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COPPER HEAT EXCHANGER FOR THE EXTERNAL AUXILIARY BUS-BARS ROUTING LINE IN THE LHC INSERTION REGIONS

C. Garion[1], A. Poncet[1], F. Seyvet[1], M. Sitko[2], B. Skoczen[2], J.P. Tock[1]

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The corrector magnets and the main quadrupoles of the LHC dispersion suppressors are powered by a special superconducting line (called auxiliary bus-bars line N), external to the cold mass and housed in a 50 mm diameter stainless steel tube fixed to the cold mass. As the line is periodically connected to the cold mass, the same gaseous and liquid helium cools both the magnets and the line.

The final sub-cooling process (from around 4.5 K down to 1.9 K) consists in the phase transformation from liquid to superfluid helium. Heat is extracted from the line through the magnets via their point of junction. In dispersion suppressor zones, approximately 40 m long, the sub-cooling of the line is slightly delayed with respect to the magnets. This might have an impact on the readiness of the accelerator for operation. In order to accelerate the process, a special heat exchanger has been designed. It is located in the middle of the dispersion suppressor portion of the line. Its main function consists in providing a local point of heat extraction, creating two additional lambda fronts that propagate in opposite directions towards the extremities of the line.

Both the numerical model and the sub-cooling analysis are presented in the paper for different configurations of the line. The design, manufacturing and integration aspects of the heat exchanger are described.

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INTRODUCTION

The externally routed auxiliary bus-bar line forms a narrow channel of 50 mm ID attached directly to the LHC main magnets and connected via interface boxes to the cold-mass every half-cell (2 dipoles and 1 quadrupole in the LHC dispersion suppressors). A simplified typical cryogenic layout in the LHC dispersion suppressors is shown Fig. 1. Polyethylene fillers are introduced in the line N to reduce the helium volume and to increase the λ front velocity.

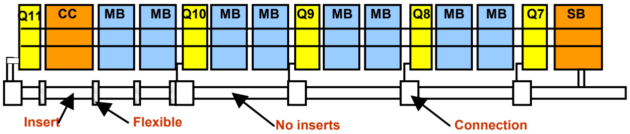


Figure 1: Typical general layout of the LHC DS.

Line N and cold mass have the same operating conditions (temperature of 1.9 K and pressure of 1.3 bar). Nevertheless, a delay of subcooling (between 4.5 K and 1.9 K) is observed for the transient regime. To ensure the high availability of the LHC, this delay has to be reduced as much as possible, in such a way that the cooling down of the line remains in the shadow of the cold mass. A simplified 1-D model of the lambda front propagation has been developed to evaluate the subcooling time and the benefits of the implementation of a copper heat exchanger. This model gives a reasonably good approximation of the single front propagation speed.

NUMERICAL MODEL

First a channel of constant cross-section, without bus-bars, is considered. It is supposed to be initially filled with 4.5 K helium and subcooled to 1.9 K by the left extremity. It is assumed that the heat transport regime is turbulent and steady-state. No radial heat transfer across the wall of the tube is considered [1].

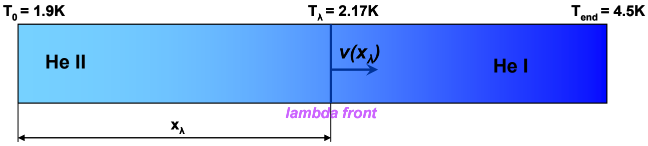


Figure 2: λ front propagation in a channel.

The heat transfer in the superfluid helium is governed by the Gorter-Mellink equation [2], for the heat flux $\dot{q}$:

$$f(T)\frac{dT}{dx} = \dot{q}^3$$

where dT/dx and $f(T)$ denote the temperature gradient and the heat conductivity function, respectively. The conductivity as a function of temperature below the lambda point is given Fig. 3.

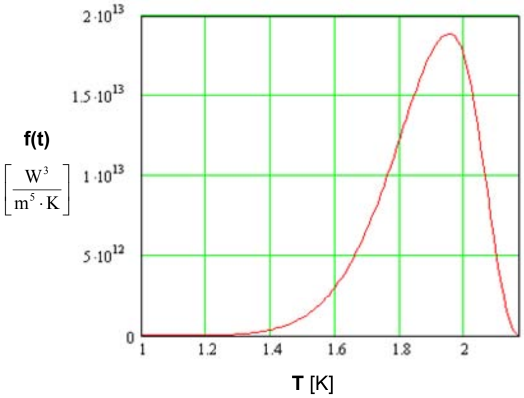


Figure 3: Helium heat conductivity as a function of temperature (below the λ point).

