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UPDATE OF A COOLDOWN AND WARMUP STUDY FOR THE LARGE HADRON COLLIDER

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Abstract

The paper presents the inventory of components and materials for LHC magnets, especially for main dipoles and quadrupoles. A mathematical model for LHC transient modes, such as cooldown and warmup of a magnet, a standard cell and the eight LHC sectors, has been developed on the basis of the up-to-date layout of the LHC machine, and validated by experimental data. The model considers the momentum and continuity equations, as well as the energy equations for helium and materials. Based on the simulation results, the heat transfer in the magnets has been studied and the transient modes optimized.

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ABSTRACT

The paper presents the inventory of components and materials for LHC magnets, especially for main dipoles and quadrupoles. A mathematical model for LHC transient modes, such as cooldown and warmup of a magnet, a standard cell and the eight LHC sectors, has been developed on the basis of the up-to-date layout of the LHC machine, and validated by experimental data. The model considers the momentum and continuity equations, as well as the energy equations for helium and materials. Based on the simulation results, the heat transfer in the magnets has been studied and the transient modes optimized.

INTRODUCTION

The LHC cryogenic system [1] is based on a five-point feed scheme with eight refrigerators serving the eight sectors of the LHC machine [2]. Four existing refrigerators, previously working for LEP, are being upgraded from 12 kW to 18 kW at 4.5 K equivalent cooling power and adapted to the LHC cryogenic needs. Four new refrigerators of 18 kW at 4.5 K equivalent cooling power are being added. Within a 3.3 km long sector, a separate cryogenic distribution line feeds elementary cooling loops corresponding each to the length of a standard cell (107 m). Each refrigerator will have to cool down and warm up about 4600 tons of cold mass.

Since 1997, the previous studies on transient modes of a LHC cell [3] were carried out and the structure of LHC magnets has been updated. According to the updated structure, this paper presents a set of transient mathematical models not only suitable for a single magnet or a cell but also for a whole sector. The models have been validated by the data provided by a LHC prototype main dipole tested in February 2001.

THE UPDATED DESIGN OF LHC MAGNETS INVOLVING HEAT TRANSFER

There are 1232 main dipoles (MB) and 400 main quadrupoles (MQ) in LHC in which helium flows through several parallel channels (CH) of various sizes. The updated details of channels and materials used for the MB and MQ are described in TABLE 1 (where D_w is the wetted perimeter, A_f is the cross-section area, D_h is the hydraulic diameter) and TABLE 2, whereas the location of the channels is illustrated in FIGURE 1.

TABLE 1. Channel structures of Main Dipoles and Quadrupoles

Channels	Main Dipole			Main Quadrupole		
	D_w [m]	A_f [m^2]	D_h [m]	D_w [m]	A_f [m^2]	D_h [m]
1	0.377	2.83×10^{-3}	3.00×10^{-2}	2.808	9.30×10^{-3}	1.32×10^{-2}
2	0.293	7.98×10^{-4}	1.09×10^{-2}	2.288	3.30×10^{-3}	5.80×10^{-3}
3	0.248	5.65×10^{-4}	9.10×10^{-3}	0.372	5.73×10^{-4}	6.20×10^{-3}
4	0.274	5.33×10^{-4}	7.80×10^{-3}	0.685	5.14×10^{-4}	3.00×10^{-3}
5	0.259	4.22×10^{-4}	6.50×10^{-3}	0.371	1.85×10^{-4}	2.00×10^{-3}
6	0.168	2.68×10^{-4}	6.40×10^{-3}	0.096	4.00×10^{-5}	1.70×10^{-3}
7	0.355	3.74×10^{-4}	4.20×10^{-3}	--------	--------	--------
8	0.372	5.73×10^{-4}	6.20×10^{-3}	--------	--------	--------
9	0.694	5.16×10^{-4}	3.00×10^{-3}	--------	--------	--------
10	0.382	3.07×10^{-4}	3.20×10^{-3}	--------	--------	--------
11	0.341	3.04×10^{-5}	4.00×10^{-4}	--------	--------	--------

