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CONCEPTUAL STUDY OF THE SUPERFLUID HELIUM CRYOGENIC SYSTEM FOR THE

CERN LARGE HADRON COLLIDER (LHC)

by

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Studies are presently being made on the possibility of installing a Large Hadron Collider (LHC) in the existing underground tunnel of the LEP accelerator at CERN. The main element of the LHC would be a ring of 10 T superconducting magnets, distributed over the 26.7 km circumference of the machine. One of the current ideas is to use Nb-Ti magnets operated in superfluid helium. This paper presents possible solutions for a long distributed superfluid helium system within the constraints of an accelerator environment.

INTRODUCTION

CERN, the European Laboratory for Particle Physics located in Geneva, Switzerland, is presently constructing a 100 GeV electron-positron collider called LEP(1). This machine, the world's largest of its kind, is being installed in an annular underground tunnel having a circumference of 26.7 km, straddling the border between France and Switzerland (Fig. 1); it is due to begin operation in 1989. In order to explore physics at even higher energies, CERN is also considering the possibility of later installing in the same tunnel, in a way fully compatible with LEP operation, a proton-proton collider referred to as the Large Hadron Collider (LHC) (2, 3, 4). The strong superconducting magnets required to bend and focus the stiffer proton beams would be installed on top of the conventional (resistive) magnet system of LEP (Fig. 2). Since most of the civil engineering and infrastructure, which represent a significant fraction of the total cost of modern large accelerators, already exist and would be shared with LEP, LHC could be a very cost-effective research facility; in counterpart, in order to reach beam energies of about 8 TeV in the existing LEP tunnel, LHC would have to make use of very high field (10 T) magnets, at the limit of today's state of the art. Such magnets can be made by using either Nb₃Sn at the normal boiling point of helium or the widely-used Nb-Ti alloy at reduced temperature in superfluid helium (6, 8).

This paper deals with the superfluid helium cryogenic system for LHC.

1. General Layout and Main Features of LHC

Due to geotechnical reasons, the LEP/LHC tunnel is excavated at depths ranging between 30 m and 150 m below ground, and lays on a plane inclined 1.4% with respect to horizontal, resulting in an elevation difference of about 120 m between the highest and lowest points. Access to the tunnel is provided through vertical shafts at eight points equally spaced around the machine perimeter; the sections between access points are called octants. The standard cross-section of LEP/LHC tunnel is shown in Fig. 2: a large

fraction of this cross-section must remain unobstructed for installation and accessibility reasons, thus limiting the transverse space available for LHC.

LHC accelerates two proton beams, circulating in opposite directions and colliding in eight interaction points. The beams are guided by a string of dipole, quadrupole, sextupole and correction magnets distributed in a regular pattern along the tunnel. The two magnetic channels required to guide the counter-circulating beams are combined in a single item (two in one magnet). The magnets are housed in cryostat elements of about 10 m length, which can be transported and installed in the tunnel before being electrically and cryogenically connected in situ. All magnets feature a cold iron yoke and will be operated in pressurised superfluid helium: the total mass to be cooled down to below 2 K is approximately 31×10^6 kg.

2. Duties and Constraints for the Cryogenic System

The main duties of the LHC cryogenic systems are:

- a) to maintain all the magnets at a temperature below 1.95 K during steady operation;
- b) to cool down the machine starting from room temperature in a time not longer than 20 days;
- c) to recool a short string of magnets (less than four elements) in a few hours after an accidental quench.

In designing the cryogenic system, it is imperative to take into account the constraints deriving from the actual LEP configuration which cannot be modified. The main constraints are:

- a) The 1.4% slope of the plane on which LHC lies. Because of this slope, it is advisable to avoid circulation of two-phase helium over long distances.
- b) The distance between access pits. Access pits are separated by a tunnel length of 3332 m, corresponding to an octant of the machine. Large active cryogenic equipment (e.g. pumps, compressors, cold boxes, etc.) can only be accommodated, by reason of available space, in the access pits or in their immediate neighbourhood. In practice, this means that cryogenic power has to be transported over at least half an octant, i.e. over 1666 m.

The small cross-section of the tunnel and the limited space available for LHC. This means that the magnet cryostat, accommodating the piping required to transport the cryogenic power, has to be of very compact design.

3. Cryogenic Power Requirements

3.1 Steady Operation

Three heat sources are considered: a) the environment, b) the ohmic heat load in the resistive parts of the winding (e.g. the non-superconducting joints), c) the circulating beams.

