Large Hadron Collider Project

LHC Project Report 204

THERMAL PERFORMANCE OF THE LHC EXTERNAL AUXILIARY BUS-BAR TUBE: MATHEMATICAL MODELLING

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Abstract

The Large Hadron Collider (LHC) externally routed auxiliary bus-bar tube (EAB) will house the electrical feeders of the LHC short straight section (SSS) correcting magnets. The superconducting wires will be contained in a stainless steel tube and immersed in a quasi-static helium bath. The EAB thermal performance during the cooling of the magnets down to the operating temperature of 1.9 K is studied. A 3-d finite element thermal model of the EAB during a cooling process from 293 K to 4.5 K is described. The semi-analytical model of the EAB cool-down from 4.5 K to 1.9 K is also presented.

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1. INTRODUCTION

The LHC auxiliary bus-bar tube feeding the SSS correcting magnets will be routed outside the cold masses. The electrical feeding will consist of a pair of cables comprising a number (varying from 40 to 80 in total depending on the position along the arc) of ∅ 1.6 mm superconducting copper wires. The cables will be immersed in a quasi-static helium bath and contained in a 50 x 54 mm stainless steel tube located between the cold masses outer wall and the radiation screen (Figure 1).

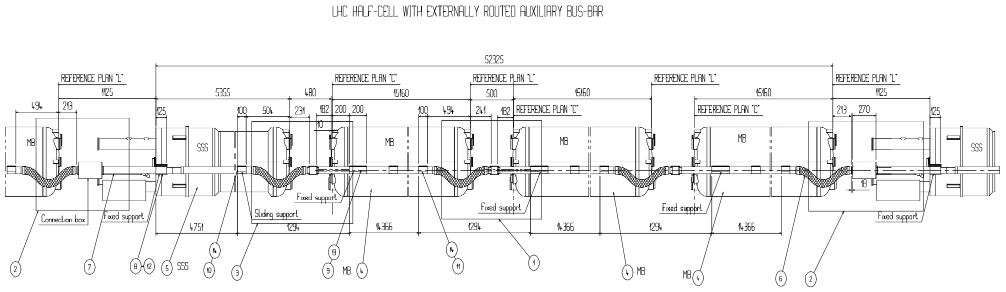


Figure 1: Layout of the LHC half-cell with the EAB tube

Every LHC half-cell, eight superconducting wires will pass through the interconnection box to the cold mass to allow connection to their individual SSS correctors. The mechanical stability of the tube requires one fixed support point for each dipole magnet and SSS, [1]. Over a half-cell this results in four thermalisation points of the tube along the EAB and two full thermalisation points (tube + cable) at the ends. In addition, optional supplementary thermalisation points in a form of copper braids are considered, one for each cold mass. The tube will take the form of an appendix to the cold mass. Therefore, the helium inflow will be possible only from one end of a half-cell. The other end will be closed with a plug.

2. COOL-DOWN PROCESS FROM 293 K TO 4.5 K

2.1 Finite element model description

A 3-d thermal model of the half-cell EAB during a cool-down was developed using the ANSYS® finite element program. The model represents the full geometry of the tube together with the fixed supports to the LHC cold masses. In order to simplify the model, only one solid cable of a mass equivalent to eighty ∅ 1.6 mm wires was located in the center of the tube.

The modelling of the heat transfer includes conduction in the solids and in the helium as well as radiation. In the quasi-static conditions resulting from the one-sided helium inflow to the EAB, only a natural convection can occur. It is not included in the model as its contribution to the cooling process is negligible compared to the two other heat transfer modes.

The conduction is simulated using the temperature-dependent thermal conductivity coefficients for the appropriate materials (Table 1). For the helium, a pressure drop from 10 bar to 1.3 bar during a cool-down is assumed. The conduction through the fixed supports is assumed to occur only through the welded joints. It is considered that these joints are 3 mm wide on both ends of the support all around the tube, and 6 mm wide horizontally on the cold mass along the support.

Radiation heat transfer occurs between the tube surface and both the cold mass and the radiation screen. Due to this complex geometry, a simplified model consisting of a surrounding coaxial ∅ 80 mm cylinder was considered. The cylinder's diameter was determined so that the radiation heat load was equivalent or smaller than in the real system in order to keep the model within conservative limits. The EAB as well as the cold mass shrinking cylinder will be made of stainless steel, whereas the radiation screen is of aluminium. As the emissivity values of stainless steel and aluminium do not differ very much, the temperature-dependent emissivity of stainless steel was used both for the tube and for the cylinder surfaces (Table 2).