TABLE 2. Mass of Materials of a Main Dipole and Quadrupole

Magnets	Mass of Materials [kg/m]					
	Iron	Copper	Nb-Ti	Teflon	Glass	St. Steel
Dipole	1.18×10^{3}	8.11×10^{1}	1.95×10^{1}	1.78×10^{1}	6.87	5.90×10^{2}
Quadrupole	7.79×10^{2}	6.27×10^{1}	2.52×10^{1}	5.06×10^{1}	9.18	4.40×10^{2}

Changes in materials and structure of magnets, such as replacing the previous aluminum collar material by stainless steel, led to a change of the specific heat. The present specific heat of MB has increased by about 8% in comparison with the previous design, which is shown in FIGURE 2.

FLOW SCHEME AND CONSTRAINTS FOR COOLDOWN AND WARMUP

The mass flow and cooling capacity for the cooldown and warmup of LHC magnets are supplied by the refrigerators dedicated to each sector. The refrigerators are hydraulically connected to the corresponding sector via five cooling headers. The cooldown/warmup of the magnet cold mass is performed by forced circulation of gaseous helium at decreasing/increasing temperature supplied by the refrigerators. The general flow scheme for the cooldown and warmup as well as the different regions of a LHC sector are shown in FIGURE 3.

The regular arc corresponds to the main part of the sector and is formed of 23 standard cells. The Dispersion Suppressor left and right (respectively DSL and DSR) are composed of 2 non-standard cells each. The Long Straight Section left and right (respectively LSSL and LSSR) are composed of 1 to 5 non-standard cells each.

