre-of-mass energies of up to 14 TeV. Guidance and focusing of the very stiff proton beams impose the use of high-field superconducting magnets, operated in pressurized superfluid helium at a nominal temperature of 1.9 K¹. Given the constraints of limited access and underground implantation in a sloping tunnel, the cryogenic system of the LHC, unprecedented in size and complexity, must produce and distribute adequate refrigeration matching the heat loads of the cryomagnets. By careful design of the cryostats², low-resistance splices in the high-current bus and interception of beam-induced heating, it is possible to stage the steady heat loads and thus limit the refrigeration duty at the lowest temperature (Table 1).

Table 1. Estimation of distributed heat loads in steady operation [W/m].

Temperature level	50-75 K	5-20 K	1.9 K
Heat inleakage	6	0.4	0.15
Resistive heating	-	-	0.15
Beam-induced heating	-	1.7	0.01
Total	6	2.1	0.31

Moreover, transient heating produced by current ramp or discharge will be thermally buffered by the 20 L/m pressurized helium II content of the cryostats. A special cryogenic distribution system, based on independent 50-m long cryoloops, was designed to maintain all cryomagnets at their working temperature^{1,5}, irrespective of their position in the LHC ring. A 20 m-long thermohydraulic model of such a superfluid helium cryoloop was designed, built and operated, addressing key issues such as flow stability, steady-state heat transfer, transient response to varying loads, control strategies, and influence of slope.

THE 1.9 K MAGNET COOLING SYSTEM

Absorbing the 1.9 K heat load of the LHC with minimum temperature drop can only be done using the latent heat of vaporization of helium, and thus requires the presence of two-phase saturated helium II, acting as a constant temperature heat sink, distributed along the circumference of the machine^{3,4}. The high apparent thermal conductivity of superfluid helium, pressurized at 0.1 MPa, which permeates the superconducting windings thanks to its low viscosity, is exploited to transport the heat to the two-phase saturated helium II flowing inside a heat exchanger tube threading its way along the magnet string (Figure 1). This acts as a linear cold source of large heat exchange area and at quasi-constant temperature. Provided the tube is made of a good thermal conductor, e.g. copper, and its inner surface is properly wetted by liquid, the applied heat load can be extracted across a small temperature difference.

THE THERMOHYDRAULIC MODEL CRYOLOOP

The thermohydraulic model cryoloop is shown in Figure 2. The magnets are represented by two 10 m-long cylindrical vessels containing pressurized superfluid helium, connected through a small capillary. Resistive heaters (EH6, EH7, EH8) in the pressurized helium are used to simulate distributed and localised heat loads at 1.9 K.

Figure 1. Principle of LHC magnet cooling scheme.

Figure 2. Flow-scheme of the superfluid helium model cryoloop.

The cross-section in Figure 3 shows the inner liquid helium supply tube, the corrugated heat exchanger tube and the pressurized helium chamber, the characteristics of which are given in Table 2.

Liquid helium at 4.2 K and 0.1 MPa is taken from the reservoir. It passes through a liquid-gas heat exchanger where it gets cooled down to 2.17 K. After subcooling to 1.8 K in a liquid-liquid heat exchanger, it undergoes a Joule-Thomson expansion to saturation pressure at valve WK1. The 1.8 K saturated helium is transported via the supply tube to the far end of the heat exchanger. When flowing back to the phase separator it vaporizes as it takes the heat from the pressurized helium chambers. The saturation pressure is maintained by pumping in the phase separator. By adjusting the temperature T21 at the liquid-gas heat exchanger exit using heater EH3 and by heating in the phase separator with EH4 we can vary the returning liquid fraction. Temperatures are determined using calibrated carbon resistors at several locations in the pressurized as well as in the saturated helium. Some of these gauges, azimuthally distributed on the heat exchanger tube wall, are used as wetting indicators.

Table 2. Characteristics of pipes in cryoloop.

	Material	Inner diameter [mm]	Wall thickness [mm]
Pressurized helium chamber	AISI 304L	56	2
Heat exchanger tube	Cu DHP	39/43	0.5
Liquid supply tube	Cu DHP	12	1

Figure 3. Cross-section of helium chamber, showing corrugated heat exchanger and liquid supply tube.

Tests were performed at 1.8 K saturation temperature, with slopes varying from -1.4% to 1.4% and varying the liquid return fraction. Two different control strategies were tested, one aimed at regulating the liquid level in the phase separator, and the other at regulating the temperature in the pressurized helium.

CO-CURRENT TWO-PHASE HELIUM II FLOW

As indicated by level variation in the phase separator and by differential pressure drop measurements along the corrugated heat exchanger tube, the co-current two-phase helium II flow proved very stable for horizontal or downward flow. Instabilities occurred in upward flows, provoking geysering in the tube.