Temperature [K]	100 RRR Copper	Stainless Steel AISI 304	Helium
300	397	15	0.157
200	407	13	0.118
150	419	11	0.097
100	461	9.5	0.074
15	2400	2.6	0.022
4	624	0.24	0.019

Table 1: Thermal conductivity coefficients [W/m·K], [2,3,4]

Temperature [K]	Emissivity coefficient
300	0.20
80	0.12
4	0.10

Table 2: Emissivity coefficient for stainless steel, [5]

The boundary conditions for the EAB are determined by the temperatures of the cold masses and the radiation screen. An assumption is made that the cold masses and the radiation screen have the same uniform temperature and that cool-down follows a linear decreasing function of time. The initial value is set to 293 K and the final value to 4.5 K at the end of the cool-down. For the EAB the initial temperature value of 293 K was assumed. Two scenarios of the magnets cool-down process were considered: a standard 12-day and a fast 6-day cool-down.

The temperature profiles along the copper cable obtained using the model for fast and standard cool-downs are presented in figure 2. Looking from left to right, a SSS followed by three dipole magnets can be seen. The thermalisation points are visible as the minima on the plots. The two curves on each plot correspond to the two possible system layouts, one with fixed supports as the only thermalisation, the other one with supplementary thermalisation in the form of copper braids, one for each cold mass.

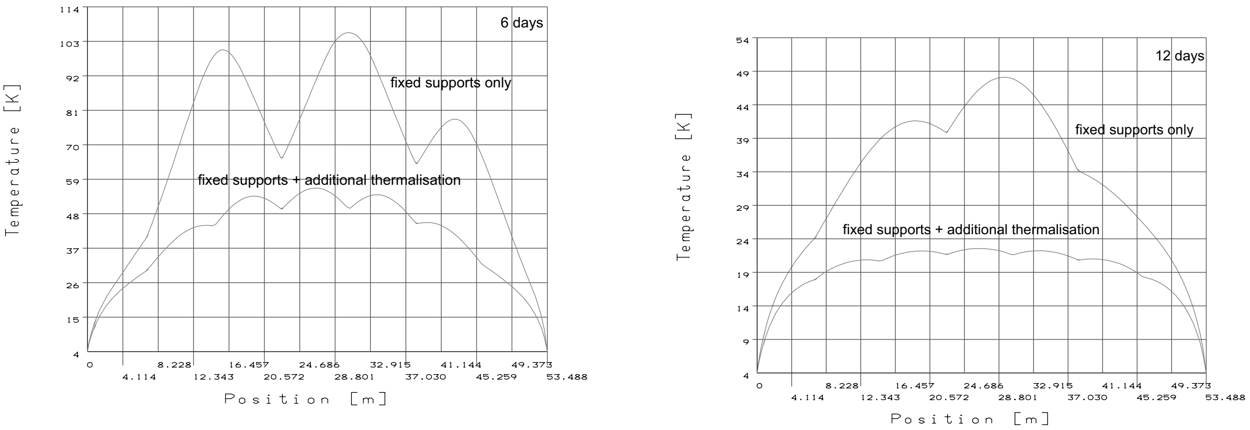


Figure 2: Calculated temperature distributions along a half cell EAB after a fast and a standard cooldown

2.2 Final cool-down to 4.5 K-qualitative description

After cooling down the cold mass to 4.5 K and filling it with He I, the gaseous He in the EAB will still have the average temperature of 20-50 K (see Figure 2). The next step will be to cool it down to 4.5 K. It will require some additional time determined by the following transient processes :

- heat conduction via the fixed supports
- residual radiation
- increase in the density of He gas with the decreasing temperature at the constant pressure of 1.3 bar
- quasi-static inflow of cold liquid He from the cold mass to the EAB tube via the interconnection box.

The saturated He I will stay in thermal and hydraulic equilibrium with the gaseous He, pushing it progressively out of the EAB through the capillary linking the connection box with the cold mass. The density of He I at 4.5 K is 119 kg/m^3 whereas for gaseous He at 50 K it is 1.25 kg/m^3. Therefore, He gas filling the EAB tube completely at 50 K will constitute only 1% of the tube volume after cooling down to 4.5 K and 99% of the tube volume will be filled progressively with He I [4]. This transient thermo-hydraulic process is rather difficult to model mathematically and the time required has been determined from experiment. A test made in the LHC Test String showed that the above described process was terminated within 2 h 40 min. However, it was made in a slightly different configuration and can only be roughly applied to the EAB.

3. COOLING PROCESS FROM 4.5 K TO 1.9 K

The temperature range between 4.5 K and 1.9 K in helium 4 at 1.3 bar includes the “λ-transition” at $T_\lambda = 2.17$ K, where helium becomes superfluid. In the present calculation, the tube is supposed to be filled with liquid helium at 4.5 K, when the leftmost extremity of the tube is (abruptly) cooled to 1.9 K. This corresponds to the arrival of the λ-front in the magnet cold masses at the location close to the interconnection box. Following this the λ-front propagates in the EAB tube with a velocity **c** (Figure 3), which determines the time needed for all the helium in the EAB to become superfluid.

In order to estimate this time, the heat diffusion equation should be solved in two different regions separated by the moving λ-front. Unlike melting or condensation, the λ-transition is not characterized by any latent heat, so the condition to be satisfied at the λ-front is that the longitudinal heat fluxes are equal on both sides. Given the thermal properties of copper and liquid helium at 4.5 K, this condition is approximately equivalent to equalizing heat fluxes in the superfluid helium and the copper cable.