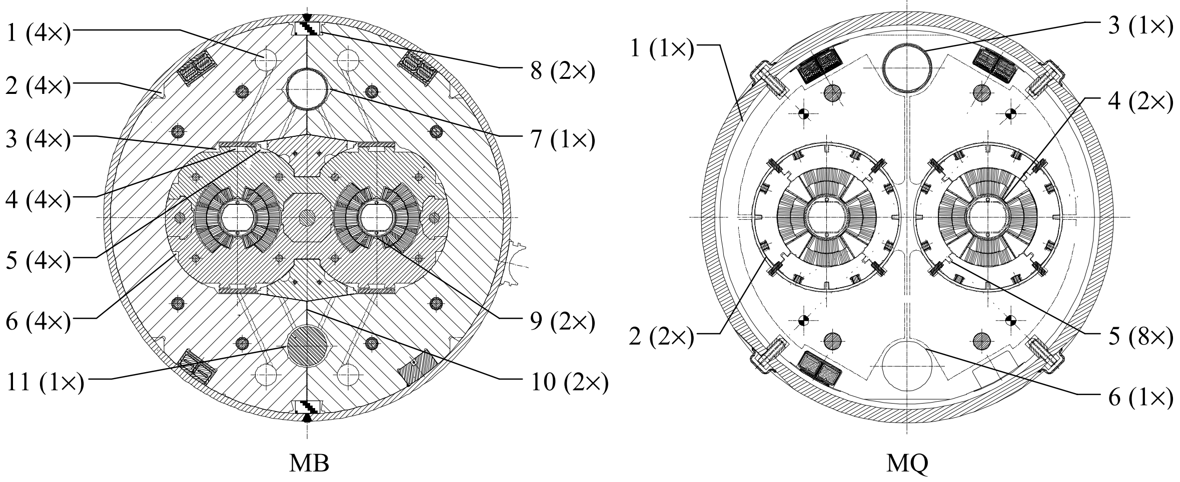

FIGURE 1. Cross-section of MB and MQ showing cooling channels

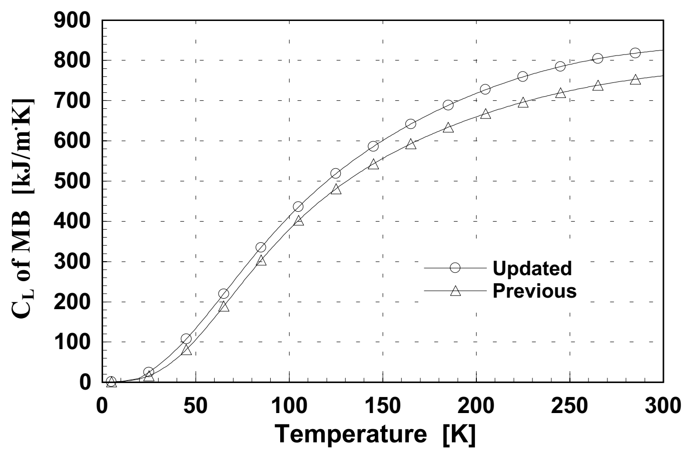

FIGURE 2. Heat capacity of material per unit length (C_L) of MB

In FIGURE 3, the helium to the magnet cold mass is supplied via header C and returned via header D. Headers C, E and F can be interconnected using valves in order to form one single supply path. Each standard cell consists of 6 MBs and 2 MQs. According to the cooling scheme for the standard cells, as shown in the left side of FIGURE 4, there are two types of standard cell as shown in the right side of FIGURE 4. All LHC cells are cooled down and warmed up in parallel. During a "Normal" cooldown and warmup, one refrigerator is used to supply one sector, while for a "Fast" process, two neighboring refrigerators are coupled to one sector with twice the flow and capacity.

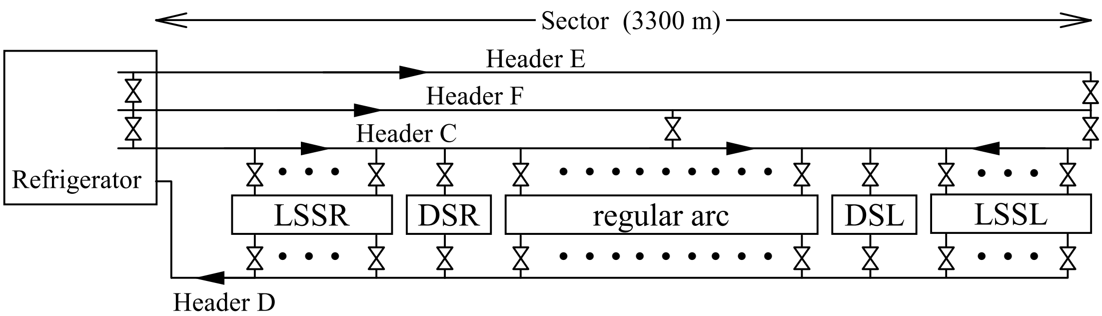

FIGURE 3. Flow-scheme for the cooldown and warmup of a LHC sector

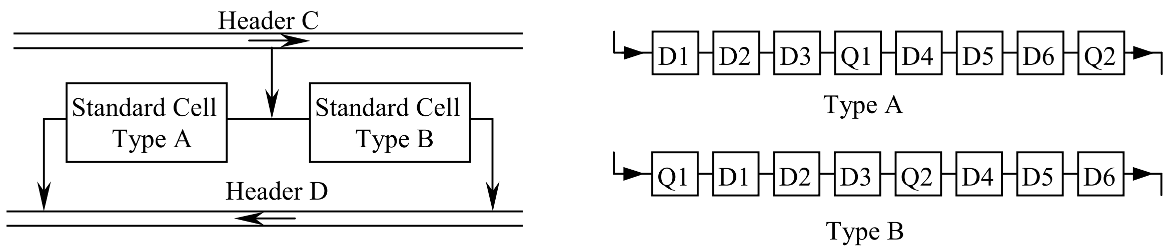

FIGURE 4. Flow scheme for two types of standard cell

The operational constrains for a sector cooldown and warmup are given in TABLE 3. To limit thermal stresses in the magnets, the boundary condition that the maximum temperature difference over any magnet must not exceed 75 K is introduced. To increase the cooling capacity above 80 K, a LN_2 heat exchanger of 600 kW is used.

