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CURRENT LEADS SYSTEM FOR A SUPERCONDUCTING CYCLOTRON

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Résumé - Dans ce papier sont présentés les résultats d'une étude concernant l'optimisation des amenées de courant du cyclotron supraconducteur en cours de réalisation à Milan.

Abstract - In this paper the data and the criteria for the optimisation of the Milan superconducting cyclotron current leads are presented.

1- INTRODUCTION

In the project of the current leads for the Milan superconducting cyclotron /1,2/ we have planned to realize a system which fulfils the following conditions:
- the heat flow into the helium bath is kept at low levels (typically 1.0 - 1.2 mW/A);
- in the case of coolant loss the leads must survive during a slow coil discharge (survival time must be of the order of 1000 s);
- the pressure drop in the leads is hold within a few tens of mbar to assure an helium bath temperature lower than 4.3 °K .

The same current lead type, as realized for the BEBC and EHS magnets /3,4/, has been chosen. The lead, machined from a full copper cylinder, has slotted discs, as shown in Fig. 1, and the cooling gas channel is obtained by shrinking on a stainless steel tube.

The leads project study has been worked out considering as free parameters the copper purity and the magnetic field.

2 - HEAT FLOW

The problem of minimising the heat flow into the helium bath has been extensively studied in the literature /5-8/, therefore we will recall only the salient points.

At the stationary conditions and in the ideal cooling hypothesis the temperature profile on a lead of length L is described by the differential equation:

$$\frac{d^2T}{du^2} + \frac{1}{k}\frac{dk}{dT}\left(\frac{dT}{du}\right)^2 + \frac{\varrho}{k}\frac{I^2L^2}{S^2} - \dot{m}\frac{c_p}{k}\frac{L}{S}\frac{dT}{du} = 0 \qquad (1)$$

where $u = x/L$ is the normalized coordinate along the lead axis, S is the effective electrical and thermal conductivity section (see paragraph 5), ϱ and k are the copper resistivity and thermal conductivity, c_p is the helium specific heat at constant pressure and $\dot{m} = \dot{m}_{self} + \dot{m}_{ext}$ is the total helium mass flow. The helium mass flow $\dot{m}_{self} = \dot{Q}_o/c_L$ (where c_L is the latent heat at the bath temperature and $\dot{Q}_o = k\ L^{-1} S\ (dT/du)_{u=0}$ is the heat flow into the bath) is produced only by the leads; $\dot{m}_{ext}$ is the mass flow available by any

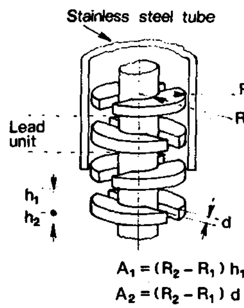

Fig. 1 - Current lead sketch

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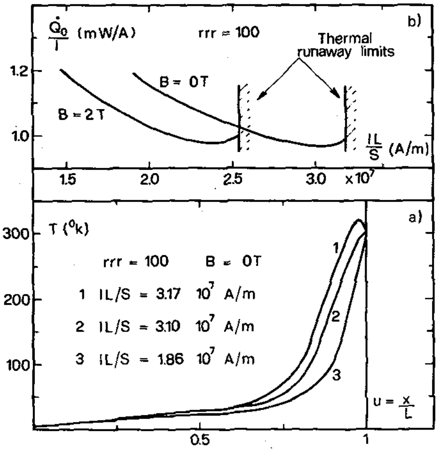

Fig. 2 - a) Temperature profile versus the normalized coordinate $u = x/L$.
b) Specific heat flow $\dot{Q}_o/I$ versus IL/S

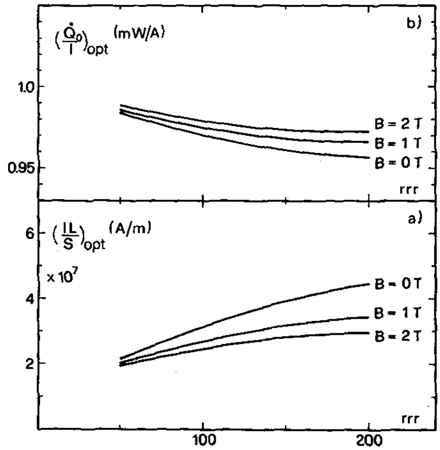

Fig. 3 - $(IL/S)_{opt}$ and $(\dot{Q}_o/I)_{opt}$ versus the copper residual resistivity ratio and the magnetic field.

other cryostat loss. The solution of the equation (1) with the extreme conditions:

$$T(u=0) = 4.2\ °K \qquad T(u=1) = 300\ °K \qquad (2)$$

has been obtained by the Runge Kutta method. The c_p, ϱ and k values are drawn from the NBS tables; for the last two quantities analytical expressions have been derived as a function of the absolute temperature, the residual resistivity ratio (rrr = $\varrho_{273} / \varrho_{4.2}$) and the magnetic field. The results of this study (with $\dot{m}_{ext} = 0$) are summarized in the Figs. 2-4, where the normalized parameters IL/S and $\dot{Q}_o/I$ are used in order to be indipendent of any particular length L or current I.

