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THERMAL PERFORMANCE OF THE LHC CONNECTION CRYOSTAT

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Abstract

The 16 connection cryostats for the Large Hadron Collider (LHC) being built at CERN are designed to fill the gap existing between the dispersion suppressor zones and the standard arcs of the accelerator. The first connection cryostat was cold tested down to superfluid helium temperature in August 2005, and the measured thermal performance was as expected. This paper presents the test results and a new thermal modeling of the connection cryostat based on the measurement of the thermal resistances of the braids used for thermalisation, allowing the precise determination of cool down times and equilibrium temperatures of the shielding under various conditions such as lead heating.

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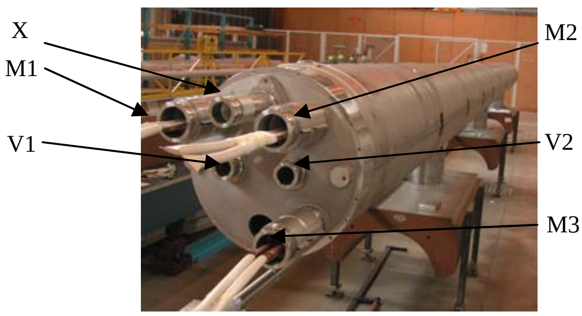
THE CONNECTION CRYOSTATS (CC)

These cryogenic assemblies of 13 m length house a pseudo cold mass comprising the set of cryogenic, electrical busbars and vacuum conduits which ensure the continuity of the LHC main cryostat utilities (see Figure 1). Two pairs of main quadrupole busbars and one pair of main dipole busbars transit respectively through the M1, M2 and M3 tubes, connected at each CC extremities to the main magnet cold masses, filled with pressurized superfluid helium at 1.9 K (see Figure 2). The V1 and V2 beam pipes are cooled via an annular bath of pressurized superfluid helium contained in coaxial tubes. This annular space has direct links with the M1 and M2 lines via flexible hoses. Half way through the cold mass, the M and X lines are connected to a central helium reservoir, the so-called shuffling module, which houses the busbar loops (lyras) used to compensate for thermal contraction between room temperature (RT) and 1.9 K. In order to protect from beam-induced radiation the sensitive components and apparatus installed around these cryostats in the LHC tunnel, lead shielding plates are installed around the beam pipes inside the cold mass.



Figures 1&2. Completed connection cryostat and its cold mass

MECHANICAL AND THERMAL DESIGN

As shown on Figure 3, the CC structure is of a “cage” type. The cold mass is composed of 10 identical segments of ~1.2 m length, each housing a ~170 kg lead box composed of plates enclosing the V1 and V2 beam tubes. The structure is thermalized via 4 OFHC copper braids (transverse section of 4*400 mm^2) clamped to the M1 and M2 heat sinks. The lead shielding is thermalized by its welded supporting structure, and by a copper link equipped with stainless steel extremities welded on the holding lead bracket and the M1 line.

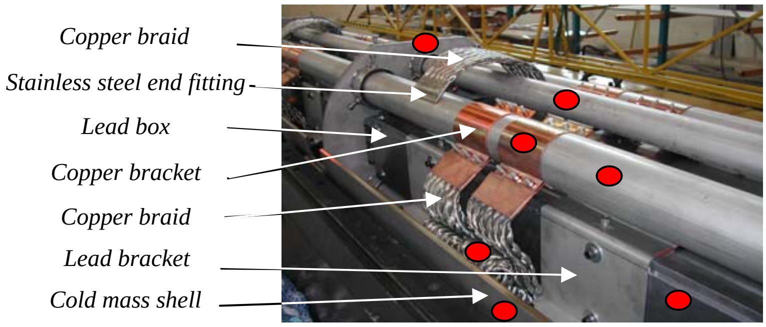


Figure 3. Thermalization of a cell of the cold mass. Position of the temperature sensors

Although the central shuffling module includes a heat exchanger with the X line, providing a few watts of cooling power at 1.9 K, the main source of heat extraction is conduction in superfluid helium through the M lines to the adjacent cryomagnets. The transverse area of the superfluid helium conduits (M, N lines, and annular space around V1 and V2) have been sized to provide a constant temperature of 1.9 K (within 0.1 K) for the maximum specified heat loads of 0.95 W/m, of which 0.2 W/m are deposited in each of the V1 and V2 beam lines. The cool down of the whole structure from RT to a stable operating temperature must take less than 6 days [1]. Between RT and 4.5 K the cool-down is ensured by a forced flow of gaseous helium through the M lines (100 g/s). During cool down, temperature gradients across the mechanical structure must remain within allowable limits [2].