TABLE 3. Constraints for cooldown and warmup of a LHC sector

	Operation		Remarks
	Normal	Fast	
Mass to be cooled [t]	4600	4600	
ΔT max. per magnet [K]	75	75	
No. of refrigerator [-]	1	2	
Supply headers [-]	C+E+F	C+E+F	E & F for T > 80K
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 160–85 K [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
Max. warmup capacity 4.5 – 300 K [kW]	600	1200	electrical heaters

MATHEMATICAL MODEL

A simplified model for a single magnet has been developed by considering the following assumptions:

1) a one dimensional compressible flow of helium in each of the channels with zero longitudinal thermal conductivity,
2) a one dimensional wall made of several kinds of materials with infinite transverse thermal conductivity and without longitudinal heat conduction (due to the laminated structure of the cold mass)

According to these assumptions the control equations are one-dimensional and can be written as follows:

– *the gas continuity equation per channel*:

$$\frac{\partial(\rho_k u_k)}{\partial x} + \frac{\partial \rho_k}{\partial t} = 0 \tag{1}$$

where the subscript k indicates the different channels, ρ is the density of helium and u its velocity and x is the longitudinal dimension.

– *the gas momentum equation per channel*:

$$-\frac{dp_k}{dx} = f_k \frac{1}{D_{hk}} \left(\frac{\rho_k u_k^2}{2} \right) \tag{2}$$

where f is the friction factor, p is the pressure of helium.
– *the energy equations for materials*:

$$\sum_k \alpha_k D_{wk}(T_{fk} - T_m) = \sum_j (m_j C_{mj}) \frac{\partial T_m}{\partial t} \tag{3}$$

where T is the temperature of helium or materials and the subscript f refers to helium, m to the materials, j to the sort of the materials. The term $\sum(mC_m)$ represents the total heat capacity of the materials involved per unit length, m is the mass of each material per unit length and C_m is the mass specific heat of each material. The heat transfer coefficient α between helium and materials can be derived from the Nu number estimated as follows: when Re ≤ 2000, Nu = 3.7[4]; when Re ≥ 2200, α should be determined by Dittus-Boelter Correlation, that is Nu = $0.023Re^{0.8}Pr^{n}$, where n is 0.4 for heating and 0.3 for cooling; when 2000 < Re < 2200, α is assumed to be proportional to Re and the values at the endpoints are continuous with the equations valid outside the interval.
– *the energy equations for helium per channel*:

$$\frac{\partial(\rho_k u_k h_k)}{\partial x} + \alpha_k \frac{D_{wk}}{A_{fk}}(T_{fk} - T_m) + \frac{\partial(\rho_k h_k)}{\partial t} - \frac{\partial p_k}{\partial t} = 0 \tag{4}$$

where h is the enthalpy of helium.

The real gas state equation and property equations of materials have been used.

The mathematical model for the standard cell, the LHC sector and the headers can be derived from the model for a single magnet. Between each magnet there is an interconnection region, which is, in the model, represented by a node without any heat capacity. In this case the energy equation for helium is expressed as follows:

$$\frac{\partial(\rho u h)}{\partial x} + \frac{\partial(\rho h)}{\partial t} - \frac{\partial p}{\partial t} = 0 \tag{5}$$

To meet the requirement of a maximum temperature gradient in a magnet (75 K), in this model the inlet helium temperature is regulated using one or two linear ramps until the maximum cooling/warming capacity is reached.

SIMULATION RESULTS AND DISCUSSION

Cooldown of a Main Dipole

To validate the mathematical model, it was used to simulate a cooldown process of a MB, which was tested in Feb. 2001. During the test, the flow rate was kept at 80 g/s and no limit for the temperature difference across the magnet was set. Good agreement was found between measured and simulated results shown in FIGURE 5.

Before understanding the thermal process of a complete sector and of a cell, a normal cooldown of a single magnet has been investigated in detail. During the simulation, the mass flow rate of 30 g/s is used and the temperature difference over the magnet is considered.

FIGURE 6 shows the details of the helium velocity and heat transfer capacity in this cooldown configuration. We can see from FIGURE 6 that larger channels have larger velocities and as a consequence higher mass flow. Due to the higher heat capacity, the largest channels contribute to the heat transfer mostly. The same phenomenon also occurs during the cooldown of MQ, where the largest channel, CH1, plays the major role in heat transfer.

