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Cooldown and Warmup Studies for the Large Hadron Collider

Philippe Lebrun, Germana Riddone, Laurent Tavian and Udo Wagner

Abstract

The Large Hadron Collider (LHC) [1], currently under construction at CERN, will make use of superconducting magnets operating in superfluid helium below 2 K. The LHC ring is divided in 8 sectors, each of them cooled by a refrigerator of 18 kW at 4.5 K [2] equivalent cooling power. For the cooldown and warmup of a 3.3 km long LHC sector, the flow available above 80 K per refrigerator is 770 g/s and the corresponding capacity is 600 kW.

This paper presents the results of cooldown and warmup simulations, as concerns time delays, temperature difference across magnets, available power and flow-rates, and estimates of energy and liquid nitrogen consumption.

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Cooldown and Warmup Studies for the Large Hadron Collider

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The Large Hadron Collider (LHC) [1], currently under construction at CERN, will make use of superconducting magnets operating in superfluid helium below 2 K. The LHC ring is divided in 8 sectors, each of them cooled by a refrigerator of 18 kW at 4.5 K [2] equivalent cooling power. For the cooldown and warmup of a 3.3 km long LHC sector, the flow available above 80 K per refrigerator is 770 g/s and the corresponding capacity is 600 kW.

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1 INTRODUCTION

The LHC cryogenic system is based on a five-point feed scheme with eight refrigerators serving the eight sectors of the LHC machine [3].

Four existing refrigerators, presently working for LEP, will be upgraded in power from 12 kW to 18 kW at 4.5 K equivalent and adapted to the LHC cryogenic needs. Four new refrigerators of 18 kW at 4.5 K equivalent cooling power will be added. Within a 3.3 km long sector, a separate cryogenic distribution header feeds elementary cooling loops corresponding each to the length of a cell (107 m).

Each of these refrigerators will have to cool down and warm up about 4500 tons of stainless steel and aluminium and to liquefy about eight tons of helium. To benefit from redundancy and to reduce the necessary times for unscheduled interventions on the machine, it is possible to couple two neighbouring refrigerators for the cooldown and warmup of one sector. Further transients that will be seen regularly by the refrigerators are recovery operations on a limited number of magnets after a quench.

For the cooldown and warmup of the LHC machine different scenarios have been studied according to the available cooling capacity and the maximum acceptable temperature gradients in the magnets. Forced-flow cooldown and warmup have been simulated using a non-linear, one-dimensional thermal model. This has been checked and validated against experimental data obtained from the quasi full-scale LHC prototype magnet string [4].

2 FLOW SCHEME AND CONSTRAINTS FOR COOLDOWN AND WARMUP

The flow and capacity for the cooldown and warmup of the LHC magnets is supplied by refrigerators dedicated to each sector. Each refrigerator is hydraulically connected to one sector of the LHC machine via five headers, as described in [5]. The general flow scheme for the cool down and warmup of an LHC arc is shown in Figure 1. The cooldown/warmup of the magnet cold mass is performed by forced circulation of gaseous helium at decreasing/increasing temperature supplied by the refrigerators.

During a “Normal” cooldown and warmup, one refrigerator is used to supply one LHC sector, which is composed out of 27 cells. The helium to the magnet cold mass is supplied via header C and returned via header D. Headers C, E and F are connected using the valves indicated with “v” in Figure 1, in order to form one single supply path. The pumping header “B” is cooled by a small flow once the temperature of the cold mass is below 50 K and used for the cool down between 4.5 K and 1.9 K in connection with the 1.8 K refrigeration unit [3,6]. The LHC cells are cooled in parallel and each of them comprises 2 lattice quadrupoles and 6 dipoles. The total flow available for cooldown and warmup above 80 K is 770 g/s per refrigerator, which corresponds to what can be provided by the compressors of the refrigeration cycle, used as circulators.

