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LHC Project Report 50

INVESTIGATION OF THERMAL AND VACUUM TRANSIENTS ON THE LHC PROTOTYPE MAGNET STRING

P. Cruikshank, N. Kos, G. Riddone and L. Tavian

Abstract

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Investigation of Thermal and Vacuum Transients on the LHC Prototype Magnet String

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The prototype magnet string, described in a companion paper, is a full-scale working model of a 50-m length of the future Large Hadron Collider (LHC), CERN's new accelerator project, which will use high-field superconducting magnets operating below 2 K in superfluid helium. As such, it provides an excellent test bed for practising standard operating modes of LHC insulation vacuum and cryogenics, as well as for experimentally assessing accidental behaviour and failure modes, and thus verifying design calculations. We present experimental investigation of insulation vacuum pumpdown, magnet forced-flow cooldown and warmup, and evolution of residual vacuum pressures and temperatures in natural warmup, as well as catastrophic loss of insulation vacuum. In all these transient modes, experimental results are compared with simulated behaviour, using a non-linear, one-dimensional thermal model of the magnet string.

INTRODUCTION

The Large Hadron Collider (LHC) project [1], currently under design at CERN, will make use of high field superconducting magnets operating below 1.9 K in a pressurised bath of helium II. Superconducting magnet cold masses are housed in horizontal cryostats [2] with several layers of heat interception and screening. Prototype full-scale models [3] have been built, tested and assembled into a test String [4,5] in order to validate nominal and accidental operational modes.

The superinsulation system is composed of an intermediate shielding at 50-75 K and a radiative insulation at 4.5-20 K. The thermal shield at 50-75 K is covered with 30 layers of multilayer reflective insulation and the cold mass is wrapped with 10 layers of the same superinsulation [6].

Nominal insulation vacuum of 10^{-4} Pa can be achieved first by insulation vacuum pumpdown and then by cryopumping during cool-down. Pumpdown experiments on the String have been made to identify times, the effect of conditioning of the multilayer reflective insulation (MLI) and the acceptable initial pressure for cooldown.

Thermal transients represent standard operation modes which have to be studied in order to be able to assess maximum thermal gradients in the magnet during fast cooldown and warmup. Interventions on the LHC machine may require forced-flow warming of only a few magnets. It is of interest to know the time required for warming up, pumping down and cooling down for nominal operation and to understand how the reminder of the machine will behave in a passive state.

Another transient mode is produced by accidental loss of insulation vacuum. It may occur because of an air leak from the ambient surroundings or an internal helium leak from a cryogenic circuit. The vacuum vessel for the LHC dipole cryostat is made of ISO 430 carbon steel and in case of loss of insulation vacuum it will progressively cool down, but must not reach the embrittlement temperature of the material.

INSULATION VACUUM PUMPDOWN

LHC cryostats must be pre-evacuated, to achieve both rapid and efficient cooldown. The insulation vacuum space of the String is characterised by the 10 m^3 volume and the surface outgassing from 10^4 m^2 of MLI. First pumpdown of the insulation vacuum shows high water vapour gas load from the MLI surface.

prolonged exposure to ambient air during a 3 month shutdown, returned the system to initial conditions.

Pumping of vacuum enclosures is characterised by a volumetric and outgassing component. On String pumpdowns where the system has been exposed to air, the outgassing component dominates after a few hours pumping, between 10^2 and 10^3 Pa. In the case of conditioning and repumping, the outgassing component dominates in the region 1 to 10 Pa. For the two scenarios, a pressure of 1 Pa was achieved in approximately 30 and 3 hours respectively.

A series of experiments have been performed to investigate the upper pressure limit to begin cooldown, and show a pressure of about 1 Pa as acceptable. This value is anyway a requirement for room temperature leak testing of the vacuum enclosure using helium mass spectrometer technology.

FORCED-FLOW COOLDOWN AND WARMUP

Cooling down from room temperature to 80 K and warming up from 80 K to 300 K are achieved by flowing gaseous helium respectively at decreasing and increasing temperatures. The inlet helium temperature is regulated on the total string gradient in order to avoid thermal stresses in the magnets.

The evolution of magnet and helium temperatures have been simulated by a one-dimensional non-linear computer model, shown schematically in figure 1. 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. The mass and the specific heat of the cold mass (Cp_M) have been calculated from magnet design and the helium specific heat (Cp_{He}) from property tables [7]. Helium flows through several channels connected in parallel and only those which see turbulent flow, contribute to the heat exchange. The cold mass laminated structure allows longitudinal heat conduction to be neglected. 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:

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

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

Boundary conditions: 1) at any location, $T_M(t=0)$=constant
2) at any time, $T_{He}(x=0)$=constant

At each node, we calculate cold mass temperature (T_M) and helium temperature (T_{He}) as a function of time (t).