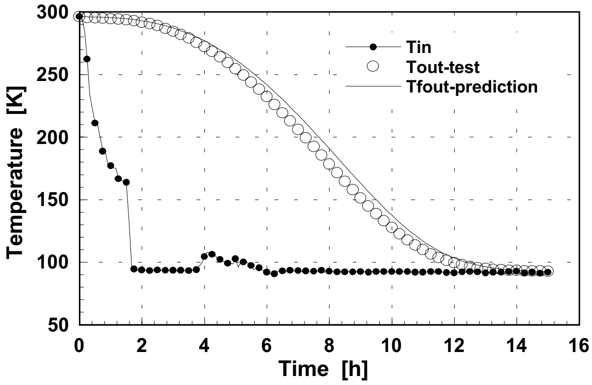

FIGURE 5. Simulation results and test data (02.2001) of MB cooldown

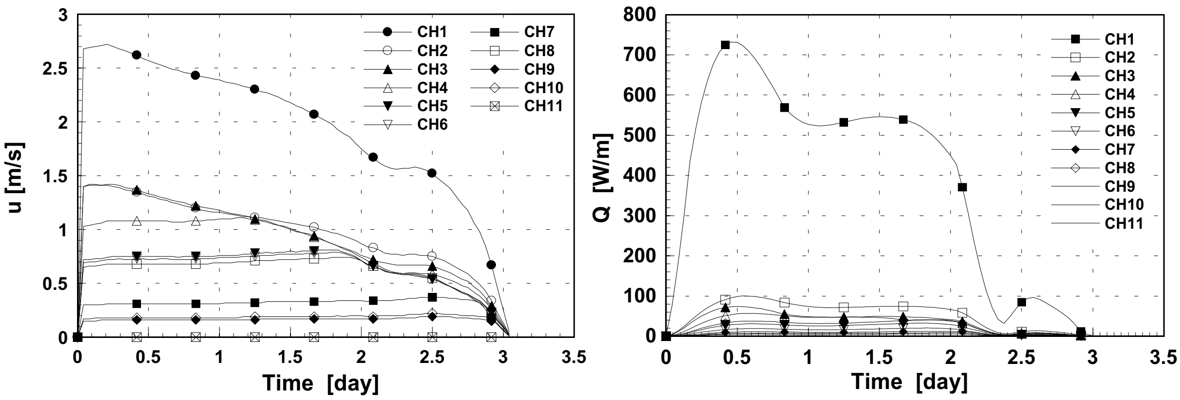

FIGURE 6. Helium velocity and heat transfer capacity at the middle of a MB during a normal cooldown

Cooldown and Warmup of a Standard Cell

FIGURE 7 and FIGURE 8 show the temperature evolutions and profiles of the cold mass for the normal cooldown of a LHC standard cell of type A and B, respectively. FIGURE 9 shows the temperature evolutions and profiles of the cold mass for the normal warmup of a LHC standard cell of type A. In these cases, the mass flow rate is 28.6 g/s, corresponding to the distribution of flow available for a sector proportional to the mass to be cooled, and the helium inlet temperature optimized to keep the maximum temperature difference along each magnet as close as possible to 75 K to obtain the fastest process. As a result, the cooldown process both for type A and B standard cell takes a little more than 11 days, and the warmup process less than 9.5 days.