The Fig. 2b shows, for a given rrr value, an upper limit for the IL/S values: above it the solutions of the equation (1) are unstable and a thermal runaway is rising in the lead. This limit is close to the value $(IL/S)_{opt}$ (corresponding to the minimum heat flow $\dot{Q}_o/I$),therefore we can consider the latter as the unsurpassable limit in the lead project.For a conservative lead project is convenient to choose an IL/S value lower than $(IL/S)_{opt}$ of about 20-30%. This choice removes the danger of the thermal runaway (at the maximum current) keeping within acceptables values the heat flow into the bath. For example if IL/S = 0.7 $(IL/S)_{opt}$ the maximum heat flow increase is 10% (rrr = 50) or 17% (rrr = 200), as shown in Fig. 4a. The minimum heat flow is nearly independent on the copper purity (Fig. 3b); this result and the data reported in the Fig. 4a point out the advantage to use copper of low purity /5/.

3 - LOSS OF COOLANT

When there is a loss of coolant the lead must allow a slow discharge of the coil current without reaching a dangerous temperature (T_{max} = 800 - 1000 °K). For a conservative project we have examined the time evolution of the temperature profile in the case I = const. (no discharge). This process is governed by the differential equation:

$$\frac{d^2T}{du^2} + \frac{1}{k}\frac{dk}{dT}\left(\frac{dT}{du}\right)^2 + \frac{\varrho}{k}\frac{I^2L^2}{S^2} - L^2\nu\frac{C}{k}\frac{dT}{dt} = 0 \qquad (3)$$

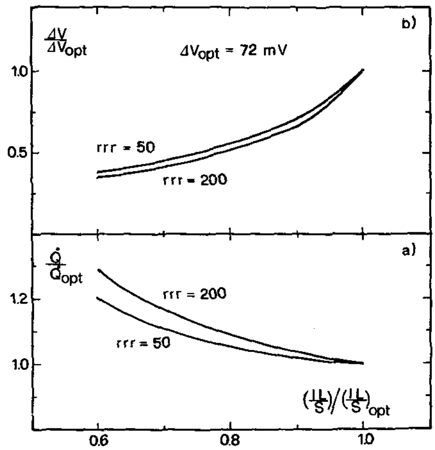

Fig. 4 - Plots of $\dot{Q}/\dot{Q}_{opt}$ and $\Delta V/\Delta V_{opt}$ versus $(IL/S)/(IL/S)_{opt}$.
The ratios are almost independent on the magnetic field.

where C is the copper specific heat and ν the lead equivalent density, defined by $\nu = (V_t/V_e)\ \nu_o$, where V_t is the total lead volume, V_e is the electrical and thermal conductivity volume and ν_o the copper density.

The equation has been solved neglecting the conductivity terms (at the beginning of the thermal runaway the conductivity power is only 1-2% of the Joule power). With this adiabatic approximation we have:

$$\tau = \frac{t}{\nu L^2} = \frac{1}{(IL/S)^2} \int_{T_1}^{T_2} \frac{C}{\varrho}\, dT \qquad (4)$$

where T_2 is the maximum temperature in the lead. We assume as temperature T_1 the mean initial temperature deduced by the following expression:

$$\int_{4.2}^{T_1} C(T)\,dT = \int_0^1 du \int_{4.2}^{T(u)} C(T)\,dT \qquad (5)$$

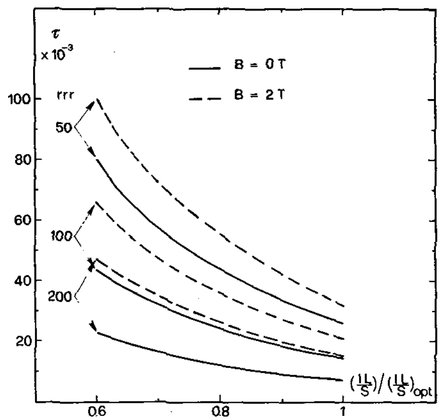

Fig. 5 - Time coefficient τ (for T_{max} = 800 °K) versus $(IL/S)/(IL/S)_{opt}$

where T(u) is the initial temperature profile. In the Fig. 5 are reported the τ values as a function of the $(IL/S)/(IL/S)_{opt}$ ratio, the residual resistivity ratio and the maximum lead temperature.

