MODEL OF HE I/HE II PHASE TRANSITION FOR THE SUPERCONDUCTING LINE POWERING LHC CORRECTORS

M. Sitko, B. Skoczeń, Cracow University of Technology, Cracow, Poland

Abstract

The array of corrector magnets in the LHC is powered by means of a superconducting line attached to the main magnets. The subcooling time of the line has to be minimized in order not to delay the operation of the collider. The corresponding cable-in-conduit problem is formulated in the framework of two-fluid model and the Gorter-Mellink law of heat transport in superfluid helium. A model of lambda front propagation along the narrow channel containing superconductors and liquid helium is presented. The one-dimensional model adopts plane wave equations to describe lambda front propagation. This approach to normal-to-superfluid phase transition in liquid helium allows to calculate the time of subcooling and the temperature profile on either side of the travelling front in long channels containing superconducting bus-bars. The model has been verified by comparing the analytical solutions with the experimental results obtained in the LHC String 2 experiment. The process of the LHC Dispersion Suppressors subcooling has been optimized by using the presented model. Based on the results, a novel concept of copper heat exchanger for LHC DS operating in superfluid helium is introduced.

INTRODUCTION

Application of liquid helium in particle accelerators allows to transport energy efficiently over long distances by using superconducting cables and achieve high field in magnets. Liquid helium, which undergoes the second-order phase transition at low temperatures from normal-liquid to superfluid state (lambda transition), appears to be a perfect coolant not only because it provides the proper temperature for superconducting cables but also due to its extraordinary heat transport properties. However, the mathematical description of subcooling process (cooling down from 4.5K to 1.9K) becomes very complicated when taking into account the superfluid state and lambda transition.

HEAT TRANSFER IN SUPERFLUID HELIUM

Heat transport in a long, narrow channel of constant diameter, filled with He II can be described in terms of the Gorter–Mellink equation [1], [2]:

$$\dot{q}^3 = f(T)\,dT \tag{1}$$

where $\dot{q}$ is the heat flux, *f(T)* represents the conductivity function of superfluid helium and T is the temperature. One-dimensional model of heat transfer is considered. The use of 1D model is justified when modelling heat transport in long channels of small diameter when compared to its length.

Since the second-order phase transition excludes the possibility of stable coexistence of phases, it is assumed that during subcooling from the temperature T_{end} to T_0 the lambda front moves along the channel at a speed v (Fig.1). Furthermore, it is assumed that both He I and He II are in quasi-steady state, heat transport in superfluid helium is turbulent (above the critical heat flux) and there is no radial heat transfer across the wall of the channel.

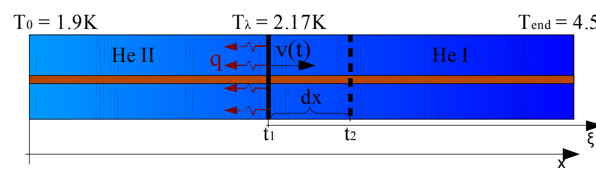

Figure 1: Channel filled with liquid helium.

Lambda front velocity can be calculated based on the amount of heat extracted from He I:

$$v(x_\lambda) = \frac{\dot{q}(x_\lambda)}{\int_{T_\lambda}^{T_{end}} \rho_{HeI}(T)\, c_{pHeI}(T)\, dT} \tag{2}$$

where ρ_{HeI} and c_{pHeI} are the density and the heat capacity of He I respectively. Knowing the velocity of lambda front propagation, the time of subcooling can be derived as:

$$t = \int_0^L \frac{dx}{v(x_\lambda)} \tag{3}$$

where L is the length of the channel.

Heat transport in the tube filled with liquid helium and containing a copper barrier inside is modelled by using the Gorter – Mellink law (Eq.1) in the superfluid helium region and the Fourier law in the copper. Additionally, at the interface between helium and copper, thermal boundary conductance occurs. This phenomenon, discovered by Kapitza, consists in a big temperature drop across the liquid/solid interface and can be mathematically described by the following equation:

$$\dot{q} = h_K \cdot \Delta T_s \tag{4}$$

where h_K is the Kapitza coefficient and ΔT denotes the temperature difference across the surface between helium and copper.

MODELLING LAMBDA FRONT PROPAGATION

The above presented models were used in order to model subcooling process and lambda front propagation in the superconducting line powering corrector magnets, placed in the dispersion suppressors of the LHC accelerator.

There are 16 dispersion suppressor (DS) zones in the LHC machine. They are placed in the ring between DFB's and the arcs. Typical layout of dispersion suppressor consists of a string of magnets: 4 quadrupoles, each followed by 2 dipoles, and a connection cryostat. In the superconducting line in this part of accelerator auxiliary 600 A busbars and additionally 6 kA superconductors are pulled through the total length of each DS.