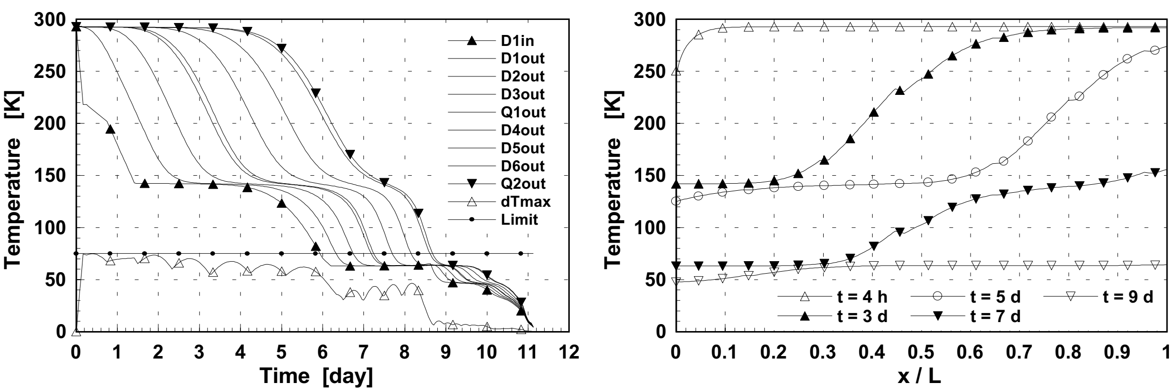

FIGURE 7. Normal cooldown of a standard cell of type A

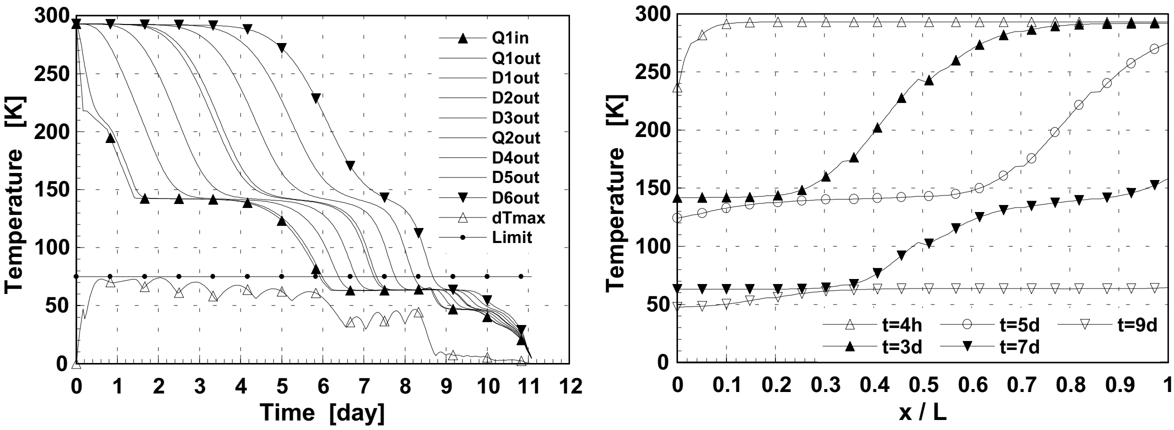

FIGURE 8. Normal cooldown of a standard cell of type B

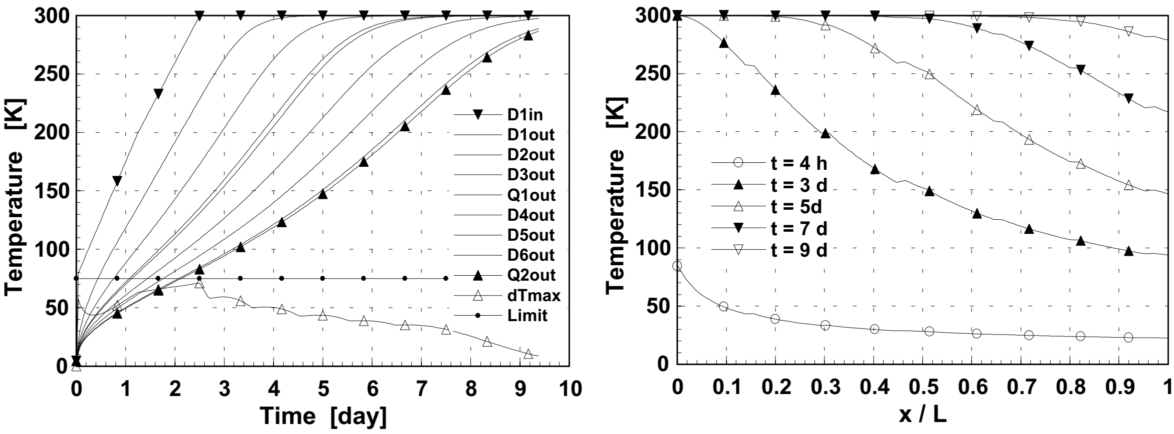

FIGURE 9. Normal warmup of a standard cell of type A

Cooldown and Warmup of a Sector

While operating a sector, attention should be paid to the flow distribution to each cell. A typical LHC sector (sector 8-1) has been studied using the model developed for the standard cell.