In stable conditions, with the heat exchanger tube wetted over its whole length, the vapor mass fraction increases from about 3% at the supply tube outlet up to 50 to 90% at the phase separator, depending upon temperature T21 and heating power EH4. More than 90% of the tube cross-section is occupied by the vapor, which accelerates from practically zero at the supply tube outlet, to 2 m/s at the heat exchanger tube outlet. It flows much faster than the liquid phase (about 0.1 m/s with little dependence on the slope). The flow is separated, according to the wetting indicators. The measured heat conductance data suggest that the liquid wets a large fraction of the tube perimeter.

The pressure drop is less than 30 Pa and could be accurately determined by temperature measurements along the heat exchanger tube. The pressure drop is entirely determined by the vapor flow; the measurements are very well described by assuming a frictional flow with the vapor occupying the whole cross-section and a friction factor of 0.072 ± 0.004 , in accordance with hydraulic resistance data on such corrugated tubes⁶.

HEAT EXCHANGE

Heat exchange measurements have been performed in steady state with the heat exchanger tube wetted over its full length. The temperature difference across the heat exchanger reproducibly shows a linear dependence on the distributed heat load in the pressurized helium (Figure 4). No sign of deviation from this linear relationship was observed by applying heat loads up to 2.4 W/m, a limit set by the installed pumping capacity. The heat exchange can therefore be characterised by a conductance, measured to vary between 140 W/K.m and 80 W/K.m along the cryoloop length.

The measured temperature drop is largely dominated by the Kapitza resistance at the inner and outer copper-helium interfaces. From data on Kapitza resistance⁷ and measurement of the thermal conductivity of copper⁸, we deduce that the corrugated tube wall is wetted between 50% and 30% of its perimeter. The influence of liquid mass fraction and of slope on the conductance are shown in Figure 5. The conductance increases linearly with increasing liquid mass fraction; it decreases by about 20% as the slope goes from 0 to 1.4%.

STEADY-STATE PERFORMANCE

Steady state performance has been assessed with the heat exchanger tube wetted over its full length. The observed temperature profiles in the pressurized helium, shown in Figure 6, result from an interplay between the variation in heat exchange coefficient along the length, the pressure drop in the two-phase flow, and the longitudinal conduction in the pressurized helium. The heat exchange coefficient degrades as the liquid mass fraction gradually diminishes along the flow; this effect alone would enhance the heat exchange close to the liquid helium inlet. The pressure drop along the tube however lowers the temperature of the two-phase saturated liquid. It therefore favours heat exchange near the phase separator. Both effects are of the same order of magnitude, and the measured temperature profile shows that the pressure drop effect slightly dominates. The capillary connecting the two pressurized helium chambers has a small diameter and thus constitutes a restriction to thermal conduction; as a result the temperature difference between the chambers becomes apparent, while the longitudinal conduction in the pressurized helium equalizes the temperature inside each chamber.

Figure 4. Measured heat transfer across the superfluid helium heat exchanger tube.

Figure 5. Influence of slope and liquid mass fraction on heat exchanger performance.

Figure 6. Measured temperature profile in the pressurized superfluid helium vs. applied heat load.

PROCESS CONTROL AND RESPONSE TO VARIABLE HEAT LOADS

When the heat exchanger tube is wetted over its full length the temperature difference between the pressurized helium and the saturated liquid ΔT is minimal and depends only on the heat load. An interesting alternative is to maintain ΔT around a setpoint ΔT_{set} slightly higher than the minimum. The heat exchanger tube is then wetted only over a variable fraction of its length, depending upon the applied heat load. This control mode relies on the

fact that thermal information is conducted very fast along the length of the pressurized helium chambers, thus eliminating time delays related to the slow velocity of the saturated liquid.

The temperature control adjusts the supplied helium flow by means of a proportional-and-derivative algorithm (Figure 7):

$$\frac{dm}{dt} = P(\Delta T - \Delta T_{set}) + D \frac{d}{dt} \Delta T$$

We have chosen a relation between the derivative and proportional gains D and P such that the system will evolve like a critically damped oscillator:

$$D^2 = \frac{4PMC_p}{L_v}$$

where MC_p is the heat capacity of the total amount of pressurized helium, and L_v the heat of vaporization of the saturated liquid.

Figure 8 shows the response of the controlled temperature as one increases the heat load stepwise from 0.3 W/m to 0.6 W/m.

CONCLUSIONS

The results obtained show that the superfluid helium model cryoloop is capable to handle adequately the head loads of the LHC, and maintain the magnet temperature in the expected operating range. Final validation of the superfluid helium cooling system will be done on a 50 m-long string of full-scale magnet prototypes, presently in construction.

Figure 7. Control scheme regulating pressurized helium temperature.

Figure 8. Temperature response to a step increase of applied heat load.

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