The superconducting line is the last part of the accelerator to be subcooled. The goal to achieve was reduction of the subcooling time of the line to around 2 hours more when compared to the cool-down time of magnets. Thus, in the LHC dispersion suppressors a special copper heat exchanger had to be used in order to reduce the time of subcooling. The heat exchanger is a unique solution aiming at initiation of propagation of second-order phase transition in helium, without changing the configuration of sectors of the superconducting line. (Fig. 2)

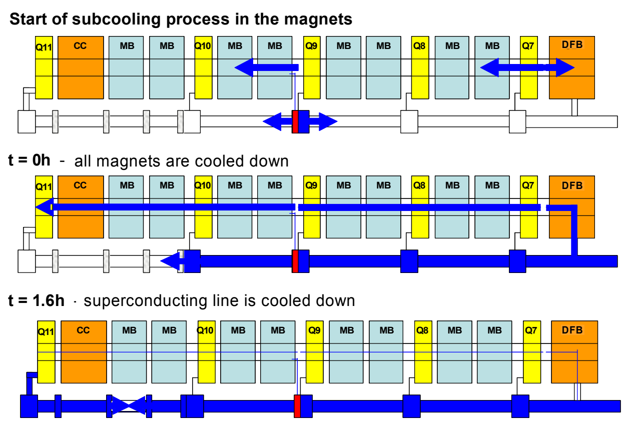

Figure 2: Subcooling of dispersion suppressor with copper heat exchanger integrated.

The heat exchanger is modelled as a copper barrier placed in the middle of the channel. Position of the heat exchanger allows to start cool down of the superconducting line in the same time when magnets are being cooled down. The heat exchanger is connected to the magnets by a small helium inlet channel and lambda front propagates starting from the magnets, across copper barrier and then along the superconducting line in two directions. One can change the heat flux by modifying the design parameters, such as inlet channel diameter, copper barrier thickness and heat exchange area as well as copper surface cleanness, which is related to Kapitza resistance.

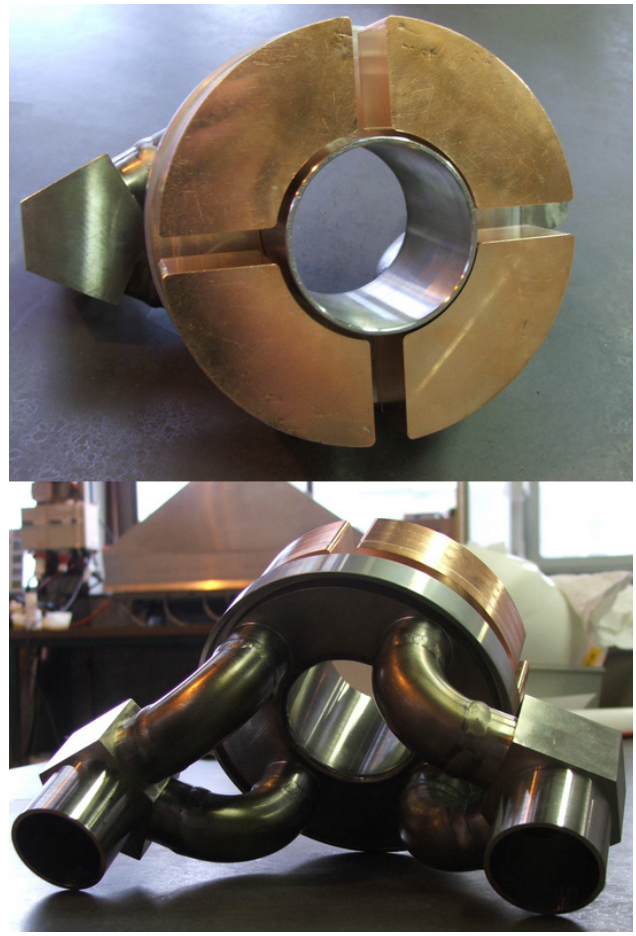

Figure 3: Copper heat exchanger.

TEMPERATURE PROFILES IN NORMAL AND SUPERFLUID HELIUM

The temperature profile in He II is derived by integration of the Gorter-Mellink law (Eq. 1):

$$x(T)=\frac{\int_{T_0}^{T} f(\eta)\, d\eta}{\dot{q}^{3}_{HeII}} \tag{5}$$

where, for the sake of simplicity, it is assumed that the heat flux along the channel is constant.

The temperature profile in He I is obtained based on "cable-in-conduit" problem by considering concentric configuration of superconductor located in the middle of long, narrow channel filled with liquid helium [3]. The Fourier law written both for cable and helium, with the assumption of perfect heat transport between both in the radial direction reads [4]:

$$\left[(\rho c_p A)_{HeI}+(\rho c_p A)_{Cu}\right]\frac{\partial T}{\partial t}= \left[(k A)_{HeI}+(k A)_{Cu}\right]\frac{\partial^2 T}{\partial x^2} \tag{6}$$

For a spacio - temporary problem the change of variables is applied: $\xi = x - vt$ as well as the assumption that the beginning of coordinate system moves together with lambda front. As the specific heat of copper is small when compared to helium and the conductivity of liquid helium is insignificant when compared to copper, one can simplify Eq. 6 to the following form:

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial \xi^2} - v(t)\frac{\partial T}{\partial \xi} \tag{7}$$

where $D = (kA)_{Cu}/(\rho c_p A)_{HeI}$ is a combined thermal diffusivity and is assumed to be constant here.