- a) The heat in-leak from the environment essentially depends on the cryostat design. A cross-section of a preliminary dipole cryostat is shown in Fig. 3. In this design, which has been used to assess the heat input, there are three nominal temperature

levels, i.e. 80 K, 5 K and 1.8 K. These temperatures have been chosen for design simplicity and do not necessarily correspond to a thermodynamic optimum. Coils and magnet structure (items 1,2,3 and 4) are kept at 1.8 K. The inner and outer radiation shields (5 and 6) are maintained at 5 K; the second radiation shield (7) is kept at 80 K. The magnet rests on low conduction support posts (8) featuring heat intercepts thermally bridged to the radiation shields. The calculated values for steady heat input to the cryostat are summarized in the table below.

- b) Heat input at 1.8 K due to ohmic heat load in the coil winding is estimated to be less than 0.15 W per meter of cryostat. This value is calculated assuming an ohmic resistance of $5.5 \cdot 10^{-10} \Omega$ per joint and a current of 15 kA.
- c) The circulating beam will produce distributed heat loads of about 0.3 Wm^{-1} which are almost totally intercepted by the inner radiation shield at 5 K. The residual beam-induced heat load at 1.8 K is of the order of $0.01 \text{ W}\cdot\text{m}^{-1}$. In addition, however, a locally scattered beam can produce a concentrated heat load of 25 W over a few cryostat lengths. It is assumed that there is one such high-heat-load section per half-octant.

Calculated values of distributed heat input in steady operation ($\text{W}\cdot\text{m}^{-1}$)

TEMPERATURE LEVEL	80 K	5 K	1.8 K	REMARKS
Environment	7 (*)	0.5 (*)	0.15 (*)	(*) No contingency included
Ohmic heat loads	-	-	0.15	
Beam	-	0.3	0.01	
Total	7	0.8	0.31 (**)	(**) Local heat input of 25 W per half-octant to be added

3.2 Transient Modes

Additional heat loads, due to eddy currents, are produced during ramping up and down of the magnet current. When raising the current to its nominal value in 1200 s, the power generated is approximately $0.4 \text{ W}\cdot\text{m}^{-1}$, corresponding to an energy dissipation of $480 \text{ J}\cdot\text{m}^{-1}$. In case of a magnet quench or in an emergency, it must be possible to ramp down the current in 80 s. The energy dissipated in the non-quenched magnets during the ramping-down is 3000 J per meter of cryostat.

The transient heat input must be almost entirely absorbed by the heat capacity of the helium contained in the magnet cryostat. In fact, the transient heat loads determine the minimum amount of liquid helium required per metre of cryostat.

4. Cooling Scheme

In a first cooling scheme, previously studied in some detail (5), superfluid helium is static and its very high thermal conductivity is used to cool elements situated at some distance

from the cold source. The scheme of ref. 5 is adequate to cope with the steady distributed heat loads of LHC; it is less adequate to absorb transient and localized heat loads which were not known at the time of the previous study. For this reason, a second scheme, based on forced circulation of superfluid helium, is considered here. The basic scheme is represented in Fig. 4. A pump generates a pressure drop Δp and circulates a mass flow $\dot{m}$ of superfluid helium in a closed loop including N cooling stations and N strings of magnets, each one of length L/N ; L is the length of a half-octant of LHC. The forced-flow superfluid helium circulates in a heat exchanger which is immersed in the static superfluid helium surrounding the magnet. In practice, this heat exchanger can be reduced to a straight pipe of equivalent diameter D .

The design problem consists in defining values of Δp , $\dot{m}$, N and D consistent with the LHC cooling requirements and constraints. The basic equations used for the design are:

$$W_h = \dot{m} \sum_1^N [H(T_{out}, P_{out}) - H(T_{in}, P_{in})] \quad (1)$$

where W_h = heat input in a half-octant
 $H(T_{out}, P_{out})$ = enthalpy of helium at outlet of string
 $H(T_{in}, P_{in})$ = enthalpy of helium at inlet of string;

$$W_p = \dot{m} \Delta p / \eta \rho \quad (2)$$

where W_p = power dissipated by the helium circulation in the pump-loop system
 η = efficiency factor ($\eta < 1$)
 ρ = helium density;

$$\Delta p = 2f \dot{m}^2 L / D^5 \quad (3)$$

where f = friction factor.

It must be noted that in the case of superfluid helium, isenthalpic expansion produces a temperature rise. Consequently, for practical purposes, for a given loop the pressure drop must be limited to a few hundred mbar.