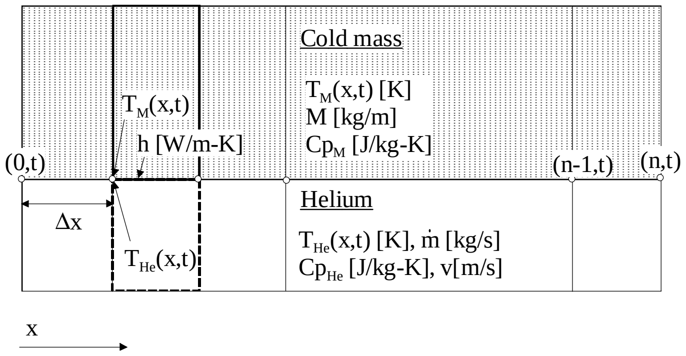

Figure 1: Mathematical model scheme of forced-flow string cooldown and warmup

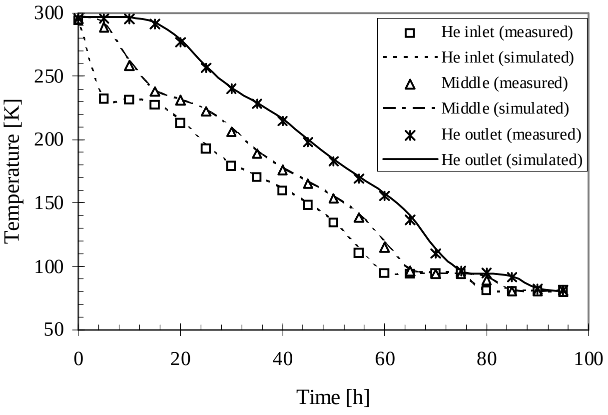

Figure 2: Forced-flow cooldown of LHC prototype String (300-80 K)

difference (ΔT_{max}) between helium and magnet during the different measurement runs. The time needed for cooldown and warmup strongly depends on the imposed maximum driving temperature difference between helium and cold mass as well as on the mass-flow.

For the first three runs, string cooldown started once the insulation vacuum was around 10^{-2} Pa whereas during Run2B residual gas pressure was maintained at about 1 Pa. Residual gas pressure of 1 Pa did not affect the cooldown time because the added heat inleak is negligible in comparison with the high heat capacity of the cold mass.

Figure 2 shows the forced-flow cooldown of the LHC prototype magnet String (Run2A) and compares simulated and measured data.

Table 1: Main parameters of the string forced-flow cooldown and warmup

	Cooldown				**Warmup**		
	M [kg]	$\dot{m}$ [g/s]	ΔT_{max} [K]	Time 300-80 K [h]	$\dot{m}$ [g/s]	ΔT_{max} [K]	Time 50-300 K [h]
Run0	$45 \cdot 10^3$	50	50	85	50	50	100
Run1	$45 \cdot 10^3$	50	60	70	80	60	55
Run2A	$65 \cdot 10^3$	60	60	85	natural and accelerated warmup		
Run2B	$65 \cdot 10^3$	80	60	70	— — — — — — — — — — — —		

NATURAL AND ACCELERATED WARMUP

Figure 3 shows the thermal flow-scheme used for the one-dimensional radial model simulating heat transfer during warmup [3]. Convection in nitrogen gas is negligible in the case of natural warmup, whereas it is relevant in case of accelerated warmup. Solid conduction through the insulation spacers and radiation between the layers of superinsulation are negligible in both the cases. Convection cannot occur in the superinsulation due to the restrict space between spacers.