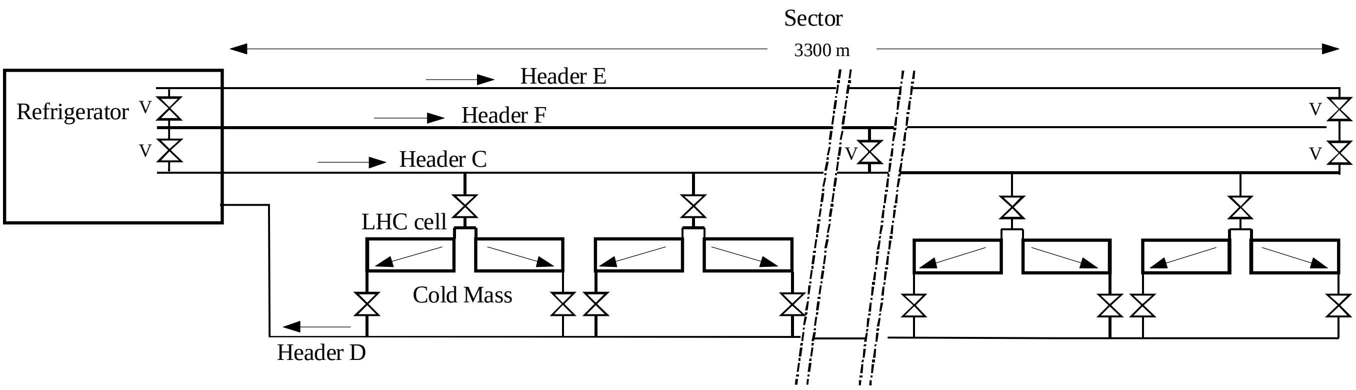

Figure 1 Flow-scheme for the cooldown and warmup of an LHC arc.

To shorten the time for cooldown and warmup it is possible to couple two neighbouring refrigerators to one LHC sector allowing for a “Fast” process with twice the flow and capacity.

In Table 1 the constraints for the cooldown and warmup operations are given. A boundary condition for the cool down imposed by the magnets is given by the fact that the maximum temperature difference over any one magnet must not exceed 75 K. Knowing that the available flow-rate for cooldown is 770 g/s per refrigerator, the remaining free parameter for estimating the cooling capacity above 80 K results to be the temperature difference (T_{He}-80 K). At most this difference is equal to 225 K which would give a capacity of 900 kW. However, such capacity would be used only at the beginning of cooldown when the magnets are warm. For this reason it was decided to install a LN_2 vaporiser of 600 kW.

Table 1 Constraints for cooldown and warmup

		Operation		Remarks
		Normal	Fast	
Mass to be cooled	[t]	4500	4500	
ΔT max. per magnet	[K]	75	75	
No. of refrigerators	[-]	1	2	
Supply headers	[-]	C+E+F	C+E+F	E & F for T>80 K
Return headers	[-]	D	D	
Max. He flow	[g/s]	770	1540	available at cycle compressors
Max. cooling capacity 300-160 K	[kW]	600	1200	LN_2 vaporisation
Max. cooling capacity 160-85K	[kW]	600 to 55	1200 to 110	LN_2 vaporisation and He turbines
Max. cooling capacity 85-4.5 K	[kW]	55 to 12	110 to 24	He turbines
Liquefaction rate	[g/s]	100	200	calculated for existing refrigerators
Vaporisation rate (warmup)	[g/s]	200	400	heaters in magnet cold mass
Warmup capacity 4.5-300 K	[kW]	600	1200	electrical heaters

3 MATHEMATICAL MODEL

The evolution of magnet (T_M) and helium (T_{He}) temperatures has been simulated by a one-dimensional non-linear computer model. The heat transfer coefficient (h) between helium and magnets has been estimated at 200 W/K·m from design characteristics and validated from experimental data [4]. The laminated structure of the cold mass renders longitudinal heat conduction negligible. Following this assumption only convective heat exchange contributes to the heat transfer between cold mass and helium. From the heat balance equation we obtain a system of partial differential equations which can be solved explicitly using the finite difference method:

