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LHC Note 191

**DESIGN CONCEPT AND FIRST EXPERIMENTAL VALIDATION
OF THE SUPERFLUID HELIUM SYSTEM
FOR THE LARGE HADRON COLLIDER (LHC) PROJECT AT CERN**

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*Paper presented at the
International Cryogenic Engineering Conference and
International Cryogenic Materials Conference
Kiev, Ukraine, June 8-12, 1992*

Geneva, Switzerland
June 1992

DESIGN CONCEPT AND FIRST EXPERIMENTAL VALIDATION OF THE SUPERFLUID HELIUM SYSTEM FOR THE LARGE HADRON COLLIDER (LHC) PROJECT AT CERN

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The superconducting magnets of the CERN Large Hadron Collider (LHC) project must be kept at their operating temperature of 1.9 K all around the 26.7 km circumference of the machine ring. For this purpose, they are immersed in static baths of pressurized helium II, acting as heat transport medium to a heat exchanger tube running along the magnet string, in which flowing saturated helium II absorbs the deposited heat at constant temperature. Proper operation of this cooling scheme requires stability of the two-phase helium flow and adequate heat transport across the helium II heat exchanger. To investigate these issues, we have conducted tests on heated two-phase flow of saturated helium II in a 24 m long tube simulating the magnet heat exchanger.

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 center-of-mass energies of up to 16 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 K [1]. Given the constraints of limited access and underground implantation in a sloping tunnel, the cryogenic system for 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 cryostats [2], low-resistance splices in the 15 kA current bus and interception of beam-induced heating, it is possible to stage the steady-state loads and thus limit the refrigeration duty at the lowest temperature (Table 1).

Moreover, transient heating produced by current ramp or discharge will be thermally buffered by the 20 $\ell \cdot \text{m}^{-1}$ pressurized helium II content of the cryostats. Still, maintaining all cryomagnets at their working temperature, irrespective of their position in the 3330 m-long sectors (minimum distance between cryoplants), and throughout all phases of LHC operation, requires novel solutions in helium II cryogenics.

THE MAGNET COOLING SYSTEM

As previous studies [3,4] have demonstrated, 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 constant temperature heat sink, distributed along the circumference of the machine. This conflicts, however, with the attempt to avoid two-phase flows, which could develop instabilities in view of the long transfer distances and the 1.4% slope of the LHC tunnel.

In the proposed system, the high apparent thermal conductivity of superfluid helium, pressurized at 0.1 MPa (1 bar), which permeates the superconducting windings thanks to its low viscosity, is exploited to transport the heat to two-phase saturated helium II, flowing inside a heat exchanger tube threading its way along the magnet string (Figure 2). This acts as a linear cold source of large developed heat exchange area and at quasi-constant temperature, irrespective of the magnet position in the string. Provided the tube is made of a good thermal conductor, e.g. copper, and its inner surface properly wetted by liquid, the applied heat load can be extracted over a small temperature difference.

Table 1 Estimation of distributed heat loads in steady operation [$\text{W}\cdot\text{m}^{-1}$]

Temperature level	50-75 K	5-10 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

The practical length of such a scheme is limited by the pressure drop in the gaseous phase, which raises the saturation temperature, by the control delays due to the rather low flow velocities, as well as by the development of possible flow instabilities in the tube.

The elementary LHC cooling loop, shown in Figure 1, is 50 m long and matches the periodicity of the machine lattice. Subcooled liquid helium is tapped from line A, expanded to saturation through valve LCV and sent to the end of the loop, from where it returns, gradually vaporizing as it gathers heat in the heat exchanger tube. To guarantee adequate cooling of the last magnet in the string, there must be excess liquid returning to the phase separator vessel. The heat of vaporization of this excess liquid is used to subcool the incoming helium. The whole loop including heat exchanger tube and phase separator is maintained at saturation pressure by line B, through which cold helium vapor is pumped back to the cryoplant. In steady operation, the excess liquid fraction is determined by the supply temperature in line A, irrespective of the heat load applied to the cooling loop; as an example it amounts to 10% for a 2.25 K supply.

The magnet cooling system also comprises other lines, previously described in [4], to distribute refrigeration at higher temperatures and to perform transient phases of operation i.e. cooldown, liquid fill, warm-up and quench recovery.

THE TWO-PHASE HELIUM II FLOW TEST

A first attempt at simulating the proposed magnet cooling scheme was performed [5] using the experimental set-up of Figure 3: saturated helium II flows in a 25 mm-diameter, 24 m-long stainless-steel tube, with a 2 m-long copper section surrounded by a heated pressurized helium chamber. The flow at the tube outlet is decanted in a phase separator, maintained at low pressure by a pump. Calibrated carbon resistors measure the temperature at several locations in the pressurized as well as in the saturated helium; some of these gauges, azimuthally distributed on the tube wall, are used as wetting indicators.

Tests were performed at saturation temperatures between 1.9 and 2.0 K. As indicated by level variation in the phase separator, the two-phase helium II flow proved very stable for horizontal or downward flow, while instabilities occurred in upward flows, provoking geysering in the tube. In stable conditions, more than 90% of the tube cross-section is occupied by vapor, which flows at velocity of 1 to $3 \text{ m}\cdot\text{s}^{-1}$, much faster than the liquid phase (about $0.1 \text{ m}\cdot\text{s}^{-1}$). The flow is separated, with a clear indication, both from the wetting indicators and from the measured heat conductance data, of the liquid wetting a large fraction of the wall area. The heat transfer characteristic (Figure 4) reproducibly shows a good conductance, of about $50 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; the measured temperature difference is dominated by Kapitza resistance. This thermal conductance, which enables to extract LHC heat loads over a few tens of mK, is preserved up to the dryout point inside the heat exchanger, thus allowing to operate the cooling loop with minimum excess liquid.

Results obtained in this test give good confidence that the proposed magnet cooling system is adequate to handle the heat loads of the LHC.

FUTURE DEVELOPMENTS

- Final validation of the proposed cooling scheme is being done on a full-scale thermohydraulic model of a cryogenic loop, simulating steady-state as well as transient modes, and addressing control issues. In parallel, detailed investigation of two-phase saturated helium II flow will be performed on a dedicated test loop under construction at CEA Grenoble, France.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge fruitful discussions with our colleagues of the Cryogenics Group at CERN, as well as with G. Claudet, A. Gauthier, A. Ravex and B. Rousset of CEA Grenoble.

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Figure 1 Cryogenic flow-scheme of LHC ring

Figure 2 Principle of magnet cooling scheme

Figure 3 Schematic of experimental set-up for two-phase helium II flow

Figure 4 Thermal performance of helium II heat exchangers