Using equations (1), (2) and (3), three out of the six quantities D , W_p , $(T_{out} - T_{in})$, N , Δp , $\dot{m}$ can be calculated if the other three have been fixed.

However, the following constraints must be taken into account:

- At first, the largest acceptable value of $T_{out} - T_{in}$ is dictated by the magnet requirements.
- D cannot be very large because of the space limitations in the cryostat cross-section.
- W_p must be small with respect to W_h : a solution where the refrigerator is considerably oversized to cover the circulation losses would hardly be defensible.

A solution without intermediate cooling stations (i.e. $N = 1$) would be highly desirable. Unfortunately, this solution yields exceedingly large values of D and W_p . The solution which has been studied in some detail is based on $N = 8$. A more complete scheme of this solution is given in Fig. 5. The cooling stations are heat exchangers immersed in a saturated liquid helium bath pumped down to a pressure corresponding to the desired

temperature, through cold line C connected to the cold compressor. The cryostats are connected through fill and relief valves to cold line D, which will recover the boil-off helium after a magnet quench. Liquid helium at 5 K, fed through line E and returned as vapour through D, maintains the first heat intercept of the magnet support and the first radiation shield at the right temperature. Finally, liquid nitrogen at approximately 80 K is circulated in line F and provides cooling for the second heat intercept and the second radiation shield.

Initial cool-down from room temperature to about 5 K is obtained by introducing pressurized helium of progressively decreasing temperature in line B (V_1 open, V_2 closed) and returning it through the magnet string line A. Helium fed through line D and the open fill valves is condensed into the magnet cryostats. When all the magnets are filled with liquid helium at about 5 K, the circulation pump and the cold compressor are started and the magnet temperature is lowered to 1.8 K.

In case of quench of one magnet, it has been assumed that the quench does not propagate to the adjacent elements by heat conduction through line A. This assumption needs experimental verification. Recooling of the quenched magnet, which will have an average final temperature of about 40 K, will be done by circulating helium in the loop A-B.

The main parameters relative to the cooling scheme of Fig. 5 are summarized below:

W_h	=	steady heat input in half octant	=	680 W
N	=	number of cooling stations per half octant	=	8
L/N	=	distance between cooling stations	≈	200 m
$T_{out} - T_{in}$	=	string temperature difference	=	0.15 K
$\dot{m}$	=	mass flow of superfluid helium	=	230 g·s ⁻¹
Δp	=	pressure drop in the loop	=	0.32 bar
η	=	efficiency of the circulation pump	=	0.7
W_p	=	circulation dissipated power	=	73 W
V	=	average helium content of cryostat	=	30 l·m ⁻¹

5. Technical Developments Required

Some technical developments and tests are necessary to progress with the design work.

Forced circulation of superfluid helium has up to now only been tested in small scale configurations. Large scale experimentation in pipes a few centimeters in diameter and several hundred metres long is required. This will be done in a large multi-purpose experimental setup, which is presently being installed at CEA-SBT, Grenoble. The same set-up will allow circulation pumps and cold compressors to be developed and tested, and it will also be used to investigate the specific problem of quench propagation from one magnet to the next.

A full-scale cryostat is presently being built for a 10 m long prototype dipole magnet. In addition to the magnet test, the cryostat can be used to measure the heat input and to compare experimental and calculated results.

Finally, it is worth noting that the forced-flow cooling scheme could be very well combined with magnetic refrigeration (7). Magnetic refrigerators operated between 5 K and 1.8 K as intermediate cooling stations would permit the suppression of the cold pumping

line and the cold compressors. The forced-flow scheme would allow to bring to the point required, e.g. to a quenched magnet, the power produced by all the magnetic refrigerators installed on the loop independently from their individual size and location. However, the choice of magnetic refrigerators would imply a dedicated programme to develop devices sufficiently reliable and of a size suitable for installation in the LHC.

CONCLUSION

The design of the LHC cryogenic system has been updated taking into account the progress in the machine and magnet studies.

A scheme based on forced circulation of superfluid helium fulfils the present requirements of LHC and, although further studies and developments are required, seems to be feasible.

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Fig. 1 General lay-out of LEP

Fig. 2 Cross-section of LEP/LHC tunnel

Fig. 3 Cross-section of LHC standard two-in-one dipole cryostat

Fig. 4 Basic forced-flow cooling loop

Fig. 5 Flow scheme of LHC half-octant