By solving Eq.7 one obtains the temperature profile in He I [4]:

$$\begin{aligned} T(\xi,t) = T_{end} &+ \frac{T_{end} - T_\lambda}{\lambda_1 - \lambda_2}\left(\lambda_2 e^{\lambda_1 \xi} - \lambda_1 e^{\lambda_2 \xi}\right) \\ &+ \frac{\tilde{D}\dot{q}_\lambda}{\lambda_1 - \lambda_2}\left(e^{\lambda_1 \xi} - e^{\lambda_2 \xi}\right) \end{aligned} \tag{8}$$

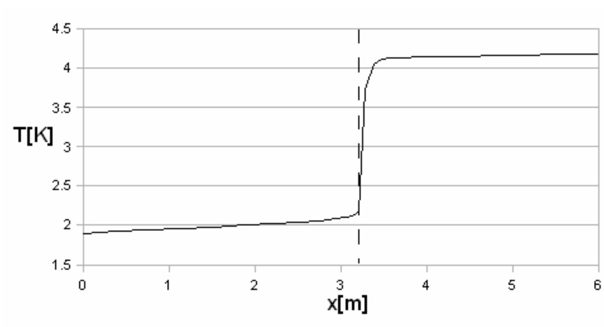

Figure 4: Calculated temperature profile.

EXPERIMENTAL VERIFICATION

String 2 was a full-size unit of the LHC accelerator consisting of 2 quadrupoles and 6 dipoles, built in order to check compatibility of all systems under working conditions (Fig. 5).

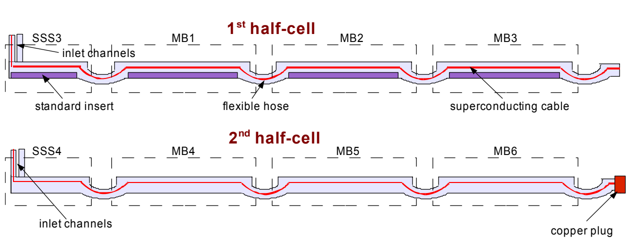

Figure 5: String 2 configuration of superconducting line.

The comparison of measured and calculated of subcooling time superconducting line in String 2 is shown in Table 1. In the 2nd half-cell in Part II of the experiment three scenarios were considered: subcooling of superconducting line only by the lambda front coming from the inlet channels (1st lambda front), subcooling by the lambda front coming from the copper plug (2nd lambda front) and simultaneous subcooling by the 1st and the 2nd lambda fronts.

Table 1: Time of subcooling – comparison of experiments and calculations

Time of subcooling		Measurements [h]	Calculations [h]
Part I	1st half-cell	3.1	3.5
	2nd half-cell	5.5	4.3
Part II	1st half-cell	1.9	3.1
	2nd half-cell		
	1st front	3.7	3.4
	2nd front	11.5	10.9
	1st & 2nd front	2.2	2.4

Because of good agreement between the numerical and experimental results, one-dimensional model appears to be sufficient and the calculations made by means of this model are acceptable.

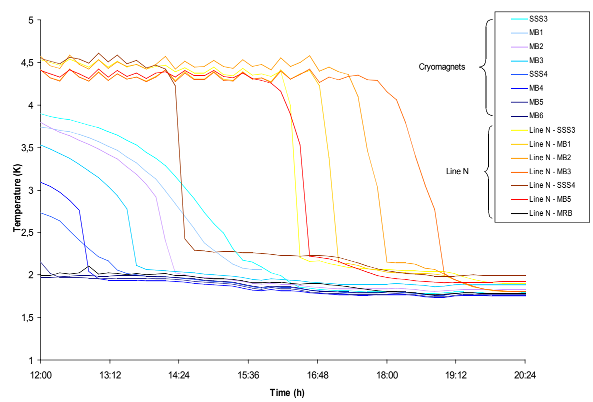

Figure 6: Temperature profiles measured in String 2.

CONCLUSIONS

The above derived model of He I – He II travelling phase transition can be easily applied to simulate subcooling process of modern particle accelerators equipped with superconducting magnets. Numerical simulation of subcooling process implies the possibility of faster and better design as well as parametric optimisation of topology of the lines containing superconductors.

REFERENCES

[1] C. J. Gorter, On the Thermodynamics of the Two Fluid Model of Helium II, Physica 15 (1949).

[2] S. W. Van Sciver, Helium Cryogenics, Plenum Press (1986).

[3] L. Dresner, Transient Heat Transfer in Superfluid Helium - Part II, Advances In Cryogenic Engineering 29 (1984).

[4] M. Sitko, B. Skoczeń, Modelling He I – He II phase transformation in long channels containing superconductors, Int. Journal of Heat and Mass Transfer 52 (2009).