4 - PRESSURE DROP

Generally for the helium transfer pipes from the cryostat to the liquifier approximately a 100 mbar pressure drop is necessary; this overpressure in the cryostat corresponds at a bath temperature of 4.3 °K. To avoid a further reduction of the temperature gap between the superconductor critical temperature and the bath temperature, the lead pressure drop must be hold within a few tens of mbar.

For the pressure drop calculation we have assumed that the helium gas undergoes three sudden deviations in each lead unit and the mass flow is uniformly divided in the lead channels. With these assumptions the total pressure drop in the lead of length L is given by:

$$\Delta p_t = k_g\, k_T \frac{\dot{m}^2}{4\,\delta_{300}} \frac{L}{h_1 + h_2} \left(\frac{1}{8A_1^2} + \frac{1}{A_2^2} \right) \qquad (N/m^2) \qquad (6)$$

and for $h_1 = h_2 = h$ and $A_2 = 2\ A_1$ (see Fig. 1) the expression (6) becomes:

$$\Delta p_t = \frac{3}{64} k_g\, k_T \frac{\dot{m}^2}{\delta_{300}} \frac{L}{(R_2 - R_1)^2} \frac{1}{h^3} \qquad (N/m^2) \qquad (7)$$

where $\dot{m}$ is the mass flow, δ_{300} is the helium density at T = 300 °K, k_g is the kinetic energy loss rate at each sudden deviation, k_T is a temperature coefficient defined by:

$$k_T = \frac{L}{h_1 + h_2} \sum_{i=1}^{N} \frac{\delta_{300}}{\delta_{T_i}} \qquad N = \frac{L}{h_1 + h_2}$$

δ_{T_i} being the helium density at the mean temperature in the unit i. The parameter k_g must be determined experimentally whereas the k_T coef-

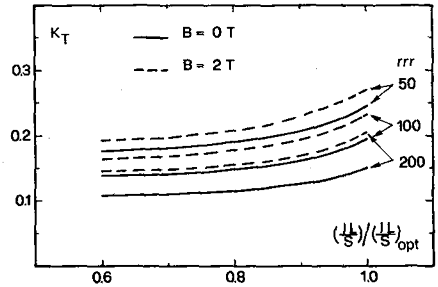

Fig. 6 - The parameter k_T versus $(IL/S)/(IL/S)_{opt}$ for different rrr and B values.

ficient can be calculated from the stationary temperature profile (Fig. 6).

5 - EXPERIMENTAL DATA AND RESULTS

The lead effective section coefficient ($k_s = S/\pi R_1^2$) has been determined for different disc heigths as the ratio between the voltage at the end of the lead and of a copper cylinder. The parameters k_g has been obtained as the ratio between the measured pressure drop and the calculated one in the case of nitrogen mass flow through different leads at room temperature ($k_T = 1$). The experimental data, expressed as a function of the channel or disc heigth in the lead, are reported in Fig. 7.

The Milan current leads have been dimensioned for a copper rrr= 120 and B = 1 Tesla with the following criteria: $IL/S = 0.8\ (IL/S)_{opt}$, survival time greater than 1000 s for a maximum temperature T_{max} = 800 °K, a pressure drop less than 10 mbar. The dimensions and the expected characteristics for the leads are summarized in Table I.

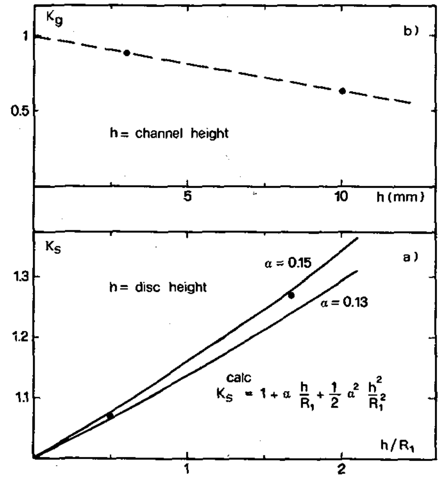

Fig. 7 - Measured values of the parameters k_s and k_g as a function of the disc or channel heigth.

TABLE I

Max. lead current	L (mm)	R_1 (mm)	R_2 (mm)	h (mm)	IL/S (A/m)	$\dot{Q}_o/I$ (mW/A)	ΔV (mV)	t (s)	Δp (mbar)
I = 2200 A	1240	6.05	16.0	3.0	$2.4\ 10^7$	1.1	42	1000	~ 3
I = 2750 A	1240	6.75	16.0	3.0					

Preliminary tests on the leads,made in a low capacity cryostat, showed higher values than the expected ones ($\dot{Q}_o/I$ = 1.5 - 1.6 mW/A, ΔV = 60 mV, $\Delta p \sim$10 mbar). The larger helium consumption rate can be explicated with the frequent helium transfers necessary to maintain the desired level in the cryostat and/or with the non ideal cooling. Most precise measurements on the parameters will be possible only in the high capacity cyclotron cryostat.

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