Following [6], the equations can be solved analytically supposing that the λ-front propagation has a travelling wave dependence. For the He I region, the heat diffusion equation can be written as :

$$(\rho c_p S)_{HeI} \cdot \frac{\partial T}{\partial t} = (kS)_{Cu} \cdot \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where: ρ, c_p – density and specific heat of He I, k – conductivity of copper, S – cross-section area. The terms $(\rho c_p S)_{Cu}$ and $(kS)_{HeI}$ are neglected as they are small compared to the two others. The postulated solution is in the form of a plane wave T=T(x-ct), where c is a wave front propagation speed. After substituting it in (1) and integrating once, one obtains:

$$(\rho c_p S)_{HeI} \cdot c \cdot T + (kS)_{Cu} \cdot \frac{\partial T}{\partial (x-ct)} + f(x-ct) = 0$$

There are two boundary conditions for this equation : equality of the fluxes at the λ-front and $T_f = 4.5$ K and $\partial T/\partial(x-ct) = 0$ (approximately) at the other end of the He I region. These two conditions permit the unknown function f(x-ct) to be eliminated :

$$(\rho c_p S)_{HeI} \cdot c \cdot T_\lambda + (kS)_{Cu} \cdot \left.\frac{\partial T}{\partial (x-ct)}\right|_\lambda = (\rho c_p S)_{HeI} \cdot c \cdot T_f + (kS)_{Cu} \cdot \left.\frac{\partial T}{\partial (x-ct)}\right|_f$$

$$(\rho c_p S)_{HeI} \cdot c \cdot T_\lambda + \left[y(1.9K) \cdot \frac{T_\lambda - 1.9K}{x_\lambda} \right]^{0.294} = (\rho c_p S)_{HeI} \cdot c \cdot T_f$$

where: y(T) – thermal conductivity of He II, [7,8], x_λ - λ-front position along the tube. Assuming a constant wave velocity c and substituting x_λ by c·t, one can calculate the time at which x_λ equals to the tube length of 53 m. An improvement on this solution is obtained if one takes into account the conduction in the copper cable through the plug into the neighbouring half-cell of the EAB (considered to be at 1.9 K), combined with the length dependence of the critical heat flux. Figure 4 below shows the time needed to cool the whole tube and shows the importance of the latter contribution. From the present calculation, this time is about 3 h 50 min.

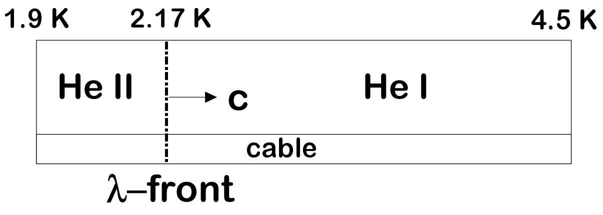
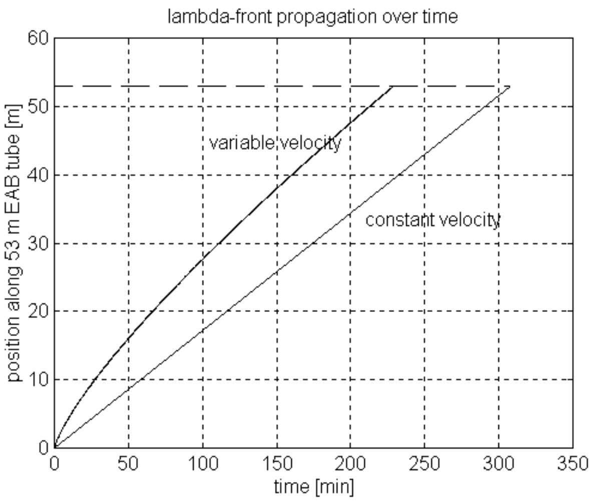


Figure 3: Schematic view of the λ-front propagation in the EAB tube



4 CONCLUSIONS

The thermal behaviour of the LHC externally routed auxiliary bus-bar tube during the cool-down of the magnets was studied in three distinct stages. First, from the ambient temperature to the filling of the cold mass with liquid He I at 4.5 K, the finite element model was used. The temperature profiles were calculated and the maximum temperatures were found to be perspectively with or without the optional thermalisation points: 55 K and 105 K for the fast cool-down and 20 K and 47 K for the standard cool-down. This shows the effect of the optional additional thermalisation. The next stage, filling of the EAB with liquid He I, was described qualitatively as the processes involved are too complex for any simple mathematical model. The experimental estimate of the time measured on the LHC Test String in a slightly different configuration was 2 h 40 min. Finally, the EAB cooling from 4.5 K to 1.9 K with the λ-front propagation in helium was solved semi-analytically. It yielded the estimation of an additional 3 h 50 min needed to transform He I into superfluid He II in the EAB.

5 REFERENCES

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