At first we tried to distribute the mass flow proportional to the cold mass of each cell, which resulted in a long overall cooldown time (nearly 20 days for normal cooldown). This was due to the cooldown speed of the magnets of the LSS limited by the small mass flow. Considering that the heat transfer coefficient between helium and the magnet is high and the temperature difference across each magnet cannot exceed 75 K, the helium inlet temperature of the whole section, had to be increased accordingly. In addition, the helium inlet temperature in some small cells far away from the refrigerator was warmer due to the cooldown of the supply headers.

Therefore, we doubled the flow in the LSSR/L, increasing the flow in the two smallest cells. Following this optimization of the total mass flow distribution of 770 g/s, the flow in a standard cell is about 27.5 g/s, the flow in LSS is about 40 g/s and in DS about 30 g/s. With this mass flow consideration, the normal cooldown of sector 8-1 takes about 12 days, the fast cooldown about 6½ days (FIGURE 10), the normal warmup about 11 days, and the fast warmup less than 6 days (FIGURE 11).

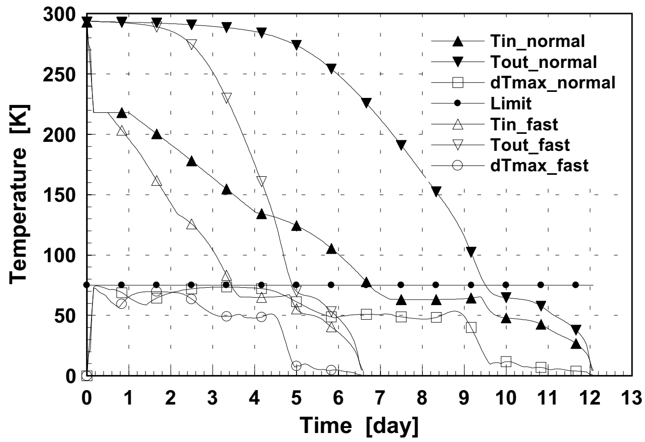

FIGURE 10. Normal and fast cooldown of sector 8-1

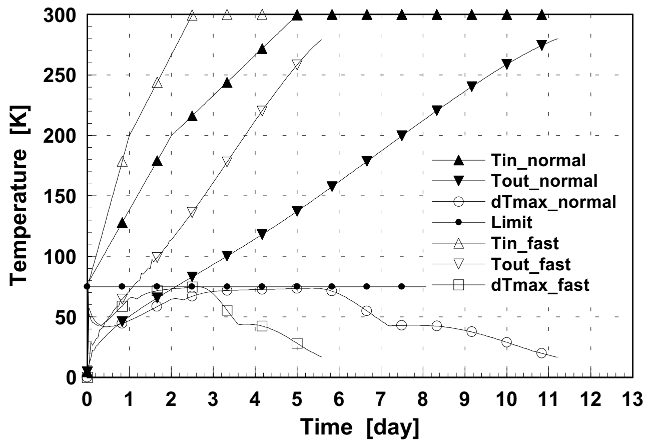

FIGURE 11. Normal and fast warmup of sector 8-1

CONCLUSIONS

The mathematical models for LHC transient modes such as cooldown and warmup of a magnet, followed by a standard cell and those for the eight LHC sectors, have been developed on the basis of the up-to-date layout of the LHC machine and validated by test data. Using the models, the simulation of cooldown and warmup of these items have been made, the heat transfer in magnets studied, and the transient modes of a typical sector have been optimized. It is possible to cool down a LHC sector in about 12 days in normal operation and in about 6½ days in case of fast operation. With respect to the previous estimation [3], the cooldown time of a sector has been increased by about 10%.

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