THERMAL PERFORMANCE

A CC equipped with 40 calibrated carbon-type temperature sensors, placed in strategic locations of the cold mass (see Figure 3), was connected to an LHC magnet cold test feed-box providing helium gas for the cool down, liquid helium to fill the tubes of the cold mass, and a pumping line connected to the X tube heat exchanger.

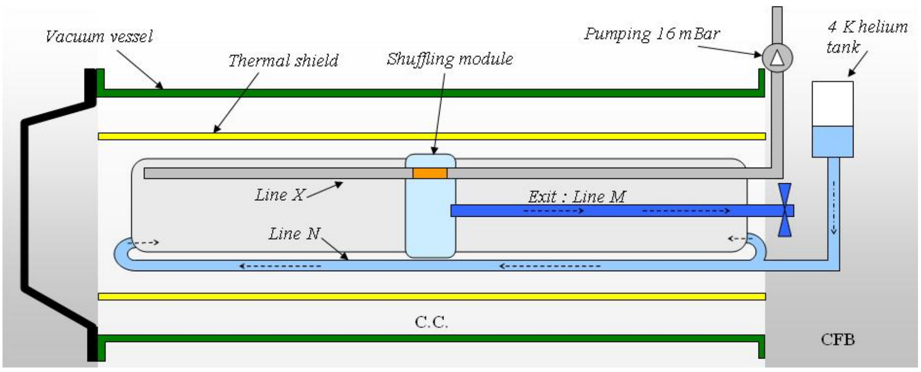


Figure 4. Schematic of the test-set-up, with the CC connected to CFB (Cooling Feed Box)

Table 1 gives a summary of the values obtained for the cooling rates in various parts of the cold mass and the equilibrium temperatures achieved, in line with the expectations, despite the limited cooling power available and parasitic heat in-leaks of the test stand [3].

Table 1. A summary of cool down rates and final equilibrium temperatures, expected and achieved

	Cool down 300K to 90K after 33 hours			**Cool down** From 90K to 4K (136 hours)		**Final state** at 1.9K (42 hours)
	Tempera-ture	End state	expected	Tempera-ture	expected	Temperature
M tubes	115 K	*stabilised*		4.1 K	4K	1.9 K
Cold mass up	240 K	*1.83 K/hour*	*2.11 K/hour*	9.8 K	7.1 K	6.9 K
Cold mass down	225 K	*1.83 K/hour*	*2.11 K/hour*	9.1 K	5.3 K	5.5 K
Copper braid hot clamps	200 K	*2.63 K/hour*		4.3 K		2.2 K
Copper braid cold bracket	150 K	*stabilised*		4.6 K		4.5 K
Lead block	230 K	*2.18 K/hour*		5.8 K	5 K - 7 K	4.5 K

The efficiency of the copper thermalization braids was confirmed. The final state equilibrium temperatures were as expected. However the fact that the lead shielding blocks could reach temperatures at which it would be superconducting (lead critical temperature, no field, of 7.2 K), was identified as a potential problem to the LHC beams in case of resistive transition [5].

A SIMPLIFIED THERMAL SIMULATION MODEL

To determine precisely the equilibrium temperatures of the lead shielding and therefore assess the real risk of having the lead superconducting in nominal machine conditions, a semi-empirical thermal model based on the measured thermal resistances linking together the cold mass shell, the lead shielding, and the lines M (cold sink) was used [4]. This model, based on the schematic shown in Figure 5, solves the time dependent heat transfer equations of a segment of CC containing one lead shielding block, for the two positions relevant to the thermal structure for which temperatures were recorded:

$$\frac{dH^L}{dt} + \frac{1}{R_3}(T_1 - T_3) + \frac{1}{R_1}(T_1 - T_2) - P_1 = 0$$

$$\frac{dH^S}{dt} + \frac{1}{R_2}(T_2 - T_3) - \frac{1}{R_1}(T_1 - T_2) - P_2 = 0$$