$$M \cdot Cp_M \cdot \frac{T_M^{(x,t+1)} - T_M^{(x,t)}}{\Delta t} = -h \cdot \left(T_M{}^{(x,t)} - T_{He}{}^{(x,t)}\right)$$

$$\dot{m} \cdot Cp_{He} \cdot \left(\frac{T_{He}^{(x+1,t)} - T_{He}^{(x,t)}}{\Delta x} + \frac{1}{v} \cdot \frac{T_{He}^{(x,t+1)} - T_{He}^{(x,t)}}{\Delta t}\right) = h \cdot \left(T_M{}^{(x,t)} - T_{He}{}^{(x,t)}\right)$$

where Cp_M and M are respectively the specific heat and mass of the cold mass, and Cp_{He}, $\dot{m}$ and v are respectively the specific heat, mass flow and velocity of helium.

At each node x, we calculate cold mass temperature and helium temperature as a function of time t. In order not to exceed 75 K across magnets, at the beginning of the cooldown/warmup the inlet helium temperature is regulated using a linear ramp until the cooling power becomes limited by the LN_2 refrigeration capacity.

4 RESULTS

Different scenarios of cooldown and warmup have been investigated according to the available cooling capacity and the temperature difference across magnets. Figure 2 shows the temperature evolution and profile of the cold mass for the normal cooldown of the LHC cell. The initial helium temperature value of 235 K and ramp slope of 1.56 K/h have been optimised in order to keep the maximum temperature difference along each magnet around 75 K.

Figure 3 shows the temperature evolution and profile of the cold mass during the warmup of a LHC cell. For the first 24 h the inlet helium temperature was regulated on a linear ramp of 5.2 K/h not to exceed the maximum temperature difference along each magnet of 75 K. The warmup simulation was stopped when the outlet temperature of the last magnet reached 275 K. For the LHC it is foreseen to complete the warmup by breaking the insulation vacuum.

The different scenarios of cooldown and warmup with the corresponding duration time, energy and LN_2 consumption have been summarised in Table 2. For the cooldown the phase 4.5-1.8 K includes the cold mass filling with LHe at 4.2 K followed by the cooldown from 4.2 K to 1.8 K. For the warmup this phase corresponds to vaporising all liquid helium from the cold mass.

Other transients simulating recovery operations on a limited number of magnets after a quench have been also considered. Starting from a cold mass temperature of 30 K, with the available refrigeration capacity of 40 kW and a mass flow-rate of 80 g/s per cell (4 cells), the time necessary to cool the magnets back to 1.9 K is estimated to 6 h. If a full sector quench occurs, the recovery would take about 2.3 days.