For a constant diameter tube, the integration of the Gorter-Mellink equation leads to :

$$\dot{q}(x_\lambda)=\left[\frac{\int_{T_0}^{T_\lambda} f(T)dT}{x_\lambda}\right]^{\frac{1}{3}}$$

Knowing the heat flux, the velocity of the lambda front is calculated by using the amount of energy that can be extracted from He I:

$$v(x_\lambda)=\frac{\dot{q}(x_\lambda)}{\int_{T_\lambda}^{4.5K}\rho_{HeI}(T).c_{p\_HeI}(T)dT}$$

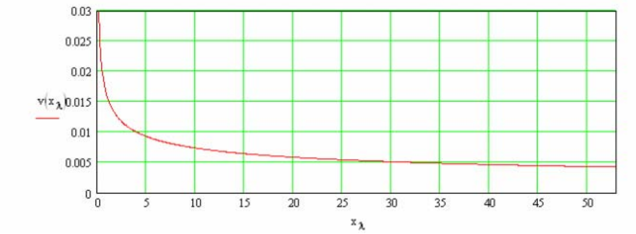


Figure 4: Velocity of λ front along the channel.

Finally, the time for complete cool down is derived as:

$$t=\int_0^L \frac{1}{v(x_\lambda)}dx$$

where: L is the length of the tube

A similar approach can be used for a channel with transverse section discontinuities by considering conservation of heat flux ($\dot{q}_i S_i$ constant along the channel, $\dot{q}_i$ denotes the heat flux in the channel portion *i* of length and cross-section l_i, S_i, respectively). For the λ-front in the portion *n*, the general form of the heat flux reads:

$$\dot{q}_n(x_\lambda)=\frac{1}{S_n}\left[\int_{T_0}^{T_\lambda}F(T)dT \Big/ \sum_{i=1}^{n-1}\frac{l_i}{S_i^3}+\frac{(x_\lambda-\sum_{i=1}^{n-1}l_i)}{S_n^3}\right]^{\frac{1}{3}}$$

The method has been applied also for a T-shaped configuration.

Heat transport in the tube filled with liquid helium and containing a copper barrier inside is modelled by using the Gorter-Mellink law in the superfluid helium area and the Fourier conduction law in case of copper.

Additionally, at the interface between helium and copper a thermal surface resistance exists. This induces a temperature difference at the interface, through which the heat flux is given by:

$$\dot{q}=h_K\cdot\Delta T$$

where h_K is the Kapitza coefficient and ΔT denotes the temperature difference across the boundary.

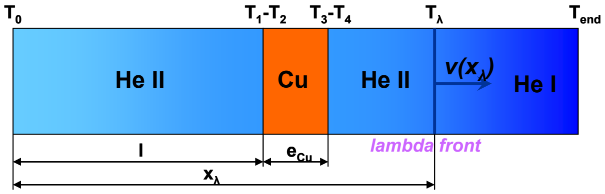


Figure 5: channel with a copper barrier.

On the temperature profile shown in Fig. 6 it is easy to identify the transition from nonlinear temperature distribution in liquid helium to linear in copper and "jumps" across the boundary area due to the Kapitza resistance.

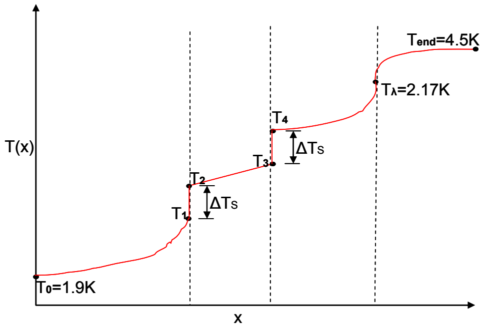
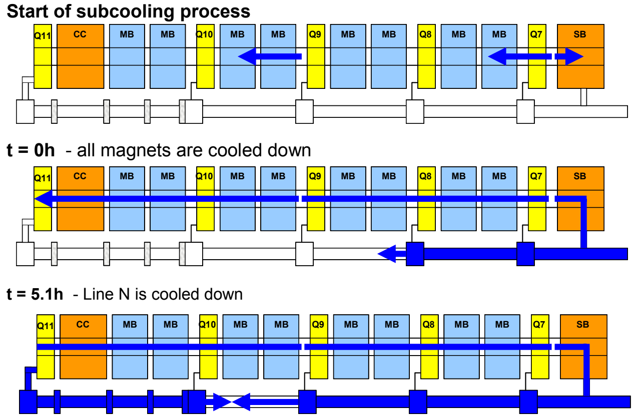


Figure 6: Temperature profile along the tube with copper plug.

SUB-COOLING ANALYSIS OF LHC DISPERSION SUPPRESSORS

The model has been benchmarked using the results of tests preformed in String 2, a full-scale model of the LHC cell. It has been applied to the dispersion suppressors. The velocity of the lambda front propagation in the magnets is assumed to be constant and equal to 6.5 mm/s (according to the average measured value [3]). The time of Line N cool-down is counted from the moment when all magnets are already at 1.9 K.