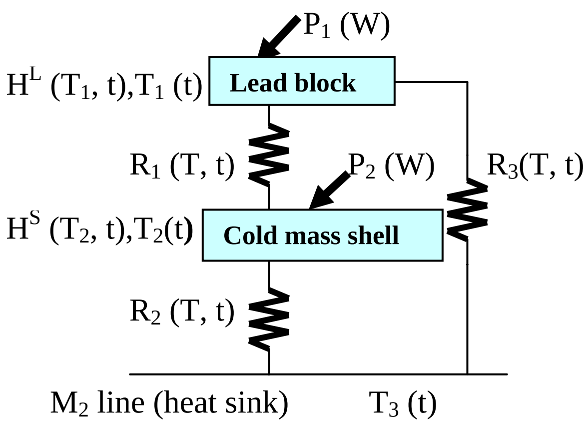


Figure 5. Schematic of a three thermal resistance model of the CC and governing equations

H^L and H^S are respectively the lead block and shell segment enthalpies at temperatures T_1 (lead) and T_2 (shell) during cool down. T_3 is the temperature of the heat sink (M lines), R_2 and R_3 are the thermal resistances of the two types of copper braids used respectively to thermalize the cold mass shell (R_2) and the lead block holding bracket to the M1 tube (R_3). R_1 is the thermal resistance of the stainless steel supports of the lead block. R_1, R_2 and R_3 include the thermal contact resistances. P_1 and P_2 are respectively an optional power injected into the lead block (thermal or beam induced), and the power radiated to the shell by the 65 K cold mass thermal shield. R_1, R_2 and R_3 are obtained over the whole temperature range (see Figure 6) during cool down from estimated enthalpy fluxes and measured temperatures at their boundaries [4]. The thermal model reproduced within a few percent the measured temperatures of the CC (see Figure 6), and confirmed sub-critical equilibrium temperatures of 6-7 K of the lead shielding blocks when nominal machine conditions will be applied.

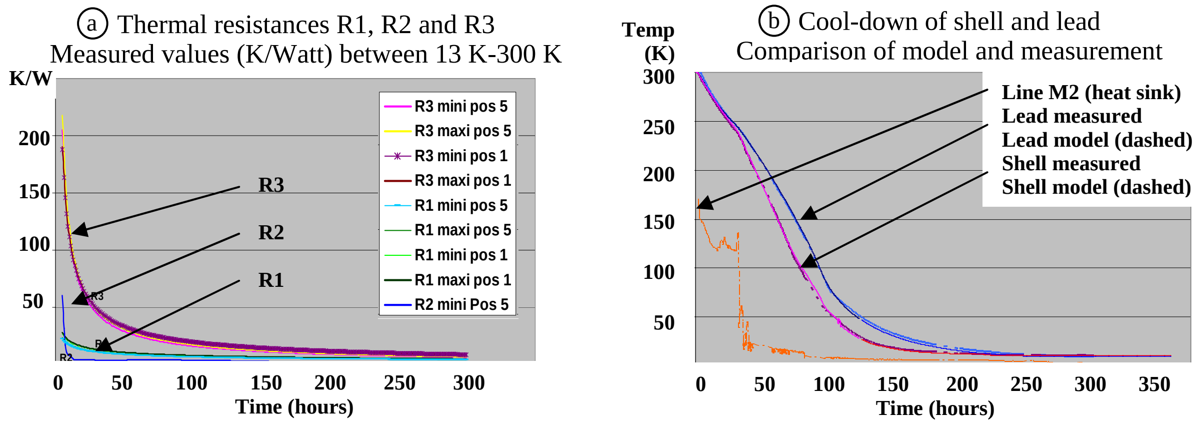


Figure 6. CC thermal resistances R_1, R2 and R_3 and model prediction of the test cool down

CONCLUSIONS

The thermal time constants and equilibrium temperatures of the shielding lead blocks and of the cold mass of the CC in nominal machine conditions, i.e. with the nominal radiated power from the thermal shield, are conform to the expected values.

A simplified thermal model of the connection cryostats based on three thermal resistances has been derived. The model allowed the determination of the lowest power that would have to be injected into the lead shielding in order to keep it from being superconducting. A power of 0.2 watts will be fed into the lead blocks via aluminum wires of 25 cm length and 2.5 mm in diameter, representing an additional extracted power per CC of 2 watts by the 1.9 K cooling system.

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