Natural warmup without active pumping on the insulation vacuum started after a quench when the cold mass temperature was around 30 K and the thermal shield at 90 K. After about 20 hours of natural warmup residual gas pressure in the insulation vacuum degraded rapidly to 1 Pa. The end composition at 50 K was mainly composed of hydrogen (10 %) and carbon monoxide (25 %) from the superinsulation outgassing and of nitrogen (40 %) and oxygen (10 %) from a known air leak. The gas species at this pressure is not relevant since the thermal impedance given by radiation is at least a factor 5 higher than that due to conduction in residual gas. The test was stopped after 6 days when the cold mass was at 90 K and the thermal shield at 180 K

In order to simulate an accidental loss of vacuum insulation, warmup was then accelerated by injecting N_2 in the insulation space of the cryostat. Atmospheric pressure inside the cryostat was reached after 30 minutes. After another 30 minutes, condensation followed by frost was observed in distinct cold spots on the external surface of the cryostat beneath the lower end of each dipole. They could be attributed to the longitudinal heat transfer by natural convection. The lowest of these cold spots was at 230 K. In order to prevent embrittlement of the carbon steel wall of the vacuum vessel the insulation vacuum was pumped down to $5 \cdot 10^4$ Pa. The String temperatures were allowed to evolve at this pressure for 2 weeks until they reached 300 K.

Figure 4 shows the evolution of the String average temperatures during natural (1 Pa) and accelerated warmup ($5 \cdot 10^4$ Pa) and compares experimental and simulated data. Thermal impedance due to conduction in residual gas is not negligible and this underlines the important role of superinsulation in case of an accidental loss of insulation vacuum.

The maximum calculated heat flux from the thermal shield to the cold mass was 300 W/m and it was reached after a few hours. In nominal conditions the heat inleak at 1.9 K is about 0.4 W/m and during a magnetic resistive transition is of the order of 100 kW/m.

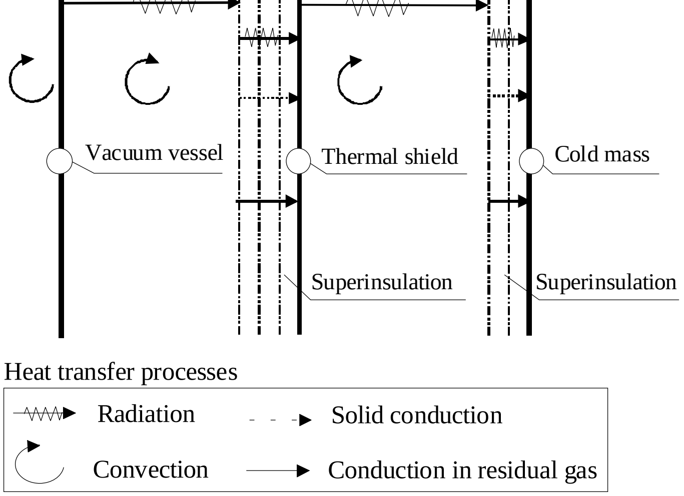

Figure 3: Flow scheme of natural and accelerated warmup

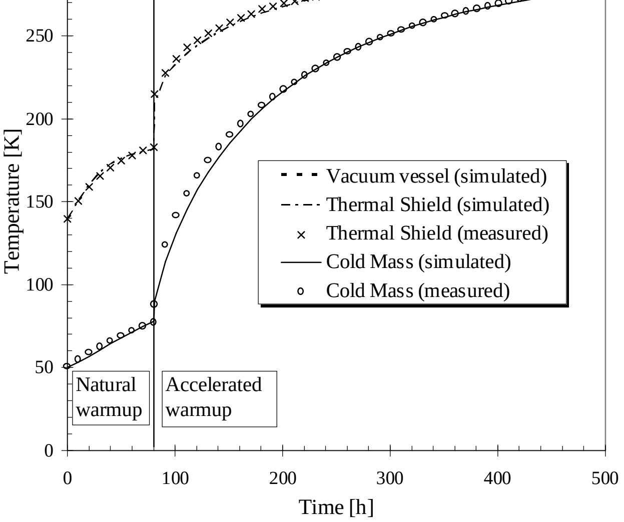

Figure 4: LHC prototype String temperatures during natural and accelerated warmup

CONCLUSIONS

Thermal and vacuum transient modes in a full scale LHC prototype string have been performed successfully and confirmed the basic design choices. It has been showed that it is possible to cooldown or warmup the $65\cdot10^3$ kg of the LHC string cold mass in less than 4 days with 60 g/s of gaseous helium and a maximum longitudinal thermal gradient in the magnet of 60 K.

Simulation of loss of vacuum insulation by nitrogen gas injection at $5\cdot10^4$ Pa is not considered catastrophic and the vacuum vessel minimum temperature of 230 K is still within the limit accepted for carbon steel embrittlement. The power received by the cold mass is small in comparison with that dissipated after a magnetic resistive transition .

Mathematical models developed for studying forced cooldown and warmup, natural warmup and accidental loss of insulation have been checked and validated against experimental data. These simple models can be used to predict the behaviour of the LHC machine cryostats under nominal and accidental conditions.

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