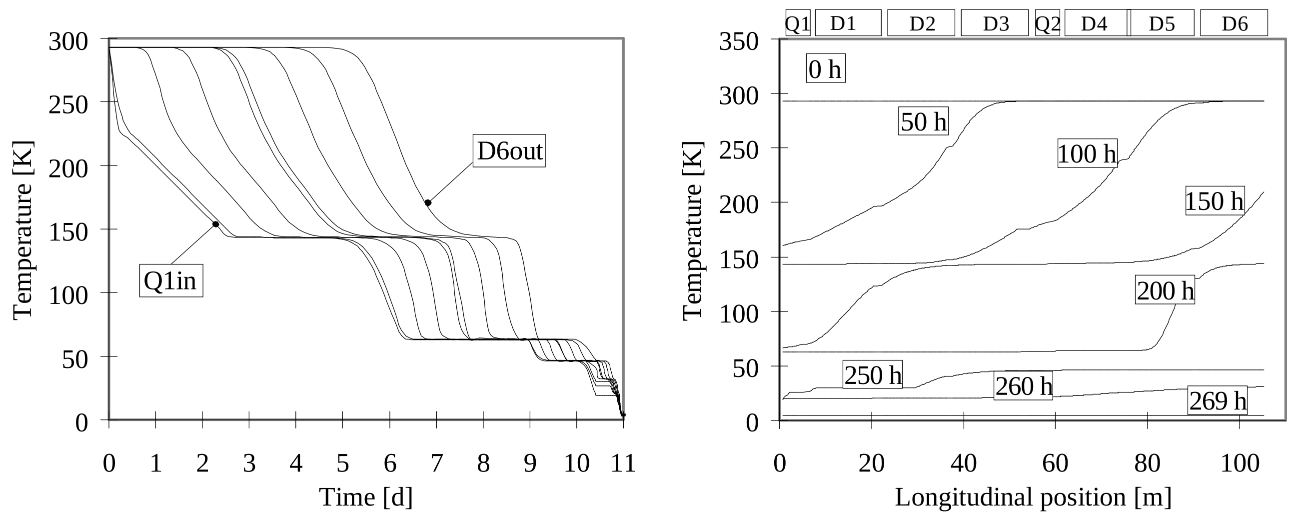

Figure 2 Normal cooldown of the LHC cell

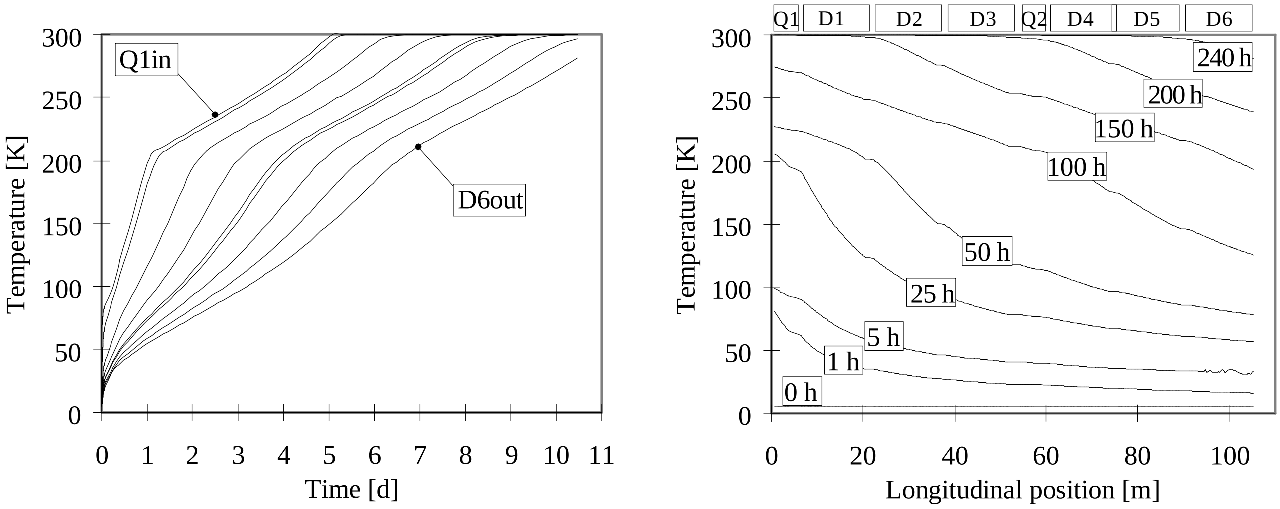

Figure 3 Normal warmup of the LHC cell

Table 2 Summary of LHC cooldown (CD) and warmup (WU).

	Normal CD	Fast CD	Normal WU	Fast WU
300-4.5 K time [d]	11.2	5.8	10	5.2
4.5-1.8 K time [d]	2.0	1.3	0.8	0.4
Total time [d]	13.2	7.1	10.8	5.6
Energy consumption [MWh]	590	590	880	910
LN_2 consumption [m^3]	1600	1600	=	=

5 CONCLUSION

Cooldown and warmup of the LHC have been simulated by a non linear one-dimensional mathematical model validated against experimental results obtained from the full-scale LHC prototype magnet string. The model permits to investigate different scenarios of cooldown and warmup by easily changing the boundary conditions. The 4500-ton LHC sector can be normally cooled down to 1.9 K or warmed up to 300 K in less than 2 weeks. This time can be halved if two neighbouring refrigerators are coupled together. The simulations showed that most of the heat exchange between helium and magnets takes place over a length of 50 m.

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