Start of subcooling process

t = 0h - all magnets are cooled down

t = 5.1h - Line N is cooled down

Figure 7: Sub-cooling process in line N without heat exchanger.

In order to accelerate the process, a special heat exchanger has been designed. It is located in the middle of the dispersion suppressor portion of the line. Its main function consists in creating a local heat sink, providing two additional lambda fronts that propagate in opposite directions towards the extremities of the line. The sub-cooling process is illustrated in Fig. 8. The following main parameters of the heat exchanger were used [3]:

- Cross section of the link between the heat exchanger and the cold mass higher than 16 cm^2
- Copper surface area higher than 400 cm^2
- Kapitza coefficient: 0.5 W/cm^2K

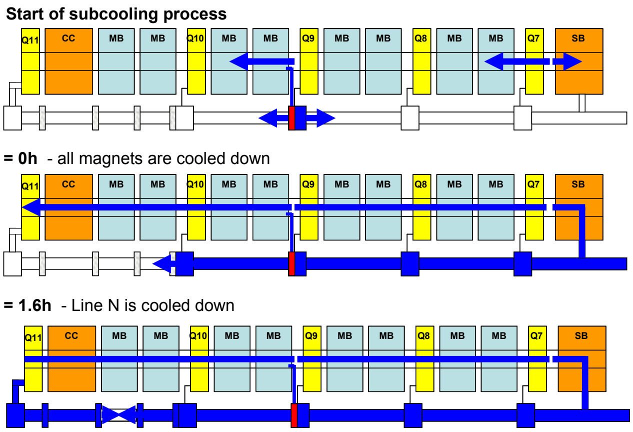


Figure 8: Sub-cooling process in line N with heat exchanger in the middle of LHC Dispersion suppressor.

The delay of sub-cooling of line N with respect to the cold masses is shown in Table 1 for different LHC DS zones.

Table 1: Delay of sub-cooling with copper heat exchanger.

DS zone	Delay [h]
DS1L	1.32
DS2L & DS8L	1.32
DS4L	1.23
DS5L	1.19
DS6L	1.15
DS1R	0.63
DS2R & DS8R	0.67
DS4R	1.34
DS5R	1.34
DS6R	0.44

HEAT EXCHANGER: TECHNOLOGICAL ASPECTS

A picture of the copper heat exchanger is presented in Fig. 9. Due to space constraints, the link between the cold mass and the line N is made of two pipes of 32 mm inner diameter and the connection to the copper heat exchanger pieces comprises 4 pipes, each of 22.9 mm inner diameter. The heat exchanger consists of 4 copper boxes. Each box is composed of a main body and a cap that are soldered together using Ag-Pd-Cu at ~810°C. Then the boxes are soldered on the stainless steel flange with a Cu-Ag eutectic at 780°C. To ensure a good soldering, the maximum gap between pieces is limited to 0.05 mm.

A model of the heat exchanger integration is shown in Fig. 10. The heat exchanger is linked to two sleeves that close the bus-bar lines in the interconnections. Metal hoses have been introduced to allow for differential thermal contraction and to compensate for the geometrical defects during the installation.

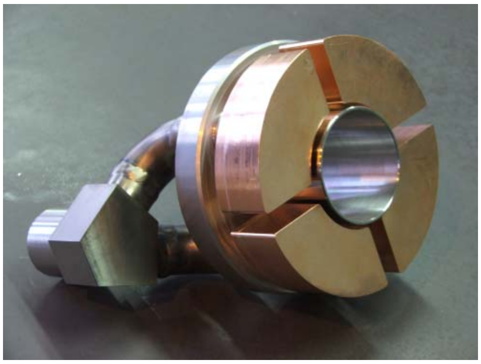


Figure 9: The heat exchanger.

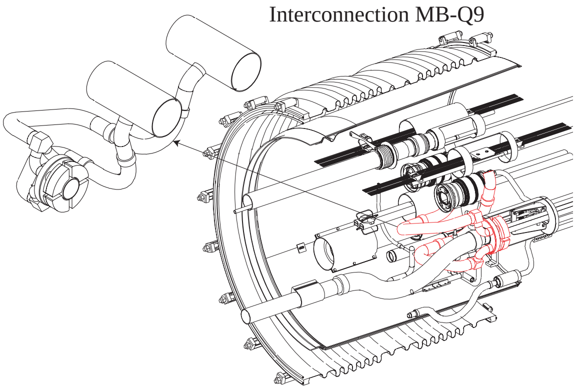


Figure 10: Integration of the heat exchanger in the LHC interconnection.

CONCLUSION

A 1-D model of heat transfer in superfluid helium has been developed to evaluate the sub-cooling time of the LHC external bus-bar line. A copper heat exchanger is installed in a LHC dispersion suppressor interconnection to reduce the sub-cooling delay by creating a local heat sink, providing two additional λ fronts. Its performance is being tested at CERN.

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